A theory of loosening earth pressure above a shallow tunnel in unsaturated ground

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ABSTRACT

A theory is proposed to evaluate the loosening earth pressure (vertical earth pressure after excavation) acting on a shallow tunnel in unsaturated ground with an arbitrary groundwater level. The theory is developed based on the limit equilibrium theory, combining soil–water characteristic curves, Mohr-Coulomb failure criteria and effective stress for unsaturated soils. The proposed theory is applied to predict the vertical distribution of loosening earth pressure in unsaturated ground, which shows a significant difference from that in saturated ground. In unsaturated ground, suction contributes to the increase in effective loosening earth pressure and shear resistance. The remarkable effects of groundwater depth, soil type, and scale of overburden height and trapdoor width on loosening earth pressure are also revealed. Based on the soil–water characteristic curve, the degree of saturation decreases, which causes wet density to decrease and the total and effective loosening earth pressures to have contrary tendencies. Moreover, effective loosening earth pressures vary with soil type as the degree of saturation varies. The total loosening earth pressures are, however, very similar regardless of soil type, because wet density and shear resistance have similar tendencies. The proposed theory provides a valid model for loosening earth pressure in unsaturated ground that will be useful for shallow tunnel excavations.

Keywords: modelling; loosening earth pressure; shallow tunnel; unsaturated ground; limit equilibrium theory

Notation

D	trapdoor width
e	void ratio
H	overburden height
H_w	groundwater level
g	gravity
K	coefficient of earth pressure
s	suction
S_{max}, S_{min}	maximum and minimum degrees of saturation
S_r	degree of saturation
u_a, u_w	pore air and pore water pressure
z	vertical coordinate
α, m, n	material parameters for van Genuchten's soil–water characteristic curve
$\rho_d, \rho_t, \rho_{sat}$	dry, wet and saturation density
ρ_s	solid density
ρ_w	the density of water
σ_z	total vertical stress
σ_z^{net}	net vertical stress
$\sigma_x{}'$, $\sigma_z^{'}$	Bishop's horizontal and vertical effective stresses
τ	shear stress
ϕ	internal friction angle
χ	effective stress parameter

Introduction

The stability of a shallow tunnel may be affected by variations in pressure that result from a rise in the groundwater level. However, the ground above a tunnel is usually assumed to be in a fully-dried or fully-saturated state in practical designs so that classical theories[1] can be applied to evaluate loosening earth pressures.[2,3] Although numerical methods can be used to investigate the detailed behavior of ground during tunneling,[4,5] they require many parameters and those based on the mechanics of unsaturated soils have yet to be applied to tunneling problems. Hence, a rational method for evaluating loosening earth pressure on a tunnel in unsaturated ground is needed.

Theories for unsaturated soils have been gradually established over the past few decades.[6] The shear strength of unsaturated soils is usually evaluated using two independent stress state variables such as net normal stress and suction.[7–9] The effective stress tensor for unsaturated soils proposed by Bishop (1959) has also been applied widely to model the stress–strain behavior of unsaturated soils.[10–11] This tensor can uniquely describe the critical state stress ratio regardless of the degree of saturation.[12] Furthermore, various soil–water characteristic curve (SWCC) models have been proposed to describe the relationship between suction and degree of saturation.[13–15]

The objective of this paper is to develop a simple theory to evaluate loosening earth pressure in unsaturated ground based on the mechanics of unsaturated soils. Specifically, the aim is to model vertical earth pressure in unsaturated ground above a shallow tunnel after excavation. For this, a trapdoor problem is used,[16–19] in which tunnel excavation is directly modeled by stress release triggered by the lowering of a trapdoor (a part of the bottom boundary of the ground). The earth pressure acting on the trapdoor corresponds to the vertical earth pressure that acts on the crown of the tunnel after excavation. The theory is verified through the comparison with a classical theory for loosening earth pressure in fully-dried or fully-saturated ground.[1] Through a series of simulations using the proposed theory, differences in loosening earth pressures in different soil types such as sand, loam, and silty clay are investigated. The effects of groundwater level, the scale of overburden height, and trapdoor width on loosening earth pressure are also evaluated.

