Journal of Mining and Environment (JME), Vol. 14, No. 3, 2023, 799-811

Shahrood University of Technology

Journal of Mining and Environment (JME)

Journal homepage: www.jme.shahroodut.ac.ir

Iranian Society of Mining Engineering (IRSME)

Numerical Analysis of Strip Footing Behaviour on a Hollow Pile Stabilized Clay Slope

Lokeshwar Singh Dilta* and Ravi Kumar Sharma

Civil Engineering Department, National Institute of Technology Hamirpur, Himachal Pradesh, India

Article Info

Received 30 March 2023

Received in Revised form 27 April 2023

Accepted 8 May 2023

Published online 8 May 2023

DOI:10.22044/jme.2023.12893.2340

Keywords

Load carrying capacity

Hollow pile

Strip footing

Slope

Stabilization

Abstract

This study highlights the results from a series of analytical model experiments that investigate the behaviour of a strip footing supported by hollow steel piles installed to stabilize a clay slope. The effects of changing the pile diameter, pile length, spacing between piles, slope angle, the position of the pile row from the top of slope, and the footing placement are all examined. After determining the load-carrying capacity of unstabilized slopes, it is compared with the load-carrying capacity of stabilized slopes. The results are then analysed to see how each parameter affects the load carrying capacity of strip footing. The results of unstabilized cases reveal that the load carrying capacity of a footing decreases as the slope angle increases and increases when the footing is positioned away from the slope. In addition, the findings imply that by reinforcing clay slope with a sequence of hollow steel piles significantly enhances the load carrying capacity of strip footing. As the distance between piles is decreased and their length is increased, the bearing capacity of the footing increases, and this improvement is enhanced by increasing the diameter of the piles. When the row of pile is positioned away from the top of the slope, the footing's load carrying capacity decreases. Also positioning the footing a quite distance apart from the crest slope shows reduction in bearing capacity ratio.

1. Introduction

A foundation may sometimes be constructed at or near the top of a slope. These situations start as a result of space constraints or design requirements. Some of the examples include the construction of foundations or roads in hilly areas and the position of bridge abutment foundations near slopes. It may be possible to reduce building costs by employing shallow foundations instead of deep ones or by increasing the allowable load carrying capacity with the use of suitable soil improvement technologies. This behaviour is explained with theoretical approaches used to determine the load carrying capacity of shallow foundations situated in or on the slope's upper surface [1-4]. In several circumstances, it may not be convenient to employ shallow foundation; thus it becomes necessary to use a costly foundation (e.g. caissons or piles). Hence, the issue of enhancing the load carrying capacity of footings on slopes and reinforcing the soil slopes has gained a great deal of interest and become one of the most significant fields of geotechnical study throughout the years. There are several methods that may be used to improve the stability of a slope and the load carrying capacity of the soil in the area, i.e. by altering the surface geometry of the slope, reinforcement of soil or adding retaining structures such as retaining walls or piles. There have been numerous studies on the use of slope reinforcement to improve the load carrying capacity of a footing on the slope [5-12]. These research works have shown that the slope stability can be increased, the load carrying capacity of the foundation can be greatly improved, and the settlement behaviour of the footing may significantly improve by including reinforcing layers in the earth slope in the form of geogrid, strips or geosynthetics. Much of the research on slope stabilisation was done with the reinforcement applied in the traditional horizontal fashion. Throughout the course of the last several decades,

Corresponding author: 21mce008@nith.ac.in (R.K. Sharma)

one of the most significant strategies for slope reinforcement has been the stabilisation of slopes using piles to sustain an active earth slope. Several studies reported the success of using piles as a vertical reinforcement in many situations in order to improve slope stability [13-16]. Several analytical methods were suggested to determine the effects of pile on slope stability [17-20].

Other analytical methods were presented in design of slopes reinforced with a single row of piles in static condition [13, 21, 22]. An approach was described for the design of pile reinforced slopes [22]. They concluded that total shear strength and maximum shear strength from each pile are required to improve the safety factor in this analysis. Type of pile, number of piles, and the best location of such piles within the slope were considered.

Many researchers conducted study to determine the optimal placement of pile rows. This was accomplished by selecting the location of the row of pile that offered the greatest resistance and factor of safety. However, the published results were rather diverse and conflicting [13, 23-26]. In addition, numerical techniques were used to calculate the safety factor of the reinforced slope with pile row [27].

Experimental tests were conducted to determine the load carrying capacity of strip footing over stabilized sand using pile and sheet pile wall [28]. Also numerical studies were reported about bearing capacity of footing on the pile stabilized slopes as well [29].

The earlier studies on pile-reinforced slopes focused only on slope stability and very little work was done to improve the load carrying capacity of shallow footings supported by pile-reinforced slopes. Hence, in order to fill the research gaps, a numerical analysis was conducted to find out the load-carrying capacity of strip footings built on clay slopes and strengthened with hollow steel piles. The primary goals of this research work are to evaluate the impact of different factors on the load carrying capacity of strip footing on hollow pile reinforced slope and to discover the ideal position of pile row that delivers the maximum load carrying capacity of footing in various situations.

In the present study, the improvement in load carrying capacity of the footing due to reinforcement of slope is expressed by Bearing Capacity Ratio (BCR). It is characterized as the ratio of ultimate load carrying capacity of reinforced soil $q_{u\ stabilized}$ to the ultimate load carrying capacity of unreinforced soil q_u or the ratio of load carrying capacity of reinforced soil at settlement (s) to load carrying capacity of unreinforced soil at settlement(s).

$$\text{BCR} = \frac{Q_{sr}}{Q_{sur}}$$

2. Problem Domain and Parameters Varied

Numerical study is performed on a strip footing having dimensions 7.5 m in length and 1.5 m in width. This model footing is resting on clay slope reinforced with hollow steel piles as displayed in Figure 1. The depth of soil model was 7.5 m, which is five times the width of the footing. The height of slope was taken to be 6.75 m, i.e. 4.5 times the width of the footing [28]. The lateral boundaries of the model were selected such that pressure bulb does not intersect the boundaries of the model soil. The parameters considered for the analytical study were dimensions of piles (length and diameter), pile spacing, slope angle, position of pile row from slope crest, and placement of footing with respect to slope crest. The values considered for these parameters are displayed in Table 1.

