Stability of Unsaturated Soil Slopes considering the Effect of Wetting Front Suction Loss

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Abstract : This paper describes the rainfall–induced slope failures caused by infiltration due to prolonged rainfall. The emphasis was on quantifying the effect of fine-grained contents which are influencing on the infiltration rate in the wetting front of initially unsaturated slopes during rainfall. Suction tests by tensiometer were performed for five mixture specimens with varying fine-grained contents and then, numerical analyses for the stability of unsaturated slopes are carried out for different relative densities and mixture portions based on the soil water characteristic curves obtained by GCTS pressure plate. It is shown that the fines are highly influenced on wetting front suction of unsaturated soil slopes. Based on the results, it is found that until 15% fine content is the limit showing different wetting front suction, beyond which the wetting band depth do not affect considerably the stability of unsaturated slopes.

Keywords : Unsaturated soil, GCTS pressure plate, Wetting front, Rainfall induced landslides, Fine-grained content

1. Introduction

While the stability of homogeneous slope has been thoroughly studied for a long time in many engineering field (Hassiotis et al., 1997; Kim et al., 2004), little attention has been paid to the behavior of heterogeneous slopes (Rotterdam et al., 1990; Poulos, 1995), let alone stability on unsaturated slopes. It is true that in the real situation it is not usual to find a soil slope consisting of pure homogeneous soils. Many of natural soil slopes in South Korea are composed of soil mixtures with certain amount of clay content in natural soil deposits. The behavior of soils as a slope material varies greatly depending on the amount of clay content. The wetting band depth due to prolonged rainfall is a main reason of unsaturated soil slope failures. Therefore, it is important to analyze the effect of the fines on the stability of unsaturated soil slopes.

Most of the land areas of Korea peninsula are composed of soils formed from the in situ weathering of granite and gneiss. Many slope failures in these weathered soils are triggered by heavy rainfall. These failures are characterized by relatively shallow failure surfaces that develop parallel to the original slope. These failures may be attributed to the deepening of a wetting front into the slope due to rainfall infiltration which results in an increase in moisture content, a decrease in soil matric suction and a decrease in shear strength on the potential failure surface (Lumb, 1975; Rahardjo et al., 1995; Ng and Shi, 1998; Fourie et al., 1999; Kim et al., 2004). It is generally said that the unsaturated soil slope failures due to rainfall are mainly caused by the decrease in suction of unsaturated soil with the increase the water content and wetting band depth.

Many weathered soils in Korea can be classified as SW or SM according to the Unified Soil Classification System (USCS). These soils consist of soil mixture with certain amount of clay fractions in natural soil deposits. This paper describes the results of a series of soil-water characteristic curve tests and numerical analyses aimed at clarifying the effect of the magnitude of wetting band depth on unsaturated soil slopes. Special attention is given to the prediction of approximate limit of clay content which influences the magnitude of wetting band depth in soil mixtures.

2. Soil-water characteristic curve testing

The soil-water characteristic curve (SWCC) is the relationship between water content and soil suction in an unsaturated soil. The SWCC has been used to estimate the permeability and shear strength functions of unsaturated soils. This curve can be used to derive permeability functions for use in unsaturated groundwater flow problems (Fredlund and Rahardjo, 1993). It is also possible to use SWCC to establish unsaturated shear strength parameters (Vanapalli et al., 1996).

2.1 GCTS pressure plate

This apparatus manufactured by Geotechnical Consulting and Testing Systems (GCTS) is a pressure plate apparatus modified shortcomings for measurement of suction (Pham and Fredlund, 2004). In this study, the GCTS pressure plate was used for defining the SWCC for test soils. This plate uses the axis-translation technique to control matric suction in the soil specimen (Fredlund and Rahardjo, 1993). The GCTS overcomes the restrictions associated with the conventional measuring devices of matric suction, such as pressure plate cell, filter paper and tensiometer, etc. The specimen volume change and water content can be continuously measured without dismantling the device. Also only one soil specimen is needed to determine the entire drying and wetting SWCCs, providing a simple procedure and more consistent results compared with the results by filter paper method (Kim et al, 2004)

As shown in Fig. 1, the GCTS pressure plate consists of two main parts which are a pressure chamber and a loading system. The pressure chamber was designed for measuring soil-water characteristic curves. The pressure chamber is stainless steel and can be subjected to extremely high air pressure. The soil specimen is rammed into a stainless steel ring and placed on top of the high air entry ceramic stone. Different high air entry ceramic stones can be inserted into the base of the apparatus and used for different soil types.

