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Research Article

Comparison of the effect of foundation analysis methods on structural analysis results of tall buildings

Ömer Özer [a,*] ***and S. Bahadır Yüksel*** [a]

[a]*Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, 42130, Konya, Turkey*

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ABSTRACT

In structural analysis, there are serious interactions between soil-foundation and structure. The fixed base analysis method ignores this interaction but many analysis methods have been developed that take into account the soil-structure interaction (SSI). This paper revealed the effects of SSI analysis methods on tall buildings analysis results on soft soil sites. 6 different structural models with 20 story buildings and two different coefficients of subgrade reactions were analyzed with three different analysis methods which are fixed base method, Winkler method and pseudo-coupled method. As a result of all the analysis, 6 different structural models compared and discussed in terms of structural period, displacements, lateral loads, column, shear wall and foundation reactions and structural economy. It has been observed that the structure may remain on the unsafe side in the analysis made with the fixed base analysis method.

1. Introduction

The production of the structures starts with the projecting process and is completed with the application process. In addition to being compatible with the architectural project at the project planning stage, the most important principle that civil engineers should consider is modeling as close as possible to the reality. When modeling is done, it is necessary to take into consideration both the superstructure conditions of the building and the geotechnical conditions of the region and the ground. In this context, it is very important that the ground survey reports should be evaluated correctly and used completely in the project.

In the analysis of the buildings, the soil structure interaction (SSI) is widely ignored. However, when we look at the studies in the literature, the local soil properties have significant effects on the behavior of the structure, under both vertical and horizontal loads [1]. Under vertical static loads, there is a tendency of displacement and rotation effects on the foundation of the structure and a tendency to move differently between the structure and the foundation under horizontal dynamic loads. According to this situation, fixed base foundation acceptance is away from realism and analysis methods which take into account SSI is necessary.

Winkler method [2] is widely used in SSI models. However, in Winkler method, a realistic calculation of foundation shape changes cannot be made [3]. In addition to the Winkler method, the horizontal springs have also been introduced to achieve more realistic results, but additional difficulties have arisen in this method [4].

The normal stress between the foundation and the ground varies depending on the stiffness of the foundation system and the load distribution of the structure and the soil group [5]. The equivalent coefficient of subgrade reaction method, idealizing the difference of deformations arising from these differences, has been proposed by Vallabhan and Daloglu [6].

2.2.1.5 of Turkish Earthquake Code 2007 which was previous earthquake code required SSI analysis for soil group C and D [7]. General belief is that the period of the building will increase in the SSI solution, and the earthquake load affected by the building will also decrease, and the building performance will be improved.

* Corresponding author. Tel.: +90-536-516-1941 ; Fax: +90-332-238-2727.
E-mail addresses: omer@anahtarmuhendislik.com *(Ö. Özer)*, sbyuksel@ktun.edu.tr *(S.B. Yüksel)*
ORCID: 0000-0002-5126-6832 *(Ö.Özer)*, 0000-0002-4175-1156 *(S.B. Yüksel)*,
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For the same reason, Turkish Building Earthquake Code 2018 16C.1.2 suggests that SSI can be neglected in to stay on the safe side. On the other hand, studies in the literature have shown that SSI do not only affect structural period but also other parameters. Fatahi et al. [8] investigated that the structural displacements and inter-storey drifts caused by SSI are larger than the corresponding values while only local site effect is included. The numerical results clearly indicate that the structural displacements and inter-storey drifts caused by SSI are larger than the corresponding values while only local site effect is included. Tomeo et al. [9] emphasized that SSI effects are important for soft soils. Moghaddasi et al. [10] emphasized that major earthquakes has highlighted the possibility of detrimental effects or increase in the structural response due to SSI. Çelebi et al. [11] stated that dynamic response is more pronounced for resonance case, when the frequency content of the seismic ground motion is close to that of the SSI system.

The purpose of this study is to show that the SSI affects many parameters other than the structural period only, and to show that the fixed base acceptance is not always on the safe side.

