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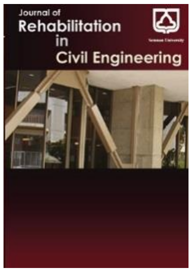

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Determining the Dynamic Settlement of the Foundation Adjacent to Slope Using Analytical Method

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ABSTRACT

Based on field studies, the topographic slope effects worsen the structural damage in an earthquake. It is very vital to determine the amount of foundation settlement adjacent to the slope. In this study, a new analytical model is proposed to determine the amount of vertical settlement of the shallow foundation near the slope. In this analytical model, the inertia force due to the sliding zone mass is considered in the dynamic equilibrium equations. Moreover, it was assumed that stiffness and damping under the foundation linearly increased as the distance from the slope edge increased. In this case, the maximum stiffness and damping at a distance five times as large as the foundation width from the slope edge were considered to be the same as maximum stiffness and damping in the non-slope scenario. The foundation was loaded harmonically by changing the frequency. Comparing the results of this study with the laboratory results leads to this observation that the offered analytical model can well determine the settlement located near the slope. Furthermore, the results showed that the settlement of the foundation near the slope edge was twice as large as the settlement in the absence of a slope. Also, the settlement of the foundation became equal to that of the non-slope foundation at a distance of 4 times as large as the foundation width from the slope edge. Furthermore, with increasing slope angle and declining the foundation distance from the slope edge, due to vertical harmonic load, the foundation settlement amount increases.

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1. Introduction

The seismic response of shallow foundations adjacent to the slope is different from their dynamic response on flat ground. Consequently, in determining the dynamic bearing capacity, it is essential to consider the slope's effects. Structures such as retaining walls, transmission towers, retaining walls along bridges, and bridge foundations have foundations that are often located on or vicinity to the slope. Studies conducted on structures situated adjacent to the slope relative to the flat ground reveal an increase in the seismic response of these structures [1-4]. Determination of the bearing capacity of shallow foundations adjacent to the slope has been offered in several analytical, laboratory, and numerical studies. In previous studies, by the means of the limit analysis method and considering the horizontal acceleration of the earthquake in a quasi-static method have considered the bearing capacity of shallow foundations adjacent to the slope [5, 6]. Likewise, Choudhury and Rao based on the limit equilibrium method and considering the horizontal and vertical acceleration of the earthquake inspected the bearing capacity of the foundations buried in the slope quasi-statically [7]. Arabshahi et al. [8] via the discrete element method, determined the bearing capacity of shallow foundations along the slope under the horizontal acceleration of the earthquake. Furthermore, the determination of foundation bearing capacity using laboratory and numerical modeling and considering pseudo-static loading in the studies have been considered done by previous researchers [9-12]. In these studies, the consequence of external load frequency, the effect of foundation distance from the slope edge, and the reinforcement of the slope with geosynthetic elements were considered.

Previous studies mostly applied dynamic loads in quasi-static form and did not examine the direct effects of the dynamic load. Moreover, the effects of the applied load frequency on the settlement of the foundation in the vicinity of the slope were not addressed. Previous studies did not use the ground frequency-dependent stiffness and damping. To bring about economic savings in the design and reduce the risks of large earthquakes, a more applicable model should be offered for the seismic performance of shallow foundations vicinity to the slope. This performance can upsurge the efficiency of these foundations after the earthquake and during use for the structures situated on them.

Based on Fig. 1, Lysmer and Richart [13] indicated that the vertical vibration of a rigid circular foundation dependent on an elastic half-space can be modeled by a mass-spring-damper system. Later, this method was developed by other researchers for non-circular foundations. In line with the shallow foundations adjacent to the slope, since the elastic half-space is not completely present in the problem, the stiffness and damping coefficients offered for the foundations situated on the elastic half-space cannot be used. Consequently, Varzaghani and Ghanbri [14] considering the level of sliding under the foundation, considered the stiffness and damping in different parts of this level of sliding as a variable in the calculations and studied the seismic response of the foundation by writing the dynamics equilibrium equations.

In this study, according to the conducted analysis studies, considering the sliding under the foundation, its inertial force was also mentioned in the calculations. Besides, stiffness and damping are considered as a linear distribution that rises with distance from the slope's edge. Lastly, by writing the dynamic equilibrium for the foundation sliding zone under the foundation, the displacement values are obtained for the sliding surfaces with different angles, and the sliding surface with the most strain is selected as the critical sliding level. When the critical sliding level is determined by solving the dynamic equilibrium equation for the foundation and soil setting, the foundation settlement will be calculated.

