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Effect of Soil-Water Characteristic Curve on the Stability of Unsupported Vertical Trenches in Unsaturated Soils

Won-Taek Oh[1]*, *Mahsa* Bajestani[1]

[1]Department of Civil Engineering, University of New Brunswick, Fredericton, NB, Canada

Abstract. In geotechnical engineering practice, unsupported vertical trenches are typically excavated in unsaturated soils. In this case, the variation of shear strength and hydraulic conductivity with respect to soil suction is key information to analyze the stability of an unsupported vertical trench. Most shear strength and hydraulic conductivity models use the soil-water characteristic curve (SWCC) as a main tool. Various models are available to determine SWCC, shear strength, and hydraulic conductivity for unsaturated soils. Scholars or practitioners use one the existing models in numerical analyses to estimate the stability of unsupported vertical trench considering rainfall events. However, limited studies have been undertaken to investigate the effect of SWCC and hydraulic conductivity functions on the stability of unsupported vertical trenches in unsaturated soils. In the present study, numerical stability analyses are carried out by using different SWCCs and hydraulic conductivity functions to investigate their influence on the estimated safe height and stand-up time of unsupported vertical trenches. The same shear strength model was used for entire numerical analyses.

1 Introduction

Excavation of an unsupported (i.e., unprotected) trench is the most fundamental construction operation in geotechnical engineering practice. However, it is also the most hazardous construction operation as well since the failures (i.e., cave-in) in unsupported trenches take place suddenly without any warnings in many scenarios. Evidence suggests that one cubic meter of collapsed soil can cause suffocation or significant injuries for people who work in the unsupported trenches. This indicates that unsupported trenches should be designed and excavated with extreme precaution.

The sources of construction accidents were analyzed using the accident causation models [1]. The data were collected from several health and safety agencies, including the Bureau of Labor and Statistics (BLS), the Occupational Safety and Health Administration (OSHA), the National Safety Council (NSC), and the National Institute for Occupational Safety and Health (NIOSH). The results showed that the fatality rate for excavation work is higher than that for general construction. Due to this reason, in Canada, significant and continuous ongoing efforts have been in place by organizations (e.g. Canadian Centre for Occupational Health and Safety, CCOHS) and provinces by enforcing strict regulations or guidelines to prevent serious injuries or fatalities resulting from trench failures. Nonetheless, worker injuries and deaths owing to trench failures are reported each year.

Trenches are typically excavated into soils that are in a state of unsaturated conditions. Hence, the stability of an unsupported trench is governed by the matric suction profile since the shear strength of unsaturated soil is primarily dependent on the matric suction. Previous studies showed that level of groundwater table, soil type and rainfall events are considered three main contributing factors to the matric suction profile [2,3,4].

Critical height (i.e., maximum depth of an unsupported trench that can be excavated without a failure) and stand-up time (i.e., time elapsed from the instant an unsupported trench is excavated until it fails) are two main factors that should be considered in the design of an unsupported vertical trench (hereafter referred to as UVT). In practice, UVTs are usually excavated up to the safe height (i.e., critical height/FOS) to avoid unexpected failure [5]. However, UVTs can fail anytime due to the decrease in shear strength in association with rainfall infiltration. This means that stand-up time of UVTs should be estimated reliably considering local environmental conditions before field workers enter the UVTs.

Stand-up time of an UVT can be estimated by conducting coupled hydro-mechanical (hereafter referred to as coupled) numerical analysis. This requires the information of variation of shear strength and hydraulic conductivity with respect to matric suction, which can be obtained using the Soil-Water Characteristic Curve (SWCC) as a main tool. Various models are available in the literature to determine the SWCC, shear strength, and hydraulic conductivity for unsaturated soils. It is common in practice that scholar or practitioners use the preferred SWCC, shear strength, and hydraulic conductivity model to conduct the coupled analysis. However, previous study [6] showed that the stability of unsaturated slopes is significantly

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* Corresponding author: woh@unb.ca

affected by the SWCC used in the coupled analysis since it governs the shear strength and hydraulic conductivity profile in field. In the present study, a series of coupled analyses are carried out to investigate the effect of SWCC and hydraulic conductivity function on the safe height and stand-up time of UVTs in unsaturated soils. The same shear strength model was used for entire coupled numerical analyses.

