

Bearing Capacity of Strip Footing Built on Geogrid-Reinforced Sand over Soft Clay Slope and Subjected to a Vertical Load.

A. Hamidi, K. Abbeche

Department of civil engineering, University of Banta 2, Algeria

ABSTRACT: The present work deals with the study of the behavior of a rigid striped footing, resting on a sand slope reinforced by geo-grids and located above a soft clay layer. For this purpose, numerical analysis was conducted using finite element program; Plaxis software package; where the effects of some parameters on the strip footing behavior were studied. The affecting parameters such as the number of layers of geogrids, the vertical spacing, and the slope of the sand, the depth of reinforcement and the angle of friction of the sand were considered in soil reinforcement by geogrids based on multi-series of tests. The analysis results show an improvement in the soil bearing capacity at the level of the reinforcement depth, whatever the slope of the sand and its density (loose, moderately dense and dense). This improvement was related to the important number of reinforcing elements represented by a small vertical spacing of strips. Whereas, a significant deterioration of the soil bearing capacity was detected in the case of steep slopes of sand whatever the number of reinforcing strips and their vertical spacing.

KEYWORDS: Strip footing, sand, soft clay, bearing capacity, geogrids, slope.

1 INTRODUCTION

Stabilizing a soil, in the broad sense of term, consists of the soil properties modification to improve its technical performance. In the last several years, the soil reinforcement below superficial foundations has been applied to improve the bearing capacity and the settlement of the foundations; in this aspect several research works were treated; (Dash et al. 2003); Boushehrian & Hataf (2003); Ghosh & Bera, (2005); (Bera et al. 2005); (Patra et al. 2005-2006); Sommers & Viswanadham(2009); Madhavi & Somwanshi (2009); Lavas & Ghazavi (2012); Abu-farsakh & Qiming(2013); (Boussadia et al .2014); (Demir et al .2014); Abu-farsakh & Qiming (2015); (Enas et al.2015);(Sahu et al.2016). Thus, the stabilization of the slopes of soil has become the most interesting field in soil mechanics. As a part of research, various techniques have been suggested to improve slope stability and improve bearing capacity including the geometry of the sloping surface changing, chemical treatment, and the use of reinforced soil or the installation of retaining structures such as walls or piles. The success achieved in reinforcing the weak casings of pavements by geogrid as in soft clay has been described by several authors (Tsukada et al. 1993); Alawaji (2001); Maharaj (2003). The research study established by (Tsukada et al. 1993) was devoted for strengthening the foundations of roads by geogrids. The distributions of pressures as well as the settlement related to the thickness and configuration of the reinforced soil layers were reported by these authors. Alawaji

(2000), studied the effect of reinforcing a block of sand below a collapsible soil, it reported that the rate of slump reduction has been reached a threshold of 75% (after reinforcements), Maharaj(2003) studied the behavior of strip footings constructed on a reinforced layer of clay. It was noted that compaction was reduced with the increasing of reinforcement size, stiffness and the number of reinforcement layers. Several research works have been carried out to study of the behavior of superficial foundations built on sloping sands, (Huang et al .1994); yoo(2001); El sawwaf & Nazir(2010-2011); Saeed & Hataf(2009); Sommers & Viswanadham(2009); (Choudhary et al .2010); (Turker et al .2014);(Dhiraj et al.2017);(Moradi et al.2019). However, few works have been devoted to analyze the behavior of a superficial foundation resting on a soil reinforced by rubbing geo grids and located above a soft clay slope. In this aspect, El asswaf & Mustafa (2007) studied the reinforcing effect on the behavior of a strip foundation built on reinforced sand crowd and located above a layer of soft clay sloping. It has been reported that the effect of the reinforcing elements on the behavior of the strip footing depends on its location with respect to the crest of the slope, and the reinforcing elements are more effective when the foundation is placed on the crest of the slope.

This work highlights the case of the construction of strip footing resting on reinforced sand above a soft clay slope and draws attention to the parameters that affect its behavior. For this purpose, two major problems were treated; the reduction of the bearing capacity of the clay layer and the breaking potential

of the slope itself. The study concerns the variation of specific parameters including the depth of the reinforced sand, the location, the number of geogrids layers, the variation of the angle of slope, and the angle of friction of the reinforced sand.

2 FINITE ELEMENT ANALYSES

In all the analyzes performed in this study, we assume that the footings are located on the soil surface which consists of two different soil layers, where the first layer is a sand reinforced by geosynthetic materials and the second is a Soft clay located below the first layer of sand. The two-dimensional modeling is performed considering a transversal section of the footing. The initial state of the stresses in the massif is assumed to be geostatic of the K0 type. The calculation is carried out in several stages:

the first is related to the construction of the model, and the second represents the stages of the foundation loading.

