Influence of tension cracks on the stability of unsupported vertical trenches in vadose zone

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ABSTRACT
Tension cracks typically occur behind the crests of slopes and cuts, which is considered to be a primary contributor to the instability of slopes and cuts. This is because tension cracks not only decrease shear resistance to slip failure but also can exert an additional lateral force when filled with water. Moreover, tension cracks act as an active pathway for rainfall to infiltrate into soil and leads to rapid increase in permeability and decrease in shear strength of soil in the vicinity of tension cracks. In the present study, the influence of tension cracks on the stability of unsupported trenches in vadose zone is investigated. For this, a series of hydro-mechanical coupled analyses was carried out considering various factors such as depth of tension crack, distance from the crest to the tension crack, and rainfall intensity.

RÉSUMÉ
Les fissures de tension se produisent généralement derrière les crêtes des pentes et des coupes; ils sont considéré un facteur essentiel de l'instabilité. En effet, les fissures de tension non seulement réduisent la résistance au cisaillement à la rupture par glissement, mais peuvent également exercer une force latérale supplémentaire lorsqu'elles sont remplies d'eau. De plus, les fissures de tension constituent une voie active d'infiltration des pluies dans le sol et entraînent une augmentation rapide de la perméabilité et une diminution de la résistance au cisaillement du sol dans la proximité des fissures de tension. Dans la présente étude, l’influence des fissures de tension sur la stabilité des tranchées non-supportés dans la zone vadose est étudiée. Pour cela, une série d'analyses couplées hydro-mécaniques a été réalisée en tenant compte de divers facteurs tels que la profondeur de la fissure de tension, la distance entre la crête et la fissure de tension, et l'intensité des précipitations.

1 INTRODUCTION

Trenching is the primary and an important activity in geotechnical engineering practice since most projects ranging from mining to infrastructure development initiate from trenching. However, trenching is also a root for many work-related injuries and deaths. Canadian provinces have enforced their own regulations for trenching to safeguard workers from hazards caused by trench failures. Typically, trenches greater than 1.2 m deep (i.e. safe height) must be sloped at a gradient based on the soil type (Figure 1, Table 1) in case workers do not need to enter the trenches. If workers do, designers should determine adequate size and spacing of the support system’s structural members. Nonetheless, according to BLS (Bureau of Labor Statistics) (2010), 350 workers died due to trenching (or excavation) cave-ins between 2000 and 2009, which leads to average of 35 fatalities per year. OSHA data also showed that majority of trenching cave-ins occurred at a depth of less than 3 m (Arboleda and Abraham 2004). Trench cave-ins claims for not only work-related injuries and deaths, but also lost time in constructions BLS (2010, Figure 2).

Trench boxes are often a practical solution in protecting workers since they allow them to safely access the work space. However, typical trench boxes are eight meters in length and weigh multiple tons (Richard 2018). Hence, the process of lifting a box, setting it in place, and repositioning it when necessary can be very time consuming. They also create an obstacle for the workers and the equipment that are used for setting infrastructure. Lost production time results in lost profit, making it desirable to excavate and work in unsupported trenches whenever possible. In this case, it is fundamental to estimate critical height (maximum depth of a trench that can be excavated without failure of a trench) of an unsupported trench to avoid any work-related injuries and deaths and subsequent time loss due to trench cave-ins.

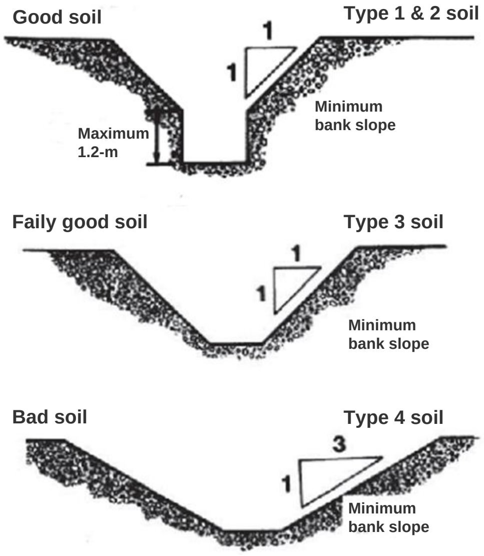


Figure 1. Slope banks at a gradient based on soil type (Infrastructure Health & Safety Association, IHSA 2017)

Table 1. Soil type classification for trench design (Ontario 2018)

