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Ankastre Temel, Winkler ve Psödo-eşlenik Yöntemlerine Göre Üstyapı Performansının İncelenmesi

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ÖZET

Bu çalışmada, orta sıkı kumlu zemin üzerine oturan 5 katlı bir binanın performansı ankastre temel, Winkler ve Pseudo-eşlenik yöntemleriyle analiz edilmiştir. Yapının periyodu, kolonlara etki eden eksenel yükler ve kesme kuvvetleri, deprem kuvvetleri, kat yer değiştirmeleri, temel taban basıncı ve yer değiştirme değerleri statik ve dinamik yükleme durumlarında belirlenmiştir. Yapısal mühendislikte kullanılan temel çözüm yöntemi, çeşitli yükleme koşullarında binaların dinamik ve statik davranışlarını derinden etkilemektedir. Winkler ve Pseudo-eşlenik yöntemlerinin ankastre temele göre karşılaştırılmasıyla, birkaç önemli fark ortaya çıkmıştır: Winkler ve Pseudo-eşlenik yöntemlerinde bina periyotları birbirine yakın iken ankastre temel çözümünde periyot %6,7 daha fazla olmaktadır. Ölü ve hareketli yük (G+Q) altında kolonlara etki eden eksenel yükler temel analiz yönteminden oldukça az etkilenmektedir, ancak deprem (EQx) yükü altında Winkler ve Pseudo-eşlenik yöntemleri, ankastre temel yöntemine göre 1. ve 5. kat kolonlarındaki eksenel yükleri önemli ölçüde azalmaktadır. Köşe kolonlarındaki kesme kuvvetleri Winkler ve Pseudo-eşlenik yöntemlerinde %46 daha düşük elde edilmiştir. Ayrıca, bu yöntemler deprem kuvvetinde %7 artış ve ankastre temel yöntemine göre %4,7 daha az kat yer değiştirmesi sonucunu vermiştir. Maksimum temel basıncı, oturma ve farklı oturmanın konumu, kullanılan temel analiz yöntemine bağlı olarak değişmektedir. Bu bulgular, özellikle deprem olayları gibi farklı yükleme senaryoları altında yapısal stabilite, performans ve dayanıklılığın optimize edilmesinde temel seçiminin kritik rolünü vurgulamaktadır.

Investigation of Superstructure Performance Based on the Fixed Base Foundation, Winkler, and Pseudo-Coupled Methods

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ABSTRACT

In the present study, the performance of 5-story building resting on medium dense sandy soil was analyzed by fixed-base, Winkler and Pseudo-coupled methods. The period of structure, axial loads and shear forces acting on columns, earthquake forces, story displacements, foundation base pressure and settlement values were determined in static and dynamic loading cases. The choice of foundation solution method in structural engineering profoundly influences the dynamic and static behavior of buildings under various loading conditions. Comparing Winkler and Pseudo-coupled methods to the fixed-base foundation, several key differences emerge: building periods are closer together in Winkler and Pseudo-coupled methods, with fixed-base periods being 6.7% longer. Axial loads on columns under gravity plus live load (G+Q) are minimally affected by the foundation method, but under earthquake (EQx) loading, Winkler and Pseudo-coupled methods significantly reduce axial loads on 1st and 5th floor columns compared to the fixed-base method. Shear forces on corner columns are 46% lower with Winkler and Pseudo-coupled methods. Moreover, these methods result in a 7% increase in earthquake force and 4.7% less story displacement than the fixed-base method. Additionally, the location of maximum base pressure, settlement, and differential settlement varies depending on the foundation analysis method employed. These findings emphasize the critical role of foundation selection in optimizing structural stability, performance, and resilience under different loading scenarios, particularly seismic events.

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INTRODUCTION

The stability and structural integrity of any building rely fundamentally on the efficacy of its foundation system [1]. In civil engineering, the choice of foundation analysis method plays a pivotal role in ensuring the safety and longevity of structures, particularly in the context of varying soil conditions, structural loads, and environmental factors [2,3,4]. Among the myriad techniques available, three prominent methodologies stand out: the fixed base method [5,6], the Winkler method [7,8,9], and the pseudo-coupled approach [10]. Each of these methods offers distinct advantages and considerations in analyzing foundation behavior and subsequently influencing the stability and performance of the superstructure they support.

The fixed base method represents a classical approach to foundation analysis, assuming a rigid connection between the foundation and the underlying soil. This method simplifies the analysis by negating the effects of soil-structure interaction, thereby treating the structure as isolated from its supporting medium [11,12]. While this assumption facilitates straightforward analysis and design processes, it may lead to inaccuracies in predicting structural response, particularly in situations where soil characteristics significantly influence structural behavior [13,14].

In contrast, the Winkler method acknowledges the interaction between the structure and the underlying soil through a simplified representation of soil behavior [15,16,17]. It divides the soil into discrete springs or elements, each characterized by stiffness parameters such as the modulus of subgrade reaction. By incorporating soil-structure interaction in this manner, the Winkler method offers a more realistic representation of foundation behavior compared to the fixed base approach [18,19,20]. However, its accuracy is contingent upon appropriate selection and calibration of soil parameters, which can pose challenges in practice, especially for heterogeneous soil profiles [18,21].

In the analysis of building structures, the fixed-base assumption can be preferred. However, since this method typically neglects soil effects, it may lead to inaccurate modeling of dynamic behavior. Fixed-base analysis often underestimates the natural period of the building while overestimating its frequency. In contrast, when soil springs are introduced using the Winkler method, dynamic behaviors, such as the increase in the natural period due to poor soil conditions, are more realistically represented. Neglecting soil effects, particularly for weak soils, can result in incorrect calculation of seismic loads. Therefore, the Winkler method provides more accurate results and should be favored over the fixed-base assumption in building design and analysis [22].

