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Comparative Safety Analyses of Slope-Shallow Foundation Interaction under Static and Dynamic Loading Conditions

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Abstract

This study is focused on the safety analysis of the shallow foundations located on cohesive homogenous slopes that has different shear strength characteristics. Static and dynamic analyses have been conducted with a well-known commercial finite element logic-based two dimensional numerical software. Dynamic analyses are performed with regard to the consideration of the Samos-İzmir earth-quake that happened in 30 October 2020. The change of the slope geometry depending on the differentiation of the slope height and inclination is also considered. The interaction between the slope-shallow foundation is investigated regarding different relative distances of the foundation from the slope edge and considering various loading magnitudes for the foundation. The results of the analyses are evaluated in terms of the factor of safety values to interpret the degree of the effects of foreseen variants on the integrated system stability.

Anahtar Kelimeler: Finite element, Slope, Shallow foundation, Interaction, Safety, Dynamic loading

Statik ve Dinamik Yükleme Koşulları Altında Şev-Yüzeysel Temel Etkileşiminin Karşılaştırmalı Güvenlik Analizi

Öz

Bu çalışma, farklı kayma dayanımı özelliklerine sahip kohezyonlu homojen şevler üzerinde yer alan yüzeysel temellerin güvenlik analizine odaklanmıştır. İyi bilinen bir ticari sonlu elemanlar mantığı tabanlı

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iki boyutlu sayısal bir yazılım kullanılarak statik ve dinamik analizler gerçekleştirmiştir. 30 Ekim 2020'de meydana gelen Samos-İzmir depremi dikkate alınarak dinamik analizler uygulanmıştır. Şev yüksekliği ve eğiminin farklılaşmasına bağlı olarak şev geometrisinin değişimi de dikkate alınmıştır. Şev-yüzeysel temel etkileşimi, temelin şev kenarından farklı göreli mesafeleri ve temel için çeşitli yükleme büyüklükleri dikkate alınarak incelenmiştir. Analiz sonuçları, öngörülen değişkenlerin bütünsel sistem stabilitesi üzerindeki etkilerinin derecesini yorumlamak için güvenlik faktörü değerleri açısından yorumlanmıştır.

Keywords: Sonlu elemanlar, Şev, Yüzeysel temel, Etkileşim, Güvenlik, Dinamik yükleme

1. INTRODUCTION

The problems that arise due to the placement of the structures adjacent to the existing slopes are a frequently encountered and still researched issue in civil engineering applications. In such a case, the determination of the ultimate bearing capacity of the foundation and the interpretation of its effect on the stability of the slope forms an important engineering problem. The evaluation of the related literature studies shows that the direction and type of the loading acting on the foundation, the embedment depth of the foundation, the inclination and height of the slope, the hydrogeological situation, and the shear strength characteristics of the soil are the effective parameters on the bearing capacity of a foundation built on a slope [1,2]. In addition, the examination of the slope-foundation interaction behavior under dynamic loading conditions further raises the number of the design components and makes this engineering problem more complicated [3]. Several types of studies have been conducted and lots of methods were applied considering this challenging situation to ease the evaluation process of the mentioned complicated behavior and discover the unforeseen hazardous cases. In this context, Yamamoto et al. (2010) presented an analytical study which was using the upper-bound limit analysis and the pseudo-static approach for the determination of the seismic bearing capacity of embedded and spread foundations that are built near a slope. As the result, the researchers proposed a non-symmetrical failure mechanism for the interacted system, and also some design chart forms for the prediction of seismic bearing capacity factors are given [4]. Cascone and Casablanca (2016) evaluated static and dynamic bearing capacity factors for shallow strip foundations. In their study, the characteristics method was used to derive the bearing capacity factors for both smooth and rough foundations. The results of their analyses were compared with the finite element analysis and the effect of seismic acceleration on the generated plastic mechanisms was highlighted. In addition, the researchers have proposed empirical formulas for computing static values of bearing capacity coefficients [5]. Cong et al. (2018) investigated the dynamic behavior of the shallow foundation on the slope with 3D simulation. The boundary conditions on the seismic response of the shallow foundation on the top of the slope are emphasized [6]. Raj et al. (2018) investigated the seismic bearing capacity of shallow strip foundations built on a slope using finite element limit analysis. The seismic effects on the soil and foundation were taken into account with the pseudo-static approach. In the study, the effect of parameters such as foundation embedment depth ratio, slope angle, horizontal seismic coefficient, and angle of internal friction on the bearing capacity of the foundation was investigated. It was emphasized that the results obtained from the study were well consistent with the results obtained from previous studies [7]. Xiao et al. (2019) investigated the undrained bearing capacity behavior of strip foundations built adjacent to two-layered slopes. They used adaptive finite-element limit analysis to calculate the lower and upper limits of the undrained bearing capacity factor for strip foundations. The results were compared with the previous studies and the failure mechanisms were also investigated. The results showed that the conclusions obtained from the study were compatible with the existing solutions. The charts and tables were created for engineers to use in design calculations [8]. Yang et al. (2019) proposed an analytical approach to estimate the bearing capacity of shallow foundations affected by the slope. In their study, the researchers determined the bearing capacity of shallow foundations constructed near slopes using the modified bearing capacity factors with the traditional bearing capacity equation developed by Terzaghi [9]. Izadi et al. (2019) applied the limit equilibrium method coupled with Coulomb failure mechanism to search for the effect of variation of undrained shear strength with depth on seismic bearing capacity of shallow foundations on heterogeneous marine deposits [10]. Fatahi et al. (2020) investigated the effects of slopes on the seismic behavior of nearby buildings by conducting three dimensional numerical analyses. They conducted the analysis with the nonlinear differentiations of the soil stiffness and damping varying distances between the edge of the building and crest of the slope [11]. Yang et al. (2021) conducted analytical determinations depending on upper-bound kinematic limit analysis. They aimed to isolate the mechanism of failure and bearing capacity factors for shallow foundations near slopes subject to seismic action without utilizing the principles of superposition. As the result of their study, the analytical determinations of ultimate seismic bearing capacity present good accuracy compared with numerical solutions. The authors also assessed the seismic bearing capacity factors regarding the changes of soil properties and finite configurations of both slope and foundation geometry [12]. These studies generally represent that the evaluation process of the dynamic behavior of the interacted slope-shallow foundation systems was generally focused on the determination of ultimate bearing capacity values of the foundations.

