Research Paper

Analysis of Bearing Capacity of Shallow Foundations Located on the Reinforced Sandy Soils by Limit Analysis Method

Mohammad Ahmadi[1*], Alireza Bagherieh[1] and Hadis Moosali[2]

1. Assistant Professor, Faculty of Civil Engineering and Architecture, Malayer University, Malayer, Iran,
*Corresponding Author; email: m.ahmadi@malayeru.ac.ir
2. M.Sc. Graduate in Civil Engineering, Faculty of Civil Engineering and Architecture, Malayer University, Malayer, Iran

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ABSTRACT

Considering the high seismicity of Iran, the study of seismic force's effects on the foundations' bearing capacity is always of interest to researchers. The current study investigated the bearing capacity of a shallow foundation reinforced with geogrid using the limit analysis method in static and seismic modes. The Optum G2 software is used for this purpose. An attempt has been made to calculate the static and seismic bearing capacity of the foundation by conducting a parametric study on the geogrid length (1B, 2B, 3B, 4B and 5B), geogrid burial depth (0.1B, 0.2B, 0.5B, 0.7B, 0.9B, 1.1B and 1.8B), geogrid layers distance (0.1B, 0.2B, 0.4B, 0.6B and 0.8B) and the number of geogrid layers (1, 2, 3 and 4). Also, these analyses were performed on different internal friction angles of sandy soil (25, 30, 35 and 40 degrees) and various foundation depths (0, 0.3B and 0.5B). The results show that the effective length of geogrid is estimated to be between 2B and 3B. Also, the geogrid's maximum effective depth is between 0.7B and 1.1B. The optimal distance of geogrid layers was estimated between 0.2B and 0.6B. Also, the optimal number of geogrid layers varies from 2 to 4, depending on the soil's internal friction angle and the foundation's burial depth. The seismic bearing capacity of the foundation estimated to be less than the static condition, and the percentage decrease of the seismic bearing capacity of the foundation compared to the static mode was varied between 7% and 20%.

Keywords:
Seismic bearing capacity;
Shallow foundation;
Reinforced soil;
Limit analysis method;
Geogrid

1. Introduction

Determining the seismic bearing capacity of foundations is essential because Iran is located in a seismic region. So far, various researchers have made extensive efforts in this field. The foundation's bearing capacity reduction during an earthquake causes many financial and human losses. Most of the foundations used in typical buildings are shallow foundations. Therefore, studying the seismic behavior of this type of foundation to reduce damage to structures is particularly important. There are various methods to increase the bearing capacity of shallow foundations, among which soil reinforcement can be pointed out using materials such as geogrid. The reduction of the bearing capacity of the foundation due to the earthquake and the use of reinforcements to improve the bearing capacity is noticeable. However, some questions must be answered accurately: a) What are the changes in bearing capacity before and after the earthquake? How does the arrangement of reinforcements, such as burial depth and length, affect the bearing capacity?

Askari et al. (2005) obtained shallow foundations' seismic bearing capacity using the upper bound limit analysis method. The conducted investigations show that considering the inertial force of the soil leads to a further reduction of the bearing capacity. By studying the bearing capacity of strip foundations in earthquake-prone areas, (a) by placing a stronger soil layer under the foundation, and (b) by placing geogrid reinforcing layers in the soil and using the limit analysis method, Kumar and Chakraborty (2020) showed that when the foundation subjected to different horizontal and vertical seismic acceleration, the bearing capacity coefficients are changed, and the bearing capacity is improved. By the result of a physical modeling test of a strip foundation located on sandy soil in the laboratory, which was reinforced using geogrid, Das et al., (1992) concluded that: a) if the ratio of the depth of the first layer of geogrid to the width of the foundation is less than one, then the bearing capacity of reinforced soil is greater than the unreinforced one, b) The number of reinforcing layers should be more than three to achieve a suitable bearing capacity. Also, the optimal number of reinforcing layers is about five to six. Omar et al. (1993) compared the bearing capacity of strip foundation and square foundation placed on reinforced sand and found that: (a) the optimal number of layers is six for strip foundation and four for square foundation, (b) The optimal reinforcement depth is 2B (B is equal to the width of the foundation) for the strip foundation and 1.4B for a square foundation, (c) The effective length for strip footing is 8B, and for square footing is 4.5B. Shin and Das (2000) conducted a small-scale model test of a strip foundation on medium and dense sand reinforced by geogrid. Tests were performed for shallow foundations with different depths. Based on the results, the optimal length of the reinforcement was obtained between 4B and 6B. By conducting a numerical and laboratory study for foundations placed on reinforced sand, Tahidifar and Vafaian (2008) found that the optimal depth of the first reinforcing layer was between 2.5B and 0.5B, and the optimal distance between them was 0.25B. Chen et al. (2020) investigated the effect of length and number of reinforcements on bearing capacity by modeling a shallow foundation in the laboratory.

The primary purpose of this research is to investigate the effect of earthquakes on the bearing capacity of shallow foundations placed on reinforced soil using the quasi-static method. This research attempted to investigate this issue with a series of numerical analyses based on the limit analysis method by using Optum G2 software to evaluate the analysis's simplicity and the calculation speed. The effects of reinforcement burial depth, their optimal length, the number of geogrid layers, and the optimal distance between geogrids were investigated in two static and seismic conditions. Although many experiments have been done in the field of analysis and design of reinforcement beneath the shallow foundation, more work is needed to examine their optimal design. The innovation of the current research is comparing the bearing capacity in static and seismic modes and the investigation of the optimal design of the reinforcement used in this study in many aspects. Another purpose of this research is to show the need to pay attention to the optimal values of the parameters affecting the bearing capacity of the foundation on reinforced soil. From the point of view of time and cost, this issue is important. Also, the results were presented in dimensionless value, so the results of this research can be used for similar cases.

2. Numerical Modeling

This research used a numerical modeling solution to calculate the bearing capacity of shallow foundations on reinforced soil in static and seismic conditions. Many numerical methods exist to achieve this purpose, such as limit equilibrium. However, as discussed further, the limit analysis method was chosen as the appropriate method in the current study.

2.1. Limit Analysis Method

The limit analysis method obtains the failure load. This method obtains two upper and lower bounds for the actual failure load. This method determines what limits the actual failure load, but this limit is unclear in a method like limit equilibrium. In the limit analysis method, the foundation's final bearing capacity is calculated by using the relationship between stresses and relative deformations in continuum mechanics and using the failure criterion (Binquet & Lee, 1975).

The concept of upper bound indicates that the failure load is found by equating the internal energy loss with the work of external forces. It is obtained by assuming a kinematically admissible collapse mechanism (i.e., satisfying the equilibrium and compatibility conditions) but may not be the most critical or limiting mechanism. The upper bound solution provides an upper limit on the failure load, ensuring that the actual failure load is equal to or less than this value. On the other hand, the lower bound solution represents an underestimation of the collapse load. It is obtained by assuming a collapse mechanism that is statically admissible (i.e., satisfying only the equilibrium conditions) but may not satisfy the compatibility conditions. The lower bound solution provides a lower limit on the collapse load, ensuring that the actual collapse load is equal to or greater than this value. The actual failure load lies between the upper and lower bounds. The difference between the upper and lower bounds is known as the "gap" or "error" in limit analysis. Limit analysis aims to minimize this gap and obtain a more accurate estimation of the collapse load.

Limit analysis can be computationally more efficient than limit equilibrium methods. It involves solving an optimization problem, often formulated as a linear or nonlinear programming problem. These types of problems can be efficiently solved using various numerical algorithms.

2.2. Optum G2 Software

In the current study, Optum G2 software was used based on its ability to provide bearing capacity of shallow foundations in different conditions. OPTUM G2 is a comprehensive finite element program for geotechnical stability and deformation analysis in plane strain or axisymmetry. This software uses the limit analysis method, which allows for a rapid assessment of geostructures' bearing capacity without going through a time-consuming incremental elastoplastic analysis.