Proposed Theory for loosening earth pressure in unsaturated ground

This study uses a trapdoor problem in unsaturated ground as shown in Fig. 1. The z coordinate is taken vertically downward with the ground surface as the origin and groundwater level is set as H_w. A trapdoor of width D, located near the ground surface at a depth H, simulates stress release during tunnel excavation by its downward movement. The ground is assumed to be uniform, having a solid density of ρ_s and dry density of ρ_d (void ratio, $e = \frac{\rho_s}{\rho_d} - 1$).

Failure mode, equilibrium, and boundary conditions

Several studies have indicated that shear bands tend to develop vertically upward from both ends of a trapdoor and reach the ground surface when the overburden height, H, is no more than 2–3 times larger than the trapdoor width, D.[20–23] As our model uses a shallow trapdoor problem, vertical failure surfaces were assumed as shown in Fig. 1. For this failure mode, an equation of equilibrium of vertical force acting on a small soil element above the trapdoor is given as:

$$-\sigma_z(z + dz)D - 2\tau dz + \sigma_z(z)D + \rho_t gDdz = 0, \quad (1)$$

where $\sigma_z(z)$ is the vertical earth pressure in the ground above the trapdoor at a depth of z; τ is shear stress on the side boundary of the soil element; ρ_t is the wet density of soil; and g is the acceleration due to gravity. Applying Taylor's expansion, the equilibrium equation (1) reduces to Equation (2).

$$\frac{d\sigma_z}{dz} = \rho_t g - \frac{2}{D}\tau \tag{2}$$

As we consider a traction-free condition at the ground surface, the boundary condition is given as $\sigma_z(0) = 0$ kPa.

Pore pressure and soil suction

Pore air pressure ($u_a(z)$) and pore water pressure ($u_w(z)$) are assumed to be under static pressure conditions. The value of u_a is usually assumed to be zero (atmospheric pressure) at any depth as the density of air is negligible[8,24,25] and u_w is assumed to have a linear distribution in the vertical direction with a slope of $\rho_w g$ (ρ_w is the density of water).[8,24,26] The value of u_w becomes zero at the groundwater surface, is negative above the groundwater level, and can be written as:

$$u_w = \rho_w g(z - H_w). \tag{3}$$

Soil suction, s, is given as the difference between pore air pressure, u_a, and pore water pressure, u_w.

$$s = (u_a - u_w) = \rho_w g(H_w - z) \tag{4}$$

A simple, linear suction profile is assumed herein. However, the proposed method can incorporate the effects of infiltration and evaporation further by introducing a nonlinear suction profile.[27]

Degree of saturation and wet density

The degree of saturation, S_r, is usually given as a function of suction. Although any SWCC can be applied to the proposed theory, the classical equation proposed by van Genuchten[14] is employed herein:

$$S_r = (S_{max} - S_{min})\{1 + \langle \alpha s\rangle^n\}^{-m} + S_{min}, \tag{5}$$

where ⟨ ⟩ denotes Macaulay brackets; S_{max} and S_{min} are the maximum and minimum degrees of saturation, respectively; and α, m, and n are material parameters. From Equations (4) and (5), S_r is given as a function of depth, $S_r(z)$. It is noted that the proposed method can incorporate several factors affecting the SWCC, such as air-entry suction,[15] hydraulic hysteresis,[28] or the effect of density,[29] by replacing Equation (5) with an advanced SWCC model.[11,30]

Wet density, ρ_t, is given as a function of the degree of saturation, $S_r(z)$, by its definition, which is written as:

$$\rho_t = \frac{\rho_s + eS_r(z)\rho_w}{1+e}. \tag{6}$$

From Equations (4) to (6), S_r and ρ_t are uniquely given by depth z, respectively; ρ_t equals saturation density (ρ_{sat}) at the saturated state ($S_r = 1$) and equals dry density (ρ_d) at the dry state ($S_r = 0$).

