# ANALYSIS OF RAFT FOUNDATION ON SANDY SOILS BY WINKLER AND PSEUDO-COUPLED METHODS

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**Keywords**

*subgrade reaction coefficient, Winkler method, Pseudo-Coupled method, rigid, flexible*

**Abstract**

*The settlements occurred in building foundations depend on many soil parameters. Thus, these parameters make the solution both difficult and complex during the calculating process. Therefore, finite element programs use the subgrade reaction coefficient to facilitate the foundation solution. Two different methods, which are Winkler method and Pseudo coupled method, are used in the basic solutions with the coefficient of subgrade reaction. While the Winkler method can be solved with a single field, the pseudo method can be solved with 2 or more fields. In this study, a 10 story building with a 36 m x 36 m square foundation was separately designed on four different sand soils. Two of these soils are classified as C and the others are classified as D according to Eurocode 8. The foundation of this building built on four different soils was divided into six different areas (one region, two regions, three regions, five regions, seven regions, 10 regions). Consequently, 24 analyzes were performed by using the ETABS program. According to the results obtained from these analyzes, while it is appropriate to use the Winkler method in weak sand soils for rigid foundation acceptance, it is more appropriate to use the Pseudo-coupled method in dense sand soils. Pseudo-coupled method should be used in flexible foundation solutions built on weak sand soils. The Winkler method should be used for flexible foundations built on dense sand soils. In the Pseudo-coupled method, the highest settlements were obtained in the two-region solutions. An optimum number of fields was found to be 7 for Pseudo-coupled method.*

# KUMLU ZEMİN ÜZERİNDEKİ RADYE TEMELLERİN WİNKLER VE PSÜDO-EŞLENİK YÖNTEMLERİ İLE ANALİZİ

**Anahtar Kelimeler**

*Zemin yatak katsayısı, Winkler metot, Psüdo-Eşlenik metot, rijit, esnek*

**Öz**

*Bina temellerinde meydana gelen oturmalar birçok zemin parametresine bağlıdır. Dolayısıyla bu parametreler, hesaplama sürecinde çözümü hem zor hem de karmaşık hale getirmektedir. Bu nedenle, sonlu elemanlar programları, temel çözümünü kolaylaştırmak için zeminin yatak katsayısını kullanır. Zemin yatak katsayısına sahip temel, çözümlerde Winkler yöntemi ve Psüdo-Eşlenik yöntem olmak üzere iki farklı metot kullanılarak çözülmektedir. Winkler yöntemi tek bir alanla çözülebilirken, Psüdo-Eşlenik yöntem 2 veya daha fazla alanla çözülebilir. Bu çalışmada dört farklı kum zemin üzerinde, 36 m x 36 m ölçülerinde kare temelli 10 katlı bir bina ayrı ayrı tasarlanmıştır. Bu zeminlerden ikisi Eurocode 8'e göre C, diğerleri D sınıfındadır. Dört farklı zemin üzerine inşa edilen bu binanın temeli altı farklı bölgeye (bir bölge, iki bölge, üç bölge, beş bölge, yedi bölge, 10 bölge) bölünmüştür. Sonuç olarak, 24 adet analiz ETABS programını kullanarak yapılmıştır. Bu analizler elde edilen sonuçlara göre, rijit temel kabulü için zayıf kum zeminlerde Winkler metodu kullanılması uygun iken, sıkı kum zeminlerde ise Pseudo-coupled metodunun kullanılması daha uygundur. Zayıf kum zeminler üzerine inşa edilen esnek temel çözümlerinde Psüdo-Eşlenik yöntemi kullanılmalıdır. Sıkı kum zeminler üzerine inşa edilen esnek temeller için ise Winkler metodu kullanılmalıdır.*

*Psüdo-Eşlenik yöntemde en yüksek oturmalar iki bölgeli çözümlerde elde edilmiştir. Psüdo-Eşlenik yöntemi için optimum alan sayısı 7 olarak bulunmuştur.*

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## 1. Introduction

The behaviors of structures subjected to horizontal and vertical loads generally depend on the local soil properties under the building foundation. While the foundations of structures exposed to vertical static loads tend to settle and rotate, the connection between foundations and soils gradually reduces under the horizontal dynamic loads. Thus, the interaction between the soil and structure should be correctly determined during the structural analysis (Özer and Yüksel, 2021).

The differential settlements occasionally occur at the structure foundations built on the weak soil layers due to the loads and moments. Structural damage will occur if the differential settlement at the foundation base exceeds the allowable value. In weak soils, raft foundation design should be preferred so that the structural loads can be transferred to the ground uniformly. The installation of raft foundations reduces differential settlements but does not stop completely. Differential settlements are also affected by many factors such as column loads, soil layers under the structures (coefficient of subgrade reaction), the geometry of the foundation plate (shape, thickness, and width), foundation girders, the shape, etc. (Ma and Chen, 2019).

The mechanism of soil-structure interaction affects the raft foundation behavior. A raft foundation may be analyzed as either a rigid or flexible foundation due to the stiffness of the foundation and subsoil. In these designs, several linear elastic springs represent subgrade soil under the raft foundation. The stiffness of springs is determined according to the coefficient of subgrade reaction obtained from either plate load test or correlations of field/laboratory tests. The coefficient of subgrade reaction depends on many parameters of the foundation (shape, size, thickness, rigidity), soil layer (soil type, durability, void ratio, compressibility), superstructure (stiffness of structural elements, geometry), and loading (location, magnitude, eccentricity) (ACI, 2002; Teodaru and Toma, 2009).

The coefficient of subgrade reaction, one of the considerable parameters in the raft foundation analysis, is called base pressure. This pressure develops until its magnitude reaches up to the bearing capacity of soil when the superstructure load is transferred to subsoil layers. Two considerable parameters that are physical and mechanical properties of subsoil and the elastic properties of the foundation affect the base pressure. Moreover, the ratio of contact pressure to settlement in any place of foundation varies in every place of the raft foundation. This situation complicates the raft foundation analysis. Therefore, the behavior of the raft foundation under loading should be properly specified. The behavior of the raft foundation depends on the subgrade reaction coefficient and raft thickness that causes the foundation to be flexible or rigid. In many cases, raft foundation is generally analyzed by accepting rigid behavior as the solution complexity diminishes. However, flexible behavior is valid for most of the raft foundations under real conditions (Todorovska et al., 2001; Rashedul and Chowdhury, 2013; Bhartiya, 2020; Teli et al., 2020; Modak and Singh, 2022).

The assumption of defining the soils with spring constants ensures that the raft foundation analysis can be performed quickly. Structural software analyzes the foundations according to this assumption and is preferred by many structural engineers. However, there is a handicap to determine the value of the coefficient of subgrade reaction or spring constant by many different approaches. Therefore, analyses made according to this assumption can yield many different results (Bhartiya, 2020).

The elastic raft foundation can be analyzed as an elastic plate. A square flexible raft foundation has been shown as a suitable example of this acceptance. Some researchers stated that a boundary element method, based on the Winkler spring approach, has been utilized for elastic raft foundation analyses. However, the settlements obtained from this method are not reliable due to only one soil parameter, which is the subgrade reaction coefficient, calculated from either plate load test or indirect methods (Fox, 1948; Cheung and Zienkiewicz, 1965; Fraser and Wardle, 1976; Katsikadelis and Armenkas, 1984; Costa and Brebia, 1985; Mandal and Ghosh, 1999; Subramanian et al. 2005).

The Winkler approach is a mathematical method based on the coefficient of subgrade reaction. In this method, the soil under the structure represents by a group of springs that have stiffness. This method is used by many structural analysis software for the solution of soil-foundation problems. The main handicap of this method is the determination of the coefficient of subgrade reaction since it alters due to soil properties, foundation rigidity, loads, etc. (El-garhy and Osman, 2002).