2 Background

In the present study, commercial geotechnical software, SLOPE/W and SEEP/W (GeoStudio 2020, Seequent Int. Ltd.) was used to conduct stability and seepage analyses, respectively. The SWCCs, and the variation of shar strength and hydraulic conductivity with respect to matric suction used in the coupled numerical analyses were obtained as follows.

2.1 Soil-Water Characteristic Curves (SWCC)

The best-fit SWCCs were established using three different SWCC fit models as shown in Eq. (1) ([7], BC-SWCC), Eq. (2) ([8], vG-SWCC), and Eq. (3) ([9], FX-SWCC). The fitting parameters for each SWCC fit model were obtained using the nonlinear fitting program (*SWRC Fit*) [10].

$$S_e = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = \begin{cases} \left(\dfrac{\psi}{\psi_b}\right)^{-\lambda} & \psi > \psi_b \\ 1 & \psi_b \geq \psi \end{cases} \qquad (1)$$

$$S_e = \left[\frac{1}{1 + (\alpha\psi)^{n_{vG}}}\right]^{m_{vG}} \qquad (2)$$

$$S_e = \frac{1}{\left\{\ln\left[e + (\psi/a)^{n_{FX}}\right]\right\}^{m_{FX}}} \qquad (3)$$

where S_e is the effective saturation, θ is the volumetric water content, θ_s and θ_r are the saturated and residual volumetric water contents, respectively, ψ is the soil suction, ψ_b is the air-entry value, λ is the pore-size distribution index, α, n_{vG}, and m_{vG} (= 1- 1/n_{vG}) are fitting parameters in Eq. (2) [8], a, n_{FX}, and m_{FX} are fitting parameters in Eq. (3) [9], $C(\psi)$ is the correction factor, and e is Euler's number.

2.2 Total cohesion of unsaturated soils

Various approaches are available for interpreting, predicting, or estimating the shear strength of unsaturated soils [11]. Among those, GeoStudio (ver. 2020) adopts Eq. (4) to estimate the variation of total cohesion with respect to matric suction [12].

$$C = c' + (u_a - u_w)\tan\phi'\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) \qquad (4)$$

where c' is the effective cohesion, C is total cohesion, ϕ' is effective internal friction angle, σ is the total stress, ($\sigma - u_a$) is the net normal stress, u_a and u_w are pore-air and pore-water pressure, respectively, and ($u_a - u_w$) is the matric suction.

2.3 Hydraulic conductivity function

Eq. (5) ([7], BC-k), Eq. (6) ([8], vG-k) and Eq. (7) ([13], F-k) show the hydraulic conductivity models used in this study.

$$k_r(\psi) = \frac{k(\psi)}{k_{sat}} = \begin{cases} \left(\dfrac{\psi}{\psi_b}\right) & \psi > \psi_b \\ 1 & \psi \leq \psi_b \end{cases} \qquad (5)$$

$$k_r(\psi) = \left[\frac{\left\{1 - (\alpha\psi)^{(n_{vG}-1)}\left[1 + (\alpha\psi)^{n_{vG}}\right]^{-m_{vG}}\right\}^2}{\left[1 + (\alpha\psi)^{n_{vG}}\right]^{(1/2 - n_{vG}/2)}}\right] \qquad (6)$$

$$k_r(\psi) = \left\{\frac{\int_{ln(\psi)}^{b} \left(\theta(e^y) - \theta(\psi)\right)/e^y\theta'(e^y)\,dy}{\int_{ln(\psi_b)}^{b} \left(\theta(e^y) - \theta_s\right)/e^y\theta'(e^y)\,dy}\right\} \qquad (7)$$

where $k_r(\psi)$ is the relative hydraulic conductivity, $k(\psi)$ is the hydraulic conductivity at any soil suction of ψ, k_{sat} is the saturated hydraulic conductivity, y is the dummy variable of integration representing the logarithm of the soil suction, θ' is the first derivative of Eq. (8), and b is the upper limit of integration.

$$\theta = C(\psi)\frac{\theta_s}{\left\{\ln\left[e + (\psi/a)^{n_{FX}}\right]\right\}^{m_{FX}}} \qquad (8)$$

