E3S Web of Conferences 9, 15003 (2016) DOI: 10.1051/e3sconf/20160915003
E-UNSAT 2016

Estimation of the variation of matric suction with respect to depth in a vertical unsaturated soil trench associated with rainfall infiltration

Won Taek Oh[1,a], Sai K. Vanapalli[2], Shunchao Qi[2], and Zhong Han[2]

[1]*Department of Civil Engineering, University of New Brunswick, Fredericton, NB, Canada*
[2]*Department of Civil Engineering, University of Ottawa, Ottawa, ON, Canada*

Abstract. Soil trenching is extensively used in geotechnical, mining, tunneling and geo-environmental infrastructures. Safe height and stand-up time are two key factors that are required for the rational design of soil trenches. Rainfall infiltration has a significant influence on the safe height and stand-up time of unsaturated soil trenches since it can significantly alter the shear strength of soils by influencing the matric suction. In other words, predicting the variation of matric suction of soils associated with rainfall infiltration is vital to the design of unsaturated soil trenches. In this paper, finite element analysis is carried out to reproduce the variation of matric suction profile in unsaturated soil trenches associated with rainfall infiltration using the published results of a full scale instrumented test trench at the site of BBRI at Limelette, Belgium. The analysis results showed that the variation of matric suction in unsaturated soil trenches can be reliably estimated using the information of environmental factors such as the rainfall measurements.

1 Introduction

Soil trenching is extensively used in geotechnical, mining, tunneling and geo-environmental infrastructures (Brachman and Krushelnitzky 2005, Oshati et al. 2012, Widisinghe and Sivakugan 2014). Extensive precaution should be taken in the design and excavation of soil trenches. This is because trenches of relatively shallow depths (less than 3 m) can also pose short- and long-term safety hazards due to their failure (OSHA Data Base 1985 - 1989). Provinces in Canada have published guidebooks that emphasize occupational health and safety concerns associated with trench failures (e.g. New Brunswick - Excavation Trenching; Manitoba - Guideline for Excavation Work; Ontario - Trenching Safety - Introduction to Trenching Hazards). Nonetheless, a large number of worker deaths are still reported each year associated with soil trench failures. Safe height (i.e. maximum depth of a trench that can be excavated without failure; H_{safe}) and stand-up time (T_{stup}) are two key factors that are required for the rational design of soil trenches, which can be estimated based on shear strength parameters of soils. The existing approaches to estimate H_{safe} and T_{stup} in various guidebooks may not be reasonable since they do not consider local environmental factors such as rainfall infiltration, which contributes to the significant decreases in the shear strength of soils (Tomboy et al. 2008, Van Alboom and Whenham 2003, Whenham et al. 2007, Vanapalli et al. 2009, Vanapalli and Oh 2012). In other words, estimation of the variation of matric suction associated with rainfall infiltration is vital to the rational design of unsupported unsaturated vertical trenches. In the present study, an attempt is made to simulate the variation of matric suction in unsaturated soil trenches using commercial finite element software, SEEP/W (product of GeoStudio 2012, Geo-Slope Int. Ltd.). The variation of matric suction associated with rainfall infiltration simulated from the finite element analysis (FEA) were compared with published results of a full scale instrumented test trench at the site of BBRI at Limelette, Belgium (Whenham et al. 2007). The comparison showed that the variation of matric suction in unsaturated soil trenches can be reliably estimated using the information of environmental factors such as the rainfall measurements.

2 Background

2.1 Full scale instrumented test trench

Whenham et al. (2007) investigated the influence of rainfall infiltration on the stability of an unsupported vertical trench (3 m deep, 6 m wide and 20 m long). The trench was excavated at a site that was initially in a state of unsaturated condition. Both weekly averaged rainfall measurements and averaged suction values with depth were recorded over 12 months. The variation of matric suction profile with time were monitored using tensiometers installed at different depths. The first local failures and general failures were observed in January and February 2005, respectively, due to the decrease in

[a] Corresponding author: woh@unb.ca

matric suction values associated with the precipitation activity. Figure 1 shows the variation of matric suction values at the depth of 1m, 1.5m, 2.5m, and 3.5m for initial condition (before excavation), first local failures, and general failures. The data from this field study is used in the finite element analysis to estimate the variation of matric suction with depth due to rainfall infiltration into the trench.