Table 1. Test parameters.

Parameter	Value
Angle of slope (θ)	26.6°, 33.7°, 38.6°
Spacing of pile (x)	0.75B, B, 1.5B, 2B
Length of pile (L)	B, 1.5B, 2B, 3B
Diameter of pile (D)	0.1B, 0.2B, 0.3B
Location of pile row (d)	0, 0.25B, 0.5B
Location of footing (b)	0, 0.25B, 0.5B, 0.75B, B

3. Numerical Modelling

3.1. Finite element modelling and boundary conditions

Several numerical model tests were done on a model footing slope system using 3D finite element method. The analysis was carried out using the PLAXIS 3D CE V20 software package. The non-linear behaviour of clay was modelled using hardening soil model. A basic feature of the hardening soil model is the stress dependency of soil stiffness. The limiting state of stress is described by means of the secant stiffness in standard drained triaxial test E_{50}^{ref}, the unloading/reloading stiffness E_{ur}^{ref}, and the tangent stiffness for primary oedometer loading E_{oed}^{ref}, power for stress-level dependency of stiffness m. The properties of clay soil required for hardening soil model were referred from [30] and are shown in Table 2.

The footing was assumed to be surface footing resting on top of clay slope. The concrete footing was modelled as a plate and assumed to be rigid body in reference to Plaxis 3D software tutorials. The hollow steel piles were modelled as embedded beams as circular tube under predefined beam type. The characteristics of hollow steel pile and footing are shown in Table 3.

Table 2. Hardening soil model parameters used for clay soil.

Material property	Marine clay	Unit
E_{50}^{ref}	3400	kN/m^3
E_{oed}^{ref}	3600	kN/m^3
E_{ur}^{ref}	12000	kN/m^3
Power (m)	0.7	-
ν'_{ur}	0.2	-
K_0^{nc}	0.6991	-
c'_{ref}	33.58	kN/m^2
ϕ' (phi)	17.51	°
ψ (psi)	1.60	°
R_f	0.90	-
γ_{unsat}	20.00	kN/m^3
γ_{sat}	22.00	kN/m^3

The water table was considered far below the surface of the footing such that pore water pressure has no relation with the bearing capacity, and hence, no flow conditions were required for the modelling. Load control method was used to apply a prescribed load in increments while iterative analysis was performed up to the point of failure.

Table 3. Properties of footing and pile considered for modelling.

Property	Footing	Hollow pile
Material	Concrete	Steel
Unit weight (γ, kN/m^3)	24	78.5
Young's modulus (E, MPa)	3×10^4	2×10^5
Poisson's ratio (ν)	0.15	0.2
Thickness (t, m)	0.3	0.005

3.2. Mesh sensitivity analysis

In this section, number of meshing elements have been varied to determine the optimum mesh so that the results of the analysis would not be influenced with further increase in number of elements. The soil elements in 3D finite element mesh are modelled as tetrahedral elements with 10 nodes. By adding more mesh elements, the element size was varied up to a certain number, after which the change in stress with more mesh elements was found to be insignificant. Table 4 shows the variation of stress corresponding to 20% settlement with different mesh sizes.

Table 4. Stress variation for different sizes of mesh.

Mesh type	Relative element size	Stress, σ (kPa)
Very coarse	2.0	82.3
Coarse	1.5	78.9
Medium	1	75.6
Fine	0.7	75.1
Very fine	0.5	74.9

From Table 4, the stress values in soil after medium mesh remains almost constant. Therefore, the medium size mesh was found optimum for this analysis.

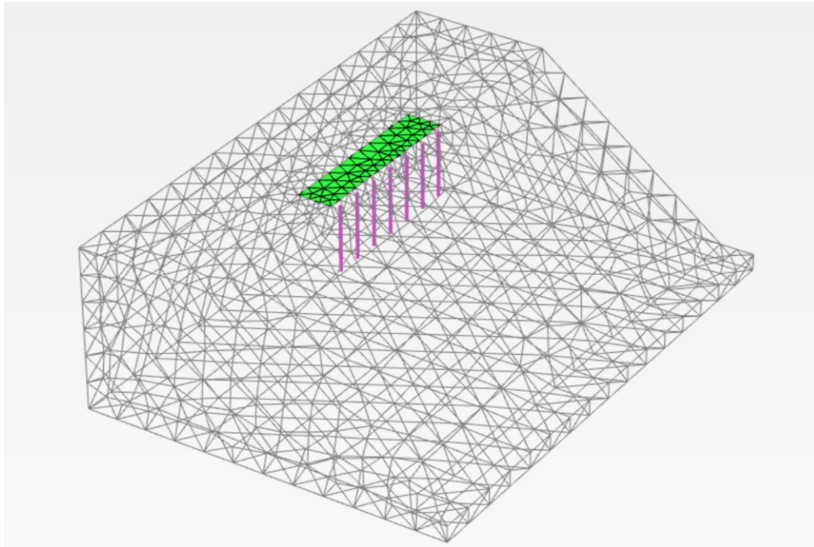

Figure 1. Model geometry with defined mesh.

4. Software Validation

An additional investigation was performed to validate the software, and the findings were compared with those reported in [28]. For the purpose of numerical analysis, the values of soil like unit weight are 18.90 kN/m^3, cohesion 0 kN/m^2, poisson's ratio 0.3, primary loading stiffness 40 MPa, friction angle 40°, dilatancy angle 10°, power in stiffness law 0.7, failure ratio 0.9, and interface reduction factor 0.8. The unit weight of concrete pile is reported to be 24 kN/m^3 and elastic modulus is 3 * 10^4 MPa. All the above values are considered for software validation. The experimental study was conducted in a tank box having internal dimensions 1000 mm × 500 mm × 500 mm. Steel plate with the dimensions 498 mm × 80 mm ×20 mm was used for the footing. The present numerical analysis was compared with the experimental results reported by [28]. Table 5 depicts the comparison of results. Study of this table reveals that the variance in the load carrying capacity was about 8.81%. The fact that the parameters for the sand modelling procedure were chosen based on empirical correlation may be the source of this discrepancy in the results.