Three different hydraulic conductivity functions (i.e., variation of coefficient of hydraulic conductivity with respect to matric suction) were established using following three combinations.

i) BC-SWCC [Eq. (1)] + BC-k [Eq. (5)]
ii) vG-SWCC [Eq. (2)] + vG-k [Eq. (6)]
iii) FX-SWCC [Eq. (3)], F-k [Eq. (7)]

3 Methodology

3.1 Soil properties

It was assumed that UVTs were excavated into two different types of soils: sandy soil (Edosaki sand, ES) and glacial till (Indian Head till, IHT). ES was chosen in the present study not because it is practical to excavate UVTs in sandy soils but because its SWCC is different from that of IHT even though the shear strength parameters of both soils are similar. Basic soil properties are summarized in Table 1. Figure 1 shows the grain size distribution curves of ES and IHT. Three SWCCs and hydraulic conductivity functions for ES and IHT are shown in Figure 2 and Figure 3, respectively. The focus of this study is to investigate the influence of SWCCs obtained with the data available in the literature only; hence, the discussion on what model is more reasonable and appropriate is out of scope. The θ_r/θ_s ratio of FX-SWCC is significantly low for both soils in comparison to those of BC-SWCC and vG-SWCC. The effective shear strength parameters determined from the direct shear strength tests are (c' = 4.8 kPa, ϕ' = 28.6°) and (c' = 5.0 kPa, ϕ' = 23.1°) for ES and IHT, respectively.

According to Table 1, ES is classified as a NP soil, which may justify reanalyzing the same direct shear test results by forcing the trendline to pass the origin. This leads to c' = 0 kPa and ϕ' = 35.8° with high R^2 value (i.e., 0.977). It is common practice to neglect the effective cohesion for conservative stability analysis. Hence, numerical analyses were carried out with two sets of shear strength parameters, which were denoted as Scenario I and Scenario II as shown in Table 2.

Table 1. Basic properties of Edosaki sand and Indian Head till ([14]-[18]).

Properties	ES	IHT
Specific gravity, G_s	2.75	2.72
Plasticity index (%)	NP	15.5
USCS	SM	CL
Effective cohesion, c' (kPa)	4.8 (0[a])	5
Effective internal friction angle, ϕ' (°)	28.6 (35.8[a])	23.1
Saturated hydraulic conductivity, k_{sat} (m/s)	4.45×10^{-5}	10^{-7}

[a]: reanalyzed data by forcing the trendline to pass the origin

Table 2. Shear strength parameters used in numerical analysis for two different scenarios

Scenario	ES		IHT	
	c' (kPa)	ϕ' (°)	c' (kPa)	ϕ' (°)
I	4.8	28.6	5	23.1
II	0	35.8	0	23.1°

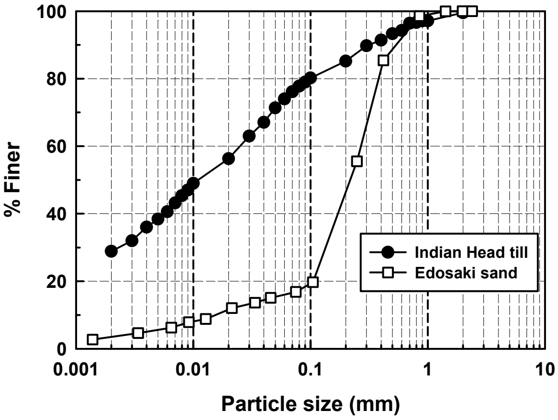
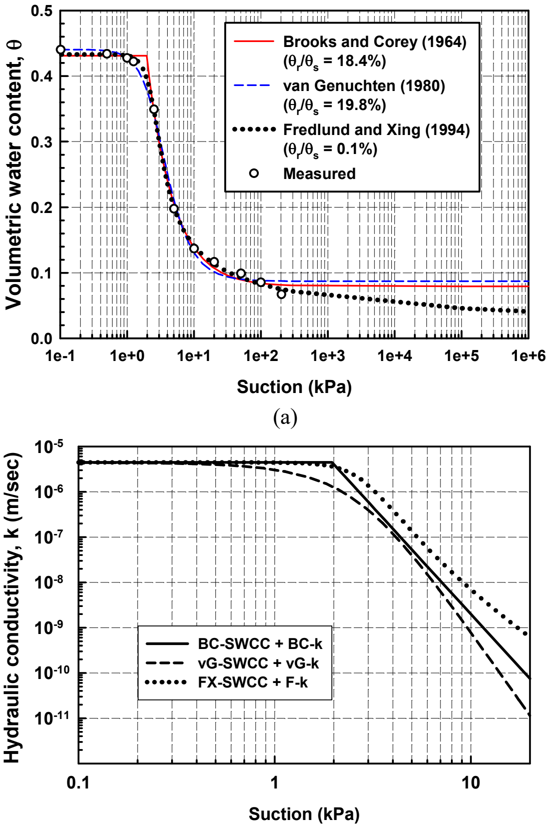