The Pseudo-coupled method is an alternative method preferred instead of the Winkler method. In this method, the mat foundation is carried by springs that represent the soils underneath the structure. The main difference between the Winkler and the Pseudo-coupled methods is the value of the coefficient of subgrade reaction used in the analysis. While the value of the coefficient of subgrade reaction is the same in every point of the raft foundation in the Winkler method, this value changes for any position of the raft foundation in the Pseudo-coupled method. The alteration of this value in the pseudo-coupled method is generally done for improving the Winkler method during soil-foundation problems (Loukidis and Tamiolakis, 2017).

Most of the structural analysis software that uses the finite element method generally takes the Winkler approach into account to make the calculations simpler and easier during the raft foundation analysis. However, the same value of the coefficient of subgrade reaction is defined in every part of the raft foundations solved with this approach. During the analysis, this condition results in that all points on the raft foundation are independent of each other (Prabhu and Mutalikdesai, 2023). Considering the real conditions, this analysis is far from giving accurate results, especially for soil that has low bearing capacity. To solve this problem, the Pseudo-coupled approach has been developed in the literature. In this approach, the raft foundation is divided into two or more regions, and different coefficients of subgrade reaction are defined for each region. Thus, it is assumed that all points on the raft foundation move together.

In the present study, a 36m·36m raft foundation of a 10-story symmetrical building was separately analyzed on four different sand soil layers that have different coefficients of subgrade reaction. First, the raft foundation was analyzed for all soil layers with the Winkler approach. Because most of the software package programs make calculations using only the Winkler method. However, when this solution is considered under real conditions, settlement values can often be calculated incorrectly. Then, the raft foundation was analyzed according to the Pseudo-coupled method by dividing it into 2, 3, 4, 7, and 10 regions. The purpose of the study is to compare the Winkler and Pseudo-coupled approaches, which are used by package program, during raft foundation analysis by considering local subsoil properties. The raft foundation behaves either rigid or flexible according to the subsoil conditions. Moreover, the optimum number of regions was determined if the raft foundation is analyzed by using the Pseudo-coupled method. In addition, the effect of subsoil properties on both approaches was also examined.

## 2. Materials and Methods

### 2.1 Materials

A raft foundation of the 10 story-building was separately analyzed with two different methods that are the has a Winkler and the Pseudo-coupled methods. The building symmetrical structure (Figure 1). The floor plan of the building is given in Figure 2. The raft foundation of the building was square by 36m in width and 36m in length. The thickness of the foundation is 75 cm. The other parameters of the building are given in Table 1.

### 2.2 Methods

The soil layer under the raft foundation was simulated with springs in the Winkler and Pseudo-coupled methods. The stiffness of the springs is the most essential parameter in the analysis of these methods. The stiffness of spring is the coefficient of subgrade reaction (k) calculated by using Equation 1.

$$k = \frac{q}{s} \left(\frac{kN}{m^3}\right) \qquad Eq. 1$$

where k is the coefficient of subgrade reaction, q is the base pressure, and s is the settlement resulted from base pressure.

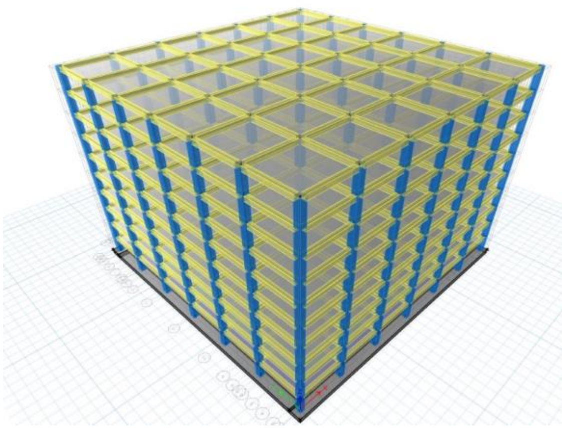


Figure 1. The perspective view of 10 story building

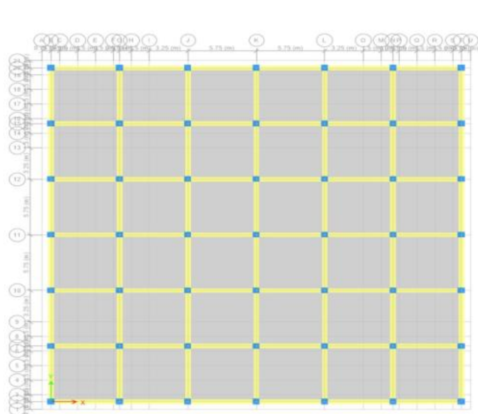


Figure 2. The floor plan of the building

Table 1. Analysis parameters of the building

| | | | |
|---|---|---|---|
| **Number of Story** | 10 | **Column Dimensions (m)** | 60 x 60 |
| **Story Height (m)** | 3 | **Beam Dimensions (m)** | 40 x 60 |
| **Structure Height (m)** | 30 | **Slab Thickness (m)** | 0.15 |
| **Span X-Y (m)** | 5.75 | **Dead Load (t/m²)** | 0.250 |
| **Number of Span X-Y** | 6 | **Live Load (t/m²)** | 0.350 |
| **Building Dimensions (m)** | 34.5 x 34.5 | **Concrete Class** | C30/37 |
| **Analysis Type** | Vertical | **Reinforcement** | S420a |

### 2.2.1 Winkler Method

The basic assumption of the Winkler method is no relationship between the springs. In other words, each spring is independent of the others. All springs that represent the soil have the same value which is the coefficient of the subgrade reaction of the soil layer. Furthermore, these springs are presumed to have both tension and compression capacity.

In Winkler method, all springs have same subgrade reaction coefficient during the analysis (Figure 3). This assumption reveals that the stresses on the foundation are applied only to the point at which they act.

Considering the real conditions, the shape of the raft foundation becomes dishing shape after it is subjected to uniform loading (Figure 4). Thus, the loading at each point of the raft foundation affects other points. Therefore, the spring constant or the value of the coefficient subgrade reaction varies from point to the point of the raft foundation. In summary, this state is the most critical handicap of the Winkler springs method during the raft foundation analysis (Subramanian et al. 2005). Winkler method may be applied for the foundation soils that are very stiff layers such as bedrock since foundation settlements are uniform.

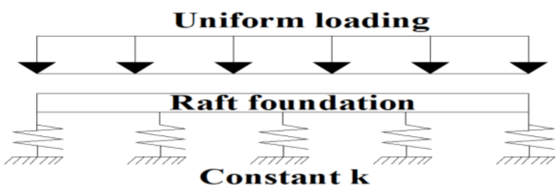



Figure 3. Winkler spring method

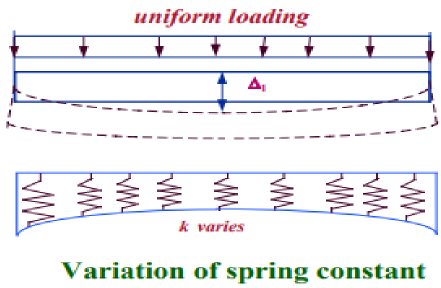



Figure 4. Dishing shape of raft foundation (Subramanian et al. 2005)

### 2.2.2 Pseudo-coupled Method

The soil underneath the structure should have continuity space when the real condition was taken into consideration. Loading at each point on the foundation affects all other points placed at the foundation. This situation is tried to be achieved by reducing the subgrade reaction coefficient defined by the Pseudo-coupled method. Thus, each spring affects the surrounding springs. While the most affected springs are located in the center region of the raft foundation, the less affected springs are positioned at the corner region of the raft foundation (Figure 4). In conclusion, the Pseudo-coupled method was developed for solving this shortcoming of the Winkler method.

