Influence of rainfall infiltration on the stand-up time of unsupported vertical trench in an unsaturated sand

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ABSTRACT: Trenches are typically excavated in soils that are in a state of unsaturated condition. Stability of trenches in unsaturated soils, therefore, primarily depends on matric suction distribution profiles, which has a great influence on the shear strength of unsaturated soils. Types of soil, depth of the groundwater table and local climate conditions such as rainfall are contributing factors to the matric suction distribution profile, and thus the stability of unsupported vertical trenches. In the present study, numerical analyses were conducted to investigate the influence of rainfall intensity and the level of ground water table on the stand-up time of unsupported vertical trenches. In addition, the effectiveness of temporary trench cover using a water proof material towards stand-up time was also investigated. The commercial geotechnical software, GeoStudio 2016 (SIGMA/W, SEEP/W and SLOPE/W) was used for excavation, seepage and slope stability analysis, respectively.

1 INTRODUCTION

Trenching is the most common practice in geotechnical engineering especially in mining, tunneling, building foundations, drainage construction and installation of piping systems, etc. Trench cave-ins are blamed for many work-related injuries and deaths in the construction industry. In the U.S., between 60 and 100 deaths per year in the construction industry are attributed to trench cave-ins (Thompson and Tanenbaum 1977, Suruda et al. 1988, White 2008). According to the OSHA Data Base (1985 - 1989) most deaths related to trench failures occurred in sewer line construction.

Trenches are typically excavated in soils that are in a state of unsaturated condition. Stability of trenches in unsaturated soils, therefore, primarily depends on matric suction distribution profile which has a great influence on the shear strength of unsaturated soils. Types of soil, depth of the groundwater table, and local climate conditions (including rainfall) are contributing factors to the matric suction distribution profile, and thus the stability of unsupported vertical trenches (Pufahl et al. 1983, Stanier & Tarantino 2013, Vanapalli & Oh 2012, Whenham et al. 2007).

Critical height (i.e. maximum depth of an unsupported trench that can be excavated without failure) and stand-up time (time elapsed from the instant a trench is excavated till it fails; T_{stup}) are two important factors that should be considered in the design of unsupported trenches. Richard et al. (2017) investigated the critical height of unsupported vertical trenches in an unsaturated sand (Unimin 7030) for various levels of groundwater table. This present study is a step further in the work of Richard et al. (2017) whereby an attempt is made to investigate the influence of rainfall infiltration on the stand-up time of unsupported vertical trench in an unsaturated sand (Unimin 7030 sand). The analyses were carried out for three different rainfall intensities (10 mm/hr, 15 mm/hr and 25 mm/hr) using commercial geotechnical software, SEEP/W, SIGMA/W and SLOPE/W (product of GeoStudio 2016, Geo-Slope Int. Ltd.). The levels of ground water table were assumed to be at the depths of 50cm and 80cm from the soil surface. The shallow ground water tables (50cm and 80cm) were assumed in this study since the Soil-Water Characteristic of Unimin 7030 sand has a narrow suction range, which leads to a low residual suction value. One of the practicable ways of delaying the rainfall infiltration into vertical trenches is covering the surface of soil from the edge of vertical excavation to a certain distance with waterproof materials. Hence, additional analyses were also carried out to investigate the influence of temporary surface covering (20%, 25%, 50%, 75% and 100% of excavation depth) on the stand-up time of unsupported vertical trenches.

2 SOIL PROPERTIES

In this paper, it was assumed that trenches were excavated into a sand (Unimin 7030). Table 1 summarizes the soil properties of the sand. Hydraulic conductivity and elastic modulus for saturated conditions were assumed to be 5×10^{-5} m/s and 10000 kPa, respectively. Grain size distribution curve of the soil is shown in Figure 1.