Soil type	Description
1	• hard, very dense and only able to be penetrated with difficulty by a small sharp object • has a low natural moisture content and a high degree of internal strength • has no signs of water seepage • can be excavated only by mechanical equipment
2	• very stiff, dense and can be penetrated with moderate difficulty by a small sharp object • has a low to medium natural moisture content • has a damp appearance after it is excavated • has a medium degree of internal strength
3	• previously excavated soil or soil that is stiff to firm or compact to loose in consistency • exhibits signs of surface cracking or water seepage • if dry, it may run easily into a well-defined conical pile • has a low degree of internal strength
4	• soft to very soft and very loose in consistency, very sensitive • runs easily or flows, unless completely supported before excavating procedures • has almost no internal strength and upon disturbance is significantly reduced in natural strength • exerts substantial fluid pressure on its supporting system

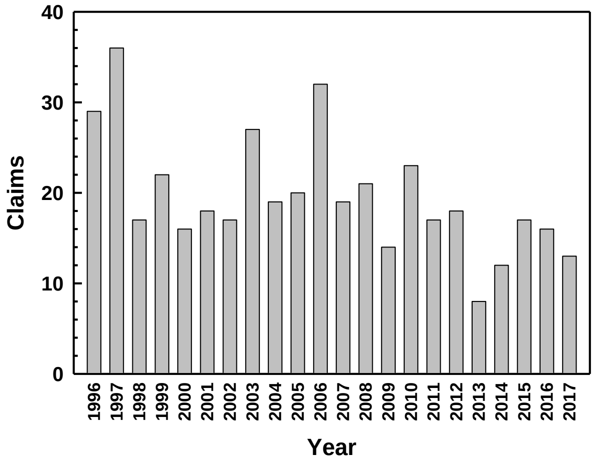


Figure 2. Annual lost time claims due to excavation and trenching cave-ins (Bureau of Labor Statistics 2010)

Trenching is commonly carried out in soils that are in a state of unsaturated condition. This implies that the stability of a trench is governed by the initial matric suction distribution and change in matric suction. However, as mentioned previously, current trenching safety regulations mainly depend on field observations. To overcome the disadvantages of current trenching safety regulations, Richard (2018) proposed methodologies to estimate the critical height of unsupported trenches considering soil type, matric suction distribution, and surcharge pressure. Research was also performed by Ileme (2018) to study the influence of rainfall intensity, level of ground water table, and soil surface impermeable membrane on the stability of unsupported vertical trenches. However, limited studies have been conducted to investigate the influence of tension cracks on the stability of unsupported vertical trenches in vadose zone.

Tension crack is one of the governing factors that affect the stability of slopes and unsupported cuts since they form a part of slip surface. In practice, however, this aspect is often overlooked in the design of unsupported trenches. Tension cracks are found near the crest of slopes and unsupported trenches when tensile stress exceeds tensile strength (Bagge 1985). Desiccation, differential settlement and temperature changes are considered to be main reasons for the tension cracks (Li and Zhang, 2010). Tension cracks are detrimental during rainfall, as they act as pathway for rainfall to seep through the soil and further reducing its shear strength. A rainfall induced open coal mine landslide which happened in December 2002 in Airlaya Indonesia (Gofar et al. 2006) directly points towards influence of tension crack on slope failure. The primary cause for this landslide was attributed to the reduction in shear strength due to seepage caused by tension crack. As rainfall infiltrated through the tension crack, the pore-water pressure around the crack increased, which led to decrease in matric suction and shear strength of the soil (Hu 2000). During rainfall, these pre-existing cracks are highly influential towards the deep failures (Hu 2000, Fan et al. 2005, Wang et al. 2010)

In the present study, an attempt was made to investigate the influence of tension cracks on stability of unsupported vertical trenches in vadose zone. Geotechnical modeling software, GeoStudio (SEEP/W, SLOPE/W and SIGMA/W; ver. 2016, GeoSlope Int. Ltd.) was used for the numerical analysis.

