Drained Bearing Capacity of Strip Footings on Two-Layered Sand Soil Slope

Redha Benali
Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria
r.benali@univ-batna2.dz

Badis Mazouz
Laboratory of Applied Civil Engineering (LGCA), Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria
b.mazouz@univ-batna2.dz (corresponding author)

Ahmed Abderraouf Belkadi
Department of Civil Engineering, Faculty of Technology, University of Bordj Bou Arreridj, Algeria
ahmedabderraouf.belkadi@univ-bba.dz

Tarek Mansouri
Department of Civil Engineering, Faculty of Technology, University of Batna 2, Algeria
t.mansouri@univ-batna2.dz

Kamel Goudjil
Department of Civil Engineering, Faculty of Technology, University of Souk Ahras, Algeria
k.goudjil@uni-soukahras.dz

Received: 17 July 2024 | Revised: 29 July 2024 | Accepted: 4 August 2024

 DOI: https://doi.org/10.48084/etasr.8426

ABSTRACT

The objective of this study is to investigate the drained bearing capacity of a strip footing on a two-layered sand slope through the use of numerical analysis. The analysis is conducted using Plaxis, a two-dimensional finite element software. The behavior of the sand is modeled utilizing the non-linear Mohr-Coulomb criteria. The research examines the influence of various parameters on the footing's behavior, including the normalized thickness of the top layer h_1/B, slope angle β, and friction angles of both loose and dense sand, φ_1 and φ_2, respectively. The findings indicate that for the scenarios with a denser top layer $\varphi_1/\varphi_2 > 1$, the bearing capacity increases with rising h_1/B. Conversely, for the cases with a looser top layer $\varphi_1/\varphi_2 < 1$, the bearing capacity declines with increasing h_1/B. Moreover, irrespective of the slope angle β, the bearing capacity rises with a higher sand friction angle φ.

Keywords-bearing capacity; strip footings; finite element; sand; two-layered slope

I. INTRODUCTION

The construction of a foundation is one of the oldest and most fundamental activities in the field of building and public works. Even today, the study of foundations remains a central concern within the discipline of geotechnics. A substantial body of literature exists that analyzes the bearing capacity of a strip footing resting on homogeneous ground with a horizontal surface, employing a variety of methods. The ultimate bearing capacity of strip footings on flat, homogeneous sand has been extensively investigated through numerical, analytical, and experimental methods. However, in real-world engineering scenarios, space limitations and the increasing pace of urbanization often necessitate placing foundations on or near slopes. This is particularly common for infrastructure projects like roads in mountainous areas, power transmission line towers, and bridge abutments. Over time, numerous researchers have proposed a range of methods for calculating the bearing capacity of strip footings situated on uniform soil slopes. These methods include experimental investigations [1-3], numerical techniques [4-6], and analytical studies [7]. The findings of these experimental and analytical studies suggest that the bearing capacity of strip foundations is significantly influenced by the slope angle and the distance from the foundation to the crest of the slope. Additionally, the type of charges applied to the foundation plays a crucial role in determining the bearing capacity. Therefore, it is essential to consider the type of charges used in the construction process. Prior research has concentrated exclusively on the analysis of footing bearing capacity on uniform, sloping ground. However, it should be noted that natural soils are comprised of distinct layers with varying physical and mechanical properties, which are the result of geological processes. It is therefore imperative to consider the impact of soil stratification when evaluating the bearing capacity of surface foundations. The existing methods have addressed the bearing capacity of strip footings resting on two-layered, horizontal soil profiles. A variety of techniques have been utilized to assess the bearing capacity of strip footings on layered soils. These include theoretical approaches such as the limit equilibrium method [8, 9] and kinematic limit analysis [10, 11], as well as empirical and semi-empirical methods [12]. Furthermore, numerical techniques [13, 14], such as the finite element method and finite difference codes [15], are also valuable tools. Moreover, experimental studies [3, 16-18] offer invaluable data for validation purposes.