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

Properties	Value
Plasticity index, I_p	NP
Effective cohesion, c'	0
Effective internal friction angle, ϕ'	36.2°
Saturated unit weight, γ_{sat} (kN/m^3)	19.75
Saturated volumetric water content, θ_s	0.38
Void ratio, e	0.63
Specific gravity, G_s	2.65
Saturated hydraulic conductivity, k_{sat} (m/s)	5×10^{-5}
Elastic modulus for saturated condition, E_{sat} (kPa)	10,000

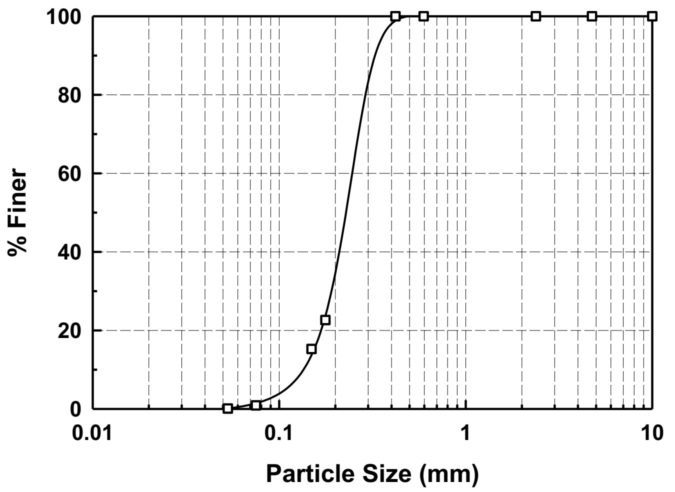

Figure 1. Grain size distribution curve of Unimin 7030 sand (modified after Mohamed 2006).

2.1 *Soil-Water Characteristic Curve*

The Soil-Water Characteristic Curve (SWCC) of the sand is shown in Figure 2, which was measured using Tempe Cell. Best-fit analysis for the SWCC was obtained using the model proposed by Fredlund and Xing (1994) (Eq.(1)).

$$S_e(\psi)=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)=\left[\frac{1}{\ln\left(e+\left(\frac{\psi}{a}\right)^n\right)}\right]^m \quad (1)$$

where $S_e(\psi)$ = effective degree of saturation corresponding to suction, ψ, e = Euler's number, and a (= 9.1638), m (= 16.544), n (= 4.8624) = fitting parameters

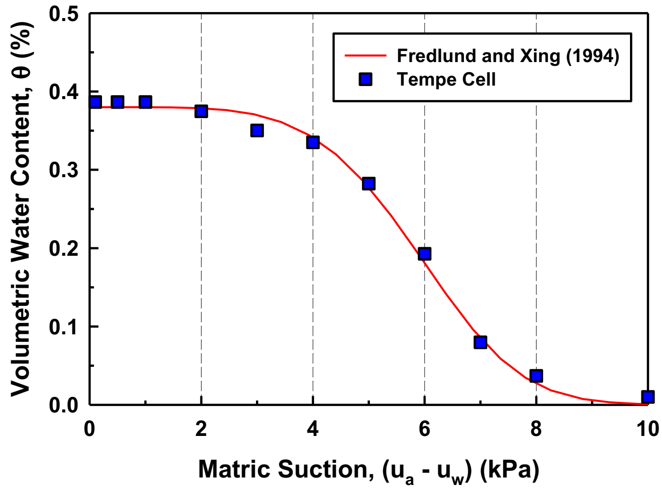

Figure 2. Soil-Water Characteristic Curve of Unimin 7030 (modified after Mohammed 2006).

2.2 *Shear strength of unsaturated soils*

Partial saturation plays an important role in the stability of trenches (Vanapalli & Oh 2012). Since trenches are mostly excavated into unsaturated soils, its stability depends largely on the matric suction distribution profile between the soil surface and the ground water table and also the types of soil (Pufahl et al. 1983, Whenham et al. 2007, De Vita et al. 2008, Vanapalli & Oh 2012).

The shear strength equation for unsaturated soils proposed by Fredlund et al. (1978) is written as Eq. (2).

$$\begin{aligned}\tau &= c'+(\sigma-u_a)\tan\phi'+(u_a-u_w)\tan\phi^b\\ &=\left[c'+(u_a-u_w)\tan\phi^b\right]+(\sigma-u_a)\tan\phi'\\ &=c+(\sigma-u_a)\tan\phi'\end{aligned} \quad (2)$$

where c' = effective cohesion, c = total cohesion, ϕ' = effective friction angle, $(\sigma-u_a)$ = net normal stress, ϕ^b = friction angle associated with a change in matric suction, (u_a-u_w)

