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Research Article

Numerical investigation on the Effect of the Setback and the Geosynthetic Reinforcement for a strip footing on sloping ground

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Abstract **–** Foundations are often placed on sloping land for the construction of various structures such as buildings, transmission towers, retaining walls and bridge abutments. The stability of the foundation placed on such soils largely depends on a number of factors such as, soil friction angle, soil slope angles and loads imposed on the foundation. Moreover, recent scientific research has shown that the introduction of a single layer or several layers of geosynthetic can considerably improve the bearing capacity and reduce settlements and therefore proves to be a cost-effective solution compared to a deep foundation. In this context, the present numerical study is a contribution which permits to more understand the behavior of foundations on a slope. The results of the study show that the load-settling behavior and ultimate bearing capacity can be significantly improved by including a geogrid at an appropriate depth below the foundation. It is also shown that for both reinforced and unreinforced slopes, the bearing capacity decreases with increasing slope angle and decreasing distance from the edge of the slope. At a critical distance from the edge of the slope, the bearing capacity becomes independent of the angle of the slope. The results obtained agree well with the results of the literature. Stress contours are also plotted to understand the failure mechanism of slopes.

Keywords – Bearing Capacity, Numerical Modelling, Foundation, Slope, Reinforcement

I. Introduction

Foundations are often placed near sloping soils for the construction of various structures such as buildings, retaining walls and bridge abutments. The bearing capacity of shallow foundations near the crest of a slope is affected by its setback. When the setback is greater than a critical value, the bearing capacity remains the same as if the foundation were placed on a horizontal support. Beyond a distance less than the critical setback value, the bearing capacity decreases and reaches its minimum value when the setback vanishes. Safe and economical design of such footings requires a good knowledge of both the settlement and bearing capacity relating to footings near slopes. The bearing capacity of shallow foundations has been extensively studied for many decades. However, very few attempts have been made to study the bearing capacity of footings near slopes (e.g.,[1]–[7]).

Studies of soil reinforcement by geosynthetics under the foundation revealed a substantial increase in bearing capacity. This technique for improving bearing capacity, by virtue of its ease of implementation, and its distinctly economical character compared to other methods of improving soil, has attracted the attention of a large number of scientific researchers and a considerable number of experimental and numerical studies on the effect of geosynthetics on the performance of reinforced slopes has been carried out (e.g., [8]–[12]).

The aim of this work is to carry out numerical computations using the software FLAC (Fast Lagrangian Analysis of Continua, 2011) to evaluate the soil-bearing capacity factors N_γ for rough strip footings placed near both unreinforced and reinforced slopes. The computational results are compared with previous published results available in the literature.

The bearing capacity of a shallow strip footing on a horizontal ground is commonly determined by using the Terzaghi [13] formula:

$$q_u = cN_c + qN_q + {}^1\!/_2\, B\gamma N_\gamma \qquad (1)$$

Where q_u is the ultimate bearing capacity, c is the soil cohesion, q is the surcharge above the base level of the footing, γ is the soil unit weight, B is the footing width, N_c, N_q, N_γ are the bearing capacity factors representing the effect of cohesion c, surcharge q and unit weight γ respectively.

There are several methods in the literature for the evaluation of N_γ, which are the limit equilibrium method, the limit analysis method, the method of characteristics and the finite element method.

Terzaghi's bearing capacity equation (1) has been substantially generalised for other types of footing shapes by numerous investigators as follows:

$$q_u = \lambda_c c N_c + \lambda_q q N_q + \lambda_\gamma\, {}^1\!/_2\, B\gamma N_\gamma \qquad (2)$$

Where λ_c, λ_q, λ_γ are called correction factors.

These correction factors are determined empirically, permitting to take into account other foundation contexts other than a strip footing on a horizontal surface, such as the shape of the foundation, the inclination of the loading, the proximity of the foundation of a slope, etc.

II. Numerical Modelling Procedure

This paper deals with the numerical study of bearing capacity of rough rigid strip footings resting near the edge of sandy slopes. The footing is subjected to a vertical central static load, and located on the surface of a cohesionless frictional associative soil adjacent to a slope of an angle β. To take into account the influence of the position of the foundation with respect to the edge on the bearing capacity, several setback values were considered. The computations have been done for the values of the *b/B* ratio 0, 1, 2, 3, 4, 5, 6, 7, and 8, where B is the width of the strip footing and b is the setback. These values of setbacks are justified by the fact that beyond a setback b/B of 8, the value of the load-bearing capacity converges towards its maximum value obtained on horizontal ground whatever the friction angle.

In order to minimise boundary effects, the top and the depth of the study domain have a dimension of 20 B. The bottom has a dimension of 20B + 12B/tanβ + 12 B. The domain is therefore extended by 12 B beyond the foot of the slope as depicted in Fig. 1.

The bottom boundary was assumed to be fixed, and the vertical boundaries were restrained in the horizontal direction as shown in Fig. 1. The reinforcement geogrid is embedded at a depth d below the foundation.