Table 5. Comparison between results for software validation.

Diameter (mm)	Experimental values of bearing capacity for L/B = 2 and x/B = 0.5 (kPa)	Numerical values of bearing capacity for L/B = 2 and x/B = 0.5 (kPa)	%Error in results
6	29.88	27.95	6.45
8	31.45	28.64	8.93
12	33.02	29.37	11.05

5. Results and Discussion

The settlement of footing(s) is represented as relative settlement as the ratio of s/B%. The clayey soil taken for analysis demonstrates punching shear failure, hence the BCR is calculated for s/B 10%. The load carrying capacity of the soil-footing system is estimated using the load-settlement graphs obtained from the software. The measured bearing capacities for non-stabilized cases for different footing positions and different angles of slope are displayed in Table 6.

Table 6. Load carrying capacity (kN/m^2) values for non-stabilized slopes.

Slope angle	b/B				
	0	0.25	0.5	0.75	1
26.5°	103.29	108.48	113.18	116.57	121.26
33.69°	83.73	91.5	99.94	102.41	106.35
38.6°	75.6	83.18	89.28	92.59	97.28

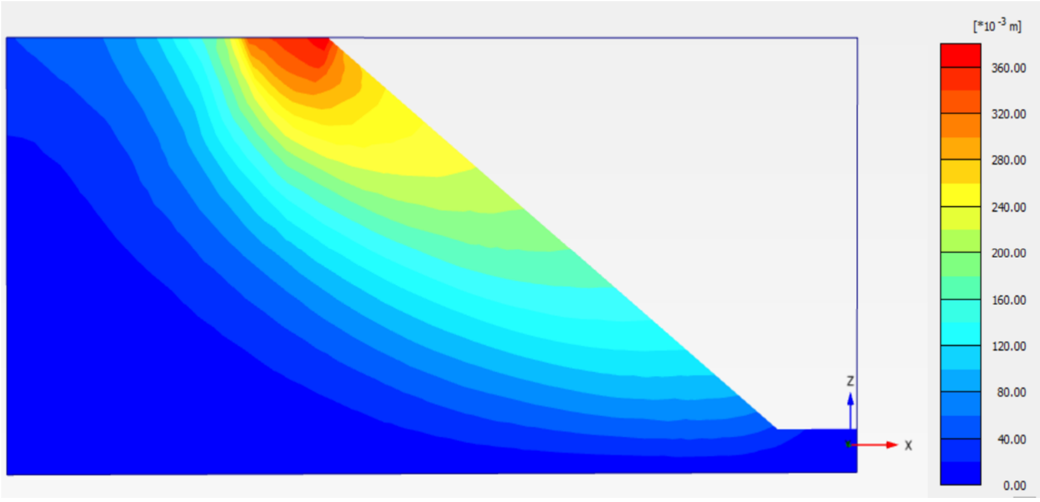

Figure 2. Total displacement contours for unreinforced clay slope.

5.1. Slope stabilisation with a row of piles

Figure 3. represents the plot of BCR with the relative settlement s/B for a strip footing resting on both reinforced and unreinforced clay slope. In this series, all the variable were kept constant with variation in pile spacing. It can be seen from the graph that the placement of piles increases the stiffness and the load carrying capacity at the same settlement level for reinforced slope in comparison to the unreinforced slope. Furthermore, Figure 3 depicts that the BCR is entirely dependent on spacing between the piles. The graph demonstrates that installing a pile row with x/B = 0.75 at the top of slope shows an increment of 54% in BCR over the unstabilized case. The bearing capacity for various types of clay slopes stabilised by steel piles are listed in Tables 7 to 10. The outcomes of these factors are explored in the sections that follow.

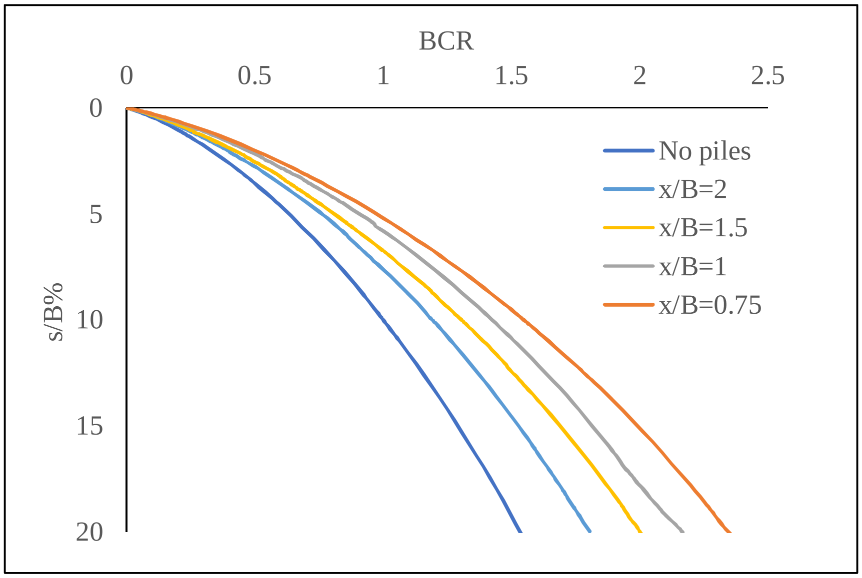

Figure 3. BCR v/s settlement ratio (s/B%) for different pile spacing (x/B).