2 DEPTH OF TENSION CRACK IN VADOSE ZONE

When the backfill surface is horizontal, Rankine active earth pressure for saturated soils can be calculated with Eq. [1].

$$\sigma_a = \gamma z K_a - 2c'\sqrt{K_a} \qquad [1]$$

where σ_a = active earth pressure, γ = unit weight of soil, z = depth, c' = effective cohesion, and K_a = active earth pressure coefficient

Pufahl et al. (1983) modified Eq. [1] and proposed an equation to estimate active and passive earth pressure in vadose zone considering the influence of matric suction. Figure 3 shows lateral earth pressure states for saturated and unsaturated conditions using the Mohr-Coulomb failure criteria. The active earth pressure decreases as a soil desaturates due to increasing contribution from matric suction. From the geometrics of the Mohr circle in Figure 3, the net horizontal pressure for active case can be written as Eq. [2] by incorporating the influence of matric suction.

$$\left(\sigma_h - u_a\right) = \left(\sigma_v - u_a\right)K_a - 2\left[c' + \left(u_a - u_w\right)\tan\phi^b\right]\sqrt{K_a} \qquad [2]$$

where, (σ_h – u_a) = net horizontal pressure, (σ_v – u_a) = net vertical pressure, (u_a – u_w) = matric suction, u_a = pore-air pressure, u_w = pore-water pressure, ϕ^b = angle indicating the rate of increase in shear strength with respect to a change in matric suction

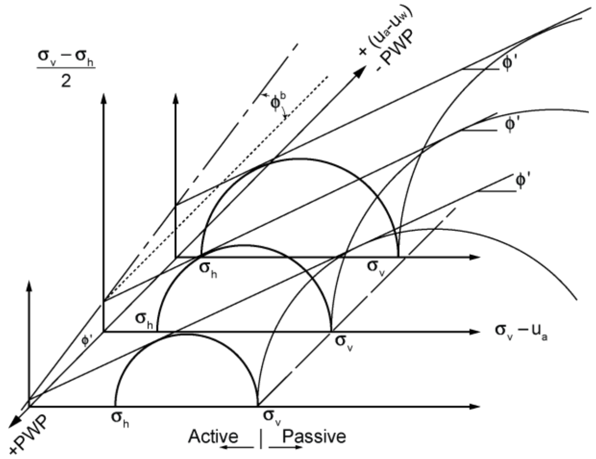


Figure 3. Lateral earth pressure states for saturated and unsaturated conditions (Pufahl et al. 1983)

Vanapalli et al. (1996) proposed Eq. [3] to estimate the variation of ϕ^b with respect to matric suction.

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

Where, S = degree of saturation, k = fitting parameter (function of plasticity index, Eq. [4]) and ϕ' = effective internal friction angle

$$\kappa = -0.0016(I_p)^2 + 0.0975(I_p) + 1 \qquad [4]$$

Substituting Eq. [3] into Eq. [2] yields Eq. [5].

$$\left(\sigma_h - u_a\right) = \left(\sigma_v - u_a\right)K_a - 2\left[c' + \left(u_a - u_w\right)\left(S^\kappa\right)\tan\phi'\right]\sqrt{K_a} \qquad [5]$$

If the pore-air pressure is assumed to be atmospheric pressure (i.e. $u_a = 0$), the net active earth pressure in vadose zone can be calculated using Eq. [6].

$$\begin{aligned}\sigma_a &= \sigma_v K_a - 2\left[c' + \left(u_a - u_w\right)\left(S^\kappa\right)\tan\phi'\right]\sqrt{K_a} \\ &= \sigma_v K_a - 2C\sqrt{K_a}\end{aligned} \qquad [6]$$

where, C = total cohesion

Based on the active earth pressure distribution, depth of tension crack in vadose zone can be estimated by locating a depth with zero net active earth pressure as shown in Figure 4.

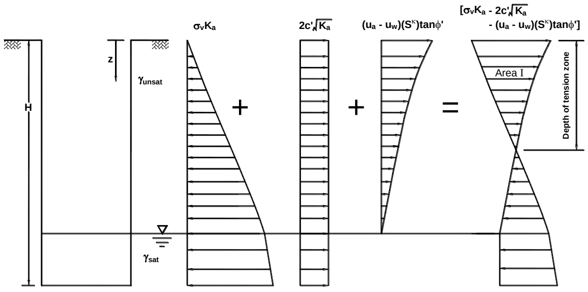


Figure 4. Determination of depth of tension crack based on net active earth pressure distribution in vadose zone

3 METHODOLOGY

3.1 Soil Properties

It was assumed that trenches were excavated into the fine-grained soil that was used by Wang et al. (2012). Basic soil properties are summarized in Table 2. Wang (2011) proposed a methodology to estimate SWCC (Soil-Water Characteristic Curve) and hydraulic conductivity function of a tension crack by analyzing random aperture distribution of cracks. Extending this concept, Wang et al. (2012) conducted slope stability analysis by simulating a tension crack as a material with zero strength rather than as a boundary condition. SWCCs and hydraulic conductivity functions of fine-grained soil and tension crack used in the present study are shown in Figure 5 and Figure 6, respectively.