The analysis is carried out using the computer code FLAC [14] (2011) which is a commercially available finite difference explicit program. With this program, the solution of a static problem is obtained by including dynamic equations of motion. Damping terms are included to gradually remove the kinetic energy from the system.

The elastic perfectly plastic Mohr Coulomb model encoded in FLAC is used. Physical and mechanical characteristics used in the present study are: a shear modulus $G = 10$ MPa, an elastic bulk modulus $K = 20$ MPa, a soil unit weight $\gamma = 18$ KN/m^3, a series of four values of the angle of soil internal friction φ = 30° to 45° with an increment of 5°. The soil behavior is considered to be associated (ψ = φ) in order to compare the results of this study with the literature, but the study could be extended to the cases of non-associated soils.

In order to develop an acceptable analysis scheme for later computations, preliminary simulations have been carried out, by testing the size of the domain, the grid, and the boundary conditions.

The model domain for this study is shown in Fig. 2. In the vicinity of the footing, the grid is refined to capture the large gradients in strain. A detail of this region is shown in Fig. 2. The highest strain gradient will be in the region adjacent to the footing. The grid is therefore very fine in this area.

The proposed modelling procedure of the bearing capacity factors follows two steps. In the first one, the geostatic stresses are computed assuming the soil to be elastic. At this stage, some stepping is required to bring the model to equilibrium. In the second step, a downward velocity of 10^{-7}m/step was applied to the gridpoints representing the footing.

on both sides of the geogrid, with friction angles determined by the two interface properties. In this study, the following characteristics were retained: an axial stiffness EA = 2000 KN/m, where E is the elastic modulus of the geosynthetic and A is the

