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Experimental Study on the Critical Height of an Unsupported Vertical Cut

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ABSTRACT
In this study, a laboratory test was conducted to investigate the stability of an unsupported vertical cut into engineered sand contained in a large-scale soil tank (W × L × H = 1.5 m × 2.2 m × 2.4 m). The apparatus was equipped to induce saturated and unsaturated conditions by adjusting the water table depth. The sand was supported by removable panels; drawing them away simulated an idealised staged excavation, i.e. a vertical cut was exposed without disturbing adjacent soil. The maximum attainable depth for an unsupported vertical cut, i.e. the critical height, from the test was compared with those estimated using analytical and limit equilibrium methods (Bishop's simplified method). Good comparison was observed between the measured and estimated critical height.

RÉSUMÉ
Dans cette étude, un test de laboratoire a été effectué pour étudier la stabilité d'une coupe verticale non supportée à l'aide de sable artificiel contenu dans un réservoir de sol à grande échelle (L × L × H = 1,5 m × 2.2 m × 2,4 m). L'appareil était équipé pour simuler des conditions saturées et insaturées en ajustant la nappe phréatique, et des panneaux amovibles ont été installés pour simuler une excavation par étapes idéalisée, c'est-à-dire sans perturber le sol adjacent. La profondeur maximale atteignable pour une coupe verticale non prise en charge (c.-à-d. La hauteur critique) du test a été comparée à celles estimées à l'aide de la méthode analytique et de l'équilibre limite (simplifiée par Bishop). Une bonne comparaison a été obtenue entre les hauteurs critiques mesurées et estimées.

1 INTRODUCTION

Unsupported vertical trenching or excavation is common in geotechnical engineering practice. Projects involving mining, tunneling, foundation construction, drainage, and pipe installation are often initiated with an unsupported vertical cut. Working in an unsupported trench is inherently dangerous due to the possibility of a cave-in occurring, or, slope failure. The Bureau of Labor Statistics reported between 2011 and 2016, 130 fatalities were associated with unsupported trenching or excavation operations. Regulations exist to safeguard workers, e.g. Canadian provinces limit the maximum allowable height of unsupported cuts to 1.2 m - 1.5 m. The Occupational Safety and Health Administration (OHSA 2020) of the United States Department of Labor provides a trenching and excavation safety manual and prescribes a maximum trench depth of 1.5 m before a protection system is required.

Unsupported cuts are often made into unsaturated soil; therefore, the influence of matric suction is dependent on depth to the groundwater table and should be taken into account to consistently estimate a safe or critical height for a given site. Researchers have investigated this topic (Pufahl et al. 1983, Whenham et al. 2007, De Vita et al. 2008, Stanier and Tarantino 2013, Ileme and Oh 2019, Richard et al. 2020, Yanamandra 2020); however, limited studies were carried out to validate the approaches and methodologies available in the literature through laboratory or field tests.

In this study, a laboratory test was performed to determine the critical height of an unsupported vertical cut into unsaturated sand. To do so, a large-scale soil tank with removable panels was built (W × L × H = 1.5 m × 2.2 m × 2.4 m) at the Department of Civil Engineering, University of New Brunswick, to simulate unsupported vertical excavation into unsaturated soil by means of a variable water table depth. As a preliminary study, a single test was performed to observe failure when the critical height was attained for a water table set to 0.7 m below the ground surface. The experimental critical height was compared with results from analytical and limit equilibrium methods. Numerical analysis was done using geotechnical modelling software, SIGMA/W and SLOPE/W (GeoStudio 2019 R2, GeoSlope Ltd. Inc.).

2 TESTING PROGRAM

2.1 Soil Properties

In this study, an engineered sand (Unimin 7030, hereafter referred to as sand) was used. Physical and mechanical properties of the sand are summarized in Table 1. Figure 1 shows the grain size distribution curve of the sand. The soil-water characteristic curve (SWCC) was measured using a Tempe cell and the best-fit curve was obtained using the Fredlund and Xing (1994) fitting model (

Figure 2.). Fitting parameters *a*, *m*, and *n* were equal to 11.415, 54.202, and 5.132, respectively. Unsaturated unit weight was calculated based on the SWCC; residual volumetric water content was assumed as 5% of the saturated volumetric water content.

