UCTEA Turkish Chamber of Civil Engineers
TMMOB İnşaat Mühendisleri Odası

Turkish Journal of Civil Engineering

(formerly Teknik Dergi)

Volume 34 Issue 1 January 2023

TURKISH JOURNAL OF CIVIL ENGINEERING (FORMERLY TEKNIK DERGI) PUBLICATION PRINCIPLES

Turkish Journal of Civil Engineering (TJCE), a non-profit, open access scientific and technical periodical of UCTEA Chamber of Civil Engineers, publishes papers reporting original research work and major projects of interest in the area of civil engineering. TJCE annually publishes six issues and is open to papers in English and Turkish. It should be noted that TJCE (formerly, Teknik Dergi/ Technical Journal of Turkish Chamber of Civil Engineers) is being published regularly for more than 30 years since 1990. Main publication principles of TJCE are summarized below:

1. Articles reporting original scientific research and those reflecting interesting engineering applications are accepted for publication. To be classified as original, the work should either produce new scientific knowledge or add a genuinely new dimension to the existing knowledge or develop a totally new method or substantially improve an existing method.
2. Articles reporting preliminary results of scientific studies and those which do not qualify as full articles but provide useful information for the reader can be considered for publication as technical notes.
3. Discussions received from the readers of the published articles within three months from publication are reviewed by the Editorial Board and then published together with the closing remarks of the author.
4. Manuscripts submitted for publication are evaluated by two or three reviewers unknown to the authors. In the light of their reports, final decision to accept or decline is taken by the Editorial Board. General policy of the Board is to get the insufficient manuscripts improved in line with the reviewers' proposals. Articles that fail to reach the desired level are declined. Reasons behind decisions are not declared.
5. A signed statement is taken from the authors, declaring that the article has not been published as a "journal article or book chapter". In case the Editorial Board is in the opinion that the article has already been published elsewhere with minor changes or suspects plagiarism or a similar violation of ethics, then not only that article, but none of the articles of the same authors are published.
6. Papers reporting works presented as conference papers and developed further may be considered for publication. The conference it was presented to is given as a footnote in the first page.
7. Additionally, a document signed by all authors, transferring the copyright to UCTEA Chamber of Civil Engineers is submitted together with the manuscript.

UCTEA Turkish Chamber of Civil Engineers
TMMOB İnşaat Mühendisleri Odası

Turkish Journal of Civil Engineering

(formerly Teknik Dergi)

Volume 34 Issue 1 January 2023

UCTEA Turkish Chamber of Civil Engineers
TMMOB İnşaat Mühendisleri Odası
Necatibey St. No: 57, Kızılay 06440 Ankara, Turkey
Tel: +90.312.294 30 00 - Faks: +90.312.294 30 88
E-mail: imo@imo.org.tr - www.imo.org.tr

Publisher *(Sahibi)*:
Taner YÜZGEÇ
On behalf of UCTEA Turkish Chamber of Civil Engineers

Administrative Officer *(Yazı İşleri Müdürü)*:
Özer AKKUŞ

Volume 34 - Issue 1 - January 2023 *(Cilt 34 - Sayı 1 - Ocak 2023)*

Published bi-monthly. Local periodical. *(İki ayda bir yayınlanır, yerel süreli yayın)*

Date of Print: January 1, 2023 *(Baskı Tarihi: 1 Ocak 2023)*

Number of copies: 800 *(800 adet basılmıştır)*

Quotations require written approval of the Editorial Board.
(Yayın Kurulunun yazılı onayı olmaksızın alıntı yapılamaz.)

ISSN: 2822-6836

Turkish Journal of Civil Engineering (formerly Teknik Dergi) is indexed by

- Science Citation Index Expanded
- Scopus
- Journal Citation Reports / Science Edition
- Engineering Index
- Concrete Abstracts (American Concrete Institute)
- National Technical Information Service (US NTIS)
- CITIS
- Ulrich's International Periodical's Directory
- Google Scholar
- TR Index

Turkish Journal of Civil Engineering (formerly Teknik Dergi) is a peer reviewed open access periodical publishing papers of original research and interesting practice cases. It addresses both the research community and the practicing engineers.

UCTEA Turkish Chamber of Civil Engineers

Turkish Journal of Civil Engineering
(formerly Teknik Dergi)

Editor in Chief:
Alper İLKİ

Co-Editors:
İsmail AYDIN
Özer ÇİNİCİOĞLU
Metin GER
Gürkan Emre GÜRCANLI
Kutay ORAKÇAL
İsmail ŞAHİN
Özkan ŞENGÜL
Tuğrul TANKUT
Emine Beyhan YEĞEN

English Style Oversight Provided by:
İsmail AYDIN
Özer ÇİNİCİOĞLU
Metin GER
Polat GÜLKAN
Gürkan Emre GÜRCANLI
İsmail ŞAHİN
Özkan ŞENGÜL
Mehmet UTKU
Emine Beyhan YEĞEN

Secretary:
Cemal ÇİMEN

Advisory Board:
Prof. M. Aral, USA
Prof. D. Arditi, USA
Prof. A. Aydilek, USA
Prof. K. Beyer, Switzerland
Prof. N. Çatbaş, USA
Prof. M. Çetin, USA
Prof. M. Dewoolkar, USA
Prof. T. Edil, USA
Prof. K. Elwood, New Zealand
Prof. M. Fardis, Greece
Prof. G. Gazetas, Greece
Prof. P. Gülkan, Türkiye
Prof. J. Han, USA
Prof. I. Hansen, Nederlands
Prof. T. Hartmann, Germany
Prof. F. Imamura, Japan
Prof. T. Kang, Korea
Prof. K. Kusunoki, Japan
Prof. S. Lacasse, Norway
Prof. R. Al-Mahaidi, Australia
Prof. K. Özbay, USA
Prof. H. Özer, USA
Prof. G. Özmen, Türkiye
Prof. S. Pampanin, Italy
Prof. A. J. Puppala, USA
Prof. M. Saatçioğlu, Canada
Prof. C. Santamarina, Saudi Arabia
Prof. S. Sheikh, Canada
Prof. E. C. Shin, South Korea
Prof. J. Smallwood, South Africa
Prof. M. Sümer, Türkiye
Dr. H. A. Şentürk, Türkiye
Dr. S. S. Torisu, Japan
Prof. E. Tutumluer, USA
Prof. M. Tümay, USA

Reviewers:

This list is renewed each year and includes reviewers who served in the last two years of publication.

Şükran AÇIKEL
Merve AÇIKGENÇ ULAŞ
Perviz AHMEDZADE
Bülent AKBAŞ
Şeref Doğuşcan AKBAŞ
Rıfat AKBIYIKLI
Özge AKBOĞA KALE
Sarven AKCELYAN
Burcu AKÇAY ALDANMAZ
Cihan Taylan AKDAĞ
Cem AKGÜNER
Çağlar AKKAYA
Fevziye AKÖZ
Erkan AKPINAR
Muhammet Vefa AKPINAR
Atakan AKSOY
Hafzullah AKSOY
Tülay AKSU ÖZKUL
Uğurhan AKYÜZ
Sadık ALASHAN
Cenk ALHAN
Ayşe Burcu ALTAN SAKARYA
Sinan ALTIN
Adlen ALTUNBAŞ
Ahmet Can ALTUNIŞIK
Yalçın ALVER
Bahadır ALYAVUZ
Özgür ANIL
Necati ARAS
Davit ARDİTİ
Yalın ARICI
Deniz ARTAN İLTER
Ali Osman ATAHAN
Hakan Nuri ATAHAN
Ali Osman ATEŞ
Bekir Özer AY
Gökçe AYDIN
Metin AYDOĞDU
Hakan AYGÖREN
Mustafa Tamer AYVAZ
Ülker Güner BACANLI
İhsan Engin BAL
Selim BARADAN
Eray BARAN
Özgür Uğraş BARAN
Türkay BARAN
Bekir Oğuz BARTIN
Mustafa Gökçe BAYDOĞAN
Cüneyt BAYKAL
Niyazi Özgür BEZGİN
Senem BİLİR MAHÇİÇEK
Gökçen BOMBAR
Burak BOYACI
İlknur BOZBEY
Ali BOZER
Zafer BOZKUŞ
Erdem CANBAY
Zekai CELEP
Cihan CENGİZ
Halim CEYLAN
Hüseyin CEYLAN
Ömer CİVALEK
Joao Ramoa CORREIA
Ayşe COŞKUN BEYAN
Ali Fırat ÇABALAR
Barlas Özden ÇAĞLAYAN
Melih ÇALAMAK
Gülben ÇALIŞ
Umut ÇALIŞKAN
Süheyla Pelin ÇALIŞKANELLİ
Mehmet Alper ÇANKAYA
Dilay ÇELEBİ
Tevfik Kutay ÇELEBİOĞLU
Ahmet Ozan ÇELİK
Oğuz Cem ÇELİK
Semet ÇELİK
Hilmi Berk ÇELİKOĞLU
Kemal Önder ÇETİN
Mahmut ÇETİN
Mecit ÇETİN
Erdal ÇOKÇA
Semra ÇOMU
İsmail DABANLI
Ömer DABANLI
Atilla DAMCI
Yakup DARAMA
Osama M.F. DAWOUD
Tayfun DEDE
Abdullah DEMİR
Cem DEMİR
Emre DEMİR
Uğur DEMİR (İTÜ)
Uğur DEMİR (İYTE)
Munise Didem DEMİRBAŞ
Ender DEMİREL
Mehmet Cüneyd DEMİREL
Seyyit Ümit DİKMEN
Ali Ersin DİNÇER
İsmail DURANYILDIZ
Selim DÜNDAR
Nurhan ECEMİŞ ZEREN
Volkan Ş. EDİGER
Özgür EKİNCİOĞLU
Murat Altuğ ERBERİK
Ali ERCAN
Sinan Turhan ERDOĞAN
Şakir ERDOĞDU
Ramazan Cüneyt ERENOĞLU
Esin ERGEN PEHLEVAN
Gökmen ERGÜN
Bülent ERKMEN
Barış ERKUŞ
Yusuf Çağtay ERŞAN
Kağan ERYÜRÜK
Tuğba ESKİŞAR TEFÇİ
Burak FELEKOĞLU
Mahmut FIRAT
Okan FISTIKOĞLU
Onur GEDİK
Abdullah GEDİKLİ
Ahmet Talha GEZGİN
Sadık Can GİRGİN
Zehra Canan GİRGİN
Ilgın GÖKAŞAR
Serdar GÖKTEPE
Rahmi GÜÇLÜ
Ali GÜL
Fazlı Erol GÜLER
Ilgın GÜLER
Hamza GÜLLÜ
Gürkan GÜNAY
Taylan GÜNAY
Murat GÜNAYDIN
Samet GÜNER
Oğuz GÜNEŞ
Mehmet Şükrü GÜNEY
Tuba GÜRBÜZ BÜYÜKKAYIKÇI
Aslı Pelin GÜRGÜN
Soner HALDENBİLEN
Murat HAMDERİ
Ingo A. HANSEN
Umut HASGÜL
Bo-Tao HUANG
Zeynep IŞIK
Sabriye Banu İKİZLER
Erol İSKENDER
Medine İSPİR ARSLAN
Recep İYİSAN
Nihat KABAY
Mehmet Sedat KABDAŞLI
Mehmet Rifat KAHYAOĞLU
Özkan KALE
Volkan KALPAKÇI
Elif Çağda KANDEMİR
Tanay KARADEMİR
Hüseyin Faruk KARADOĞAN
Ümit KARADOĞAN
Mustafa Erkan KARAGÜLER
Halil KARAHAN
Zülküf KAYA
Oğuz KAYABAŞI
Hasan Ahmed KAZMEE
Mustafa Kubilay KELEŞOĞLU
Elçin KENTEL
Hadi KHANBABAZADEH
Havvanur KILIÇ
Ufuk KIRBAŞ
Veysel Şadan Özgür KIRCA
Cem KIRLANGIÇOĞLU
Güven KIYMAZ
Gökhan KİRKİL
Esat Selim KOCAMAN
Kasım KOÇAK
Salih KOÇAK
Niyazi Uğur KOÇKAL
Baha Vural KÖK
Mete KÖKEN
Hasan KURTARAN
Murat KURUOĞLU
Akif KUTLU
Abdullah KÜRKÇÜ
Hilmi LUŞ
Kasım MERMERTAŞ
Mahmoud MIARI
Yetiş Şazi MURAT
Öcal NECMİOĞLU
Fuad OKAY
Umut OKKAN
Derviş Volkan OKUR
Mehmet Hakkı OMURTAG
Sezan ORAK
Engin ORAKDÖĞEN
Akın ÖNALP
Bihrat ÖNÖZ
Ali Hakan ÖREN
Ceyhun ÖZÇELİK
Yiğit ÖZÇELİK
Gökhan ÖZDEMİR
Murat ÖZEN
Pelin ÖZENER
Hasan ÖZER
Hakkı Oral ÖZHAN
Mehmet Fatih ÖZKAL
Zeynep Huri ÖZKUL BİRGÖREN
Ahmet ÖZTOPAL
Sadık ÖZTOPRAK
Turan ÖZTURAN
Mustafa ÖZUYSAL
Tolga Yılmaz ÖZÜDOĞRU
Atilla ÖZÜTOK
Nilüfer ÖZYURT ZİHNİOĞLU
Ahmet Onur PEHLİVAN
Seval PINARBAŞI ÇUHADAROĞLU
Elişan Filiz PİROĞLU
Selman SAĞLAM
Mehmet SALTAN
Metin SARIGÖL
Altuğ SAYGILI
Serdar SELAMET
Osman SİVRİKAYA
Behzad SOLTANBEIGI
Serdar SOYÖZ
Rifat SÖNMEZ
Tayfun Altuğ SÖYLEV
Erol ŞADOĞLU
Olcay ŞAHİN
Yuşa ŞAHİN
Zekai ŞEN
Burak ŞENGÖZ
Karin ŞEŞETYAN
Ali Ünal ŞORMAN
Gülüm TANIRCAN
Serhan TANYEL
Kerem TAŞTAN
Gökmen TAYFUR
Rasim TEMÜR
Serdal TERZİ
Berrak TEYMUR
Hüseyin Onur TEZCAN
Mesut TIĞDEMİR
Salih TİLEYLİOĞLU
Vedat TOĞAN
Onur Behzat TOKDEMİR
İrem Dikmen Toker TOKER
Ali TOPAL
Cem TOPKAYA
Kamile TOSUN FELEKOĞLU
Erkan TÖRE
Ülgen Mert TUĞSAL
Gürsoy TURAN
Ö. Tuğrul TURAN
Cüneyt TÜZÜN
Eren UÇKAN
Latif Onur UĞUR
Ergin ULUTAŞ
Dilay UNCU
Tayfun UYGUNOĞLU
Volkan Emre UZ
İbrahim Mert UZUN
Deniz ÜLGEN
Mehmet Barış Can ÜLKER
Yurdanur ÜNAL
Cüneyt VATANSEVER
Syed Tanvir WASTI
Ahmet YAKUT
Erkut YALÇIN
Mehmet Cem YALÇIN
Aslı YALÇIN DAYIOĞLU
Mustafa Sinan YARDIM
Mert Yücel YARDIMCI
Ufuk YAZGAN
Anıl YAZICI
Gökhan YAZICI
Halit YAZICI
Mehmet YETMEZ
Tahsin Alper YIKICI
İrem Zeynep YILDIRIM
Mehmet YILDIRIMOĞLU
Abdülazim YILDIZ
Mustafa Tolga YILMAZ
Berivan YILMAZER POLAT
İsmail YÜCEL
Yeliz YÜKSELEN AKSOY
Shaban Isamel Albrka Ali ZANGENA
Abdullah Can ZÜLFİKAR

UCTEA Turkish Chamber of Civil Engineers
Turkish Journal of Civil Engineering
(formerly Teknik Dergi)

Volume: 34 Issue: 1 January 2023

CONTENTS

*Turkish Journal of Civil Engineering, 2023 1-23, Paper 715, **Research Article***

Stress Analysis of Laminated HSDT Beams Considering Bending Extension Coupling

Yonca BAB[1]
Akif KUTLU[2]

ABSTRACT

This study demonstrates a mixed finite element formulation procedure for the bending and stress analyses of laminated composite beams. The finite element method is based on the Hellinger-Reissner variational principle, while the beam assumptions are based on the Higher Order Shear Deformation Theory (HSDT). Reddy's shear function is employed for the beam theory where the beam is discretized by two-noded linear elements. The displacements and stress resultants are obtained directly at the nodes according to the proposed mixed formulation. The validation of current study is performed by comparison and convergence analyzes for various lamination cases under different boundary conditions.

Keywords: Higher Order theory, laminated composite beam, Hellinger-Reissner, mixed finite element formulation, stress analysis.

1. INTRODUCTION

Nowadays, composite structures are frequently used in engineering fields such as construction, machinery, biomechanics, nuclear, automotive, aerospace and defense industries [1]. These composite materials, based on the physical properties of the different materials, provide advantages such as heat, sound and water insulation, fire safety, high resistance, corrosion resistance, low cost and low weight in the structures they are integrated. Accurate prediction of bearing capacity, failure load, and damage conditions are critical in the structural design of composite materials to be more efficient as intended. In this context, the need for detailed and accurate static analysis of composite structures is inevitable. Since the financial situation or the physical environment is not always suitable for experimental works, it is much more efficient to employ numerical analyses with possibly most realistic reflection of the mechanical behavior depending on the problem type. Although elasticity based analytical solutions may provide exact behavior of structural elements, the application

---

Note:

- This paper was received on November 28, 2021 and accepted for publication by the Editorial Board on August 29, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

• https://doi.org/10.18400/tjce.1206777

1 Istanbul Technical University, Department of Civil Engineering, Istanbul, Türkiye
bab@itu.edu.tr - https://orcid.org/0000-0002-1807-9306

2 Istanbul Technical University, Department of Civil Engineering, Istanbul, Türkiye
kutluak@itu.edu.tr - https://orcid.org/0000-0001-6865-3022

of such an approach is limited to certain types of boundary conditions, loading case and geometries [2]. In the literature, different theories have been put forward to perform static or dynamic analyses of beam type structures. Classical Theory (CT), First-Order Shear Deformation Theory (FSDT), Higher-Order Shear Deformation Theory (HSDT) and Zigzag Theories (ZZT) [3,4] are among the leading theories. CT, also known as Bernoulli-Euler theory, was proposed by Euler [5] and Bernoulli [6] about 280 years ago and provides good enough predictions of mechanical behavior when the beam is thin. Boley [7] can be given as an example of the early usage of CT, and Modaress-Aval et al. [8] can be given as an example of the resent usage of this theory. FSDT, developed by Timoshenko [9] and also named after him, takes into account rotational inertia and first-order shear effects. Some examples of studies that analyzed composite beams with FSDT can be cited as Wagner and Gruttman [10] and Lee and Jang [11]. On the other hand, HSDT can describe along-thickness transverse deformations so that taking cross-sectional distortion into account by introducing higher-order shear terms in the forms of polynomial-based, trigonometric, and exponential functions etc. Researchers working on beam-plate theories include Reddy [12], Reissner [13], Soldatos [14] who have derived and tested various shear terms in their formulations. Ferreira et al. [15], Murthy et al. [16] and Madenci [17] analyzed composite beams with HSDT. Chandrashekhara and Bangera [18] investigated the free vibration behavior of laminated composite beams by using HSDT, including the effect of Poisson ratio, which is generally neglected in one-dimensional models. Maiti and Sinha [19] have developed a finite element (FE) model based on HSDT, that takes into account the deformations in the thickness direction while examining the bending and free vibration behavior of laminated composite beams. Xiaoping and Liangxin [20] introduced a third-order shear deformation theory that ensures the continuity of in-plane displacements and transverse shear stresses between adjacent layers. Meanwhile, the representation of the displacement variables is similar to the FSDT. While focusing on the bending behavior of cross-layered composite and sandwich beams, Zenkour [21] used the HSDT and included the deformation in the thickness direction into the calculations. Matsunaga [22] studied the natural frequency and buckling behavior of laminated composite beams subjected to axial stress by benefiting from the one-dimensional HSDT and Hamilton's principle. Here, the transverse shear assumption takes into account the full effects of normal stress in the thickness direction as well as rotational inertia. Subramanian [23] carried out a free vibration analysis of laminated composite beams based on finite element method (FEM) with two different HSDTs that take into account the deformation in the beam thickness direction. In these two theories, there are five and four variations of the in-plane and transverse displacements through the thickness coordinates of the beams, respectively, and zero transverse shear stress conditions on the upper and lower surfaces of the beams are satisfied. Zhen and Wanji [24] examined the static and dynamic behavior of sandwich and laminated composite beams using displacement-based HSDT. Ozutok and Madenci [25] combined mixed finite element method (MFEM) and HSDT to perform static analysis of laminated composite beams. Kutlu et al. [26–28] and Aribas et al. [29–31] revealed some advantages of MFEM based formulations on the prediction of accurate stress resultants and stress components of various beam, helix and plate type structures. Shao et al. [32] proposed a new HSDT for the free vibration analysis of laminated composite beams. Based on the kinematic assumptions of this theory, bending and transverse shear strains are independent from each other, such that the beam deflection is defined as the resultant of bending and shear related terms. A generalized approach is presented to satisfy the condition of zero shear stress on the lower and upper free surfaces of the beam. Sayyad and Ghugal [33] compiled studies that performed bending, buckling and free vibration analysis of laminated composite and sandwich beams in their literature review article.

When the literature is examined, it can be seen that CT, which ignores the shear effects, and FSDT, which needs a shear correction coefficient, are insufficient in solving relatively thick elements used in composite construction. For this reason, in this study, HSDT is used in the mechanical model of laminated composite beams and the shear function proposed by Reddy is employed. By introducing an efficient mixed finite element formulation, it is aimed to provide accurate determination of stress components alongside displacement terms. In this regard, this study extends the idea presented in Bab and Kutlu [34] by adding axial displacement into kinematic field. Thus, bending-extension coupling effect can be considered in the analyses. The Hellinger-Reissner principle was used to describe the energy expression of the laminated composite beam in linear elastic regime. In the displacement field, one axial displacement, one deflection and one rotation term are assigned. The corresponding finite element functional is of a mixed form and involves stress resultant terms besides displacement components. In generating the system finite element equations, two-noded elements are described with linear shape functions, and integrals of energy expressions are calculated numerically over a two-point Gauss quadrature scheme. By solving the finite element equations, the bending moment, higher order bending moment and the shear force, alongside the axial displacement, deflection and rotation components, are obtained directly at the nodal points. This way, strain measures can be calculated using sectional compliance matrices without using derivatives, thus the accuracy of the axial stress calculation compared to displacement-based finite elements is improved satisfactorily. Transverse shear stresses are obtained along the thickness of the laminated beam by placing the calculated axial stresses in the equilibrium equations presented by the theory of elasticity. By increasing the number of elements in the beam domain some convergence analyses were carried out with repeated solutions, and comparison analyzes were carried out considering the elasticity solutions in the literature and various numerical procedures. Afterwards, solutions are presented in which various layout, loading, and boundary conditions are taken into account to demonstrate the effectiveness of the proposed finite element formulation in the displacement and stress calculation of laminated composite beams. Also, the influence of the bending-extension coupling in nonsymmetrically laminated beams with axially constrained end conditions is examined.

2. FIELD EQUATIONS AND NUMERICAL FORMULATION

Consider the beam in Figure 1a, loaded in its x, z plane, where x describes the beam axis and the cross-section lies within the y, z plane. The kinematic field of the beam under the distributed load acting in the z -direction along the beam axis can be described according to the HSDT as follows:

$$
\begin{aligned}
u^* &= u - z\,w,_x + f(z)\theta_x \\
w^* &= w
\end{aligned}
\tag{1}
$$

Here, $u^*(x,z)$ and $w^*(x,z)$ denote axial and transverse displacement field of the beam, respectively, whereas $u(x)$ is the axial displacement and $w(x)$ is the deflection of the beam at its centroid. Also, $\theta_x(x)$ describes the rotation of the section about the y-axis. In addition, $f(z)$ is the shear function defined to reflect the distortion of the section. In the current study, Reddy's [35] shear function is employed:

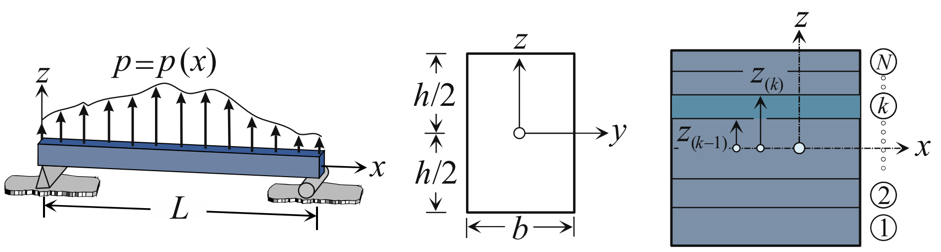
$$f(z) = z\left(1 - \frac{4z^2}{3h^2}\right) \tag{2}$$

In this expression, h denotes the height of the beam (See Figure 1b). The strain components along the beam section are written over the displacement field described in equation (1) as follows:

$$\begin{aligned} \varepsilon_{xx} &= u,_x^* = u,_x - z\,w,_{xx} + f\theta_{x,x} \\ \gamma_{xz} &= u,_z^* + w,_x^* = f'\theta_x \end{aligned} \tag{3}$$

The commas in the subscript indicates that the derivatives are taken according to the axis variables that follow it. In Equation (3), the strain measures can be denoted as follows:

$$\begin{Bmatrix} \varepsilon_m \\ \kappa_0 \\ \kappa_1 \\ \varepsilon_s \end{Bmatrix} = \begin{Bmatrix} u,_x \\ -w,_{xx} \\ \theta_{x,x} \\ \theta_x \end{Bmatrix} \tag{4}$$



(a) (b) (c)

Figure 1 - Laminated composite beam a) Beam axis b) Beam cross-section and dimensions c) Lamination

The stress-strain relationships in any k'th layer of the composite beam shown in Figure 1c can be written by using Hooke's law in the form:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{xz} \end{Bmatrix}^{(k)} = \begin{bmatrix} \bar{Q}_{11} & 0 \\ 0 & \bar{Q}_{55} \end{bmatrix}^{(k)} \begin{Bmatrix} \varepsilon_{xx} \\ \gamma_{xz} \end{Bmatrix}^{(k)} \tag{5}$$

Here, $\bar{Q}_{11}$ and $\bar{Q}_{55}$ correspond to the transformed material stiffness terms of the orthotropic material in the k 'th layer to the global axis of the beam [36]. $\sigma_{xx}^{(k)}$ and $\sigma_{xz}^{(k)}$ are axial normal stress and transverse shear stress components in the layer. The first variation of the functional of an elastic system can be stated according to the Hellinger-Reissner principle as follows [37,38].

$$\delta\Pi_{HR} = \int_V \left(\boldsymbol{\varepsilon}^{\mathbf{u}} - \boldsymbol{\varepsilon}^{\boldsymbol{\sigma}}\right)^T \delta\boldsymbol{\sigma}^{\boldsymbol{\sigma}} \mathrm{d}V + \int_V \left(\left(\boldsymbol{\sigma}^{\boldsymbol{\sigma}}\right)^T \delta\boldsymbol{\varepsilon}^{\mathbf{u}} - \mathbf{q}^T \delta\mathbf{u}\right) \mathrm{d}V - \int_\Gamma \hat{\mathbf{t}}^T \delta\mathbf{u} \mathrm{d}\Gamma = 0 \tag{6}$$

In this equation, the first integral corresponds to the weak form of the compatibility conditions of the strain $(\boldsymbol{\varepsilon})$ field, while the second integral corresponds to the weak form of the equilibrium equations in the volume (V) domain under the influence of external load $\mathbf{q}$. In the first integral, the compatibility between the description of the strain field $(\boldsymbol{\varepsilon}^{\mathbf{u}})$ over the kinematic relations and the description $(\boldsymbol{\varepsilon}^{\boldsymbol{\sigma}})$ over the stresses is determined. The last integral shows the work done by the stresses $\hat{\mathbf{t}}^T$ at the boundary of the region Γ . Here δ is the variation operator. When the equation (6) given for the general three-dimensional case is to be reduced to the beam problem, the integrals of the stress components along the thickness are calculated and instead of stress and strain components, stress resultants and strain measures are placed:

$$\delta\Pi_{HR} = \int_L \left(\mathbf{e}^{\mathbf{u}} - \mathbf{e}^{\mathbf{P}}\right)^T \delta\,\mathbf{P}\,\mathrm{d}L + \int_L \left(\mathbf{P}^T \delta\,\mathbf{e}^{\mathbf{u}} - \mathbf{p}^T \delta\,\mathbf{u}\right) \mathrm{d}L - \int_\Gamma \hat{\mathbf{t}}^T \delta\mathbf{u} \mathrm{d}\Gamma = 0 \tag{7}$$

Here, $\mathbf{e}^{\mathbf{u}} = [\varepsilon_m \quad \kappa_0 \quad \kappa_1 \quad \varepsilon_s]^T$ is strain measures vector expressed over kinematic relations while $\mathbf{e}^{\mathbf{P}}$ collects strain measures in terms of stress resultants. $\mathbf{P}^T = [N_{xx} \quad M_{xx} \quad M_{xx}^f \quad Q_{xz}]$ is stress resultants vector and $\mathbf{p}$ denotes transversely applied load acting along the beam. The expression of axial force N_{xx}, bending moment M_{xx}, higher order bending moment M_{xx}^f and shear force Q_{xz} in terms of stress components is as follows:

$$\left(N_{xx}, M_{xx}, M_{xx}^f, Q_{xz}\right) = b\sum_{k=1}^{N} \int_{z_{(k-1)}}^{z_{(k)}} \left(\sigma_{xx}^{(k)}, z\sigma_{xx}^{(k)}, f(z)\sigma_{xx}^{(k)}, (\mathrm{d}f(z)/\mathrm{d}z)\sigma_{xz}^{(k)}\right) \mathrm{d}z \tag{8}$$

Here, b is the beam width (see Figure 1b) and N is the total number of layers in the section. When the constitutive relations given in Equation (5) are placed in Equation (8), the relationship between strain measures $\mathbf{e}^{\mathbf{u}}$ and stress resultants $\mathbf{P}$ is found as follows:

$$\mathbf{P} = \mathbf{E}\mathbf{e}^{\mathbf{u}} \quad \text{or} \quad \begin{Bmatrix} N_{xx} \\ M_{xx} \\ M_{xx}^{f} \\ Q_{xz} \end{Bmatrix} = \begin{bmatrix} A_{11} & B_{11} & E_{11} & 0 \\ B_{11} & D_{11} & F_{11} & 0 \\ E_{11} & F_{11} & H_{11} & 0 \\ 0 & 0 & 0 & A^{s} \end{bmatrix} \begin{Bmatrix} \varepsilon_{m} \\ \kappa_{0} \\ \kappa_{1} \\ \varepsilon_{s} \end{Bmatrix} \tag{9}$$

Here, the terms of the sectional stiffness matrix $\mathbf{E}$ are calculated as follows:

$$\begin{gathered} \left(A_{11} \quad B_{11} \quad D_{11} \right) = b \sum_{k=1}^{N} \int_{z_{(k-1)}}^{z_{(k)}} \bar{Q}_{11}^{(k)} \left(1 \quad z \quad z^{2} \right) \mathrm{d}z \\ \left(E_{11} \quad F_{11} \quad H_{11} \right) = b \sum_{k=1}^{N} \int_{z_{(k-1)}}^{z_{(k)}} \bar{Q}_{11}^{(k)} \left(f(z) \quad zf(z) \quad f(z)^{2} \right) \mathrm{d}z \end{gathered} \tag{10}$$

$$A^{s} = b \sum_{k=1}^{N} \int_{z_{(k-1)}}^{z_{(k)}} \bar{Q}_{55}^{(k)} \left(f'(z) \right)^{2} \mathrm{d}z \tag{11}$$

If equation (9) is arranged for use in equation (7) by describing the compliance matrix $\mathbf{S} = \mathbf{E}^{-1}$, the new form is obtained as:

$$\mathbf{e}^{\mathbf{P}} = \mathbf{S}\mathbf{P} \quad \text{or} \quad \begin{Bmatrix} \varepsilon_{m} \\ \kappa_{0} \\ \kappa_{1} \\ \varepsilon_{s} \end{Bmatrix} = \begin{bmatrix} A'_{11} & B'_{11} & E'_{11} & 0 \\ B'_{11} & D'_{11} & F'_{11} & 0 \\ E'_{11} & F'_{11} & H'_{11} & 0 \\ 0 & 0 & 0 & A'^{s} \end{bmatrix} \begin{Bmatrix} N_{xx} \\ M_{xx} \\ M_{xx}^{f} \\ Q_{xz} \end{Bmatrix} \tag{12}$$

Equilibrium equations of the laminated composite beam, in which higher order shear effects are taken into account, are given as follows:

$$\left. \begin{aligned} & N_{xx,x} = 0 \\ & p + M_{xx,xx} = 0 \\ & M_{xx,x}^{f} - Q_{xz} = 0 \end{aligned} \right\} \tag{13}$$

Finally, using equations (13), (12) and (4) in equation (7), the first variation of the functional of the laminated composite beam becomes:

$$\begin{aligned}\delta\Pi_{HR} &= \int_L \left[w_{,x}\delta M_{xx,x} - \left(\bar{D}_{11}M_{xx} + \bar{F}_{11}M_{xx}^f\right)\delta M_{xx} \right]\mathrm{d}L \\ &+ \int_L \left[\theta_{x,x} - \left(\bar{F}_{11}M_{xx} + \bar{H}_{11}M_{xx}^f\right)\right]\delta M_{xx}^f \mathrm{d}L + \int_L \left[\theta_x - \left(\bar{A}^s Q_{xz}\right)\right]\delta Q_{xz}\mathrm{d}L \\ &- \int_L \delta wp\mathrm{d}L + \int_L \left(M_{xx,x}\,\delta w_{,x} + M_{xx}^f \delta\theta_{x,x} + V_{xz}\delta\theta_x\right)\mathrm{d}L - \int_\Gamma \hat{\mathbf{t}}^T\delta\mathbf{u}\mathrm{d}\Gamma = 0\end{aligned} \tag{14}$$

In Equation (14), L represents the beam length and Γ represents the beam boundary. This equation contains both displacement and force-force couple type field variables. In the expression of the first variation of the functional given by Equation (14), the second order derivatives on the terms are reduced to the first order using partial integration, as an advantage of the mixed finite element formulation. In this way, it is ensured that the shape functions to be used in the finite element discretization to be created have C_0 continuity. The generated two-node linear shape functions (Figure 2a) for any coordinate ξ in the interval $-1 \le \xi \le 1$ (Figure 2b) can be expressed as:

$$\varphi_i(\xi) = \tfrac{1}{2}\left(1 + \xi\xi_i\right), \quad i = 1,2 \tag{15}$$

When equation (14) is discretized with the introduced two-noded linear elements, the finite element equations are obtained in the following form:

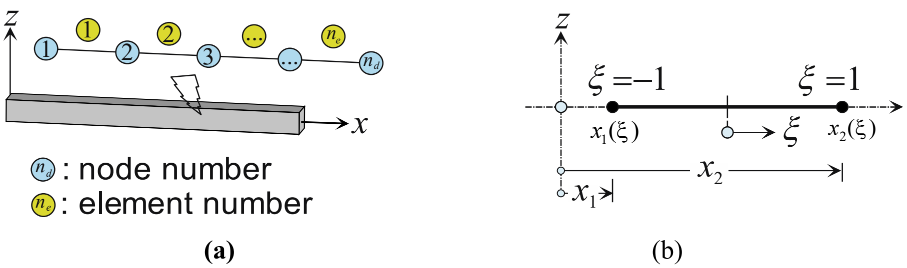


Figure 2 - Finite element definition a) Linear two-noded element discretization in beam domain, b) Global and local coordinate systems in a general element

$$\mathbf{KX} = \mathbf{F} \tag{16}$$

In Equation (16), $\mathbf{K}$ corresponds to the system matrix, $\mathbf{F}$ corresponds to the external force vector, and $\mathbf{X}$, whose expansion is given for any node (i) in Equation (17), corresponds to the unknowns vector.

$$\mathbf{X}^i = \left[u^i \quad w^i \quad \theta_x^i \quad N_{xx}^i \quad M_{xx}^i \quad M_{xx}^{fi} \quad Q_{xz}^i\right]^T \tag{17}$$

By solving Equation (16), both the displacement type and the stress resultant type field variables for the laminated composite beam are obtained directly at the nodal points. In this way, strain measures can be calculated directly by matrix operations using Equation (12) without requiring any numerical derivative operations. Then, by using kinematic and constitutive relations, the distribution of stress components along the cross-section can be obtained again at the nodal points. However, due to the assumptions of higher order shear deformation theory the calculation of transverse shear stresses with the help of constitutive relations can produce unrealistic results. If the equilibrium equations of the theory of elasticity are used to overcome this problem, the transverse shear stress component can be determined at any thickness coordinate as follows:

$$\sigma_{xz} = -\int_{-h}^{z} (\partial \sigma_{xx} / \partial x) \mathrm{d}\bar{z} \tag{18}$$

3. NUMERICAL RESULTS

A number of numerical examples have been studied in order to show the performance and efficiency of the proposed mixed finite element formulation in stress and displacement calculation under static loading for laminated composite beams and the results are interpreted. The solutions are obtained through a Fortran-based program developed by the authors. Firstly, the convergence behavior of the numerical solution method was examined and by making comparisons with 3D elasticity solution of Pagano [39] which is accepted as a reference solution in the literature; the accuracy of the formulation and the developed program has been tested. Afterwards, solutions were presented for various lamination, loading and support conditions, and the effectiveness of the formulation was investigated by comparing its results with studies such as Hasim (isogeometric zigzag formulation) [40], Vidal and Polit [41] (sinusoidal zigzag), Khdeir and Reddy [42] (analytical solution of higher order theory), Kapuria et al. [43] (zigzag) and Zenkour [21] (simple higher order theory). In the presented problems, common engineering material constants are defined as follows:

Material 1: $E_1 / E_2 = 25, G_{12} = G_{13} = 0.5E_2, G_{23} = 0.2E_2, \nu_{12} = \nu_{23} = 0.25$

Material 2: $\left(E_1 = 181\text{ , } E_2 = 10.3\text{ , } G_{12} = G_{13} = 7.17\text{ , } G_{23} = 2.87\right)$[GPa]

$\nu_{12} = 0.25, \nu_{23} = 0.33$

Here, E_1 and E_2 are Young's moduli of orthotropic material in material principal directions. G_{ij}, $((i,j) = 1,2,3)$ stands for the shear moduli and υ_{ij}, $((i,j) = 1,2,3)$ represents Poisson's ratio. Material 2 is employed for the comparison study of Kapuria et al. [43] (see Table 3). The rest of the examples and comparison studies are performed according to the Material 1 properties.

3.1. Symmetric - Antisymmetric Laminated Beam under Sinusoidal Load

The solution of the one end simple supported and the other end is sliding symmetric and antisymmetric laminated beam using the proposed mixed finite element formulation has been compared with the literature. The beam is under the effect of a distributed transverse sinusoidal load $p(x) = p_0 \sin(\pi x/L)$ along its axis. The cross section layouts [0/90] and [0/90/0] are described with material lamination angles and each layer of equal thickness is considered to be formed with Material 1. The antisymmetrically laminated beam is also compared with simply supported but not sliding (fixed axial displacement) boundary conditions. $\rho = L/h = 4, 20, 40$ values were taken as the beam span to thickness ratio, and solutions were obtained by using the number of elements $n_e = 10, 20, 30, 40$ along the beam to observe the convergence behavior of the results of deflection and stress components. In order to evaluate the results presented in Table 1 in general way, the following non-dimensionalization procedures have been carried out:

$$\bar{w} = \frac{10^2 E_2 h^3 b w(L/2,0)}{p_0 L^4} \quad , \quad \bar{\sigma}_{xx} = \tfrac{b}{p_0}\sigma_{xx}(L/2,-h/2)$$
$$(\bar{\sigma}^a_{xz}, \bar{\sigma}^b_{xz}) = \tfrac{b}{p_0}\left(\sigma_{xz}(0,0)\ ,\ \sigma_{xz}(0,-h/4)\right) \tag{19}$$

Table 1 - Symmetric and antisymmetric simply supported laminated composite beam (one end is sliding) under sinusoidal loading

		$\rho = 4$			$\rho = 20$			$\rho = 40$		
Layups	Theory	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$
[0/90/0][a]	MHBT ($n_e = 10$)	2.656	-16.850	1.521	0.593	-257.232	8.586	0.525	-1007.5	17.237
	MHBT ($n_e = 20$)	2.689	-16.955	1.549	0.600	-258.822	8.747	0.532	-1013.7	17.560
	MHBT ($n_e = 30$)	2.695	-16.974	1.554	0.601	-259.119	8.777	0.533	-1014.8	17.620
	MHBT ($n_e = 40$)	2.697	-16.981	1.556	0.602	-259.222	8.788	0.533	-1015.3	17.641
	Hasim	2.804	-15.9	1.44	0.6134	-258.9	8.681	0.5362	-1015.3	17.563
	Vidal and Polit	2.803	-19.5	1.42	0.6151	-265.4	8.699	0.5371	-1024.4	17.540
	Pagano (Exact)	2.8899	-18.8	1.432	0.618	-263.2	8.748	0.5379	-1019.7	17.761
[0/90][b]	MHBT ($n_e = 10$)	4.3779	-33.3	2.908	2.6556	-697.7	14.327	2.6007	-2773.5	28.641
	MHBT ($n_e = 20$)	4.4324	-33.5	2.962	2.6885	-702.0	14.595	2.6329	-2790.6	29.177
	MHBT ($n_e = 30$)	4.4425	-33.6	2.973	2.6946	-702.8	14.646	2.6389	-2793.8	29.277
	MHBT ($n_e = 40$)	4.4461	-33.6	2.976	2.6968	-703.1	14.663	2.6410	-2795.0	29.313
	Hasim	4.5175	-26.8	2.871	2.6996	-692.5	14.644	2.6419	-2788.1	29.372
	Vidal and Polit	4.5438	-31.8	2.843	2.7036	-703.6	14.574	2.6450	-2803.1	29.174
	Pagano (Exact)	4.7076	-30	2.706	2.7092	-699.7	14.62	2.6462	-2793.0	29.325

In the Table 1, MHBT (Mixed Higher Order Beam Theory) represents the present theory of this study. As it can be followed from Table 1, the proposed numerical solution method exhibits a stable convergence behavior. A case of converging values for both displacement and stress components from below (growing with increasing number of elements) is observed. In the case of very thick beams, it can be seen that the displacement results are noticeably different from the elasticity results, which is a natural consequence of the higher order shear deformation theory. Nevertheless, it has been observed that the stress values obtained in this study for the symmetrical laminated case fit the elasticity solution with a much better approximation (except $\bar{\sigma}_{xz}$ value for $\rho = 4$) compared to the rather advanced lamination theories and solution methods. This case is valid for all thicknesses of the laminated beam. Although the antisymmetric lamination is a challenging situation, the presented numerical solution procedure can produce very realistic results. To give an example for the convergence values, regarding the comparison made with the elasticity solution for $\rho = 40$ in the Table 1 and the finest element mesh (40 elements), it has been observed that the normal stress of the symmetrical structure has a difference of 0.43%, while the antisymmetric structure has a difference of 0.07%.

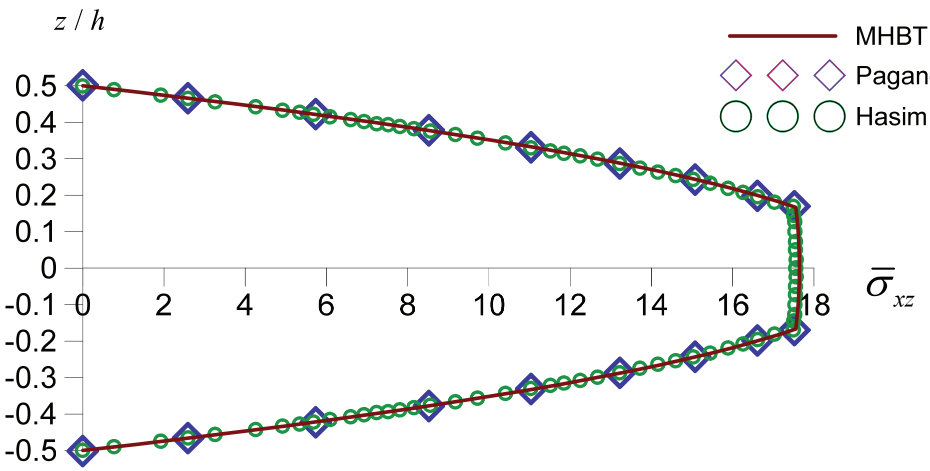


Figure 3 - Transverse shear stress distribution in a sinusoidal loaded, simply supported laminated composite beam (Material 1)

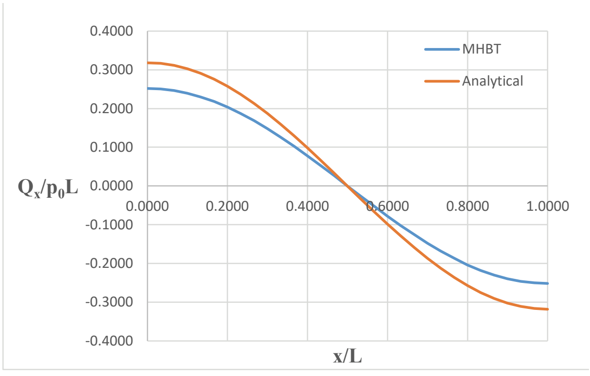


Figure 4 - Shear force distribution in a sinusoidally loaded, simply supported laminated composite beam (Material 1)

Figure 3 shows the shear stress distribution in the thickness direction of the sinusoidally loaded laminated composite beam with [0/90/0] layout scheme. Solution was made for $\rho = 40$ ratio employing 40 elements. The results of MHBT are also compared with the solutions offered by Pagano [39] ve Hasim [40]. As can be seen in the figure, it was observed that the transverse shear stress values obtained from all three solutions overlapped one another.

In Figure 4, the comparison between the shear force calculated by the proposed numerical method and the shear force obtained by using the classical equilibrium equations of the composite beam with sinusoidal load and simple support is given. Due to the assumptions of the higher order beam theory, shear force establishes an equilibrium state with higher order moments. Therefore, the shear force obtained directly from the finite element solution as the field variable is not equal to the resultant of the (real) transverse shear stress that is distributed in the cross section. If it is desired to calculate more realistic shear force values within the framework of a higher order shear theory, integrals of shear stresses along the cross-section obtained by using the equilibrium equations of the elasticity theory can be evaluated.

In Figure 5, the moment distribution of the analytical solution for the symmetrically laminated composite beam under sinusoidal loading is compared with the distribution obtained by the mixed finite element method and it has been observed that the proposed finite element method perfectly reflects the equilibrium equations.

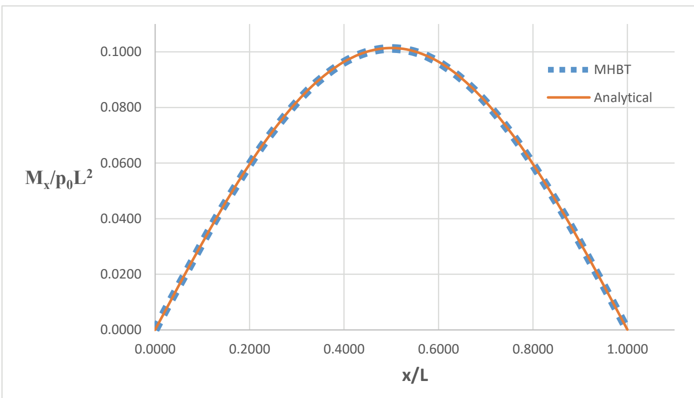


Figure 5 - Bending moment distribution in a sinusoidally loaded, simply supported laminated composite beam with $\rho = 20$ ratio (Material 1)

In Figure 6, deflection (nondimensionalized according to Equation (19)) variations along the beam length for simply-simply supported and simply-sliding supported conditions under sinusoidal loading are presented. For the simply-sliding case, the maximum deflection value is 1.93 times larger than the simply-simply case. The reason of this difference is that for simply-simply supported case, the extension bending coupling effect takes place so the deflections of the beam reduce when compared to sliding case.

In Figure 7, moment distribution along the beam length for simply-simply supported and simply-sliding supported conditions can be observed. As can be seen from the figure, moment distribution overlaps in both boundary conditions.

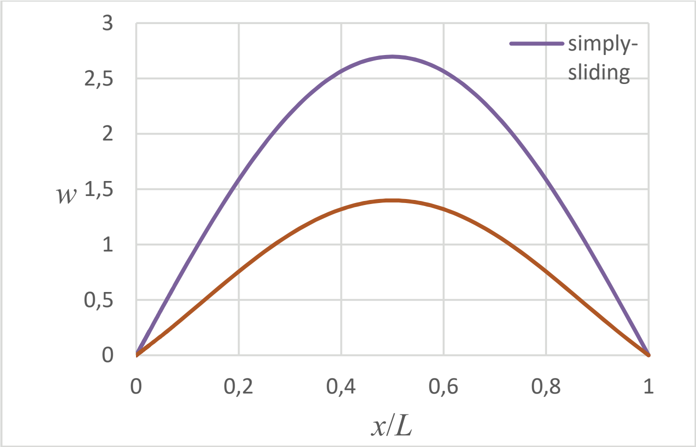


Figure 6 - Deflection (dimensionless) along the beam axis for antisymmetric [0/90] laminated composite beam with $\rho = 20$ *ratio*

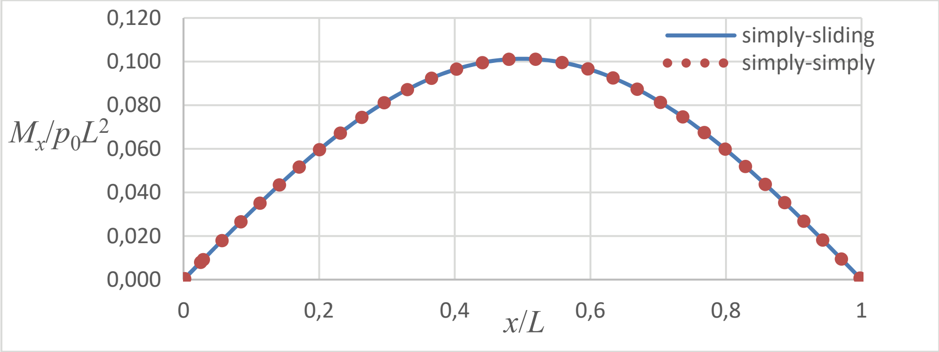


Figure 7 - Moment distribution along the beam axis for antisymmetric [0/90] laminated composite beam with $\rho = 20$ *ratio under sinusoidal loading*

3.2. Various Laminated Beams under Uniform Load

Uniformly $p(x) = p_0$ loaded beams with [0/90], [0/90/0] and [0/90/90/0] lamination layouts are discussed in this section. While the simple support condition is considered for all lamination layouts, only the layout of [0/90/0] is taken into account in the clamped support condition. In Table 2, the mid-span deflection values of the clamped beam made of Material 1 are presented for various thickness to span ratios and number of elements. The predictions of MHBT are also compared with the analytical solution provided by Khdeir and Reddy [42] for the higher-order beam theory. When Table 2 is examined, it can be stated that the proposed solution method shows a consistent convergence behavior also under the clamped boundary condition. It can be said that mixed finite element results are in good agreement with the analytical results for all thickness ratios. Another important result that can be extracted from the Table 2 is that with the increase of the beam span-thickness ratio, the deflection values demonstrate a faster convergence regarding the mesh refinement.

Table 2 - Symmetric laminated composite beam under uniform loading

		$\bar{w}$		
Layup	Theory	$\rho = 5$	$\rho = 10$	$\rho = 50$
[0/90/0]	MHBT $(n_e = 10)$	1.5081	0.5130	0.1456
	MHBT $(n_e = 20)$	1.5351	0.5286	0.1466
	MHBT $(n_e = 30)$	1.5371	0.5310	0.1469
	MHBT $(n_e = 40)$	1.5376	0.5316	0.1471
	Khdeir and Reddy	1.537	0.532	0.147

In Table 3, the comparison of the displacement and stress components of a uniformly loaded composite simply supported beam having a symmetrical [0/90/90/0] layout with the elasticity solution and a third order theory solution is made. Nondimensional parameters in this table are calculated according to the following expressions,

$$\begin{aligned} &\bar{w} = \frac{10^2 E_2 h^3 b}{p_0 L^4} w(L/2,0) \quad , \quad \bar{\sigma}_{xx} = \frac{h^2 b}{p_0 L^2} \sigma_{xx}(L/2,h/2) \quad , \\ &\bar{\sigma}^*_{xx} = \frac{h^2 b}{p_0 L^2} \sigma_{xx}(L/2,-h/2) \quad , \quad \bar{\sigma}_{xz} = \frac{hb}{p_0 L} \sigma_{xz}(0,0) \end{aligned} \tag{20}$$

calculated percentage (%) differences compared to the elasticity solution are presented in Table 3. As seen in this table, the finite element formulation for the lamination and loading state exhibits consistent convergence. It is observed that as the beam span-to thickness ratio increases, the results obtained with the proposed method agree better with the elasticity solution. The convergence of the transverse shear stress values is slower compared to deflection and axial stress components, except for the thick beam ($\rho = 5$) example. However, for the ratios $\rho = 5$, $\rho = 10$, and $\rho = 20$, it is observed that the results obtained from this study show a closer agreement with the elasticity solution compared to the results obtained from the finite element solution based on the third order theory.

In Table 4, the displacement and stress components of a uniformly loaded simply supported beam with symmetric [0/90/0] and antisymmetric [0/90] layouts are given in nondimensional forms according to Equation (21). In this example, a comparison has been made with the analytical solution that Zenkour [21] obtained according to the simple higher order theory. In addition, only the deflection values are compared with Khdeir and Reddy's analytical results. In this problem, it should be noted that the transverse shear stress (σ_{xz}) values presented in Table 4 are calculated over the constitutive relations, instead of equilibrium equations. The handling of the relevant problem by Zenkour [21] in this way has led to this necessity. As seen in Table 4, the proposed mixed finite element solution exhibits a stable convergence behavior. A high level of agreement has been achieved between the analytical results with the mixed finite element solutions for all presented beam span-to-thickness ratios. As can be clearly followed from Table 4, it has been determined that the axial normal stress (σ_{xx}) values converge faster than the other parameters. It can be seen that the results obtained even with the very loose element mesh ($n_e = 10$) coincide well enough with the analytical result.

Table 3 - Comparison of the analysis results of symmetrical laminated, simply supported and uniformly loaded composites with the elasticity solution (percent difference) (Material 2)

	$\rho=5$				$\rho=10$			
Theory	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xx}^*$	$\bar{\sigma}_{xz}$	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xx}^*$	$\bar{\sigma}_{xz}$
MHBT ($n_e = 10$)	5.25	5.84	4.87	3.55	3.31	1.78	1.48	5.64
MHBT ($n_e = 20$)	4.72	5.72	4.75	1.62	2.75	1.74	1.44	1.65
MHBT ($n_e = 30$)	4.63	5.73	4.76	1.83	2.65	1.74	1.44	0.90
MHBT ($n_e = 40$)	4.60	5.73	4.76	2.17	2.61	1.74	1.44	0.76
Kapuria et al.	4.6	5.7	4.8	4.3	2.6	1.7	1.4	1.8
Pagano	2.6748	1.0711	-1.0602	1.432	1.4343	0.9059	-0.9031	8.748
Theory	$\rho=20$				$\rho=100$			
MHBT ($n_e = 10$)	1.65	0.47	0.39	7.51	0.84	0.02	0.02	9.39
MHBT ($n_e = 20$)	1.06	0.46	0.38	2.73	0.24	0.02	0.02	4.37
MHBT ($n_e = 30$)	0.95	0.46	0.38	1.35	0.13	0.02	0.02	2.71
MHBT ($n_e = 40$)	0.91	0.46	0.38	0.80	0.09	0.02	0.02	1.89
Kapuria et al.	0.9	0.5	0.4	0.7	0.0	0.0	0.0	0.0
Pagano	1.1152	0.8641	-0.8635	2.706	1.0123	0.8508	-0.8508	14.62

$$\bar{w} = \frac{10^2 E_2 b h^3}{p_0 L^4} w(L/2,0) \;,\; \bar{\sigma}_{xx} = \frac{bh^2}{p_0 L^2} \sigma_{xx}(L/2,h/2) \;,\; \bar{\sigma}_{xz} = \frac{bh}{p_0 L} \sigma_{xz}(0,0) \tag{21}$$

Table 4 - Mechanical components of uniformly loaded composite beams with simply supported symmetric and antisymmetric layouts (Material 1)

		$\rho=5$			$\rho=10$			$\rho=50$		
Layups	Theory	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$	$\bar{w}$	$\bar{\sigma}_{xx}$	$\bar{\sigma}_{xz}$
[0/90/0]	MHBT $(n_e=10)$	2.3968	-1.0654	0.5330	1.0897	-0.8494	0.5982	0.661	-0.7805	0.6241
	MHBT $(n_e=20)$	2.4098	-1.0670	0.5275	1.0959	-0.8500	0.6138	0.665	-0.7805	0.6577
	MHBT $(n_e=30)$	2.4122	-1.0669	0.5201	1.0970	-0.8500	0.6133	0.666	-0.7805	0.6682
	MHBT $(n_e=40)$	2.4130	-1.0669	0.5150	1.0974	-0.8500	0.6111	0.666	-0.7805	0.6729
	Zenkour	2.4141	-1.0669	0.4057	1.0980	-0.8500	0.4311	0.661	-0.7805	0.4514
	Khdeir and Reddy	2.412			1.096			0.665		
[0/90]	MHBT $(n_e=10)$	4.7487	0.2361	0.2450	3.6675	0.2342	0.2680	3.3179	0.2336	0.2763
	MHBT $(n_e=20)$	4.7761	0.2361	0.2412	3.6894	0.2342	0.2762	3.3379	0.2336	0.2913
	MHBT $(n_e=30)$	4.7811	0.2361	0.2355	3.6934	0.2342	0.2758	3.3417	0.2336	0.2961
	MHBT $(n_e=40)$	4.7829	0.2361	0.2314	3.6948	0.2342	0.2743	3.3430	0.2336	0.2983
	Zenkour	4.7879	0.2362	0.9211	3.6973	0.2343	0.9572	3.3447	0.2336	0.9860
	Khdeir and Reddy	4.777			3.688			3.336		

In Figure 8 (for [0/90/0] layout), the distribution of the transverse shear stress along the cross section of the laminated beam is presented both by calculating in accordance with Hooke's law and by calculating with the equilibrium equations of elasticity. As can be seen from the figure, the transverse shear stress distribution calculated by Hooke's law produces unrealistic results. The reason is that the transverse strain distribution according to the displacement field assumed by the HSDT is continuous throughout the cross section. Therefore, the same

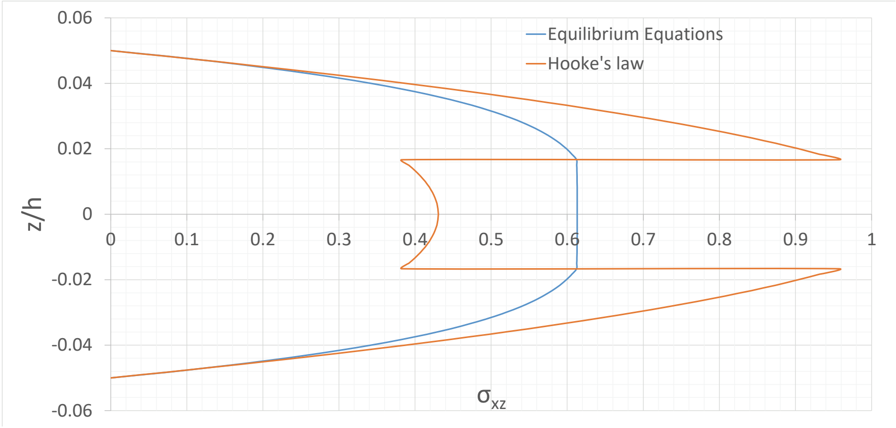


Figure 8 - Uniformly loaded, symmetrical simply supported laminated composite beam with $\rho=20$ ratio and 30 elements (Material 1)

strain and the presence of different material constants in the layer interface cause the transverse shear stress distribution to show discontinuity at these points and need to be calculated incorrectly. In Figure 8, the large difference between the transverse shear stresses calculated using Hooke's law and the equilibrium equation method, which provides a more realistic prediction, can be observed.