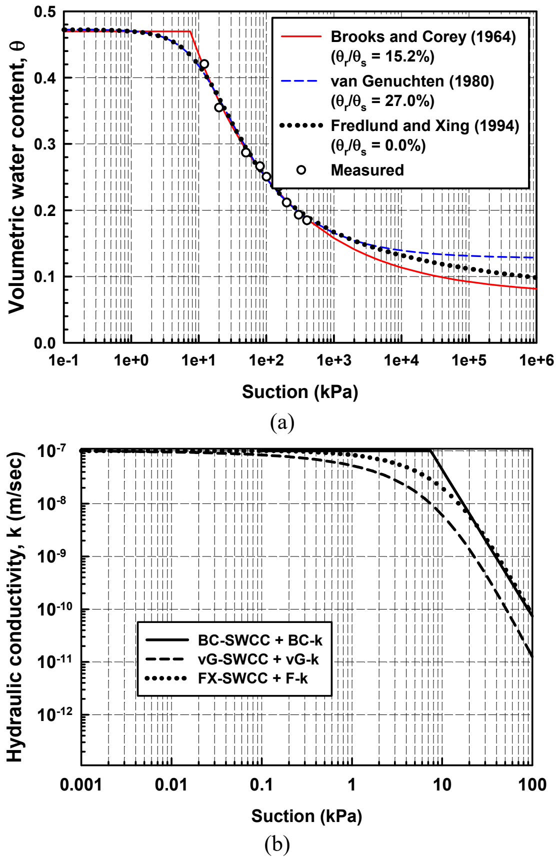
Figure 1. Grain size distribution curves for IHT and ES.



(a)

(b)

Figure 2. Edosaki sand: (a) SWCCs and (b) hydraulic conductivity functions.



(a)

(b)

Figure 3. Indian Head till: (a) SWCCs and (b) hydraulic conductivity functions.

Figure 4 shows the variation of total cohesion with respect to suction obtained with Eq. (4) along with three different SWCCs. For IHT, although the θ_r/θ_s ratio of FX-SWCC is remarkably low in comparison to those of BC-SWCC and vG-SWCC, no significant difference was observed between the curves. On the other hand, for ES, total cohesion values were significantly high when estimated with FX-SWCC, which can overestimate safe height and stand-up time.

3.2 Numerical analysis

Safe heights for different levels of groundwater table (GWT) (i.e., 0 m, 0.3 m, 0.5 m, 1.0 m, and 2 m from the ground surface) were first determined using SLOPE/W. Initial GWT was assigned by drawing ‘piezometric line’. The analysis with GWT = 0 m was carried out for the purpose of comparison. Trenching was simulated by deactivating regions in 0.02 m increments until FOS = 1.2 is obtained (Figure 5(a)). It was assumed that the potential failure surfaces exit through the toe of UVTs [19]. The drop of phreatic line due to trenching was ignored for conservative analysis.