The two important rules given below are taken into account in the Pseudo-coupled analysis method.

1- The raft foundation is divided into two or more loading areas. The innermost region should be arranged to have half of the width and length of the raft foundation.
2- The coefficient of subgrade reaction is determined for each region. At this stage, it should be noted that the bearing coefficient of the innermost region increases from the innermost region to the outside and that the bearing coefficient of the outermost region is approximate twice the bearing coefficient of the innermost region (Horwath, 1993).

To sum up, the coefficient of the subgrade reaction should be increased from the center region to the corner region during the analysis (Figure 3 and Table 4).

### 2.3 ETABS Analysis

The raft foundation is meshed into parts with different areas with respect to the number of regions of the model for finite element analysis performed with the ETABS program. Then both settlement and pressure applied to the raft foundation are calculated using Equation 1 by the program.

A 36m·36m raft foundation belonging to a 10-story symmetrical building was separately designed on four different sand soil subgrade layers that have different coefficient of subgrade reaction. The subgrade soil was assumed as homogeneous and infinite in depth. First, raft foundation was analyzed for all soil layers with the Winkler method. Then, the raft foundation was divided into 2, 3, 4, 7, and 10 regions and it was separately analyzed five more times with the Pseudo-coupled approach. Each model is illustrated in Figure 5. The regions in each model are numbered from the inside to the outside, such as $A_1$, $A_2$, $A_3$...

The raft foundation was divided into different regions in each model to be identified different coefficients of subgrade reaction. Thus, each region placed in these models has a different coefficient of subgrade reaction.

The values of the coefficient of subgrade reaction were calculated by using Equation 2.

$$k_1 \cdot A_1 + k_2 \cdot A_2 + \cdots + k_n \cdot A_n = k_{avg} \cdot A_{total} \qquad Eq. 2$$

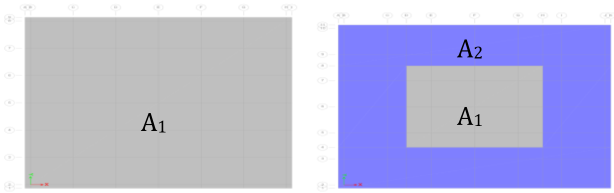
where $k_n$ is the coefficient of subgrade reaction at the region n, $A_n$ is the area of region n, $k_{avg}$ is a value of the coefficient of subgrade reaction used in the Winkler method, and $A_{total}$ is the total area of the raft foundation.

The area of each region in six models is given in Table 3. The unit of each value given in Table 3 is $m^2$.

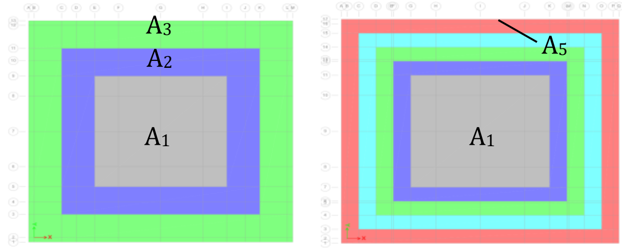
The coefficients of subgrade reaction identified for each region in the model are in relationship. Equation 3 shows this relationship between these parameters used in this study. Provided that x, n positive integer, $\boldsymbol{x} \geq \mathbf{2}$ and $\boldsymbol{x} \geq \boldsymbol{n}$, Eq. 3 can be used for any model.

$$k_1 = \cdots = \frac{(x-1) \cdot k_{x-n}}{2x-6} = \cdots = \frac{(x-1) \cdot k_{x-3}}{2x-5} = \frac{(x-1) \cdot k_{x-2}}{2x-4} = \frac{(x-1) \cdot k_{x-1}}{2x-3} = \frac{k_x}{2} \qquad Eq. 3$$

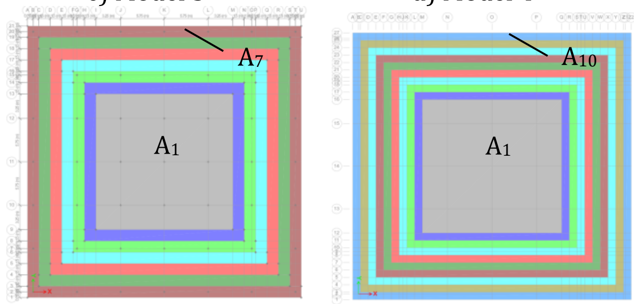
When the above equation is examined, the coefficients of subgrade reaction values should be multiplied by a separate ratio for both each model and each region. These ratios are given in Table 4.




a) Model 1 b) Model 2




c) Model 3 d) Model 4




e) Model 5 f) Model 6

Figure 5. Division of the foundation into suitable regions: a) The Winkler Method and Pseudo-Coupled Method by b) 2 regions, c) 3 regions, d) 5 regions, e) 7 regions, and f) 10 regions

Table 3. The area of each region in six models

| Region | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| $A_1$ | 1296 | 324 | 324 | 324 | 324 | 324 |
| $A_2$ | - | 972 | 405 | 182.25 | 117 | 76 |
| $A_3$ | - | - | 567 | 222.75 | 135 | 84 |
| $A_4$ | - | - | - | 263.25 | 153 | 92 |
| $A_5$ | - | - | - | 303.75 | 171 | 100 |
| $A_6$ | - | - | - | - | 189 | 108 |
| $A_7$ | - | - | - | - | 207 | 116 |
| $A_8$ | - | - | - | - | - | 124 |
| $A_9$ | - | - | - | - | - | 132 |
| $A_{10}$ | - | - | - | - | - | 140 |
| $A_{total}$ | 1296 | 1296 | 1296 | 1296 | 1296 | 1296 |

Table 4. Ratios of subgrade reaction coefficients for both each model and each region

| Region | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 | Model 6 |
|---|---|---|---|---|---|---|
| $A_1$ | 1.000 | 0.571 | 0.627 | 0.663 | 0.688 | 0.686 |
| $A_2$ | - | 1.142 | 0.941 | 0.829 | 0.801 | 0.762 |
| $A_3$ | - | - | 1.254 | 0.994 | 0.915 | 0.838 |
| $A_4$ | - | - | - | 1.160 | 1.030 | 0.914 |
| $A_5$ | - | - | - | 1.326 | 1.144 | 0.990 |
| $A_6$ | - | - | - | - | 1.259 | 1.067 |
| $A_7$ | - | - | - | - | 1.373 | 1.143 |
| $A_8$ | - | - | - | - | - | 1.219 |
| $A_9$ | - | - | - | - | - | 1.295 |
| $A_{10}$ | - | - | - | - | - | 1.371 |

The coefficient of subgrade reaction can be calculated from SPT-N values for sandy soils (Equation 4) (Scott, 1984).

$$k = 1800 \cdot N \quad \text{Eq. 4}$$

In the raft foundation analysis, four soils are defined under the foundation to represent the different subsoil conditions. According to Eurocode 8, the local soil class of Soil 1 and Soil 2 is C, and Soil 3 and Soil 4 is D. In addition, the SPT-N value of each soil is different. In this way, different soil conditions from low to high bearing capacity and durability were taken into account in the foundation analysis. SPT-N values and subgrade reaction values of the soils are given in the Table 5.

Table 5. SPT-N values and subgrade reaction values of foundation soils

| Soils | Local soil class | $SPT-N$ | k $(kN/m^3)$ |
|---|---|---|---|
| Soil 1 | D | 5 | 9000 |
| Soil 2 | D | 14.999 | 26999 |
| Soil 3 | C | 30 | 54000 |
| Soil 4 | C | 50 | 90000 |

The 10-story building were individually analyzed by using subgrade reaction values given in Table 5 with ETABS software. As a result of these analyzes, the change of the raft foundation shape and the settlements (at center point and corner point) were examined.