2. Material and Method

In this paper, 6 different structural models with 20 story (Figure 1-2) and two different soil groups (Table 1) were analyzed with three different analysis methods which are fixed base method, the Winkler method and the pseudo-coupled method.

Within the soil group D and C, the coefficients of subgrade reaction were selected as 12753 kN/m³ and 17167 kN/m³, respectively. The other important parameter of the soil group is "allowable bearing value" taken as 98 kN/m^2, and 147 kN/m^2.

In order to examine the effect of soil groups on foundation analysis methods, two different soil groups were examined. In this way, it is aimed not only to compare the fixed base and SSI, but also to show how the solutions can differ according to soil groups.

In our country, the PGA value can rise up to 0.780 in the eastern Anatolian region. However, in our study, we wanted to choose a region where the population is high in addition to high earthquake acceleration (Table 2). For this reason, we preferred the ground acceleration of the Gölcük region, which caused great damage in 1999 [12].

Table 1. The properties of soil groups according to TBEC (2018) [13]

Soil Group	Description of Soil Group
C	Highly tight sand gravel and hard clay layers or with cracked weak rock
D	Medium-firm - firm sand, gravel or solid clay

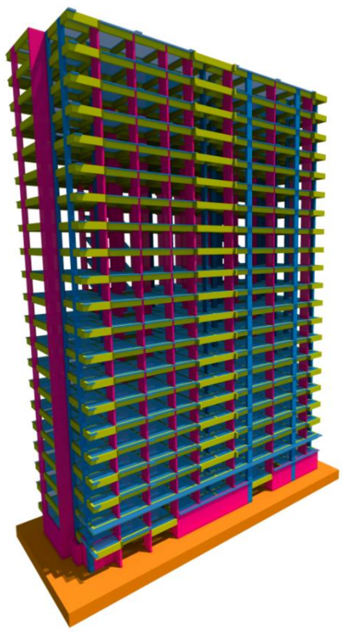

Figure 1. The perspective view of 20-storey building

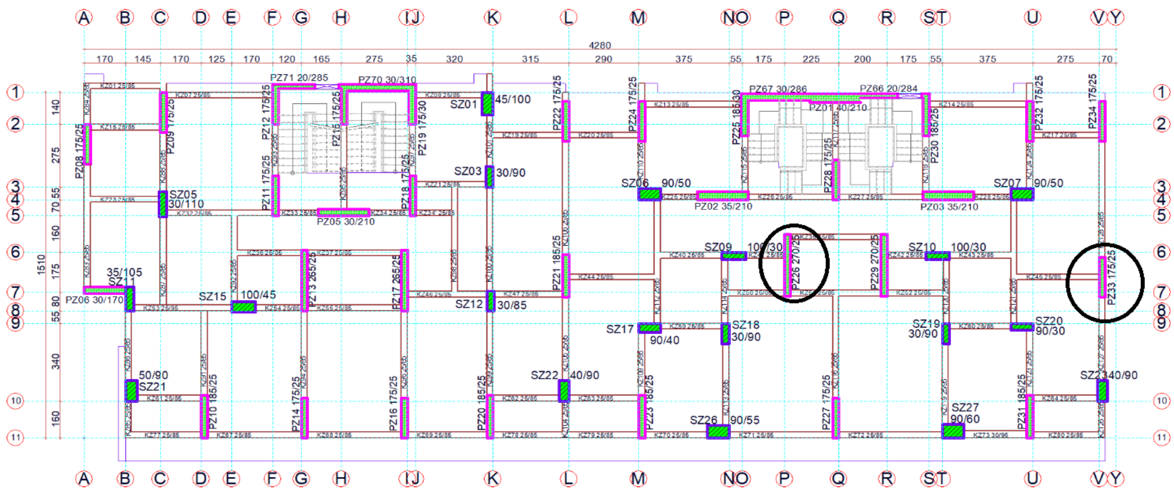

Figure 2. The floor plan of all structural models

Table 2. Population affected by Gölcük earthquake [12]