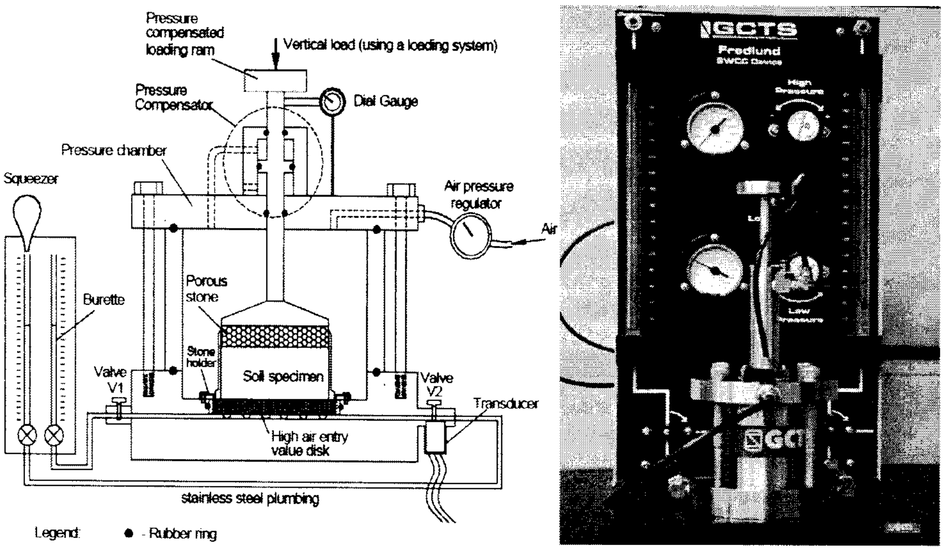

Figure 1. The GCTS pressure plate apparatus

2.2 Soil specimen and test procedures

Majority of weathered soil in Korea can be classified as well-grade sand (SW) according to the Unified Soil Classification System (USCS). This soil consists of soil mixture with certain amount of clay (CH) fractions in natural soil (SW) deposits. The grain-size distribution curves of weathered soil (SW) and high plasticity clay (CH) are shown in Fig. 2. The plasticity chart of CH is shown in Fig. 3. The clay soil had a liquid limit, LL = 63, plastic limit, PL = 29.3, specific gravity, G_s = 2.604.

For measuring soil-water characteristic curves, sample with different clay contents of 0, 5, 10, 15, and 20% were formed. The soil-water characteristic curve and coefficient of permeability were measured for different densities (D_r = 70, 90%). The clay contents of 0, 5, 10, 15 and 20% were used for D_r = 70 % whereas, five clay contents of 0, 5, 10, 15, 20% were used for D_r = 90%. For measuring wetting front suction (ψ) of mixed soils, samples with different clay contents of 0, 5, 10, 20 and 30% were formed.

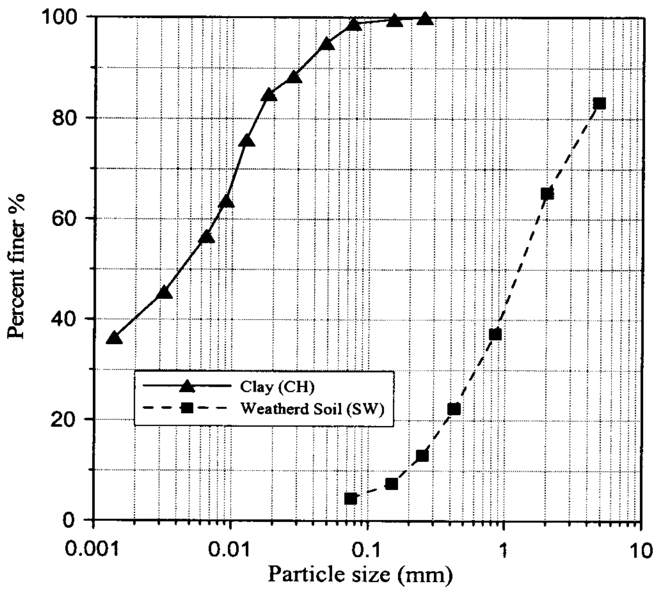

Figure 2. Grain-size distribution curves

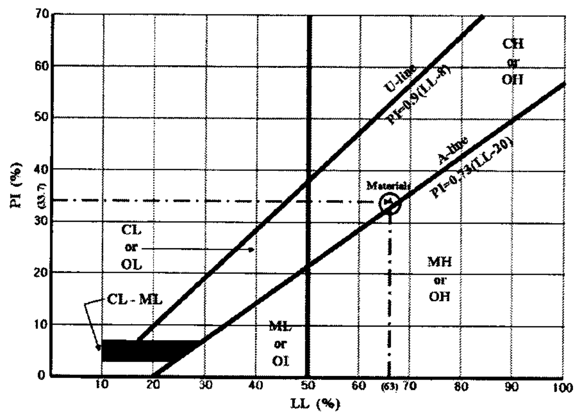

Figure 3. Plasticity chart of clay (CH)

In order to measure the soil-water characteristic curve of the soil specimens in the GCTS pressure plate, the saturated soil specimen is placed on a saturated ceramic disk and mounted on the bottom plate (Fredlund and Rahardjo, 1993). The ceramic disk acts like a semi-permeable medium and allows water, but not air, to pass through the disk up to a rated air pressure value (i.e., air-entry value of the ceramic). The bottom of the ceramic disk is maintained more or less at atmospheric pressure by connecting the drain holes to two tubes filled with water. The applied air pressure represents the applied matric suction. In response to the applied suction the water move out from the soil specimen and drain through the ceramic disk until the equilibrium is established. The magnitude of the applied matric suction is the same for each soil specimen (i.e., 4, 10, 20, 40, 100, 200 and 400 kPa).