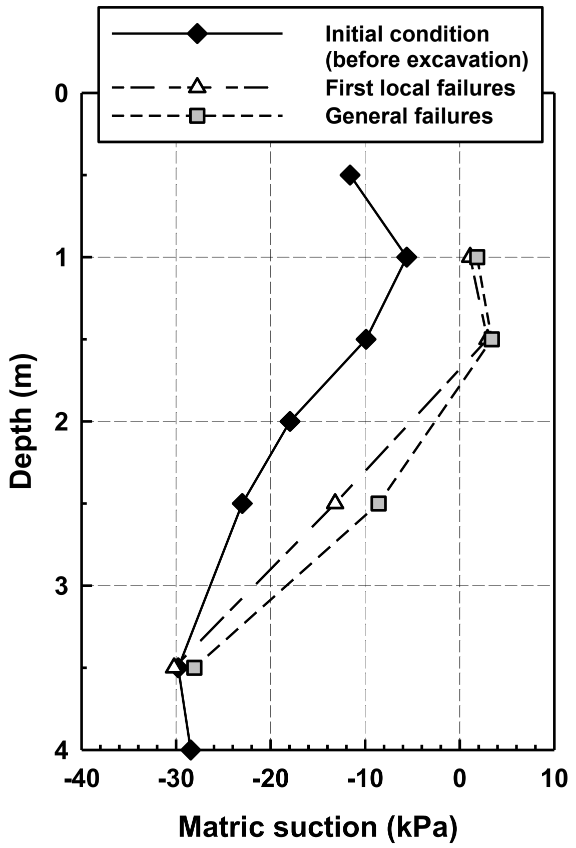

Figure 1. Variation of matric suction with respect to depth for initial condition (before excavation), first local failures and general failures

2.2 MODIFIED EFFECTIVE AND MODIFIED TOTAL STRESS APPROACH

Vanapalli and Oh (2012) analyzed stability of the trench detailed in 'Section 2' taking account of the variation of matric suction associated with rainfall infiltration extending the mechanics of unsaturated soils. Two different approaches, namely, Modified Effective Stress Approach (*MESA*) and Modified Total Stress Approach (*MTSA*), were used for the stability analysis. *MESA* and *MTSA* were originally developed to estimate the bearing capacity of unsaturated soils (Oh and Vanapalli 2013). Vanapalli and Oh (2012) suggested that stability of the test trench can be more reliably analyzed using *MTSA* rather than *MESA*.

2.2.1 Modified effective stress approach

MESA uses the effective shear strength parameters, c', ϕ' and ϕ^b (rate of increase in shear strength with matric suction) assuming both the pore-air and pore-water are in drained conditions. The active earth pressure at a depth z ($\sigma_a(z)$) in a trench excavated into an unsaturated soil can be calculated using Eq. (1) extending *MESA*.

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

where $(u_a - u_w)$ = matric suction, and $\phi_e^b = \phi^b$ for effective stress approach

By adopting the model to predict the nonlinear behavior of $\tan\phi^b$ (Eq. (2); Vanapalli et al. 1996), Eq. (1) can be rewritten as Eq. (3).

$$\tan\phi_e^b = S^\kappa \tan\phi' \qquad (2)$$

$$\sigma_a(z) = \gamma z K_a - 2\left[c' + \left(u_a - u_w\right)\left(S^\kappa\right)\tan\phi'\right]\sqrt{K_a} \qquad (3)$$

where γ = unit weight of a soil, z = depth of interest, K_a = coefficient of active earth pressure, S = degree of saturation, and κ = fitting parameter that is a function of plasticity index (Garven and Vanapalli, 2006).