The pseudo-coupled method represents a more advanced approach that seeks to reconcile the advantages of both the fixed base and Winkler methods while mitigating their respective limitations. This method employs numerical techniques, such as finite element analysis, to simulate the interaction between the structure and the underlying soil in a more comprehensive manner [10]. By considering the dynamic and nonlinear behavior of both the structure and the soil, the pseudo-coupled method offers enhanced accuracy in predicting foundation response and superstructure stability under various loading conditions [21,23,24]. However, its implementation may require specialized expertise and computational resources, making it less accessible for routine engineering applications.

The Winkler and Pseudo-coupled methods differ in their handling of raft foundation settlements and soil-structure interaction. The Winkler method is simpler and effective for rigid foundations, particularly on D-class soils, where settlements are nearly uniform. In contrast, the Pseudo-coupled method is more suitable for flexible foundations or rigid foundations on stronger C-class soils, as it accounts for differential settlements by dividing the raft foundation into multiple regions. Increasing the number of regions in the Pseudo-coupled method improves accuracy, reducing both settlement and differential settlement values. Both methods rely heavily on the accurate determination of the subgrade reaction coefficient, which directly affects settlement behavior. While the Winkler method offers simplicity, the Pseudo-coupled approach provides greater precision, especially for complex soil conditions [9].

Understanding the effects of foundation analyses with fixed base, Winkler, and pseudo-coupled methods is crucial for ensuring the safety, efficiency, and cost-effectiveness of structural designs. By elucidating the interplay between these methodologies and their impact on superstructure stability, engineers can make informed decisions in selecting the most appropriate foundation analysis technique for a given project, thereby optimizing the performance and resilience of built infrastructure in diverse geotechnical environments.

In the present study, the performance of 5-story building resting on medium dense sandy soil was analyzed by fixed-base, Winkler and Pseudo-coupled methods. The period of structure, axial loads and shear forces acting on columns, earthquake forces, story displacements, foundation base pressure and settlement values were determined in static and dynamic loading cases.

MATERIALS AND METHODS

Site Conditions

A location was chosen in Hatay, one of the provinces most affected by the Kahramanmaraş earthquake on February 6, 2023 to determine local ground properties. The selected location (latitude: 36.198535, longitudal:36.159735) belongs to one of the buildings located by the Asi River in the center of Hatay.

The sediments in the Antakya region primarily consist of clay, sand, and gravel within alluvial deposits. The local soil class is generally weak, with some areas classified as ZD [25].

A medium dense sandy soil profile with infinite depth was designed under the structure. Geotechnical properties and seismic parameters of the soil are given in Table 1.

Table 1
Geotechnical and seismic properties of local soil.

Property	Value
Standard penetration blow count, N_{SPT}	15.0
Bulk unit weight, γ_n (kN/m^3)	17.3
Poisson ratio, ν	0.3
Oedometric Modulus, E (MPa)	18.6
Coefficient of subgrade, k (kN/m^3)	18000
Local soil class (TBEC, 2019)	ZD
Local soil class (EN 1998-1, 2004)	C
Short period design spectral acceleration coefficient, S_{DS}	1.1399
Short period map spectral acceleration coefficient, S_S	1.0590
Map spectral acceleration coefficient for 1.0 second period, S_1	0.2760
Design spectral acceleration coefficient for 1.0 second period, S_{D1}	0.5652
Local soil impact coefficient for short period region, Fs	1.0764
Local soil impact coefficient for 1.0 second period, F_1	2.0480

Structure information

In the central area of Hatay, a variety of buildings of varying heights could be found at the located along the banks of the Asi River. Notably, the 5-story structures exhibited superior seismic performance during the February 6 earthquake when compared to taller buildings [26]. In the study, the performance of 5-story building is investigated based on the foundation analyses methods. The properties of building are presented in Table 2. The building is symmetrical and has a square raft foundation. The 3D visual and typical floor and foundation plan of the building modeled with Etabs program, which analyzes with finite element method, are presented in Figure 1 and Figure 2.

Table 2
The properties of building.

Number of Story	5
Story Height (m)	3
Structure Height (m)	15
Span X-Y (m)	5.75
Number of Span X-Y	6
Building Dimensions (m)	34.50 x 34.50
Column Dimensions (m)	50 x 50
Beam Dimensions (m)	40 x 60
Slab Thickness (m)	0.150
Dead Load (kN/m^2)	2.50
Live Load (kN/m^2)	3.50
Concrete Class	C30/37
Reinforcement	B420C
Analysis type	Vertical+Horizontal
Load-bearing system behavior coefficient, R	8.00
Resistance excess coefficient, D	3.00
Building importance coefficient, I	1.00

