Determination of Critical Height of Unsupported Vertical Cuts Using Experimental and Numerical Methods

Z. Nil Kutlu, Gregory Brennan, and Won Taek Oh

Abstract Stability of unsupported cuts are commonly analyzed numerically as a 2-dimensional problem using commercial geotechnical software such as SLOPE/W. This is also true for the unsupported cuts excavated into unsaturated soils. However, limited experimental studies have been undertaken to validate the numerical approaches in estimating the critical heights of unsupported cuts in unsaturated soils. To bridge this gap, laboratory test was conducted using a large-scale soil tank (W × L × H = 1.5 × 2.2 × 2.4 m) to determine the critical height of an unsupported vertical cut in sand with water table at 0.7 m from the surface. Excavation was simulated by removing 0.1 m height retaining panels until general failure took place. The matric suction profile in sand above the water table was established based on the suction values measured from various depths with high capacity tensiometers (i.e., T5X). The critical height determined in the laboratory test was compared with the one estimated using PLAXIS (3D).

Keywords Unsupported vertical cut · Critical height · Stability analysis · Matric suction · Numerical analysis

1 Introduction

In many cases, geotechnical projects such as construction of foundations and pipelines are initiated by excavating unsupported cuts. It is common practice for field workers to enter the unsupported cuts during the construction; hence, the design of unsupported cuts should be carried out with the utmost caution since the collapse of even 1.5 m height of an unsupported can suffocate the field workers [1, 2]. Two factors should be taken into account in designing an unsupported cut: critical height

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and stand-up time. Critical height is a maximum depth of an unsupported cut that can be excavated without failure, while stand-up time is defined as time elapsed from the instant a trench is excavated until it fails. Unsupported cuts are typically excavated in soils that are in a state of unsaturated conditions. This indicates that stability of unsupported cuts is governed by the matric suction distribution with depth in field. Recently, several research has been undertaken to estimate critical height [3–6] and stand-up time [7] of unsupported vertical cuts in unsaturated fine- and coarse-grained soils. However, these previous studies were limited to analytical and numerical (2-dimensional) estimations of critical height and stand-up time of unsupported cuts without experimental validation.

In the present study, a large-scale soil tank (W × L × H = 1.5 × 2.2 × 2.4 m) available at the Geotechnical Lab, UNB is used to experimentally determine a critical height of an unsupported cut in a sand. The soil tank was designed in a way that both saturated and unsaturated conditions can be achieved in sand by adjusting the level of water. The experimentally determined critical height was compared with the one estimated using the finite element software, PLAXIS (3D) to check the validity of numerical approach.

2 Testing Program

The critical height of unsupported vertical cut was determined in Unimin 7030 industrial sand (hereafter referred to as sand). Basic soil properties of the sand are summarized in Table 1. The grain size distribution of sand is shown in Fig. 1.

Figure 2a shows initial set-up in the soil tank to determine the critical height of an unsupported vertical cut in sand. The sand was first fully saturated using upward flow

Table 1 Basic soil properties of Unimin 7030 sand [8]

Property	Value	Remark
Plasticity index, I_p	NP	
Saturated unit weight, γ_{sat} (kN/m^3)	20.4	
Saturated volumetric water content, θ	0.387	
Void ratio, e	0.63	
Effective cohesion, c' (kPa)	0	
Effective internal friction angle, ϕ'(°)	36.2	
Elasticity modulus, E^* (kPa)	10,000	Assumed value in numerical analysis
Poisson's ratio, ν^*	0.33	Assumed value in numerical analysis