2.2.2 Modified Total Stress Approach

MTSA is based on the assumption that the pore-air and pore-water are in a mode of drained and undrained condition, respectively. This approach requires results from constant water content (*CW*) tests (Thu et al. 2006). Hence, if total cohesion, c from the *CW* test (i.e. c_{CW}) is used, the active earth pressure at a depth z in an unsaturated soil trench can be estimated using Eq. (4) extending *MTSA*.

$$\begin{aligned}\sigma_a(z) &= \gamma z K_a - 2\left[c + \left(u_a - u_w\right)\tan\phi_t^b\right]\sqrt{K_a} \\ &= \gamma z K_a - 2c_{CW}\sqrt{K_a}\end{aligned} \qquad (4)$$

where $\phi_t^b = \phi^b$ for total stress approach

As can be seen in Eq. (3) and Eq. (4), matric suction value is the key factor for analyzing the unsaturated soils behavior using *MESA* and *MTSA*. In the present study, an attempt is made to simulate the variation of matric suction in unsaturated soil trenches based on the rainfall measurements using a commercial finite element software, SEEP/W (product of GeoStudio 2012, Geo-Slope Int. Ltd.).

3 Finite element analysis

3.1 Numerical model

Figure 2 shows the numerical model in SEEP/W used for the rainfall infiltration analysis for the test trench. The Soil-Water Characteristic Curve (*SWCC*), which is the main tool to estimate the variation of mechanical properties of unsaturated soils with matric suction, was measured at the depths of 1.5m, 2.5m and 3.5m. Hence, the soil was divided into three layers; namely, 0 to 2m, 2 to 3m, and 3m to bottom. Rainfall was simulated by applying 'unit flux, *q*' boundary on the top surface based the measured rainfall.

In SEEP/W, initial (positive or negative) pore-water pressure can be specified by either (i) drawing the initial water table, (ii) using activation values, or (iii) using spatial function (SEEP/W manual, 2012 edition). Option (i) is useful to define hydrostatic variation of pore-water pressure with distance above and below the water table. Option (ii) can be used when a new soil region become active with a certain initial pore-water and pore-air pressure. Option (iii) allows the users to directly assign non-hydrostatic pressure heads to the soils at different depths using the feature 'Spatial Functions'. Hence, in the present study, negative pressure heads were assigned to the soils by using option (iii) based on the initial matric suction distribution profile shown in Figure 1 (Figure 3). Matric suction values between specified points are linearly interpolated in SEEP/W. The measured initial matric suctions values with depth and those simulated in SEEP/W using spatial functions are compared in Figure 4.

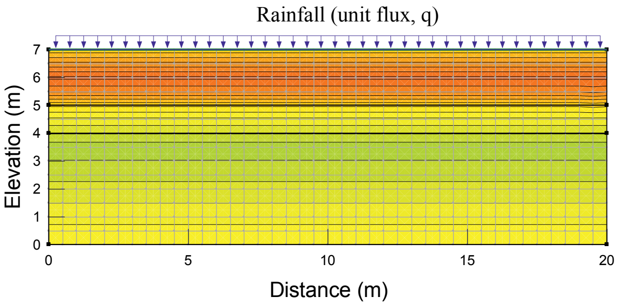

Figure 2. Numerical model of soil trench

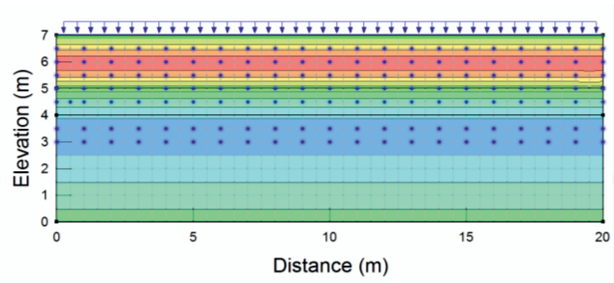

Figure 3. Assignment of non-hydrostatic pore-water pressure distribution using 'Spatial Functions' in SEEP/W

3.2 Soil-Water Characteristic Curve

Soil-Water Characteristic Curves (*SWCC*) from the three depths (1.5m, 2.5m and 3.5m) in the trench are shown in Figure 5. Minor differences were observed between the *SWCC*s.