Table 1. Soil properties of Unimin 7030 sand (Mohamed and Vanapalli 2006).

Property	Value
Plasticity index, I_p (%)	NP
Specific gravity, G_s	2.65
Void ratio, e	0.63
Saturated unit weight, γ_{sat} (kN/m^3)	20.4
Effective cohesion, c' (kN/m^2)	0
Effective internal friction angle, ϕ' (°)	36.2
Saturated volumetric water content, θ_{sat}	0.387
USCS	SP

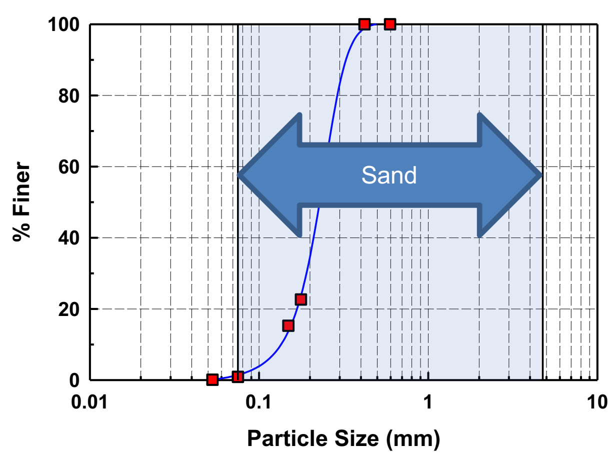

Figure 1. Grain size distribution curve of Unimin 7030 sand (modified after Mohamed and Vanapalli 2006).

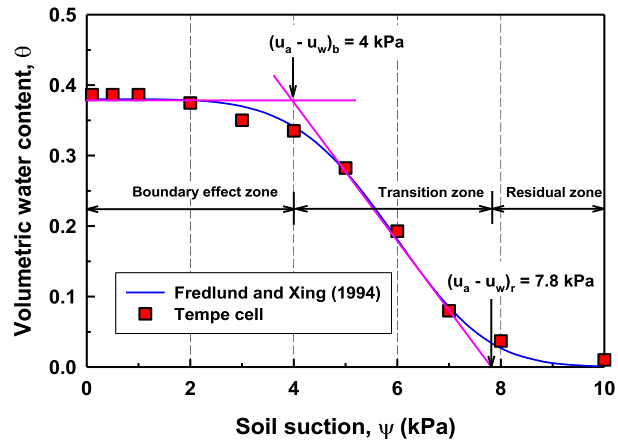

Figure 2. Soil-Water Characteristic Curve of Unimin 7030 sand (modified after Mohamed and Vanapalli 2006).

2.2 Soil Tank

A large timber-framed soil tank with an impermeable liner was used to perform the experiment. In the field, vertical cuts are performed incrementally by machines that cause disturbance in adjacent soil which is not considered when in neither the analytical nor the numerical models. To physically emulate an idealized excavation with minimal disturbance, no actual digging occurred throughout the test. Instead, one of the four walls containing the sand was made of removable 0.1 m retaining panels. The panels were sequentially drawn away from the soil to expose an unsupported vertical face. Figure 3 shows a schematic of the soil tank with some of the panels removed. The side wall of the tank was omitted from the drawing for illustrative purposes. A floorplan showing how the bottom plates of the tank's walls were laid out can be seen in Figure 4.