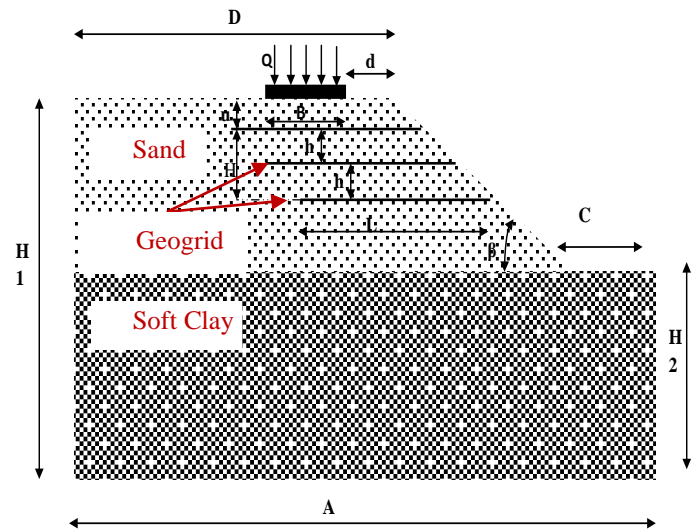


Figure 1. Geometric parameters of reinforced sand slop overlying soft clay.

2.1 Test material

The clay material is supposed to follow a soft soil behavior law and the rupture criterion is considered as the one of Cam Clay. However, for the sand, the behavior is supposed perfect and elastoplastic, where Mohr-Coloumb rupture criterion is used. The foundation is supposed to follow a linear elasticity law where the Young's modulus is equal to 32000 MPa; Poisson's ratio of 0.2 and the density is equal to 25 kN / m³. Geosynthetics are represented by special tensile elements (geogrid elements) in the Plaxis 2D code. The only property of geo synthetic is the elastic axial stiffness EA. Tables 1-2, present the different characteristics of the studied materials.

Table1. Physico-mechanical properties of the studied soil.

Parameters	Name	Sand 1	Sand 2	Sand 3	Soft clay	Unit
Model type		Mohr- Coulomb	Mohr Coulomb	Mohr Coulomb	Cam clay	
Dry density	γ	16	17	19	17	[kN/m ³]
Wet density	γ_{sat}	19	19	21	18	[kN/m ³]
Poisson coefficient	ν	0,3	0,30	0,3	0.30	-
Cohesion	c	1	1	1	50	[kN/m ²]
Angle of friction	ϕ	30°	35°	40°	1	[°]
Angle of dilatation	ψ	0°	5°	10°	0	[°]
Young's module	E	2,73.10 ⁴	3,65.10 ⁴	4,56.10 ⁴	-	[kN/m ²]
Slope of loading	K^*	-	-	-	0.15	[-]
Virgin consolidation slope	λ^*	-	-	-	0.01	[-]

Table 2. Physico-mechanical properties of the geogrid

Material type	Polystere/PET transparent
Weight per area [g / m ²]	380
Tensile strength [kN / m]	20 ≤ R _T ≤ 80
Lengthening [%]	20 ≤ Δ _L ≤ 80
Tensile strength at 1% elongation [kN / m]	16
Tensile strength at 2% elongation [kN / m]	28
Tensile strength at 5% elongation [kN / m]	56
Opening of the stitches [mm × mm]	73 × 30
Lengthening before service [%]	0
Roll dimension width and length [m × m]	4,75×100
EA [kPa]	500

2.2 Meshes

In all cases, the first elaborated meshes were considered relatively coarse, with triangular elements too elongated. Although these elements are located in sparsely concerned areas, new narrower meshes have been developed which guarantees a better representation of the stress field around the foundation.

For all the models, the boundary conditions in displacements are similar: null vertical displacements at the base of the massif (at 10B of depth) and null horizontal displacements on the vertical borders of the model.

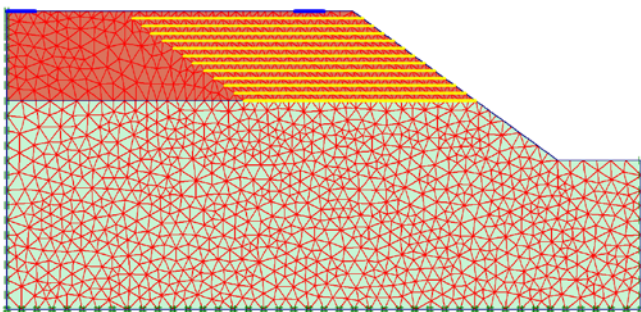


Figure 2. Prototype slope geometry, generated mesh, and boundary conditions

Table 3, presents the geometric characteristics of FE models in each studied case. All these meshes are built according to the same principle of configuration.

