Bearing capacity of shallow footing on an unsaturated embankment upon infiltration

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Abstract. Due to rapid urbanization and population growth, construction activities have been increased on slopes of unsaturated hilly regions. Thus, constructing shallow footings on these slopes is a common method for supporting infrastructure construction. The main factor causing instability of these unsaturated slopes is the loss of suction upon infiltration resulting in footing failures. Thus, in this study, a shallow footing resting on an unsaturated embankment modelled using Barcelona basic model (BBM) has been numerically analysed to investigate the influence of various factors affecting the bearing capacity upon infiltration. The influence of various critical design parameters, like the distance from the crest of the slope and water table positions, slope angle, and infiltration rate, has been studied comprehensively. As the footing distance increases from the crest (setback distance), soil provides higher bearing capacity upon infiltration due to the confinement. Moreover, it is noticed that the bearing capacity reduces monotonically as the water table rises above the toe, thus depicting the Prandtl-type of failure. Further, as the slope angle increases, bearing capacity decreases at various footing distances upon infiltration. The effect of infiltration rate on bearing capacity of footings depends on the air entry value of the soil. As the air-entry value increases, bearing capacity reduces drastically upon infiltration. This approach helps the design engineers consider these factors while constructing footings on unsaturated slopes.

1 Introduction

Footings are typically built on slopes for practical uses due to space limitations. Bearing capacity of footings on unsaturated slopes is governed by both the shear strength of soil and the slope stability than the levelled ground where the shear strength of soil mainly governs the behaviour. During infiltration, the main reason for unsaturated slope failure is the decrease in suction [1,2]. The water table positions significantly affect the bearing capacity of footings on unsaturated soils [3]. Pantelidis and Griffiths [4] suggested that footings on slopes may either be constructed as conventional foundations or may also be designed as a surcharge over a conventional slope stability system. Both human, as well as property loss, has been reported due to the devastating foundation-slope failures. Several studies have been undertaken to understand the behaviour of foundation-slope failure [5-7]. Huang and Kang [8] evaluated the effect of distance of footing from the crest of slope on the ultimate bearing capacity of surface footings using a limit equilibrium method. They expressed the setback distance as a function of friction angle regardless of slope inclination between 0° and 35°. Castelli et al. [9] evaluated the bearing capacity of footings by taking into account the effect of distance of footing from the edge of sloping ground. Keskin and Laman [10] investigated the bearing capacity of footings on a sandy slope experimentally and numerically.

Parametrical investigations like the influence of setback distance from the slope, relative density, slope angle and footing width on the bearing capacity. They concluded that the bearing capacity gets increased with the increase in footing distance, footing width, relative density and the decrease in slope inclination. These studies provide a valuable insight into the foundation-slope behaviour considering the factors like the influence of slope angle, footing width, distance of footing from the crest of slope etc. But most of these studies considered the behaviour of footings on saturated soil slopes [11]. Only a few studies like [2,12] considered the case of bearing capacity of footings on unsaturated soil slopes. However, the constitutive model used for representing the stress-strain, collapse behaviour of footings on unsaturated slopes was usually the traditional Mohr-Columb model which presents several limitations for predicting the collapse behaviour of unsaturated soils. Till date, no study has been undertaken in which a proper constitutive model for unsaturated soils i.e, Barcelona basic model (BBM) has been used for representing the behaviour of footings placed on the slope and observing the influence of above listed parameters. For practical applications, the effect of rainfall infiltration with varying durations on the bearing capacity of shallow footing resting on unsaturated embankment modelled using BBM was analysed. The parametric influence like distance of footing from the crest of slope, water table fluctuations, slope angle, infiltration rate has been studied. The effect

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of infiltration rate on the bearing capacity of embankment has been considered considering three different types of soils modelled using BBM.

