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Research Article

Selection of Pile Foundation Systems:An Integrated Multi-Criteria Decision Making

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ABSTRACT

Pile foundations have been used for transmitting loads from structure to the soil. Design of pile foundation involves the determination of the design parameters such as pile type, pile diameter, pile length, pile layout etc. This study proposes an integrated methodology for selecting the most appropriate pile foundation design for a given soil profile. The methodology incorporates Analytical Hierarchy Process (AHP) and Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR)/Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) and Finite Element Analysis (FEM). While AHP is used for determining the weights of criteria, VIKOR and PROMETHEE are employed in order to acquire final rankings of alternatives. Then, a finite element analysis is applied on a selected set of best alternatives to provide precise results. Finally, a case study is conducted to show the effectiveness of the proposed methodology. Based on the findings of the case study, the methodology proposed paves the way for making an efficient decision for pile foundation selection.

Introduction

Structures may be subjected to heavy loads through horizontal and vertical directions as the size of them getting larger due to the contemporary legal or architectural needs. These loads must be transferred safely to the soil by the foundation systems. However, in some cases it's very difficult to achieve this by shallow foundation design because of poor soil condition or heavy load. In such cases, deep foundation systems are required to transfer loads from the structure through weak soils or to the stiff soils or rocks at depth. One of the most well-known deep foundation is the pile foundation systems. In the design of pile foundation, the design parameters (pile type, pile diameter, pile length, pile layout etc.) that satisfy technical and economic criteria should be determined. Different design methods such as finite element, finite difference methods etc. are used to determine the design parameters. Although finite element method (FEM) analysis gives accurate results, it requires large amount of experimental data, time and effort in order to build and solve the pile foundation problems on it. Moreover, different pile foundation alternatives that satisfy technical and economic constraints can be obtained by combining different sets of

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design parameters. Choosing the most appropriate alternative among these combinations considering the priorities of the designer is a decision-making problem. The increase in the number of parameters and alternatives makes it difficult to determine design parameters by using FEM. In most of real-world applications, decision makers select the appropriate pile foundation based on their experience and knowledge. A design that completely based on the knowledge and the experience may lead to poor pile foundations that may not completely satisfy economic and technical criteria. A best pile design alternative should correspond to the cost-efficient solution attaining a compromise among the number of the piles, pile diameter and pile length etc. considering the priorities of the decision makers. Therefore, the decision makers need methodologies that can be applied easily, are able to give results in timely manner and consider their point of view in decision making process.

Selecting the best pile alternative is characterized by several aspects which makes it suitable for the Multi Criteria Decision Making (MCDM) approach. MCDM techniques generally rank the alternatives from best to the worst considering several conflicting criteria. MCDM techniques are widely used in engineering for design problems [1]–[3]. Moreover, MCDM techniques have been used in civil engineering problems in a variety of areas such as water resources, construction building technology, transportation etc. [4]–[6] .

It is observed that there have been a limited number of MCDM studies on pile foundations. Kolios et al., [7] proposed a systematic methodology for classification and evaluation of the different available offshore wind turbines support structure alternatives using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. They identified 13 unrelated technical and non-technical criteria for evaluating 11 different options of support structures.

Zavadskas, Turskis and Vilutiene [8], present a process of selection the most appropriate foundation instalment alternative for buildings which stands on the soil. They considered the aforementioned suggestions and references of experts and evaluated three alternatives by Additive Ratio Assessment (ARAS) method. The set of criteria considers include costs of installation, instalment duration, index of advantages, index of loses, the complexity of maintenance, transferability of decisions.

Sušinskas et al. [9], propose a MCDM based methodology to select the best pile foundation instalment alternatives. They evaluated seven different pile instalment methods considering the criteria such as cost of instalment, labor expenditures, machinery expenditures, earthwork amount and instalment tolerance. Criteria weights were determined by entropy method. The solution of the problem was made by applying ARAS method.

Zavadskas et al. [10], have developed a MCDM methodology for selecting a pile-column technology. They evaluated five different technological alternatives for installing pile columns. They considered a set of cost-based criteria consisting labor expenditures, cost of installation, consumption of concrete, consumption of steel, machinery expenditures, and consumption of energy. Their methodology incorporates TOPSIS, ARAS, COPRAS (Complex Proportional Assessment) methods. Integrated criteria weights are determined by using the AHP and the expert judgement method.

Dachowski and Gałek [11] presented a MCDM based methodology in which PROMETHEE II method was used in ranking of selected methods of underpinning foundations. They considered five different underpinning pile foundation methods.

Turskis et al. [12], used a methodology based on Weighted Aggregated Sum Product Assessment method with grey numbers (WASPAS-G) and AHP for selecting the type of foundation for a single-storey house. The criteria weights were determined by using the AHP and experts' judgement methods.

