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Correlations between variables related to slope during rainfall and factor of safety and displacement by coupling analysis

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Abstract. This study aims to establish the correlations between variables related to a slope during rainfall and factor of safety (FOS) and displacement using a coupling analysis method that is designed to consider both in rainfall conditions. With the recent development of measurement technologies, the approach of using the measurement data in the field has become easier. Particularly, they have been obtained in tests to determine the real-time safety and movement of a slope; however, a specific method has not been finalized. In addition, collected measurement data for recognizing the FOS and displacement in real-time with a specific relevance is difficult, and risks of uncertainty, such as in soil parameters and time, exist. In this study, the correlations between various slope-related variables (i.e., rainfall intensity, rainfall duration, angle of the slope, and mechanical properties including strength parameters of selected three types of soil; loamy sand, silt loam, sand) and the FOS and displacement are analyzed in order of seepage analysis, slope stability analysis and slope displacement analysis. Moreover, the methodology of coupling analysis is verified and a fundamental understanding of the factors that need to be considered in real-time observations is gained. The results show that the contributions of the abovementioned variables vary according to the soil type. Thus, the tendency of the displacement also differs by the soil type and variables but not same tendency with FOS. The friction angle and cohesion are negative while the rainfall duration and rainfall intensity are positive with the displacement. This suggests that understanding their correlations is necessary to determine the safety of a slope in real-time using displacement data. Additionally, databases considering rainfall conditions and a wide range of soil characteristics, including hydraulic and mechanical parameters, should be accumulated.

Keywords: displacement; factor of safety; rainfall; seepage; slope stability

1. Introduction

Recently, many slope failures have been caused by concentrated rainfalls resulting from climate change. In the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, the global annual average precipitation was reported to increase by approximately 5–10% compared to the current value. Additionally, although the change in the number of days with or without precipitation was not clarified, increase in the frequency of extreme rainfall events and rainfall intensity was suggested to occur. Similarly, in Korea, the annual precipitation has been increasing since the 1980s (Korea Meteorological Administration 2020). Moreover, the uncertainty of rainfall is high, and because of climate features, the majority of the rainfall occurs in a few months from June to August.

In Korea, significant damage to humans and properties is caused by slope hazards. Among deaths by natural disasters, slope hazards accounted for 46.2%, 67.9%, and 100% in 2009, 2011, and 2013, respectively (Jun and Yune 2015). Slope failure can be caused by a natural disaster, such as an earthquake and rainfall. Particularly, rainfall is a direct factor when it occurs continuously for a long period or is concentrated in a short period, causing the seepage of water into slopes. Slope hazards have similar paths and ranges of influence as typhoons (accompanied by rain) (Jun and Yune 2015). Therefore, careful monitoring of slopes is necessary in Korea. In terms of topographical features, approximately 65.2% territory is composed of mountainous terrain; thus, many slopes need to be observed.

The influence of water on slope stability is important but complex. Many geotechnical analyses require investigating water flow within a partially saturated soil zone to incorporate the effect of climatic conditions (Satyanage *et al.* 2022). In general, the effects of water manifest in many ways, such as soil suction reduction and pore water pressure increase (Liu and Li 2015). Among them, variations in hydraulic boundary conditions, such as those related to rain events, can cause noticeable pore water pressure changes with negligible total stress variations. Tran *et al.* (2019) claimed that the correlation between permeability and rainfall intensity plays an important role in changing the pore water pressure. Consequently, the effective stress, shear strength, and safety factor can significantly vary (Perrone *et al.* 2008). Therefore, considering pore water pressure is important to evaluate slope stability.

With the recent development of measurement technologies, collecting measurement data (e.g.,

