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Effect of Soil-Water Characteristic on the Stability of Unsupported Vertical Cuts

Mahsa Shafaei Bajestani, Won-Taek Oh, Othman Nasir
Department of Civil Engineering – University of New Brunswick, Fredericton, New Brunswick, Canada

ABSTRACT

A variety of geotechnical projects are initiated with unsupported vertical cuts in vadose zone. In this case, it is crucial to consider the contribution of soil suction in analyzing the stability of unsupported vertical cuts. Soil-Water Characteristic Curve (SWCC) is a main tool that can be used to estimate the variation of shear strength of soil with respect to soil suction. SWCC can be obtained using different fitting models based on experimental data. In this study, a series of numerical analyses are carried out to investigate the influence of SWCCs obtained using different SWCC fit models (i.e. Brooks & Corey, van Genuchten, and Fredlund & Xing models) on the safe height of unsupported vertical cuts in sandy soil. The analysis results showed that the safe heights estimated with the van Genuchten model are most reasonable for various levels of ground water tables.

RÉSUMÉ

Divers projets géotechniques sont lancés avec des coupes verticales non prises en charge dans la zone vadose. Dans ce cas, il est crucial de considérer la contribution de l'aspiration du sol dans l'analyse de la stabilité des coupes verticales non supportées. La courbe caractéristique sol-eau (SWCC) est un outil principal qui peut être utilisé pour estimer la variation de la résistance au cisaillement du sol par rapport à l'aspiration du sol. SWCC peut être obtenu en utilisant différents modèles d'ajustement basés sur des données expérimentales. Dans cette étude, une série d'analyses numériques est effectuée pour étudier l'influence des SWCC obtenus à l'aide de différents modèles d'ajustement SWCC (c.-à-d. Brooks & Corey, van Genuchten et Fredlund & Xing) sur la hauteur de sécurité des coupes verticales non prises en charge dans le sol sablonneux. Les résultats de l'analyse ont montré que les hauteurs de sécurité estimées avec le modèle de van Genuchten sont les plus raisonnables pour différents niveaux de nappes phréatiques.

1 INTRODUCTION

In geotechnical engineering practice, many projects, involving foundations, landfills, pipelines, storm drains etc. are initiated with unsupported vertical cuts (i.e. excavations or trenches). Designing of unsupported cuts requires utmost precaution since failures in unsupported vertical cuts can cause not only damages to the adjacent structures but also severe injuries and death of field workers (Richard et al. 2020). Changes in pore-water pressure, surface loading, and vibration are the most predominant causes of failures in unsupported cuts. According to Occupational Health and Safety Code (OHSC, Alberta 2009), failures in unsupported vertical cuts can involve multiple tons of soil. This is more than enough weight to suffocate a human. The Guide for Excavation Work categorized the failure mechanisms in unsupported vertical cuts into four types: spoil pile slide, side wall shear, slough-in (cave-in) and rotation (Workplace Safety and Health Division 2007).

For the sake of preventing fatalities and severe injuries of field workers, each Canadian province imposes strict regulations. The regulations identify the maximum allowable height of an unsupported vertical trench (i.e. safe height, Table 1), maximum sloping and benching angles, minimum allowable distance from other structures, and minimum distance for stockpiling of excavated or backfill materials from the trench.

Table 1. Maximum allowable height of an unsupported vertical trench in Canadian provinces

Provinces in Canada	Safe height (m)
BC, NB, ON, QC, SK, NL, PE	1.20 (4 ft)
AB, MB	1.50 (5 ft)

The problem with enforcing a universal safe height throughout each province is that the standards are solely based on empirical data rather than considering the practical and field conditions. This may lead to over, or under conservative protective measures being used during construction. A typical preliminary phase of any construction project involves trenching and setting infrastructure within the unsaturated zone of the proposed site; thus, the safe height of unsupported vertical cut should be determined by extending the mechanics of unsaturated soils considering the distribution of matric suction between the ground surface and ground water table. De Vita et al. (2008) reported that stable unsupported vertical cuts can be approximately 15 m deep in a Pozzolan deposit. Richard et al. (2020) concluded that the critical height of an unsupported vertical cut in sand increases with increasing depth of the ground water table up to a point and then decreases rapidly as the depth of the ground water table is further increased.