2 Methodology

A shallow strip footing resting on an unsaturated compacted embankment with the geometry given as shown in Fig. 1. This case has been considered inorder to analyse the behaviour of footing resting on slope regions. The geometry consists of 10m high, 26.5° slope angle, bottom width of 40 m and top width of 10m. The depth of the foundation of the embankment is 5m simulated using Mohr-Columb model with friction angle equal to 23°, and modulus of elasticity, E equal to 32 MPa. The width of the shallow strip footing is taken to be 2m. In order to represent the depth of embedment of 1.5m, a surcharge load of 25 kN/m2 is considered to be acting on the embankment surface. To represent the constitutive behaviour of the embankment soil, BBM has been used with the parameters listed in Table 1. Based on symmetry, only half of the embankment has been considered in the analysis. Mechanical boundary conditions consist of bottom of the embankment being restrained against the movement in both x and y directions, while the two vertical sides were restrained against x direction only. To represent the footing area, a downward velocity of magnitude 3.5×10^ (-7) m/step was applied on the footing area. This value is sufficiently small to minimize the inertial effects. The strip footing was simulated by fixing the x -velocity component equal to zero over the grid points representing the footing in FLAC.

For the rainfall infiltration, the hydraulic boundary conditions consist of bottom of the embankment and the vertical sides below water table to be impermeable boundaries. The slope surface and crest of the embankment surface has been considered as the flux boundary conditions for the applied rainfall. Rainfall event as considered for the initial soil block was taken for the analysis of the footing on embankment. Flux boundary condition equal to rainfall intensity was applied on the to the top surface of embankment. However, for the sloping portion subjected to rainfall, in FLAC a fish function adjust_discharge was written to account for the rainfall applied over this portion.

The bearing capacity of footings on unsaturated embankments gets influenced by factors like distance of footing from the crest of the slope of embankment, footing width and the depth of embedment. Parametric studies have been carried out in order to investigate the bearing capacity of unsaturated embankment.

3 Results and discussions

3.1 Effect of distance from crest of slope

Fig. 2 shows the variation of bearing capacity with footing positions indicated by the setback d / B ratio where d represents the distance of footing from crest of the embankment and B refers to the width of footing at various rainfall durations. It is found that the bearing capacity increases as the distance of footing increases upto a critical value beyond which the bearing capacity becomes independent of distance. The improvement in bearing capacity is due to the increased soil confinement on the slope which provides additional resistance as the stress state of soil lies within the yield surface of BBM and doesn't result in plastic collapse. This indicates that for a lower value of distance of footing from crest of slope, the behaviour of footing is governed by the soil on the sloping side which results in potential failure plane along the slope surface during rainfall as is accurately modelled in BBM corresponding to suction increase (SI) and yield surface changes subsequently. When the distance is increased from slope, it enables contribution of soil resistance from both sides of footing and a higher value of bearing capacity is observed. For a distance greater than critical value, soil strength on both sides of footing gets equally mobilized; thus, bearing capacity becomes independent of distance. As the rainfall duration increases, soil becomes prone to collapse and critical footing distance decreases [2, 13].

