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## Stability analysis of unsupported vertical cuts using the modified total stress approach

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**ABSTRACT:** Kwan (1971) investigated the behavior of a deep unsupported vertical cut that was excavated in Haldimand clay at Welland, Ontario with the measurements of pore-water pressures within the cut. In this study, Kwan (1971)'s field test results are revisited to simulate the failure of the unsupported vertical cut. For this, geotechnical modelling software, SIGMA/W and SLOPE/W (GeoStudio 2019 R2) are used to simulate staged excavations and estimate its stability, respectively extending the modified total stress approach. The results showed that the failure of unsupported vertical cut in unsaturated fine-grained soils can be reliably predicted extending the modified total stress approach considering the influence of matric suction on the mechanical properties of unsaturated soils and field conditions (i.e., tension crack).

**Keywords:** unsupported cut, modified total stress approach, suction, tension crack

### 1 INTRODUCTION

Excavating unsupported cuts is one of the most fundamental activities in geotechnical engineering practice. This is especially true when projects involve the construction of foundations, roadways, and infrastructure. Among those projects, construction of infrastructure such as pipelines is performed in a narrow trench that typically remains unsupported during whole construction process. This can present potential risks to field workers in case they are required to enter the trench. According to National Institute for Occupational Safety & Health (NIOSH, 2013), between 1992 and 2007, an average of 50 fatalities were reported each year in association with the collapse of trenches. Due to this reason, each province in Canada limits the maximum allowable height of unsupported trench (i.e., safe height) to 1.2 m (or 1.5 m in some provinces) for safe excavation practices (Richard et al. 2017). In most cases, trenches are excavated into soils that are in a state of unsaturated condition. Hence, safe height should be estimated by considering the matric suction distribution with depth depending on soil type and level of ground water table. This means that it may not be reasonable to specify a certain safe height without considering in-situ field conditions.

In the present study, a methodology is presented that can be used to estimate the critical height of an unsupported vertical trench in unsaturated soils. Critical height is defined as a maximum depth of a trench that can be excavated without failure. For this, the behaviors of a deep unsupported vertical cut made into a clay

(Kwan 1971) are revisited. Numerical analyses were carried out using commercial geotechnical modelling software, GeoStudio (2019 R2, GeoSlope Int. Ltd.) to simulate staged excavation (SIGMA/W) and to conduct stability analysis (SLOPE/W). Good comparison was achieved between the excavation depth at failure in field and the one numerically determined extending the modified total stress approach.

### 2 MODIFIED EFFECTIVE AND TOTAL STRESS APPROACH

The behaviours of saturated soils can be analyzed using either effective stress approach (Terzaghi 1943) or total stress approach (Skempton 1948). These conventional approaches can also be extended towards analyzing the behaviours of unsaturated soils by considering the influence of matric suction. Vanapalli et al. (1996) proposed a model that can be used to estimate the variation of shear strength of unsaturated soils extending the effective stress approach (i.e., modified effective stress approach). Their approach requires the effective shear strength parameters (i.e.,  $c'$  and  $\phi'$ ), matric suction, and the Soil-Water Characteristic Curve (i.e., SWCC) (Eq. (1)).

$$\tau_{unsat} = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \left[ \tan \phi' \left( \frac{\theta - \theta_r}{\theta_s - \theta_r} \right) \right] \quad (1)$$

where  $\tau_{unsat}$  = shear strength of unsaturated soil,  $c'$  =

effective cohesion,  $\sigma_n$  = normal stress,  $u_a$  = pore-air pressure,  $(\sigma_n - u_a)$  = net normal stress,  $\phi'$  = effective internal friction angle,  $u_w$  = pore-water pressure,  $(u_a - u_w)$  = matric suction,  $\theta$  = volumetric water content, and  $\theta_r$ ,  $\theta_s$  = residual and saturated volumetric water content, respectively

Oh and Vanapalli (2013) conducted laboratory model footing ( $B \times L \times H = 50 \text{ mm} \times 50 \text{ mm} \times 20 \text{ mm}$ ) tests on a fine-grained soil ( $I_p = 15.5 \%$ ) statically compacted in a plastic high-strength plastic tank (300 mm diameter  $\times$  300 mm height  $\times$  12.7 mm thickness). The tests were conducted for five different average matric suction values (i.e., 0 (saturated), 55, 100, 160 and 200 kPa). Based on the experiment results, they suggested that the bearing capacity of unsaturated fine-grained soils can be estimated using the unconfined compressive strength for unsaturated condition extending Skempton (1948)'s total stress approach (Eq. (2)).