Despite the existing literature on the subject, there is still a paucity of research exploring the ultimate bearing capacity of footings placed on a two-layer system in the vicinity of slopes. As a case in point, the work of the authors in [19] may be cited, who investigated the response of two-layered slopes to surcharge loads through model tests and numerical simulations. The proposal introduces criteria based on the relative cohesion ratio, with the objective of distinguishing changes in slope behavior. The study revealed that the interface between the two layers plays a pivotal role in determining the failure mechanism and slope stability. Building on previous research, the authors in [20] employed finite element limit analysis to investigate the impact of earthquakes on the bearing capacity of strip footings on two-layered slopes. The results of their investigation indicate that an increase in bearing capacity is associated with deeper footing embedment. Moreover, the failure mechanisms were found to vary in accordance with the strength of the soil layers and the intensity of the seismic activity. In a subsequent study [21], the researchers employed a pseudo-static approach in conjunction with a Particle Swarm Optimization (PSO) algorithm to analyze the ultimate bearing capacity of shallow strip footings on two-layered soil. This research included a comprehensive parametric analysis and the formulation of design charts. The results demonstrated a high degree of correlation with existing analytical, numerical, and experimental data. In their most recent study, authors in [22] introduced a novel method, random adaptive finite element limit analysis, for assessing the bearing capacity of strip footings on two-layered cohesive soil slopes, accounting for spatial variations within the soil itself.

The study compares the results with those of prior studies, analyzes the undrained shear strength with spatial variability, and identifies the key parameters affecting the bearing capacity. While prior research has addressed the bearing capacity of strip footings on layered soils, there is a paucity of information concerning footings situated on two sand layers in proximity to slopes, particularly in scenarios where the top layer is denser or looser than the bottom layer. This study bridges this gap by employing finite element analysis to investigate the drained bearing capacity of such footings subjected to a uniform distributed load. The analysis investigates the relationships between bearing capacity and key parameters, including the normalized thickness of the top layer h_1/B, slope inclination, friction angles of the sand layers, and the resulting collapse mechanisms.

II. FINITE ELEMENT MODEL

This study employed Plaxis (2D) finite element software to conduct a series of two-dimensional calculations and investigate the bearing capacity of strip footings on a two-layered sand slope. The analysis considered two scenarios: a loose sand layer over a dense sand layer, and vice versa. The Mohr-Coulomb criteria were employed to model the nonlinear behavior of the sand. This criterion represents an elastic, perfectly plastic material with a friction angle φ that is independent of the dilation angle ψ. The Mohr-Coulomb model was selected for its simplicity, practical application in geotechnical engineering, and the ease of obtaining the necessary parameters. The foundation was modeled as an elastic beam element with high normal stiffness (EA) and flexural rigidity (EI). Table I summarizes the specific material properties used in the analysis.

TABLE I. FINITE ELEMENT ANALYSIS PARAMETERS

Parameters	Name	Unit	Loose sand	Dense sand
Model type	Model	-	Mohr-Coulomb	
Dry density	γ_{unsat}	KN/m^3	14	18
Wet density	γ_{sat}	KN/m^3	16	20
Young's Module	E_{ref}	KPa	1.2 10^4	1.5 10^4
Poisson's ratio	v	KPa	0.30	0.30
Cohesion	c	KN/m^3	0.1	0.1
Angle of friction	φ	(°)	30°	40°
Angle of dilation	ψ	(°)	0°	10°

All models were subjected to the same boundary conditions, meaning that they were fixed along the bottom and horizontally constrained on the sides, thereby allowing vertical movement. Once the geometry is defined, Plaxis automatically generates a refined mesh for the subsequent analysis. The mesh comprised 15-node triangular elements for the soil and 3-node beam elements for the footing. The mesh was particularly refined in the vicinity of the foundation and in proximity to the crest of the slope, with the objective of accurately capturing the stress distribution and enhancing the accuracy of the results. Figure 1 depicts the boundary conditions and the finite element mesh utilized in this investigation.

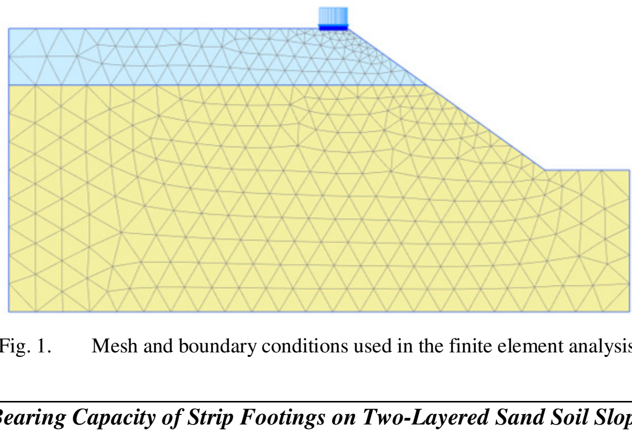

Fig. 1. Mesh and boundary conditions used in the finite element analysis.

