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Ali Rajabi, Mostafa Baghjari, Rana Azizi

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Numerical study of topography and inclined load effects on bearing capacity of strip foundations adjacent to a sandy slope

Ali Rajabi [1,*], Mostafa Baghjari [2], Rana Azizi [1]

[1] School of Geology, College of Science, University of Tehran, Iran
[2] Department of Civil Engineering, University of Qom, Qom, Iran

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Abstract
Rapid urbanization near the mountainous areas and sloping grounds and its effect on bearing capacity of shallow foundations have become one of the foremost geotechnical challenges in some regions. Bearing capacity of a strip foundation adjacent to a slope depends on many factors including slope angle (β), inclined load angle (θ), soil friction angle (φ), slope height (H), distance of the edge of foundation from the slope (λ) and depth of the foundation (D). Although there have been many studies on these parameters in recent years, the effect of the mentioned parameters on bearing capacity of shallow foundations and simultaneously under the inclined load effect is still not investigated. In this concept and by modeling foundation and sloping ground in ABAQUS 6.14.1, the bearing capacity of shallow foundation underlaid by drained sandy soil and under the effect of the inclined load and the mentioned parameters is studied. The results show that by increasing slope angle and slope height, the bearing capacity of the adjacent strip foundation decreases. Also, by increasing the distance of the edge of foundation from the slope and the load angle, the bearing capacity of the adjacent strip foundation increases. Numerical studies show that the effective distance of the slope on the bearing capacity of adjacent strip foundation is about 4B (B represents the width of strip foundation). In this article, the results of the current study are compared with the studies of the other researchers in cohesive and granular soils. The results show that by taking into account the concurrent effect of all the parameters in design, the effect of slope angle on the bearing capacity of shallow foundation should be significantly noticed.

Keywords: Bearing capacity, Strip foundation, Numerical method.

Introduction

Rapid development of population, roads and industrial factories in suburbs and limited plain areas may lead to construct engineering structures adjacent to slopes. Although there are extensive studies on bearing capacity of foundations located on flat surfaces underlaid by different soil types and geotechnical conditions, limited studies are conducted to find out the topography and inclined load effects on bearing capacity of foundations as well. Slope angle, inclined load angle, soil friction angle, and distance of the edge of foundation from the slope are of the most important parameters which have a significant effect on bearing capacity of foundations adjacent to slopes in compare with plain areas. By applying a load to a foundation located adjacent to a slope, the entire mobilized passive pressure will not be transferred to its corresponding failure wedge, as it is when the foundation is located on flat ground. Moreover, the lack of soil on the slope side causes greater instability compared to flat ground, and the plastic zone beneath the foundation adjacent to the slope is considerably smaller than that beneath a foundation on level ground. Consequently, the bearing capacity of a foundation adjacent to a slope is reduced (Meyerhof, 1957).

* Corresponding author e-mail: amrajabi@ut.ac.ir

Foundation Depth	D
Soil Unit Weight	γ
Internal Friction Angle of Soil	ϕ°
Normalized Internal Friction Angle of Soil	$\dfrac{\phi^\circ}{\beta^\circ}$
Applied Load Angle	θ°
Normalized Angle of Inclined Load	$\dfrac{\theta^\circ}{\beta^\circ}$
Distance of Foundation from Slope Edge	b
Normalized Foundation Depth	$\dfrac{D}{H}, \dfrac{D}{B}$
Foundation Width	B
Normalized Distance of Foundation from Slope Edge	$\lambda = \dfrac{b}{B}$
Slope Angle	β°
Slope Height	H

Among the previous studies on bearing capacity of a foundation adjacent to a slope the ones performed by Meyerhof (1957), Hansen (1970), Vesic (1973), Shields (1997), Graham & Andrew (1987), Gemperline (1988), Saran & Sud (1989), Ben (2015), Atazadeh et al. (2016) are remarkable. These researchers have used analytical methods including characteristics curve, limit equilibrium, limit analysis, and numerical methods to investigate bearing capacity of foundations adjacent to slopes. These methods and the relevant results are briefly discussed herein. Meyerhof (1957) presented research to determine the ultimate bearing capacity of a foundation adjacent to a slope. The developed plastic region beneath a foundation located adjacent to a slope is illustrated in Figure1. In this method, location of the foundation on the slope is effective on the developed plastic region and consequently the bearing capacity of the foundation. According to Meyerhof (1975), in a distance equal to two to six times of the width of foundation from the slope, bearing capacity follows the principles of a foundation located on a flat surface, regardless of the angle that the slope has.

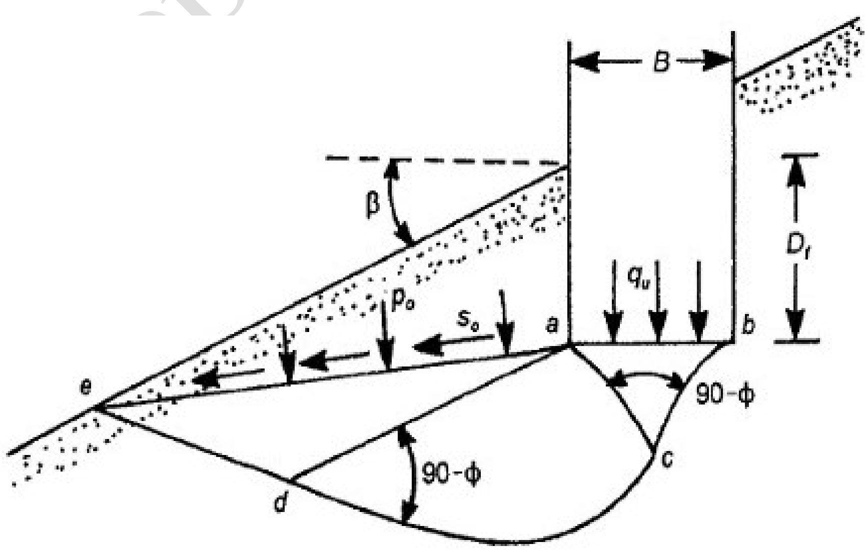

Figure 1. The failure region created under the foundation according to Meyerhof's method (1975)