$$q_{ult(unsat)} = (c_u \xi N_c)_{unsat} = \left[ \frac{q_{u(unsat)}}{2} \right] \left[ 1 + 0.2 \left( \frac{B}{L} \right) \right] N_{c(unsat)} \quad (2)$$

where  $q_{ult}$  = ultimate bearing capacity,  $c_u$  = undrained shear strength,  $\xi = [1 + 0.2(B/L)]$  ( $B$  = Breadth,  $L$  = length) proposed by Meyerhof (1963) and Vesić (1973) for undrained condition,  $N_c$  = bearing capacity factor,  $q_u$  = unconfined compressive strength, and subscript  $unsat$  = unsaturated condition

Eq. (2) implies that the ultimate bearing capacity of an unsaturated soil can be predicted with a model that can predict the variation of undrained shear strength (i.e. a half of unconfined compressive strength) with respect to matric suction. Extending this concept, Oh and Vanapalli (2018) proposed a model to estimate the variation of undrained shear strength of unsaturated soils with respect to matric suction (Eq. (3)).

$$c_{u(unsat)} = c_{u(sat)} \left\{ 1 + \left( \frac{\psi}{\mu} \right) \left( \frac{P_a}{101.3} \right) (S_r)^v \right\} \quad (3)$$

where  $c_{u(sat)}$ ,  $c_{u(unsat)}$  = undrained shear strength for saturated and unsaturated conditions, respectively,  $\psi$  = suction,  $\mu$ ,  $v$  = fitting parameters,  $P_a$  = atmospheric pressure,  $S_r$  = degree of saturation

The fitting parameter,  $v = 2$  is required for fine-grained soils and  $\mu$  is function of plasticity index (Fig. 1).

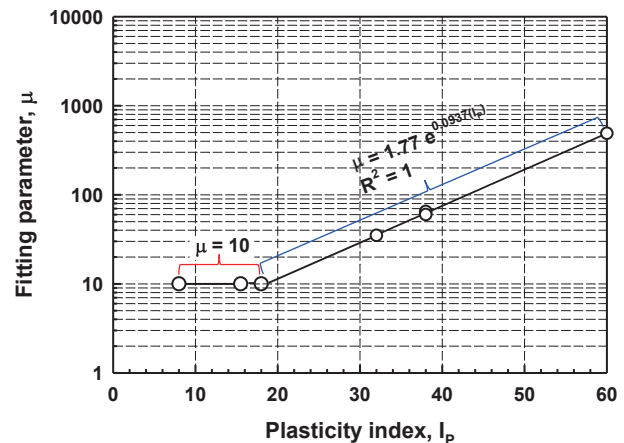


Fig. 1. Relationship between the fitting parameter,  $\mu$  (Eq. (3)) and plasticity index (modified after Oh and Vanapalli (2018)).

### 3 INSTRUMENTED TEST EXCAVATION

#### 3.1 Description of project

Kwan (1971) investigated the stability of unsupported vertical cut excavated in Haldiman clay at Welland, Ontario. Location of the test site is shown Fig. 2. Excavation was conducted in two stages. First, 5.2 m of top desiccated sediment was removed, followed by the excavation of 9.75 m of deep vertical cut. Pore-water pressures during excavation process were monitored using multiple piezometers. Two additional vertical cuts were excavated at both ends of the initial vertical cuts to eliminate end effects (Fig. 3). Failure of the vertical cut was attributed to the formation of tension cracks at the berm. Two tension cracks were formed, and the failure was initiated from the second tension crack (Fig. 4).

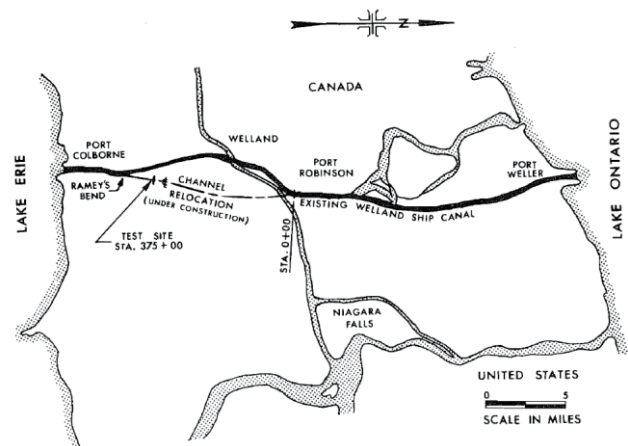


Fig. 2. Location of test site (Kwan 1971).

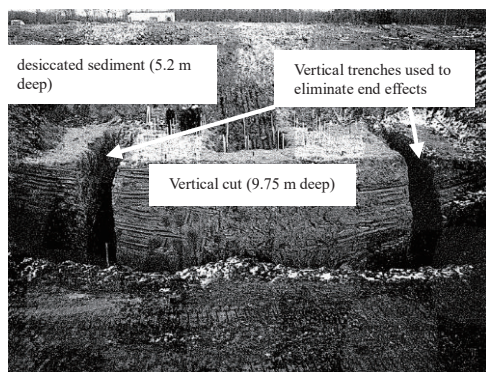


Fig. 3. Front view of vertical cut and two vertical trenches excavated to eliminate end effects.