2.3 Test results

The results of the SWCCs for soil mixtures were obtained in laboratory using the GCTS pressure plate. The SWCC equation is the function regarding soil suction and volumetric water content, and was determined considering the equation suggested by Fredlund and Xing (1994) as follow,

$$\Theta = \left[\frac{1}{\ln\{e + (\psi / a)^n\}} \right]^m \tag{1}$$

where e is the natural base of logarithm, a, m and n are curve fitting parameters, ψ is the soil suction and Θ is the normalized volumetric water content defined as:

$$\Theta = \frac{\theta_w - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where θ_w is the volumetric water content, θ_s and θ_r are the saturated and residual volumetric water contents, respectively. The values of a, m and n determined from these tests can describe a shape of the SWCC, and the results of the parameters are shown in Table 1.

Table 1. Curve-fitting parameters for the SWCC and permeability

	D_r = 70%					D_r = 90%				
	SW100 %	+CH5 %	+CH10 %	+CH15 %	+CH20 %	SW100 %	+CH5 %	+CH10 %	+CH15 %	+CH20 %
a	4.811	8.819	5.452	7.827	8.368	10.064	10.295	9.283	8.164	9.477
n	2.536	8.637	1.690	1.305	1.849	2.655	3.270	2.515	2.366	1.51
m	0.637	0.151	0.27	0.302	0.221	0.336	0.243	0.294	0.226	0.217
K_{sat}(m/s)	5.05e-6	1.13e-6	7.84e-7	5.87e-7	2.58e-7	3.29e-6	5.34e-7	2.94e-7	7.84e-8	3.45e-8
θ_r	0.038	0.034	0.017	0.026	0.035	0.038	0.034	0.017	0.026	0.035

Note: θ_r is the residual volumetric water content

The results of the soil-water characteristic curve tests for each soil mixture, normalizing the volumetric water content, are shown in Fig. 4. It is shown that there were some differences between the measured SWCCs due to the different fine contents and relative densities. At soil suctions lower than the air entry value of soils, the slope of the SWCC of fully sandy soil (SW 100%), is quite stiff. As the fine content of the each soil mixture was increased, the volumetric water content of the air entry value of soil mixtures was increased. This behavior is more significant for D_r = 90% than for D_r = 70% and is the typical trend of the SWCCs observed by increasing soil suction.

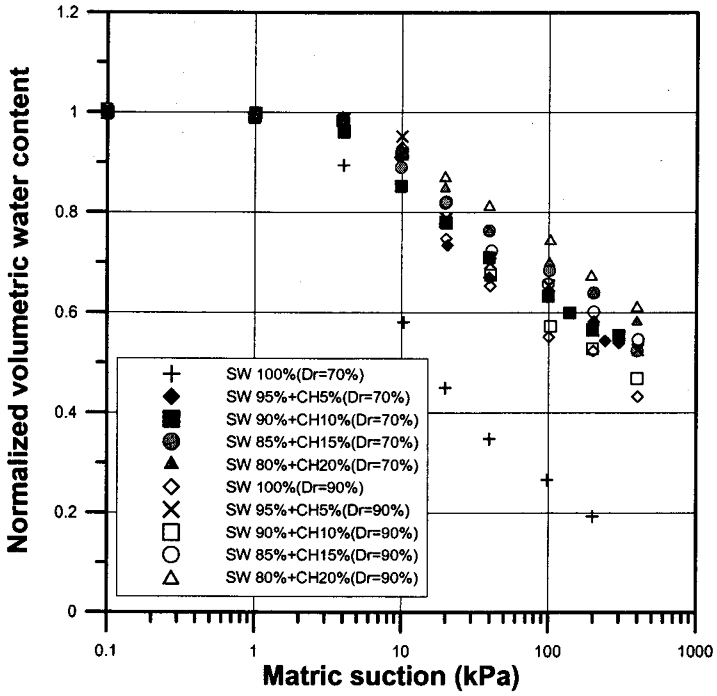

Figure 4. Results of the SWCC tests

3. Wetting front suction

Wetting front suction (ψ) represents the residual value of soil suction just before the soil becomes saturated due to water infiltration. Its value for a given soil can be obtained experimentally or using empirical relationships (Green and Ampt, 1911; Bouwer, 1966; Chow, et al., 1988) and its magnitude depends primarily on the grain size of the soils (Mein and Farrell, 1974).

The soils used in this study are well-graded sand (SW) and high plasticity clay (CH) in Korea. For measuring ψ of various mixed soils, samples with different clay contents of 0, 5, 10, 20 and 30% were formed. The pertinent information regarding the physical properties of the mixture soil is given in Table 2.

A tensiometer was used as an indirect means of measuring ψ. The schematic diagram of tensiometer test for measuring the wetting front suction is shown in Fig. 5 The tensiometer was installed in a mold and the residual suction of a compacted soil, just before the soil is saturated by infiltration, was measured when seepage approaches the porous ceramic cup of the tensiometer. The wetting front suction with varying time is shown in Fig. 6. As a result, each value of the wetting front suction measured was typically proportional to both clay content and density, as shown in Fig. 7.