2.3 Calculation stages and loading increment

The simulation of the problem was carried out in three stages: the first corresponds to the creation of the initial state, the second is the construction of the sand layers with the laying of the reinforcement elements, and the last is the loading of the strip footing.

The initial state corresponds to a state of stress such that the vertical stress balances the land weight and the effective horizontal stress is a fraction of the effective vertical stress. The resting earth pressure in this case (sloping ground), was calculated from the gravitational force according to the Plaxis code.

For each simulation model, the solicitation is carried out in controlled displacement in the form of an increment of uniform displacements, up to a maximum value equal to (B / 10), applied on the lower part of the footing, which corresponds conventionally to settlement of the foundation when exceeding the bearing capacity of the soil.

Table 3. Characteristics of meshes in the different studied FE models.

Slope β(°)	Number of element	Number of nodes	Finite elements size [m]	Dimension of the model in FE in [m]				
				H1	H2	A	D	C
15	2519	20499	336.480*10 ⁻³	10	5	28.52	10	0.00
20	2657	21599	306.740*10 ⁻³	10	5	25	11	0.00
25	2373	19279	304.480*10 ⁻³	10	5	22	10	2.00
30	2401	19503	302.700*10 ⁻³	10	5	22	12	1.63
35	2483	20183	297.66*10 ⁻³	10	5	22	12	3.00

3 VALIDATION OF THE MODEL IN FINITE ELEMENTS

During the finite element model definition process, multitude approximations are applied (mesh, finite element type, number of nodes, behavior laws, etc.). In order to validate our numerical model, we compared the capacity factor values due to cohesion (N_c) of a flexible strip footing obtained by finite element method with the ones given by the literary or the classical theory of the bearing capacity.

The simulation of a flexible strip footing resting on a purely coherent and undrained soil layer ($\phi_u = 0$ and $\nu = 0.5$) is a very simple example of validation.

In this validation, the sand layer is replaced by a purely coherent and undrained clay layer having same parameters of the lower soil layer, where the ratio $c_1 / c_2 = 1$. Then, we impose a uniform vertical pressure on a strip footing realized on the ground surface, and placed on the left vertical part of the model, which means that the effect of the slope is much neglected, and the footing behaves as a foundation built on a horizontal floor.

The maximum pressures that have been applied are 140 kPa for soft clay, 350 kPa for firm clay and 1300 kPa for stiff clay.

The different mechanical characteristics that have been taken into consideration according to Mohr coloumb criteria are: $c_u = 20\text{kPa}$ and $E_u = 5\text{MPa}$ for soft clay and $c_u = 50\text{ kPa}$ and $E_u = 20\text{MPa}$ for firm clay, on the other side $c_u = 200\text{ kPa}$ and $E_u = 40\text{MP}$ for steep clay.

The general formula of the bearing capacity of a flexible footing for a purely coherent soil ($\phi_u = 0$) is written as.

$$q_l = N_c * C_u \text{ et } N_\gamma = N_q = 0 \tag{1}$$

and the factor of cohesion is given by:

$$N_c = q_{lc} / C_u \tag{2}$$

Table 4, presents the test results corresponding to the cohesion factor of the bearing capacity of the different finite element models, in addition to the ones given by literary and the classical theory of bearing capacity.

Table4. Cohesion factor calculation results of the bearing capacity of a strip footing subjected to a uniform vertical pressure.

Slope $\beta[^\circ]$	Present study			solution exacted Prandtl	Lower bound (Merifield et al. (1999)	Upper bound (Merifield et al (1999)	FEM (Merifield et al. (2001)	Michalowski (2002).
	Case (1)	Case (2)	Case (3)					
15	5.28	5.27	5.28					
20	5.30	5.29	5.29					
25	5.23	5.28	5.28	5.14	4.94	5.32	5.11	5.141
30	5.31	5.31	5.30					
35	5.13	5.24	5.24					

According to the calculation results in a flexible strip foundation, it was noticed that the factor due to cohesion and given by FEM (Plaxis) is almost the same as the one given by the literature and theory at a maximum deviation of 3.5 %. This very good concordance can be considered as a validation of the fi-

nite element model designed during this study. Table 5 presents the details of the various parameters considered in this study, corresponding to a continuous footing, where its width (B) is equal to 1m.

Table5. Model test program.