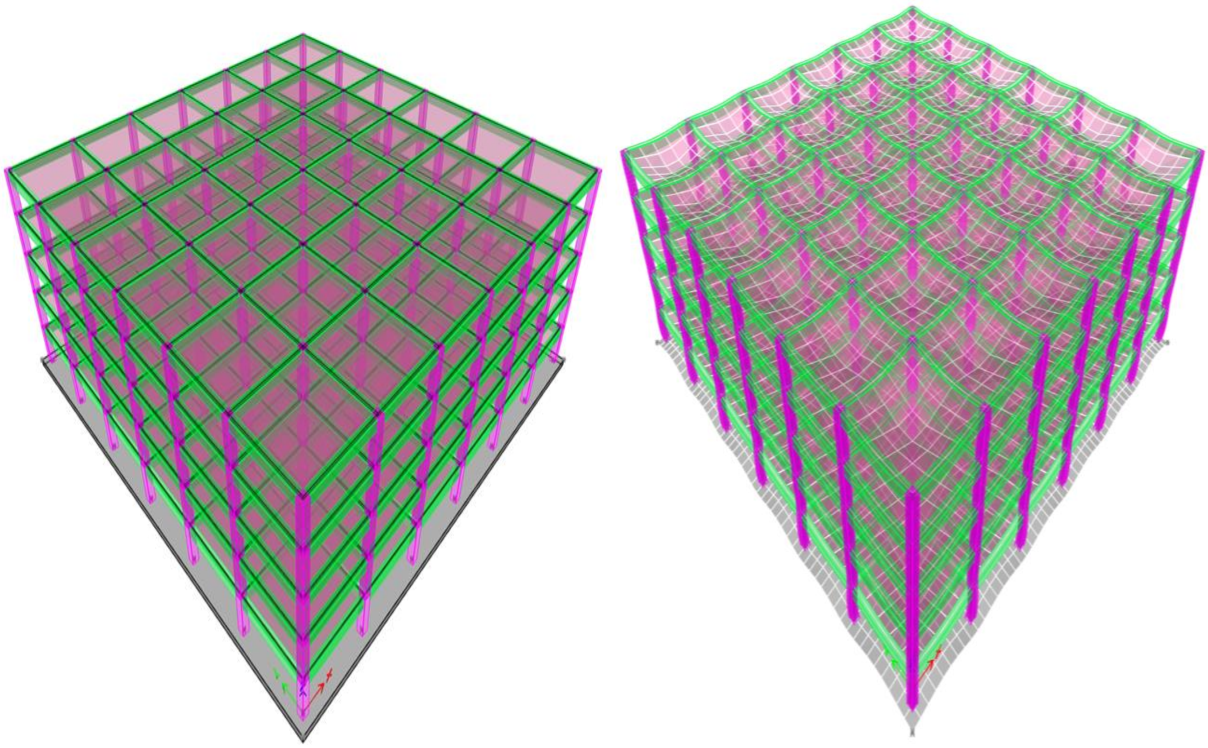

Figure 1
The perspective and meshed view of building.

In the analyzes, the effective section stiffnesses, which are required to be used in TBDY 2018, were taken into consideration. The effective section stiffness multipliers for horizontal and vertical elements are shown in Table 3.

Table 3
Effective section stiffness multipliers.

Reinforced Concrete Structural System Element	Effective Cross Section Stiffness Multiplier	
Slab (In plane)	**Axial**	**Shear**
Slab	0.25	0.25
Slab (Out of Plane)	**Bending**	**Shear**
Slab	0.25	1.00
Frame	**Bending**	**Shear**
Beam	0.35	1.00
Column	0.70	1.00