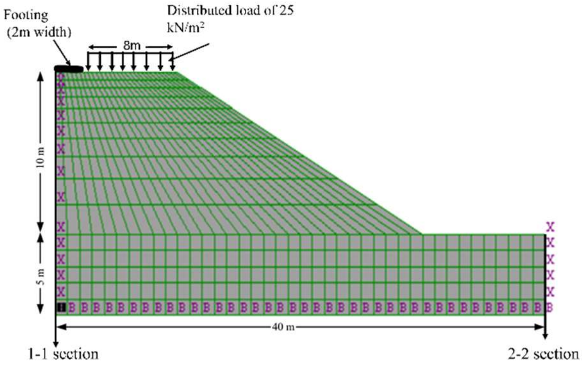

Fig. 1. Geometry of the embankment

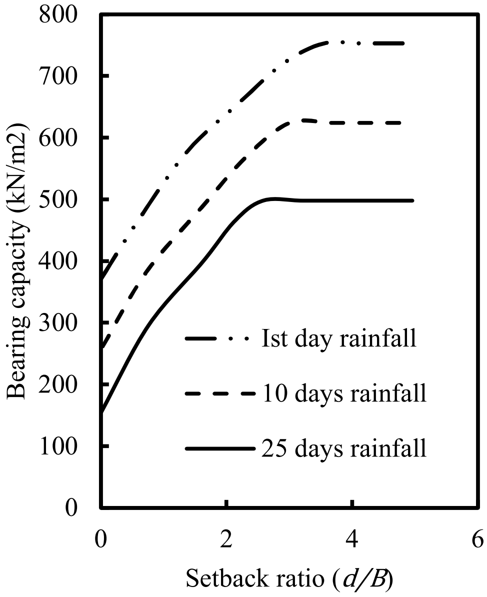

Fig. 2. Variation of bearing capacity with setback ratio

Table 1. Parameters for embankment (Josa 1988)

$G(MPa)$	M	$\lambda(0)$	k	$P_0^*(MPa)$
10	0.82	0.14	0.015	0.055
k_{su}	k_c	r	β(MPa^{-1})	
0.01	1.24	0.24	16.4	

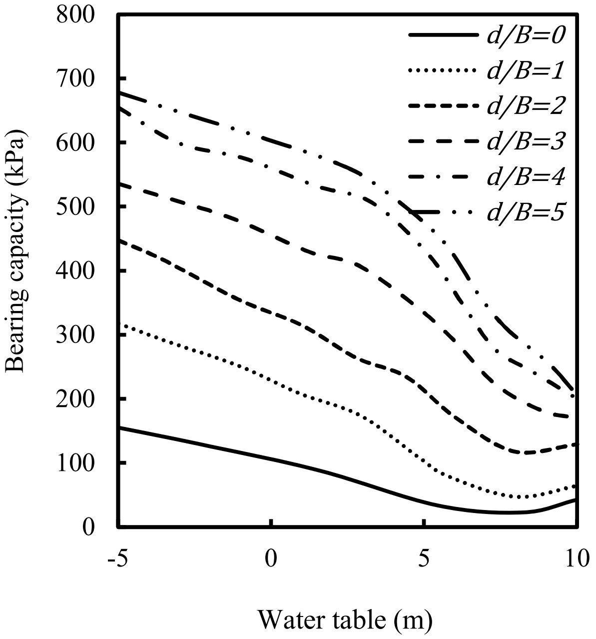

Fig. 3. Plot of bearing capacity with water table positions

Fig. 3 demonstrates the plot of bearing capacity with water table positions at various footing positions. It is predicted that when the depth of water table lies in the foundation portion of embankment (toe region), bearing capacity decreases with footing distances. Moreover, it is noticed that the bearing capacity reduces monotonically as the water table rises above the toe, thus depicting Prandtl-type of failure. The main reason is the reduction of matric suction due to infiltration as implicated by the reduction of preconsolidation pressure in the yield surface of BBM due to movement of both loading collapse and SI plane during infiltration, which results in low value of bearing capacity. In the same Fig. 3, considering the width of footing to be 2m, it is seen that at lower values of setback ratio, bearing capacity reaches to the minimum value when the position of water table lies above the middle of slope. This decrease in bearing capacity can be described by the fact that if the passive resistance provided by the soil block immediately below the footing exceeds the effect of suction reduction due to infiltration, bearing capacity increases with an increase in water table [14]. Otherwise, the decrease in bearing capacity with the rise of water table is due to the reduction of matric suction which decreases the shearing strength and the unit weight.