Test	L/B	H/B	d/B	h/B	$\beta(^\circ)$	u/B	$\phi(^\circ)$
01		0.25 à 3	1	0.25, 0.50, 0.75	15, 20, 25, 30,35	0.25	35
02	8	0.25 à 3	1	0.25	15, 20, 25, 30,35	0.25 ;0.50 ;0.75	1.00
03		0.25 à 3	1	0.25	15, 20, 25, 30,35	0.25	30,35, 40

4 RESULTS AND DISCUSSIONS

Over the last thirty years, several research projects have been carried out in order to study the behavior of geo-synthetically reinforced foundation soils. All of this work indicated that the use of geogrids increases the bearing capacity and decreases settlement of foundations. The effect of reinforcement on increasing bearing capacity is usually expressed in terms of a dimensionless parameter called the BearingCapacity Ratio (BCR). BCR is the ratio of the value of the bearing capacity of the reinforced soil than the unreinforced soil.

$$BCR = q_{ur} / q_u \quad (3)$$

With q_{ur} : bearing capacity of soil after reinforcement, and q_u : bearing capacity of the soil before the reinforcement.

4.1 Effect of reinforcement depth

The reinforcement depth is a very important parameter in terms of improving the bearing capacity of the reinforced surface foundations, in this aspect; we examine a series of tests on sand reinforced with many layer of geogrid. In this test, we fixed the vertical spacing between the bottom of the footing and the first reinforcing element (u), which is equal to $0.25B$, and the vertical spacing between the consecutive reinforcing elements (h), which is equal to $0.25B$. Then, we vary the value of the angle of the slope (β) which was equal to 15° , 20° , 25° , 30° , 35° , and the depth of the reinforced zone has been varied between $0.25B$ and $3B$. The sand that has been simulated is moderately dense sand (sand 2 table 1).

Figure.3 Presents the variation of the improvement factor (BCR) as a function of the vertical spacing between the reinforcing elements. Moreover, it can be recognized that the increase in the depth of the reinforcement zone (H) results from a considerable increase in the factor (BCR), regardless of the slope (β). Thus, we note the existence of a threshold distance, noted H_{lim} , beyond which the depth of the reinforcement zone has no effect on the variation of the improvement factor (BCR).

Figure.4 presents the variation of the vertical pressure calculated in term of the variation of the vertical displacement (s / B). It has been found that the increase in the numbers of reinforcing elements results from a considerable increase in the vertical pressure whatever the slope (β).

The values of the reinforcement depth (H), noted for this test, are $1.25B$, $1.50B$, $2.0B$, $2.25B$, and $2.75B$, according to the different slopes that have

been studied, 15° , 20° , 25° , 30° and 35° respectively. The maximum values of the departure improvement factor (BCR), which have been found are 1.29, 1.48, 1.64, 1.78, 2.2, according to the different slopes (β), which have been varied between 15° , 20° , 25° , 30° and 35° respectively.

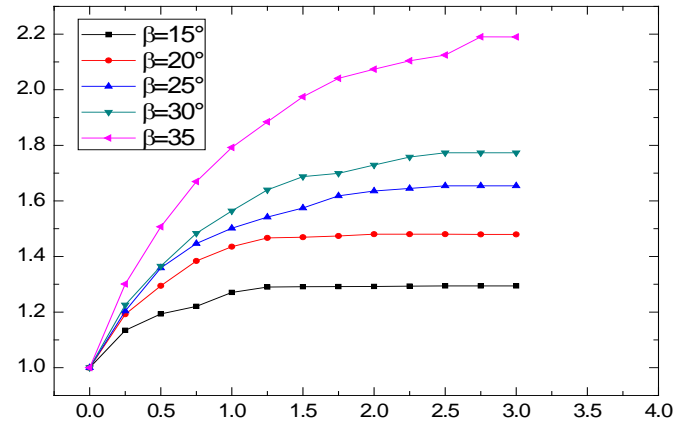


Figure 3. Improvement factor (BCR) variation in terms of reinforcement depth (H / B). $u / B = h / B = 0.25$, $\phi = 35^\circ$

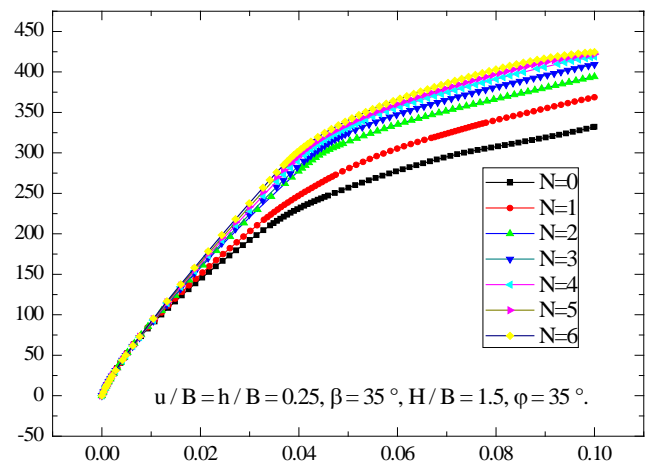


Figure 4. Load curve of vertical pressure in relation to displacement (S / B)