City	Center	Villages	Total
Bilecik	116004	76056	192060
Bolu	265052	287970	553022
Bursa	1484838	473691	1958529
Eskişehir	518643	142200	660843
İstanbul	8506026	692783	9198809
Kocaeli	629333	548046	1177379
Sakarya	331431	400369	731800
Tekirdağ	358878	208518	567396
Yalova	110106	53810	163916
Zonguldak	239186	373536	612722
Total	12.559.497	3.256.979	15.816.476

Table 3. Seismic parameters of analysis model

Structure Location	Kocaeli Gölcük
Latitude	40.720382
Longitude	29.811135
S_S	1.683
S_1	0.399
S_{D1}	0.599
S_{DS}	2.02
PGA	0.687
PGV	43.509

Analysis model's seismic location parameters are given in Table 3 according to TBEC 2018 [13]. The meanings of the symbols in Table 3 are given below:

S_s: Short period map spectral acceleration coefficient

S_1: 1 second period map spectral acceleration coefficient

S_{d1}: 1 second period design spectral acceleration coefficient

S_{ds}: Short period design spectral acceleration coefficient

PGA: Peek ground acceleration (g)

PGV: Peek ground velocity (cm/sec)

Analysis model's general seismic design parameters are given in Table 4.

Analysis methods can be summarized as follows:

Fixed base method:

In this method, it is assumed that the bottom floor columns and the shear walls were connected to the base in an infinitely rigid manner. Therefore, it was assumed that the foundation was not affected by the structure, and the structure was not affected by the foundation. In this case, foundation and structure are analyzed independently of each other.

Winkler method:

It was assumed that the shape of the springs changed only when loaded directly and formed a counter reaction, but each spring was considered to be independent of neighboring springs. That is, the ground was modeled by independent linear springs defined by the coefficient of subgrade reaction, but the continuity of the (soil) space was not taken into consideration. As a result, the ground was considered as a completely discontinuous environment. This inadequacy in the Winkler method has attracted the attention of researchers, and for this reason, the criticism and the recommendation for the improvement of the classical Winkler method were widely published in the literature [14].

Pseudo-coupled method:

In this method, the foundation was divided into three parts and three different coefficients of subgrade reaction selected for each part. In this method, the lower coefficient of subgrade is used in the structure core, while the coefficient of subgrade is increased as it moves to the foundation corners. The basis of the pseudo-coupled practice is shown in Figure 3 [15]. In this study, this method will be used as the third foundation analysis method.

Table 4. General design parameters of analysis model

Analysis Model Parameters			
Number of Story	21	Beam Dimensions	30 cm x 85 cm
Story Height	3 m	Beam Reinforcement - Confinement	6Φ22 - Up 6Φ22 - Down Φ10/9 Str.
Structure Dimensions (X-Y)	47 m x 20.8 m		
Structure Height	63 m	Slab Height	12-15 cm
Structure Height Classes	BYS 2	Slab Dead / Live Load	2.06 / 3.43 kN/m^2
Response Modification Coefficient R	8	Building Risk Category	BRC 3
Overstrenght Factor D	2.5		
Concrete	C40	Analysis Method	Strength Based Design
Reinforcement Material	B420C	Ductility	High
Seismic Design Category	DTS 1	Total Weight of the Structure	168516 kN

In the study, sizes and reinforcements for columns and shear walls are shown in Table 4 and Table 5 (columns and shear walls of the same dimensions have the same number of reinforcement).

Each analysis method used in this study has serious effects on the analysis result of the structure. Figure 4 shows the effect of the foundation analysis methods on the foundation deformation under the same loading.