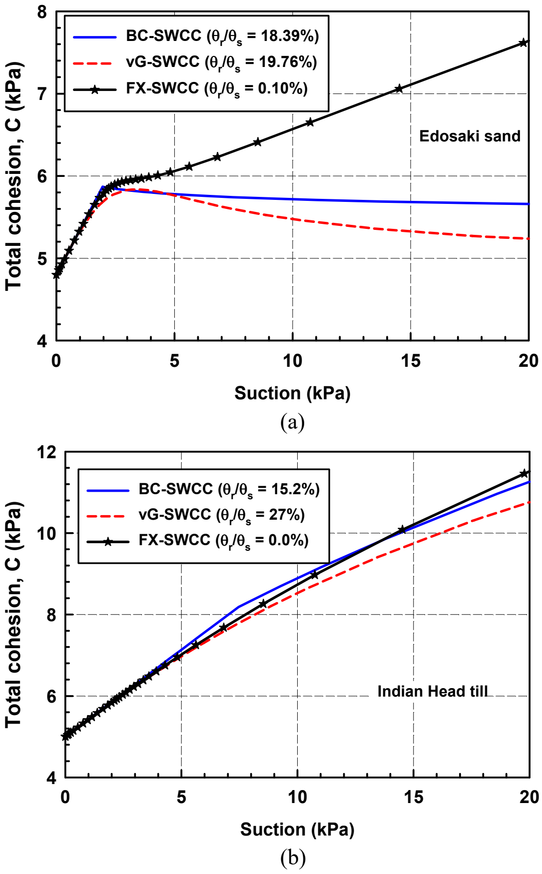


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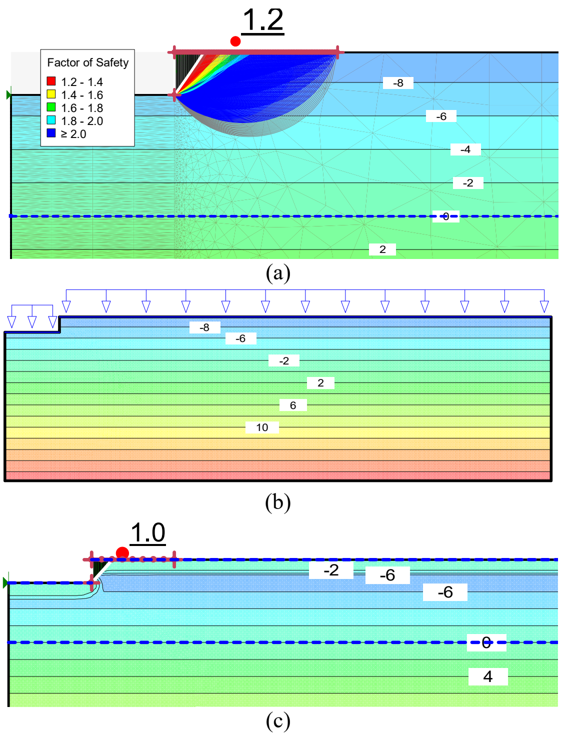
Figure 4. Variation of total cohesion with respect to suction obtained with three different SWCC fit models and Eq. (4): (a) ES and (b) IHT.



(a)

(b)

(c)

Figure 5. Coupled numerical analysis: (a) determination of safe height, (b) application of water-flux boundary condition to simulate rainfall event, and (c) determination of stand-up time.

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According to previous study [20], stand-up times of UVTs excavated into cohesive soils are unrealistically long when compared to local environmental data. Hence, stand-up times were estimated only for ES with zero cohesion (i.e., Scenario II) with GWT at 1 m to study the influence of SWCC and hydraulic conductivity function. For this, SEEP/W and SLOPE/W were jointly used by assigning water-flux boundary conditions on the ground surface and at the bottom of UVTs (Figure 5(b)) until failures take place (i.e., FOS = 1) (Figure 5(c)).

4 Results of numerical analyses

The safe height versus depth of GWT relationships for ES and IHT are shown in Figure 6 and Figure 7, respectively considering Scenario I and Scenario II. For Scenario I, the safe heights with shallow GWTs (up to 0.5 m for ES and 1.0 m for ITH) are higher than those for deep GWT. This is because the hydrostatic pressure within UVT increased the stability of UVT. In case of ES, the highest safe height was observed with FX-SWCC, which is attributed to the overestimation of total cohesion in association with the significantly low θ_r/θ_s ratio. On the other hand, safe heights obtained with BC-SWCC and vG-SWCC are approximately the same. This indicates that θ_r/θ_s ratio is a key factor that governs the safe height of an UVT in unsaturated sandy soils. However, negligible difference was observed between the safe heights of UVT in IHT even though the θ_r/θ_s ratio of FX-SWCC is significantly low. It is interesting to note that these two opposite behaviours were observed for the soils with similar shear strength parameters (**Table 1**). Hence, it can be concluded that the safe height of an UVT is affected by the θ_r/θ_s ratio of SWCC in case where an UVT is excavated into sandy soil. The safe heights significantly decrease when *c'* is neglected in the analysis and become close to zero as GWT approaches the ground surface for both IHT and ES.