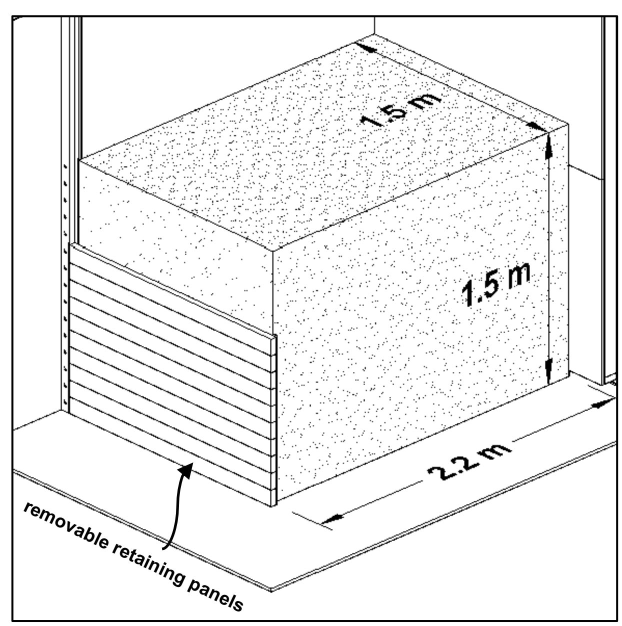

Figure 3. Schematic of soil tank with removable retaining panels.

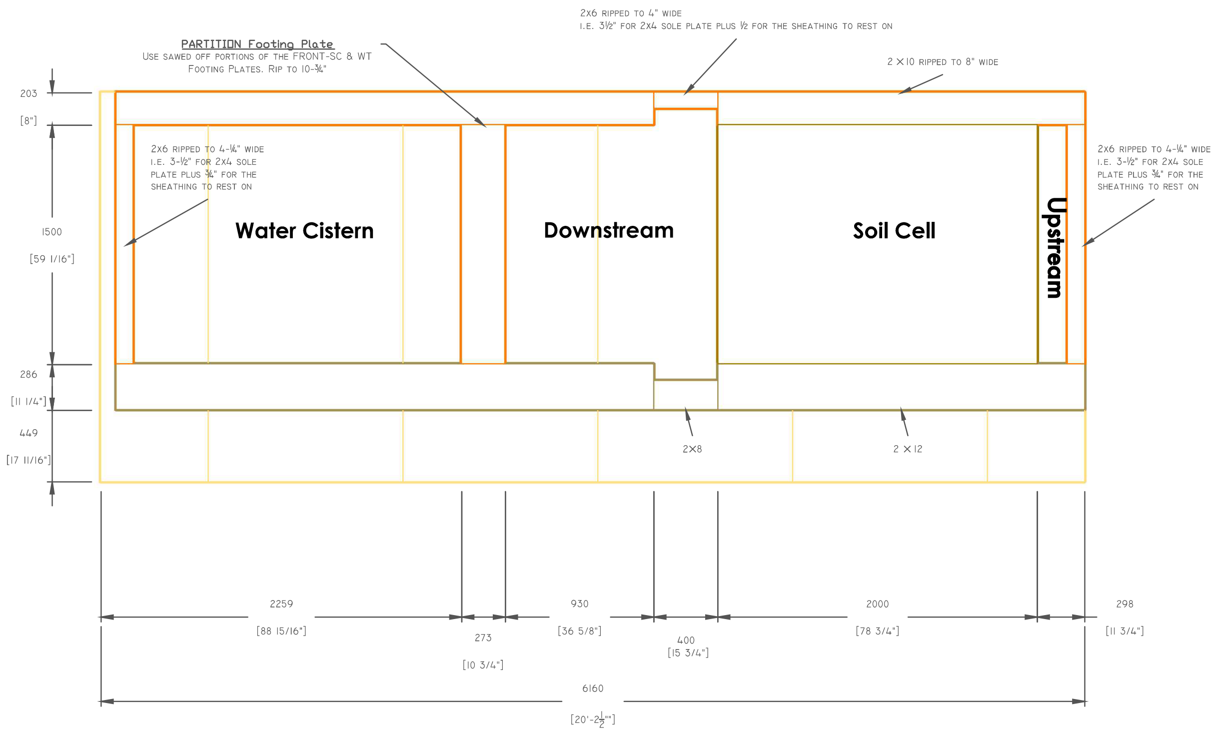

Figure 4. Floorplan depicting bottom plates of soil tank walls with dimensions shown in millimetres above and inches below in brackets.