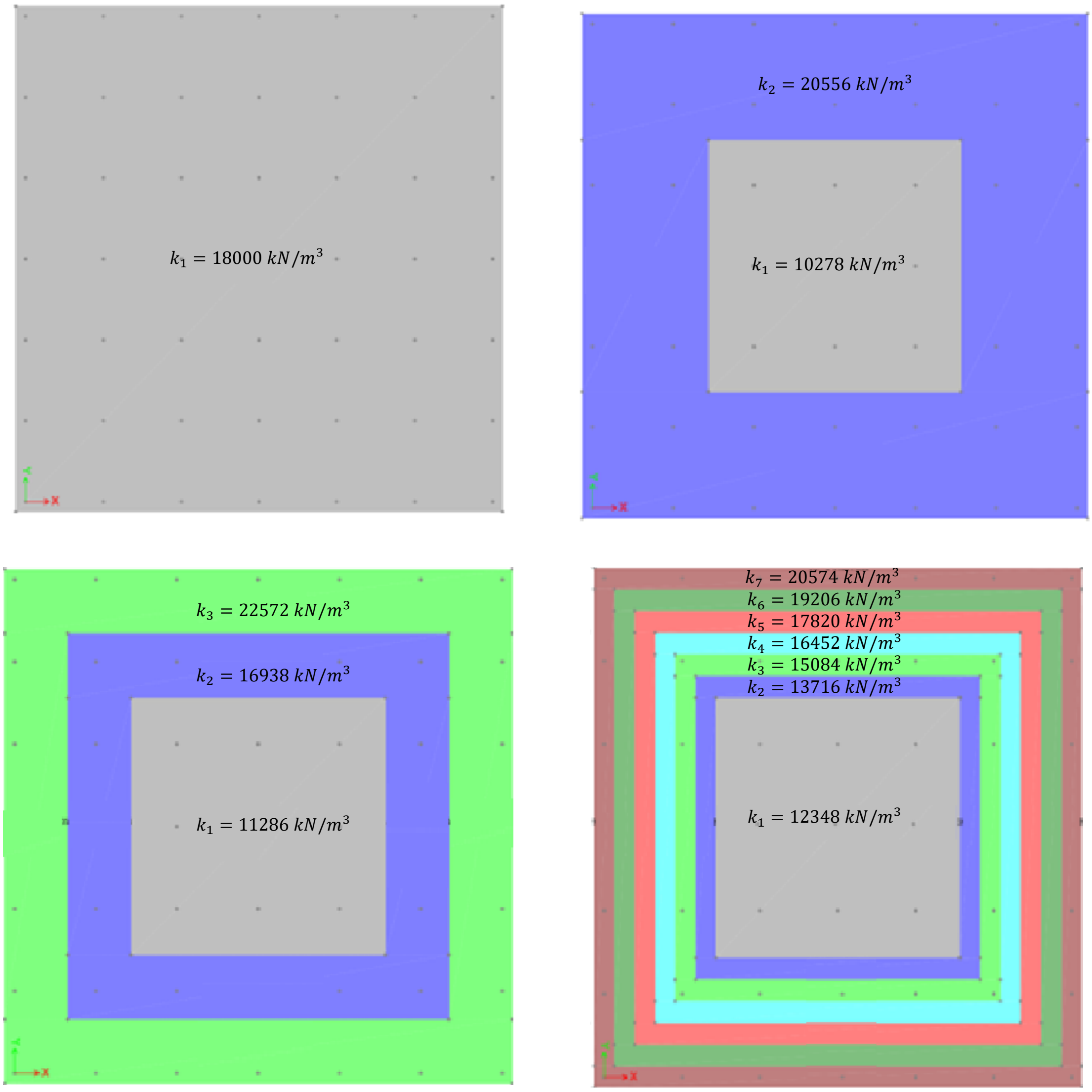

Figure 2
The foundation modelling and assigned area springs of models.

Methodology

The foundation of building has a width and length of 34.5m and 34.5 m, respectively. A soil has an 18000 kN/m^3 of subgrade reaction is defined under the foundation. The foundation is analyzed based on the fixed base, Winkler, and Pseudo-coupled methods.

In the fixed base analysis, any soil is not defined under the foundation and therefore the soil-structure interaction is not existing.

In the Winkler method [9], the soil under the foundation is modeled with springs of equivalent stiffness. The spring coefficient corresponds to the subgrade coefficient of the soil (k_s), and it is assumed that each spring operates independently of each other. The soil subgrade coefficient is obtained by dividing the stress applied to the soil by the amount of settlement that occurs (see Eq. 1). The stress occurring in the foundation base arises from the loads transferred from the superstructure to the foundation (dead load, live load, earthquake forces, etc.). As long as the soil subgrade coefficient and foundation base pressure are known, settlements under the foundation can be determined. Analysis of the soil-structure interaction examines the settlement profile under the foundation and the resulting changes in the performance of the superstructure. However, modeling the soil under the foundation with equivalent springs in the Winkler method provides only an approximate solution for soil-structure interaction. It is known that the actual settlement profile varies according to differences in soil-foundation stiffness. To address this limitation of the Winkler method, the pseudo-coupled method was developed.

$$k_s = \frac{q_0}{s} \tag{1}$$

where, k_s is subgrade coefficient of soil, q_0 is base pressure of foundation, s is the settlement.

In the pseudo-coupled method, the foundation is divided into different regions and a different bearing coefficient is defined under each region. While the foundation is divided into different regions, the edge lengths of the innermost region are half of the foundation edges in both directions. In addition, the subgrade coefficient of the outer zone is defined to be twice that of the inner one. In this method, the settlement profile can be obtained more realistically as the subgrade coefficient increases from the center of the foundation to the outside.

In the analysis of the structure-foundation system, while the foundation is a single area (1 area) in the Winkler method, it is divided into 2, 3, 7 areas in the Pseudo coupled method (Figure 3). In different foundation modifications, the subgrade coefficient values to be used for each area were calculated with Equations 2 and 3. The area of each region and the subgrade coefficient values are presented in Table 4.

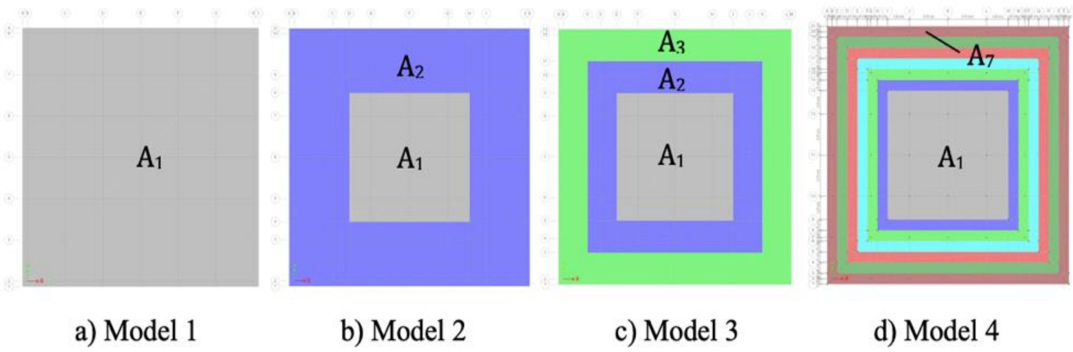

Figure 3
Foundation modifications based on different analysis method: a) The Winkler Method (1 area) and Pseudo-Coupled Method by b) 2 regions, c) 3 regions, and d) 7 regions

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

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

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, x and n are positive integer, $x \geq 2$ and $x \geq n$.

Table 4.

The area and subgrade coefficient values of each region

Region	Area, A (m^2)				Subgrade coefficient, ks (kN/m^3)			
	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
1	1296	324	324	324	18000	10278	11286	12348
2	-	972	405	117	-	20556	16938	13716
3	-	-	567	135	-	-	22572	15084
4	-	-	-	153	-	-	-	16452
5	-	-	-	171	-	-	-	17820
6	-	-	-	189	-	-	-	19206
7	-	-	-	207	-	-	-	20574

The structure-foundation system was analyzed in G+Q and E loading cases separately. The effect of the loading combinations of G+Q and 1.4G+1.6Q cases on the superstructure in percentages is same. Therefore, G+Q and EQx loading cases were investigated separately to see the effect of each loading. Axial force, shear force, moment, base pressure and settlement values were determined for the columns of C25, C28, and C7 at the center, edge and corner points of the foundation, respectively. The earthquake force was considered only in the x direction since the structure is symmetrical.

