KGS Spring Conference 2002 / March 21~22, 2002 / Seoul / Korea

Assessment of a Slope Stability of Unsaturated Soils
불포화 자연사면의 안정성 평가

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SYNOPSIS : 강우시 불포화 자연사면의 파괴메커니즘을 규명하기 위하여 사면내 모관흡수력의 변화를 고려한 안정해석을 수행하였다. 사면에는 강우계, Tensiometer, Pizometer, Water mock, 경사계 등이 설치되었으며 강우시 사면내 부간극수압과 임시지하수위의 거동을 관찰하였다. 실내실험으로부터 불포화 사면의 안정해석을 위하여 입력 값으로 사용되는 불포화투수계수, 불포화강도정수를 시료의 No.200체 통과량과 건조밀도를 기준으로 경험계수를 이용하여 추정 사용하였다. 강우의 침투로 인한 사면내 부간극수압의 분포는 계측값과 수치해석결과가 차이를 보였으며 이는 불포화 흐름시 흙속의 공기의 영향, 강우의 나무와 수풀에 의한 중간차단효과 및 증발의 영향을 해석에 고려하지 못했기 때문으로 사료된다. 사면안정해석결과 강우초기 모관흡수력을 고려하는 경우 약 10%의 안전율의 증가를 나타냈으며, 침투가 진행되면서 그 차이는 좁아져 임시지하수위가 표층까지 도달했을 때 흡수력을 고려하지 않는 해석과 안전율은 일치하였다.

Key words : 강우, 모관흡수력, 경험계수, 임시지하수위

1. Introduction

Landslides often occur during or soon after rainfall because pore water pressure within a slope increases. When a slope is dry, the pore pressure exhibits a negative value, which is suction pressure. The change of suction pressure during infiltration of rainwater into a slope results in the variation of safety factor on sliding for the slope.

Natural slopes are usually unsaturated soils. When the stability analysis for the slopes is performed, the relationship between volumetric water content and suction pressure for the materials must be first established. Brooks and Corey(1966) and van Gunucheten(1976) proposed empirical formula through experiments so that suction pressure could be estimated from volumetric water content. Fredlund et al.(1978) proposed a shear strength formula that can apply for unsaturated soils. Fredulund and Xing(1994) also suggested empirical formula that can establish the relationship between volumetric water content and suction pressure.

A natural slope in the landslide-prone area was selected and the measurements of suction pressure were taken at different level of the slope during rainy season. On the other hand, the suction pressure within the slope was predicted from the relationship established for the materials of the slope, using empirical parameters. With the pressures measured, the change of safety factor on sliding for the slope was evaluated. It is featured that landslides occur at shallow depth in the studied area because the ground surface of the slope is covered with weathered soils and the underlying layer is weathered rock.

2. Determination of empirical parameters

Weathered granite soils are widely distributed across the middle parts of the Korean Peninsula and those compose of the ground surface of slopes. Therefore, the first thing to treat with unsaturated soils is to predict their soil-water characteristics.

Ryu(1998) has performed a series of the lab tests for the weathered soils and found that there were some relationship between van Genucheten's parameters a, m, and n and fine contents of the weathered soil. Shown in Figure 1 is a graphical representation of the relationship.

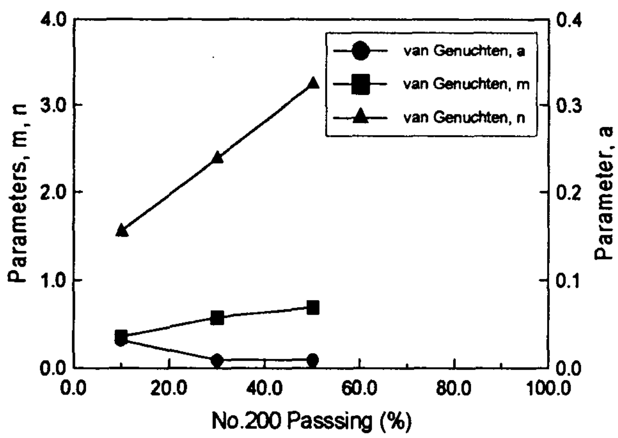

Fig 1. Empirical parameters of van Genuchten, a, m, and n as function of % passing sieve No. 200.