The analysis was conducted in two phases to ensure the inclusion of non-horizontal soil layers. In the initial phase, the K0 procedure, which is not appropriate for such geometries, could not be employed to generate the initial stresses. Accordingly, the initial stress state within the slope was established by applying gravity loading due to the soil's self-weight. The second phase entailed the activation of the footing and interface elements, as well as the application of the vertical load on the strip footing in incremental steps. Each analysis was conducted using iterative calculations until convergence was achieved. The peak observed in the load-displacement curves for each model was taken as an indicator of the failure load.

III. VALIDATION OF THE MODEL IN FINITE ELEMENTS

In order to ascertain the veracity of the numerical model, the ultimate bearing capacity q_{ult} of a strip footing on homogeneous loose, medium, and dense sand was calculated using finite element analysis and compared with the analytical solutions presented in [23, 24]. Table II presents the results obtained from both methods. As anticipated, the ultimate bearing capacity q_{ult} increases in conjunction with an increase in the friction angle φ. It is noteworthy that the numerical results demonstrate an excellent degree of agreement with those presented in [23] and [24], with a maximum discrepancy of less than 6%. This strong correlation serves to validate the numerical model developed in the course of this study.

TABLE II. COMPARISON OF BEARING CAPACITY OF HOMOGENEOUS SAND

Soil type	γ	φ °	Present study	[23]	[24]
Medium sand	14	30	108.29	105.49	109.69
Loose sand	16	35	248.24	271.36	297.2
Danse sand	18	40	820.17	716.86	843.21

IV. TEST PROGRAM

Figure 2 demonstrates the essential geometric characteristics of the model. A strip footing of width B is situated on the crest of a two-layered sand slope with height H and inclination angle β. The upper layer, defined by a friction angle φ_1 and thickness h_1, is situated above a lower layer with a thickness h_2 and a friction angle φ_2. For the purposes of facilitating analysis, normalized parameters were introduced. The normalized thickness of the top layer h_1/B varies from 0.25 to 5 in increments of 0.25 and 0.5. The friction angles selected for loose and dense sand were within the ranges deemed practical. The range for loose sand is 30° to 36°, while the range for dense sand is 40°. In accordance with [25], three slope angles β were considered: 15°, 30°, and 45°, which cover a wide range of real-world scenarios. It is crucial to highlight that the ratio φ_1/φ_2 serves to distinguish between the two scenarios. A value of $\varphi_1/\varphi_2 < 1$ indicates the presence of a loose sand layer over a dense sand layer, whereas a value of $\varphi_1/\varphi_2 > 1$ represents the inverse situation. Each parameter set was examined independently, with all other variables having been maintained at a constant level. Table III provides a summary of the various combinations of the parameters that were analyzed in this study.

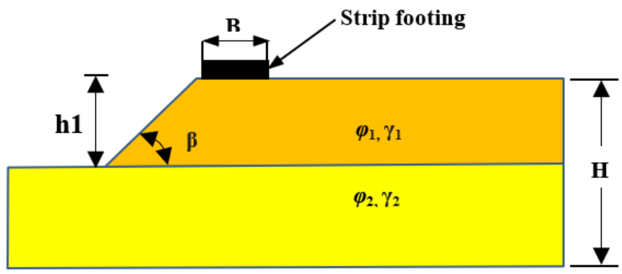

Fig. 2. Geometry parameters.

TABLE III. VARIABLE OF TEST PROGRAM

Test series	Cases	Variable parameters			Fixed parameters
		β	φ	h_1/B	
1	$\varphi_1/\varphi_2 < 1$	15° 30° 35° 45°	30 32 34 36 40	0.25 0.5 0.75 1 1.5 2 3 4 5	B=1 d/B=0.5 H=10m
2	$\varphi_1/\varphi_2 > 1$				

V. RESULTS AND DISCUSSION

To investigate the combined effects of various parameters, 80 finite element simulations were performed for a strip footing on a two-layer sand slope subjected to vertical loading. The parameters investigated included the normalized thickness of the top layer h_1/B, slope angles β, and friction angles φ of the sand layers. For comparison, the ultimate bearing capacity of a strip footing on a single-layered horizontal sand deposit was calculated using Terzaghi's formula [26]:

$$qu = \frac{1}{2} B\gamma N_\gamma \quad (1)$$

For strip footings located near or on slopes, researchers have proposed analytical expressions to estimate correction factors, also known as shape factors, denoted by $i\beta$. These factors account for the influence of slope geometry and are introduced into (2):

$$qu = \frac{1}{2} B\gamma N_\gamma i_\beta \quad (2)$$

To simplify the use of Terzaghi's equation in this context, the ultimate bearing capacity of strip footings on two-layered cohesive soils is presented as a normalized drained bearing capacity factor N_γ^*. This factor is defined as:

$$N_\gamma^* = \frac{qu_{two\ layerd}}{\gamma_1 B} \quad (3)$$

where N_γ^* is the dimensionless ratio between the ultimate bearing capacity of a strip footing on two-layered sand q_{utl} and s is the product of the average shear strength of the soil layers, γ the unit weight of the soil, and B the width of the footing.