Table 2. Characteristics of the fine-grained soil

Properties	
Saturated volumetric water content, θ_s	0.41
Dry unit weight, γ_{dry} (kN/m^3)	17.4
Saturated unit weight, γ_{sat} (kN/m^3)	19.6
Effective cohesion, c'	22
Effective internal friction angle, ϕ'	13

3.2 Numerical Analysis

Numerical analysis was conducted with a total domain size of 10 m wide and 10 m deep as shown in Figure 7. The size of the trench is designed to be 4.5 m deep. The mesh size is taken as ratio of 0.1 to global element size of 1 m for each element. A total number of 6006 nodes and 5925 quadrilateral and triangular elements were generated. This global element size allows efficient discretization while outputting reliable results.

The left and right sides were restrained in the x-direction whereas the base of the domain was restrained in both the x- and y-directions (hollow triangles). Initial pore-water condition was assigned using 'Insitu' analysis type by drawing ground water table at 5 m depth from the ground surface. The width of tension crack was set 0.1 m. The maximum depth of tension crack was estimated to be 3.6

m based on the net active earth pressure distribution ($z_{c(max)}$ in Figure 8).

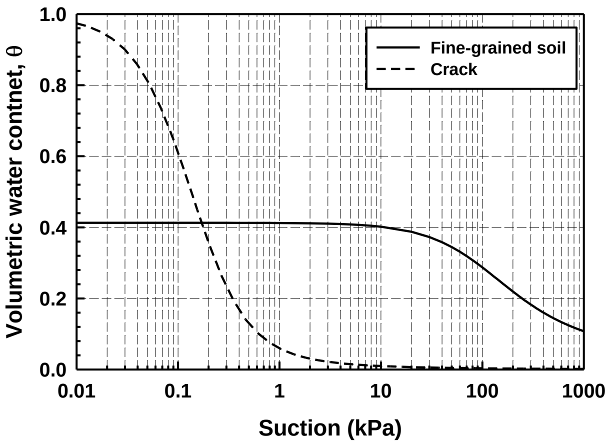


Figure 5. SWCCs of fine-grained soil and crack (modified after Li and Zhang 2011)

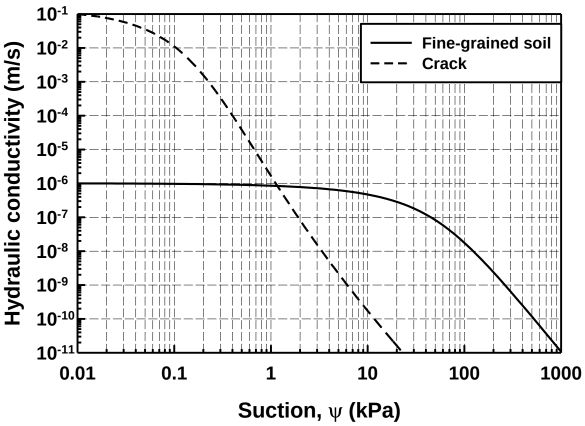


Figure 6. SWCCs of fine-grained soil and crack (modified after Li and Zhang 2011)

Staged excavation was simulated in SIGMA/W by deactivating regions up to EL 5.5 m. It was assumed that 4 staged excavations were made to reach the targeted excavation depth. Excavation resulted in the drop of water table, which induced increase in negative pore-water pressure. Since this phenomenon, in return, increases shear strength of soil, enough time was allowed between the staged excavations until the pore-water pressure reaches equilibrium condition. Slope stability analyses were then conducted with SLOPE/W after final excavation stage is completed based on the SIGMA/W results as the parent analysis. Bishop (1960)'s simplified method was used for stability analysis with the 'Entry and Exit' slip surface option. The toe of trench was used as an exit point to consider only general failure condition (i.e. slip surfaces pass through the toe of vertical trench). At the end of excavation, the FOS was close to 1.5 when the tension crack was not considered. It was assumed that slip surfaces extend up vertically in case where slip surfaces meet tension crack.

