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NON-DIMENSIONAL PARAMETERS CONTROLLING OCCURRENCE AND CHARACTERISTIC OF LANDSLIDES THAT PROVIDE SEDIMENT FOR DEBRIS FLOW DEVELOPMENT

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ABSTRACT

Landslides are one of the most important processes supplying debris flow materials into channels. We need to predict the timing, location, and volume of landslides for better estimation of the occurrence of debris flows. However, a number of soil parameters (e.g., the angle of internal friction, cohesion, and porosity), which have significant spatial variability, are needed to predict landslide occurrence. Therefore, it is important to make clear the contribution of these parameters to overall slope stability and their relationships to one another. In this study, we normalized the safety factor equation for infinite slope model, and introduced multi soil layer structure into the model. We also tried to clarify factors affecting the pore water pressure on the basis of the equations for the vertical infiltration process (i.e., continuity equation and Darcy's law). Depth gradient of the pore-water pressure at the given soil layer is controlled by the ratio of the water velocity in saturated zone to the hydraulic conductivity at that layer. New, non-dimensional representations for the effects of groundwater table and cohesion of soil were obtained by the normalization of the safety factor equation. They are evaluated relative to each other by comparison to the stability of dry non-cohesive soil. The effect of the groundwater table and the cohesion of soil on the slope stability are both affected by depth of the sliding surface. We also found that the effect of cohesion should be evaluated from the comparison with the maximum effect of groundwater table to the stability. This can explain the immunity of post-landslide slopes to immediately subsequent landslides, as well as the cyclical nature of landslide processes.

KEY WORDS: *landslide, non-dimensional parameters, infinite slope model*

INTRODUCTION

Landslides are one of the most important processes supplying debris flow materials into channels. The ability to predict the timing, location, and volume of landslides would improve the estimation of debris-flow occurrence. Many physical models that predict the occurrence of landslides have been proposed for the mitigation of landslide and debris-flow disasters, as well as the estimation of sediment supply rates into channel networks (e.g., BURTON *et alii*, 1998; DYMOND *et alii*, 1999; SIDLE & OCHIAI, 2006). Several studies have used sensibility analysis and numerical simulations to determine that the occurrence of landslides is affected by multiple parameters, including topographic factors, i.e., slope gradient and shape geometry (OKIMURA AND NAKAGAWA, 1988; OHSAKA *et alii*, 1992; MONTGOMERY & DIETRICH, 1994; SASAHARA *et alii*, 1995), soil constants (SAMMORI *et alii*, 1993; MONTGOMERY & DIETRICH, 1994; WO & SIDLE, 1995), and hydraulic conductivities (HIRAMATSU *et alii*, 1990; SAMMORI *et alii*, 1993). Field studies have also empirically documented the influence of many parameters on slope stabilities (e.g., DUMAN *et alii*, 2004). To improve the prediction of debris flows into channel networks, we must be able to estimate the occurrence of landslides in the entire area supplying debris-flow material. However, significant spatial variability in these parameters prevents us from accurately predicting landslides at the catchment area scale. Therefore, the extraction of control parameters for the occurrence of landslides from numerous soil and topographic parameters is necessary for the effective prediction of landslides.

Some studies have revealed that landslide volume and depth are affected by the magnitude and pattern of rainfall (DAI & LEE, 2001; HATTANJI, 2003). Therefore, the depth profile of hydraulic conductivity, which controls temporal changes in the depth profile of pore-water pressure, should be considered in the estimation of landslide volume.

To extract the important parameters controlling the occurrence and volume of landslides, their interrelationships and contributions to overall slope stability must be clarified. In this study, we discuss a simple but versatile model for the prediction of landslides based on the stability of an infinite slope (e.g., SIDLE & OCHIAI, 2006). We assume the multi-layer soil structure to reflect the depth distribution of soil parameters for the slope stability analysis. First, we identify important factors affecting the magnitude of pore-water pressure that induce shallow landslides during rainfall events. Because the infinite model is employed in this study, the groundwater table should be parallel to the ground surface. We thus analyze the pore-water pressure far from the top of the slope, where the water table is parallel to the ground surface. This allows us to consider only the vertical infiltration of groundwater in the analysis of pore water pressure. Second, we normalize the safety factor equation for an infinite slope to obtain the non-dimensional parameters controlling the occurrence of landslides. Given the nature of the infinite slope, we consider the spatial distribution of soil parameters only in the direction of depth. To simplify the model, a constant is used to describe the parameters of each soil layer.