2. Proposed model

In this analytical study, the vertical settlement of the shallow foundation near the slope under cyclic loading was investigated. The failure surface under the foundation was treated to be a plane. Then, using the dynamic limiting equilibrium of the foundation and failure wedge, different deformation values were found at different failure surface angles. Finally, the surface with the highest strain was selected as the critical failure surface. The failure wedge mass can be found using the failure angle to be employed in the equilibrium equations. Therefore, a failure angle is found for each model with a given height or type of soil. The considered assumptions in this analysis are as follows:

1. A sliding level is a plane that starts from the end of the foundation and crashes with the slope.
2. The foundation located on a slope is a strip foundation and acts as a plane strain.
3. The behavior of soil beneath the foundation was considered linear elastic.
4. The foundation is shallow and the load on the foundation is dependent on time and it is cyclic.
5. The zone sliding under the rigid foundation and its weight are used in the equations.
6. Vertical stiffness and damping will increase linearly with increasing distance from the slope edge.

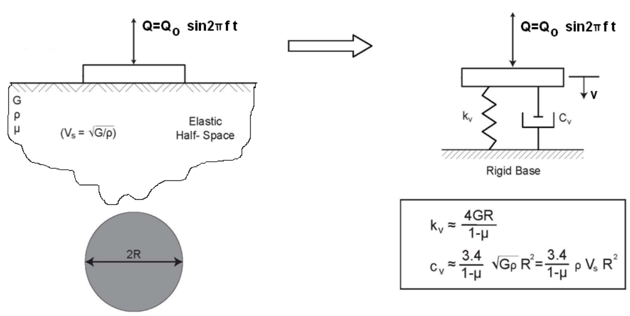

Fig 1. Modeling of the foundation by the mass-spring-damper system by Lysmer and Richart [13].

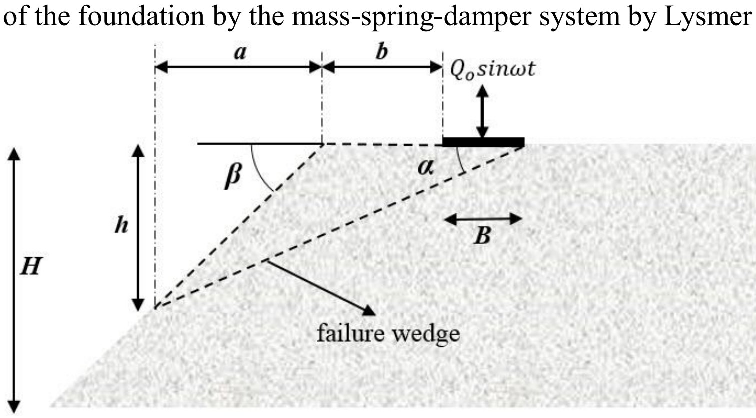

Fig 2. The plane sliding level considered below the foundation.

Based on Fig. 2, due to the application of dynamic force, the zone sliding under the foundation shifts rigidly. To attain the foundation settlement, the dynamic equilibrium equation underneath the foundation in the vertical direction and considering the zone sliding mass is as follows:

$$m\ddot{u}_z + c\dot{u}_z + ku_z = Q_0\, sin\omega t \tag{1}$$

Where m is the whole system mass, c is the damping indicator and k is the stiffness indicator. Q_0 is the excitation amplitude applied to the system with angular frequency ω. The mass of the whole system (m) is obtained from the total foundation mass (m_f) and the soil mass (m_s). The soil mass can be determined using Eq. (3). The system displacement equation in the vertical direction is defined using Eq. (4):

$$m = m_f + m_s \tag{2}$$

$$m_s = \frac{1}{2}(b+B)^2\left(1+\frac{tan\alpha}{tan\beta - tan\alpha}\right)\rho_s \tag{3}$$

$$u = A_1\, sin\omega t + A_2\, cos\omega t \tag{4}$$

By placing Eq. (4) in Eq. (1), the coefficients A1 and A2 are obtained as follows:

$$A_1 = \frac{(k-m\omega^2)Q_0}{(k-m\omega^2)^2 + c^2\omega^2} \tag{5}$$

$$A_1 = \frac{-cmQ_0}{(k-m\omega^2)^2 + c^2\omega^2} \tag{6}$$

Excitation applied to the system is vertical and vertical behavior of foundation is anticipated. Consequently, according to Mylonakis et al. [15] and using the following equation the static vertical stiffness under the shallow strip foundation is determined.