Table 5. Column dimensions and reinforcements bars

Column	b	h	Major	Minor	Confinement
SZ01	45	100	8Ø20	10Ø20	ø10/10/10
SZ03	30	90	4Ø20	6Ø20	ø10/12/8/10
SZ05	30	110	4Ø20	8Ø20	ø10/10/10
SZ07	90	50	8Ø20	10Ø20	ø10/20/10/10
SZ09	100	30	4Ø20	6Ø20	ø10/12/8/10
SZ11	35	105	6Ø20	6Ø20	ø10/10/10
SZ12	30	85	4Ø20	6Ø20	ø10/15/10/10
SZ17	90	40	6Ø20	6Ø20	ø10/20/10/10
SZ26	90	55	10Ø20	8Ø20	ø10/20/10/10
SZ27	90	60	10Ø20	8Ø20	ø10/20/10/10

Table 6. Shear wall dimensions and reinforcements bars

Shear Wall	b	h	Vertical Bar			Confinement		
PZ02	35	210	20	Ø	14	ø8	/	11
PZ05	30	210	36	Ø	14	ø8	/	13
PZ06	30	170	32	Ø	18	ø8	/	13
PZ08	25	175	18	Ø	14	ø8	/	16
PZ10	25	185	28	Ø	14	ø8	/	16
PZ13	25	265	30	Ø	14	ø8	/	16
PZ19	30	175	24	Ø	14	ø8	/	13
PZ25	30	185	22	Ø	14	ø8	/	13
PZ26	25	270	32	Ø	14	ø8	/	16
PZ66	20	284	42	Ø	14	ø12	/	10
PZ70	30	310	46	Ø	16	ø12	/	14
PZ71	25	285	46	Ø	14	ø12	/	12
PZ01	40	210	20	Ø	14	ø12	/	13
PZ67	30	286	56	Ø	16	ø12	/	12

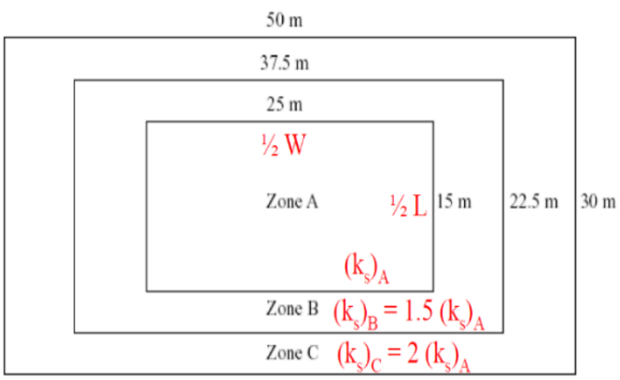

Figure 3. The coefficient of subgrade reaction in the regularly formed foundation area in the pseudo-coupled method [15]