Using the advantage of the mixed finite element formulation, stress resultants such as shear force and bending moment are obtained directly (Figure 9, 10 and 11). Figure 9 shows the shear force distribution in a uniformly loaded and simply supported laminated composite beam discretized with 30 elements for $\rho = 5, 10, 50$ ratios. This distribution overlaps on a large part of the beam for different thickness ratios, and shows slight differences near the supports, where the shear force takes its extremum values.

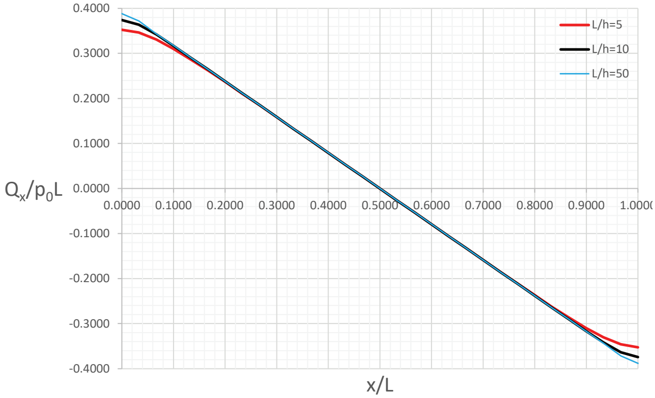


Figure 9 - Shear force distribution of uniformly loaded, symmetrical simply supported laminated composite beam with $\rho = 20$ ratio and 30 elements (Material 1)

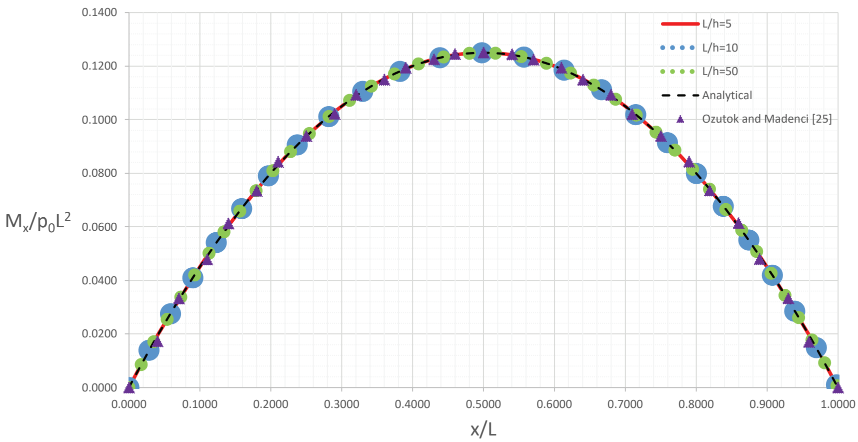


Figure 10 - Moment distribution of uniformly loaded, symmetrical simply supported laminated composite beam (Material 1)

Under the same beam configuration, moment distribution is given for different thickness ratios, and comparison with Ozutok and Madenci [25] can be seen in Figure 10. In this distribution, dimensionless moment values predicted by the MHBT and analytical calculation for all thickness ratios overlap along the beam axis. Therefore, it can be stated that the effect of the transverse shear stresses is not observed in the moment values.

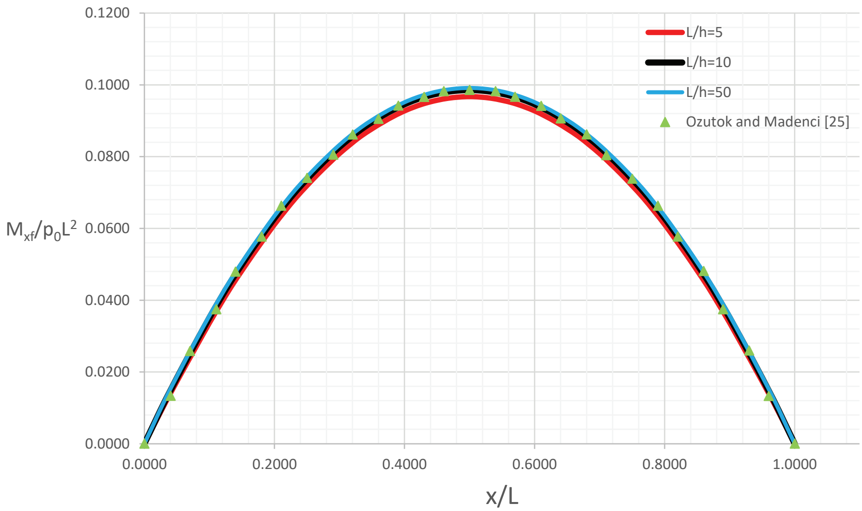


Figure 11 - Higher order Moment distribution of uniformly loaded, symmetrical simply supported laminated composite beam (Material 1)

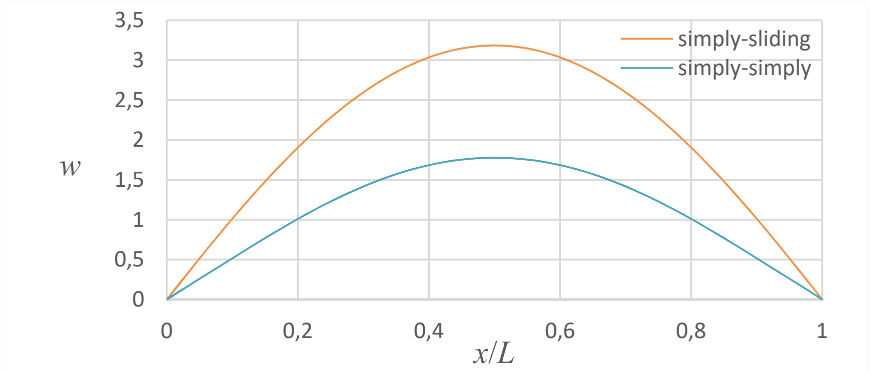


Figure 12 - Deflection (dimensionless) along the beam axis for antisymmetric [0/90] laminated composite beam with $\rho = 20$ ratio

For the same beam, higher order moment distributions are presented for various thickness ratios and also comparison study with Ozutok and Madenci can be followed in Figure 11. Since the higher order moment values along the beam are dependent on the transverse shear effect, they demonstrate small changes for different thickness ratios. Both for Figure 10 and 11, current study mostly agrees with Ozutok and Madenci [25] $(L/h = 10)$.

In Figure 12, variations of the deflection (nondimensionalized according to Equation (21)) along the beam length for simply-simply supported and simply-sliding supported conditions under uniform loading are displayed. For the simply-sliding case, the maximum deflection value becomes 1.79 times higher than simply-simply case.

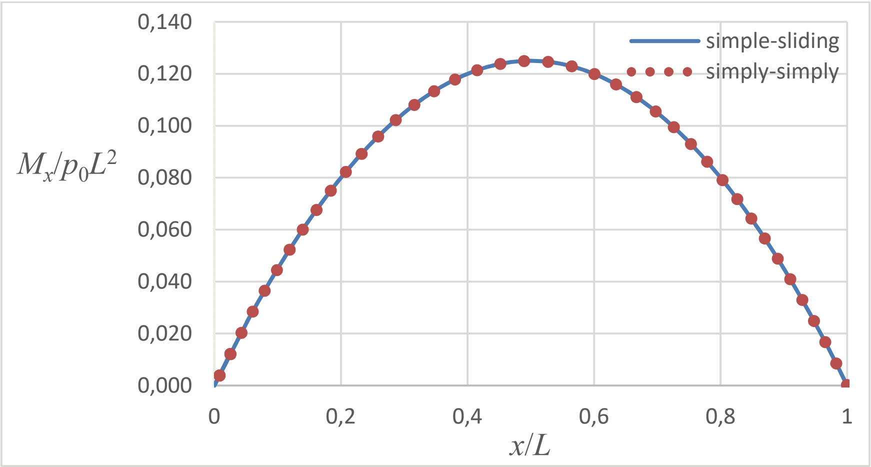


Figure 13 – Moment distribution along the beam axis for antisymmetric [0/90] laminated composite beam with $\rho = 20$ ratio under uniform loading

In Figure 13, the moment distributions along the beam length for simply-simply supported and simply-sliding supported conditions are presented. Both moment distributions overlap similar to the previous example (See Figure 7).

4. CONCLUSION

In this study, displacement and stress distributions of laminated composite beams under various boundary and loading conditions were investigated. For this purpose, a mixed finite element formulation is proposed where governing equations of the laminated beam is obtained by means of a Higher Order Beam Theory. Finite element equations derived using the Hellinger-Reissner variational principle require C_0 continuity. Hence, beam domain is discretized by using linear one-dimensional two-noded elements. As an advantage of the mixed finite element formulation, force and force couple components are calculated directly at the nodes alongside the displacement type field variables. In this way, strain components can be obtained through matrix operations using cross-sectional compliance matrices. In the post-processing, the axial normal stress components are calculated according to Hooke's laws, and the transverse shear stress components are obtained by using the equilibrium equations of the theory of elasticity. In this way the continuity of transverse shear stresses is ensured along the thickness of the laminated beam. Convergence and comparison analyses were performed in the numerical examples discussed and it was observed that the results were in satisfactory agreement with the exact solutions obtained from the theory of elasticity, analytical solutions and finite element solutions. The effect of extension-bending coupling is demonstrated through some numerical results and it is observed that deflection values are significantly influenced when this coupling takes place. It has been observed that the results are compatible with many advanced finite element solutions that stand out in the literature and can produce even better results in some cases, especially in stress calculations. It is thought that the proposed formulation offers the opportunity to be developed for many types of analysis in the future, and to be adjusted for various problems.

Symbols

$\delta \Pi_{HR}$: First variation of the functional

$\boldsymbol{\varepsilon}^{\mathbf{u}}$: Strain vector in terms of displacement components

$\boldsymbol{\varepsilon}^{\boldsymbol{\sigma}}$: Strain vector in terms of the stress components

$\boldsymbol{\sigma}^{\boldsymbol{\sigma}}$: Stress vector

δ : Variational operator

$\hat{\mathbf{t}}$: Traction vector

Γ : Boundary of the structure

E_1, E_2 : Young's moduli

v_{ij} : Poison's ratio

G_α : Shear moduli ($\alpha = 23, 31, 12$)

$f(z)$: Shear functions

h : Thickness

z : Any coordinate along the thickness

$\theta_x(x)$: Shear rotation about y axis

$\sigma_{xx}^{(k)}$: In-plane stress component at k^{th} layer

$\sigma_{xz}^{(k)}$: Transverse shear stress component at k^{th} layer

N_{xx} : In-plane force resultant of stress components

M_{xx} : Resultant moment of stress components

M_{xx}^{f} : Resultant higher order moment of stress components

Q_{xz} : Resultants of transverse shear stress components

b : Beam width

N : Total number of laminates

$\mathbf{P}$: Stress resultants

$\mathbf{e}^{\mathbf{u}}$: Strain measures in terms of kinematical variables

$\mathbf{E}$: Section stiffness matrix

$\mathbf{e}^{\mathbf{P}}$: Strain measures in terms of stress resultants

$\mathbf{p}$: Applied load vector

L : Beam length

$\mathbf{K}$: System matrix

$\mathbf{F}$: External force vector

$\mathbf{X}$: Unknown vector

Acknowledgements

This research is supported by the Research Foundation of ITU under project no MYL-2020-42679. This support is gratefully acknowledged by the authors.

References

[1] V.V. Vasiliev, E.V. Morozov, Advanced Mechanics of Composite Materials and Structural Elements, Elsevier, London, UNITED KINGDOM, 2013. http://ebookcentral.proquest.com/lib/itup/detail.action?docID=1221537 (accessed April 9, 2021).

[2] İ. Çömez, U.N. Aribas, A. Kutlu, M.H. Omurtag, An Exact Elasticity Solution for Monoclinic Functionally Graded Beams, Arab J Sci Eng. 46 (2021) 5135–5155. https://doi.org/10.1007/s13369-021-05434-9.

[3] M. Dorduncu, Peridynamic modeling of delaminations in laminated composite beams using refined zigzag theory, Theoretical and Applied Fracture Mechanics. 112 (2021) 102832. https://doi.org/10.1016/j.tafmec.2020.102832.

[4] M. Dorduncu, Stress analysis of laminated composite beams using refined zigzag theory and peridynamic differential operator, Composite Structures. 218 (2019) 193–203. https://doi.org/10.1016/j.compstruct.2019.03.035.

[5] L. Euler, Methodus inveniendi lineas curvas maximi minimive proprietate gaudentes, apud Marcum-Michaelem Bousquet, 1744.

[6] J. Bernoulli, Curvatura laminae elasticae, Acta Eruditorum Lipsiae. 1694 (1964) 262–276.

[7] B.A. Boley, On the Accuracy of the Bernoulli-Euler Theory for Beams of Variable Section, Journal of Applied Mechanics. 30 (1963) 373–378. https://doi.org/10.1115/1.3636564.

[8] A.H. Modaress-Aval, F. Bakhtiari-Nejad, E.H. Dowell, H. Shahverdi, H. Rostami, D.A. Peters, Aeroelastic analysis of cantilever plates using Peters' aerodynamic model, and the influence of choosing beam or plate theories as the structural model, Journal of Fluids and Structures. 96 (2020) 103010. https://doi.org/10.1016/j.jfluidstructs.2020.103010.

[9] S.P. Timoshenko, LXVI. On the correction for shear of the differential equation for transverse vibrations of prismatic bars, (1921) 3.

[10] W. Wagner, F. Gruttmann, A displacement method for the analysis of flexural shear stresses in thin-walled isotropic composite beams, Computers & Structures. 80 (2002) 1843–1851. https://doi.org/10.1016/S0045-7949(02)00223-7.

[11] U. Lee, I. Jang, Spectral element model for axially loaded bending–shear–torsion coupled composite Timoshenko beams, Composite Structures. 92 (2010) 2860–2870. https://doi.org/10.1016/j.compstruct.2010.04.012.

[12] J.N. Reddy, A simple higher-order theory for laminated composite plates, Journal of Applied Mechanics. 51 (1984) 745–752. https://doi.org/10.1115/1.3167719.

[13] E. Reissner, On transverse bending of plates, including the effect of transverse shear deformation, International Journal of Solids and Structures. 11 (1974) 569–573.

[14] K.P. Soldatos, A transverse shear deformation theory for homogeneous monoclinic plates, Acta Mechanica. 94 (1992) 195–220. https://doi.org/10.1007/BF01176650.

[15] A.J.M. Ferreira, C.M.C. Roque, P.A.L.S. Martins, Radial basis functions and higher-order shear deformation theories in the analysis of laminated composite beams and plates, Composite Structures. 66 (2004) 287–293. https://doi.org/10.1016/j.compstruct.2004.04.050.

[16] M.V.V.S. Murthy, D. Roy Mahapatra, K. Badarinarayana, S. Gopalakrishnan, A refined higher order finite element for asymmetric composite beams, Composite Structures. 67 (2005) 27–35. https://doi.org/10.1016/j.compstruct.2004.01.005.

[17] E. Madenci, Yüksek Mertebe Kayma Deformasyon Teorisine Dayali Çapraz Tabakali Kompozit Plaklarin Karisik Sonlu Eleman Yöntemi İle Analizi, Selcuk Universitesi, 2016.

[18] K. Chandrashekhara, K.M. Bangera, Free vibration of composite beams using a refined shear flexible beam element, Computers & Structures. 43 (1992) 719–727. https://doi.org/10.1016/0045-7949(92)90514-Z.

[19] D.K. Maiti, P.K. Sinha, Bending and free vibration analysis of shear deformable laminated composite beams by finite element method, Composite Structures. 29 (1994) 421–431.

[20] S. Xiaoping, S. Liangxin, An improved simple higher-order theory for laminated composite plates, Computers & Structures. 50 (1994) 231–236. https://doi.org/10.1016/0045-7949(94)90298-4.

[21] A.M. Zenkour, Transverse shear and normal deformation theory for bending analysis of laminated and sandwich elastic beams, Mech. of Adv. Mat. & Structures. 6 (1999) 267–283. https://doi.org/10.1080/107594199305566.

[22] H. Matsunaga, Vibration and buckling of multilayered composite beams according to higher order deformation theories, Journal of Sound and Vibration. 246 (2001) 47–62. https://doi.org/10.1006/jsvi.2000.3627.

[23] P. Subramanian, Dynamic analysis of laminated composite beams using higher order theories and finite elements, Composite Structures. 73 (2006) 342–353. https://doi.org/10.1016/j.compstruct.2005.02.002.

[24] W. Zhen, C. Wanji, An assessment of several displacement-based theories for the vibration and stability analysis of laminated composite and sandwich beams, Composite Structures. 84 (2008) 337–349. https://doi.org/10.1016/j.compstruct.2007.10.005.

[25] A. Ozutok, E. Madenci, Static analysis of laminated composite beams based on higher-order shear deformation theory by using mixed-type finite element method, Int. J. Mech. Sci. 130 (2017) 234–243. https://doi.org/10.1016/j.ijmecsci.2017.06.013.

[26] A. Kutlu, M. Dorduncu, T. Rabczuk, A novel mixed finite element formulation based on the refined zigzag theory for the stress analysis of laminated composite plates, Composite Structures. 267 (2021) 113886. https://doi.org/10.1016/j.compstruct.2021.113886.

[27] A. Kutlu, Mixed finite element formulation for bending of laminated beams using the refined zigzag theory, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications. 235 (2021) 1712–1722. https://doi.org/10.1177/14644207211018839.

[28] A. Kutlu, G. Meschke, M.H. Omurtag, A new mixed finite-element approach for the elastoplastic analysis of Mindlin plates, J Eng Math. 99 (2016) 137–155. https://doi.org/10.1007/s10665-015-9825-7.

[29] U.N. Aribas, M. Ermis, N. Eratli, M.H. Omurtag, The static and dynamic analyses of warping included composite exact conical helix by mixed FEM | Elsevier Enhanced Reader, Composites Part B: Engineering. 160 (2019) 285–297. https://doi.org/10.1016/j.compositesb.2018.10.018.

[30] U.N. Aribas, M. Ermis, A. Kutlu, N. Eratli, M.H. Omurtag, Forced vibration analysis of composite-geometrically exact elliptical cone helices via mixed FEM, Mechanics of Advanced Materials and Structures. (2020) 1–19. https://doi.org/10.1080/15376494.2020.1824048.

[31] U.N. Aribas, M. Ermis, M.H. Omurtag, The static and stress analyses of axially functionally graded exact super-elliptical beams via mixed FEM, Arch Appl Mech. 91 (2021) 4783–4796. https://doi.org/10.1007/s00419-021-02033-w.

[32] D. Shao, S. Hu, Q. Wang, F. Pang, Free vibration of refined higher-order shear deformation composite laminated beams with general boundary conditions, Composites Part B: Engineering. 108 (2017) 75–90. https://doi.org/10.1016/j.compositesb.2016.09.093.

[33] A.S. Sayyad, Y.M. Ghugal, Bending, buckling and free vibration of laminated composite and sandwich beams: A critical review of literature, Composite Structures. 171 (2017) 486–504. https://doi.org/10.1016/j.compstruct.2017.03.053.

[34] Y. Bab, A. Kutlu, Mixed finite element formulation based on higher order theory for stress calculation of laminated composite beams, in: Proceedings 22. National Mechanics Congress, Adana, Turkey, September 06-10.

[35] P. Shi, C. Dong, F. Sun, W. Liu, Q. Hu, A new higher order shear deformation theory for static, vibration and buckling responses of laminated plates with the isogeometric analysis, Composite Structures. 204 (2018) 342–358. https://doi.org/10.1016/j.compstruct.2018.07.080.

[36] R.M. Jones, Mechanics of composite materials, CRC Press, 1999.

[37] E. Hellinger, Die Allgemeinen Ansätze der Mechanik der Kontinua, in: F. Klein, Conr. Müller (Eds.), Mechanik, Vieweg+Teubner Verlag, Wiesbaden, 1907: pp. 601–694. https://doi.org/10.1007/978-3-663-16028-1_9.

[38] E. Reissner, On a Variational Theorem in Elasticity, Journal of Mathematics and Physics. 29 (1950) 90–95. https://doi.org/10.1002/sapm195029190.

[39] N.J. Pagano, Exact solutions for rectangular bidirectional composites and sandwich plates, (n.d.) 15.

[40] K.A. Hasim, Isogeometric static analysis of laminated composite plane beams by using refined zigzag theory, Composite Structures. 186 (2018) 365–374. https://doi.org/10.1016/j.compstruct.2017.12.033.

[41] P. Vidal, O. Polit, A sine finite element using a zig-zag function for the analysis of laminated composite beams, Composites Part B: Engineering. 42 (2011) 1671–1682. https://doi.org/10.1016/j.compositesb.2011.03.012.

[42] A.A. Khdeir, J.N. Reddy, An exact solution for the bending of thin and thick cross-ply laminated beams, Composite Structures. 37 (1997) 195–203.

[43] S. Kapuria, P.C. Dumir, N.K. Jain, Assessment of zigzag theory for static loading, buckling, free and forced response of composite and sandwich beams, Composite Structures. 64 (2004) 317–327. https://doi.org/10.1016/j.compstruct.2003.08.013.

Turkish Journal of Civil Engineering, 2023 25-58, Paper 716, ***Research Article***

Ability, Motivation, Opportunity-oriented HR Practices, Organisational Citizenship Behaviour and Performance Outcomes Relationship in Project-based Construction Organisations

Bilge AKBIYIKLI[1]
Şerife EYÜPOĞLU[2]
Rıfat AKBIYIKLI[3]

ABSTRACT

The purpose of this study is to contribute to the project management literature by testing a model that combines ability, motivation and opportunity (AMO) oriented human resource management practices, organizational citizenship behaviour (OCB) and performance outcomes in project-based construction organisations. The data were collected from questionnaires completed by 320 construction site civil engineers operating in the Marmara region of Turkey. The findings of the study indicate that there are positive relationships between AMO-oriented human resource practices and performance outcomes; however, organisational citizenship behaviour does not mediate these relationships.

Keywords: Ability motivation opportunity, organisational citizenship behaviour, performance outcomes, human resource management, project management; construction industry, civil engineers, Turkey.

INTRODUCTION

A vast body of research has been and is still being conducted to solve the 'black box' issue that questions the value human resource management (HRM) adds to organisations [1]. To investigate HRM's contribution to organisational performance and achieve a higher competitive advantage, further thorough explorations on the relationship between HR practices and organizational performance is of importance [2]. This is especially vital in

Note:

- This paper was received on January 31, 2022 and accepted for publication by the Editorial Board on September 10, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

- https://doi.org/10.18400/tjce.1209164

1 Near East University, Department of Business Administration, Nicosia, North Cyprus
bilgeakbiyikli@gmail.com - https://orcid.org/0000-0001-9446-2342

2 Near East University, Department of Business Administration, Nicosia, North Cyprus
serife.eyupoglu@neu.edu.tr - https://orcid.org/0000-0001-7678-1729

3 Düzce University, Department of Civil Engineering, Düzce, Türkiye
rifatakbiyikli@duzce.edu.tr - https://orcid.org/0000-0003-1584-9384

industries where employees generally work on temporary contracts that face high demands on meeting time and cost expectations, such as the project-based temporary organisations of the construction industry.

The Turkish construction industry is one of the largest in the world which also has a significant impact on the overall economy of the country [3]. However, the identification of human resource (HR) practices that function best to achieve competitive advantage is not clear within the construction industry [4]. Different data produce different results and the large variety of HR practices and performance measures used within investigations make it difficult to reach firm and industry conclusions [5].

The HR practices that are adopted by project-based temporary organisations should support the project-based work conditions [6], [7] where management of resources and immediate knowledge sharing is vital. The effective management of workforce and how they add value in order to be strategically aligned with organisational goals is an issue of attention by project managers. Project managers face ongoing challenges in balancing the projects' immediate needs, learning opportunities, knowledge sharing and integration of novelties of the industry into the organisational structure they manage [8], [9]. In construction projects, the fundamental and traditional HRM methods are organisational planning, staffing, team building and maintaining high morale levels. Project managers in Turkish construction sites are responsible for applying these functions. Thus, project managers must be capable of understanding HR parameters and work closely with HR departments. The manpower of projects is one of the fundamental inputs to run the transformation and value creation process. The relationship between the social system and technical system is administered through the management system by project managers for a successful project. The structures of the teams on a construction site are loosely knitted temporary coalitions and they are subject to change due to their temporariness, new recruits, and leavers during the project.

The production location and the non-repetitive feature of a project cause the external factors to shape the future of construction projects. Many construction managers in Turkey apply hard HRM features concentrating on the relevant resources through adopting a rational approach that considers the worker as a cost to the organisation and the project. Project managers affect and transform the project at hand and influence its site engineers to solve problems that are faced during a project, which is why research on HRM issues within the construction industry is of high importance.

In context with the above, it becomes imperative to incorporate new HR perspectives in this field of study to broaden the understanding of HR practice relationships with performance outcomes. According to Pak et al. [10], the existing literature on HRM in relation to ability, motivation, opportunity (AMO) and their effective impact on employees is unclear. Therefore, practitioners face difficulties deciding which approaches and efforts will alter employee efficiency and effectiveness in various industries, including project-based temporary organisations where restrictions caused by time, cost, budget and quality are high [10], [11], [12]. Hence, research concentrating on HRM issues within project-based temporary organisations are limited [7], [12], [13], [14]. The AMO framework proposes three dimensions for employees to perform well. Employees are able to execute their duties with high performance when they have the necessary skills to do the job (ability), are willing to do the job (motivation), and are given the necessary support and room for expression (opportunity) [15]. Having observed the above in the existing literature, ability, motivation and opportunity-oriented HR practices have been identified as parameters which will add significant value to this field of study. The relationships between ability, motivation, opportunity-oriented HR practices and performance outcomes have not been investigated in project-based Turkish construction organisations on site level.

A previous study on ability, motivation and opportunity-oriented HR practices, job satisfaction and performance outcomes relationship in the Dutch public sector has revealed valuable results. However, it is noted that other important factors such as employee attitudes and behaviours should be an area of additional consideration [16].Organisational citizenship behaviour (OCB) refers to the discretionary behaviour of employees that is not directly or indirectly recognised by the formal reward system but in the aggregate elevates organisational effectiveness [17]. Industrial managers have a growing interest in OCB due to positive results being revealed by investigations carried out on the relationship between OCB and employee performance in several industries [18], [19]. Concerning the construction industry, OCB is evident in large construction organisations that have more than 250 employees; however, OCB's existence is less noticeable in smaller organisations. Although large construction organisations have experienced an increase in some dimensions of performance due to OCB, authenticating this outcome has not been attainable since studies on the matter within the industry are both academically and professionally inadequate [19].

Paauwe et al. [20] suggested a multidimensional view on organisational performance where the possible competitive mechanisms are pointed out to be efficiency, effectiveness, fairness, quality, and innovation. Project-based temporary organisations consist of diverse resources and competencies to handle the complex nature of projects [8], [21], [22]. According to Sydow et al. [8] there are four levels in which projects occur: 1) organisational units, in which the project is embedded in a functional or business unit; 2) entire organisations, in which the organisation is entirely based on projects; 3) networks that provide inter-organisational cooperation on projects; and lastly, 4) organisational fields in a particular region or industry that provide a specific context for project-based organising [22]. This research acknowledges projects at the unit level, where the performance outcomes refer to the overall effectiveness, efficiency and fairness of units executed by site civil engineers in construction organisations.

In light of the above, this study will shed light on the gaps in the literature, through testing a model that investigates the relationships between ability, motivation, opportunity-oriented HR practices and performance outcomes both individually and through the mediating lens of OCB. This combination of variables has not been a topic of study in Turkey while addressing construction organisations, which brings about a unique approach by this research.

Among the roles of a site civil engineer is to manage different units of a construction firm and/or parts of a construction project, where they provide technical advice, supervision on site and ensure projects are finalised within a given time and budget. Certain skills, abilities and knowledge are expected of engineers to execute their responsibilities such as teamwork and relationship building, technical skills, problem solving, effective communication, attention to detail and a solid understanding on how actions may affect the profitability of a certain project. With the high expectations organisations have of their engineers who are under time and budget constraints, having the right people in the right place, sustaining their motivation, and making them feel that they matter to the organisation by facilitating them with an environment of opportunities are highly important. Since site civil engineers have managerial duties; they are both the executers of their roles and can also be seen as functions that view how fair, effective and efficient units are.

AMO-oriented HR practices and performance research has high significance for the region and the industry in general, as it helps to determine the current situations and act as a means to enhance present systems and processes for further developments concerning site civil engineers. Having presented AMO-oriented HR practices as a new outlook in relation to performance outcomes within the unique idiosyncratic nature of the Turkish construction industry, this study carries a significant degree of novelty. The purpose of the present study is to fill the existing gap in the project-management literature by examining whether a positive correlation is detectable between ability, motivation, opportunity-oriented HR practices and performance outcomes and also to investigate the possible mediating effect of OCB within such relationships through site civil engineers working in project-based temporary organisations of the Turkish construction industry. Identifying functional HR parameters and their relationships with performance are vital in sustaining the existing and growing construction economy.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1. Human Resource Management and Organizational Performance

Although a substantial volume of research has taken place to examine the relationship between human resource management practices and organizational performance [23], [24] there is still significant lack of knowledge about how this relationship occurs [1].

Industries require different skills and knowledge. HR practices develop firm specific employee competencies to sustain competitive advantage [25]. Complementing this view, Schuler & Jackson [26] saw HR practices as systems that attracts, develops, motivates and retains employees to ensure the effective implementation of policies and the survival of the organization and its members. Although there is no agreement on how HR practices affect performance, many researchers believe that HR practices alter performance through their impact on staff attitudes and behaviour which results in increased productivity and quality of goods and services and thus improves organizational financial performance [27], [28], [29].

HR practices that improve employee skills and attitudes stimulate positive behaviour, increase motivation, and give employees enlarged responsibilities to fully use their existing skills and abilities are suggested to increase company performance [30], [31], [32]. Appropriate HR practices and strategies that are organised as a bundle have a positive direct impact on human resource outcomes (turnover, absenteeism, job satisfaction) which lead to higher positive organizational outcomes (productivity, quality, service), financial accounting outcomes (return of assets, rate of return, profitability index) and capital market outcomes (stock price, growth, returns). These are the four possible measurements for organizational performance [33]. Nevertheless, scholars debate on which bundled HR practices specifically succeed in altering organizational performance and how the organisational performance of firms can be identified in the best possible way in practice [28], [34], [35].

Drawing on two distinct dimensions, Paauwe et al. [20] suggested a multidimensional view on organizational performance. The first dimension, economic rationality, refers to the competitive mechanisms which are efficiency, effectiveness, quality, and innovation. The second dimension, relational rationality, pays attention to the institutional mechanisms such as fairness and legitimacy. HR practices will have no strategic impact if they lack in their effectiveness in bringing out positive attitudes and behaviours among employees as achieving organizational objectives are in line with their commitment [36] and it is therefore essential to pay attention to the direct effect HR practices have on employees [29], [33], [37], [38]. Huselid [32] categorized personnel selection, performance appraisal, incentive compensation, formal grievance procedures, information sharing, labour/management participation, recruiting intensity and more training hours as relevant HR practices. Similarly, Delaney & Huselid [39] highlighted these HR practices as recruitment and selection, training and development, participation, and reward.

2.2. Ability, Motivation and Opportunity Framework

Starting with Huselid's [32] study, where he disclosed that HR practices were related to turnover, accounting profits and a firm's market value, a high interest in the HRM-performance research has focused on determining the relevant HR practices for organisations. Furthermore, HRM research in the more recent years focuses on bundles of HR practices in examining the effects of HRM on employee and organizational outcomes (the systems approach) rather than the traditional way (instrumental approach) which emphasizes the impact of individual HR practices [40].

The origins of the AMO framework have derived from a previous model proposed by Bailey [30] which was later developed by Appelbaum et al. [41]. With its growing popularity the AMO framework has received close attention in the literature for the HRM-performance link [20]; proposing that employees perform well when they have the necessary skills to do the job (ability), are willing to do the job (motivation) and are given the environment to be heard [15] and are provided the necessary support and room for expression (opportunity to perform). A positive relationship has been found between HR practices that improve employees' ability, motivation and opportunity and better performance services, higher quality, greater financial performance, lower turnover, and stronger commitment [32], [42], [43], [44].

The ability-oriented HR practices aim to alter employee competences and build on their existing expertise for performing their tasks effectively [45]. These practices positively affect individual performance, due to their impact on achieving increased job-specific knowledge and skills, which often include recruitment and selection, extensive training and development and job rotation [39], [45], [46], [47]. Recruitment and selection and training and development are the two HR practices selected to measure ability [45], [48]. Recruitment and selection allow organization to attract, choose and place the most suitable candidates for a certain position where in return employees may realise their full potential by being placed in a right position. Training and development opportunities build on existing employee knowledge and add new knowledge and skills. Employees that receive regular training and development opportunities are likely to feel valued with less job and task ambiguity [46]. In the construction context, recruitment and selection can enable the construction projects to have the right workforce with the right technical skills needed, training and development are crucial for building on existing knowledge as well as to keep up to date with the strict health and safety regulations required in the industry. According to Mohammad et al. [49]

recruitment and selection and training and development have a direct impact on organizational performance. In relation to the social exchange theory [50], exercising ability-oriented HR practices make employees feel that the organisation supports and benefits them while creating a higher sense of belongingness where, in return, employees are likely to demonstrate favourable attitudes [46]. Based on the above information we hypothesize that:

H1a: There is a positive relationship between ability-oriented HR practices and performance outcomes in project-based construction organisations.

The motivation-oriented HR practices are designed to build on individual achievements to attain specific job-related objectives including performance evaluation, incentives, benefits, career-advancement schemes and a diligent appraisal. Reward schemes are important as they lead individuals to behavioural decisions [45], [51]. All above-mentioned practices aim to improve the motivation of employees in order to encourage efforts in meeting organisational goals and enhance the overall performance. Extrinsic and intrinsic motivations are the two types of motivation. Extrinsic factors are more related to economic rewards whereas intrinsic factors are more related to an employee’s values and interests [52]. Performance appraisal and rewards are the two HR practices selected to measure motivation [45], [48]. Performance appraisal relates to both financial and non-financial incentives. It is used by organisations to fairly evaluate activities which organizations seek to assess employees and develop their competence, enhance performance, and distribute rewards [53]. Rewards refer to what organisations offer their employees for the services they provide. Rewards need to be designed in a way to meet employee expectations to receive better employee performance. They come in the forms of salary, recognition, promotion advancement as well as personal growth [54], [55]. In the construction context, performance appraisal can form the basis for engineers’ further development areas and create a feedback culture where employees are informed both on their performance and how their work contributes to the unit achievement goals. Rewards are an important means of motivation considering the focused working conditions and high responsibility of engineers. These practices make it clear for the employees to understand organisational expectations in relation to their tasks and in which way their contributions through these tasks are rewarded. Employees tend to behave in line with organisational objectives when sensing the application of evaluation schemes and existence of reward programs. This results in increased employee productivity and decreases turnover signalling a social exchange relationship [46], [56], [57], [58]. Based on the above information we hypothesize that:

H1b: There is a positive relationship between motivation-oriented HR practices and performance outcomes in project-based construction organisations.

The opportunity-oriented HR practices delegates the decision-making authority and fosters employee voice where employees feel they are involved [59]. It is suggested that organizations must provide the environment for dialogue among hierarchies and create systems for knowledge sharing as well as decentralised decision-making which will enable employees to enjoy higher levels of autonomy while performing their tasks [2], [46], [60]. Opportunity-oriented practices are participation processes that function formally. Regular communication and information sharing as well as autonomy in task-related decisions are also included [61], [62]. Autonomy and participation are the two HR practices selected to measure opportunity [45], [48]. Autonomy is the freedom employees have to make choices for their own behaviour regarding schedules, deadlines, and projects with little direction from others [63]. Participation refers to the process of employees being involved in the decisions regarding their work and its conditions where the decision-making process is a shared power between employees and superiors [64]. Organizations that are willing to foster a participative environment should improve the involvement of employees in decision making processes, knowledge sharing, job enrichment and horizontal communication [45]. These practices enable employees to find more meaning in their jobs as they foster teamwork and cooperative integration among employees [47]. Autonomy is needed for engineers working in an organised yet complex environment such as the construction site and lastly, participation is highly important for a clear communication, voicing opinions and being a part of work-related decisions. Making employees feel that they are being treated favourably through communication, autonomy and participation would express their commitment to the organisation with positive behaviour in return as implied by social exchange [62]. Based on the above information we hypothesize that:

H1c: There is a positive relationship between opportunity-oriented HR practices and performance outcomes in project-based construction organisations.

2.3. Human Resource Practices and Organizational Citizenship Behaviour

In order to determine the relationship between HR practices and performance the role of organizational citizenship behaviour (OCB) is a powerful factor [18] which is achieved through maximised employee efforts and contributions [65]. In its simplistic way OCB is defined by Organ [17] (p.4) as "individual behaviour that is discretionary, not directly or explicitly recognized by the formal reward system and that in the aggregate promotes the effective functioning of the organization". Researchers advise organizations to pay close attention to promoting OCB due to its effect on outcomes such as sales performance, product quality, overall profits and operating efficiency and performance quality [66], [67], [68]. OCB is composed of altruism (employees helping one another), civic virtue (employees staying informed with organisational issues), conscientiousness (employees being careful and diligent), courtesy (employees exercising considered behaviour prior to taking action), and sportsmanship (employees seeing over insignificant matters) [17].

HRM systems are composed of aligned and bundled HR practices that aim to achieve the goals of the organization [45]. Specifically selected HR practices in bundles can create committed, motivated, and satisfied employees [69] and are believed to function better rather than individually, leaving employees exposed to multiple practices simultaneously [32], [45]. Bundles are also seen as the primary unit of analysis when examining the impact HRM systems have on both individual and organizational level outcomes [32], [43], [70].

Researchers pointed out that HR practices have the ability to enhance OCB [71], [72]. Carefully recruited, trained, empowered, and motivated employees are expected to perform high levels of OCB. Creating and maintaining a positive climate through HR practices within an organization ignites employees' will to perform extra-role behaviour [71]. HR practices have the power to define the relationship between employee and employer thus serving as a source of motivation for employees to exercise OCB [73]. The relationships characterised by social exchange have been proven to increase the exercise of extra-role behaviour [50]. It is also highlighted that through social exchange constructive changes in behaviour will eventually lead to an improved employee and organisational performance [74], [75].

Practices such as recruitment and selection make employees feel that they are the chosen elite [76], where training and development pass on a message that the organization is being committed to the growth of its employees. Performance appraisal, rewards and incentives create a sense of recognition and fair treatment, and lastly, practising employee participation in decision-making and autonomy adds to the feeling of importance and freedom in executing their tasks [77].

2.4. Organizational Citizenship Behaviour and Organisational Performance

OCB's capacity to improve the productivity level of employees facilitate the efficient use of organizational resources while enhancing teamwork effectiveness, increasing workplace desirability and attracting competent employees [67] are a result of the employee-employer relationship which stimulates the extra-role behaviour in employees through social exchange [50], [76] rather than a purely economic one. Extra-role behaviours are crucial in the sense that employees go beyond the call of duty to helping co-workers and suggesting ideas to improve the functioning of the organization. The employee with extra-role behaviour also creates an example on group level where higher individual performance is seen to positively influence group performance thus overall effectiveness of an organization [17], [78].

The employee-employer relationship is linked to the relationship between HR practices and OCB which is the fundamentals of the social exchange theory, taking into consideration employees' social interaction and the benefits they receive in exchange of their contribution [79].Reciprocity is the underlying core of social exchange meaning favours being returned by employees who receive benefits [50]. It is a socio-emotional exchange relationship shaped by mutual trust, commitment and obligation among employees and employers [80]. Employees that enjoy the high level of social exchange are likely to demonstrate behaviours and attitudes that match organisational values and interests [81]. Employees with a better relationship with their managers show higher level of OCB but those managers sometimes fail to realize the impact OCB has on performance [17], [67].It is also indicated that OCB enhances the effectiveness and efficiency of an organisation, which is vital to improve the organisation's capability of adapting itself to changes in the environment [82]. Researchers argue that OCB is the main source distinguishing best-performing organisations from average ones. Employees that engage in OCB help to increase the quality of services [76], [83].

2.5. Organisational Citizenship Behaviour as a Mediator

The AMO framework [41] has been used in many industries such as the service sector, construction, manufacturing and financial sectors, marketing, consultancy, and production [52], however, the identification of which and how HR practices function best and create extra-role behaviour is unclear within the construction industry [4]. According to the AMO framework organizational performance is affected by HR practices as they increase employees' knowledge, skills, abilities, motivation and enable employee empowerment. The key role of HR practices in this respect is to eliminate any barrier that stops employees from exercising discretionary efforts [76]. Employees' willingness in creating extra-role behaviour is triggered through HR practices that create and maintain a positive climate. Carefully recruited, trained, motivated, and empowered employees are expected to perform high levels of OCB [44], [76]. Through social exchange theory, constructive changes in behaviour will eventually lead to an improved employee and organisational performance [75]. Therefore, employees go beyond the call of duty to help their co-workers and suggest ideas to improve the functioning of the organization. As a result, higher individual performance and group performance increases the overall effectiveness of the organization [17], [78].

Regarding the black-box issue of the HRM-performance linkage, researchers suggested examining this relationship through mediating variables concerning employee attitudes and behaviours [45]. In this respect, OCB is a powerful factor in determining the relationship between HR practices and performance [18] which is achieved by taking full advantage of employees' contributions [65]. Performance outcomes such as the effectiveness and efficiency of an organization which are enhanced by OCB are also vital to improve the organization's capability in adapting itself to changes in the environment [82]. Chiang & Hsieh [84] in their study on the hotel industry in Taiwan found a significant mediating effect of OCB among perceived organizational support and job performance confirming OCB being a potential mediator between HR practices and outcomes. Research conducted on employees of several hotels in China [18] revealed that OCB mediated the relationship between high performance human resource practices, turnover, and productivity [85]. Moreover, Taamneh et al. [76] found that OCB partially mediated the relationship between HR practices and organizational performance in the banking sector in Jordan. Lastly, Cesário & Magalhães [86] examined the Portuguese public administrations and found that OCB mediates the relationship between HR practices and turnover intention.

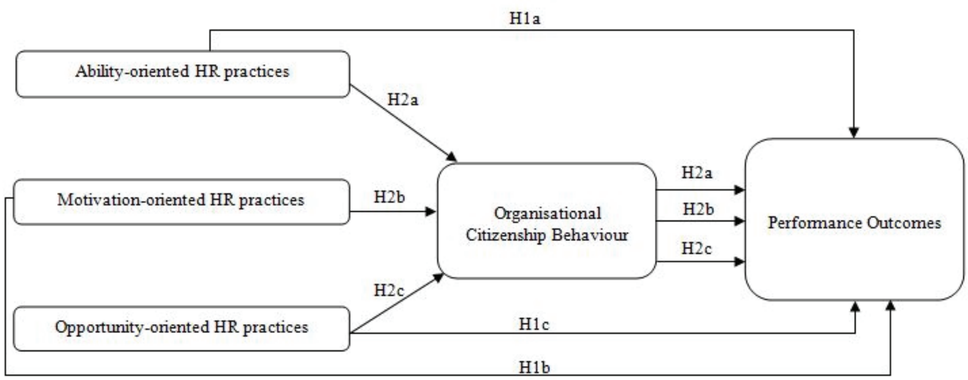


Figure 1 - Research Model

It is believed that the published research that investigates which and how HR practices impact organizational performance is limited, however, researchers suggest that OCB contributes to the effective and efficient functioning of the organization [17], [78]. It is unclear whether similar positive outcomes will occur in the construction industry. Thus, to explore the effect of OCB we hypothesis that:

H2a: The positive relationship between ability-oriented HR practices and performance outcomes is mediated by OCB in project-based construction organisations.

H2b: The positive relationship between motivation-oriented HR practices and performance outcomes is mediated by OCB in project-based construction organisations.

H2c: The positive relationship between opportunity-oriented HR practices and performance outcomes is mediated by OCB in project-based construction organisations.

3. MATERIALS AND METHODS

3.1. Sample and Data Collection

To test the stated hypotheses, the current research adopted a quantitative approach to reveal statistical confirmation of variables and the conceptual model. According to the Turkish Architects and Engineers Chamber (TMMOB) there are 133.583 civil engineers in Turkey. The Marmara region is home to some of the largest construction firms that lead the construction economy, and the construction industry is one of the largest sectors of the Turkish economy [87]. Any research that is to be conducted in this region will help to determine the current situations and may act as a means to enhance present systems and processes for further developments. The snowball sampling method was used for the data collection process. The benefits of using snowball sampling are that finding samples are quick and cost-effective, and participants hesitate less about anonymity knowing the request comes from reliable sources [88].

Data has been collected via the Chambers of Civil Engineers (IMO) of the Marmara region which in total consists of 46.538 civil engineers. Among the 46.538 civil engineers 1.900 are managing site civil engineers currently working on various sites. The online questionnaire, which included a consent form and assurance of anonymity, was distributed via the Chambers. According to Sekaran & Bougie [89], the suggested sample size for a population of 1.900 is 320, which coincide with the received sample size for the present study.

3.2. Measures

In order to measure each variable, a structured questionnaire that consisted of demographic questions and three main sections was used. Questionnaires are methods that can bring forth answers that are easy to organise and analyse. Administering questionnaires anonymously encourages respondents to be truthful when answering the questions. Reaching respondents that are afar is also another advantage if the questionnaire is distributed via electronic mediums which are also economical [90]. Online designed questionnaires are practical tools that allow the researcher to collect the needed data immediately. While responses accumulate on the database the researcher is able to conduct preliminary analyses on the so-far collected data if needed [91].

The questionnaire's first section covered the demographic questions that include age, education level, years of service in the industry and years of service in the current organisation. In the second section participants were asked to score a 5-point Likert scale from 1 to 5 (1: strongly disagree, 5: strongly agree). This part covered the main body of the questionnaire that was divided into 3 main scales including 84 items in total. The distribution of the questionnaire items is outlined below, and the items are represented in detail in Appendix 1.

Firstly, the AMO-oriented HR practices were measured through a scale which included a total of 39 items [92]. For ability 14 items, for motivation 13 items, and for opportunity 12 items were used. The second scale measured OCB with a total number of 24 items [93] and lastly, the third scale covered the performance outcomes with a total of 21 items [94].

3.3. Data Analysis

Data (n=320) was analysed using IBM SPSS 23 and SPSS PROCESS Macro. In order to summarise the data set, the mean, median, standard deviation and interquartile range value scores of the scales were calculated for the descriptive statistical analysis. Categorical variables were presented as percentages. In addition, Pearson correlation coefficients were calculated to determine the direction and degree of the relationship between the variables. Also, traditional regression-based mediation (simple mediation) analysis was performed to estimate the mediating effect of Ability-oriented HR practices (AB), Motivation-oriented HR practices (MO) and Opportunity-oriented HR practices (OP) on Performance Outcomes through Organisational Citizenship Behaviour. According to Baron & Kenny's steps [95], a simple mediation model analysis consists of three regression models: $X \rightarrow Y$, $X \rightarrow M$, and $X + M \rightarrow Y$. In the models, the explanatory variable is indicated by (X), mediating variable by (M) and the response variable by (Y). In order to prove the existence of the mediating effect, the provision of the three conditions is necessary [96].

The indirect effect in the models was tested using the bootstrap test [97]. The bootstrap test analysis results are based on 95% confidence intervals with 5000 samples with replacement. The bootstrap test is a nonparametric alternative resampling technique to test the mediating effect which includes continually sampling from the data and estimating the indirect effect for each sample. By continuing this process several times (usually between 1000 and 5000), a confidence interval for indirect effect on the response variable by the mediator is constructed using an empirical approximation of the sampling distribution of indirect effect [97]. The bootstrapping method also allows the Sobel test to be carried out and increases the test's power. Sobel test [98] was used to determine if Organisational Citizenship Behaviour mediated the association between Ability-oriented HR practices (AB), Motivation-oriented HR practices (MO) Opportunity-oriented HR practices (OP) and Performance Outcomes. Sobel test searches whether explanatory and response variables have a significant indirect relationship, meaning that it explores if the effect of the explanatory variable of the response variable is significantly decreased by the inclusion of a mediating variable.

Hayes's Process Macro automatically calculates the relevant statistics and inference methods without requiring additional effort and programming skills. Structural equation modelling (SEM) applies analyses as Process handles while it needs more code writing skills and requires obtaining various statistics that Process obtains automatically. Also, not all SEM programs can produce all statistics Process computes; nor apply bootstrapping method in a way that makes easy inference. Regression-based approaches are not applied simply through the use of SEM, but with Process they are applied in a simple and understandable manner [99]. SEM is an effective approach that can improve mediation analysis in different ways. SEM's ability to handle both model specification and missing data professionally, and its ability to account for random measurement error in estimating effects on latent variables, makes it attractive. However, its complexity presents various difficulties and therefore inexperienced analysts may encounter some erroneous results when using it [99]. For models based entirely on observed variables, the results will largely be the same. Therefore, regression-based bootstrapping methods (Process Macro) are recommended for models that rely entirely on observed variables. In the current study, Hayes's Process Macro was preferred as the models are also based on observed variables [99].

Within the scope of validity and reliability analyses for the scales, first Kaiser-Meyer Olkin (KMO) coefficient and Bartlett's Sphericity Test were computed to check whether the dataset was appropriate for factor analysis and then Explanatory Factor Analysis (EFA) was performed using principal component analysis with varimax rotation to examine whether the items were loaded on the assumed underlying factors for construct validity [100]. Cronbach's alpha values were calculated as an internal consistency coefficient to evaluate the reliability of the scales. In this study, p-value less than 0.05 was considered statistically significant.

4. RESULTS

This section presents the data analysis results, including the descriptive statistics about demographic variables. Correlation analyses, item analysis and reliability of scales are demonstrated. Then, explanatory factor analysis results and mediation analysis results are represented.

The demographic information regarding the participants is presented in Table 1 below. These results are similar to the current demographic structure of the Turkish construction industry. The Turkish construction industry is also male-dominated where the age range generally appears to be between 25-50. Similarly, the majority of the civil engineers in Turkey hold only undergraduate degrees [101], [102], [103]. Considering the working experience in the sector and in the current organisations, it is evident that the majority of the respondents have been working within the sector between 6 to 10 years, and 3 to 5 years within their current organisation. This information coincides with the temporary nature of the project-based construction organisations.

The mean ($\bar{x}$), median, standard deviation (s), interquartile range values (IQR), minimum (min) maximum (max) of the AB, MO, OP, OCB and PO scale scores have been calculated in Table 2. When the descriptive statistics presented in Table 2 below are examined; the scores of the scales ranged from 1 to 5, the mean score of the Organizational Citizenship Behaviour scale was the highest ($\bar{x}$=4.35; s=0.56), and the average score of the Motivation-oriented HR practices scale was the lowest ($\bar{x}$=3.01; s=1.16).

When item, validity and reliability analyses of the Ability-oriented HR practices scale were conducted, it was observed that the general Cronbach's Alpha coefficient (internal consistency coefficient) of the scale was found to be quite high with 0.958. The item-total correlation values of the items in the scale ranged from 0.648 to 0.847. Cronbach's Alpha coefficients obtained when the items in the scale are deleted separately vary between 0.954 and 0.958, which are not higher than the general Cronbach's Alpha coefficient of 0.958. Cronbach's Alpha coefficients for recruitment and selection, training and development sub-scales were obtained as 0.935 and 0.949, respectively. As a result, when the results of all item analysis were evaluated, it was determined that all items were suitable for use. The Kaiser Mayer Olkin (KMO) of Sampling Adequacy value of Ability-oriented HR practices scale was obtained as 0.940. This value shows that the sample is sufficient for explanatory factor analysis. The result of Bartlett's sphericity test ($\chi 2$=4468.974; df=666, p=0.001) was found to be statistically significant. Varimax rotation was used in the explanatory factor analysis. There are two sub-scales in the original scale. As a result of factor analysis, the scale was gathered under two factors. The first factor alone accounted for 42.96% and two factors together explain 73.57% of the total variance. Item factor loadings vary between 0.631 to 0.879.

Table 1 - Demographic information

Variable	Categories	Frequency	%
Gender	Female	90	28.13
	Male	230	71.87
Age	20-29	103	32.19
	30-39	147	45.94
	40-49	55	17.19
	50-59	11	3.43
	>60	4	1.25
Education level	Undergraduate	223	69.69
	Master degree	85	26.56
	PhD degree	12	3.75
Working experience in the sector (year)	<1	20	6.25
	1-2	31	9.69
	3-5	59	18.44
	6-10	110	34.38
	11-14	49	15.31
	15-19	22	6.87
	>20	29	9.06
Working experience in the current organization (year)	<1	68	21.25
	1-2	64	20.00
	3-5	85	26.56
	6-10	68	21.25
	11-14	18	5.63
	15-19	8	2.50
	>20	9	2.81

Table 2 - Descriptive statistics of the scales

Scale	Cronbach's α	Min-max	$\bar{x}$(s)	Median (IQR)
Ability-oriented HR practices (AB)	0.958	1-5	3.36(1.01)	4.00(1.50)
Motivation-oriented HR practices (MO)	0.967	1-5	3.01(1.16)	3.00(2.00)
Opportunity-oriented HR practices (OP)	0.967	1-5	3.34(1.09)	4.00(1.50)
Organisational Citizenship Behaviour (OCB)	0.953	1-5	4.35(0.56)	4.50(1.00)
Performance Outcomes (PO)	0.967	1-5	3.93(0.79)	4.00(1.00)

After conducting item, validity, and reliability analyses of the Motivation-oriented HR practices scale, it was seen that the general Cronbach's Alpha coefficient of the scale was found to be quite high with 0.967. The item-total correlation values of the items in the scale ranged from 0.709 to 0.874. Cronbach's Alpha coefficients obtained when the items in the scale are deleted separately vary between 0.963 and 0.967, which are not higher than the general Cronbach's Alpha coefficient of 0.967. Cronbach's Alpha coefficients for performance appraisal and rewards sub-scales were obtained as 0.954 and 0.937, respectively. As a result, when the results of all item analysis were evaluated, it was determined that all items were suitable for use. The KMO value of the Motivation-oriented-HR practices scale was obtained as 0.957. This value shows that the sample is sufficient for explanatory factor analysis. The result of the Bartlett's sphericity test ($\chi 2$=4379.812; df=78, p=0.001) was found to be statistically significant. There are two sub-scales in the original scale. As a result of factor analysis, the scale was gathered under two factors. The first factor alone accounted for 41.11% and two factors together explain 77.88% of the total variance. Item factor loadings vary between 0.650 to 0.839.

As a result of item, validity and reliability analyses of the Opportunity-oriented HR practices scale, the general Cronbach's Alpha coefficient of the scale was found to be quite high with 0.967. The item-total correlation values of the items in the scale ranged from 0.711 to 0.883. Cronbach's Alpha coefficients obtained when the items in the scale are deleted separately vary between 0.963 and 0.967, which are not higher than the general Cronbach's Alpha coefficient of 0.967. Cronbach's Alpha coefficients for autonomy, participation sub-scales were obtained as 0.950 and 0.939, respectively. As a result, when the results of all item analysis were evaluated, it was determined that all items were suitable for use. The Kaiser Mayer Olkin (KMO) value of Opportunity-oriented HR practices scale was obtained as 0.957. This value shows that the sample is sufficient for explanatory factor analysis. The result of the Bartlett's sphericity test ($\chi 2$=4379.812; df=78, p=0.001) was found to be statistically significant. This shows that the data are suitable for explanatory factor analysis. There are two sub-scales in the original scale. As a result of factor analysis, the scale was gathered under two factors. The first factor alone accounted for 41.11% and two factors together explain 77.88% of the total variance. Item factor loadings vary between 0.645 to 0.871.

According to item, validity and reliability analyses of the Organizational Citizenship Behaviour scale, the general Cronbach's Alpha coefficient of the scale was found to be quite high with 0.953. The item-total correlation values of the items in the scale ranged from 0.621 to 0.730. The Cronbach's Alpha coefficients obtained when the items in the scale are deleted separately vary between 0.951 and 0.953, which are not higher than the general Cronbach's Alpha coefficient of 0.953. As a result, when the results of all item analysis were evaluated, it was determined that all items were suitable for use. The KMO value of the Organizational Citizenship Behaviour scale was obtained as 0.936. The result of the Bartlett's sphericity test ($\chi2$=5598.522; df=276, p=0.001) was found to be statistically significant. Factor analysis indicated that one factor explains 67.75% of the total variance. Item factor loadings vary between 0.344 to 0.848.

Lastly, according to the item analysis of the Performance Outcomes scale, the general Cronbach's Alpha coefficient of the scale was found to be quite high with 0.967. The item-total correlation values of the items in the scale ranged from 0.590 to 0.823. Cronbach's Alpha coefficients obtained when the items in the scale are deleted separately vary between 0.963 and 0.965, which are not higher than the general Cronbach's Alpha coefficient of 0.967. Cronbach's Alpha coefficients for effectiveness, efficiency, fairness sub-scales were obtained as 0.918, 0.926, and 0.906, respectively. As a result, when the results of all item analyses were evaluated, it was determined that all items were suitable for use. The KMO value of the Performance Outcomes scale was obtained as 0.961. This value shows that the sample is sufficient for explanatory factor analysis. The result of the Bartlett's sphericity test ($\chi2$=5702.425; df=210, p=0.001) was found to be statistically significant. As a result of the factor analysis, the scale was gathered under three factors. The first factor alone accounted for 30.93%, two factors together explain 51.19% of the total variance, and all three factors explain 69.73% of the total variance. Item factor loadings vary between 0.459 to 0.844.

4.1. Hypotheses Testing

Correlation analysis was conducted to test the proposed hypotheses (H1a, H1b, H1c) and mediation analysis technique to test the mediating effects in the stated hypotheses (H2a, H2b, H2c). The Pearson correlation coefficients between the variables are shown in Table 3 below**.** The correlation analysis results indicate significant moderate positive relationship between ability-oriented HR practices and performance outcomes ($r=0.575$, $p<0.01$). Based on these results, our first hypothesis, H1a is supported by the data. Moreover, according to correlation analysis results, it is observed that there is a statistically significant moderate positive correlation between motivation-oriented HR practices and performance outcomes ($r=0.479$, $p<0.01$) which supports the H1b hypothesis. Lastly, in line with the analysis results, there is a statistically significant moderate positive correlation between opportunity-oriented HR practices and performance outcomes ($r=0.499$, $p<0.01$). This indicates that the H1c hypothesis is supported. The results stating that H1a, H1b and H1c are supported by the data is also consistent with the regression analysis results that are revealed in the Model 1 sections of Table 4,5 and 6 ($p<0.05$).