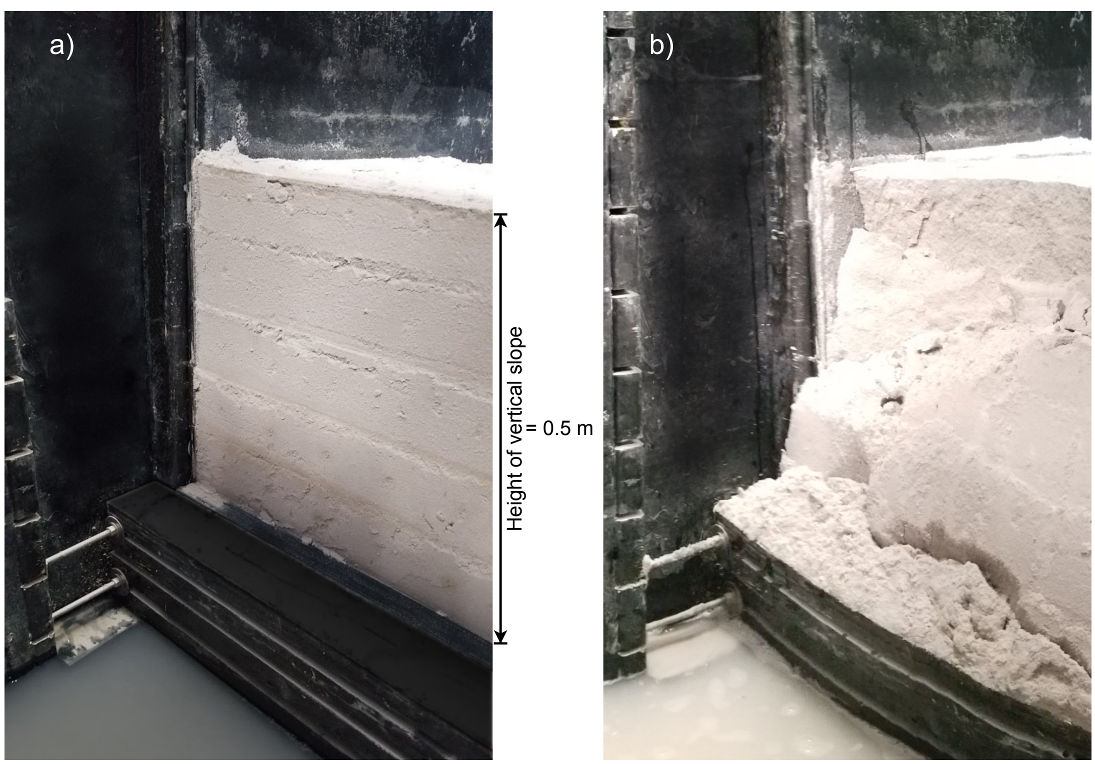

Figure 5. Large scale laboratory test: (a) removal of five retaining panels; (b) failure of unsupported vertical cut.

The test began with the sand being fully saturated from the bottom up by feeding water into the base and allowing pore-air to drain upwards until the water table coincided with ground level. The water table was then lowered to a depth of 0.7 m from the soil surface. If a hydrostatic matric suction distribution profile is assumed (Mohamed and Vanapalli 2006), the suction value will range from 0 to 7 kPa between the water table and the soil surface. The residual suction value for the sand is 7.8 kPa (see Figure 2); therefore, the chosen water table depth suggests that the range of suction does not exceed the residual suction value. The water level was maintained to allow pore-water pressures to equilibrate, and the duration of the test was assumed short enough to neglect evaporation. The retaining panels were then sequentially pulled away from the sand until a slope failure was observed for the exposed unsupported vertical cut.