Since determination of ϕ^b experimentally requires elaborate equipment and time-consuming the model proposed by Vanapalli et al. (1996) was adopted in the present study to estimate the nonlinear variation of shear strength of soil with respect to matric suction (Eq. (3)).

$$\begin{aligned}c &= c'+(u_a-u_w)\tan\phi^b\\ &=c'+(u_a-u_w)\left[\frac{(\theta-\theta_r)}{(\theta_s-\theta_r)}\right]\tan\phi'\end{aligned} \quad (3)$$

where θ = volumetric water content, θ_s = volumetric water content at saturation, θ_r = volumetric water content for residual condition.

In the case where the volume change in a soil is negligible Eq. (3) can be rewritten as (4).

$$c = c' + (u_a - u_w)\left[\frac{(S - S_r)}{(S_s - S_r)}\right]\tan\phi' \quad (4)$$

where S = degree of saturation, S_s = degree of saturation at saturation, and S_r = degree of saturation for residual condition

SIGMA/W and SLOPE/W adopt Eq. (3) to calculate the shear strength of unsaturated soil assuming that volumetric water content equal to 5% of θ_s is θ_r. Figure 3 shows the variation of total cohesion, c (Eq. (3) with respect to depth depending on the level of ground water table used in the present study (i.e. 50cm and 80cm from the soil surface). Hydrostatic variation of pore-water pressure with distance above and below the water table was assumed in the analyses.

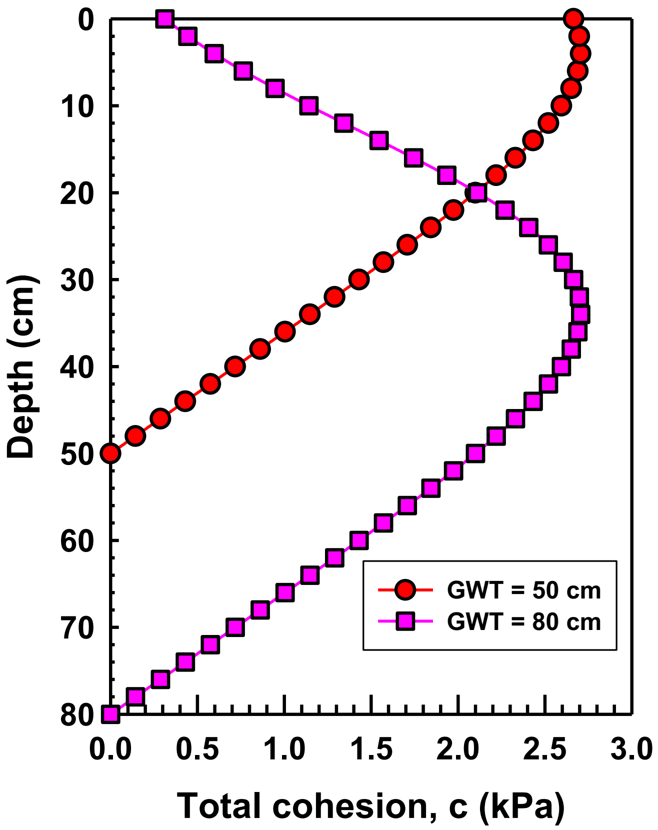

Figure 3. Variation of total cohesion, c with respect to depth depending on the level of ground water table.

2.3 *Hydraulic conductivity function*

This paper focuses on the influence of rainfall infiltration on the stand-up time of unsupported vertical trench. Hence, the hydraulic conductivity function plays important role in the numerical analysis.

The flow of water through a saturated soil is generally described using Darcy's law. According to Childs & Collis-George (1950), Darcy's law can also be applied to the flow of water through unsaturated soils. The coefficient of permeability, k, however, is not constant, but, varies depending on degree of saturation or matric suction. The ability of water to move through the pores of the soil particles under both saturated and unsaturated conditions is defined by the hydraulic conductivity function. Hydraulic conductivity decreases as soils move from saturated condition to unsaturated condition. This is because in saturated condition all the pore spaces between the soil particles are filled with water and this makes it easier for water to flow from one end to the other. Beyond air-entry value, air starts to enter the pores causing obstructions on the flow path thereby decreasing the ease with which water moves through the pores of the soil. The ability of water to move through the pores of the soil keeps decreasing as pore water pressure become increasingly negative and more pores are filled with air. Direct measurement of hydraulic conductivity for unsaturated soil is time consuming, cumbersome and require elaborate equipment. This can be overcome by using existing hydraulic conductivity function to predict the variation of hydraulic conductivity with respect to matric suction.