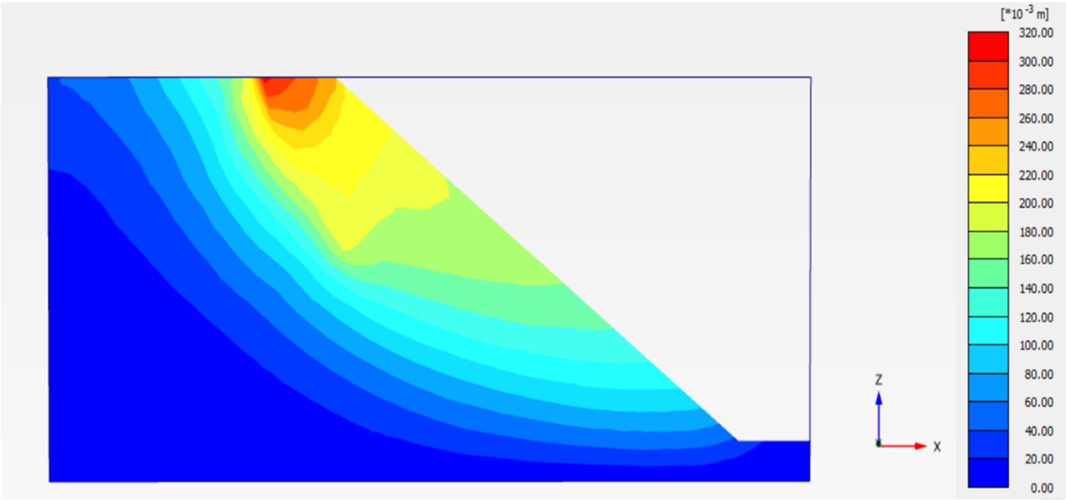

Figure 4. Total displacement contours for hollow steel pile reinforced clay slope.

Table 7. Load carrying capacity (kN/m^2) values for various hollow pile stabilized cases.

Diameter (D/B)	L/B	x/B			
		0.75	1	1.5	2
0.1B	1	88.5	85.46	81.66	78.69
	1.5	98.6	95.23	90.23	81.26
	2	109.13	104.46	95.14	85.87
	3	137.12	119.32	112.43	105.76
0.2B	1	94.11	89.76	85.69	81.36
	1.5	107.1	100.33	92.48	84.8
	2	116.98	107.63	98.63	89.04
	3	155.53	137.51	126.36	116.69
0.3B	1	103.63	92.95	87.54	83.76
	1.5	114.71	105.12	95.55	90.21
	2	126.05	112.09	104.04	98.74
	3	163.26	145.63	135.47	121.69

Table 8. Load carrying capacity (kN/m^2) values for different pile row location.

Diameter (D/B)	d/B		
	0	0.25	0.5
0.1	109.13	81.16	77.1
0.2	116.98	84.38	78.07
0.3	126.05	91.12	79.21

Table 9. Load carrying capacity (kN/m^2) values for different slope angles.

Diameter (D/B)	Slope (θ)		
	26.5°	33.69°	38.6°
0.1	126.39	114.99	109.13
0.2	138.82	124.09	116.98
0.3	149.34	132.92	126.05

Table 10. Load carrying capacity (kN/m^2) values for different footing positions.

Slope	b/B				
	0	**0.25**	**0.5**	**0.75**	**1**
26.5	138.82	120.77	122.89	116.81	122.97
33.69	124.09	105.15	105.74	104.91	106.54
38.6	116.98	97.27	95.8	93.56	97.77

5.2. Effect of diameter of pile

To understand the influence of pile diameters, several experiments were conducted with row of hollow steel piles placed at slope crest with L/B = 3 and diameters D = 0.15, 0.3, and 0.45 m. Figure 5 displays the correlation between BCR and the relative settlement s/B% for the footing placed at the top, i.e. b/B = 0. The graph demonstrates that as pile diameter increases, footing bearing capacity significantly improves. Using a normalised pile diameter D/B of 0.3 results in increase of BCR up to 2.16 times that of non-stabilized slope. The increase in diameter of the steel piles results in increase in the lateral stiffness of the piles hence reducing movement of soil particles. Not only the lateral stiffness but also the reduction in the clear gap between the piles also restricts the clay to get entrapped in between the piles hence increasing its BCR. In addition, the arching effect of the clay particles due to the cohesion also improves load carrying capacity.

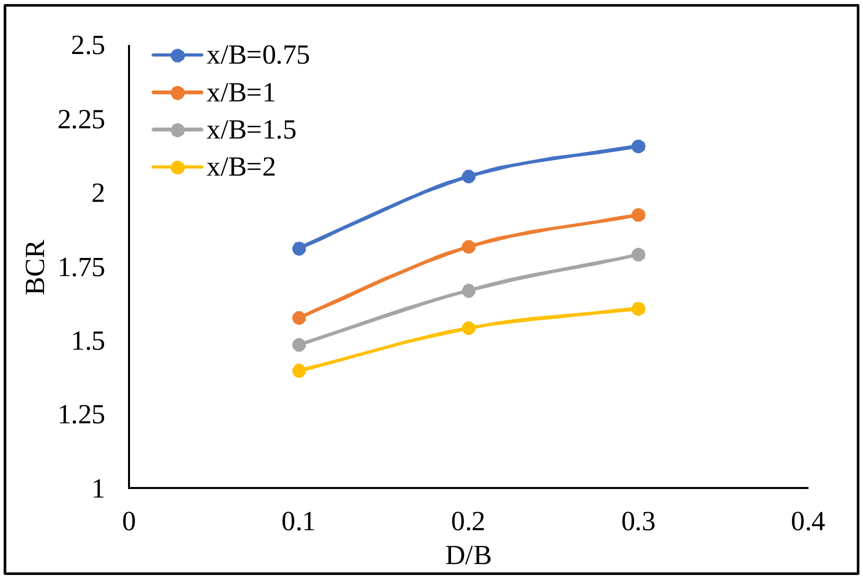

Figure 5. BCR v/s D/B for different pile spacing (b/B = 0, L/B = 3).