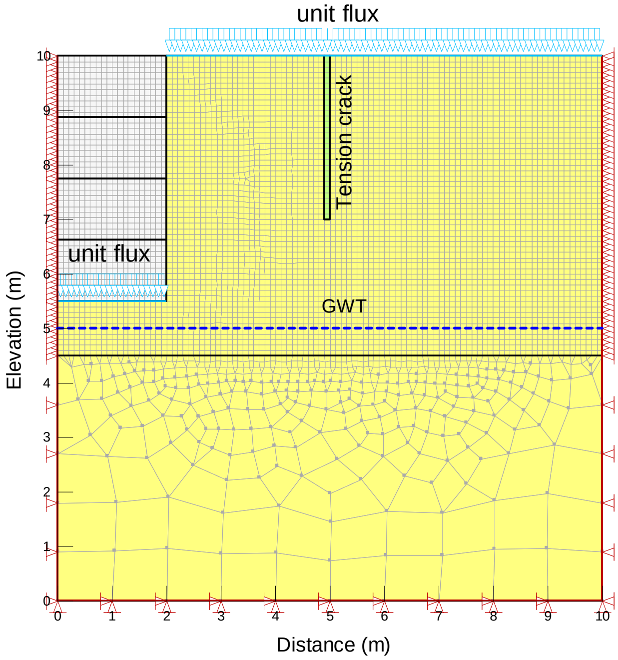


Figure 7. Meshes and boundary conditions in numerical analysis

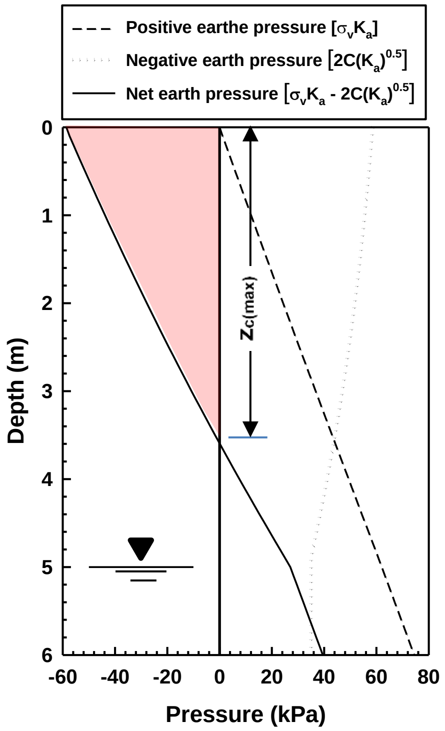


Figure 8. Determination of maximum depth of tension crack based on positive, negative and net active earth pressure

To investigate the influence of rainfall on the stability of vertical trench, unit flux boundary condition (i.e. 10 mm/hr) was applied to the ground surface and bottom of trench using SEEP/W to simulate rainfall infiltration. Stability analysis was then conducted based on the pore-water pressure distribution from SEEP/W.

4 ANALYSIS RESULTS

4.1 Stability Analysis without Rainfall

For the purpose of comparison, stability analyses without rainfall event were performed using two different methods.

4.1.1 Method 1

In this method, stability analyses were conducted by directly assigning depth of tension crack using ‘tension crack line’ option in SLOPE/W. Figure 9 shows the example with a depth of tension crack at 2 m from the ground surface. Factor of safety (FOS) decreased from 1.5 to 1.12 with the tension crack at distance of 2 m. Figure 10 shows the variation of FOS for different tension crack depth and distance. It is obvious that FOS decreases with increasing the tension crack depth. The distance from the crest to the opening of tension crack for critical slip surface decreases with increasing the depth of tension crack. Critical condition (FOS ≤ 1) took place with the combination of Distance = 1.2 m & Depth = 3 m.

4.1.2 Method 2

In this method, stability analysis was conducted by simulating tension cracks as explained in Section 3.2. Three distances (i.e. 2, 3 and 4 m) and depths (1, 2, 3.6, and 4 m) of tension cracks were considered in the analyses. Table 3 summarizes the analyses results. The advantage of this method over Method 1 is that the variation of FOS can be visualized as a tension crack propagate into soils. As expected, FOS decrease with increasing the depth of tension crack. FOS then becomes constant once the depth of tension crack reaches a certain level (i.e. 2.5m). This indicates that the slip surface with minimum FOS takes place before the depth of tension crack is fully developed (i.e. 3.6 m). Minimum FOS was observed with Distance = 2 m & Depth = 2.5m.