Figure 8 shows the safe height and stand-up time of UVTs in ES obtained with GWT at 1 m. Three different combinations of SWCC + k models were used as detained in Section 2.2. Stand-up times are significantly low (i.e., less than 11 mins) since the analyses were carried out for Scenario II. As explained through Figure 6, the highest safe height was obtained with FX-SWCC, and the safe heights obtained with BC-SWCC and vG-SWCC were similar to each other. On the contrary, the lowest stand-up time was obtained with (FX-SWCC + F-k) and also noticeable difference between the stand-up times obtained with (BC-SWCC + BC- k) and (vG-SWCC + vG-k). There results clearly show that the higher safe height dose not necessarily mean the longer stand-up time.

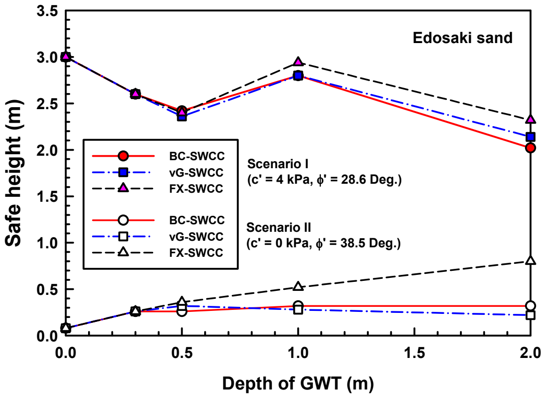

Figure 6. Variation of safe height with depth for Scenario I and Scenario II (ES).

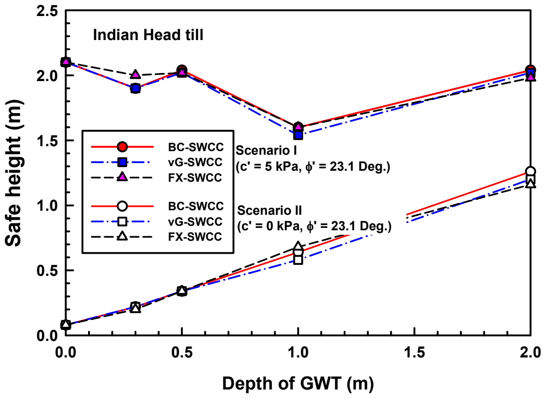

Figure 7. Variation of safe height with depth for Scenario I and Scenario II (IHT).

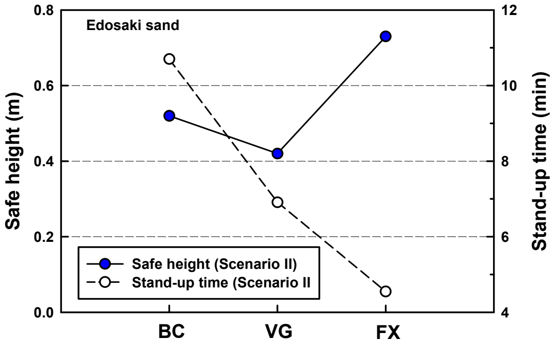

Figure 8. Safe height and stand-up time of UVTs in ES obtained with different SWCC + k model combinations (Scenario II, GWT = 1 m, rainfall intensity = 1 mm/hr)).

5 Summary and conclusions

In this study, a series of coupled numerical analyses were conducted to investigate the influence of SWCC and hydraulic conductivity function on the safe height and stand-up time of an unsupported vertical trench (UVT) excavated in unsaturated sandy soil and glacial till. The influence of SWCC on the safe height of UVTs in glacial till was negligible. On the other hand, the ratio of θ_r/θ_s was determined to be a governing parameter of safe height of UVTs in sandy soils. In case of UVTs in sandy soil, noticeable difference was observed between the stand-up times obtained with three different (SWCC

+ k) combinations; however, no correlation was observed between the safe heigh and stand-up time. It is interesting to note that the higher safe height dose not necessarily mean the longer stand-up time.

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