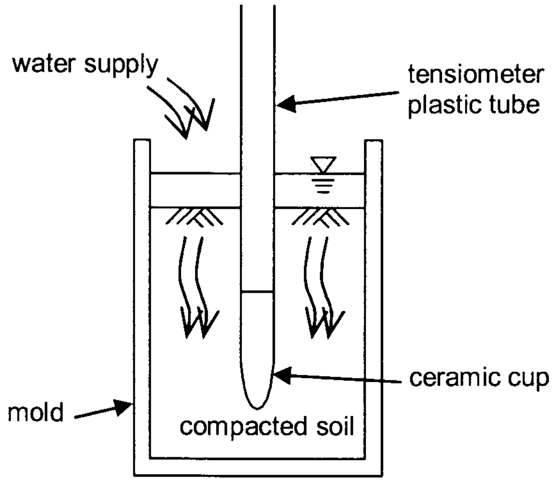

Figure 5. Schematic diagram for measuring ψ

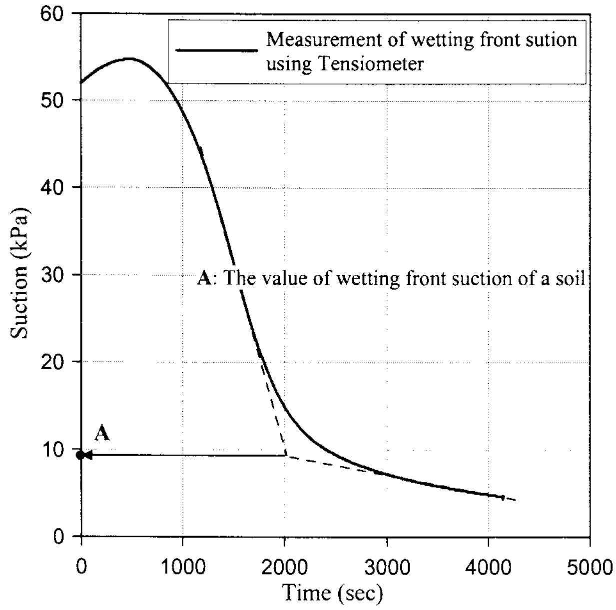

Figure 6. Measurement of wetting front suction

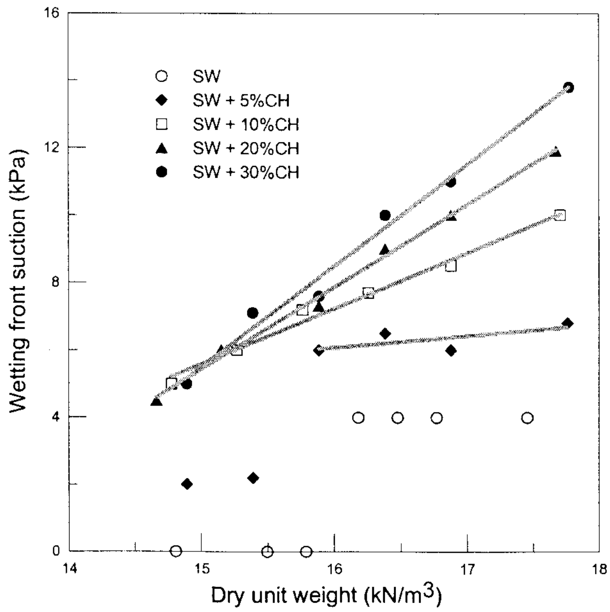

Figure 7. Wetting front suction vs. unit weight of specimen

4. Numerical simulations

In order to investigate the influence of SWCCs and wetting front suction (ψ) on the predictions of pore-water pressure distributions in a unsaturated soil slope and its stability, a series of finite-element transient seepage and limit equilibrium analyses are performed using commercial programs, GEO-SLOPE (SEEP/W and SLOPE/W, 2004), respectively. The computed results from the transient seepage analyses are used as input parameters for a subsequent limit equilibrium analysis of the stability of the slope.

4.1 Transient water flow in unsaturated soils

Transient seepage analyses of rainfall infiltration were carried out by means of the two-dimensional finite element program SEEP/W (Geo-Slope, 2004). The typical finite element mesh used in these analyses is shown in Fig. 8. The groundwater table is located at the bedrock-mixture soil interface. The top boundary is subjected to a rainfall intensity that is equal to the saturated permeability of the mixture soil to ensure downward infiltration into the mixture soil layer. The permeability function of unsaturated soils is fitted by a nonlinear equation proposed by Fredlund and Xing (1994) through the measured saturated water permeability coefficient, K_{sat} of the mixture soils as shown in Fig. 9.

The total duration of rainfall is 96 hours. It was divided into 11 time stages (0.1, 0.5, 1, 2, 3, 5, 10, 24, 48, 72 and 96 hours) and wetting band depth was obtained for each of these stages. For simplicity, the intensity of rainfall was kept constant for the entire duration of rainfall. Similarly, the wetting band depth from a transient seepage analysis is calculate as the normal distance from the surface of the mesh at which a contour of -0.2 m pressure head is located. The contour for -0.2 m pressure head is chosen based on the observation from slope stability analysis that normal distance between the critical failure plane and the surface of the slope was always equal to normal distance between this contour and the surface of the slope (Kim et al., 2006).