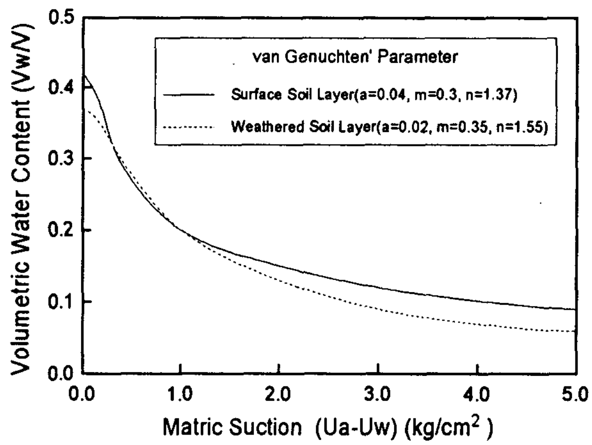

Fig 2. Relationship between volume water content and matric suction for two weathered soils.

The relationship between volumetric water content and suction pressure can also be established using following van Genucheten's formula(1976).

$$\theta_w = \frac{\theta_s}{\left[1 + \left(\frac{\Psi}{a}\right)^n\right]^m} \tag{1}$$

where θ_w = volumetric water content; θ_s = saturated volumetric water content; a = a suction value related to the air-entry value of the soil; n = a soil related to the slope of the soil-water characteristics curve; Ψ = soil suction; and m = parameter related to the residual water content.

Figure 2 shows the relationship between volumetric water content and matric suction, which is calculated using van Genucheten's parameters in equation 1. There appear two curves on the figure, one is for the finer weathered soil covering the ground surface, another is for the coarse weathered soil. Shear strength for unsaturated soils is calculated using the following formula(Fredlund et al. 1978).

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{2}$$

where τ = unsaturated shear strength; c' and ϕ' = effective strength parameters; σ_n = normal stress; u_a = pore air pressure; u_w = pore water pressure; and ϕ^b = apparent cohesion.

Ryu(1998) also did a lot of shear tests in order to correlate apparent cohesion to both suction pressure and fine contents of weathered soil. He found that apparent cohesion ϕ^b varies with both suction pressure and fine contents of soil as shown in Figure 3.

Effective friction angles of soils can be determined by drained test. Apparent cohesion ϕ^b can be estimated from Figure 3, as mentioned before. Then undrained shear stress with respect to matric suction can be predicted using Figure 4.

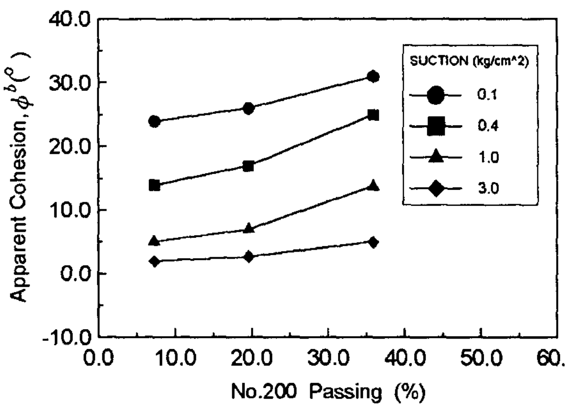

Fig 3. Estimation of apparent cohesion with suction pressure and % passing sieve No. 200.

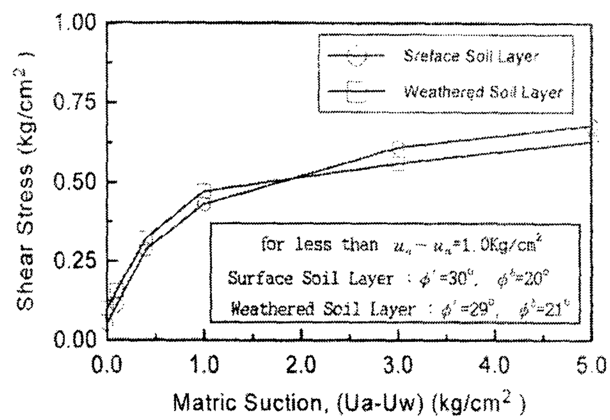

Fig 4. Estimation of undrained shear stress as function of effective strength parameters and matric suction.

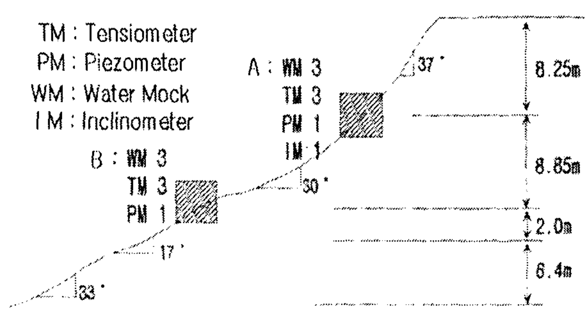

Fig 5. Section of the slope instrumented(Hyundai 1997).