Soil-Water Characteristic Curve (SWCC) is a main tool in determining the variation of shear strength of unsaturated soil. Various SWCC fit models are available in the literature. However, it is time consuming to determine the fitting parameters of SWCC. Seki (2007) developed a program that can be used to estimate the fitting parameters of the existing SWCC fit models in quick and efficient way. In the present study, an attempt was made to estimate the safe heights of unsupported vertical cuts in unsaturated sand using the SWCCs established with three different SWCC fit models. It was assumed that safe height is a depth of which factor of safety (FOS) is 1.2.

2 SOIL PROPERTIES

It was assumed that unsupported vertical trenches were excavated into Edosaki sand. This soil was used by Gallage et al. (2013) to study the hydraulic conductivity of unsaturated sandy soil. Grain-size distribution of the soil is shown in Figure 1. Basic properties of the soil are summarized in Table 2.

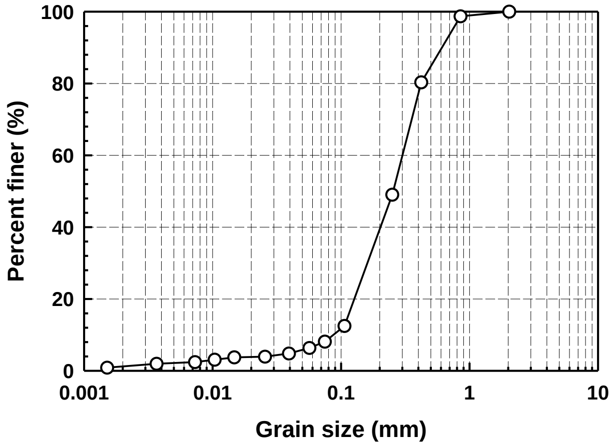


Figure 1. Grain-size distribution of Edosaki sand (after Gallage et al. (2013))

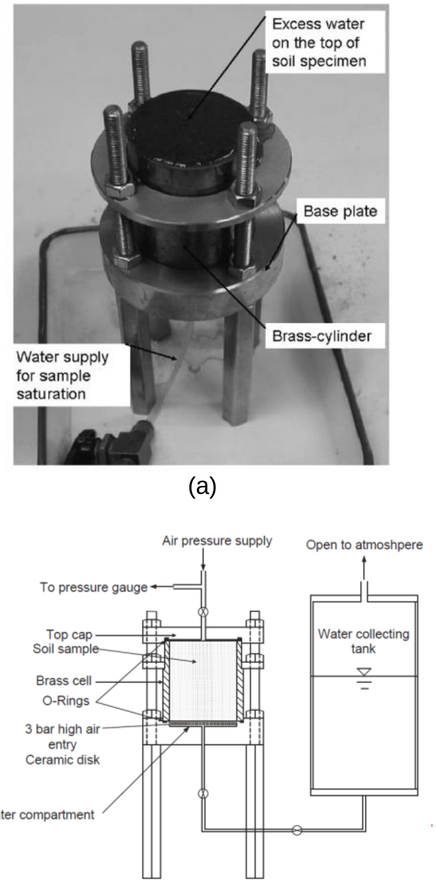
Table 2. Basic properties of Edosaki sand (Gallage et al. 2013; Eab et al. 2015)

Properties	Edosaki sand
Specific gravity, G_s	2.75
Sand content (%)	83.6
Fines content (%)	16.4
Plasticity index (%)	NP
Soil classification (USCS)	SM
Maximum dry density, $\gamma_{d(max)}$ (kN/m^3)	16.9
Saturated unit weight density, γ_{sat} (kN/m^3)	17.4

Gallage et al. (2013) used a Tempe pressure cell (Figure 2) to achieve several volumetric water contents versus suction measurements. In this study, these measured data were used to obtain best-fit curves using three different SWCC fit models as follow:

a. Brooks and Corey (1964) (B&C) Eq. 1,
b. van Genuchten (1980) (VG), Eq. 2, and
c. Fredlund and Xing (1994) (F&X) Eq. 3.