As can be seen from the literature given above, MCDM techniques such as TOPSIS, ARAS, COPRAS, AHP have been used in order to select pile types, pile technology or pile layout for a given soil profile considering the only one aspect of the problem. In addition, researchers generally used cost-based criteria sets. In this study, we proposed an integrated MCDM based methodology in order to select the best pile foundation alternative for a given soil profile considering multiple criteria. The proposed methodology comprises AHP, VIKOR, PROMETHEE. In the first phase of the methodology, criteria values of the alternatives were calculated empirically for the ease of computation. Criteria weights are determined by AHP method. Then the feasible alternatives were ranked by VIKOR and PROMETHEE methods. The final ranking is obtained by averaging the VIKOR and PROMETHEE ranks of alternatives. Finally, finite element analysis is applied for the selected number of the best alternatives to provide more precise criteria values.

The novelty of the work reported in this paper can be summarized as follows.

- For the first time, VIKOR and PROMETHEE methods are used for selecting the best pile foundation alternatives.
- Pile foundation alternatives are evaluated by taking into consideration qualitative, and quantitative criteria based on economic and technical point of view. Different from the current literature we have considered a set of criteria that combines settlement (S), safety factor of bearing capacity (SFBC), cost (C), ease of installation (EI), length - diameter ratio (LDR).
- In most of the current literature, the MCDM methods are generally used to determine the best pile types, most appropriate pile foundation technology and pile layout etc. considering only one aspect of the problem. This study differs from its predecessors since proposed methodology determines the most appropriate pile foundation alternative considering pile design parameters such as pile diameter, pile length, number of piles and pile foundation layout.

This paper is organized as follows. Section 2 presents multiple criteria decision-making methods used in this study. Next section covers the details of the proposed methodology and its application on a hypothetical case study. The last section includes concluding remarks and suggestions for future studies.

Multiple Criteria Decision-Making (MCDM)

Selecting the most appropriate pile foundation process requires balancing multiple conflicting objectives. MCDM provides a compromise solution when there is not a certain solution that fully satisfies all criteria simultaneously.

In this study, we have proposed an integrated methodology that employs AHP, VIKOR, PROMETHEE together in order to select the most appropriate pile foundation for e given soil profile. Following sections contain brief information about the techniques employed in the proposed methodology. The flowchart of the proposed methodology is illustrated in Fig.1.

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) introduced by Saaty [13], is a quantification process for dealing with complex decision making, and it also helps the decision makers set his/her priorities. AHP uses pairwise comparison matrix which can be used both to compare the alternatives with respect to multiple criteria and to determine weights of criteria. Classical AHP procedure has five steps:

1. *Define objectives*: In this step the unstructured problem and their characteristics should be stated clearly (i.e. objectives and outcomes).
2. *Build structures*: The complex problem is decomposed into a hierarchical structure with decision elements (objective, attributes i.e. criterion map layer and alternatives).
3. *Calculate pairwise comparisons*: The relative importance between two criteria is measured using Saaty's Pairwise Comparison Scale which is a numerical scale from 1 to 9 [13].
4. *Calculate weights*: The criteria weights are computed as the row average of the normalized matrix.
5. *Evaluate alternatives based on their weights*: The alternatives are sorted, and the top alternative is selected as the best. This is an optional step if AHP method is used for determining criteria weights.

AHP method provides consistency checking on decision makers' judgments. The consistency ratio shows whether the relationship between the values given in the pairwise comparison is consistent. Consistency ratio is bigger than 0.1, indicates inconsistency in pairwise comparison matrix.

The pairwise comparisons can allow decision makers for determining the weight coefficients relative easily. In this study, AHP method is used for determining the weights of criteria.