Among the features of this software, the following can be mentioned: accurate and easy calculation of specific loads in seismic mode by calculating the horizontal and vertical earthquake coefficient of the soil, the possibility of calculating the bearing capacity of various geotechnical issues without performing step-by-step elastoplastic analysis, the possibility of calculating the upper and lower limits, no need to form a stiffness matrix, the use of automatic mesh updating by the software, short analysis time, the possibility of calculating the upper and lower bounds of the analysis with the help of the resistance reduction factor by applying a specific load and finally, absence of convergence problems.

2.3. Verification of Model

For each numerical model, verifying the model by using reliable data is an essential part of the investigation. For this purpose, a relevant study was chosen to be modeled numerically using Optum G2 software. Chen et al. (2020) investigated the bearing capacity of a geogrid-reinforced soil in the laboratory. The physical model comprises a soil box, a loading system, a digital camera, and two laser transmitters. The internal dimensions of the soil box are 800 mm × 200 mm × 590 mm. The soil box is made of 19 mm thick tempered glass. Deformation of soil and reinforcement layers during loading can be seen through the glass wall. The loading system includes an actuator and a steel plate with a width of 80 mm and a length of 198 mm for modeling the strip foundation. The length of the steel plate is 2 mm less than the inner width of the soil box to minimize the interaction between the foundation and the walls.

A professional wide-lens digital camera was used to take photographs of the entire model foundation during testing. Figure (1) shows the photo of the model reinforced with geogrid during preparation.

After modeling by the software according to Table (1), each experiment's lower and upper bounds were obtained and compared with the results of Chen et al. (2020). According to the results of Table (1) and Figure (2), in all cases, the laboratory bearing capacity is between the upper limit and the lower limit calculated by the Optum G2 model, which indicates the appropriate accuracy of the analysis. This accuracy shows

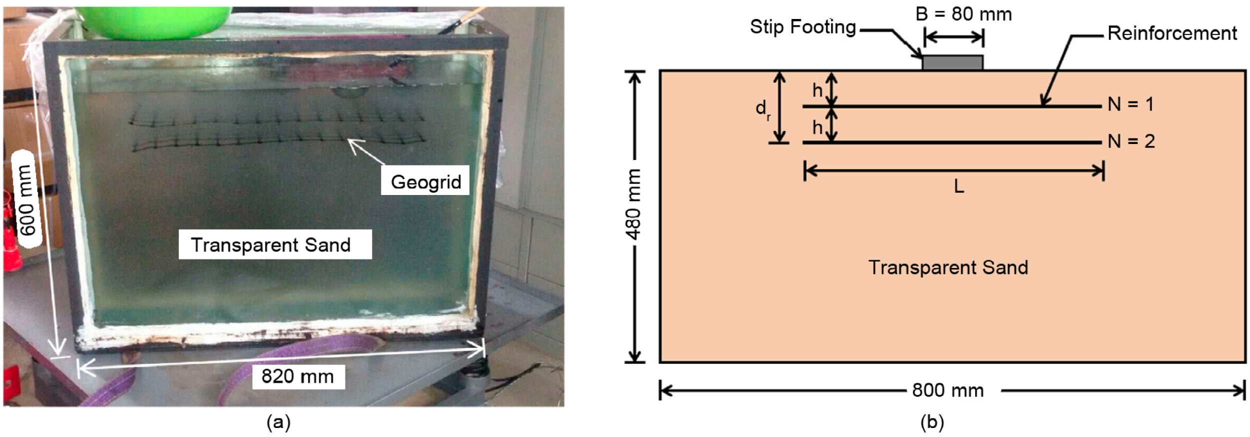


Figure 1. (a) Geogrid-reinforced foundation model during model preparation and (b) Schematics view of physical model (Chen, et al., 2020).

Table 1. Validation of the numerical model using the results obtained by Chen et al. (2020).

Test No.	h/B	L/B	N	Bearing Capacity of Physical Model (kPa)	Lower Bound of Bearing Capacity (kPa)	Upper Bound of Bearing Capacity (kPa)
1	-	-	-	340	336	431
2	0.25	1	4	960	665	980
3	0.25	3	2	740	595	758
4	0.25	3	4	1060	1051	1441
5	0.25	3	6	1420	1377	2181
6	0.25	7	4	1080	1064	1430

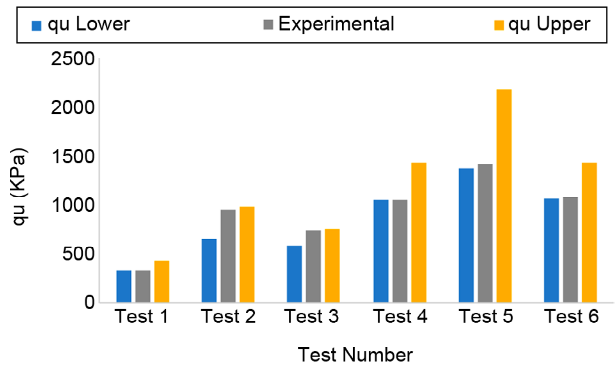


Figure 2. The comparison of the numerical model and the laboratory results of Chen et al. (2020).

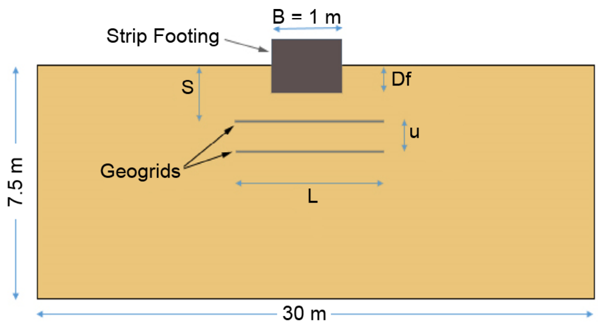


Figure 3. Geometry of the model.

that using Optum G2 software to investigate the current study is reliable.

2.4. Geometry of Model and Tests Schedule

In order to determine the optimal value for various parameters affecting the bearing capacity of the strip foundation on reinforced soil, to determine the proper arrangement of geogrid layers, and to achieve the best performance of reinforcements, a foundation with width B equal to 1 meter on soil with dimensions of 7.5BÍ30B was modeled according to the Kumar and Chakraborty (2020). The geometry of the numerical model is shown in Figure (3). In this model, Df is the depth of the foundation, *B* is the width of the foundation, *S* is the burial depth of geogrid layers, u is the distance between two geogrids, and *L* is the length of the geogrid. The test schedule, variable parameters, and geogrid specifications are given in Table (2). The ultimate tensile strength of geogrids is assumed to be 12 kN/m.

2.5. Seismic Model

In this research, only the effects of the horizontal earthquake coefficient, kh, are considered, and the vertical earthquake coefficient, k_v, is negligible. For this purpose, using the software, k_{multi}, which means the highest earthquake

Table 2. Physical characteristics of the soil and geogrid used in the model.

Parameter	Geogrid					Soil		
	Depth of Foundation- D_f	Burial Depth of Geogrid – S	Length of Geogrid- L	Distance between Two Geogrids – u	Number of Geogrid Layers	Internal Friction Angle- φ (Degree)	Cohesion- c (kN/m²)	Unit Weight – γ (kN/m³)
Value	0-0.3B-0.5B	0.1B-0.2B-0.5B-0.7B-0.9B-1.1B-1.8B	1B-2B-3B-4B-5B	0.1B-0.2B-0.4B-0.6B-0.8B	1-2-3-4	25-30-35-40	zero	16

coefficient the soil can tolerate without applying vertical load, was determined. This value is variable for different internal friction angle values and other geometrical parameters. For each analysis, the horizontal earthquake coefficient was considered variable from $k_h = 0$ (static mode) to $k_h = k_{multi}$. These analyses consider the lowest to the highest seismic force that may be applied to the soil. In this paper, only the results of models with $k_h = 0.2$ are presented. In this paper, the value of the k_h coefficient was chosen in such a way that it is not so low that the seismic effects cannot be identified in the analysis, nor is it so large that it has a significant difference from the static analysis results and cannot be compared.

