

Numerical Analysis of the Bearing Capacity of Strip Footing on Reinforced Soil Slope

Mohammadreza Hamzhepour Ahmadi¹, Adel Asakereh²

¹Department of Civil Engineering, University of Hormozgan, Pardis-E-Qeshm

²Assistant Professor, Department of Civil Engineering, University of Hormozgan

Abstract— In some projects, such as the foundations of high-rise buildings adjacent the excavation, bridge abutments and tower footings for electrical transmission lines, foundations may be built on a slope. In these cases, the behavior of the mentioned foundation will be affected by the slope. In this study the results of a series of numerical analyses using finite element method on strip footing rested on both reinforced and unreinforced soil slopes were presented. The developed model was validated by some of the existing theories. Afterwards, the parametric studies were performed to determine the geometrical effective parameters and their effects on the behaviour of this type of footing. Results indicated that the bearing capacity of footing can be considerably improved by the inclusion of reinforcing layer and amount of improvement is function of the depth and spacing of reinforcement layers, slope angle and distance of footing from the slope. By evaluate the effect of number of geogrid layers it was found that significant increase in the bearing capacity is occurred by increasing the number of geogrid layers up to four layers.

Keywords — Bearing Capacity, Strip Footing, Reinforced Slope, Numerical Analysis

I. INTRODUCTION

Foundations are a fundamental pillar to any structure, which transmit the load of the superstructure to the layers of the soil. Due to the space constraints as well as economical and architectural objectives in a project, the foundation may be built near a slope. Some common examples of these foundations include basement excavations for high-rise buildings, bridge abutments and tower footings for electrical transmission lines. Slope stability and bearing capacity of foundation are important factors in such projects. When a foundation is constructed near a slope, one side of the foundation will be subject to the slope and plastic regions will be developed and significant changes will be occurred in the slope stability and subsequently bearing capacity of the foundation. Bearing capacity is a major concern in geotechnical engineering and correct determine of bearing capacity of the foundation near a slope is a challenging task for an engineer. For a footing near the slope, the ultimate bearing capacity may be governed by either the foundation bearing capacity or the overall stability of the slope. Hence the

combination of these two factors makes the problem difficult to solve [1]. The bearing capacity of a shallow strip footing resting on level homogenous ground is generally evaluated using the superposition formula proposed by Terzaghi [2]. After Terzaghi, further studies on bearing capacity of the foundation on level ground developed by other researchers such as Meyerhof [3], Hansen [4] and Vesic [5].

Meyerhof [6], investigated general failure mechanisms for bearing capacity of footings placed on purely cohesionless or cohesive soils adjacent to slopes. After Meyerhof, Hansen [4] and Vesic [7], evaluated the bearing capacity for the condition that the foundation is located at the slope crest. After them, numerous researchers have studied this problem via various method and solutions, including limit equilibrium techniques [8, 9], yield design theory [10], finite element method [11], upper bound technique [1, 12] and lower bound technique [1].

Slope reinforcement using geosynthetic layers with high tensile strength is one of the solutions to improve the performance of foundations near the slope. Few studies on the bearing capacity of the footings resting on reinforced soil slopes have been reported in the literature. Selvadurai and Gnanendran [13], conducted a series of laboratory tests on the strip foundation adjacent to a soil slope reinforced by a single layer of geogrid. They observed that the maximum improvement in bearing capacity is obtained when the geogrid layer is located at a depth of between 0.5 and 0.9 times the width of the footing.

Lee and Manjunath [14], performed an experimental and numerical study to investigate the bearing capacity behaviour of a strip footing on a geogrid reinforced sand slope. They concluded that the optimum depth of placement of the reinforcement that lead to maximum bearing capacity of foundation, will be equal to 0.5 times the width of the foundation.

Yoo [15], presented results of laboratory tests on a strip footing on a geogrid reinforced sand slope. His results showed that the maximum improvement of bearing capacity of the footing using a single layer of geogrid is obtained when it is embedded at the depth equal to the width of the footing.

Bathurst et al. [16], carried out an experimental study on two large geosynthetic reinforced soil embankments and one unreinforced soil

embankment which was subjected to collapse by loading a strip footing placed close to the crest of the slope. They observed that depending on the geogrid stiffness, the reinforced soil embankments have a bearing capacity up to 1.6–2.0 times that of the unreinforced embankment.