VI. EFFECT OF SAND LAYER THICKNESS H_1/B

The impact of the top layer thickness h_1/B was examined by incrementally augmenting its value from 0.25 to 2.0 for the loose sand over dense sand scenario and from 0.25 to 5.0 for the dense sand over loose sand scenario. Figure 3 presents the variation of the normalized drained bearing capacity factor N_γ* with h_1/B for diverse combinations of the slope angle β in the context of dense sand overlying loose sand. As shown in Figure 3, for all slope angles β, the value of N_γ* monotonically increases with respect to h_1/B until reaching a plateau at h_1/B = 5. Beyond this point, the increase becomes negligible. In simpler terms, for h_1/B greater than 5, the soil's bearing capacity approaches that of a homogeneous dense sand layer. This behavior can be attributed to the fact that a thicker top layer, with higher shear strength compared to the bottom layer, is engaged as h_1/B increases, consequently leading to a rise in bearing capacity. Figure 4 represents the variation of N_γ* with h_1/B ratio for different combinations of β, for the case of loose sand over the dense sand.

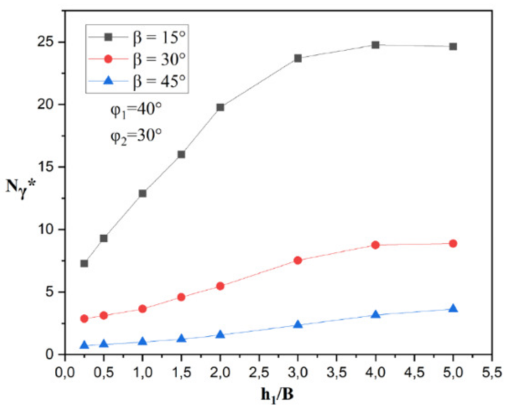

Fig. 3. Variation of N_γ^* as a function of *h1/B* for different values of β (φ_1=40° and φ_2=30°).

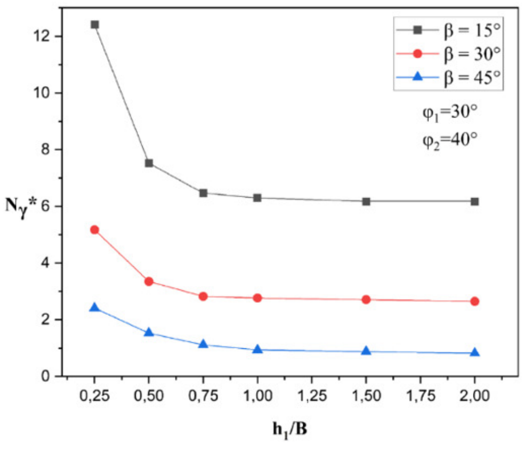

Fig. 4. Variation of N_γ^* as a function of *h1/B* for different values of β (φ_1=30° and φ_2=40°).

In contrast, for the loose sand over dense sand scenario (for which a separate figure is provided), the trend is reversed. As h_1/B increases, the value of N_γ* decreases. It is noteworthy that this decrease reaches a plateau at h_1/B = 2, with the value remaining relatively constant beyond that point. In other words, for h_1/B greater than 2, the contribution of the bottom layer (denser sand) becomes negligible, and the bearing capacity primarily depends on the weaker top layer, which resembles a homogeneous loose sand case. In this scenario, the influence of h_1/B on bearing capacity is rendered insignificant due to the additional thickness comprising only weaker material, which fails to significantly enhance the overall strength.

VII. EFFECT OF ANGLE FRICTION Φ

In order to investigate the influence of the friction angle φ, a series of analyses were conducted, in which five values were considered. The values were 30°, 32°, 34°, 36°, and 40°. The methodology entailed fixing the friction angle of one layer φ_1 or φ_2 and varying the friction angle of the other. Three cases were considered in this investigation.

- In case 1, the friction angle φ_2 was fixed at 40°, while the other angle φ_1 was varied.
- In case 2, the friction angle of layer 2 φ_2 was fixed at 30°, while the friction angle of layer 1 φ_1 was varied.
- In case 3, the friction angle of the top layer φ_2 was held constant at 40°, while the friction angle of the bottom layer φ_1 was varied.