5.3. Effect of length of pile

Figure 6 displays the correlation between BCR and L/B for a foundation placed at the top of slope (b/B = 0) with hollow steel piles installed at crest. A similar behaviour is depicted for different diameter of piles as displayed in the figure. The increase in length of pile when placed at top of crest with x/B = 0.75 and D/B = 0.3 increases the BCR for the strip footing by 57% (1.37 to 2.15) when the L/B is increased from 1 to 3. This increase in the BCR can be explained on the basis that increasing the length of pile increases its embedment in the soil increasing its lateral resistance to the displacement and overturning about the pivot point due to the resistance provided by the soil on the opposite side of the pile.

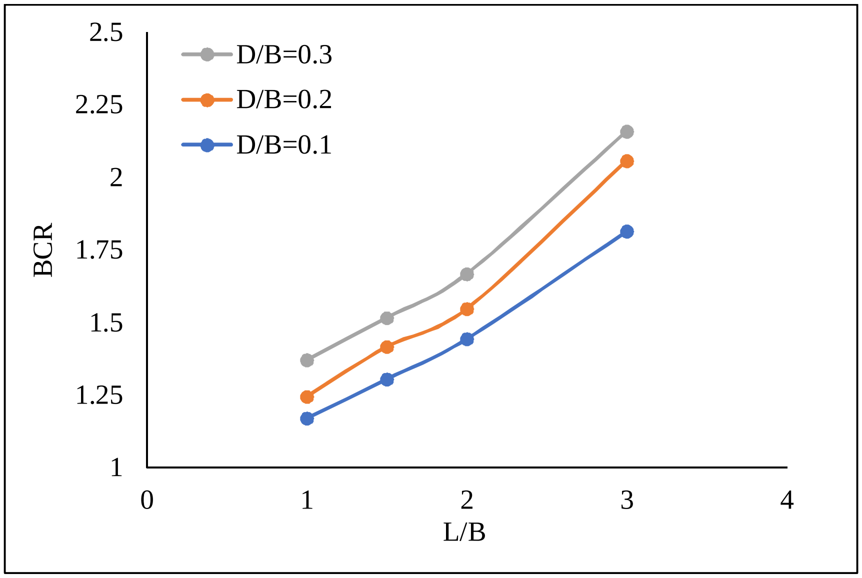

Figure 6. BCR v/s L/B for different pile diameter (d/B = 0 and x/B = 0.75).

5.4. Effect of spacing between pile

To study the impact of centre to centre spacing between piles on the load carrying capacity of the footing, a series of tests were conducted using hollow steel piles. The centre-to-centre distance between the piles was varied as x/B = 0.75, 1, 1.5, and 2. Figure 7 displays the correlation between BCR and x/B for different lengths of pile. The BCR increased as a consequence of decreasing the centre-to-centre distance between the piles. From the figure it can be seen that using a row of piles with L/B = 3 and pile spacing of x/B = 0.75 brings out an improvement of 2.15 times the load carrying capacity of unreinforced slope. However, for same parameters when the pile spacing is increased to 2 the BCR is reduced to 1.61. This implies that a reduction of 34% (2.15 to 1.61) in BCR is seen by increasing the centre-to-centre spacing from 0.75 to 2.

The following two explanations can be used to explain this anticipated rise in the footing's bearing capacity. The open space increases between piles when pile spacing is increased, enabling more soil to pass through and greater lateral soil movement to take place under the footing. The second fact is that decreasing the spacing between piles decreases the length of the arch formed by the clay particles increasing its capacity to restrict the soil particles in the lateral direction.

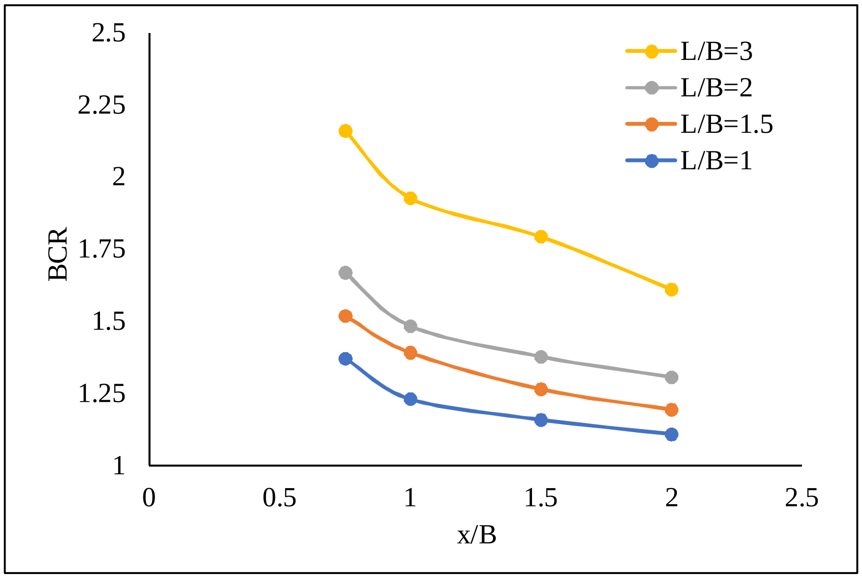

Figure 7. BCR v/s x/B for different pile length (d/B = 0 and D/B = 0.3).

5.5. Effect of position of pile row from slope crest

To understand the effect of position of pile row on the load carrying capacity of footing, a series of tests were conducted using hollow steel piles with x/B = 0.75 and L/B = 2 at three different positions from the top of slope as d = 0, 0.375, and 0.75 m. Figure 8 displays the correlation between BCR and d/B for diameter of piles corresponding to D/B = 0.1, 0.2, and 0.3. The figure reveals that when the piles are placed at slope crest the response of the footing is better than any other position. Furthermore, as the piles are placed away from the top, the improvement in BCR becomes almost negligible. Tests conducted on other pile diameters also display the same behaviour.

This may be explained by the fact that as the piles are placed at the top of the slope close to the footing the relatively small distance between the piles and the edge of footing imparts a large lateral load on the piles due to the tentative large movement of the soil beneath the footing which is restricted by the piles. However, when the piles are placed a far distance from the top of the slope the load from the horizontal movement of the soil decreases due to the possible overtopping of the soil over the top of the piles resulting in negligible increase in BCR.