Table 3 - Pearson correlation coefficients between the variables

Variables	AB	MO	OP	OCB	PO
AB	1				
MO	**0.859****	1			
OP	**0.816****	**0.871**	1		
OCB	**0.100**	**0.036**	**0.084**	1	
PO	**0.575****	**0.479****	**0.499****	**0.384****	1

*p<0.05, **p<0.01; (n=320)

Table 4 below shows mediation analysis results for the effect of ability-oriented HR practices on performance outcomes through organisational citizenship behaviour as a mediator variable. In the mediation Model 1, the regression of ability-oriented HR practices on performance outcomes, disregarding the mediator (organisational citizenship behaviour), was significant (B = 0.444, t= 12.542, p=0.000<0.05). Then, the analysis results in Model 2 showed that the regression of ability-oriented HR practices on the mediator, organizational

Table 4 - The effect of Ability-oriented HR practices on Performance Outcomes through Organisational Citizenship Behaviour as mediator variable

	B	Std.Error	t	p	95% CI
Model 1 (AB→ PO)					
Constant	2.436	0.124	19.626	0.000	(2.192,2.680)
AB	0.444	0.035	12.542	0.000	(0.374,0.513)

Model 1 summary: $R^2 = 0.331$; MSE = 0.405; F (1,318) = 157.289; p = 0.000

Model 2 (AB→ OCB)					
Constant	4.161	0.109	38.168	0.000	(3.947,4.376)
AB	0.056	0.031	1.790	0.074	(-0.006,0.117)

Model 2 summary: $R^2 = 0.010$; MSE = 0.313; F (1,318) = 3.205; p = 0.074

Model 3 (AB+OCB → PO)					
Constant	0.534	0.269	1.984	0.048	(0.005,1.063)
AB	0.418	.033	12.824	0.000	(0.354,0.482)
OCB	0.457	0.059	7.806	0.000	(0.342,0.572)

Model 3 summary: $R^2 = 0.439$; MSE = 0.341; F (2,317) = 123.939; p = 0.000

CI: Confidence interval

citizenship behaviour, was not significant (B = 0.056, t = 1.790, p =0.074 >0.05). The mediating effect is significant only if the independent variable significantly affects the mediator. Thus, our result in Model 2 does not prove the existence of the mediating effect. Moreover, according to the results in Model 3, both ability-oriented HR practices (B=0.418, t=12.824, p=0.000<0.05) and organisational citizenship behaviour (B=0.457, t=7.806, p=0.000<0.05) are significant, positive predictors of performance outcomes. The Sobel test also supports that the relationship between ability-oriented HR practices and performance outcomes was not mediated by organisational citizenship behaviour (z=1.743, p=0.081>0.05). Also, the results of the indirect effect based on 5000 bootstrap samples prove that there is no significant indirect relationship between ability-oriented HR practices and performance outcomes mediated by organisational citizenship behaviour (effect= 0.026, Bootstrap 95%CI = -0.025 and 0.051) as seen in Table 7. Based on this result, the hypothesis H2a is not supported by the data.

Table 5 below shows the mediation analysis results for the effect of motivation-oriented HR practices on performance outcomes, through organisational citizenship behaviour as a mediator variable. In the mediation Model 1, the regression of motivation-oriented HR practices on performance outcomes, disregarding the mediator (organisational citizenship behaviour), was significant (B = 0.321, t=9.729, p=0.000<0.05). Then the analysis results in Model 2 showed that the regression of motivation-oriented HR practices on the mediator,

Table 5 - The effect of Motivation-oriented HR practices on Performance Outcomes through Organisational Citizenship Behaviour as mediator variable

	B	Std.Error	t	p	95% CI
Model 1 (MO→ PO)					
Constant	2.963	0.106	27.896	0.000	(2.754,3.172)
AB	0.321	0.033	9.729	0.000	(0.256,0.386)

Model 1 summary: $R^2 = 0.229$; MSE = 0.467; F (1,318) = 94.648; p = 0.000

Model 2 (MO→ OCB)					
Constant	4.296	0.087	49.202	0.000	(4.124,4.468)
AB	0.017	0.027	0.640	0.523	(-0.036,0.071)

Model 2 summary: R2 = 0.001; MSE = 0.315; F (1,318) = 0.410; p = 0.523

Model 3 (MO+OCB → PO)					
Constant	0.776	0.284	2.737	0.007	(0.218,1.334)
MO	0.312	0.030	10.394	0.000	(0.253,0.371)
OCB	0.509	0.062	8.203	0.000	(0.387,0.631)

Model 3 summary: $R^2 = 0.364$; MSE = 0.386; F (2,317) = 90.832; p = 0.000

CI: Confidence interval

organisational citizenship behaviour, was not significant (B = 0.017, t = 0.640, p =0.523 >0.05). The mediating effect is significant only if the independent variable significantly affects the mediator. Thus, our result in Model 2 does not prove the existence of the mediating effect. Moreover, according to the results in Model 3, both motivation-oriented HR practices (B=0.312, t=10.394, p=0.000<0.05) and organisational citizenship behaviour (B=0.509, t=8.203, p=0.000<0.05) are significant, positive predictors of performance outcomes. The Sobel test also indicates that the relationship between the motivation-oriented HR practices and the performance outcomes was not mediated by organisational citizenship behaviour (z=0.636, p=0.525>0.05). Also, the results of the indirect effect based on 5000 bootstrap samples prove that there is no significant indirect relationship between motivation-oriented HR practices and performance outcomes mediated by organisational citizenship behaviour (effect= 0.009, Bootstrap 95%CI = -0.017 and 0.033) as seen in Table 7. Based on this result, the hypothesis, H2b is not supported by the data.

Table 6 below shows mediation analysis results for the effect of opportunity-oriented HR practices on performance outcomes through organisational citizenship behaviour as a mediation variable. In the mediation Model 1, the regression of opportunity-oriented HR practices on performance outcomes, disregarding the mediator (organisational citizenship behaviour), was significant (B = 0.354, t=10.255, p=0.000<0.05). Then the analysis results in Model 2 showed that the regression of opportunity-oriented HR practices on the mediator,

Table 6 - The effect of Opportunity-oriented HR practices on Performance Outcomes through Organisational Citizenship Behaviour as mediator variable

	B	Std.Error	t	p	95% CI
Model 1 (OP→ PO)					
Constant	2.746	0.121	22.641	0.000	(2.507,2.984)
OP	0.354	0.035	10.255	0.000	(0.286,0.422)
Model 1 summary: R^2 = 0.249; MSE = 0.313; F (1,318) = 105.171; p = 0.000					
Model 2 (OP→ OCB)					
Constant	4.204	0.101	41.766	0.000	(4.006,4.402)
OP	0.043	0.029	1.511	0.132	(-0.013,0.100)
Model 2 summary: R^2 = 0.007; MSE = 0.313; F (1,318) = 2.284; p = 0.132					
Model 3 (OP+OCB → PO)					
Constant	0.739	0.284	2.603	0.009	(0.180,1.298)
OP	0.333	0.032	10.463	0.000	(0.271,0.396)
OCB	0.477	0.062	7.681	0.000	(0.355,0.599)
Model 3 summary: R^2 = 0.367; MSE = 0.385; F (2,317) = 91.679; p = 0.000					

CI: Confidence interval

organisational citizenship behaviour, was not significant (B = 0.043, t = 1.511, p =0.132>0.05). The mediating effect is significant only if the independent variable significantly affects the mediator. Thus, our result in Model 2 does not prove the existence of the mediating effect. Moreover, according to results in Model 3, both opportunity-HR practices (B=0.333, t=10.463, p=0.000<0.05) and organisational citizenship behaviour (B=0.477, t=7.681, p=0.000<0.05) are significant, positive predictors of performance outcomes. The Sobel test also indicates that relationship between the opportunity-oriented HR practices and the performance outcomes was not mediated by organisational citizenship behaviour (z=1.485, p=0.137>0.05). Also, the results of the indirect effect based on 5000 bootstrap samples prove that there is no significant indirect relationship between opportunity-oriented HR practices and performance outcomes mediated by organisational citizenship behaviour (effect= 0.021, Bootstrap 95%CI = -0.003 and 0.044) as seen in Table 7 below. In line with these results, the hypothesis, H2c is not supported by the data.

Table 7 - Total, direct, and indirect effects

		Effect	SE	t	p	LLCI	ULCI
Ability-oriented HR practices	Total effect	0.444**	0.035	12.542	0.000	0.374	0.513
	Direct Effect	**0.418****	**0.033**	**12.824**	**0.000**	**0.354**	**0.482**
	Indirect effect[1]	**0.026**	**0.013**	-	-	**-0.025**	**0.051**
Motivation-oriented HR practices	Total effect	**0.321****	**0.033**	**9.729**	0.000	0.256	0.386
	Direct Effect	**0.312 ****	**0.030**	**10.394**	0.000	**0.253**	0.371
	Indirect effect[1]	**0.009**	0.013	-	-	-0.017	0.033
Opportunity-oriented HR practices	Total effect	**0.354 ****	**0.035**	**10.255**	0.000	0.286	0.422
	Direct Effect	**0.333 ****	0.032	10.463	0.000	0.271	0.396
	Indirect effect[1]	**0.021**	0.012	-	-	-0.003	0.044

**p <0.01, [1]Based on 5000 bootstrap samples

5. DISCUSSION

The purpose of this research was to examine whether a positive correlation was detectable between AMO-oriented HR practices and performance outcomes and to investigate the possible mediation of OCB within such relationships which was investigated through site civil engineers working in project-based temporary organisations of the Turkish construction industry. In this context, the AMO-orientation was found to be useful in determining the various effects of grouped HR practices on performance outcomes. The inclusion of OCB as a mediator in researching the relationship between HR practices and performance outcomes was found to be positive in various industries. However, the construction industry did not show similar results. The findings of the collected data indicate that OCB does not mediate the relationship between AMO-oriented HR practices and performance outcomes in the temporary natured construction projects. This indicates that the project-based nature of the construction industry and the job specification of site civil engineers are not suitable to generate a certain level of OCB to mediate the AMO-performance outcomes relationship. These results are likely to serve as a map in considering which set of HR practices to select for specific desired outcomes and the further development of site civil engineers working in temporary construction projects.

As it was hypothesised in H1a, the findings indicate that there was a positive relationship between ability-oriented HR practices and performance outcomes. This is also consistent with the current literature and research conducted in different industries [39], [45], [47]. This implies that site engineers with the right technical skills and education and who are trained well for certain strict regulations perform more effectively and efficiently on an individual level reflecting on the overall performance. Site engineers exposed to ability-oriented HR practices such as recruitment and selection and training and development develop and get encouraged to demonstrate dedication to the project while feeling valued by the project manager [47], [50]. In this way, the project manager will be the person to disperse his/her situation-based managerial abilities to the civil engineers by continuously transferring his managerial effectiveness and motivation.

The findings supported the second hypothesis, H1b, which revealed a positive relationship between motivation-oriented HR practices and performance outcomes. Current literature also states similar positive results [45], [46], [50]. Exposing site engineers to motivation-oriented HR practices such as performance appraisal and rewards clarifies their understanding of what the project manager expects regarding their task and how their contributions will be rewarded or punished in return. Employees by being informed about the performance appraisal and rewards structure will behave in line with their assigned goals and at the same time adhere to the cost-minimisation aim of their project by performing in their optimum time. As a result, value and quality features will be more evident in employee performance and the project outcomes. Investing in these practices is likely to result in increased engineer productivity and prevent them from quitting during the project as the construction site teams are frequently subject to change due to their temporariness.

The third hypothesis H1c was also supported by the findings which indicate a positive relationship between opportunity-oriented HR practices and performance outcomes. This positive relationship is consistent with the current literature [45], [59]. Although the job description of site engineers is very technical and time bound, expanding their autonomy in possible areas such as daily schedules is likely to increase their performance. Engineers desire autonomy specifically in terms of managing their own work [104]. Involving engineers in decisions regarding their work and its conditions fosters a participative environment where knowledge-sharing and communication are strengthened. Autonomy and participation create a feeling of cooperative integration and feeling of being valued resulting in better performance and positive attitudes [47], [62]. The results from H1a, H1b and H1c point out that project-based temporary organisations are dependent on investing in ability, motivation, and opportunity-based activities such as HR practices or other related facilities specifically designed for engineers.

Among the hypotheses H2a, H2b and H2c which investigated the mediating effect of OCB between ability, motivation, opportunity-oriented HR practices and performance outcomes, none were significant. Concerning the findings, this shows that OCB does not mediate the relationship between AMO-oriented HR practices and performance outcomes in the project-based temporary organisations of the construction industry. The results of H2a, H2b and H2c are not consistent with the current literature [76], [85], [86] which may be due to the complex and temporary nature of the construction industry and the job description of site civil engineers. Site civil engineers work on temporary projects of certain construction firms that approximately last between 3-6 years. As a result, they may not feel any relevance to get attached or develop OCB towards the organisation that owns the project as that relationship is limited in time. The construction industry constantly focuses on performing projects at an optimum-cost, time and efficiency and is generally based on less teamwork but more instant decision-making processes such as saving the day by managing the employee turnover rapidly. Hence, our study findings fill a relevant gap in the literature by pointing out that there is a need to focus on increasing teamwork in temporary projects.

The results of this research indicate that ability, motivation, and opportunity-oriented HR practices can potentially increase the performance outcomes of engineers in construction site projects. As mentioned, the site engineers do not generate OCB towards the organisation that owns the projects as they do not have contact or relationship with the organisation they work for. Therefore, site engineers have their loyalty toward the project manager and thus OCB is likely to be generated only towards the project manager. Our study suggests that, construction companies focus on attracting a competent project manager as well as competent teams of engineers to minimise problems that are common in the complex nature of projects. Furthermore, as the total picture of the construction industry is unpredictable in terms of keeping the employee on the project, generally HR departments take action on the instant needs of the projects that are situation-based. AMO-oriented HR practices can be suitable to be adapted on the general management processes of civil engineers working on on-site projects. These practices should be implemented carefully on construction sites since their instant nature is always subject to change and it is likely that their absence can cause greater negative effects. HR activities must be properly planned and managed in construction sites for the maximum performance where HR and project managers work closely and collaborate to achieve the best performance and belongingness from engineers.

6. THEORETICAL & PRACTICAL IMPLICATIONS

The theoretical implications of this study outline that ability-oriented HR practices to have the highest impact on performance outcomes. This indicates that site civil engineers are likely to perform better if their education and technical skills are satisfactory, and if they receive ongoing trainings on job-related matters. Opportunity-oriented HR practices are second in their effect on performance outcomes. This outcome implies that engineers need a certain degree of autonomy and a participative environment that welcomes them to be involved in decisions that may influence their work conditions. In third place, motivation-oriented HR practices have the lowest effect on performance outcomes. This may indicate that motivational matters such as rewards and performance appraisals are essential for engineers, but that they are not delivered on a satisfactory level by their organisation. OCB not mediating the relationships among ability, motivation, opportunity-oriented HR practices and performance outcomes in the project-based temporary organisations of the Turkish construction industry, is an interesting implication which may be due to the complex and temporary nature of the construction industry and the job specifications of site civil engineers.

Regarding the practical implications, the managerial bodies of the construction organisations are firstly advised to carefully select the HR practices that will function best on the construction site level. In this respect, AMO-oriented HR practices are found to be effective and suitable to be adopted, and should be integrated in constant cooperation with their project manager. Considering the ability-oriented HR practices having the highest impact on performance outcomes, it is suggested that the construction organisations strong emphasise them to achieve higher performance through their site civil engineers. Construction organisations that adopt ability-oriented HR practices are thus likely to alter their project and organisational performance. Although the opportunity-oriented HR practices were not as effective on performance outcomes as ability-oriented HR practices, they are still high in their effect. Construction organisations should plan their HR-related functions in a direction where they adopt and facilitate opportunity-oriented HR practices in a dynamic manner. In this way, their level of effectiveness on performance outcomes may increase to the level of ability-oriented HR practices' effectiveness level. In comparison to ability and opportunity-oriented HR practices, the motivation-oriented HR practices have the lowest effect on performance outcomes. Although it is the lowest, its effect is still considerably sufficient. Motivational matters are vital for site civil engineers as they have both technical and managerial responsibilities and are expected to meet strict expectations of the projects. Construction organisations should adopt motivation-oriented HR practices and transparently communicate the performance appraisal and rewards structure. As site teams are frequently subject to change due to their temporariness, motivational parameters can be seen as critical aspects for sustaining continuity on projects. Construction organisations should pay close attention to motivation-oriented HR practices and should aim to integrate attractive reward and appraisal systems and to exercise them in a way that increases them to the ability-oriented HR practices level. In order for the construction organisations to achieve maximum performance from site civil engineers, they should also focus on OCB. Engineers who are willing to go the extra mile and exercise discretionary behaviour will also become high performers as a result of being valued by their organisation. As site civil engineers are generally working with the project owner organisation for a limited time, OCB is mainly being generated towards the project managers rather than the organisation itself. Implementing and effectively exercising AMO-oriented HR practices are likely to facilitate higher levels of OCB.

In light of the above, construction organisations are advised to change their view on seeing their employees solely as a cost, but to acknowledge them as resources who are game changers. Although organisations' time with their engineers is generally limited, site civil engineers have crucial responsibilities for projects and are thus worth being invested in. This will not only maximise site civil engineer performances but will also create a quality-based construction project culture that is based on the right skills, learning, participation, autonomy and suitable reward and appraisal schemes. Giving site civil engineers professional value will also reflect on the reputation of the organisations which will result in attracting and working with the most competent civil engineers on their sites. If the majority of the construction organisations adopt these views and follow suitable up-to-date managerial innovations, it is believed that the outcomes will eventually result in higher quality projects for the Turkish construction industry in general.

7. CONCLUSION & LIMITATIONS

Construction sites hold temporary organisational features where engineers of the project disperse once the project is finalised, and they move on to their next project in their new organisation. This study contributes to the HRM and project management literature by providing insight into the relationships between AMO-oriented HR practices, OCB and performance outcomes of project-based temporary organisations through site civil engineers operating in the construction industry in Turkey. The findings indicate that the nature of the construction industry and construction projects are likely to require relevant HR practices based on the ability, motivation, and opportunity features for an enhanced performance. For achieving a successful project, HR practices must be an integral part of all construction activities. The implementation of these practices should be executed in collaboration with the project manager. The AMO-oriented HR practices are likely to strengthen the employee-employer relations and more precisely, they can assist the project manager to manage the performances of engineers, reduce the possible conflicts between management and engineers and can alter the belongingness towards the site. As a result, effective communication is likely to be generated by investing in the engineer trainings and thus a learning organization culture that is in line with organisational goals and strategies will be adopted. In short, engineers that are exposed to recruitment and selection, training and development, performance appraisal, rewards, autonomy, and participation practices can permanently modify their attitudes and behaviours incrementally through increased motivation. This positive transformation may possibly lead to a structural change that may reflect on their quality of work which they will exercise in every current and future project they work in.

This study has several limitations. Firstly, the sample does not represent all civil engineers working on sites in Turkey but was concentrated on civil engineers working in the Marmara region which limits the generalisability of the findings when conducted to a larger population. For the study's generalisability it also needs to be conducted in different countries and economies considering cultural implications. Secondly, the current study focused on site civil engineer rated answers, but further research may choose to get project managers' input for a different perspective on the issues investigated in this study. Thirdly, the data used in this study was cross-sectional which is likely to limit the causality tests and therefore a longitudinal data is believed to generate better results. Fourthly, the effect of different mediating or moderating variables such as employee perceptions, organisational commitment and leadership styles are potential topics that can be integrated for further research. Lastly, research on site civil engineers can be distinguished according to which type of construction area they operate in, such as roads, buildings, airports, tunnels, bridges, and water supply.

Acknowledgments

Authors of this study would like to thank the site civil engineers who participated to the survey.

References

[1] Purcell J, Kinnie N, Hutchinson S, Rayton B, Swart J. Understanding the people and performance link: unlocking the black box, Chartered Institute of Personnel and Development. Performance Management in Action. Current trends and practices. 2003.

[2] Sarikwal L, Gupta J. The impact of highperformance work practices and organisational citizenship behaviour on turnover intentions. Journal of Strategic Human Resource Management. 2(3), 11, 2013.

[3] Aydinli S, Mustafa OR, Emel OR. Wage determinants and wage inequalities–case of construction engineers in Turkey. TeknikDergi. 30(2), 8961-85, 2019.

[4] Abuazoom Mohamed Imhmed M, Hanafi HB, Bin Ahmad ZZ. Do Human Resource Management (HRM) Practices improve Project Quality Performance? Evidence from Construction Industry. Quality-Access to Success. 20(169), 2019.

[5] Alagaraja M. HRD and HRM perspectives on organizational performance: A review of literature. Human Resource Development Review. 12(2), 117-43, 2013.

[6] Huemann M, Keegan A, Turner JR. Human resource management in the project-oriented company: A review. International journal of project management. 25(3), 315-23, 2007.

[7] Wickramasinghe V, Liyanage S. Effects of high performance work practices on job performance in project-based organizations. Project Management Journal. 44(3), 64-77, 2013.

[8] Sydow J, Lindkvist L, DeFillippi R. Project-based organizations, embeddedness and repositories of knowledge. Organization studies. 25(9), 1475-89, 2004.

[9] Bhatti SH, Zakariya R, Vrontis D, Santoro G, Christofi M. High-performance work systems, innovation and knowledge sharing: An empirical analysis in the context of project-based organizations. Employee Relations: The International Journal. 2020.

[10] Pak K, Kooij DT, De Lange AH, Van Veldhoven MJ. Human Resource Management and the ability, motivation and opportunity to continue working: A review of quantitative studies. Human Resource Management Review. 29(3), 336-52, 2019.

[11] Briner RB, Rousseau DM. Evidence-based I–O psychology: Not there yet. Industrial and Organizational Psychology. 4(1), 3-22, 2011.

[12] Prieto-Pastor I, Martín-Pérez V, Martín-Cruz N. Social capital, knowledge integration and learning in project-based organizations: a CEO-based study. Journal of Knowledge Management. 2018.

[13] Huemann M. Human resource management in the project-oriented organization: towards a viable system for project personnel. Routledge; 2016.

[14] Bryde DJ, Wright GH. Project management priorities and the link with performance management systems. Project Management Journal. 38(4), 5-11, 2007.

[15] Boxall P, Purcell J. Strategy and human resource management. Macmillan International Higher Education; 2011.

[16] Vermeeren, B. Influencing public sector performance: studying the impact of ability-, motivation- and opportunity-enhancing human resources practices on various performance outcomes in the public sector. International Review of Administrative Sciences; 2015

[17] Organ DW. Organizational citizenship behavior: The good soldier syndrome. Lexington Books/DC Heath and Com; 1988.

[18] Sun LY, Aryee S, Law KS. High-performance human resource practices, citizenship behavior, and organizational performance: A relational perspective. Academy of management Journal. 50(3), 558-77, 2007.

[19] Kissi E, Asare OA, Agyekum K, Agyemang DY, Labaran M. Ascertaining the interaction effects among organisational citizenship behaviour, work overload and employees' performance in the Ghanaian construction industry. International Journal of Productivity and Performance Management. 2019.

[20] Paauwe J, Guest DE, Wright PM, editors. HRM and performance: Achievements and challenges. John Wiley & Sons; 2012.

[21] Turner R, Huemann M, Keegan A. Human resource management in the project-oriented organization: Employee well-being and ethical treatment. International Journal of Project Management. 26(5), 577-85, 2008.

[22] Popaitoon S, Siengthai S. The moderating effect of human resource management practices on the relationship between knowledge absorptive capacity and project performance in project-oriented companies. International Journal of Project Management. 32(6), 908-20, 2014.

[23] Nguyen TN, Quang T, Buyens D. The relationship between training and firm performance: A literature review. Research and practice in human resource management. 18(1), 28-45, 2010.

[24] Wright PM, Nishii LH. Strategic HRM and organizational behavior: Integrating multiple levels of analysis. CAHRS Working Paper Series. 2007.

[25] Minbaeva DB. HRM practices and MNC knowledge transfer. Personnel review. 2005

[26] Schuler RS, Jackson SE. Organizational strategy and organization level as determinants of human resource management practices. People and Strategy. 10(3), 125, 1987.

[27] Guest D, Conway N. The impact of HR practices, HR effectiveness and a 'strong HR system'on organisational outcomes: a stakeholder perspective. The international journal of human resource management. 22(8), 1686-702, 2011.

[28] Singh S, Darwish TK, Costa AC, Anderson N. Measuring HRM and organisational performance: concepts, issues, and framework. Management decision. 2012.

[29] Kooij DT, Guest DE, Clinton M, Knight T, Jansen PG, Dikkers JS. How the impact of HR practices on employee well-being and performance changes with age. Human Resource Management Journal. 23(1), 18-35, 2013.

[30] Bailey TR. Discretionary effort and the organization of work: Employee participation and work reform since Hawthorne. Teachers College and Conservation of Human Resources, Columbia University; 1993.

[31] Guest DE. Human resource management and performance: a review and research agenda. International journal of human resource management. 8(3), 263-76, 1997.

[32] Huselid MA. The impact of human resource management practices on turnover, productivity, and corporate financial performance. Academy of management journal. 38(3), 635-72, 1995.

[33] Dyer L, Reeves T. Human resource strategies and firm performance: what do we know and where do we need to go? International Journal of human resource management. 6(3), 656-70, 1995.

[34] Guest DE. Human resource management and performance: still searching for some answers. Human resource management journal. 21(1), 3-13, 2011.

[35] Darwish TK, Singh S, Wood G. The impact of human resource practices on actual and perceived organizational performance in a Middle Eastern emerging market. Human Resource Management. 55(2), 261-81, 2016.

[36] Inkson K, Gunz H, Ganesh S, Roper J. Boundaryless careers: Bringing back boundaries. Organization studies. 33(3), 323-40, 2012.

[37] Latorre F, Guest D, Ramos J, Gracia FJ. High commitment HR practices, the employment relationship and job performance: A test of a mediation model. European Management Journal. 34(4), 328-37, 2016.

[38] Veth KN, Korzilius HP, Van der Heijden BI, Emans BJ, De Lange AH. Which HRM practices enhance employee outcomes at work across the life-span?. The international journal of human resource management. 30(19), 2777-808, 2019.

[39] Delaney JT, Huselid MA. The impact of human resource management practices on perceptions of organizational performance. Academy of Management journal. 39(4), 949-69, 1996.

[40] Wright PM, McMahan GC. Theoretical perspectives for strategic human resource management. Journal of management. 18(2), 295-320, 1992.

[41] Appelbaum E, Bailey T, Berg P, Kalleberg AL, Bailey TA. Manufacturing advantage: Why high-performance work systems pay off. Cornell University Press; 2000.

[42] Chuang CH, Liao HU. Strategic human resource management in service context: Taking care of business by taking care of employees and customers. Personnel psychology. 63(1), 153-96. 2010.

[43] MacDuffie JP. Human resource bundles and manufacturing performance: Organizational logic and flexible production systems in the world auto industry. ilr Review. 48(2), 197-221, 1995.

[44] Gong Y, Law KS, Chang S, Xin KR. Human resources management and firm performance: The differential role of managerial affective and continuance commitment. Journal of Applied Psychology. 94(1), 263, 2009.

[45] Jiang K, Lepak DP, Hu J, Baer JC. How does human resource management influence organizational outcomes? A meta-analytic investigation of mediating mechanisms. Academy of management Journal. 55(6), 1264-94, 2012.

[46] Boon C, Belschak FD, Den Hartog DN, Pijnenburg M. Perceived human resource management practices:Their effect on employee absenteeism and time allocation at work. Journal of Personnel Psychology. *13*(1), 21–33, 2014.

[47] Chung GH, Pak J. Is there internal fit among ability-, motivation-, and opportunity-enhancing HR practices? Evidence from South Korea. Review of Managerial Science. 1-26, 2020.

[48] Lepak DP, Liao H, Chung Y, Harden EE. A conceptual review of human resource management systems in strategic human resource management research. Research in personnel and human resources management. 25, 217-71, 2006.

[49] Mohammad T, Darwish TK, Singh S, Khassawneh O. Human Resource Management and Organisational Performance: The Mediating Role of Social Exchange. European Management Review. 18(1), 125-36, 2021.

[50] Blau PM. Justice in social exchange. Sociological inquiry. 34(2), 193-206, 1964.

[51] Gardner TM, Wright PM, Moynihan LM. The impact of motivation, empowerment, and skill-enhancing practices on aggregate voluntary turnover: The mediating effect of collective affective commitment. Personnel psychology. 64(2), 315-50, 2011.

[52] Marin-Garcia JA, Tomas JM. Deconstructing AMO framework: A systematic review. Intangible Capital. 12(4), 1040-87,2016.

[53] Fletcher C. Performance appraisal and management: The developing research agenda. Journal of Occupational and organizational Psychology. 74(4), 473-87, 2001.

[54] Piaralal SK, Bhatti MA, Piaralal NK, Juhari AS. Factors affecting service recovery performance and customer service employees: A study of Malaysian life insurance industry. International Journal of Productivity and Performance Management. 65(7), 898-924, 2016.

[55] Mihardjo LW, Jermsittiparsert K, Ahmed U, Chankoson T, Hussain HI. Impact of key HR practices (human capital, training and rewards) on service recovery performance with mediating role of employee commitment of the Takaful industry of the Southeast Asian region. Education+ Training. 63(1), 1-21, 2020.

[56] Shore LM, Tetrick LE, Lynch P, Barksdale K. Social and economic exchange: Construct development and validation. Journal of applied social psychology. 36(4), 837-67, 2006.

[57] Kampkötter P, Marggraf K, Zimmermann JH. Determinants and effects of formal target agreements: an empirical investigation of German firms. Review of Managerial Science. 11(1), 1-8, 2017.

[58] O'Halloran PL. Performance pay and employee turnover. Journal of economic studies. 39(6), 653-74, 2012.

[59] Demortier AL, Delobbe N, El Akremi A. Opening the black box of hr practices-performance relationship: Testing a three pathways AMO model. In Academy of Management Proceedings, Academy of Management. 1(1), 14932, 2014.

[60] Minbaeva DB. Strategic HRM in building micro-foundations of organizational knowledge-based performance. Human Resource Management Review. 23(4), 378-90, 2013.

[61] Kehoe RR, Wright PM. The impact of high-performance human resource practices on employees' attitudes and behaviors. Journal of management. 39(2), 366-91, 2013.

[62] Morales-Sánchez R, Pasamar S. How to improve organisational citizenship behaviour by combining ability, motivation and opportunity: The moderator role of perceived organisational support. Employee Relations: The International Journal. 42(2), 398-416, 2019.

[63] Baard PP, Deci EL, Ryan RM. Intrinsic need satisfaction: a motivational basis of performance and weil-being in two work settings 1. Journal of applied social psychology. 34(10), 2045-68, 2004.

[64] Strauss G. Worker participation—some under-considered issues. Industrial Relations: A Journal of Economy and Society. 45(4), 778-803, 2006.

[65] Organ DW, Podsakoff PM, MacKenzie SB. Organizational citizenship behavior: Its nature, antecedents, and consequences. Sage Publications; 2005.

[66] Lloyd KJ, Boer D, Keller JW, Voelpel S. Is my boss really listening to me? The impact of perceived supervisor listening on emotional exhaustion, turnover intention, and organizational citizenship behavior. Journal of Business Ethics. 130(3), 509-24, 2015.

[67] Podsakoff PM, MacKenzie SB. Impact of organizational citizenship behavior on organizational performance: A review and suggestion for future research. Human performance. 10(2), 133-51, 1997.

[68] Schlechter AF, Engelbrecht AS The relationship between transformational leadership, meaning and organisational citizenship behaviour. Management Dynamics: Journal of the Southern African Institute for Management Scientists. 15(4), 2-16, 2006.

[69] Alnajdawi S, Emeagwali OL, Elrehail H. The interplay among green human resource practices, organization citizenship behavior for environment and sustainable corporate performance: evidence from Jordan. Journal of Environmental Accounting and Management. 5(3), 171-84, 2017.

[70] Kepes S, Delery JE. HRM systems and the problem of internal fit. InThe Oxford handbook of human resource management; 2007.

[71] Gong Y, Chang S, Cheung SY. High performance work system and collective OCB: A collective social exchange perspective. Human Resource Management Journal. 20(2), 119-37, 2010.

[72] Wei YC, Han TS, Hsu IC. High-performance HR practices and OCB: A cross-level investigation of a causal path. The International Journal of Human Resource Management. 21(10), 1631-48, 2010.

[73] Rurkkhum S, Bartlett KR. The relationship between employee engagement and organizational citizenship behaviour in Thailand. Human Resource Development International. 15(2), 157-74, 2012.

[74] Purcell J, Hutchinson S. Front-line managers as agents in the HRM-performance causal chain: theory, analysis and evidence. Human Resource management journal. 17(1), 3-20, 2007.

[75] Wright PM, Gardner TM, Moynihan LM, Allen MR. The relationship between HR practices and firm performance: Examining causal order. Personnel psychology. 58(2), 409-46, 2005.

[76] Taamneh A, Alsaad AK, Elrehail H. HRM practices and the multifaceted nature of organization performance: The mediation effect of organizational citizenship behavior. EuroMed Journal of Business. 13(3), 315-34, 2018.

[77] Kumar SP, Saha S. Influence of trust and participation in decision making on employee attitudes in Indian public sector undertakings. Sage Open. 7(3),2017.

[78] Schnake ME, Dumler MP. Levels of measurement and analysis issues in organizational citizenship behaviour research. Journal of occupational and organizational psychology. 76(3), 283-301, 2003.

[79] Tsui AS, Pearce JL, Porter LW, Tripoli AM. Alternative approaches to the employee-organization relationship: does investment in employees pay off?. Academy of Management journal. 40(5), 1089-121, 1997.

[80] Colquitt JA, Baer MD, Long DM, Halvorsen-Ganepola MD. Scale indicators of social exchange relationships: A comparison of relative content validity. Journal of Applied Psychology. 99(4), 599, 2014.

[81] Zhang J, Bal PM, Akhtar MN, Long L, Zhang Y, Ma Z. High-performance work system and employee performance: the mediating roles of social exchange and thriving and the moderating effect of employee proactive personality. Asia Pacific Journal of Human Resources. 57(3), 369-95, 2019.

[82] Saxena S, Saxena R. Impact of job involvement and organizational commitment on organizational citizenship behavior. International Journal of Management and Business Research. 5(1), 19-30, 2015.

[83] Morrison EW. Organizational citizenship behavior as a critical link between HRM practices and service quality. Human resource management. 35(4), 493-512, 1996.

[84] Chiang CF, Hsieh TS. The impacts of perceived organizational support and psychological empowerment on job performance: The mediating effects of organizational citizenship behavior. International journal of hospitality management. 31(1), 180-90, 2012.

[85] Memon MA, Sallaeh R, Baharom MN, Nordin SM, Ting H. The relationship between training satisfaction, organisational citizenship behaviour, and turnover intention: A PLS-SEM approach. Journal of Organizational Effectiveness: People and Performance. 4, 267-90, 2017.

[86] Cesário F, Magalhães S. Human resources management, citizenship behavior, and turnover intention in the Portuguese public administration. International Journal of Public Administration. 40(11), 979-88,2017.

[87] Aydinli S, Mustafa OR, Emel OR. Wage determinants and wage inequalities–case of construction engineers in Turkey. Teknik Dergi. 30(2), 8961-85, 2019.

[88] Saunders M, Lewis PH, Thornhill AD. Research methods. Business Students 8th edition Pearson Education Limited, England; 2019.

[89] Sekaran U, Bougie R. Research Methods For Business: A Skill Building 7 ed. Wily; 2016.

[90] Patten M, Questionnaire Research: A Practical Guide (4th ed.). Routledge; 2014.

[91] Llieva J, Baron S, Healey NM. Online surveys in marketing research. International Journal of Market Research, 44(3), 1-14, 2002.

[92] Vermeeren B, Steijn B, Tummers L, Lankhaar M, Poerstamper RJ, Van Beek S. HRM and its effect on employee, organizational and financial outcomes in health care organizations. Human resources for health. 12(1), 1-9, 2014.

[93] Podsakoff PM, MacKenzie SB, Moorman RH, Fetter R. Transformational leader behaviors and their effects on followers' trust in leader, satisfaction, and organizational citizenship behaviors. The leadership quarterly. 1(2), 107-42, 1990.

[94] Kim S. Individual-level factors and organizational performance in government organizations. Journal of public administration research and theory. 15(2), 245-61, 2004.

[95] Baron, RM, Kenny, DA. The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. Journal of Personality & SocialPsychology, 51, 1173-1182, 1986.

[96] Preacher, KJ, Hayes, AF. Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models. Behavior research methods, 40(3), 879-891,2008.

[97] Preacher KJ, Hayes AF. SPSS and SAS procedures for estimating indirect effects in simple mediation models. Behavior research methods, instruments, & computers. 36(4), 717-31, 2004.

[98] Sobel ME. Asymptotic confidence intervals for indirect effects in structural equation models. Sociological methodology. 13, 290-312, 1982.

[99] Hayes AF, Montoya AK, Rockwood NJ. The analysis of mechanisms and their contingencies: PROCESS versus structural equation modeling. Australasian Marketing Journal (AMJ), 25(1), 76-81, 2017.

[100] Uyumaz G, Mor-Dirlik E, Çokluk Ö. Açımlayıcı factor analizinde tekrar edilebilirlik: kavramveuygulama. Abant İzzet Baysal Üniversitesi Eğitim Fakültesi Dergisi, 16(2), 659- 675, 2016.

[101] İŞKUR, https://media.iskur.gov.tr/51150/insaat-sektoru.pdf, 2021, accessed on 17.06.22.

[102] TÜİK, Hane Halkı İşgücü Anketi Veri Setleri, 2016

[103] İNTES, İnşaat Sektörü Raporu, Türkiye İnşaat Sanayicileri İşveren Sendikası, Ocak, Ankara, 2019

[104] Meiksins PF, Watson JM. Professional autonomy and organizational constraint: The case of engineers. The Sociological Quarterly. 30(4), 561-85, 1989.

Appendices:

Appendix 1

Ability, motivation, opportunity (AMO) scale
a. Ability-oriented HR practices
Recruitment and selection
1. My organization conducts a careful selection and recruitment procedure before employing the employees.
2. During the selection procedure, my organization verifies carefully whether the skills of employees are in line with the function.
3. During the selection procedure, my organization verifies carefully whether the employee fits within the unit.
4. During the selection procedure, my organization verifies carefully whether training is in line with the functional requirements of the unit.
Training and development
5. My organization gives the opportunity to employees to take part in training, courses, and workshops.
6. My organization gives employees the opportunity to climb in position.
7. My organization increases the responsibilities of the employees depending on their performance.
8. My organization respects career appointments.
9. My organization enables employees to work in different units.
10. My organization tailors development opportunities of employees depending on the needs of the organization.
11. My organization encourages the skills development of employees.
12. My organization supports future development plans of employees.
13. My organization offers introduction programs to execute different job requirements (styles) of employees.
14. My organization designs specific training programs with respect to different jobs.
b. Motivation-oriented HR practices
Performance appraisal
15. My organization reviews periodically the performance of employees.
16. My organization considers the assessment of the employees as a basis for their further development.
17. My organization keeps employees informed about the performance criteria of the unit they work in.
18. My organization sends the assessment results on paper.
19. My organization addresses their functioning and the functioning of the employees in a formal meeting.
20. My organization uses clear procedures for the assessment of the employees.
21. My organization makes it clear to the employees how their work contributes to the unit achievement goals.

Rewards
22. My organization rewards employees due to their performance.
23. My organization gives pay schemes similar with other organizations.
24. My organization gives sufficient opportunities for financial growth of employees.
25. My organization offers employees attractive fringe benefits (e.g., working hours, holidays, pension scheme, childcare, parental leave, compensation for travel costs).
26. My organization allows employees to engage in the composition of their employment package.
27. My organization gives employees the opportunity to achieve a balance between their work and private life.
c. Opportunity-oriented HR practices
Autonomy
28. My organization allows the employees to decide about the execution of their duties.
29. My organization allows the employees to set their own work pace.
30. My organization allows the employees to influence on the fulfilment of their job.
31. My organization allows the employees to have the opportunity to further develop ideas about their jobs.
32. My organization allows the employees to decide on the order of their work routine.
33. My organization allows the employees to have flexible working hours.
Participation
34. My organization allows the employees to have the opportunity to get involved in the decision-making process.
35. My organization allows the employees to give their opinion in work related issues.
36. In meetings, my organization allows the employees to get involved in the decisions that are made.
37. My organization makes sure that employees are well informed about their views and policies of the organization.
38. My organization allows me to participate through the works council.
39. During work meetings, my organization makes sure agreements are made clear.
Organizational Citizenship Behaviour Scale
40. My attendance at work is above the norm.
41. I do not take extra breaks.
42. I obey company rules and regulations even when no one is watching.
43. I am one of the most conscientious employees.
44. I believe in giving an honest day‘s work for an honest day’s pay.
45. I do not consume a lot of time complaining about trivial matters.
46. I do not always focus on what‘s wrong, rather than the positive side.
47. I tend not to make a “mountain out of molehill”.
48. I do not always find fault with what the organization is doing.
49. I am not the classic “squeaky wheel” that always needs greasing.
50. I attend meetings that are not mandatory but are considered important.
51. I attend functions that are not required but help the company image.

52. I keep abreast of changes in the organization.
53. I read and keep up with organization announcements, memos, etc.
54. I take steps to try to prevent problems with other workers.
55. I am mindful of how my behaviour affects other people's jobs.
56. I do not abuse the rights of others.
57. I try to avoid creating problems for co-workers.
58. I consider the impact of my actions on co-workers.
59. I help others who have been absent.
60. I help others who have heavy workloads.
61. I help orient new people even though it is not required.
62. I willingly help others who have work related problems.
63. I am always ready to lend a helping hand to those around me.
Performance Outcomes Scale
Effectiveness
64. My work unit achieves the goals that are set.
65. My work unit performs high quality work.
66. My work unit successfully contributes to the achievement of organizational goals.
67. In my work unit, activities/projects are successfully completed.
68. My work unit performs large amounts of work.
69. The work performed by my work unit provides the public worthwhile return on their tax.
70. My work unit rarely gets complaints from stakeholders about our work activities.
71. Overall, my work unit performs well.
Efficiency
72. My work unit makes sure that an effort is performed with minimal time and money.
73. In my work unit no time is wasted.
74. My work unit makes good use of employees' knowledge and skills.
75. My work unit learns from mistakes.
76. In my work unit, no money is wasted.
77. In my work unit, people and resources are properly deployed.
78. My work unit adequately conducts relations with external parties.
Fairness
79. My work unit treats stakeholders in a fair and equitable manner.
80. No laws or rules are violated when delivering the project/service to customers, businesses, and other stakeholders.
81. The work of my unit is important for the organization.
82. The work of my work unit makes an important contribution to the quality of the organization as a whole.
83. The customer satisfaction toward my work unit is very high.
84. In general, my work unit has a good image in the organization.

Turkish Journal of Civil Engineering, 2023 59-78, Paper 717, ***Research Article***

An Experimental and Numerical Investigation on the Bending Behavior of Fiber Reinforced Concrete Beams

Mehmet Alper ÇANKAYA[1]
Çetin AKAN[2]

ABSTRACT

The effects of hooked end steel and polypropylene (PP) fibers on the behavior of large-scale doubly reinforced concrete beams under flexure were investigated using experimental and numeric methods. For this purpose, a total of eight beam specimens consisting in two groups were produced in the laboratory and three-point bending tests were conducted under monotonically increasing load. The beams in the groups were designed to have 0.86 and 1.30% tensile reinforcement ratios leading to either flexural or shear critical sections. Three out of eight were produced to be control samples and did not have any fiber additive while remaining five had 0, 0.5 and 1.0% steel or PP fibers by volume. Experimental results showed that the existence of 0.5% either type of fiber in densely reinforced specimens contributed to shear strength and allowed flexural capacities to be fully used instead of an improvement in the capacity. However, when the steel fiber ratio increased to 1.0% flexural capacity was enhanced by 10% for both type of beams. After the experimental study, the beams numerically modeled using nonlinear finite element method and flexural stiffness before yielding as well as yield strength with load carrying capacities were found to be consistent with that of experiments specifically for the beams having stirrup and steel fibers.

Keywords: Fiber reinforced concrete (FRC), bending behavior of FRC beams, polypropylene and hooked end steel fibers, nonlinear finite element analysis.

1. INTRODUCTION

Fiber reinforced concrete (FRC) has been widely used in non-critical members of civil engineering structures basically for crack control and durability [1]. Precast tunnel lining segments, concrete pavements and industrial building floors are some of the application areas

---

Note:

- This paper was received on October 25, 2021 and accepted for publication by the Editorial Board on October 10, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

• https://doi.org/10.18400/tjce.1209152

1 Izmir Katip Celebi University, Department of Civil Engineering, İzmir, Türkiye
mehmetalper.cankaya@ikcu.edu.tr - https://orcid.org/0000-0002-5491-3425

2 Izmir Katip Celebi University, Department of Civil Engineering, İzmir, Türkiye
Y190227018@ogr.ikcu.edu.tr - https://orcid.org/0000-0003-2807-4266

of FRC. Although FRC was being used only for crack width control initially, it has been started to be considered in the strength analysis of structural members [2]. However, the full potential of FRC is not still being used such as fully or partially replacement of costly and labor-intensive shear reinforcements [3].

In the literature, many studies have been undertaken regarding the shear and flexural characteristics of FRC members more specifically on the steel fiber reinforced concrete beams [3-9]. Studies concerning the shear strength revealed that elimination of stirrups is possible when hooked-type steel fibers in a volume ratio of at least 0.75% are included in the normal and high strength concrete [10, 11]. However, increasing the volumetric ratio of fibers up to 2.0% or higher might end up with a less ductile failure type [12] depending on the shear length to effective depth ratio [7]. Apart from the contribution to shear, inclusion of steel fiber was also found to be beneficial in terms of cracking and deformational behavior of RC beams subjected to flexure [8, 9]. The existence of steel fibers inhibited crack propagation, decreased the width, length and spacing of cracks [9, 13]. Additionally, it enhanced the flexural rigidity at any given load level [8] and therefore, deflection and strain in reinforcing steel substantially reduced. Besides, steel fibers were found to be effective in increasing the yield and ultimate bending moment capacity of the RC beams [7, 14]. Moreover, SFRC shows significant ductility at failure [15]. The efficiency of steel fibers regarding the performance and behavior of RC members also depends on the longitudinal reinforcement ratio. Specifically, in lightly reinforced RC beams the effect was detected to be more pronounced [13, 16] compared to that of heavily reinforced sections. However, in either case this observation was made for the beams designed to be critical in flexure and premature shear failure was prevented by providing shear reinforcements into the shear span.

PP fiber is a synthetic type of fiber with low density and modulus of elasticity [17]. From the conducted studies it was detected to be beneficial to increase the tensile and flexural strength, providing resistance to shrinkage cracking as well as good toughness in concrete structures [18-22]. In the literature it is also possible to encounter with a comparison of effect of different types of fibers into the mechanical behavior RC beams. For example, the structural tests were conducted in the study performed by [23] using hooked-end steel, PP and hybrid types of fibers. Based on the results of beam specimens failed from flexure, it was observed that the beams having 1.1% PPF exhibited a higher ductility compared to that of beam having 2.0% steel fibers for a specific amount of longitudinal reinforcement ratio. However, an opposite conclusion was reported in another experimental study [24] which can be interpreted as there is no consensus on the issue.

A significant amount of work has been conducted to investigate the effects of fibers on the behavior of RC members but very few studies [6, 10 and 11] were performed on the full or large scale, doubly reinforced RC beams similar to that of practical applications. Moreover, longitudinal reinforcement ratio as a variable was generally investigated on the beams designed to perform full flexural capacity. The current study aims not only providing an experimental insight into the effects of fiber ratio and type on the shear and flexural critical beam behavior but also attempts to understand the appropriateness and limits of selected numerical approach in modeling. For this purpose, a total of eight doubly reinforced, large-scale concrete beam specimens were constructed at the Structural Mechanics Laboratory of İzmir Katip Çelebi University and three-point bending tests were carried out under monotonically increasing load. Fiber volume fractions (V_f) and type were selected to be the main variables. Additionally, the beam specimens were designed to have two different tensile reinforcement ratios leading to either shear or flexure critical sections. Three out of eight were selected to be control specimens while the remaining five had varying volumetric fiber ratios. Except one of the beams in the control specimens, none of them had stirrups to observe the behavior free from the shear reinforcement effect. Once the experimental study completed, modified compression field theory (MCFT) based non-linear finite element (NLFE) analysis was conducted using VecTor2 [25] software. Force versus mid-span deflection curves and crack profiles were compared with that of the experiment.

2. EXPERIMENTAL STUDY

To investigate the behavior of FRC beams, eight large-scale and doubly reinforced beam specimens having 20 mm typical clear concrete cover were produced and tested, as shown in Figure 1. All the specimens had 150x200x2450 mm prismatic geometry and consisted of two groups. The first group (B1 series) was designed to have 1.30% tensile reinforcement ratio while the second group (B2 series) had 0.86% as can be seen in Figure 1. Two of those reinforcements were equipped with strain gauges from the mid-length of each beam specimen. Thus, the force occurring on the rebars could be followed. Two beams from B1 series were selected to be control specimens. One of which had a minimum shear reinforcement ratio according to TS500 [26] and calculated from Equation (1). However, rest of the specimens, including the remaining control beam, did not have any stirrups. In Equation (1), A_{sw}, b_w, s, f_{ctd} and f_{ywd} are shear reinforcement area, web thickness, spacing between stirrups, design tensile strength of concrete and design yield strength of shear reinforcement, respectively. Calculated minimum shear reinforcement ratio (0.95×10^{-3}) consequently led “s” to exceed the maximum spacing dictated by TS500 as half effective depth (d/2). Therefore, the distance between each stirrup was taken as d/2.

$$\rho_{min} = \frac{A_{sw}}{b_w s} = 0.30\,\frac{f_{ctd}}{f_{ywd}} \tag{1}$$

Table 1 - Specimen reinforcement and fiber ratios

Beam Specimen	Longitudinal Reinforcement (Bottom and Top)	Tensile Reinforcement Ratio	Fiber Type and Volumetric Ratio (%)
B1- Control w/o str	3Ø12 - 2Ø12	0.0130	No fiber
B1-Control w/str	3Ø12 - 2Ø12	0.0130	No fiber
B1-SF05	3Ø12 - 2Ø12	0.0130	Steel - 0.5
B1-SF10	3Ø12 - 2Ø12	0.0130	Steel - 1.0
B1-PPF05	3Ø12 - 2Ø12	0.0130	PP – 0.5
B2-Control w/o str	2Ø12 - 2Ø12	0.0086	No fiber
B2-SF10	2Ø12 - 2Ø12	0.0086	Steel – 1.0
B2-PPF05	2Ø12 - 2Ø12	0.0086	PP – 0.5

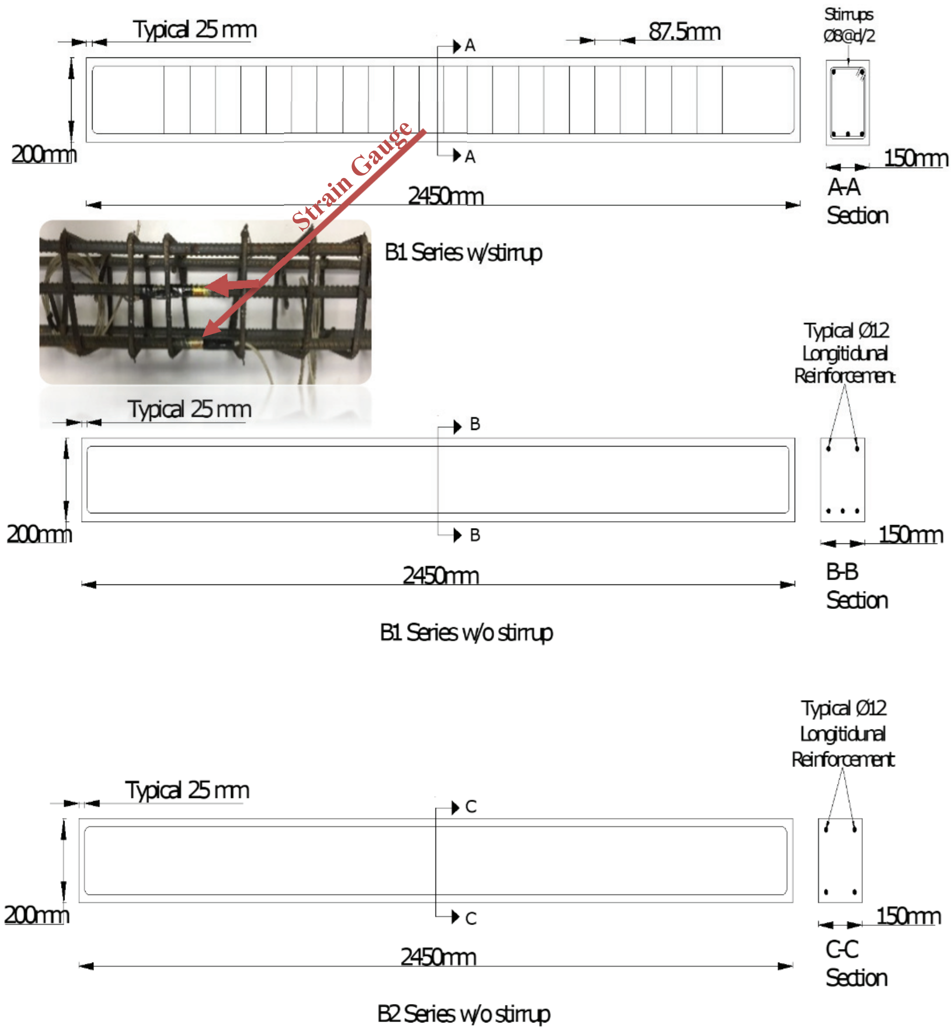


Figure 1 - Side-view and cross sections of specimen groups

Relatively low tensile reinforcement ratio in B2 series caused a tendency to flexural type of failure. Therefore, the effectiveness of stirrups was not investigated in B2 series. As a result, only one beam was selected to be the control specimen without stirrup. None of the control beams had fiber content while the remaining beams had various ratios of steel and PP fibers. A detailed list of beams that includes the fiber reinforcement type and ratio is presented in Table 1.

According to naming convention given in Table 1, first letter and the following number stand for the group of beams related to tensile reinforcement ratio. The letters with numbers after the group name represent the type and ratio of fiber reinforcement. For example, B1-SF05 is for the beam having 1.3% tensile reinforcement and V_f=0.5% steel fiber. In the current study, the ratio of shear span (a=1000 mm) to effective depth (d= 174 mm) was calculated to be 5.75 for both B1 and B2 series. This ratio yields to either diagonal tension failure or flexural failure in the beams that does not have any stirrups or fibers depending on the flexural capacity provided by tensile reinforcement.

Commercially available B420C grade deformed bars were ordered and used for longitudinal and shear reinforcements. Yield and ultimate strength of reinforcements were obtained through the tension tests as 500 and 670 MPa, respectively. Three 30-cm long coupons were used for the tests and the average of the results was taken. On the other hand, necessary limited volume of each batch of concrete was mixed in the laboratory utilizing a concrete mixer and poured into the formworks, as shown in Figure 2. ACI 211.1 [27] code, which is nearly identical to TS-802 [28], was followed to determine mixture ingredients and proportions of concrete considering slump, maximum aggregate size, mixing water, air volume, water/cement (W/C) ratio, cement and aggregate amount. According to sieve analysis maximum aggregate size was detected as 16 mm and W/C ratio was selected based on the aimed strength (at least 20 MPa cylinder compressive strength) of concrete. Mixture design is given in Table 2.

Figure 2 - Steps of concrete pouring

Table 2 - Mix proportions of concrete

W/C ratio	Cement content (kg/m³)	Water (kg/m³)	Aggregate (kg/m³)	Steel Fiber (kg/m³)	PP Fiber (kg/m³)	Air content
0.55	414.5	228.0	1557	39.25 and 78.50 (0.5% and 1.0%)	4.550 (0.5%)	2.5%

The workability of concrete decreased during the pouring process as the fiber content increased. Such an observation was also reported by [22]. Therefore, a proper vibration was given to the fresh concrete in the formworks. Next, concrete samples were randomly taken from different batches to perform compression tests. Six standard cubes were used for this purpose. The cube samples were kept by the beam specimens in the same curing conditions with beam specimens. Once the concrete hardened the formworks were removed. Afterwards, the cubes and beam specimens were wrapped with cloth sheeting and then the surfaces were properly ponded with water for 28 days. Compression tests of cube samples were performed at the day of experiment which is not less than 28 days after casting. Strength values of the cube samples were converted to equivalent cylinder values by multiplication of 0.85 based on [29]. Mean cylinder strength of the concrete was calculated as 25 MPa. Hooked end type “Betonfiber 1050” steel, and “Betonfiber BF19” polypropylene (PP) fibers were used in the study and the mechanical and geometric properties were obtained from the manufacturer and presented in Table 3.

Table 3 - Physical properties of fibers

Material	Length (mm)	Diameter	Density	Tensile Strength
Steel Fiber	50 mm	1.0 mm	7850 kg/m^3	1100 MPa
PP Fiber	19 mm	20 µm	910 kg/m^3	575 MPa

Figure 3 - Overview of test setup (left) and instrumentation for experiments (right)

Static three-point bending test setup is given in Figure 3. As seen from the figure above, beam specimens were placed into the rigid frame and clear span between roller and pin supports was 2000 mm. The beams were pushed downwards by a single load from the mid-span using a 300 kN capacity hydraulic jack. A load cell was placed under the hydraulic jack for detecting the load exerted to beam, and mid-span deflection was monitored via two linear resistance potentiometer transducers (LRPT). The sensors were connected to an 8-channel data acquisition device for gathering the data.

The loading protocol was monotonic until the empirically calculated plastic moment capacity (M_p) is reached in the experiments except for B1 and B2 cases without stirrup. The specified load is regarded as load carrying capacity of each test specimen. M_p was calculated based on Equation (2) as given in Turkish Seismic Code 2018 [31].

$$M_p = 1.4M_r \tag{2}$$

Due to the complexity in calculating the ultimate moment capacity (M_r) of the beams having fiber additive, an approximation was made in Equation (2) by replacing M_r with yield moment capacity (M_{ry}). However, it is understood from the study performed by [32] such a simplification will end up with a higher capacity than it is supposed to be, specifically for the beams having relatively high tensile reinforcement ratio. As reported in [32] the error could be up to 15%. Considering this error, the capacity was defined to be $1.20M_{ry}$ in the current study. Consequently, the experiments were stopped when the load exceeded the yield capacity by 20%.

3. RESULTS AND DISCUSSION

3.1. Sectional Analysis

Beam sections of the control specimens without stirrup were analyzed to capture yield and ultimate moment capacities. Contribution of tension stiffening effect and strain hardening in rebars were considered in the analyses. As it can be seen from Figure 5, in the experiments tension reinforcements yielded at an approximate strain of 2.5×10^{-3}. This value corresponds to 500 MPa tensile stress and used in the cross-sectional analysis. Concrete crushing strain was taken to be 3.0×10^{-3} as suggested in TS500. In both beam types, tension reinforcements were detected to be yielded before the compression crush of concrete. In addition to flexural analysis, diagonal tensile (shear) strength of beams was also calculated. For this purpose, Equation (3) suggested by ACI 318-19 [30] code was used since size effect (depth of member) and contribution of longitudinal reinforcement ratio on shear strength are taken into consideration.

$$V_c = 0.66\lambda_s\lambda\rho^{1/3}\sqrt{f_c'}b_w d \tag{3}$$

In the equation, V_c, λ_s, λ, ρ, f_c', b_w and d represent shear strength of concrete, size effect factor, modification factor for concrete material, tensile reinforcement ratio, compressive strength of concrete, width of beam and effective depth, respectively. Based on the findings in sectional analyses, shear failure type is expected for B1 control specimen since the load carrying capacity provided by shear strength of the beams is less than that of flexure. However, the capacities gathered from flexure and shear were approximate to each other for B2 control specimen, therefore, a specific failure type could not be estimated. Analysis results are tabularized in Table 4 and further details of flexural analysis can be found in [33].

Table 4 - Sectional analysis of control specimens

Specimen	Flexure				Shear		Expected type of failure
	M_{ry} (kNm)	P_{ry} (kN)	M_r (kNm)	P_r (kN)	V_s (kN)	P_s (kN)	
B1 Control w/o Stirrup	25.6	51.3	27.1	54.2	20.2	40.5	Shear before yield
B2 Control w/o Stirrup	18.4	36.9	19.8	39.5	17.7	35.4	Flexure and/or shear

*P_{ry} and P_r are yield and ultimate load capacities, respectively. V_s and P_s are shear strength and corresponding point load.