The present study has diverged from other studies which have been regarding the dynamic interaction of slope-foundation system by considering the change of the safety degrees in terms of the Factor of Safety (FoS) values under both static and dynamic situations respectively performing strength reduction method by the commercial software Plaxis 2D V2021. Within this context, several cases were fictionalized to reflect the probable effects of design variables on safety. In addition, the dynamic analyses are performed with regard to the consideration of the actual Samos-İzmir earth-quake that happened in 30 October 2020. The undrained shear strength of the soil slope, the geometry of the slope, the interaction distance of the slope- foundation system, the amount of the structural static loading was considered in both static and pseudo-static analysis. As the result of the parametrical analyses, comparative interpretations were performed to reflect the change of the safety degrees obtained for static and dynamic analysis under different conditions that can be probable.

2. MATERIAL AND METHODS

The dynamic numerical analyses were performed with the use of the pseudo-static analysis method that can be defined as one of the main and keep-up-to-date seismic stability analysis methods used for slopes. The pseudo-static analysis method evaluates the earthquake loads as a constant single force that is acting directly to the center of the sliding slope mass [13,14]. Thereafter, the factor of safety value of the slope can be determined with the use of the traditional limit equilibrium method. In this connection, the Plaxis software utilizes the Newmark implicit time history integration scheme to determine the equilibrium equation (dynamics) of the system [15]. Characteristically, a factor of safety against sliding of bigger than 1 is necessitated for the ground motion that is caused by the safety evaluation of the earthquake [16]. The finite element analyses were conducted within the mentioned perspective and the results of the analyses were presented considering the change of FoS values throughout the study. In addition, plain strain conditions were considered to model the system and 15-noded triangular elements were used. The boundaries of the slope-foundation system were modeled enough large to reflect but not restrict the possible distributions of stress and strains for all the considered cases. The clayey soil was defined with the use of elastic-perfectly plastic constitutive material model (Mohr-Coulomb). The phases of all the analysis were started from the initial condition which represents the initial virgin condition of the slope to model an existing structure. Then, a weightless plate element was used to model the shallow foundation structure and additional structural static loads were applied on the plate considering different magnitudes with the assumption of undrained loading in the plastic situations. A representative cross-section and related geometrical and geotechnical parameters of the slope-shallow foundation system are presented in Figure 1. In Figure 1, the width of the foundation, the height of the slope, the inclination of the slope, the magnitude of the structural static loading, the interaction distance of the slope-shallow foundation, the undrained shear strength of the soil, the unit weight of the soil, the Young Modulus of the soil, the poison ratio of the soil is represented by *B, H, β, q, L,* c_u*, γ, E, v* respectively. The foundation width is selected as a constant value at 24 m. The slope height is assumed to be 3 m, 6 m and 9 m and the inclination of the slope is 30° and 45°. The interaction distance of the slope-foundation system is selected 0, B/8, B/4, B/2 and B as the function of the width of the foundation. The structural static loads were applied as uniform surcharge with the magnitude of 20, 60, 120 kPa respectively. The undrained shear strength of the soil is assumed to be 50 kPa and 100 kPa. The fine meshed model of the interacted system has also been given in Figure 1 for H= 3 m, β= 45° and L= 3 m.