4.2 Effect of number of geogrid layers

To understand the effect of number of reinforcing elements, we examine a series of tests on sand reinforced by several sheets of geogrid. In this test, we fixed the vertical spacing between the bottom of the footing and the first reinforcing element (u) which is equal to $0.25B$, and the vertical spacing between the consecutive reinforcing elements (h), which is equal to $0.25B$. Then, we vary the value of the angle of the slope (β) which was equal to 15° , 20° , 25° , 30° , 35° , and the depth of the reinforced zone was varied between $0.25B$ and $3B$. The sand that has been simulated is moderately dense sand (sand 2 table 1).

Figure.5 presents the variation of the improvement factor (BCR) in term of reinforcement elements (N). Furthermore, it can be seen that the increase in reinforcement elements results from a considerable increase in the improvement factor (BCR), regardless of the slope (β). Thus, we have found the existence of a threshold distance, noted N_{lim} , beyond which the number of reinforcement has no effect on the variation of the improvement factor (BCR).

The values of the number of reinforcing N_{lim} , which have been identified are 4, 5, 7, 9,11 according to the different studied slopes which were equal to 15 °, 20 °, 25 °, 30 ° and 35 ° respectively. The maximum values of the improvement factor (BCR) are 1.29, 1.48, 1.64, 1.78, 2.20 depending on the different slopes of the studied model, 15 °, 20 °, 25 °, 30 ° and 35 ° respectively.

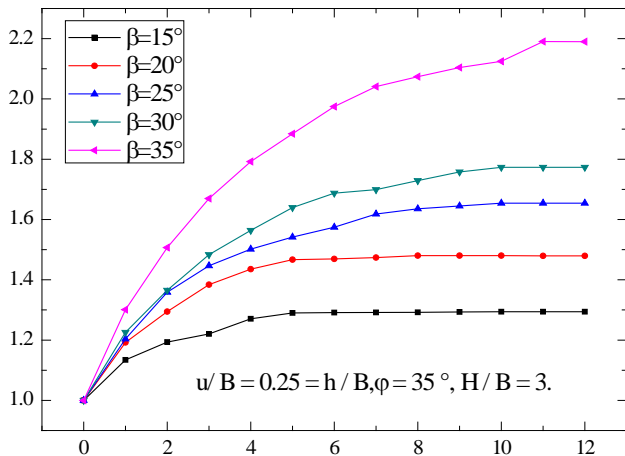


Figure 5. Improvement factor (BCR) variation in relation to geogrid layer number (N),

4.3 Effect of vertical spacing of the geogrid

To evaluate the effect of the spacing between the reinforcing elements, we examine two series of tests. In the first series of tests, we set the ratio (h / B) which was equal to 0.25, the depth of the reinforcement zone (H) which has been equal to 3B, and the vertical spacing between the bottom of the footing and the first reinforcing element (u / B) which have been equal to 0.25, 0.50, 0.75, 1.00, and the slope (β) which were equal 15 °, 20 °, 25 °, 30 °, 35 °. In the second series of tests, we fix the ratio (u / B) which is equal to 0.25, the reinforcement depth (H) which is equal to 3B, and we vary the vertical spacing between the consecutive reinforcing elements (h / B). which were equal to 0.25, 0.50, 0.75, and the slope (β) that were equal to 15 °, 20 °, 25 °, 30 °, 35

°. The sand that has been simulated is moderately dense sand with a 35 ° angle of friction (sand 2) as shown in Table 1.

Figure .6 presents the variation of improvement factor (BCR) in term of vertical spacing (u / B) of each slope (β) of the studied model. It has been observed that the increase in the spacing between the bottom of the footing and the first reinforcing element results from a decreasing of the improvement factor (BCR), whatever the slope (β). The values of the latter decreased from 2.20 to 1.54 when the slope (β) is equal to 35 °, from 1.78 to 1.29 when the slope (β) is equal to 30 °, and 1.64 to 1.21 for (β) is equal to 25 °, and from 1.30 to 1.06 when the slope (β) is equal to 15 °.

Figure.7 represents the variation of improvement factor (BCR) in term of the vertical spacing between the reinforcing elements (h / B), of each slope (β) of the studied model. A considerable decreasing in the improvement factor (BCR) has been observed when the spacing between the reinforcing elements increases, whatever the slope (β). The values of the latter decreased from 2.20 to 1.68 when the slope (β) is equal to 35 °, from 1.78 to 1.45 when the slope (β) is equal to 30 °, and 1.65 to 1.38 for (β) is equal to 25 °, and from 1.28 to 1.16 when the slope (β) is equal to 15 °.