3.2. Behavior under Load

The load-midspan deflection curves of the tested beams were presented in Figure 4 to investigate the behavior under loading. It can be deduced from the curves that B1 control specimen w/o stirrup yielded at 44.0 kN. However, the yield strength was detected to be 51.3 kN in the pure flexural analysis of cross-section, indicating an error of 16%. The reason for this error can be attributed to additional strain on longitudinal reinforcements caused by shear [34]. Due to safety concerns and expectation of brittle type of failure, the experiment was stopped when the load reached to 48.5 kN and a corresponding mid-span deflection of 20 mm. Therefore, 48.5 kN is assumed to be the experimental load carrying capacity of the specimen in the study. On the other hand, introducing a minimum amount of shear reinforcement (B1 control w/stirrup), 0.5% steel (B1-SF05) and PP (B1-PPF05) fibers did not promote the yield moment capacity, but instead, allowed the beams to fully employ their yield moment capacity by reaching a load almost identical to that of flexural analysis as 51.0 kN. In other words, the shear critical behavior of those beams shifted into the flexural. However, increasing the volumetric ratio of steel fibers to 1.0% did not only transform the shear critical behavior into flexural but also slightly enhanced the yield loading (10%) of B1-SF10 specimen, basically depending on the increase in the moment capacity of the cross-section. Such an enhancement in moment capacity was also reported by [23] on the moment-curvature diagrams of beams including 2.0% and 1.1% steel and PP fibers. Loading of beams continued after yielding and resulted in strain hardening of reinforcements. Strain hardening behavior consequently increased the load carrying capacity of members rapidly until crushing of the outermost shell of concrete and resulted in a minor reduction in load carrying capacity, see Figure 4 (left). Of course, this is not the case for B1 control w/o stirrup since the loading was stopped at relatively earlier stage. As previously mentioned, the tests were continued until 1.20 times of yield strength, which was regarded as load carrying capacity. Three beam specimens, namely: B1 control w/stirrup, B1-SF05, and B1-PPF05, attained load-carrying capacities in the vicinity of 60.0 kN. This is equal to the analytically calculated capacity ($1.20P_{ry}$) of B1 control w/o stirrup but at least 1.25 times that of the experiment. As expected, B1-SF10 beam specimen performed the highest bearing capacity compared to the remaining beams of the B1 series and enhanced the load carrying capacity by 10% with respect to the specimens that can fully use their flexural capacity.

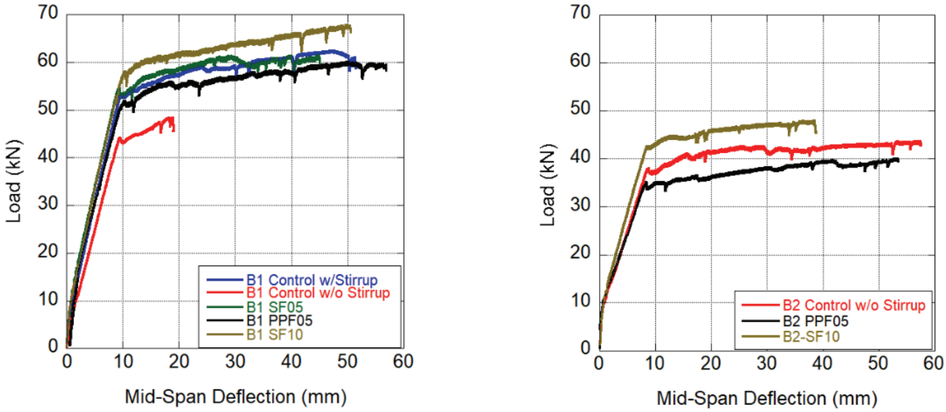


Figure 4 - Load-displacement curves of B1 (left) and B2 (right) series

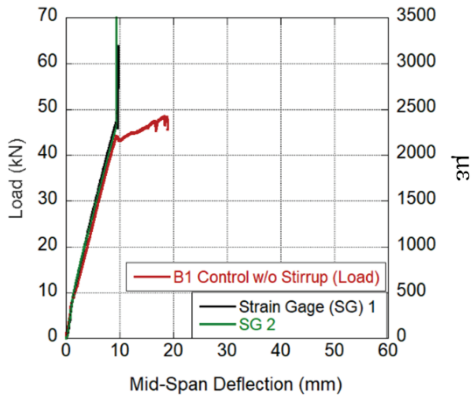


Figure 5 - Relationship of midspan deflection with load and rebar strain history

In B2 series, lower tensile reinforcement ratio resulted in a dominating flexural behavior and led control specimen to employ fully its yield strength by reaching 37.0 kN being identical to that of analytically calculated case. The experiment of this specimen was stopped at 42.0 kN load corresponding to $1.13M_{ry}$ instead of $1.20M_{ry}$. This was mainly to prevent a sudden failure since the strength provided by flexural and shear capacities was in proximity with each other though the specimen was fully used its yield moment capacity. Existence of 1.0% steel fibers in B2-SF10 beam has increased the yield load capacity approximately by 8% compared to the experimentally and analytically detected yield loading capacity of B2 control w/o stirrup. Interestingly, a slight reduction approximately 7% in the yield load capacity of B2-PPF05 beam was noticed. The reason for this might be explained by reduced compressive strength of fiber reinforced concrete mixture as detected in [35] depending on a higher porosity and air content in the matrix as reported in [36]. Load carrying capacity was observed to be highest for the specimen having 1.0% steel fiber. It is 1.10 times that of B2 control specimen experimental and analytical results. In fact, the enhancement in load capacity was found to be identical with that of B1-SF10 beam. Such an increase in the ultimate strength was also reported in the parametric study conducted by [14] for the large-scale and normal-strength concrete beams which were designed to fail in flexure. The enhancement was detected to be 11, 12, and 8.0% for the beams having 1.00% steel fiber and 1.18, 1.77, and 2.37% longitudinal reinforcement ratios, respectively. Therefore, it is understood that the strength improvement is almost free from the reinforcement ratio based on the findings of [14] and the current study. The minor reduction in the capacity of specimen having 0.5% PP fiber did not change throughout the loading history and kept 7% decrease in load bearing capacity compared to B2 control beam.

3.3. Ductility

Ductility index (μ) of a beam was defined as the ratio of the deflection at load carrying capacity to the deflection in which the specimens ceased to exhibit their linear behavior. Table 5 summarizes the ductility index values of whole specimens.

Table 5 - Ductility index of B1 and B2 series

Specimen	B1 Control w/o str.	B1 Control w/str.	B1 SF05	B1 SF10	B1 PPF05	B2 Control w/o str.	B2 SF10	B2 PPF05
Ductility index (μ)	2.00	4.77	4.45	5.00	5.68	7.12	4.75	6.80

In B1 series, all the specimens having fiber content performed better ductility response when compared to B1 control w/o stirrup. Interestingly, the highest ductility performance was observed at B1-PPF05 specimen. In other words, PP fibers provided better ductility response compared to that of the beam having a minimum shear reinforcement ratio based on TS500 and steel fiber. A similar finding was indicated in [35] for the full-scale beams that were critical in flexure. In the study, the specimen having 1.0% PP fiber performed superior ductility performance not only against the beams having 0.5 and 1.0% SF but also the beam with stirrup. On the other hand, it can be said that addition of 0.5% steel fibers also improved the ductility quite good and exhibit almost identical performance relative to the beam having minimum amount of shear reinforcement (B1 Control w/stirrup). Increasing the steel fiber ratio to 1.0% caused a very limited contribution (12% enhancement) on the ductility when compared to addition of 0.5% steel fiber. Ductility also affected by the ratio of tensile reinforcement and was greatly enhanced in B2 series except B2-SF10 beam. However, fibers were detected to have reverse effect when compared to B1 series since the ductility of specimens having fibers in B2 series was below the control specimen. Therefore, it can be concluded that depending on the tensile reinforcement ratio fibers decreased the ductility performance of beams. On the other hand, as in B1 series 0.5% PP fiber provided higher ductility than that of specimen having 1.0% steel fiber.

3.4. Crack Patterns

The final state of crack patterns is presented in Figure 6 and 7 for B1 and B2 series respectively. As can be seen from Figure 6, in B1 control beam w/o stirrup a major flexural crack (2-3 mm wide) was observed in the maximum moment region by some additional hairline thick flexural-shear cracks distributed along the length of beam.

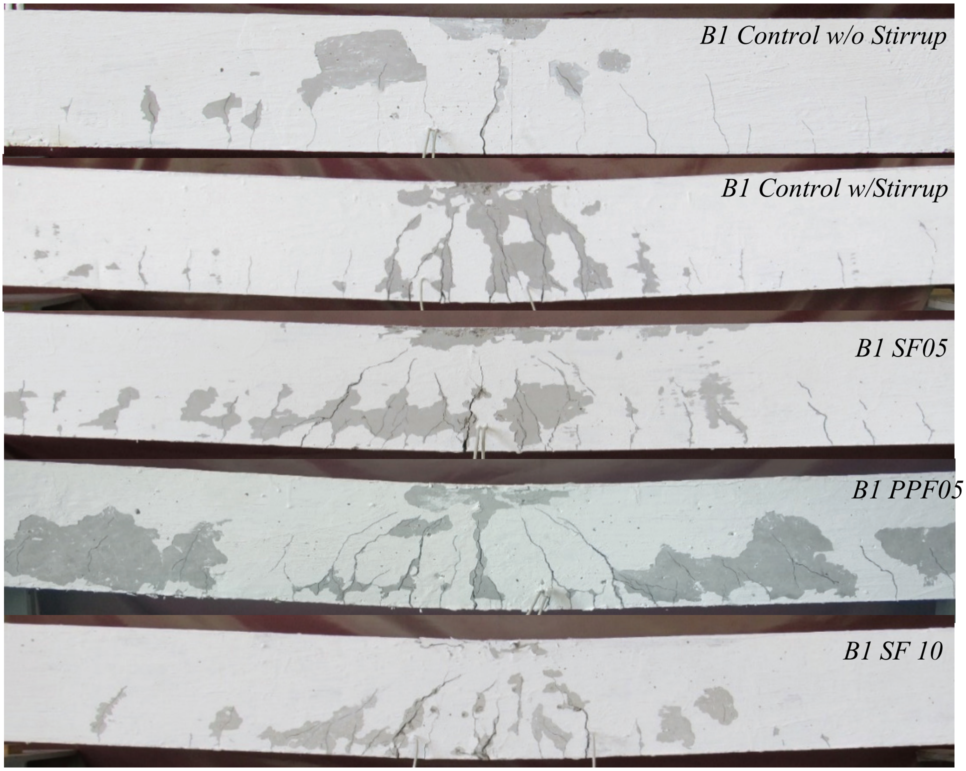


Figure 6 - Final state of crack patterns in B1 series

Widespread and almost equally spaced, hairline thick flexural cracks shifting to inclined shear cracks were observed on both sides of the B1 control specimen w/stirrup. Additionally, major flexural cracks (4-5 mm thick) starting from the bottom towards the load were noticed specifically at the loading cone. Shear cracks were more prominent in B1-SF05 specimen compared to B1 control w/stirrup as shown in Figure 6. Formation of approximately 1 mm wide and symmetrically located shear cracks on both sides were detected as well as hairline thick web shear cracks along the beam length. In the loading zone of both sides, flexural cracks reached the width of 5 mm identical to B1 control specimen w/stirrup. When it comes to B1-SF10 specimen, approximately 2 mm thick and symmetrically located flexural-shear cracks were observed on both sides of the specimen in addition to web shear cracks identical to B1-SF05. Again, major flexural cracks such as 3 to 5 mm wide were observed in both faces of the beam specifically at the loading cone. However, in B1-SF10 specimen the number of crack formation decreased while only a few cracks widen significantly more than the other cracks compared to B1-SF05 and B1 control w/stirrup (Figure 6). This is consistent with the findings of [1]. In B1-PPF05 specimen, the total number of cracks spreading on the sides slightly increased when compared to the beams having steel fiber (Figure 7). In fact, the reason for this might be the higher deformation level as well. However, most of the cracks were in web shear crack form similar to that of beams having steel fiber. Another interesting point was observing narrower flexural cracks (~2mm) especially in the loading cone. As in B1 series beams, most of the major cracks in B2 control specimen w/o stirrup were located in the loading cone. These were 2 to 3 mm wide flexure and flexural-shear cracks in both sides of the beam. Other than that, widely distributed hairline thick flexural-shear cracks were observed. However, in B2-SF10 beam cracks were formed less in quantity specifically on one side compared to control specimen, and they were concentrated in the loading region. Maximum width of flexural cracks detected was 2 to 4 mm. Shear cracks were in the vicinity of 1 mm. In B2-PPF05 the shear cracks observed in the loading region were more prominent, which is reaching to 2~2.5 mm, relative to B2-SF10.

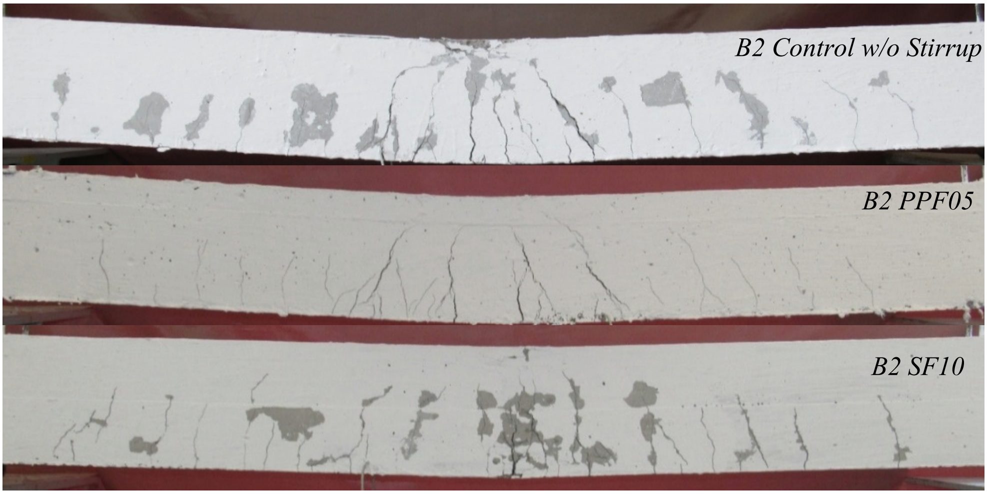


Figure 7 - Final state of crack patterns in B2 series

4. NUMERICAL MODELING AND COMPARATIVE RESULTS

Three-point bending test simulations were conducted by VecTor2 (VT2) [25] software. It is a two-dimensional nonlinear finite element code developed for the analysis of RC members in plane stress conditions and based on Modified Compression Field Theory (MCFT) formulations [37]. This theory is an analytical tool for predicting the load-deformation response of RC membrane elements subjected to shear and normal stresses. It is a combination of three sets of relationships, namely: (1) compatibility conditions of concrete and reinforcement average strains, (2) equilibrium conditions relating the external loads and internal resisting forces in concrete and reinforcement and (3) constitutive relationships which are required to provide a connection between average stresses in the equilibrium relations and average strains in the compatibility relationships for both the reinforcement and the concrete. Further details of the theory and finite element implementation can be found in elsewhere [25, 37].

Full-scale models of the beam specimens were created using preprocessor FormWorks [25] software. In the analyses, concrete and rebars were modelled using four-node plane stress rectangular elements and two-node truss bar elements, respectively. Between concrete and rebars perfect bond assumption was made and truss elements of rebars shared the same node with that of rectangular elements of concrete. Selected constitutive models for concrete and steel reinforcement is presented in Table 6. The compressive strength of concrete, yield, and ultimate strength of steel rebars as well as length, diameter and tensile strength of fibers were taken from the conducted material tests. Rest of the required parameters were taken as software default which can be found out in [25].

Table 6 - Selected constitutive models for materials used.

Material and property	Model
Concrete - Compression Pre-Peak	Beams w/o fibers: Hognestad (Parabola) Beams w/SF and PPF: Lee et al 2011 (FRC) Beams w/PPF: Popovics (NSC)
Concrete - Compression Post-Peak	Beams w/o fiber: Modified Kent-Park Beams w/SF: Lee et al 2011 (FRC) Beams w/PPF: Montoya 2003
Concrete – Compression Softening	Vecchio 1992-A (e1/e2 form)
Concrete – Tension Stiffening	Beams w/o PP fibers: Lee 2010 (w/Post Yield) Beams w/PP fiber: Modified Bentz 2003
Concrete – Tension Softening	Beams w/o fiber: Linear Beams w/PP fiber: Bilinear Beams w/steel fibers: Exponential
FRC Tension	SDEM – Monotonic
Steel Reinforcement - Dowel Action	Tassios (Crack Slip)
Steel Reinforcement -Buckling	Akkaya 2012 (Modified Dhakal - Maekawa)

* *FRC and NSC stand for fiber reinforced concrete and normal strength concrete.*

Pin and roller supports of the beam specimens were not explicitly modeled, instead; translational restraints were assigned in X, Y and Z directions and the beam specimens were subjected to monotonically increasing deflection (0.1 mm increments) from the mid-span until failure. The optimum mesh density was selected based on the mesh sensitivity analysis as 15 mm with a limitation in the aspect ratio to be two.

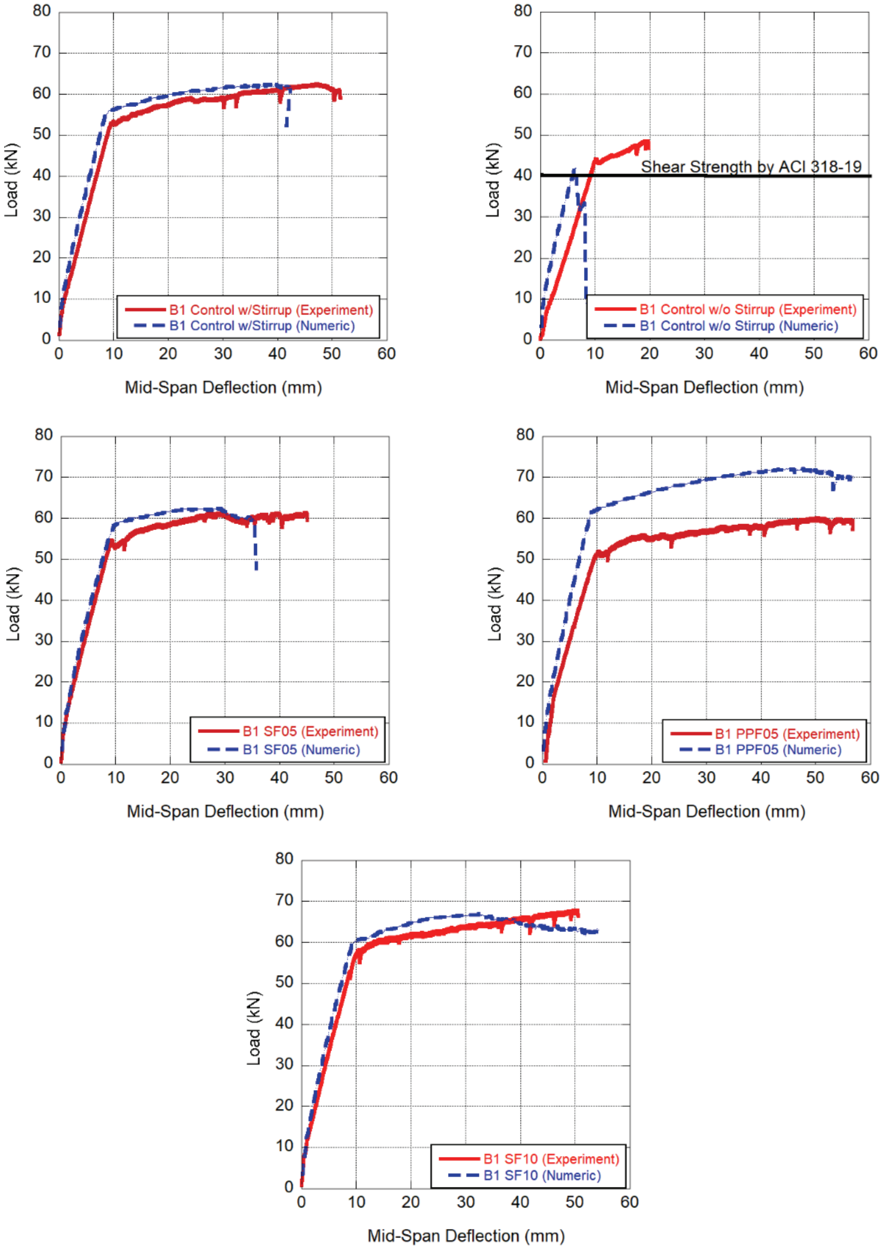


Figure 8 - Comparison of numerical and experimental results for load-deflection curves of B1 series

Numerically and experimentally obtained load-deflection responses of B1 series are presented comparatively in Figure 8 and crack patterns are given in Figure 9. In the analysis, the yield strength and load carrying capacity of B1 control beam w/stirrup was estimated quite close but with a slight overestimation to that of experiment (Figure 8). Additionally, flexural stiffness before yielding was also in close proximity with that of experiment. This was observed from the slope of load-deflection responses. Similar to the experiment the major flexural and flexural-shear cracks were located in the maximum moment region and consequently flexural failure was observed in the numerical analysis as seen in Figure 9. On the other hand, numerical analysis results of B1 control beam w/o stirrup indicated a premature failure before yielding of tensile reinforcements which is a sign of brittle shear fail. In fact, this coincides well with that of analytically calculated shear strength being less than the flexural capacity. Moreover, the crack pattern obtained through numerical analysis also confirmed a shear failure by diagonal (shear) cracks located on the web, Figure 9. Finally, the flexural stiffness of this beam was calculated to be 1.35 times higher than that of experiment. The reason for higher stiffness can be attributed to the difference between the obtained crack patterns of the experiment and analysis.

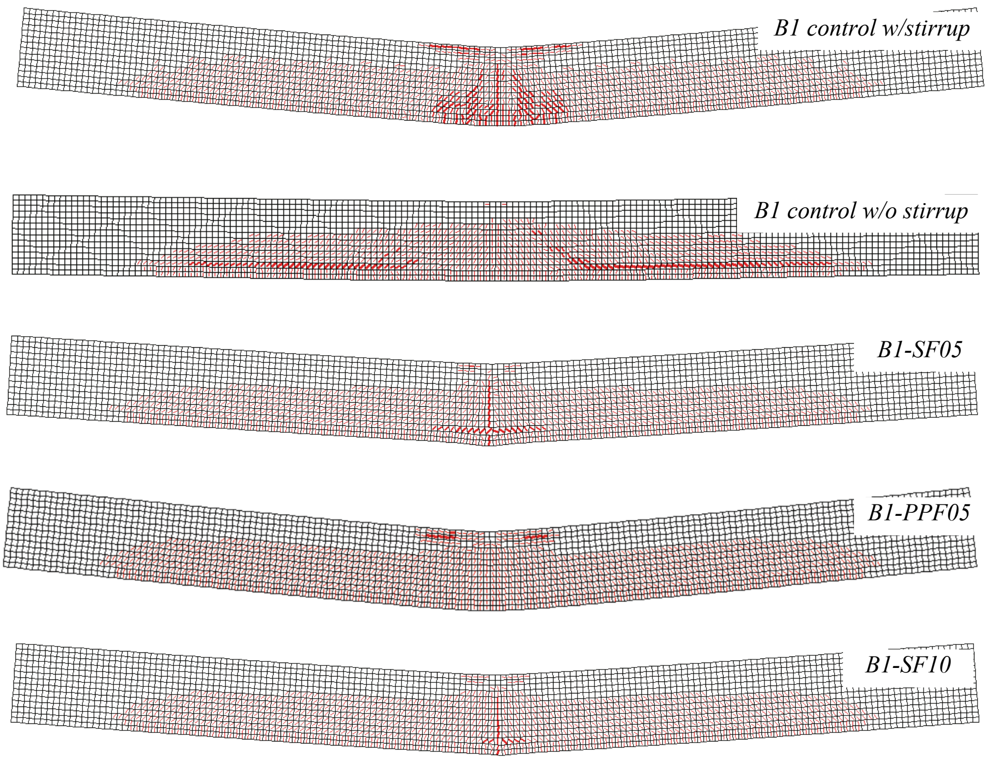


Figure 9 - Crack patterns of B1 series corresponding to peak load

Figure 8 shows that the existence of any type of fiber prevented the premature shear failure and allowed the tensile reinforcements to be yielded. In the analysis of beams having 0.5 and 1.0% steel fiber, the yield strength and corresponding deformation as well as the load carrying capacity and flexural stiffness were satisfactorily captured by a slight and negligible overestimation. However, the yield strength, load carrying capacity and flexural stiffness were estimated above from the experimental results of B1-PPF05 beam. On the other hand, once the capacity load was reached for the beams having steel fibers, localized flexural cracks were developed in the maximum moment region with the shear cracks in the tension region (Figure 9). This shear cracks were suddenly propagated along that region as the deflection increased and caused strength loss.

Load-deflection curves of B2 series from experiments and numerical analysis are presented in Figure 10. Crack patterns are given in Figure 11. Similar to B1 control beam, a premature shear failure before yielding of tensile reinforcements was observed in the numerical analysis of B2 control w/o stirrup. The shear strength is almost consistent with the one analytically calculated. Additionally, the failure type can be also confirmed by the shear cracks at the reinforcement layer, which is then extended into the compression zone, Figure 11. Finally, the flexural stiffness before yielding was estimated well.

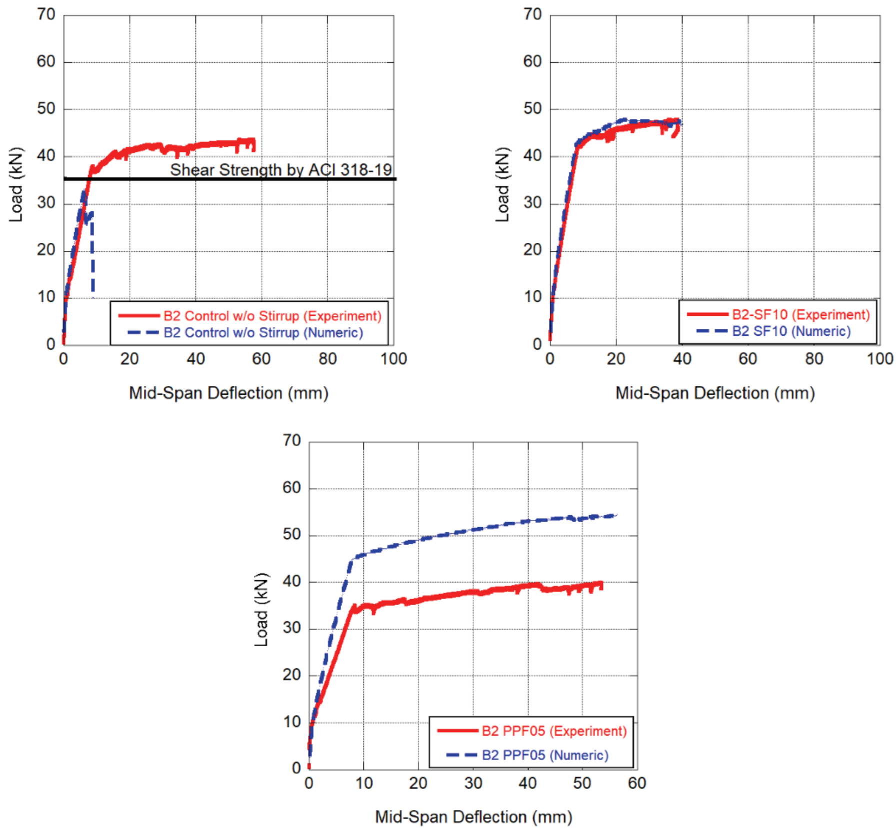


Figure 10 - Comparison of numerical and experimental results for load-deflection curves of B2 series

Identical to B1 series, inclusion of fibers into the beams of B2 series allowed flexural capacity to be fully used for both B2-PPF05 and B2-SF10 beams. The yield strength and the load carrying capacity of the beam having SF could be estimated precisely. On the other hand, similar to B1-PPF05 beam, they were overestimated for the beam having PPF in the analysis. However, it should be noted that the overestimation exaggerated in B2-PPF05. The flexural stiffness before yielding was investigated next. The numerical analysis results of B2 control and B2-SF10 beams agreed well with that of the experiment while 1.45 times higher stiffness was detected for the beam containing PPF. When it comes to crack patterns, it can be said that once B2-SF10 beam attained the load carrying capacity, a localized flexural crack in the maximum moment region was detected. As the load increased the shear cracks propagated along the tension region.

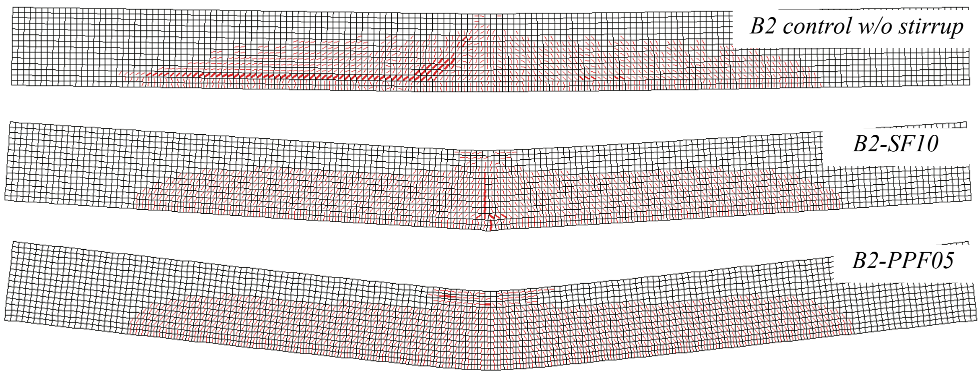


Figure 11 - Crack patterns of B2 series corresponding to peak load

5. CONCLUSION

The effect of fiber type and ratio on the bending behavior of large-scale, doubly reinforced RC beams having various tensile reinforcement ratios that lead to shear and flexural critical designs were investigated experimentally and numerically. Beyond these, the study also aims to provide experimental data into the literature.

The following conclusions can be deduced based on the above discussions.

- In densely reinforced beams (as in B1 series) providing at least 0.5% hooked end steel or PP fiber led the beam specimens to fully use their flexural capacity instead of an enhancement in flexural capacity. However, in lightly reinforced beams (as in B2 series) inclusion of 0.5% PP fibers was not found to be beneficial to improve the flexural capacity. Therefore, the effect of 0.5% fiber content on the behavior was detected to be dependent on the tensile reinforcement ratio.

- Both fiber types with V_f= 0.5% contribute to the shear strength similar to the beam having a minimum amount of stirrup in B1 series. For that reason, replacement of the minimum amount of stirrups according to TS500 by a fiber ratio of at least 0.5% seems feasible in such types of beams as offered in ACI318 code.

- The existence of 1.0% steel fiber was found to be beneficial to improve the flexural strength regardless of the tensile reinforcement ratio. Consequently, the load carrying capacity enhanced by 10% in both beam series.
- Usage of PP fiber was found to be beneficial in improving ductility in the B1 series compared to steel fibers. Moreover, steel fibers substantially decreased the ductility in the B2 series.
- MCFT based nonlinear finite element analysis provided acceptable results in prediction of yield and ultimate strength as well as stiffness before yielding specifically for the beams having steel fiber and stirrup. The behavior could not be estimated accurately for the control beams w/o stirrups. A brittle shear failure was detected, and the tensile reinforcements did not even yield. The reason for this premature failure might be explained by the difference between the actual and assumed tensile strength of concrete material.
- The general trend of load-deflection response of beams having PP fibers in B1 and B2 series could be predicted in good accordance with the experiment. But yield and ultimate strengths were overestimated in the analysis. Therefore, the selected constitutive models for PP fiber reinforced concrete and the second order effects such as tension stiffening were found to be partly successful.

Acknowledgements

This work was supported by the Scientific Research Division of Katip Çelebi University with the grant number 2021-TYL-FEBE-002.

References

[1] Saatçi, S., ve Batarlar, B., Çelik fiber katkılı etriyesiz betonarme kirişlerin davranışı. Journal of the Faculty of Engineering and Architecture of Gazi University, 32:4, 1143-1154, 2017

[2] Folino, P., et. al., Comprehensive analysis of fiber reinforced concrete beams with conventional reinforcement. Engineering Structures, 202, 2020

[3] Amin, A. and Foster, S. J., Shear strength of steel fibre reinforced concrete beams with stirrups. Engineering Structures, 111, 323-332, 2016

[4] Arslan, G., et al. An experimental study on the shear strength of SFRC beams without stirrups. Journal of Theoretical and Applied Mechanics, 55:4, 1205-1217, 2017

[5] Lee, S.,-G., et al. Analysis of steel fiber-reinforced concrete elements subjected to shear. ACI Structural Journal, 113:2, 275-285, 2016

[6] Mahmood, S., M., F., et al. Flexural performance of steel fibre reinforced concrete beams designed for moment redistribution. Engineering Structures, 177, 695-706, 2018

[7] Xu, C., et al. Experimental investigation of the behavior composite steel-concrete composite beams containing different amounts of steel fibres and conventional reinforcement. Construction and Building Materials, 202, 23-36, 2019

[8] Dwarakanath, H., V., and Nagaraj, T., S., Deformational Behavior of Reinforced Fiber Reinforced Concrete Beams in Bending. Journal of Structural Engineering, ASCE, 118:10, 2691-2698, 1992.

[9] Vandewalle, L., Cracking behavior of concrete beams reinforced with a combination of ordinary reinforcement and steel fibers. Materials and Structures, 33, 164-170, 2000.

[10] Dinh, H., H., et al. Shear behavior of steel fiber reinforced concrete beams without stirrup reinforcement. ACI Structural Journal, 107:5, 597-606, 2010

[11] Yoo, D., -Y., et al. Feasibility of replacing minimum shear reinforcement with steel fibers for suitable high-strength concrete beams. Engineering Structures, 147, 207-222, 2017

[12] Abbas, A., A., et al. Shear behavior of steel-fibre-reinforced concrete simply supported beams. Structures and Buildings, 167:SB9, 544-558, 2014

[13] Oh, B., H., Flexural Analysis of Reinforced Concrete Beams Containing Steel Fibers. Journal of Structural Engineering, ASCE, 118:10, 2821-2835, 1992.

[14] Ashour, S., A., et al., Effect of the concrete compressive strength and tensile reinforcement ratio on the flexural behavior of fibrous concrete beams. Engineering Structures, 22, 1145-1158, 2000.

[15] Lim, T-Y., et al., Behavior of Reinforced Steel-Fiber-Concrete Beams in Flexure. Journal of Structural Engineering, ASCE, 113:12, 2439-2458, 1987.

[16] Ning, X., et al., Experimental study and prediction model for flexural behavior of reinforced SCC beam containing steel fibers. Construction and Building Materials, 93, 644-653, 2015.

[17] Wu, Y., Flexural Strength and Behavior of Polypropylene Fiber Reinforced Concrete Beams. Journal of Wuhan University of Technology- Mater. Sci. Ed., 17:2, 54-57, 2002.

[18] Alhozaimy, A., M., et al., Mechanical Properties of Polypropylene Fiber Reinforced Concrete and the Effects of Pozzolanic Materials. Cement and Concrete Composites, 18, 85-92, 1996.

[19] Tutanji, H., A., Properties of polypropylene fiber reinforced silica fume expansive-cement concrete. Construction and Building Materials, 13, 171-177, 1999.

[20] Banthia, N., and Gupta, R., Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. Cement and Concrete Research, 36, 1263-1267, 2006.

[21] Sivakumar, A. and Santhanam, M., Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres. Cement and Concrete Composites, 29, 603-608, 2007.

[22] Hsie, M., et al., Mechanical properties of polypropylene hybrid fiber-reinforced concrete. Materials Science and Engineering A, 494, 153-157, 2008.

[23] Monteiro, V., M., A., M., et al. On the mechanical behavior of polypropylene, steel and hybrid fiber reinforced self-consolidating concrete. Construction and Building Materials, 188, 290-291, 2018

[24] Karimipour, A., and Ghalehnovi, M., Comparison of the effect of the steel and polypropylene fibres on the flexural behavior of recycled aggregate concrete beams. Structures, 29, 129-146, 2021

[25] Vecchio, F. J., and Wong, P., S., VecTor2 & FormWorks User's Manual. 2002

[26] TS500, Requirements for design and construction of reinforced concrete structures. Turkish Standard Institutes, Ankara, 2000

[27] ACI 211.1, Standard practice for selecting proportions for normal, heavyweight and mass concrete, ACI Manual of Concrete Practice, Part 1, 211.1-1 to 211.1-38, 1994

[28] TS802, Design of concrete mixes, Turkish Standard Institute, Ankara, 2016

[29] TS EN 206, Concrete – Specification, performance, production and conformity, Turkish Standard Institute, Ankara, 2014

[30] ACI318, Building code requirements for structural concrete, American Concrete Institute, 2019

[31] TBDY, Türkiye bina deprem yönetmeliği, Afet ve Acil Durum Yönetimi Başkanlığı, Resmî Gazete, 2018

[32] Ersoy, U., Betonarme kiriş ve kolonların moment kapasitelerinin saptanması. İMO Teknik Dergi, 9:44, 1781-1798, 1998

[33] Akan, Ç., Lif katkılı betonarme kirişlerin deneysel ve sayısal incelenmesi. Yüksek Lisans Tezi, İzmir Kâtip Çelebi Üniversitesi, 2022.

[34] Ersoy, U., Özcebe, G. and Tankut, T., Reinforced concrete. METU Press, Ankara, 2016

[35] Sahoo, D., R., et al. Influence of steel and polypropylene fibers on flexural behavior of RC beams. Journal of Materials in Civil Engineering, 27:8, 2015

[36] Meda, A., et al. Flexural behavior of RC beams in fibre reinforced concrete. Composites: Part B, 43:8, 2930-2937, 2012.

[37] Vecchio, F., J., and Collins, M., P., The modified compression-field theory for reinforced concrete elements subjected to shear. ACI Structural Journal, 83:2, 219-231, 1986.

Turkish Journal of Civil Engineering, 2023 79-104, Paper 718, ***Research Article***

Severity Assessment of Problems in Turkish Building Audit System: A Fuzzy AHP Approach

Murat ÇEVIKBAŞ[1]
Ozan OKUDAN[2]
Zeynep IŞIK[3]

ABSTRACT

The Building Audit system (BAS) has often been criticized due to its various drawbacks by researchers, construction practitioners, and professional chambers. Existing studies, however, do not comprehensively investigate the problems seen in Turkish BAS. Since the decision-makers are provided with little knowledge about the drawbacks of the system, they can barely develop new strategies to improve its effectiveness and efficiency. To bridge this gap, this study aimed to identify the drawbacks seen in the implementation of the Turkish Building Audit System (BAS). In addition, the severity of each drawback was also determined to further provide comprehensive guidance to policymakers and non-governmental organizations (NGOs). Initially, an extensive literature review was conducted to identify problems of Turkish BAS. Identified problems were then validated through Focus Group Discussion (FGD) sessions with the participation of 12 experts who have diverse experience in the related field. Later, a questionnaire survey was designed to measure the severity of each problem/drawback and the data was collected from 15 construction practitioners. The data were then analysed using the Fuzzy Analytical Hierarchy Process (FAHP) method to measure the severities of problems seen in Turkish BAS. Then, the problems were prioritized based on their severities. At the final step, sensitivity analysis was conducted to measure the robustness and reliability of the results derived from the FAHP method. Results revealed that problems such as "Lack of practical knowledge of technical staff", "Absence of site supervisor at the site" "Political pressure" and "Neglecting technical specifications and procedures" were determined as the most severe problems that need urgent attention of decision-makers. It is highly believed that this study will guide decision-makers

Note:

- This paper was received on March 14, 2022 and accepted for publication by the Editorial Board on October 10, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

- https://doi.org/10.18400/tjce.1209174

1 Isparta University of Applied Sciences, Department of Civil Engineering, Isparta, Türkiye
muratcevikbas@isparta.edu.tr - https://orcid.org/0000-0002-8421-6591

2 Yildiz Technical University, Department of Civil Engineering, Istanbul, Türkiye
okudan@yildiz.edu.tr - https://orcid.org/0000-0001-7816-2761

3 Yildiz Technical University, Department of Civil Engineering, Istanbul, Türkiye
zeynep@yildiz.edu.tr - https://orcid.org/0000-0001-8825-0001

for the improvement of existing legislation. Additionally, it is also believed that practitioners will take necessary precautions beforehand by using the outputs of this study.

Keywords: Building audit system, quality control, quality assurance, construction.

1. INTRODUCTION

Turkey - where active plate movements are very common - is located on the Alpine-Himalayan belt [1]. Earthquake constitutes a great danger in Turkey where 96% of the lands are detected as earthquake zones [2]. As a result of earthquake disasters, countless people in our country have suffered [3]. In 1999, 18.373 people died and many people were suffered from the Gölcük Earthquake which was one of the last major earthquakes [4]. After the examination of the structures which were damaged during the earthquakes that occurred in Gölcük, Düzce, Bingöl, Van, Elazığ and İzmir respectively, it was stated that the main factors for the damages occurring in the buildings are mistakes in the designs and ineffective audits made by the building audit firms [5]. By the same token, it can be inferred that uncontrolled structures caused the death of innocent people, not earthquakes [6].

BAS brings along many problems during its practice. Pala and Demir [3] stated that "*As a result of the inspections carried out by the General Directorate of Construction Affairs under the Ministry of Environment and Urbanization, it was revealed that many building audit firms do not even know the locations of the structures*". They concluded that building audit firms inspected the structures only on paper and suggested that the firms performing the inspection should be very strict and have work ethics. In the wake of the Gölcük Earthquake, Ergünay [2] concluded that although many laws and regulations have been enacted to regulate and supervise the constructions, it is an obvious fact that the constructions are rarely inspected. Guner [5] investigated the effects of the earthquake on the damages of structures and concluded that there is a remarkable relationship between the construction period of the buildings and the damage of structures resulting from earthquakes. This can prove that legislations superseding each other have improved the BAS to some extent. Sakalı [6] detected the drawbacks concerning BAS up until 2008. It was stated that since the Gölcük earthquake, significant improvements have been recorded in the BAS system with the lessons learned after the earthquakes; however, he also spotted the continual problems concerning the BAS. Later, regional studies concerning the improvements in the BAS system were conducted in Turkey [7]–[11]. It was highlighted in these studies that there are still major drawbacks occurring during the application of building audit in Turkey and significant precautions shall be taken in advance of any future earthquake. Afterwards, Akbıyıklı et al. [12] investigated the BAS system in 2017 and they also stated that there are still major drawbacks in BAS System. Yılmaz and Koymen [13] evaluated 22 academic research concerning building audits and pinpointed that continual problems still exist and loss of life and property in possible earthquakes affects not only the building owner or their partners but also the demographic structure in the cities and the country's economy. Furthermore, Bayram et al. [14] highlighted that there are major ethical problems in the execution and auditing of the construction in Turkey. Although these studies aimed to identify the problems of Turkish BAS which is considered as the main vulnerability against earthquake disasters, none of them determines the severity of each problem encountered during the application of BAS in Turkey. In other words, existing studies do not determine the relative importance of problems. Instead, these studies propose that problems have equal severities so that they should be resolved at once by the decision-makers. Considering that resolving all problems seen in Turkish BAS is not a feasible and even possible, the findings of these studies can hardly be utilized by the decision-makers. Due to the lack of this theoretical basis, the decision-makers can barely develop a roadmap to improve Turkish BAS. Consequently, these limitations of the existing studies triggered much of this research and the study aims to identify the existing drawbacks of Turkish BAS and their severities. To detect the problems with regard to BAS, an in-depth literature review was conducted at the outset. Afterwards, detected problems were verified and outdated problems were removed through an FGD session conducted with the participation of 12 experts experienced in Turkish BAS. Later, another FGD session was conducted with the same experts to identify further drawbacks that are not identified in the existing body of knowledge. Next, a questionnaire survey was developed and distributed to 15 experts who were experienced in the domain of building audits. The collected data were analysed by using the FAHP method to detect the severity of each problem. Finally, a sensitivity analysis was conducted to further validate the outputs of the FAHP method. It is believed that this study has great potential to guide decision-makers when it comes to the improvement of existing BAS. By using the findings of this study, the decision-makers can determine and prioritize the vital improvements that should be made to improve BAS regulation. Considering that the quality of the building stocks in Turkey is not at the desired level most probably due to the problems of Turkish BAS, this study is believed to have vigorous practical implications.

2. THEORETICAL BACKGROUND AND RESEARCH MOTIVATION

2.1. Building Audit System in Turkey

Being an essential component of project management, project controlling is a function that is critical for achieving successful project outcomes [15]. Project Control is defined as a process of monitoring a project. Project control helps a project to gather data with the help of inspection, audits, and other mediums. It is the data management process to understand and predict project outcomes [16]. Being required by one or more project stakeholders, inspections and audits are vital mechanisms for the successful management of a project. Inspections aim to check the suitability of completed works according to project requirements. The PMBOK (2017) [16] defines inspections as activities such as measuring, examining, and validating to determine whether work and deliverables meet requirements and product acceptance criteria. A quality audit is a structured and neutral process to determine if project activities comply with organizational policies and procedures as well as the project contract [11]. By the same token, audits help the project team to measure how well a product and process align with project requirements. Audits can be performed by a third party or a self-check of a contractor. In Turkey, the audit is carried out by the audit firms appointed by the concerning ministry [17]. To put forward the duties of building audit organizations, the concept of inspection must be well explained first. The audit is the comparison between the plan and the execution. On the other hand, the building audit concept is a system that controls the structure, ensures the safety of life and property, includes modern standards, and prevents uncontrolled and poor quality in construction [12]. In this sense, building inspection companies play the most crucial role in ensuring life and property safety. The renewal of the auditing mechanism of structures in accordance with the development of science over time is extremely important for the people who always desire to benefit from safer and more comfortable structures.

In parallel with the development of industry and technology, the construction inspection process is also being developed and complex. Member states of the European Union, which are extremely advanced in this regard, have established "The Consortium of European Building Control" under the leadership of England to develop their inspection systems. There are two building inspection systems in general in Europe. The first of these is the insurance system model adopted by France, and the other is the strict control model applied by Germany [6]. Countries in the European Union apply a similar or mixed of these two building audit systems [6]. Germany, which constitutes 19 per cent of the construction sector in Europe, has established the basis of the building inspection system on discipline and strict supervision [18]. The main principle of the building inspection system implemented in Germany is based on the strict supervision of the construction from the project stage to the operation stage [6]. Structures being carried out by the private sector are supervised by state-established organizations. An audit system should be regarded as a sub-system of an inspection system in a country, because the former focuses that a site is required to do by a compliance obligation but the audit is the process of checking that compliance obligations have been met or not, including that the required inspections have been done before and throughout the construction project. Audit engineers - who are well-equipped and independent engineers working in local administration - are responsible for the buildings for 30 years [19]. France, which has the second largest construction sector in Europe with a percentage of 16 per cent, has a well-established inspection and insurance practice [18]. Administrative Mechanisms for Building Insurance (MARC) carry out the audit process [20]. There are two types of insurance for buildings. The first is ten-year compulsory insurance that directly affects the safety of the building, which starts after final acceptance, and the other is two-year optional insurance that covers parts that wear out over time [21]. When the building inspection system in the USA, which is one of the leading countries in the world in terms of engineering education, is examined, it is seen that the trust in engineers and architects with the title of Professional Engineer (PE) forms the basis of this system. These engineers can apply to official authorities for the preparation and approval of the projects [22]. To have the title of PE, it is necessary to graduate from a four-year university program and to be successful in the Fundamentals of Engineering (FE) exam [23]. Considering its fundamental features, the building inspection system in Turkey is similar to Europe; however, it has been differentiated by undergoing many revisions after the disasters occurred in Turkey.

As it is in Europe and the USA, the construction inspection system to ensure safety and comfort in Turkey has pursued constant development by eliminating the shortcomings. Foundations of the building audit system in Turkey were started to be laid by “Municipal Law” with Law# 1580 in 1930, “General Hygiene Law” with Law # 1593 in 1930, “Municipal Building and Roads Act” with Law # 2290 in 1933, Building “Construction Incentive Law” with Law # 5228 in 1948, “Regulation on Precautions Before and After the Ground Shaking” in 1949. However, as a result of migrations following unplanned industrialization after 1950, the number of illegal buildings increased rapidly, and consequently, laws and regulations on building audits became inapplicable [2]. As a solution after these migrations, the power regarding the zoning plan was gathered in a center with the Zoning Law No. 6785, which could be considered to be quite advanced compared to the time in 1956. Afterwards, the Ministry of Development and Housing was established in 1958.

Although economic losses and loss of life and property in natural disasters resulted from unaudited construction, most of the laws and regulations concerning BAS entered into force were related to covering the losses after natural disasters. [6]. Since continuous problems arose from zoning plan due to gathering the powers in the central government in 1956, 'Zoning Law' came into force with Law# 3194 in 1985, and physical planning activities were separated from the central management, and the zoning planning authority was left to the municipalities within the borders of the adjacent area and the governorships outside the borders of the adjacent area. After 1980, two major successive earthquakes occurred in Erzincan and Dinar in 1992 and 1995, respectively. As a consequence, "Regulation on Structures to be Made in Disaster Areas" entered into force in 1997. After the Marmara earthquake (1999) where 20,000 people lost their lives, 40,000 citizens were injured and financial losses occurred, the building inspection system was further questioned and as a result, "Decree-Law Concerning Building Audit" came into force with Law# 595 in 2000. After publication, the Constitutional Court decided to stop the execution, and "Building Audit Law" with Law# 4708 was legislated in 2001. The building audit system was planned to be implemented in 27 pilot provinces in the first phase, and then this number was reduced to 19. After the 1999 Marmara earthquake, several decree-laws, decrees, regulations, notifications and circulars entered into force with respect to BAS, and the severe problems continued due to intense bureaucracy. To eliminate the deficiencies in BAS, "Regulation on the Amendment to the Building Audit Implementation" was enacted as of 29th December 2018 through Official Gazette No. 30640 and started its implementation on 1st January 2019 [24]. Through this regulation, many drawbacks such as delegation of building audit firms, termination of building audit service agreement, building audit service fees were intended to be overcome. Additionally, the application, which paves the way for electronic monitoring of concrete quality by placing a chip in the concrete samples, has been launched via this regulation.

2.2. Fundamentals of Multi-Criteria Decision Making (MCDM) and Fuzzy AHP

A decision that reaches the goal is very needed in construction projects. However, the existence of various sets of alternatives turns the construction project into a very sophisticated environment in terms of decision-making. Additionally, the existence of conflicting criteria makes the task of decision-makers even more difficult. The term conflicting criteria are defined as the criteria that are inversely proportional to each other. While there are difficulties in making the right decision, it is difficult for decision-makers to choose the most appropriate alternative. To overcome these problems, Multi-criteria Decision Making (MCDM) has been very essential for decision-makers and discussed in the literature comprehensively [25]. MCDM is a term that describes the nature of decision-making and numerous MCDM methods have been proposed in the literature to aid decision-makers. The most frequently adopted methods by the researchers are AHP, VIKOR, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and their integration with fuzzy set theory. Saaty [26] developed the AHP method which has become one of the most popular MCDM methods [27], [28] due to its capability to handle intangibles presented in any decision-making process [29]. Additionally, consistency in the pairwise comparison of the experts can be detected by the AHP method and thus this ensures the reliability of the outputs [26]. The method fractionates a decision-making problem into a system of hierarchies of objectives, criteria and alternatives, and the mechanism of the AHP is designed to accomplish decompositions, pairwise comparisons, priority vector generation and synthesis [30]. Notwithstanding the advantages of the AHP method, while the experts evaluate the alternatives and criteria, crisp numbers are not sufficient due to imprecision, subjectivity and indefinite source of human judgment in numerous circumstances [31]. Therefore, integration of fuzzy set theory into AHP seems essential to evaluate linguistic variables and deal with ambiguous problems [29]. The decision-making problems involving complexity are not able to be picturized quantitatively. However, the human brain which has a unique feature can cope with these problems by using indefinite knowledge. The fuzzy set theory is proficient to imitate the unique features of the human brain. By the same token, the specific objective of the fuzzy set theory is a numeric illustration of the uncertainty to deliver a formalized medium for dealing with imprecision. The fuzzy set theory proposed by Zadeh [32] adopts a similar mechanism concerning human reasoning which can come to conclusion by using approximate and uncertain information [33]. Thus, the Fuzzy AHP method was developed by Chang [34] to overcome the aforementioned disadvantages of the AHP method.

3. METHODOLOGY

In this study, it was primarily aimed to identify and prioritize the problems observed in BAS in Turkey. In this way, the decision-makers and construction practitioners as well as non-governmental institutions (NGOs) will be provided with a deep insight into the challenges of the existing BAS. Accordingly, the research methodology given in Figure 1 was followed to achieve the objectives of this study. As depicted in Figure 1, the research methodology was established on two pillars, namely problem detection and verification, and problem evaluation. In the problem detection and verification stage, the construction management literature was initially reviewed to identify problems unfolded by researchers. In the wake of

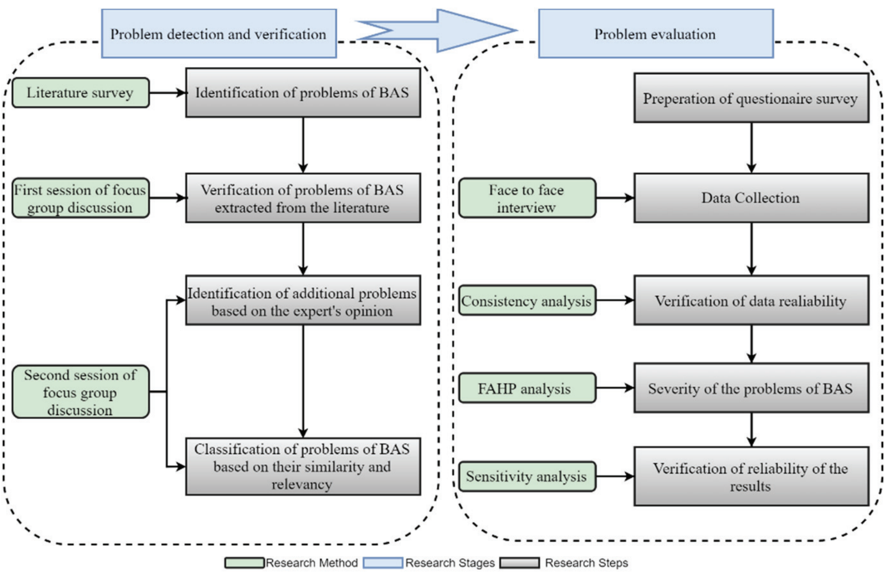


Figure 1 - Flowchart of the analysis procedure

the literature review, FGD sessions were organized with the participation of the 12 experts who have diverse experiences with the BAS in Turkey. In the first FGD session, the experts assessed the validity of the problems of BAS extracted from the literature. Next, experts proposed additional problems that are encountered in the engineering practice. In this respect, it is believed that this study presents vigorous theoretical contribution since it provided a fertile ground to merge the theoretical knowledge of the researchers and practical knowledge of the construction practitioners. At the end of the session, the experts also categorized the problems of BAS based on their similarity and relevancy. It should be noted that this categorization formed the basis of FAHP analysis conducted in the problem evaluation stage. In the problem evaluation stage, the questionnaire survey was designed and distributed to 15 construction practitioners to evaluate the severities of the problems identified through literature review and FGD sessions conducted with the participation. The questionnaire survey was analyzed with FAHP analysis and severities of the problems encountered in BAS were determined. Furthermore, the consistency and sensitivity analyses were conducted to test the reliability, stability and robustness of the results derived from the survey.

3.1. Problem detection and verification

As depicted in Figure 1, two different methods were adopted to identify and verify the problems of Turkish BAS. Initially, an extensive literature review was conducted to obtain detailed knowledge about the fundamentals of Turkish BAS. The existing studies were also examined to comprehend the existing body of knowledge. Based on this examination, as also presented in Section 2, the research gaps that should be bridged to maximize the effectiveness of Turkish BAS were also identified. The second literature review was then conducted to identify the problems of Turkish BAS unfolded by researchers. During this literature review, the search engine Scopus was preferred since Scopus has long been known as one of the most comprehensive and effective search engines [35]–[37]. It should be noted that only peer-reviewed research articles and papers presented in prestigious conferences were utilized to maximize the reliability of the framework. Consequently, the 25 problems and their sources were identified as depicted in Table 1.

Table 1 - Turkish BAS's problems identified through a literature review.

ID	Problems of Turkish BAS	A	B	C	D	E
P1	Inadequate wages given to staff		X		X	X
P2	Lack of practical knowledge of technical staff				X	X
P3	The insufficiency of occupational discipline and ethics concepts		X			X
P4	Insufficient examination of projects					X
P5	Overloaded audit firms and hiring diplomas			X		X
P6	Incomplete project control forms	X				
P7	Problems arising from an insufficient educational background of professional members				X	X
P8	Forgery of documents	X				

ID	Problems of Turkish BAS	A	B	C	D	E
P9	Missing signatures of the parties in the building audit service contracts	X				
P10	Obtaining building licenses despite incompatibilities between projects	X				X
P11	Applications that are not part of the project	X	X	X		X
P12	Absence of the Site supervisor at the site	X				
P13	Problems arising from regulations concerning Building Audit System				X	X
P14	Lack of practices to encourage employees		X			
P15	Frequent change of building audit legislation		X			
P16	Inadequate quality control due to insufficient staff		X	X		X
P17	Differences in practices of administrations of provinces and districts			X	X	
P18	Paying attention to the cost of the audit, not the quality		X	X	X	X
P19	Political pressure		X	X		
P20	Failure of the building owner to assign the building inspection firm			X	X	X
P21	Time consumption due to bureaucratic procedures			X		
P22	Contractors' lack of workforce to meet their technical requirements		X	X		
P23	Unequal and Unfair treatment by administrations to the audit firms		X	X	X	X
P24	Lack of inspections on a continuous basis at the site				X	X
P25	Providing services under the minimum service fee		X	X		X

Note-1: A: Erdiş and Gerek [11], **B:** Doğan [8], **C:** Kural and Ünal [10], **D:** Pala and Demir [7], **E:** Tantekin Çelik and Ünal [9]

The FGD sessions were followed the abovementioned literature review. The FGD is defined as a qualitative research technique that can bridge the scientific research and practical experience of the participants [38]. In particular, the technique aids researchers when it comes to drawing conclusions from sophisticated personal experiences, perceptions and attitudes of experts with the help of dynamic and interactive discussions [39]. The dynamic and interactive discussions differentiate the FGD from other techniques such as unstructured, structured and semi-structured interviews since this feature of FGD allows ideas, experiences and perspectives of participants could be exchanged and finessed [40]. Furthermore, the technique provides a fertile ground to arise individual differences of opinions together with gaining insight into the shared understanding and groups' beliefs [41]. Thus, FGD emerges as a promising technique when a research subject under investigation needs to be extensively examined from the various aspect that cannot be achieved by a single expert in a confined medium [42]. Owing to these promising and vital benefits, the implementation of the FGD technique in scientific studies has skyrocketed in recent years [43]. Nyumba et al. (2018) [43] emphasized that selecting an appropriate sample size is a crucial factor affecting the extraction of interesting and valuable ideas from the FGD sessions. The authors however pinpointed that there are no strict rules and/or equations revealing the appropriate sample size. The experience of the researchers highlighted that a sample size larger than 20 significantly complicated the moderation of FGD while accommodating a small sample size such as 3-5 experts inhibits the extraction of innovative and inventive ideas and the subject cannot be assessed from various perspectives [44]. Besides the sample size, the competency of the experts is another determinant of the reliability of the FGD method. In other words, identifying eligible participants is of paramount importance for the FGD method. Nyumba et al. [43] recommended using purposive sampling rather than convenience sampling. In purposive sampling, participants' backgrounds are deeply and detailly investigated to check whether they fit the needs of the study or not. Accordingly, the expert selection framework as depicted in Figure 2 was developed for this study and all participants were interviewed to test their eligibility. Consequently, 12 experts who were determined to have diverse experience in the Turkish BAS were invited to FGD discussions. It should be noted that the profile of the experts is provided in Table 2 and sessions were organized and moderated in full accordance with Nyumba et al. [43].