The results were plotted as a series of curves, with the normalized drained bearing capacity factor $N\gamma$* on the vertical axis and the top layer thickness h_1/B on the horizontal axis, for different combinations of φ and slope angle β. Figure 5 is dedicated to case 1 (φ_2 fixed at 40° and φ_2 varied). As illustrated in Figure 5, there is an inverse relationship between N_γ* and h_1/B, with an increase in φ_1 resulting in an enhancement in N_γ*. It is noteworthy that N_γ* attains a diminished maximum value at a specific value of h_1/B. Subsequently, N_γ* remains relatively constant, irrespective of the slope angle β or φ_1. This indicates that for h_1/B values greater than 1, the impact of h_1/B on bearing capacity becomes more considerable in comparison to the combined influence of the internal friction angle φ_1 and the slope angle β. In case 2, the value of φ_2 was fixed at 30° and that of φ_1 was varied. As evidenced in Figure 6, the N_γ* is influenced by h_1/B and φ_1. Moreover, the value of N_γ* increases with increasing φ_1, indicating that soils with higher internal friction angles (i.e., more granular and coarse soils) provide greater resistance and higher bearing capacity. This finding is consistent with the bearing capacity theory proposed by Terzaghi and Meyerhof. It is noteworthy that for h_1/B = 3, N_γ* remains constant regardless of the value of φ_1. This can be attributed to the fact that the influence of h_1/B on bearing capacity is particularly pronounced in this instance. In case 3 (φ_1=40° fixed and φ_2 varied), Figure 7 demonstrates that the dimensionless bearing capacity factor N_γ* is significantly influenced by h_1/B and φ_2, showing that the dimensionless bearing capacity factor N_γ* increases monotonically with both the increase of the normalized ratio h_1/B and the friction angle of the second layer φ_2. Furthermore, higher friction angles φ_2 result in greater resistance and, consequently, higher bearing capacities. This indicates that the friction angle φ_2 of the second layer has a significant impact on the assessment of soil bearing capacity. Nevertheless, for h_1/B = 5, the N_γ* is approximately constant for all values of the friction angle φ_2. This indicates that the bearing capacity reaches that of the homogeneous soil, or that h_1/B and φ_2 have no impact on the ultimate bearing capacity.

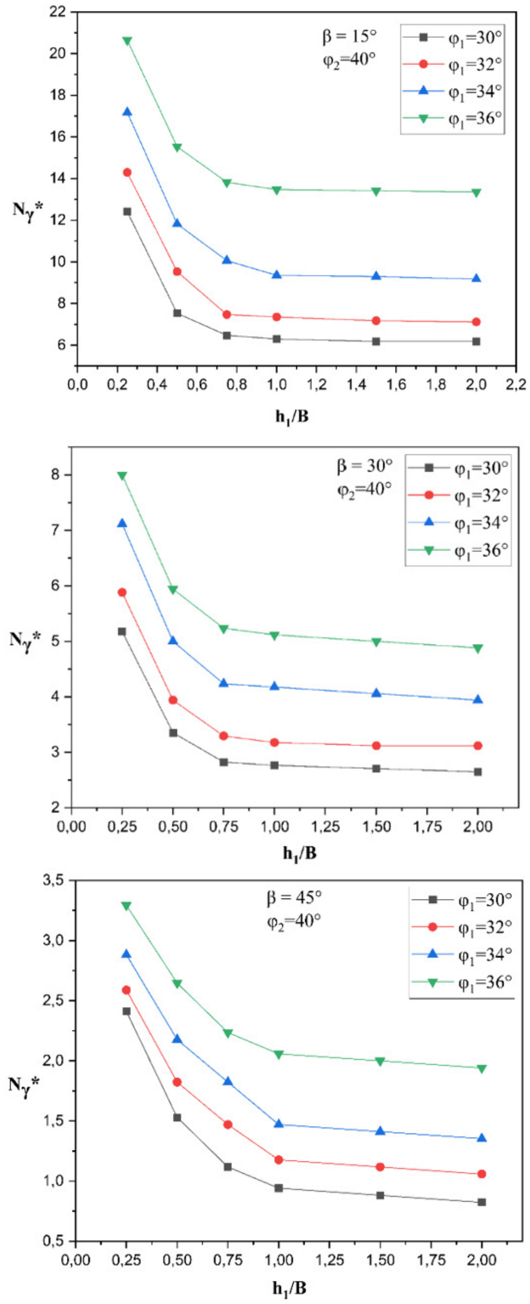

Fig. 5. Variation of N_γ* as a function of h_1/B for different values of φ_2 and β (case 1 φ_2=40° fixed and φ_1 varied), (a) β=15°, (b) β=30°, β=45°.