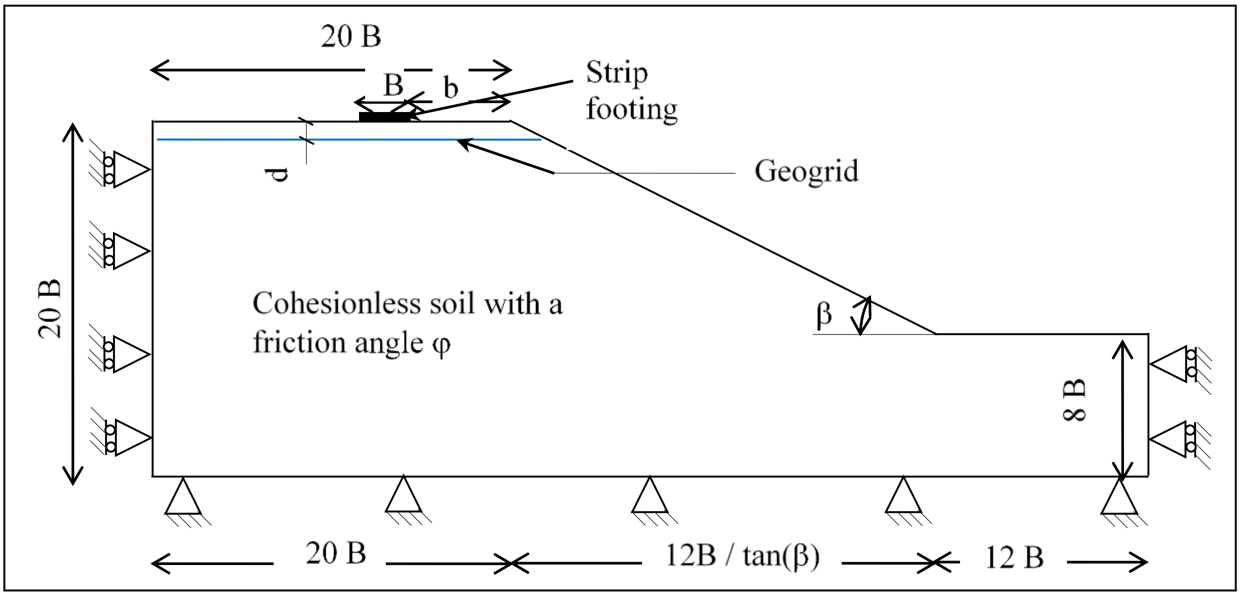


Fig. 1. Model boundary conditions

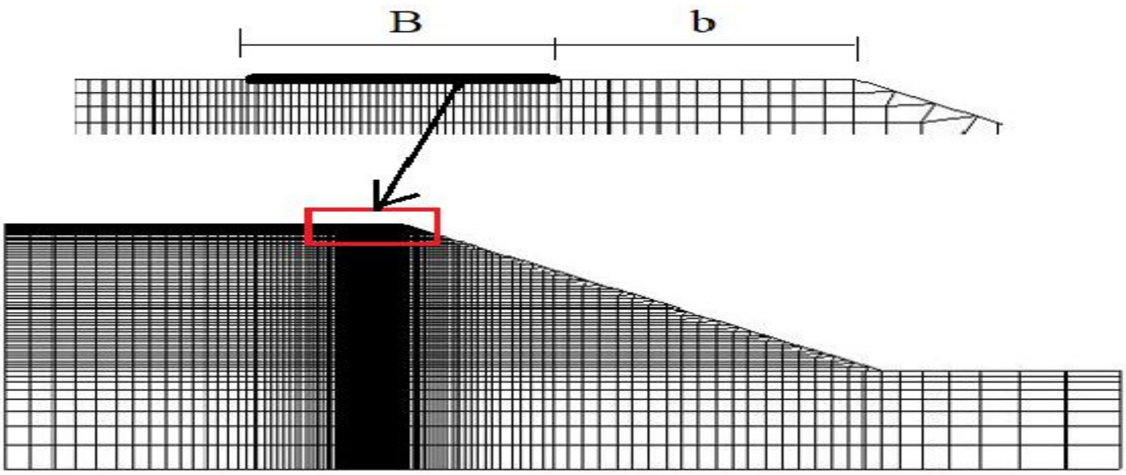


Fig. 2. Mesh used in FLAC simulations

Since the footing considered herein is rough it was simulated by fixing the displacement in the horizontal direction to zero for the gridpoints representing the footing.

The reinforcement acts to improve the shear resistance of the soil, the geogrid was modeled as a structural beam, as defined by FLAC [14]. The beam adopted has zero inertia, to characterize the membrane effect of the geogrid. Sliding is possible

section of the geogrid. The interface soil/geogrid is governed by Mohr Coulomb law where the interface friction angle φ_{int} is equal to 0.7 φ, where φ is the value of the soil friction angle. For the normal stiffness kn and the shear stiffness ks of the interface, they were both taken equal to 3.10^6 KN/m^3. This value is adopted in accordance with the recommendations of FLAC [14].

III. Results and Discussion

III.1 UNREINFORCED SLOPE

The bearing capacity factor N_{γ} is dependent on the soil unit weight γ and was calculated assuming cohesionless soil (c = 0) with no surcharge (q = 0).

bearing capacity equation (2) becomes as follows:

$$q_u = \frac{1}{2} B\gamma i_{\gamma\beta} N_{\gamma} = \frac{1}{2} B\gamma N'_{\gamma} \quad (3)$$

$$i_{\gamma\beta} = N'_{\gamma}/N_{\gamma} \quad (4)$$

Where N'_{γ} is the bearing capacity factor for the strip footing placed near a slope, N_{γ} is the bearing capacity factor for the strip footing placed on a horizontal ground, and $i_{\gamma\beta}$ is the reduction correction factor taking into account the presence of a slope close to the footing.

Fig. 3. presents the results of simulations with FLAC [14]. The figure shows the variation of the reducing coefficient of bearing capacity $i_{\gamma\beta}$ with the variation of the distance of the strip footing from the edge of the slope.

The results concern five friction angles (φ = 25, 30, 35, 40, 45°) and for each friction angle four slope angles were considered (β = 20°, 26.6° (slope 1/2), 30°, and β = 33.7° (slope 2/3)). The values of $i_{\gamma\beta}$ increase when the friction angle decreases and $i_{\gamma\beta}$ decreases when the slope β increases and that for all the values of φ and b/B. In addition, the correction coefficient increases when the foundation moves away from the edge of the slope up to a critical distance where $i_{\gamma\beta}$ will reach the value 1. This critical distance for which the effect of the slope on the bearing capacity canceled out is of the order of 2B to 6B depending both on the angles of slope and soil friction, it is smaller for low slopes and low friction and it is greater for high slope angles and significant friction angles.

Fig. 4. presents a comparison of the results of the present study with the results of Mabrouki et al. [3] which study was carried out using FLAC 3D. Fig. 4a concerns the comparison for a ground of an internal friction angle of 35 ° and two different slopes β = 26.6 ° (slope 1/2), and β=33.7° (slope 2/3). Fig. 4a shows that for each slope angle, the variation of the correction factor as a function of the distance from the foundation to the edge presents the same trend for the two studies and the differences between the two results are quite small. Similar conclusions can be deduced from Fig. 4b, namely that for a friction angle of 40°, the results of the