It is shown that increase of the fine content affects the infiltration rate was decreased for all soil mixtures (Fig. 10). And the increasing rate of wetting band depth was decreased as the fine contents in the mixtures and the relative densities were increased. Theses results come from the decrease of coefficient of permeability and the increase of the soil suction (Fig.7).

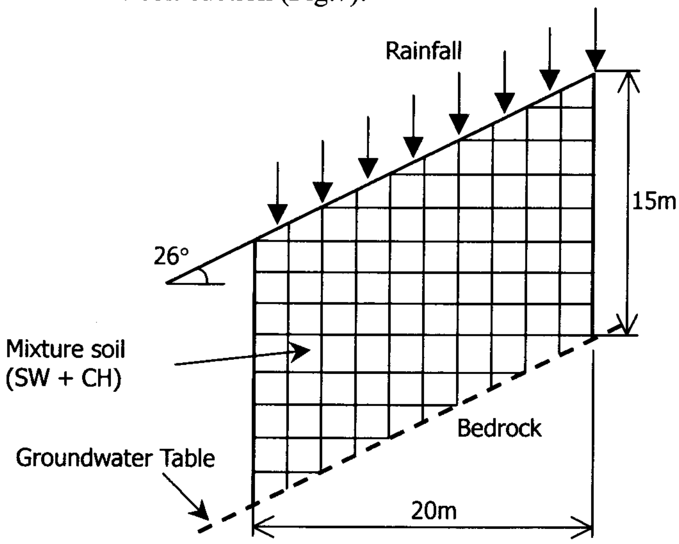

Figure 8. Finite element mesh of seepage analysis

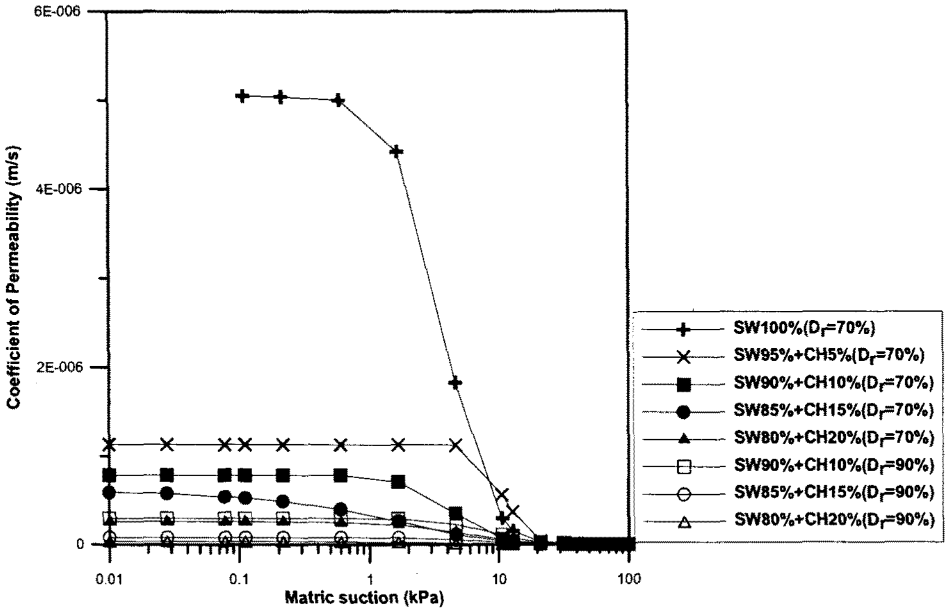

Figure 9. Permeability of unsaturated soils

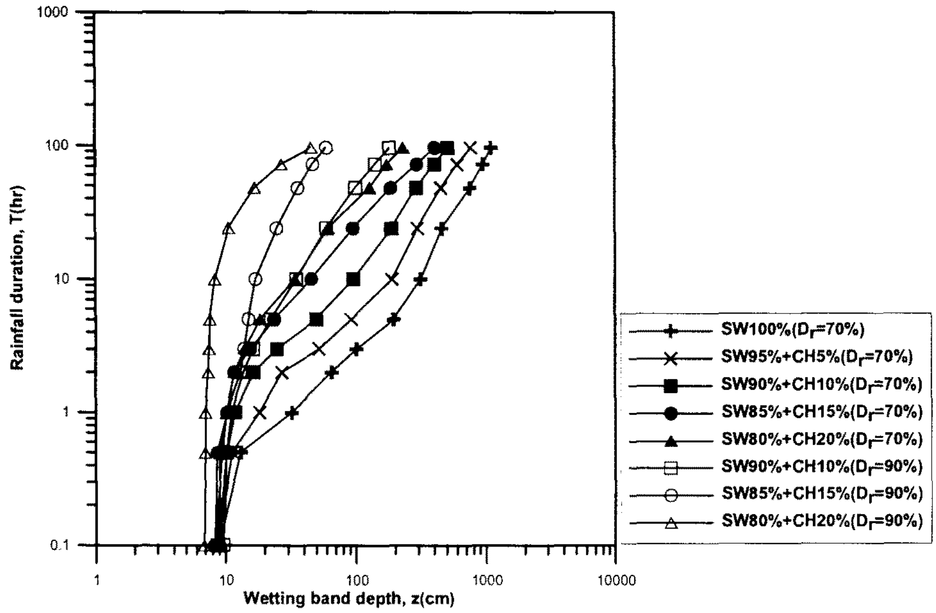

Figure 10. Wetting band depth *vs*. Rainfall duration

4.2 Strength parameter and slope stability analysis

Limit equilibrium analyses are carried out to determine the factor of safety of the slope based on the pore water pressure distributions from the transient seepage analyses. Strength parameters of saturated and unsaturated soils are needed for estimating the factor of safety using Bishop's simplified method. The shear strength parameters of saturated soils are assumed to be governed by the extended Mohr-Coulomb failure criterion and those of unsaturated soils, an internal friction angle associated with matric suction which was called the ϕ^b can be estimated as an alternative solution. For the friction angle of unsaturated soils, Eq. (3) (Vanapalli et al., 1996) in this study is used.

$$\tan(\phi^b) = \tan(\phi')\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) \tag{3}$$

where ϕ' is the angle of internal friction, θ is the volumetric water content, θ_r is the residual volumetric water content (Table 1), θ_s is the saturated volumetric water content and ϕ^b is the angle indicating the rate of increase in shear strength relative to the matric suction.