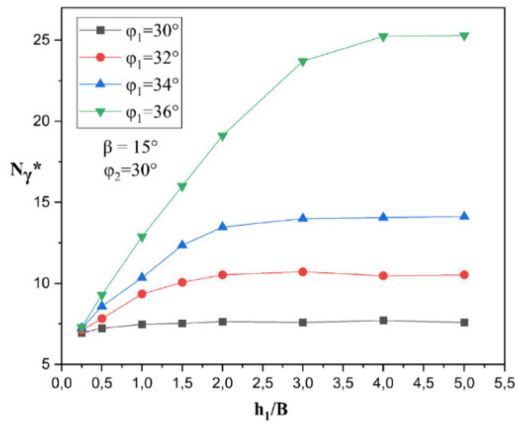

Fig. 6. Variation of N_γ* as a function of h_1/B for different values of φ_1 and β =15° (case 2 φ_2=40° fixed and φ_1 varied).

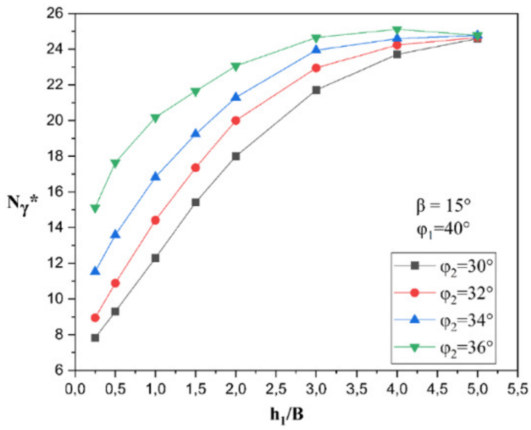

Fig. 7. Variation of N_γ* as a function of h_1/B for different values of φ_2 and β =15° (case 3 φ_1=40° fixed and φ_2 varied).

VIII. EFFECT OF SLOPE ANGLE *Β*

Figure 8 displays the variation of the normalized drained bearing capacity factor N_γ* with the slope angle β for a range of combinations of h_1/B. The figure presents the results of two scenarios: dense sand over loose sand and loose sand over dense sand. In both cases, it is evident that N_γ* decreases as the slope angle β increases, irrespective of the specific value of h_1/B. This observation indicates that an increase in slope angle results in a reduction in the bearing capacity and stability of the soil, regardless of the soil's friction angle. This finding corroborates the results in [25], for footings on uniform slopes. The highest N_γ* values are observed for h_1/B = 0.25 and β = 15°.Conversely, at a steeper slope angle of β = 45°, the N_γ* values become relatively constant across all h_1/B values. This suggests that for slopes of a considerable degree of steepness, the impact of the top layer thickness on bearing capacity is negligible.

IX. CONCLUSIONS

A numerical analysis was performed using Plaxis finite element software to investigate the drained bearing capacity of strip footings situated on the crest of two-layered sand slopes.

(a)

(b)

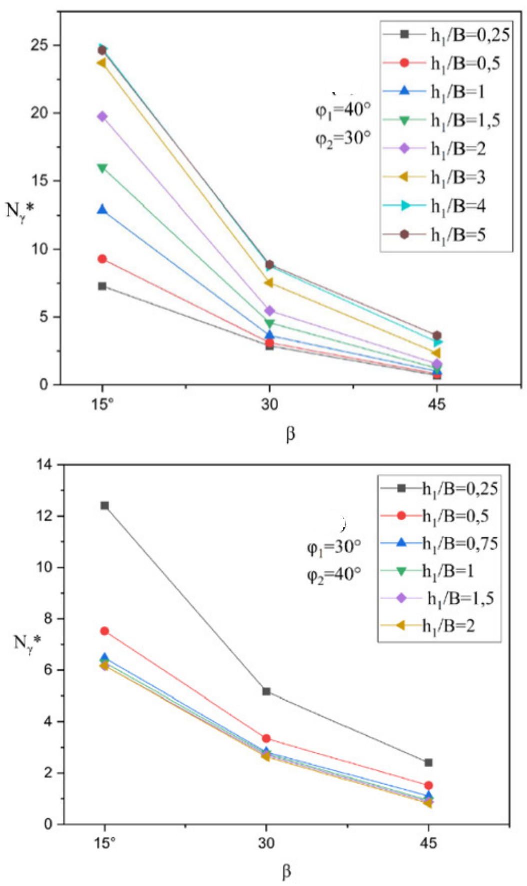

Fig. 8. Variation of $N\gamma$* as a function of β for different values of $h1/B$ (φ_1=30° and φ_2=40°), (a) dense sand over loose sand, (b) loose sand over dense sand.