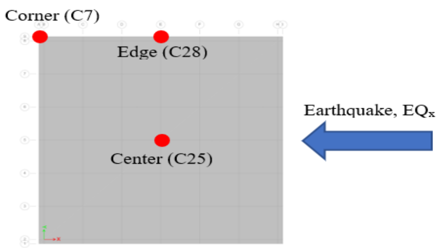

Figure 4
The location of columns and the direction of the earthquake.

RESULTS

Periods

Buildings vibrate according to their rigidity and the loads (earthquake, wind, etc.) they are exposed to. These vibrations occur within a specific time frame and sequence. The period of time until the structure returns to its previous state after undergoing a unit displacement, i.e., vibration, from its current position to the right or left, is termed the structure period. This period varies depending on the characteristics of the structural system of each building. The two most important factors determining the period are the mass and rigidity of the structure. Consequently, the force acting on the structure depends on both the mass and acceleration of the structure. The building period calculated by program was obtained as 0.907 s for the fixed-based solution, 0.967 s for the Winkler method, and 0.959-0.966 s for the pseudo-coupled methods. Since the building is symmetrical, the period values of the 1st and 2nd modes in the x and y directions are equal in all models. The 3rd mode was obtained as a torsional mode (Figure 5). The period values calculated by the program and used in the calculation of the base shear force are also given in Figure 5. It has been observed that the analysis method of the building foundation does not considerably affect the period of the superstructure since it is mostly affected by the weight and rigidity of the structure. In addition, the lowest period is obtained in fixed-base foundation since there is no soil-structure interaction. However, in the Winkler and Pseudo-coupled methods, structure period increases since the subsoil conditions are taken into consideration due by soil-structure interaction. Settlements under the foundation base increases the periods.

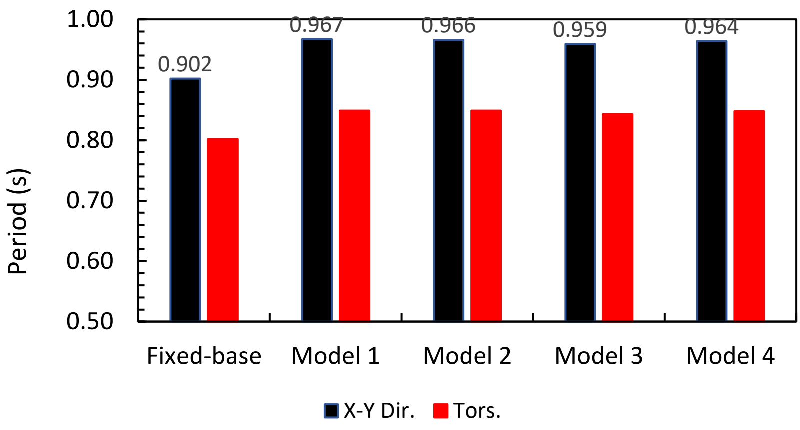

Figure 5
Structure periods.

Axial loads

Axial loads at columns of C7, C28, C25 for G+Q loading cases and C7 column for EQx loading case are presented in Figure 6. In the G+Q loading cases, there is a 2-3% difference between axial loads on columns depending on the foundation analysis methods. In the static loading case, axial loads on columns depends on the structural loads and soil-structure interactions do not affect the axial load distribution on the structure even if the foundation is analyzed by fixed-base, Winkler, and Pseudo-coupled methods.

Axial load distribution at each story on columns of C25 (edge column) and C28 (center column) is same for G+Q and EQx loading cases because these columns are located on the center axis of floor plan, that is earthquake force is not applied. There is a 4.2% difference between axial loads of EQx loading case since soil-structure interaction is considered by Winkler and Pseudo-coupled methods (Figure 6d). However, axial load increases 83% and 30% at stories 5 and 1, respectively, for fixed-base solution compared with the Winkler and Pseudo-coupled methods. Considering soil-structure interaction in EQx loading cases decreases axial loads on each story.