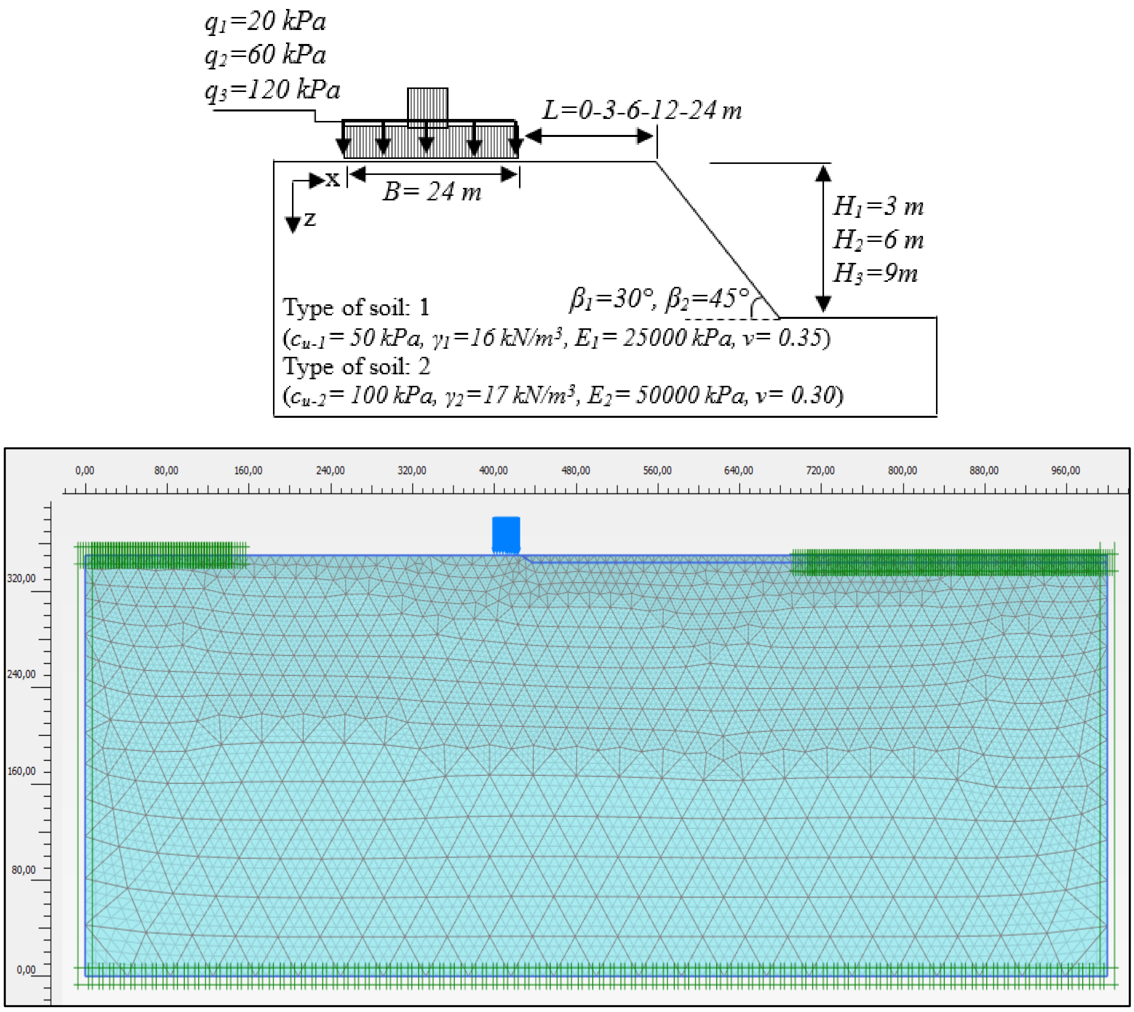


Figure 1. The cross section and the variables of the slope-shallow foundation system

The other geotechnical parameters were selected according to the envisaged limit values given by Bowles (1988) depending on the selected undrained shear strength values [17]. Besides, it is significant to obtain the characteristics of the evaluated earthquake on the soil surface for the field examined in seismic hazard analysis. These characteristics require to be achieved using a detailed soil investigation and acceleration records consistent with local seismic hazard findings. In the scope of current research, the effects of the Samos-Izmir earthquake were used to be modeled in the dynamic analysis of the slope-foundation system. The accelerogram of the mentioned earthquake is presented in Figure 2 considering acceleration, velocity, and displacement.