4.1.3 Stability Analysis with Rainfall

Figure 11 shows pore-water distribution and FOS 20 hours after the rainfall starts for the case with Distance = 3 m & Depth = 3.6 m. FOS drops from 1.23 to 1.09 when compared to no rainfall condition. Although FOS decreased due to rainfall infiltration it is still greater than ‘1’. This indicates that, for certain cases, an unsupported trench may not fail even considering tension crack and rainfall infiltration.

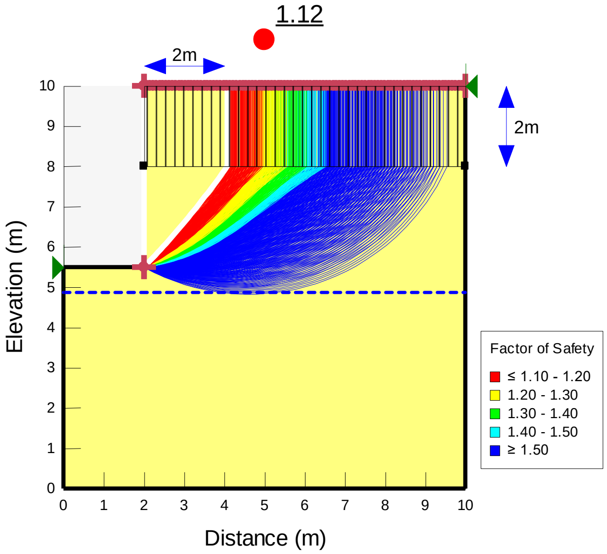


Figure 9. Stability analysis assuming the critical slip surface initiate from the bottom of a tension crack