El Sawwaf [17], investigated the bearing capacity behavior of a strip footing resting on replaced sand layer (partially replaced) constructed on a soft clay slope. Test results indicated that the inclusion of geogrid layers in the replaced sand not only significantly improves the footing performance but also leads to great reduction in the depth of reinforced sand layer required to achieve the allowable settlement. He found that significant improvement in the footing bearing capacity is achieved with increasing the number and lengths of geogrid layers.

Keskin and Laman [18], investigated the bearing capacity of the strip footings on a geogrid reinforced sand slope experimentally and numerically. The results showed that bearing capacity of footing increases by increasing the geogrid stiffness and number of geogrid layers up to three layers.

In this paper a numerical simulation carried out on the reinforced and unreinforced strip footing near the slope and effects of geometrical characteristics of the model on the bearing capacity, were investigated.

II. NUMERICAL ANALYSIS

Two-dimensional plane strain FE numerical simulations were performed using Plaxis commercial program [19]. The left and right boundaries were only permitted to move vertically and the bottom of the model was constrained against both horizontal and vertical movements. To eliminate boundary effects due to loading, the horizontal and vertical boundaries must be located at a suitable distance from the foundation. In this study, a sensitivity analysis was conducted on influence of boundaries and it was found that a distance of 30 meters is appropriate. Description of the geometric parameters and distance of boundaries is presented in Fig. 1.

It was assumed that foundation is rigid. Hence, a uniform settlement applied in the vertical direction to all nodes at the soil-footing interface. The model mesh was generated using 15-node triangular elements. The interaction between the geogrid and soil was modeled at both sides of geogrid by means of interface elements, which have zero physical thickness and are defined by five pairs of nodes. The interface friction angle and adhesion between the contact surfaces were modelled by assigning a suitable value for the strength reduction factor (R_{inter}) in the interface compared with the corresponding soil strengths. Due to the stress concentration around the foundation, the mesh size

was locally refined in these regions. Typical adopted mesh is shown in Fig. 2. An elastic-plastic Mohr Coulomb (MC) model was selected for the soil beneath the foundation. Material properties that have been adopted in this study are presented in table 1.

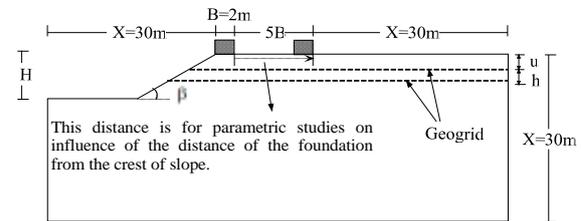


Fig. 1 Description of the geometric parameters and distance of boundaries

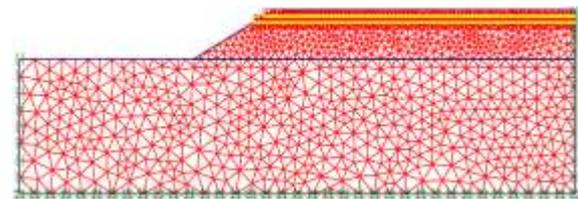


Fig. 2 Typical mesh shape for numerical analysis

TABLE I
MATERIAL PROPERTIES

Parameter	Soil	Geogrid
E_{soil} (kPa)	20000	-
$EA_{geogrid}$ (kPa)	-	3000
ν	0.3	-
ϕ' (°)	25	-
ψ (°)	-	-
C' (kPa)	9	-
γ (kN/m ³)	18	-
R_{inter}	0.7	-

Accuracy of the developed model was verified by bearing capacity equations proposed by other researchers [2-7] in two ways: 1. Strip foundation on level ground and 2. Strip foundation on purely cohesionless soils adjacent to slopes.

In the level ground, it was assumed that the properties of materials is in accordance with table 1 and foundation width is equal to 2 meters. Table 2 shows the results of this verification.

In the sloped cohesionless ground, material properties was taken according to table 1, except the cohesion of the soil that was equal to 0. The verification results for sloped ground are shown in Fig. 3. It should be noted that in this figure, b and N_γ are distance of the foundation from the slope crest and bearing capacity factor, respectively.