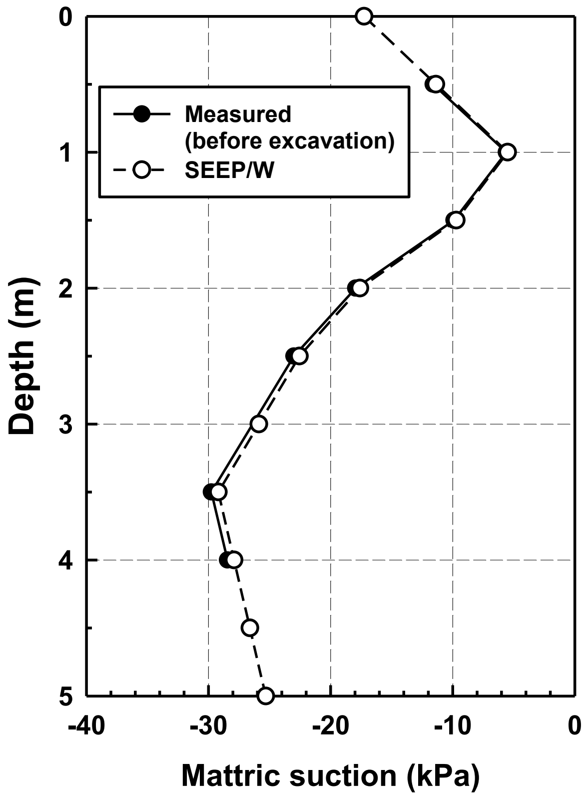

Figure 4. Measured initial matric suction values with depth and those simulated using SEEP/W (before excavation)

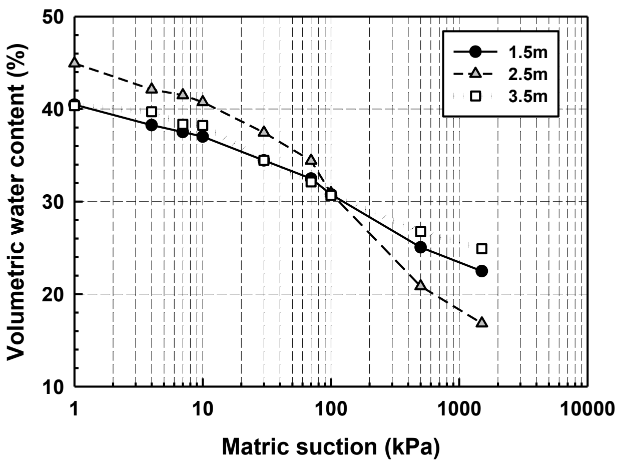

Figure 5. Soil-Water Characteristic Curves (from Whenham et al. 2007)

3.3 Hydraulic conductivity function

The variation of hydraulic conductivity with respect to matric suction (i.e. hydraulic conductivity function) was estimated using the model proposed by Fredlund et al. (1994) (Eq. (5)). Figure 6 shows the hydraulic functions generated in SEEP/W using the *SWCC*s (Figure 5) the hydraulic conductivity for saturated condition (i.e. k_{sat}). The similarities in the *SWCC*s and hydraulic functions for three different depths indicate that the soils consisting of the trench are relatively homogeneous within the investigated depth in terms of hydraulic properties.

$$k_{unsat} = k_{sat} \frac{\sum_{i=j}^{N} \frac{\Theta(e^{y}) - \Theta(\Psi)}{e^{y_i}} \Theta'(e^{y_i})}{\sum_{i=1}^{N} \frac{\Theta(e^{y}) - \Theta_{sat}}{e^{y_i}} \Theta'(e^{y_i})} \quad (5)$$

where:

k_{unsat} = the calculated conductivity for a specified water content or negative pore-water pressure,
k_{sat} = the measured saturated conductivity,
Θ_{sat} = the saturated volumetric water content,
e = the natural number 2.71828,
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, and
Θ' = the first derivative of the equation.

4 Analysis results

Whenham et al. (2007) provided 'weekly averaged rain measurements' in litres per square meter (l/m^2). These rainfall measurements may not be useful when carrying out seepage analysis in the trench since the duration of each rainfall measurement was not provided. Hence, the seepage analyses were conducted by assuming that each rain measurement was collected for (i) one day intervals (i.e. daily intensity; (Figure 7)) and (ii) one hour intervals (hourly intensity; measured for one hour from midnight to 1:00 AM; Figure 8).