Some other researchers like Hansen (1970), Vesic (1975), and Saran et al. (1989) have proposed analytical equations to determine bearing capacity of foundations adjacent to a slope. The difference between these methods is in the assumed failure surface under the foundation. Graham et al. (1987) considered the concurrent effect of overburden and specific weight of the soil and presented an analytical method in sandy soil by defining bearing capacity coefficient ($N_{\gamma q}$) for shallow foundations adjacent to a slope. This method is based on stress characteristics line analysis with a concentration on boundary and real model conditions. They presented charts to determine bearing capacity of foundations. Gemperline et al. (1988) presented an equation for $N_{\gamma q}$ based on 215 centrifuge tests on foundations adjacent to a slope in non-cohesive soils. This coefficient is used to calculate the bearing capacity of foundations in different shapes and dimensions and different distances of the slope. Choudhury et al. (2006) investigated seismic bearing capacity of foundations adjacent to a slope using limit equilibrium and quasi-static methods. In this method failure is consisted of log-spiral and planar surfaces. As a result, an increase in ground angle will cause a significant decrease in seismic bearing capacity coefficients of foundation. Also, as the critical failure surface is considered, the least seismic bearing capacity results in this method in compare with the other ones. Bransby and Davidson (2008) investigated bearing capacity of foundations adjacent to a slope. The conclusion was that the bearing capacity of these foundations also depends on foundation fixity against any horizontal and oriental movements in addition to the other factors including soil properties, foundation distance from slope, and slope angle.

Shiau et al. (2011) investigated stability of a foundation adjacent to a slope in cohesive soil using finite element method. In this study, stability of the underlaid soil and the slope are considered concurrently. They concluded that a critical value exists for the ratio of $C_u/\gamma B$ (C_u represents cohesion of the soil, γ is the specific weight of the soil, and B is the foundation width) which is a state line to distinguish between underlaid soil failure and slope failure. This is a significant parameter in designing a foundation adjacent to a slope. Keshavarz & Aryan (2014) investigated the undrained bearing capacity of a strip foundation on the slope using Discontinuity Layout Optimization (DLO) method in the GeoStudio. They concluded that this method and the finite element method have almost same results. By the way, an increase in the ratio of distance from the edge of slope to foundation width (L/B) increases the bearing capacity coefficient (N_c). In higher values of (L/B), increase in distance does not have effect on bearing capacity anymore (Keshavarz & Aryan, 2014). Riccio et al. (2014) assessed the behaviour of a slope, reinforced by geo-grid and concrete blocks and investigated the bearing capacity of its adjacent foundation. The result was that the bearing capacity of adjacent foundation increases by use of geo-grid reinforcements. Ben (2015) investigated the bearing capacity of a strip foundation adjacent to a slope using finite element method. By considering a reducing factor based on the ratio of foundation width to slope height (B\H) and slope angle some charts were presented by Ben (2015). The charts determine the reduced bearing capacity of a strip foundation adjacent to a slope. It was concluded that an increase in slope angle decreases the bearing capacity of the adjacent foundation. Atazadeh et al. (2016) investigated the bearing capacity of shallow foundations adjacent to a slope by taking into account the distance of the foundation from the slope and slope angle using PLAXIS. The results showed that the bearing capacity increases with an increase in distance or a decrease in slope angle. It was concluded that the slope affects the adjacent foundation in distances less than 3B (B represents foundation width). Also, by increasing soil friction angle, the effect of the slope angle on the bearing capacity of adjacent foundation becomes more significant. Cascone et al. (2016) investigated the seismic bearing capacity if a strip foundation adjacent to a slope using stress characteristics line method. The results showed a decrease in bearing capacity of the strip foundation under the horizontal earthquake component effect. Lotfizadeh et al. (2017) investigated the bearing capacity of a strip foundation underlaid by alternative layers of soft and stiff clays using stress characteristics line method. It was concluded that as the ratio of the first layer's depth (stiff clay) to foundation width increases, the bearing capacity of the strip foundation on the multilayer soil strata decreases.

Afsharfarnia et al. (2018) investigated the bearing capacity of the foundation located on the reinforced retaining wall with geogrids in adjacent to the slope. The results showed that using geo-grid reinforcements and increasing the distance of foundation from the slope both increases the bearing capacity of the foundation. Also, it was concluded that the effective distance is 3B (B represents foundation width). The experimental studies show changes in bearing capacity of foundation as an inclined load applies in different angles. This change is due to a different wedge failure under the foundation which is shaped due to a different boundary condition. Huang (2018) proposed a different concept by conducting a set of analysis on a strip foundation adjacent to slopes with different angles. It was concluded that a decrease in slope angle results in increase in bearing capacity of the strip foundation adjacent to the slope. Li et al. (2019) investigated the undrained bearing capacity of foundations adjacent to a slope using Total Extend Mobilizable Strength Design (T-EMSD) method. This method presents a proper solution for finding out the effect of slope on undrained bearing capacity of foundations. The results show that an increase in slope angle and slope height decreases the value of N_c. Also, Nc increases with an increase in normalized distance of foundation from the slope. Foroutan Kalourazi et al. (2020) explored the influence of shear strength anisotropy on the bearing capacity of shallow foundations near slopes using the finite element method combined with linear programming techniques. The study aimed to quantify ultimate pressure as a function of internal friction parameters, slope angle (β), and the foundation-to-slope distance. The results indicate that the bearing capacity is significantly influenced by the slope geometry for foundations located up to three times the foundation width (3B) from the slope crest. Haghgouei et al. (2020) proposed a novel method for evaluating stress distribution in slopes and validated their results against ABAQUS finite element simulations. Their findings reveal that the relationship between the cohesion-bearing capacity factor (N_c) and slope angle (β) is linear, with N_c decreasing as β increases. Conversely, the relationship between the bearing capacity factor related to footing width (N_γ) and β is nonlinear, with N_γ decreasing at a slower rate as β increases. Additionally, as the normalized footing size ratio ($c/\gamma x$, where c is cohesion, γ is unit weight, and x is footing size) increases, the value of N_c increases. At greater normalized footing distances (λ), the influence of slope geometry on ultimate bearing capacity diminishes. Ke et al. (2021) investigated the undrained bearing capacity of strip foundations near slopes using the finite-element limit analysis (FELA) method. Their findings indicate that horizontal loading applied to the strip foundation significantly influences both the bearing capacity and the development of wedge-shaped failure zones. Brahmi et al. (2021) analyzed the undrained bearing capacity of a strip foundation placed on cohesive soil subjected to vertical loading near a slope. The results revealed that for a relative distance ($\lambda = 0$) and a coefficient of variation of undrained shear strength ($CovS_u = 50\%$), an increase in the spatial correlation length (θ) leads to a slight increase in the mean bearing capacity (μq_u, measured in kN/m), while the coefficient of variation of bearing capacity ($Covq_u$) exhibits a steeper increase. When $\lambda = 0$ and $\theta = 0.5$, an increase in $CovS_u$ (%) results in a linear decrease in μqu and a corresponding linear increase in $Covq_u$. Furthermore, as the foundation approaches the slope edge, the bearing capacity factor (N_c) decreases. Ouria et al. (2022) conducted a comprehensive study on the impact of restraining stresses exerted on strip foundations in poorly graded sandy soil. The findings indicate that the method of nailing and the spatial arrangement of nails play a critical role in enhancing foundation bearing capacity. Specifically, increasing the reinforcement thickness to two or four layers resulted in an approximate 80% increase in bearing capacity compared to unreinforced soil. Additionally, increasing both the number of reinforcement layers and the length of reinforcing bars beyond 4B (where B represents the foundation width) led to a 76%