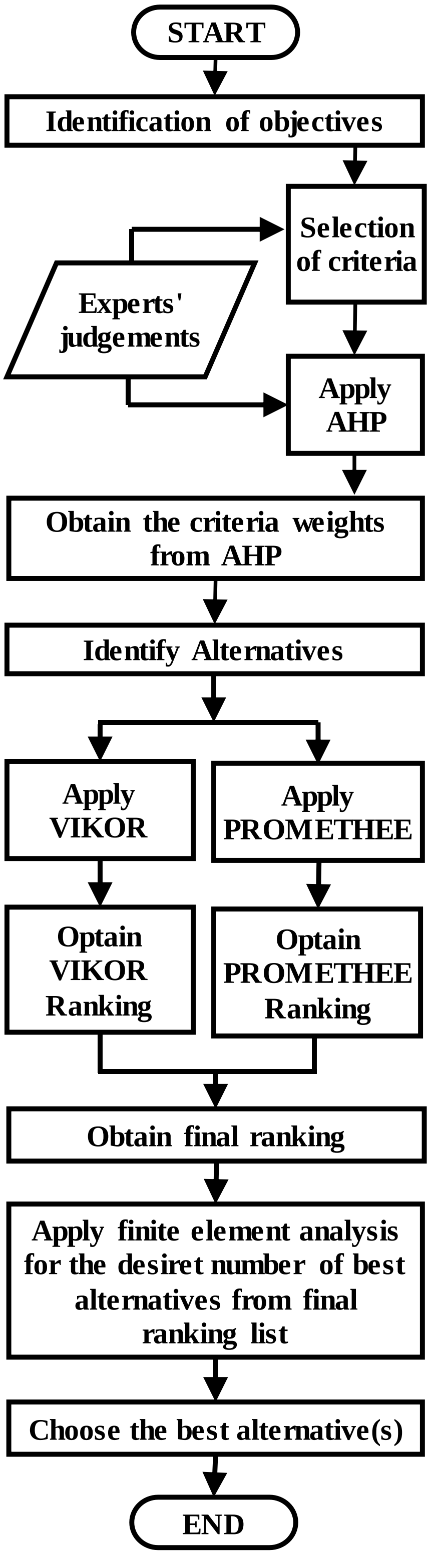

Figure 1. Flowchart of the methodology

Vise Kriterijumska Optimizacijja I Compromising Resenje (VIKOR)

VIKOR is a multi-criteria decision-making method proposed by Opricovic [14]. In this method, a compromise solution (F^c) of the problem is obtained by comparing the measure of closeness to the ideal solution. The compromise solution (F^c) is the closest solution to the ideal solution (F^*), and provides an agreement established by mutual concessions. Distance of alternative a_j from ideal solution (F^*) is expressed by L_p – metric in Eq. 1 that is the distance function called as the group regret for a decision.

$$L_{pj} = \left\{\sum_{i=1}^{n}\left[\frac{w_i(f_i^*-f_{ij})}{f_i^*-f_i^-}\right]^p\right\}^{\frac{1}{p}} \quad 1 \le p \le \infty;\ j=1,2,..\ J \qquad (1)$$

where n, J, f_{ij}, p are number of criteria, number of alternatives, evaluation value of the i^{th} criterion for alternative a_j, respectively. For p=1, L_{pi} becomes $L_{1,p}$ and is expressed S_j, that means concordance. It provides information about maximum group utility (majority). For p=∞, L_{pi} becomes $L_{\infty,p}$ and is expressed R_j, that means discordance. It provides information about minimum individual regret of the opponent. The VIKOR method can be summarized as follows:

Step 1: According to the benefit or cost of the criterion, the best f_i^* and worst f_i^- value of each criterion a_j is calculated as in Eq. 2 and Eq. 3;

$$f_i^- = \begin{cases} \min\limits_j f_{ij}, \text{ if the criterion represents benefit} \\ \max\limits_j f_{ij}, \text{ if the criterion represents cost} \end{cases} \qquad (2)$$

$$j=1,2,\ \dots,\ J$$

$$f_i^* = \begin{cases} \max\limits_j f_{ij}, \text{ if the criterion represents benefit} \\ \min\limits_j f_{ij}, \text{ if the criterion represents cost} \end{cases} \qquad (3)$$

$$i=1,2,\ \dots,\ I,\quad j=1,2,\ \dots,\ J$$

Step 2: For each alternative, the average group score S_j and the worst group score R_j are calculated as in Eq. 4 and Eq. 5;

$$S_j = \sum_{i=1}^{n} \frac{w_i(f_i^* - f_{ij})}{(f_i^* - f_i^-)} \quad (4)$$

$$R_j = \max_i \left[\frac{w_i(f_i^* - f_{ij})}{f_i^* - f_i^-}\right] \quad (5)$$

Step 3: For each group, maximum group benefit Q_j is calculated as in Eq. 6;

$$Q_j = v * \frac{S_j - S^*}{S^- - S^*} + \frac{(1-v)(R_j - R^*)}{R^- - R^*} \quad (6)$$

where $S^* = \min_j S_j$, $S^- = \max_j S_j$, , $R^* = \min_j R_j$, $R^- = \max_j R_j$. $v \in [0,1]$ is called the weight of the strategy of the "*the majority of criteria*" or "*the maximum group utility*" and is usually equal to 0.5.

Step4: *S*, *R* and *Q* values of alternatives are ranked in decreasing order.

Step 5: The alternative that has minimum *Q* value chosen as the best alternative, if following two conditions are satisfied. The first condition, C_1, called as "*the acceptable advantage*" in Eq. 7.

$$Q(a'') - Q(a') \geq DQ \quad (7)$$

where *a'*, *a''* are alternatives at first and second position by *Q* ranking list, respectively. *DQ* is given in Eq. 8.

$$DQ = \frac{1}{J-1} \quad (8)$$

The second condition "C_2" called as the "*the acceptable stability in decision making*"; in order to determine that *a'* alternative is the best, it must be the best alternative in at least one by *S* or *R* ranking list. For a stable compromise solution, which could be: "*voting by majority rule*" (when v>0.5 is needed), "*by consensus*" v≈0.5, or "*with veto*" (v<0.5).

The weight of the decision-making strategy is denoted by "v" that called "*the majority of criteria*" or "*the maximum group utility*".

