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Evaluation of clay layer presence on shallow foundation settlement in dry sand under an earthquake

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Abstract: Seismically, settlement of buildings with shallow foundations lying above dry sand soils has caused severe destruction in recent earthquakes. This study investigated the effect of seismic loads with shallow foundations located above sandy soil containing an intermediate soft clay layer. The impact of a clay layer’s existence with different thickness and closeness to the base of foundation when subjected to El Centro earthquake with 6.9 magnitude. This investigation has been carried out with the help of a three-dimensional PLAXIS 3D, which has been used to solve many geotechnical issues. A database was created for the various dynamic and static parameters of soils in seismically active areas of Iran and Iraq and USA. In this research, important factors are recognized, including relative density. Clay layer thickness and proximity to the foundation, the soil relative density the results of this research indicated that shallow foundation settlement increased on the dry sand and decreased with the presence of clay layer thickness and wave propagation in cohesion soil is less than cohesion-less soil. In addition, it was reached that as close as the clay layer to the foundation the settlement increased.

Keywords: shallow foundation, soft soil layer, Plaxis 3D

1 Introduction

The geotechnical engineering understanding of the seismic shallow foundation behavior has industrialized over the historical 60 years with the appearance and modification of solutions to some separate features of the overall problem, encouraged and motivated by field interpretations. Shallow foundations are the most public types of foundations used to support mid-rise constructions in a height seismic risk. The inadequate design of structures during recent earthquakes has interested many researchers to study the existing methods and improve new approaches for seismic-resistant design. Foundations of structures constructed in seismic regions and the demands to withstand the load and deformation through an earthquake will perhaps be the most severe in their design life. Owing to the seismic loading, shallow foundations may experience a high increase in settlement. The influence of sandy soils in various conditions (loose, medium, dense) placed on a soft clay layer with different thicknesses and exposed to seismic waves and the closeness of the soft clay layer to the base of the foundation was also studied. Moreover, the influence of earthquake on a shallow foundation was investigated. Many types of research have exposed that the dynamic interaction between the soil, foundation, and structure can influence the seismic response of the building through an earthquake. Using the finite element method (FEM), positioned on multilayer soil on a resistant building’s seismic response is investigated. Effective post- and preprocessing abilities make it easier to analyze and model. The information. If an analysis is repeated, over a period, it is relatively straightforward to make modifications. These soil parameters are critical for the hardening soil model to be employed in this work as data inputs. It also requires the use of data input from a 1940 earthquake (the El Centro earthquake) to analyze the behavior of shallow foundations under seismic waves using the finite element program PLAXIS 3D. As a result, it should be highlighted that soil is a common element in seismic wave transmission to the foundation.

This study investigation concentrates on the key problems of what effect the presence of a soft clay layer beneath the foundation has on the foundation’s output

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during an earthquake to find out the ability of the soft clay layer. Does the soft clay layer decrease or increase the settlement?

In addition, there is a difference between a foundation constructed on sandy soil and one built on sandy soil with a soft clay layer within it. The model’s results will be compared and discussed.

2 Research objectives

– One of the key objectives of this study is to assess the impact of a soft clay layer, with varying thickness and closeness distances, on the performance of a shallow foundation subjected to different seismic loads. The presence of such a layer, located beneath loose sand, can significantly affect the behavior of the foundation during an earthquake, making it crucial to evaluate its influence.

– The other objective is to evaluate the activity of shallow foundations under seismic excitation using real seismic data from Iraq, the USA, and Iran. To conduct the analyses, PLAXIS 3D finite element tools were used.

3 Literature review and research

The behavior of shallow foundations in earthquakes has advanced progressively over the last 60 years, such as the appearance and improvement solutions for several different surfaces of the overall challenges, prompted and stimulated by field observations. The growth of insights and strategies for the various facets of seismic foundation activity has been more rapid in recent years. Total solutions, predictably, necessitate numerical solution methods that make them less diaphanous than their predecessors. The analysis starts by looking at relevant aspects of soil and rock actions, some of which have not yet been fully studied. An analysis of the literature on the action of shallow foundations under seismic loading is presented in this chapter. This study highlights earthquake fundamentals, soil–structure interaction, and shallow foundations under earthquake activity.

