TABLE OF CONTENTS

Open Pit Mining Slopes Stability Analysis incorporating Unsaturated Soil Mechanics Principles

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ABSTRAK: Mekanika tanah tak jenuh telah muncul sebagai bagian penting dalam praktik rekayasa untuk memberikan solusi bagi sejumlah masalah geoteknik. Banyak masalah geoteknik terjadi di dalam tanah yang di mana tekanan air pori adalah negatif terhadap tekanan udara pori (disebut hisap matrik). Tekanan air pori bisa sangat negatif untuk tanah di daerah kering dan semi-kering atau dalam kondisi permukaan air tanah yang dalam. Selain itu, tekanan air pori dalam tanah bisa menjadi negatif akibat penggalian, pengeringan dan pemadatan tanah. Tekanan air pori negatif memberikan kekuatan geser tambahan pada tanah tak jenuh yang menghasilkan faktor keamanan yang lebih tinggi dalam analisis stabilitas lereng, termasuk tanggul, dinding penahan tanah, penggalian, penambangan terbuka dan lereng tepi sungai. Makalah ini menggambarkan penerapan teori mekanika tanah tak jenuh untuk menyelesaikan masalah rembesan dan stabilitas lereng yang diterapkan pada penambangan terbuka. Dasar-dasar dan teori mekanika tanah tak jenuh dirangkum. Pengukuran sifat tanah tak jenuh menggunakan metode uji cepat disajikan untuk mendeskripsikan teknologi pengukuran dipercepat yang tersedia untuk pengujian laboratorium terhadap tanah tak jenuh. Analisis lereng dengan variasi profil hisap matriks dan sifat kuat geser tak jenuh disajikan untuk menggambarkan keefektifan hisap matriks dalam menjaga stabilitas lereng

Kata kunci: mekanika tanah tak jenuh, penambangan terbuka, rembesan, stabilitas lereng

ABSTRACT: Unsaturated soil mechanics has emerged as an important part in geotechnical engineering practice to provide solutions for a number of key problems. A significant number of geotechnical problems occur within soils that are commonly unsaturated in nature where the pore-water pressures are negative relative to the pore-air pressure (called matric suction). The pore-water pressure can be highly negative for soils in arid and semi-arid regions or in conditions where the groundwater table is deep. In addition, pore-water pressure in soils can become negative as a result of the excavation, dewatering and the compaction of the soils. The negative pore-water pressure contributes additional shear strength to the unsaturated soil which results in a higher factor of safety in the stability analysis of many slopes, including embankments, retaining walls, excavations, open pit mining and riverbank slopes. This paper illustrates the application of unsaturated soil mechanics theory for solving seepage and slope stability problems related to open pit mining activities. The fundamentals and theories of unsaturated soil mechanics are summarized. Measurements of unsaturated soil properties using rapid test methods are presented to describe the expedited measurement technology that is available for the laboratory testing of unsaturated soil. The analyses of slopes with different matric suction profiles and different unsaturated shear strength properties are presented to illustrate the effectiveness of matric suction in maintaining slope stability. This study also shows that proper compaction of fill materials is necessary to control the unsaturated shear strength of the fill materials and to maintain its stability.

Keywords: unsaturated soil mechanics, open pit mining, seepage, slope stability

1 INTRODUCTION

The global demand for raw materials is on the increase as the nations of the world continue to grow and develop. This has led to an increase in the number of mining operations conducted in less than ideal geological conditions. Increased numbers of open pit mining operations are being developed in regions where chemical weathering has produced deep zones of residual soils (Arikan et al., 2010). The decreasing grade of many mining operations means that many new mines are starting to be developed that would previously have remained undeveloped because their grades were too low. An excellent example of this is a 162-million-ton lateritic nickel resource located approximately 40 km from the east coast of the island of Sulawesi, straddling the border of Central and South East Sulawesi provinces (Ilyas et al., 2016). The area is part of a larger mineralized province containing other lateritic nickel resources such as Soroako and Bahodopi.