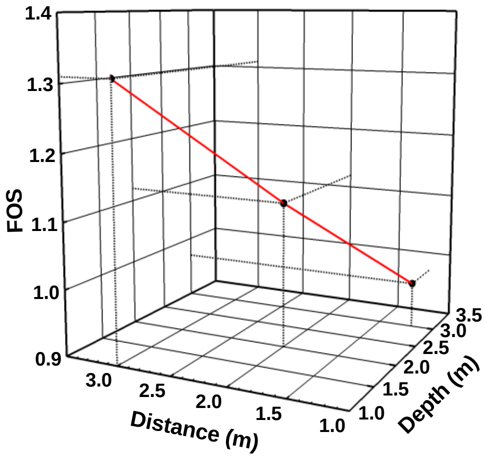


Figure 10. Depth-distance-FOS relationship

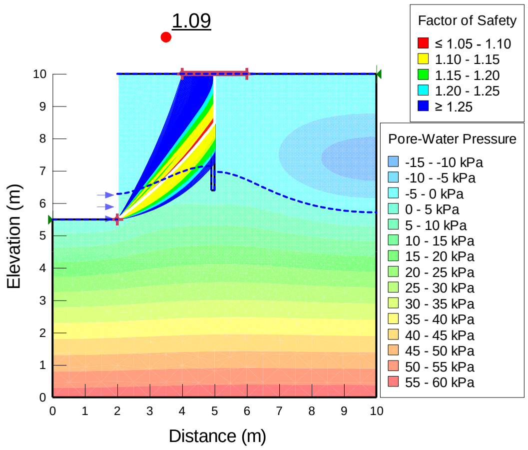
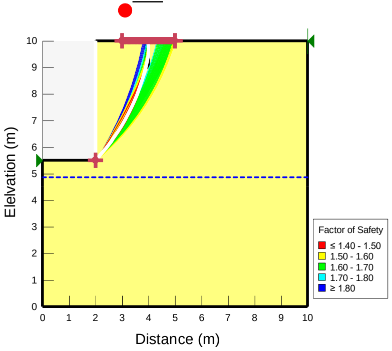
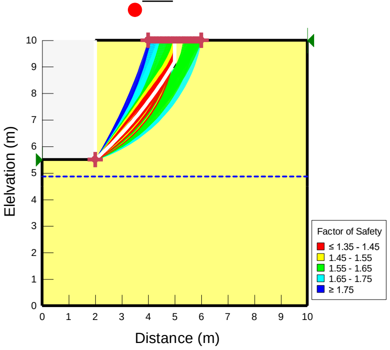
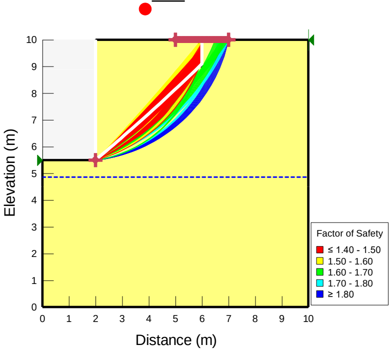
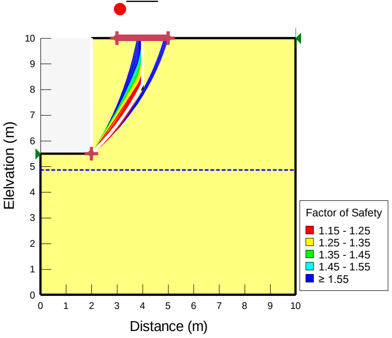
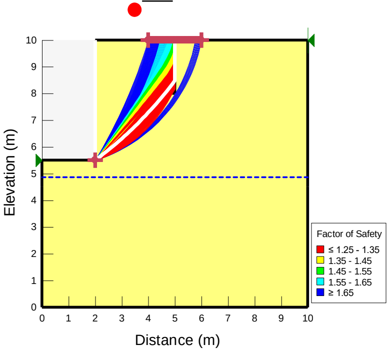
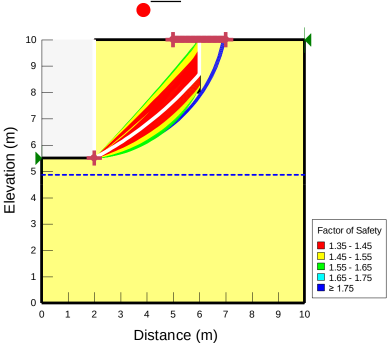
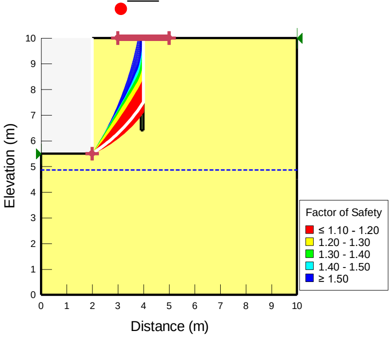
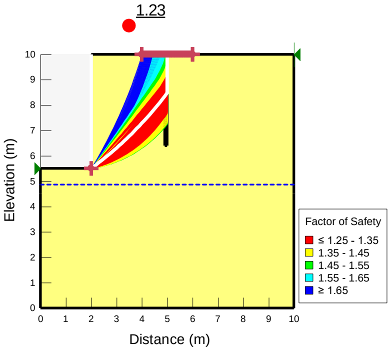
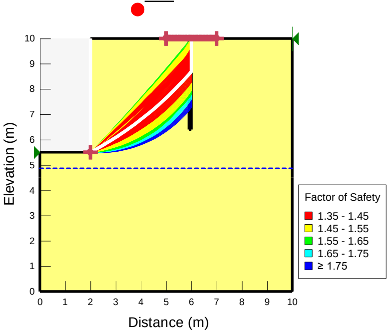
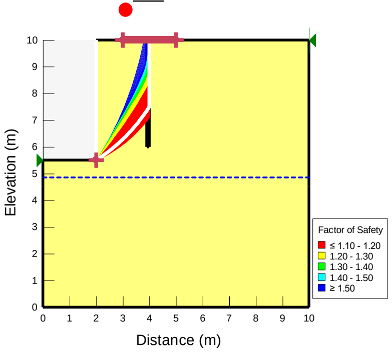
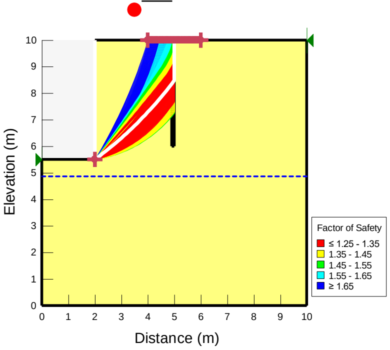
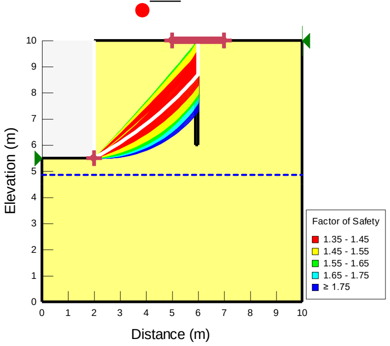


Figure 11. Pore-water pressure and FOS after 20 hours rainfall infiltration (10 mm/hr)

Table 3. Summary of stability analysis using Method 2

Depth (m)	Distance (m)		
	2	3	4
1	1.41 	1.34 	1.38 
2	1.15 	1.23 	1.35 
3.6	1.09 	1.23 	1.35 
4	1.09 	1.23 	1.35 

5 SUMMARY AND CONCLUSIONS

In the present study, an attempt was made to investigate the influence of tension crack on the stability of unsupported vertical trenches using geotechnical modeling software, GeoStudio 2016. Numerical analyses were carried out considering various depth of tension crack, distance from the crest to the opening of tension crack, and rainfall intensity.