improvement in bearing capacity compared to a single layer reinforced foundation. Zhang et al. (2023) examined the effect of rainfall on the bearing capacity of soil near slopes using the finite element method implemented in ABAQUS. Key parameters in the study included rainfall intensity, rainfall distribution patterns, soil resistance properties (effective cohesion c' and effective friction angle φ'), foundation width (B), edge distance ratio (L/B), and embedded depth ratio (D/B). The results demonstrate that rainfall alters the shape of the failure wedge and reduces the soil's bearing capacity. Ismael and Al-Ne'aimi (2024) investigated the stability and bearing capacity of continuous foundations near slopes using Plaxis 2D. Their results indicate that beyond a distance of 6B (where B is the foundation width) from the footing edge to the slope crest, the impact of the slope on foundation performance becomes negligible. Additionally, the factor of safety (FOS) increases as the foundation distance from the slope edge grows. Ahmadi et al. (2024) examined the influence of geogrid length, distance from the slope edge, and soil internal friction angle on the dynamic and static bearing capacities of foundations positioned near slopes. Their analysis utilized the upper and lower bound finite element limit analysis method, implemented through Optum G2 software. The results demonstrate that the effective geogrid length is directly correlated with the internal friction angle of the soil, ranging between 2B and 3B. Furthermore, the optimal distance from the slope edge (X/B, where X is the distance between the foundation center and the slope edge) is highly dependent on the internal friction angle, which exerts a greater influence than the slope inclination itself. For a slope with a 10-degree inclination, the recommended safe foundation distance varies between 2B and 4B for internal friction angles of 25, 30, 35, and 40 degrees, while for an internal friction angle of 45 degrees, a minimum distance of 5B is required. When the slope angle increases to 20 degrees and the internal friction angle reaches 40 or 45 degrees, the safe foundation distance extends beyond 5B. Under seismic conditions, when a horizontal seismic coefficient of $k_h = 0.1$ is applied to the geogrid-reinforced sloped ground, the seismic bearing capacity exhibits a reduction ranging from 2 to 12%, depending on the specific site conditions and reinforcement configurations.

A review of the previous studies shows that simplifying assumptions and different methods of calculating the bearing capacity coefficients have led to different results in determining the bearing capacity coefficients of the foundations adjacent to slope. Among the effective parameters in bearing capacity of foundations adjacent to slopes the parameters of slope angle, inclined load angle, soil friction angle, slope height, foundation depth, and distance of the edge of foundation from the slope are remarkable. It is noticeable that the concurrent effects of the mentioned parameters and the inclined load angle are not considered in previous studies. Therefore, in this article, the concurrent effects of several parameters on bearing capacity of a strip foundation under inclined load and in a sloping ground consisted of drained sandy soil are studied. Nowadays, numerical methods are of the most usual calculating methods in analyzing different engineering problems. One of the preferable points in numerical methods in compare with the other analytical methods in calculating bearing capacity is that the other methods including stress characteristics line, limit equilibrium, and limit analysis methods only calculate bearing capacity value but in numerical methods deformations can also be detectable. On this basis, in this article it is endeavored to investigate the effects of the mentioned parameters on the bearing capacity of strip foundations adjacent to slopes in sandy soil using ABAQUS.

Data and Method

In this study the software of ABAQUS is used to determine the bearing capacity of a strip foundation adjacent to a slope in a sandy soil. The width and depth of the strip foundation are assumed to be constant and equal to 2 meters and the parameters of distance of the edge of foundation from the slope, foundation depth, slope height, inclined load angle, slope angle, and soil friction angle are assumed to be variables of the model. In this research the sensitivity of the model in response to these variables is investigated. This section presents a discussion on soil properties, foundation properties, and geometry and mesh elements used in the numerical model.

Soil and Foundation Properties

A drained sandy soil with friction angles of 25, 30, and 40 degrees, cohesion of zero, and elastic modulus of 75 MPa is considered in this study Table1. Different soil behaviors are presented to define failure criteria in soils. Soil is neither a perfectly elastic nor an ideally plastic material. So, the best criterion to define soil behaviour is elastoplastic soil behaviour. In this study because of few specified parameters required and ease of access to them, elastic perfectly plastic model of Mohr-Coulomb is used.

A strip foundation is analyzed in this study and the values of Poisson's ratio, elastic modulus, and density for this material is assigned 0.2, 21.8 GPa, and 2500 kg/m^3 respectively.

Geometry and Mesh Elements

As illustrated in Figure 2, after drawing the geometry of the model, properties of the material are assigned, boundary conditions are defined, and mesh elements are generated in ABAQUS. The basis of calculations in a finite element model is to divide the geometry of the model into finite smaller elements. Therefore, in order to generate mesh elements through the model in ABAQUS, continuous elements with linear interpolation and four-node reduced integration elements (CPE4R) are used. To analyze the effects of model dimensions and mesh element type on the results, finer meshes using both triangular and square elements were also modeled.
The conducted models showed that mesh size and type do not have a significant effect on the results. As a strip foundation is investigated in this study, plain-strain model is used in analysis. As illustrated in Figure3, a strip foundation with the width of B, the slope height of H, the slope angle of β, the normalized distance of the edge of foundation from the slope of $\lambda = {}^{b}\!/_{B}$, the inclined load angle of θ, and the foundation depth of D is modeled in ABAQUS. The parameters of the modeled geometry are shown in Table2.