Fredlund et al. (1994) developed a method of estimating the unsaturated hydraulic conductivity function by integrating along the entire curve of the volumetric water content function as shown in Eq. (5) Figure 4 shows the hydraulic conductivity function used in the present study.

$$k(\psi) = k_s \frac{\displaystyle\sum_{i=j}^{N} \frac{\theta(e^y) - \theta(\psi)}{e^{y_i}} \theta'(e^{y_i})}{\displaystyle\sum_{i=1}^{N} \frac{\theta(e^y) - \theta_s}{e^{y_i}} \theta'(e^{y_i})} \quad (5)$$

Where

$k(\psi)$ = the calculated conductivity for a specified water content or matric suction (m/s),
k_s = the measured conductivity for saturated condition (m/s),
θ = the volumetric water content,
θ_s = the volumetric water content for saturated condition
e = Napier's constant,
y = a dummy variable of integration representing the logarithm of negative pore-water pressure,
i = the interval between the range of j to N,
j = the least negative pore-water pressure to be described by the final function,
N = the maximum negative pore-water pressure to be described by the final function,
ψ = the suction corresponding to the j^{th} interval,
θ' = the first derivative of the equation

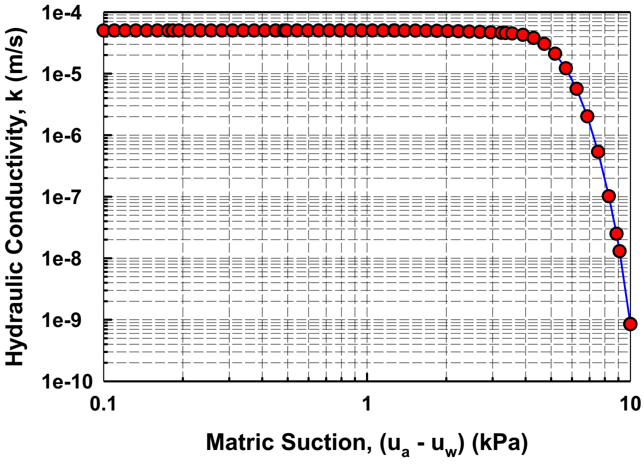

Figure 4. Hydraulic conductivity function used in the analysis.

3 METHODOLOGY

First, staged excavation was simulated in SIGMA/W by removing material from the regions (i.e. deactivating regions) in 0.01 m increments. After each excavation, slope stability analysis was carried out using SLOPE/W until the depth at which the Factor of Safety becomes close to 1.2 (Figure 5). The excavation process causes change in pore-water pressure (or groundwater table). Hence, this slope stability analyses were performed when the matric suction (or pore-water pressure) in the soil reached the equilibrium condition based on the results from SEEP/W. Unit flux boundary conditions were applied to the surface of soil and bottom of the excavation to simulate rainfall (Figure 6). For each time step, after applying certain unit flux boundary condition, slope stability analyses were repeated until the first rotational general failure takes place through the toe of vertical trench (i.e. FS = 1) (Figure 7). From the time of initial excavation to the time of this rotational failure is observed and defined as stand-up time. Table 2 summarizes the scenarios used in the present study.

Table 2. Scenarios used in the analyses

Scenario	a	b	c
1	50	47	10, 15, 20, 25
2	80	60	10, 15, 20, 25

a: level of water table (cm)
b: depth of excavation to achieve FS close to 1.2 (cm)
c. rainfall infiltration (mm/hr)

One of the most practical ways of minimizing the influence of rainfall infiltration on the stand-up time of unsupported vertical trenches is covering the top of a trench with a light-weight water-proof material. This practice is also simulated in this study assuming that the trenches were covered up to 20%, 25%, 50%, 75% and 100% of the excavation depths. This was simulated in the SEEP/W by apply a zero unit flux on the assumed covered areas as shown in Figure 8.