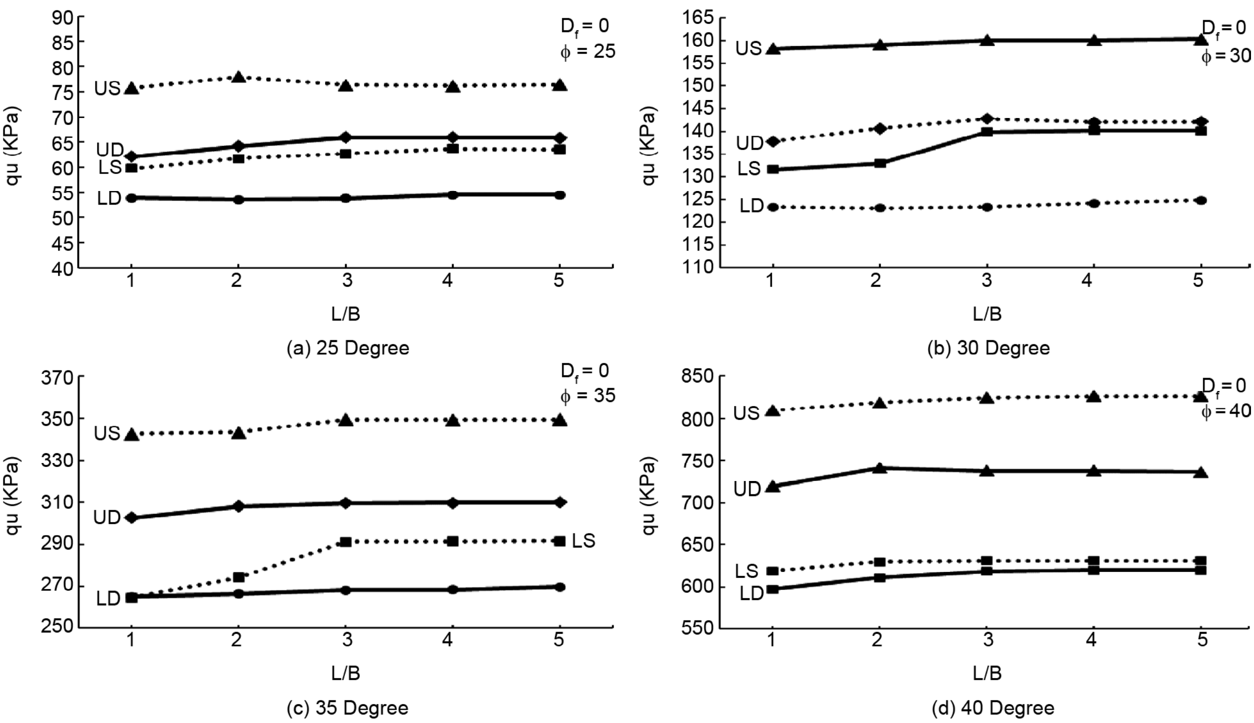
3. Results

This section discusses the most important results obtained from numerical models.

3.1. The Effect of the Effective Length of the Geogrid

One of the most important parameters in real projects where reinforcement is used is the effective length of the reinforcement. The geogrid's effective length is the reinforcement's length under which the maximum bearing capacity is obtained. If the reinforcement's length increases, the bearing capacity will not increase significantly. To determine the effective length of the geogrids, the bearing capacity of the foundation was calculated by changing the geogrid length (1B, 2B, 3B, and 4B) and the internal friction angles (25, 30, 35 and 40 degrees) of the soil. Also, the depth of the foundation changes from zero to 0.3B and 0.5B. The results are discussed here.

Figure (4) shows the variation of the bearing capacity's upper and lower bounds against the reinforcement's length in static and seismic



(a) 25 Degree (b) 30 Degree (c) 35 Degree (d) 40 Degree

Figure 4. Variation of bearing capacity against reinforcement length with $D_f = 0$ and $K_h = 0.2$ in both static and seismic condition for internal friction angle.

conditions (k_h = 0.2) for different internal friction angles. Due to limitations, other similar figures could not be presented here. It should be noted that in all presented figures in the current paper, US and LS show the upper and lower bounds of static analysis, respectively. Similarly, UD and LD represent the upper and lower bounds of seismic (dynamic) analysis.

These figures show that the effective length of the geogrid for internal friction angles of 25 to 35 degrees is about 3B. For example, in Figure (4b), it is clear that the increase in the length of the geogrid from 3B to 4B does not have a significant difference in the bearing capacity. Meanwhile, the effective length decreases to two meters for soil with an internal friction angle of 40 degrees. In this case, better locking of soil particles with geogrid can reduce the effective length of geogrid. Also, the results show that by increasing the depth of the foundation, the bearing capacity increases, which was expected. For example, in Figure (4a), the average bearing capacity is 75 kPa for the upper bound in static condition with zero foundation depth. Meanwhile, in Figure (5a), where the foundation depth is 0.3B, the average bearing capacity increases to 175 kPa.

A similar trend was observed when the foundation depth changed to 0.3B and 0.5B from zero. Figure (5) shows the results for the foundation with a 0.3B depth. It is evident that by increasing the burial depth of the foundation, bearing capacity increases, as can be compared by the results of Figures (4) and (5).

Also, by comparing the static and seismic analysis results, it was found that the upper bound bearing capacity decreases by 9 to 15 percent by applying seismic force (k_h = 0.2), as demonstrated in Table (3). It should be noted that the variation of lower bound bearing capacity is similar to upper bound, so it is not presented here. This trend was observed in all burial depths of foundations. It should be noted that this percentage decrease in bearing capacity is for the seismic force equal to k_h =0.2, and if the seismic coefficient increases, this amount will decrease more. Table (3) compares the upper bound of the bearing capacity for the geogrid length equal to 3B with different burial depths. With the increase of internal friction angle, the percentage decrease of bearing capacity decreases. In other words, the geogrid works better in soil with a higher internal friction angle in seismic conditions.

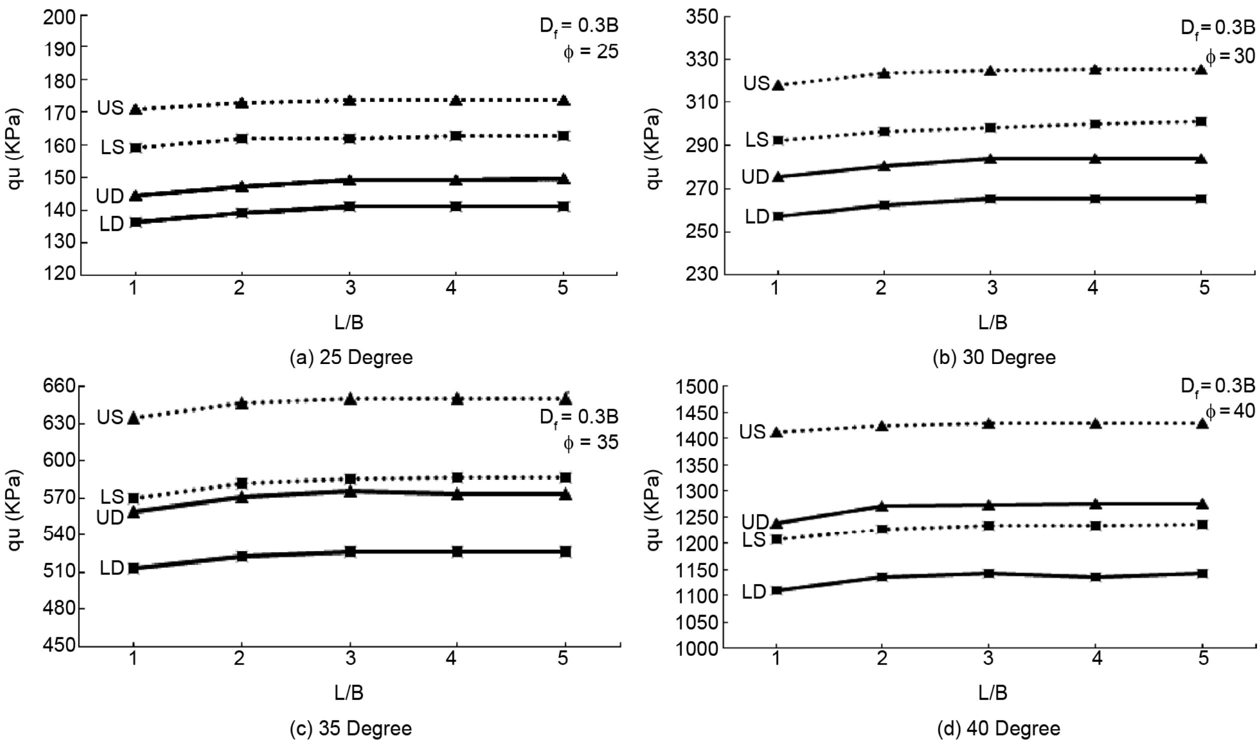


Figure 5. Variation of bearing capacity against reinforcement length with D_f = 0.3B and K_h = 0.2 in both static and seismic condition for internal friction angle.