Table 1. Soil Characteristics Used In Modeling

Friction angle (degree)	The coefficient of earth pressure at rest	Cohesive (kg/m^2)	Void ratio	Density (kg per m^3)	Young's modulus	Poisson's ratio
25	0.58	0	0.40	1700	75	0.30
30	0.50	0	0.40	1700	75	0.30
40	0.35	0	0.40	1700	75	0.30

Table 2. Different values of the parameters used in the models

Slope Height, H (meter)	Embedded depth of foundation, D (meter)	The distance of foundation from the edge of the slope, B (meter)	Load angle, θ (degree)	Slope angle β (degree)
0	0.25	0	15	0
2	0.50	2	30	15
4	0.75	4	45	30
8	1	8	60	45
14	1.5	10	90	60
-	2	-	-	-

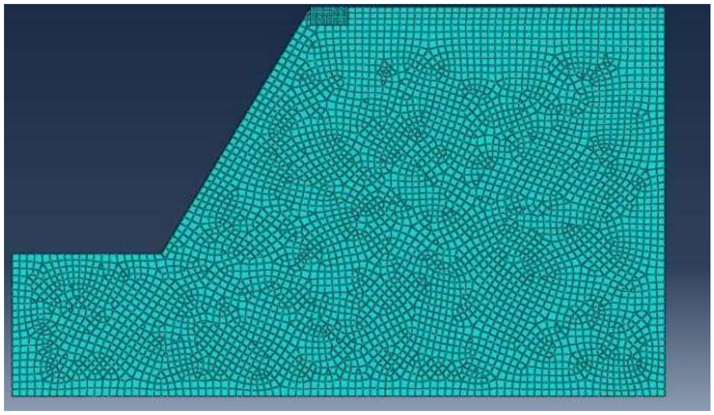

Figure 2. Mesh of general modeling in this study

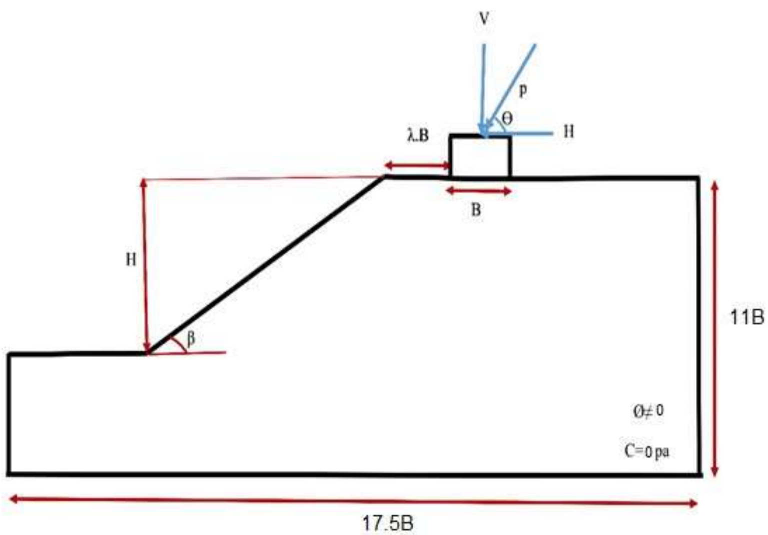

Figure 3. Schematic geometry of the foundation and the type studied in this study

Model Verification

In numerical studies one of the most important verifying features is to compare the results obtained from the numerical software used with the results obtained from valid conducted research. To verify the outputs of ABAQUS in this study, the results from the research conducted by Georgiadis (2010) are used. In order to verify the outputs of this study, undrained bearing capacity of a strip foundation adjacent to a slope under an inclined load angle of θ=0˚ is modeled in ABAQUS 2D using elastic perfectly plastic model of Mohr-Coulumb and the results are compared with Georgiadis (2010) and shown in Figure4. As illustrated in Figure4, the values of vertical load versus settlement for inclined load angle of θ=0˚ are in an acceptable convergence with Georgiadis (2010).

Results and Discussion

In this study a strip foundation with the depth and width of 2 meters in different distances of foundation from the slope, foundation depths, slope heights, inclined load angles, slope angles, and soil friction angles are modeled. After that the effects of these parameters on bearing capacity of the strip foundation adjacent to the slope in sandy soil are investigated and finally the results from this study are compared with those from previous studies.

Parametric Study

The effects of slope angle (β) and distance of foundation from the slope to its width ratio (λ)

In this section the effects of distance of foundation from the slope to its width ratio (λ) and slope angles (β) of 0˚, 15˚, 30˚, and 60˚ in sandy soil on normalized bearing capacity of foundation with regard to different soil friction angles and inclined load angles are analyzed. In this article the strip foundation with the width of B=2 meters in different distances from the slope (b≠0) is modeled (Figure5). In Figure5, the maximum bearing capacity belongs to the foundation on a flat surface and with a slope angle of 0˚and the minimum belongs to a foundation adjacent to a slope with the slope angle of 60˚. As illustrated in Figure5, concurrent increases in friction angle of granular soil and load angle from 30˚ to 40˚and 45˚ to 60˚ respectively result in increase of bearing capacity of the strip foundation adjacent to the slope which is due to the dominant effect of shear resistance in soil.

The effects of inclined load angle (θ) and the foundation depth to its width ratio $\boldsymbol{(\frac{D}{B})}$

The effects of foundation depth to its width ratio (D/B) and inclined load angle on the normalized bearing capacity of a strip foundation in a sandy soil with a soil friction angle of 30˚ and a slope angle of 45˚ (Figure6(a)) and also a soil friction angle of 40˚ and a slope angle of 15˚ (Figure 6(b)) are presented.

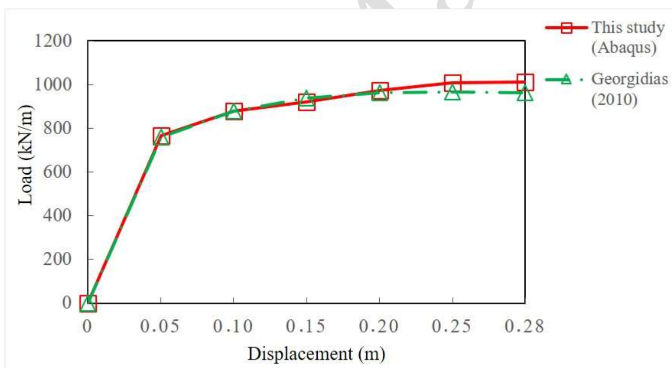

Figure 4. Comparison of vertical load-settlement changes for θ=0 in this study and Georgiadis (2010)