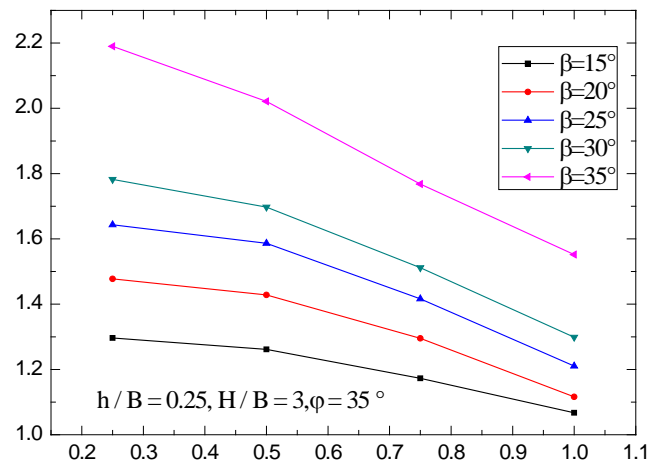


Figure 6. Improvement factor variation in terms of vertical spacing (u / B).

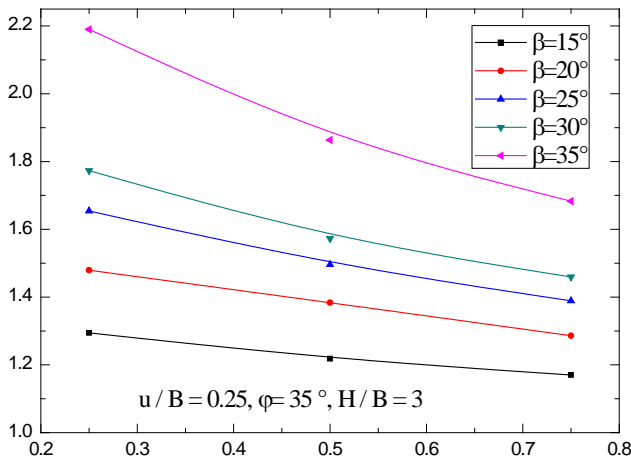


Figure 7. Improvement factor (BCR) variation in terms of vertical spacing (h / B).

4.4 Effect of slope β

The particular configuration of a foundation located near a slope is a frequently encountered case in practice. This problem has been the subject of full-scale tests or centrifuged or normal gravity models.

To evaluate the effect of the slope (β) on the variation of the bearing capacity of the reinforced soils, we examine a series of tests of moderately dense sand reinforced by several layers of geogrid, with an angle of friction (ϕ) equal to 35° . The principle of this test is to fix the vertical spacing between the bottom of the footing and the first reinforcing element (u) which is equal to $0.25B$, the vertical spacing between the consecutive reinforcement elements (h) which is equals $0.25B$, the depth of the reinforced zone which is equal to $3B$. Then, we vary the angle of the slope (β) which was equal to 15° , 20° , 25° , 30° , 35° .

The evaluation of the effect of the slope (β) on the variation of the bearing capacity has been expressed by a non-dimensional term called the coefficient of reduction of bearing capacity (i_β). The value of the latter is estimated by a ratio between the bearing capacities of a top slope, with the bearing capacity of a small slope (β), as written in equation (4)

$$i_\beta = q_{\beta_{\max}} / q_{\beta_{\min}} \quad (4)$$

In this part of the work we suppose that the slope is weak, when (β) is equal to 15° and important when (β) is equal to 20° , 25° ; 30° , 35° .

Figure.8 presents the variation of the reducing coefficient of the bearing capacity (i_β) in relation to the slope (β) of a foundation in the vicinity of the slope. The values of the reduction coefficient of bearing capacity are decreasing when the slope (β)

increases, and this was observed in all the cases as shown in fig 8. It is interesting to note that the results obtained by the present study noticed a considerable effect of the slope (β) on the reducing coefficient of bearing capacity (i_β). This influence becomes weak when the number of geogrid reinforcement elements is important. The coefficient (i_β), varies between 0.96 and 0.84 for a weak slope which is equal to 20° , of 0.82 and 0.55 for a top slope (β) which is equal to 35° .

Figure.9 presents the variation of the rate of reduction of the bearing capacity in terms of the slope (β). The latter results from a considerable increase, when the sand is unreinforced, and becomes a weak increase for reinforced sand, related to an important number of reinforcing elements. The maximum rate found is of the order of 44% for unreinforced sand and 14.5% for reinforced sand related to an important number of reinforcing elements.