A shallow foundation is usually located at a shallow depth and transmits loads to the near-surface strata. A foundation is shallow: according to Terzaghi and Peck (1967) if the structural bases with the least dimension (usually the width B) is equal to or greater than the foundation depth (Df). This is a criterion. It is appropriate for regular shallow foundations, but not for narrow or very small foundations. Df has been estimated to be as large as 3–4B by some scholars. Df is used in this situation. The masonry footings were dimension-stone footings made up of stones that had been carved and dressed to a precise size and shape [1]. An earthquake creates a series of waves, which move across the earth and inflict damage depending on their intensity. Instruments capable of tracking thousands of miles away from the epicenter can be used. The type of earthquake that occurred is revealed by the seismic wave. Individual wave paths separate in all directions as they move away from the source.

Waves of seismic activity: Huge strain energy emitted during an earthquake passes through the Earth’s layers as seismic waves in all directions, reflecting and refracting at each interface, as shown in Figure 1 [2].

4 Finite element program

Soil behavior is simulated using advanced foundational models. PLAXIS 3D is used to characterize the soil model and to simulate the performance of shallow foundations subjected to earthquake excitation. Since the relationship between soil, base, and structure influences the dynamic properties and seismic response of the building, the construction engineer must carefully consider these parameters to ensure a secure and cost-effective seismic design.

Since 1960, FEM has been used to solve geotechnical engineering problems. It was the beginning to insert this method and link it into geotechnical engineering. PLAXIS 3D is a full-featured 3D geotechnical element program that was created exactly for deformation study, stability, and flux in geotechnical engineering constructions.

Figure 1: Arrival of seismic waves at a site.
FEM is a powerful tool for analyzing complex engineering problems. Developed over a decade, FEM divides large problems into smaller parts, minimizing the solution process. FEM is an effective and important method, widely used to solve complex engineering problems [4].

4.1 Geometry of the 3D model

The model has three dimensions: a width of 1.5 m, a length of 1.5 m, and a height of 0.5 m (X = 200 m, Y = 100 m, and Z = 40 m). The point load on the shallow base and prescribed displacements under the soil mode are shown in Figure 2a and b.

5 Sensitivity for the model dimension

The depth of the numerical model has been considered to be equal to 40 m since the position of the rock layer has been assumed to be at a depth of 40 m from the natural ground surface; a similar modeling approach has been used in other numerical analyses in the literature as mentioned by Van Nguyen et al. [5]. The width of the model has been considered equal to 200 m. The width has been selected based on parametric analyses conducted to investigate the influence of the FEM width on the settlement results. The parametric analyses have been carried out by simulating different model widths. It was found that the results of the analysis were not influenced by the FEM extension. The results of the model width study are shown in Figure 3.

This clearly shows that the model width has an insignificant influence on the obtained results after an extension of x ≥ 200 m.

6 Modeling of soil

Soil representation models (soil models) are a quantitative representation of soil behavior since model parameters are used to determine soil properties. The more experience dealing with PLAXIS, the more accurate the results will be. The wider the understanding of soil models and the limits of the use of each model and the method of determining model parameters, the greater the judgment and the ability to understand the nature of the results in PLAXIS OUTPUT.

Table 1 gives the hardening soil parameters [6].

**Parameters of the Soft Soil model**

- c: cohesion
- ϕ: friction angle
- ψ: dilatancy angle
- λ: modified compression index

![Figure 2](image1.png)

**Figure 2:** (a) Geometric model and soil layers and (b) shallow foundation and displacement.

![Figure 3](image2.png)

**Figure 3:** Sensitivity of soil dimensions.
κ: modified swelling index
νur: Poisson’s ratio for unloading/reloading.
K0nc: horizontal/vertical stress ratio in normally consolidated 1D compression (determines the shape parameter M)

In addition, you need to define the initial size of the yield surface by appropriate POP/OCR value [7].

### 7 Verification model

The verification of PLAXIS 3D of a shallow foundation resting on a dense sand layer and influenced by the El Centro earthquake, which has 6.9 intensity, was performed by comparing the results with the experimental work of Al-Neami et al. (2021), which used a multi-degree freedom shaking table and a fixed container, which was manufactured in order to study the influence of earthquake intensity and soil relative density on the shallow foundation’s settlement. A series of shaking experiments were conducted using a 0.7 × 0.7 × 0.8 m container to study the shallow foundation behavior. The shallow foundation was resting at the center of dry sandy soil having two relative densities (55 and 80%) and influenced by two local magnitudes of earthquakes Jalisco and Guerrero having intensities of 6.4 and 7.2, respectively [8].