Effective stress and shear resistance

The effective stress proposed by Bishop[10] is usually used for unsaturated soils, as it can uniquely arrange the critical state stress ratio of unsaturated soils regardless of suction, s, as shown in Fig. 2. By using this, σ_z in Equation (2) is given as:

$$\sigma_z^{'} = \sigma_z - \{\chi u_w + (1-\chi)u_a\}, \tag{7}$$

where χ is the effective stress parameter, for which S_r is usually applied.[11,31–33] Borja[34] proved that χ is equal to S_r based on the principles of thermodynamics. Therefore, in the proposed theory, Equation (7) can be written as:

$$\sigma_z^{'} = \sigma_z - u_a + S_r s. \tag{8}$$

The Mohr-Coulomb failure criterion is assumed to be satisfied by Bishop's effective stress along vertical failure surfaces (Fig. 1).

$$\tau = \sigma_x^{'} \; tan\,\phi\,, \tag{9}$$

where σ_x' is Bishop's horizontal effective stress; and ϕ is the internal friction angle of soil. Herein, the internal friction angle is a constant regardless of the degree of saturation.

Earth pressure coefficient

A coefficient of earth pressure, K, is considered for Bishop's effective stress in the ground above the trapdoor similarly as the saturated ground:[1]

$$K = \frac{\sigma_x^{'}}{\sigma_z^{'}}. \tag{10}$$

Terzaghi[1] empirically recommended K to be at unity. According to numerical simulation of the trapdoor problem in fully–dried ground, K tends to be larger than the earth pressure coefficient at rest and is near unity.[35]

Loosening earth pressure

Substituting Equations (4) to (10) into Equation (2), we can write the ordinary differential equation as:

$$\frac{d\sigma_z}{dz} = \frac{\rho_s + eS_r\rho_w}{1+e}g - \frac{2}{D}K[\sigma_z - u_a + S_r(z)\rho_w g(H_w - z)]tan\phi. \tag{11}$$

Then, the loosening earth pressure, $\sigma_z(z)$, is derived by solving Equation (11) under the boundary condition that $\sigma_z(0) = 0$ kPa. For this, a simple, explicit numerical scheme with incremental depth Δz was applied:

$$\sigma_z(z + \Delta z) - \sigma_z(z) = \frac{d\sigma_z}{dz}\Delta z\,. \tag{12}$$

Evaluation of loosening earth pressure

The proposed theory was first applied to evaluate loosening earth pressure (vertical earth pressure after lowering the trapdoor) in loamy ground under fully-dried and fully-saturated conditions to check the validity of the theory against the classical Terzaghi's theory. The loosening earth pressure in an unsaturated, loamy ground was then evaluated using the proposed theory. Afterward, the loosening earth pressures in three types of unsaturated ground (sandy, loamy, and silty clay soils) were investigated. The simulations in this section were performed under an overburden height, H, of 10.0 m and trapdoor width, D, of 10.0 m. Thus, the overburden ratio (H/D) was 1.0, for which a shallow failure mechanism with vertical failure surfaces was expected. For simulation of unsaturated ground, the groundwater level was set to 5.0 m and the vertical distributions of pore pressure and suction in the different ground types were the same, as shown in Fig. 3(a) and (b). The principal difference between the different soils is their water holding capacity. In general, water holding capacity is controlled primarily by the particle size distribution of the soil. Small particles, such as clay and silt, tend to be richer in capillaries than large sand particles, as they tend to present small pore sizes and induce a strong capillary action. Therefore, fine soils rich in capillaries retain a higher degree of saturation. Parameters for the SWCCs of the ground types were determined following Hodnett and Tomasella[36] (Table 1). The physical properties (such as density and friction angle) were the same for the different soils (Table 2). The SWCCs are compared in Fig. 4, and the vertical distributions of the degree of saturation, S_r, for sand, loam, and silty clay are shown in Fig. 3(c).