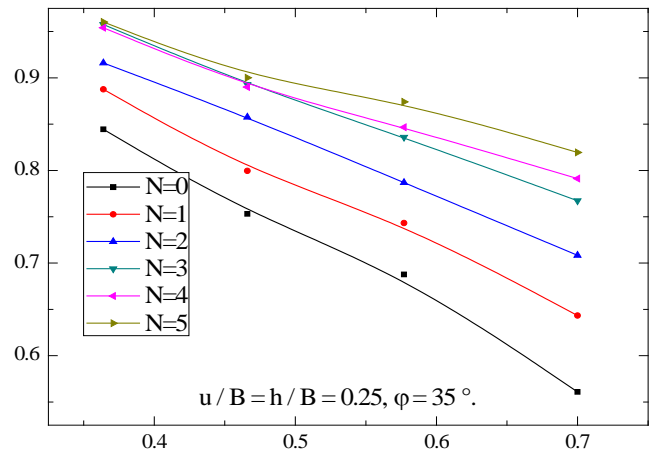


Figure 8. Variation of reduction coefficient of bearing capacity (i_β) in relation to the Slope (β).

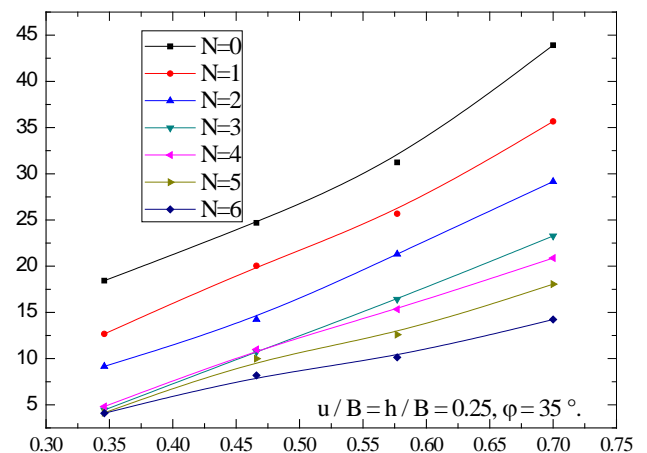


Figure 9. Rate of reduction of bearing capacity related to the slope (β).

4.5 Effect of friction angle (ϕ)

During the construction of the layer of sand reinforced by geosynthetic materials (geogrid), the physical and mechanical parameters of the soils, are very important factors in terms of sizing of the superficial foundations, by these parameters the angle of friction of the sand. To evaluate the effect of the latter, we examine a series of tests that carry three different types of sand (loose, dense and moderately dense) reinforced by several sheets of geogrid. The principle of this test is to fix the vertical spacing between the bottom of the footing and the first reinforcing element (u) which is equal to $0.25B$, the vertical spacing between the consecutive reinforcing elements (h) which equals $0.25B$, the depth of the reinforced zone (H) which is equal to $3B$. Then, we vary the angle of the slope (β) which is equal to 15° , 20° , 25° , 30° , 35° , and the angle of friction (ϕ) that is equal to 30° , 35° , 40° .

The evaluation of the effect of the angle of friction on the bearing capacity was expressed by a non-dimensional term called friction angle factor (I_f). The value of the latter is estimated by the ratio between the bearing capacities of a high angle of friction, with the bearing capacity of a low angle of friction, as written in equation (5).

$$i_f = q_{\phi_{max}} / q_{\phi_{min}} \quad (5)$$

With $q_{\phi_{max}}$: bearing capacity of soils with a high friction angle, which is equal to 35° , 40° , and $q_{\phi_{min}}$: bearing capacity of soils with a low angle of friction, which is equal to 30° .

Figure. 10 represents of the variation of the improvement factor (BCR) in terms of the internal friction angle of the sand. A considerable increase in the factor of improvements of the Bearing capacity has been observed when the angle of friction (ϕ) increases in all cases as shown in figure.10. It is interesting to note that the results obtained by the present study show an effect of the soil internal friction angle (ϕ) on the improvements factor (BCR).

The results of this study show that with the increase of the internal friction angle (ϕ) of the soil, the coefficient of the angle of friction (I_f) increases as shown in figure 11, whatever the slope (β). The values of the latter are varied linearly from 1 to 1.76 in all the studied cases, with a maximum variation of 0.07 in the case where the angle of friction is equal to 40° .

Figur.12 presents the effect of the angle of friction on the variation of the rate of bearing capacity improvements. In this part of work we notice that there is a great improvement of the bearing capacity according to the increase of the friction angle of the sand, whatever the number of reinforcing elements. The rate of improvement is varied between 300%

and 65% for dense sand with an angle of friction equal to 40° , by wearing loose sand with an angle of friction equal to 30° .