$$k_z = \frac{GB}{(1-\vartheta)}\left(0.73 + 1.54\left(\frac{A_b}{B^2}\right)^{0.75}\right) \tag{7}$$

Where G is the soil shear modulus, B is the foundation width, υ is the Poisson's ratio and A_b is the foundation area. Based on the dynamic study of the problem, frequency-dependent dynamic stiffness is used. In this case, the frequency-dependent dynamic stiffness ($\bar{k}_z(\omega)$) is obtained by applying a dynamic stiffness coefficient ($k(\omega)$) to the static stiffness (Eq. (8)). The dynamic stiffness coefficient can be obtained from Fig. 3 based on the L/B ratio and $a_0 = \frac{\omega B}{V_s}$.

$$\bar{k}_z(\omega) = k_z \cdot k(\omega) \tag{8}$$

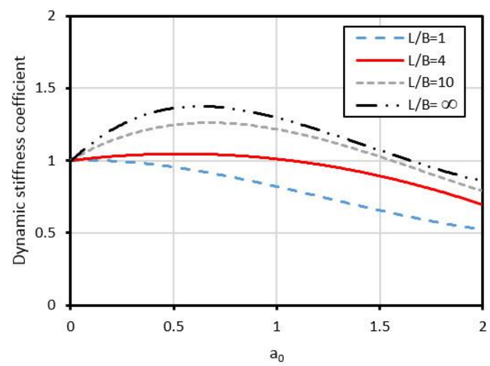

Fig 3. Dynamic stiffness coefficient curve [15].

The study of El Sawwaf and Nazir's [10] on small-scale strip foundations disclosed that when the foundation is located at a distance of $3B$ from the slope edge, the consequence of slope on the displacement of the foundation is insignificant and at the end of the slope the stiffness changes reach zero. Varzaghani and Ghanbari [14] recommend the stiffness ratio of the foundation at different distances from the slope's edge to the stiffness of the same foundation on the flat ground as shown in Fig. 4. These researchers have revealed that if the foundation is located more than $3B$ to $5B$ from the slope edge, the effect of the slope on the foundation settlement will be insignificant. A distance of $3B$ was recommended for a very gentle slope (20°) and a distance of $5B$ for a steep slope (45°). Based on these studies, in the current study, it is expected that soil stiffness will increase linearly from the slope edge up to $5B$. Likewise, vertical stiffness at a distance of more than $5B$ from the slope edge is considered consistent with the ground condition without slope. Stiffness changes from the slope edge are shown in Fig. 5a. Regarding this figure, in equilibrium equations, the average stiffness underneath the foundation is used in different positions of the edge of slope (Fig. 5b).

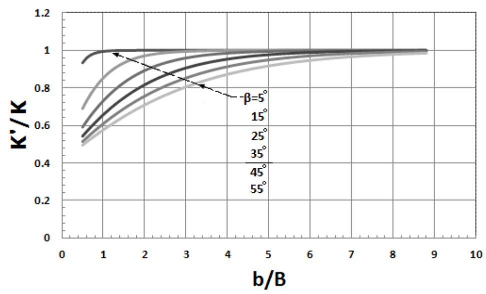

Fig 4. Changes in the stiffness ratio of the foundation adjacent to the slope to the foundation located on the flat ground [14].

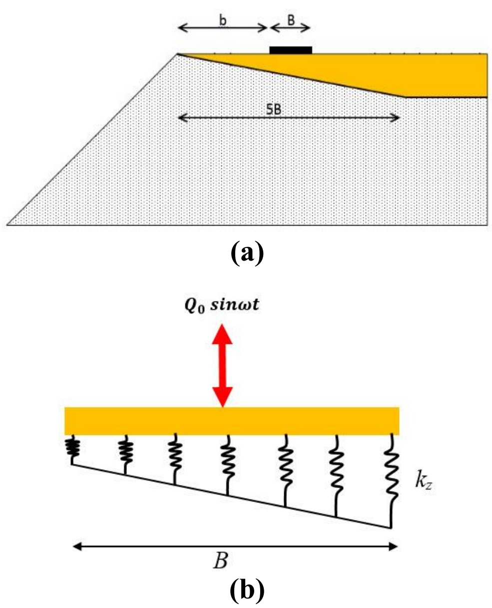

Fig 5. Changes in stiffness and damping (a) from the slope edge and (b) beneath the foundation.