Loosening earth pressure in fully-dried or fully-saturated ground (comparison with Terzaghi's theory)

Loosening earth pressures in loamy ground under fully-dried and fully-saturated conditions were evaluated by the proposed theory and Terzaghi's theory. To model the fully-dried condition using the proposed theory for unsaturated soils, the groundwater level, H_w, was set to be very deep (10^6 m) so that soil suction, s, was remarkably large and the degree of saturation, S_r, was almost zero. For fully-saturated ground, H_w was set to 0.0 m.

Loosening earth pressure was evaluated by the proposed theory and Terzaghi's theory in the fully-dried and fully-saturated conditions (Figs 5 and 6). The initial earth pressure distribution was calculated as the overburden pressure, which represents the earth pressure at rest before lowering of the trapdoor. The saturation density, $\rho_{sat}\left(= \rho_d - \frac{\rho_s-\rho_d}{\rho_s}\rho_w\right)$, is 1.90 g/cm^3. Figures 5 and 6, show that both the total and effective loosening earth pressures are lower than the corresponding initial values. This suggests that the earth pressure becomes reduced by vertical-upward shear stress along failure surfaces acting on the ground above the trapdoor. Both the total and effective loosening earth pressures calculated by the proposed theory were identical with those calculated by Terzaghi's theory, which validates the consistency of the proposed theory.

Loosening earth pressure in the unsaturated ground

The proposed theory was applied further to investigate loosening earth pressure in unsaturated loamy ground. Total and effective loosening earth pressures were lower than the corresponding initial earth pressures at all depths (Figure 7). In the unsaturated zone above the groundwater level (z < 5 m), the effective loosening earth pressure was larger than the total loosening earth pressure. This indicates that the proposed theory can consider the contribution of matric suction to the increase in effective confining pressure and increase in frictional resistance (τ) in the unsaturated zone. Therefore, the more significant arching effect in unsaturated ground, which is known to occur, can be appropriately evaluated. On the other hand, the correlation between total and effective loosening earth pressure magnitudes is reversed in the saturated zone below the groundwater level.

Loosening earth pressure in different types of unsaturated ground (sand, loam, and silty clay soils)

The loosening earth pressure in three types of unsaturated ground (sandy, loamy, and silty clay soils) were investigated. The distributions of soil suction in the different ground types were identical, as shown in Fig. 3(b). The same physical properties were assumed for the different ground types as shown in Table 2. This is because the groundwater levels were identical (H_w= 5.0 m). However, vertical distribution of the degree of saturation were different (Fig. 3(c)) as different sets of parameters (Table 1; Hodnett and Tomasella[38]) were applied for the SWCCs. Differences in the distributions of degree of saturation resulted in differences in the distribution of wet density as shown in Fig. 3(d).

Figure 8 shows the distributions of the loosening earth pressure for the three ground types. The effective earth pressure in clay and loam ground is much higher than that in the sandy ground. This suggests that shear resistance of the soil along the sliding surfaces, which is usually referred to as "arching effect", becomes more substantial in the clayey and loamy ground compared with the sandy ground. This can explain why the excavation of a tunnel in sandy ground is relatively more challenging than doing so in clayey and loamy ground. However, the differences between the total loosening earth pressures of the ground types is small, although the total loosening earth pressure in the sandy ground is slightly higher than that in the other types of soils.

Effect of the groundwater level on loosening earth pressure

A series of simulations was carried out using the proposed theory utilizing different groundwater levels to explore its effect on loosening earth pressure. The trapdoor width, D, was fixed to 10.0 m and the parameters for loam given in Table 1 were used throughout this section.