TABLE II
VERIFICATION OF DEVELOPED MODEL FOR LEVEL GROUND

Method	Parameters		
	N_c	N_γ	q_u (kPa)
Terzaghi[2]	25.13	8.34	376.29
Meyerhof[3]	20.72	6.77	307.34
Hansen[4]	20.72	6.76	308.16
Vesic[5]	20.72	10.88	382.32
Plaxis	-	-	365

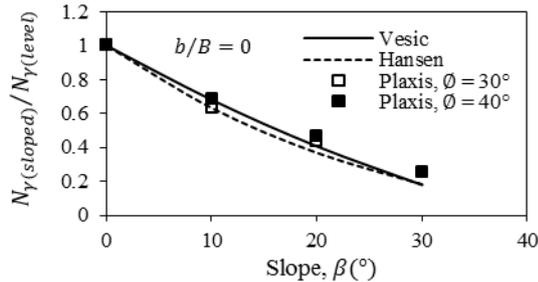


Fig. 3 Verification of developed model for unreinforced cohesionless sloped ground (foundation at slope crest)

III. RESULTS

In the parametric analysis of the this section, behaviour of the foundation near the slopes, is evaluated through a dimensionless parameter (BCR), which is defined as follows:

$$BCR = \frac{q_{ur}}{q_u} \tag{1}$$

Where, q_{ur} and q_u are ultimate bearing capacities of the foundation on reinforced sloped ground and on unreinforced sloped ground, respectively. Should be noted that in this study, the ultimate bearing capacity was considered equal to pressure at a settlement of 10% of the footing width, unless before this settlement, the maximum pressure is observed.

A. Effect of depth of first reinforcement layer (u/B)

A series of FEM analysis were conducted to investigate the effect of normalized depth of first reinforcement layer. In all analyzes presented in this section the number of geogrid layers (n) was kept constant at $n=1$.

It was assumed that the footing is located at a distance equal to the width of the footing from the slope crest ($d/B = 1$). Analysis were performed for (u/B) values of 0.25, 0.5, 0.75, 1, 1.25 and 1.5.

Fig. 4 is shown obtained values of BCR versus u/B. As can be seen, depth of reinforcement layer has a significant impact on the improvement of the bearing capacity. Initially, with the increase in u/B up to 0.5, BCR increases and then decreases. At u/B

values between 0.5 to 1, a small reduction occurs in BCR. Whereas, after that, the reduction becomes greater, because by increasing the geogrid depth, geogrid placed under the failure surface and therefore the reinforced slope behaviour tends to unreinforced slope behaviour.

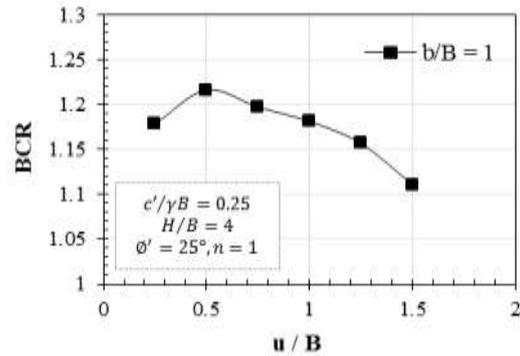


Fig. 4 BCR versus u/B

B. Effect of slope angle (β)

In order to study the effect of the slope angle (β), it was assumed that the geogrid layer is located at a depth of half the width of the footing ($u/B = 0.5$). All the parameters were kept constant and just effect of slope angle was evaluated. The variation of BCR with slope angle (β) is shown in Fig.5. According to this figure, with the increase in slope angle (β) up to 30, BCR is increased initially, and then decreased with the further increase of β .