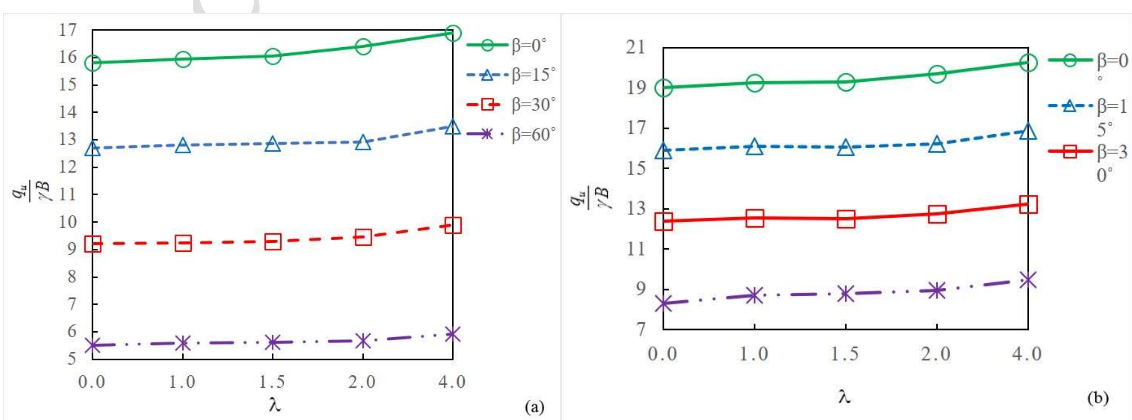

Figure 5. Changes in the normalized bearing capacity to the slope angle (β) and the ratio of the distance of foundation from edge of slope to the it's width (λ) for (a): $\emptyset = 30^{\circ}, \theta = 45^{\circ}, B = 2$ and (b): $\emptyset = 40^{\circ}, \theta = 60^{\circ}, B = 2$

In these analyses a strip foundation under inclined load angles of 15˚, 30˚, 45˚, 60˚, and 90˚ and foundation width of 2 meters are modeled. As illustrated in Figure6(a), the maximum normalized bearing capacity of the strip foundation belongs to the inclined load angle of 90˚ and foundation depth to width ratio of 1, equal to 19.92 and the minimum belongs to the inclined load angle of 15˚ and foundation depth to width ratio of 0.25, equal to 0.6. Also as illustrated in Figure6(b), the maximum normalized bearing capacity of the strip foundation belongs to the inclined load angle of 90˚ and foundation depth to width ratio of 1, equal to 21.88 and the minimum belongs to the inclined load angle of 15˚ and foundation depth to width ratio of 0.25, equal to 2.36. The results show an increase in values of inclined load angle and foundation depth to width ratio increases bearing capacity of the strip foundation and also an increase in soil friction angle from 30˚ to 40˚ and a decrease in slope angle from 45˚ to 15˚ lead to at least 25% increase in bearing capacity of the strip foundation. It shows that bearing capacity of the strip foundation adjacent to the slope increases with an increase in soil friction angle and a decrease in slope angle.

The effect of foundation distance from the slope to its width ratio (λ) with regard to soil friction angle (β=45˚)

The effect of foundation distance from the slope to foundation width ratio with regard to different soil friction angles in a slope angle of β=45˚ is shown in Figure7. The foundation width is 2 meters and the considered distances from the slope in the numerical model are 0, 2, 4, 8, and 10 meters. As illustrated in Figure7, by increasing the foundation distance from the slope, the bearing capacity increases as it reaches a more stable state. Figure7, shows that the effective distance on bearing capacity of the foundation is b=4B and in greater distances it is negligible.

The effect of slope height to foundation width ratio $(\frac{\boldsymbol{H}}{\boldsymbol{B}})$

In this section the effect of slope height to foundation width ratio (H/B) with regard to different soil friction angles on the bearing capacity of strip foundation is discussed. In these analyses numerical models containing a strip foundation with a width of 2 meters exactly adjacent to a slope with heights of 2, 4, 6, and 8 meters are investigated (b=0, λ=0) (Figure8). In Figure8, increase in slope height to foundation width ratios result in linear decrease in bearing capacity. The results show the most and the least bearing capacities of strip foundation belong to slope height to foundation width ratios (H/B) of 1 and 4 respectively.

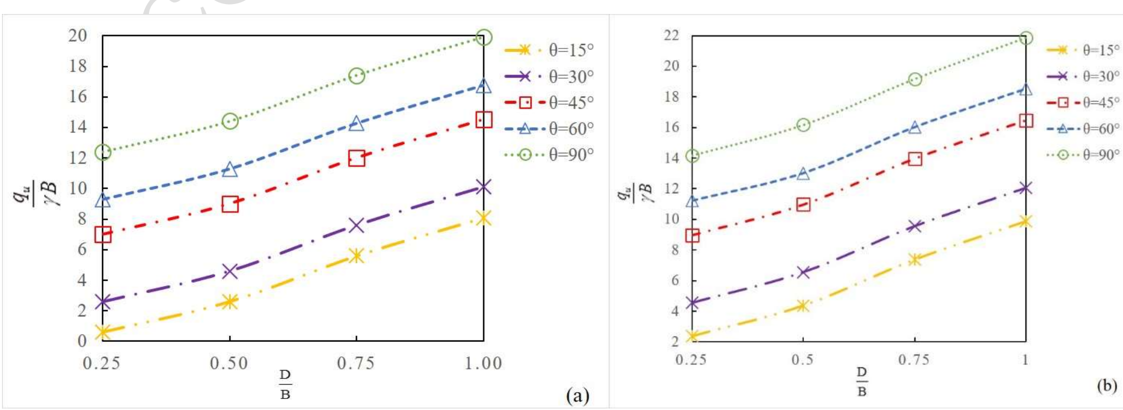

Figure 6. Changes in normalized bearing capacity to load angle (θ) and ratio of embedded Depth to width of foundation ($\frac{D}{B}$) for (a): $\emptyset = 30^{\circ}, \beta = 45^{\circ}, B = 2$ and (b): $\emptyset = 40^{\circ}, \beta = 15^{\circ}, B = 2$