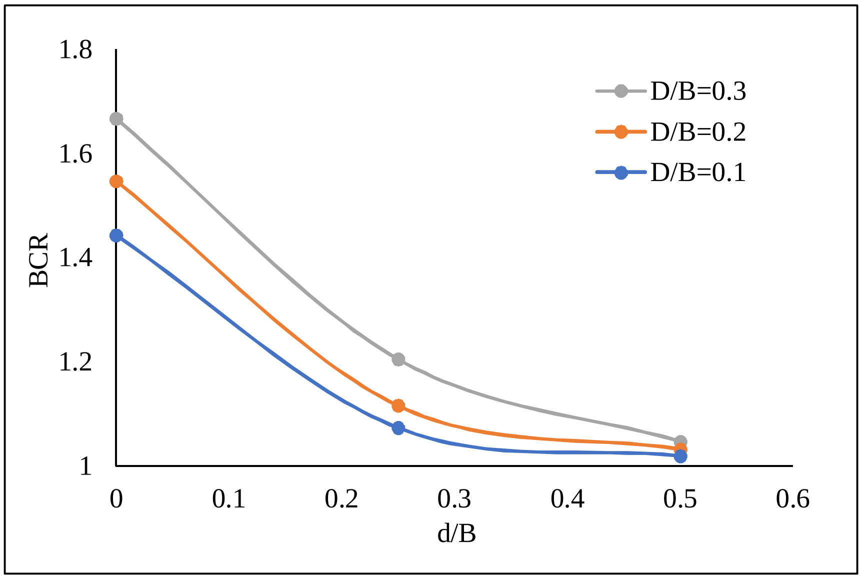

Figure 8. BCR v/s d/B for different pile diameter (x/B = 0.75 and L/B = 2).

5.6. Effect of location of footing

To understand the impact of location of foundation on its load carrying capacity, a series of tests were conducted on non-stabilized and stabilized earth slopes. The tests on non-stabilized earth slopes in Table 6 show that when the foundation is moved away from the top of slope, the load carrying capacity increases and the same trend is seen for different slope angles.

Then several tests were conducted on stabilized earth slopes with the position of pile row fixed at crest, x/B = 0.75, L/B = 2, and D/B = 0.2 with the location of footing varying from b = 0 to b = B. Figure 9 displays the correlation between BCR and b/B at different slope angles. It is clear from the figure that as the foundation is placed away from the slope crest, the improvement in BCR decreases and becomes almost negligible. The same trend is followed for three different values of slope angle. For the same row of piles and slope angle θ = 38.6°, the value of BCR when the foundation is located at slope crest (i.e. b = 0) is 1.54, whereas when it is placed at b = B from the slope crest, the value of BCR is almost 1. Hence, the maximum improvement in load carrying capacity is when the foundation is placed closer to the slope crest.

The fact that the improvement in BCR is almost negligible when footing is positioned away from the slope crest leads to the conclusion that there is no effect of pile reinforcement on footings placed away from the crest. This is because as the footing is away from the top the pressure bulbs due to the load distribution do not reach up to the slope and hence, the use of piles becomes ineffective.

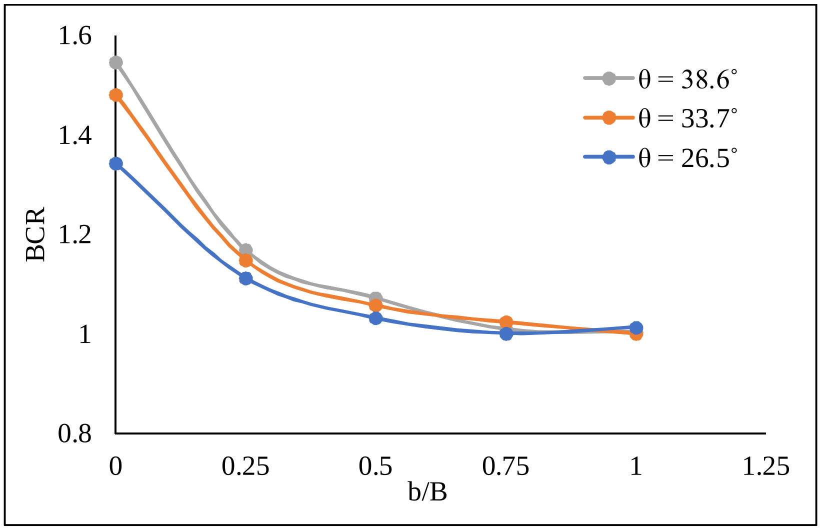

Figure 9. BCR v/s b/B for different slope angles(θ) (d/B = 0, x/B = 0.75, L/B = 2, and D/B = 0.2).

5.7. Effect of angle of slope

To study the impact of slope angle on the load carrying capacity improvement of footing, a series of tests were conducted considering the following parameters (L/B = 2, x/B = 0.75, d = 0, and b = 0) with three different slope angles of 26.5˚, 33.69˚, and 38.6˚, respectively. Figure 10. displays the change of BCR with angle of slope (θ) for various pile diameters. A significant improvement in the BCR can be noticed as the angle of slope increases. For a pile row with x/B = 0.75, L/B = 2, and D/B = 0.3 for slope angle 26.5˚ brings out an improvement in bearing capacity of 1.44. However, for the same row of piles with slope angle θ = 38.6˚, the improvement in bearing capacity goes as high as 1.66. Therefore, increasing the slope angle from θ = 26.5˚ to 38.6˚ increases the bearing capacity ratio by about 15%.

The high value of slope angle with respect to the horizontal describes a relatively more unstable slope. Hence, the use of piles for the higher slopes helps in stabilizing the slope more effectively as compared to the flat slopes.