3. Measurements of suction pressure

3.1 Sites

In order to understand the mechanism of landslides taking place during rainfall, a slope was selected and then instrumentation was heavily installed. The site selected is a landslide-prone area, where 23 people were dead by the landslide due to heavy rainfall in 1994. The natural slope is steep at the upper part and becomes gentle downwards as shown in Figure 5. Shrubs and trees cover the slope surface. Two locations were selected for the installation of instrumentation including tensiometers, piezometers, water mocks and inclinometers. Those were installed at different elevations but their imbedded depth is less than 110 cm, because the weathered depth of the slope is shallow.

3.2 Measurements of suction pressure

Shown in Figure 6 is the change of suction pressure measured for 50 days of the rainy season. Tensiometers were installed at three different levels of the slope. When there is no rain, suction pressure is high at the ground surface, as expected, but the pressure suddenly decreases as soon as the rain starts. The following rains cause the fluctuation of suction pressure depending on the intensity and duration of the rain. After rainfall and thereby the decrease of the suction pressure, it start to increase because of evaporation of soil moisture. Despite prolonged rains for 50 days, pore water pressure did not reach positive values. Piezometers installed into the soil mass did not respond at all. Since the water table was located much below the ground surface, the frequent rainfall was likely not to affect the rise of the table.

The response of suction pressure based on hourly rainfall, can be seen in Figure 7. This figure shows the pressure at different depths changing for 60 hours. As shown in the figure, there is no change of suction pressure at depth 110 cm below the ground surface, in spite of producing 10 mm of hourly rainfall. This is because leaves of trees and shrubs have prevented the infiltration of rainwater into the ground. However, the following rainfall of 15 mm/hr after 12 hours of the first rainfall caused sudden increase of suction pressure until the depth of 70 cm. With this rain intensity, the rain water is not likely to have penetrated to the depth of 110cm below ground level. Previous works(Greenway et al. 1984) reported that trees and shrubs prevented seepage of rainwater into the ground. The quantitative effect of the vegetation on infiltration of rainwater has not been informed from those studies. Our study shows that the initial hourly rainfall of less than 10 mm is completely retained by the vegetation and even the following rainfall of 15 mm/hr only penetrates in part into ground. Of course, this amount does not give rising to positive pore water pressure.

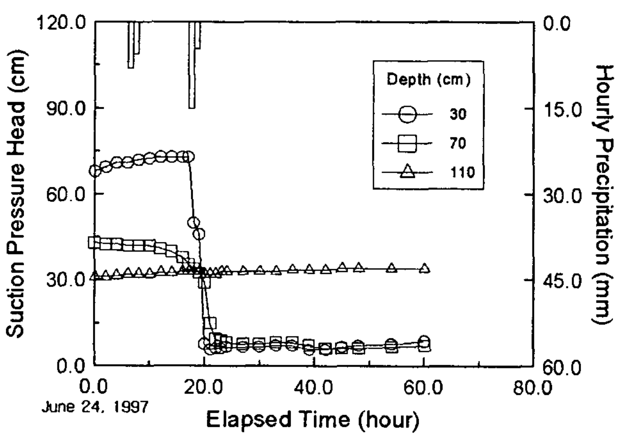

Fig 6. Changes of suction pressure with daily rainfall.

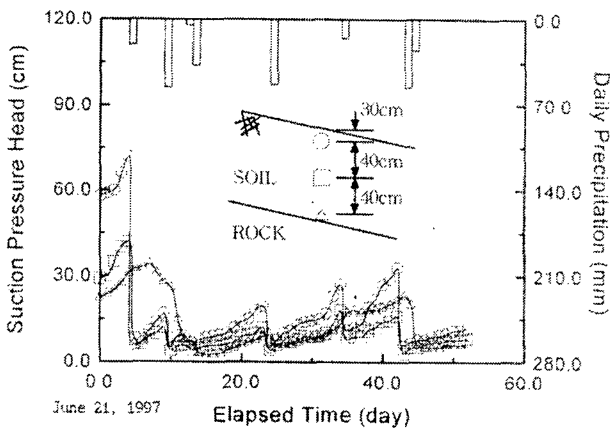

Fig 7. Changes of negative pore pressure with hourly rainfall.

4. Numerical analysis and comparison

4.1 Pore pressure head

A comparison of suction pressures predicted with measured ones for suction pressure is shown in Figure 8. The prediction of suction pressure was made using the SEEP software that is enable to deal with unsaturated flow with empirical parameters determined from Figure 1. It is known from Figure 8 that the predicted values of suction pressures do not agree with the measured ones.