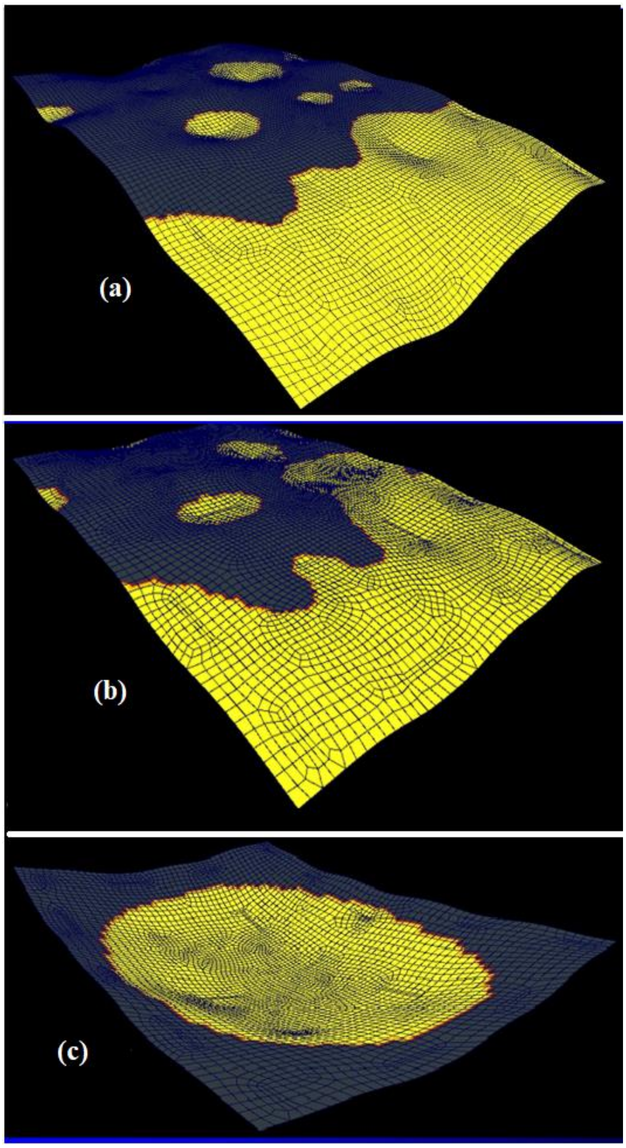

Figure 4. Effect of the foundation analysis methods on the foundation deformation under the same loading
a) Fixed base, b) Winkler, c) Pseudo-coupled

3. Research Results

As in many studies [16-18], it has been observed that the period of the structure increases in the acceptance of the SSI. Similarly, in this study, it has been observed that the building period increases in the SSI solutions (Figure 5). Similar to previous studies [9], when the top floor displacement values were examined, it was seen that the total displacement of the structure increased in SSI solutions (Figure 6), when the top floor earthquake loads and torsional moments are examined, it has been seen that the fixed base acceptance gets higher values (Figure 7 - 8).

In this study, the analysis results of all columns were examined in detail under headings of column capacity ratios, axial loads, earthquake loads and bending moments. The results of the research showed that the columns in the fixed base analysis system were subjected to higher axial loads, on the other hand the columns in the SSI systems were subjected to higher moments (Figure 9).

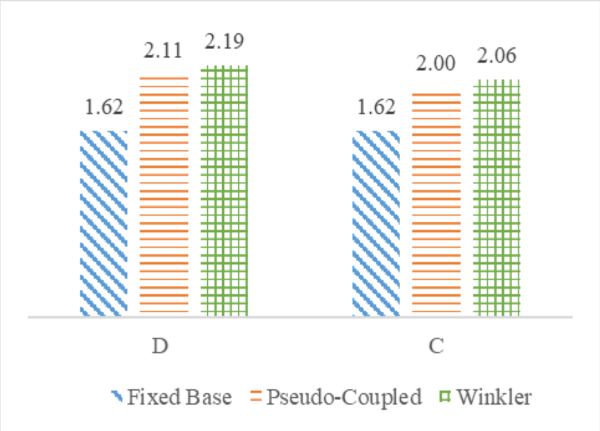

Figure 5. The structural periods (sec)

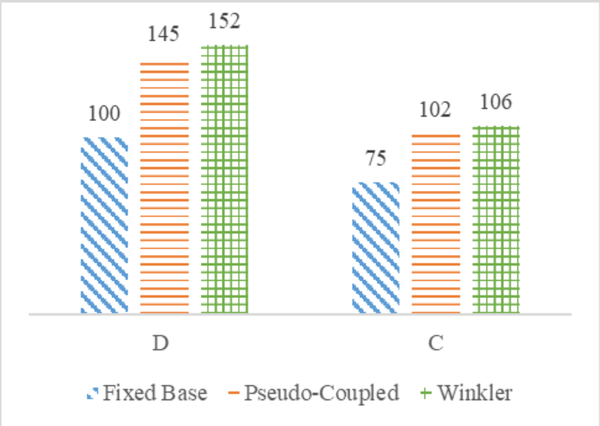

Figure 6. Relative top floor displacement (mm)