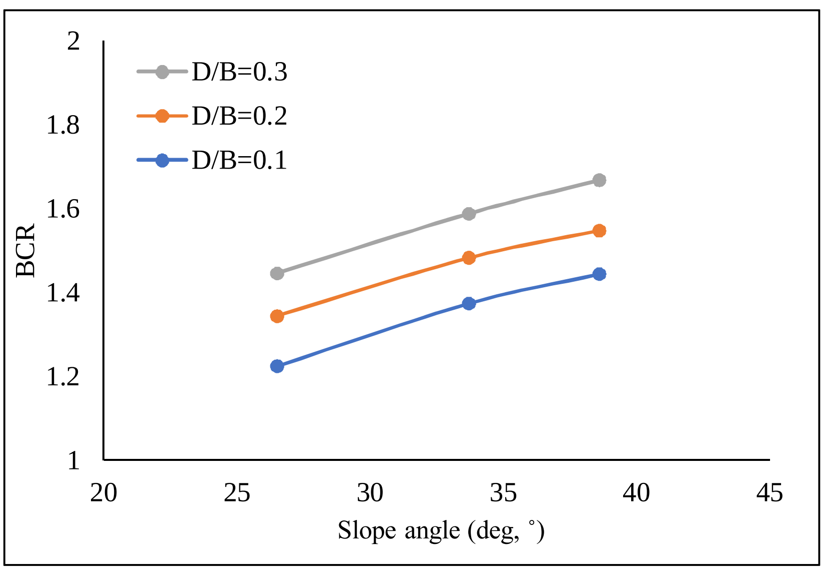

Figure 10. BCR v/s slope angle (θ) for different pile diameters (x/B = 0.75, L/B = 2, d/B = 0, and b/B = 0).

6. Conclusions

In this research work, the load carrying capacity of a strip footing resting on hollow pile stabilized slope was investigated through numerical analysis. The study was carried out on soft clay stabilized with hollow steel piles. The following conclusions were drawn from the results discussed above:

1. The load carrying capacity of a strip footing on clayey soil close to a slope crest is significantly affected by the installation of a row of hollow steel piles to stabilise the earth slope.
2. Minimum pile spacing and maximum pile length both result in maximum bearing capacity. The load carrying capacity of the footing is further enhanced by increasing pile diameter.
3. The distance between the footing and the slope's crest has a considerable influence on the improvement in load carrying capacity. There is a decrease in bearing capacity improvement as the footing is located away from the slope crest and this becomes almost negligible when footing is placed at a distance B from slope crest.
4. The best position for pile row to enhance the load carrying capacity of the footing rather than slope stability is at the slope crest.
5. With the increase in angle of slope the load carrying capacity of footing reduces. However, the BCR improves with increase in slope angle.
6. In the examined problem geometry condition, footing failure is determined not by the stability of the slope but by lateral displacements of soil particles below the foundation towards slope. The footing rotates towards the slope and settled vertically but this had no effect on the stability of the slope.

Notations

B	Width of footing
L	Length of pile
D	Diameter of pile
b	Distance of footing from slope crest
x	Spacing of pile
d	Distance of pile row from crest
θ	Slope angle
γ	Unit weight
γ_{unsat}	Unsaturated unit weight
γ_{sat}	Saturated unit weight
ϕ	Friction angle
ψ	Angle of dilatancy
ν	Poisson's ratio
c	Cohesion
s	Settlement
E	Young's modulus
E_{50}^{ref}	Secant stiffness in standard drained triaxial test
E_{oed}^{ref}	The tangent stiffness for primary oedometer loading
E_{ur}^{ref}	The unloading/reloading stiffness
m	Power for stress-level dependency of stiffness
R_f	Failure ratio
R_{int}	Interface reduction factor

References

[1]. Meyerhof, G.G. (1957). The ultimate bearing capacity of foundations on slopes. In Proc., 4th Int. Conf. on Soil Mechanics and Foundation Engineering (Vol. 1, pp. 384-386).

[2]. Graham, J., Andrews, M., and Shields, D.H. (1988). Stress characteristics for shallow footings in cohesionless slopes. Canadian Geotechnical Journal, 25 (2): 238-249.

[3]. Saran, S., Sud, V.K., and Handa, S.C. (1989). Bearing capacity of footings adjacent to slopes. Journal of geotechnical engineering, 115 (4): 553-573.

[4]. Narita, K. and Yamaguchi, H. (1990). Bearing capacity analysis of foundations on slopes by use of log-spiral sliding surfaces. Soils and Foundations, 30 (3): 144-152.

[5]. Selvadurai, A.P.S. and Gnanendran, C.T. (1989). An experimental study of a footing located on a sloped fill: influence of a soil reinforcement layer. Canadian Geotechnical Journal, 26 (3): 467-473.

[6]. Yoo, C. (2001). Laboratory investigation of bearing capacity behavior of strip footing on geogrid-reinforced sand slope. Geotextiles and Geomembranes, 19 (5): 279-298.

[7]. Saleh, N.M. (2002). Behavior of footings under centric and eccentric loads adjacent to reinforced slopes. Ain Shams Univ Sci Bull, 37 (4): 41-63.

[8]. Kaur, A. and Sharma, R.K. (2016). Slope stability analysis techniques: A review. International Journal of Engineering Applied Sciences and Technology, 1 (4): 52-57.

[9]. Sharma, R.K. and Bhardwaj, A. (2019). Effect of construction demolition and glass waste on stabilization of clayey soil. In Proceedings of the 1st International Conference on Sustainable Waste Management through Design: IC_SWMD 2018 1 (pp. 87-94). Springer International Publishing.

[10]. Bhardwaj, A. and Sharma, R.K. (2020). Effect of industrial wastes and lime on strength characteristics of clayey soil. Journal of Engineering, Design and Technology.

[11]. Bhardwaj, A., Sharma, R.K., and Sharma, A. (2021). Stabilization of clayey soil using waste foundry sand and molasses. In Sustainable Development Through Engineering Innovations: Select Proceedings of SDEI 2020 (pp. 641-649). Springer Singapore.

[12]. Bhardwaj, A., and Sharma, R.K. (2022). Bearing Capacity Evaluation of Shallow Foundations on Stabilized Layered Soil using ABAQUS. Studia Geotechnica et Mechanica.