The fitting parameters used for each model are obtained using the nonlinear fit program developed by Seki (2007) (available at https://seki.webmasters.gr.jp/swrc/). The best-fit curves and fitting parameters are shown in Figure 3 and Table 3, respectively.



(a)

(b)

Figure 2. (a) Photo and (b) schematic diagram of Tempe pressure cell used to measure data points for SWCC (Gallage et al. 2013)

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \begin{cases} \left(\dfrac{\psi}{\psi_b}\right)^{-\lambda} & \psi > \psi_b \\ 1 & \psi_b \ge \psi \end{cases} \qquad [1]$$

$$S_e = \left[\frac{1}{1+(\alpha\psi)^{n_{VG}}}\right]^{m_{VG}} \qquad (m = 1 - 1/n) \qquad [2]$$

$$S_e = \left[\frac{1}{ln\left[e+(\psi/a)^{n_{FX}}\right]}\right]^{m_{FX}} \qquad [3]$$

where, S_e = effective degree of saturation, θ = volumetric water content, θ_s = saturated volumetric water content, θ_r = residual volumetric water content, ψ = suction, ψ_b = air-entry value, λ = pore-size distribution index, a, n_{VG}, m_{VG} = fitting parameter for VG model, e = Euler's number, and α, n_{FX}, m_{FX} = fitting parameters for F&X model.

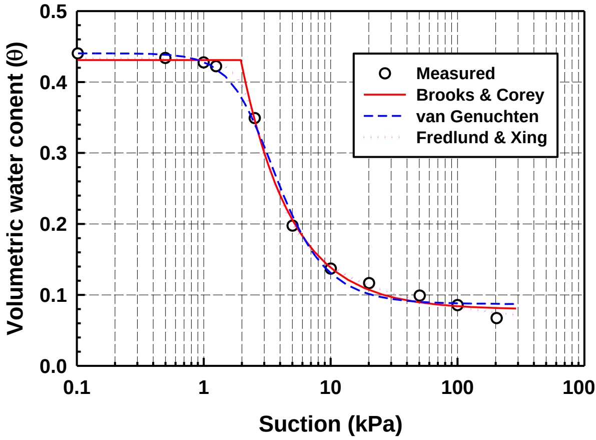


Figure 3. Measured data from Tempe pressure cell tests (Gallage et al. 2013) and SWCCs obtained with three different SWCC fit models

Table 3. Fitting parameters used for each SWCC fit models in Figure 3.

Brooks & Corey		van Genuchten		Fredlund & Xing	
λ	1.094	α_{VG}	0.34	a_{FX}	2.27
ψ_b	1.96	n_{VG}	2.66	n_{FX}	4.82
θ_r	0.079	θ_r	0.08	m_{FX}	0.57
θ_s	0.43	θ_s	0.44	θ_r	0.0004
				θ_s	0.43

3 METHODOLOGY

Slope stability analyses were performed to evaluate the safe height of unsupported vertical cuts in unsaturated sand (i.e., Edosaki sand) using commercial geotechnical modeling software, SLOPE/W (GeoStudio 2020). Analyses were carried out for four levels of ground water table: 0.3, 0.5, 1 and 2 m from the soil surface. Initial pore-water pressures were specified by drawing an initial water table, which distributes hydrostatic positive and negative pore-water pressures below and above the water table, respectively.