Fig. 4(a, b) presents the plot of bearing capacity with water table positions at various setback distances for various slope inclinations. As the slope angle increases from 10° to 35°, bearing capacity decreases at various footing distances upon infiltration. Fig. 3 represents the load bearing capacity of embankment corresponding to an angle of 26.5°. The decrease in bearing capacity is due to the inadequate soil resistance on the sloping ground than on the levelled ground as the soil loses suction upon infiltration easily compared to a levelled ground. As the slope angle increases, less stress concentration is mobilized near the footing than the case when the flat ground is present, and the plastic deformations occur. For various slope inclination, the predominant failure was observed to be the slope failure [12, 15] The decrease in bearing capacity also depends on the footing distance. With an increase in slope angle, bearing capacity decrease when the footing lies near the crest of slope. Therefore, it can be concluded that the bearing capacity gets markedly influenced by the inclination of the slope of embankment.

3.2 Effect of infiltration rate

In order to study the influence of infiltration rate on the load-bearing capacity of footing on an unsaturated embankment, a comparative study has been conducted by taking three soils ranging from fine-grained to coarse-grained soils viz, heavy clay (HC), silty clay (STC) and sand with their SWCC's given in Fig. 5 [16]. Permeabilities of the soils were estimated using the method proposed in [17] for sand and using the methodology in [18] for HC and STC soils. Table 2 presents the BBM parameters and the permeability values for the three soils adopted during the analysis [19,20, 21-23].

Fig. 6 (a,b,c) shows the bearing capacity plot with the infiltration duration at the two rainfall events for the three soils. It is found that as the rainfall duration increases, the soil's bearing capacity decreases. For the footing on heavy clay embankment as in Fig. 6(a), it is shown that the bearing capacity reduces drastically for both the rainfall events. The reason for the drastic decrease with infiltration duration is that clay undergoes large collapse settlements due to reduction of suction upon infiltration as properly modelled using BBM. For the footing on silty clay embankment as in Fig. 6(b), the bearing capacity also reduces with the infiltration duration at various footing distances due to the high air entry value of fine-grained soils. However, for the footing on sandy soil embankment as in Fig.6 (c), bearing capacity initially increased, and bearing capacity gets decreased as the duration increased. The initial increase in bearing capacity is due to the rise in suction stress due to the development of capillary tension in unsaturated sands. As the duration increases, soil suction decreases and degree of saturation of the soil increases due to the filling of water voids which contributes to the decrease in bearing capacity. This study proves to be beneficial for assessing the impact of rainfall infiltration on the bearing capacity of footings on unsaturated soil slope. Moreover, the parametric study conducted would be helpful to the practising engineers in designing the footings on slopes.