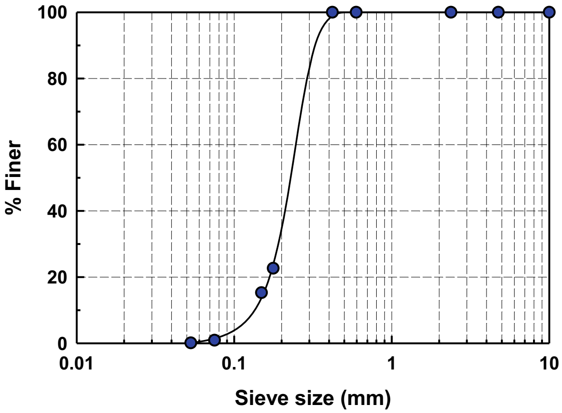


Fig. 1 Grain size distribution curve of Unimin 7030 sand

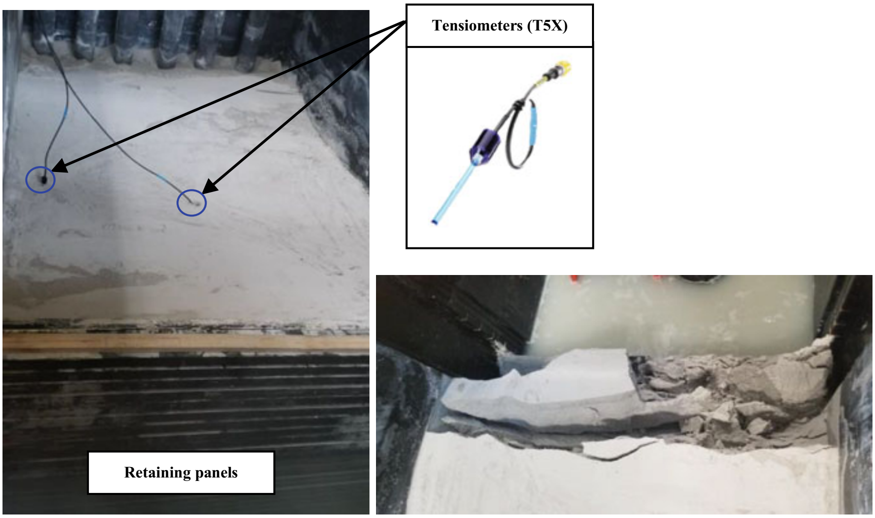
of water from the bottom of the tank. The unsaturated condition was then obtained by lowering water table to the targeted level (i.e., 0.7 m from the soil surface in this study). The matric suction values measured from different depths using T5X (i.e., high capacity tensiometers; METER Group) indicated that hydrostatic negative pore-water pressure (i.e., matric suction) distribution can be assumed without introducing significant error. To simulate vertical excavation, 0.1 m height retaining panels were removed one by one until general failure took place. Failure in sand was observed when the eighth panel was removed, which indicates that the critical height is between 0.7 and 0.8 m. The plan view at the moment of failure in sand is shown in Fig. 2b.

3 Numerical Analysis

The testing program detailed in Sect. 2 was also simulated with PLAXIS 3D (2018) to estimate a critical height of an unsupported vertical cut extending finite element method considering boundary effects. The sand was modelled as a Mohr–Coulomb material with effective shear strength parameters and unit weight as shown in Table 1 for saturated condition. The standard Mohr–Coulomb model is sufficient for the performed stability analysis since the stress dependent stiffness behaviour is not included in the safety type calculations in Plaxis 3D. The water table in the soil tank was set to a constant value of 0.7 m from the soil surface by defining water head. This generates negative and positive hydrostatic pore-water pressure distributions in soils above and below water table, respectively. The negative hydrostatic pore-water pressure above water table is also supported by the T5X tensiometer measurements.

The Soil–Water Characteristic Curve (Fig. 3) in PLAXIS 3D was established using van Genuchten [9]'s model (Eq. (1)) based on the measured data [9].

$$S(\psi) = S_{res} + (S_{sat} - S_{res})\left[1 + g_a|\psi|^{g_n}\right]^{g_c} \quad g_c = \left(\frac{1 - g_n}{g_n}\right) \tag{1}$$



(a) (b)

Fig. 2 Laboratory test in a soil tank to determine the critical height of unsupported cut; **a** initial set-up with water table at 0.7 m from the soil surface, **b** plan view after failure in sand

where S_{res}, S_{sat} = saturation for residual and full saturated conditions, respectively, g_a, g_n, g_c = fitting parameters, and ψ = matric suction.

Vanapalli et al. [10] proposed a model that can be used to estimate the variation of total cohesion with respect to matric suction (Eq. (2)). The fitting parameter, κ is a function of plasticity index, I_p and $\kappa = 1$ can be used for cohesionless soil. Similar approach is adopted in PLAXIS 3D to consider the influence of matric suction on cohesion by introducing the term, effective suction. The total cohesion values that are normalized in terms of the maximum cohesion C_{max}, obtained at 0.25 m, is shown