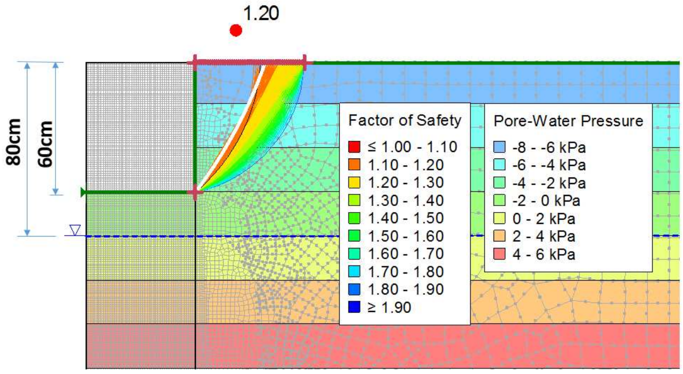

Figure 5. Excavation of a vertical trench up to a depth of FS = 1.2.

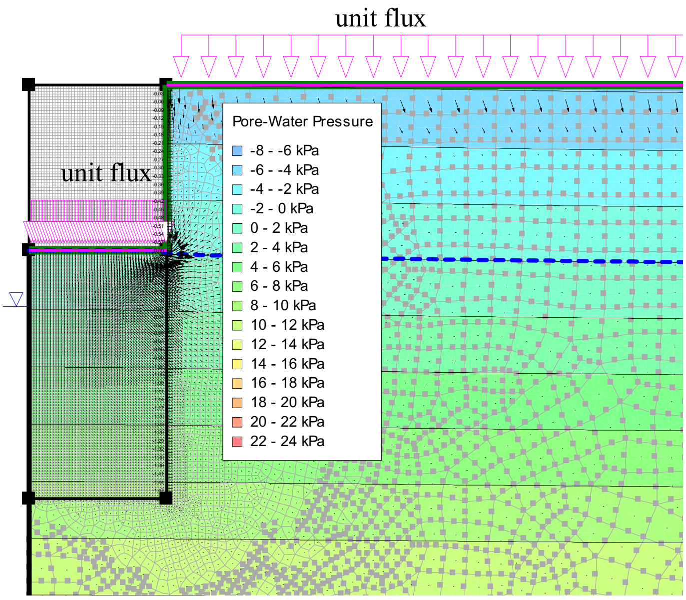

Figure 6. Application of unit flux boundary condition to simulate rainfall infiltration.

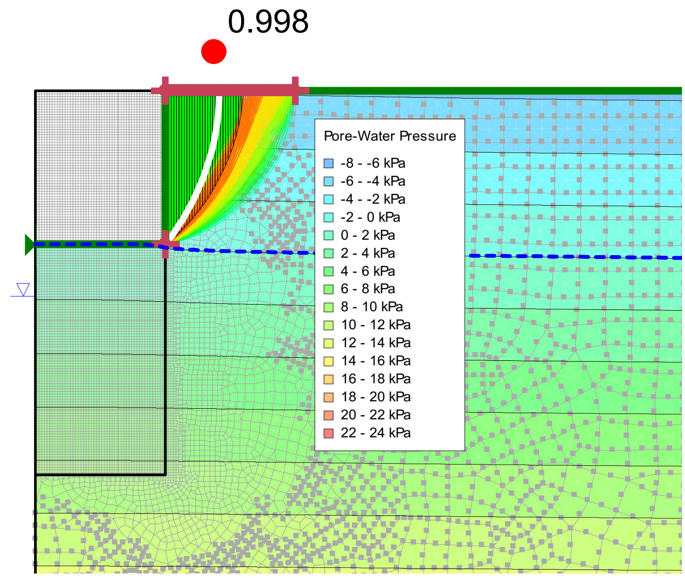

Figure 7. Determination of stand-up time based on slope stability analysis.