The study revealed several key factors that exert a significant influence on bearing capacity.

- The normalized top layer thickness h_1/B has a significant impact on bearing capacity.
- A critical top layer thickness h_1/B_{cr} exists beyond which the influence of h1/B on footing stability is considered to be negligible.
- Irrespective of the thickness of the top layer h_1/B, the bearing capacity is observed to decrease as the slope angle increases.
- The ratio between these angles φ_1/φ_2 is of great consequence. In the case of a dense layer of sand over a loose layer, with a ratio of φ_1/φ_2 greater than 1, N_γ* is observed to increase with rising values of h_1/B. In the case of a loose sand layer over a dense sand layer, with a ratio of φ_1/φ_2 less than 1, N_γ* declines with increasing h_1/B until it reaches a critical thickness h_1/B_{cr}, beyond which its impact becomes inconsequential.

In conclusion, the study demonstrates the complex interaction between the thickness of the top layer, the slope angle, and the friction angles of the sand layers in determining the drained bearing capacity of strip footings on two-layered slopes.

REFERENCES

[1] B. Mazouz, K. Abbeche, A. Abdi, and M. Baazouzi, "Model experiments to assess effect of eccentric loading on the ultimate bearing capacity of a strip footing near a dry sand slope," *International Journal of Geotechnical Engineering*, vol. 15, no. 10, pp. 1241–1251, Nov. 2021, https://doi.org/10.1080/19386362.2019.1665385.

[2] A. Abdi, K. Abbeche, B. Mazouz, and R. Boufarh, "Bearing Capacity of an Eccentrically Loaded Strip Footing on Reinforced Sand Slope," *Soil Mechanics and Foundation Engineering*, vol. 56, no. 4, pp. 232–238, Sep. 2019, https://doi.org/10.1007/s11204-019-09596-5.

[3] R. A. Alamaar and A. A. Al-Jazaairry, "Experimental study on bearing capacity of footing near sand slope," in *4th International Conference on Civil and Environmental Engineering Technology (ICCEET 2022)*, Kufa, Iraq, Jul. 2023, Art. no. 040008, https://doi.org/ 10.1063/5.0141042.

[4] B. Mazouz, T. Mansouri, M. Baazouzi, and K. Abbeche, "Assessing the Effect of Underground Void on Strip Footing Sitting on a Reinforced Sand Slope with Numerical Modeling," *Engineering, Technology & Applied Science Research*, vol. 12, no. 4, pp. 9005–9011, Aug. 2022, https://doi.org/10.48084/etasr.5131.

[5] M. H. Vahedi, M. R. Arvin, and J. Shiau, "Numerical study on bearing capacity of geocell-reinforced strip footings resting on slopes," *Arabian Journal of Geosciences*, vol. 17, no. 5, Apr. 2024, Art. no. 149, https://doi.org/10.1007/s12517-024-11958-9.

[6] A. Firoozfar, A. Rostami, H. Ghaderi, H. Zamani, and A. Rostamkhani, "Assessing the Effects of Length, Slope and Distance between Piles on the Bearing Capacity of a Pile Group under Axial Loading in Granular Soil," *Engineering, Technology & Applied Science Research*, vol. 7, no. 5, pp. 1894–1899, Oct. 2017, https://doi.org/10.48084/etasr.1352.

[7] G. G. Meyerhof, "The Ultimate Bearing Capacity of Foundations on Slopes," in *4th International Conference on Soil Mechanics and Foundation Engineering*, London, Aug. 1957, pp. 384–386

[8] V. Joshi, R. K. Dutta, and R. Shrivastava, "Ultimate bearing capacity of circular footing on layered soil," *Journal of GeoEngineering*, vol. 10, no. 1, pp. 25–34, Apr. 2015, https://doi.org/org/10.6310/jog.2015.10(1).4.

[9] G. G. Meyerhof, "Ultimate Bearing Capacity of Footings on Sand Layer Overlying Clay," *Canadian Geotechnical Journal*, vol. 11, no. 2, pp. 223–229, May 1974, https://doi.org/10.1139/t74-018.

[10] R. L. Michalowski and L. Shi, "Bearing Capacity of Footings over Two-Layer Foundation Soils," *Journal of Geotechnical Engineering*, vol. 121, no. 5, pp. 421–428, May 1995, https://doi.org/10.1061/(ASCE)0733-9410(1995)121:5(421).