The overburden height, H, was set to $1.0D$ and the groundwater level, H_w was set to different depths (0.0 m, 2.5 m, 5.0 m, 7.5 m, and 10.0 m) for each simulation. Figure 9 shows the vertical distributions of the degree of saturation, S_r, the product of suction and degree of saturation, sS_r, and total and effective loosening earth pressures. As the effective stress, $\sigma_z^{'}$, in Equation (8) can be decomposed into net stress, $\sigma_z^{net}(=\sigma_z-u_a)$, sS_r represents the contribution of suction on the increase in effective confining pressure. In the case of a deeper H_w, the degree of saturation was smaller at any depth in the unsaturated zone (Fig. 9(a)) and the wet density was also lower. This made overburden pressure lower in the deeper H_w case. Meanwhile, sS_r is larger (Fig. 9(b)) in the deeper H_w case, which made effective earth pressure higher (Fig. 9(d)) and total earth pressure lower (Fig. 9(c)). According to Equation (9), the shear resistance along the vertical slip surfaces, which works to reduce the vertical earth pressure on the trapdoor, also becomes more substantial in the case of a deeper H_w. Owing to the effects of a lower overburden pressure and higher shear resistance, the total loosening pressure becomes significantly smaller in the deeper H_w case.

The effect of the groundwater level on the loosening earth pressure acting on the trapdoor was further investigated under different overburden heights, $H(\leq 30.0\text{ m})$, and groundwater levels, $H_w(=0.0, 5.0, 10.0, 15.0, \text{and } 20.0\text{ m})$. Figures 10(a) and 10(b) show the total and effective loosening pressures normalized by total and effective overburden pressure at the depth, H, of $1.0D$, respectively (where ρ_{sat} and ρ_{sub} are the saturation and submerged densities, respectively).

The total loosening earth pressure became higher both with the increase in overburden height, H, and decrease in the groundwater level, H_w. Therefore, groundwater level and overburden height had a significant effect on the total loosening pressure. On the other hand, the mean effective stress varied depending on whether the groundwater level is shallower or deeper than the overburden height. The effective earth pressure increased monotonically with the overburden height in the unsaturated zone where the overburden height, H, was less than the groundwater level H_w. In the case where the trapdoor is located below the groundwater level ($H > H_w$), the effective loosening earth pressure would still increase with the increase in the overburden when H_w = 5.0 m, but it would decrease with the overburden when H_w is 10.0 m or larger.

Scale effects on loosening earth pressure

The characteristics of the loosening earth pressures in unsaturated ground were further investigated in terms of the scale effect. In this section, a series of simulations was carried out using the parameters for loamy ground (Table 1) by varying the width of the trapdoor, D (i.e., 5.0 m, 10.0 m, and 20.0 m). For each trapdoor width, the overburden height, H, was varied from 0.0 to $3.0D$ with keeping the ratio of the groundwater level, H_w, to the trapdoor width, D, constant.

Scale effect in fully-saturated ground ($H_w/D = 0$)

The scale effect on the total and effective loosening earth pressures in the fully-saturated ground ($H_w = 0.0$ m) was investigated herein. Figure 11 shows the total and effective loosening earth pressures normalized by the corresponding overburden pressures for the overburden height of $1.0D$. The normalized total and effective loosening earth pressures were identical, regardless of the width of the trapdoor, D. Therefore, trapdoor scale can be ignored in fully-saturated ground, which has been demonstrated by previous studies.[21]

Scale effect in unsaturated ground ($H_w/D > 0$)

The scale effect on the total and effective loosening earth pressures in the partially-saturated ground for three kinds of groundwater level ratio, H_w/D, were investigated. The total and effective loosening earth pressures were normalized by their initial values of saturated ground for the overburden depth of $1.0D$.

Figure 12 shows the vertical distribution of the normalized total and effective loosening earth pressures, degree of saturation, and wet density for the case where the groundwater level, H_w, was $1.5D$. The normalized total and effective pressures in the unsaturated zone for the different trapdoor widths were different, which implies trapdoor scale affects the normalized loosening earth pressure in the unsaturated ground. For the case of the larger trapdoor width, the normalized effective loosening earth pressure in the unsaturated zone tended to be lower and the normalized total loosening earth pressure tended to be higher. These differences in the distributions of the normalized loosening pressures are related to the differences in the distributions of saturation degree and wet density.