FOS increases with increasing distance; but, decreases with increasing depth of tension cracks. However, the minimum FOS was observed when there was critical combination of distance and depth of tension crack. For example, for the scenarios considered in the present study, the combinations of Distance = 1.2 m & Depth = 3 m and Distance = 2 m & Depth = 2.5 m caused minimum FOS when analyzed with 'tension crack line option (Method 1)' and 'simulated tension crack (Method 2). Therefore, it can be postulated that there is high possibility of trench failure in case where a tension crack is initiated at the distance between 1.2 m and 2 m from the crest with a depth in the range of 2.5 m to 3 m. FOS further decreased when rainfall events were taken into account in stability analysis. For the practical scenario used in the present study, however, FOS did not drop below '1' even with long period of rainfall event under 10 mm/hr intensity. Nonetheless, it is strongly recommended that stability analyses be done considering worst case scenario with different rainfall intensity and duration.

6 REFERENCES

Arboleda, C.A. and Abraham, D.M. 2004. Fatalities in trenching operations analysis using models of accident causation. *Journal of Construction Engineering and Management*, 130(2): 273-280.

Bagge, G. 1985. Tension cracks in saturated clay cuttings. *Proceeding of the 11th international conference on soil mechanics and foundation engineering*, San Francisco, (Balkema): 393-395.

Bishop, A.W. and Morgenstern, N. 1960. Stability coefficients for earth slopes. *Géotechnique*, 10(4): 164-169.

BLS (Bureau of Labor Statistics). 2010. Census of fatal occupational injuries (2000−2009). Washington, D.C. Bureau of Labor Statistics.

Fan, P., Liu, Q.Q., Li, J.C. and Sun, J.P. 2005. Numerical analysis of rainfall infiltration in the slope with a fracture. *Science in China,* 48(S): 107-120.

Gofar, N., Min, L. L. and Asof, M. 2006. Transient seepage and slope stability analysis for rainfall-induced landslide: a case study, *Malaysian Journal of Civil Engineering,* 18(1): 1-13.

Hu, S. 2000. Reliability of Slope Stability Considering Infiltration through Surface Cracks, M.Phil. Thesis, Hong Kong University of Science and Technology, Hong Kong.

Li, J.H. and Zhang, L.M. 2010. Geometric parameters and REV of a crack network in soil. *Computers and Géotechnics*, 37(4): 466-475.

Ileme, V. 2018. Influence of rainfall infiltration on the stand-up time of unsupported vertical trenches. Master's thesis, University of New Brunswick.

Infrastructure Health & Safety Association (IHSA). 2017. Construction Health & Safety Manual – Chapter 31 Trenching.

Ontario. 2018. Occupational Health and Safety Act. Ontario Regulation 213/91, Construction Projects.

Pufahl, D.E., Fredlund, D.G. and Rahardjo, H. 1983. Lateral earth pressure in expansive clay soils, *Canadian Geotechnical Journal*, 20(2): 228-241.

Richard, A. 2018. Estimating the critical height of unsupported trenches in unsaturated soil. Master's thesis, University of New Brunswick.

Vanapalli, S.K., Fredlund, D.G. and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction, *Canadian Geotechnical Journal*, 33(3): 379-392.

Wang, Z. F. 2011. Unsaturated hydraulic properties of a single crack and its effects on slope stability. MPhil thesis, Harbin Institute of Technology, PRC.

Wang, Z.F., Li, J.H. and Zhang, L.M. 2012. Influence of cracks on the stability of a cracked soil slope. *Proceeding of the 5th Asia-Pacific Conference on Unsaturated Soils*, Pattaya, Thailand, 2: 594-600.

Wang, R., Zhang, G., Zhang, J.M. 2010. Centrifuge modelling of clay slope with montmorillonite weak layer under rainfall conditions. *Applied Clay Science,* 50 (3): 386-394.