Transient Analysis on Infiltration and Stability for Unsaturated Soils in Busan Landslide Area

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Abstract: - Several areas in Busan have been recognized to experience actual failure due to heavy rainfall precipitation. Case histories are shown in Busan landslide area. The time dependent infiltration in unsaturated layers are assessed by using one-dimensional model, and the stability of the layers are calculated in the infinite slope. As a result, in the actual failure zones, the slopes become nearly or fully saturated and experience failure as the factor of safety reduces into ~1.0. It is found that the transient infiltration and stability analyses under three constitutive relations (soil water characteristic curve-hydraulic conductivity function-suction stress characteristic curve) framework can simulate the failure in the landslide area.

Key-Words: - Infiltration, Stability analysis, Suction stress, Unsaturated soils, Shallow landslide

1 Introduction

Heavy rainfall-induced landslide is one of crucial climatic problems in Busan [1,2]. Busan has annual average precipitation of 1,591 mm with the highest daily normal of 172 mm [3]. Such concentrated high intensity of rainfall occasionally causes slope failures. In addition, most of land sites in Busan are intrinsically composed of weathered soils which are sensitive to weaken the shear strength when water saturates the soils [4,5]. It corroborates the occurrence of landslides due to prolonged heavy rainfall in Busan.

In recent years, numerical studies have been carried out to understand the stability of slopes subjected to rainfall infiltration [1,4,6-8]. Analytical and numerical solutions simulating unsaturated flow are increasingly used to assess the influence of infiltration to the slope stability. Thus, a comprehensive understanding of hydro-mechanical behavior of unsaturated soils is required when conducting infiltration and stability analysis.

Two hydraulic properties of soil, namely, soil-water retention and hydraulic conductivity function, are the primary intrinsic factors that mainly affect the hydro-mechanical behavior of unsaturated soils [6]. For decades, unsaturated effective stress has been acknowledged as a cornerstone for shear strength considerations in unsaturated soils. Recently, effective stress for unsaturated soils based on Terzaghi's theory [9] under suction stress framework was developed by Lu *et al.* [10] in closed-form equations. The aforementioned properties (i.e. soil-water retention, hydraulic conductivity function, and effective stress under suction stress framework) can concurrently describe fluid flow, soil strength, and deformation behavior of variably saturated soils. Moreover, the three properties reconcile a constitutive relation which can be defined fully by a common set of hydro-mechanical parameters [11].

In the study, a one-dimensional finite element model has been carried out to investigate the influence of hydro-mechanical behavior on the transient infiltration in Busan landslide area. For the examination of stability of the soils, the results from the infiltration analysis were treated as input for limit equilibrium calculations. Factor of safety is computed from the Mohr-Coulomb failure criterion and effective stress principle based on suction stress framework [8,10].

2 Theoretical Considerations

The transient unsaturated flow is usually described by the Richards' equation [12] which, for one-dimensional vertical flow, can be written in the form of suction head as

$$\frac{\delta\theta(h)}{\delta t} = \frac{\delta}{\delta z}\left[k(h)\frac{\delta h}{\delta z} - k(h)\right] \quad (1)$$

where θ is the volumetric water content, h the water pressure head, $k(h)$ the hydraulic conductivity function (HCF), z the distance (positive downward), and t is the time. The use of equation (1) requires knowledge of two soil hydraulic properties: soil-water retention, $\theta(h)$, and the unsaturated HCF, $k(h)$ [13,14].

Oh *et al.* [15] developed satisfying mathematical equations for describing soil-water retention curve (SWRC). The equations were basically derived from van Genuchten's soil-water retention model [16] with several corrections.

A non-smooth curve within the range of low matric suction was introduced to fix extreme sensitivity of van Genuchten's model near saturation and overcome several shortcomings in numerical analysis subjected to steep hydraulic conductivity function caused by the sensitivity [15]. The equations are represented by relationship between effective saturation, Θ, and matric suction, p, as follows

$$p = \frac{1}{\alpha}\left[\frac{1}{\Theta^{1/m}} - 1\right]^{1/n}, \Theta < \Theta_b{}' \tag{2}$$

$$p = p_b' exp\{a(\Theta - \Theta_b{}')\}, \Theta_b{}' \leq \Theta < 1 \tag{3}$$

where

$$a = \frac{\{1 + (\alpha p_b{}')^n\}^{m+1}}{-mn(\alpha p_b{}')^n}, \tag{4}$$

θ_s and θ_r are saturated and residual water content, respectively. α (kPa^{-1}) is the inverse of the air entry pressure, p_b (kPa). n (>1) is a measure of pore size distribution and m is related to n as $m = 1 - 1/n$ [16]. After parametric study, $p_b{}'$ (kPa) which is an estimated arbitrary suction, has been assumed to be 0.02 of p_b. $\Theta_b{}'$ is effective saturation corresponding to $p_b{}'$.