Another example of huge mining industry in Indonesia is coal mining. Coal production in Indonesia has been started since 1846 in the Mahakam Coal Field, East Kalimantan. In Sumatera Island, the first discovery of coal is in Ombilin, West Sumatera in 1868 and the production started in 1891, followed by the production in Bukit Asam area in South Sumatera in 1919 (van Leeuwen, 1994). The production of coal in Indonesia in 1941 reached its peak with production rate of 2 million tons. In 1986, total of coal production in Indonesia reach 2.6 million tons, increased 600 hundred tons from previous year (British Petroleum 2014). Coal production Indonesia until the end of 1980s is likely only come from Ombilin and Bukit Asam area, since coal extraction was mainly driven by government owned company, PT. Bukit Asam, the owner of two coal sites in West Sumatera and South Sumatera. Intensive coal exploration during 1980s in Kalimantan has resulted the discovery of large coal reserve in East Kalimantan and South Kalimantan. Based on the latest geological survey, coal was discovered in 21 provinces in Indonesia (van Leeuwen, 1994). All of big islands have coal deposit, and Maluku is become the only small island with coal resource in it. Kalimantan Island is estimated to have the largest deposits with 53.28 per cent of national reserve.

The open pit mining operation, which involve removal and disposal of overburden soil, is a situation related closely to the application of unsaturated soil mechanics. Study on the effect of the changes in soil water content due to rainfall on the behavior of the mining slope was conducted by Rivai et al. (2003). They observed the increase in water content led to the increase in pore-water pressure and the decrease in shear strength of clay soil forming the slope up to 80 % of the original shear strength value. In conclusion, the rainfall may attribute to the higher weathering process on the slope face and the decrease in clay shear strength. Hence, it will result in the instability of the mining slope in long term condition. Asof et al. (2005) investigated the landslide of fill slope Outside Dump Air Laya Coal Mining in South Sumatra Indonesia occurred on 27 November 2002. The results from their numerical analyses using Slope/W indicated that the landslide was caused by the rainwater infiltration seeping through cracks formed at the crest of the slope. Further study was performed by Gofar et al. (2006). They did transient seepage and stability analyses to investigate the actual mechanism of the landslide using VADOSE/W and SLOPE/W. The results indicated that the main factor contributing to the landslide is the reduction of shear strength of the clay material due to increase in soil moisture content during heavy rainfall periods between April 2001 and December 2002.

The comprehensive studies on rainfall-induced slope failures incorporating unsaturated soil mechanics principles were conducted by Gofar and Rahardjo (2017). They performed transient seepage and stability analyses using SIGMA/W and SLOPE/W on residual soil slope with different slope angles. Their study showed that the critical condition for sandy slope occurred at the end of rainfall while the clayey slope failed at some specified time after the rainfall stopped. This is in agreement with the previous study (Gofar and Lee, 2008) in Malaysia which shows that the critical rainfall duration for sandy slope was one day while 30-days of antecedent rainfall was required for clayey slope to fail.

Based on the past studies, it is concluded that the main concern related to any open pit mining excavation is obviously the stability of slope during excavation as well as the stability of the dumping area. Seepage and stability analyses for the walls of open pits developed in sediments and highly to completely weathered in-situ rock, have historically been performed using the principles of classical (saturated) soil mechanics. However, this method does not account for the additional benefit of unsaturated shear strength that can develop in the pit walls. The unsaturated state of these materials may develop as a result of them being situated either above a pre-mining water table or due to phreatic surface drawdown from dewatering activities during mining. In both cases, an unsaturated zone will be formed within the cut slope forming the excavation. The excavation of the soil within open pit mining is normally associated with the fill of the waste or refuse material nearby mining area. The slope of the waste fill materials should be taken care properly to avoid the failure of the fill slope. Resistance to the initiation of the slope failure mechanisms is provided by soil properties, such as shear strength, in-place density, hydraulic conductivity, particle size distribution, and clay content and type. Therefore, greater emphasis must be placed on controlling the material properties. The shear strength and hydraulic conductivity of the refuse material can be improved by increasing in-place density by compaction. The in-place density is particularly important since the materials becomes unsaturated and the negative pore-water pressure within the unsaturated condition of soil contributes to the additional shear strength to maintain the stability of the slope.