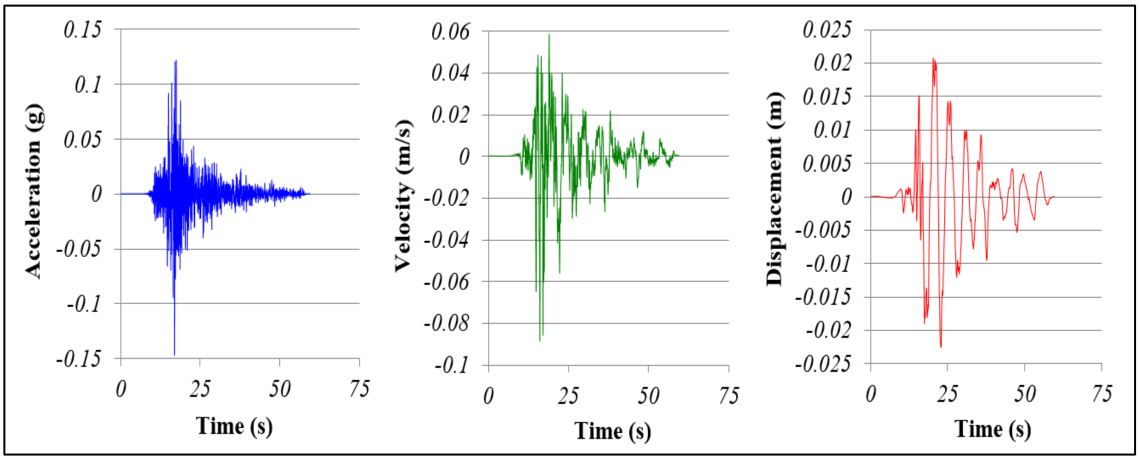


Figure 2. The accelerogram of the Samos-Izmir earthquake [18]

3. RESULTS AND DISCUSSION

In the context of this study, a total of 720 numerical analyses was performed to compare the static and dynamic safety degrees determined considering the interaction of slope-foundation. The outcomes of the conducted analyses were separated and presented according to the foreseen special cases to ease to form selective perception. The drawn graphs are given according to the change of the FoS values against the change of the interaction distance in the whole of the study. The effects of the changes in loading type, shear strength, the height of slope, the inclination of the slope, the magnitude of structural static load on the FoS values are interpreted into sub-sections with the use of variable couples as an integrated presentation.

3.1. The Effects of Loading Type and Undrained Shear Strength Angle Change

In Figure 3, the evaluation of the change of loading type and also the change of undrained shear strength is done. In such a case, some other variables of the design problem are selected as constant (H= 3 m, q= 20 kPa, β= 30°). Within the parameters considered, it can be clearly seen in Figure 3 that as a result of the doubling of the undrained shear strength value, the system safety level increases approximately twice for both under static and dynamic conditions. In addition, the increase of the interaction distance of the slope-foundation system leads to a significant increase in the degree of safety especially after exceeding a distance nearly the same as the foundation width B. Apart from this situation, the increase in the degree of safety happens gradually and linearly with the increasing L. It is an important situation that the percentage of the decrease of safety during dynamic loading is determined approximately the same for both considered undrained shear strength values.

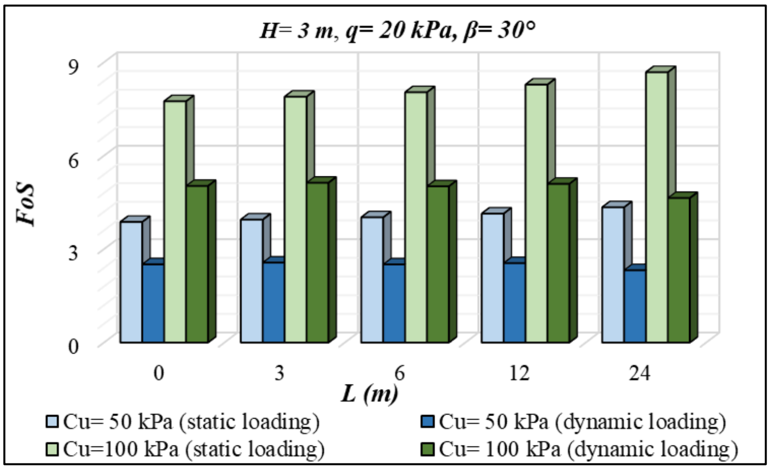


Figure 3. The change of FoS values against L for H= 3 m, q= 20 kPa

Therefore, it can be said that the value of the undrained shear strength is not effective on the rate of the decrease in safety that happened while dynamic loading. These ratios changed 35%, 35%, 37%, 38%, 47% for L= 0, 3, 6, 12, 24 meters respectively. In Figure 4, the constant parameters of the design are changed. It is assumed that H= 6 m, q= 60 kPa, β= 30°. The height of the slope and the structural static loading magnitude are increased compared with Figure 3. If Figure 3 and Figure 4 are compared, the decrease in the value of safety can be understood from the decrease in the numerical values on the vertical axis. Besides, the change of the safety ratios depending on the static and dynamic conditions foreseen for Figure 4 are determined 31%, 32%, 33%, 36%, 40% for L= 0, 3, 6, 12, 24 meters respectively. The differentiation between the static and dynamic conditions in terms of safety is decreased with the increase of slope height and structural static loading magnitude.

In Figure 5, it is assumed that H= 9 m, q= 120 kPa, β= 30°. In such a case, the change of the safety ratios depending on the static and dynamic conditions foreseen for Figure 5 is determined 4%, 6%, 10%, 17% for L= 3, 6, 12, 24 meters respectively. This mentioned case is dissimilar to the case considered in Figure 3 and Figure 4 according to the rate of the change of the safety degrees between static and dynamic situations. The increase of both the height of the slope and the amount of loading leads the system to be failed when the foundation is located at the edge of the slope. Besides, the static safety of the slope is almost in danger too when the undrained shear strength is 50 kPa. The increase of the shear strength angle prevented to be a failure of the system in both static and dynamic conditions.