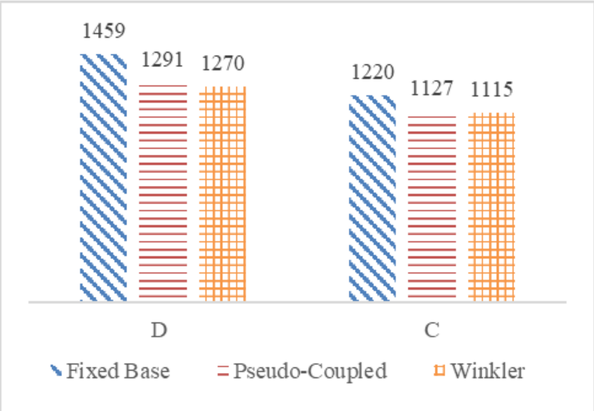

Figure 7. Top floor horizontal force (kN)

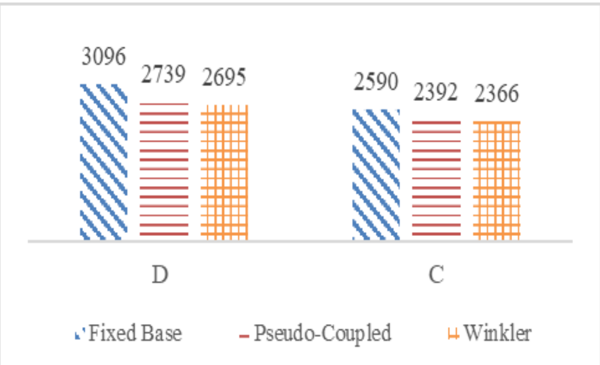

Figure 8. Top floor torsional moment (kNm)

N_{dMax}: Maximum axial force acting on column

N_{max}: Maximum column axial force capacity

M_d: Column bending moment

M_r: Column bending moment capacity.

In this study, analysis results of PZ26 and PZ33 shear walls which was shown in Figure 2 was evaluated. Maximum axial loads of PZ26 and PZ33 shear walls are shown in Figure 10.

However, when the earthquake loads and M_3 bending moments were examined, it was seen that the fixed base acceptance received higher results than SSI acceptance (Figure 11-12).

In this study, raft foundation was preferred. The dimensions of the raft foundation were 4700 x 2080 cm and the foundation height were 170 cm for 20-story buildings.

Another subject that was compared in this study is soil stresses which were compared in detail for three different analysis methods and two different soil groups. When the research results were examined, it was seen the analysis results are varied for all analysis methods. The results of the analysis are shown graphically as minimum, average and maximum stress (Figure 13).

When the bending moments are examined, the biggest bending moment in the X direction was seen in the fixed base model, but when the Y direction is examined the biggest bending moment was seen in the pseudo-coupled model (Figure 14).

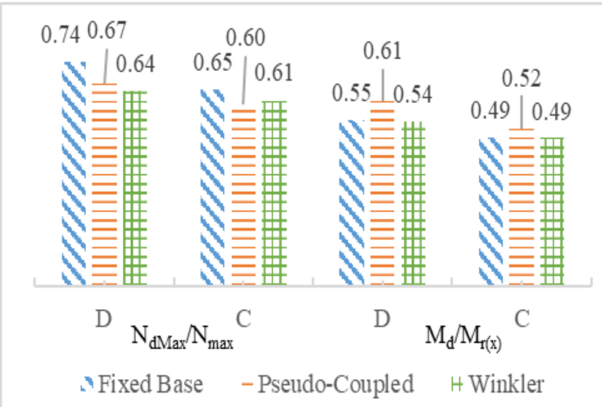

Figure 9. Ground floor columns average capacity ratios

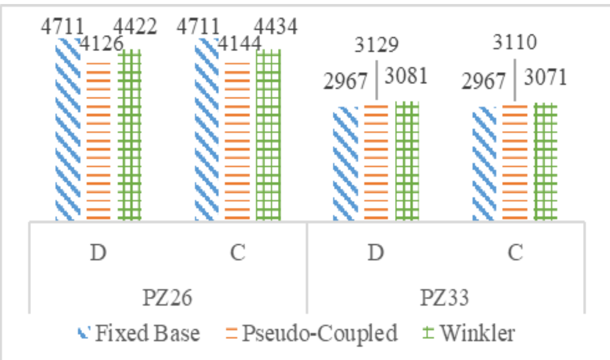

Figure 10. Axial load values of PZ26 and PZ33 shear walls (kN)