When soils become unsaturated, the pore-water pressure within the soil become negative with respect to the atmospheric pressure. The negative pore-water pressure or matric suction contributes to the shear strength and overall stability of the cut slope around the excavation. The slope however, may become more susceptible to failure during the rainy season as the infiltration of rainwater will result in a partial reduction of the shear strength of the unsaturated soil. Nevertheless, it is reasonable and advantageous to incorporate unsaturated soil properties in the stability analyses of open pit excavation, particularly in rapidly mined pits, provided rainfall is accounted for.

This paper illustrates the application of unsaturated soil mechanics theory for solving seepage and slope stability problems applied to open pit mining (cut and fill slopes). The fundamentals and theories of unsaturated soil mechanics are summarized. Measurements of unsaturated soil properties are presented to describe the measurement technology that is available for the laboratory testing of unsaturated soil. The analyses of slopes with different matric suction profiles and different unsaturated shear strength properties are presented to illustrate the effectiveness of matric suction in maintaining slope stability.

2 UNSATURATED SOIL MECHANICS - THEORIES AND PROPERTIES

Two stress state variables are required to determine the behavior of unsaturated soils (Fredlund and Morgenstern, 1977): net normal stress (σ-u_a) and matric suction (u_a-u_w), where σ is total stress, u_a is the total pore-air pressure and u_w is the total pore-water pressure. Relationships between stress state variables and shear strength or volume change of soils are expressed as constitutive equations. All constitutive equations used to describe the mechanical behavior of unsaturated soils can be presented as an extension of the equations used for saturated soils. Table 1 summarizes several unsaturated soil mechanics equations related to seepage and slope stability problems (Fredlund and Rahardjo,1993).

A study by Fredlund and Rahardjo (1993) indicated that the behavior of unsaturated soil is significantly dependent on its soil-water characteristic curve (SWCC). There are many conventional methods for determining SWCC. Tempe and pressure plate apparatuses are commonly utilized in the laboratory to measure it (Rahardjo et al., 2012; Fredlund et al., 2012). A Tempe cell is used to generate SWCC up to 100 kPa since it is provided with 1 bar high air-entry disc (Rahardjo et al., 2018). A pressure plate cell (provided with a 5 or 15 bar high air-entry ceramic disc) is used to establish SWCC at suction ranges from 100 to 1500 kPa in combination with SWCC tests using the Tempe cell. These methods are known to be reliable for SWCC determination; however, they are tedious and time consuming (Fredlund, 2007).

There has been a wide interest among researchers studying unsaturated soil mechanics in exploring alternative and faster methods to evaluate SWCC for engineering practice. In this paper, SWCC tests were performed based on the concept of an evaporation method using HYPROP. HYPROP was utilized for SWCC measurements up to 100 kPa soil suction. The results are analyzed using an interpolation method by taking the average suction value from measurements recorded in two tensiometers at different depths. The assumption was made that linearization errors were insignificant so that interpolation can be done accurately, as proven in previous investigations (Satyanaga et al., 2019).

Table 1. Principles and Equations for Unsaturated Soil Mechanics (after Fredlund and Rahardjo, 1993)

Principle	Unsaturated soil	Equation
Stress state variables	$(\sigma - u_a) \, and \, (u_a - u_w)$	1
Shear strength	$\tau = c' + (u_a - u_w)\tan\phi^b + (\sigma - u_a)\tan\phi'$	2
	$c = c' + (u_a - u_w)\tan\varphi^b$	3
Flow law for water (Darcy's law)	$v_w = -k_w(u_a - u_w)(\partial h_w / \partial_y)$	4
	$h_w = y + (u_w / \rho_w g)$	5
Unsteady state seepage	$\frac{\partial}{\partial x}\left(k_w \frac{\partial h_w}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) = m_2^w \rho_w g \frac{\partial h_w}{\partial t}$	6
Slope stability based on limit equilibrium		
Moment equilibrium	$F_m = \frac{\Sigma\left[c'\beta R + \left\{N - u_w \beta \frac{\tan\phi^b}{\tan\phi'}\right\} R\tan\phi'\right]}{\Sigma Wx - \Sigma Nf}$	7
Force equilibrium	$F_f = \frac{\Sigma\left[c'\beta\cos\alpha + \left\{N - u_w \beta \frac{\tan\phi^b}{\tan\phi'}\right\}\tan\phi'\cos\alpha\right]}{\Sigma N\sin\alpha}$	8