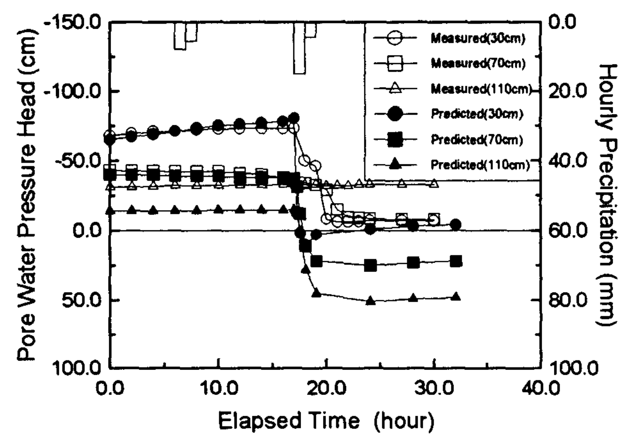

Fig 8. Comparison of measured and predicted pore pressure during rainfall.

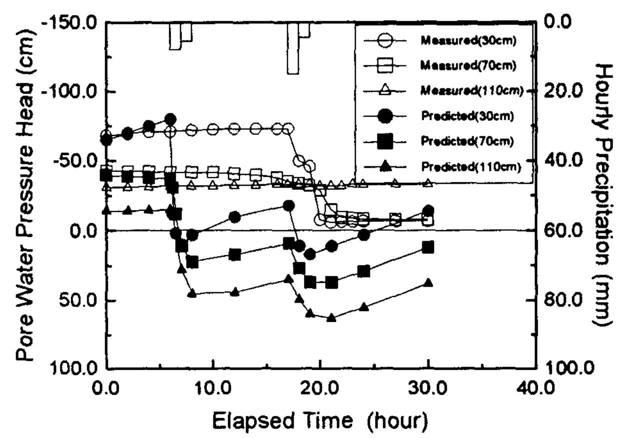

Fig 9. Comparison of the measured and predicted pore pressure during rainfall.

The discrepancy probably comes from the neglect of the canopy effect in the numerical analysis. In reality, the first rainfall less than 10 mm/hr was held by leaves of trees and shrub as mentioned before. Though the predicted pressure exhibited positive values soon after the first rainfall, the measured values remain negative throughout the period of the measurements.

Similar comparison was made in Figure 9. In this figure, it is assumed that the infiltration of the first rainfall is completely prevented from the canopy effect and that the second rainfall of only two third of its intensity has penetrated into the ground. The agreement is much better but in reality the canopy effect is likely to be larger than that assumed, according to our comparison.

5. Change of the safety factor of the slope during rainfall

The safety factors on sliding for the slope can be calculated using software programs written by many authors. The Bishop and Janbu methods for scope failures were applied in this study. Needless to say, the safety factor on sliding for a slope changes with the increase or decrease of suction pressure.

Figure 10 shows the variation of the safety factor of the slope during two events of rainfall. The safety factors are high in dry condition but the factors decrease when rainfall is produced. It is noted that two events of rainfall occurred with ten-hour interval decreases remarkably the safety factors. This means that accumulated rainfall is very important in landslide occurrences.

Since the suction pressure only contributed to the safety factor for dry condition and only minimum safety factors are required, the consideration of suction pressure is likely to be negligible in general practice.

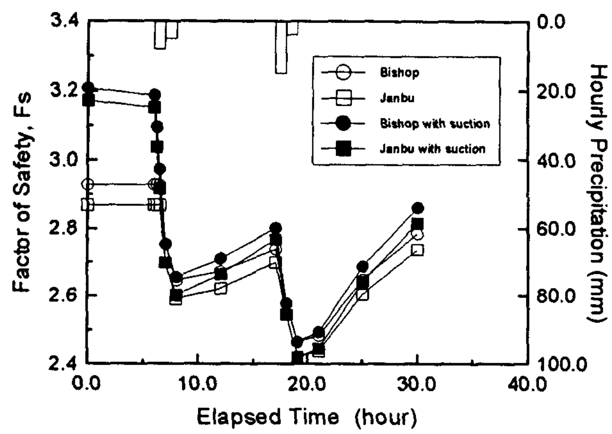

Fig 10. Change of safety factor with time during rainfall.

6. Conclusions

Field measurements of suction pressure were taken during the rainy season for a slope. Suction pressure varied with the intensity and duration of rainfall. With the use of numerical analysis, the variation of suction pressure during the infiltration of rainwater into the slope was predicted. The predicted suction pressures do not agree well with the measured values. The discrepancy comes mainly from canopy phenomenon by trees and shrubs covering the slope and partly from evaporation. It is known from the comparison that the first rain incident of less than 10 mm/hr does not penetrate into ground because of the canopy phenomenon. When considering suction pressure in calculating stability analysis, the safety factors would be increased. However, the suction pressure does not generally affect the minimum safety factor that is applied for practical use.

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