Table 3. Percentage decrease of upper bound of bearing capacity at different depth in which geogrid length is 3B and k_h = 0.2

Foundation Depth-Df	Internal Friction Angle of Soil-φ (degree)	Static Upper Bound Bearing Capacity (kPa)	Seismic Upper Bound Bearing Capacity (kPa)	Percentage Decrease of Bearing Capacity (%)
0	25	76	65	14.4
	30	160	142	11.2
	35	349	309	11.4
	40	826	737	10.8
0.3B	25	173	149	13.9
	30	324	283	12.6
	35	649	575	11.4
	40	1428	1272	10.9
0.5B	25	227	196	13.7
	30	419	367	12.4
	35	823	733	10.9
	40	1769	1605	9.3

3.2. The Effect of Burial Depth of Geogrid

Using reinforcement up to a certain depth from the foundation increases the bearing capacity. Beyond this depth, the bearing capacity will not increase significantly. Therefore, the optimal depth of the geogrid will be the one that achieves the maximum bearing capacity for a geogrid of a certain length. The bearing capacity of the foundation was calculated on reinforced soil with a 3B-long geogrid with varying burial depth and internal friction angles. The bearing capacity ratio parameter (BCR) was defined as the ratio of bearing capacity in reinforced to unreinforced soil. When the BCR for a certain depth is about 1, it shows that a greater burial depth does not significantly increase the bearing capacity. Figures (6) and (7) show the variation of BCR for different values of foundation depth and internal friction angle against geogrid burial depth in both static and seismic modes.

It should be noted that two upper and lower bounds of bearing capacity were calculated for

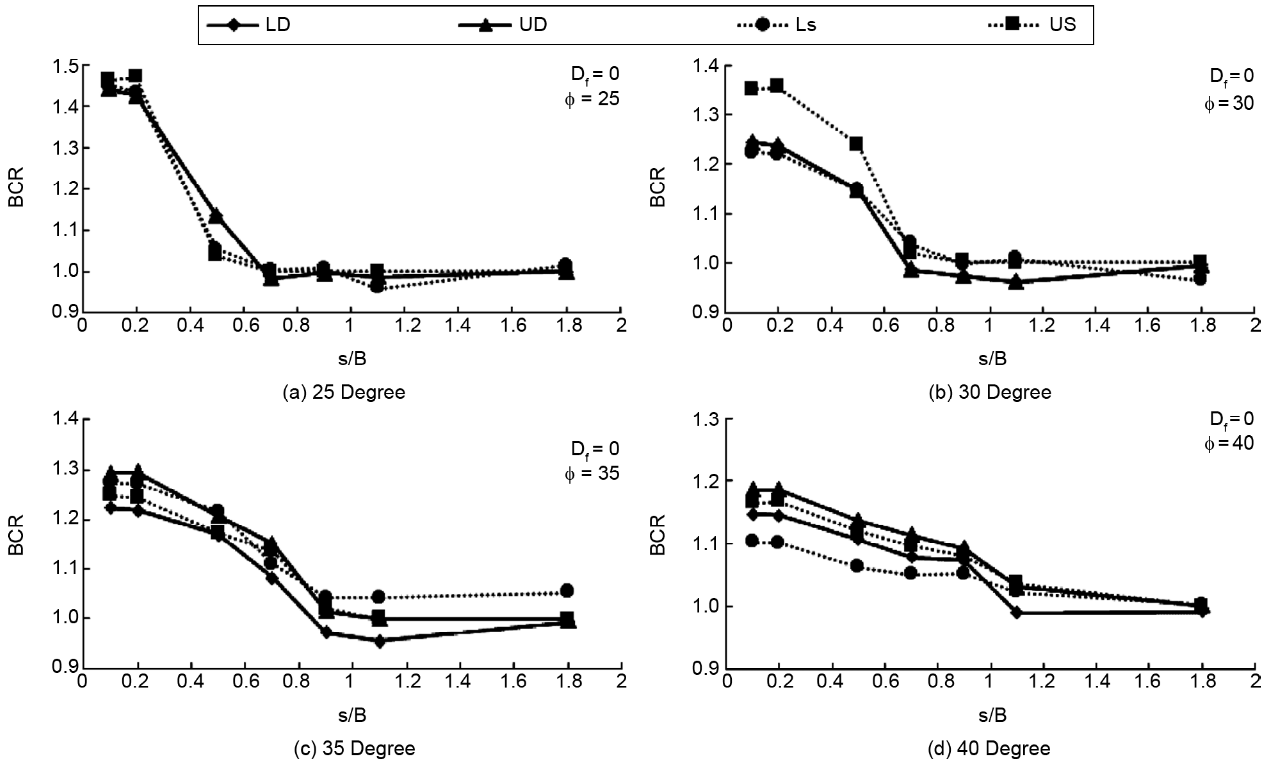


Figure 6. Variation of BCR against burial depth of geogrid with D_f = 0 and K_h = 0.2 in both static and seismic modes for internal friction angle.