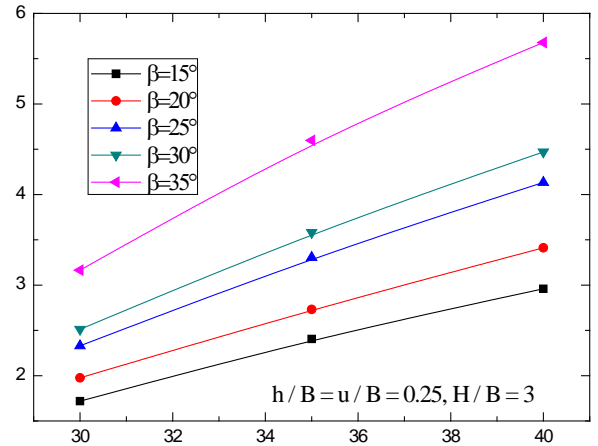


Figure.10 Variation of improvement factor (BCR) in terms of friction angle ϕ .

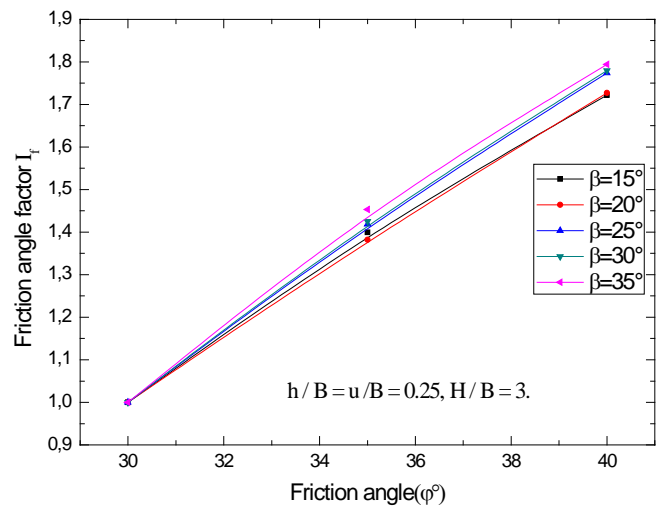


Figure 11. Variation of friction angle factor in terms of internal friction angle (ϕ),

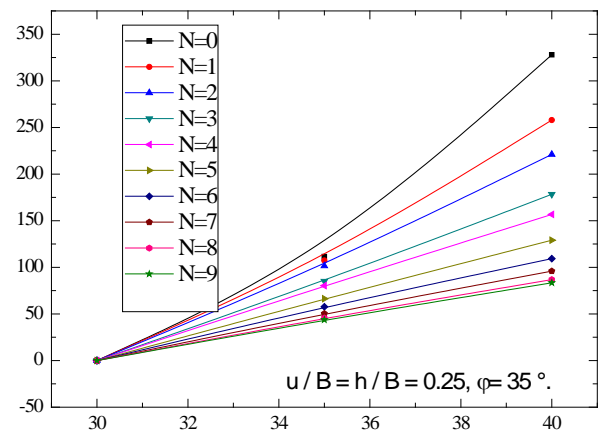


Figure 12. Rate of improvement of the bearing capacity in terms of friction angle (ϕ)

5 CONCLUSIONS

The presented work aims at analyzing the bearing capacity behavior of a rigid strip footing resting on a layer of sand reinforced by geogrids, above a layer of soft clay that is purely consistent in slope, and subjected to a vertical load. For this purpose, a numerical study was conducted using finite element method. Based on the results get from this investigation, the following conclusions can be drawn:

(1) Soil improvement of soft clay ground slope by partial replacement with sand layer significantly increases the load bearing capacity of a footing placed on near to the crest of sloping ground.

(2) The depths of reinforcement (H_{lim}) that were found are 1.25B, 1.50B, 2.0B, 2.25B, 2.75B for the different slopes of the studied models, which are equal to 15° , 20° , 25° , 30° and 35° respectively.

(3) The values of the number of reinforcement (N_{lim}) which have been observed are 4, 5, 7, 9, 11 for the different slopes of the studied model which are equal to 15° , 20° , 25° , 30° and 35° respectively.

(4) A considerable improvement of the bearing capacity is noticed if the spacing between reinforcement elements (u/B) and (h/B) is low, in particular when it was equal to 0.25.

(5) A reduction of the bearing capacity of 45% for a slope of 35° , and 15% for a slope of 15° .

(6) A good improvement of the bearing capacity if the angle of internal friction increases whatever the slope (β).

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