In line with the equation offered for vertical soil stiffness above, frequency-dependent damping is also applied in the current study. Based on Mylonakis et al.'s [15] study, the vertical damping (c_z) is determined using the following equation:

$$c_z = (\rho \cdot V_{Lb} \cdot A_b)\bar{c}_z \quad (9)$$

Regarding this equation, vertical damping depends on soil density (ρ), Lysmer's analog wave velocity ($V_{Lb} = \frac{3.4}{\pi(1-\vartheta)} V_s$), foundation area ($A_b$), and dynamic damping coefficient ($\bar{c}_z$). The parameter $\bar{c}_z$ can be determined by the means of Fig. 6. Lastly, frequency-dependent damping is determined using Eq. (10), in which $\xi = 0.05$ was considered [15]. In the current study, the damping reduction process is considered as the foundation approaches the slope edge such as a reduction in stiffness. As a result, the average damping value under the foundation is used in the dynamic equation.

$$\bar{c}_z(\omega) = c_z + \frac{2\bar{k}_z(\omega)\xi}{\omega} \quad (10)$$

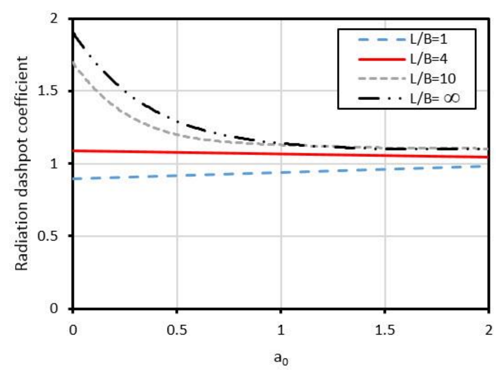

Fig 6. Dynamic damping coefficient curve [15].

3. Results

By the formulation achieved in this study, due to the application of a harmonic load near the slope, the maximum foundation settlement can be obtained. The equations were analyzed using MATLAB. To this end, the characteristics of three soil types have been used (Table 1). The geometry features of the models studied in the current study can be seen in Table 2. Based on this table, in this study, the effect of dynamic load frequency, foundation distance from the slope edge, slope angle, increasing soil stiffness, and dynamic load amplitude have been examined. Moreover, a comparison between the results of the proposed model and laboratory and analytical studies is provided.

The natural period of the flat ground (4m deep) was found to be 0.29, 0.21, and 0.16 sec for loose, mid-dense, and dense soils, respectively. Based on the equation $T = \frac{2\pi}{\omega} = \frac{2\pi\sqrt{m}}{\sqrt{k}}$ and the fact that ground stiffness k is lower in the sloped ground than in the non-slope one, the natural period of the sloped ground is lower [16]. Hence, the natural period of the slope is 0.24, 0.18, and 0.14 s for loose, mid-dense, and dense sandy soils, respectively.

One of the effective parameters in determining the settlement (S) in the case of applying harmonic load on the foundation is the dynamic load frequency effect. In Fig. 7, the harmonic load frequency effect on the foundation settlement ratio (S/B) is depicted in different foundation placement locations from the slope edge. The results reveal that the load frequency has a great effect on the settlement and the maximum cyclic settlement at the normal frequency of the system is higher than other frequencies. Furthermore, the cyclic settlement amount decreases with increasing distance from the slope edge.

Table 1. Characteristics of studied sandy soils [10].

Type of soil	γ (kN/m^3)	υ	G (kN/m^2)
Loose sand	16	0.3	5000
Medium sand	18	0.3	10000
Dense sand	20	0.3	20000

Table 2. Geometrical specifications of the studied models.

No		B(mm)	β(degree)	Height Foundation (mm)	Thickness of Soil Layer, H (mm)
1	Proposed method	800	35	200	4000
2	Proposed method	800	33.69	200	4000
	El Sawwaf and Nazir [10]	80	33.69	20	400
	Varzaghani and Ghanbari [14]	800	33.69	200	4000
3	Proposed method	1300	33.69	300	400
	Islam and Gnanendran [11]	130	33.69	30	400
	Varzaghani and Ghanbari [14]	1300	26.56	300	400
4	Proposed method	1300	26.56	300	400
	Islam and Gnanendran [11]	130	26.56	30	400
	Varzaghani and Ghanbari [14]	1300	26.56	300	400

The effect of increasing soil stiffness that leads to increasing the shear wave velocity of the soil was also examined on the foundation. For this study, a slope profile with a 35-degree angle was used and the foundation was placed at a distance of b/B = (0, 1, 2, 3, 4). The results of this study are presented in the form of settlement to foundation width ratio (S/B) in Fig. 8. As it is evident, the foundations located at the slope edge have the most settlement compared to other modes. Furthermore, with increasing soil stiffness, the amount of foundation settlement will decrease.