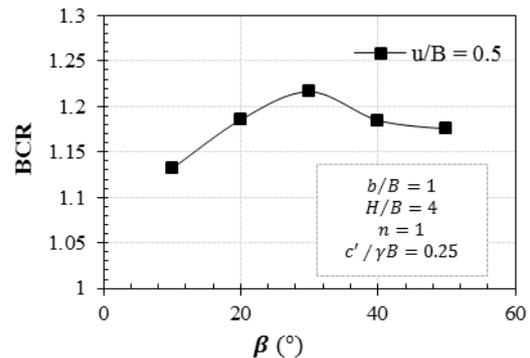


Fig. 5 BCR versus β

C. Effect of edge distance of footing from the slope crest (b/B)

It was assumed that the geogrid layer is located at a depth of half the width of the footing ($u/B = 0.5$). Effect of (b/B) were evaluated by keeping constant other parameters and taking b/B values equal to 0, 1, 2, 3, 4 and 5. The variation of BCR with b/B is shown in Fig.6. According to this figure, , BCR is increased with increase b/B up to a value equal to 1

and then decreased. After the b/B value equal to 4, significant changes do not occur in BCR with further increases in b/B . Because the behaviour of footing tends to behaviour of the footing on level ground.

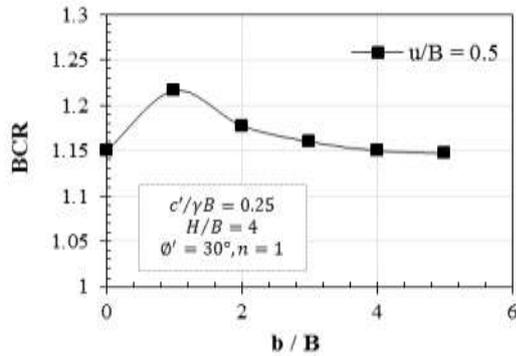


Fig. 6 BCR versus b/B

D. Effect of spacing of reinforcement layers (h/B)

In this part it was assumed that the soil slope is reinforced with two layers of geogrid. It was considered that the first layer of geogrid is embedded at a depth equal to half the width of the footing ($u/B=0.5$). Fig. 7 shows obtained values of BCR versus b/B . It is seen that with the increase in h/B , BCR is increased initially and then in h/B equal to 0.5 is reached to its maximum value. After that, with further increase in h/B , reduction in the BCR is occurred.

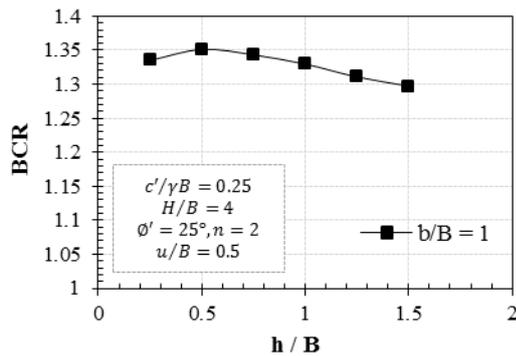


Fig. 7 BCR versus h/B

E. Effect of number of reinforcement layers (n)

Soil layers can be reinforced with more layers of geogrid for further improvement. But On the other hand, the economic feasibility of these improvement projects is valuable. In this study a series of parametric studies were carried out to examine the

effectiveness of more layers of geogrid on further improvement of sloped ground. Both parameters of u/B and h/B were considered to be constant and equal to 0.5. Fig. 8 shows obtained values of BCR versus b/B . From this figure it is found that bearing capacity of the footing is increased with increase in number of geogrid layers. A sharp increase in BCR is occurred by increasing the number of geogrid up to four layers. After that, the rate of this increase, decrease. It can be concluded that the number of four layers of reinforcement is economically.

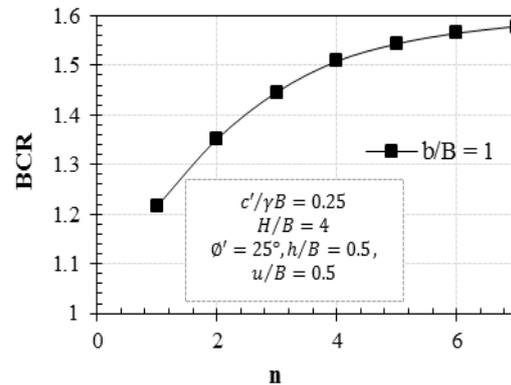


Fig. 8 BCR versus n

CONCLUSIONS

In this study numerical investigations were performed to evaluate the behaviour of strip footing on the reinforced soil slope. Mohr–Coulomb failure criterion considered for the soil beneath the footing. Based on performed analyses, the following conclusions are drawn:

- Depth of reinforcement layer has a significant impact on the improvement of the bearing capacity. With the increase in u/B , BCR increases initially and then decreases. In this study maximum bearing capacity was found in the case that geogrid layer was embedded at a depth of half the width of the footing ($u/B=0.5$).
- For soil slope reinforced with two layers of geogrid, optimal spacing of reinforcement layers was equal to half the width of the footing ($h/B=0.5$).
- A significant increase in the bearing capacity is occurred by increasing the number of layers of geogrid up to four layers. With further increases in the number of geogrid layers significant increase in the bearing capacity was not observed in this study.