Excavation causes a temporary drop in the phreatic line, which eventually rebounds with time after the completion of excavation. In other words, stability of an unsupported cut continuously varies throughout the excavation process. Richard (2018) conducted numerical analysis to investigate the critical height of unsupported vertical cut in cohesionless soil. The results showed that factor of safety (FOS) decreases with time due to the rebound of phreatic line until the pore-water pressure reaches an equilibrium condition (Figure 4). The magnitude of drop in phreatic line and its rebound time are governed by excavation rate and permeability function of the soil, respectively. Hence, in the present study, it was assumed that phreatic line is not affected by soil excavation for conservative analysis (i.e. the location of phreatic line at the end of excavation is the same as the original level). Excavation was simulated by removing the material from the regions (i.e. deactivating regions) in 0.02 m increments.

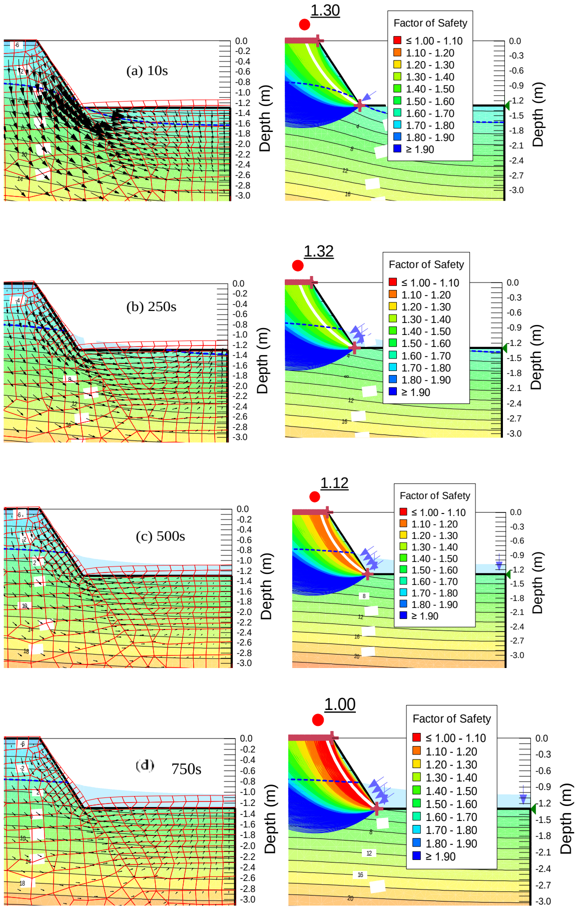


Figure 4. Variation of deformation, pore-water pressure, and FOS with time for (a) 10, (b) 250 (c) 500, and (d) 750 seconds after 1.3m excavation stage in sand with initial ground water table at 0.7 m (Richard 2018).

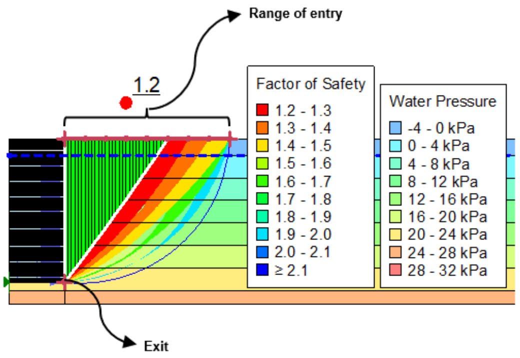


Figure 5. Staged excavation in SLOPE/W

After each excavation stability analysis was carried out using Morgenstern-Price method (Limit Equilibrium Method) until FOS = 1.2 is achieved. This depth was then denoted as safe height. 'Entry and Exit' slip surface opting in SLOPE/W was used, assuming the failure surface passes through the toe of unsupported vertical cuts (Figure 5).

Eab et al. (2015) performed direct shear tests to determine the shear strength parameters of Edosaki sand compacted at optimum moisture content. The cohesion (c') and internal friction angle (ϕ') were estimated to be 4.8 kPa and 28.58°, respectively. However, when the measure data were reanalyzed, forcing the best-fit line to pass the origin the internal friction angle was estimated to be 35.79° with relatively high R-squared value (i.e. 0.977) (Figure 6). Hence, in this study, both sets of shear strength parameters (i.e. 4.8 kPa – 25.85° and 0 kPa – 35.79°) were used in determining the safe height of the unsupported vertical cuts.