3.2. The Effects of Slope Geometry Change

The slope inclination and slope height are evaluated as the geometric variables of the analysis and they are also taken into consideration throughout the conducted analysis. To address the steepening of the slope, the slope angle has been set to 45°. The change of the slope angle to 45° from 30° is investigated in Figure 6, Figure 7, and Figure 8 in connection with the change of the slope height 3 m, 6 m, 9 m respectively. In this part of the study, critical situations are evaluated and visualized in terms of the safety values obtained. Therefore, the analyses which consider the undrained shear strength 50 kPa, and the structural static loading magnitude 120 kPa are evaluated.

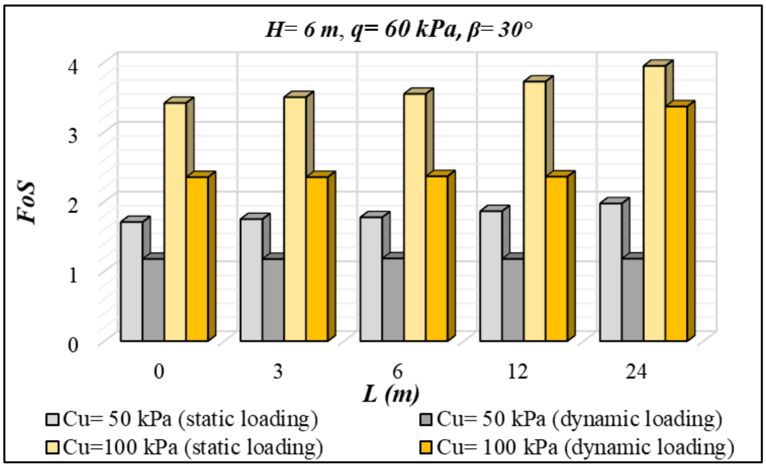


Figure 4. The change of FoS values against L for H= 6 m, q= 60 kPa

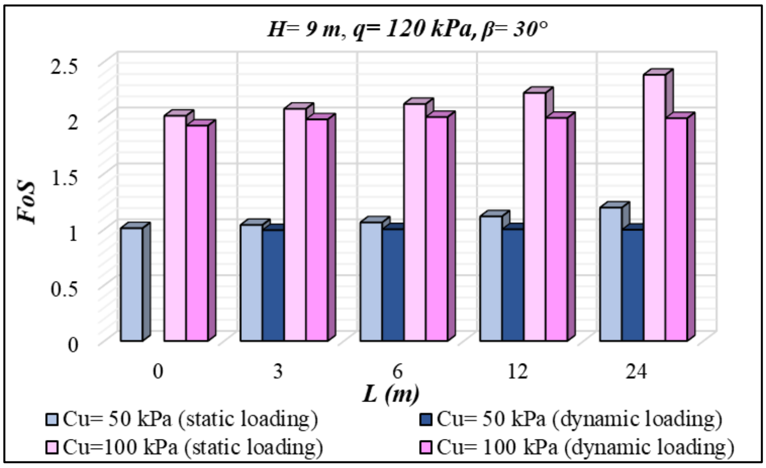
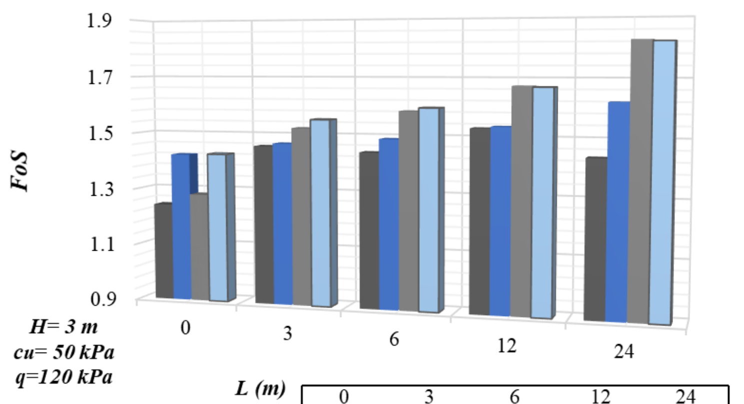


Figure 5. The change of FoS values against L for H= 9 m, q= 120 kPa

The reason for choosing this case is the determination of the minimum safety values within all the performed analyzes. In Figure 6, the height of the slope is 3 m, and also both static and dynamic analysis results are shown into the same graph depending on the change of the slope inclination.

The increase of the slope angle leads to a decrease in the FoS value, especially for the case that the L distance is relatively small during static analysis. The relative difference between the FoS values at static conditions approximately determined equally when the L value becomes the quarter width of the foundation base (6 meters). This might be the result of the decrease of the interaction between slope and foundation when static conditions were evaluated it the slope height is relatively small (for this case H= 3 m) the safety of the shallow foundation becomes independent from the stability of the slope. But dynamic loading conditions change the trend of the interacted response of the slope-foundation system. In the case in which dynamic loading conditions dominate the system, the safety level decreased with the increase of the slope angle.

The FoS values approximately determined at the same degree when L becomes 3 meters for both inclinations.