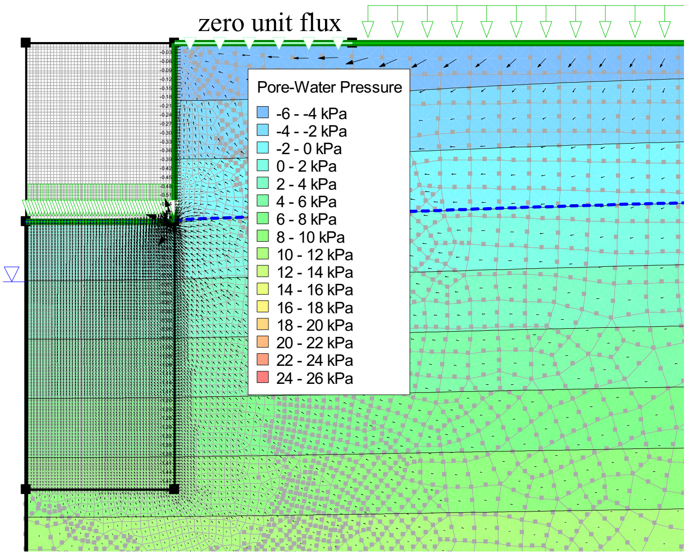

Figure 8. Numerical modeling to simulate rainfall infiltration with a cover on top of soil.

4 ANALYSIS OF RESULTS

Figure 9 and Figure 10 show the variation of FS with time for different rainfall intensities for GWT = 50cm and GWT = 80cm, respectively. As expected, FS decreases with time and maximum stand-up time was estimated to be 0.8 hrs and 4.4 hrs for 'GWT = 50cm, 10 mm/hr' and 'GWT = 80cm, 10 mm/hr', respectively. These figures can be effectively used in practice to determine necessary work hours under certain rainfall incident. For example, work hours in an unsupported vertical trench should not exceed 2 hrs maximum when GWT = 80cm and rainfall intensity is 20 mm/hr.

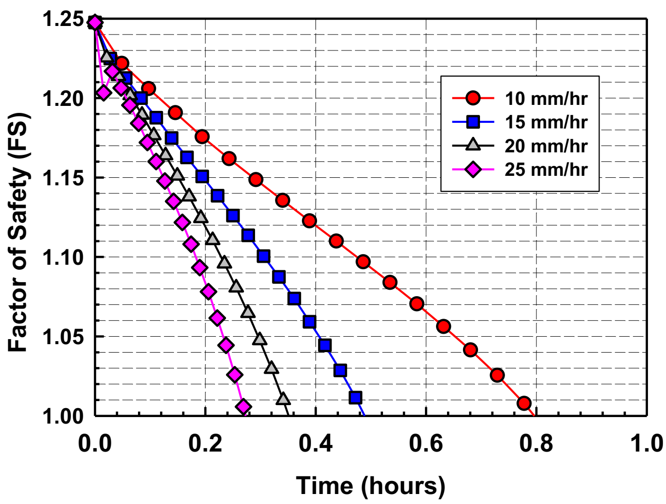

Figure 9. Variation of FS with time for different rainfall intensity (GWT = 50cm).

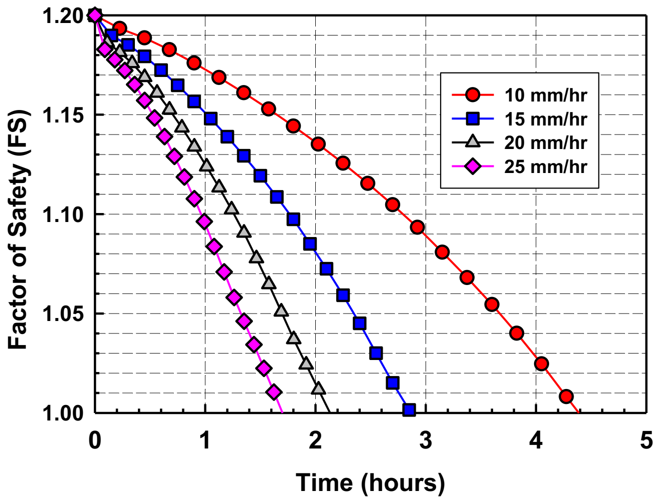

Figure 10. Variation of FS with time for different rainfall intensity (GWT = 80cm).