According to van Genuchten [16], a closed-form equation for predicting unsaturated hydraulic conductivity is based on equation that derived by Mualem [17]. The predictive model by Mualem describes the relative conductivity function, k_r, with respect to Θ as follows:

$$k_r(\Theta) = \Theta^q \left(\int_0^\Theta \frac{d\Theta}{p}\right)^2 \bigg/ \left(\int_0^1 \frac{d\Theta}{p}\right)^2 \tag{5}$$

where q is the empirical parameter of pore connectivity. By substituting equations (2) and (3) into equation (5), the corresponding hydraulic conductivity function is expressed as analytical solutions.

On the other hand, unsaturated soil strength represented by effective stress principle under suction stress framework [10] is expressed as

$$\sigma' = (\sigma - u_a) - \sigma^s \tag{6}$$

where u_a is pore air pressure, σ is the total stress, and σ^s is defined as the suction stress characteristic curve (SSCC). Suction stress is an interparticle stress called tensile stress that characteristically depends on water content or matric suction, thus correlating the concepts of the soil water retention and hydraulic conductivity function for unsaturated soils. Recent studies stated that SSCC represents the effective stress for the shear strength behavior of unsaturated soils [10]. The suction stress characteristic curve, σ^s, is defined as [10]

$$\sigma^s = -(u_a - u_w);\ u_a - u_w \leq 0 \tag{7}$$

$$\sigma^s = -\Theta(u_a - u_w);\ u_a - u_w \leq 0 \tag{8}$$

This relation implies that the change in effective stress due to the change of saturation [10].

3 Numerical Infiltration Analysis

Busan landslide area is generally classified into two zones based on the number of recorded landslides: actual failure zone and non-failure zone.

Two soils, namely BS-1 and BS-2, were taken from the actual failure zones and non-failure zones, respectively. The soils were then examined by volumetric pressure plate extractor (VPPE) to obtain hydro-mechanical properties data. Subsequently, soil-water retention curve and hydraulic conductivity function were determined and fitted from the obtained data using equation (2)-(3), and (5), respectively.

The two soils are classified as SM according to the Unified Soil Classification System (USCS). Geotechnical and hydro-mechanical properties of both soils are listed in Table 1. Of all properties, the notable differences between two soils lies on the value of slope angle (β) and air-entry value ($1/\alpha$). BS-1 has steeper slope angle and higher air-entry value than BS-2. The rest properties e.g. internal friction angle (ϕ'), dry unit weight (γ_d), and saturated permeability (k_s) are quite similar. The saturated cohesion (c') is assumed to be zero since the type of investigated soils are sands.

Infiltration of rainfall into the slopes utilized by the numerical model based on finite element method, SEEP/W [18]. The seepage model of SEEP/W made use of the measured soil-water retention and hydraulic conductivity function to simulate movement of water through the unsaturated slopes.

the end of simulation, the soil was still partially saturated (around 80% of saturation).

Table 1
Geotechnical and hydro-mechanical properties of soils in Busan landslide area

Soils	ϕ' (°)	γ_d (kN/m³)	k_s (m/s)	c' (kPa)	β (°)	θ_s	θ_r	α (kPa⁻¹)	n	q
BS-1	34.573	13.589	5.12E-05	0	34.328	0.414	0.029	0.174	1.220	-3.5
BS-2	35.523	14.375	5.56E-05	0	22.343	0.502	0.122	3.441	1.365	-3.5

The dimension of the soil column was set to 2 m in height and 1 m in width, considering the occurrence of shallow failure. A constant suction of 15 kPa was assigned from the top (surface) to the bottom (impermeable layer) of the model as the initial suction. The left and right edge of the soil column were assigned as no flow boundaries. On the top surface of the soil column, a prescribed probability based rainfall, 10mm/hr, was applied. The analyses were terminated after 24 hours in simulation. For simplicity, the intensity of rainfall was kept constant for the entire duration of rainfall. The illustration of initial and boundary conditions of one-dimensional model used in the present study is depicted in Fig. 1.