Figures 13 and 14 show the distributions of the normalized loosening pressures, degree of saturation, and wet density for the cases where the groundwater level, H_w, was $0.5D$ and $2.0D$, respectively. The scale effect was more significant in the higher H_w case. This is because, in the higher H_w case, the unsaturated zone was thicker, suction tended to be stronger, and the shear resistance along the slip surfaces was larger. These results suggest that the scale effect on the normalized total and effective loosening earth pressure exists in unsaturated grounds, particularly for the deeper groundwater levels. This should be considered in the excavation of tunnels in unsaturated ground.

However, by scaling down the α parameter of the SWCC with the increase in the trapdoor width, the distributions of the normalized total and effective loosening earth pressures in the partially-saturated ground became identical regardless of the trapdoor width. For the case of the overburden height of 3D and groundwater level of 2D, the loosening earth pressures were calculated for three different trapdoor widths (5 m, 10 m, and 20 m), with the scaled parameter α given in Table 3. The distributions of the degree of saturation, wet density, and the normalized total and effective loosening earth pressures became identical regardless of the overburden height ratio, as shown in Figure 15.

Conclusions

A simple theory for evaluating loosening earth pressure acting on a shallow trapdoor in unsaturated ground is proposed in this paper. The proposed theory was developed based on the limit equilibrium method by combining Bishop's effective stress for unsaturated soils, a classic SWCC curve, and Mohr-Coulomb failure criteria. The proposed theory predicted valid loosening earth pressures in both fully-saturated and fully-dried grounds compared to pressures calculated by Terzaghi’s theory.

Differences in effective loosening earth pressure were demonstrated for different types of unsaturated ground (sandy, loamy, and silty clay grounds). In unsaturated ground with high water retention (such as clay soils), higher effective confining pressure and higher shear resistance along the slip surfaces can be expected.

Depth of the groundwater level was shown to have a significant effect on total and effective loosening earth pressures. In unsaturated ground, the total loosening earth pressure was lower than that in the saturated ground, but the effective loosening earth pressure tended to be higher. Therefore, the mechanical stability of a shallow tunnel in unsaturated ground will vary with groundwater level fluctuations.

The normalized loosening pressure was identical irrespective of scale in fully-saturated ground, confirming that the scale effect is not significant in fully-saturated ground. In unsaturated ground, however, the scale effect on the normalized loosening earth pressure was significant, particularly in the case of deeper groundwater level. With a broader trapdoor, the normalized effective loosening earth pressure in the unsaturated zone tended to be smaller, but the normalized total loosening earth pressure tended to be more significant. However, by scaling down the SWCC parameter α with the increase in the width of the trapdoor, unique distributions for the normalized loosening earth pressures could be achieved and the scale effect in the unsaturated ground disappeared.

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REFERENCES

1. Terzaghi K. Theoretical soil mechanics. New York: John Wiley & Sons; 1943. 528 p.
2. Zhang HF, Zhang P, Zhou W, Dong S, Ma BS. A new model to predict soil pressure acting on deep burial jacked pipes. Tunneling Underground Space Technol 2016;60:183-196.
3. Chen KH, Peng FL. An improved method to calculate the vertical earth pressure for deep shield tunnel in Shanghai soil clay. Tunneling Underground Space Technol 2018;75:43-66.
4. Shahin HM, Nakai T, Zhang F, Kikumoto M, Nakahara E. Behavior of ground and response of existing foundation due to tunneling. Soils Found 2011;51(3):395-409.
5. Kong XX, Liu QS, Zhang QB, Wu YX, Zhao J. A method to estimate the pressure arch formation above underground excavation in rock mass. Tunneling Underground Space Technol 2018;71:382-390.
6. Fredlund DG, Rahardjo H. Soil Mechanics for Unsaturated Soils. New York: Wiley-Interscience; 1993. 517 p.
7. Fredlund DG, Morgenstern NR, Widger RA. The shear stress of unsaturated soils. Can Geotech J 1978;15:313-321.