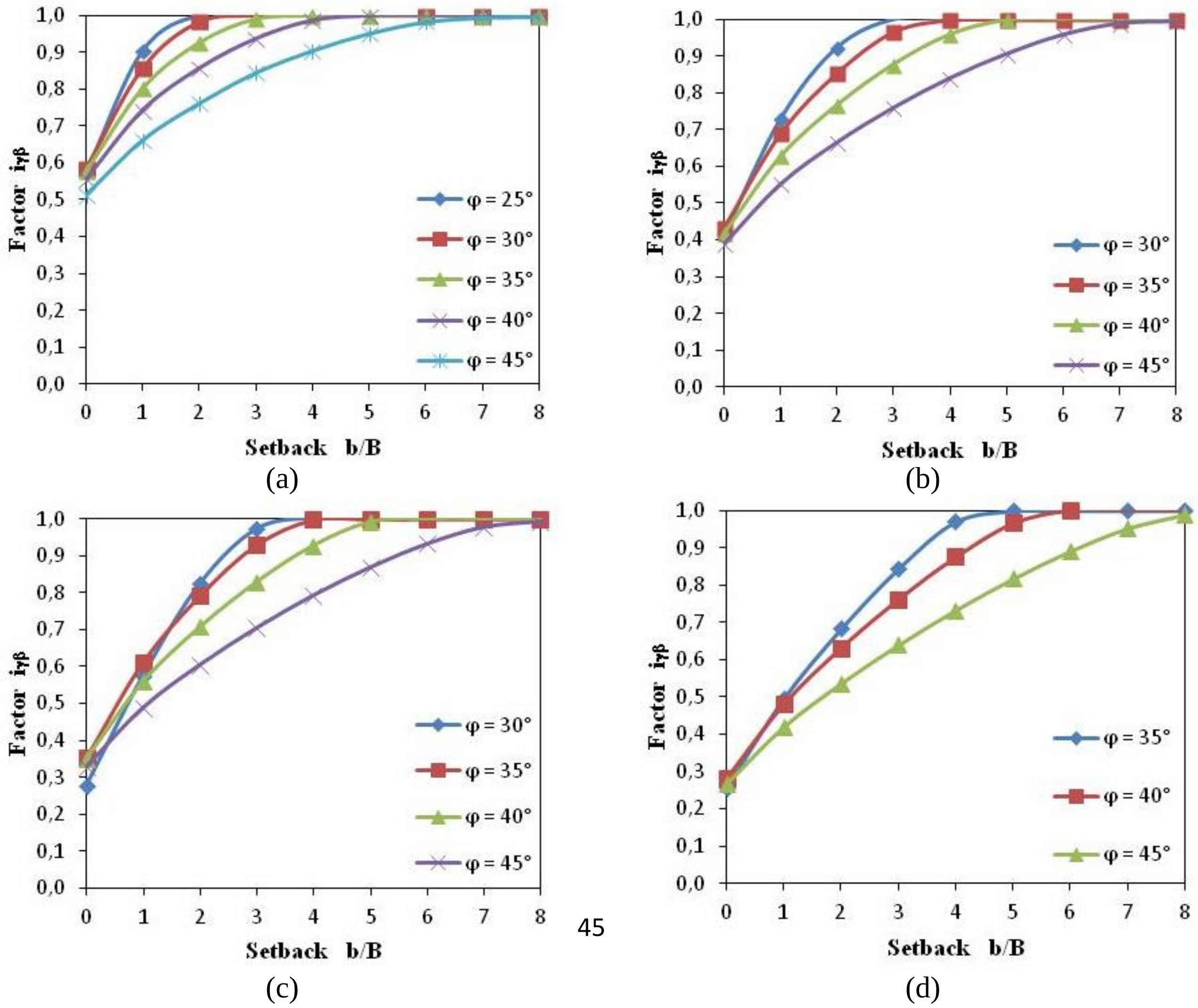


Fig. 3. Variation of the reduction factor of $i_{\gamma\beta}$ with soil friction angle and the setback from the edge (a) β = 20 °, (b) β = 26.6 ° (slope 1/2), (c) β = 30 °, and (d) β = 33.7 ° (slope 2/3).

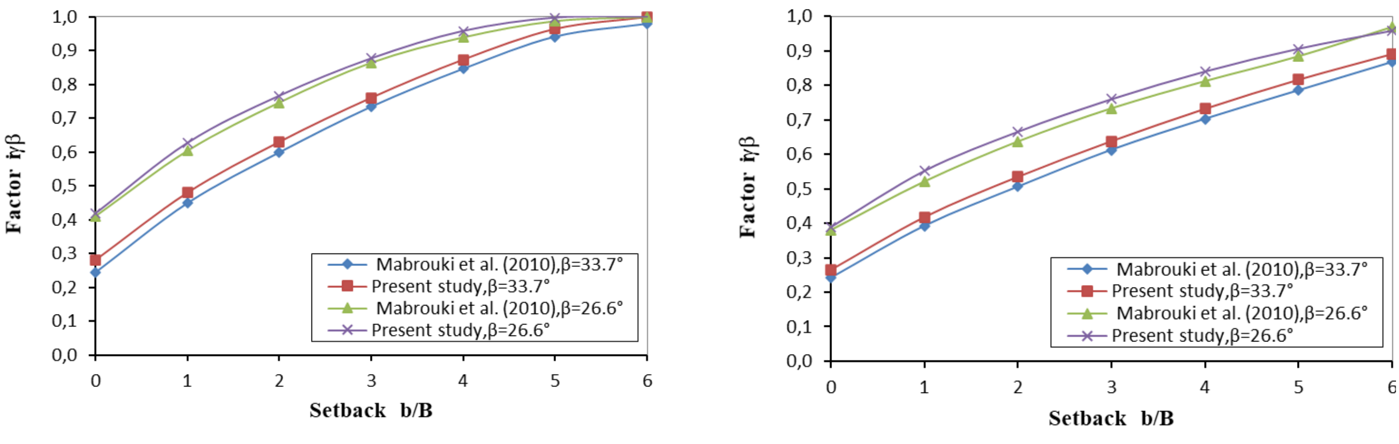


Fig. 4. Comparison of the results of the variation of $i_{\gamma\beta}$ with b/B from the present study with Mabrouki et al. (2010) in the cases β = 26.6 ° and β = 33.7 ° (a) φ=35°, (b) φ=40°