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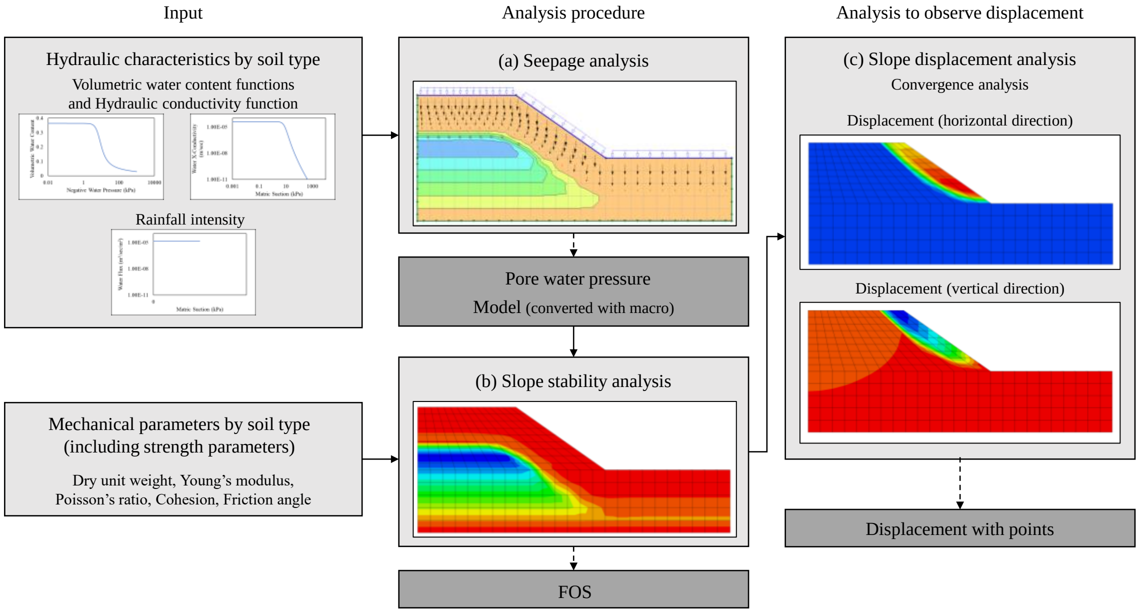


Fig. 1 Procedure of designed coupling analysis

displacement, rotation, and pore water pressure) has become possible. Moreover, the costs of collecting data are decreasing. Accordingly, it is expected that the observation of slope safety using this technology will be applied broadly. Liu *et al.* (2022) studied slope instability using past slope performance records and monitoring data. In addition, studies are building databases by developing a system to evaluate real-time slope safety. Zhang *et al.* (2018) proposed a real-time safety evaluation method by coupling construction progress with the numerical analysis of slope safety. However, cases considering rainfall conditions are lacking. Besides, there are attempts to reduce slope failure with the monitoring system at the national level in several countries including Korea. (Ministry of Public Safety and Security 2016) The present limitations are the standards. In most attempts, the deformation's velocity or rainfall intensity became the standard. These were considered empirically with the limited amount of data. In the 1970s in Hong Kong, the Geotechnical Engineering Office carried out pilot trials standardized by the limit equilibrium slope stability analysis, and it was found that the mechanical parameters were assumed conservatively compared to the actual field. (Ho *et al.* 2016) Thus, a system that can be specialized in the field and give intuitive standards such as a factor of safety (FOS) is necessary.

In current studies, various slope stability analysis methods are being used to monitor the FOS, such as the limit equilibrium method (LEM), finite element method (FEM), and finite difference method (FDM). The LEM cannot consider displacements, whereas the FEM and the FDM can. In the LEM, the strength and displacement characteristics of soil are assumed to be nonbrittle and the shear strength is unchanged even in case of large displacements. Moreover, stresses on a certain surface are computed approximately, and deformation is not considered. (Itasca 2017) In the FEM and FDM, slope stability is evaluated using the shear strength reduction method (SSRM). The SSRM can estimate the deformation, stress, and pore water pressure of the ground (Kim 1999). Kim and Jeong (2017) developed a coupled model to model shallow landslides in an unsaturated soil slope; however, they did not consider displacement. Since the measurement data can be obtained as the displacement, it is the meaningful that represents the deformation of the slope. Thus, the FDM is selected in this study to consider the displacement according to the change in the FOS.

Therefore, this study is fundamental research having the purpose of establishing a procedure and system to accumulate the FOS decided by the displacement while observing the deformation of the slope in real-time. The coupling analysis that was designed to apply the FDM can suggest the required data when judging the slope stability with rainfall overcoming the limitation of the studies evaluating the stability not in real-time. The data and related parameters in this study will be the standard for the future.

To define the assumption that real-time observation is necessary since the deformation of slope under rainfall conditions is unexpected for now, this study will be carried out considering the variables to decide them. Accordingly, a basic understanding will be achieved that which variables should be a concern in the future to contribute the trying to observe the slope in Korea.