## 3. Results and discussions

The load combination (G+Q) acting on the structure during the analysis includes dead (G) and live (Q) loads. In addition, there is no horizontal force acting on the structure.

The foundation of the structure had 10 story building were separately analyzed for six models by using both Winkler and Pseudo-Coupled method. All analyzes were performed by using ETABS software.

### 3.1. Axial force and moment at column base

In the foundation analyses according to the Winkler method, the axial force transferred to the center column base is not much affected by the local soil class (Figure 6). In the analyzes performed according to the Pseudo-Coupled method, the axial force decreases by approximately 13% in Soil 1 in Model 2, and the axial force increases as the number of regions in the foundation increases. Similar behavior is observed in designs of other local soil classes. Especially as the bearing capacity of the soil increases (C class subsoil), the axial force transferred to the central column base comes closer to the Winkler solution. Since the building in which the foundation system is analyzed is symmetrical and has a square floor area, no moment is transferred to the central column because all the effects that come from the beams neutralize each other.

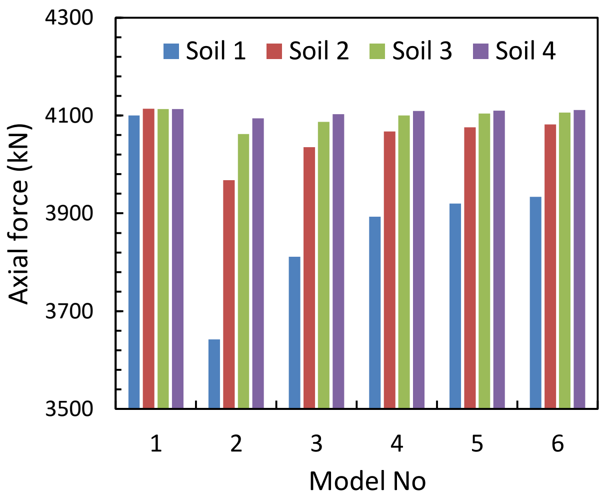



Figure 6. Axial force at center column base

The axial load transferred to the corner columns is about one-third of the center column. In all analyses in Winkler and Pseudo-Coupled methods, the axial force transferred to the corner column base increases as the bearing capacity of the foundation soil increases (from Soil 1 to Soil 4). In addition, as the number of regions in the foundation increases, the axial force at the corner column base increases (Figure 7). Moreover, contrary to the axial force, the moment values transferred to the corner column base decrease as the number of regions in the foundation and the bearing capacity of the foundation soil increase (Figure 8). The changes in the axial force and moment values vary according to the analysis type and the characteristics of the foundation soil, and this is due to the different settlements in the foundation (see Figure 15). Yao and Zhang (1985) reported that forces in members of superstructures affect the relatively stiffness between raft foundation and subgrade soils. The large internal forces in members of superstructures resulted from the differential settlement occurred in raft foundation (Zilch, 1993).

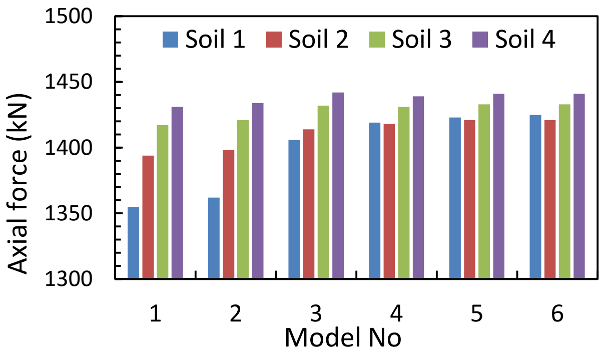



Figure 7. Axial force at corner column base

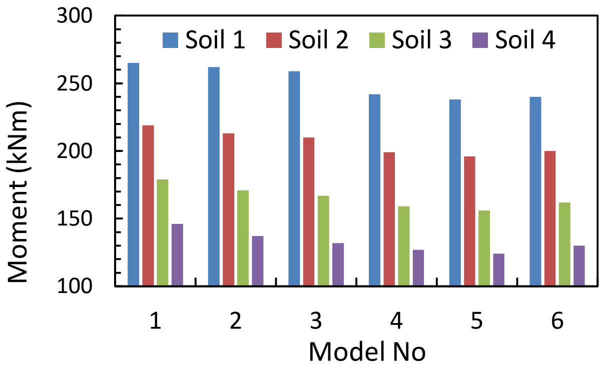



Figure 8. Moment values at corner column base

### 3.2. Subgrade reaction coefficient

The raft foundation built on the sandy soils with different subgrade coefficient values was analyzed with six different models. In the first model, the raft foundation has one area and each point of this foundation that has same subgrade coefficient. In other models, the raft foundation is divided into two or more areas. The subgrade coefficient values for these areas were multiplied with the ratios given in Table 4. As the raft foundation is square, the ratios defined for these regions in each model are shown according to the width and length of the foundation in Figure 9.

As seen in the Figure 9, ratios of subgrade reaction coefficients give very close values for solutions with 5 regions (Model 5) and greater regions.

### 3.2. Settlements of foundation

The foundation shapes obtained from analyzes are given in Figure 10 and Figure 11.

After ETABS analyzes for each model, the settlements that were calculated at the corner and center points of the raft foundation are given in Table 6.

Model 1 was analyzed by using Winkler method that each point placed in the raft foundation has same subgrade reaction coefficient. Although the maximum settlement is formed at corner points of raft foundation, the settlements occurred under the foundation are approximately close each other. In other words, there is a very little differences between the corner settlements and center settlements. In addition to this, the increase of subgrade coefficient of soil result in the reduction of differential settlements. The foundation shape obtained from this analysis is almost similar to the shape of the rigid foundation. In addition, the behavior of rigid raft foundation depends on the value of subgrade reaction of soil since the greater the subgrade reaction of soil leads to more rigid behavior of raft foundation. Model 1 could be used for analysis of the rigid raft foundation. However, the increase in subgrade reaction value triggers the rigid behavior of raft foundation.

Models, other than Model 1, were analyzed with respect to Pseudo-coupled method. The values of subgrade reaction coefficient changes at the different foundation regions identified in this method.

Five different models prepared with Pseudo-coupled method were analyzed by using ETABS software. While the maximum settlements of these models were occurred at the center point of the raft foundation, the minimum settlements were occurred at the corner point of the raft foundation. These outputs means that the raft foundation behave flexible.