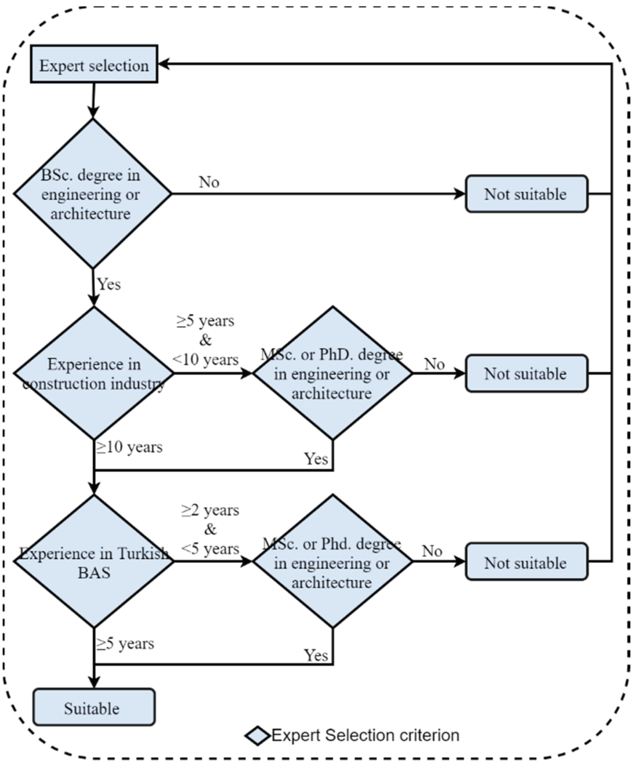


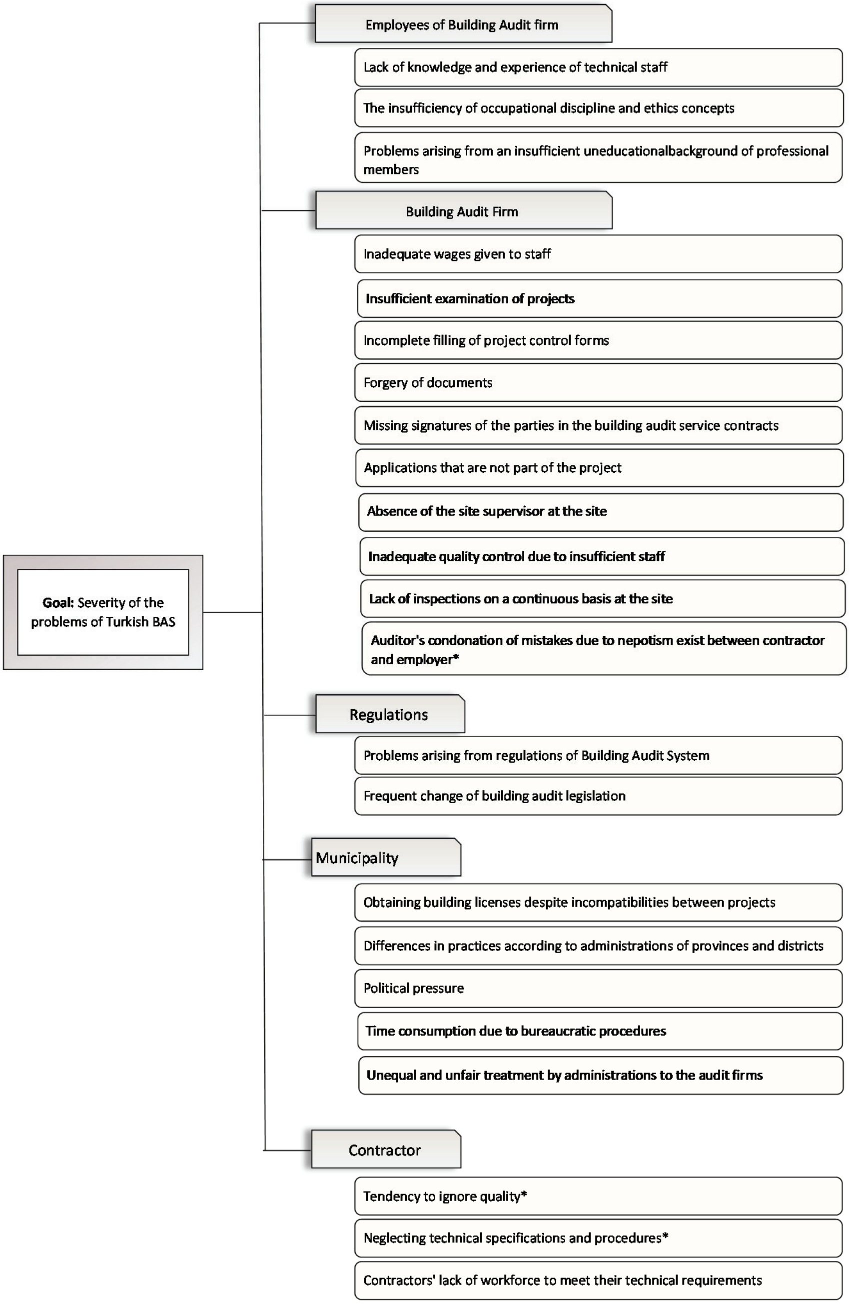
Figure 2 - Expert selection procedure

At the beginning of the first FGD session, extensive theoretical information regarding the existing BAS and its related regulations were provided to experts to further strengthen their knowledge. In this respect, the sessions successfully surfaced the experts' practical knowledge and merged it with the theoretical knowledge of the researchers. Following this, all participants were asked about their general opinions about Turkish BAS. All participants agreed that there are significant problems when it comes to enforcing Turkish BAS. They stated that it is of paramount importance to identify potential problems and measure their severity so that policymakers are provided with a clear decision-support framework when it comes to addressing these problems.

Table 2 - Profiles of respondents participating in FGD sessions.

ID	BSc. Degree	Degree	Firm	Experience in the construction industry (Year)	Experience in BAS (Year)
1	Civil Engineer	MSc.	Ministry of Environment, Urbanization and Climate Change	12	10
2	Civil Engineer	PhD.	Building Audit Firm	12	7
3	Mechanical Engineer	BSc.	Building Audit Firm	15	15
4	Architect	BSc.	Municipality	10	5
5	Electrical Engineer	BSc.	Building Audit Firm	10	7
6	Civil Engineer	MSc.	Building Audit Firm	6	6
7	Civil Engineer	MSc.	Municipality	10	8
8	Mechanical Engineer	BSc.	Building Audit Firm	10	10
9	Architect	BSc.	Building Audit Firm	11	9
10	Electrical Engineer	BSc.	Municipality	18	12
11	Civil Engineer	BSc.	Building Audit Firm	17	15
12	Mechanical Engineer	MSc.	Building Audit Firm	18	18

Then, the experts were asked to assess the validity of the problems extracted from the literature. Given the fact that some of the studies were published earlier than 2022, the step was crucial to ensure that the problems extracted from the literature are still valid nowadays. During this validity assessment, each of the problems provided in Table 1 was discussed by the experts. The final decision for each problem was made when the experts reached a



***Problems identified through FGD sessions**

Figure 3 - Decision framework of the study.

consensus about the validity of the problems. If the experts failed to reach a consensus, the final decision was made based on the opinions of the majority. Accordingly, it was detected that some of the problems illustrated in Table 1 were overcome through, "Regulation on the Amendment to the Building Audit Implementation" entering into force on 29 December 2018. It was suggested that problems, namely P5 and P20 were omitted since building inspection firms are appointed electronically by the Ministry. Additionally, P18 and P25 were removed since building audit service fees were standardized in the latest regulation. Furthermore, there was a joint decision during the session that "P14- Lack of practices to encourage employees" was suggested to be removed from the list since this is not related to the auditing system but firms.

Upon refining the list illustrated in Table 1, experts were asked to suggest additional problems that are overlooked in the existing literature. Each suggestion of the experts was discussed, and the final decision was made using the same consensus mechanism explained above. At the final step, experts were asked to categorize identified problems based on their similarity and relevancy. In other words, problems identified through literature review and FGD sessions were categorized as per their common themes. Consequently, the structure given in Figure 3 was obtained.

3.2. Problem evaluation

Problem evaluation is one of the most critical aspects of this study since policymakers can prepare their roadmap based on the findings obtained from the problem evaluation step. There are many MCDM methods available in the literature such as AHP, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR). Among them, the VIKOR method aims to determine a compromise solution for a discrete decision-making problem in the presence of conflicting criteria [45]. The VIKOR method becomes an ideal method especially when decision-makers cannot select or do not know how to decide on the most suitable alternatives. Unlike the TOPSIS which considers only group utility maximization and individual regret minimization, VIKOR is capable of fully reflecting the experts' subjective preferences in the results [46], [47].

On the other hand, the AHP proposed by Saaty [26] has various advantages over other MCDM methods such as TOPSIS and VIKOR. First, the research design could be represented hierarchically as shown in Figure 3, which, in turn, decision-making processes could be easily comprehended [48]. Second, the method does not require a large sample size to provide reliable results since it can eliminate unreliable datasets by measuring the consistency of each dataset [49]. Finally, the method has been successfully applied to a wide range of disciplines so that its effectiveness has been proven many times [50].

In general, the MCDM methods have widely been criticized for being inapplicable when it comes to solving ambiguous decision problems which are frequently encountered in engineering practice [51]. The integration of MCDM methods with fuzzy set theory is key to further strengthen their abilities to cope with sources of uncertainty. The fuzzy set theory - which was proposed by Zadeh [32] - uses a sophisticated mechanism similar to the human brain. This makes it ideal to solve decision-making problems having imprecise information stemming from experts' subjective judgements. The theory becomes an appropriate concept for mapping perception, incomplete information, and approximations. By doing so, the effect of imprecision that exists within the datasets could be minimized [52]. In this respect, the fuzzy set theory maximizes the reliability and effectiveness of the MDCM methods [50]. Owing to the unprecedented benefits of fuzzy set theory, the FAHP method outperforms the conventional AHP by effectively dealing with inherent fuzziness and vagueness in the expert's judgements [50]. Therefore, the triangular FAHP method developed by Chang [34] was implemented in this study. The adopted approach involves the research steps shown below:

Step 1. Data collection with pairwise comparison matrices: As stated above, the FAHP method emphasizes the data quality rather than the sample size. In this respect, purposive sampling was recommended in FAHP applications as is in the FGD technique. Accordingly, before the data collection step, the experts' background was deeply examined using the procedure illustrated in Figure 2. To achieve the evaluation of the subject from multiple perspectives, the experts who participated in the FGD sessions were not invited to participate in the questionnaire survey. Instead, another set of respondents was identified specifically for the questionnaire survey. The demographics of the experts were provided in Table 3. Accordingly, it is not controversial to assert that experts certainly meet the needs of this study. Thus, the conclusions drawn from their judgements were presents vigorous practical implications. Besides the data quality, many studies have been investigated in the decision science domain and the sample size was found adequate [53]–[56].

Following the expert selection step, the questionnaire survey was distributed to participants. The survey consisted of three sections. The first section included the questions about the experts and their companies as well as brief information about the research objectives and design. In the second section, the experts were asked to make pairwise comparisons between main problem categories such as regulation, contractor, municipality, etc. Finally, the importance of each problem was assessed by the experts through pairwise comparison. It should be noted that experts were given an opportunity to use linguistic variables given in Table 4 rather than crisp numbers so that they could reflect their judgements clearly [57].

Table 3 - Profiles of respondents participating in the FAHP questionnaire.

Expert #	BSc. Degree	Experience in the construction industry (Year)	Experience in BAS (Year)	Degree	Current Firm	Experience in Project Types
1	Civil Engineer	12	10	M.Sc.	Ministry of Environment, Urbanization and Climate Change	Single-Family Dwellings, Collective Housing, Institutional Projects
2	Civil Engineer	12	7	B.Sc	Building Audit Firm	Single-Family Dwellings, Collective Housing, Hotel Projects
3	Mechanical Engineer	15	15	B.Sc	Building Audit Firm	Single-Family Dwellings, Roads&Bridges Projects
4	Architect	10	5	B.Sc	Municipality	Single-Family Dwellings, Dam Projects

5	Electrical Engineer	10	7	B.Sc	Building Audit Firm	Single-Family Dwellings, Collective Housing, Institutional Projects
6	Civil Engineer	6	6	B.Sc	Building Audit Firm	Single-Family Dwellings, Roads&Bridges, Dam Projects
7	Civil Engineer	10	8	M.Sc.	Municipality	Single-Family Dwellings, Hospital, Commercial Projects
8	Mechanica l Engineer	10	10	B.Sc	Building Audit Firm	Single-Family Dwellings, Airport Projects
9	Architect	11	9	B.Sc	Building Audit Firm	Single-Family Dwellings, Dam Projects
10	Electrical Engineer	18	12	B.Sc	Municipality	Single-Family Dwellings, Roads&Bridges Projects
11	Civil Engineer	17	15	PhD	Building Audit Firm	Single-Family Dwellings, Collective Housing, Harbour, Industrial Projects
12	Mechanica l Engineer	18	18	M.Sc.	Building Audit Firm	Single-Family Dwellings, Collective Housing, Harbour Projects
13	Mechanica l Engineer	15	8	B.Sc	Building Audit Firm	Single-Family Dwellings, Collective Housing, Institutional Projects
14	Electrical Engineer	20	10	B.Sc	Municipality	Single-Family Dwellings, Collective Housing Projects
15	Mechanica l Engineer	12	6	M.Sc.	Ministry of Environment, Urbanization and Climate Change	Single-Family Dwellings, Collective Housing Projects

Table 4 - The linguistic variables used during the pairwise comparison

Linguistic variables	**Triangular fuzzy numbers**	**Triangular fuzzy reciprocals**
Just Equal	(1, 1, 1)	(1, 1, 1)
Equally Important	(1/2, 1, 3/2)	(2/3, 1, 2)
Weakly Important	(1, 3/2, 2)	(1/2, 2/3, 1)
Strongly More Important	(3/2, 2, 5/2)	(2/5, ½, 2/3)
Very Strongly More Important	(2, 5/2, 3)	(1/3, 2/5, ½)
Absolutely More Important	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Step 2. Consistency check: As elaborated above, consistency control is one of the main advantages of AHP over other methods. Following data collection, consistency analysis was conducted for each dataset and only consistent datasets were taken into consideration. In case a dataset was found inconsistent, the corresponding respondent was informed, and the survey was repeated. In this way, the reliability of the survey was maximized. The details of the consistency analysis are provided below. Accordingly, the CR of each dataset should be less than 10% to be considered consistent [58]. In the following equations, the λ_{max} is called as the maximum eigenvalue of the corresponding matrix, while RI, CI, and n are called as, the

random index, consistency index and the number of criteria of the corresponding matrix, respectively.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

Step 3. Aggregation of decision matrices: Once the consistency of each dataset was found adequate, the pairwise comparison matrices of all experts were aggregated to obtain group decisions. This was achieved by initially converting linguistic variables into triangular fuzzy numbers using the values depicted in Table 4. Then, the geometric means of the scores provided by all experts were calculated to form aggregated decision matrices [52], [57]:

$$l_{ij} = \left(\prod_{k=1}^{K} l_{ijk}\right)^{1/K},\ m_{ij} = \left(\prod_{k=1}^{K} m_{ijk}\right)^{1/K},\ u_{ij} = \left(\prod_{k=1}^{K} u_{ijk}\right)^{1/K} \tag{3}$$

where K is the total number of respondents.

Step 4. Application of Chang's extent analysis: Noting that $X = \{x_1, x_2, x_3, \dots\dots\dots, x_n\}$, and $U = \{u_1, u_2, u_3, \dots\dots\dots u_m\}$ are object and goal sets, the fuzzy synthetic extent value belonging to *i^th^* object was computed using the following equations developed by Chang [59]. It should be noted that triangular fuzzy numbers are denoted as M_{gi}^{j} in the following equations.

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \times \left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \tag{4}$$

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{5}$$

$$\left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right] = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{6}$$

$$\left[\sum_{j=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{n} u_i}, \frac{1}{\sum_{j=1}^{n} um_i}, \frac{1}{\sum_{j=1}^{n} l_i}\right) \tag{7}$$

Following this, the degree of possibility should be determined by using a fuzzy synthetic extent value. The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ was found using Equations 8 and 9. It should be noted that $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ were denoted as triangular fuzzy numbers.

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min\left(\mu_{M1}(x), \mu_{M2}(y)\right)\right] \tag{8}$$

$$V(M_2 \geq M_1) = htg(M_1 \cap M_2) = \begin{cases} 1 & if\ m_2 \geq m_1 \\ 0 & if\ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \tag{9}$$

M_2 and M_1 are compared by considering two cases of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$. Eq. 10, therefore, reveals the degree of possibility for a convex fuzzy number.

$$V(M \geq M_1, M_2, \ldots, M_k) = V[(M \geq M_1),(M \geq M_2),\ldots,(M \geq M_k)] = minV(M \geq M_i) \quad (10)$$

where $i = 1, 2, 3, \ldots \ldots \ldots, k$.

Noting that $d'(A_i) = \min V(S_i \geq S_k)$ for k =1, 2, …, n; k ≠ I; Eq. 11 was implemented to calculate the weights of each criterion or problem.

$$W' = (d'(A_1), d'(A_2), \ldots, d'(A_n))^T \quad (11)$$

where $A_i(i = 1, 2, 3, \ldots \ldots \ldots, n)$ are n elements. Finally, the weights of each problem were normalized by employing the following equation. The "W" in the following equation is expressed as a crisp number.

$$W = \left(d(A_1), d(A_2), \ldots, d(A_n)\right)^T \quad (12)$$

Consequently, the normalized weights of problems of Turkish BAS are provided in Table 5.

The last analysis conducted in this study was the sensitivity analysis as shown in Figure 1. The sensitivity analysis measures the stability and robustness of the FAHP procedure by measuring the covariance of the results and the input data [60]. Sensitivity analysis is eminent to ensure robustness and stability of the decision-making process since complex decision-making problems are often considered unstable due to high-degree of subjectivity [61]. Furthermore, owing to its utmost importance, sensitivity analysis was widely adopted in the decision-making domain to maximize reliability [60], [62], [63]. In the light of this information, the sensitivity analysis was performed in this study to verify the applicability of the results. In essence, the sensitivity analysis was conducted by iterating the FAHP analysis with various degrees of fuzziness. These values were taken as 0.2, 0.4, 0.5 and 0.6 as also proposed by Aladağ and Işık [64] and Tseng and Lin [62]. After completing the FAHP analysis for these values of degree of fuzziness, the variations in the rank of each BAS problem were observed. If the ranks remain stable for all values of degree of fuzziness, the analysis was deemed robust and stable [61]. Consequently, the sensitivity analysis was completed as described above and the results are presented in Figure 4.

4. FINDINGS AND DISCUSSIONS

The results of the FAHP analysis are given in Table 5. Accordingly, the severities of all categorizations were detected as very similar due to their equal effects on the building audit. It was spotted that the most important category is "Employees of Building Audit Firm" which was followed by categories such as "Contractor", "Building Audit Firm", "Regulations" and "Municipality", respectively. Ethical principles of employees in building audit firms are very important and for this reason, the employees must perform their controls in full accordance with the regulations and take the necessary precautions [14]. Furthermore, their technical knowledge is also very critical to conduct their control thoroughly [10]. To attract the most appropriate employees to the building audit firms for the building inspections, it is highly suggested that there should be a lower limit on the wages. Additionally, certain experiences for employees are to be sought. "Contractor" – which was the second important category – plays a very crucial role in building audits. The contractor shall execute and control his work according to drawings, specifications, and any other documents defined in the project contract. Therefore, contractors should be selected according to their qualification certificates, and it is believed that this will pave the way for future structures to be built properly. Supervision is conducted by "Building Audit Firm" which was a relatively third important category. A building audit firm should have a work ethic and conduct its inspection as per existing regulations. "Regulation on the Amendment to the Building Audit Implementation" entered into force on 29th December 2018 through Official Gazette No. 30640 and started to be enforced on 1st January 2019 [24]. Through this regulation, the delegation of building audit firms, termination of building audit service agreement, building audit service fees were reformed and previous practices were improved. With this regulation, the commercial relationship of building audit companies with the contractor was eliminated and this has enabled building audit firms to supervise the works of the contractors efficiently. As is mentioned in the section of "Building Audit System in Turkey", there have been many legislations enacted and superseded each other. However, constant and rapid change in the regulations prevents the practitioner to carry out the work consistently. Interpretation of the changes in the regulations affects the supervision of municipalities and ends up with significant inconsistency in the applications of different municipalities [10]. Additionally, work training concerning the building audit should be given to the concerned staff in the municipalities to enable them to execute the work in line with the regulations [8]. Moreover, their work should also be supervised by the concerned government agencies and sanctions should be imposed in case of any adverse condition.

In the category of "Employees of Building Audit Firm", the most important problem was identified as "Lack of practical knowledge of technical staff". In contrast to BAS in Turkey, knowledge of the technical staff is deemed as vital in Europe and the USA. The main drawback behind the lack of practical knowledge of the technical staff is due to the low-profit margins of building inspection companies. Therefore, audit firms cannot pay high wages to their employees and sometimes they even pay minimum wages. Additionally, there is no qualification limit requested for the employees. These drawbacks lead to acquiring unqualified staff in the building audit firms. "Lack of practical knowledge of technical staff" was followed by "The insufficiency of occupational discipline and ethics concepts" and "Problems arising from an insufficient educational background of professional members" respectively. Thus, decision-makers should consider these problems for the improvement of Turkish BAS.

In the category of "Building Audit Firm", "Absence of the Site supervisor at the site" came into prominence since it can diminish the quality of building inspection. It was followed by "Insufficient examination of projects", "Inadequate quality control due to insufficient staff" and "Lack of inspection on a continuous basis at the site" whose weights were very close to each other. Since all executions conducted by the contractor are to be inspected by building audit firms, building audit firms should provide adequate number and skilled personnel to the construction site to continuously control the work. These results pinpoint that a mechanism to measure and monitor the qualifications of employees working at the building audit firms could be developed in the forthcoming regulations.

Related to the category of “Municipality”, “Political pressure” was rated as the most important problem that undermines the effective implementation of Turkish BAS. Since the mayors have organic bonds with political parties, political relationships can cause significant deviations in the implementation of BAS. Therefore, inappropriate situations arising from political pressures should be prevented and controlled by the concerned government entity. Additionally, “Time consumption due to bureaucratic procedures” was scored as the second most important implementation problem. One of the common problems in Turkey is bureaucracy which is mostly encountered during investment projects, and even a simple permit can take weeks or even months to obtain [8]. It is recommended that procedures such as work permits should have a maximum due date since the duration of obtaining work permits varies from one municipality to another due to time-consuming bureaucratic procedures.

With respect to “Regulations”, “Problems arising from regulations concerning Building Audit System” was scored as the first important implementation problem that hinders the implementation of Turkish BAS. It was followed by “Frequent change of building audit legislation”. Interpretation of the regulation and vagueness in terms may result in inconsistent applications and disputes between the parties. Therefore, regulations and instructions should be reviewed to avoid readability and sematic issues in the regulation concerning Turkish BAS. In this way, the municipalities could be enabled to execute their work consistently.

Table 5 - The weights and ranks of problems and their categories

Problem ID	**Problems of BAS**	**Weights (Priorities)**
Employees of Building Audit Firm		***0.2359 (1)***
EBAF-1	Lack of practical knowledge of technical staff	0.3695 (1)
EBAF-2	The insufficiency of occupational discipline and ethics concepts	0.3308 (2)
EBAF-3	Problems arising from an insufficient educational background of professional members members	0.2997 (3)
Building Audit Firm		***0.2104 (3)***
BAF-1	Inadequate wages given to staff	0.08951 (6)
BAF-2	Insufficiently examination of projects	0.13180 (2)
BAF-3	Incomplete project control forms	0.07582 (7)
BAF-4	Forgery of documents	0.07244 (8)
BAF-5	Missing signatures of the parties in the building audit service contracts	0.06164 (10)
BAF-6	Applications that are not part of the project	0.10065 (5)
BAF-7	Absence of the Site supervisor at site	0.15109 (1)
BAF-8	Inadequate quality control due to insufficient staff of building audit firm	0.12772 (3)
BAF-9	Lack of inspection on a continuous basis at the site	0.12144 (4)

Problem ID	**Problems of BAS**	**Weights (Priorities)**
BAF-10	Auditor's condonation of mistakes due to nepotism exist between contractor and employer*	0.06791 (9)
Municipality		***0.1538 (6)***
MNC-1	Obtaining building licenses despite incompatibilities between projects	0.1429 (5)
MNC-2	Differences in practices of administrations of provinces and districts	0.2124 (3)
MNC-3	Political pressure	0.2392 (1)
MNC-4	Time consumption due to bureaucratic procedures	0.2261 (2)
MNC-5	Unequal and Unfair treatment by administrations to the audit firms	0.1794 (4)
Regulations		***0.1876 (5)***
RGL-1	Problems arising from regulations concerning Building Audit System	0.6853 (1)
RGL-2	Frequent change of building audit legislation	0.3147 (2)
Contractor		***0.2122 (2)***
CNT-1	Contractors' lack of workforce to meet their technical requirements	0.2997 (3)
CNT-2	Neglecting technical specifications and procedures*	0.3695 (1)
CNT-3	Tendency to ignore quality*	0.3308 (2)

In the category of the contractor, "Neglecting technical specifications and procedures" was given the highest priority by the experts. It is a widely known fact that contractors tend to neglect technical specifications and procedures to minimize the project duration. For instance, in engineering practice, adding water into the concrete mixer after taking sampling is one of the major problems. Although the latest regulation brought chip which is added to concrete samples [24], experts indicated that samples were mostly taken by the first concrete mixer and later mixer operators tend to add water to the mixer to increase the slump of the concrete. This application however diminishes the strength of the concrete. Moreover, "Tendency to ignore quality" was rated as the second important factor. Most of the construction firms do not have an internal auditing system because there is no sanction in case of any poor-quality executions. Therefore, the effectiveness of the building audit firms must be improved, and penalties should be given for poor-quality executions.

4.1. Sensitivity Analysis

The results obtained from FAHP analysis were deeply discussed in the previous section. However, the stability and reliability of the analysis needed to be further validated [52], [61], [63]. Therefore, for each cluster, a sensitivity analysis was conducted. Hence, as is also specified before, FAHP analysis was repeated as per the degree of fuzziness of 0.2, 0.4, 0.5, and 0.6, respectively. Consequently, the results of the sensitivity analysis were found as depicted in Figure 4. In the sensitivity analysis, to consider the FAHP analysis as reliable, the rankings of factors should not change according to changes in the degree of fuzziness [57], [65]. More specifically, lines illustrating the weights of factors should not intersect with each other. If any lines were crossed in any figure, the analysis would be considered unreliable because of the occurrence of rank reversal. As is seen in Figure 4, lines do not intersect with each other so that the developed model could be considered stable and robust.

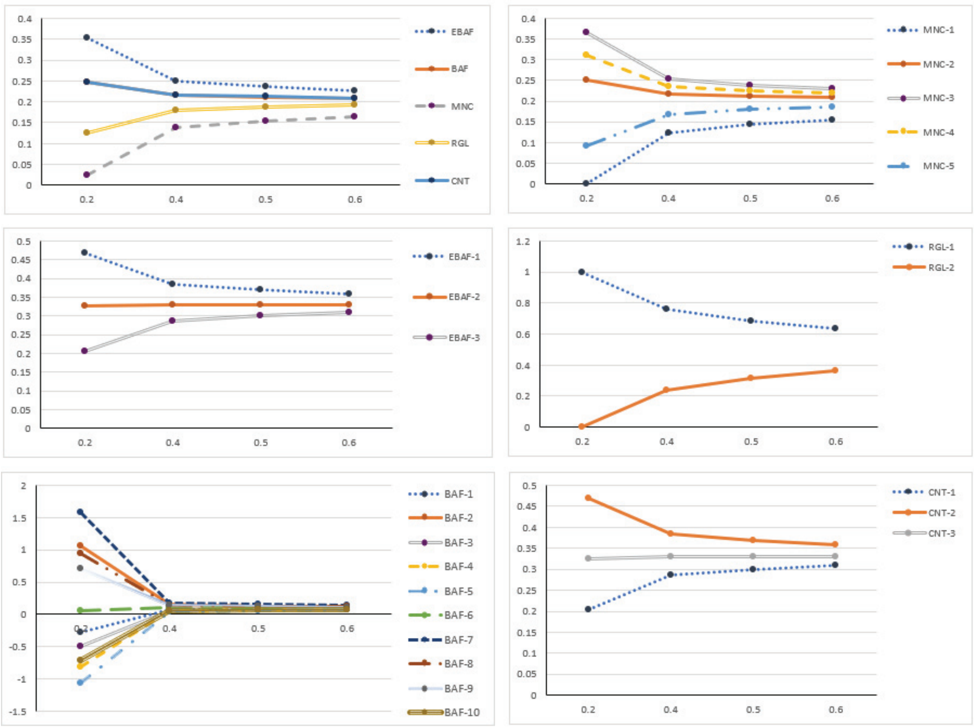


Figure 4 - Sensitivity Analysis

5. CONCLUSION AND RECOMMENDATIONS

This study aims to identify the problems of Turkish BAS and their severities. To achieve this, an in-depth literature review and FGD sessions with 12 experts were conducted to identify and categorize the drawbacks of Turkish BAS. Later, the problems were evaluated with 15 experts with the help of questionnaires and the obtained data were analyzed via FAHP analysis to detect the most important problems affecting building audits in Turkey. Lastly, a sensitivity analysis was conducted to validate the outputs of the FAHP method.

It is beyond the question that the biggest pitfalls in BAS result from the owner who does not pay the attention to the quality of work. The owner must be more proactive and sensitive concerning the quality of work. At the other end of the spectrum, laboratories can be owned by public institutions or universities to plummet the defects in quality issues. An expert stated that "*maintaining the independency of laboratories can force the contractors to obey the standards concerning safety, rebar and concrete*". It is worth bearing in mind that the minimum limit of the staff wages should be regulated to further strengthen the implementation of BAS. One of the interviewees contributed to this proposal by stating that "*the engineering service cannot be given with the minimum wage*'. Also, it is believed that defining the lower limit of wages upsurges the number of qualified employees. In addition to this, the competency levels of employees working in the building audit firm should be increased by vocational exams and certifications. Also, the staffs working in the building audit firm are to be supervised and penalties may be given for the negative actions of employees. Another point worth mentioning is that contractors should be certified and their performance during the execution of works should be measured. Furthermore, differences in practices of BAS among administrations of provinces and districts should be eliminated by providing an in-service training certificate to the administrations. It seems to have drawbacks in regulations concerning BAS; therefore, detected problems are believed to shed light on the development of new legislation concerning BAS.

The aggregated judgments of the participants were utilized to determine severities of the problems seen in Turkish BAS. However, the perception differences that exist between different occupations such as civil engineers, architects, and electrical engineers might also provide valuable information about the existing BAS system in Turkey. Thus, the subject could be examined by forthcoming studies.

References

[1] Z. Y. İlerisoy, F. Gökşen, A. Soyluk, and Y. Takva, "Deprem Kaynaklı İkincil Afetler ve Türkiye Örneklemi," *Online J. Art Des.*, vol. 10, no. 2, pp. 138–148, 2022.

[2] O. Ergünay, "Ülkemizde Yapı Denetiminin Gelişimi ve 595 Sayılı Kanun Hükmünde Kararname ile Getirilen Yeni Yapı Denetim Sistemi," *Türkiye Mühendislik Haberleri Sayısı 410-2000/6*, pp. 15–17, 2000.

[3] S. Cansız, "Türkiye'de Kullanılan Deprem Yönetmeliklerinin Özellikleri ve Eşdeğer Yatay Deprem Yükü Hesabının Değişimi," *Int. J. Eng. Res. Dev.*, vol. 14, no. 1, pp. 58–71, 2022.

[4] "17 Ağustos 1999 Gölcük Depremi," *AFAD*, 1999. .

[5] B. GÜNER, "Türkiye'deki Deprem Hasarlarına Dönemsel bir Yaklaşım; 3 Dönem 3 Deprem," *East. Geogr. Rev.*, vol. 25, no. 43, pp. 139–152, 2020.

[6] F. Sakallı, "Yapı Denetim Sisteminde Yaşanan Sorunlar, 4708 Sayılı Yapı Denetim Hakkında Kanun'daki Eksiklikler ve Çözüm Önerileri," Istanbul Technical University, 2008.

[7] M. Pala and M. Ş. Demir, "Güneydoğu Anadolu Bölgesinde Yapı Denetimi Uygulamasında Karşılaşılan Sorunlar ve Bu Sorunlara İlişkin Çözüm Önerileri," *Adıyaman Üniversitesi Mühendislik Bilim. Derg.*, vol. 6, pp. 20–33, 2017.

[8] A. Doğan, "Ankara'da Yapi Denetim Sorunlarinin Belirlenmesiyle Ilgili Bir Saha Çalişmasi," Deaty Yayıncılık, Ankara, 2013.

[9] G. Tantekin Çelik and C. Ünal, "Yapı Denetim Firmalarının Sorunlarının Belirlenmesi ve Adana Örneği," 2017.

[10] R. Kural and O. Ünal, "İnşaat Sektöründe Yapı Denetimi ve Afyonkarahisar İlindeki Uygulamaların Araştırılması," *Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilim. Derg. Afyon*, vol. 15, pp. 1–10, 2015, doi: 10.5578/fmbd.10675.

[11] E. Erdiş and İ. H. Gerek, "Yapı Denetim Sisteminde KarşılaÇılan Sorunlar ve Çözüm Önerileri," in *6. İnşaat Yönetimi Kongresi*, 2011, pp. 298–306.

[12] R. Akbıyıklı, G. Opçin, M. Akdemir, and E. Gündüz, "Türkiye'de Yapı Denetim Kavramı, Amacı, Yasal Dayanağı ve Uygulamaları Üzerine Bir İnceleme," in *Uluslararası Katılımlı 7. İnşaat Yönetimi Kongresi*, 2017, pp. 217–229.

[13] M. Yılmaz and E. Köymen, "Türkiye'de Yapı Denetim Sistemi ve Sorunları Üzerine Teorik Bir İnceleme," *J. Soc. Humanit. Sci. Res.*, vol. 7, no. 50, pp. 330–339, 2020.

[14] S. Bayram, S. Aydınlı, A. Budak, and E. Oral, "Ethical problems in the production and inspection of construction in Turkey," *Pamukkale Univ. J. Eng. Sci.*, vol. 24, no. 3, pp. 461–467, 2018, doi: 10.5505/pajes.2017.65481.

[15] Society of Construction Law, "The society of construction law delay and disruption protocol," Leicestershire (United Kingdom), 2017.

[16] PMI, *A Guide to the Project Management Body of Knowledge*, 6th ed. Pennsylvania: Project Management Institute, 2017.

[17] Ministry of Environment Urbanization and Climate Change, *YAPI DENETİM SİSTEMİNDE DEĞİŞİKLİK*. Türkey, 2018.

[18] IMO, "AVRUPA'DA İNŞAAT MÜHENDİSLİĞİ SEKTÖRÜ," 1995.

[19] İMO, "Yapı Denetim Çalıştayı," ANtalya, 2016.

[20] C. ŞERİFOĞLU, "Mevcut Yapı Denetim Sisteminin Eleştirisi ve Sertifika Esaslı - Başarım Tabanlı Bir Bütünleşik Değerlendirme ve Denetim Modeli Önerisi," İstanbul Technical University, 2019.

[21] S. S. Tezcan *et al.*, "Yapida denetim ve sertifikali mühendis," *İzmir, İnşaat Mühendisleri Odası İzmir Şubesi Haber Bülteni*, no. 62, pp. 20–25, 1995.

[22] National Society of Professional Engineers, "What is a PE?," 2022. .

[23] National Society of Professional Engineers, "NCEES FE exam information," 2022. .

[24] Ministry of Environment and Urban Planning, *Yapi Denetimi Uygulama Yönetmeliğinde Değişiklik Yapilmasina Dair Yönetmelik*. Turkey, 2018.

[25] M. Velasquez and P. T. Hester, "An analysis of multi-criteria decision making methods Systemic Decision Making View project Maritime Cybersecurity View project An Analysis of Multi-Criteria Decision Making Methods," *Int. J. Oper. Res.*, vol. 10, no. 2, pp. 56–66, 2013.

[26] T. L. Saaty, *The analytic hierarchy process*. New York: McGraw-Hill, 1980.

[27] C. Kahraman, U. Cebeci, and Z. Ulukan, "Multi-criteria supplier selection using fuzzy AHP," *Logist. Inf. Manag.*, vol. 16, no. 6, pp. 382–394, Dec. 2003, doi: 10.1108/09576050310503367.

[28] R. V. Rao, *Decision Making in the Manufacturing Environment*, 1st ed. London: Springer-Verlag London, 2007.

[29] M. B. Javanbarg, C. Scawthorn, J. Kiyono, and B. Shahbodaghkhan, "Fuzzy AHP-based multicriteria decision making systems using particle swarm optimization," *Expert Syst. Appl.*, vol. 39, no. 1, pp. 960–966, Jan. 2012, doi: 10.1016/j.eswa.2011.07.095.

[30] Ö. Ekmekcioğlu, K. Koc, and M. Özger, "District based flood risk assessment in Istanbul using fuzzy analytical hierarchy process," *Stoch. Environ. Res. Risk Assess.*, vol. 8, pp. 617–637, 2020, doi: 10.1007/s00477-020-01924-8.

[31] R. Rostamzadeh, K. Govindan, A. Esmaeili, and M. Sabaghi, "Application of fuzzy VIKOR for evaluation of green supply chain management practices," *Ecol. Indic.*, vol. 49, pp. 188–203, 2015, doi: 10.1016/j.ecolind.2014.09.045.

[32] L. Zadeh, "Fuzzy sets," *Inf. Control*, vol. 8, no. 1, pp. 338–353, 1965.

[33] M. B. Ayhan, "A Fuzzy Ahp Approach For Supplier Selection Problem: A Case Study In A Gearmotor Company," *Int. J. Manag. Value Supply Chain.*, vol. 4, no. 3, pp. 11–23, 2013, doi: 10.5121/ijmvsc.2013.4302.

[34] D.-Y. Y. Chang, "Applications of the extent analysis method on fuzzy AHP," *Eur. J. Oper. Res.*, vol. 95, no. 3, pp. 649–655, Dec. 1996, doi: 10.1016/0377-2217(95)00300-2.

[35] P. Graham, N. Nikolova, and S. Sankaran, "Tension between leadership archetypes: systematic review to inform construction research and practice," *J. Manag. Eng.*, vol. 36, no. 1, p. 03119002, Jan. 2020, doi: 10.1061/(ASCE)ME.1943-5479.0000722.

[36] O. Okudan, C. Budayan, and I. Dikmen, "Development of a conceptual life cycle performance measurement system for build–operate–transfer (BOT) projects," *Eng. Constr. Archit. Manag.*, vol. 28, no. 6, pp. 1635–1656, Jun. 2021, doi: 10.1108/ECAM-01-2020-0071.

[37] W. Yi and A. P. C. Chan, "Critical review of labor productivity research in construction journals," *J. Manag. Eng.*, vol. 30, no. 2, pp. 214–225, Mar. 2014, doi: 10.1061/(ASCE)ME.1943-5479.0000194.

[38] A. Parker and J. Tritter, "Focus group method and methodology: current practice and recent debate," *Int. J. Res. Method Educ.*, vol. 29, no. 1, pp. 23–37, Apr. 2006, doi: 10.1080/01406720500537304.

[39] I. Y. S. Chan, M. Leung, and S. S. W. Yu, "Managing the Stress of Hong Kong Expatriate Construction Professionals in Mainland China: Focus Group Study Exploring Individual Coping Strategies and Organizational Support," *J. Constr. Eng. Manag.*, vol. 138, no. 10, pp. 1150–1160, 2012, doi: 10.1061/(asce)co.1943-7862.0000533.

[40] M. M. Hennink, *Focus Group Dicussions: Understanding Qualitative Research*. New York: Oxford, 2013.

[41] A. R. J. Dainty, M. I. Cheng, and D. R. Moore, "Redefining performance measures for construction project managers: An empirical evaluation," *Constr. Manag. Econ.*, vol. 21, no. 2, pp. 209–218, Feb. 2003, doi: 10.1080/0144619032000049737.

[42] A. Hasan, A. Elmualim, R. Rameezdeen, B. Baroudi, and A. Marshall, "An exploratory study on the impact of mobile ICT on productivity in construction projects," *Built Environ. Proj. Asset Manag.*, vol. 8, no. 3, pp. 320–332, 2018, doi: 10.1108/BEPAM-10-2017-0080.

[43] T. O. Nyumba, K. Wilson, C. J. Derrick, and N. Mukherjee, "The use of focus group discussion methodology: Insights from two decades of application in conservation," *Methods Ecol. Evol.*, vol. 9, no. 1, pp. 20–32, Jan. 2018, doi: 10.1111/2041-210X.12860.

[44] C. Budayan, "Evaluation of delay causes for BOT projects based on perceptions of different stakeholders in Turkey," *J. Manag. Eng.*, vol. 35, no. 1, p. 04018057, 2019, doi: 10.1061/(asce)me.1943-5479.0000668.

[45] S. Opricovic, "Fuzzy VIKOR with an application to water resources planning," *Expert Syst. Appl.*, vol. 38, no. 10, pp. 12983–12990, 2011, doi: 10.1016/j.eswa.2011.04.097.

[46] P. Liu and X. Wu, "A competency evaluation method of human resources managers based on multi-granularity linguistic variables and VIKOR method," *Technol. Econ. Dev. Econ.*, vol. 18, no. 4, pp. 696–710, 2012, doi: 10.3846/20294913.2012.753169.

[47] S. Opricovic and G. H. Tzeng, "Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS," *Eur. J. Oper. Res.*, vol. 156, no. 2, pp. 445–455, 2004, doi: 10.1016/S0377-2217(03)00020-1.

[48] J. R. Ribas, M. E. Arce, F. A. Sohler, and A. Suárez-García, "Multi-criteria risk assessment: Case study of a large hydroelectric project," *J. Clean. Prod.*, vol. 227, pp. 237–247, 2019, doi: 10.1016/j.jclepro.2019.04.043.

[49] X. ling Yang, J. hua Ding, and H. Hou, "Application of a triangular fuzzy AHP approach for flood risk evaluation and response measures analysis," *Nat. Hazards*, vol. 68, no. 2, pp. 657–674, 2013, doi: 10.1007/s11069-013-0642-x.

[50] A. Darko, A. P. C. Chan, E. E. Ameyaw, E. K. Owusu, E. Pärn, and D. J. Edwards, "Review of application of analytic hierarchy process (AHP) in construction," *Int. J. Constr. Manag.*, vol. 19, no. 5, pp. 436–452, Sep. 2019, doi: 10.1080/15623599.2018.1452098.

[51] M. B. Javanbarg, C. Scawthorn, J. Kiyono, and B. Shahbodaghkhan, "Fuzzy AHP-based multicriteria decision making systems using particle swarm optimization," *Expert Syst. Appl.*, vol. 39, no. 1, pp. 960–966, Jan. 2012, doi: 10.1016/j.eswa.2011.07.095.

[52] S. H. Zyoud, L. G. Kaufmann, H. Shaheen, S. Samhan, and D. Fuchs-Hanusch, "A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS," *Expert Syst. Appl.*, vol. 61, pp. 86–105, 2016, doi: 10.1016/j.eswa.2016.05.016.

[53] L. M. P. Beltrão and M. T. M. Carvalho, "Prioritizing Construction Risks Using Fuzzy AHP in Brazilian Public Enterprises," *J. Constr. Eng. Manag.*, vol. 145, no. 2, p. 05018018, 2019, doi: 10.1061/(ASCE)CO.1943-7862.0001606.

[54] L. Gigović, D. Pamučar, Z. Bajić, and S. Drobnjak, "Application of GIS-interval rough AHP methodology for flood hazard mapping in Urban areas," *Water (Switzerland)*, vol. 9, no. 6, pp. 1–26, 2017, doi: 10.3390/w9060360.

[55] N. Dahri and H. Abida, "Monte Carlo simulation-aided analytical hierarchy process (AHP) for flood susceptibility mapping in Gabes Basin (southeastern Tunisia)," *Environ. Earth Sci.*, vol. 76, no. 7, pp. 1–14, 2017, doi: 10.1007/s12665-017-6619-4.

[56] G. Papaioannou, L. Vasiliades, and A. Loukas, "Multi-Criteria Analysis Framework for Potential Flood Prone Areas Mapping," *Water Resour. Manag.*, vol. 29, no. 2, pp. 399–418, 2015, doi: 10.1007/s11269-014-0817-6.

[57] K. Koc and O. Okudan, "Assessment of Life Cycle Risks of Deconstruction in Urban Regeneration Projects," 2021, doi: 10.1061/(ASCE)CO.1943-7862.0002161.

[58] T. L. Saaty, "Decision making — the Analytic Hierarchy and Network Processes (AHP/ANP)," *J. Syst. Sci. Syst. Eng.*, vol. 13, no. 1, pp. 1–35, 2004, doi: 10.1007/s11518-006-0151-5.

[59] D.-Y. Chang, "Applications of the extent analysis method on fuzzy AHP," *Eur. J. Oper. Res.*, vol. 95, no. 3, pp. 649–655, Dec. 1996, doi: 10.1016/0377-2217(95)00300-2.

[60] K. Kamvysi, K. Gotzamani, A. Andronikidis, and A. C. Georgiou, "Capturing and prioritizing students' requirements for course design by embedding Fuzzy-AHP and linear programming in QFD," *Eur. J. Oper. Res.*, vol. 237, no. 3, pp. 1083–1094, 2014, doi: 10.1016/j.ejor.2014.02.042.

[61] A. Ishizaka and A. Labib, "Review of the main developments in the analytic hierarchy process," *Expert Syst. Appl.*, vol. 38, no. 11, pp. 14336–14345, 2011, doi: 10.1016/j.eswa.2011.04.143.

[62] M. L. Tseng and Y. H. Lin, "Selection of competitive advantages in TQM implementation using fuzzy AHP and sensitivity analysis," *Asia Pacific Manag. Rev.*, vol. 13, no. 3, pp. 583–599, 2008, doi: 10.6126/APMR.2008.13.3.03.

[63] Ö. Ekmekcioğlu, K. Koc, and M. Özger, "District based flood risk assessment in Istanbul using fuzzy analytical hierarchy process," *Stoch. Environ. Res. Risk Assess.*, 2020, doi: 10.1007/s00477-020-01924-8.

[64] H. Aladağ and Z. Işık, "Design and construction risks in BOT type mega transportation projects," *Eng. Constr. Archit. Manag.*, vol. 26, no. 10, pp. 2223–2242, 2019, doi: 10.1108/ECAM-08-2018-0351.

[65] H. Aladağ and Z. Işik, "The Effect of Stakeholder-Associated Risks in Mega-Engineering Projects: A Case Study of a PPP Airport Project," *IEEE Trans. Eng. Manag.*, vol. 67, no. 1, pp. 174–186, 2020, doi: 10.1109/TEM.2018.2866269.

Turkish Journal of Civil Engineering, 2023 105-134, Paper 719, ***Research Article***

An Integrated Simulation-Optimization Approach for Dynamic Design of the Urban Wastewater Collection Systems

Abbas GHOLAMI[1]
Pınar Gökçe DURGUT[2]
M. Tamer AYVAZ[3]

ABSTRACT

In this study, a simulation-optimization approach is proposed for dynamic design of the urban wastewater collection systems. The proposed approach consists of the mutual integration of the Storm Water Management Model (SWMM), developed by the U.S. Environmental Protection Agency (US-EPA) and the heuristic Harmony Search (HS) optimization approach. Unlike the previous approaches developed to solve wastewater collection system design problems, the proposed approach simulates the hydraulic flow process by considering unsteady state flow conditions based on the dynamic wave model. The objective of the HS-based optimization model is to determine the pipe slopes so that the total system cost is minimized. After determining the pipe slopes, the corresponding pipe diameters were determined by developing an internal solution approach. All the physical and managerial constraints that should be considered during the search process have been considered by means of the penalty function approach. The applicability of the proposed approach was evaluated by solving two example problems. Identified results indicated that the proposed approach can effectively solve the dynamic design problems of the wastewater collection systems.

Keywords: Wastewater collection system, SWMM, harmony search, dynamic design.

Note:

- This paper was received on March 29, 2022 and accepted for publication by the Editorial Board on October 10, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

• https://doi.org/10.18400/tjce.1209180

1 Department of Civil Engineering, Pamukkale University, Denizli, Türkiye
abbasgholami999@gmail.com - https://orcid.org/0000-0003-0129-2546

2 Department of Civil Engineering, Pamukkale University, Denizli, Türkiye
pgkargi@gmail.com - https://orcid.org/0000-0002-8089-9030

3 Department of Civil Engineering, Pamukkale University, Denizli, Türkiye
tayvaz@pamukkale.edu.tr - https://orcid.org/0000-0002-8566-2825

1. INTRODUCTION

One of the most important tasks of civil and environmental engineering is to dispose the used water from residential or industrial areas by means of the wastewater collection systems. These systems include high number of equipment, such as pipes, manholes, pumping facilities, and require significant excavation works. Therefore, costs of these systems are usually high and a small amount of reduction in their installation costs corresponds to significant savings [1]. Depending on these facts, the concept of optimum design by using the integrated simulation-optimization approaches is crucial nowadays to find a solution with minimum cost.

In practice, the problem of optimum wastewater collection system design can be solved by considering both combined and separated sewer systems depending on the project requirements. Note that both systems consider the same solution procedure such that commercial pipe diameters and/or pipe slopes are selected as the decision variables of the optimization model [1]. For the first case, the commercial pipe diameters are determined by the optimization model and the corresponding pipe slopes are calculated by means of the Manning's equation. Since diameters of the pipes are selected from the set of commercial pipes, it is required to solve a discrete optimization problem. In the second case, the optimization model considers pipe slopes as decision variables and the corresponding pipe diameters are calculated again by using the Manning's equation. However, it is required to convert the calculated pipe diameters into the commercial sizes and this process also makes the problem discrete although the associated decision variables of the problem are continuous. The last case consists of the more general case where both pipe diameters and their slopes are considered as the decision variables. However, this kind of use increases the number of decision variables twofold. Therefore, mathematical search space of the problem becomes more complex and finding an optimum solution becomes difficult especially for the systems with excessive number of pipes [2]. Note that there is a strong interaction between diameters and slopes of the pipes for three cases mentioned above. For instance, although increasing the pipe slopes allows to transmit the same flow with the smaller pipe diameters, it increases the excavation cost due to the increased pipe slopes. On the contrary, reducing the pipe slopes decreases the excavation cost, but it is required to use larger pipe diameters to transmit the same flow, and this increases the pipe costs [1-2]. Therefore, finding a trade-off between pipe diameters and their corresponding slopes by using the optimization approaches is important.

The current literature includes various solution approaches to solve both storm and urban sewer system design optimization problems. Depending on the branched nature of the sewer systems, the problem was previously solved by using the dynamic programming (DP) based approaches [3-6]. Furthermore, linear and nonlinear programming approaches were also employed to the solution of the optimum sewer system design problems [7-10]. Although these optimization approaches are well effective on solving the problem, there may be possibilities of stucking to local optimum solutions especially for the problems with non-convex and/or discontinuous search spaces [1, 11]. Therefore, nowadays, heuristic optimization approaches became the popular tools to solve the sewer system design problems. Note that the main idea of the heuristic optimization approaches is to mimic the processes in nature, mathematically. Unlike the traditional approaches, heuristic optimization approaches can easily find the global optimum or near global optimum solutions even if the search space of the problem is non-convex and/or discontinuous. Furthermore, they do not require special initial points to find an optimum solution since the search process is conducted by using multiple solutions [12]. By using heuristic optimization approaches, the optimum sewer system design problem was previously solved by many researchers. Although these conducted studies have some similarities in terms of their computational structures, their main differences are due to the considered optimization approaches. For example, genetic algorithm (GA), which applies the genetic evolution processes in nature to the optimization problems, was previously applied in some studies [2, 13-15]. Similarly, particle swarm optimization (PSO), which is developed based on the social behavior of animals, such as bird flocking or fish schooling, was also used to solve the associated problem in different studies [16-20]. In addition to these studies, different heuristic optimization approaches have also been applied to the solution of optimum sewer system design problems, and the details of these studies can be found in [1, 20-29].

It should be noted that, in all the studies mentioned above, design process of sewer systems was conducted by considering the peak value of the flow hydrograph as design discharge. In other words, the optimum system is designed by considering the steady-state flow conditions. This design strategy requires the assumption that the shape of the flow hydrograph remains unchanged as the water moves from upstream to downstream through the pipes. However, this assumption is not satisfied in real life and the shape of the flow hydrograph changes during operation of the system. This change results with a time lag and the attenuated peak value of the downstream flow hydrograph [30]. Although these attenuations are usually negligible in small systems, they may be significant for the big sewer systems such that the shape of the upstream flow hydrographs significantly change when it comes to the downstream locations. If this fact is not considered during design, larger design discharges are calculated at downstream locations than they should actually be. This situation results with a calculation of the larger pipe diameters at downstream locations, and consequently, increases the cost of the system. Therefore, it would be better to consider the unsteady flow conditions during design of the sewer systems to fully address the flow routing process in real life.

There are limited studies in literature that consider unsteady flow simulations in designing the sewer network systems. Afshar et al. [31] developed a GA based optimization approach for hydrograph-based design of the storm sewer systems. In their model, unsteady flow simulations through pipes have been conducted by means of the transport module of the United States Environmental Protection Agency (US-EPA) Storm Water Management Model (SWMM). Shao et al. [32] proposed a SWMM based approach to solve the storm sewer network design problems. In the proposed approach, an automated algorithm is proposed by considering two computational steps where the pipe diameters and their corresponding slopes are determined sequentially without using an optimization approach. Note that these two studies given above focused on designing the storm sewer collection systems by considering the transient flow conditions. Regarding the household wastewater collection system design, Zaheri et al. [33] developed a solution approach where a cellular automata (CA) is used as the optimization tool and SWMM is used as the simulation tool. Their approach considers the diameters and nodal elevations of the pipes as decision variables and solves the problem in two phases. However, they applied a constant flow hydrograph from upstream manhole locations of the pipes and not considered the diurnal wastewater discharge patterns of the residential buildings and/or industrial facilities during design process.

In this study, a simulation-optimization approach is proposed for dynamic design of the urban wastewater collection system design problems. In the proposed approach, SWMM is used as the simulation model for performing the dynamic simulations of the network. This simulation model is then integrated to an optimization model where heuristic harmony search (HS) optimization approach is used. Note that HS based optimization approach was previously used to solve a similar problem in a conference proceeding [27] and this study is an extension of the related study. The key difference of the proposed approach from the one given in [27] is that the problem has been solved by considering unsteady diurnal wastewater discharge patterns of the residential buildings and/or industrial facilities whereas the classical steady-state solution was conducted in [27]. According to the authors' knowledge, this is the first application of HS and SWMM for designing the urban wastewater collection networks by considering the unsteady flow conditions. Applicability of the proposed simulation-optimization approach is evaluated by solving two example networks. Identified results indicated that the proposed approach not only finds similar or better results than those obtained in literature, but also effectively solve the problem by considering the time dependent wastewater discharges during the optimum design process.

2. MODEL DEVELOPMENT

The problem of optimum urban wastewater collection system design is dynamically solved by using the proposed simulation-optimization approach. In the following sections, first, the problem of optimum sewer system design is formulated. After that, the main computational structures of the simulation and optimization models are described. Finally, how to integrate them in an optimization framework is defined.

2.1. Optimum Sewer System Design Problem

As stated in the previous section, the problem of optimum sewer systems design can be formulated as an optimization problem. In this formulation, the objective is to minimize the total system cost by adjusting the diameters and/or nodal elevations of the pipes. During the search process, it is required to satisfy some physical and managerial constraints. Depending on these definitions, the optimum design problem by considering the unsteady state flow conditions can be mathematically stated as follows:

Let n_p and n_m be the number of pipes and manholes; D_i and L_i be the diameter and length of the i^{th} pipe $\left(i = 1,2,3,\cdots,n_p\right)$; $\bar{Z}_i$ be the mean excavation depth of the i^{th} pipe; and H_k be the depth of the k^{th} manhole $(k = 1,2,3,\cdots,n_m)$ in the system. Using these definitions, the following objective function and constraints can be defined for the problem [2, 33]:

$$\Phi = \min\left\{\sum_{i=1}^{n_p} L_i \cdot \mathcal{C}_1(D_i, \bar{Z}_i) + \sum_{k=1}^{n_m} \mathcal{C}_2(H_k)\right\} \tag{1}$$

subject to

$$g_{i1}:\ \max\{q_i(t)\} \geq \max\{Q_i(t)\} \tag{2}$$

$$g_{i2}: \ \max\{V_i(t)\} \leq V_{\max} \tag{3}$$

$$g_{i3}: \ \min\{V_i(t)\} \geq V_{\min} \tag{4}$$

$$g_{i4}: \ \frac{\max\{y_i(t)\}}{D_i} \leq \alpha \tag{5}$$

$$g_{i5}: \ S_i \geq S_{\min} \tag{6}$$

$$g_{i6}: \ E_i^u \leq E_{\max} \tag{7}$$

$$g_{i7}: \ E_i^u \geq E_{\min} \tag{8}$$

$$g_{i8}: \ E_i^d \leq E_{\max} \tag{9}$$

$$g_{i9}: \ E_i^d \geq E_{\min} \tag{10}$$

where Φ is the objective function to be minimized; $C_1(\bullet,\bullet)$ and $C_2(\bullet)$ are the cost functions for the pipes and manholes, respectively; $q_i(t)$ is the flow discharge of the i^{th} pipe at t^{th} time period; $Q_i(t)$ is the design discharge hydrograph of the i^{th} pipe at t^{th} time period; $V_i(t)$ is the flow velocity of the i^{th} pipe at t^{th} time period; $V_{\min}$ and $V_{\max}$ are the minimum and maximum allowable velocity values, respectively; $y_i(t)$ is the flow depth in the i^{th} pipe at t^{th} time period; α is the maximum allowable ratio of flow depth to pipe diameter; S_i is the slope of the i^{th} pipe; $S_{\min}$ is the minimum pipe slope; E_i^u and E_i^d are the cover depths at upstream and downstream ends of the i^{th} pipe, respectively; $E_{\min}$ and $E_{\max}$ are the minimum and maximum allowable values of the cover depths, respectively. These variables can be seen on the schematic profile in Figure 1.

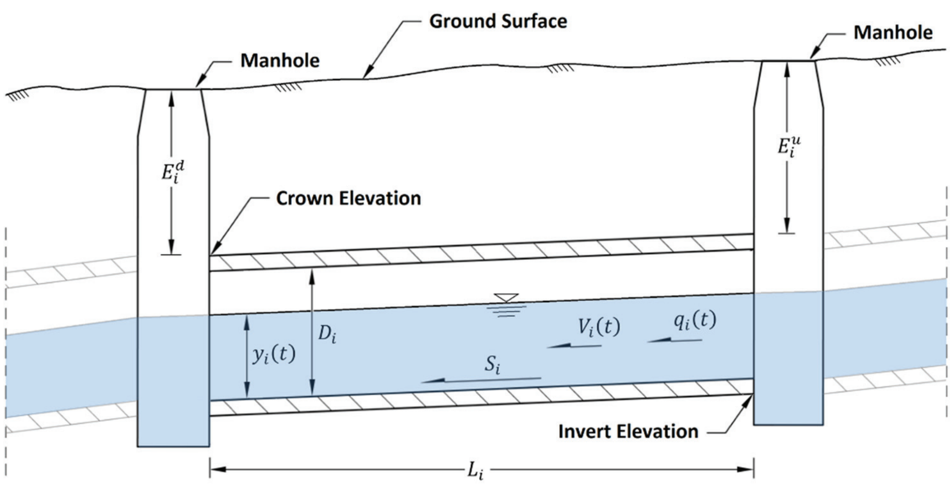


Figure 1 - Illustration of the variables used in the optimization process (adapted from [1])

The formulation given above states that the optimum sewer system design problem is a constrained optimization problem. Therefore, during minimization of Equation (1), all the constraints between Equations (2) to (10) need to be satisfied to obtain a feasible solution. Among these constraints, Equation (2) is used to control if flow discharge of the pipes is equal or greater than the design flow hydrograph. This constraint is very important since diameters of the pipes are determined based on these flow values during design process. Equations (3) and (4) are used to maintain the flow velocities between specified minimum and maximum values. This is also important since these constraints are used to prevent sediment accumulation and internal erosion of the pipe materials, respectively. Equation (5) is used to guarantee the free surface flow conditions through pipes of the system. Equation (6) is used to satisfy the minimum pipe slope value, and Equations (7) to (10) are used to satisfy the minimum and maximum allowable cover depths on upstream and downstream ends of the pipes, respectively. Note that the problem given above is stated by considering unsteady flow conditions through pipes. Thus, value of the design discharge hydrograph should be routed hydraulically as water moves from upstream to downstream locations of the system and this process is conducted by modeling the hydraulic flow process on SWMM.