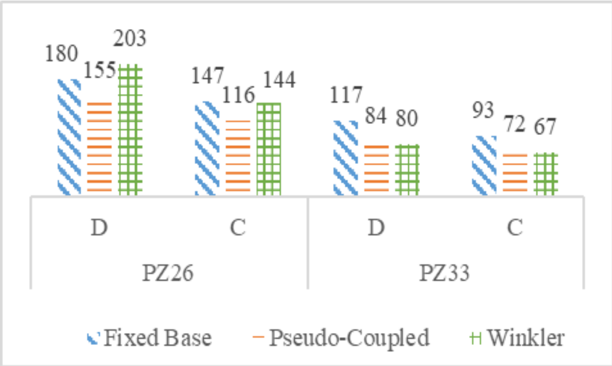

Figure 11. E_y earthquake load of PZ26 and PZ33 shear walls (kN)

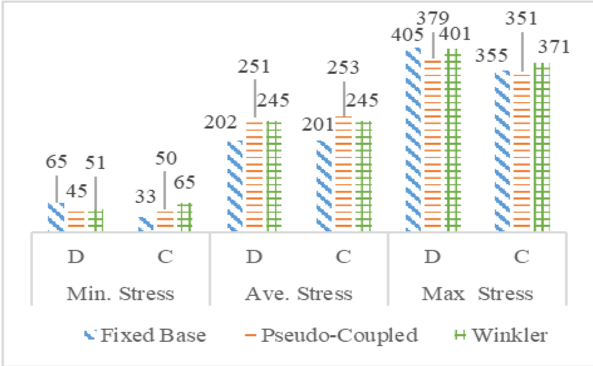

Figure 13. The soil stresses of the raft foundation (kN/m^2)

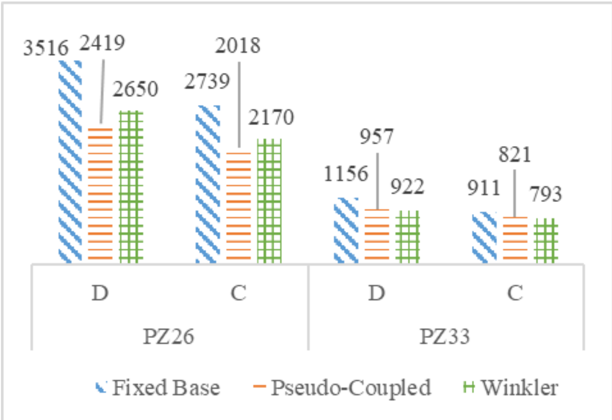

Figure 12. M_3 bending moments of PZ26 and PZ33 shear walls (kNm)