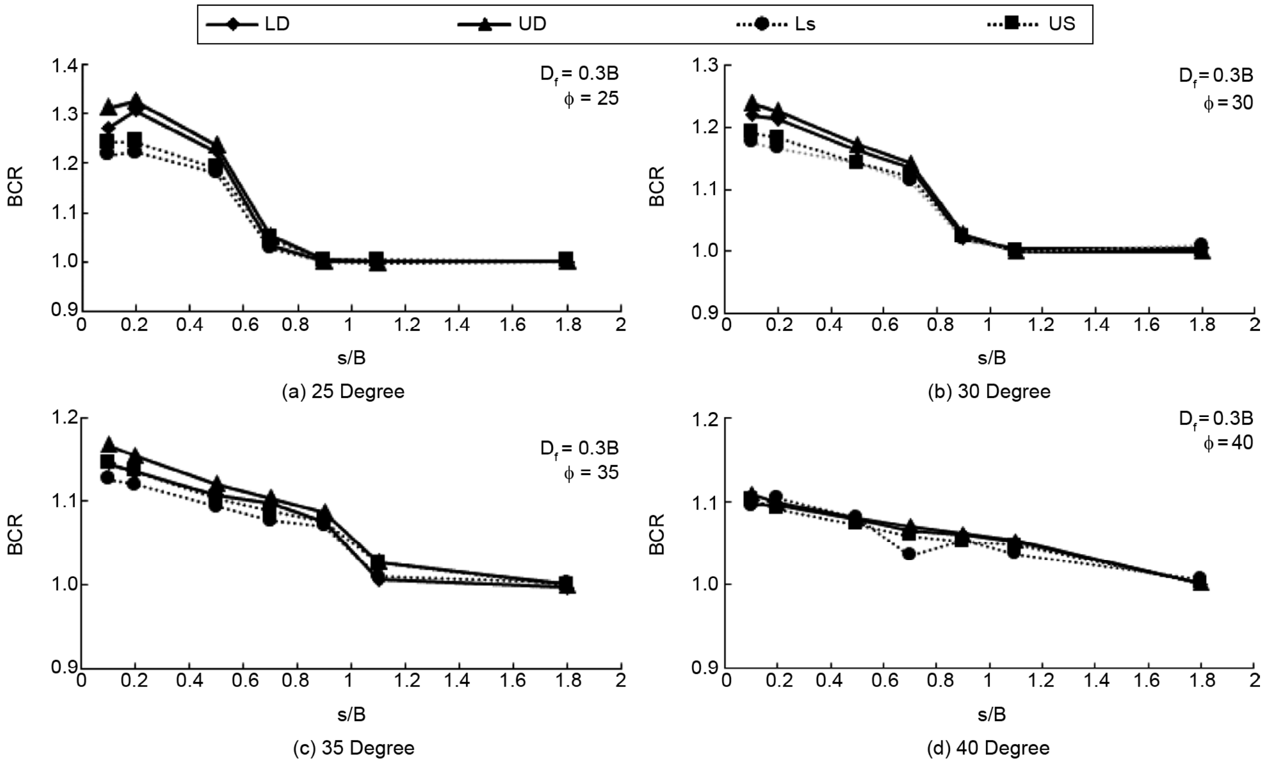


Figure 7. Variation of BCR against burial depth of geogrid with D_f = 0.3B and K_h = 0.2 in both static and seismic modes for internal friction angle.

each static and seismic mode, as shown in these figures. Some numerical models were conducted in which the burial depth of geogrid from the surface are 0.1B, 0.2B, 0.5B, 0.7B, 1.1B and 1.8B. The other variables are the same as section 3-1. The results show that the maximum effective depth of geogrid depends on the foundation's burial depth and the soil's internal friction angle. For example, based on Figure (6), The maximum effective depth of the geogrid is about 0.7B, 0.8B, 0.9B and 1.1B for internal friction angles of 25, 30, 35 and 40, respectively. It can be concluded that increasing the soil's internal friction angle increases the geogrid's maximum effective depth, and the BCR reaches about one at a greater depth below the foundation.

On the other hand, the foundation depth also affects the maximum effective depth of the geogrid. For example, when the foundation depth is zero, the maximum effective depth of the geogrid is 0.7B; when the foundation depth is 0.3B, the effective depth of the geogrid is 0.9B. Generally, the effective depth of the geogrid increases with the increase of the depth of the foundation, and the BCR reaches the value of 1 at a greater depth.

The important point is that the geogrid works when it intersects at least one of the failure surfaces created under the foundation. In this case, the differential movement of the failure surfaces causes tension in the geogrid and thus increases the bearing capacity of the foundation. This result can be seen in Figure (8a). In this example (D_f= 0.5B and ϕ = 40°), the burial depth of geogrid is 1.8B, which can be seen as not intersecting failure surfaces beneath the foundation. Therefore, it is expected that the bearing capacity is not increased, as seen in Figure (8b).

The findings of the current study are in good agreement with other research. Tohidifar & Vafaeian determine the effective depth of geogrid between 0.5 and 2.5 m (Tahidifar & Vafaian, 2008). Omar et al. (1993), Binquet and Lee (1975), and Latha an Somwanshi (2009) estimated this depth to be 2, 2.5 and 2 m, respectively. As in the current study, more variables were considered, and the maximum effective depth was calculated to be between 0.5B and 1.1B.

Table (4) shows the upper and lower bounds of bearing capacity in static and seismic calculations when D_f= 0.5B and k_h = 0.2. As expected, seismic bearing capacity is less than static one.

Table 4. Percentage decrease of the upper and lower bounds of bearing when D_f = 0.5B and k_h = 0.2.

Internal Friction Angle of Soil-φ (Degree)	Static Bearing Capacity (kPa)		Seismic Bearing Capacity (kPa)		Percentage Decrease of Bearing Capacity (%)	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
25	215	228	187	198	13.0	13.2
30	389	421	348	371	10.5	11.9
35	753	826	682	738	9.4	10.6
40	1553	1779	1448	1616	6.8	9.2

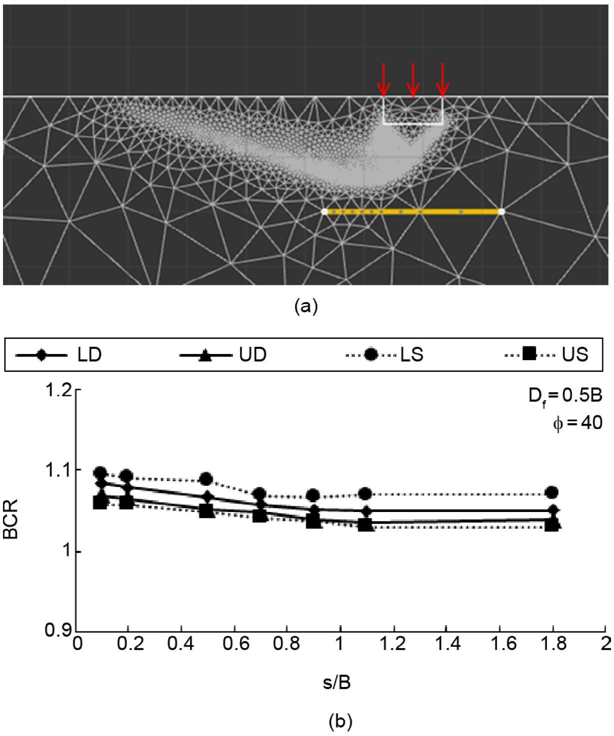


Figure 8. (a) Failure surfaces beneath the foundation that did not intersect with geogrid calculated by Optum G2 and (b) Variation of BCR when D_f = 0.5B and φ = 40° by geogrid burial depth.

By increasing the internal friction of soil, the difference between seismic and static bearing capacity decreases, and the interlocking between soil particles and geogrid significantly affects seismic mode. Askari et al. (2005) stated that by increasing the internal friction angle of the soil, the effect of inertial force in reducing the bearing capacity decreases. Their findings are in perfect agreement with the results of the current study.

3.3. The Effect of Distance between the Geogrid Layers

In order to obtain the optimal distance between the reinforcements, two geogrids with a length of 3B have been used. The analysis was done by assuming different values of the internal friction angle and the foundation's depth to calculate the bearing capacity's upper and lower bounds. Due to the direct effect of reinforcement depth, the geogrids were placed so that the center of the two geogrid layers is always at a depth of 0.5B. With these assumptions, the distance between two geogrids was considered 0.1B, 0.2B, 0.4B, 0.6B, and a maximum of 0.8B meters. In the last case, the burial depth of the upper layer is only 0.1B. Also, for seismic analysis, k_h is assumed to be 0.2.

The results showed that it is not easy to identify a specific trend for the effect of foundation depth and internal friction angle on the optimal distance between geogrids where the bearing capacity reaches its maximum value. According to Figures (9) and (10), the optimal distance of geogrids can be estimated between 0.2B and 0.6B. However, due to the complexity of the results in the upper and lower static and seismic bounds, the range has uncertainty and varies in a wide range. The optimal distance of geogrids calculated in the current study is compatible with other research. Tohidifar and Vafaeian (2008), Latha and Somwanshi (2009), and Altalhe et al. (2015) estimated the optimal distance of geogrids equal 0.3, 0.4 and 0.25 m, respectively. The noteworthy point is that the previous research has yet to investigate the effect of foundation depth on the optimal distance of geogrids.

Figure (11) shows a view of the soil mesh generated under the foundation. In the Optum G2 software, the generated meshes represent stress concentration and how stress is distributed under the foundation. The finer the meshes, the higher the stress in that area. At the foundation depth of 0.3B (according to Figure (11), the optimal distance is 0.2B), when the distance between the geogrids is 0.1B (u = 0.1B), all applied stress has been carried out by the first geogrid. The second geogrid has not been used (Figure 11a). When u = 0.2B, the two geogrids layer comes into play, and the bearing capacity increases (Figure 11b).