If C_1 and C_2 are not satisfied, a set of compromise solutions is obtained by the following rules;

- Alternatives *a'* and *a''* if only condition C_2 is not satisfied, or
- Alternatives *a'*, *a''*,…, $a^{(M)}$ if condition C_1 is not satisfied and $a^{(M)}$ is determined by the relation for $Q(a^{(M)})-Q(a')<DQ$ for maximum *M* (the positions of these alternatives are "in closeness")

This paper is organized as follows. Section 2 presents multiple criteria decision-making methods used in this study. Next section covers the details of the proposed methodology and its application on a hypothetical case study. The last section includes concluding remarks and suggestions for future studies.

Preference Ranking Organization Method for Enrichment Evaluations *(PROMETHEE)*

PROMETHEE is a multi-criteria decision-making method proposed by Brans [15]. The PROMETHEE steps are as follows.

Step 1: In order to compare two alternatives a_i and a_k, the difference of their values ($d_j(a_i, a_k)$) on each criterion is determined by Eq. 9.

$$d_j(a_i, a_k) = g_j(a_i) - g_j(a_k) \quad (9)$$

Step 2: For each pair of actions, *a* preference function $F_i(a_i, a_k)$ that represents preference level of a_i over a_k on criterion *j* can be defined. Brans and Vincke [16] proposed six different preference functions as: (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) V-shape within deference criterion and (6) Gaussian criterion. In this study, v-shaped function with indifference criterion is used. According to this preference function, $F_i(a_i, a_k)$ represents the preference level of a_i on criterion *j* can be defined as in Eq. 10:

$$F(a_i, a_k) = \begin{cases} 0, d_j(a_i, a_k) \leq q_j \\ \frac{d_j(a_i - a_k) - q_j}{q_j - p_j}, p_j \leq d_j(a_i, a_k) \leq q_j \\ 1, > d_j(a_i, a_k) \geq p_j \end{cases} \quad (10)$$

where q_j is the predefined in difference threshold and p_j is the predefined preference threshold.

Step 3: The preferences aggregated by weights, w_j, in order to evaluate alternatives considering more than one criterion with Eq.11.

$$\prod(a_i, a_k) = \sum w_j F_j(a_i, a_k) \quad (11)$$

Step 4: Entering flow and leaving flow are determined in order to show how alternative a_i is outranked by all other alternatives as in Eq. 12 and Eq. 13.

$$\emptyset^+(a) = \frac{1}{n-1}\sum_{x\epsilon A}\prod(a, x)\ leaving\ flow \quad (12)$$

$$\emptyset^-(a) = \frac{1}{n-1}\sum_{x\epsilon A}\prod(x, a)\ entering\ flow \quad (13)$$

Step 5: In PROMETHEE I, alternative a_i is preferred to alternative a_k, $a_i\ P\ a_k$, if the following conditions are satisfied;

$a_i\ P\ a_k$ if: $\emptyset^+(a_i) \geq \emptyset^+(a_k)$ and $\emptyset^-(a_i) \leq \emptyset^-(a_k)$

In the indifference situation ($a_i\ I\ a_k$), we cannot say that any alternative is preferred to the other since a_i and a_k alternatives have the same leaving and entering flows as stated below;

$a_i\ I\ a_k$ if: $\emptyset^+(a_i) = \emptyset^+(a_k)$ and $\emptyset^-(a_i) = \emptyset^-(a_k)$

Step 6: Alternatives a_i and a_k are considered as incomparable, $a_i\ R\ a_k$ if a_i has a greater leaving flow than a_k, while a_i has smaller entering flow than a_k or vice versa;

$a_i\ R\ a_k$ if: $\emptyset^+(a_i) > \emptyset^+(a_k)$ and $\emptyset^-(a_i) > \emptyset^-(a_k)$ or $\emptyset^+(a_i) < \emptyset^+(a_k)$ and $\emptyset^-(a_i) < \emptyset^-(a_k)$

Two alternatives are considered incomparable, $a_i\ R\ a_k$, if alternative a_i has larger leaving flow than alternative a_k, while a_i_has smaller entering flow than alternative a_k, or vise verse.

Since PROMETHEE I evaluation produces in difference and incomparability situations between alternatives, it provides partial rankings. PROMETHEE II can be preferred if decision maker wants to obtain a complete ranking. PROMETHEE II uses the net flow of each alternative which quantifies the position of each alternative with respect to the remaining alternatives. On the other hand, the larger the net flow "$\emptyset(a)$" the better the alternative.

$$\emptyset(a) = \emptyset^+(a_i) - \emptyset^-(a_k)$$

Proposed Methodology and Its Application

The proposed methodology incorporates three MCDA methods; namely AHP, VIKOR, PROMETHEE. In the first step the objective of the study is identified as selecting the best pile foundation alternative. Then, the set of criteria is determined by literature review results and experts' opinions. In the third step, AHP method is used for determining criteria weights. In the next step, all feasible alternatives are identified, and criteria scores of the alternatives were calculated by using conventional methods of geotechnics for ease of computation. Then the feasible alternatives were ranked by VIKOR and PROMETHEE methods. In the next step, Spearman rank correlation analysis is performed to check if there is a correlation between VIKOR and PROMETHEE results. Then the final ranking based on VIKOR and PROMETHEE results is obtained by averaging the ranks of the alternatives. Finally, finite element analysis is applied for the selected number of the best alternatives to provide more precise results.