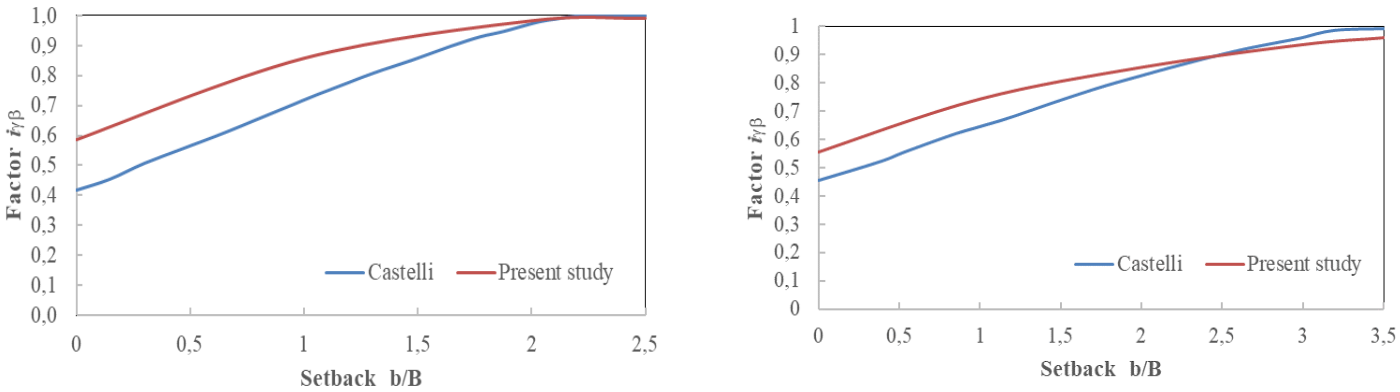


Fig. 5. Comparison of the results of the variation of $i_{\gamma\beta}$ with b/B from the present study with Castelli & Motta (2010) for the case β = 20° (a) φ=30°, (b) φ=40°

present study are very consistent with those of Mabrouki et al. [3].

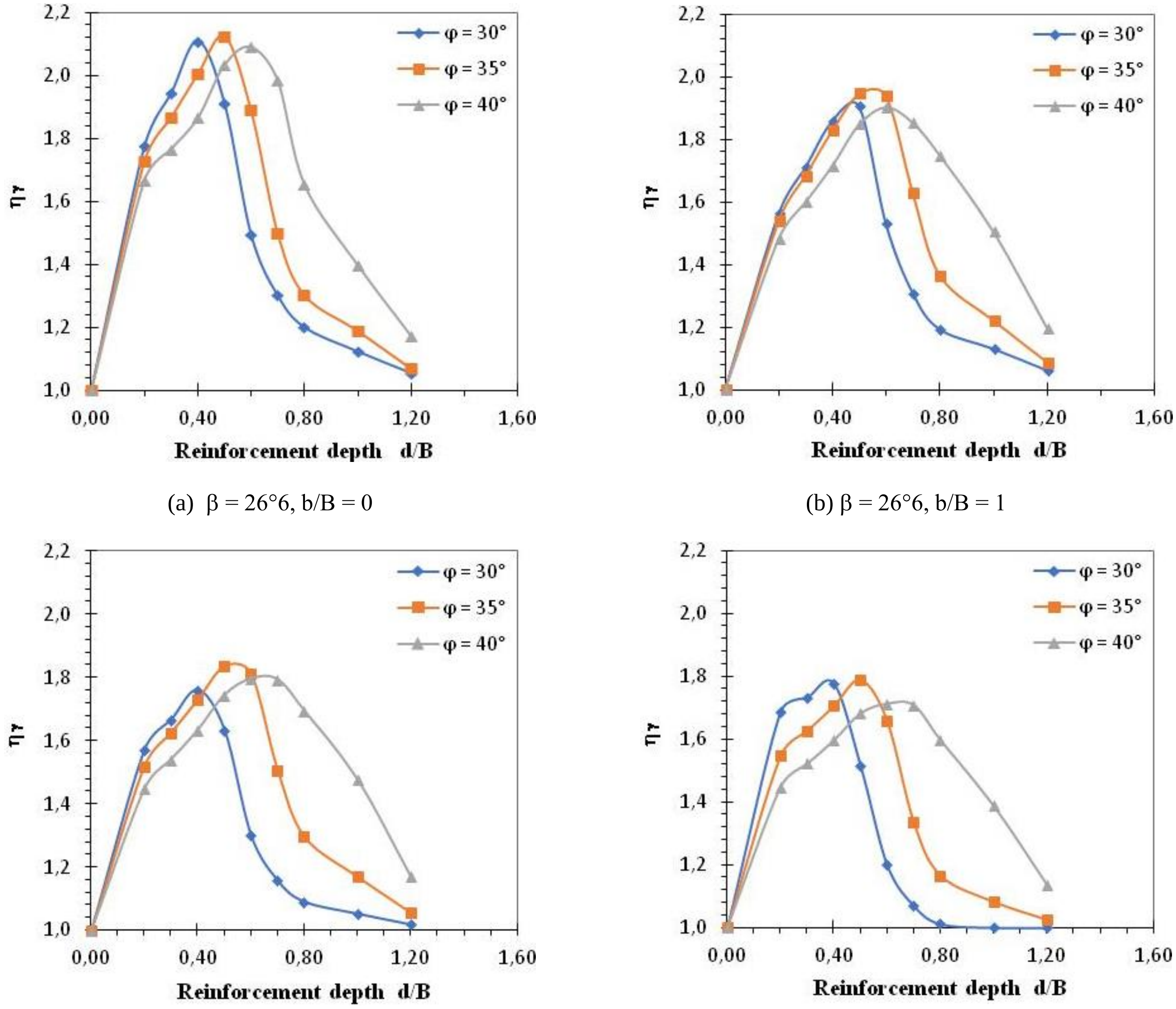
Fig. 5 presents a comparison of the results of the present study with the results of Castelli and Motta [4] whose study was conducted by using a model that has been developed based on the limit equilibrium method, considering a circular surface propagates towards the slope until the sloping ground is reached. Fig. 5a concerns the comparison for a soil with a friction angle of 30° and a slope β = 20°.