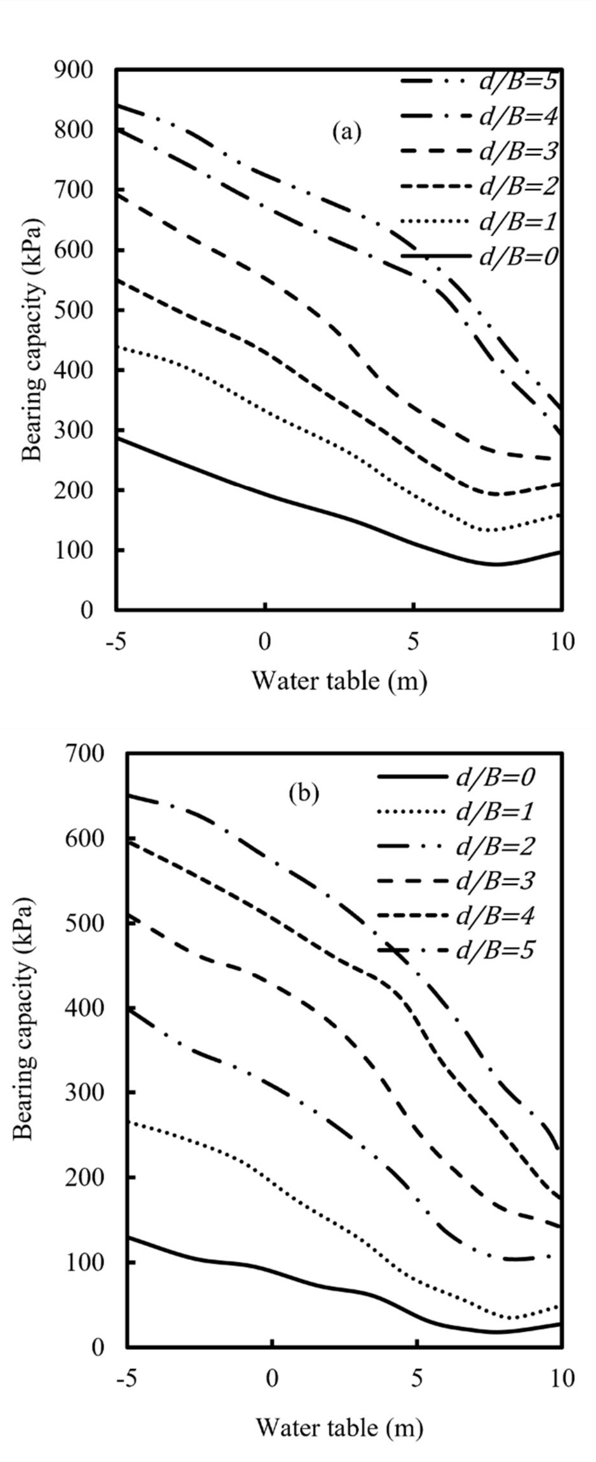

Fig. 4. Plot of bearing capacity with slope angle a) 10° b) 35°

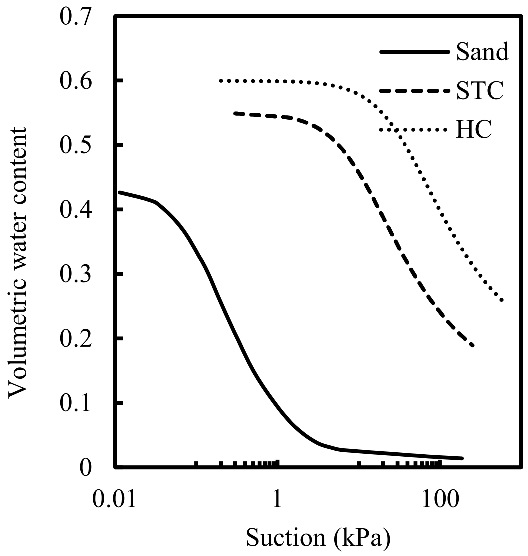

Fig. 5. SWCC for the three types of soils

Table 2. BBM parameters for the three soils

Soil type			
Sand	$G(MPa)$	M	$\lambda(0)$
	15.5	1.11	0.146
	k	$P_0^*(MPa)$	k_c
	0.031	0.064	1.30
	r	β(MPa^{-1})	Permeability (m/sec)
	0.649	8.95	$2*10^{-5}$
STC	$G(MPa)$	M	$\lambda(0)$
	10	1.03	0.014
	k	$P_0^*(MPa)$	k_c
	0.01	0.048	1.20
	r	β(MPa^{-1})	Permeability (m/sec)
	0.465	7	$7.9*10^{-7}$
HC	$G(MPa)$	M	$\lambda(0)$
	5.5	1.01	0.26
	k	$P_0^*(MPa)$	k_c
	0.0013	0.041	1.17
	r	β(MPa^{-1})	Permeability (m/sec)
	0.52	4	$6.5*10^{-8}$