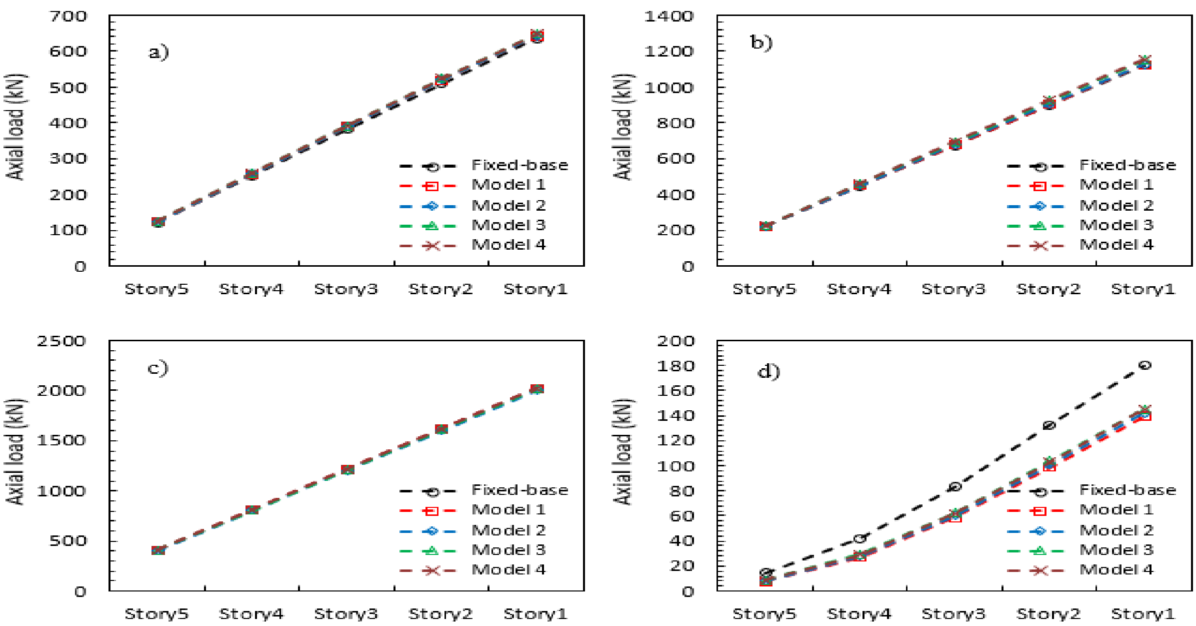

Figure 6
Axial loads at columns of a) C7, b) C28, c) C25 for G+Q loading cases and d) C7 column for EQx loading case

Shear force

Shear forces at columns of C7, C28, C25 for EQx loading case are presented in Figure 7. Shear forces at the columns on the symmetry axis (C25 and C28) are very close even if the foundation analysis methods are different. However, shear force at the corner column (C7) is obtained greater for fixed-base solution (no soil-structure interaction) than Winkler and Pseudo-coupled methods. Considering soil-structure interaction decreases the shear forces acting on each story. In addition, increasing ratio of shear force from story 5 to story 1 decreases in the Winkler and Pseudo-coupled methods, but it increases in the fixed-base solution. Shear force of C7 column at story 1 in fixed-base solution is 46% greater than Winkler and Pseudo-coupled methods.

Earthquake forces and story displacements

Earthquake forces acting on each story and the displacements occurs resulting of these earthquake forces are presented in Figure 8. In the fixed-base foundation, earthquake forces acting at the story 5 is largest and 7% greater than soil-structure systems (Winkler and Pseudo-coupled methods). However, displacement of story 5 due to fixed-base solution is 4.7% smaller than Winkler and Pseudo-coupled methods. Soil-structure systems are less affected by earthquake forces but capable of large deformations.

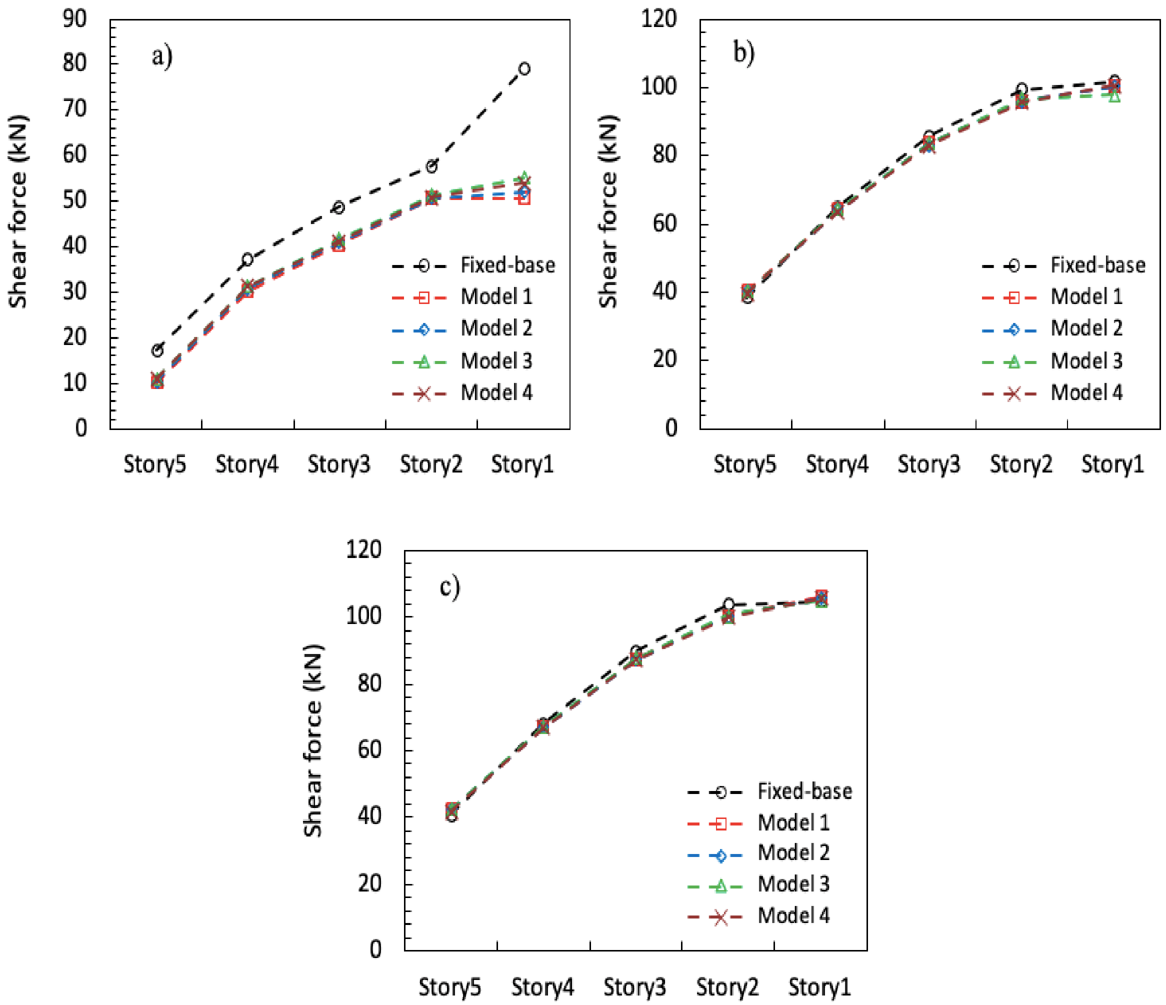

Figure 7
Shear forces at columns of a) C7, b) C28, c) C25 for EQx loading cases)