BASIC EQUATIONS FOR THE VERTICAL INFILTRATION PROCESS

VERTICAL INFILTRATION IN THE SATURATED ZONE

To estimate the pore water pressure above a sliding surface, we must first develop basic equations for groundwater in multi-layer soil structure (Fig. 1). In

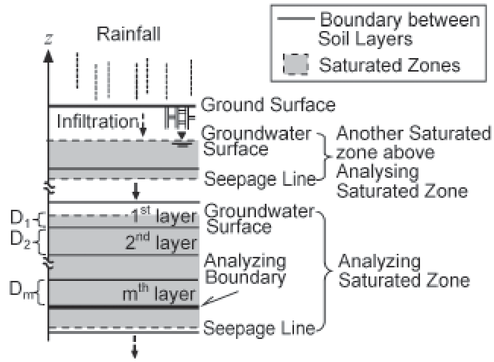

Fig. 1 - Schematic diagram of vertical infiltration

this study, soil porosity is considered to be constant throughout all soil layers to clarify the relationship between the spatial distribution of hydraulic conductivity and pore-water pressure. As demonstrated by many field surveys, hydraulic conductivity is generally lower in deeper soil layers (e.g., HIRAMATSU *et alii*, 1993; IRASAWA *et alii*, 1997; HIRAMATSU & BITO, 2001). Therefore, we set a smaller hydraulic conductivity for deeper soil layers. The continuity of vertical infiltration of incompressible water can be expressed as following equation:

$$\rho n \frac{\partial S}{\partial t} + \rho n \frac{\partial S u}{\partial z} = 0 \qquad (1)$$

where ρ is the mass density of water, n is the porosity of soil, S is the degree of saturation, u is the vertical (z-axis) water flow velocity. As S equals 1 in the saturated zone, equation (1) in the saturated zone can be rewritten as:

$$\frac{\partial u}{\partial z} = 0 \qquad (2)$$

When we treat groundwater as the steady state, the equation of motion is described by the following equation:

$$0 = -\rho g - \frac{\partial p}{\partial z} \qquad (3)$$

where $\partial p / \partial z$ is the pressure gradient, and g is the gravitational acceleration.

The pressure gradient $\partial p / \partial z$ consists of the pore-water-pressure gradient $\partial p_s / \partial z$ and the hydraulic gradient $\partial p_d / \partial z$:

$$\frac{\partial p}{\partial z} = \frac{\partial p_s}{\partial z} + \frac{\partial p_d}{\partial z} \qquad (4)$$

The relationship between the hydraulic gradient and water velocity is expressed by Darcy's law:

$$u = \frac{K}{\rho g} \frac{\partial p_d}{\partial z} \qquad (5)$$

where K is hydraulic conductivity. By substituting equations (4) and (5) into equation (3), the pore-water-pressure gradient can be expressed by the following equation:

$$\frac{\partial p_s}{\partial z} = -\rho g\left(1+\frac{u}{K}\right) \quad (6)$$

The pore-water pressure at a boundary between soil layers can be obtained by integrating equation (6) from the groundwater table of the saturated zone with the soil layer boundary. By setting the boundary condition p_s = 0 at the groundwater table, the pore water pressure is:

$$p_s = -\sum_{i=1}^{m} \rho g D_i\left(1+\frac{u}{K_i}\right) \quad (7)$$

where m is number of soil layers above the analyzed boundary, K_i is the hydraulic conductivity, and D_i is the thickness of ith soil layer in the saturated zone. Equation (7) indicates that pore-water pressure is controlled not only by the hydraulic conductivity of an individual layer (K_i), but also by the downward velocity of water in the saturated zone (u). As demonstrated by equation (7), this downward velocity is constant in the saturated zone. In cases where the saturated zone is formed on impermeable bedrock, the vertical water velocity is equal to 0. Therefore, pore-water pressure on impermeable bedrock is:

$$p_s = -\sum_{i=1}^{m} \rho g D_i \quad (8)$$

Equation (8) indicates that pore water pressure agrees with hydrostatic pressure. As presented in equation (8), the presence of another saturated zone above the analyzed zone (Fig. 1) does not affect the magnitude of pore-water pressure on the analyzed soil layer boundary.