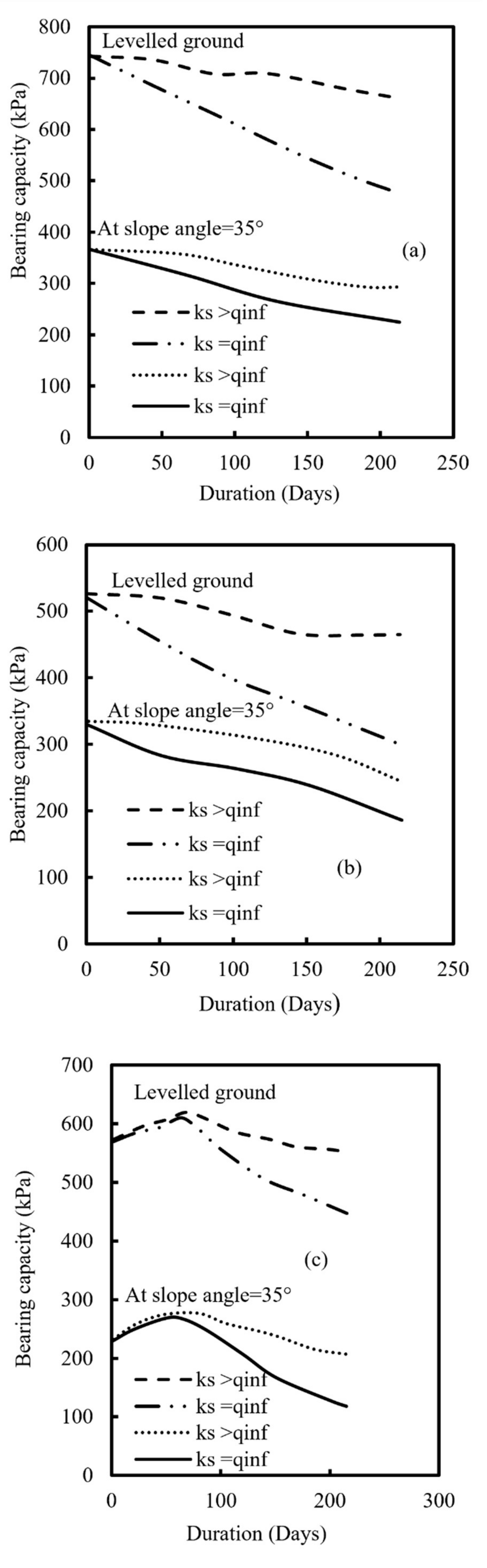

Fig. 6. Plot of bearing capacity with rainfall duration a) Heavy clay b) Silty clay c) Sand

4 Conclusions

The bearing capacity of a footing is negatively impacted by slopes, which is influenced by various factors like the distance from the crest of the slope and water table positions, slope angle, and infiltration rate, has been studied comprehensively. As the footing distance increases from the crest (setback distance), soil provides higher bearing capacity upon infiltration due to the confinement. The load-bearing capacity of slopes composed of clay and silt declines quickly as water infiltrates the soil. Conversely, sand slopes experience a slight increase in their load-bearing capacity after water infiltrates. Due to the larger collapse domain of slope-type failures compared to Prandtl-type failures, water infiltration has a lesser impact on the load-bearing capacity of strip footing on slopes than on flat ground.

References

1. D.G. Fredlund H. Rahardjo, M.D. Fredlund, *Unsaturated Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc., New York; (2012).
2. J. Du, F. Ye, The bearing capacity of strip footings adjacent to the crest of unsaturated soil slopes. Environmental Earth Sciences. Oct;**80**(19):1-20, (2021).
3. Y. Xu, Bearing capacity of unsaturated expansive soils. *Geotechnical & Geological Engineering*, *22*(4), 611-625, (2004). doi:10.1023/B: GEGE.0000047043.29898.17.
4. L. Pantelidis, & D.V. Griffiths, Footing on the crest of slope: slope stability or bearing capacity. In *Engineering Geology for Society and Territory*- **2 (**pp. 1231-1234). Springer, Cham, (*2015).*
5. G.G. Meyerhof, The ultimate bearing capacity of foundations on slopes. In *Proc., 4th Int. Conf. on Soil Mechanics and Foundation Engineering*, (**1**, pp. 384-386), (1957).
6. J.B. Hansen, A revised and extended formula for bearing capacity. Dan. Geotech. Ins., (1970) Bulletin 28.
7. O. Kusakabe, T. Kimura, & H. Yamaguchi, Bearing capacity of slopes under strip loads on the top surfaces. *Soils and foundations*,**21**(4), 29-40, (1981).
8. C.C. Huang, & W.W. Kang, The effects of a setback on the bearing capacity of a surface footing near a slope. *Journal of GeoEngineering*,*3*(1), 25-32, (2008)
9. F. Castelli, V. Lentini, & E.T.R. Dean, Discussion: Evaluation of the bearing capacity of footings on slopes. *International Journal of Physical Modelling in Geotechnics*, **15**(3), 165-168, 2015.
10. M. Salih Keskin, & M. Laman, Model studies of bearing capacity of strip footing on sand slope. *KSCE Journal of Civil Engineering*, **17**(4), 699-711, (2013)