2. Procedure and theories for designed coupling analysis

In this study, the displacement according to the variation of the FOS, which can consider the stability of a slope based on hydraulic characteristics, is considered. Moreover, seepage analysis (using Seep/W, Geostudio) and slope stability analysis (using FLAC3D, Itasca) are coupled to consider the influence of rainfall. And the slope displacement analysis to observe the displacement will be

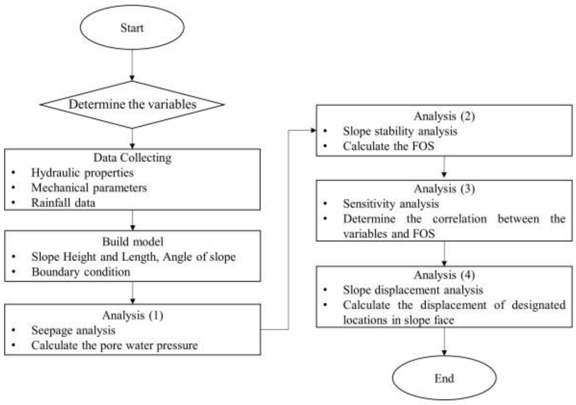


Fig. 2 Flow of research works

preceded (using FLAC3D). The procedure of the designed coupling analysis is shown in Fig. 1 and the flow of research works is shown in Fig. 2

First, the model and its properties are defined. In the entire process, the model size and shape are kept the same while maintaining the composition of the grid points, i.e., the mesh of the model is identical. The material properties are divided by the soil type, because of the differences in the inputs in each of software. However, the important uncertainty that sets in geotechnical engineering is the variability associated with soil properties (Lombardi *et al.* 2017). Therefore, mechanical parameters (including strength parameters) are varied in a limited range between the maximum and minimum values of each soil type.

2.1 Seepage analysis

Seepage analysis should be preceded to calculate the pore water pressure after rainfall, which affects the strength of a slope, to evaluate the degree of seepage. In Seep/W, to observe the change in the pore water pressure caused by rainfall, the analysis process is designed in two steps. These are steady-state analysis including the initial condition of the water level and transient analysis that changes with time.

A saturated-unsaturated seepage model is employed to calculate the transient pore water pressure field in a slope under rainfall and water level fluctuations (Liu and Li 2015). Groundwater is assumed to be at a certain level when setting the boundary condition (with the water total head). In addition, rainfall is considered as the boundary condition with a step data point function.

For the slope materials, volumetric water content and hydraulic conductivity functions are defined. The Fredlund and Xing (1994) method (see Eq. (1)) is a closed-form solution that is used to formulate the volumetric water content function. (GEO-SLOPE International Ltd. 2012). Thus, the solution is automatically calculated from the input using this form. The ability of soil to transport or conduct water under both saturated and unsaturated conditions is reflected by the hydraulic conductivity function. Seep/W has built-in predictive methods that can be used to estimate it, once the volumetric water content function and the K_{sat} (saturated hydraulic conductivity) values are specified (GEO-SLOPE International Ltd. 2012).

The seepage analysis results show that the pore water pressure is maintained at each node, and its value is exported as the input of the slope stability analysis using FLAC3D.

$$\Theta_{\mathrm{w}} = C_{\psi} \frac{\Theta_s}{\left\{\ln\left[e + \left(\frac{\Psi}{\mathrm{a}}\right)^{\mathrm{n}}\right]\right\}^{m}} \tag{1}$$

* Θ_{w}: volumetric water content; C_{ψ}: correction function described above; Θ_s: saturated volumetric water content; e: natural number (2.71828); Ψ: negative pore water pressure; $\mathrm{a, n, m}$: curve fitting parameters (see Eqs. (2)-(4))

$$\mathrm{a} = \Psi_{\mathrm{i}} \tag{2}$$

Ψ_{i}: suction pressure corresponding to the water content occurring at the inflection point of the curve

$$\mathrm{m} = 3.67\ln\left(\frac{\Theta_s}{\Theta_i}\right) \tag{3}$$

$$n = \frac{1.31^{m+1}}{m\Theta_s} 3.72 s \Psi_{\mathrm{i}} \tag{4}$$

*s: slope of the line tangent to the function that passes through the inflection point

2.2 Slope stability analysis

In the slope stability analysis, the FOS is calculated using the SSRM. The SSRM introduces a trial FOS (F^{trial}), and determines the ultimate lower limit of the FOS (F^{LL}), which is the value when the slope is unstable in the further calculation stage, by increasing or decreasing F^{trial}. Moreover, the trial parameters to be input into the FOS calculation process, i.e., c^{trial} and ϕ^{trial}, are introduced, whereas the initial parameters (c and ϕ) are fixed.

The SSRM has been used extensively in the context of Mohr-Coulomb materials, particularly for the simultaneous reduction in the cohesion and the frictional strength (Itasca 2017).