where:

τ = shear stress, c' = effective cohesion, c = total cohesion as the sum of c' and the increase in shear strength due to matric suction, ϕ' = effective angle of internal friction, ϕ^b = angle indicating the rate of increase in shear strength due to increase in matric suction, k_w = unsaturated coefficient of permeability, v_w = flow rate of water, $\partial h_w/\partial_y$ = hydraulic head gradient in the y-direction, g = gravitational acceleration, y = elevation at certain point above the datum, ρ_w = density of water, h_w = hydraulic head, t = time, N = the total normal force on the base of the slice, W = the total weight of the slice of width "b" and height "h", β = the sloping distance across the base of a slice, α = the angle between the tangent to the center of the base of each slice and the horizontal, f = the perpendicular offset of the normal force from the center of rotation or from the center of moments, x = the horizontal distance from the centerline of each slice to the center of rotation or the center of moments, R = the radius for a circular slip surface of the moment arm associated with the mobilized shear force, S_m for any shape of slip surface.

The working principle of HYPROP is illustrated in Fig. 1a. Fig. 1b shows the actual laboratory test setup of HYPROP apparatus. The test uses a pair of tensiometers with ceramic tips located at different depths of the specimen. One tensiometer was positioned ¼ of the height of the specimen from the soil surface and the other at ¾ of the height of the specimen. The tensiometers could measure suctions within the range zero to 100 kPa. The two tensiometer readings were then averaged to obtain the representative suction of the specimen at the time of measurement. The tensiometers and electronic balance were connected to the computer to record the soil suction and the mass of the specimen at regular time intervals.

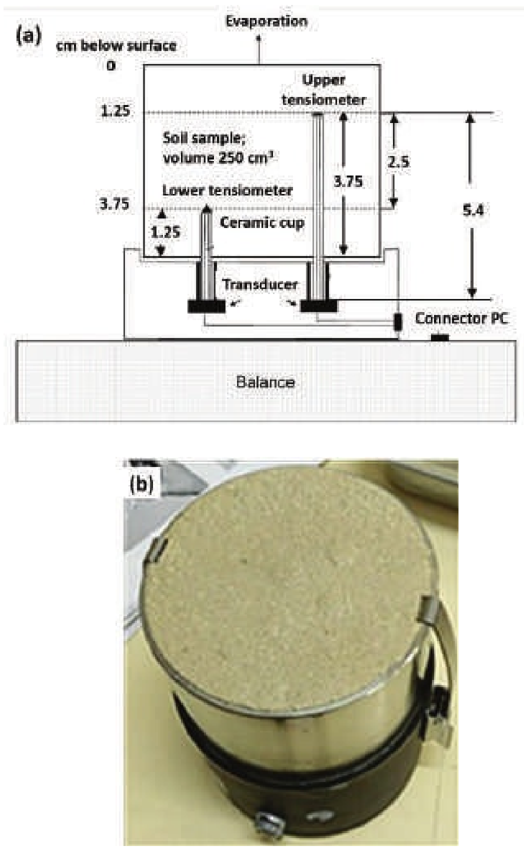

Fig. 1. (a) Schematic diagram of HYPROP (Schindler et al., 2010) and (b) Actual experimental setup of HYPROP