NORMALIZATION OF THE SAFETY FACTOR EQUATION

By introducing the coordinate system shown in Fig. 2, the safety factor equation for a sliding surface can be expressed by the following equations:

$$F = \frac{\tau_r}{\tau} \quad (9)$$

$$\tau_r = c + \left[\int_{z_1}^{h}\{(1-n)\sigma g + nS\rho g\}dz - p_s\right]\cos\theta\tan\phi \quad (10)$$

$$\tau = \int_{z_1}^{h}\{(1-n)\sigma g + nS\rho g\}dz \sin\theta \quad (11)$$

where F is the safety factor, τ_r is the shear strength of soil on the sliding surface, τ is the shear stress on the sliding surface, σ is the mass density of soil particles, ϕ is the angle of internal friction, and c is the cohesion of soil at the sliding surface.

As shown in equations (10) and (11), the safety factor is affected by the spatial distribution of n and

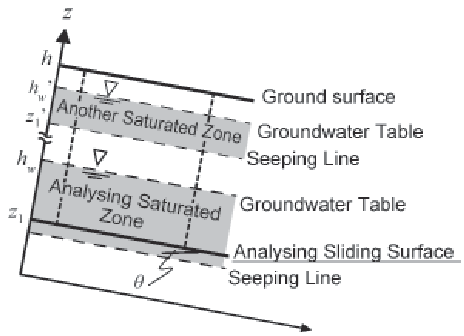

Fig. 2 - Schematic diagram of the infinite slope

S in the direction of depth. The integrals in equations (10) and (11) can be performed as follows:

$$\tau_r = c + \left[(h-z_1)\left\{(1-n)\sigma g + (1-\eta_w)n\bar{S}\rho g + \eta_w n\rho g\right\} - p_s\right] \cdot \cos\theta\tan\phi \quad (12)$$

$$\tau = (h-z_1)\left\{(1-n)\sigma g + (1-\eta_w)n\bar{S}\rho g + \eta_w n\rho g\right\}\sin\theta \quad (13)$$

where η_w, $\bar{S}$ are:

$$\eta_w = \frac{h_w - z_1}{h - z_1} \quad (14)$$

$$\bar{S} = \frac{\int_{h_w}^{h} nSdz}{\int_{h_w}^{h} ndz} \quad (15)$$

By substituting equations (12) and (13) into equation (9) and multiplying the equation by tanθ / *tan*ϕ, the normalized safety factor equation is

$$F\frac{\tan\theta}{\tan\phi} = 1 - F_w + F_c \quad (16)$$

where F_w and F_c are:

$$F_w = \frac{\varepsilon\eta_w}{\left\{(1-n)\frac{\sigma}{\rho} + n\eta_w\right\} + n(1-\eta_w)\bar{S}} \quad (17)$$

$$F_c = \frac{\eta_c}{\left\{(1-n)\frac{\sigma}{\rho} + n\eta_w\right\} + n(1-\eta_w)\bar{S}} \quad (18)$$

$$\varepsilon = \frac{p_s}{\rho g(h_w - z_1)} \quad (19)$$

$$\eta_c = \frac{c}{(h-z_1)\rho g\cos\theta\tan\phi} \quad (20)$$

F_w (groundwater term) and F_c (cohesion term) are the non-dimensional parameters describing the effects of groundwater and cohesion on the safety factor, respectively. The effects of these terms on slope stability are evaluated by their scale relative to the first term on the right side of member “1” in equation (16), and also as the linear sum of the first term. The safety factor equation for the soil layers without the saturated zone and soil cohesion ($(h_w - z_1) = 0$, $c = 0$) is considered the basic part of equation (16):

$$F\frac{\tan\theta}{\tan\phi} = 1 \tag{21}$$

Equation (21) indicates that neither porosity (n) nor degree of saturation (S) affects the safety factor in cases lacking a saturated layer and soil cohesion.

EFFECT OF GROUNDWATER ON SLOPE STABILITY

The denominator of the second term on the right side of equation (16) (hereafter called $\overline{W}$), which is identical to that of the third term, indicates the average specific gravity of the soil layer. The denominator is deformed as:

$$\overline{W} = \left\{(1-n)\frac{\sigma}{\rho} + n\overline{S}\right\} + n\left(1-\overline{S}\right)\eta_w \tag{22}$$

Comparison of the denominator of equation (17) with equation (22) shows that η_w and $\overline{S}$ in $\overline{W}$ are symmetrical. Given that the range of both η_w and $\overline{S}$ values is 0 to 1, $\overline{W}$ ranges from $(1\text{-}n)\sigma/\rho$ to $(1\text{-}n)\sigma/\rho + n$. Thus, in cases where $n \approx 0.5$ and $\sigma/\rho \approx 2.6$, $\overline{W}$ ranges from 1.3 to 1.8.