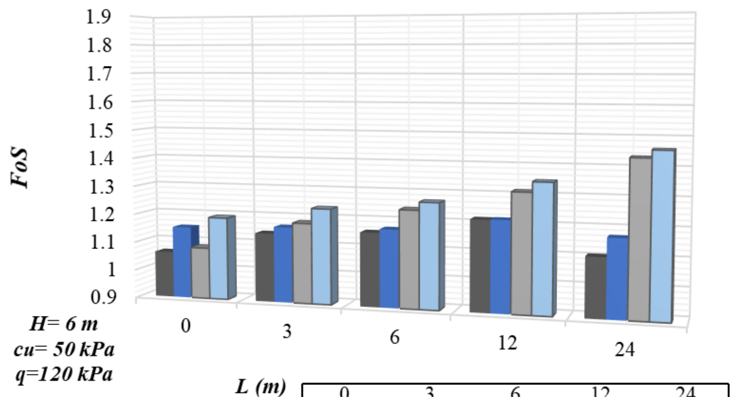


	0	3	6	12	24
β = 45° (dynamic analysis)	1.242	1.458	1.443	1.531	1.439
β = 30° (dynamic analysis)	1.423	1.468	1.49	1.537	1.622
β = 45° (static analysis)	1.281	1.523	1.586	1.673	1.825
β = 30° (static analysis)	1.426	1.553	1.597	1.669	1.82

Figure 6. The change of FoS values against H= 3 m

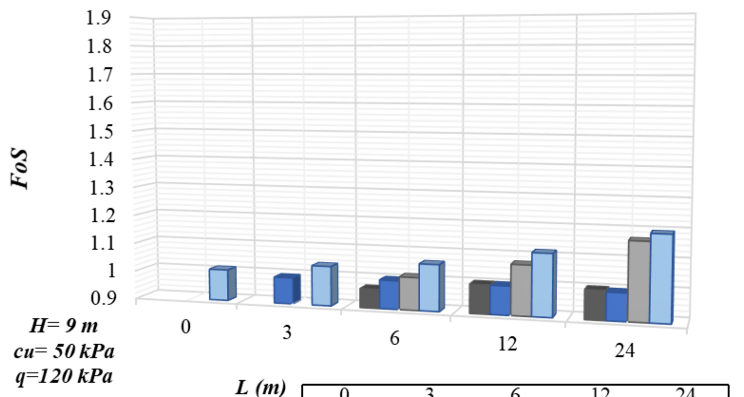
But an interesting situation has been arising at L= 24 meters. In such a case, the FoS value significantly decreases when the the inclination of the slope is increased. The relative change between the calculated values of FoS at L= 0 and L= 24 meters has been the same at 12 %. This might be the response of the slope which dynamic response is dominantly found more dangerous than the safety of the foundation. It is thought that the finite element analysis considered the FoS value depending on the stability of slope at L=0 and L= 24 meters. At L= 0 and L= 24 meters distance, the interaction of the slope-foundation system depended on the stability of the slope but at L=0 the effective forces on the system stability were activated via the earthquake loading, foundation weight, and the soil mass which forms the slope but at L=24 meters the effective forces on the system stability were activated only the earthquake loading and the soil mass which forms the slope. The increase of the interaction distance leads to the absence of the foundation weight and increases the FoS value. In addition, the relative difference between the determined values of FoS for static and dynamic conditions at the same inclination, has been determined maximum for L= 24 meters. In Figure 7, the height of the slope is assumed to be 6 m. The increase of the H causes to decrease the FoS values as expected but the FoS values have been determined bigger than 1.0 considering all envisaged situations.

The increase of the height of the slope leads to an increase in the effect of the slope mass depending on the distribution of the stresses to a large area. If the static loading conditions and dynamic conditions have been considered individually, it can be seen that although the L distance tends to increase, the relative difference between the calculated values of FoS for both inclination values cannot intersect at a certain value. But this situation changes for dynamic loading conditions and FoS values have been accessed to a common value only at L=12 meters. At L=24 meters, the same characteristic behavior trend (Figure 6) has been followed again in dynamic conditions. In addition, it is a remarkable condition that FoS=1.061 for L=0, β=45° for dynamic analysis. This mentioned value of FoS shows that the system is almost at the limit loading situation. On the other hand, the relative maximum difference between the FoS values that have been obtained for the case that L= 24 meters comparing static and dynamic loading conditions. This relative difference has been calculated as 23 % for β=45° and 20% for β=30°. In Figure 8, the height of the slope is assumed to be 9 m.