During the test, the gravimetric water content of the soil decreased due to evaporation while the soil suction increased. The SWCC can then be obtained by plotting gravimetric water content against average soil suction, where average soil suction is calculated from the two tensiometer readings. The volumetric water content and degree of saturation of the soil specimen can be computed by measuring the volume change of the soil specimen at different suctions via an independent shrinkage test. In HYPROP, it is assumed that the water flows through a horizontal plane at midpoint between the tensiometer tips for a given interval of time. As a result, the permeability of the soil specimen at this midpoint during the water flow process can be calculated using Eqn. (9). This is similar to the instantaneous profile method as presented by Krisdani et al. (2009):

$$q_i = \frac{\Delta V_i/\Delta t_i}{2A} \quad (9)$$

where: ΔV_i is water reduction (cm^3) over the mass change, q_i is the rate of water flow (m/s), A is the cross-sectional area (cm^2) of the column, Δt_i is the interval of time between two measurements.

The permeability of soil is then calculated from Darcy's equation:

$$k_i(h_i) = -\frac{q_i}{\left\{\left(\frac{\Delta h_i}{\Delta z}\right) - 1\right\}} \quad (10)$$

where: h_i is time- and space-averaged suction, Δh_i is the difference of the two suctions measured at two measuring levels, Δz is the height difference of the tensiometer tips. Based on Eqn. (10), different values of the coefficient of permeability can be calculated for each average soil suction obtained from HYPROP at individual time intervals. The instantaneous value of permeability can be plotted against the corresponding soil suction to obtain the unsaturated permeability of the soil.

In this paper, WP4C (Fig. 2a) was also introduced to obtain the experimental data of SWCC in conjunction with HYPROP to produce SWCC with a wide range of suction from low to high values. Upon completion of the SWCC tests using HYPROP, the specimen was trimmed using a cutter customized specifically for the test using WP4C. The diameter and height of specimens for the WP4C test are 37 mm and 10 mm, respectively. WP4C measured soil suction in a soil specimen by measuring the water vapor pressure of the air in the chamber which was in equilibrium with the suction of the soil specimen (Satyanaga et al., 2019). The temperature inside the chamber was set at 25°C throughout the experiment. A schematic diagram of the WP4C apparatus is shown in Fig. 2b.

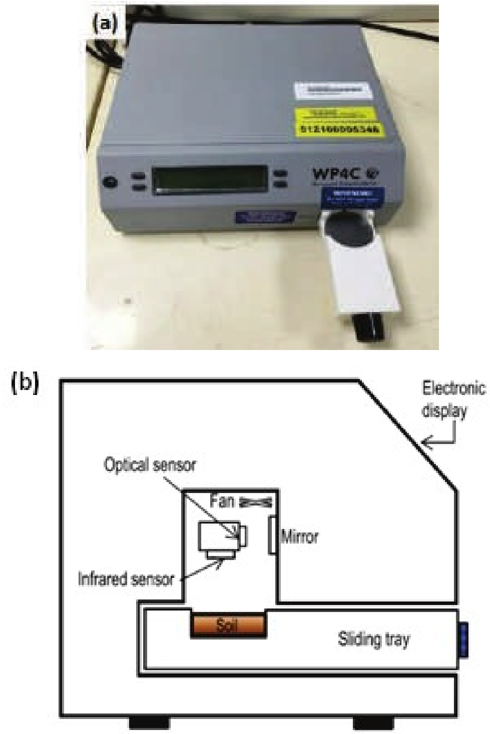

Fig. 2. (a) Photo of WP4C and (b) Schematic diagram of chilled mirror hygrometer (WP4C)

The total suction was calculated using the Kelvin equation, as given in Eqn. (11) (ASTM D 6836-02 (2008)).

$$\psi = \left(\frac{RT}{M}\right) * \ln(a_w) \quad (11)$$

where: ψ is the corresponding suction of the soil specimen (kPa), R is the constant for gas, aw is the water activity, M is the water molecular mass and T is room temperature inside the chamber of the WP4C (°K).