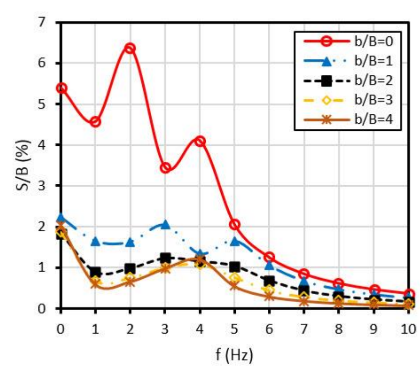

Fig 7. The effect of dynamic load frequency on the foundation settlement ratio ($G = 5000\ kPa, Q_0 = 50\ kN$).

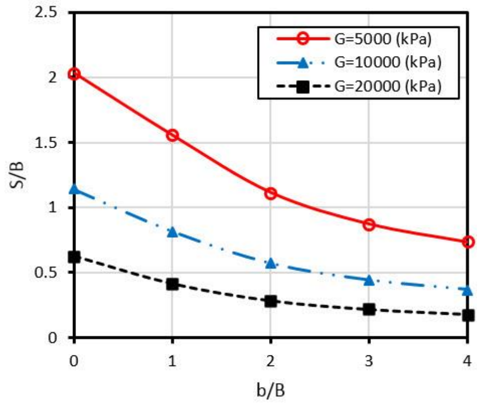

Fig 8. Effect of soil stiffness on the foundation settlement ratio.

4. Comparing results

By experimental modeling of the foundation adjacent to the slope crest, El Sawwaf and Nazir [10] examined the effect of harmonic load on vertical settlement (Fig. 9). A comparison between the cyclic settlement ratio obtained from the laboratory studies of El Sawwaf and Nazir [10] with the results of the proposed model is accessible in Fig. 10. In this comparison, the foundation is placed at different distances from the crest and the input excitation frequency is 1 Hz. Regarding this figure, it is well clear that both studies give the same approach for decreasing settlement by increasing the foundation distance from the slope crest. Nevertheless, in the laboratory study, due to the effects of load waves in areas close to the edge, the ratio of the settlement vicinity to the slope is higher than other points. Furthermore, the settlement created for the foundations at the edge of the slope in the laboratory study is affected by a greater shear strain than the analytical study.

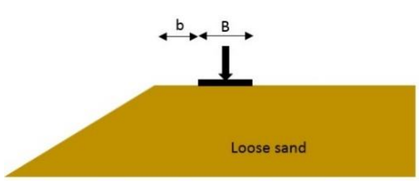

Fig 9. A laboratory model of the foundation adjacent to the slope.

According to Fig. 10, the seismic response of the foundation near the slope edge will be the same as that in the non-slope. Also, the free vibration period of the sloped ground at large enough distances from the slope edge becomes similar to that of the flat ground [17]. Therefore, it can be concluded that the seismic response of the foundation at different locations of the slope edge is dependent on the free vibration frequency of the system and the input excitation frequency. According to Fig. 7, the settlement significantly increases at close frequencies.

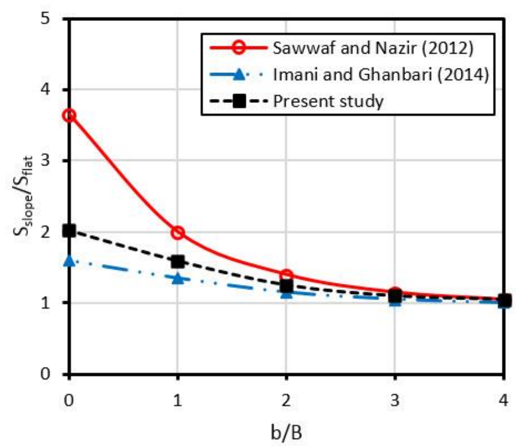

Fig 10. Comparison of settlement ratio in the proposed model with studies of others.