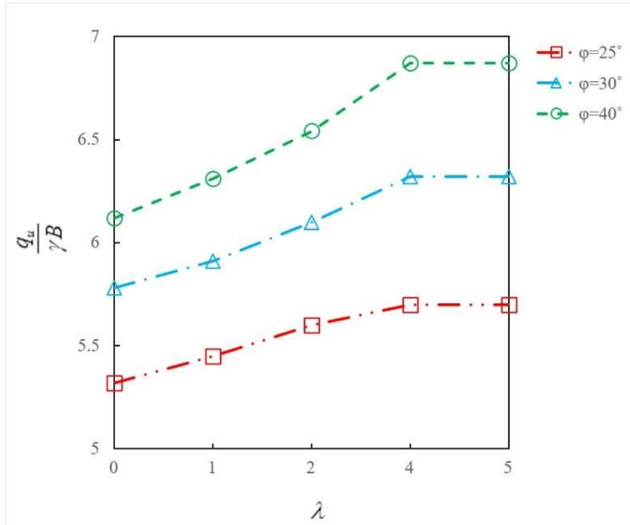

Figure 7. Changes in normalized bearing capacity to relative the distance of the foundation from the slope to the width of the foundation (λ) for: $\lambda \neq 0\,, \beta = 45^{\circ}, B = 2$

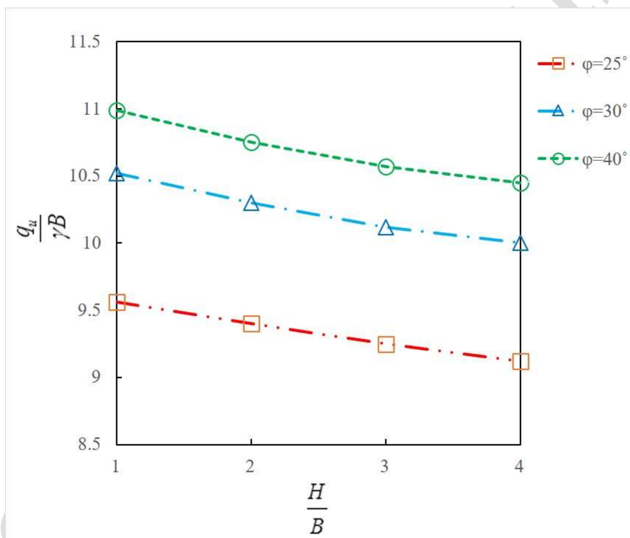

Figure 8. Changes in normalized bearing capacity to relative the height of slope to the width of foundation ($\frac{H}{B}$) for: $\lambda = 0\,, D \neq 0\,, B = 2$

A comparison between current study and the previous studies

In this section the results from this study are compared with the results from previous studies in granular and cohesive soils. In order to make this comparison, a soil friction angle of 40˚ is used for granular soil and a soil friction angle and cohesion of 20˚ and 20 KPa are respectively used for cohesive soil and also different values of foundation distance from the slope to its width ratios (λ) are considered in numerical models. As illustrated in Figure9, for all the methods including the current method, by increasing foundation distance from the slope to its width ratio the bearing capacity of foundation increases linearly. Also in cohesive soils, the limit analysis method conducted by Sud et al. (1988) is more conservative in compare with the numerical method conducted by Li et al. (2019).

This section continues by comparing the effect of foundation depth to its width ratio on bearing capacity obtained from this study with the studies conducted by Meyerhof (1957), Hansen (1970), and Sud and Saran (1988) in sandy and clayey soils (Figure10). The results show that for all the methods including current study, bearing capacity of foundation adjacent to the slope increases by increasing foundation depth. Hansen's study based on characteristics line method is more conservative than Sud and Saran's study which is based on limit analysis. Also bearing capacity of foundation in cohesive soils in these methods is less than Meyerhof's (1975) method and current study (non-cohesive soil used).

As illustrated in Figure11, a comparison is made between the slope angle effect on bearing capacity obtained from this study and the studies conducted by Meyerhof (1957), Sud and Saran (1988), Ben (2015), and Li et al. (2019) in sandy and clayey soils. The results show that in all the methods, by increasing the slope angle, the bearing capacity of the foundation adjacent to the slope decreases and the bearing capacity values obtained from Meyerhof (1957) and Ben (2015) which are respectively based on characteristics line method and DLO analysis are in convergence with the values obtained from this study.

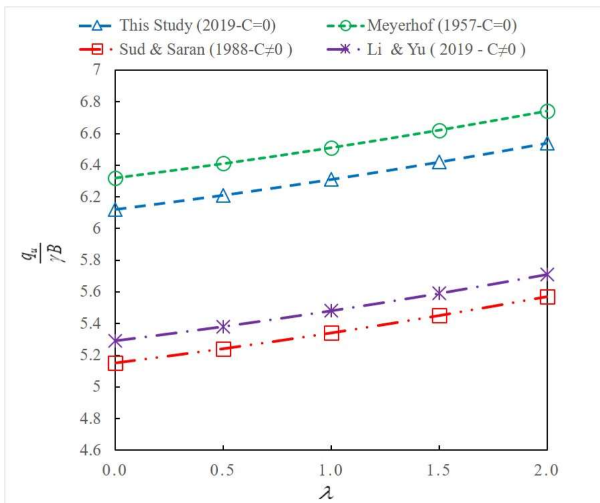

Figure 9. Comparison of the present study with other researchers in different positions of the foundation from edge of slope relative to its width (λ) in the inclined land on cohesive and non-cohesive soils in for: $\emptyset = 40^{\circ}, \beta = 45^{\circ}, B = 2$

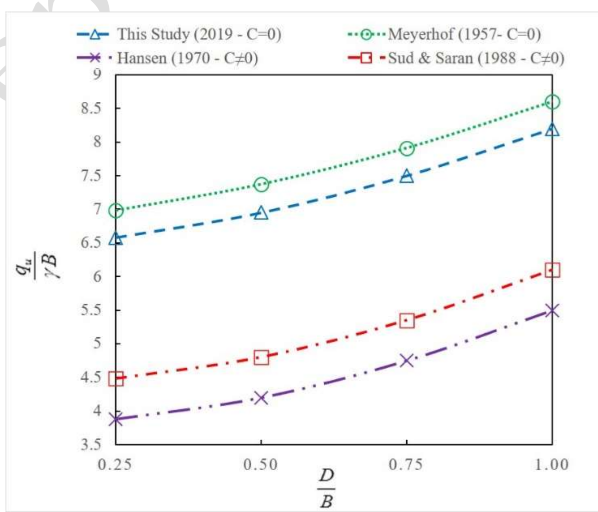

Figure 10. Comparison of the present study with other researchers in different positions of embedded Depth relative to the width of foundation $\left(\frac{D}{B}\right)$ in the inclined land on cohesive and non-cohesive soils in for: $\emptyset = 40^{\circ}, \beta = 45^{\circ}, B = 2$

In Figure12, the results obtained from slope height effect on bearing capacity in this study and the studies conducted by Ben (2015) and Li et al. (2019) in sandy soil are compared. The results show that in all these methods an increase in slope height decreases the bearing capacity of the foundation adjacent to the slope. The values obtained by Ben (2015) based on DLO analysis, are in convergence with the current values.