The determination of unsaturated coefficient of permeability can also be conducted using an indirect method based on a statistical model. This method is commonly used to predict the permeability function from the saturated coefficient of permeability, k_s, and the SWCC (Millington & Quirk, 1959; Marshall, 1958). The statistical method is based on the assumption that the permeability function and the SWCC are primarily determined by the pore-size distribution of the soil (Fredlund and Rahardjo, 1993). Typical SWCC and permeability functions for a sand and a silty clay are presented in Fig. 3.

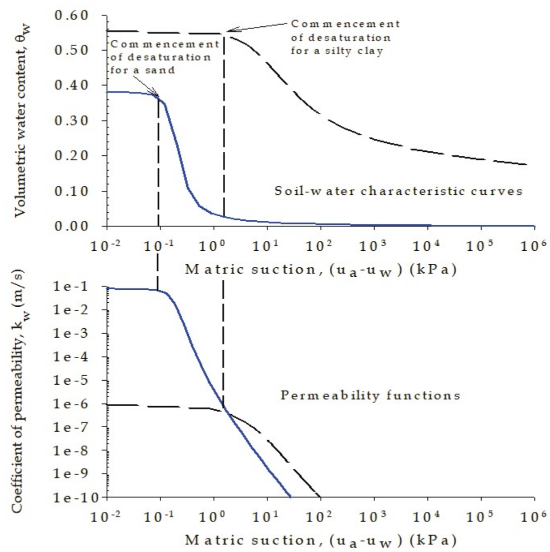

Fig. 3. Relationship between SWCC and permeability functions for a sand and a silty clay (Rahardjo et al., 2014)

The measurement of the unsaturated shear strength is time consuming and tedious. Based on study by Fredlund et al. (2012), the unsaturated shear strength parameter, ϕ^b, can be considered as half of ϕ'. Many studies have been carried out to estimate the unsaturated shear strength from SWCC. Vanapalli and Fredlund (2000) suggested to modify Eqn. (2) by scaling the matric suction by χ Eqn. (12).

$$\chi = (\theta_w - \theta_r)/(\theta_s - \theta_r) \quad (12)$$

where: θr = Residual volumetric water content

The final form of the equation is shown in Eqn. (13).

$$\tau = c' + [\chi(u_a - u_w) + (\sigma - u_a)]\tan\phi'] \quad (13)$$

Another common equation to predict shear strength from SWCC is proposed Goh et al. (2010). Detail of the equation is given below.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \quad (14)$$

if (u_a-u_w) < air-entry value (AEV)

$$\tau = c' + [(\sigma - u_a) + (u_a - u_w)_b]\, tan\,\phi'$$
$$+[(u_a - u_w) - (u_a - u_w)_b] b\Theta^k \, tan\,\phi'$$

if $(u_a-u_w) \geq$ air-entry value

$$k = [log(u_a - u_w) - log(AEV)]^y$$
$$y = 0.502\, ln(PI + 2.7) - 0.387$$
$$b = -0.245\{ln[n(PI + 4.4)]\}^2$$
$$+2.114\{ln[n(PI + 4.4)]\} - 3.522$$

Where $\phi' =$ ϕ^b
PI = plasticity index of soil while y and b are constant parameters.

3 SLOPE STABILITY ANALYSES

Two types of unsaturated slope stability analyses are used to illustrate the effect of the matric suction on the stability of an open pit slope. The stability analyses were carried out using the total cohesion method to obtain the variation in factor of safety (FoS) for slopes with 35° and 40° overall slope angles, under different matric suction profiles and with different ϕ^b angles. In the total cohesion method, the stability analysis was carried out by incorporating matric suction into the cohesion of the soil (Fredlund and Rahardjo, 1993). In this method, the matric suction was considered as a percentage of the hydrostatic negative pore-water pressures above the groundwater table (25, 50, 75 and 100%), (Fig. 4a). Matric suction was multiplied by tan ϕ^b to give an increase in total cohesion due to matric suction (Eqn. (3) in Table 1).