2.2. Simulation Model: SWMM

SWMM, developed by US-EPA, is a widely used mathematical simulation model and used for simulating the flow and pollution transport processes in sewer and drainage networks [34]. SWMM considers the drainage system as a set of interrelated elements called objects which are placed in a series of layers. These objects can be visual elements (e.g., junctions, conduits, reservoirs, pumps, etc.) or non-visual elements (e.g. general specifications of the system) and all of them can be used to conduct hydrological, hydraulic or pollution transport analyses [35]. Note that hydraulic routing process on SWMM is simulated by sequentially solving the continuity and momentum equations by considering the unsteady free surface flow process through pipes. Mathematical definition of the continuity and momentum equations which are called as the St. Venant equations can be expressed as follows:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \tag{11}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial (Q^2/A)}{\partial x} + gA\frac{\partial y}{\partial x} - gA\left(S - S_f\right) = 0 \tag{12}$$

where x is the distance; t is the time; Q is the flow rate; A is the cross-sectional flow area; g is acceleration of gravity; S is the pipe bed slope; and S_f is the friction slope. The value of friction slope S_f is expressed by using the Manning's equation as follows:

$$S_f = \frac{n^2 Q|Q| P^{4/3}}{A^{10/3}} \tag{13}$$

where n is the Manning's surface friction and P is the wetted perimeter. Note that this equation system is mostly solved by means of the numerical solution approaches and these solutions are conducted by considering kinematic wave, diffusion wave, and dynamic wave approaches. In kinematic wave approach, the solution is conducted by just taking the last term of Equation (12) into account. For diffusion wave, approach the last two terms of Equation (12) are considered. Compared to kinematic wave approach, diffusion wave approach provides more information about the flow process since more data is used. Lastly, in dynamic wave approach, all the terms of Equation (12) are considered, and this solution provides most accurate results compared to the others [34]. Note that SWMM can numerically solve this equation system by using both diffusion and dynamic wave approaches. During this solution, SWMM uses an implicit backwards Euler method which solves the equation system by means of the Picard's iteration approach [34].

2.2. Optimization Model: Harmony Search (HS) Optimization Approach

HS is a musical-based heuristic optimization approach which is inspired by the observation that the aim of the music is to seek for a perfect state of harmony [36]. This process in music is analogous to the optimization process since the main objective of the optimization is to seek for a globally optimum solution. This analogy between musical improvisation and optimization processes was first established by Geem et al. [37]. In this adaptation, the musicians, for example in a jazz trio, correspond to decision variables of the optimization problem, and the notes in the musicians' memories correspond to the potential values of the decision variables. Note that the musicians can produce a new harmony by considering three musical operations: (i) by playing a series of pitches in their memory; (ii) by playing slightly adjusted pitches from previously played ones in their memory; (iii) by playing a series of pitches randomly without considering their memory. These three musical operations have

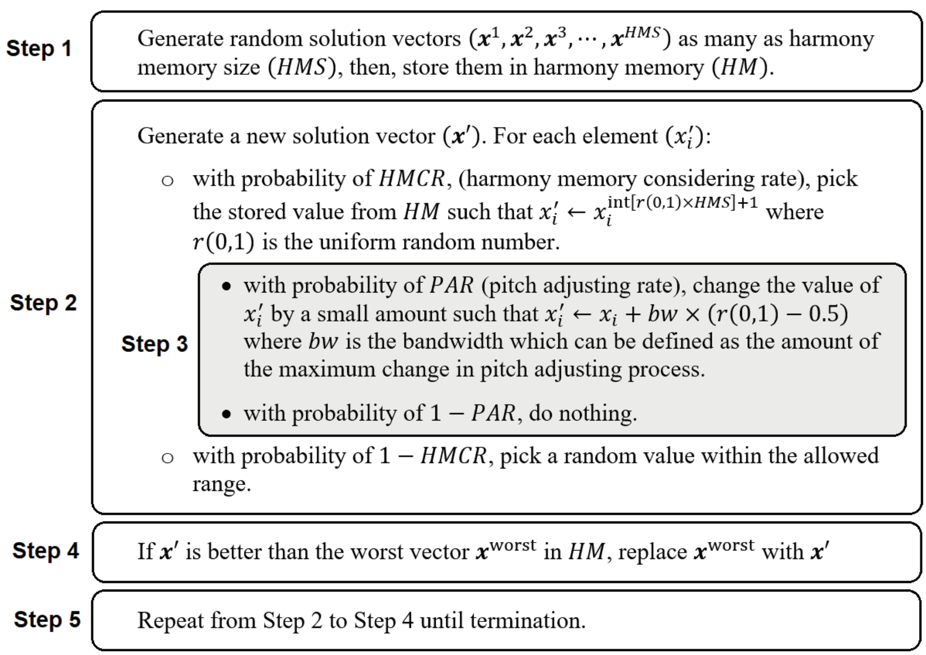


Figure 2 - Computational sequence of HS optimization algorithm.

been mathematically formulated by Geem et al. [37] and they proposed three operational processes of HS: (i) memory consideration; (ii) pitch adjusting; (iii) random selection. Note that combination of these three operations is used to generate a new solution vector. If this new generated solution vector provides better objective function value than the worst one in harmony memory, the vector with the worst function value in harmony memory is replaced with the new generated solution vector and this process is repeated until termination. This computational sequence can be summarized in Figure 2.

To solve an optimization problem based on the solution sequence given in Figure 2, it is required to provide the solution parameters of HS which are: harmony memory size (HMS), harmony memory considering rate ($HMCR$), pitch adjusting rate (PAR), and bandwidth (bw). HM is a matrix where the decision variables and the corresponding objective function values are stored, $HMCR$ and PAR are the probabilities which are used to explore the search space globally and locally, and bw is used for the pitch adjusting process. Detailed explanation of this computational procedure is summarized in Figure 3.

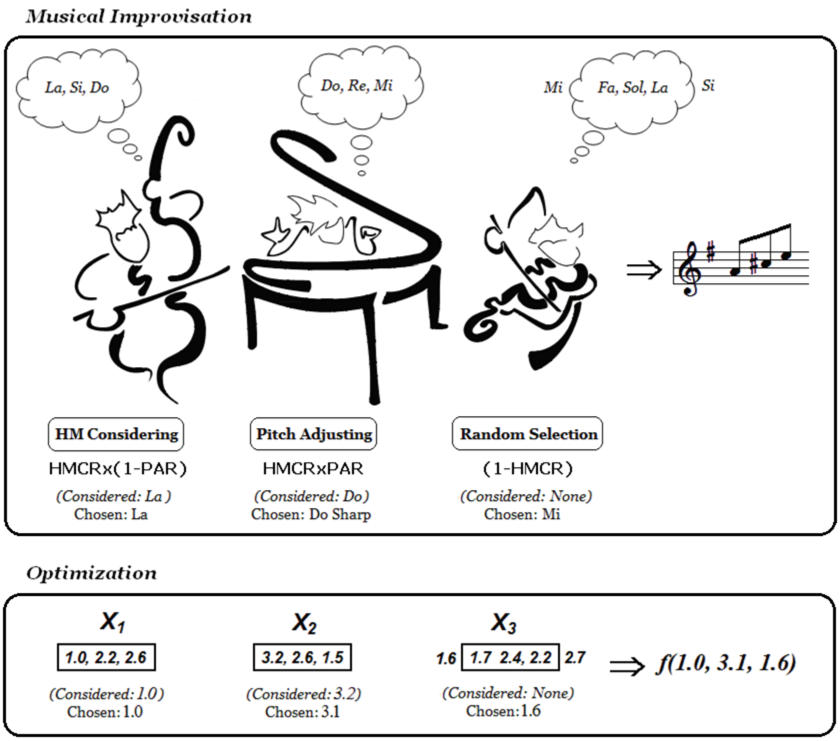


Figure 3 - Analogy between musical improvisation and optimization (adapted from [38]).

It can be seen from Figure 2 that the musicians have different notes in their HM. As indicated previously, their aim is to find a musically pleasing or fantastic harmony by making some improvisations. Depending on the computational structure of HS, this process is conducted as follows [27]:

i) The first musician in Figure 3 has three notes in HM. With probability $HMCR \times (1 - PAR)$, he considers and plays La. Since La, Si, Do in HM corresponds to the values of 1.0, 2.2, 2.6 in the optimization process, choosing and playing La corresponds choosing and using 1.0 as the potential value of the first decision variable. Therefore, the first decision variable value is determined based on the memory consideration rule of HS. *ii)* The second musician in Figure 3 also has three notes in HM. Unlike the first musician, with probability $HMCR \times PAR$, he selects Do and plays its neighbor Do#. Since Do corresponds to 3.2 in the optimization process, its neighbor note Do# corresponds to 3.1 which is a slightly adjusted value of 3.2. Therefore, the second decision variable value is determined based on the pitch adjusting rule of HS. *iii)* The third musician in Figure 3 also has three notes, Fa, Sol, La in HM. Although his HM was previously used, for the current improvisation, he decides to select and play a random note, Mi for this case. Unlike the first and second variables, this note corresponds to a random value (1.6) in the search space. Depending on this result, the value of the third decision variable is determined based on the random selection rule of HS.

Depending on the memory consideration, pitch adjusting, random selection processes, the new harmony is composed as (La, Do#, Mi) and these notes correspond to the decision variable values of (1.0, 3.1, 1.6). After this process, these values are used as input of the objective function. If this newly calculated objective function value is better than the worst one in HM, the solution with the worst objective function value is excluded from HM and the newly generated one is included, and this solution sequence is repeated until termination.

2.3. Problem Formulation

As indicated in Section 2.1, the problem of optimum sewer system design is a constrained optimization problem. Therefore, minimization of Equation (1) should be conducted by considering the constraint set given between Equations (2) and (10). At this point, there is an important issue that requires further analysis. Just as the other heuristics, HS is an unconstrained optimization approach and cannot directly consider the constraint set during minimization or maximization of an objective function. Since the optimization problem here is a constrained one, it is required to convert this problem to an unconstrained optimization problem by means of the penalty function approach. For the problem considered here, this process is conducted as follows:

$$\Phi' = \min\{\Phi + \boldsymbol{\lambda} \cdot \mathcal{P}(\boldsymbol{g})\} \qquad (14)$$

where Φ' is the penalized objective function value; $\boldsymbol{g} = [g_{ij}]$ is a constraint matrix ($i = 1,2,3,\cdots,n_p$; $j = 1,2,3,\cdots,9$) which stores the problem constraints given between Equations (2) and (10); $\mathcal{P}(\bullet)$ is the penalty function which is used to prevent constraint violation; and $\boldsymbol{\lambda} = \{\lambda_j\}$ is a vector ($j = 1,2,3,\cdots,9$) including the penalty coefficients which are used to adjust the magnitude of the penalty terms. Note that selection of the values of penalty coefficients is very important to prevent constraint violations. Since there is not any mathematical approach to determine their exact values, their magnitudes are usually adjusted by means of the trial-and-error approaches. A general procedure is that use of the larger values for λ_j means greater effort to satisfy the constraint sets [38]. In literature, there are various penalty function approaches proposed to solve the constrained optimization problems. Among them, the following structure is used:

$$\mathcal{P}(g_{ij}) = \begin{cases} 0 & ; \quad \hat{g}_{ij} \leq 0 \\ (\hat{g}_{ij})^2 & ; \quad \text{otherwise} \end{cases} \tag{15}$$

where $\hat{g}_{ij}$ is the normalized constraint function which is modified as to be equal to or lower than zero. Depending on this definition, the optimum sewer system design problem can be stated mathematically as follows:

$$\Phi' = \min\left\{\sum_{i=1}^{n_p} L_i \cdot \mathcal{C}_1(D_i, \bar{Z}_i) + \sum_{k=1}^{n_m} \mathcal{C}_2(H_k) + \sum_{j=1}^{9} \lambda_j \sum_{i=1}^{n_p} \mathcal{P}(g_{ij})\right\} \tag{16}$$

subject to

$$\hat{g}_{i1}: \left(1 - \frac{\max\{q_i(t)\}}{\max\{Q_i(t)\}}\right) \leq 0 \tag{17}$$

$$\hat{g}_{i2}: \left(\frac{\max\{V_i(t)\}}{V_{\max}} - 1\right) \leq 0 \tag{18}$$

$$\hat{g}_{i3}: \left(1 - \frac{\min\{V_i(t)\}}{V_{\min}}\right) \leq 0 \tag{19}$$

$$\hat{g}_{i4}: \left(\frac{\max\{y_i(t)\}}{\alpha \cdot D_i} - 1\right) \leq 0 \tag{20}$$

$$\hat{g}_{i5}: \left(1 - \frac{S_i}{S_{\min}}\right) \leq 0 \tag{21}$$

$$\hat{g}_{i6}: \left(\frac{E_i^u}{E_{\max}} - 1\right) \leq 0 \tag{22}$$

$$\hat{g}_{i7}: \left(1 - \frac{E_i^u}{E_{\min}}\right) \leq 0 \tag{23}$$

$$\hat{g}_{i8}: \left(\frac{E_i^d}{E_{\max}} - 1\right) \leq 0 \tag{24}$$

$$\hat{g}_{i9}: \left(1 - \frac{E_i^d}{E_{\min}}\right) \leq 0 \tag{25}$$

By using the penalty function definition in Equation (15) and the problem formulation between Equations (16) and (25), the problem of optimum sewer system design can be solved for unsteady flow conditions by using the proposed simulation-optimization approach. The decision variables of the HS based optimization model is the bed slope S_i for each pipe $(i = 1,2,3,\cdots,n_p)$.

2.4. Integration of Simulation and Optimization Models

As stated previously, the proposed simulation-optimization approach consists of the mutual integration of SWMM and HS. For this purpose, a code in Visual Basic for Applications (VBA) platform has been developed. The structure of this code is given in Figure 4.

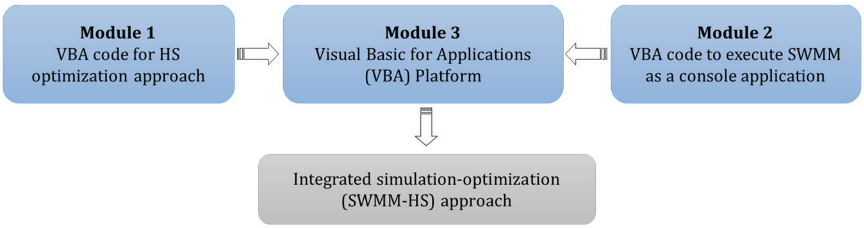


Figure 4 - Integration of HS-SWMM on VBA platform.

As can be seen from Figure 4, the developed VBA code has three modules. The first module includes the VBA code of the HS optimization approach which is an independent code and can be used to solve any optimization problem. The second module is developed for executing the SWMM as a console application. This process can be conducted from the command line within a DOS window. Therefore, the second module aims to write the input data of the problem to INP file of the SWMM, to execute SWMM from the DOS platform for the generated INP file, and to read the generated RPT file to get the results of the unsteady model simulation for the provided INP file. Finally, the last module aims to integrate these two modules in an optimization framework. Note that Module 3 also includes an implicit solution procedure for determining the pipe diameters for the generated pipe slopes by HS optimization approach. This solution procedure is based on the solution sequence given in Figure 5.

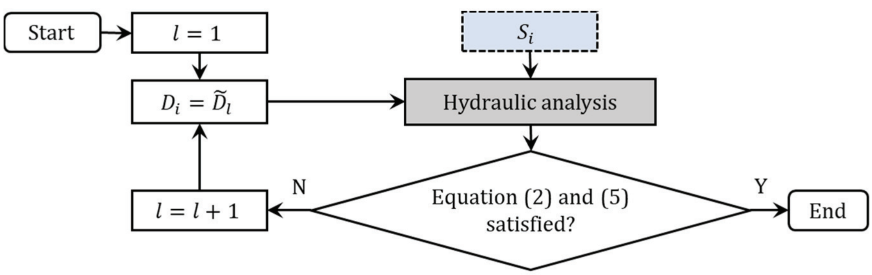


Figure 5 - Implicit pipe diameter selection procedure.

where $\widetilde{\boldsymbol{D}} = \{\widetilde{D}_1, \widetilde{D}_2, \widetilde{D}_3, \cdots, \widetilde{D}_l\}$ is a vector which includes commercial pipe diameters in the market. As can be seen from Figure 5, the hydraulic analysis is started by using the smallest pipe diameter. After execution of SWMM model for that diameter, the flow in the pipe is evaluated in terms of the constraints given in Equations (2) and (5). If both constraints are satisfied, the selected pipe diameter is used for the other analyses. Otherwise, its value is increased to the next one and the same procedure is repeated until satisfying Equations (2) and (5). Note that evaluation of Equations (3) and (4) is not considered here since their values are forced to control by using the penalty functions.

3. NUMERICAL APPLICATIONS

The applicability of the proposed simulation-optimization approach is evaluated by solving two example design problems. The first problem is used to verify the HS based optimization model by solving a well-known benchmark example system given in literature. The second example is used to evaluate the applicability of the proposed dynamic design approach considering diurnal wastewater discharge patterns for residential and industrial areas. These two examples have been solved by considering the optimization formulation between Equations (16) and (25) based on the integration scheme given in Figure 4. In this integration, the values of the penalty coefficients are assumed to be $\lambda_{1-9} = 10^9$ depending on some previous model executions. Although HS is an efficient optimization approach on solving various optimization problems, its efficiency should be evaluated for different solution parameters. As indicated previously, there are 4 solution parameters of HS which are the HMS, $HMCR$, PAR, and bw. Among them, the value of bw is usually adjusted based on the lower ($\boldsymbol{x}_{\min}$) and upper ($\boldsymbol{x}_{\max}$) bounds of the decision variables. Therefore, its value is taken as $bw = (\boldsymbol{x}_{\max} - \boldsymbol{x}_{\min})/100$ for all the decision variables. For the other solution parameters, a detailed sensitivity analysis has been conducted to evaluate the algorithm's performance for different parameter combinations. Note that two different scenarios have been considered in this analysis. In Scenario A, it is assumed that each HS solution parameter gets the following discrete values: $HMS \in [10, 20, 30, 40]$, $HMCR \in [0.80, 0.85, 0.90, 0.95]$ and $PAR \in [0.20, 0.30, 0.40, 0.50]$. Using these parameter values, the proposed approach is

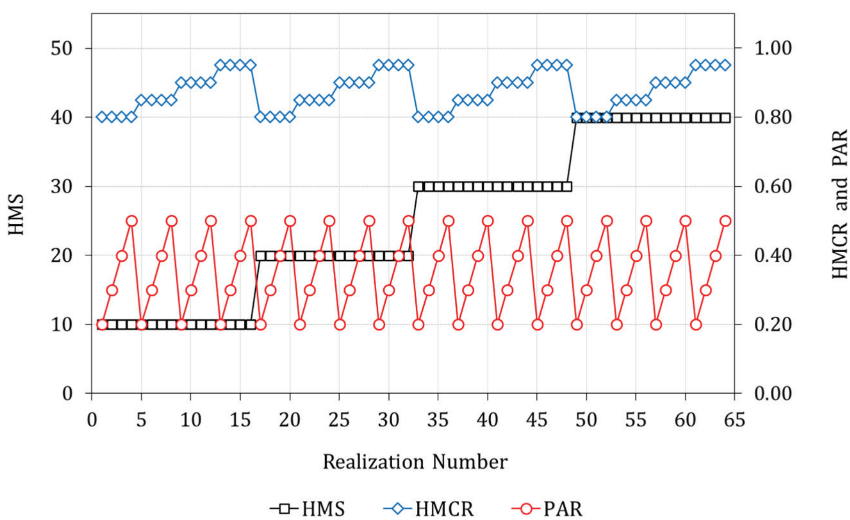


Figure 6 - HS optimization parameter combinations used in Scenario A

executed for $4^3 = 64$ different parameter combinations where the variation of these parameters relative to each other is considered. The value of the parameter sets for each model realization can be seen in Figure 6. After obtaining the best parameter combination providing the minimum objective function value, these parameter values are fixed, and the problem is solved 10 times again in Scenario B by considering different random number seeds. Therefore, the model performance is also evaluated for different random numbers in the optimization model.

3.1. Example Problem 1

The first example consists of a well-known storm sewer system which was first solved by Mays and Wenzel [3] by means of the discrete differential dynamic programing approach. After that study, the problem has been investigated by many researchers by using different solution approaches for steady and unsteady flow conditions [1-4, 8, 20, 31-33, 39]. The schematic view of this network is given in Figure 7. The network consists of 21 manholes which are connected through 20 pipes with the total length of 2.6 km. Characteristics of the system including ground elevations at manhole locations, pipe lengths, and design discharges are given in Table 1. As given in Afshar et al. [31], design discharges of the system are given as the constant flow hydrographs in which the values in Table 1 correspond to their maximum. The network should be designed by satisfying the minimum and maximum velocity values of 0.60 m/s and 3.60 m/s, respectively. Similarly, the cover depths over the pipes should be minimum 2.40 m and maximum 6.00 m. Note that all the previous studies given above used the sum of the functions given in Equations (26) and (27) as the cost function [40]. Therefore, the same cost function is also considered in this study to obtain comparable results.

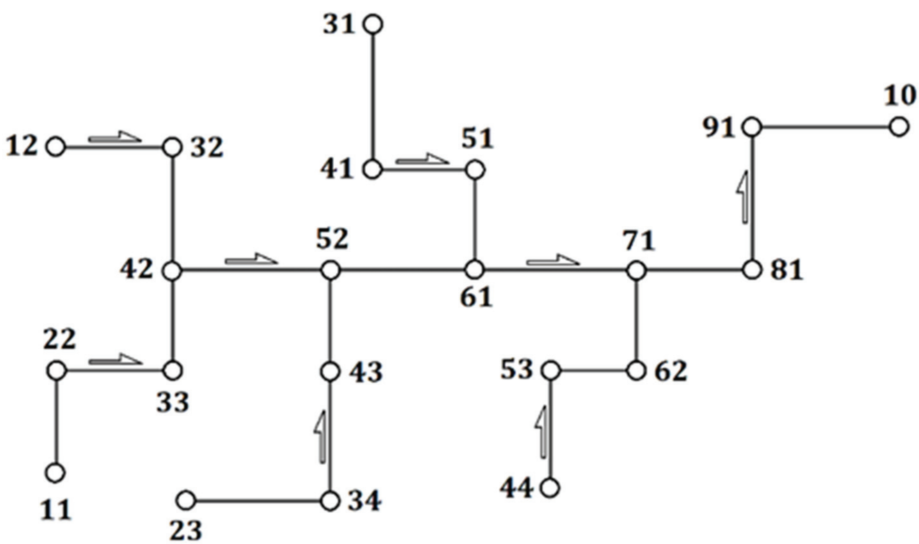


Figure 7 - Schematic view of the storm sewer system in Example 1

$$\mathcal{C}_1(D_i, \bar{Z}_i) = \begin{cases} 10.98D_i + 0.80\bar{Z}_i - 5.98 & ; \quad D_i \le 3, \bar{Z}_i < 10 \\ 5.94D_i + 1.166\bar{Z}_i + 0.504\bar{Z}_i D_i - 9.64 & ; \quad D_i \le 3, \bar{Z}_i \ge 10 \\ 30.00D_i + 4.90\bar{Z}_i - 105.90 & ; \quad D_i > 3 \end{cases} \tag{26}$$

$$\mathcal{C}_2(H_k) = 250 + (H_k)^2 \tag{27}$$

Table 1 - Characteristics of the sewer network for Example 1.

Pipe	Ground Elevations (m)		L_i	$\max\{Q_i(t)\}$
	Upstream	Downstream	(m)	(m^3/s)
11-22	152.40	150.88	106.68	0.1132
22-33	150.88	148.49	121.92	0.1982
33-42	148.49	146.30	106.68	0.2548
12-32	149.35	147.83	121.92	0.1132
32-42	147.83	146.30	131.08	0.2265
42-52	146.30	143.26	167.68	0.6229
23-34	149.35	147.83	147.64	0.2265
34-43	147.83	144.78	137.16	0.3398
43-52	144.78	143.26	106.68	0.4530
52-61	143.26	141.73	152.40	1.2459
31-41	147.83	144.78	152.40	0.2548
41-51	144.78	143.26	106.68	0.4530
51-61	143.26	141.73	106.68	0.5663
61-71	141.73	138.65	172.21	2.0104
44-53	142.65	141.43	121.92	0.1132
53-62	141.43	140.21	91.44	0.1699
62-71	140.21	138.65	105.23	0.2548
71-81	138.65	137.46	121.92	2.4635
81-91	137.46	136.55	152.40	2.5201
91-10	136.55	135.64	186.54	2.6617

where $\mathcal{C}_1(D_i, \bar{Z}_i)$ and $\mathcal{C}_2(H_k)$, previously defined in Equation (1), represent the pipe ($/ft) and manhole ($) cost terms, respectively. By using these definitions, the objective of the proposed approach is to determine the optimum system design by minimizing the total cost. This design process is conducted by adjusting the pipe slopes ($S_i\,;\ i = 1,2,3,\cdots,20$) as decision variables of the optimization model. After determination of these slopes by the optimization model, the corresponding pipe diameters are determined based on the implicit approach given in Figure 5. Note that the pipe diameters for this example are selected from the following commercial diameter set: $D_i \in$ {304.8 mm (12 in), 381.0 mm (15 in), 457.2 mm (18 in), 533.4 mm (21 in), 762 mm (30 in), 914.4 mm (36 in), 1066.8 mm (42 in), and

1219.2 mm (48 in)}. During the search process, Manning's surface roughness and maximum allowable ratio of flow depth to pipe diameter values are used as $n = 0.013$ and $\alpha = 0.82$, respectively. As indicated previously, the performance of the proposed approach has been evaluated by considering two scenarios (A and B) and the maximum number of HS improvisations for these scenarios are used as 100,000 and 500,000, respectively. After these definitions, the proposed simulation-optimization approach is executed for Scenario A. Figure 8 shows the convergence profiles for these model executions which are obtained by using different optimization parameter combinations. As can be seen from Figure 5, all the solutions start the search process from different initial solutions and converge roughly to the same solutions. Regarding the solution profiles, it is observed that each model execution starts with penalties due to constraint violations at early solutions and values of these penalties significantly reduce as the solution proceed. Statistical evaluation of these 64 model executions for Scenario A is given Table 2.

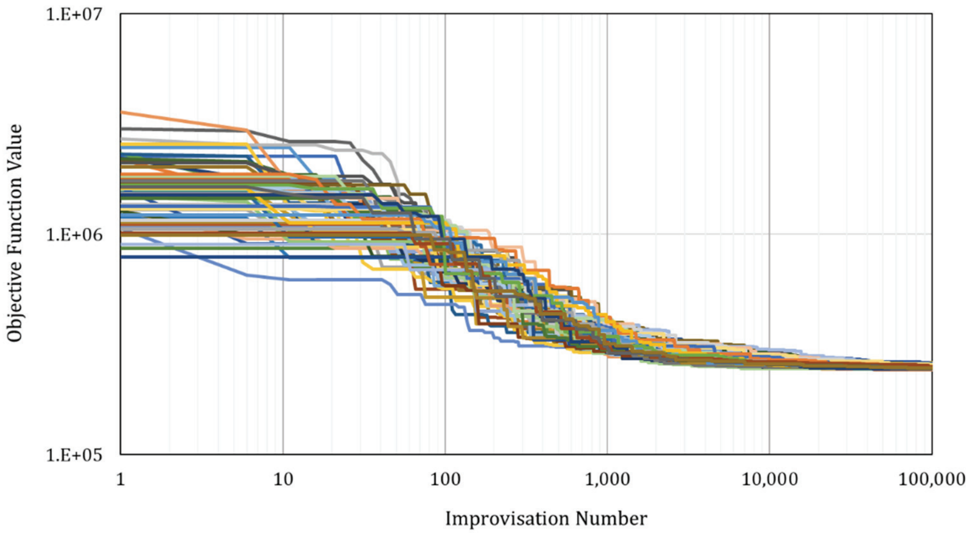


Figure 8 - Convergence profiles for 64 different model executions by using different optimization parameter combinations (Scenario A).

Table 2 - Statistical evaluation of the final objective function values obtained from Scenario A and B for Example 1

	Total System Cost (US $)	
	Scenario A	Scenario B
Number of Solutions	64	10
Minimum	241,797	240,068
Maximum	254,058	241,033
Mean	244,343	240,579
Standard Deviation	2,388	352

It can be seen from Table 2 that, in Scenario A, the proposed approach resulted with the minimum and maximum system costs of 241,797 $ and 254,058 $, respectively. For 64 model executions, the mean system cost has been obtained as 244,343 $. All the solutions are scattered around the mean solution with a standard deviation of 2,388 $. Note that the minimum system cost has been obtained for 14th parameter combination which has the parameter values of $HMS = 10$, $HMCR = 0.95$, and $PAR = 0.30$. After determining the best parameter combination in Scenario A, these parameter values are fixed and the problem is solved 10 times again to evaluate the model performance for different random number seeds in Scenario B. As stated previously, this is an important analysis for the heuristic optimization approaches since the computational structures of these approaches require the use of the uniformly distributed random numbers. The convergence profiles for 10 different model executions in Scenario B can be seen in Figure 9.

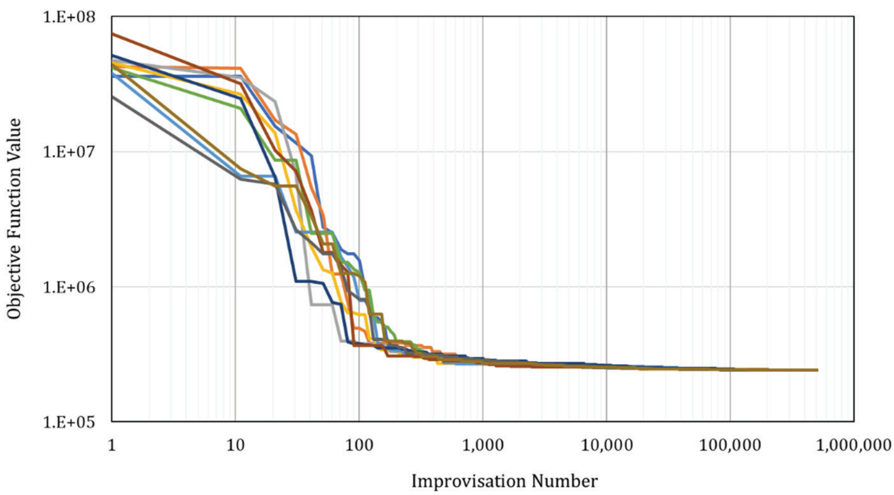


Figure 9 - Convergence profiles for 10 different model executions by using different random number seeds (Scenario B).

As can be seen from Figure 9, all the solutions start the search process with different initial solutions and converge to the approximately the same final solutions no matter where the solution starts. Table 2 also includes the statistical evaluation of the identified solutions in Scenario B. As can be seen, the minimum and maximum system costs have been obtained as 240,068 $ and 241,033 $, respectively. For these solutions, the mean system cost is 240,579 $ with the standard deviation of 352 $. This evaluation states that the convergence behavior of the proposed approach does not influence from both initial solutions and random number seeds. For the best solution in Scenario B, the identified decision variable values (e.g. slope of each pipe), pipe diameters, and manhole depths are schematized in Figure 10. The other identified system characteristics can be seen in Table 3.

As can be seen from Table 3, diameters of the pipes have been selected from the provided diameter set by means of the proposed implicit procedure given in Figure 5. As indicated previously, pipe design discharges for this example have been given to SWMM model as constant flow hydrographs. Therefore, flow characteristics, such as the flow velocity and water depths in the pipes, are also obtained in a constant hydrograph format. Table 3 includes only the maximum values of the velocity and relative water depth hydrographs observed in the pipes. Since output hydrographs are also of constant format, the minimum values of the velocity and relative water depth are the same as the respective maximum values; that is why they have not been included in Table 3. As can be seen, all the constraints of the problem are satisfied without any violation. Note that this example was previously investigated by many researchers by using steady and unsteady state model simulations. The final results obtained for some of the studies are compared in Table 4. As can be seen from Table 4, the final objective function value (240,068 US $) of the proposed approach is better than the previously conducted studies except for Tan et al. [1] (239,961 US $) where the problem was solved by using differential evolution (DE) optimization approach. It is worth reminding that most of the previous studies considered steady-state hydraulic simulations and there are very limited studies that solve the problem for unsteady-state flow simulations. When the identified results are compared with them given in Table 4, it can be concluded that the proposed approach again provides similar or better results in terms of the final objective function values.

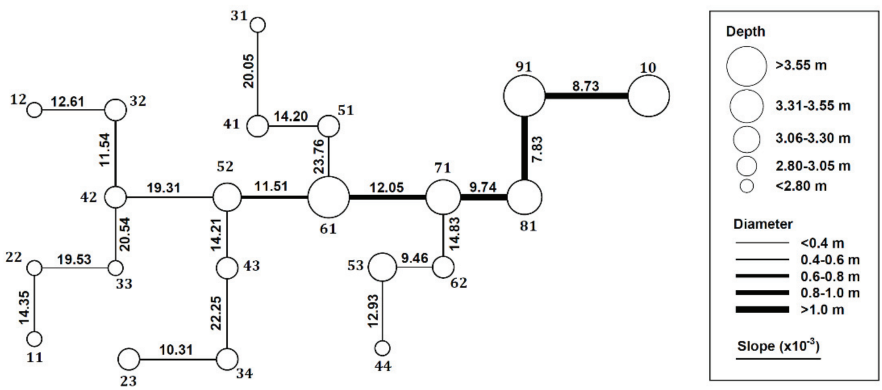


Figure 10 - Schematic representation of the identification results for Example 1.

Table 3 - Identified pipe slopes and the other characteristics of the network for Example 1.

Pipe	Diameter	Maximum Velocity	Relative Water Depth	Cover Depths	
	D_i (mm)	max $\{V_i(t)\}$ (m/s)	max $\{y_i(t)\}/D_i$ (m/m)	E_i^u (m)	E_i^d (m)
11-22	304.80	1.89	0.77	2.40	2.41
22-33	381.00	2.47	0.67	2.41	2.40
33-42	381.00	2.62	0.80	2.40	2.40
12-32	304.80	1.77	0.82	2.40	2.42
32-42	457.20	2.10	0.63	2.42	2.40

Table 3 - Identified pipe slopes and the other characteristics of the network for Example 1. (continue)

Pipe	Diameter	Maximum Velocity	Relative Water Depth	Cover Depths	
	D_i (mm)	$\max\{V_i(t)\}$ (m/s)	$\max\{y_i(t)\}/D_i$ (m/m)	E_i^u (m)	E_i^d (m)
42-52	533.40	3.18	0.82	2.40	2.60
23-34	457.20	2.02	0.65	2.40	2.40
34-43	457.20	2.97	0.66	2.40	2.40
43-52	533.40	2.68	0.71	2.40	2.40
52-61	762.00	3.11	0.82	2.40	2.62
31-41	381.00	2.59	0.80	2.40	2.40
41-51	533.40	2.68	0.71	2.40	2.40
51-61	533.40	3.44	0.69	2.40	3.40
61-71	914.40	3.60	0.80	3.40	2.40
44-53	304.80	1.79	0.81	2.40	2.76
53-62	381.00	1.78	0.79	2.76	2.40
62-71	457.20	2.38	0.62	2.40	2.40
71-81	1066.80	3.54	0.73	2.40	2.40
81-91	1066.80	3.21	0.82	2.40	2.68
91-10	1066.80	3.40	0.82	2.68	3.40

Table 4 - Comparison of the obtained system costs for different solution approaches.

	Solution Type	Solution Approach	Total System Cost (US $)
Mays and Wenzel [3]	SS	DP	265,775
Robinson and Labadie [4]	SS	DP	275,218
Afshar [20]	SS	ACO	241,496
Afshar [2]	SS	GA	241,896
Tan et al. [1]	SS	DE	239,961
Tan et al. [27]	SS	HS	240,981
Afshar [19]	SS	PSO	242,889
Afshar et al. [41]	SS	CA	253,484
Afshar et al. [31]	USS	GA	244,747
Zaheri et al. [33]	USS	CA	240,084
Proposed Approach	USS	HS	240,068

SS: Steady-State, USS: Unsteady-State, DP: Dynamic Programming, ACO: Ant Colony Optimization; GA: Genetic Algorithm, DE: Differential Evolution; HS: Harmony Search, PSO: Particle Swarm Optimization, CA: Cellular Automata

3.1. Example Problem 2

This example aims to evaluate the applicability of the proposed approach including the diurnal discharge patterns of the residential or industrial areas during the dynamic design process. As indicated previously, inclusion of diurnal discharge patterns may be an important improvement especially for analysis of big systems since the shape of the upstream discharge hydrographs can change when they arrive to downstream locations. For this case, the considered example system is given in Figure 11. As can be seen, the example network includes 42 manholes which are connected through 41 pipes with the total length about 2.4 km. Characteristics of the system including ground elevations at manhole locations, pipe lengths, and design discharges are given in Table 5.

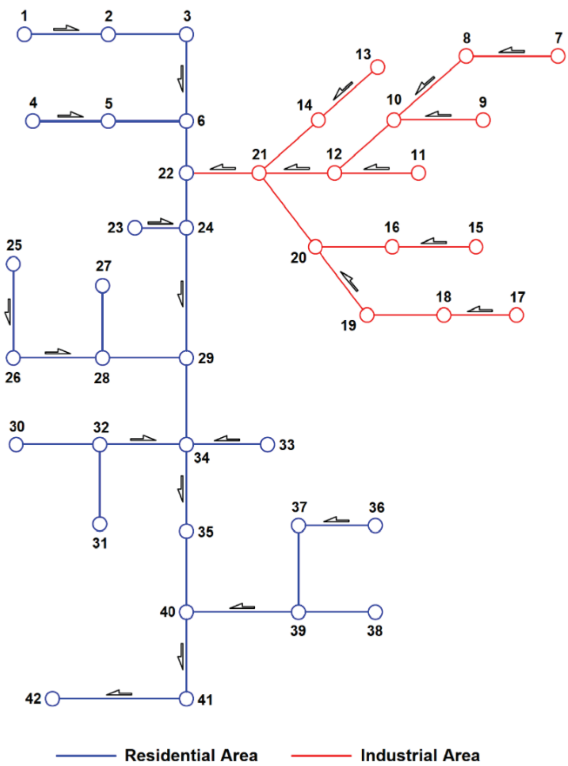


Figure 11 - Schematic view of the household sewer system in Example 2

The example network system in Figure 11 includes two areas where residential buildings (blue lines) and industrial facilities (red lines) are located. Note that these areas have different wastewater discharge characteristics due to the change of their hourly water consumption patterns. There are different diurnal patterns in literature which are used for obtaining the hourly variation of wastewater discharges. These patterns consist of some multiplication factors which are used to convert a peak flow into the hourly wastewater discharges. Among them, the diurnal patterns given in Qasim [42] have been used. Figure 12 shows these patterns for residential and industrial areas, respectively. As can be seen, there are two peaks in the diurnal pattern of the residential areas which are observed at early noon and evening times. For the industrial areas, it is assumed that wastewater discharge process starts at morning and ends at the late afternoon. By using these patterns, the discharge hydrographs of each pipe are obtained by multiplying the max $\{Q_i(t)\}$ values in Table 5 with the multiplication factors given in Figure 12 (a) and (b) for the residential and industrial areas.

After obtaining the design discharge hydrographs for each pipe, the dynamic design process is conducted by considering the maximum velocity value of 3 m/s. Note that minimum velocity constraint is not considered for this example since the industrial facilities (red lines in Figure 11) have some periods without any discharge according to their diurnal patterns. However, this situation is only valid for this example, and it is not a general case where both residential and industrial areas release the wastewater to the same manhole locations. For such cases, the minimum velocity constraints can also be defined just as given in Example 1. Similar to Example 1, the network should be designed with the minimum and maximum cover depths of 2.40 m and 6.00 m, respectively. Manning's surface roughness and maximum allowable ratio of flow depth to pipe diameter values are taken as $n = 0.013$ and $\alpha = 0.82$, respectively. Note that the following cost function given in Afshar et al. [41] is used in calculation of the objective function.

$$\mathcal{C}_1(D_i, \bar{Z}_i) = 1.93e^{3.43D_i} + 0.812\bar{Z}_i^{1.53} + 0.437D_i\bar{Z}_i^{1.47} \tag{28}$$

$$\mathcal{C}_2(H_k) = 41.46H_k \tag{29}$$

Table 5 - Characteristics of the sewer network for Example 2.

Pipe	Ground Elevations (m)		L_i	max $\{Q_i(t)\}$
	Upstream	Downstream	(m)	(m^3/s)
1-2	495.00	494.37	60	2.33
2-3	494.37	493.67	56	2.18
3-6	493.67	493.00	60	2.33
4-5	494.27	493.70	54	2.10
5-6	493.70	493.00	56	2.18
6-22	493.00	492.17	36	1.40
7-8	492.93	492.76	66	4.51
8-10	492.76	492.63	68	4.64
9-10	492.80	492.63	64	4.37
10-12	492.63	492.43	56	3.82
11-12	492.51	492.43	60	4.10
12-21	492.43	492.33	54	3.69
13-14	492.55	492.47	56	3.82
14-21	492.47	492.33	56	3.82

Table 5 - Characteristics of the sewer network for Example 2. (continue)

Pipe	Ground Elevations (m)		L_i (m)	$\max\{Q_i(t)\}$ (m^3/s)
	Upstream	Downstream		
15-16	492.78	492.64	60	4.10
16-20	492.64	492.53	55	3.75
17-18	493.13	492.93	52	3.55
18-19	492.93	492.70	55	3.75
19-20	492.70	492.53	60	4.10
20-21	492.53	492.33	65	4.44
21-22	492.33	492.17	52	3.55
22-24	492.17	491.71	38	1.48
23-24	492.13	491.71	37	1.44
24-29	491.71	490.60	90	3.50
25-26	492.81	492.19	65	2.53
26-28	492.19	491.60	64	2.49
27-28	492.04	491.60	50	1.94
28-29	491.60	490.60	60	2.33
29-34	490.60	489.87	60	2.33
30-32	491.19	490.56	60	2.33
31-32	491.25	490.56	55	2.14
32-34	490.56	489.87	62	2.41
33-34	490.48	489.87	58	2.26
34-35	489.87	489.12	60	2.33
35-40	489.12	487.83	56	2.18
36-37	490.52	489.84	55	2.14
37-39	489.84	489.27	60	2.33
38-39	489.99	489.27	55	2.14
39-40	489.27	487.83	80	3.11
40-41	487.83	487.43	60	2.33
41-42	487.43	486.54	96	3.73

where $C_1(D_i, \bar{Z}_i)$ and $C_2(H_k)$ represent the pipe (\$/m) and manhole (\$) cost terms, respectively. By using these cost function definitions, the objective of the proposed approach is to determine the pipe slopes (S_i ; $i = 1,2,3,\cdots,41$) by minimizing the total system cost. Just as in Example 1, the pipe diameters are determined by means of the proposed implicit procedure given in Figure 5. Pipe diameters have been selected from the following commercial diameter set: $D_i \in$ {150 mm, 200 mm, 250 mm, 300 mm, 400 mm, 500 mm, 600 mm, and 700 mm}. Like Example 1, the performance of this example is also evaluated for two scenarios. Previous trials on this example indicates that the HS based optimization model converges faster than those in Example 1, and therefore, maximum numbers of HS improvisations for Scenario A and B are set to 20,000 and 100,000, respectively. After these definitions, the proposed approach is executed for Scenario A for different HS parameter combinations. Figure 13 shows convergence profiles for each model executions.

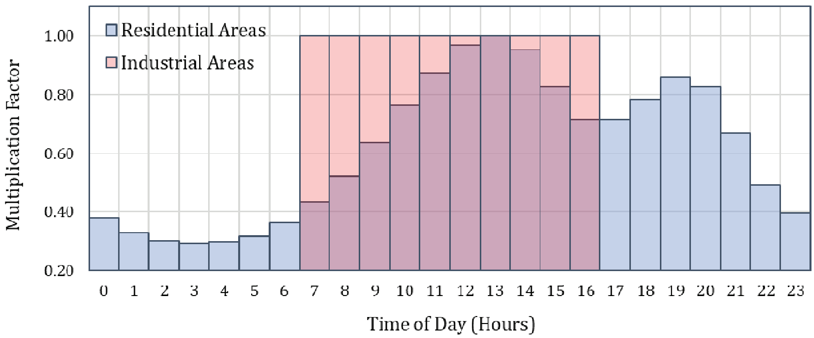


Figure 12 - Diurnal wastewater discharge patterns [42].

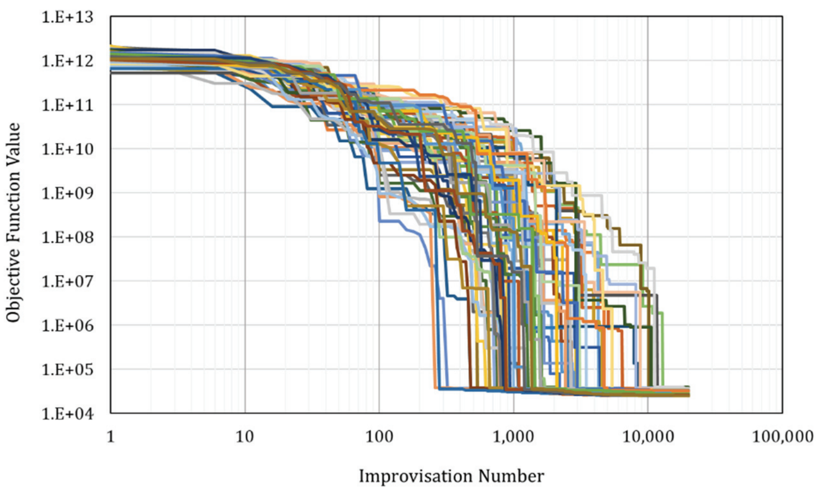


Figure 13 - Convergence profiles for 64 different model executions by using different optimization parameter combinations (Scenario A).

As can be seen from Figure 13, all the solutions start the optimization process with very high penalty values due to violation of constraints in early solutions. As the search process proceed, the solutions evolve and generate results without any penalties due to constraint violation. The profiles indicate that there is no significant change in the objective function values after 13,000th improvisation. For the final solutions at 20,000th improvisation, statistical evaluation of 64 different model executions can be seen in Table 6. As can be seen, the minimum and maximum objective function values have been obtained as 24,925 $ and 38,958 $, respectively. For 64 different executions, the mean system cost is obtained as 29,664 $ and all the solutions are scattered around this mean value with a standard deviation of 3,815 $. According to the final objective function values, the best solution is obtained for 15th model execution which has the optimization parameters of $HMS = 10$, $HMCR = 0.95$, and $PAR = 0.40$. After this process, these parameter values are fixed and the proposed approach is executed 10 more times to evaluate model performance for different random number seeds in Scenario B. Figure 14 shows convergence profiles for these model executions. Like Scenario A, all the solutions in Figure 14 starts the optimization process with large penalty values and these penalties significantly reduce as the solutions proceed. After about 5,000th improvisation, the system cost does not change significantly.

Table 6 - Statistical evaluation of the final objective function values obtained from Scenario A and B for Example 2

	Total System Cost (US $)	
	Scenario A	Scenario B
Number of Solutions	64	10
Minimum	24,925	24,407
Maximum	38,958	24,964
Mean	29,664	24,598
Standard Deviation	3,815	169

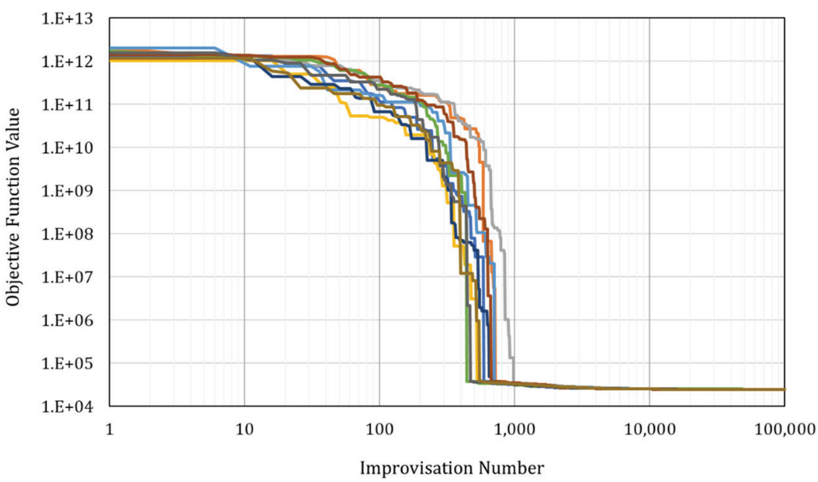


Figure 14 - Convergence profiles for 10 different model executions by using different random number seeds (Scenario B).

For the final values, the performance of 10 different model executions is compared statistically in Table 6. As can be seen, the minimum and maximum systems costs are obtained as 24,407 $ and 24,964 $, respectively. The mean and standard deviation values are 24,598 $ and 169 $, respectively. These results indicate that the proposed approach is not significantly influenced from the random number seeds in the optimization process. For the best solution of Scenario B, the final pipe slopes, diameters, and manhole depths are schematized in Figure 15. The other identified system characteristics are summarized in Table 7.

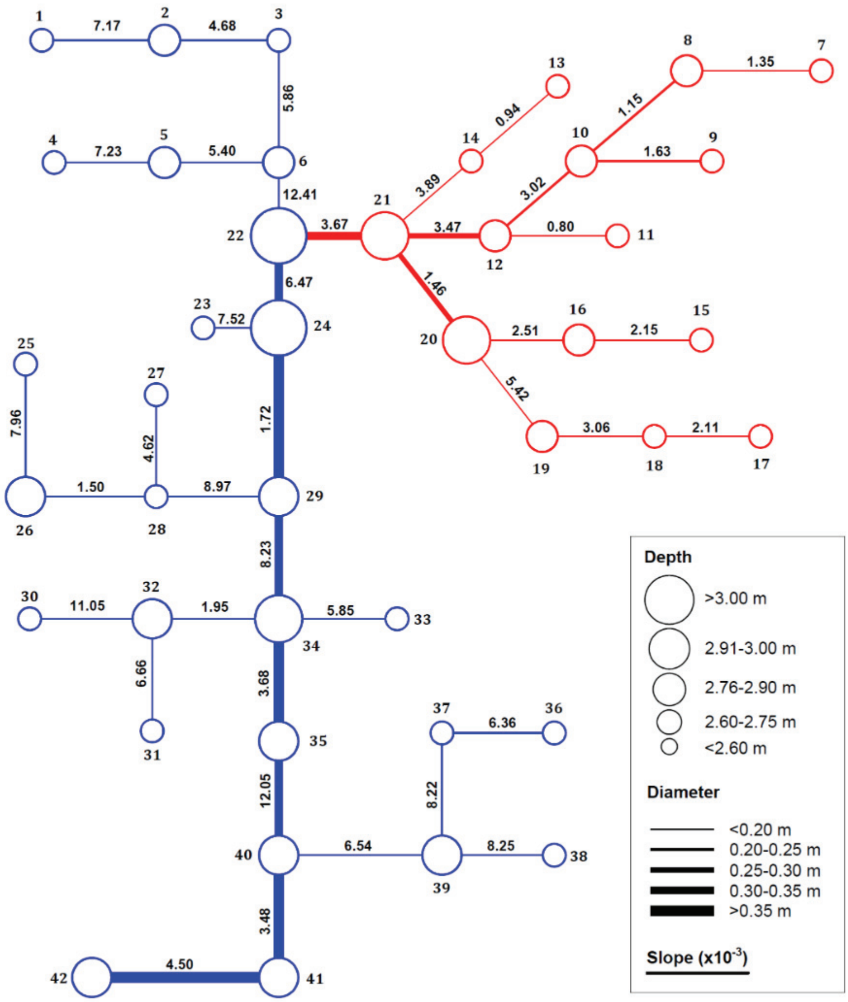


Figure 15 - Schematic representation of the identification results for Example 2.

Table 7 - Identified pipe slopes and the other characteristics of the network for Example 2.

Pipe	Diameter	Maximum Velocity	Relative Water Depth	Cover Depths	
	D_i (mm)	$\max\{V_i(t)\}$ (m/s)	$\max\{y_i(t)\}/D_i$ (m/m)	E_i^u (m)	E_i^d (m)
1-2	150	0.39	0.37	2.40	2.52
2-3	150	0.50	0.51	2.52	2.43
3-6	150	0.69	0.55	2.43	2.45
4-5	150	0.38	0.35	2.40	2.51
5-6	150	0.45	0.53	2.51	2.46
6-22	150	1.05	0.64	2.46	2.49
7-8	150	0.39	0.66	2.40	2.41
8-10	200	0.37	0.78	2.41	2.42
9-10	150	0.40	0.70	2.40	2.42
10-12	200	0.74	0.70	2.42	2.49
11-12	150	0.37	0.59	2.40	2.41
12-21	250	0.85	0.58	2.49	2.63
13-14	150	0.32	0.71	2.40	2.41
14-21	150	0.65	0.63	2.41	2.56
15-16	150	0.40	0.74	2.40	2.46
16-20	150	0.56	0.73	2.46	2.54
17-18	150	0.33	0.61	2.40	2.41
18-19	150	0.53	0.80	2.41	2.46
19-20	150	0.77	0.81	2.46	2.70
20-21	250	0.57	0.82	2.70	2.70
21-22	300	1.02	0.81	2.70	2.81
22-24	300	1.23	0.80	2.81	2.83
23-24	150	0.49	0.22	2.40	2.47
24-29	400	0.78	0.76	2.83	2.42
25-26	150	0.36	0.52	2.40	2.61
26-28	150	0.41	0.65	2.61	2.41
27-28	150	0.34	0.44	2.40	2.41
28-29	150	0.84	0.65	2.41	2.45
29-34	300	1.46	0.82	2.45	2.58
30-32	150	0.40	0.59	2.40	2.75
31-32	150	0.53	0.28	2.40	2.42
32-34	150	0.51	0.72	2.75	2.52
33-34	150	0.52	0.29	2.40	2.43
34-35	400	1.06	0.71	2.58	2.43
35-40	300	1.71	0.80	2.43	2.45
36-37	150	0.41	0.34	2.40	2.41
37-39	150	0.46	0.54	2.41	2.61
38-39	150	0.88	0.27	2.40	2.49
39-40	150	0.80	0.65	2.61	2.42
40-41	400	1.15	0.75	2.45	2.46
41-42	400	1.33	0.67	2.46	2.45

As can be seen from Table 7, the identified results satisfy all the constraints of the problem. Similar to Example 1, the pipe design discharges are specified to the system as flow hydrographs. Unlike the Example 1, the given hydrographs have not constant flow values against time due to the diurnal patterns given in Figure 12. Since input of the model consists of the time varied flow values, their corresponding outflows have also the same structures considering the routing process of flow through the pipes. Therefore, only maximum values of the routed velocity and relative water depth hydrographs are given in Table 7.

4. DISCUSSION AND CONCLUSIONS

In this study, a new simulation-optimization approach is proposed for solving the dynamic urban wastewater collection system design problems by considering unsteady flow conditions. The proposed approach consists of the mutual integration of US-EPA SWMM with heuristic HS optimization approach. In this integration, SWMM aims to solve the governing equations by means of the dynamic wave flow routing approach and HS aims to determine the pipe slopes by minimizing the total cost of the system including pipe, excavation, and manhole costs. The applicability of the proposed approach is evaluated by solving two examples. The first example is a well-known benchmark example given in literature and solution of this example aims to evaluate the performance of the HS based optimization model. After demonstrating the efficiency of HS on this example, the performance of the proposed approach is evaluated on the second example which is developed by considering the diurnal wastewater discharge patterns for residential and industrial areas. Regarding the outcomes of the proposed approach, the following discussions and conclusions can be drawn:

The concept of optimum design is crucial on solving the sewer system design problems. In practice, design process of the sewer system is conducted by manually adjusting the bed slope of the pipes and determining the pipe diameters by including the associated slope values and the other design criteria to the Manning's equation. Although this process looks useful, it cannot be easy especially for the big systems since there is a strong conflicting relation between the slopes and diameters of the pipes. For example, increasing the pipe slopes lead to use the smaller pipe diameters. However, use of large slopes increases the excavation costs. On the contrary, increasing the pipe diameters results with the requirement of less pipe slope. However, there is an increase of the pipe costs compared to excavation works. Therefore, use of the optimization-based solution approaches makes solution of the problem easy due to their efficiencies on handling these conflicting relations.

In practice, design process of the sewer systems is conducted by considering the peak values of the discharge hydrographs as the design flows of the pipes. In another words, the design process is conducted by considering steady state flow conditions in the system. Although this is a useful approach for many cases, it does not represent the true flow process in real life. Normally, the design flow discharges of the pipes are not constant in a day due to diurnal discharge patterns. Since the shape of the discharge hydrograph changes as the water flows through pipes, the peak values of them are attenuated together with a time lag. Although these attenuations are not significant in small systems, they might be important for the big systems such that larger design discharges can be obtained at downstream locations if routing process through pipes are not considered. This outcome results with the determination of larger pipe diameters at those locations which increases the cost of the system. Therefore, use of the proposed approach can be a good alternative to prevent these problems.

Although the proposed approach is effective on solving the optimum design problem by considering unsteady flow conditions, its main difficulty is the requirement of the high computational times for the big systems. This is due to the association of the approach with the hydraulic simulation process by SWMM model which is based on the numerical solution of the St. Venant equations. Since HS based optimization approach requires the execution of the SWMM model for each generated decision variable values, obtaining the optimum system design may require long computational times on the classical personal computers. For such cases, the problem can be solved on supercomputers or cloud computing platforms which are the beyond of the scope of this study.

In the proposed approach, it is considered the bed slope of the pipes as decision variables of the optimization model. As indicated previously, the corresponding pipe diameters are determined by using the proposed implicit diameter selection procedure in Figure 5. Although this procedure can effectively determine the pipe diameters for the generated slope values, it also increases the computation time since additional SWMM model executions are required during determination of the appropriate pipe diameters. To overcome this difficulty, the pipe diameters can also be considered as additional decision variables of the optimization model. However, this kind of use increases the number of variables twofold, and thus increases the complexity of the mathematical search space. Therefore, this approach is not considered in this study.

For all the solutions in this study, the optimum system design is determined by considering the open channel flow conditions in the pipes. However, in some cases, pressurized flow conditions together with the pumping facilities can also be considered. These issues are not considered in this study and may be investigated as a future work.

Software Availability

The open-source form of the developed VBA code can be accessible by requesting from the corresponding author.

Acknowledgement

The authors would like to acknowledge the editor and two anonymous reviewers for their constructive comments and recommendations.

References

[1] Tan, E., Sadak, D., Ayvaz, M. T. Kanalizasyon Sistemlerinin Diferansiyel Evrim Algoritması Kullanılarak Optimum Tasarımı. Teknik Dergi, 31, 5, 10229-10250, 2020 (In Turkish).

[2] Afshar, M. H., Rebirthing Genetic Algorithm for Storm Sewer Network Design. Scientica Iranica Transactions A: Civil Engineering, 19, 1, 11-19, 2012.

[3] Mays, L. W., Wenzel, H. G., Optimal Design of Multilevel Branching Sewer Systems. Water Resources Research, 12, 5, 913-917, 1976.