L (m)	0	3	6	12	24
β = 45° (dynamic analysis)	1.061	1.141	1.158	1.216	1.106
β = 30° (dynamic analysis)	1.152	1.165	1.171	1.217	1.171
β = 45° (static analysis)	1.08	1.181	1.24	1.312	1.433
β = 30° (static analysis)	1.19	1.234	1.268	1.347	1.459

Figure 7. The change of FoS values against L at H= 6 m



L (m)	0	3	6	12	24
β = 45° (dynamic analysis)			0.966	1.000	1.000
β = 30° (dynamic analysis)		0.9917	0.9992	0.9993	0.995
β = 45° (static analysis)			1.013	1.073	1.167
β = 30° (static analysis)	1.009	1.038	1.061	1.115	1.193

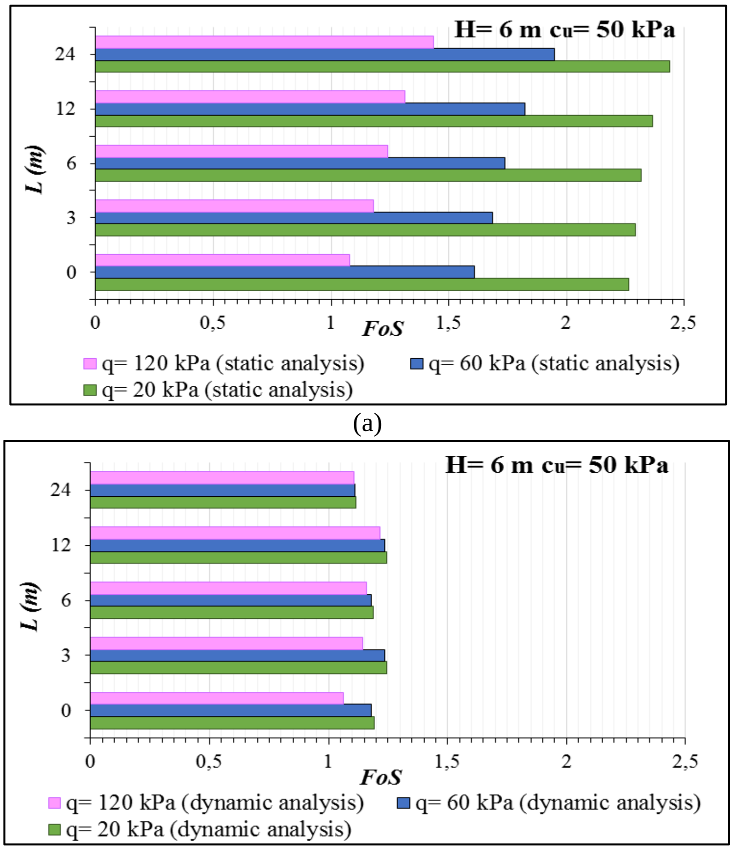
Figure 8. The change of FoS values against L at H= 9 m

The increase of the slope height leads some interaction cases to fail or reach a condition almost to fail. The maximum value of the FoS value has been calculated for L=24, β=30° for static analysis. But depending on the closeness of the obtained values from the numerical analysis, it can be possible to say that the effect of the inclination of the slope is decreased depending on the increase of the slope height. The increase in the slope height has more effect than the increase in the slope inclination and after the slope height reaches a certain value, the effect of the slope inclination on the behavior becomes negligible.

Considering the data used in this study, it can be argued that the presence of slope has a very significant effect on the failure behavior of shallow foundations located within a quarter of the width of the foundation and should be carefully examined for both static and dynamic loading conditions. In addition, it can be stated that the safety of a shallow foundation, which is behind the slope by the width of the foundation, is not affected by the presence of the slope.

3.3. The Effect of the Magnitude of Structural Static Load Change

The effect of the change of the static loading magnitude has been considered with the use of three different values of surcharge. The magnitude of the static loading has been assumed to be 20 kPa, 60 kPa and 120 kPa respectively. Evaluations have been conducted considering the case that c_u= 50 kPa. In this context, Figure 9 and Figure 10 are prepared to reflect the interaction behavior of slope-foundation at H= 6 meters and H= 9 meters respectively. The sub-divisions of the figures have been drawn individually to separate the static and dynamic responses of the system.



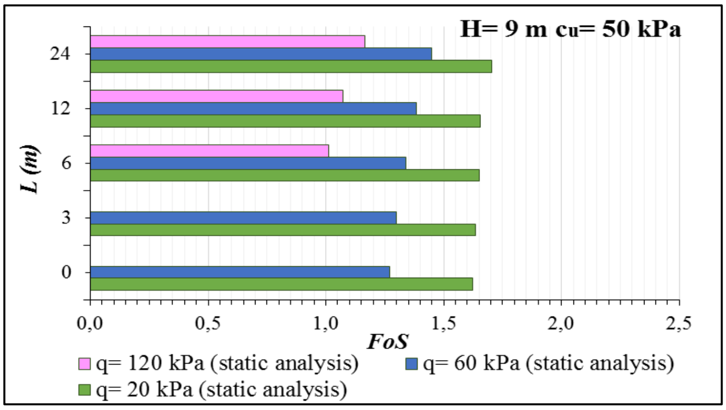
(b)