Twenty-four slope stability analyses were carried out using this method. Analyses 1 to 12 were carried out on a slope with a 40° slope angle. Analyses 1 to 4 were conducted using four different percentages of matric suction profiles with $\phi^b = 25\% \phi'$ (Fig. 4b). Analyses 5 to 8 were conducted using $\phi^b = 50\% \phi'$ (Fig. 5a). Analyses 9 to 12 were performed using $\phi^b = 75\% \phi'$ (Fig. 5b). Analyses 13 to 24 utilized the same soil properties as those used in analyses 1 to 12, but they were conducted on a slope with 35° slope angle.

The slope stability analyses were performed using SLOPE/W (GEO-SLOPE International Ltd., 2007a) in accordance with the Bishop's simplified method of slices. The height of the slope model was 100 m and the groundwater table was assumed at 10 m below the toe of the slope (Fig. 6). The soil within the slope layer was considered to be silty clay with an effective cohesion of 30 kPa and an effective friction angle of 32°. The shear strength contribution from matric suction was incorporated into the total cohesion of soil (Eqn. (3)). The unsaturated zone above the groundwater table was divided into seven sub-layers (Fig. 6). The thickness of each sub-layer for layers 1 and 2 was 5 m. The thickness of each sub-layer for layers 3 - 7 was 20 m. Each layer had a total cohesion corresponding to its distance from the water table as given in Fig. 4b, 5a and 5b for different values of ϕ^b angle.

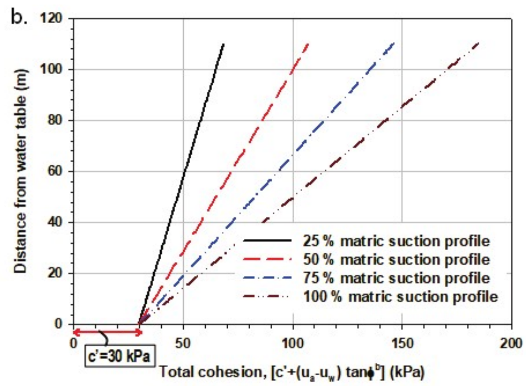

Fig. 4(a). Different matric suction profiles as a percentage of the hydrostatic profile above the groundwater table. (Rahardjo et al 2014)

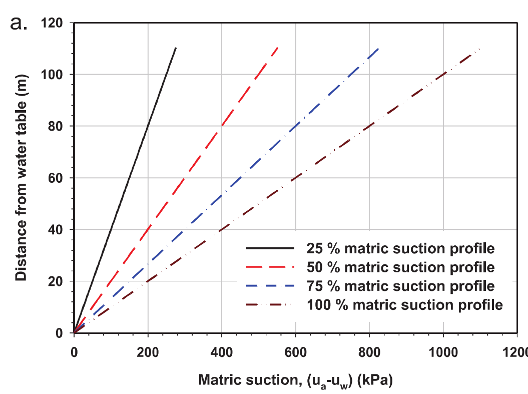

Fig. 4(b). Total cohesion profiles corresponding to the different matric suction profiles for $\phi^b = 25\%$ ϕ'. (Rahardjo et al 2014)

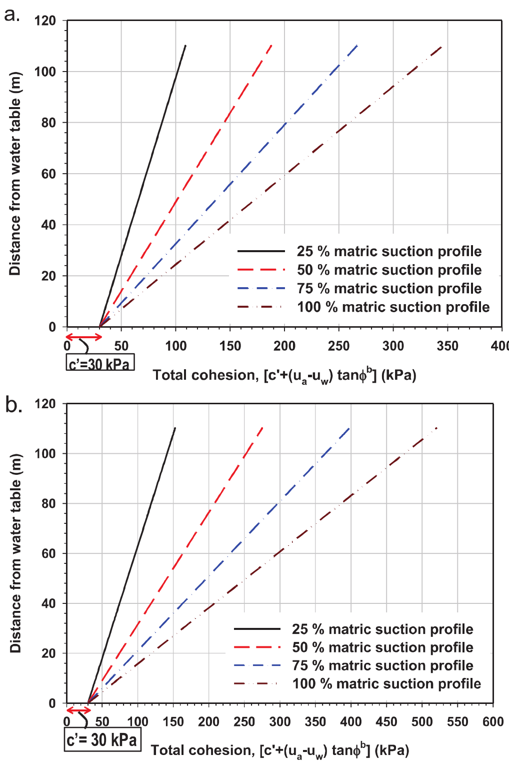

Fig. 5. Total cohesion profiles corresponding to the different matric suction profiles a) ϕ^b = 50% ϕ' and b) ϕ^b = 75% ϕ' (Rahardjo, et al 2014)