[4] Robinson, D. K., Labadie, J. W., Optimal Design of Urban Storm Water Drainage System. Int. Symposium on Urban Hydrology, Hydraulics and Sediment Control, University of Kentucky, Lexington, KY, USA, 145-156, 1981.

[5] Kulkarin, V. S., Khanna, P., Pumped Wastewater Collection Systems Optimization. Jorunal of Environmental Engineering, 111, 5, 589-601, 1985.

[6] Li, G., Matthew, R. G. S., New Approach for Optimization of Urban Drainage Systems. Journal of Environmental Engineering, 116, 5, 927-944, 1990.

[7] Elimam, A. A., Charalambous, C., Ghobrial, F. H., Optimum Design of Large Sewer Networks. Journal of Environmental Engineering, 115, 6, 1171-1190, 1989.

[8] Swamee, P. K., Sharma, A. K., Optimal Design of A Sewer Line Using Linear Programming. Applied Mathematical Modelling, 37, 4430-4439, 2012.

[9] Price, R. K., Design of Storm Water Sewers for Minimum Construction Cost. Proc. 1st International Conference on Urban Strom Drainage, Southampton, United Kingdom, 636-647, 1978.

[10] Swamee, P. K., Design of Sewer Line. Journal of Environmental Engineering, 127, 9, 776-781, 2001.

[11] Yeh, S. F., Chu, C. W., Applying Tabu Search and Simulated Annealing to the Optimal Design of Sewer Networks. Engineering Optimization, 43, 2, 159-174, 2011.

[12] Ayvaz, M. T., A Linked Simulation-Optimization Model for Solving the Unknown Groundwater Pollution Source Identification Problems. Journal of Contaminant Hydrology, 117, 46-59, 2010.

[13] Haghighi, A., Bakhshipour, A. E., Optimization of Sewer Networks Using an Adaptive Genetic Algorithm. Water Resour Manage, 26, 3441-3456, 2012.

[14] Afshar, M. H., Sotoodeh, M. H., Optimal Design of the Sewer Networks with the Genetic Algorithm. J. Eng. Sci. Iran Univ. Sci. Technol, 2, 19, 37-48, 2008.

[15] Afshar, M. H., Aplication of A Genetic Algorithm to Storm Sewer Network Optimization. Scientia Iranica, 13, 3, 234-244, 2006.

[16] Izquierdo, J., Montalvo, I., Pérez, R., Fuertes, V. S., Design Optimization of Wastewater Collection Networks by PSO. Comput. Math. Appl., 56, 3, 777-784, 2008.

[17] Navin, P. K., Mathur Y. P., Layout and Component Size Optimization of Sewer Network Using Spanning Tree and Modified PSO Algorithm. Water Resources Management, 30, 10, 3627-3643, 2016.

[18] Nafisi, M., Ahmadi, A., Sewer Networks Optimization by Particle Swarm Optimization with Abilities of Fly-Back Mechanism and Harmony Memory. J. Water Wastewater, 25, 4, 76-87, 2014.

[19] Afshar, M. H., Rebirthing Particle Swarm Optimization Algorithm: Application to Storm Water Network Design. Can. J. Civ. Eng., 35, 10, 1120-1127, 2008.

[20] Afshar, M. H., Improving the Efficiency of Ant Algorithms Using Adaptive Refinement: Application to Storm Water Network Design. Adv. Water. Resour., 29, 9, 1371-1382, 2006.

[21] Afshar, M. H., Partially Constrained Ant Colony Optimization Algorithm for the Solution of Constrained Optimization Problems: Application to Storm Water Network Design. Adv. Water. Resour., 30, 4, 954-965, 2007.

[22] Karovic, O., Mays L. W., Sewer System Design Using Simulated Annealing in Excel. Water Resources Management, 28, 13, 4551-4565, 2014.

[23] Kumar, S., Navin, P. K., Mathur, Y.P., Optimization of Sewerage System Using Simulated Annealing. International Journal of Engineering Research & Technology, 6, 11, 1-6, 2018.

[24] Liang, L. Y., Thompson, R. G., Young, D. M., Optimizing the Design of Sewer Networks Using Genetic Algorithms and Tabu Search. Eng. Constr. Archit. Manage., 11, 2, 101-112, 2004.

[25] Haghighi, A., Bakhshipour A. E., Deterministic Integrated Optimization Model for Sewage Collection Networks Using Tabu Search. J. Water. Resour. Plann. Manage., 141, 1, 1-11, 2014.

[26] Liu, C., Han, H., Wang C., Qiao, J., An adaptive Differential Evolution Algorithm for Sewer Networks Design, Proceeding of the 11th World Congress on Intelligent Control and Automation Shenyang, China, 2014.

[27] Tan, E., Sadak, D., Ayvaz, M.T., Optimum Design of Storm Sewer Systems by using Harmony Search Optimization Approach, 38th IAHR World Congress, Water–Connecting the World, Sep 1-6, 2019, Panama City, Panama.

[28] Afshar, M. H., Zaheri, M. M., Kim, J. H. Improving the efficiency of Cellular Automata for sewer network design optimization problems using Adaptive Refinement. Proc. Eng., 154, 1439–1447, 2016.

[29] Karovic, O., Mays, L. W., Sewer system design using simulated annealing in excel. Water Resources Management, 28, 4551–4565, 2014.

[30] Chow V. T, Maidment D. R, Mays L.W., Applied Hydrology. McGraw1Hill International Editions, Singapore, 1988.

[31] Afshar, M. H., Afshar, A., Marino, M. A., Darbandi A. A. S., Hydrograph-Based Storm Sewer Design Optimization by Genetic Algorithm. Can. J. Civ. Eng., 33, 3, 319-325, 2006.

[32] Shao, Z., Zhang, X., Li, S., Deng, S., Chai, H., A Novel SWMM Based Algorithm Application to Storm Sewer Network Design, Water, 9, 10, 747, 2017.

[33] Zaheri, M. M., Ghanbari, R., Afshar, M. H., A two-phase simulation–optimization cellular automata method for sewer network design optimization. Engineering Optimization, 52, 4, 620-636, 2020.

[34] Rossman, L. A., Storm Water Management Model Reference Manual Volume II-Hydraulics. EPA United States Environmental Protection Agency, EPA/600/R-17/111, 2017.

[35] Anta, J., Naves, A., Naves, J., An introduction to sewer network design using SWMM. A Coruña. University of A Coruna Press. ISBN 978-84-9749-790-9, 2020.

[36] Yang,X. S., Harmony Search as a Metaheuristic Algorithm, in: Music-Inspired Harmony Search Algorithm: Theory and Applications (Editor Z. W. Geem), Studies in Computational Intelligence, Springer Berlin, 191, 1-14, 2009.

[37] Geem, Z. W., Kim, J. H., Loganathan, G. V., A new heuristic optimization algorithm: Harmony search. Simulation, 76, 60-68, 2001.

[38] Ayvaz, M. T., Solution of Groundwater Management Problems using Harmony Search Algorithm, Recent Advances in Harmony Search Algorithm, Studies in Computational Intelligence Series, Edited by Zong Woo Geem, Springer Berlin/Heidelberg (ISBN: 978-3-642-04316-1), 2010.

[39] Miles, S. W., Heaney, J. P., Better Than Optimal Method For Designing Drainage Systems. Journal of Water Resources Planning and Management, 114, 5, 477-499, 1988.

[40] Meredith, D.D., Dynamic Programming with Case Study on Planning and Design of Urban Water Facilities, Treatise on Urban Water Systems, Colorado State University, Fort Collins, 1972.

[41] Afshar, M. H., Shahidi, M., Rohani, M., Sargolzei, M., Application of Cellular Automata to Sewer Network Optimization Problems. Scientia Iranica Transactions A: Civil Engineering, 18, 3, 304-312, 2011.

[42] Qasim, S. R.,Wastewater Treatment Plants; Planning, Design and Operation, CRC Press, USA, 1999.

Turkish Journal of Civil Engineering, 2023 135-152, Paper 720, ***Research Article***

The Investigation of the Addition of Sodium Lignosulfonate to Lime Column Used For Improving the Expansive Soils

İlyas ÖZKAN[1]
Erdal ÇOKÇA[2]

ABSTRACT

The lime column (LC) technique has been commonly used for the improvement of expansive soils. The achievement of this technique depends on the lime diffusion into the expansive soils, but lime diffusion into the expansive soil is generally a slow process due to the low permeability of these soils. In this study, sodium lignosulfonate, which is used as a superplasticizer in the concrete industry, was added to lime columns to accelerate the diffusion of lime particles. First, treated expansive clay specimens with thirty-seven 4.5 mm diameter columns were prepared in an oedometer ring. These columns were filled with two different mixtures: water-lime and water-lime-sodium lignosulphonate to investigate the effect of the addition of sodium lignosulphonate. Free swell tests were done on these treated expansive clay specimens that were subjected to different curing periods, it was observed that the treated specimens with sodium lignosulphonate lime columns (NaLS-LC) are more effective than the treated specimens with lime columns (LC). A treated expansive clay specimen (in a 30cmx30cm mold) with seven pieces of 45 mm diameter sodium lignosulphonate lime columns were prepared to observe the alteration of engineering properties of untreated expansive clay specimen (US) located between the columns. Free swell and unconfined compressive strength tests were done on the undisturbed expansive clay specimens taken from the mold between the columns. SEM-EDX analyses were made to investigate whether the ettringite mineral, which leads to swelling of the expansive soil during lime stabilization, forms or not. While the ettringite mineral formed during the curing period in the lime column stabilization method, the addition of sodium lignosulphonate to lime columns blocked the formation of the ettringite mineral. It can be stated that sodium lignosulphonate lime columns (NaLS-LC) show better performance than lime columns (LC), in the treatment of expansive clays.

Note:

- This paper was received on April 21, 2022 and accepted for publication by the Editorial Board on October 10, 2022.
- Discussions on this paper will be accepted by March 31, 2022.

• https://doi.org/10.18400/tjce.1209185

1 Middle East Technical University, Department of Civil Engineering, Ankara, Türkiye
ozkan.ilyas@hotmail.com - https://orcid.org/0000-0001-9660-8229

2 Middle East Technical University, Department of Civil Engineering, Ankara, Türkiye
ecokca@metu.edu.tr - https://orcid.org/0000-0001-8367-2539

Keywords: Sodium lignosulphonate, expansive soil, lime column, stabilization, swelling potential.

1. INTRODUCTION

Expansive soils cause damage to lightweight structures such as one or two-story buildings, pavements, etc. Expansive clays can be found in semi-arid and arid regions [1]. As the volume change of expansive soils depends on the water contents, their volumes are affected by both arid and wet weather conditions, these soils shrink due to the loss of water and their volumes increase due to the absorption of water. Although these alterations of their volumes do not result in the loss of life, they can cause great economic loss [2].

The improvement methods for these soils have been developed in the last decades. Chemical stabilization, one of these improvement methods, is commonly applied to stabilize these soils. Lime is a more preferable additive for the chemical stabilization of expansive soils. Treated specimens with lime, gain higher strength and durability properties during the stabilization process. Lime stabilization of expansive soils can be done by two different methods that are chemical additive technique and the lime column technique. Lime column techniques have been applied for many purposes such as slope stability, improving the properties of soft soil, etc. [3-4-5].

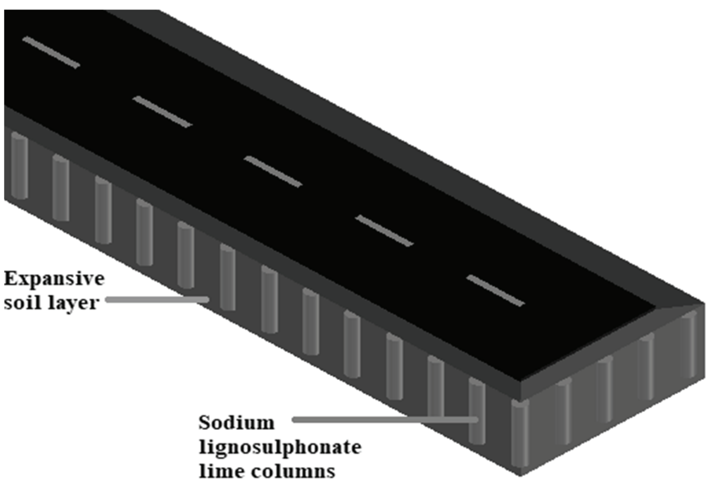


Figure 1 - Sodium lignosulphonate lime columns under the pavement and embankment load

Lime stabilization of expansive soil consists of three steps that are cation exchange, flocculation and agglomeration, and pozzolanic reaction. At the cation exchange step, calcium ions presented from lime particles are exchanged with monovalent ions presented from clay particles. After this exchange process, clay particles get closer to each other and the thickness of diffused double layer reduces. Then, the structure of clay particles, which are generally flat and parallel, convert to a more random edge-to-face orientation after the flocculation process. The first two steps that are cation exchange and flocculation and agglomeration occur in the first 72 hours after the applications. The final step of this stabilization is the pozzolanic reaction which both depends on time and consists of the reaction between the calcium ions and clay particles. The strength of the treated specimen gradually enhanced with this reaction process [6-7-8].

The lime column technique is a commonly applicable method in the field. However, the lime column, which contains sodium lignosulphonate, has not been studied until now. The main objective of this study is to investigate the influence of the addition of sodium lignosulphonate to the lime column technique. Figure 1 illustrates an example of sodium lignosulphonate lime columns in an expansive soil subgrade in the field.

Lignosulphonate is a waste material obtained from the paper industry that is produced by 50 million tons per year. This material is classified into different groups according to calcium, sodium, magnesium, and potassium in it, which depends on both type of the wood and the chemical processes. Although this waste material is an inexpensive and extensive chemical, a very small amount of this production is used as an additive such as concrete superplasticizer, agricultural chemical, and industrial binder [9-10].

Some studies related to the application of lignosulphonate on soils have been done over the past decade.

Electrostatic interactions, hydrogen bonding, covalent bonding, and cation exchange occur during the reactions between the calcium lignosulphonate and clay minerals. Then, expansive clay particles covered with this material absorb less amount of water [11].

Vinod et al. (2010) studied the physicochemical and microstructural changes of silty clay soil due to lignosulphonate addition. First, lignosulphonate was added to the water, after the hydrolysis, hydrogen (H+) and hydroxyl (OH-) ions were disintegrated and caused the protonation of the lignosulphonate. The protonated lignosulphonate releases water and forms a positively charged lignosulphonate. The positively charged lignosulphonate neutralizes the negative charges of clay minerals due to electrostatic attraction which leads to the reduction of the double-layer thickness and subsequent binding of the soil particles together to form a flocculated structure and the engineering properties of the soil were improved [12].

Vakili et. al. (2018) stated that the attractive forces between the clay particles increase while the repulsion forces decrease during the lignosulphonate stabilization [13]. Indraratna et al. (2010) used lignosulphonate for the improvement of erodible soils and the strengths of these soils were enhanced after this stabilization process [14]. Tingle and Santoni (2003) used lignosulphonate for the treatment of a low plasticity clay (CL). The unconfined compressive strength (UCS) of CL soil was measured as 1379 kPa, when %5 lignosulphonate was added to CL soil and cured in the humid room for 28 days, UCS concerning the untreated condition [15]. A study related to the deformation behavior of sandy silt under cyclic loading was done by Chen and Indraratna in 2015. According to this study, the resilient modulus of the treated specimen with lignosulphonate was significantly greater than the resilient modulus of the untreated soil specimen [16].

In this study, the efficiency of the addition of sodium lignosulphonate to the lime column is studied by carrying out scanning electron microscope (SEM) and energy dispersive x-ray diffraction (EDX) analysis on both untreated and treated specimens. Methylene blue value MBV test results were used to determine the change in specific surface area (SSA) and cation exchange capacity (CEC) of both untreated and treated samples. The curing effect on the swelling potential and unconfined compressive strength tests of both lime column and sodium lignosulphonate lime column specimens were also studied. The sodium lignosulphonate lime columns show better performance than lime columns, in the treatment of expansive clays.

2. EXPERIMENTAL WORK

An expansive soil specimen consisting of 85% kaolinite and 15% bentonite in terms of dry weight was prepared to obtain a homogenous specimen. Both kaolinite and bentonite were oven-dried for one day. They were passed through the No.40 sieve. They were mixed with a trowel in the cup. They were sieved two times through the No.20 sieve to obtain a homogeneous sample. The test specimens were compacted at maximum dry density. The water content of this specimen was %15. This expansive soil specimen is called specimen US.

Lime, which is a calcium-slaked lime, is sieved from the No. 200 sieve to accelerate the diffusion process.

Sodium lignosulphonate utilized in this study was in pulverized form and was sieved from the No. 200 sieve.

2.1. Properties of the Untreated Specimen US

The expansive soil specimen prepared in the laboratory is a high plasticity clay according to USCS. The properties of this specimen such as specific gravity, Atterberg limits, PSD, compaction, and swelling potential are determined according to ASTM standards (D422 (2007), D4318 (2017), D854 (2014), D4546 (2014)) respectively [17-18-19-20]. These properties are presented in Table 1.

Table 1 - Physical properties of the untreated specimen US from laboratory testing

*Properties, (Unit)	Value
Specific gravity	2.56
Liquid limit (%)	95.2
Plastic limit (%)	23.2
Plasticity index (%)	72.3
Clay content (%)	57
Activity	1.27
Water content (%)	15
Dry unit weight (kN/m^3)	1.495

Table 1 - Physical properties of the untreated specimen US from laboratory testing (continue)

*Properties, (Unit)	Value
Swelling potential under 7 kPa (%)	43.95
Swelling potential under 25 kPa (%)	29.47
Swelling pressure (kPa)	265

*(ASTM Standard D854, (2014), ASTM Standard D4318, (2017), ASTM Standard D422, (2007), ASTM D698-12, (2012), ASTM Standard D4546, (2014) respectively)

The swelling potential of untreated specimen US under 7 kPa surcharge pressure is approximately 44%. Thus, this specimen is classified as "very high" expansive according to the classification proposed by Seed et al. (1962) [21].

The chemical characteristics of the untreated specimen were determined in the form of major oxides in the Middle East Technical University Central Laboratory, using the X-ray fluorescence (XRF) technique. The chemical composition of untreated specimen US is provided in Table 2. Elementary sulfur can be analyzed but SO_3 (SO_4) can not be determined in the XRF technique.

Table 2 - Chemical composition of untreated specimen US

Chemical Composition	Expansive soil specimen (%)
SiO_2	51.6
Al_2O_3	41.3
Fe_2O_3	1.22
CaO	0.51
SO_3 (SO_4)	-
CO_2	3.46
K_2O	0.5
Na_2O	0.17
MgO	0.15
P_2O_5	0.06
SrO	0.02
ZrO_2	0.02

2.2 Treated Specimens with Lime Columns (LC)

The treated specimen with lime columns, which have 63.5 mm diameter and 19 mm height, consists of 37 pieces of lime columns that have 4.5 mm diameter and 19 mm height is presented in Figure 2. The lime columns were placed in a circular orbit due to the shape of the oedometer ring. The distance between the lime columns is 4.05 mm.

Water was added to lime columns to increase the lime diffusion. In addition to this, the water content of lime columns should be greater than the water content of expansive soil specimens. Thus the columns were filled with a mixture that consists of 70% lime and 30% water by weight. This mixture was in a plastic state. When the water content of this mixture was greater than 30%, this mixture was not workable material due to its sticky structure, the treated specimen was called LC.

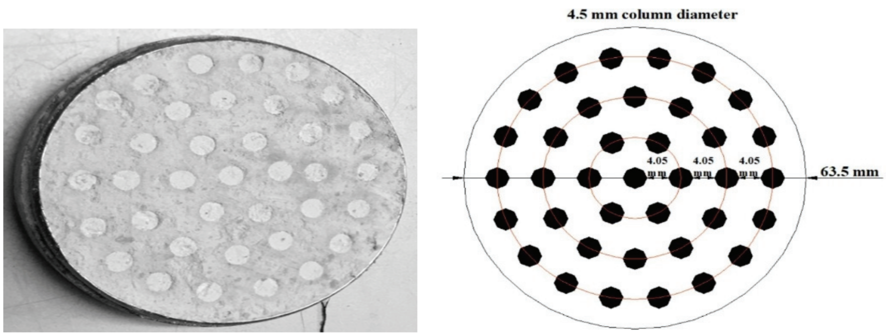


Figure 2 - Model of the treated specimen with lime columns (LC)

The properties of lime columns installed in an oedometer ring are presented in Table 3.

Table 3 - The properties of lime columns installed in the oedometer ring

Specimen Diameter (cm)	Specimen Area (cm^2)	Borehole Diameter (cm)	Borehole Area (cm^2)	Total Column Volume (cm^3)	Total Columns Surrounding Area (cm^2)	Area Ratio (%)
6.35	31.67	0.45	5.88	11.18	99.4	18.58

2.3. Treated Specimens with Sodium Lignosulphonate Lime Columns (NaLS-LC)

Sodium lignosulphonate is used as a superplasticizer in the concrete industry and was selected as an additive material in this study to accelerate the diffusion of lime particles into the expansive soil.

The sodium lignosulphonate lime columns are composed of lime, water, and sodium lignosulphonate. Since sodium lignosulphonate is a water-soluble material, first water, and sodium lignosulphonate were mixed, then lime was added to this mixture. The weight percentage of the mixture prepared in this step of the study is given in Table 4.

Table 4 - The weight percentage of the mixture consists of a water-sodium lignosulphonate-lime mixture

Percentage by weight (%)	Water	Sodium lignosulphonate	Lime
	30%	3.75%	66.25%

The optimum amount of sodium lignosulphonate is determined as 12.5% of water weight. When the amount of sodium lignosulfonate is greater than this value, lignosulfonate particles could not dissolve in water.

In this study, sodium lignosulphonate lime columns were prepared in an oedometer ring and a 30cm*30 cm mold as follows:

2.3.1. Treated Specimens in Oedometer Ring

The number and arrangement of columns in treated specimens with **sodium lignosulphonate lime columns (NaLS-LC)** are the same as in treated specimens with lime columns (LC). These treated specimens have been tested only for free swell tests to observe the change in their swelling potential of them.

*2.3.2. Treated Specimens (BG-36 and BG-50) between the Sodium Lignosulphonate Lime Columns in a 30cm*30 cm Mold*

The untreated specimen US was compacted in a mold that has 30 cm*30 cm*18 cm dimensions. Then seven boreholes were opened for the sodium lignosulphonate lime column (NaLS-LC) which has a 45 mm diameter. These boreholes were filled with sodium lignosulphonate-lime mixture, and the specimens were put into plastic bag and put into moisture room with 70% moisture and 22°C temperature for 7 days, 28 days, and 90 days curing. After the curing periods of 7 days, 28 days, and 90 days, two different diameter, undisturbed specimens were obtained from treated soil (Figure 3).

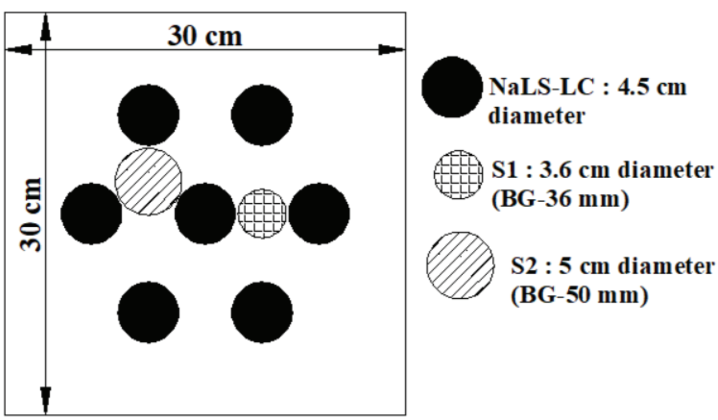


Figure 3 - Locations of undisturbed soil sampling

The specimen that has a 50 mm diameter, was tested to determine the swelling potential and permeability coefficient of treated expansive clay placed between the sodium lignosulphonate lime columns. The undisturbed specimen is called BG-50mm. The specimen which has a 36 mm diameter and was tested to measure the unconfined compressive strength of treated expansive clay placed between the sodium lignosulphonate lime columns. The undisturbed specimen is called BG-36mm. The undisturbed specimen sampling tubes were pushed into the compacted soil with a hydraulic jack (Figure 4).

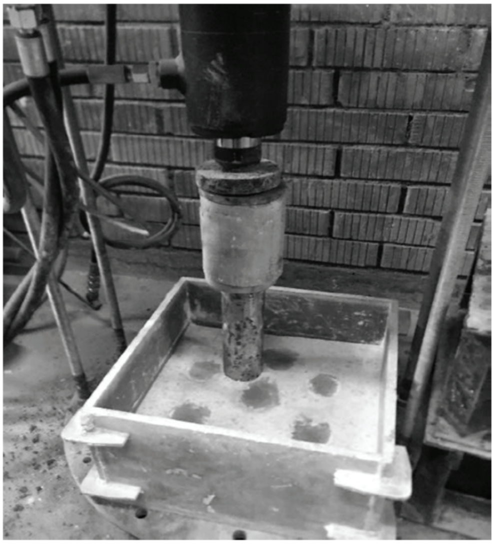


Figure 4 - The pushing process

2.4. Laboratory Tests

Free swell test, unconfined compressive strength test, and SEM-EDX analysis were done on both Specimen US and the treated specimens.

2.4.1. Free Swell Test

Untreated specimen US and treated specimens were prepared at the same dry density (1.495 g/cm^3) and water content (15%). While the densities of these specimens were selected as the maximum dry density of untreated specimen US, the water contents were lower than the optimum water content of untreated specimen US (26%) to see the effect of sodium lignosulphonate lime column stabilization better.

The volume of the soil specimen changes only in a vertical direction during the free swell test. The swelling potential is a ratio between the volume change and the initial volume of the specimen.

The swelling potential (SP) of a soil specimen is calculated as a function of the height of the soil specimen (Eqn. 1).

$$SP(\%) = \frac{(h_f - h_i)}{h_i} \times 100\% \quad (1)$$

Where h_f is the final height of the specimen and h_i is the initial height of the specimen.

Free swell tests were done to determine the swelling potentials of the treated specimens in the oedometer ring which had 6.35 cm in diameter and 1.9 cm in height and on the treated expansive clay specimens taken from the 30 cm*30 cm mold, in between the sodium lignosulphonate lime columns.

Two surcharge pressures, which are 7 kPa and 25 kPa, were applied to the specimens. The 7 kPa surcharge pressure represents a very lightweight structure such as a sidewalk, the 25 kPa surcharge pressure represents a lightweight structure such as pavement and embankment fill loading or one-two storey house loading.

7 days, 28 days, 90 days, and 180 days curing periods were applied on the treated expansive clay specimens in oedometer rings with both lime columns and sodium lignosulphonate lime columns. 7 days, 28 days, and 90 days curing periods were applied to treated expansive clay specimens taken from the 30 cm*30 cm mold, in between the sodium lignosulphonate lime columns.

Swelling potentials of untreated specimen US under 7 kPa and 25 kPa were determined as 43.95% and 29.47% respectively. These two values are reference points for the results of the other swell tests in this study.

2.4.2. Unconfined Compressive Strength (UCS) Test

Untreated specimen US (36 mm diameter and 72 mm height) for the UCS test has a water content of 15%, the dry density was 1.495g/cm^3, the degree of saturation was 53.9% and the unconfined compressive strength (ASTM D2166) was measured as 385 kPa [22]. Three curing periods of 7 days, 28 days, and 90 days were applied to treated specimens prepared to investigate the curing effect.

2.4.3. SEM-EDX Analysis

SEM-EDX analyses were done at METU Central Laboratory to examine the change in the chemical composition and structure of the expansive soil specimen during the stabilization process. The selection of the specimens for this analysis was determined according to the results of free swell tests.

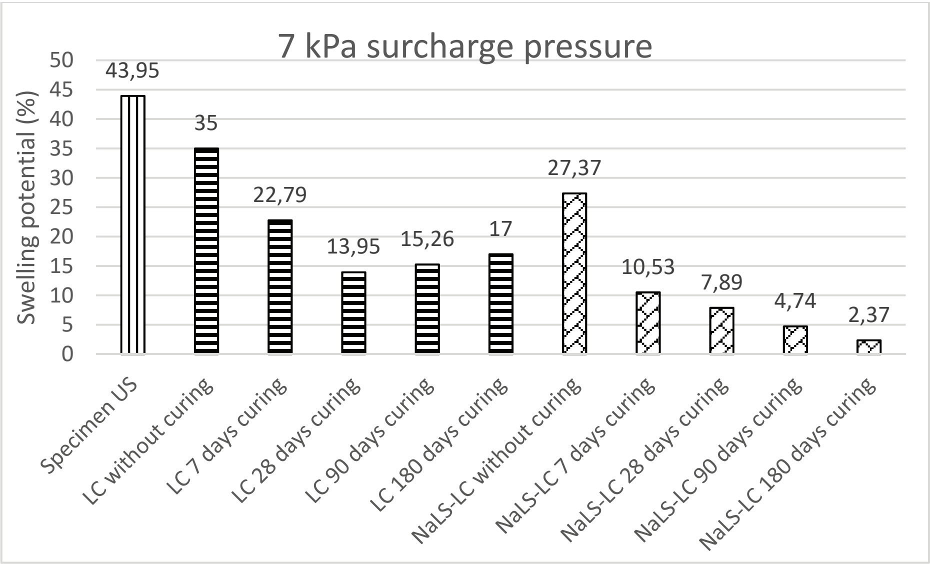
2.4.4. Methylene Blue Tests

Methylene Blue Test (MBT) was done according to NF P 94-068 standard to determine the cation exchange capacity and specific surface area of treated samples [23]. The samples for MBT were taken between the NaLS lime columns and the test samples were cured in a humid room for 90 days.

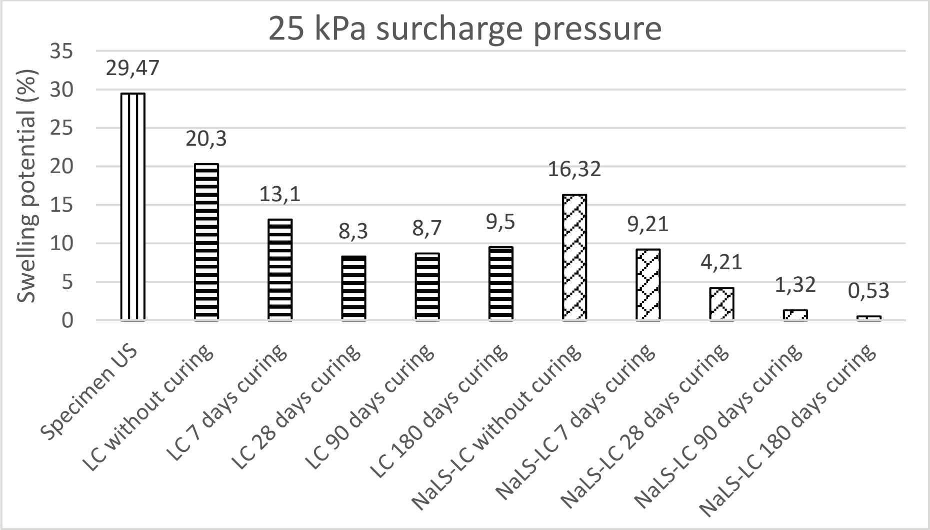
3. TEST RESULTS AND DISCUSSION

3.1. The Swelling Potentials of Treated Specimens

The swelling potentials of treated specimens under 7kPa and 25kPa (the treated specimen with lime columns, which has 63.5 mm diameter and 19 mm height (i.e. in oedometer ring), consists of 37 pieces of lime columns which have 4.5 mm diameter and 19 mm height) are presented in Figure 5.



a) Under 7 kPa surcharge pressure



b) Under 25 kPa surcharge pressure

Figure 5 - The swelling potentials of treated specimens consist of 37 columns (LC and NaLS-LC)

The swelling potentials of treated specimens including 37 columns (LC and NaLS-LC) are lower than the swelling potentials of untreated specimen US under both surcharge pressures. An optimum curing period, which was 28 days, was applied for treated specimens including 37 lime columns. After 28 days period, the swelling potentials of the treated specimens increase. The reason for this increment can be the formation of ettringite minerals during the stabilization process, which was investigated by SEM-EDX analysis. The swelling potentials of treated specimens including sodium lignosulphonate lime columns gradually decrease with the curing period. Thus, the specimens used for SEM-EDX analysis were selected as untreated specimen US and treated specimens with a 180-day curing period according to the test results of the free swell tests.

The swelling potentials of treated specimens placed between the sodium lignosulfonate lime columns in the big mold (30cmx30cm) were determined. The swelling potentials of treated specimens in this group are presented in Figure 6.

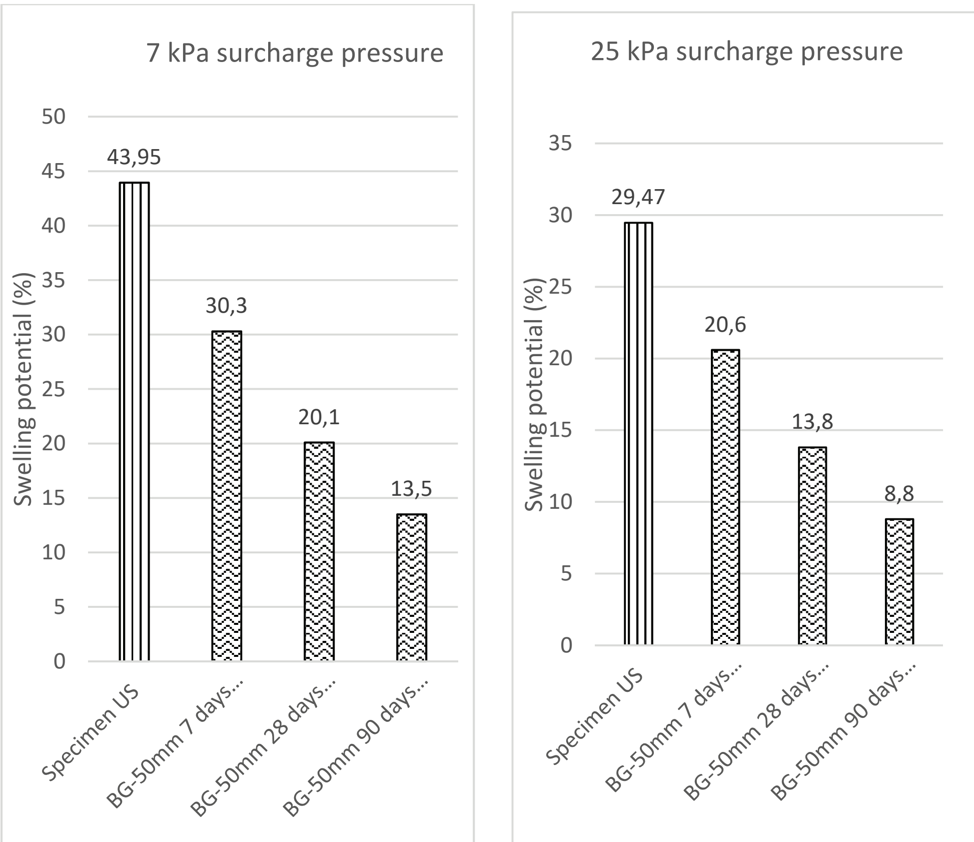


Figure 6 - The swelling potentials of treated specimens (BG-50) placed between the sodium lignosulphonate lime columns

For each surcharge pressure, the swelling potentials of treated specimens decrease with the curing period applied.

3.2. The UCS Values of Treated Specimens

The UCS values of treated specimens obtained from big mold (30cmx30cm) are presented in Figure 7. The UCS values of treated specimens are greater than the UCS of specimen US and improved with curing periods. For example, the UCS value of treated specimens called BG-3 is approximately 533 kPa after a 90-day curing period. While Specimen US behaves as a ductile material, treated specimens are converted to a brittle material with a curing period. This behavior can be explained by the formation of a flocculated structure due to the addition of lignosulphonate to the clay soil (Vinod et al., 2010).

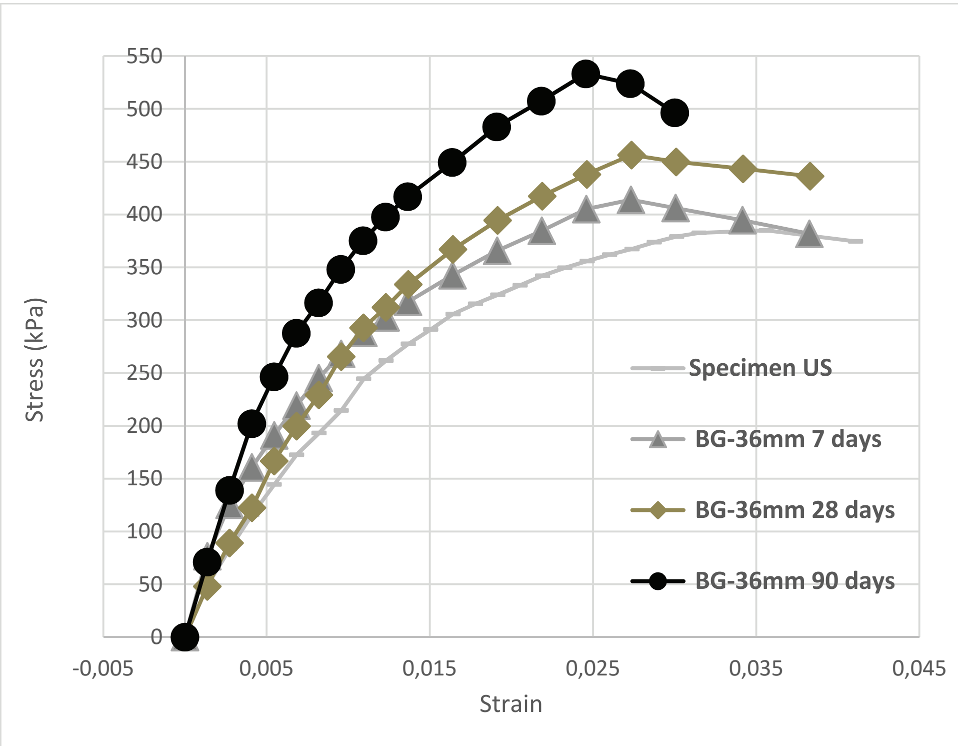


Figure 7 - Unconfined compressive strength test graphs (BG-36 specimens)

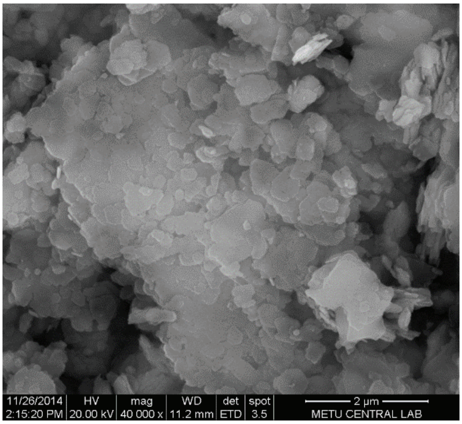
3.3. The Results of the SEM-EDX Analysis

The untreated sample US and treated samples which are named LC and NaLS-LC, with a 180-day curing period were tested. The samples for SEM-EDX analysis were taken from the midpoint of the two columns. The microstructural change of the untreated sample during the stabilization process was searched by SEM analysis. In addition to this, an Energy Dispersive

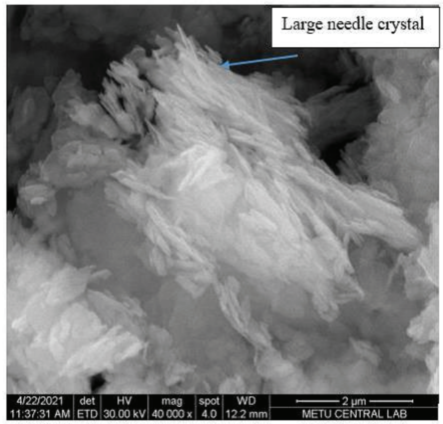
X-Ray (EDX) analysis (for 180 days of curing) was performed to get information about the chemical characterization of both untreated samples and treated samples in SEM analysis.

QUANTA 400F Field Emission Scanning Microscope was used for SEM analysis at METU Central Laboratory. First, untreated sample US was dried at 45°C and pulverized. Then, the specimens were coated with gold and palladium for SEM Analysis.

The alteration of microstructural properties of particles was investigated (Figures 8a, 8b, 8c). The magnification factor of the SEM images is x40000.

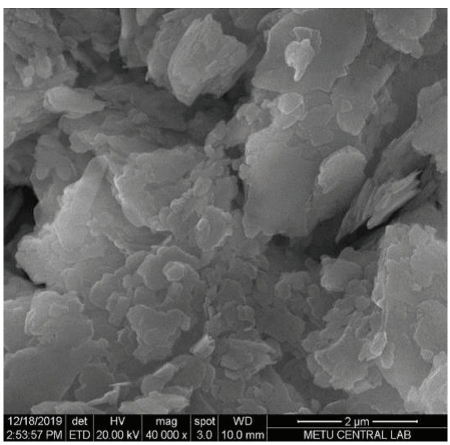


is



a) Untreated Specimen US

b) Treated specimen with Lime Columns (LC) (180 days curing)



c) Treated specimen with NaLS-Lime Columns (180 days curing)

Figure 8 - The SEM images of test specimens

The main mineral of untreated sample US is kaolinite which has plate-shaped particles in Fig 8a. According to the outputs of the free swell tests, the swelling potentials of treated specimens with lime columns increased after the 28day curing period, this might be due to the formation of ettringite mineral. When the SEM image of the treated specimen with the lime column, which was cured for 180 days, was studied (Fig. 8b), the formation of ettringite mineral was observed, ettringite formation needs sulfate ions, it is thought that the sulfate in the specimens is due to the presence of sulfate SO_4 in lime (0.79%) and/or in water (167mg/L). The major oxides of the untreated specimen were determined in the X-ray fluorescence (XRF) technique, but SO_3 (SO_4) can not be determined in the XRF technique.

To block the formation of ettringite mineral, sodium lignosulphonate was added to the lime column and the problem was solved (Fig 8c) the swelling potentials of treated specimens decreased with the curing period.

Energy Dispersive X-Ray (EDX) analysis was performed to take information about the chemical characterization of specimens during SEM analysis. Table 5 shows the microchemical compositions of test specimens obtained from EDX analysis.

Table 5 - The microchemical compositions of test specimens obtained from EDX analysis

Elements	**Untreated sample US**	LC 180 days curing	NaLS-LC 180 days curing
Al	15.57	18.25	16.91
Si	19.39	25.02	27.59
O	48.68	51.70	45.95
Ca	0.39	1.60	1.81
Na	-	0.25	0.94

Essential elements of the untreated specimen US that is aluminum, silica, and oxygen form the major part of this specimen. The change of percentages of their weight was sought during the stabilization process.

The elements listed in Table 5, which are calcium and sodium, are crucial for this stabilization process. The calcium ion of lime is an identifier element that shows the diffusion of lime particles during the stabilization process. Sodium lignosulphonate was used for the acceleration of diffusion of lime particles. For two stabilization methods, the weight percentages of both sodium ion and calcium ion increase after the 180-day curing period. However, the weight percentages of both calcium ion and sodium ion in the treated specimens with NaLS-LC are greater than in the treated specimens with the lime column, and this output verifies the beneficial effect of the sodium lignosulphonate addition on the acceleration of lime diffusion into the clay.

3.4 The Results of the Methylene Blue Test

The methylene blue value of the samples, taken between the sodium lignosulphonate lime columns, was found to investigate the change of cation exchange capacity and specific surface area of treated expansive clay specimens.

Cation exchange capacity and specific surface area of both untreated specimen US and NaLS-LC treated specimen for 90 days curing are presented in Table 6.

Table 6 - MBV, cation exchange capacity, and specific surface area of untreated expansive soil specimen the US and NaLS lime column treated specimen for 90 days curing

Specimens	Final reading (cc)	Methylene Blue value (g/100g)	Cation exchange capacity (CEC) (meq/100g)	Specific surface Area (SSA) (m^2/g)
Untreated Specimen US	180	6	18.75	146.73
NaLS-LC 90Days	125	4.167	13.02	101.89

Cation exchange capacity and specific surface area are determinant properties of the activity of expansive soils. In this stabilization process, the values of CEC and SSA decrease with the curing period. Therefore, the treated expansive clay specimens with the sodium lignosulphonate lime columns are less active soils than untreated expansive clay specimens.

4. CONCLUSIONS

This study aimed to study the effect of the addition of sodium lignosulphonate to lime columns for the stabilization of expansive clay. The swelling potential and unconfined compressive strength of untreated expansive clay specimen, treated expansive clay specimen with lime columns, and treated expansive clay specimen with sodium lignosulphonate lime columns were measured and compared.

Under 25 kPa surcharge pressure, the swelling potential of NaLS-LC specimens with 180 days of curing was measured as 0.53%. This value is smaller than both untreated expansive clay specimens (29.5%) and the LC-treated expansive clay specimens (9.5%) after 180 days of curing.

The formation of ettringite mineral during the lime column stabilization method occurred after 180 days curing period. To solve this problem, sodium lignosulphonate was added to the lime column and the formation of ettringite mineral was prevented.

The treated expansive clay specimens placed between the sodium lignosulphonate lime columns have higher unconfined compressive strength than untreated expansive clay specimens. The unconfined compressive strength of the treated specimens was measured as 533 kPa after 90 days curing period.

According to the result of the EDX analysis, the amount of both Ca^{+2} and Na^{+1} ions diffused through the expansive clay specimen during the sodium lignosulphonate lime stabilization method.

The treated expansive clay specimens with sodium lignosulphonate lime columns have lower cation exchange capacity and a specific surface area than untreated specimen US.

The swelling percent and unconfined compressive strength of the treated soils improved with the curing period due to the reactions between both the clay–lime and clay-NaLS.

In conclusion, it can be stated that the addition of sodium lignosulphonate to lime columns shows better performance than lime columns for the treatment of expansive clays.

Acknowledgments

The authors would like to express their thankfulness and a deep sense of gratitude to the Department of Civil Engineering, Middle East Technical University for providing the laboratory facilities and equipment to conduct and accomplish this study.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

References

[1] Masia, M. J., Totoev Y. Z., Kleeman P. W., Modeling Expansive Soil Movements Beneath Structures. Journal of Geotechnical and Geoenvironmental Engineering, 130(6), 572–579, 2004. doi:10.1061/(ASCE)1090-0241(2004)130:6(572)

[2] Parhi, P.S., Garanayak, L., Mahamaya, M., Das, S.K., Stabilization of expansive soil using alkali-activated fly ash based geopolymer. In Advances in Characterization and Analysis of Expansive Soils and Rocks; Hoyos, L., McCartney, J., Eds.; Springer: New York, NY, USA; pp. 36–50, 2017.

[3] Rogers, C. D., Glendinning, S., Improvement of clay soils in situ using lime piles in the UK. Engineering Geology, 47(3), 243–257, 1997.

[4] Goud, G.N., Hyma, A.; Chandra, V.S., Rani, R.S., Expansive soil stabilization with coir waste and lime for flexible pavement subgrade. In Proceedings of the International Conference on Recent Advances in Materials, Mechanical and Civil Engineering, Hyderabad, India, 1–2 June 2017; IOP Publishing: Bristol, UK, 2018; Volume 330, p. 012130.

[5] Shaqour, F, Ismeik, M., Esaifan, M., Alkali activation of natural clay using a $Ca(OH)_2/Na_2CO_3$ alkaline mixture. Clay Minerals, 52(04), 485–496, 2017.

[6] Rajasekaran, G., Narasimha Rao, S., Sulphate attack in lime-treated marine clay. Marine Georesources & Geotechnology, 23(1-2), 93–116, 2005.

[7] Prusinski, J., Bhattacharja, S., Effectiveness of Portland cement and lime in stabilizing clay soils. Transportation Research Record: Journal of the Transportation Research Board, 1652, 215–227, 1999.

[8] Muntohar, A. S., The influence of molding water content and lime content on the strength of stabilized soil with lime and rice husk ash. Civil Engineering Dimension, 7(1), Pp. 1-5, 2005.

[9] Yang D, Qiu X, Zhou M, Lou H, Properties of sodium lignosulfonate as a dispersant of coal water slurry. Energy Conversion and Management, 48(9), 2433–2438, 2007. doi:10.1016/j.enconman.2007.04.00

[10] Ekinci C. E., Ay S., Baykuş N., Ay. A., (2016), Examination of the impact of lignin sulfonate-based structure chemicals on fresh and hardened concrete. Pamukkale Univ Muh Bilim Derg., 22(6): 478-485, 2016.

[11] Alazigha, D P, Indraratna, B, Vinod, J S, Heitor A, Mechanisms of stabilization of expansive soil with lignosulphonate admixture. Transportation Geotechnics, 14 81-92., 2018 //doi.org/10.1016/j.trgeo.2017.11.001

[12] Vinod J S, Indraratna B, Mahamud M A A, Stabilization of an erodible soil using a chemical admixture, Journal of Ground Improvement, Vol. 163: 43 – 51, 2010. //doi.org/10.1680/grim.2010.163.1.43

[13] Vakili A H, Kaedi M, Mokhberi M, Selamat M R, Salimi M, Treatment of highly dispersive clay by lignosulphonate addition and electroosmosis application. Applied Clay Science. 152, 1–8, 2018. //doi.org/10.1016/j.clay.2017.11.039

[14] Indraratna, B., Mahamud, M., Vinod, J.S., and Wijeyakulasuriya, V., Stabilization of an erodible soil using chemical admixtures, in Bouassida, M, Hamdi, E & Said, I (eds), ICGE'10: Proceedings, 2nd International Conference on Geotechnical Engineering: 45-54, 2010.

[15] Tingle, J. S., and Santoni R. L., Stabilization of Clay Soils with Nontraditional Additives. In Transportation Research Record: Journal of the Transportation Research Board, No. 1819, Vol. 2, Transportation Research Board of the National Academies, Washington, D.C., pp. 72–84, 2003.

[16] Chen, Q., and Indraratna, B., Shear behavior of sandy silt treated with lignosulfonate. Canadian Geotechnical Journal, 52(8), 1180–1185, 2015.

[17] ASTM Standard D422, Standard Test Method for Particle-Size Analysis of Soils. ASTM International, West Conshohocken, PA, 2007.

[18] ASTM Standard D4318, Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils. ASTM International, West Conshohocken, PA, 2017.

[19] ASTM Standard D854, Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International, West Conshohocken, PA, 2014.

[20] ASTM Standard D4546, Standard Test Methods for One- Dimensional Swell or Collapse of Soils. ASTM International, West Conshohocken, PA, 2014.

[21] Seed, H. B., Woodward, R. J., Jr. and Lundgren, R., Prediction of swelling potential for compacted clays: J. ASCE, Soil Mechanics, and Foundation Division, Vol. 88, No. SM-3, Part 1, pp. 53–87, 1962.

[22] ASTM D2166 / D2166M-16, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM International, West Conshohocken, PA, 2016.

[23] NF P 94-068., Soils: Investigation and testing—Measuring of the methylene blue adsorption capacity of a rock soil—Determination of the methylene blue of soil using the stain test. Paris: Association Française de Normalisation, 1998.

TECHNICAL NOTE

Turkish Journal of Civil Engineering, 2023 153-165, Paper 721, ***Technical Note***

Solution Proposals based on Fuzzy AHP-TOPSIS Hybrid Model to the Problems in Public Works Procurement in Turkey

İbrahim ÖZYÜREK[1]
Mürsel ERDAL[2]

ABSTRACT

In the transition from price-based tender evaluation to multi-criteria bid evaluation process in public procurements pioneered by academic research, the aim is to ensure the delivery of the project at the desired quality without exceeding the time and budget of the contract process. In the tenders implemented according to the Public Procurement Law (PPL), while the lowest price principle was used in the bid evaluation stage, non-price elements began to be used in time. However, complexity in regulations brought about longer tender evaluation process and more conflicts. In this study, solutions to current problems such as the evaluation of abnormally low in the tenders made within the scope of the law, the long duration of the bid evaluation process, and the high number of conflicts are proposed through the model created by Fuzzy AHP-TOPSIS methods.

Keywords: Tender, MCDM, TOPSIS, contractor selection.

1. INTRODUCTION

In Turkish public procurement practice, most frequently used procedure for selecting contractors has been open tendering and mostly tenderer who offered the lowest price was awarded the contract. This made tenderers to consider the price down in tender and retrieve profits during implementation of projects benefiting from ambiguities in the documents and weakness of supervision. The price to quality evaluation has resulted in so many unfavorable results such as unfinished projects due to contractor's inability to complete project, high maintenance costs due to poor quality of structure, and environmental damage due to contractor's failure to take necessary costly measures to respect the environment. Consequently, a gradual shift from lowest price to most economically advantageous tender evaluation took place. Most economically advantageous tender involves monetary and non-

Note:

- This paper was received on December 20, 22021 and accepted for publication by the Editorial Board on November 11, 2022.
- Discussions on this paper will be accepted by March 31, 2023.

- https://doi.org/10.18400/tjce.1209197

1 Public Procurement Authority, Ankara, Türkiye
iozyurek@hotmail.com - https://orcid.org/ 0000-0002-1141-5135

2 Gazi University, Faculty of Technology, Department of Civil Engineering, Ankara, Türkiye
merdal@gazi.edu.tr - https://orcid.org/ 0000-0002-9338-6162

monetary element, making tender evaluation a multi-criteria decision making (MCDM). These elements exclude the qualification criteria. However, subject of works procurement is not a good with known specifications but a work and delivery process which is directly shaped by qualifications of tenderers. Therefore, it is important that qualifications of tenderers be put into a multi-criteria tender evaluation.

MCDM involves deciding on the best alternative from a set of potential candidates. These alternatives often contain multiple and conflicting criteria that can be qualitative or quantitative [1]. There have been numerous MCDM methods offered by researchers to select the right contractor, such as, the analytical hierarchy process (AHP) [2], ELECTRE [3], multi-attribute utility theory (MAUT) [4], PROMETHEE [5], TOPSIS [6] etc.

In this study, it is aimed that the time required to award the contract be shortened, the tenders be evaluated together with the qualifications of the bidders, the abnormally low tender inquiry and explanation processes be removed, and hence the most suitable contractor be selected in a relatively shorter time.

2. BACKGROUND

Tenderers partaking in the procurement proceedings may submit documents for evaluation of their eligibilities. The qualification documents that have to be submitted in tender are decided by the contracting authorities (CA) according to the estimated cost of the procurement. Tenderers who do not meet the thresholds are disqualified. After this stage, there exists an abnormally low tender identification, explanation, and evaluation process.

To determine abnormally low tenders, PPL uses “limit value” that is calculated using approximate cost and bid prices. However, the limit value carries a risk that it can be manipulated by tenderers. In the prevalence of abnormally low tenders, CA may ask tenderers for explanation about important components of their prices. The methods of explanation are defined in the regulations. In the next stage, CA accept the explanation if it is duly prepared or reject it otherwise.

Following the evaluation mentioned above, CA shall award the contract to the tenderer who submitted most economically advantageous tender. According to PPL article 40, the economically most advantageous tender is determined either solely on the basis of price or on the basis of both price and non-price factors such as operation and maintenance costs, cost effectiveness, productivity, quality, and technical value. Despite both types of evaluation, problems may arise during the delivery of project in conformity with the terms of the contract. Therefore, the public might not benefit from the project of interest as desired. Also, during the implementation of the project, adversarial relationship between the CA and the contractor may arise due to contractor’s inabilities and low contract price from contractor’s point.

Another pitfall of the existing procedure is that it allows tenderers offering prices under limit value to refrain from signing contract because there is no sanction in regulations to those who do not submit their explanation or submit unduly prepared explanation. This creates a region of agreement between tenderers which increases contract value. To make it clear, let’s see Table 1. In the table, Tenderers A, B and C, whose prices are abnormally low, could be awarded the contract, however, most probably due to an agreement, they do not submit explanation and contract value increase from 133 to 149.

Table 1 - A sample list of bid prices in a tender

Tenderer	*Bid Price*	*Action*
A	133	No explanation submitted – Reject tender
B	135	No explanation submitted – Reject tender
C	140	No explanation submitted – Reject tender
D	149	Explanation accepted – Award contract
Limit Value	150	Components of tenders below this value must submit explanation
E	153	Valid tender
F	165	Valid tender

The tender evaluation procedure currently applied in Turkey and the offered change in this process are shown in Figure 1.

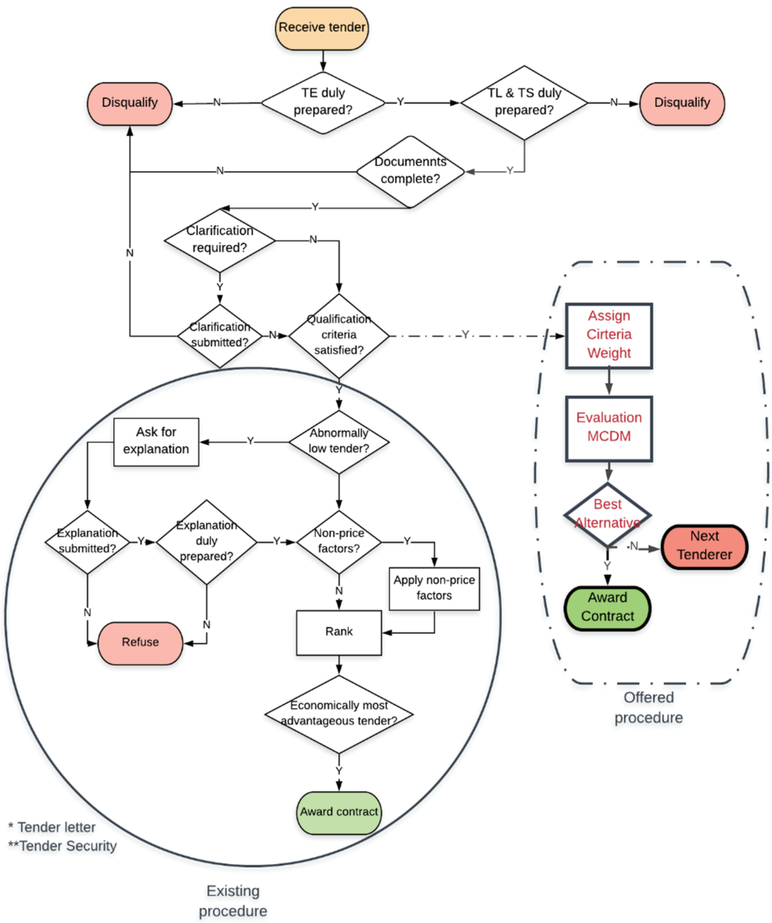


Figure 1 - Tender Evaluation Process in Public Procurement Law and offered modification

The study proposes a model to be applied in the tenders implemented by open tender procedure and negotiating procedure. The qualification criteria to be used are limited to the criteria detailed in the Construction Works Tenders Implementing Regulation.

3. METHODOLOGY

The most important advantage of multi-criteria methods is their capability to weigh conflicting interests during selection. The AHP is a technique that can be easily combined with other methods, and TOPSIS is a method that is algorithmically structured and easy to compute, especially when acting in combination with other techniques [7]

The proposed model is a fuzzy AHP-TOPSIS hybrid model, which obtains criterion weight through fuzzy AHP and ranks alternatives by TOPSIS.

This model consists of

(a) a number of tenderers, denoted as T_i ...$i=1; 2; . . . ; n$;

(b) a set of evaluation criteria consisting of qualification criteria and tender price Cj ...$j=1, 2, . . . ,m,$

(c) tenderers' qualifications and tender prices x_{ij} ...$i=1, 2, . . . , n; j=1, 2, . . . ,m;$

(d) a weight vector w = ...$w_1, w_2, . . . ,w_m$ (referred to as criteria weights) representing the relative importance of the evaluation criteria with respect to the contractor selection.