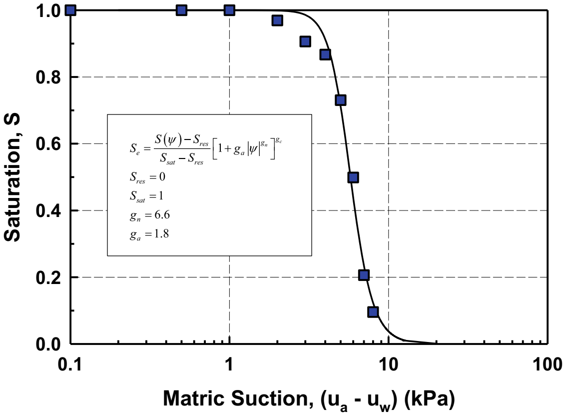
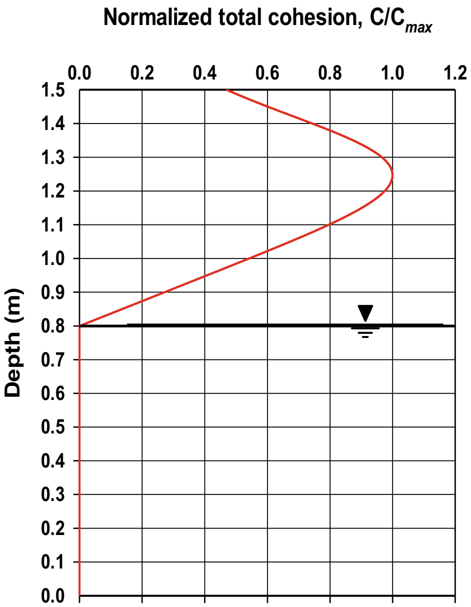


Fig. 3 Soil–water characteristic curve of Unimin 7030 sand

Fig. 4 Variation of normalized total cohesion (C/C_{max}) values with depth



in Fig. 4 with depth, for GWT at 0.7 m from the soil surface.

$$C = c' + (u_a - u_w)(S^{\kappa}) \tan \phi' \tag{2}$$

where C is total cohesion, c' is effective cohesion, u_a is pore-air pressure, u_w is pore-water pressure, $(u_a - u_w)$ is matric suction, S is degree of saturation, κ is fitting parameter ($k = 1$ for NP), and ϕ' is effective internal friction angle.

The front retaining panels (0.1 m in height each, Fig. 2) were modelled as elastic structural elements ($E = 2.1 \times 10^8$ kN/m^2, $\gamma = 78.5$ kN/m^3). Deformation fixities (horizontally fixed) boundary conditions were assigned to simulate sides of soil tank, which can reduce the stiffness difference effect on results at the boundaries. The problem was divided into several groups of phases and staged construction was performed in the analysis to simulate the removal of the retaining panels in the experiment until the soil collapses as a vertical cut. The 3D geometry model, meshes, and boundary conditions are shown in Fig. 5.

Stability of unsupported vertical cut during excavation was estimated by calculating the global safety factor ($\sum M_{sf}$) using the ϕ'/c reduction method (Eq. (3)). Table 2 summarizes the global safety factors after each excavation in Plaxis 3D.

$$\Sigma M_{sf} = \tan\left(\phi'_{input}\right) \big/ \tan \phi'_{reducted} = c'_{input} \big/ c'_{reduced} \tag{3}$$

The global safety factor dropped to 1.15 after the seventh panel was removed in the model. Removal of eighth panel caused failure in the unsupported cut. This indicates that the critical height is between 0.7 and 0.8 m, which coincides with

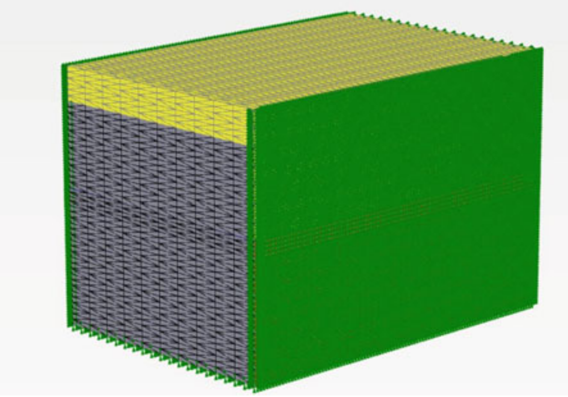


Fig. 5 3D model geometry, meshes and boundary condition used in Plaxis 3D

Table 2 Global safety factor versus excavation depth obtained in Plaxis 3D

Depth of excavation (m)	$\sum M_{sf}$
0.1	5.80
0.2	3.67
0.3	2.77
0.4	2.26
0.5	1.82
0.6	1.51
0.7	1.15
0.75	1.04
0.8	Failure

the experimental result. Additional stability analysis was carried out by dividing the eighth panel into two 0.05 m height panels and the global safety factor was determined to be 1.04 at the excavation depth of 0.75 m (see Fig. 6).