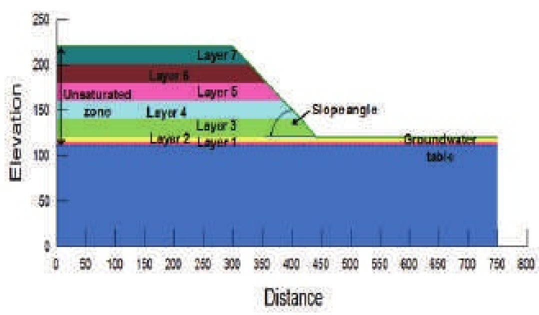

Fig. 6. Numerical model for slope stability analyses using total cohesion method (Rahardjo et al, 2014)

The variations in the FoS of slopes with 35° and 40° slope angles for different matric suction profiles and different ϕ^b angles are presented in Fig. 7. The FoS increased with the increase in the percentage of matric suction profile and the higher value of ϕ^b angle. The lowest FoS was observed when matric suction was not considered in the analysis (0 % matric suction profile). On the other hand, the highest factor of safety was observed when 100% matric suction profile was considered in the analysis.

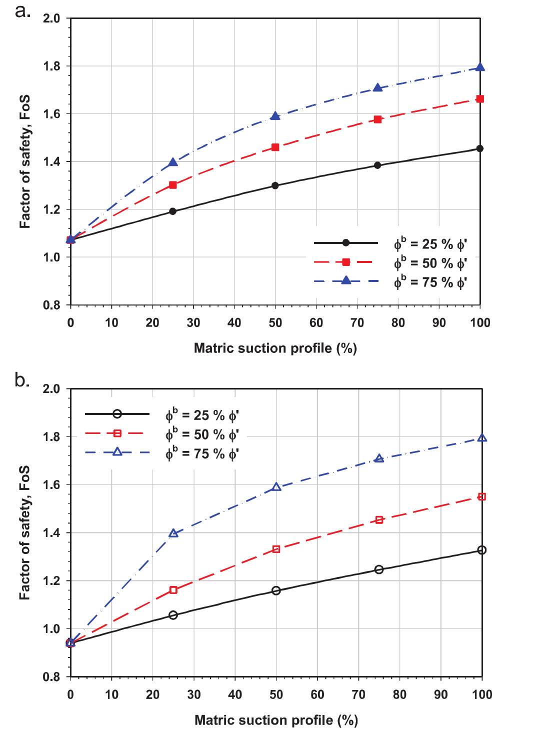

Fig. 7. Variation of FoS for slope with a. 35° slope angle and b. 40° slope angle for different matric suction profiles (Rahardjo et al., 2014)

Fig. 7 shows the importance of matric suction in maintaining the stability of the slope. If matric suction is ignored in the stability analyses, the slope should have already failed since the FoS of either slope was close to or less than 1. However, a matric suction profile as low as 25% would be sufficient to significantly improve the stability of slope in most of the cases analyzed, illustrating the benefit of considering matric suction in the stability analyses of open pit excavation.

4 CONCLUSIONS

The following concluding remarks can be drawn from this paper:

a. Unsaturated soil mechanics principles and theories are necessary for describing the behavior of real soils that are commonly unsaturated in nature.
b. Equipment for rapid measurement of unsaturated soil properties are available for application of unsaturated soil mechanics to the design of pit slopes.
c. The application of unsaturated soil properties in slope stability analysis could lead to a more beneficial factor of safety of