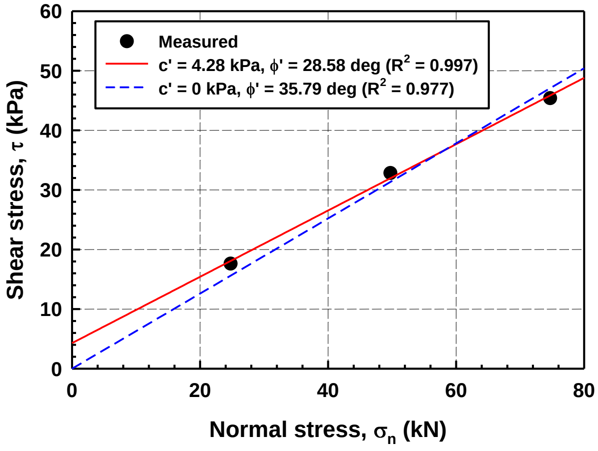


Figure 6. Direct shear test results for Edosaki sand

In SLOPE/W, contribution of matric suction towards the shear strength of unsaturated soil (i.e. total cohesion) can be modeled using either Eq. 4 (Fredlund et al. 2012) or Eq. 5 (Vanapalli et al. 1996). Eq.4 is used to model linear variation of shear strength of unsaturated soils and Eq. 5 for non-linear variation (used in this study). In case where a user is opt for Eq. 5, the user should specify the ratio of residual volumetric water content to saturated volumetric water content.

$$C = c' + (u_a - u_w)\tan\phi^b \qquad [4]$$

$$C = c' + (u_a - u_w)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi' \qquad [5]$$

where, C = total cohesion, and ϕ^b = angle defining the increase in strength due to the negative pore-water pressure

According to Table 3, the θ_r values were 18.4%, 19.8%, and 0.1% of θ_s when B&C, VG, and F&X models were used, respectively. The θ_r/θ_s ratio (in %) for F&X model was significantly low compared to the others. However, the θ_r/θ_s ratios obtained using the graphical method were approximately the same with 18.6% (B&C), 18.17% (VG), and 16.0% (F&X). Hence, the additional SWCC was also used in the analysis by having different fitting parameters for F&X model (i.e. a_{FX}, m_{FX}, n_{FX}) such that θ_r/θ_s = 16.0% (Figure 7).

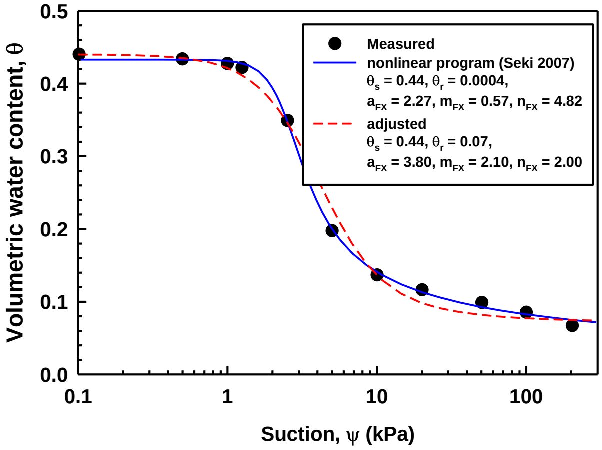


Figure 7. SWCCs established with the nonlinear fit program (Seki 2007) and adjusted to have θ_r/θ_s = 16% using F&X model

4 PRACTICAL SCENARIOS

Two scenarios were assumed in estimating the safe height of unsupported vertical cuts in Edosaki sand:

Scenario I: An engineer obtained SWCCs and θ_r using a nonlinear fitting program (Seki 2007). Effective shear strength parameters available in Eab et al. (2015) were used in computing the contribution of matric suction towards the shear strength of unsaturated soil.