Figure 9 shows the comparison between measured and estimated matric suction distribution profiles based on the assumed one day intervals (Figure 7). General failures in the trench occurred approximately 8 months after the excavation was initiated. Hence, the estimated matric suction distribution profile from SEEP/W that corresponds to 8 months were used for comparison purposes. As can be seen in Figure 9, negligible change in matric suction values was observed from the seepage analysis when compared with initial matric suction distribute profile.

Figure 10 shows the comparison between measured and estimated matric suction distribution profiles based on the assumed one hour intervals (Figure 8). At the depths of 2.5m and 3.5m the measured and estimated matric suction values were approximately the same. The estimated matric suction distribution profile well captured the trend of matric suction variation with depth with small discrepancy differences between the measured and estimated matric suction values at the depths of 1m and 1.5m. The results in Figure 10 clearly indicates that seepage analysis based on detailed rainfall intensity data can provide more reliable matric suction values with time.

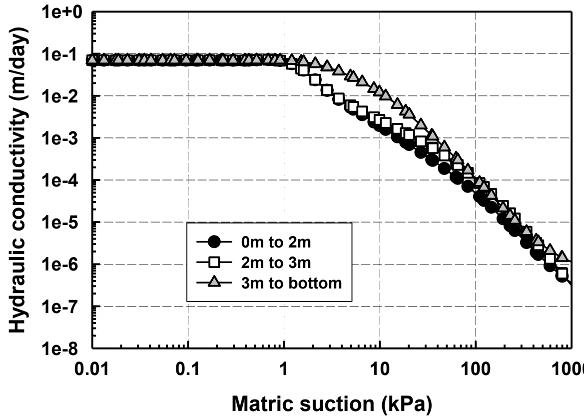

Figure 6. Hydraulic conductivity functions

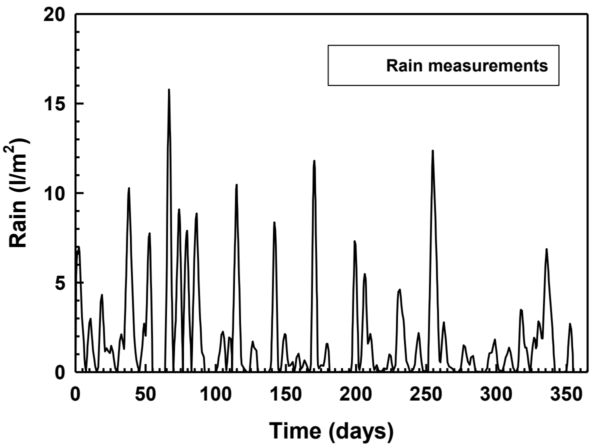

Figure 7. Assumed daily rain intensity used in the finite element analysis

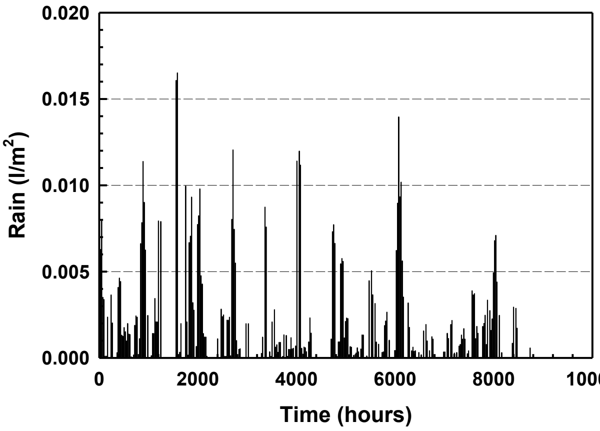

Figure 8. Assumed hourly rain intensity used in the finite element analysis

Additional seepage analysis was undertaken assuming average rain intensity of 10 mm/hr allowing ponding at the top boundary (Figure 11). For 40 days, the change (i.e. increase) in matric suction values took place within only relatively shallow depth (i.e. less than 1m from the soil surface), which is not realistic compared with the measured matric suction distribution profiles.