The numerator of the groundwater term (F_w) is the product of η_w, the ratio of thickness of the saturated zone to the depth of the sliding surface (equation 14), and ε, the ratio of pore-water pressure p_S to hydrostatic pressure. Given that both of these non-dimensional parameters range from 0 to 1, the numerator also ranges from 0 to 1. Consequently, changes in the numerator $\varepsilon\eta_w$ affect the safety factor more strongly than do changes in the denominator $\overline{W}$.

When the sliding surface is formed on impermeable bedrock, ε is equal to 1 (see equations 19 and 8). In this case, F_w can be obtained by substituting $\varepsilon = 1$ into equation (17):

$$F_w = \frac{\eta_w}{\left\{(1-n)\frac{\sigma}{\rho} + n\eta_w\right\} + n(1-\eta_w)\overline{S}} \tag{23}$$

To clarify the degree of dependence on groundwater parameters (i.e. η_w, and $\overline{S}$), changes in F_w with increasing η_w were investigated under conditions of $n = 0.5$, $\sigma / \rho = 2.6$, and several $\overline{S}$ values (0, 0.3, 0.6, 0.9; Fig. 3). The influence of $\overline{S}$ on F_w is small if porosity n is 0.5 (Fig. 3). In addition, F_w is approximately proportional to η_w. As the maximum value of F_w is 1/1.8, F_w decreases the safety factor by a maximum of 50%.

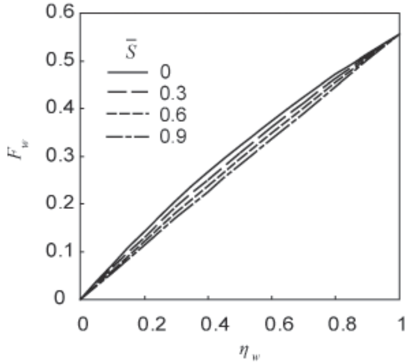

Fig. 3 - Degree of dependence of F_w on η_w and $\overline{S}$

EFFECT OF COHESION ON SLOPE STABILITY

The effect of cohesion on slope stability is represented by the cohesion term (F_c), the third term on the right side of equation (16). The magnitude of the numerator of the cohesion term (η_c) depends on soil depth (h - z_1) and cohesion (c). Equations (18) and (20) indicate that F_c is larger for shallower sliding surfaces. In the case of shallow landslides, h - z_1 is generally 1 m, and c ranges from 0 to 9800 N/m^2 (e.g., Irasawa *et alii*, 1997; Hiramatsu & Bito, 2001). In this case, the range of η_c is:

$$0 \le \eta_c \le \frac{1}{\cos\theta\tan\phi} \tag{24}$$

If $\theta°$ and $\tan\phi = 0.7$, the maximum value of the η_c is 2.0. Given that the denominator of the cohesion term ranges from 1.3 to 1.8, the maximum value of F_c is similar to or higher than the basic part of slope stability "1" on the right side of equation (16). Thus, the cohesion term (F_c) is an important factor affecting the occurrence of shallow landslides. In contrast, the maximum value of η_c for a sliding surface at a depth of 10 m is 0.2 if the other parameters (i.e., $\theta°$, ϕ) remain the same as above. Therefore, the influence of F_c on slope stability is negligible for deep-seated landslides.

Because the denominator of F_c is the same as that of F_w, the numerators of these terms (η_c and $\varepsilon\eta_w$) can be simply compared. In cases where η_c is much smaller than 1 (= maximum value of $\varepsilon\eta_w$), the influence of η_c on slope stability is negligible. To demonstrate the influence of η_c on slope stability, we assume that the slope has a gradient θ that is similar to ϕ. This hypothesis is not unusual, as many field surveys (e.g., Tsuchiya & Komoto, 1995; Hiramatsu & Bito, 2001) have found similar relationships between θ and ϕ.