A case study is performed to investigate the effectiveness of proposed methodology. In this manner, we considered a hypothetical bored pile foundation for a building which is constructed on saturated silty soil (Fig. 2). The saturated silty soils can often be encountered in provincial centers close to the sea such as İzmir, Çanakkale, Mudanya, Gemlik etc. Soil properties of foundation are given in Table 1. Representative soil parameters and layer properties are chosen appropriately İzmir – Mavişehir soil properties which were determined in the past with field and laboratory investigations. The groundwater table is 5 m below ground surface.

Table 1. Soil Properties

Layer No	Description	H_o (m)	γ_n (kN/m^3)	γ_s (kN/m^3)	L_L (%)	PI (%)	ϕ (°)	c (kN/m^2)	c_c	e_o	E_s (kN/m^2)	ν
1	Topsoil	1	18.5	-	-	-	28	0	-	-	15000	0.30
2	Silty Soil	34	18.5	20.5	48	18	30	5	0.11	0.885	30000	0.45
3	Sandy soil	26	-	21			35	0	-	-	60000	0.45
4	Gravely soil	>10	-	21			42	0	-	-	85000	0.45

γ_n: Moist unit weight of soil, γ_n: Saturated unit weight of soil, L_L: Liquid limit water content, PI: Plasticity index, ϕ: internal friction angle, c: cohesion, c_c: compression coefficient, e_o: void ratio, E_s: Modulus of elasticity, ν: Poisson ratio. H_o: Thickness of soil layers.

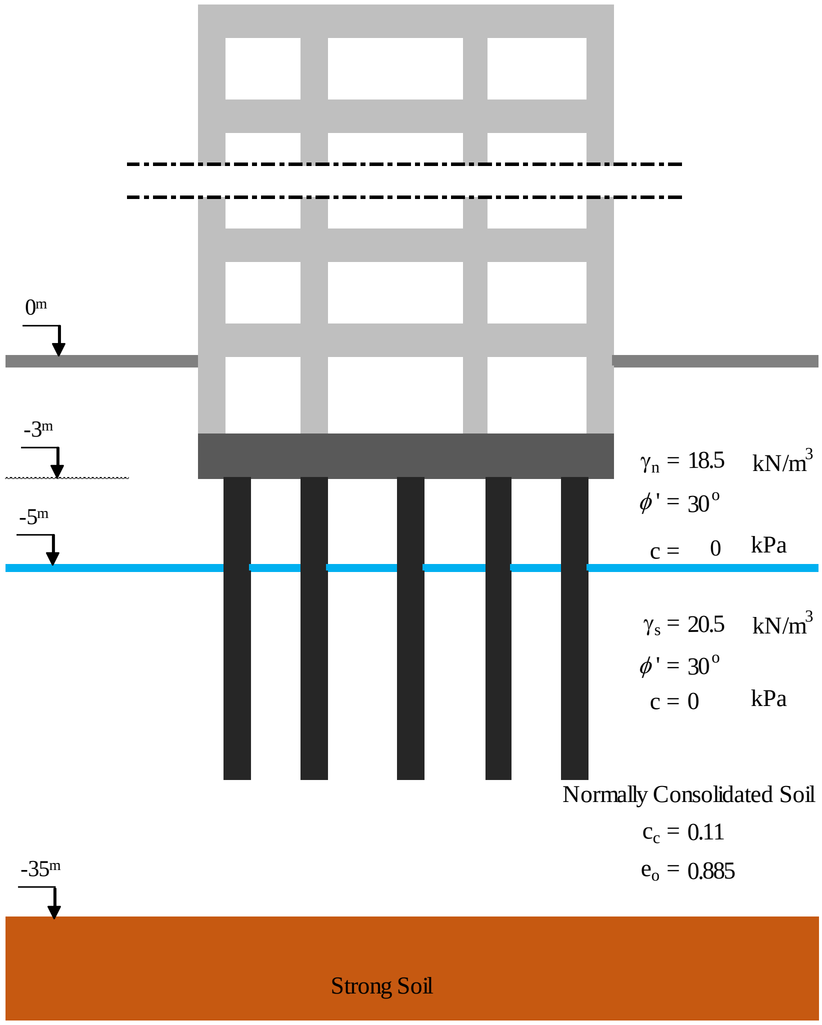

Figure 2. Considered hypothetical building, pile foundation and soil profile.

Total weight of the building was calculated as 44520 kN (Table 2). The raft foundation width, length and thickness are 15 m, 20 m, and 1 m respectively. Depth of the raft foundation base is 3 m below the ground surface.

Proposed methodology will be explained step by step and the results obtained for each steps of selected case will be given below.