[13]. Hassiotis, S., Chameau, J.L., and Gunaratne, M. (1997). Design method for stabilization of slopes with piles. Journal of Geotechnical and Geoenvironmental Engineering, 123 (4): 314-323.

[14]. Lee, C.Y., Hull, T.S., and Poulos, H.G. (1995). Simplified pile-slope stability analysis. Computers and Geotechnics, 17 (1): 1-16.

[15]. Cai, F. and Ugai, K. (2000). Numerical analysis of the stability of a slope reinforced with piles. Soils and foundations, 40 (1): 73-84.

[16]. Ausilio, E., Conte, E., and Dente, G. (2001). Stability analysis of slopes reinforced with piles. Computers and Geotechnics, 28 (8): 591-611.

[17]. Li, R.P. (2009). Stability analysis of cutting slope reinforced with anti-slide piles by FEM. In Slope Stability, Retaining Walls, and Foundations: Selected Papers from the 2009 GeoHunan International Conference (pp. 166-173).

[18]. Haghbin, M. and Ghazavi, M. (2013). Bearing capacity of footings on pile-stabilized slopes.

[19]. Mofidi Rouchi, J., Farzaneh, O., and Askari, F. (2014). Bearing capacity of strip footings near slopes using lower bound limit analysis. Civil Engineering Infrastructures Journal, 47 (1): 89-109.

[20]. Liu, Y. and Geo, F. (2015). Dynamic stability analysis on a slope supported by anchor bolts and piles. Electronic Journal of Geotechnical Engineering, 20 (7): 1887-1900.

[21]. Day, R.W., Hull, T.S., Poulos, H.G., Hassiotis, S., Chameau, J.L., and Gunaratne, N. (1999). Design method for stabilization of slopes with piles. Journal of Geotechnical and Geoenvironmental Engineering, 125 (10): 910-914.

[22]. Poulos, H. G. (1995). Design of reinforcing piles to increase slope stability. Canadian Geotechnical Journal, 32 (5): 808-818.

[23]. Ito, T. and Matsui, T. (1975). Methods to estimate lateral force acting on stabilizing piles. Soils and foundations, 15 (4): 43-59.

[24]. Ito, T., Matsui, T., and Hong, W.P. (1979). Design method for the stability analysis of the slope with landing pier. Soils and Foundations, 19 (4): 43-57.

[25]. Ito, T., Matsui, T., and Hong, W.P. (1981). Design method for stabilizing piles against landslide—one row of piles. Soils and Foundations, 21 (1): 21-37.

[26]. Ito, T., Matsui, T., and Hong, W.P. (1982). Extended design method for multi-row stabilizing piles against landslide. Soils and foundations, 22 (1): 1-13.

[27]. Wei, W.B. and Cheng, Y.M. (2009). Strength reduction analysis for slope reinforced with one row of piles. Computers and Geotechnics, 36 (7): 1176-1185.

[28]. El Sawwaf, M.A. (2005). Strip footing behavior on pile and sheet pile-stabilized sand slope. Journal of Geotechnical and Geoenvironmental Engineering, 131 (6): 705-715.

[29]. As'ad Munawir, M.D., Zaika, Y., and Agoes Soehardjono, M.D. (2013). Bearing capacity on slope modeling with composite bamboo pile reinforcement. Jurnal Terpublikasi: International Journal of Engineering and Advanced Technology (IJEAT).

[30]. Saleh, S., Mohd Yunus, N.Z., Ahmad, K., and Mat Said, K.N. (2021). Numerical simulation with hardening soil model parameters of marine clay obtained from conventional tests. SN Applied Sciences, 3, 1-13.

تحلیل عددی رفتار پایه نواری در شیب خاک رس تثبیت شده توخالی

لوکشوار سینگ دیلتا* و راوی کومار شارما

گروه مهندسی عمران، موسسه ملی فناوری هامیرپور، هیماچال پرادش، هند

ارسال 2023/03/30، پذیرش 2023/05/08

* نویسنده مسئول مکاتبات: 21mce008@nith.ac.in

چکیده:

این مطالعه نتایج حاصل از یک سری آزمایش‌های مدل تحلیلی را برجسته می‌کند که رفتار یک پایه نواری را که توسط شمع‌های فولادی توخالی نصب شده برای تثبیت شیب رسی پشتیبانی می‌شود، بررسی می‌کند. اثرات تغییر قطر شمع، طول شمع، فاصله بین شمع‌ها، زاویه شیب، موقعیت ردیف شمع از بالای شیب و محل قرارگیری پایه همگی بررسی می‌شوند. پس از تعیین ظرفیت باربری شیب‌های ناپایدار، با ظرفیت باربری شیب‌های تثبیت شده مقایسه می‌شود. سپس نتایج تجزیه و تحلیل می‌شوند تا ببینند هر پارامتر چگونه بر ظرفیت تحمل بار پایه نواری تأثیر می‌گذارد. نتایج موارد ناپایدار نشان می‌دهد که ظرفیت تحمل بار یک پایه با افزایش زاویه شیب کاهش می‌یابد و زمانی که پایه دور از شیب قرار می‌گیرد، افزایش می‌یابد. علاوه بر این، یافته‌ها حاکی از آن است که با تقویت شیب رسی با دنباله‌ای از شمع‌های فولادی توخالی، ظرفیت تحمل بار پایه نواری به طور قابل‌توجهی افزایش می‌یابد. با کاهش فاصله بین شمع‌ها و افزایش طول آنها، ظرفیت باربری پایه افزایش می‌یابد و این بهبود با افزایش قطر شمع‌ها افزایش می‌یابد. هنگامی که ردیف شمع دور از بالای شیب قرار می‌گیرد، ظرفیت تحمل بار پایه کاهش می‌یابد. همچنین قرار دادن پایه با فاصله کاملاً جدا از شیب تاج نشان دهنده کاهش نسبت ظرفیت باربری است.

کلمات کلیدی: ظرفیت حمل بار، شمع توخالی، پایه نواری، شیب، تثبیت.