Figure 11 and Figure 12 show the variation of stand-up time (T_{stup}) with respect to rainfall intensity and range of coverage for GWT = 50cm and GWT = 80cm, respectively. For GWT = 50cm, the stand-up time increased less than 0.24 hrs even with 100% coverage. The increase in stand-up time for GWT = 80cm was in the range of 0.77 and 1.42 hrs. This indicates that using a temporary cover on top of soil does not make significant difference if water table is at shallow depth in a sand. The behaviours of stand-up time versus rainfall intensity between different coverage ranges approximately parallel to each other. The investigation on critical height in the same soil (Unimin 7030) by Richard et al. (2017) showed that the critical height is governed by the level of ground water table. Hence, it can be postulated that stand-up time of an unsupported vertical trench in a sand is affected by the rainfall at the bottom of trench rather than the top of the soil.

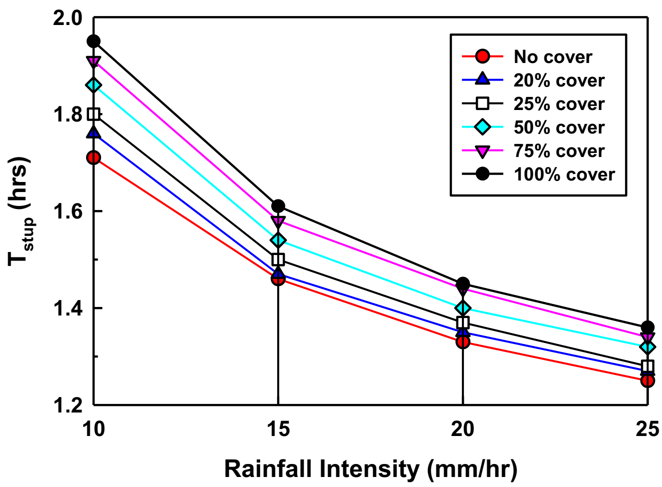

Figure 11. Variation of stand-up time with respect to rainfall intensity and range of coverage (GWT = 50cm).

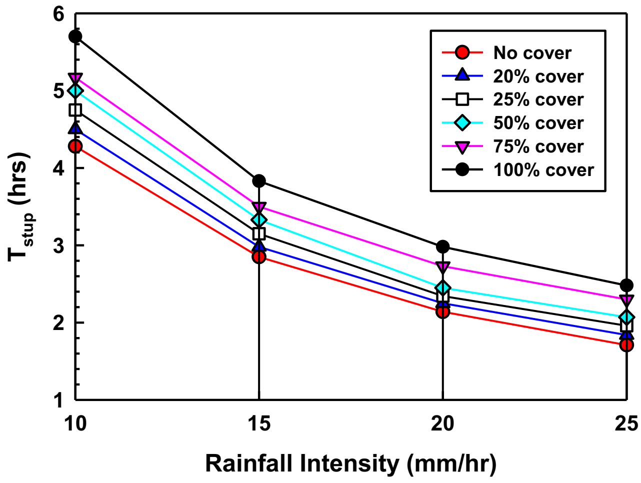

Figure 12. Variation of stand-up time with respect to rainfall intensity and range of coverage (GWT = 80cm).

5 SUMMARY AND CONCLUSIONS

An attempt was made to investigate the influence of rainfall infiltration on the stand-up time of unsupported vertical trenches using commercial geotechnical software (SIGMA/, SEEP/W, and SLOPE/W). It was assumed that trenches were excavated into unsaturated sand with two different groundwater tables (i.e. 50cm and 80cm) and four rainfall intensities (i.e. 10, 15, 20 and 25 mm/hr). The stand-up time varies from 0.8 hrs to 4.4 hrs for the level of ground water table and rainfall intensities used in the present study. The effectiveness of the practice of partially covering the top of the excavation to minimize the influence rainfall infiltration was also studied. As expected, covering the tops of trenches can delay the failure in the unsupported vertical trench (i.e. increase in stand-up time) under certain rainfall intensities. However, the results showed that the effective of range of covering is not significant since the stand-up time was affected more by the rainfall at the bottom of trenches rather than top of the soil.

Although the present study was carried for shallow excavations in a sand it is expected that the methodologies used in the study can be extended to the estimation of stand-up time of unsupported trenches in unsaturated fine-grained soils.

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