3 DETERMINATION OF CRITICAL HEIGHT

Critical height of the unsupported vertical cut in sand was determined using three different approaches.

3.1 Large Scale Test

Slope failure occurred immediately as the sixth panel was being pulled away from the base of the vertical wall of unsaturated sand. This indicates that, for the given conditions (i.e. water table depth and the resulting matric suction distribution profile), the critical height lies somewhere between 0.5 m and 0.6 m (Figure 5).

3.2 Extended Rankine Earth Pressure Theory

Pufahl et al. (1983) proposed an approach to estimate lateral earth pressure in expansive clay soils by extending Rankin's theory and including the influence of matric suction. As a soil desaturates, active earth pressure decreases due to an increase in apparent cohesion (i.e. the contribution of matric suction). The active earth pressure can then be estimated using Eq. [1], thus extending the Mohr-Coulomb failure criteria while assuming pore-air is at atmospheric pressure.

$$\sigma_a = \gamma z K_a - 2\left[c' + (u_a - u_w)\tan\phi^b\right]\sqrt{K_a} \quad [1]$$

where σ_a is active lateral earth pressure, γ is unit weight, z is depth from the ground surface, c' is effective cohesion, $(u_a - u_w)$ is matric suction, u_a is pore-water pressure, u_w is pore-water pressure, ϕ^b is the angle indicating the rate of increase in shear strength with respect to a change in matric suction, and K_a is the coefficient of earth pressure at-rest.

Unit weight of soil, γ in Eq. [1], is a function of volumetric water content and void ratio as shown in Eq. [2]. The angle, ϕ^b in Eq. [1] can be replaced with the term including degree of saturation and effective internal friction angle (Eq. [3]) as proposed by Vanapalli et al. (1996) while assuming the fitting parameter κ is equal to one (i.e. the material is cohesionless). Substituting Eq. [2] and Eq. [3] into Eq. [1] yields Eq. [4], which can be used to calculate active earth pressure in unsaturated soil thereby accounting for the nonlinear variation of unit weight and shear strength of unsaturated soil.

$$\gamma = \frac{G_s + \theta(1+e)}{1+e}\gamma_w \quad [2]$$

$$\phi^b = S^\kappa \tan\phi' \quad [3]$$

$$\sigma_a = \left[\frac{G_s + \theta(1+e)}{(1+e)}\right]\gamma_w z K_a - 2\left[c' + (u_a - u_w)S^\kappa \tan\phi'\right]\sqrt{K_a} = \left[\frac{G_s + \theta(1+e)}{(1+e)}\right]\gamma_w z K_a - 2C\sqrt{K_a} \quad [4]$$

where G_s is specific gravity, θ is volumetric water content, e is void ratio, γ_w is unit weight of water, S is degree of saturation, C is total cohesion, and κ is a fitting parameter– a function of plasticity index, I_p, shown in Eq. [5] (Garven and Vanapalli 2006).

$$\kappa = -0.0016(I_p)^2 + 0.0975(I_p) + 1 \quad [5]$$

Figure 6 illustrates an example of active earth pressure diagrams based on the extended Rankine earth pressure theory whereby the influence of matric suction is taken into account. The critical height in unsaturated soil may not simply be interpreted as two times the depth of tension zone. Instead, Figure 6 implies that the critical height can be estimated by locating the depth at which 'Area I' and 'Area II' in are equal (i.e. a net zero active thrust). A computational solver such as Wolfram|Alpha can be used to determine the areas by integrating the function representing the earth pressure profile with respect to depth. The positive, negative, and net active earth pressure distribution for a given water table depth of 0.7 m is shown in Figure 7. The resulting depths of the tension crack and critical height were estimated to be 0.41 and 0.7 m, respectively.