1. Identification of the objectives: The main objective of this study is to select the best pile foundation alternative considering multiple criteria.

2. Selection of Criteria: Settlement (S), safety factor of bearing capacity (SFBC), ease of installation (EI), length – diameter ratio (LDR) as technical criteria and cost (C) as financial criteria were determined for selection of the pile foundation alternatives considering literature review and experts' opinions. While the technical criteria were selected in terms of engineering, the cost is one of the important criteria for decision makers in today's competitive conditions. The pile foundation alternatives were described by five criteria as can be seen in Table 3.

A brief description and calculation methods of the criteria are given as follows.

Settlement (S): Soil layers under the structure are compressed and deformed because of the loads coming from the structure. Vertical deformations of the soil layers cause a vertical displacement in the foundation and structure. Total vertical displacement of the foundation or structures is called as settlement and can be calculated by Eq 14.

$$S = H_o \frac{c_c}{1+e_0} log\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right) \quad (14)$$

where, S, settlement of soil layer, H_o, initial thickness of soil layer, c_c, compression coefficient, e_o, initial void ratio of soil layer, σ_0', effective geostatic stress, and $\Delta\sigma$, induced stress due to pile foundation. Soil parameters and layer properties given above are determined by field and laboratory investigations.

Safety factor of bearing capacity (SFBC) : SFBC is a ratio of the ultimate bearing capacity and the foundation loads (Eq. 15).

Table 2. Total weight of building

Length (m) :	15
Width (m) :	20
Area (m^2) :	300
Number of Floors :	12
Foundation Thickness (m) :	1
Total Weight of Foundation (t) :	720
Total Weight of Rouf (t) :	132
Average Design Loads (t/m^2) : (Total Dead and Live Weights) :	1
Total Weights of one Floor (t) :	300
Total Weights of all Floors (t) :	3600
Total Weight of Building (t) :	4452
(kN) :	44520
$\gamma_{concrete}$ (t/m^3) :	2.4

Table 3. Set of Criteria

Criteria	Unit	Notation	Extreme
S	cm	C1	Minimum
SFBC	-	C2	Maximum
EI	-	C3	Minimum
LDR	-	C4	Minimum
C	₺	C5	Minimum

$$F_s = \frac{Q_u}{W_s} \quad (15)$$

where, safety factor of bearing capacity, ultimate bearing capacity, weight of structure are denoted by F_s, Q_u, W_s, respectively. In the conventional approach, ultimate bearing capacity of single and group piles can be calculated by Eq. 16 [17].

$$Q_u = Q_b + Q_f - W_p \quad (16)$$

where, W_p is the pile weight, Q_b and Q_f are end resistance of pile and friction resistance of pile. Different methods are proposed for estimation of the Q_b and Q_f. In this paper, bearing capacity was calculated according to Meyerhof [18].

Ease of installation (EI) : This parameter describes the relative ease of installation of the support structure on site, in terms of equipment needed and its availability, manpower and time.

Length - Diameter Ratio (LDR) : It is the ratio of pile length and the pile diameter. Length – diameter ratio of pile widely is used for pile analyses.

Cost (C) : In this study, cost of piles was calculated using unit price method and 2019-unit prices were taken into consideration. Unit prices cover the costs of labor, material, and construction. Unit prices were taken from "*Construction and Installation Unit Prices Book*" published by Turkish Ministry of Environment and Urbanism [19].

3. Determining Weights of Criteria: Determining the criteria weights is one of the important phases of a MCDA analysis. The weights show the relative importance of the criteria. In this study, AHP method is used to determine weights of the criteria. Pairwise comparison matrix is given in Table 4.

Consistency Ratio for pairwise comparison matrix in this study was obtained as 0.01615, which is smaller than 0.1. As a result of the application of AHP method, weights of criteria were obtained as shown in Table 4.

4. Identify Alternatives: In this phase the pile foundation design parameters and values of parameters are determined. At first, the pile design parameters were identified as diameter (D), length (L) and the distance between piles (DBP) through expert's opinions. Then, the levels of pile design parameters were determined according to case study as shown in Table 5.

As can be seen from Table 5, for the parameters of D, L and DBP were defined 4, 4 and 3 levels respectively.

The alternatives were created using values from Table 4. Therefore, as a total, 4x4x3=48 alternatives were obtained.

Then the criteria values of all alternatives were calculated as explained in Step 2 and applicable 48 alternatives are presented in Table 6.

5.Ranking of the Alternatives: In this study two well-known multi-criteria techniques, VIKOR and PROMETHEE are used to sort pile foundation alternatives. The weight matrix for the two MCDA methods were calculated by the AHP method and is given in Table 4.