Scenario II: An engineer used the same SWCCs as Scenario I for B&C and VG models. However, for F&X model, fitting parameters were adjusted such that θ_r/θ_s ratio become similar to those of B&C and VG models. Shear strength parameters were determined by reanalyzing the data available in Eab et al. (2015).

Table 4 summarizes the parameters used for Scenarios I and II. As explained previously, in cases of SWCCs obtained using B&C and VG models, the same SWCCs were used for both scenarios since differences in θ_r/θ_s ratios obtained using the nonlinear fit program and graphically method were not significant. Figure 8 and Figure 9 show the variation of total cohesion with respect to suction for Scenario I and II, respectively.

Table 4. Summary of the parameters used for Scenarios I and II

Scenario	c' (kPa)	ϕ' (°)	θ_r/θ_s (%)		
			B&C	VG	F&X
I	4.28	28.58	18.4	19.8	0.1
II	0	35.79	18.6	18.17	16.00

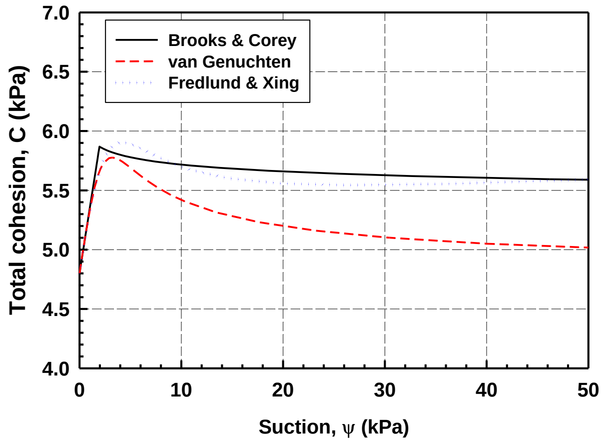


Figure 8 Variation of total cohesion with respect to suction for Scenario I

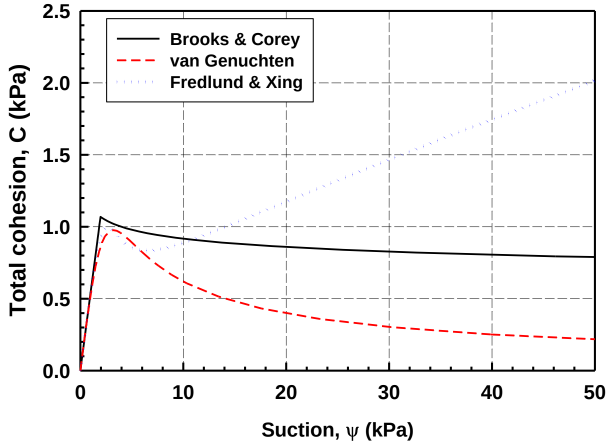


Figure 9. Variation of total cohesion with respect to suction for Scenario II

5 RESULTS AND ANALYSIS

Figure 10 shows the variation of the safe height with respect to the depth of the groundwater table for Scenario I and II. The ranges of safe height were 2 – 4 m and 0.32 – 0.68 m for Scenario I and II, respectively. This indicates that small amount of effective cohesion (i.e. c = 4.8 kPa in this study) can lead to approximately 6 times higher safe height. For Scenario I, the safe height becomes minimum with ground water table at 0.5 m. This is because when the ground water table is at a shallow depth, the contribution of total cohesion towards negative earth pressure is less than that of effective weight of soil towards positive earth pressure (Richard 2018). This behaviour is not observed in a sandy soil with zero cohesion. When compared with the safe height using B&C and VG models for the ground water table 2 m (i.e. 3.34 m), the one obtained using F&X was 1.2 times higher (i.e. 4 m). This is because the θ_r/θ_s ratio using F&X model (i.e. 0.1%) was significantly low compared to those of B&C (18.4%) and VG (19.8%) models. The suction value at the soil surface with ground water table at 2 m is 19.6 kPa (= 2 m × 9.81 kN/m^3), which is close to the residual suction value of Edosaki sand.