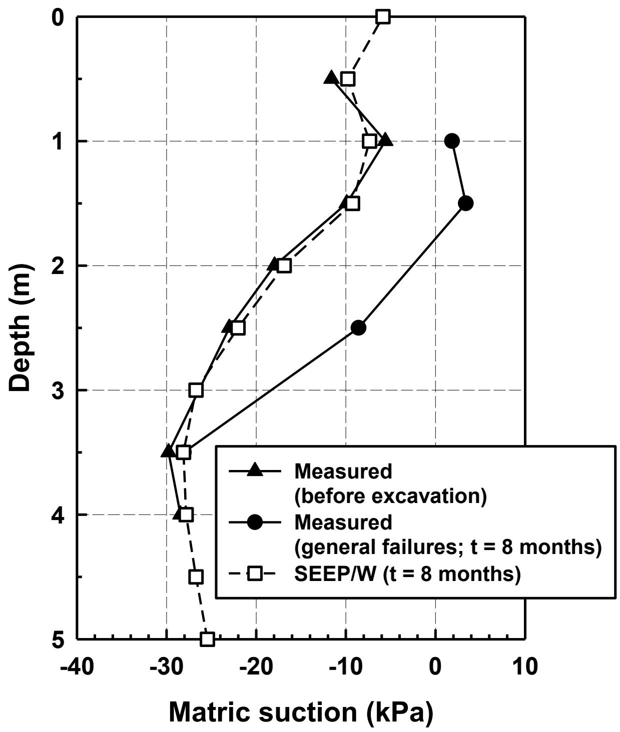

Figure 9. Comparison between measured and estimated matric suction distribution profiles based on assumed daily rain intensity

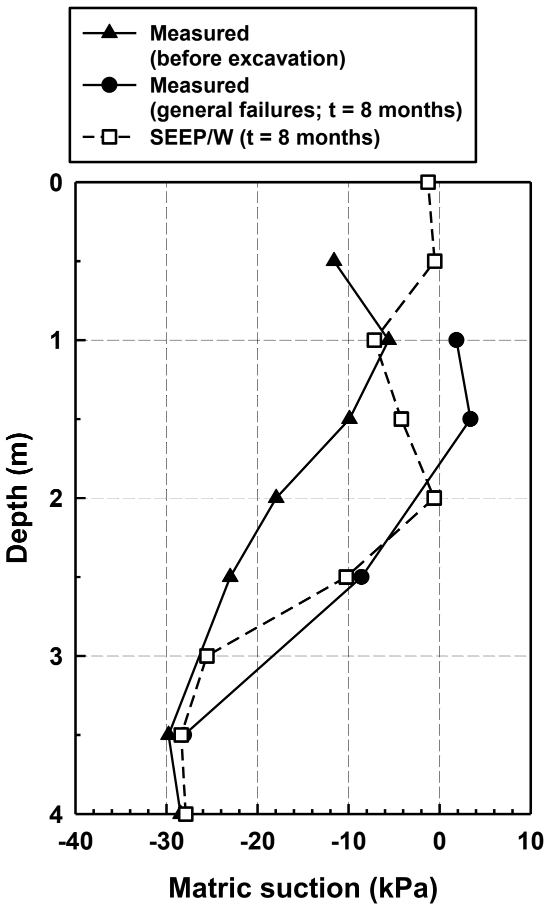

Figure 10. Comparison between measured and estimated matric suction distribution profiles (based on assumed hourly rain intensity)