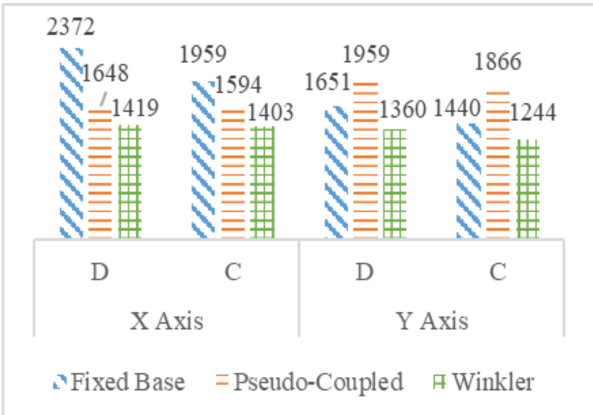

Figure 14. Maximum bending moment of the raft foundation (kNm

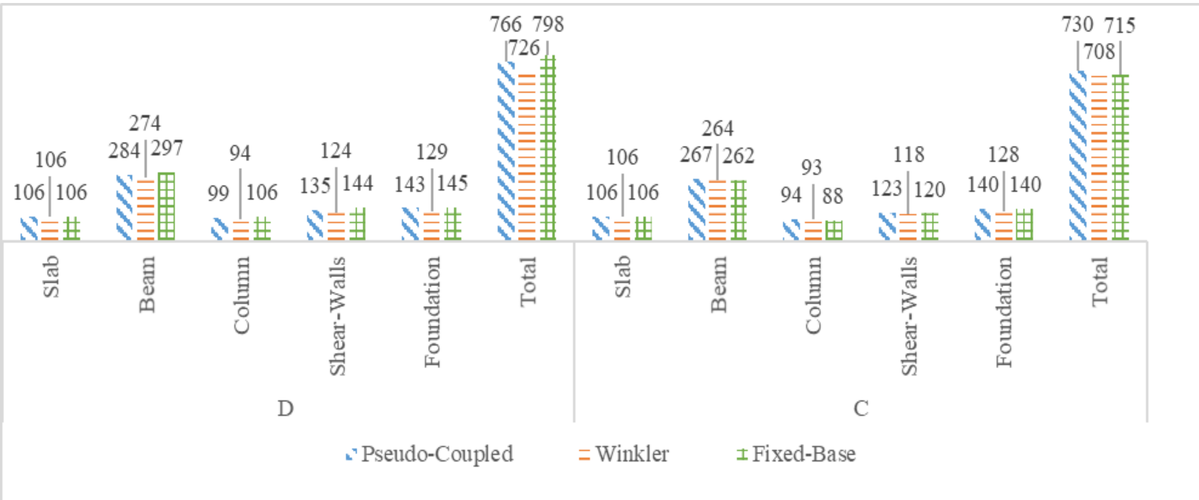

Figure 15. Reinforcement bar quantities obtained from three different analysis results (ton)

4. Conclusions

This study was conducted to examine the effects of different foundation analysis methods on the results of structure analysis. Fixed base and SSI foundation analysis methods are used in 20 storey analysis model. This study also used two different soil groups. The research results in this article have been analyzed under several headings.

- As a result of all the performed analysis, the structure periods of Winkler and pseudo-coupled showed an increase of 30-35% compared to the fixed based model.
- When the horizontal loads and the torsional moments applied on the structures were examined, it was observed that SSI solution was subjected to torsional moments with less horizontal loads of up to 20% compared to fixed base in soil group D.
- Another aim of this study was to examine the effect of the foundation analysis system on the construction economy. The results of the research showed that the most steel requirement has emerged in the fixed base model at soil group D but when analysis models at soil

group C are examined, it has been seen that the most steel requirement has emerged in the pseudo-coupled model.

- It cannot be said that the fixed base analysis system is more secure than SSI solution. Especially when the columns' moment capacities were compared, SSI solutions were much closer to the structural safety limit values
- When analysis results of the shear walls are examined very serious differences were found in shear force and bending moments. Therefore, the buildings analyzed with the fixed base system cannot be said to be on the safer side than the SSI solutions.
- The fixed base foundation system's bending moments give higher results in all soil groups. Therefore, although the fixed base solution remained on the safer side compared to SSI solutions in terms of bending moment, it is still on the more insecure side when examined in terms of the average soil stresses.
- All the results of the analysis showed that the SSI systems give up to 10% more economical results than the fixed base systems in poor soil conditions.

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

All authors contributed to data collection phase. Ö. Özer performed the analysis and wrote the manuscript. S.B. Yüksel made proofreading of manuscript.

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