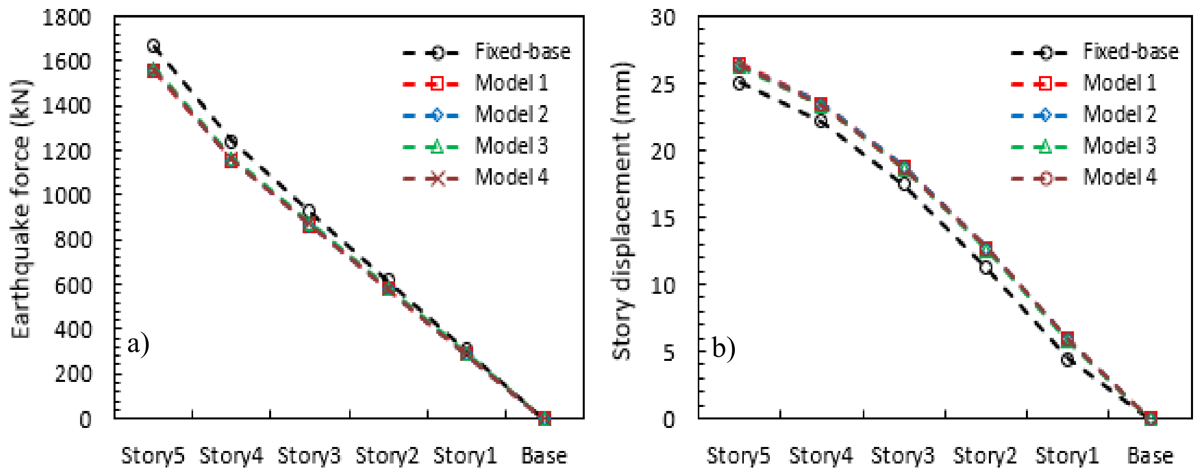

Figure 8

Shear forces at columns of a) C7, b) C28, c) C25 for EQx loading cases

Base Pressure

Base pressures at column bottom for G+Q and G+Q+EQx loading cases were presented in Figure 9. In the fixed-base solution, base pressures at any point of foundation are not exist since there is no subsoil or foundation.

In the Winkler solution for G+Q loading case, there is a 10% difference between the base pressures under the corner (C7), edge (C25) and center (C28) columns, while in the Pseudo-coupled method there is a 45% difference. In the Pseudo-coupled method, the base pressures under the corner and edge columns are lower than in the Winkler method, while they are higher under the center column. The reason for this difference is that in the Pseudo-coupled method, the subgrade coefficient increases at a certain rate as moving away from the center to the corner/edge. Additionally, as the number of areas increases (from Model 2 to Model 4), bottom pressures decrease.

For the G+Q+EQx loading case, the base pressures occurring under the edge and center column are the same as for the G+Q loading. In the Winkler solution, the base pressure under the corner column is maximum, while in the Pseudo-coupled method, the order of the base pressures from largest to smallest is center, corner and edge.

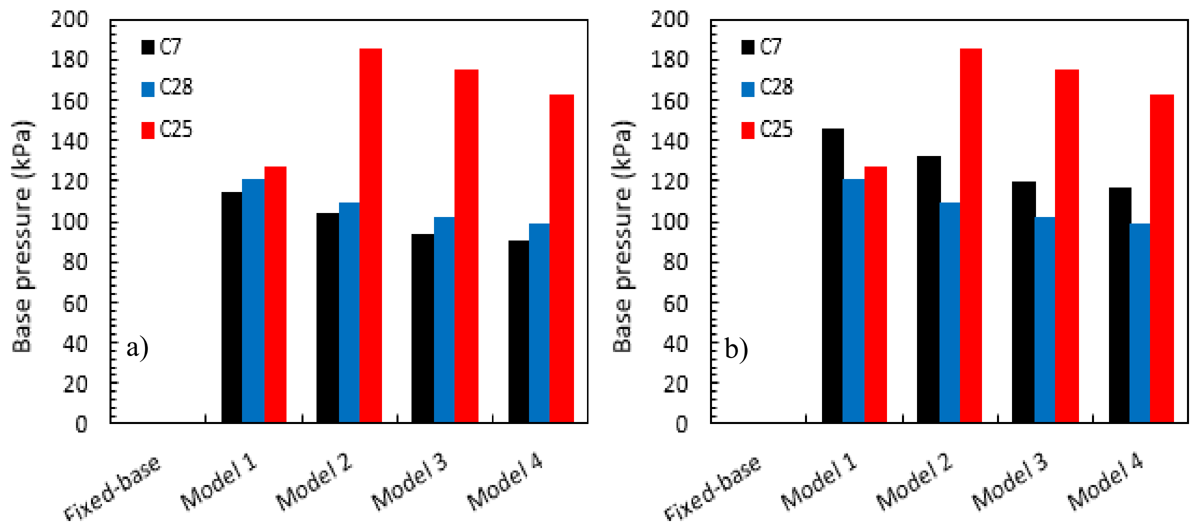

Figure 9

Base pressures at column bottom for a) G+Q and b) G+Q+EQx loading cases

Settlement

Settlements at column bottom for G+Q and G+Q+EQx loading cases were presented in Figure 10. In the fixed-base solution, settlements at any point of foundation are not exist since there is no subsoil or foundation.