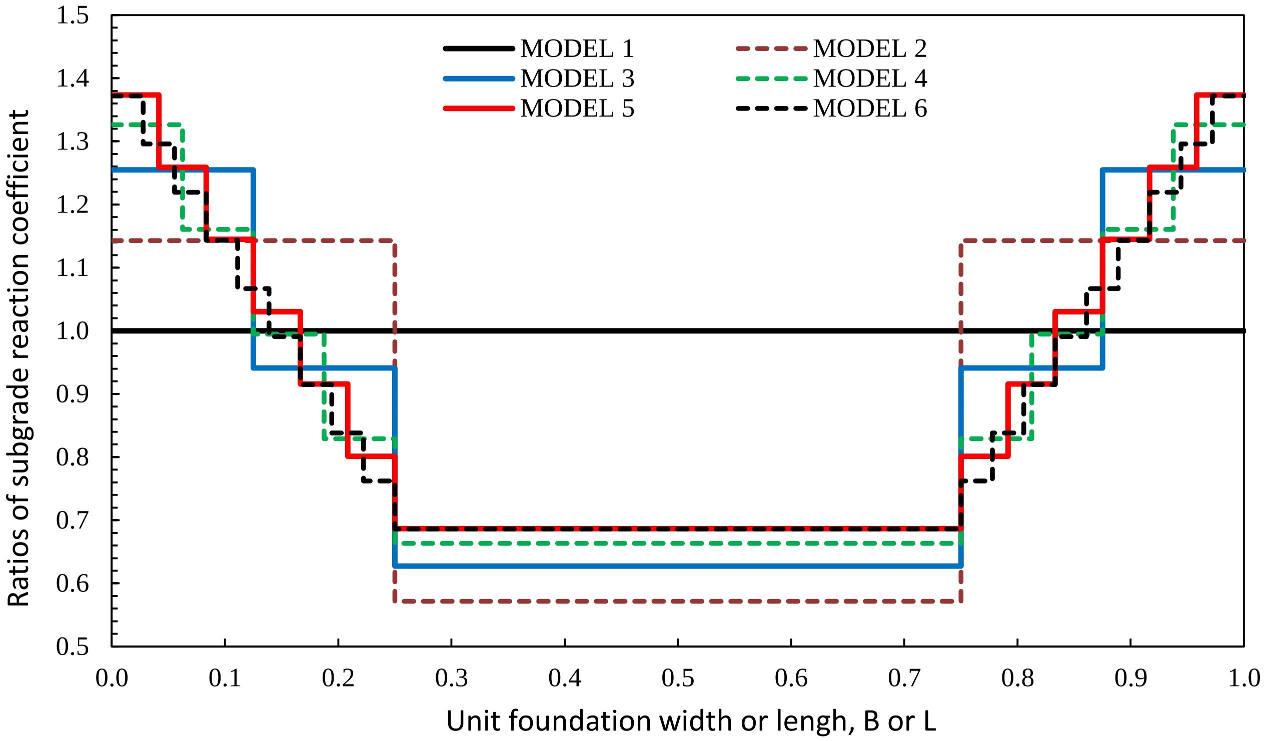



Figure 9. Ratios of subgrade reaction coefficients with respect to foundation width or length

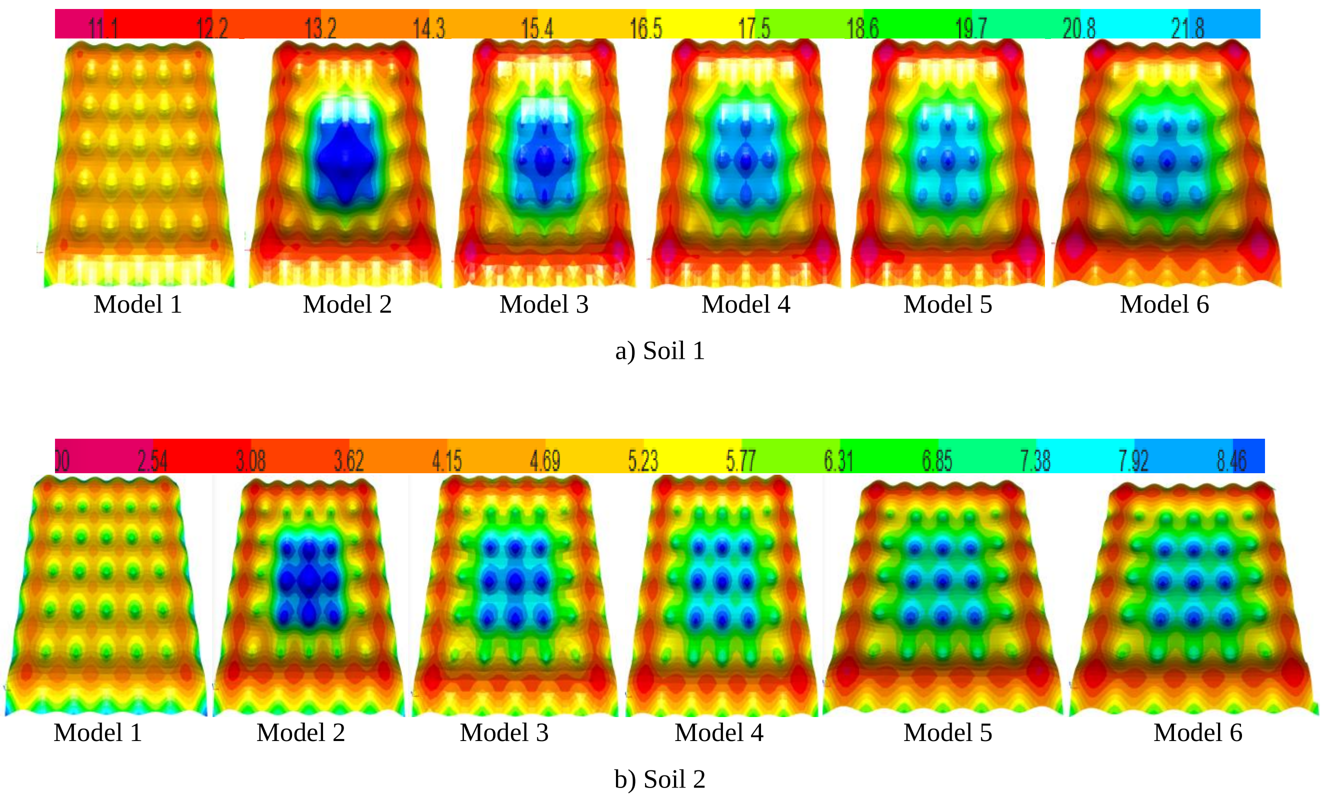


Figure 10. The foundation shapes designed on a) Soil 1 and b) Soil 2 (units in mm)