In order to evaluate the effect of wetting band depth and magnitude of the matric suction on the stability of slopes in unsaturated soils, three sets of analysis were conducted using the limit equilibrium analyses. These analyses are performed on slip surfaces passing through the wetting front as shown in Fig. 11. Three infinite slopes—inclined at 26°, 33°, 45°—were considered, and strength parameter, such as ϕ', ϕ^b and c' of each mixed soil was fixed as properties of each mixed soil to identify related to the only wetting band depth due to rainfall in a slope. The physical properties of soil mixtures are described in Table 2.

In the analyses carried out for defining the influence of the magnitude of ψ on the slope stability, the initial wetting front suction corresponding to the unit weight of slope soil was calculated from Fig. 7 and then put into slope stability to establish the available shear strength of the mixture soil. Generally an increase in clay content affects a rise of the safety factor in unsaturated soil slopes as shown on Fig. 12. However, the factor of safety decreases beyond 15% of mixture soils. If the factor of safety only affected by the magnitude of wetting front suction, it must increase as the fine content was increased in soil mixtures. However, the factor of safety decreased from a certain point. This means that the effect of the wetting front suction on slope stability is somewhat limited to fine content in soil mixtures. That is, the factor of safety is affected by the wetting front suction rather than the variation of strength parameters as the fines content increase, especially the fines content is as far as 15% approximately. Besides this range, it is affected by the variation of the strength parameters as the fines content increase over 15% clay content.

Table 2. Physical properties of soil mixtures

Soil Mixtures	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	c'(kN/m^2)	ϕ'(°)	ϕ^b (°)
SW100% (D_r=70%)	11.9	15.9	0	31.8	28.7
+CH5% (D_r=70%)	12.9	16.5	12.8	27.8	20.5
+CH10% (D_r=70%)	13.2	16.8	22.9	26.3	22.6
+CH15% (D_r=70%)	13.4	17.4	26.1	23.8	18.3
+CH20% (D_r=70%)	13.5	17.7	28.6	20.8	17.6
+CH10% (D_r=90%)	13.5	17.4	14.2	28.8	22.9
+CH15% (D_r=90%)	13.8	17.9	16.9	24.0	19.8
+CH20% (D_r=90%)	14.2	18.2	25.3	22.9	18.6