Also, the percentage decrease in bearing capacity was calculated by comparing the bearing capacity in static and seismic modes. For example, Table (5) compares the upper bound of the static and seismic bearing capacity and the condition that the distance between the reinforcements is 0.4B. The percentage decrease in bearing

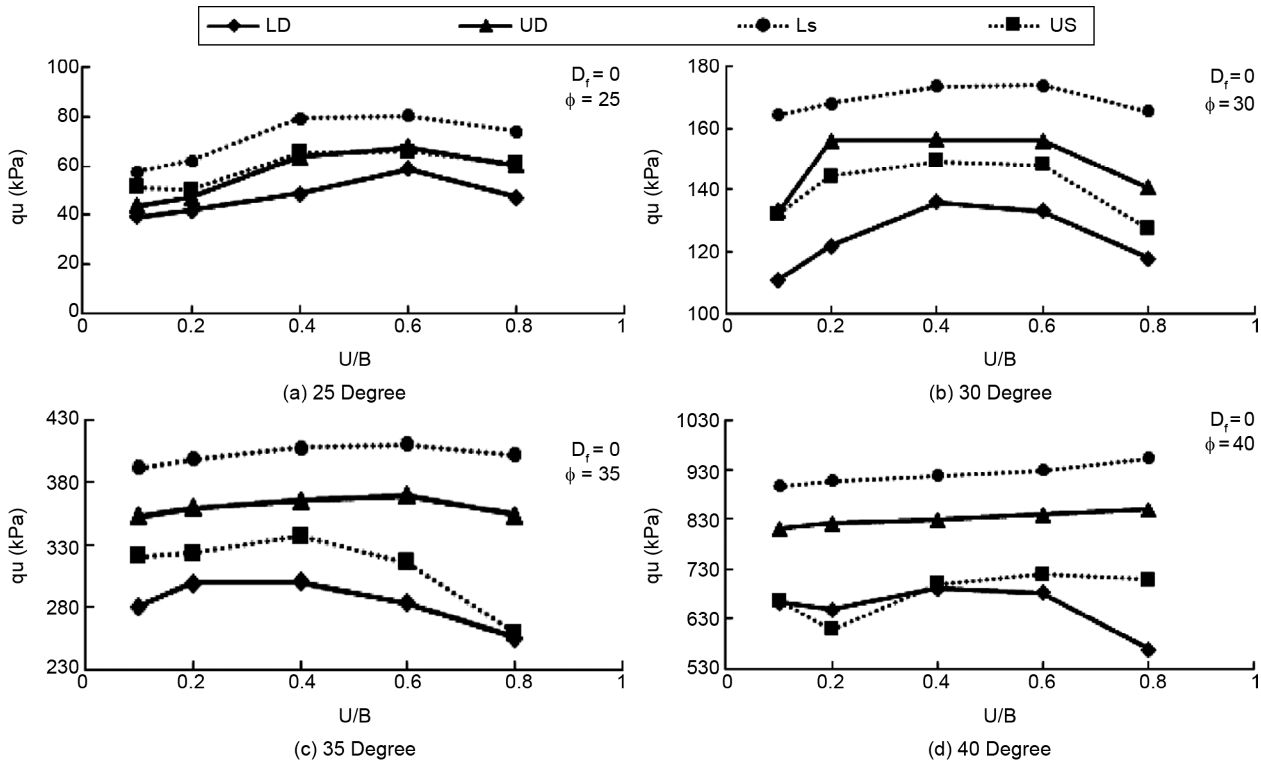


Figure 9. Variation of bearing capacity against distance between the geogrids with D_f = 0 and K_h = 0.2 in both static and seismic modes for internal friction angle.

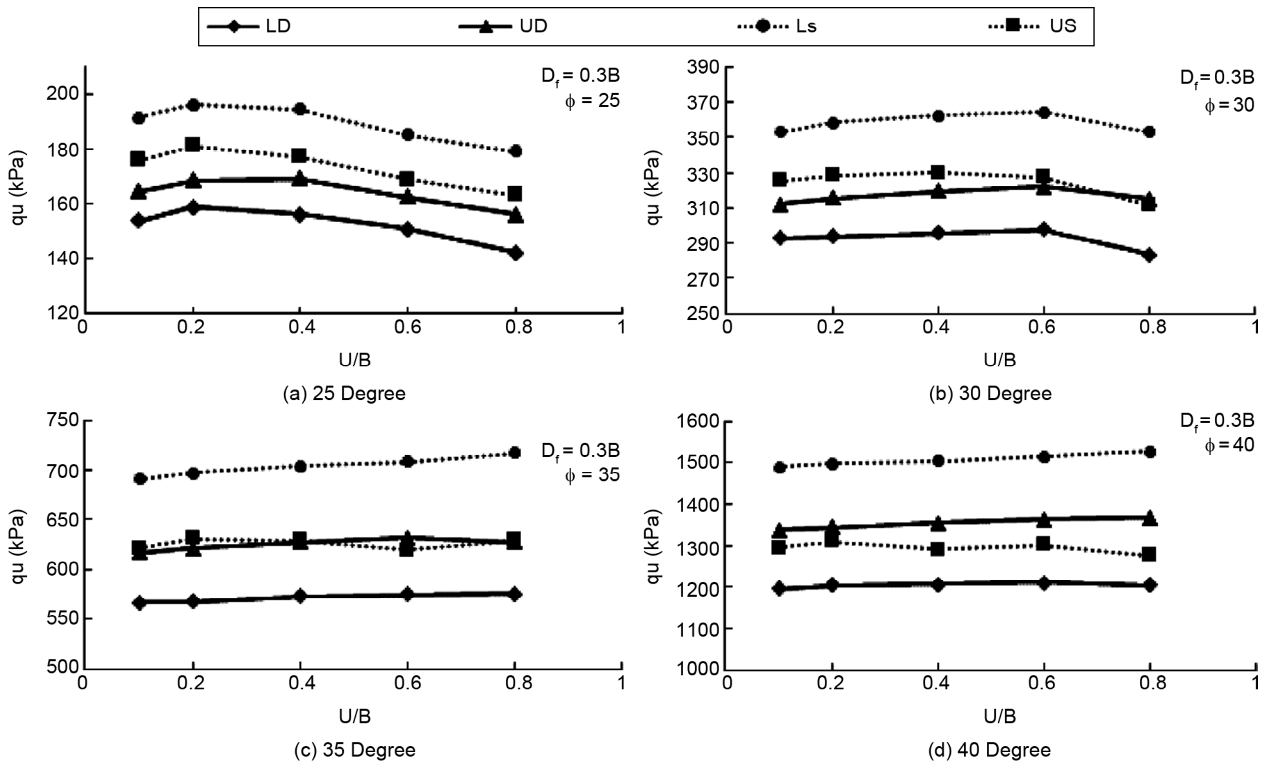
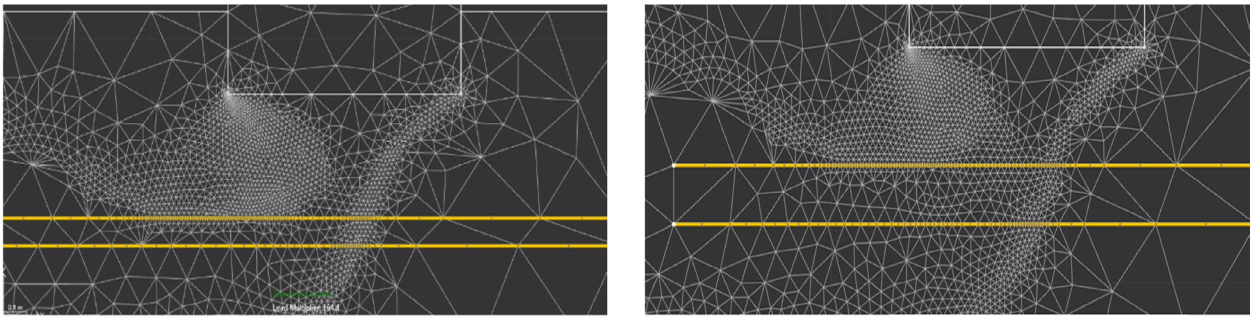


Figure 10. Variation of bearing capacity against distance between the geogrids with D_f = 0.3B and K_h = 0.2 in both static and seismic modes for internal friction angle.