Fig. 5a shows that the variation of the correction factor as a function of the distance from the foundation to the edge presents the same tendency for the two studies but with discrepancies of the order of 0.15. The results of the present study are higher than those of Castelli and Motta [4] with an average deviation of 0.15, but the two curves of $i_{\gamma\beta}$ converge when the setback reaches b/B = 2.

Similar conclusions can be deduced from Fig. 5b, namely that for a friction angle of 40°, the results of the present study are also higher than those of Castelli and Motta [4] but with a lesser average deviation of 0.10. The two curves of $i_{\gamma\beta}$ converge when the setback reaches b/B = 2.5, with $i_{\gamma\beta}$ of the present study becoming lower beyond the latter value of b/B.

III.2. REINFORCED SLOPE

Recent scientific research has shown that the introduction of a single layer or several layers of geosynthetic can considerably improve the bearing capacity and therefore proves to be a cost-effective solution compared to a deep foundation. In this context, the present numerical study is a contribution which permits to more understand the behavior of foundations on a reinforced slope.



(a) β = 26°6, b/B = 0

(b) β = 26°6, b/B = 1

(c) β = 26°6, b/B = 2

(d) β = 26°6, b/B = 3

Fig. 6. Variation of the reinforcement efficiency factor η_γ with the depth of the reinforcement d/B and the soil friction angle φ

As depicted in Fig. 1, a geogrid layer is embedded in the soil at a depth d from the bottom of the strip footing. The characteristics of the geogrid used in this study are detailed above in paragraph 2. The experimental and numerical studies on the reinforced foundations revealed that there is an optimal depth of the geogrid for which the bearing capacity is maximum. In this context several numerical simulations have been carried out by varying the depth d of the geogrid from 0.1B to 1.2B. In order to analyze the effect of the reinforcement a factor η_γ is introduced. This factor is called the factor of the efficiency of the reinforcement which is the ratio between the bearing capacity of the reinforced foundation on that not reinforced, all other parameters being equal. The factor η_γ is given by the below equation 5.

$$\eta_\gamma = N'_{\gamma\, reinforced} / N'_{\gamma\, unreinforced} \quad (5)$$

Fig. 6 shows that geogrid reinforcement is very beneficial and enhances the bearing capacity of the strip footing with improvement rates varying from η_γ = 1.7 for a setback b/B = 3 to η_γ= 2.1 for a foundation placed on the edge of the slope. The results show that the efficiency reinforcement factor increases when the setback b/B decreases.

Concerning the value of $dopt$, for a slope of β = 26°.6 (slope of 1/2), it is depending of the soil internal friction angle, $dopt$ = 0.4B for φ = 30°, $dopt$ = 0.5B for φ = 35°, $dopt$ = 0.6B for φ = 40°.

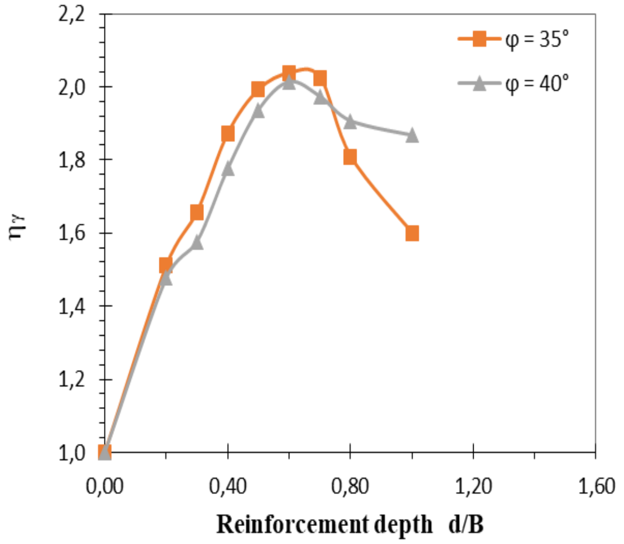


Fig. 7. Variation of the reinforcement efficiency factor ηγ with the depth of the reinforcement d/B and the soil friction angle φ (β= 33°7, b/B = 1)

Fig. 7 obtained for b/B = 1 and a slope angle β = 33°.7 (slope of 2/3) presents an optimal geogrid depth comparable to that obtained for β = 26°.6 (slope of 1/2).