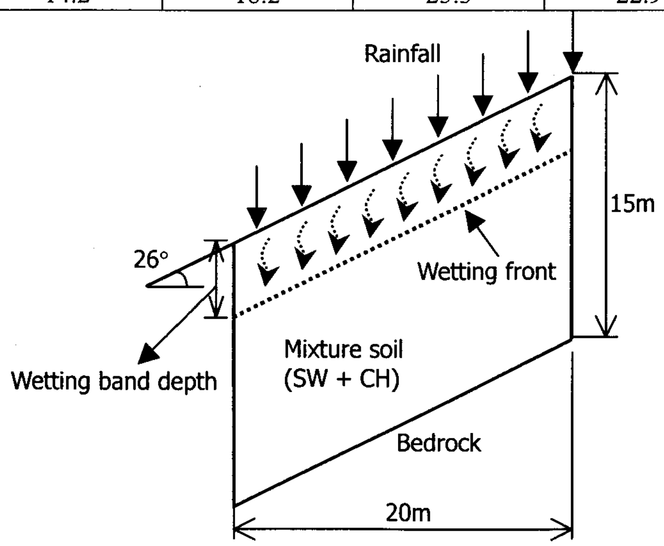

Figure 11. Unsaturated slope stability analyses

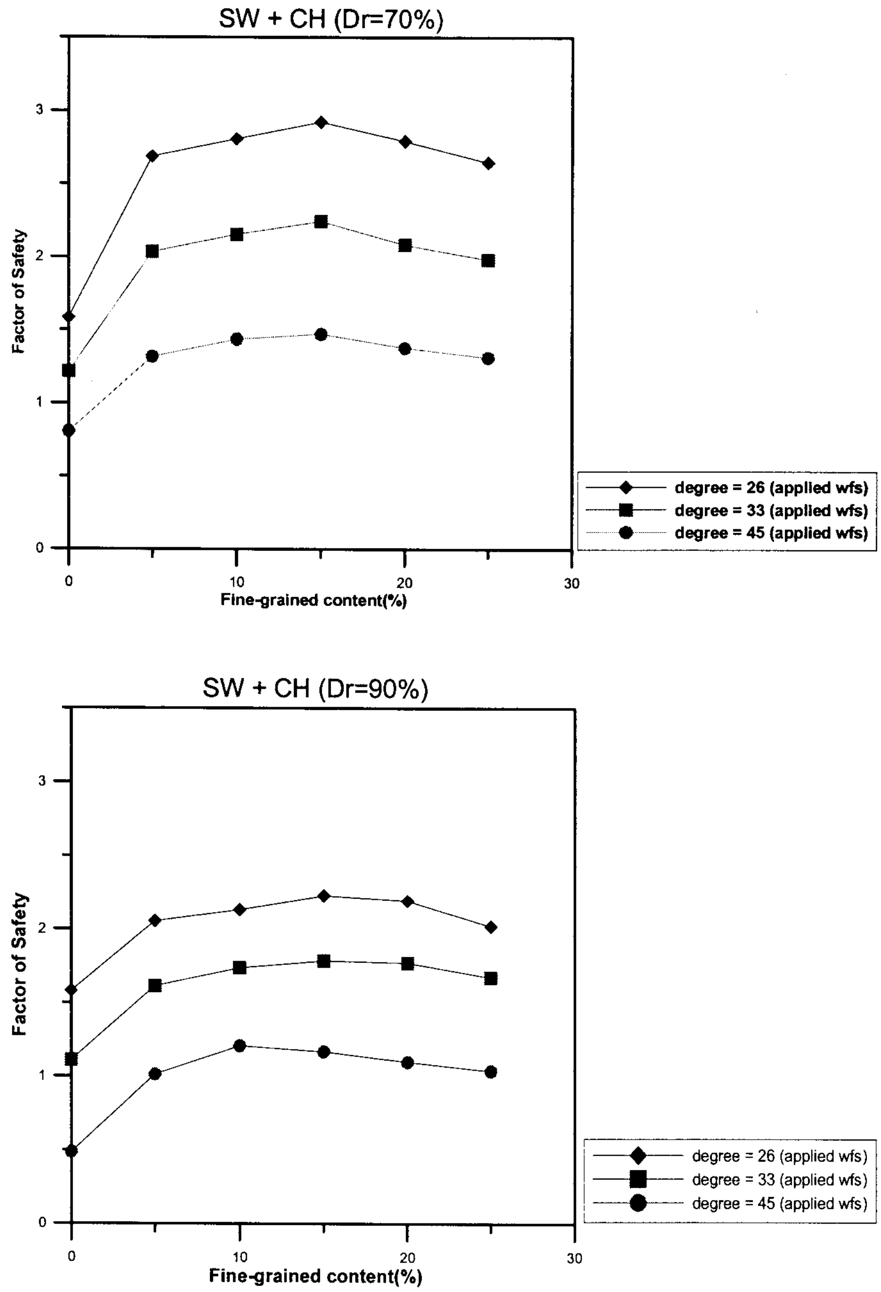

Figure 12. The Influence of fine contents on the factor of safety of the slopes

5. Strength parameters influencing the stability of slope

In order to examine the contribution of strength parameters (c', ϕ'), a series of stability analysis was performed for different clay contents.

Fig. 13 shows the rise of the safety factor with increasing value of wetting front suction. At the mixture soil (SW+CH15%), an increase in ψ determined a limited increase in the safety factor of the slopes studied because of a higher apparent cohesion at higher ψ values. However, the factor of safety decreases beyond content 15% due to the contribution of c' and ϕ', as shown in Fig. 12. Therefore, the effect of the wetting front suction on slope stability is somewhat limited to coarse-mixed soils although the ψ increases with the increasing of the clay content of mixed soils. Consequently, the factor of safety in the soil slope containing with clay contents more than 15% are dependent on physical properties of the soils rather than the ψ.