Table 4. The pairwise comparison matrix and weights of criteria

	S	SFBC	EI	LDR	C
S	1	5	2	3	0.5
SFBC	0.2	1	0.5	0.5	0.2
EI	0.5	2	1	2	0.33
LDR	0.33	2	0.5	1	0.25
C	2	5	3	4	1
Weights	0.27	0.06	0.15	0.1	0.42

Table 5. Values of parameter

Description	Unit	Value
Diameter (D)	m	0.45 0.65 0.80 1.00
Length (L)	m	15 20 25 30
Distance between piles (DBP)	m	2D 3D 4D

- ***VIKOR Results***

Firstly, the best $\widetilde{f_j^*}$ values andthe worst $\widetilde{f_j^-}$ values are calculated for all the criteria using the weight matrix given in Table 5. Obtained $\widetilde{f_j^*}$ values and $\widetilde{f_j^-}$ values are given in Table 7.

Q, S, R values are calculated for all alternatives and then they are ranked by *Q, S, R* values. *Q, R, S* values. The ranking obtained is given in Table 8 for top five alternatives.

Having obtained the rankings according to *Q, S,* and *R*, acceptable advantage and stability conditions are checked. Since the condition *C1* is not satisfied, the alternatives, A16, A12 and A11 are the same compromise solution and there are no competitive advantages among them, but these three alternatives have competitive advantage over alternatives A8 and A7.

By comparing the rankings of *Q*, *S* and *R*, as in Table 8, we can see that it follows a trend. Since A16, A12 and A11 are the top 3 alternatives in rankings by both *Q* and *S*, the second condition is satisfied. Therefore, we may conclude that A16, A12 and A11 are stable within the decision-making process.

- ***PROMETHEE Results***

PROMETHEE method was applied to the problem defined in the case study. Considering the deviations based on the pairwise comparison of the alternatives $d_j(a_i, a_k)$ values are computed. Then using a V-shaped preference function, threshold values of indifference (*q*) and difference (*p*) are computed as shown in Table 9.

Then, using weights determined by AHP, the net outranking flows are calculated considering $\emptyset^+$ and $\emptyset^-$ values, and the alternatives are ranked based on the net flows in descending order as shown in Table 10. (PROMETHEE II).

6. Obtaining the final ranking: As can be seen from Table 11, the alternative A13 is the best alternative for both methods and the rankings of other alternatives are quite similar. The similarity between VIKOR and PROMETHEE II is also measured by Spearman's rank correlation coefficient (Eq. 17).

$$\rho_{ki} = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad (17)$$

where *n* is the number of alternatives and d_i is the difference between the ranks of two MCDM methods. Rho is calculated as 0.95 which indicates a strong, positive correlation between

VIKOR and PROMETHEE II results. The ranking list is extended to six to cover top five alternatives provided by both methods. Then the final ranking based on VIKOR and PROMETHEE II result is obtained by averaging the ranks as shown in Table 11.

Table 6. Feasible alternatives

Alternative No	D (m)	L (m)	Number of Pile (#)	S (cm)	SFBC	EI	LDR	C (₺)
1	0.5	15	99	8.41	2.79	1.7	33.3	234027
2	0.5	20	99	6.02	4.7	2.1	44.4	312036
3	0.5	25	99	4.25	5.94	2.5	55.6	390045
4	0.5	30	99	2.9	7.18	3	66.7	468054
5	0.7	15	48	8.81	2.86	1.3	23.1	195305
6	0.7	20	48	6.32	3.95	1.6	30.8	279751
7	0.7	25	48	4.47	5.04	1.9	38.5	349689
8	0.7	30	48	3.06	6.13	2.2	46.2	419627
9	0.8	15	35	8.41	2.81	1.2	18.8	188764
10	0.8	20	35	6	3.94	1.5	25	275199
11	0.8	25	35	4.23	5.07	1.8	31.3	343999
12	0.8	30	35	2.89	6.2	2	37.5	412798
13	1	15	20	9.94	2.18	1	15	162759
14	1	20	20	7.14	3.13	1.2	20	241016
15	1	25	20	5.09	4.08	1.4	25	301270
16	1	30	20	3.55	5.03	1.6	30	361524
17	0.5	15	165	8.48	5.76	2.5	33.3	390045
18	0.5	20	165	6.07	7.83	3.3	44.4	520059
19	0.5	25	165	4.28	9.9	4	55.6	650074
20	0.5	30	165	2.92	12	4.7	66.7	780089
21	0.7	15	80	8.75	4.77	1.9	23.1	325509
22	0.7	20	80	6.27	6.59	2.4	30.8	466252
23	0.7	25	80	4.44	8.41	2.9	38.5	582815
24	0.7	30	80	3.05	10.2	3.4	46.2	699378
25	0.8	15	54	8.78	4.33	1.7	18.8	291237
26	0.8	20	54	6.29	6.08	2.1	25	424593
27	0.8	25	54	4.44	7.82	2.5	31.3	530741
28	0.8	30	54	3.05	9.56	2.9	37.5	636889
29	1	15	35	9.08	3.82	1.4	15	284828
30	1	20	35	6.5	5.48	1.8	20	421778
31	1	25	35	4.61	7.14	2.1	25	527223
32	1	30	35	3.17	8.8	2.4	30	632667
33	0.5	15	374	8.08	13.1	5.2	33.3	884101
34	0.5	20	374	5.77	17.8	6.8	44.4	1178801
35	0.5	25	374	4.05	22.4	8.4	55.6	1473502
36	0.5	30	374	2.76	27.1	10	66.7	1768202
37	0.7	15	180	8.22	10.7	3.8	23.1	732395
38	0.7	20	180	5.88	14.8	4.9	30.8	1049067
39	0.7	25	180	4.14	18.9	6	38.5	1311334
40	0.7	30	180	2.81	23	7.1	46.2	1573601
41	0.8	15	117	8.41	9.39	3.1	18.8	631013
42	0.8	20	117	6	13.2	4	25	919951
43	0.8	25	117	4.23	16.9	4.9	31.3	1149938
44	0.8	30	117	2.89	20.7	5.8	37.5	1379926
45	1	15	80	8.14	8.74	2.7	15	651037
46	1	20	80	5.83	12.5	3.5	20	964065
47	1	25	80	4.1	16.3	4.2	25	1205081
48	1	30	80	2.78	20.1	5	30	1446097