Islam and Gnanendran [11] have investigated the behavior of strip foundations near the slop under dynamic load experimentally. Based on Fig. 11, the foundation is placed under the foot of the bridge beside the slope and a dynamic load related to the movement of vehicles is applied to it. In these investigations, the input excitation frequency is 1 Hz and the effect of increasing the load range on the settlement ratio is compared. It should be noted that the foundation is located at a distance B from the slope edge. The results of this study were also compared with the analytical model offered by Varzaghani and Ghanbari [14]. In Table 3, the comparison of the results of the proposed model with other studies is presented. Based on this table, the results of the current study reveal a good agreement with Varzaghani's and Ghanbari's analytical model results [14]. Moreover, as the load range increases, the results of the three studies become closer to each other. According to these results, it can be seen that by decreasing the slope angle, the settlement ratio will also decrease.

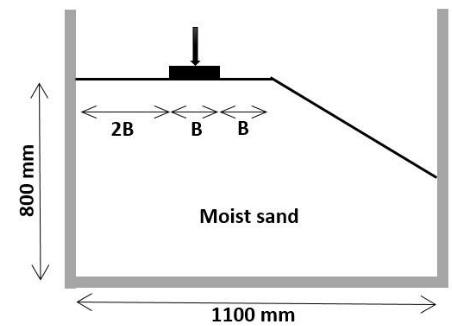

Fig 11. The base of the bridge located near the slope in Islam and Gnanendran [11] in real condition and laboratory model.

As mentioned, Fig. 7 compares the analytical results to previous studies. Moreover, the static and seismic stability analyses of the slope were performed. In these analyses, the effect of the distance of the foundation from the slope edge was studied, as reported in Table 4. As can be seen in Table 1, the static factor of safety varied from 1.22 to 2.25 at a b/B ratio of 0-4, implying slope stability. However, the seismic factor of safety was found to be lower than 1.1 at b/B≤1, leading to slope instability [18]. The safety factor was calculated to be greater than 1.27 at b/B≥2. Therefore, the dynamic load destabilized the slope for foundations at a distance lower than 2B from the slope edge. This is explained, in part, by the resonance phenomenon.

Table 3. Comparison of settlement ratio in the present study with laboratory and analytical studies.

	S/B (%)					
	β=33.42°			β=26.56°		
Q_o (kN)	Proposed Method	Islam and Gnanendran [11]	Varzaghani and Ghanbari [14]	Proposed Method	Islam and Gnanendran [11]	Varzaghani and Ghanbari [14]
5	0.27	0.14	0.26	0.20	0.17	0.20
10	0.54	0.37	0.52	0.45	0.44	0.40
15	0.81	0.50	0.78	0.67	0.45	0.61
20	1.08	0.63	1.04	0.90	0.77	0.81
25	1.35	0.88	1.30	1.12	0.96	1.01
30	1.61	1.09	1.55	1.34	1.21	1.21
35	1.89	1.47	1.81	1.57	1.44	1.41
40	2.15	2.11	2.07	1.79	1.61	1.62

5. Conclusion

In the current study, by introducing a novel analytical model, the foundation located adjacent to the slope under vertical harmonics is examined. In the suggested analytical model, the mass of failure wedge is effective and is used in the equations. Furthermore, the vertical stiffness and damping underneath the foundation were considered as a triangular distribution up to a distance of 5B from the slope edge.

Table 4. Slope stability analysis

b/B	Safety Factor (static)	Safety Factor (seismic)
0	1.22	1.02
1	1.42	1.08
2	1.63	1.27
3	2.18	1.83
4	2.25	1.98

The amount of stiffness and damping at the slope edge was expected to be zero. Based on these cases, the average stiffness and damping below the foundation were used in the equilibrium equations. Below are the most important results of this research.

1. Based on the comparisons made with preceding studies, the suggested model forecasts elastic settlements with appropriate accuracy.

2. In the offered model, along with stiffness and damping, the zone sliding mass also has a huge effect and small errors in these parameters cause an enormous difference in the results.

3. Not like static analysis and static equivalents where the amount of settlement depends on the distance of foundation from the base of the slope edge and the angle of slope, in dynamic analysis, the settlement is highly dependent on the amount of dynamic load frequency. This is because, at a certain frequency, the foundation located at the furthest distance from the slope edge relative to other points may have a maximum settlement.

4. The stiffness and damping offered in the current model are relative to the elastic behavior of the soil. In other words, it has the needed accuracy for cases where the shear strain is low. as a result, where the strains are usually very high, at close slope distances, the accuracy of the proposed model will decrease.

5. The results were obtained under the limitations of the proposed method, e.g., the planar, rigid failure wedge, for elastic soil behavior. Therefore, nonlinear soil behavior, the real slope failure surface, and waves colliding and reflected by the slope would influence the seismic response of the foundation and can be considered in future studies.

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