The efficiency factor increases as the slope angle β increases (for b/B =1, η_γ = 1.95 for β = 26°.6 and η_γ = 2.01 for β = 33°.7).

The precedent reinforcement simulations were conducted taking into account a full length of geogrid covering all the width of the study domain until the surface of the slope as showed in Fig. 1. In addition, and in order to determine the optimal length of the geogrid just necessary to obtain an improvement of the bearing capacity equal at least to 90% of that which would be obtained by a full length of geogrid. the simulations carried out consisted in varying the length of the geogrid. taking into account the optimal geogrid depth. The results of the simulations are shown in Table 1.

Table 1 shows that it is not necessary to lay long lengths of geogrid but an optimal length of geogrid is sufficient to have a good improvement of the soil. Indeed, the study shows that for L = 4.9B the reinforced bearing capacity obtained is equal to 97% of that which would be obtained by a full length. Fig. 8 shows the tension axial force in the geogrid for the case of the optimum length of 4.9 B. it can be noticed that the maximum tension (130.3 kN representing an extension strain of 7%), due to the proximity of the slope, is not located under the middle of the footing. Also, the most important part of the tension develops just under the foundation, then the tension decreases on either side of the foundation to cancel out towards the two ends of the geogrid.

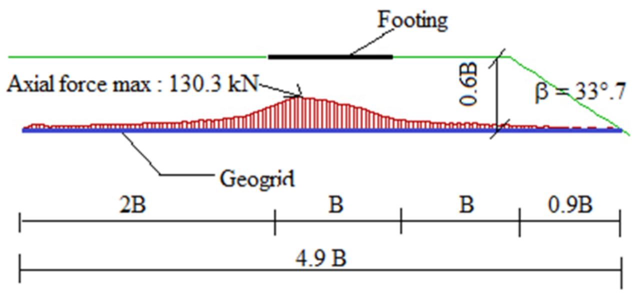


Fig. 8. Tension axial force in the reinforcement φ = 35°, β= 33°7, b/B = 1

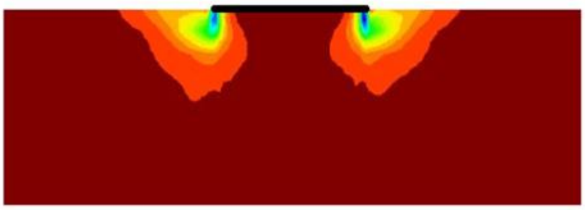
Fig. 9 presents the failure mechanism as shown by the curves of maximum shear strain increments. It can be noted different mechanisms depending on whether the foundation is placed far from the edge of the slope (case 9a) or the case of a foundation very close to the edge (9b) and, case 9c presents the effect of the reinforcement on the failure mechanism.

Fig. 10 presents a comparison of the results of the reinforcement efficiency factor ηγ (for a soil friction angle φ = 38°, β= 26°6, b/B = 1) of the present study with those of Halder and Chakraborty [8] who used a lower bound finite elements limit analysis, and Lee and Manjunath [10] who used both experimental and numerical analyses (Plaxis). It can be noted that the curves representing the efficiency factor ηγ as a function of the depth of the reinforcement d/B, have the same tendency. However, the values of this present study are greater, with a deviation of the order of 6%. Also, the optimal geogrid depth from the present study is slightly deeper.

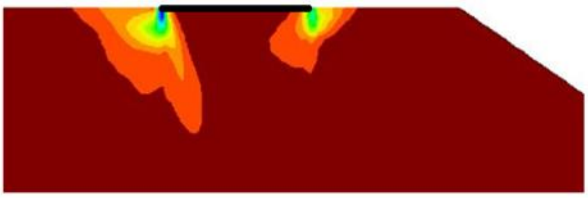
IV. CONCLUSION

Table 1. Effect of the length of the reinforcement (L) on the bearing capacity (Nγ) for a slope of β = 33°7, an angle of soil friction φ= 35° and a setback b/B = 1

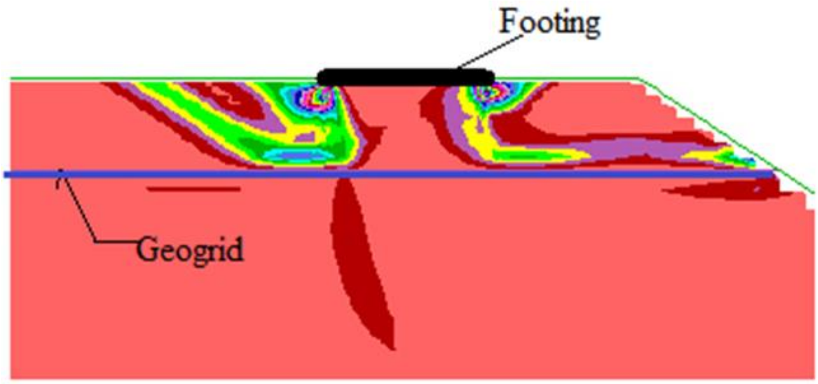
L	0	2B+0.9	2.5B+0.9	3B+0.9	4B+0.9	5B+0.9	6B+0.9	20B+0.9
				36.46				
				93%				