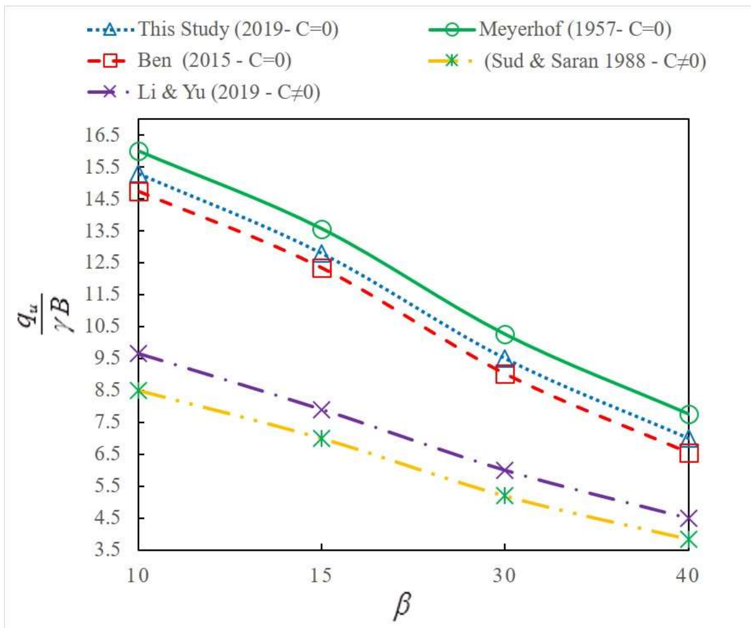

Figure 11. Comparison of the present study with other researchers in different positions of slope angle (β) of foundation in the inclined land on cohesive and non-cohesive soils in for: $\emptyset = 30^{\circ}, \beta = 45^{\circ}, B = 2$

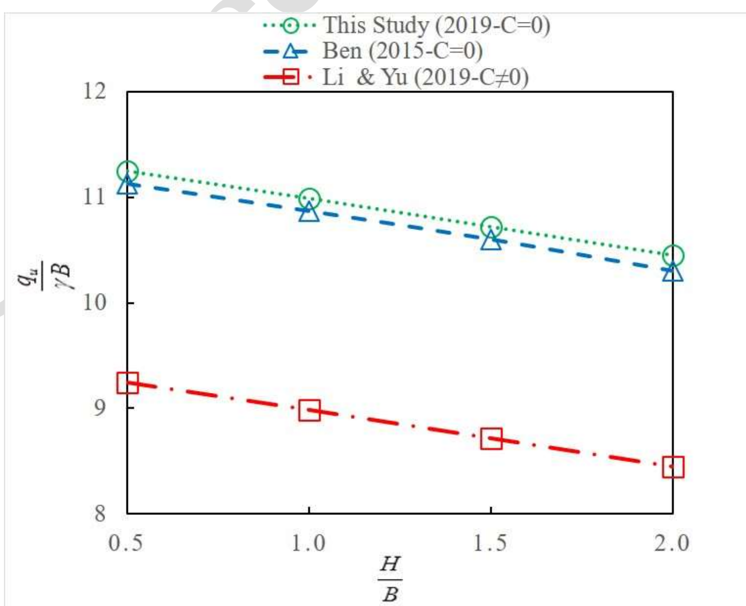

Figure 12. Comparison of the present study with other researchers in different positions of the height of slope relative to the foundation width $\left(\frac{H}{B}\right)$ in the inclined land on cohesive and non-cohesive soils in for: $\emptyset = 40^{\circ}, \beta = 45^{\circ}, B = 2$

Generally, Figure9 to Figure12 show that the normalized bearing capacity values in Meyerhof's studies (Meyerhof 1957) are significantly greater than the other studies and also comparisons show that the studies conducted by Sud and Saran (1988) and Hansen (1970) on the effect of normalized distance of foundation from slope, foundation depth, slope height, and slope angle on bearing capacity of foundation are more conservative than the other studies. As a result, it is concluded that the bearing capacity values obtained from current study are somewhat in between the other studies.

Conclusion

Considering the advantage of numerical methods in tracing deformations in compare with the other analytical methods of calculating bearing capacity of foundations, including characteristics line, limit equilibrium, and limit analysis methods, the finite element software of ABAQUS 2D is used in this study to analyze the concurrent effects of one or more variables of slope angle, soil friction angle, foundation distance from slope, slope height, and foundation depth under different inclined load angles. The following conclusions are obtained from the conducted numerical models in this research.

The results of investigations on bearing capacity of foundations adjacent to the slope versus the foundation distances from slope ranged from 0 to 10 meters showed that for a sandy soil with a friction angle of 40˚, by increasing the foundation distance from the slope to foundation width ratios from 0 to 5, the normalized bearing capacity increases about 11%. Therefore, an increase in foundation distance from the slope increases the bearing capacity of the strip foundation adjacent to the slope, in a way that by increasing distance more than 4B (B represents foundation width) slope does not have a reducing effect on the bearing capacity of the foundation anymore.

The results of investigations on bearing capacity of foundations adjacent to the slope versus the slope height to foundation width ratios showed that for a sandy soil with a friction angle of 40˚, by increasing the slope height to foundation width ratios from 1 to 4, the normalized bearing capacity reduces about 8%. The results show that by increasing slope height, the bearing capacity of the adjacent strip foundation decreases almost linearly.

The results of investigations on bearing capacity of a strip foundation adjacent to the slope versus the slope angle showed that for a sandy soil with a friction angle of 40˚, by increasing the slope angle from 0 to 60˚, the bearing capacity decreases about 54%. It shows that by increasing the slope angle, the bearing capacity of the adjacent foundation decreases.

The results of investigations on inclined load angle (θ) show that by increasing inclined load angle from 15˚ to 90˚, bearing capacity of the strip foundation adjacent to the slope increases.