The deformed mesh and failure wedge after the removal of seventh panel shown in Fig. 7 The failure plane in the soil wedge makes angle of 62° with the horizontal. This angle matches the angle of slip line for active case. The disturbed soil zone formed an arc shaped area in the plan view (Fig. 8), which is the indication of the boundary effect at the interface between the soil and sides of tank. However, this boundary effect was not observed in the experiment.

4 Summary and Conclusions

Laboratory test was conducted using a large-soil tank (W × L × H = 1.5 × 2.2 × 2.4 m) to investigate the critical height of an unsupported vertical cut in unsaturated sand. Excavation was simulated by removing 0.1 m high panels subsequently until

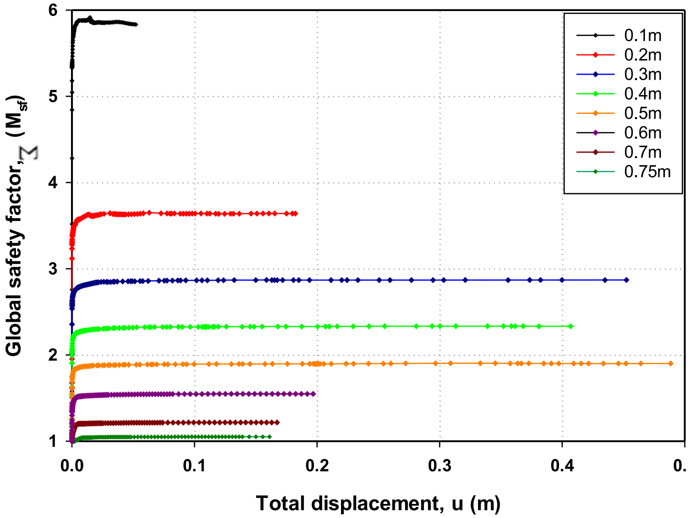


Fig. 6 Global safety factor, $\sum M_{sf}$ versus total displacement, u relationship for each excavation depth

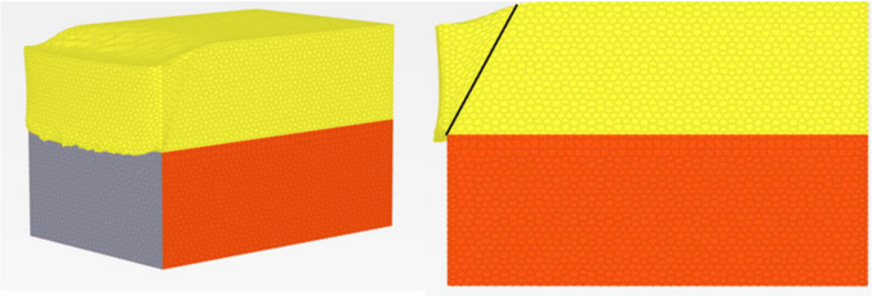


Fig. 7 **a** Deformed mesh and **b** failure wedge (excavation depth = 0.75 m, $\sum M_{sf} = 1.04$)

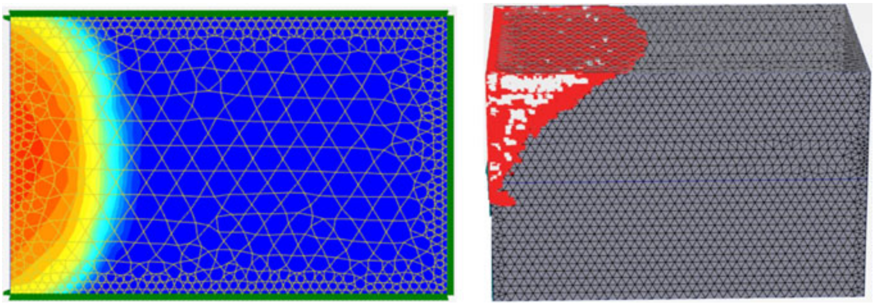


Fig. 8 Plastic points and extension of the disturbed zone due to excavation (excavation depth = 0.75 m, $\sum M_{sf} = 1.04$)

failure took place in the soil. The critical height was determined to be between 0.7 and 0.8 m with the water table at 0.7 m. Similar results were obtained from the the stability analysis undertaken with PLAXIS 3D. This good comparison indicates that the critical height of unsupported vertical cut in unsaturated soils can be reliably estimated through numerical approach by considering the influence of matric suction on the shear strength based on the measured suction distribution profile.

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