(a) unreinforced b/B = 7



(b) unreinforced b/B = 1



(c) reinforced b/B = 1

Fig. 9. Maximum shear strain at failure φ = 35°, β = 33°7

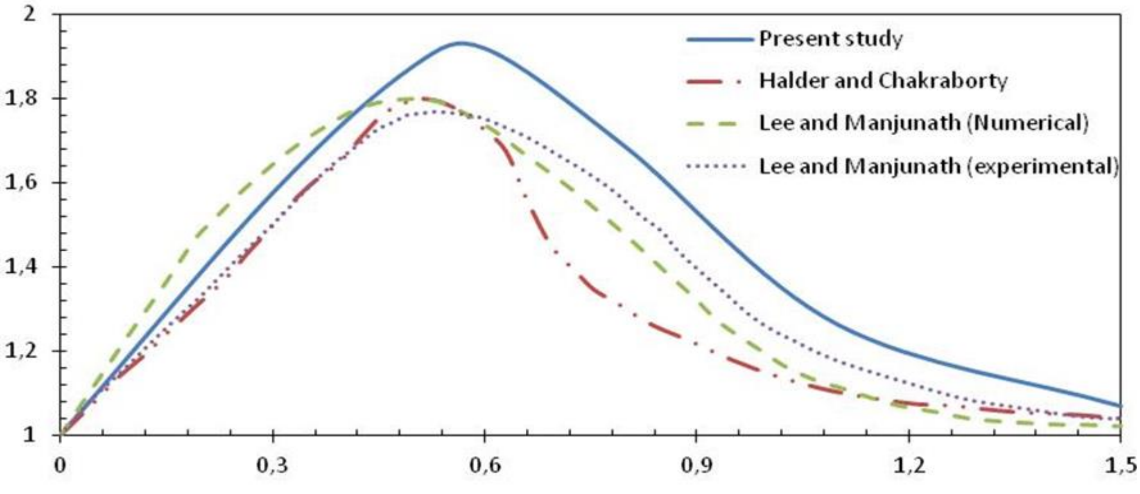


Fig. 10. Comparison of the results of the reinforcement efficiency factor ηγ (as a function of the depth of the reinforcement d/B for a soil friction angle φ = 38°, β= 26°6, b/B = 1) from this study with the results of Hadler and Chakrabory, and Lee and Manjunath.

The finite difference code FLAC was used to evaluate the soil bearing capacity factor N'_γ for rough rigid strip footings placed near a slope. From this investigation, comparing the obtained results presented in the form of design graphs and tables with the various available results given in the literature we can note the following:

- The bearing capacity of strip footings on slopes increases with an increase of the distance of the footing from the edge of the slope and decreases with an increase in the angle of the slope. Also, it decreases with an increase in friction angle. The critical distance for which the effect of the slope on the bearing capacity canceled out is of the order of 2B to 6B depending both on the angles of slope and soil friction, it is smaller for low slopes and low friction.
- The present numerical simulations show that the placement of a geogrid at an appropriate depth under the footing allows a significant improvement in the bearing capacity which can compensate for the loss of bearing capacity due to the presence of the slope. The improvement is of the order of 110% for a foundation placed on the edge of the slope.
- The optimal depth of the reinforcement depends of the soil internal friction angle (dopt = 0.4B to 0.6B for φ = 30° to 40°).
- The present study shows that it is not necessary to lay long lengths of geogrid but an optimal length of geogrid is sufficient to have a good improvement of the soil. Indeed, for the case of φ=35°, β=33°.7, b/B =1, a geogrid length L = 4.9B placed at a depth of 0.6B, gives a bearing capacity equal to 97% of the bearing capacity obtained by a full length.
- Due to the proximity of the slope, the tension axial force in the geogrid, for the case b/B=1, is not located under the middle of the footing, and the most important part of the tension develops just under the foundation, then the tension decreases on either side of the foundation to cancel out towards the two ends of the geogrid.

ACKNOWLEDGMENT

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NOMENCLATURE

q_u The ultimate bearing capacity

c The soil cohesion

q The surcharge above the base level of the footing

γ The soil unit weight

B The footing width

N'_γ The bearing capacity factor for the strip footing placed near a slope

N_γ The bearing capacity factor for the strip footing placed on a horizontal ground

$i_{\gamma\beta}$ The reduction correction factor

N_c, N_q, N_γ The bearing capacity factors

λ_c, λ_q, λ_γ The correction factors

GREEK SYMBOLS

φ The angle of soil internal friction

ψ The dilatancy angle

β The slope angle

η_γ The factor of the efficiency of the reinforcement

$dopt$ The optimal depth of the reinforcement

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