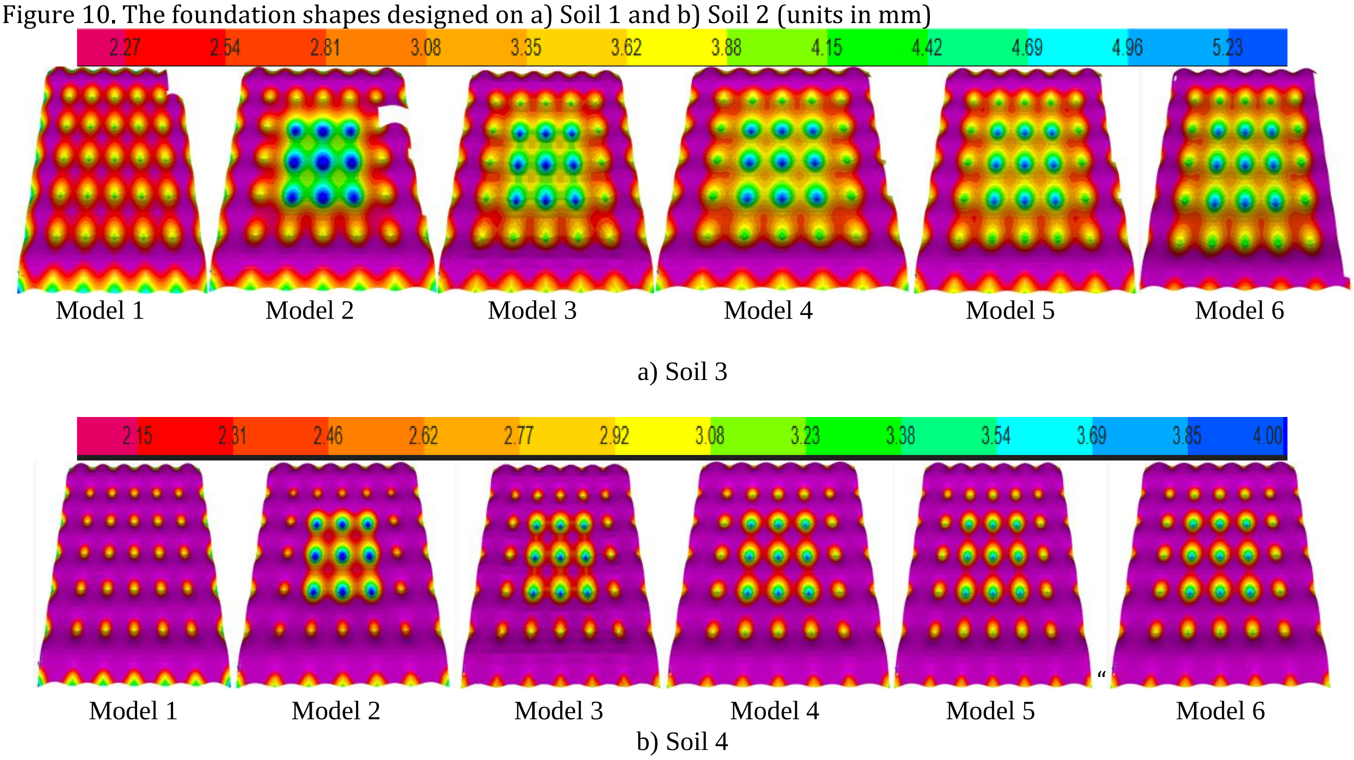



Figure 11. The foundation shapes designed on a) Soil 3 and b) Soil 4 (units in mm)

Table 6. Settlements at corner and center points of foundation

| Models | Settlements (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Soil 1 | | Soil 2 | | Soil 3 | | Soil 4 | |
| | Centre point | Corner point | Centre point | Corner point | Centre point | Corner point | Centre point | Corner point |
| **Model 1** | 17.712 | 20.287 | 7.07 | 9.06 | 4.349 | 5.711 | 3.207 | 4.093 |
| **Model 2** | 27.713 | 18.241 | 11.100 | 8.27 | 6.443 | 5.235 | 4.505 | 3.747 |
| **Model 3** | 26.161 | 16.717 | 10.304 | 7.484 | 6.029 | 4.687 | 4.263 | 3.306 |
| **Model 4** | 25.150 | 16.448 | 9.812 | 7.432 | 5.755 | 4.720 | 4.086 | 3.376 |
| **Model 5** | 24.456 | 16.139 | 9.535 | 7.281 | 5.611 | 4.617 | 3.998 | 3.297 |
| **Model 6** | 24.533 | 16.342 | 9.544 | 7.383 | 5.614 | 4.695 | 4.000 | 3.363 |

The maximum settlement value at corner and center points gives maximum differential settlement were determined in the analysis of Model 2. When the number of the regions into the model increases, the settlement values at corner and center points of the raft foundation gradually decrease. The differential settlements values decrease with the number of the regions into the model.

Figure 12 shows that ratios of center settlement to corner settlement calculated with respect to the outputs of analyzes given in Table 6.

The highest settlement ratios between center and corner points are obtained in Model 3 that has three different areas for all subsoil conditions.

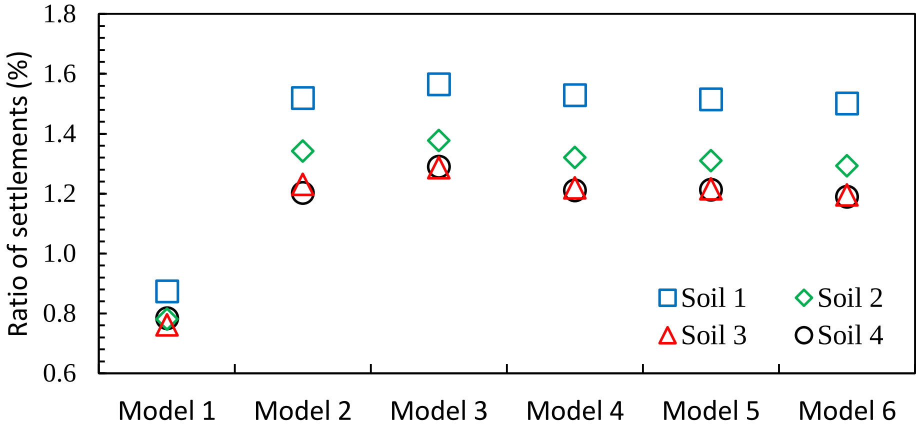
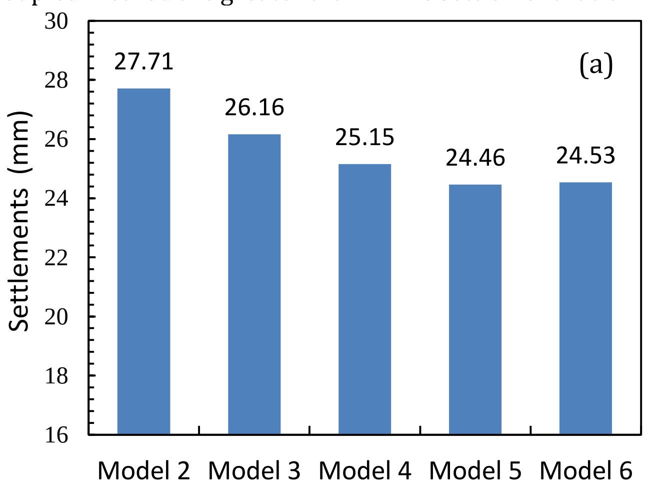



Figure 12. Ratios between center settlements and corner settlements

Maximum settlement ratios between center and corner points were obtained from analyzes performed on Soil 1 had lowest stiffness for each model. The settlement ratios gradually decrease with the increment of soil stiffness. The settlement ratios of Model 1 are lower than 1 and are approximately similar for all subsoil conditions. Thus, the settlements obtained from Winkler method are suitable for rigid foundation assumption. However, the settlement ratios obtained from Pseudo-Coupled method are greater than 1. The settlement ratio is around 1.5 for Soil 1 and the increase of soil stiffness reduces the settlement ratio.

In the Pseudo-Coupled method, settlement values at the corner and center points decreases up to Model 5 has 7 regions and then increases. Figure 13 clearly shows this phenomenon in the case of Soil 1. It is concluded that an optimal region number for foundation analysis in the Pseudo-Coupled method is 7.



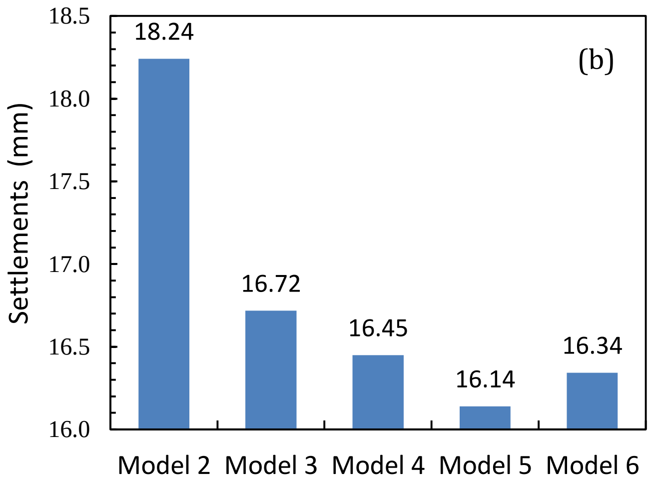




Figure 13. Settlements at the foundation a) corner and b) center points for subbase of Soil 1