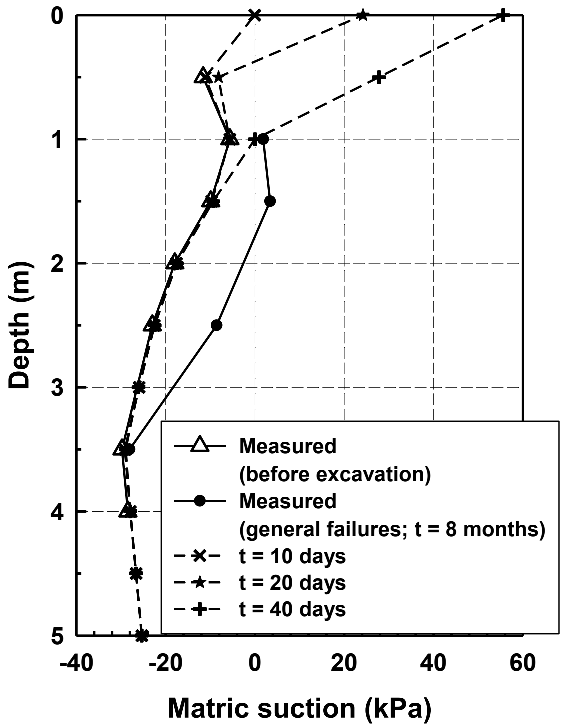

Figure 11. Comparison between measured and estimated matric suction distribution profiles assuming 10 mm/hr rain

5 Summary and conclusions

The instability of unsaturated soil trenches can be attributed to the reduction of matric suction associated with rainfall infiltration. Hence, estimating the variation of matric suction due to rainfall infiltration is fundamental to analyze the stability of unsaturated soil trenches. In this study, commercial finite element software, SEEP/W was used to simulate the variation of matric suction associated with rainfall infiltration for a test trench excavated in an unsaturated soil (Whenham et al. 2007). The analysis results showed that the variation of matric suction distribution profile with time in a trench can be reliably estimated by using rainfall measurements in the finite element analysis. However, matric suction distribution profile estimated assuming constant rainfall intensity (i.e. 10 mm/hr in the present study) provided unrealistic matric suction distribution profile.

References

1. Brachman, R.W.I. and Krushelnitzky, R.P. 2005. Response of a landfill drainage pipe buried in a trench. Canadian Geotechnical Journal, 42(3): 752-762.
2. Fredlund, D.G., Xing, A. and Huang, S. 1994. Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. Canadian Geotechnical Journal, 31(3): 521-532.
3. Occupational Safety and Health Administration (OSHA). 1990. Analysis of construction fatalities - OSHA Data Base 1985-1989.

4. Garven, E. and Vanapalli, S.K. 2006. Evaluation of empirical procedures for predicting the shear strength of unsaturated soils. Proc. of the 4th International Conference on Unsaturated Soils, Carefree, Ariz., 2-6 April 2006, 2: 2570–2581.
5. Oh, W.T. and Vanapalli, S.K. 2013. Interpreting the bearing capacity of unsaturated fine-grained soils using modified effective and total stress approaches. International Journal of Geomechanics, 13(6): 769-778.
6. Oshati, O. S., Valsangkar, A. J., Schriver, A. B. 2012. Performance of two cast-in-place box culverts under high embankments. Canadian Geotechnical Journal, 49(12): 133-346.
7. Seepage modeling with SEEP/W (2012). Geo-Slope International Ltd.
8. Tomboy, O., De Vos, M., Charlier, R., Maertens, J., and Verbrugge, J.-C. Shear strength of unsaturated soil and its influence on slope stability. Proc. of the 1st European Conference, E-UNSAT 2008, 2-4 July 2008, Durham, United Kingdom: 459-464.
9. Tu, X.B. Kwong, A.K.L., Dai, F.C. Tham, L.G. and Min, H. 2009. Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides. Engineering Geology, 105(1-2): 134-150.
10. Van Alboom, G. and Whenham, V. 2003. Soil investigation campaign at Limelette (Belgium): Results. Proc. of the 2nd Symposium on Screw Piles, May 7, Brussels, Belgium, 1: 21-70.
11. Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, 33(3): 379-392.
12. Vanapalli, S.K. and Oh, W.T. 2012. Stability analysis of unsupported vertical trenches in unsaturated soils. Proc. of Geo-Congress 2012, ASCE, 25-29 March 2012, Oakland, CA: 2502-2511.
13. Whenham, V., De Vos, V., Legrand, C., Charlier, R., Maertens, J. and Verbrugge, J.-C. 2007. Influence of soil suction on trench stability. Proc. of the 2nd International Conference on Mechanics of Unsaturated Soils, Weimar, Germany March 7-9, 2007: 495-501.
14. Widisinghe, S. and Sivakugan, N. 2014. Vertical stress isobars for trenches and mine stopes containing Granular Backfills. International Journal of Geomechanics, 14(2): 313-318.