3.3 Limit Equilibrium Method

A stability analysis was done using geotechnical modelling software, SIGMA/W and SLOPE/W (GeoStudio 2019 R2). The model is meant to represent the geometry of the soil tank described in Figure 3 and Figure 5. First, SIGMA/W was used to set an 'Insitu' analysis by applying a body load to the elements. The initial water table depth was set to 0.7 m thereby initializing an assumed idealized hydrostatic pore-water pressure distribution above and below the water table. Excavation was simulated by sequentially removing fixed-x boundary conditions that brace the soil in 0.1 m segments. This approach simulates the manner in which 0.1 m panels were pulled away from the retained soil during the laboratory experiment. Bishop's simplified method was used in SLOPE/W to estimate the critical height (i.e. factor of safety = 1) for each excavation stage.

Figure 8 shows the variation of factor of safety for different excavation depths. Critical height was determined to be 0.7 m as shown in Figure 8 and Figure 9 stemming from a calculated factor of safety equal to 1.02. In GeoStudio (2019 R2), the shear strength of unsaturated soil is computed using the model proposed by Vanapalli et al. (1996), Eq. [6].

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi' \qquad [6]$$

where τ_f is shear strength of soil, $(\sigma_n - u_a)$ is net normal stress, θ_s is saturated volumetric water content, and θ_r is residual volumetric water content

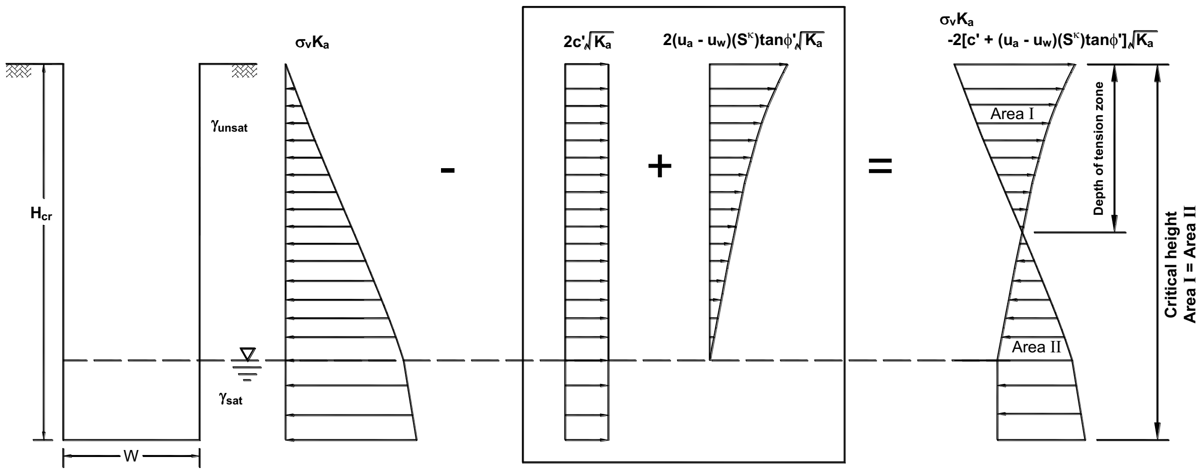

Figure 6. Active earth pressure diagrams taking account of the influence of matric suction and the determination of critical height (Richard et al. 2020).