Figure 4 demonstrates the comparison between experimental work influenced by the Guerrero earthquake having 7.2 intensity results of Al-Neami et al. (2021) and finite analysis of a dense sand case influenced by the El Centro earthquake with 6.9 intensity. Acceleration histories of the used earthquakes are shown in Figure 5.

The results show that the settlement of a shallow foundation lying on a dense sand layer and influenced by the El Centro earthquake having 6.9 intensity is 34 mm, while the experimental work of Al-Neami is 24 mm for Guerrero, which has 7.2 intensity, and 20 mm for Jalisco, which has 6.4 intensity, influenced the shallow foundation. The results indicate that the settlement using a finite element analysis increased by 42% and this difference may be due to the difference between the dimension of the experimental box and the PLAXIS 3D soil dimension, which shows more reality to the earthquake and the difference of earthquake intensity [8].

### 8 Results

#### 8.1 Effect of sandy soil condition without soft clay layer presence on foundation settlement under effect earthquake

There are great benefits in using advanced models in order to recognize the reality of the initial soil structure and its
subsequent damage caused by the applied dynamic loads. Soil deformations produced from the passageway of a seismic wave through the soil might threaten the stability of any geotechnical structure; therefore, PLAXIS 3D program was used to create different models, which include a shallow foundation with dimensions (1.5 m × 1.5 m × 0.5 m), which underlies the three layers. Two different conditions exist in two sandy soil layers (loose sand, medium, dense) and an intermediate soft clay layer with various thicknesses (3, 4, and 5 m), it was discovered that this alteration reduced settlement. Figure 6 shows the use of loose sandy soil, which produces a maximum amount for settlement of about 61.6309 mm at a 5.32 s time.

Moreover, Figure 7 shows the use of medium sandy soil, which produces a maximum settlement of about 42.78609 mm at a time of 6.16 s.

Figure 5: History of earthquake acceleration.

Figure 6: Amount of settlement in loose sand.

Figure 7: Amount of settlement in medium sand.
Moreover, Figure 8 shows the use of dense sandy soil, which produces a maximum settlement of about 34.01353 mm at a time of 6.16 s.

As a result, Figure 9 shows that dense sand reduces the settlement in the soil by a higher amount than medium sand and loose sand. Figure 10 illustrates a settlement competition for without loose sand case.

8.2 Effect of soft clay from closeness to the foundations base

In order to understand the seismic wave response, many parameters become important to discuss. As a result, to obtain the maximum benefit from many methods of seismic analysis, soil closeness to the foundation was one of the parameters that should be investigated.

8.2.1 For 2 m soft clay far from the base of the foundation case

Figure 11 illustrates the effect of a soft clay layer closeness. The 2m-thick layer of soft clay lying away from the base of the foundation and beneath a sandy soil having various conditions (loose, medium, and dense). It seems that the distance between the soft clay layer and the foundation is crucial. It is obvious that the presence of a 2 m soft clay layer affects the settlement produced due to the earthquake. The results show that the settlement under the shallow foundation reduced about 10.23, 17.2, and 19.1% for loose, medium, and dense sand cases, respectively. Because foundations are mostly placed at a depth Df below the ground surface, the term “Df” refers to the foundation’s depth in the soil. The overburdened soil’s shear strength is considered the same as the soil beneath the footing’s foundation. The depth impact may be lessened or ignored entirely if the overloaded soil is weaker than the...
foundation soil (John Wiley & Sons 2006 Analysis and Design of Shallow and Deep Foundations). Figure 12 illustrates the maximum settlement competition for 2 m soft clay layer case.

8.2.2 For 4 m soft clay far from the base of the foundation

Figure 13 illustrates the effect of a 4 m soft clay layer away from the base of the foundation having loose, medium, and dense sand. It seems the distance between the soft clay layer and the foundation affects the settlement. It is clear from the results that as farther the soft clay layer is from the foundation, the lower the settlement occurs, and the closer the soft clay layer is to the foundation, the higher the settlement occurs. The settlement reduced about 26.9, 38.1, and 33.6% with loose, medium, and dense, respectively. As a result, with increasing density, the settlement reduces greater than loose soil condition. Figure 14 illustrates the settlement competition for 4 m soft clay layer case.