Figure 9. The change of FoS values against L at H= 6 m

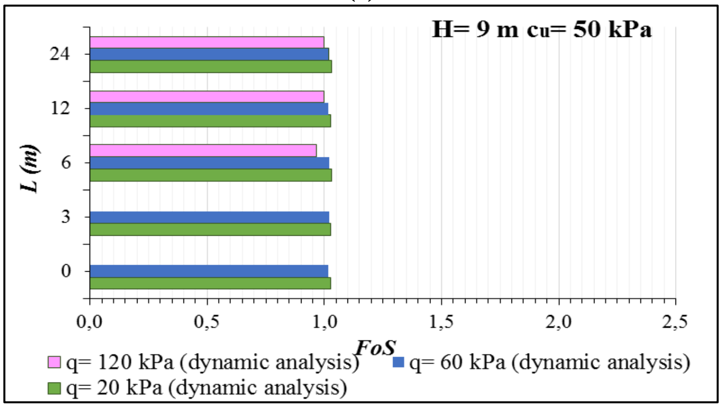
It can be seen from Figure 9 that the dominant effect of the surcharge magnitude can be perceived in static conditions. For static conditions, the increase of the surcharge magnitude leads to decrease the FoS value as expected. Besides, the increase of the L distance increases the system safety.

There can be calculated a directly proportional relationship between the increase of the FoS value with the increasing L distance for static conditions. The increasing tendency of the FoS value depending on the increase of L decreases with the decrease of the loading magnitude. The remarkable point in these analysis is that even when the load magnitude was at the lowest level, the increase in the interaction distance L could not equalize the safety number values obtained.

Therefore, it can be said that determining the foundation load at the correct level is of great importance in determining the slope-foundation interaction distance for static conditions. The dynamic response of the interacted system has been obtained very differently from the static response. The FoS values have been significantly decreased for all cases considered if a comparison is conducted between static and dynamic analysis. Besides, the increase of the magnitude of the loading has minimal effect on the safety in dynamic conditions and this effect can be neglected when the L= 24 meters. Figure 10 represents the response of the system when H becomes equal to 9 meters.



(a)



(b)

Figure 10. The change of FoS values against L at H= 9 m

A similar behavior manner as Figure 9 has been followed in Figure 10 for both static and dynamic responses. Besides, it can be a special result to determine FoS values smaller than 1.0 for L= 0 and L= 3 meters when the load is 120 kPa for both static and dynamic loading conditions. In such a case that the foundation has been located closer to the slope crest, the increase of the loading magnitude has led the system to fail. Therefore, the magnitude of the surcharge loading is especially an important state to be evaluated throughout the static analysis.

4. CONCLUSIONS

The aim of this study is to compare both the static and dynamic responses of interacted slope-shallow foundation systems considering the changes of probable effective factors on design. The variables of the analyses have been selected as the undrained shear strength of the soil, the geometry of the slope and the magnitude of the static surcharge loading. Besides, the dynamic loading has been considered by the use of the accelogram data of the Samos-İzmir earthquake. Numerical analyses were conducted with two dimensional Plaxis software regarding finite element solution logic to reflect the safety response of the foundation-slope system located adjacent to each other. The main special evaluations are obtained considering only the performed cases within this study and given as follows:

- The doubling of the c_u value leads the system safety level to be increased approximately twice for both under static and dynamic conditions.
- The increase of L leads to a significant increase in the degree of safety especially after exceeding a distance nearly the same as the foundation width B.
- It is an important situation that the percentage of the decrease of safety during dynamic loading is determined approximately the same for all considered c_u values. Therefore, it can be said that the value of c_u is not effective on the rate of the decrease in safety that happened while dynamic loading for the considered cases.
- The differentiation between the static and dynamic conditions in terms of safety is decreased with the increase of H and q.
- The increase of both H and q leads the system to be failed when the foundation is located at the edge of the slope.
- The increase of β leads to a decrease in the FoS value, especially for the case that the L distance is relatively small during static analysis.
- The relative difference between the FoS values at static conditions approximately determined equally when the L value becomes the quarter width of the foundation base (6 meters).
- In such a case that the dynamic loading conditions dominate the system, the safety level decreased with the increase of the slope angle.
- The increase in H has more effect than the increase in β and after H reaches a certain value, the effect of β on the behavior becomes negligible.

As the result, considering the data used in this study, it can be argued that the presence of slope has a very significant effect on the failure behavior of shallow foundations located within a quarter of the width of the foundation and should be carefully examined for both static and dynamic loading conditions. It can be stated that the safety of a shallow foundation, which is behind the slope by the width of the foundation, is not affected by the presence of the slope. For static conditions, the increase of q leads to decrease the FoS value as expected. Besides, the increase of the L distance increases the system safety. There can be calculated a directly proportional relationship between the increase of the FoS value with the increasing L distance for static conditions. The increasing tendency of the FoS value depending on the increase of L decreases with the decrease of the loading magnitude. In addition, the remarkable point in these analysis is that even when the load magnitude was at the lowest level, the increase in the interaction distance L could not equalize the safety number values obtained. Therefore, it can be said that determining the foundation load at the correct level is of great importance in determining the slope-foundation interaction distance for static conditions. In such a case that the foundation has been located closer to the slope crest, the increase of the loading magnitude has led the system to fail. Therefore, the magnitude of the surcharge loading is especially an important state to be evaluated throughout the static analysis.

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