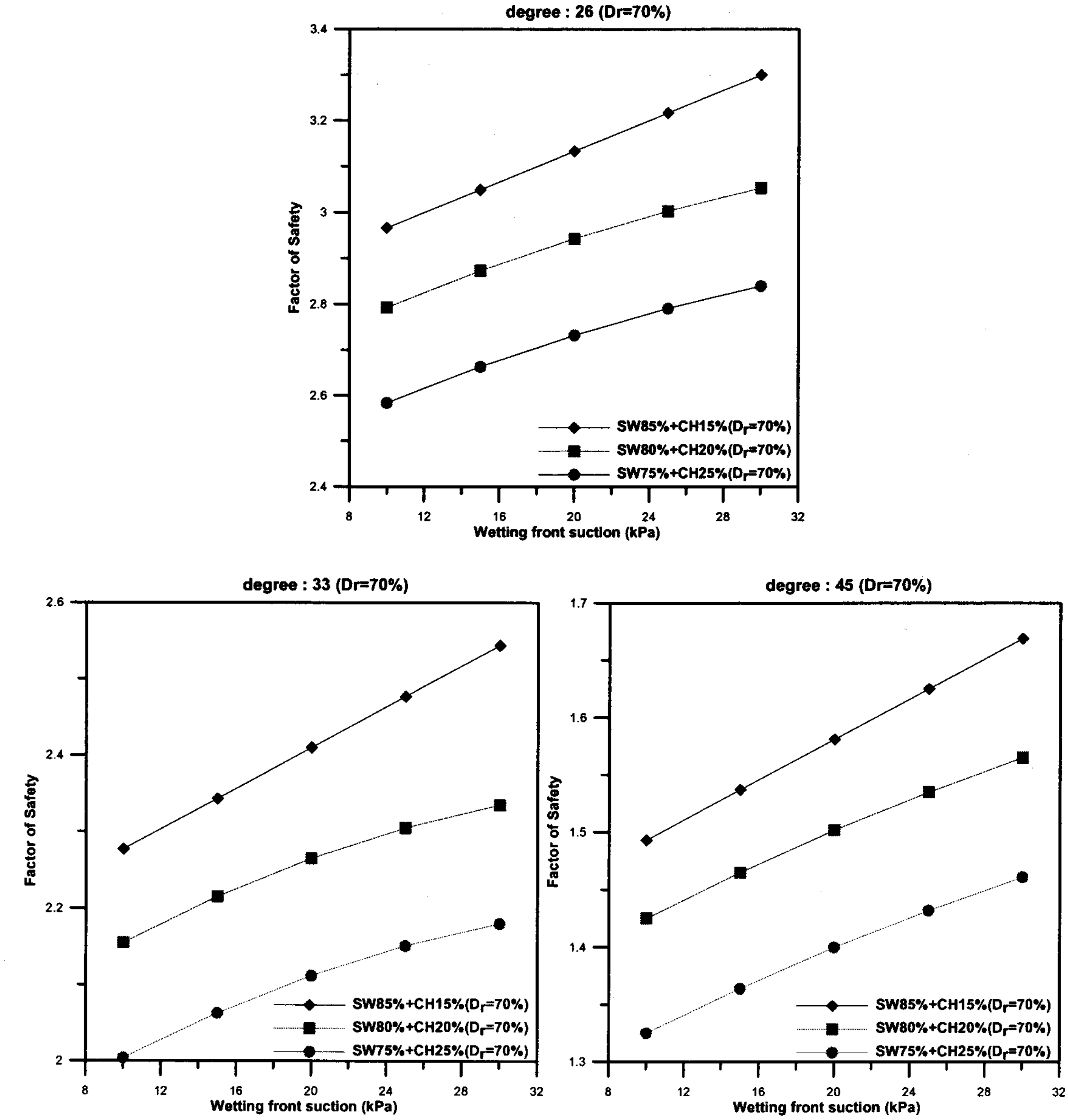

Figure 13. Wetting front suction vs. Factor of Safety

6. Conclusion

Although there are a lot of factors for rainfall-induced landslide, the present study was focused on investigating the effect of the wetting front suction generated by the infiltration of a rainfall. It describes the results of a series of laboratory tests and numerical analyses aimed at clarifying the effect of the magnitude of wetting band depth on unsaturated soil slopes. Special attention is given to the prediction of approximate limit of clay content which influences the magnitude of wetting band depth in soil mixtures. The following conclusions can be drawn from the study.

The GCTS pressure plate apparatus provides accurate measurements of SWCCs for five mixture soils concerning relative density (70 and 90%) and fine particle content (5, 10, 15, and 20%). Hence, the numerical analyses for the stability of unsaturated soil slopes calculated using the apparatus are comparable to those inferred by previously used Filter Paper method, because the SWCC results obtained by Filter Paper method have various errors, such as accuracy of balance and circumstances of a test.

The cause of surface failure for soil slopes is affected by infiltration rate on the surface of soil slopes during a rainfall. The infiltration rate is dependent on matric suction of the wetting front of seepage profile. The increase of the wetting front suction values lead to the improvement of factor of safety of a slope. The high wetting front suction values is caused by the rise of relative density and fine-grained content of mixture soils.

Based on these analysis results, there is a marginal effect in the wetting front suction values when the value reached 1.4m obtained by containing 15% of fine-grained content among sandy soils (SW). The safety factor of an infinite slope is subject to general strength parameters (c', ϕ') when fine-grained content is increased beyond 15% of mixture soils. Also when the wetting front suction were not considered for slope failures due to rain water, the existence of it can have a significant impact on the safety factor of unsaturated soil slopes.

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