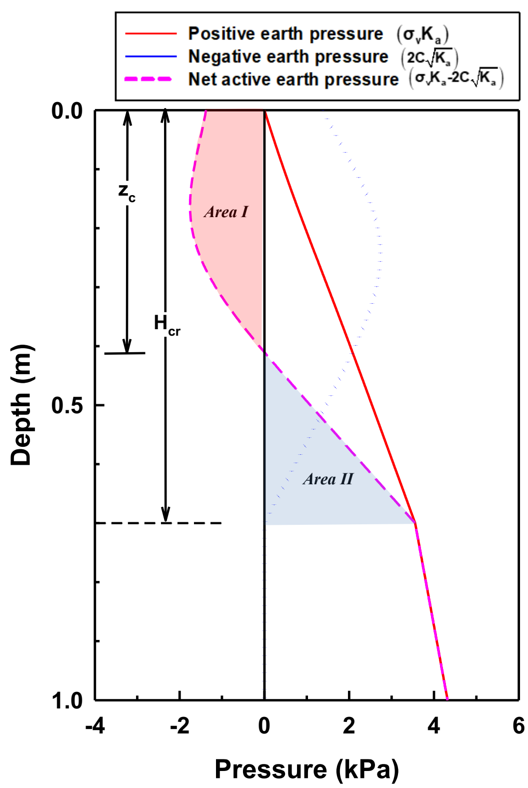

Figure 7. The positive, negative, and net active earth pressure distributions with a water table depth for 0.7 m (z_c = depth of tension crack, H_{cr} = critical height).

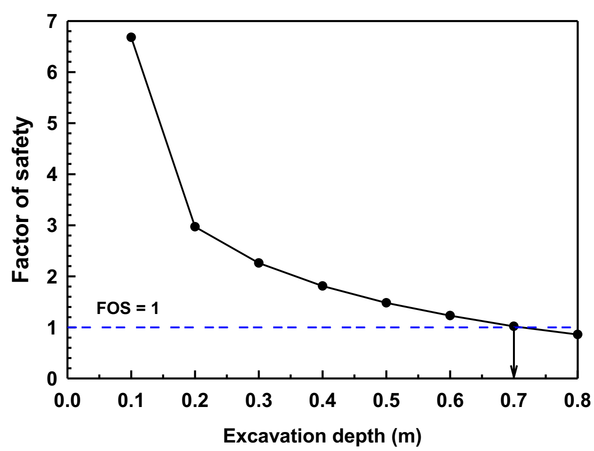

Figure 8. Variation of factor of safety with increasing excavation depths using Bishop's simplified method for a water table depth of 0.7 m.

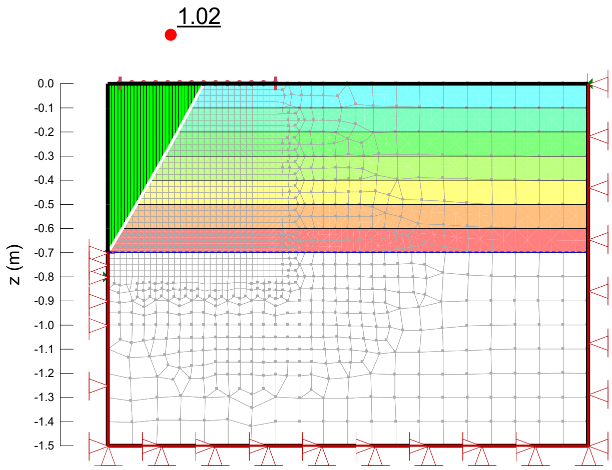

Figure 9. Determination of critical height using limit equilibrium method (Bishop's simplified method) using SIGMA/W and SLOPE/W.

4 SUMMARY AND DISCUSSION

Working in an unsupported trench is dangerous for field workers who are subjected to the risk of cave-ins. Hence, it is essential in geotechnical engineering practice to ensure an unsupported vertical cut is in a stable state in case workers are required to enter.

Stability of unsupported cuts can be estimated by different methods such as laboratory (or field) tests, analytical methods, or numerical methods. Various research has been done to determine the critical height of an unsupported cut using analytical or numerical methods. However, few of those studies were validated through laboratory or field tests.

In the present study, a laboratory test was conducted to determine the critical height of an unsupported vertical cut in unsaturated sand. Failure was observed as the sixth panel was removed, indicating the critical height lies between 0.5 and 0.6 m. The critical height was estimated to be 0.7 m using an analytical method (extended Rankine earth pressure theory) and a limit equilibrium method (Bishop's). This suggests the analytical and limit equilibrium method used in the present study are reasonably reliable for estimating the critical height of unsupported vertical cuts in unsaturated sand.

The experiment was performed considering a single water table depth of 0.7 m; more tests for different water table depths are necessary to further investigate the reliability of analytical and limit equilibrium methods for this application.

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