8.2.3 For 6 m soft clay far from the base of the foundation

Figure 15 illustrates the effect of a 6 m soft clay layer away from the base of the foundation with loose, medium, and dense sand. It seems that the distance between the soft clay layer and the foundation affects the settlement. It is so clear that with increasing the distance from the base of the foundation, the settlement gets lesser. The settlement reduced about 43.1, 46.7, and 39.6% for loose, medium, and dense sand, respectively. The less amount of settlement occurred with dense sand, so it is clear that the denser the sand is lesser, the settlement occurs. This result confirms that the uncertainty in site response results due to soft clay soil is much higher when compared to sandy soils. Figure 16 illustrates the...
maximum settlement competition for 6 m soft clay layer case.

8.3 Effect of thickness of soft clay layer

The extent of waves and degree of harm during an earthquake is powerfully influenced by the response of soil shaking. However, the most significant and usually problematic in geotechnical engineering earthquake is the estimation of ground response due to such motion. A parametric study was conducted to evaluate the effects of soft clay presence and thickness \( T = 3, 4, 5 \) m included in sandy soil models on shallow foundation performance.

8.3.1 For 3 m soft clay layer thickness

Figure 17 illustrates the effect of a 3 m soft clay layer thickness on the settlement of the foundation with the (loose, medium, and dense) sand cases. It is obvious that with the dense sand case, the settlement of the shallow foundation reduces much more than that of loose or medium sand cases. The results indicate that the settlement reduced by about 10.23, 17.2, and 19.1% for loose, medium, and dense sand cases due to the presence of a 3 m soft clay layer. It is clear from the results that dense sand cases showed less settlement. Figure 18 illustrates the maximum settlement comparison for 3 m soft clay layer case.

8.3.2 For 4 m soft clay layer thickness

Figure 19 illustrates the effect of a 4 m soft clay layer thickness on the settlement of the foundation having (loose, medium, and dense) sand cases. It is obvious that with dense sand cases, the settlement of the shallow foundation reduces much more than with loose or medium sand cases. The results indicate that the settlement reduced by about 14.65, 23.1, and 24.15% for loose, medium, and dense sand cases.

Figure 16: Maximum settlement comparison for 6 m soft clay.

Figure 17: Maximum settlement comparison for 3 m soft clay.

Figure 18: Maximum settlement comparison for 3 m soft clay.

Figure 19: Soft clay thickness (3 m) with loose, medium, and dense sand.

Figure 19: Soft clay thickness (4 m) with loose, medium, and dense sand.
cases, respectively. As the sand gets denser, the settlement of the shallow foundation decreases about 10%. Figure 20 illustrates the maximum settlement comparison for 4 m soft clay layer case.

8.3.3 For 5 m soft clay layer thickness

Figure 21 illustrates the effect of a 5 m soft clay layer thickness on the settlement of the foundation with the (loose, medium, dense) sand cases. It is obvious that with dense sand cases, the settlement of the shallow foundation reduces much more than that of loose or medium sand cases. The results indicate that the settlement reduced by about 18.96, 28.47, and 25.2%, respectively, for loose, medium, and dense sand cases due to the presence of a soft clay layer lying 5 m away from the shallow foundation. The results indicate that dense sand cases showed the highest performance. Figure 22 illustrates the maximum settlement comparison for 5 m soft clay layer case.

9 Conclusion

1. The closeness of a soft clay layer affected the performance of a shallow foundation exposed to a seismic wave. It was reached that as close the soft clay layer to the foundation as the settlement under the foundation increased.
2. With increasing the thickness of the intermediate soft clay layer, the settlement of a shallow foundation reduction was higher for all soil conditions (loose, medium, and dense).
3. A shallow foundation for cohesive soils is less sensitive to the earthquake, and that for dry cohesion less soil may be more susceptible.
4. Wave propagation in cohesion soil is less than in cohesion-less soil.
5. The stress increased with the acceleration of the earthquake increase.
6. Earthquake with higher acceleration has a higher influence on shallow foundation stability.

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