[11] R. S. Merifield, S. W. Sloan, and H. S. Yu, "Rigorous plasticity solutions for the bearing capacity of two-layered clays," *Géotechnique*, vol. 49, no. 4, pp. 471–490, Aug. 1999, https://doi.org/10.1680/ geot.1999.49.4.471.

[12] G. G. Meyerhof and A. M. Hanna, "Ultimate bearing capacity of foundations on layered soils under inclined load," *Canadian Geotechnical Journal*, vol. 15, no. 4, pp. 565–572, Nov. 1978, https://doi.org/10.1139/t78-060.

[13] S. Banu *et al.*, "Numerical Analysis of the Ultimate Bearing Capacity of Strip Footing Constructed on Sand-over-Clay Sediment," *Buildings*, vol. 14, no. 4, Apr. 2024, Art. no. 1164, https://doi.org/10.3390/ buildings14041164.

[14] P. P. Das, V. N. Khatri, R. Doley, R. K. Dutta, and J. S. Yadav, "Estimation of bearing capacity of shallow footings on layered sand using finite elements analysis," *Journal of Engineering, Design and Technology*, vol. 22, no. 2, pp. 385–403, Jan. 2022, https://doi.org/ 10.1108/JEDT-09-2021-0493.

[15] A. J. Thahab and J. K. Thajeel, "Ultimate bearing capacity under the strip footing resting on two-layer soil using by FLAC3D," *AIP Conference Proceedings*, vol. 2864, no. 1, Jan. 2024, Art. no. 030025, https://doi.org/10.1063/5.0186290.

[16] A. Bhardwaj and R. K. Sharma, "Experimental and Numerical Investigations on the Bearing Capacity of Footings on the Layered Soil,"

International Journal of Geosynthetics and Ground Engineering, vol. 9, no. 4, Jun. 2023. Art. no. 35, https://doi.org/10.1007/s40891-023-00461-y.

[17] M. Kumar and M. Subagiriraj, "Experimental Investigation of Various Shell Footings in Cohesive and Cohesionless Soil," *International Journal of Civil, Environmental and Agricultural Engineering*, vol. 1, no. 1, pp. 67–77, May 2019, https://doi.org/10.34256/ijceae19110.

[18] N. Ghazouani, "Quicklime-stabilized Tuff and Clayey Soils for Highway A3 Construction in Northern Tunisia," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13511–13516, Apr. 2024, https://doi.org/10.48084/etasr.6955.

[19] P. Ni, S. Wang, S. Zhang, and L. Mei, "Response of heterogeneous slopes to increased surcharge load," *Computers and Geotechnics*, vol. 78, pp. 99–109, Sep. 2016, https://doi.org/10.1016/j.compgeo.2016.05.007.

[20] G. Wu, M. Zhao, and H. Zhao, "Undrained seismic bearing capacity of strip footings horizontally embedded in two-layered slopes," *Earthquake Spectra*, vol. 37, no. 2, pp. 637–651, May 2021, https://doi.org/10.1177/8755293020957332.

[21] L. Debnath and S. Ghosh, "Pseudo-Static Bearing Capacity Analysis of Shallow Strip Footing over Two-Layered Soil Considering Punching Shear Failure," *Geotechnical and Geological Engineering*, vol. 37, no. 5, pp. 3749–3770, Oct. 2019, https://doi.org/10.1007/s10706-019-00866-5.

[22] H. Zhou *et al.*, "Quantitative bearing capacity assessment of strip footings adjacent to two-layered slopes considering spatial soil variability," *Acta Geotechnica*, vol. 18, no. 12, pp. 6759–6773, Dec. 2023, https://doi.org/10.1007/s11440-023-01875-8.

[23] J. B. Hansen and S. Inan, *A Revised and extended formula for bearing capacity*. Copenhagen: Geoteknisk Institut, 1970.

[24] G. G. Meyerhof, "Some Recent Research on the Bearing Capacity of Foundations," *Canadian Geotechnical Journal*, vol. 1, no. 1, pp. 16–26, Sep. 1963, https://doi.org/10.1139/t63-003.

[25] K. Georgiadis, "The influence of load inclination on the undrained bearing capacity of strip footings on slopes," *Computers and Geotechnics*, vol. 37, no. 3, pp. 311–322, Apr. 2010, https://doi.org/10.1016/j.compgeo.2009.11.004.

[26] K. Terzaghi, *Theoretical Soil Mechanics*, 1st ed. New York, New York, NY, USA: Wiley, 1943.