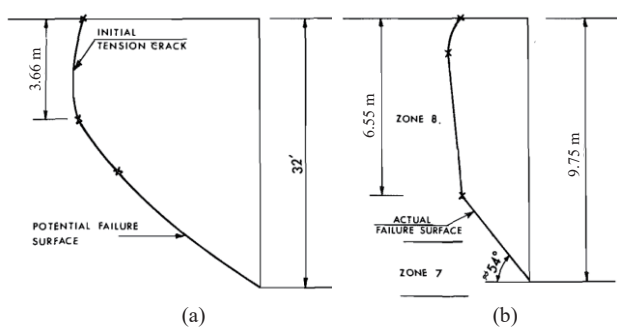


Fig. 4. (a) potential and (b) actual failure surfaces (modified after Kwan 1971).

Table 1. Undrained shear strengths used for different cases of stability analysis.

Case	$c_u$ (kPa)	Remark
1	47.9	obtained with the critical height equation, assuming one stratum condition
2	89.0	based on the actual failure plane (Fig. 4(b)) assuming one stratum condition; tension crack is considered
3	60.3	based on the first potential failure (Fig. 4(a)) assuming one stratum condition; tension crack is considered
4	47.9	the positions of the actual failure surfaces are ignored; different properties of the strata are considered
5	38.3	the positions of the actual failure surfaces are ignored; different properties of the strata are considered; the laboratory data are revised until the minimum factor of safety is equal to 1.0

Table 2. Properties of each layer used in the numerical analyses.

Layer	El. (m)	$c_{u(sat)}$ (kPa)	Saturated hydraulic conductivity, $k$ (m/s)
1	169.7 - 175.8	59.93	$5 \times 10^{-8}$
2	162.4 - 169.7	50.34	$5 \times 10^{-8}$
3	157.7 - 162.4	38.31	$5 \times 10^{-9}$

### 3.1 Stability analysis using conventional total stress approach

Kwan (1971) attempted to analyze the stability of the deep vertical cut extending the conventional total stress approach (i.e.,  $\phi_u = 0$  approach) using the undrained shear strengths,  $c_u$  obtained for various cases as shown in Table 1. It is apparent from Table 1 that slip surfaces and undrained shear strengths can be different when the stability of an unsupported cut is analyzed using the conventional total stress approach.

## 4 NUMERICAL ANALYSES

### 4.1 Soil properties

As detailed in Kwan (1971) and Banerjee et al. (1988), the soil that consists of the unsupported vertical cut was divided into three layers. Soil properties of each layer are summarized in

Table 2. The Soil-Water Characteristic Curve (SWCC) and hydraulic conductivity function of each layer is available in Yanamandra (2020). The variation of undrained shear strength with respect to matric suction was obtained using Eq. (3).

### 4.2 Methodology

Numerical analyses were carried out by using SIGMA/W and SLOPE/W jointly. First, SIGMA/W was used to establish 'In-Situ' conditions by assigning body load to the elements and drawing an initial ground water table (Fig. 5). To accommodate the drop of ground water table during the removal of top sediment and vertical excavation, 'Coupled Sigma/PWP' analysis method was used (i.e., coupled analysis). During the excavation simulation, constant hydraulic total head boundary conditions were assigned along the left and right edges of domain not to allow fluctuation of water table along the edges. Excavations were simulated by following the timeline of excavation as detailed in Kwan (1971) (Fig. 6). Tension crack was simulated as a material with zero tensile strength. In GeoStudio software, shear strength of unsaturated is calculated using Eq. (1) extending the modified effective stress approach. Hence, in the present study, the information of pore-water pressure distribution in association with excavation was first obtained from coupled analysis in SIGMA/W. This information was then used to calculate undrained shear strengths for unsaturated condition (Eq. (3)), which were later manually assigned to the elements for undrained stability analysis in SLOPE/W. Factor of safety was calculated using 'SIGMA/W Stress' method.

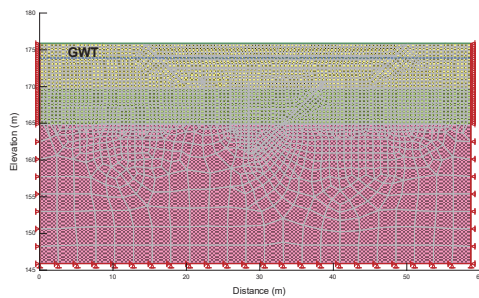


Fig. 5. Mesh, location of ground water table, and displacement boundary conditions generated in SIGMA/W to simulate initial (in-situ) condition.