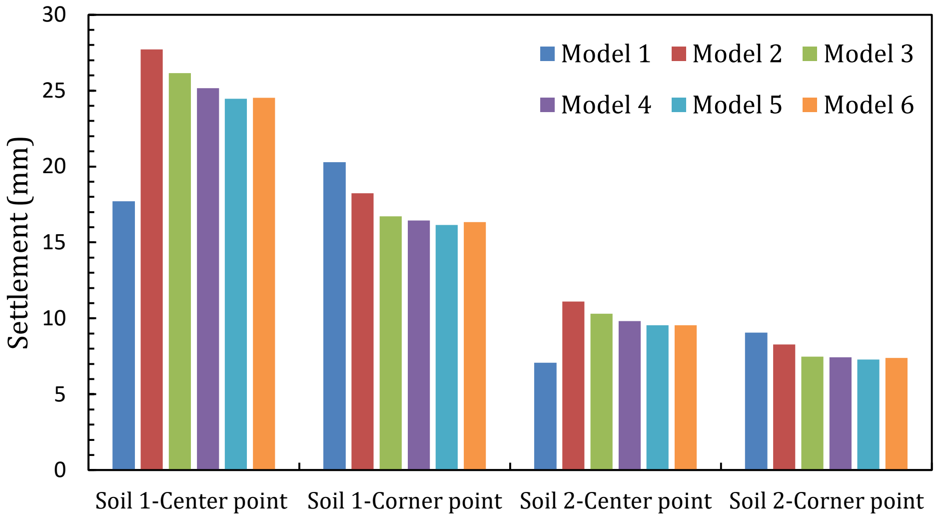
### 3.3. Effect of local soil class

The settlement values given in Table 6 has to be evaluated with respect to the local soil class of the subsoil under the superstructure. According to Eurocode 8, while Soil 1 and Soil 2 is classified as C, Soil 3 and Soil 4 is classified as D. Settlements values calculated from both center point and corner point are illustrated in Figure 14 with respect to soil types.

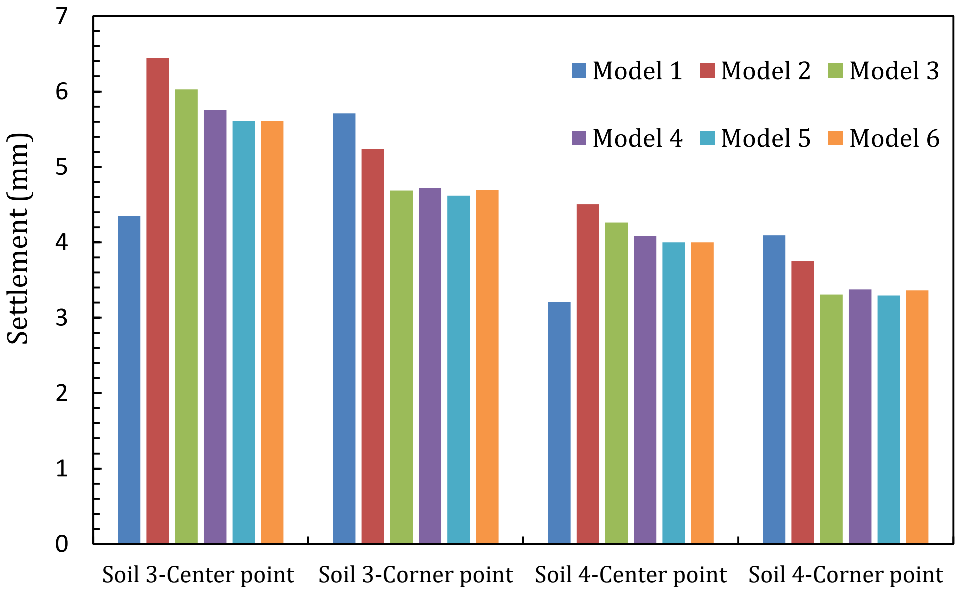
The maximum settlement of corner point of soils that are both Class C and Class D is calculated from Model 1 that has one region. The maximum settlements of center point of soils that are both Class C and Class D is calculated from Model 2 that has two regions.

Differential settlements are a considerable parameter for raft foundation. Since, one of the aims of raft foundation construction is the reduction of differential settlements. For this reason, differential settlement has to be controlled during the analysis of this foundation type. Figure 15 show the values of differential settlement calculated from analyzes done in this study. The maximum differential settlement values were calculated from Model 2 analysis for soils classified as D with respect to Eurocode 8. Thus, Model 2 is suitable for flexible foundation assumption. However, the minimum differential settlement values were calculated from Model 1 analysis for soils classified as D with respect to Eurocode 8. Thus, the rigid foundation assumption is a suitable Model 1 for the soils that is classified as D according to Eurocode 8.

The minimum values of differential settlements were calculated from the analysis of Model 6 for both Soil 3 and Soil 4. To sum up, the rigid foundation assumption is a suitable Model 6 for the soils that is classified as C according to Eurocode 8. The maximum differential settlement values were calculated from models that were divided into three or less regions for both Soil 3 and Soil 4. Flexible foundation assumption is valid for these models analyzed on C class soils. These models analyzed on C class soils. Yao and Zhang (1985) reported that both the differential settlements and forces in members of superstructures affect the relatively stiffness between raft foundation and subgrade soils. To sum up, the differential settlement reduces with the stiffness of subgrade soil in this study.

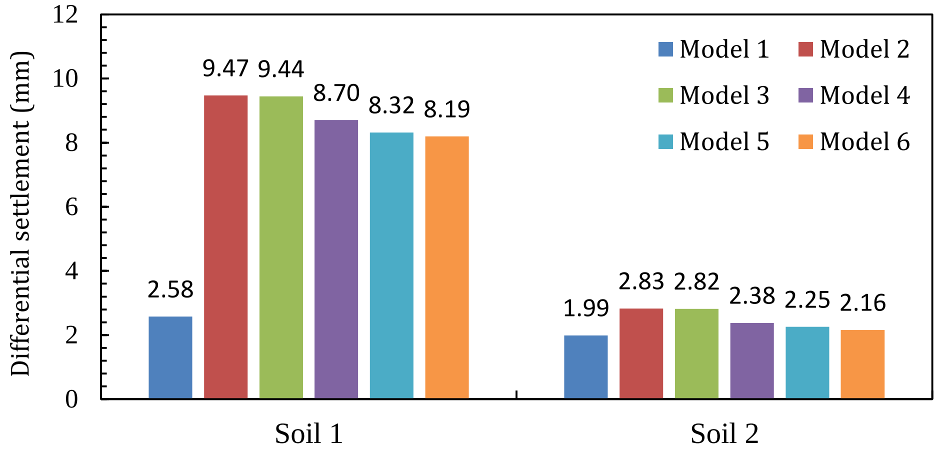



a) Settlements at the D class subsoil

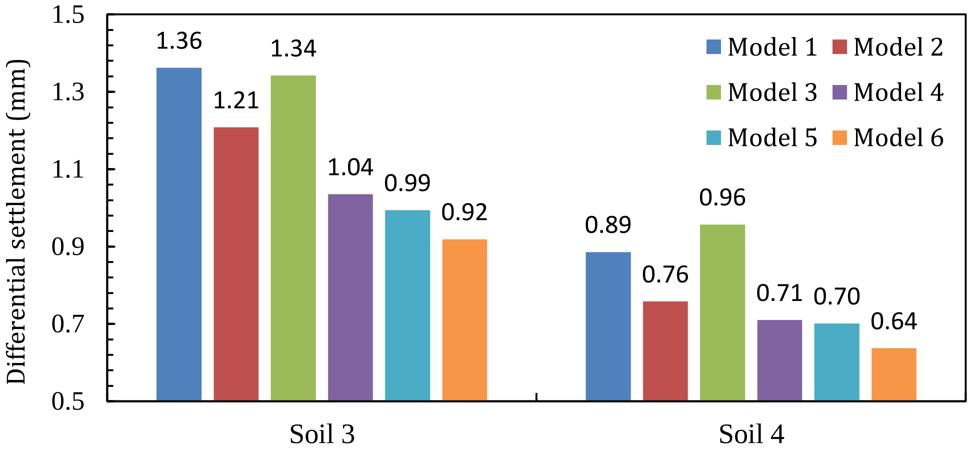



b) Settlements at the C class subsoil

Figure 14. Effect of local soil class on foundation settlement




a) D class subsoil layer




b) C class subsoil layer

Figure 15. Differential settlements values considering local soil class of subsoil

## 4. Conclusions

The settlements of raft foundation were separately analyzed by using Winkler and Pseudo-coupled methods. The main scope of this study is that the comparison of Winkler method and Pseudo-coupled method by doing ETABS analyzes. Then, the effect of subgrade reaction values on the behavior of the raft foundation were investigated by using four different sand soils. In addition to these, two of these soils are classified as C and the others are classified as D according to Eurocode 8.