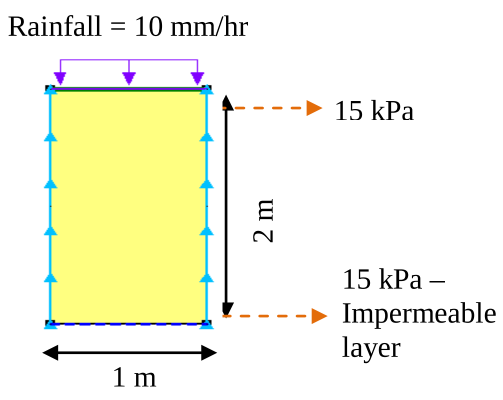

Fig. 1. Illustration of numerical model

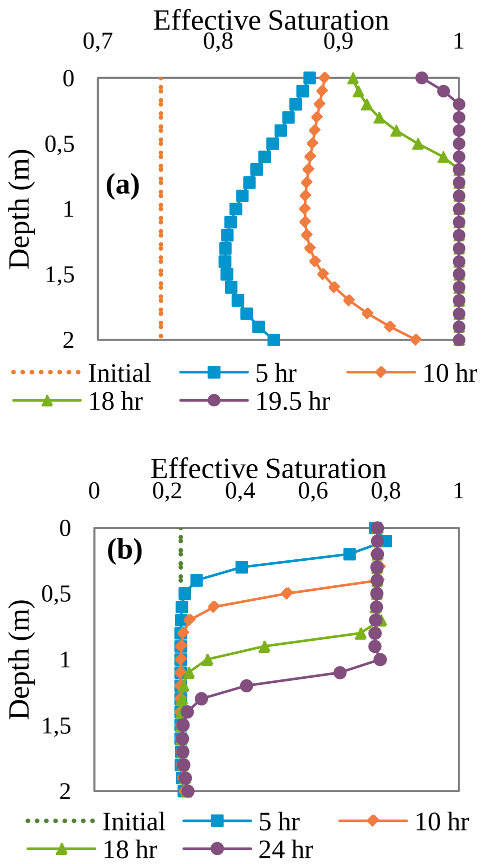

Fig. 2. Transient infiltration analysis results of (a) BS-1 (b) BS-2

Fig. 2 shows the relationships between effective saturation and depth, obtained from transient infiltration analysis. As shown in Fig. 2 (a), the soil above impermeable layer in BS-1 became nearly saturated after 10 hours of infiltration. The saturation continued to the slightly below the surface (~0.5 m) after 18 hours of infiltration. At the end of simulation, the entire depth of soil was nearly fully saturated.

From Fig. 2 (b), it can be noted that at 2 m below the surface, the saturation remained unchanged while at 1 m below the surface, a rapid saturation occurred between 10 and 18 hours of infiltration. At

4 Slope Stability Analysis

Rainfall-induced slope failures are generally shallow and the failure planes are commonly parallel to the slope surface. Therefore, the surficial stability of slope is often evaluated using a single layered infinite slope model [19] with the shear strength of soil computed from conventional Mohr-Coulomb failure criterion and the effective stress principal under suction stress framework as the basis concept.

The key indicator that represents stability of slopes is factor of safety (FOS), which commonly defined as relation between shear stress at failure and driving shear stress [7]. Based on the Mohr-Coulomb failure criterion and the limit equilibrium approach, the FOS can be expressed as [8]

$$FOS = \frac{c' + (\gamma_t z_w \cos^2\beta - \sigma^s)\tan\phi'}{\gamma_t z_w \sin\beta \cos\beta} \quad (9)$$

where z_w is the vertical depth of soil slice and γ_t is total unit weight of soil).

Fig. 3 shows factor of safety profile of both soils with respect to depth. As shown in Fig. 3 (a), factor of safety of BS-1 reduced into ~1.0 at the same moment when the soil was nearly saturated. It happened at both observation depths (1 m and 2 m below the surface). At the end of the simulation, it is shown that the factor of safety of the surface was ~1.0, indicating the failure almost occurred at the entire depth.

From Fig. 3 (b), it can be inferred that BS-2 soil were stable since the FOS was still greater than 1.5 despite the soils had been nearly saturated.