7. Finite Element Analysis (FEM) : As discussed in introduction section, more precise criteria values can be obtained by FEM analyses but it not practical to evaluate 48 alternatives since it requires large amount of data, time and effort. Therefore, in this methodology, FEM analysis is performed only for the top 5 alternatives in the final ranking list to provide more precise S and SFBC values for decision makers. Numerical models of the five alternatives was performed by using Plaxis 3D software. The numeric models were analyzed for drained condition and mohr-cloumb model with soil properties which were given in Table 1. Settlement and safety factor values obtained by FEM and conventional methods are given in Table 12. As can be seen from Table 12, S and SFBC values obtained by conventional methods and FEM follow a similar trend and they are close to each other. Having obtained more precise S and SFBC values for top five alternatives, decision makers may choose one of the alternatives that best satisfies their preferences.

Table 7. Best f_i^* values and worst f_i^- values for all the criteria

	C1	C2	C3	C4	C5
f_i^*	2.76	27.12	1	15	162759.13
f_i^-	9.94	2.18	10	66.67	1768202.2

Table 8. *Q, R, S* Values for top 5 Alternatives

Alternative No	Q	Alternative	S	Alternative	R
16	0	16	0.18	11	0.06
12	0.02	12	0.18	16	0.07
11	0.03	11	0.2	12	0.06
8	0.05	15	0.21	7	0.07
7	0.07	8	0.23	8	0.07

Table 9. *p and q values*

Parameter	S	SFBC	EI	LDR	C
Q	0	2	0	1	1000
P	7	22	8	50	1250000

Table 10. ϕ^+ and ϕ^+ values for Top Five Alternatives

Flow Value	*A16*	*A12*	*A11*	*A15*	*A8*
ϕ^+	11.03	10.92	10.11	10.35	10.31
ϕ^-	1.408	1.973	1.726	2.059	2.713
ϕ_{net}	9.622	8.949	8.387	8.29	7.594

Table 11. Final ranking

Alternative No	PROMETHEE II Rank	VIKOR Rank	Average Rank	Final Rank
16	1	1	1	1
12	2	2	2	2
11	3	3	3	3
8	5	4	4.5	4
15	4	6	5	5
7	6	5	5.5	6

Table 12. Settlement and safety factor values for the best five alternatives

Alternative No	Settlements (cm)		Safety factor of bearing capacity	
	Conventional Method	FEM analyses	Conventional Method	FEM Analyses
16	3.55	3.962	5.03	5.43
12	2.89	3.96	6.2	6.55
11	4.23	4.897	5.07	6.03
8	3.06	3.9	6.13	6.36
15	5.09	4.738	4.08	5.7

Conclusion

Selection of appropriate pile foundation is a common problem in civil engineering. In most of real-world applications, decision makers select the appropriate pile foundation based on their experience and knowledge. The methods completely based on knowledge and experience is difficult to use when it is required to evaluate so many alternatives with multiple criteria. Therefore, such methods may lead to poor pile foundations that do not well satisfy economic and technical criteria. In most cases there is not a certain solution that satisfies all criteria simultaneously. MCDM analyses are able to provide a compromise solution in such cases. In this study an integrated MCDA based methodology is proposed for selecting appropriate pile foundation for a given soil profile. The methodology proposed incorporates AHP, VIKOR/PROMETHEE and finite element analysis. The methodology provides a systematic basis for pile selection process and allows decision makers to reflect their preferences in decision making process.

Differently from the existing methodologies, in this study, VIKOR and PROMETHEE methods were used for the first time in selecting the best pile foundation problem. Moreover, the proposed methodology differs from the existing MCDM based pile selection studies by considering pile design parameters and pile foundation layout together.

The findings of the numerical analysis showed that the proposed methodology can be effectively used for selecting the most appropriate pile foundation for a given soil profile. A further study may be required to extend the methodology so that it can be used for different soil profiles in a generic manner.

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