The behavior of raft foundation analyzed by using Winkler method and Pseudo-Coupled method changes with respect to soil class that are C and D.

Winkler spring approach used at finite element analysis can be considered as a suitable method for the rigid foundation done on D class soils. Since, the settlements calculated at each point of the raft foundation are close to each other. For the flexible foundation assumption of D class soils, raft foundation should be divided into either two regions or more regions.

Pseudo-coupled spring approach used at finite element analysis can be considered as a suitable method for the rigid foundation done on C class soils. Since, the differential settlement between corner point and center point of the raft foundation was determined as a serious value. However, raft foundation should be divided into either three regions or less. Therefore, the flexible foundation assumption of C class soils is generally valid for raft foundation analyzed by using both Winkler method and Pseudo-Coupled method that has maximum three regions.

The values of both highest settlement and differential settlement were found from the two regions among the Pseudo-coupled methods. When the number of zones at Pseudo-coupled method increase, the settlement values determined at any point of the raft foundation and differential settlement generally decrease with respect to the outputs obtained from ETABS analyzes. In conclusion, the highest settlement values are determined from ETABS analysis that include two-zone Pseudo-coupled method.

Model that has 7 regions is an optimum model for Pseudo-coupled method.

The maximum settlement ratio between center point and corner point of raft foundation are determined from model that has three regions. The optimum settlement ratios can be found from models that consists of three regions.

The other output related to both Winkler and Pseudo-coupled methods is that the behavior of raft foundation (rigid or flexibly) depends on the subgrade reaction coefficients of soils placed under the structure. Since, the increase of the values of this parameter means that the less settlement value form at any point of raft foundation. Thus, the values of settlements at both corner and center point decrease and differential settlement value gradually reduces. At this point, the value of subgrade reaction coefficient should be determined properly prior to the design of raft foundation.

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**Conflict of interest**

The authors declare that there is no conflict of interest regarding the publication of this article.

**Contribution of Researchers**

İ. ÖZKAN and Y. YENGİNAR contributed to literature review, Winkler and Pseudo-coupled methods implementation and evaluation of the results of this study. A. S. ECEMİŞ contributed to design of building and raft foundation, conducted ETABS analysis, and evaluation of the results of this study.

**References**

ACI 336.2R-88 (2002) suggested analysis and design procedures for combined footings and mats, Report by ACI Committee 336

Bhartiya, P., Chakraborty, T., & Basu, D. (2020). Nonlinear subgrade modulus of sandy soils for analysis of piled raft foundations. Computers and Geotechnics, 118, 103350.

Cheung Y. K., Zienkiewicz O. C., (1965), Plates and tanks on elastic foundations-an application of finite elementmethod, Int .J. Solids Struct.,1,451–461.

Costa J. A., Brebia C. A., (1985), Bending of plates on elastic foundation using the boundary element method, Proc.2ndInt.Conf.ªariational Methods in Engineering, University of Southampton, 1985, pp. 523–533.

El-garhy, B., Osman, M. (2002). Winkler coefficient for Beams on Elastic Foundation. ERJ. Engineering Research Journal, 25(3), 1-18.

Fox E. N., (1948), The mean elastic settlement of a uniformly loaded area at a depth below the ground surface.Proc.2nd Int. Conf. on Soil Mechanics and Foundation Engg., Rotterdom, Vol 1, 1948, pp. 129–132.2.

Fraser R. A., Wardle L. J., (1976), Numerical analysis of rectangular rafts on layered foundations, Geotechnique.,26(4),613–630.

Horvath, J.S., (1993), Subgrade Modeling Jr Soil-Structure Interaction Analysis of Horizontal Foundation Elements, Manhattan College Research Report No. Celge-93-I, Manhattan College, New York.

Katsikadelis J. T., Armenakas A. E., (1984), Analysis of clamped plates on elastic foundation by BIE method , J.Appl.Mech.,51,574–586.

Loukidis D., Tamiolakis G.P., 2017, Spatial distribution of Winkler spring stiffness for rectangular mat foundation analysis, Eng Struct, 153 (2017), pp. 443-459

Ma, C.M., Chen, Y.Y. (2019). Research on the differential settlements of mat foundations. IOP Conference Series: Earth and Environmental Science, 351(1).

Mandal, J. J., & Ghosh, D. P. (1999). Prediction of elastic settlement of rectangular raft foundation—a coupled FE–BE approach. International journal for numerical and analytical methods in geomechanics, 23(3), 263-273.

Modak, R., & Singh, B. (2022). A parametric study of large piled raft foundations on clay soil. Ocean Engineering, 262, 112251.

Özer Ö., Yüksel, B., (2021), Comparison of the effect of foundation analysis methods on structural analysis results of tall buildings. International Advanced Researches and Engineering Journal, 5(1), 106-112.

Prabhu, P., & Mutalikdesai, V. G. (2023). Soil-Solid Raft Interaction Analysis Subjected To Seismic Forces. //doi.org/10.21203/rs.3.rs-2437896/v1

Rashedul H. Chowdhury, Mavinakere E. Raghunandan AM (2013) Study on the analysis of mat foundation using different approach. Icsdec 818–825

Scott, R. F. (1984). "Foundation analysis", 143. London: Prentice Hall International.

Subramanian, K.V., Kashikar, A.V., Nath, C., and Shintre, C.C. (2005). "Analysis of raft foundations for spent fuel pool in nuclear facilities." Proc. 18th Intl. Conference on Structural Mechanics in Reactor Technology, China: 3165- 3178.

Teli, S., Kundhani, P., Choksi, V., Sinha, P., & Iyer, K. K. (2020). Analytical Study on the Influence of Rigidity of Foundation and Modulus of Subgrade Reaction on Behaviour of Raft Foundation. In Advances in Computer Methods and Geomechanics: IACMAG Symposium 2019 Volume 2 (pp. 181-194). Springer Singapore.

Teodoru IB, Toma IO (2009) Numerical analyses of plate loading test. The Bulletin of the Polytechnic Institute of Jassy, Construction. Architecture Section, Romaina, Section LV (LIX), 57–65

Todorovska, M. I., Hayir, A., & Trifunac, M. D. (2001). Flexible versus rigid foundation models of soil-structure interaction: incident SH-waves. In Proc. 2nd US-Japan Workshop on Soil-Structure Interaction.

Yao Z. E. and Zhang J. R., (1985). Assessment of the effects of structure/raft/soil interaction. in Proceedings of the 5th international conference on Numerical Methods in Geomechanics, Japan Soc of Civil Engineers, pp. 813–819, A. A. Balkema, Nagoya University, Nagoya, Japan.

Zilch K., (1993). Soil - structure interaction, in Proceedings of the safety and performance concepts: contributions to the workshop-sessions "model uncertainties", "new concepts" and "full scale testing", organized by task groups of commission 1, pp. 73–98, Comit´e Euro-International du B´eton (CEB), London, United Kingdom.