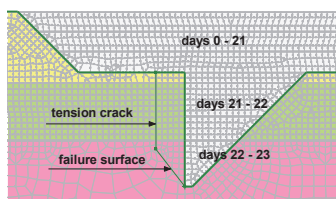


Fig. 6. Timeline of excavation and locations of tension crack and failure surface.

#### 4.2 Stability analyses results

Fig. 7 shows the pore-water pressure distribution and stability analysis results. As can be seen, the unsupported vertical cut is in a stable condition (i.e., FOS = 1.05) when analyzed without the tension crack. However, good agreement was observed between the actual failure surface and the one determined with numerical analysis considering the tension crack (Fig. 8).

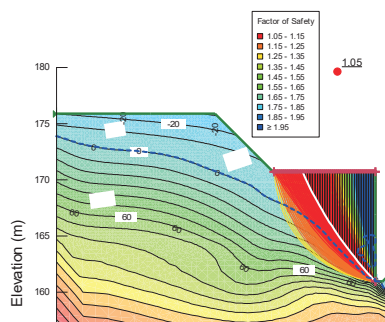


Fig. 7. Pore-water pressure distribution and FOS prior to failure without tension crack.

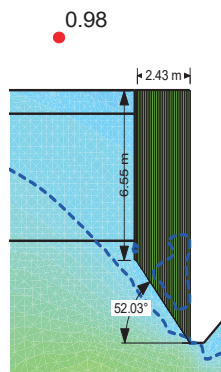


Fig. 8. Stability analysis results considering the tension crack.

#### 5 SUMMARY AND CONCLUSIONS

Excavating unsupported cuts is a key activity in geotechnical engineering practice to construct foundations and infrastructure. Since the collapse of unsupported cuts can lead to loss of lives, excavation should be done with utmost caution. An attempt was made to analyze the stability of unsupported deep vertical cut in a clay (Kwan 1971). Numerical analyses were conducted with the commercial geotechnical modelling software, SIGMA/W and SLOPE/W (GeoStudio 2019 R2) extending the modified total stress approach. The estimated failure surface geometry was identical with the field condition. The numerical analysis results indicates that the stability of unsupported vertical cut in unsaturated fine-grained soils can be reliably estimated extending the modified total stress approaches considering field conditions (i.e., fluctuation of ground water table due to excavation, tension crack, and variation of shear strength and hydraulic conductivity with respect to matric suction).

#### REFERENCES

- Banerjee, P.K., Kumbhojkar, A.S. and Yousif, N.B. 1988. Finite element analysis of the stability of a vertical cut using an anisotropic soil model. *Canadian Geotechnical Journal* 25 (1), 119-127.
- Kwan, D. 1971. Observations of the failure of a vertical cut in clay at Welland, Ontario. *Canadian Geotechnical Journal* 8(2), 283-298.
- Meyerhof, G. G. 1963. Some recent research on the bearing capacity of foundations. *Canadian Geotechnical Journal* 1(1), 16-26.
- National Institute of Occupational & Health. 2013. Trenching and Excavation – Workplace Safety and Health Topic. US Department of Health and Human Services.
- Oh, W.T. and Vanapalli, S.K. 2013. Interpretation of the bearing capacity of unsaturated fine-grained soil using the modified effective and the modified total stress approaches. *International Journal of Geomechanics* 13(6),769-778
- Oh, W.T. and S. Vanapalli. 2018. Undrained shear strength of unsaturated soils under zero or low confining pressures in the vadose zone. *Vadose Zone Journal* 17, 1-13.
- Richard, A., Brennan, G., Oh, W.T. and Ileme, V. 2017. Critical height of an unsupported vertical trench in an unsaturated sand. *Proc. Can. Geotech. Conf., Ottawa, 1 - 4 October* (CD).
- Skempton, A. W. 1948. The  $\phi_u = 0$  analysis for stability and its theoretical basis. *Proc., 2nd Int. Conf. on Soil Mechanics and Foundation Engineering*, 1, International Society for Soil Mechanics and Geotechnical Engineering, London, 72-77.
- Terzaghi, K. 1943. *Theoretical soil mechanics*, Wiley, New York.
- Vanapalli, S. K., D. G. Fredlund, D. E. Pufahl, and A. W. Clifton. 1996. Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal* 33(3), 379-392.
- Vesic, A. B. 1973. Analysis of ultimate loads of shallow foundations. *J. Soil Mech. and Found. Div.*, 99(1), 45-73.
- Yanamandra, G. 2020. Influence of excavation rate and tension crack on the stability of an unsupported vertical cut in unsaturated soil. Master's thesis, University of New Brunswick.