11. M. Tan, & S.K. Vanapalli, Performance estimation of a shallow foundation on an unsaturated expansive soil slope subjected to rainfall infiltration. In *MATEC Web of Conferences,* (**337**,p.03009), (*2021)* EDPSciences.

12. M. Tan, & S.K. Vanapalli, Foundation bearing capacity estimation on unsaturated soil slope under transient flow condition using slip line method. *Computers and Geotechnics*, **148**, 104804. (2022)
13. R.P. Shukla, R.S. Jakka, Critical setback distance for a footing resting on slopes. Acta Geotechnica Slovenica.;**14**(2):19-31, (2017)
14. H. Zhou, G. Zheng, X. Yin, R. Jia, X. Yang, The bearing capacity and failure mechanism of a vertically loaded strip footing placed on the top of slopes. Computers and Geotechnics. 1; 94:12-21, (2018 Feb).
15. N. Sherchan, & I.P. Acharya, Numerical Analysis of Bearing Capacity of Strip Footing Adjacent to Cohesionless Soil Slope. KEC Conference, April 18, (2021) "3rd International Conference on Engineering & Technology" Kantipur Engineering College, Dhapakhel, Lalitpur, Nepal
16. F.H.P. Williams, & D.J. MacLean, *The compaction of soil: a study of the performance of plant* (No. 17). HM Stationery Office (1950).
17. S.A. Kalore, S.B. GL, R.R Mahajan Probabilistic Design Framework for Granular Filters. *Journal of Geotechnical and Geoenvironmental Engineering*. 1;**147**(11):04021133, (2021 Nov).
18. R. Chitra, M. Gupta, H. Prakash & S. Noor, Prediction of Permeability Characteristics of Fine Grained Soils and its Validation. *International Journal of Recent Development in Engineering and Technology* (2018)
19. F. D'Onza, D. Gallipoli, & S.J. Wheeler, A new procedure for determining parameter values in the Barcelona Basic Model. In *Unsaturated soils: research and applications* (pp. 93-102). Springer, Berlin, Heidelberg, (2012).
20. U.D. Patil, Response of unsaturated silty sand over a wider range of suction states using a novel double-walled triaxial testing system. The University of Texas at Arlington (2014)
21. P. Sitarenios, & M. Kavvadas, A Constitutive Model for Unsaturated soils based on a Compressibility Framework dependent on Suction and Degree of Saturation. In *E3S Web of Conferences* **9**, p. 17010). EDP Sciences, (2016)
22. Z.S. Li, F.E.M. Derfouf, A. Benchouk, N. Abou-Bekr, S. Taibi, & J.M. Fleureau,. Volume change behavior of two compacted clayey soils under hydraulic and mechanical loadings. *Journal of Geotechnical and Geoenvironmental Engineering*, **144**(4), 04018013. (2018)
23. Hoyos, L. R., & Pérez-Ruiz, D. D. A refined approach to Barcelona Basic Model using the apparent tensile strength concept. In *Unsaturated soils: Research and applications* (pp. 103-110). (2012). Springer, Berlin, Heidelberg.