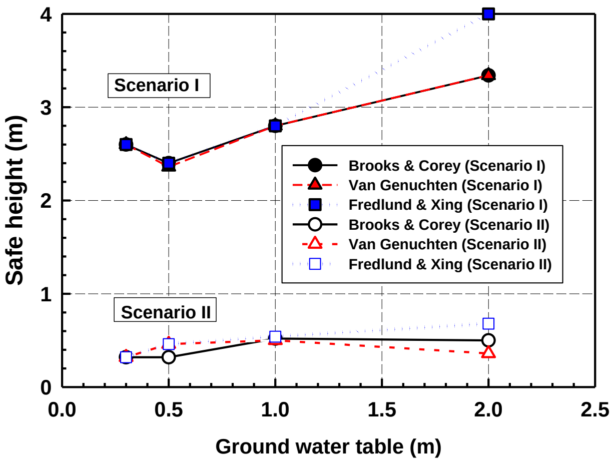


Figure 10. Variation of safe height with different groundwater table locations for Scenario I and II

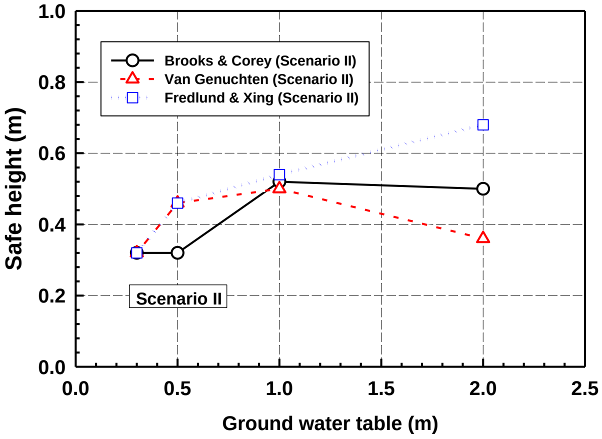


Figure 11. Variation of safe height with different groundwater table locations for Scenario II

Figure 11 shows the variation safe height with respect to the depth of ground water table for Scenario II. In case of sandy type of soils with zero cohesion, the shear strength of soil increases up to a certain suction value and then starts decreasing as suction approaches the residual suction value. For the suction value greater than the residual suction, the contribution of suction towards shear strength becomes negligible. Richard (2018) investigated the variation of critical height of unsupported vertical cut in sand through numerical analysis. The variation of critical height with respect to groundwater table shows the same trend as the shear strength. This behaviour was well captured in this study when SWCC was established using V&G model.

6 SUMMARY AND CONCLUSIONS

Excavation or trenching should be carried out with extreme caution because the failures can cause damages to the adjacent structures or fatalities. Most of unsupported cuts involve soils in vadose zone, which requires to consider the influence of soil suction in estimating their stability. In the present study, a series of numerical analyses were conducted to estimate the safe height of unsupported vertical cuts in Edosaki sand. The SWCCs were obtained using three different SWCC fit models, including Brooks and Corey (1964), van Genuchten (1980), and Fredlund and Xing (1994). The analysis results showed that even small magnitude of effective cohesion of soil (4.8 kPa in this study) can lead to the significant difference in the safe heights. This indicates that the shear strength parameters of sandy soil should be estimated carefully. Depending on the effective cohesion values (i.e 0 or 4.8 kPa), the variation of safe height with respect to the depth of ground water table showed typical behaviors of unsupported vertical cuts in cohesive or cohesionless soils.

When cohesion is considered, using different SWCC fit models showed the same trend in the variation of safe height with respect to the depths of ground water table less than 1 m. However, for the deep ground water table (i.e. 2 m in this study), there was slight discrepancy in the safe height, which was attributed to the θ_r used for each SWCC fit model. The analysis results showed that the safe heights estimated with the van Genuchten model are most reasonable for various depths of ground water tables with and without cohesion.

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