(a) u = 0.1B (b) u = 0.2B

Figure 11. Soil mesh that generates under the foundation.

Table 5. Percentage decrease of upper bound of bearing capacity at different depth in which the distance between geogrids is 0.4B and $k_h = 0.2$

Foundation Depth-D_f	Internal Friction Angle of Soil-φ (degree)	Static Upper Bound Bearing Capacity (kPa)	Seismic Upper Bound Bearing Capacity (kPa)	Percentage Decrease of Bearing Capacity (%)
0	25	79	63	20.2
	30	173	156	9.8
	35	408	366	10.3
	40	919	829	9.8
0.3B	25	194	169	12.9
	30	362	319	11.9
	35	704	627	10.9
	40	1505	1354	10.0
0.5B	25	255	222	12.9
	30	458	404	11.8
	35	878	786	10.5
	40	1862	1682	9.7

capacity was calculated between 20% to 10% with different conditions. By increasing foundation depth, this value decrease shows that differences between seismic and static bearing capacity become less than previous. A similar trend was observed with a specific foundation depth when the internal friction of the soil increased.

3.4. The Effect of the Number of Geogrid Layers

Necessarily, using many geogrids layers under the foundation will not increase the bearing capacity. The number of geogrid layers has an optimal value to increase the bearing capacity, and using more than that does not affect and only wastes money and time. This section aims to determine the optimal number of geogrid layers according to the optimal distance between them. This section chose the number of geogrid layers to be N = 1, 2, 3 and 4. Similar to previous sections, the internal friction angle of the soil and burial depth of the foundation varied between 25 to 40 degrees and 0 to 0.5B, respectively.

Figure (12) shows the changes in bearing capacity due to the change in the number of geogrid layers. In these diagrams, the burial depth of the foundation is assumed to be zero. In this case, the optimal number of geogrid layers was three layers. These findings are consistent with the results of Altalhe et al. (2015) and El Sawwaf and Nazir (2010), who suggested three effective geogrid layers. The bearing capacity decreases by increasing the number of layers from this value. However, it should be noted that the optimal number of geogrid layers increases to about 4 when the internal friction angle of the soil increases to about 40 degrees or more.

It can be interpreted by the better interaction of the soil with the geogrid layers due to the increase of the internal friction angle and the formation of deeper failure surfaces that interact with the lower layers.

Figures (13) and (14) show the changes in bearing capacity against the number of geogrid layers in the case where the foundation depth is 0.3B and 0.5B, respectively. The results show that the optimal number of layers for the foundation depth mentioned above is two, and the bearing capacity remains the same and even decreases beyond this number of geogrid numbers.

The results of this research show that the only

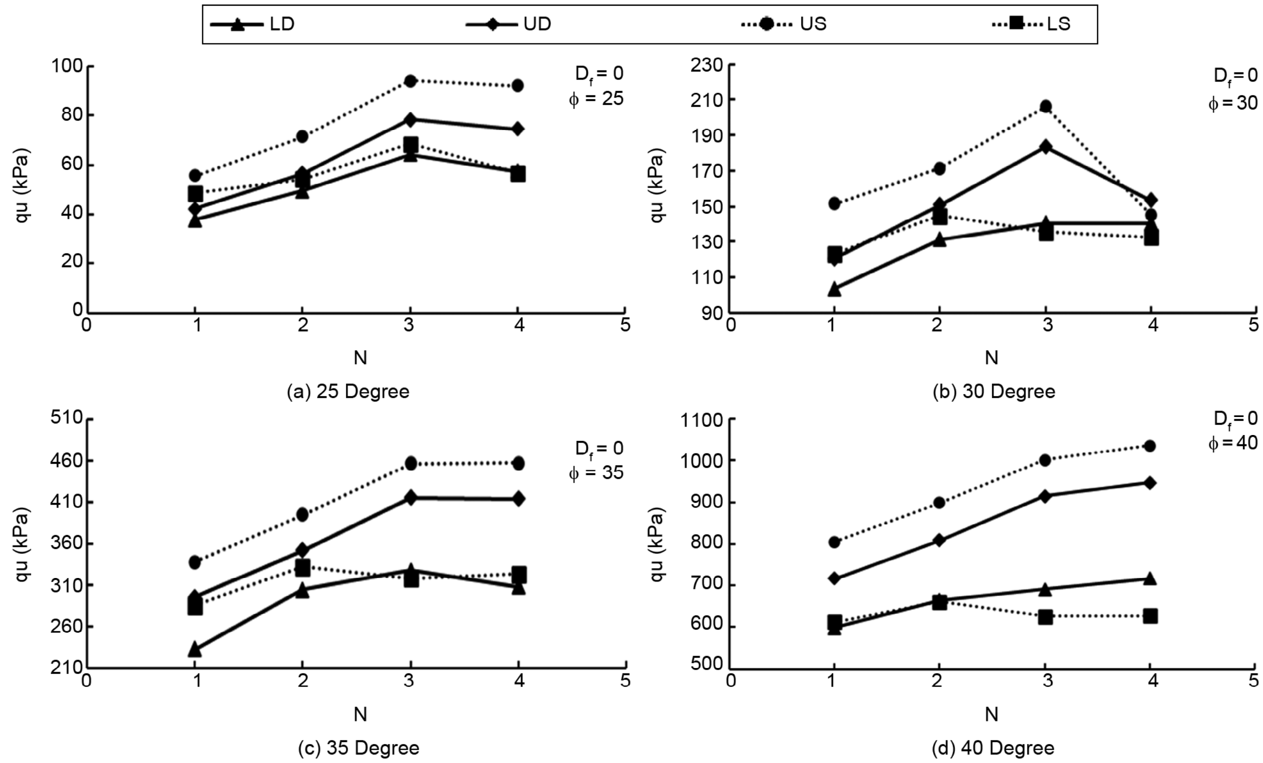


Figure 12. Variation of bearing capacity against the number of the geogrid layers with D_f = 0 and K_h = 0.2 in both static and seismic modes for internal friction angle.