The results of the study presented herein show that among the previous studies conducted by other researchers on clayey soils, the methods of Hansen (1970) and Sud and Saran (1988) are more conservative in compare with Li et al. (2019) and the same study on sandy soil shows that the method of Meyerhof (1957) results in greater bearing capacity values in compare with the other methods. The results obtained from current study are somewhat in between the other methods and are in a good convergence with the results obtained from Ben (2015).

Conflicts of interest

The authors declare that they have no relevant financial or non-financial competing interests to report.

Authors' contributions

Ali M. Rajabi: Supervision, Conceptualization, Methodology, Validation, Investigation, Writing - review & editing.
Mostafa Baghjari: Numerical Modeling, Data Gathering, Validation, Visualization, Writing - original draft.
Rana Azizi: Testing, Software, Figures designing, Writing - review & editing.

References

Ahmadi, M., Bagherieh, A.R., Mohammadipour, F., 2024. Evaluating the Seismic Bearing Capacity of Strip Foundation Adjacent to Geogrid-Reinforced Slopes Using the Finite Element Limit Analysis Method: Civil Infrastructure Researches, 10(1): 169-185.

Atazadeh, C., 2016. Investigating the effect of land slope on the bearing capacity of shallow foundations with Plaxis software: Journal of Geotechnical Engineering, Semnan University (In Persian).

Brahmi, N., Younes Ouahab, M., Mabrouki, A., Benmeddour, D., Mellas, M., 2021. Probabilistic analysis of the bearing capacity of inclined loaded strip footings near cohesive slopes: International Journal of Geotechnical Engineering, 15(6): 732- 739. FDD

Bransby, M.F., Davidson, C., 2008. The effect of foundation fixity on their capacity adjacent to slopes: In Proceedings of the BGA International Conference on Foundations.

Cascone, E., Casablanca, O., 2016. Static and seismic bearing capacity of shallow strip footings: Soil Dynamics and Earthquake Engineering, 1; 84: 204-23.

Choudhury, D., Subba Rao, K.S., 2006. Seismic bearing capacity of shallow strip footings embedded in slope: International Journal of Geomechanics, 6(3): 176-84.

Foroutan Kalourazi, A., Jamshidi Chenari, R., Veiskarami, M., 2020. Bearing Capacity of Strip Footings Adjacent to Anisotropic Slopes Using the Lower Bound Finite Element Method: International Journal of Geomechanics, 20(11).

Gemperline, M.C., 1988. Centrifuge modeling of shallow foundation: ASCE Spring Convention, Proceeding, ASCE Press, Reston, VA.

Georgiadis, K., 2010. The influence of load inclination on the undrained bearing capacity of strip footings on slopes: Computers and Geotechnics, 37(3): 311-22.

Graham, J., Andrews, M., Shields, D.H., 1988. Stress characteristics for shallow footings in cohesionless slopes: Canadian Geotechnical Journal, 1;25(2): 238-49.

Haghgouei, H., Kargar, A.R., Amini, M., Khosravi, M.H., 2020. Semianalytical Solution for Evaluating Bearing Capacity of a Footing Adjacent to a Slope: 21(2).

Hansen, J.B., 1970. A Revised and Extended Formula For Bearing Capacity: Journal Of Geotekniks Inst. Bull, 118(28): 5-11.

Huang, C.C., 2018. The influence of load on the bearing capacity of strip footings on slopes: Soil and Foundation. pp 315-322.

Ismael, K.S., Al-Ne'aimi, R. M. S., 2024. Application of Artificial Intelligence Techniques to Predict Strip Foundation Capacity Near Slope Surface: Indian Geotech, 54: 1198-1221.

Ke, L., Gao, Y., Zhao, Z., Zhou, Y., Ji, J., 2021. Undrained Bearing Capacity of Strip Footing near Slopes Considering the Orientation of Strength Increase: International Journal of Geomechanics, 21(7).

Keshavarz, A., Arian, M., 2014. The non-drained bearing capacity of strip foundations on the slope using Discontinuity Layout Optimization method: 7th National Congress of Civil Engineering. Zahedan, University of Sistan and Baluchestan (In Persian).

Leshchinsky, B., 2015. Bearing capacity of footings placed adjacent to c′-ϕ′ slopes: Journal of geotechnical and geoenvironmental engineering, 141(6): 04015022.
Li, S., Huang, M., Yu, J., 2019. Continuous field based upper-bound analysis for the undrained bearing capacity of strip footings resting near clay slopes with linearly increased strength: Computers and Geotechnics, 105: 168-82.
Lotfizadeh, M.R., Kamalian, M., 2017. Evaluation of bearing capacity of strip foundation based on consecutive layers of weak and strong clays by characteristics lines method: Sharif Civil Engineering Magazine, 33(2): 31-38.
Meyerhof, G.G., 1957. The ultimate bearing capacity of foundations on slopes: In Proc., 4th Int. Conf. on Soil Mechanics and Foundation Engineering, 1: 384-386.
Ouria, A., Heidarli, E., Enshaei, M. A., 2022. A laboratory study of the effect of wraparound anchorage, increasing reinforcement thickness and nailing in improving the bearing capacity of strip foundation on sandy soil, Civil Infrastructure Researches, 9(2): 1-16.
Riccio, M., Ehrlich, M., Dias, D., 2014. Field monitoring and analyses of the response of a block-faced geogrid wall using fine-grained tropical soils: Geotextiles and Geomembranes, 42(2): 127-38.
Rostami, V., Afshar Farnia, A., 2018. Evaluation of footing bearing capacity rest on top of retaining wall reinforced by geogrid in saturated and dry soil: Modares Civil Engineering journal, 17 (6): 1-15. https://mcej.modares.ac.ir/article-16-15806-en.html (In Persian)
Saran, S., Sud, V.K., Handa, S.C., 1989. Bearing capacity of footings adjacent to slopes: Journal of Geotechnical Engineering. 115(4): 553-573.
Shahbazi, R., Yekrangnia, M., 2014. Abaqus applied guide with civil engineering, structural and geotechnical issues: Civil Science Publisher, Second Edition (in persian).
Shiau, J.S., Merifield, R.S., Lyamin, A.V., Sloan, S.W., 2011. Undrained stability of footings on slopes. International Journal of Geomechanics: 1:11(5): 381-90.
Vesic, A.S., 1975. Analysis of ultimate loads of shallow foundations. J: Soil Mech. Found. Div. ASCE, 99(1): 45-73.
Zhang, W., Gu, X., Ou, Q., 2023. Bearing capacity and failure mechanism of strip footings lying on slopes subjected to various rainfall patterns and intensities: Geological Journal, 17 September, 2371- 2382.