In the Winkler and Pseudo-coupled methods, maximum and minimum settlements are observed at center and corner columns in G+Q loading case while at corner and edge columns, respectively, in G+Q+EQx loading case. Additionally, as the number of areas increases (from Model 2 to Model 4), settlements under column base decrease. Total settlement value for any structure should not be greater than 60mm for structural safety [27]. The building satisfies the total settlement criteria since it was at most 10mm (Figure 10a).

Differantial settlement is the difference between maximum and minimum settlement values. Differantial settlement value for any structure should not be greater than 20-30mm for structural safety [27]. Hence, differantial settlement values obtained from Winkler method is 0.71 mm and 1.39 mm in G+Q and G+Q+EQx loading cases, respectively (Figure 10b). In the Pseudo-coupled methods, differantial settlement values are 4.54 mm, 5.49 mm, 4.00 mm for Model 2, Model 3 and Model 4, respectively, for G+Q loading case. In addition, differantial settlement values decreases to 4.22 mm, 4.05mm, 3.54 mm for Model 2, Model 3 and Model 4, respectively, for G+Q+EQx loading case.

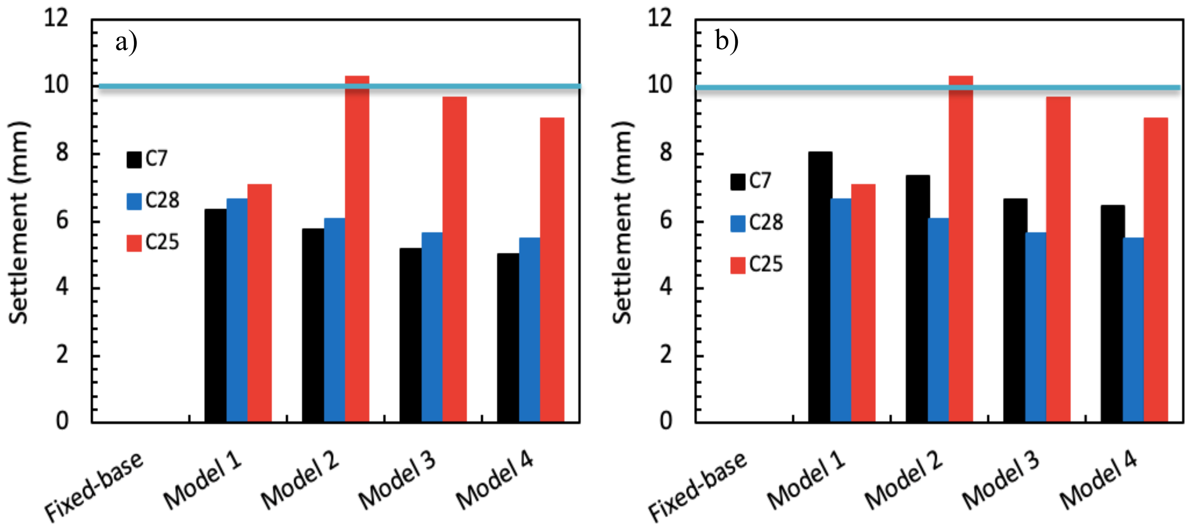

Figure 10
Settlements at column bottom for a) G+Q and b) G+Q+EQx loading cases)

CONCLUSION

In the present study, the foundation system of 5-story building resting on medium dense sandy soil was analyzed considering fixed-base, Winkler and Pseudo-coupled methods. Main findings of the study are listed below.

- The periods of building are obtained closer in Winkler and Pseudo-coupled methods but 6.7% smaller in the fixed base foundation.
- Axial loads acting on building columns in G+Q loading case are not affected much by the foundation solution method. However, in EQx loading case, the axial loads on the columns on the 1st and 5th floors are 30% and 82% less, respectively, in Winkler and Pseudo-coupled methods compared to the fixed-base foundation solution.
- In Winkler and Pseudo-coupled methods, the shear force on the corner columns is 46% less than

in the fixed-base foundation.

- In Winkler and Pseudo-coupled methods, the earthquake force is 7% greater and story displacement is 4.7% less than in the fixed-base foundation.
- The location where the maximum base pressure, settlement, and differential settlement occurs change according to the foundation analyses methods.

In the present study, a symmetrical building was analyzed with the different methods. In the symmetric building, maximum base pressure is at the center of foundation. Therefore, Winkler and Pseudo-coupled methods give similar results on soil and structure system. However, in most case, raft foundations are loaded eccentrically due to the architectural designs or non-symmetrical geometry of buildings. Based on the authors' experience, excessive base pressures or settlements were observed at the edge/corner of the foundations in the eccentrically loading structures if the Winkler method uses. This phenomenon creates difficulties in geotechnical designs. In the eccentrically loading structures, Pseudo-coupled method balanced the base pressures at the center point and corner/edge points of the foundation. Therefore, the authors suggest that foundation solution methods should be applied for the buildings having different geometries, eccentricity, and foundation depth.

Ethical Statement
This study is an original research article designed and developed by the authors.

Author Contributions
Research Design A.S.E (%33), Y.Y. (%33), İ.Ö. (%33)
Data Collection A.S.E (%20), Y.Y. (%20), İ.Ö. (%60)
Research - Data Analysis - Validation A.S.E (%60), Y.Y. (%20), İ.Ö. (%20)
Writing the Article A.S.E (%20), Y.Y. (%60), İ.Ö. (%20)
Revision and Improvement of the Text A.S.E (%33), Y.Y. (%33), İ.Ö. (%33)

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Conflict of Interest
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