8. Pufahl D, Fredlund DG, Rahardjo H. Lateral earth pressures in expansive clay soil. Can Geotech J 1983;20:228-241.
9. Gan JKM, Fredlund DG, Rahardjo H. Determination of the shear strength parameters of an unsaturated soil using the direct shear test. Can Geotech J 1988;25:500-510.
10. Bishop AW. The principle of effective stress. Tek Ukebl 1959;39:859-863.
11. Komolvilas V, Kikumoto M. Simulation of liquefaction of unsaturated soil using critical state soil model. Int J Numer Anal Meth Geomech 2017;41:1217-1246.
12. Sivakumar V. A critical state framework for unsaturated soil. Ph.D. Thesis; Univ. of Sheffield, UK; 1993.
13. Brooks RH, Corey AT. Hydraulic properties of porous medium. Am Soc Argic Eng Trans 1964;7:26-28.
14. van Genuchten MTh. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 1980;44:892-898.
15. Fredlund DG, Xing A. Equations for the soil-water characteristic curve. Can Geotech J 1994;31:521-532.
16. Terzaghi K. Stress distribution in dry and saturated sand above a yielding trapdoor. In: Proceedings of the 1st International Conference on Soil Mechanics and Foundation Engineering. Cambridge, Massachusetts; 1936:35-39.
17. Murayama S, Matsuoka H. Earth pressure on tunnels in sandy ground. Proc JSCE 1971;187:95-108 (in Japanese).
18. Adachi T, Kimura M, Kishida K. Experimental study on the distribution of earth pressure and surface settlement through three-dimension trapdoor tests. Tunneling Underground Space Technol 2003;18:171-183.
19. Costal YD, Zornberg JG, Bueno BS, Costal CL. Failure mechanisms in sand over a deep active trapdoor. J Geotech Geoenviron Eng 2009;135(11):1741-1753.

20. McNulty JW. An experiment study of arching in sand, Technical Report No. I-674, US. Waterways Experiment Station, Vicksburg; 1965.
21. Evans CH. An examination of arching in granular soils. Master's Degree Thesis; Massachusetts Institute of Technology, USA; 1984.
22. Koutsabeloulis NC, Griffiths DV. Numerical modeling of the trap door problem, Geotechnique 1989;39(1):77-89.
23. Kikumoto M, Kishida K. Mechanical behavior on the Sandy ground through the 3-D Trapdoor Experiment. In: Proceedings of the 12th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering. Vol 1. Singapore, Singapore; 2003:863-866.
24. Vahedifard F, Leshchinsky D, Mortezaei K, Lu N. Effective stress-based limit-equilibrium analysis for homogeneous unsaturated slopes. Int J Geomech 2016;16(6):D4016003.
25. Sahoo JP, Ganesh R. Active earth pressure on retaining walls with unsaturated soil backfill. In: Bouassida M, Meguid MA, eds. Ground Improvement and Earth Structures. New York: Springer; 2018.
26. Ng CWW, Menzies B. Advanced Unsaturated Soil Mechanics and Engineering. London: Taylor & Francis; 2007. 712 p.
27. Vo T, Russel AR. Bearing capacity of strip footing on unsaturated soils by the slip line theory. Comput Geotech 2016;74:122-131.
28. Hains WB. Studies in the physical properties of soil. V. The hysteresis effect in capillary properties, and the modes of moisture distribution associated therewith. J Agric Sci 1930;20:97-116.
29. Tarantino A, Tombolato S. Coupling of hydraulic and mechanical behavior in unsaturated compacted clay. Geotechnique 2005;55(4):307-317.
30. Kikumoto M, Kyokawa H, Nakai T, Shahin HM. A simple elasto–plastic model for unsaturated soils and interpretations of collapse and compaction behaviours. In: Alonso E,

Gens A, eds. Proceedings of the 5th International Conference on Unsaturated Soils. Boca Raton: CRC Press; 2010:849-855.