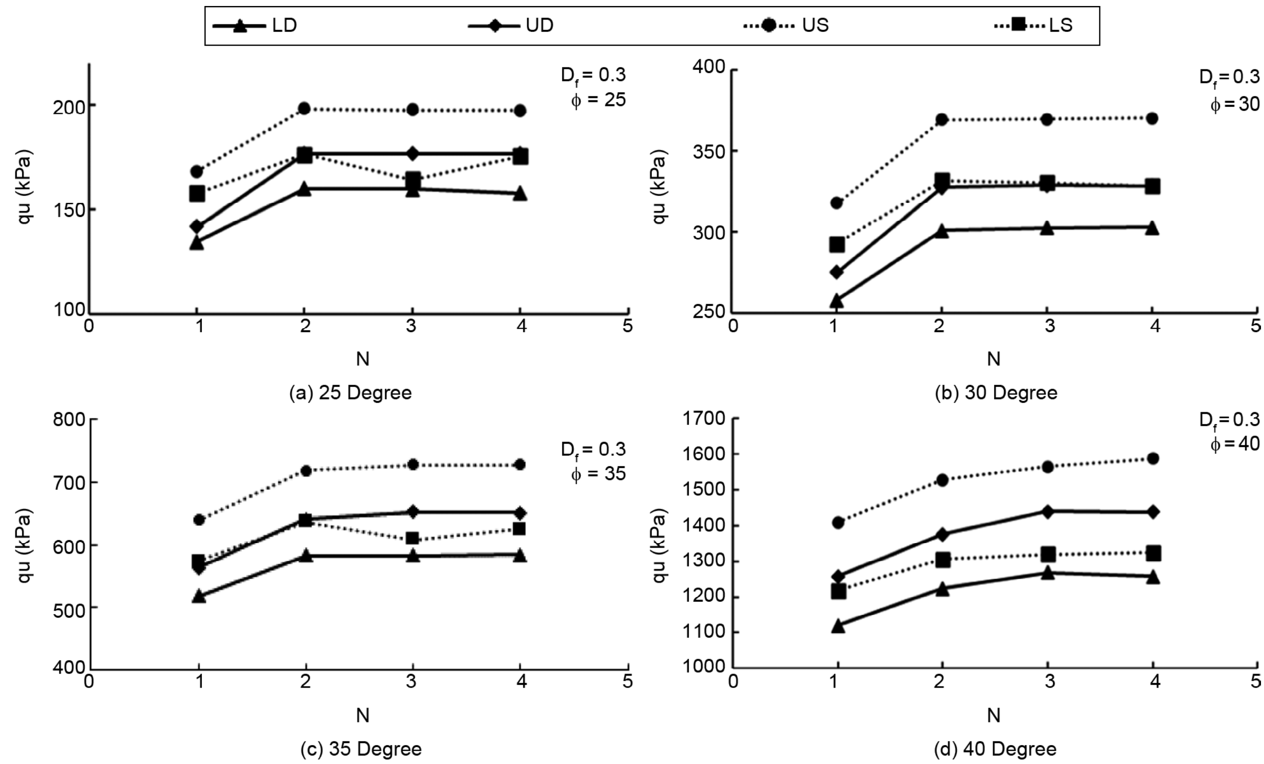


Figure 13. Variation of bearing capacity against the number of the geogrid layers with D_f = 0.3B and K_h = 0.2 in both static and seismic modes for internal friction angle.

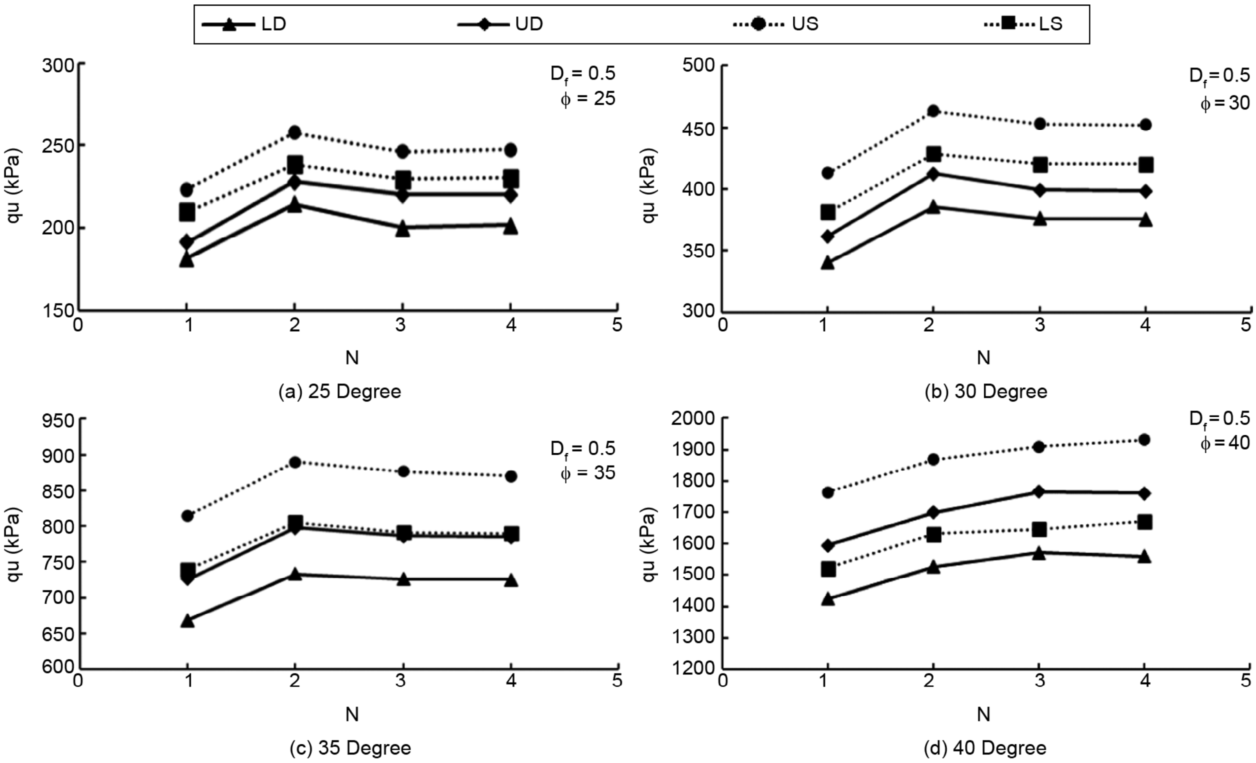


Figure 14. Variation of bearing capacity against the number of the geogrid layers with D_f = 0.5B and K_h = 0.2 in both static and seismic modes for internal friction angle.

Table 6. Percentage decrease of upper bound of bearing capacity at different foundation depth in which the optimal number of geogrid layers is 3 and k_h =0.2.

Foundation Depth- D_f	Internal Friction Angle of Soil-φ (degree)	Static UpperBound Bearing Capacity (kPa)	Seismic Upper Bound Bearing Capacity (kPa)	Percentage Decrease of Bearing Capacity (%)
0	25	94	78	17.0
	30	206	183	11.2
	35	456	415	9.0
	40	1001	913	8.8
0.3B	25	197	177	10.1
	30	369	328	11.1
	35	727	652	10.3
	40	1564	1440	7.9
0.5B	25	246	220	10.6
	30	453	399	11.9
	35	876	786	10.2
	40	1908	1766	7.4

influential factor in changing the number of optimal geogrid layers is the depth of the foundation, and even a parameter such as the internal friction angle of the soil does not significantly affect it. The results of this research show that the most influential factor in changing the number of optimal geogrid layers is the foundation's depth, and the soil's internal friction angle can only be effective for an internal friction angle of about 40 degrees or more.

Table (6) compares the upper bound of the static and seismic bearing capacity, in which the optimal number of geogrid layers is three and k_h = 0.2. The percentage decrease in bearing capacity was calculated between 17% to 7% with different conditions.

4. Conclusion

In this research, the bearing capacity of a shallow foundation reinforced with geogrid was investigated using the limit analysis method and Optum G2 software in static and seismic states. An attempt has been made to calculate the static and seismic bearing capacity by conducting a parametric study on the geogrid length, geogrid burial depth, the distance between geogrid layers, and the number of geogrid layers. Also, these analyses were performed on different soil internal friction angles and foundation depths. The following results were obtained from current research:

- The effective length of the geogrid depends on the internal friction angle of the soil so that the effective length of the geogrid is 3B at friction angles of 25 to 35 degrees. Meanwhile, for soil with an internal friction angle of 40 degrees, the effective length decreases to 2B. In this case, better locking of soil particles with geogrid can reduce the effective length of it.
- The percentage decrease of the seismic bearing capacity of the foundation compared to the static mode depends on the soil's internal friction angle and the foundation's depth. According to current research results, the percentage decrease in bearing capacity varies between 20% and 7% according to the geogrid's effective length, the geogrid burial depth, the distance between geogrid layers, and the number of geogrid layers.
- The percentage decrease of bearing capacity decreases by an increase of the soil's internal friction angle and the foundation's depth.
- The maximum effective depth of the geogrid is varied between 0.7B to 1.1B and increased by the increase of the internal friction angle of the soil.
- The optimal distance of geogrids was estimated between 0.2B and 0.6B.
- The optimal number of geogrid layers (*N*) when the foundation depth is zero was estimated to be three. By increasing the foundation depth, the optimal number of geogrid layers is reduced to 2 layers.
- The optimal number of geogrids depends on the internal friction angle of the soil and increases to $N = 4$ when the internal friction angle reaches 40 degrees.

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