REFERENCES

- [1] J. Shiao, R. Merifield, A. Lyamin, and S. Sloan, "Undrained stability of footings on slopes," *International Journal of Geomechanics*, vol. 11, pp. 381-390, 2011.
- [2] K. Terzaghi, *Theoretical soil mechanics*: Wiley, 1943.
- [3] G. Meyerhof, "The ultimate bearing capacity of foundations," *Geotechnique*, vol. 2, pp. 301-332, 1951.
- [4] J. B. Hansen, "A revised and extended formula for bearing capacity," 1970.
- [5] Vesic, "Analysis of Ultimate Loads of Shallow Foundations," in *Journal of the Soil Mechanics and Foundations Division* vol. 99, ed, 1973, pp. 45-73.
- [6] G. Meyerhof, "The ultimate bearing capacity of foundations on slopes," in *Proc., 4th Int. Conf. on Soil Mechanics and Foundation Engineering*, 1957, pp. 384-386.
- [7] A. S. Vesic, "Bearing capacity of shallow foundations," *Foundation Engineering Handbook*., pp. 121-147, 1975.
- [8] A. S. Azzouz and M. M. Baligh, "Loaded areas on cohesive slopes," *Journal of Geotechnical Engineering*, vol. 109, pp. 724-729, 1983.
- [9] F. Castelli and E. Motta, "Bearing capacity of strip footings near slopes," *Geotechnical and Geological Engineering*, vol. 28, pp. 187-198, 2010.
- [10] P. d. Buhan and D. Garnier, "Three dimensional bearing capacity analysis of a foundation near a slope," *Revue Française de Géotechnique*, vol. 38, pp. 153-163, 1998.
- [11] K. Georgiadis, "Undrained bearing capacity of strip footings on slopes," *Journal of geotechnical and geoenvironmental engineering*, vol. 136, pp. 677-685, 2010.
- [12] O. Kusakabe, T. Kimura, and H. Yamaguchi, "Bearing capacity of slopes under strip loads on the top surfaces," *Soils and foundations*, vol. 21, pp. 29-40, 1981.
- [13] P. Selvadurai and C. Gnanendran, "An experimental study of a footing located on a sloped fill: influence of a soil reinforcement layer," *Canadian Geotechnical Journal*, vol. 26, pp. 467-473, 1989.
- [14] K. Lee and V. Manjunath, "Experimental and numerical studies of geosynthetic-reinforced sand slopes loaded with a footing," *Canadian Geotechnical Journal*, vol. 37, pp. 828-842, 2000.
- [15] C. Yoo, "Laboratory investigation of bearing capacity behavior of strip footing on geogrid-reinforced sand slope," *Geotextiles and Geomembranes*, vol. 19, pp. 279-298, 2001.
- [16] R. J. Bathurst, J. A. Blatz, and M. H. Burger, "Performance of instrumented large-scale unreinforced and reinforced embankments loaded by a strip footing to failure," *Canadian Geotechnical Journal*, vol. 40, pp. 1067-1083, 2003.
- [17] M. A. El Sawwaf, "Behavior of strip footing on geogrid-reinforced sand over a soft clay slope," *Geotextiles and Geomembranes*, vol. 25, pp. 50-60, 2007.
- [18] M. S. Keskin and M. Laman, "Experimental and Numerical Studies of Strip Footings on Geogrid-Reinforced Sand Slope," *Arabian Journal for Science and Engineering*, vol. 39, pp. 1607-1619, 2014.
- [19] R. Brinkgreve, *Plaxis: finite element code for soil and rock analyses: 2D-Version 8:[user's guide]*: Balkema, 2002.