We also assume that the sliding surface is located on bedrock with a hydraulic conductivity of almost 0. In this case, F_w is expressed by equation (23). Therefore, the safety factor (F) is equal to 1 when $\eta_w - \eta_c = 0$. Given that η_w ranges from 0 to 1, landslides should occur when η_c is less than 1. Based on equation (20), the relationship between c and $h - z_1$ that satisfies is expressed as:

$$(h - z_1) = \frac{c}{\rho g \sin\theta} \tag{25}$$

The relationship between c and (h - z_1) that satisfies η_c=1 is not clearly affected by the value of $\theta°$ (= ϕ; Fig. 4). In cases where cohesion (c) ranges from 3000 to 9000 N/m^2, the range of (h - z_1) required for landslides to occur is 0.4 to 1.5 m (Fig. 4). No landslide should occur on the slopes plotted at the lower right of fig. 4 because η_c the of these slopes always exceeds 1. In contrast, the η_c of slopes plotted at the upper left of Fig. 4 is less than 1. Therefore, landslides occur on these slopes when η_w satisfies $1 \geq \eta_w = \eta_c$.

Based on these discussions, the following important characteristics of landslides may be deduced. Once a landslide occurs on a slope, the soil depth (h - z_1) approaches zero or is decreased significantly. Based on equation (20), η_c is considered to exceed 1 when little or no regolith remains on the sliding surface. Thus, a landslide should never occur on these slopes, even if surface flow is generated. Thereafter, soil depth may be recovered gradually by the weathering of bedrock and infilling from the surrounding area. Landslides can occur again when the depth of the soil layer on the sliding surface reaches a critical level that satisfies η_c=1. This explains the immunity of post-landslide slopes to immediately subsequent landslides, as well as the cyclical nature of landslide processes (e.g., Iida, 2004).

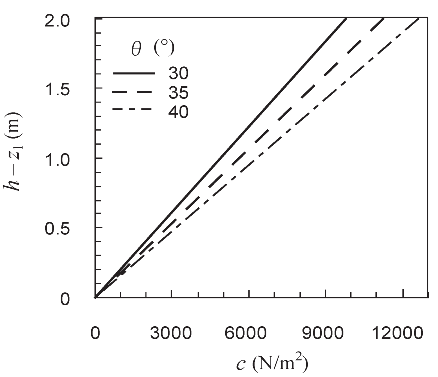

Fig. 4 - Relationship between c and h-z_1 when η_c=1

SUMMARY AND CONCLUSIONS

In this study, we tried to identify the non-dimensional parameters that control the occurrence of landslides, which are one of the most important processes by which debris-flow materials enter channel networks. We also clarified the contribution of these parameters to overall slope stability and their relationships to one another. We used the infinite slope model, which is a simple but versatile model for landslide prediction. Multi-layer soil structure was also assumed in order to reflect the depth distribution of soil parameters in the analysis of slope stability.

On the basis of equations describing the vertical infiltration process (i.e., continuity equation and Darcy's law), we identified the factors affecting pore-water pressure. Our study revealed that the depth gradient of pore water pressure in an individual soil layer is affected by the ratio of vertical water velocity in the saturated zone to hydraulic conductivity in that layer. In cases where the saturated zone is developing on impermeable bedrock, pore-water pressure agrees with hydrostatic pressure.

New non-dimensional representations of the effects of the groundwater table and soil cohesion were obtained by normalizing the safety factor equation. They were evaluated relative to the stability of dry non-cohesive soil. The effects of the groundwater table and soil cohesion on slope stability depend on the depth of the sliding surface. We also found that the effect of cohesion should be evaluated by comparison with the maximum effect of the underground water table on stability. This comparison can explain a slope's immunity to the occurrence of landslide, as well as the periodicity of landslide occurrence.

Our analysis is applicable to slopes with multiple soil layer boundaries and saturated zones (Figs. 1, 2). Because the parameters relevant to groundwater and cohesion include soil depth, the vertical structure of soil layers must be considered for the prediction of landslides. Furthermore, depth of sliding surface should be estimated in order to predict volume of the landslide sediment supplied to mountainous torrents. Therefore, analysis of slopes with multi-layer soil structure is also effective for prediction of debris flows. To predict debris flows in mountainous torrents, we need to predict the occurrence of landslides in the entire area that supplies debris-flow material. Therefore, methods for investigating the regional spatial and temporal distribution of the non-dimensional parameters should be developed to apply our results to the prediction of debris flows.

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