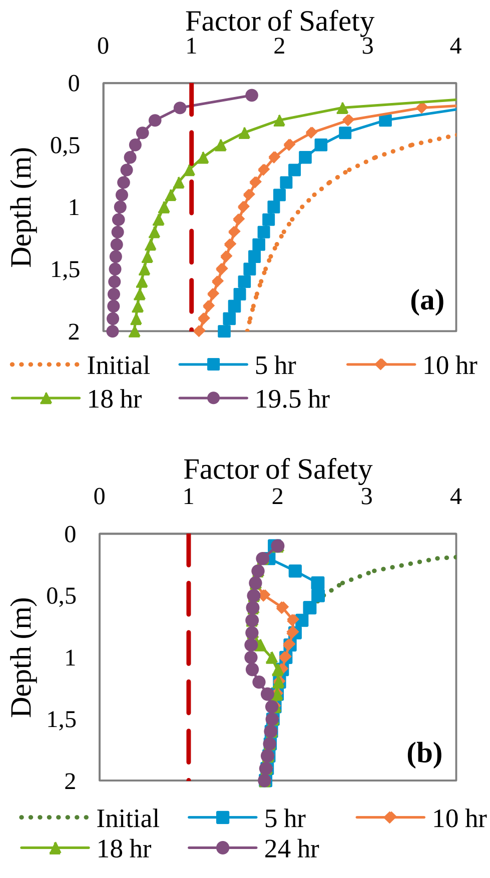

Fig. 3 Stability analysis results of (a) BS-1 (b) BS-2

5 Conclusions

The transient infiltration and stability analyses can simulate the actual failure in the landslide area under SWRC, HCF and SSCC framework. In the case history on the actual failure zones, the unsaturated slopes become nearly saturated for the entire depth. On the contrary, in the non-failure zones, the slopes are partially saturated even after the rainfall infiltrates the slopes for 24 hours. Furthermore, it is verified that failure occurs in the actual failure zones as indicated by the reduction of FOS into ~1.0 when the soil is nearly saturated. On the other hand, failure does not occur in the non-failure zones since the FOS of soil is greater than 1.5 for the entire depth.

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References:

[1] Ryu, J-H., Seo, S-H., Kim, Y., A case study for landslide of Busan-Gyeongnam area occurred in 2014, *Journal of Korean Society of Hazard Mitigation*, Vol. 15, No. 1, 2015, pp.143-151.

[2] Kim, T.W., Kang, I.J., Choi, H., Lee, B.G., Causual analysis on soil loss of safety class Oryun Tunnel area in landslide hazard map, *Journal of Korean Society for Geospatial Information System*, Vol. 24, No. 1, 2016, pp. 17-24.

[3] Korea Meteorological Administration, *1981~2010 Climatological Normals of Korea*, Korea Meteorological Administration, 2011.

[4] Kim, J., Jeong, S., Park, S., Sharma, J., Influence of rainfall-induced wetting on the stability of slopes in weathered soils, *Engineering Geology*, Vol. 75, No. 3, 2004, pp. 394-401.

[5] Choi, Y., Nam, M.S., Numerical analysis of bi-directional pile load tests for drilled shafts in rocks, in *Deformation Characteristics of Geomaterials*, IOS Press, 2011.

[6] Khalid, M., Kim, J.M., Effect of hydraulic conductivity on suction profile and stability of cut-slope during low intensity rainfall, *Journal of the Korean Geotechnical Society*, Vol. 28, No. 6, 2012, pp. 63-70.

[7] Oh, S., Lu, N., Slope stability analysis under unsaturated conditions: Case studies of rainfall-induced failure of cut slopes, *Engineering Geology*, Vol. 184, 2015, pp. 96-103.

[8] Li, W.C., Lee, L.M., Cai, H., Li, H.J., Dai, F.C., Wang, M.L., Combined roles of saturated permeability and rainfall characteristics of surficial failure of homogeneous soil slope, *Engineering Geology*, Vol. 153, 2013, pp. 105-113.
[9] Terzaghi, K., *Theoretical soil mechanics*, John Wiley & Sons, 1943.
[10] Lu, N., Godt, J.W., Wu, D.T., A closed-form equation for effective stress in unsaturated soil, *Water Resources Research*, Vol. 46, No. 5, 2010, pp. 1-4.
[11] Lu, N., Kaya, M., Godt, J.W., Interrelations among the soil-water retention, hydraulic conductivity, and suction-stress characteristic curves, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 150, No. 5, 2014, p. 4014007.
[12] Richards, L.A., Capillary conduction of liquids through porous mediums, *Journal of Applied Physics*, Vol.1, No. 5, 1931, pp. 318-333.
[13] Vogel, T., van Genuchten, M.T., Cislerova, M., Effect of the shape of the soil hydraulic functions near saturation on variably-saturated flow predictions, *Advances in Water Resources*, Vol. 24, No. 2, 2000, pp. 133-144.
[14] Wayllace, A., Lu, N., A transient water release and imbibitions method for rapidly measuring wetting and drying soil water retention and hydraulic conductivity functions, *Geotechnical Testing Journal*, Vol. 35, No. 1, 2012, pp. 1-15.
[15] Oh, S., Kim, Y.K., The modified van Genuchten-Mualem on hydraulic conductivity to improve reliability and numerical stability near saturation, in *Unsaturated Soils: Research and Applications*, Taylor & Francis Group, 2014.
[16] van Genuchten, M.T., A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society of America Journal*, Vol. 44, No. 5, 1980, pp. 892-898.
[17] Mualem, Y., A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resources Research*, Vol. 12, No. 3, 1976, pp. 513-522.
[18] GEO-SLOPE, *Seepage Modelling with SEEP/W*, GEO-SLOPE International Ltd., 2012.
[19] Lu, N., Godt, J.W., Infinite slope stability under steady unsaturated seepage conditions, *Water Resource Research*, Vol. 44, No. 11, 2008, pp. 1-13.