In order to determine the weight of these criteria in the evaluation of tenders, a questionnaire consisting of paired comparisons about the criteria was conducted. Then, 18 different scenarios were formed according to the qualification criteria that tenderers must meet in the tenders and by using the survey results, the weights for each criterion in each scenario were determined by Fuzzy AHP methods [8]. The weights obtained, were then transferred to Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. In TOPSIS applications, 15 different applications were proposed. These methods were aimed at i) mitigating with abnormally low tenders, ie. tenders below limit value, ii) mitigating with tenders above approximate cost when other tenderers have poor quality, iii) mitigating with high tender prices of over-qualified tenderers

The results of these practices were evaluated separately for four different tenders and recommendations were submitted. Only one example will be given here. For other examples readers are refered to [8].

2.1. Criterion Weight, Fuzzy AHP

AHP was selected to assign criteria weights as i) it is one of the most frequently used MCDM methods in construction management literature, ii) it has excellent performance in dealing with both tangible and intangible criteria, iii) reliability can be controlled with consistency ratio, iv) experts get better understanding about study objectives with a hierarchical representation and v) it provides easy implementation [9]

Since there were large deviations in evaluations by decision-makers, fuzzy numbers should be used. In FAHP, the pair wise comparisons of criteria were performed through the linguistic variables, which are represented by triangular numbers. The fundamental scale is transformed into triangular fuzzy numbers as in Table 4.

Table 4 - The fundamental scale used in the study

Intensity of Importance	Definition	Fuzzy Triangular Scale
1	Equal importance	(1,1,1)
3	Weak importance of one over another	(2,3,4)
5	Essential or strong importance	(4,5,6)
7	Demonstrated importance	(6,7,8)
9	Absolute importance	(9,9,9)
2	The intermittent values between two adjacent scales	(1,2,3)
4		(3,4,5)
6		(5,6,7)
8		(7,8,9)
Reciprocals of above nonzero	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value in reverse order when compared with *i, ie. ij=(2,3,4) then ji=(1/4,1/3,1/2)*	

Table 5 - Criterion weights suggested by Ozyurek [8]

Case	Bank Reference Letter (BRL)	Current Ratio (CR)	Equity Ratio (ER)	Short Term B. Loans / Euqity	Annual Turnover (AT)	Work Experience (WE)	Quality Certificate (QC)	Environment Certificate (EnC)	Tender Price (TP)	Estimated Cost (EC)
1	*No*					**26,94**	*No*		**73,06**	0-0,1 Threshold Value (TV)
2						19,36			73,06	
3	---	1,52	2,15	2,07	5,36	25,06			63,85	0,1TV-0,5TV
4	**0,95**	**1,40**	**1,98**	**1,91**	**4,87**	**25,06**			**63,85**	
7	---	1,52	2,15	2,07	5,36	20,82	4,24	---	63,85	> 0,5 TV
8	0,95	1,40	1,98	1,91	4,87	20,82	4,24	---	63,85	
9	---	1,52	2,15	2,07	5,36	21,00	---	4,06	63,85	
10	0,95	1,40	1,98	1,91	4,87	21,00	---	4,06	63,85	
15	---	1,52	2,15	2,07	5,36	17,89	3,97	3,20	63,85	
16	0,95	1,40	1,98	1,91	4,87	17,89	3,97	3,20	63,85	

Ozyurek [8] suggested the following weights for qualification criteria through processing by FAHP the outcomes of the survey among public procurement specialists at Public Procurement Authority. For details of the survey, see Ozyurek [8][10].

2.2. Ranking of Alternatives: Technique for Order Preference by Similarity to An Ideal Solution

Technique for Order Preference by Similarity to an ideal solution (TOPSIS) was introduced by Hwang and Yoon [11]. In TOPSIS method, positive ideal solution maximizes benefit criteria and minimizes cost criteria. Negative ideal solution maximizes cost criteria and minimizes benefit criteria [12]. Hence, alternatives should have shortest distance from positive ideal solution and farthest from negative ideal solution

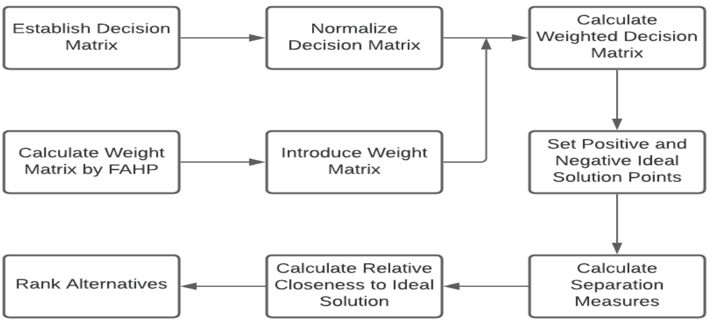


Figure 4 - TOPSIS Method

For alternatives 1 and 2 shown in Figure 5, it is seen that Alternative 2 is farther away from the negative ideal solution point and closer to the positive ideal solution point, so Alternative 2 is more similar to the ideal solution.

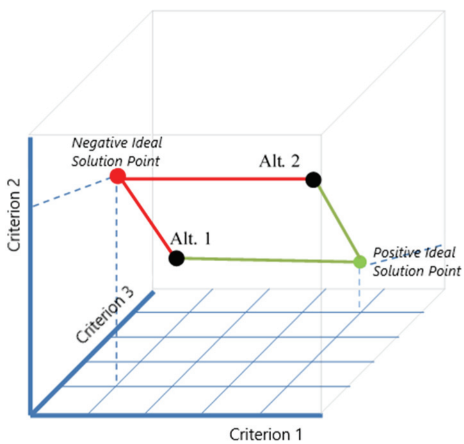


Figure 5 - Ranking of alternatives in TOPSIS

In applications where TOPSIS method is employed, it is a general approach that positive and negative ideal solutions are selected as either maximum or minimum points in each criterion. However, due to the nature of tender evaluation system, assigning max or min points as ideal solutions sometimes do not help us select the right contractor to deliver the project in desired conditions and price. It is worth to remind here that we are restricted with the qualification criteria in PPL. Therefore, within the frame of qualification criteria, some suggestions are made to select contractor to deliver project timely, safely and within the desired quality. Mostly encountered problems and suggestions are given in the next part.

4. APPLICATIONS and DISCUSSION

Scenario 1: Abnormally low tenders

The projects delivered by contractors who offered abnormally low price are generally defective and operation and maintenance costs are high. It is desired that tenderer, who offered abnormally low price compared to the other prices and/or the estimated cost determined by the CA, stop gaining price advantage beyond an appreciable value.

Solution:

In the scenario, limit value which is determined by a formula defined by Public Procurement Authority was selected as the positive ideal solution point. This reduces the price advantage of the tenderers below limit value. The lower the price beyond limit value the further it gets away from the positive ideal solution. On the other hand, it still continues to get further away from the negative ideal solution.

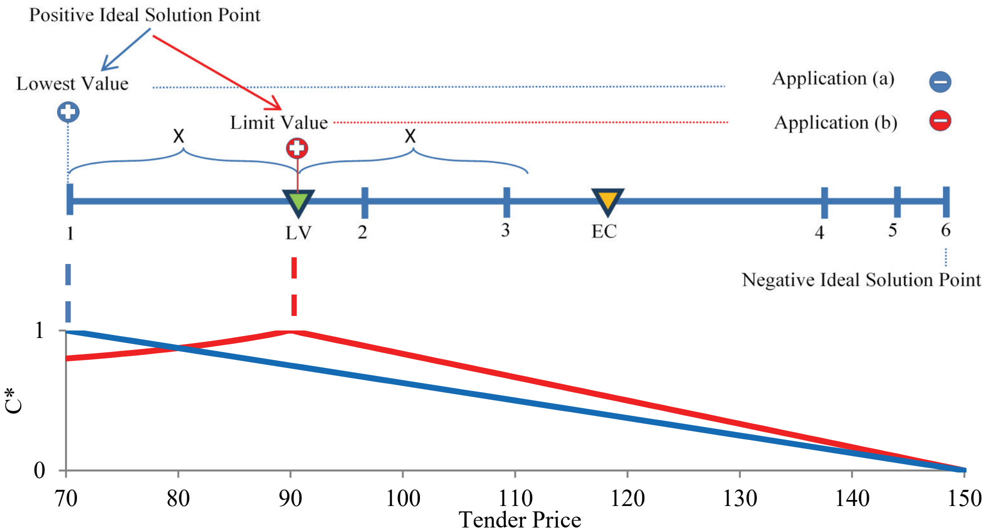


Figure 6 - Selection of positive ideal solution point for abnormally low tender evaluation

Figure 6 shows the effect of assigning limit value to positive ideal solution point. In application (a), for price criterion, the distance of Tenderer 1 to the positive ideal solution is zero while in application (b) it is (X). This makes the tenderer with low qualifications hesitate to offer abnormally low prices. In the former case, as the price goes from maximum to minimum price, the value of C in price criterion increases linearly and reaches at 1 at the minimum price while in the latter case; it reaches at 1 at the limit value and drops parabolically after then. This is the case when only the price criterion is considered that is w_{TP}=1,00.

Scenario 2 Over-qualification Problem

This problem is not the case for procurement process already in use. However, it will be a problem when tenderers' qualifications are put into evaluation in a multi criteria decision making. Tenderers with high qualifications would tend to offer higher prices to make higher profits and they would be awarded the contract, resulting in cost overrun for CA unless limits are applied for the qualification values. The aim of the tender evaluation model proposed hereby is to select the most suitable contractor who can deliver the project in time and budget and desired quality. Thus, CA should not pay for the quality beyond its necessity.

Solution: Qualification criteria should be evaluated by considering the size of the work subject to the tender. The excessive amount should not be taken into consideration for qualification criteria beyond the size comparable to the subject of the contract. Therefore, apply cut-off values to the qualification criteria so that unnecessary payment by the CA to the excessive qualification is prevented. The cut-off values can be determined by tender price or estimated cost as shown in Figure 7. In this application tender price is used. For qualification criteria, independent of tender price, the market conditions should be taken into account.

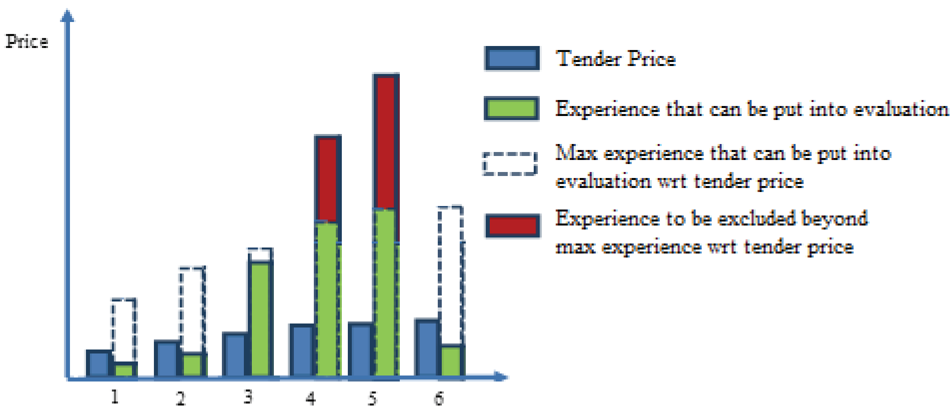


Figure 7 - Solution to over-qualification problem

Scenario 3: Promoting Successful Project Management

In this application, dimensionless numbers are assigned. The point here is that companies that have better management capacity can complete projects at lower costs so they should not be deprived of monetary qualification criteria since the same project if completed by a company with improper management capacity can cost much higher values. Let's consider a hospital tender that is made according to PPL. Also, assume that tender prices are 12, 12.5, 14, 15 and 16 million Turkish Liras, only-price based selection is applied, and all tenderers are eligible. If tenderer 1 is awarded the contract it will get 12 million work experience while if tenderer 3 is awarded, then it will get 14 million work experience. This unfair advantage can be levelled by using a dimensionless work experience parameter. The dimensionless parameter in this application is obtained by dividing work experience value by tender price as shown in Figure 8.

$$WE^{*} = \frac{\mathrm{WE}}{\mathrm{EC}}$$

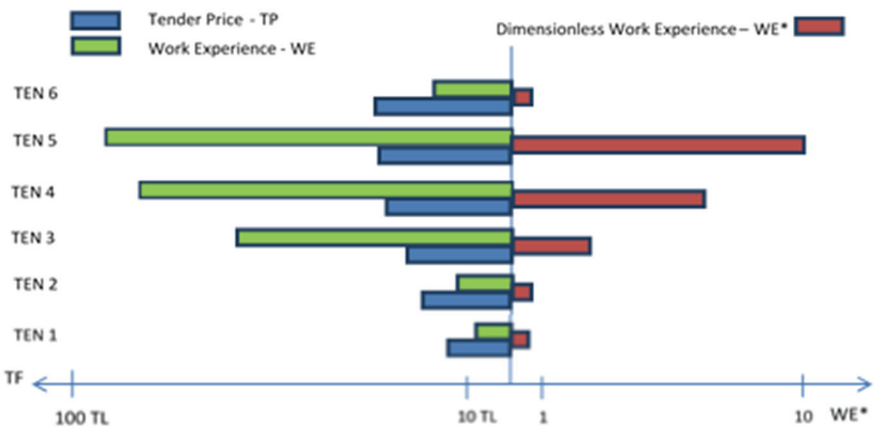


Figure 8 - Dimensionless parameters

Scenario 4: Preventing Contracts above estimated cost

Some tenders result in a contract price above the approximate cost. This is due to the lack of competitive environment, agreement between the tenderers, illegal relations between the tender authority and the tenderers and some similar situations. To prevent this, it is necessary to collect the prices higher than the estimated cost at the negative ideal solution point. In public procurement, with the effect of competition, the contract price is generally less than the estimated cost even limit value. However, in some cases, contracts above estimated costs are signed. Secondary regulations also allow this conduct. From this point of view, determining the highest bid price as the negative ideal solution point and accepting the distance of prices above estimated cost to the negative ideal solution point as zero, as shown in Figure 9, is an appropriate solution to prevent the procurement to be placed at a price above the estimated cost for the subject of the tender.

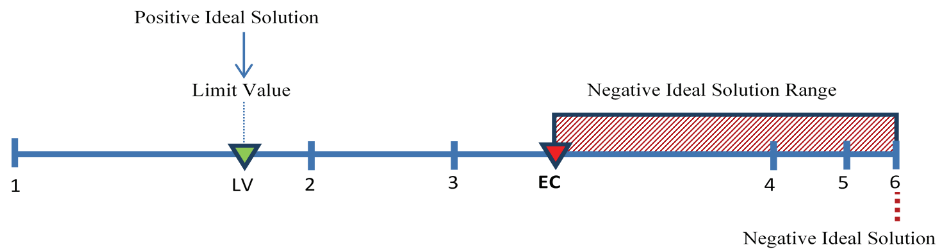


Figure 9 - Negative ideal solution to prevent contracts above estimated cost

Example

The estimated cost of the tender for a pond construction work is 7 614,15 TL. Eight tenderers participated in the tender, two tenderers were excluded from evaluation process for various reasons and the limit value was calculated as 5 901,75 TL. Tenderer with 4 400,00 TL bid price was awarded the contract. Only the work experience certificate was requested as the qualification criterion in this tender.

This tender is the tender with the minimum number of qualification criteria required. In this case, the decision tree has two branches and the weights 26,94 % for work experience and 73,06 % for tender price [8].

Table 6 - Qualifications and tender prices in Tender 1

"	Tenderer 1	Limit Value	Tenderer 2	Tenderer 3	Estimated Cost	Tenderer 4	Tenderer 5	Tenderer 6
Work Experience	2 531,46	5 901,75	3 911,15	19 464,00	7 614,15	57 719,63	93 239,57	2 531,46
Tender Price	4 400,00		6 224,36	7 372,65		8 840,67	9 313,00	9 563,00

Table 7 - Results of application (a)

Tenderer	WE	TF	C_i^*	*Rank*
Tenderer 1	2 531,46	4 400,00	0,4729	2
Tenderer 2	3 911,15	6 224,36	0,3594	4
Tenderer 3	19 464,00	7 372,65	0,3055	5
Tenderer 4	57 719,63	8 840,67	0,4179	3
Tenderer 5	93 239,57	9 313,00	0,5397	1
Tenderer 6	5 532,33	9 563,00	0,0245	6

The aforementioned four solutions were applied, and the results are as follows.

a) In application (a), the qualification values of tenderers were directly applied. Although, the tender price by Tenderer 5 was very high, it was awarded the contract since it had comparatively higher work experience value. This is the expected result of a multi-criteria decision-making application, however in public procurement applications it must be avoided. A solution to this problem will be offered in application (c).

b) In this application, a solution to evaluation of abnormally low tenders is offered. Therefore, below a limit value, which is formulated by PPA, it is assumed that the price is questionable. The solution offered is that select the limit value as the positive ideal solution point in price criterion so that remove the low-price advantage of the abnormally low tenderers. Selecting limit value as positive ideal solution point made Tenderer 4 the economically most advantageous second tenderer since Tenderer 1 lost its price advantage.

Table 8 - Results of application (b)

Tenderer	WE	TF	C_i^*	*Rank*
Tenderer 1	2 531,46	4 400,00	0,4647	3
Tenderer 2	3 911,15	6 224,36	0,3704	4
Tenderer 3	19 464,00	7 372,65	0,3321	5
Tenderer 4	57 719,63	8 840,67	0,4912	2
Tenderer 5	93 239,57	9 313,00	0,6281	1
Tenderer 6	5 532,33	9 563,00	0,0278	6

c) In this application, excessive qualification was cut off. The limit for work experience was decided to be three times tender price. Now, the contract price fell to 7 372,65 TL. Since high qualification advantage turned out to be over qualification problem and Tenderer 5 lost its advantage.

Table 9 - Results of application (c)

Tenderer	WE	TP	C_i^*	*Rank*
Tenderer 1	2 531,46	4 400,00	0,5412	4
Tenderer 2	3 911,15	6 224,36	0,4617	5
Tenderer 3	19 464,00	7 372,65	0,6356	1
Tenderer 4	26 522,01	8 840,67	0,5726	2
Tenderer 5	27 939,00	9 313,00	0,5470	3
Tenderer 6	5 532,33	9 563,00	0,0861	6

d) In application (d), dimensionless work experience took place of work experience in application (c). Dimensionless work experience was limited by 3 and limit value was selected as positive ideal solution point.

Table 10 - Results of application (d)

Tenderer	WE*	BP	C_i^*	*Rank*
Tenderer 1	0,5753	0,5778	0,5835	2
Tenderer 2	0,6284	0,8174	0,5024	4
Tenderer 3	2,6400	0,9682	0,6990	1
Tenderer 4	3,0000	1,1610	0,5394	3
Tenderer 5	3,0000	1,2230	0,4973	5
Tenderer 6	0,5785	1,2559	0,0009	6

e) In the last application, all solutions were applied together. The decreases in C* of tenderers with tender prices above estimated cost (Tenderer 4 and 5) are noteworthy.

Table 11 - Results of application (e)

Tenderer	WE*	BP	C_i^*	*Rank*
Tenderer 1	0,5753	0,58	0,5835	2
Tenderer 2	0,6284	0,82	0,5024	4
Tenderer 3	2,6400	0,97	0,6990	1
Tenderer 4	3,0000	1,16	0,5338	3
Tenderer 5	3,0000	1,22	0,4966	5
Tenderer 6	0,5785	1,26	0,0009	6

5. CONCLUSION

This paper revealed some problems inherited in the present public works procurement processes and offered a multi-criteria evaluation model to overcome these problems in a timely manner. Fuzzy numbers were used in assigning criterion weight since the survey showed large deviations in evaluations by participants. The first step offered was putting tenderers' qualifications into tender evaluation to award the contract. This method of evaluation can assure delivery of project of higher quality. Uncontrolled quality to price evaluation brought about the over-qualification problem which can result in budget overrun. Therefore, this step alone has proved to be insufficient. The over-qualification problem was successfully overcome by putting thresholds to tenderer qualifications preventing CAs from paying for quality beyond their necessities. Another major pitfall of procurement system is evaluation of abnormally low tenders which is an isolated process within tender evaluation process. In the model offered, this time- taking process was successfully replaced by assigning limit value to the positive ideal solution point. This assignment eliminated the price advantage of tenderers beyond the limit value. A rarely occurring phenomenon, however, still important for achieving financial aims is contracting with a tenderer who offered price above approximate cost. Similar to the case of abnormally low tenders but with some difference, approximate cost was assigned to negative ideal solution point providing that relative closeness of such tenders decreased.

References

[1] K. T. Cho, "Multicriteria decision methods: An attempt to evaluate and unify," Mathematical and Computer Modelling, vol. 37, no. 9-10, pp. 1099-1119, 2003.

[2] E. W. L. Cheng and H. Li, "Contractor selection using the analytic network process," Construction Management and Economics, vol. 22, no. 10, pp. 1021-2032, 2004.

[3] M. Marzouk, "An Application of ELECTRE III to Contractor Selection," in Construction Research Congress: Innovation for Reshaping Construction Practice, Banff, Alberta, Canada, 2010.

[4] S. Lambropoulos, "The use of time and cost utility for construction contract award under European Union Legislation," Building and Environment, vol. 42, no. 1, pp. 452-463, 2007.

[5] M. Araújo, L. H. Alencar and C. Mota, "Contractor Selection in Construction Industry: a Multicriteria Model," in 2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, 2015.

[6] D. Putra and P. Pratama, "Decision support system selection of tender winners project development building of STMIK STIKOM Indonesia with TOPSIS method," Journal of Physics: Conference Series, vol. 1469, pp. 12-26, 2020.

[7] M.-Y. Cheng, S.-H. Yeh and W.-C. Chang, "Multi-Criteria Decision Making of Contractor Selection in Mass Rapid Transit Station Development Using Bayesian Fuzzy Prospect Model," Sustainability, vol. 12, no. 11, p. 4606, 2020.

[8] İ. Özyürek, "An Alternative Method Proposal For Selection Of Contractor In Public Works Procurement," PhD Thesis, Graduate School of Natural and Applied Sciences, Gazi University, Ankara, 2018.

[9] A. P. Gurgun and K. Koc, "Contractor prequalification for green buildings—evidence from Turkey," Engineering, Construction and Architectural Management, vol. 27, no. 6, pp. 1377-1400, 2020.

[10] İ. Özyürek and M. Erdal, "Assessment of Qualification Criteria Described in Public Procurement Law Code 4734 in Construction Works by Analytic Hierarchy Process (AHP)," Gazi University Journal of Science, vol. 31, no. 2, pp. 437-454, 2018.

[11] H. a. Yoon, Multiple Objective Decision Making: Methods and Application, Berlin/Heidelberg/New-York: Springer Verlag, 1981.

[12] M. Amiri-Aref, N. Javadian and M. Kazemi, "A new fuzzy positive and negative ideal solution for fuzzy TOPSIS," WSEAS Transactions on Circuits and Systems, vol. 11, no. 3, pp. 92-103, 2012.

DISCUSSION

Rainfall Intensity-Duration-Frequency Analysis in Turkey, with the Emphasis of Eastern Black Sea Basin†

Discussion by Tefaruk HAKTANIR*

In the paper 672 in Teknik Dergi [1], the authors write: "In this study, only the data of eight standard durations (D=5, 15 and 30 minutes, and 1, 3, 6, 12 and 24 hours) have been employed." Hence, the data used in the study are shorter than the actually gauged durations of 5, 10, 15, 30 minutes, 1, 2, 3, 4, 5, 6, 8, 12, 18, 24 hours, which are 14 standard durations for annual maximum rainfalls (AMRs) as categorized by the Turkish State Meteorological Service (known by the Turkish acronym MGM). The authors did not give any explanation as to why they excluded those six series. Having skipped six intermediate observed AMRs series in their analyses has been a loss of valuable information. The intensity-duration-frequency (IDF) curves that would have been computed using all of the observed AMRs series of 14 durations would have been more meaningful than the IDF curves that were computed using eight AMRs series. In the publications whose citation numbers in the 'References' section of the paper 672 [1] are: [6], [12], [14], [27], [30], which are all related to the IDF relationships for AMRs in Turkey, all of the 14 standard-duration AMRs series from 5 minutes to 24 hours were included. Not having taken into account the actually observed numerical values of the AMRs of the intermediate durations of 10 minutes, 2, 4, 5, 8, 18 hours will cause a loss of real-life information from the results.

In two papers published in SCIE-covered journals, studies closely related to this paper done especially in Turkey are presented, which are listed as publications [2] and [3] in the References section of this Discussion. The authors of the paper 672 [1] overlooked these two papers [2] and [3] summarizing a comprehensive procedure leading to the IDF relationships. In the paper 672 [1], the authors cited four papers published in the journal: *Hydrological Processes* over the years between 2007 through 2020. But, somehow the authors skipped or ignored another relevant paper again in *Hydrological Processes* published in 2010 [2]. Incidentally, Asikoglu and Benzeden in their paper published in *Hydrological Processes* in 2014, which is publication number [30] in the References list of the paper 672 [1], cited these two papers by Haktanır et al (2010) [2] and by Haktanır (2003) [3] and they summarized the procedures presented in them.

In their study, the authors used only three probability distributions, which are: 2-parameter-log-Normal, Gumbel, log-Pearson-type-3. The authors computed the parameters of these

† Ömer YÜKSEK, Tuğçe ANILAN, Fatih SAKA, Emrah ÖRGÜN, Teknik Dergi Volume 34, Issue 4, July 2022. 12087-12103

* Nuh Naci Yazgan University, Department of Civil Engineering, Kayseri, Türkiye
thaktanir@nny.edu.tr - https://orcid.org/0000-0002-8111-4557

three distributions by the method of Moments only. In a relevant report by the World Meteorological Organization (WMO), the probability distributions of Gumbel, 2-parameter-log-Normal (LN2), 3-parameter-log-Normal (LN3), General Extreme Value (GEV), Pearson-3 (P3), log-Pearson-3 (LP3) are recommended for annual extreme rainfalls series [4]. In another relevant report by WMO, the parameter estimation methods of L-Moments and Maximum-Likelihood (ML) are also advocated along with the method of Moments [5]. It is a known fact that the L-Moments method gives exactly the same numerical values for the parameters of a distribution as the method of Probability-Weighted Moments (PWM). In various publications, the parameter estimation methods of ML and PWM are said to have peculiarities superior to the method of Moments on statistical grounds [e.g. 5, 6, 7].

In the paper by Haktanir et al (2010) [2], a statistical model comprising the probability distributions of Gumbel, LN3, P3, LP3, GEV for the frequency analyses of 14 standard-duration annual maximum rainfalls series adopted by MGM, whose ultimate product is the IDF curves, is presented. The reasons for having chosen these five probability distributions for IDF relationships are explained by Haktanir et al (2010) [2] citing quite a few relevant publications in their paper. The model and the resultant computer package presented by Haktanir et al (2010) [2], which has been the outcome of the research project 106Y192 supported by Tübitak (acknowledged in the paper), computes the parameters of each one of Gumbel, LN3, P3, LP3, GEV by each one of the methods of Moments (MOM), PWM, SDPWM, ML. SDPWM stands for "Self-Determined Probability-Weighted Moments" and it is a modified version of the PWM method [8]. A distribution whose parameters are computed by a different method is actually another distribution. The model by Haktanir et al (2010) [2] comprises the probability distributions of Gumbel-MOM, Gumbel-PWM, Gumbel-SDPWM, Gumbel-ML, LN3-MOM, LN3-PWM, LN3-SDPWM, LN3-ML, LN3-SC0, P3-MOM, P3-PWM, P3-SDPWM, P3-ML, LP3-MOM, LP3-PWM, LP3-SDPWM, LP3-ML, GEV-MOM, GEV-PWM, GEV-SDPWM, GEV-ML. LN3-SC0 is another version of the LN3 distribution whose parameters are computed such that the sample skewness coefficient of the normalized variable becomes zero [8]. By these symbols, in paper 672 [1], the distributions of Gumbel-MOM, LN2-MOM, LP3-MOM are used.

Another aspect of the paper 672 [1] is that the authors ignored the scaling of the parameters of those three distributions by not having taken into account their regressions against the rainfall duration. Therefore, the paper 672 [1] ignored the possibility of some of the frequency curves, curves representing the (quantile)↔(probability of exceedence) or equally the (quantile)↔(average return period) relationships, which are known as quantile functions denoted by x(F), of successively-increasing-duration AMRs series to cross each other. Graphically, when the frequency curves of all 14 standard-duration AMRs are drawn in the same graph paper, they should have diverging appearances from each other over all possible ranges of probabilities, meaning over all possible ranges of average return periods (T's) in the interval: $1<T<+\infty$. If each one of 14 frequency analyses of 14 standard-duration AMRs series are done in a straightforward manner ignoring this important constraint, then a frequency curve of a shorter-duration AMR may cross the frequency curve of a longer-duration AMR and extends above it with increasing return periods. This situation is against the rule of conservation of mass, which states that the rainfall depth of a longer-duration AMR must be greater than the rainfall depth of a shorter-duration AMR for the same T. In other words, the magnitude x_2 of a longer-duration AMR, tr_2, must be greater than x_1, of a shorter-duration AMR, tr_1, both having the same average return period, T, which necessitates that the curve of the quantile function of the tr_2-duration AMR must be divergent from that of the tr_1-duration AMR with increasing return periods. Symbolically, for any two rainfall durations such as $tr_2>tr_1$, x_2(must be)$>x_1$. If these constraints are not satisfied for all of 14 AMRs, then the resultant IDF curves will incorrectly reflect the statistical behavior of AMRs. There have been many publications proposing measures to prevent such absurd cases which are against the principle of conservation of mass. Some of these are publications numbered [2], [3], [10], [11], [12] in the References list of this Discussion.

Instead of scaling the parameters of the probability distributions in terms of logarithms of the rainfall durations, the authors of the discussed paper applied the frequency analyses on each one of those eight standard-duration AMRs in the conventional way. As explained by Burlando and Rosso (1996) [10], Benzeden (2001) [11], Porras and Porras (2001) [12], Haktanır (2003) [3], and Haktanır et al (2010) [2], the statistical characteristics like means, standard deviations, and skewness coefficients of the observed series of the successively-increasing standard-duration AMRs must be scaled by either semi-log or log-log regressions of these characteristics against the rainfall durations from 5 minutes up to 1440 minutes. And next, the parameters of the probability distributions fitted to the successively-increasing standard-duration AMRs must be scaled by again similar regressions against rainfall duration. Apparently, in the paper 672 [1] no such scalings were done, and the numerical values of the original statistics and of the original parameters were used as they were obtained by treating each one of these eight AMRs series (5, 15, 30, 60, 180, 360, 720, 1440 minutes) individually.

With the purpose of demonstrating a more rational way of obtaining the IDF curves at a particular location where MGM has been gauging pluviographic rainfall data with a fairly long record period, we have taken the case of Rize. The paper 672 [1] is somewhat like the summary of the M.Sc. Thesis by E. Örgün, one of the authors of this paper. Having read this thesis, we have understood that the authors used the recorded data of the stations gauged by MGM, and Rize data begin in the year 1940 and the last year of record is 2010. The length of each one of 14 recorded series from 5 minutes to 24 hours is 70 (instead of 71) because the data for the year 1951 are missing in the records. We have already obtained the same data from MGM. First, we typed 14 different input data files whose formats were in accordance with the computer program: FFA11.EXE. This particular code performs single-series frequency analyses comprising eight different probability distributions (including LP3) whose parameters are computed by the methods of MOM, PWM, ML, and a couple of special methods; and, it has been the outcome of related studies over a few decades [e.g. 9, 13, 14, 15]. FFA11.EXE has been used in various research and application studies so far, and it is freely provided to anybody requesting it. The magnitudes of the AMRs of all durations from 5 minutes to 24 hours having average return periods of T = 2, 5, 10, 25, 50, 100, 500 years, as done in the paper 672 [1], were computed by means of FFA11.EXE. The rainfall magnitudes divided by their durations in hours gave the same numerical values presented in Table 9 of the paper 672 [1]. This was a clearcut verification of two aspects: (1) FFA11.EXE performes the frequency analyses by LP3-MOM correctly, and more importantly (2) in the study by the paper 672 [1] the raw parameters were used, namely no scaling was performed.

Aside from the straightforward frequency analyses of 14 standard-duration AMRs series of 70 elements each recorded at Rize, the model by Haktanir et al (20210) [2] was run with the same inputa data of Rize. As mentioned before, this model performs the scaling routine for each one of those 21 probability distributions. Figures 1, 2, 3 here show the plots of both the raw (original) and the scaled sample means, sample standard deviations, and sample skewness coefficients of 14 AMRs series of Rize. We have applied the package program Y.EXE, which has been the outcome of the Tübitak-supported research project 106Y192 [2], to the same AMRs data of Rize. In Figure 4, the frequency curves of AMRs of eight durations (5, 15, 30, 60 minutes, 3, 6, 12, 24 hours) computed by the LP3-MOM distribution with the unscaled parameters for T's of 2, 5, 10, 25, 50, 100, 500 years are shown; and in Figure 5, the frequency curves of AMRs of all 14 durations (5, 10, 15, 30, 60 minutes, 2, 3, 4, 5, 6, 8, 12, 18, 24 hours) are shown. As seen in Figure 4, the frequency curve of 3-hour-duration AMR goes above the the frequency curve of 6-hour-duration AMR for return periods greater than 200 years. As seen in Figure 5, the congestion of 14 frequency curves of durations greater that 3 hours are more visible. In Figure 6, the frequency curves of AMRs of all 14 durations computed by the LP3-MOM distribution with the scaled parameters again for T's of 2, 5, 10, 25, 50, 100, 500 years, given by Y.EXE, are shown. As seen in this figure, all of the frequency curves of successively-increasing-duration AMRs are in a diverging order as they should be. Figure 7 shows the IDF curves computed by the LP3-MOM distribution with the unscaled parameters and Figure 8 shows the IDF curves computed by the LP3-MOM distribution with the scaled parameters for the same T's of 2, 5, 10, 25, 50, 100, 500 years.

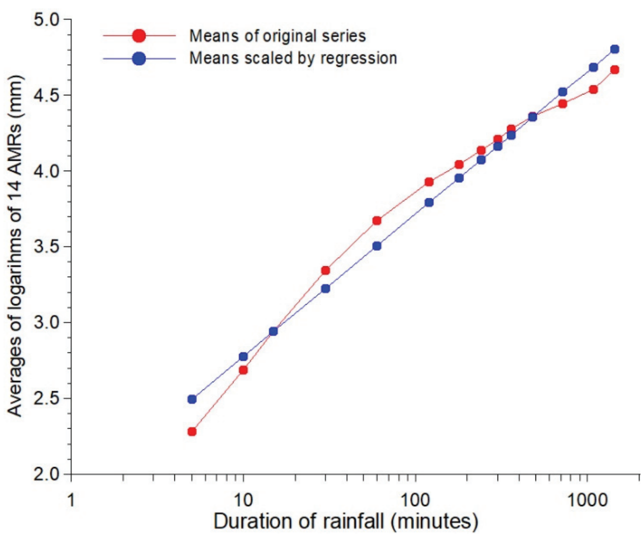


Figure 1 - Plots of (1) means of original series of the 70-year-long data of 14 successively-increasing standard-duration AMRs series of durations of 5, 10, 15, 30, 60 minutes, 2, 3, 4, 5, 6, 8, 12, 18, 24 hours gauged at Rize by MGM over the period of 1940 through 2010 and (2) the means of the same series scaled by regression.

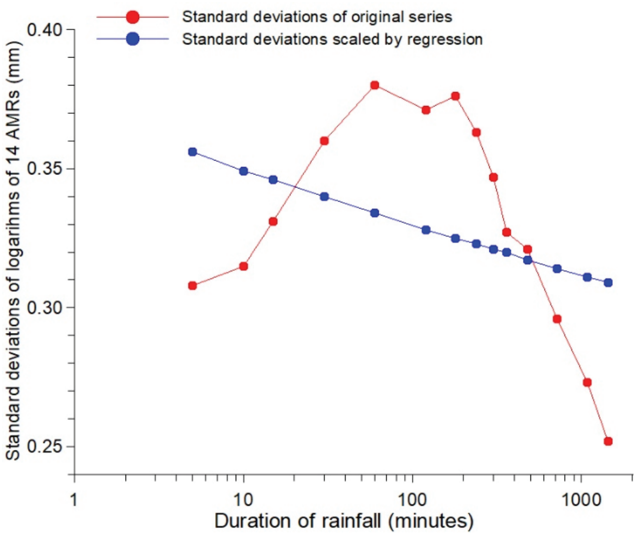


Figure 2 - Plots of (1) the standard deviations of original series of the 70-year-long data of 14 successively-increasing standard-duration AMRs series gauged at Rize by MGM and (2) the standard deviations of the same series scaled by regression.

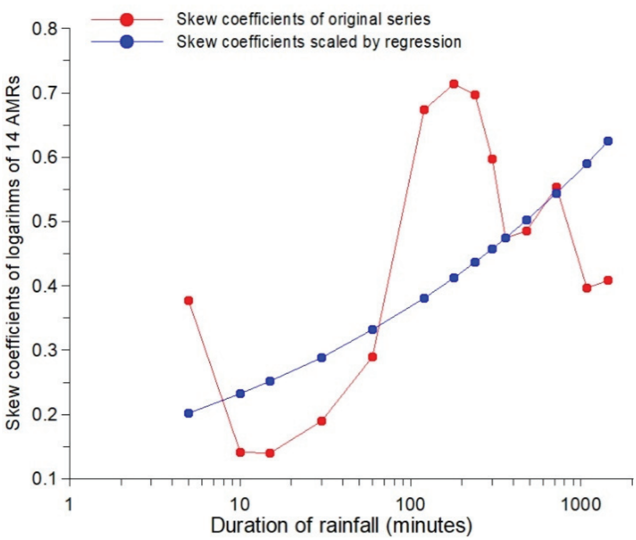


Figure 3 - Plots of (1) the skew coefficients of original series of the 70-year-long data of 14 successively-increasing standard-duration AMRs series gauged at Rize by MGM and (2) the skew coefficients of the same series scaled by regression.

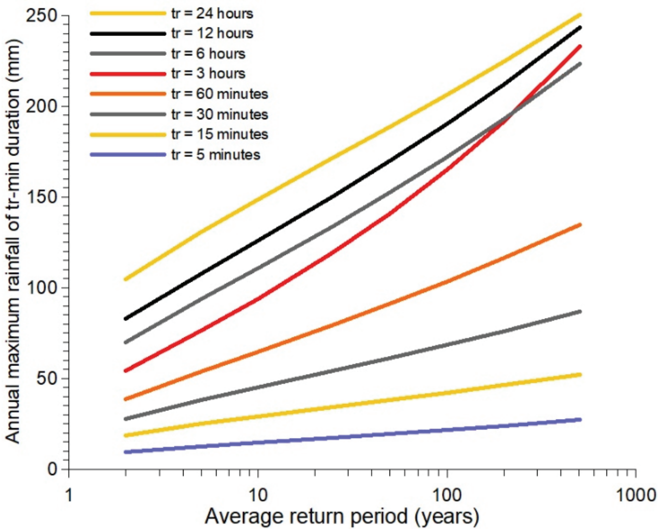


Figure 4 - Frequency curves computed by the log-Pearson-3 distribution with unscaled (raw) parameters computed by the method of Moments using the 70-year-long data of eight standard-duration AMRs series of durations of 5, 15, 30 minutes, 1, 3, 6, 12, 24 hours gauged at Rize by MGM.

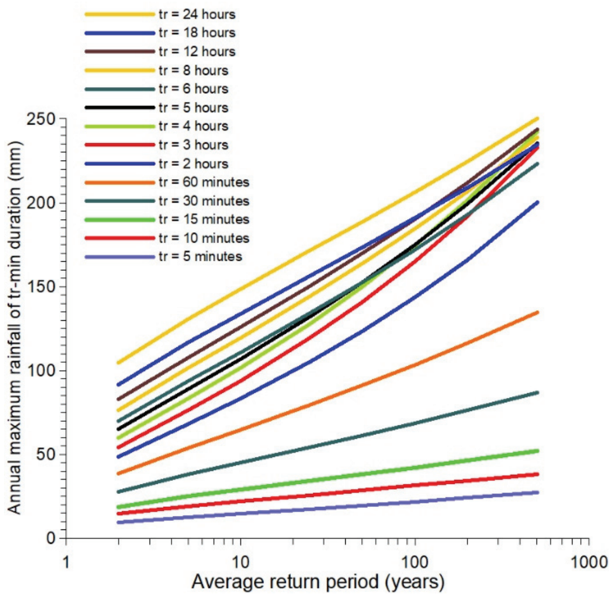


Figure 5 - Frequency curves computed by the log-Pearson-3 distribution with the unscaled (raw) parameters computed by the method of Moments using the 70-year-long data of 14 standard-duration AMRs series gauged at Rize by MGM.

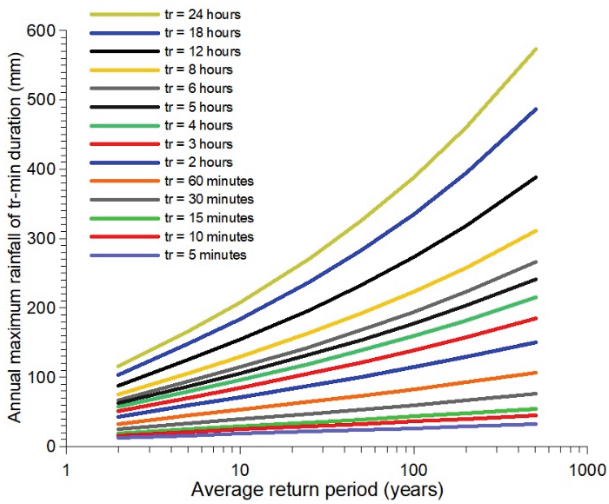


Figure 6 - Frequency curves computed by the log-Pearson-3 distribution with the scaled parameters computed by the method of Moments using the 70-year-long data of 14 standard-duration AMRs series gauged at Rize by MGM.

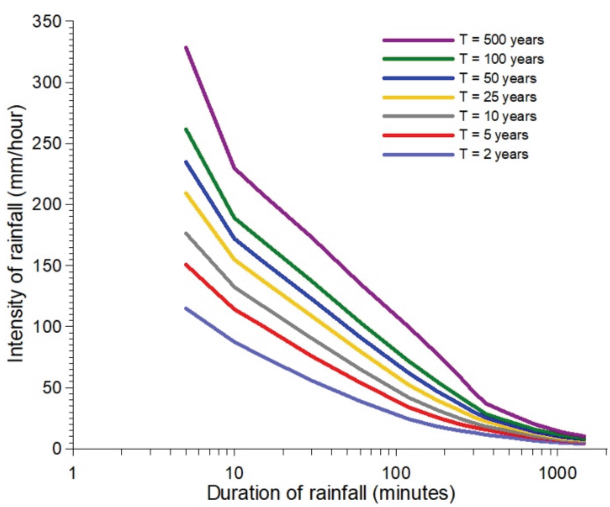


Figure 7 - Intensity-duration-frequency curves for Rize computed by the log-Pearson-3 distribution with the unscaled (raw) parameters by the method of Moments using the 70-year-long data of 14 AMRs series gauged at Rize by MGM.

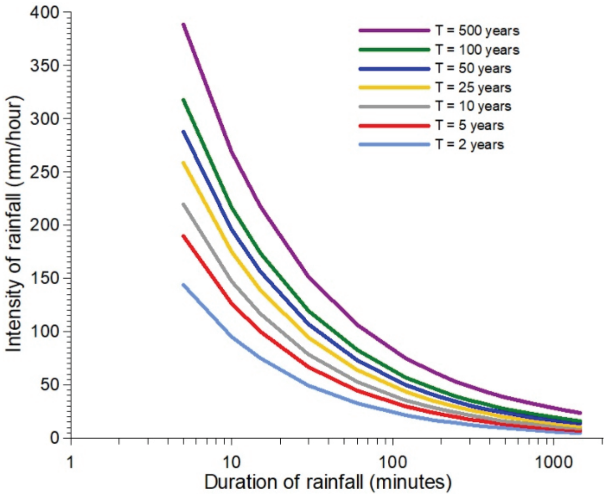


Figure 8 - Intensity-duration-frequency curves for Rize computed by the log-Pearson-3 distribution with the scaled parameters by the method of Moments using the 70-year-long data of 14 AMRs series gauged at Rize by MGM.

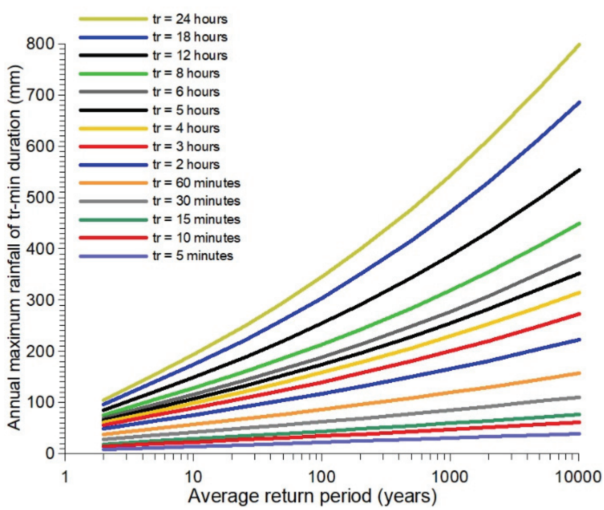


Figure 9 - Frequency curves computed by the log-Normal-3 distribution with the scaled parameters computed by the method of Probability-Weighted Moments using the 70-year-long data of 14 AMRs series gauged at Rize by MGM.

The authors of the paper 672 [1] chose the best-fit distribution among the probability distributions of Gumbel-MOM, LN2-MOM, LP3-MOM based on the goodness-of-fit tests of Chi-square and probability-plot-correlation-coefficient (PPCC). These two tests are widely used for determining the better-fitting distribution, indeed. The model by Haktanir et al (2010) [2] also applies these two goodness-of-fit tests plus another commonly used test of Kolmogorov-Smirnov and it lists so many distributions from the best-fitting down to the worst-fitting giving them numbers as the sum of goodness numbers of the three tests of Chi-square, PPCC, Kolmogorov-Smirnov. Both the source listing and the EXE forms of this computer package will be made freely available to anybody asking for them. According to the conjunctive result of these three tests, the distribution of LN3-PWM with the scaled parameters turned out to be the best-fit one among 21 distributions for the 14 standard-duration AMRs series of 70 elements each of Rize. In Figure 9, the frequency curves of AMRs of all 14 durations computed by the LN3-PWM distribution with the scaled parameters for so many T's from 2 up to 10,000 years, given by Y.EXE, are shown. The upper limit of T is purposely taken to be such a long period in order to verify that the frequency curves are in a diverging formation as they should be. And, in Figure 10, the IDF curves computed using these frequency curves by LN3-PWM for T's between 2 and 500 years are shown. Such IDF figures are automatically drawn by the computer package developed by Haktanir et al (2010) [2] with various options for the upper limits of T between 100 years and 10,000 years in compliance with the choice of the user of the program. In forming Figure 10, we opted for 500 years for the upper limit.

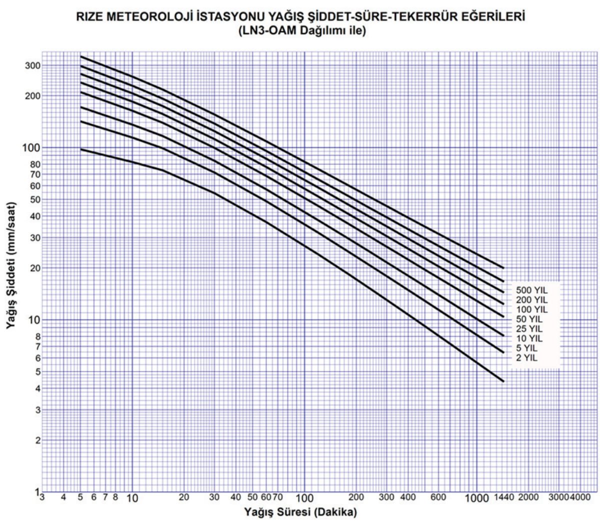


Figure 10 - Intensity-duration-frequency curves given by the computer package by Haktanır et al (2010) [2] computed by the log-Normal-3 distribution with the scaled parameters by the method of Probability-Weighted Moments using the 70-year-long data of 14 AMRs series gauged at Rize by MGM.

References

[1] Yüksek, Ö., Anılan, T., Saka, F., Örgün, E., Rainfall Intensity-Duration-Frequency Analysis in Turkey, with the Emphasis of Eastern Black Sea Basin. *Teknik Dergi*, 33(4), paper 672, 12087−12103, 2022.

[2] Haktanır, T., Çobaner, M., Kişi, O., Frequency analyses of annual extreme rainfall series from 5 minutes to 24 hours. *Hydrological Processes*, 24, 3574-3588, 2010.

[3] Haktanır, T., Divergence criteria in extreme rainfall series frequency analyses. *Hydrological Sciences Journal*, 48(6), 917–937, 2003.

[4] WMO, *Selection of Distribution Types for Extremes of Precipitation, Operational Hydrology Report No. 15*. WMO-No. 560, Geneva: World Meteorological Organization, 1981.

[5] WMO, *Guide to Hydrological Practices, Volume II, Management of Water Resources and Application of Hydrological Practices*. WMO-No. 168, Sixth edition. Geneva: World Meteorological Organization, 2009.

[6] Rao, A. R. and Hamed, H. H., *Flood Frequency Analysis*. CRC Press: Boca Raton, FA, USA, 2000.

[7] Kottegoda, N. T. and Rosso, R., *Applied Statistics for Civil and Environmental Engineers*. Second Edition, Blackwell Publishing Ltd., 2008.

[8] Haktanır, T., Self-determined probability-weighted moments method and its application to various distributions. *Journal of Hydrology*, 194(1-4), 180–200, 1997.

[9] Haktanır, T., Comparison of various flood frequency distributions using annual flood peaks data of rivers in Anatolia. *Journal of Hydrology*, 136(1-4), 1-31, 1992.

[10] Burlando, P. and Rosso, R., Scaling and multiscaling models of depth–duration–frequency curves for storm precipitation. *Journal of Hydrology*, 187: 45–64, 1996.

[11] Benzeden, E., Standart Süreli Maksimum Yağışların Frekans Analizinde Karşılaşılan Sorunlar (in Turkish) (Problems Encountered in Frequency Analyses of Standard Duration Maximum Precipitations). *III. Ulusal Hidroloji Kongresi* (*III. National Hydrology Congress*), Bildiriler Kitabı (Proceedings), 11–18, 27–29 June 2001, Dokuz Eylül Üniversitesi, İzmir, 2001.

[12] Porras, P. J. and Porras, P. J. Jr., New perspective on rainfall frequency curves. *Journal of Hydrologic Engineering, ASCE*, 6(1), 82–85, 2001.

[13] Haktanır, T. and Horlacher, H. B., Evaluation of various distributions for flood frequency analysis. *Hydrological Sciences Journal*, 38(1), 15-32, 1993.

[14] Haktanır, T., Gözlenmiş Yıllık Taşkın Pikleri Örnek Serilerinin Frekans Analizi için Paket Program (in Turkish) (Package program for frequency analysis of sample series of gauged annual flood peaks). T.C. Devlet Su İşleri Genel Müdürlüğü'nce 10-12 Mayıs 2006 tarihlerinde Ankara'da düzenlenen *I.Ulusal Taşkın Sempozyumu* (*I. National Floods Symposium*), Bildiriler Kitabı (Proceedings), 303-315, 2006.

[15] Haktanır, T., Hidrolojik değişkenlerin frekans analizi (in Turkish) (Frequency analysis of hydrologic variables). *IX. Ulusal Hidroloji Kongresi* (*IX. National Hydrology Congress*), 04−06 Ekim 2017, Dicle Üniversitesi, Diyarbakır, Bildiriler Kitabı (Proceedings), 40−58, 2017.

Authors' Closure

First of all, the Authors are grateful to Mr. Haktanır for His priceless discussion. In the following, the discussion and Authors' replies are presented:

Discussion:

In the paper 672 in Teknik Dergi [1], the authors write: "In this study, only the data of eight standard durations (D=5, 15 and 30 minutes, and 1, 3, 6, 12 and 24 hours) have been employed." Hence, the data used in the study are shorter than the actually gauged durations of 5, 10, 15, 30 minutes, 1, 2, 3, 4, 5, 6, 8, 12, 18, 24 hours, which are 14 standard durations for annual maximum rainfalls (AMRs) as categorized by the Turkish State Meteorological Service (known by the Turkish acronym MGM). The authors did not give any explanation as to why they excluded those six series. Having skipped six intermediate observed AMRs series in their analyses has been a loss of valuable information. The intensity-duration-frequency (IDF) curves that would have been computed using all of the observed AMRs series of 14 durations would have been more meaningful than the IDF curves that were computed using eight AMRs series. In the publications whose citation numbers in the 'References' section of the paper 672 [1] are: [6], [12], [14], [27], [30], which are all related to the IDF relationships for AMRs in Turkey, all of the 14 standard-duration AMRs series from 5 minutes to 24 hours were included. Not having taken into account the actually observed numerical values of the AMRs of the intermediate durations of 10 minutes, 2, 4, 5, 8, 18 hours will cause a loss of real-life information from the results.

Reply:

Of course, this is a right discussion. However, it has been concluded that, only the data of eight standard durations (D=5, 15 and 30 minutes, and 1, 3, 6, 12 and 24 hours) are sufficient for this kind of an analysis. However, it is obvious that, the use of data of all of the standard durations will enhance the quality of analysis.

Discussion:

In two papers published in SCIE-covered journals, studies closely related to this paper done especially in Turkey are presented, which are listed as publications [2] and [3] in the References section of this Discussion. The authors of the paper 672 [1] overlooked these two papers [2] and [3] summarizing a comprehensive procedure leading to the IDF relationships.In the paper 672 [1], the authors cited four papers published in the journal: Hydrological Processes over the years between 2007 through 2020. But, somehow the authors skipped or ignored another relevant paper again in Hydrological Processes published in 2010 [2]. Incidentally, Asikoglu and Benzeden in their paper published in Hydrological Processes in 2014, which is publication number [30] in the References list of the paper 672 [1], cited these two papers by Haktanır et al (2010) [2] and by Haktanır (2003) [3] and they summarized the procedures presented in them.

Reply:

The Authors have cited and have not overlooked or made little of these two papers. However, because of the limitations about the length of the paper (for sake of making the paper short to be published), no detailed analysis is given about these papers. Moreover, it is certain that, the aforementioned other papers are very important.

Discussion:

In their study, the authors used only three probability distributions, which are: 2-parameter-log-Normal, Gumbel, log-Pearson-type-3. The authors computed the parameters of these three distributions by the method of Moments only. In a relevant report by the World Meteorological Organization (WMO), the probability distributions of Gumbel, 2-parameter-log-Normal (LN2), 3-parameter-log-Normal (LN3), General Extreme Value (GEV),Pearson-3 (P3), log-Pearson-3 (LP3) are recommended for annual extreme rainfalls series [4].

Reply:

A reply to this discussion has been presented in the paper as: “There are several statistical distributions that might be suitable for rainfall intensity-frequency (or return period, T=1/F) analysis. One should select a few (say 3 to 5) distributions to test the best fit distribution. Various studies have favored the use of three suitable distributions for annual maximum precipitation (and also flood) data in Turkey: Log-Normal Distribution (LN2), Gumbel Distribution (GM) and Log-Pearson Type 3 Distribution (LPT3) [17,25]. Therefore, in this study, these three distributions were tested” (in 3.1. Obtaining IDF Values).

Discussion:

The authors computed the parameters of these three distributions by the method of Moments only. In another relevant report by WMO, the parameter estimation methods of L-Moments and Maximum-Likelihood (ML) are also advocated along with the method of Moments [5]. It is a known fact that the L-Moments method gives exactly the same numerical values for the parameters of a distribution as the method of Probability-Weighted Moments (PWM). In various publications, the parameter estimation methods of ML and PWM are said to have peculiarities superior to the method of Moments on statistical grounds [e.g. 5, 6, 7].

Reply:

The usage of various methods for parameter estimation is, of course, preferable. However, the use of methods of moments is also recommended in various studies and therefore is employed in the paper.

Other Discussions:

The other discussions are mainly related to the scaling of the parameters of the used three distributions and some statistical analyses. These are also right analyses. Of course, there may be similar techniques to be employed in the analysis. However, the Authors believe that their statistical analyses are relevant and enough.

In the end, the use of the computer package by Haktanır et al (2010) may conclude similar, and probably more precise, results.

In short, the discussion has dealt with very important issues, some of which may be used to outperform the study. Despite this fact, the Authors believe that the paper, as it is, has very great significance and has significantly contributed to the literature.

TURKISH JOURNAL OF CIVIL ENGINEERING (FORMERLY TEKNIK DERGI) MANUSCRIPT DRAFTING RULES

1. The whole manuscript (text, charts, equations, drawings etc.) should be arranged in Word and submitted in ready to print format. The article should be typed on A4 (210 x 297 mm) size paper using 10 pt (main title 15 pt) Times New Roman font, single spacing. Margins should be 40 mm on the left and right sides and 52.5 mm at the top and bottom of the page.
2. Including drawings and tables, articles should not exceed 25 pages, technical notes 10 pages.
3. Your contributed manuscript must be sent over the DergiPark system. (http://dergipark.gov.tr/tekderg)
4. The text must be written in a clear and understandable language, conform to the grammar rules. Third singular person and passive tense must be used, and no inverted sentences should be contained.
5. Title must be short (10 words maximum) and clear, and reflect the content of the paper.
6. Sections should be arranged as: (i) abstract and keywords, (ii) title, abstract and keywords in the other language, (iii) main text, (iv) symbols, (v) acknowledgements (if required) and (vi) references.
7. Both abstracts should briefly describe the object, scope, method and conclusions of the work and should not exceed 100 words. If necessary, abstracts may be re-written without consulting the author. At least three keywords must be given. Titles, abstracts and keywords must be fitted in the first page leaving ten line space at the bottom of the first page and the main text must start in the second page.
8. Section and sub-section titles must be numbered complying with the standard TS1212.
9. Symbols must conform to the international rules; each symbol must be defined where it appears first, additionally, a list of symbols must be given in alphabetic order (first Latin, then Greek alphabets) at the end of the text (before References).
10. Equations must be numbered and these numbers must be shown in brackets at the end of the line.
11. Tables, drawings and photographs must be placed inside the text, each one should have a number and title and titles should be written above the tables and below the drawings and photographs.
12. Only SI units must be used in the manuscripts.
13. Quotes must be given in inverted commas and the source must be indicated with a reference number.
14. Acknowledgement must be short and mention the people/ institutions contributed or assisted the study.
15. References must be numbered (in brackets) in the text referring to the reference list arranged in the order of appearance in the text. References must include the following information:

    <u>If the reference is an article:</u> Author's surname, his/her initials, other authors, full title of the article, name of the journal, volume, issue, starting and ending pages, year of publication.

        Example : Naghdi, P. M., Kalnins, A., On Vibrations of Elastic Spherical Shells. J. Appl. Mech., 29, 65-72, 1962.

    <u>If the reference is a book:</u> Author's surname, his/her initials, other authors, title of the book, volume number, editor if available, place of publication, year of publication.

        Example : Kraus. H., Thin Elastic Shells, New York. Wiley, 1967.

    <u>If the reference is a conference paper:</u> Author's surname, his/her initials, other authors, title of the paper, title of the conference, location and year.

    <u>If the source is a thesis:</u> Author's surname, his/her initials, thesis title, level, university, year.

    <u>If the source is a report:</u> Author's surname, his/her initials, other authors, title of the report, type, number, institution it is submitted to, publication place, year.
16. Discussions to an article published in Turkish Journal of Civil Engineering (formerly Teknik Dergi) should not exceed two pages, must briefly express the addressed points, must criticize the content, not the author and must be written in a polite language. Authors' closing remarks must also follow the above rules.
17. A separate note should accompany the manuscript. The note should include, (i) authors' names, business and home addresses and phone numbers, (ii) brief resumes of the authors and (iii) a statement "I declare in honesty that this article is the product of a genuinely original study and that a similar version of the article has not been previously published anywhere else" signed by all authors.
18. Copyright has to be transferred to UCTEA Turkish Chamber of Civil Engineers. The standard copyright form signed by the authorised author should therefore be submitted together with the manuscript.

CONTENTS

RESEARCH ARTICLE

TECHNICAL NOTE

DISCUSSION

ISSN: 2822-6836