31. Schreffler B. The finite element method in soil consolidation (with applications to surface subsidence). Ph.D. Thesis. Swansea Univ., UK; 1984.
32. Öberg A, Sällfors G. Determination of shear strength parameters of unsaturated silts and sands based on the water retention curve. Geotech Testing J 1997;20(1):40-48.
33. Lu N, Likos WJ. Suction Stress Characteristic Curve for Unsaturated Soil. J Geotech Geoenviron Eng 2006;132(2):131-142.
34. Borja RI. (2006). On the mechanical energy and effective stress in saturated and unsaturated continua. Int J Solids Struct 2006;43:1764-1786.
35. Kikumoto M, Kimura M, Kishida K, Adachi T. 3d trapdoor tests and its simulation on mechanical behavior of ground during tunneling. J JSCE 2003;750/III-65:145-158 (in Japanese).
36. Hodnett MG, Tomasella J. Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: a new water-retention pedo-transfer functions developed for tropical soils. Geoderma 2002;108:155-180.

Figure captions

Fig. 1. Trapdoor problem in unsaturated soil.

Fig. 2. Relation between mean stress, p'', and deviator stress, q, of Bishop's effective stress (replotted from Sivakumar[12]).

Fig. 3. Vertical distribution of (a) pore pressure, u_a, u_w; (b) suction, s; (c) degree of saturation, S_r; and (d) wet density, ρ_t (overburden height, H = 10.0 m, width of trapdoor, D = 10.0 m, and groundwater level, H_w = 5.0 m).

Fig. 4. Soil–water characteristic curves for sand, loam, and silty clay.

Fig. 5. Depth *vs*. loosening earth pressure in fully-dried ground.

Fig. 6. Depth *vs*. total and effective loosening earth pressures in the fully-saturated ground (groundwater level, H_w = 0.0 m).

Fig. 7. Depth *vs*. total and effective loosening earth pressures in unsaturated ground (groundwater level, H_w, = 5.0 m).

Fig. 8. Vertical distribution of (a) total loosening earth pressure; and (b) effective loosening earth pressure in sand, loam, and silty clay (overburden height, H = 10.0 m, and groundwater level, H_w = 5.0 m).

Fig. 9. Vertical distribution of (a) degree of saturation; (b) product of degree of saturation and suction; (c) total loosening earth pressure; and (d) effective loosening earth pressure in loamy ground. (overburden height, H = 10 m, and groundwater level, H_w = 0.0, 2.5, 5.0, 7.5, 10.0 m).

Fig. 10. Overburden height *vs*. (a) total loosening earth pressure and (b) effective loosening earth pressure in unsaturated ground at different groundwater levels (overburden height, H = 0–30 m, width of trapdoor, D = 10 m, and groundwater level, H_w = 0, 5, 10, 15, 20 m).

Fig. 11. Vertical distribution of (a) total loosening earth pressure; (b) effective loosening earth pressure in loamy ground (overburden ratio, H = 3.0D, and groundwater level, H_w = 0.0D).

Fig. 12. Vertical distribution of (a) degree of saturation; (b) wet density; (c) total loosening earth pressure; and (d) effective loosening earth pressure in loamy ground (overburden, H = 3.0D, and the groundwater level ratio, H_w = 1.5D).

Fig. 13. Vertical distribution of (a) degree of saturation; (b) wet density; (c) total loosening earth pressure; and (d) effective loosening earth pressure in loamy ground (overburden ratio, H = 3.0D, and the groundwater level ratio, H_w = 0.5D).

Fig. 14. Vertical distribution of (a) degree of saturation; (b) wet density; (c) total loosening earth pressure; and (d) effective loosening earth pressure in loamy ground (overburden ratio, H = 3.0D, and groundwater level ratio, H_w = 2.0D).

Fig. 15. Vertical distribution of (a) normalized degree of saturation; (b) normalized sS_r; (c) normalized effective loosening earth pressure; and (d) normalized total loosening earth pressure in loamy ground (overburden ratio, H = 0.0–3.0D, and groundwater level ratio, H_w = 2.0D).