In some calculations, the pore pressure distribution is important because it is used in the computation of the effective stress at all points in the system (Itasca 2017). Using the Mohr-Coulomb model (Eq. (5)), the shear stress, τ, and the effective stress, σ', are calculated using the pore water pressure, u (Eqs. (6) and (7)).

$$\tau = c' + \sigma' tan\phi' \tag{5}$$

$$\sigma' = \gamma_t a + \gamma_{sat} h - \gamma_w h \tag{6}$$

$$u = \gamma_w h \tag{7}$$

*h: height of water in the intercept; a: length of the intercept except the height of water; γ_t: total unit density; γ_{sat}: saturated unit density; γ_w: water density.

2.3 Slope displacement analysis

After the slope stability analysis using the SSRM, the

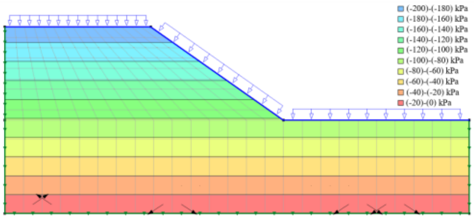


Fig. 3 Seepage analysis results of initial state of example

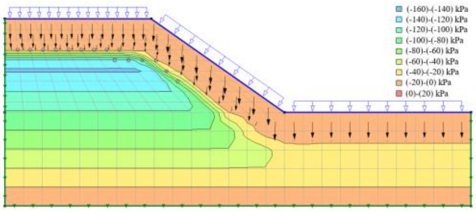


Fig. 4 Seepage analysis results of example

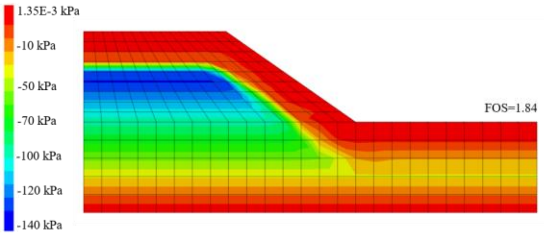


Fig. 5 Pore water pressure of example in FLAC3D

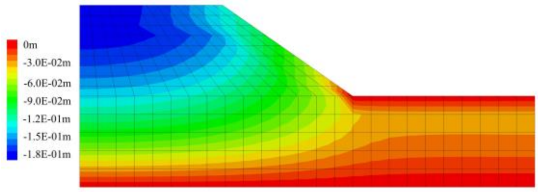


Fig. 6 Vertical displacement in FLAC3D

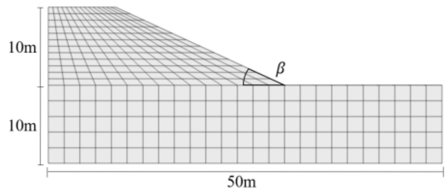


Fig. 7 Model shape and size

analysis to obtain the displacement of the current (in given condition) state is preceded. This analysis has the aim to make the model reach equilibrium. In FLAC3D, it is referred to being 'in equilibrium' when the model is fully-converged to a static solution (Itasca 2017). Therefore, in this study, the convergence of the slope with pore pressure into the static state is necessary to define the displacement with the FOS in the current state. Shen and Karakus (2013) studied the rock slope stability with three-dimensional numerical analysis, and found that when the ratio of the convergence is 1E-4 tends to produce the failure surface and the FOS value tends to stabilize. Thus, this analysis will be the one extended from the slope stability analysis only with the different solving method.

3. Example of designed coupling analysis

The abovementioned process to obtain the FOS and the displacement caused by the seepage of rainfall is used. In the studied example, the model is 50 m wide and 20 m high and has a 35° angle of the slope. The rainfall intensity is 50 mm/h and the rainfall duration is 12 h. For the material properties, the soil type is considered as loamy sand. Accordingly, the Fredlund and Xing input parameters (a (kPa) = 6.68, n = 3.398, m = 0.874, θ_s = 0.365, saturated hydraulic conductivity = 4.05E−5 m/s) are used for obtaining the hydraulic properties with Seep/W. In addition, the following mechanical parameters are taken in FLAC3D: dry unit weight = 2345.35 $\mathrm{kg/m^3}$, Young's modulus = 18 MPa, Poisson's ratio = 0.34, cohesion = 14 kPa, and friction angle = 27°.

3.1 Seepage analysis

The seepage has been occurred and the results are shown in Fig. 4 with the pore water pressure index. Compared to the initial state (see Fig. 3), which is the steady-state, and the location of the groundwater level at the bottom line, the pore water pressure increases after 12 h. Particularly, the change on the surface is distinct.

3.2 Slope stability analysis

Based on the results of the slope stability analysis, the FOS decreases from 2.41 in the initial state to 1.84. In Fig. 5, the contour of the pore water pressure is the same as from the seepage analysis, and the FOS is the output of this process.

3.3 Slope displacement analysis

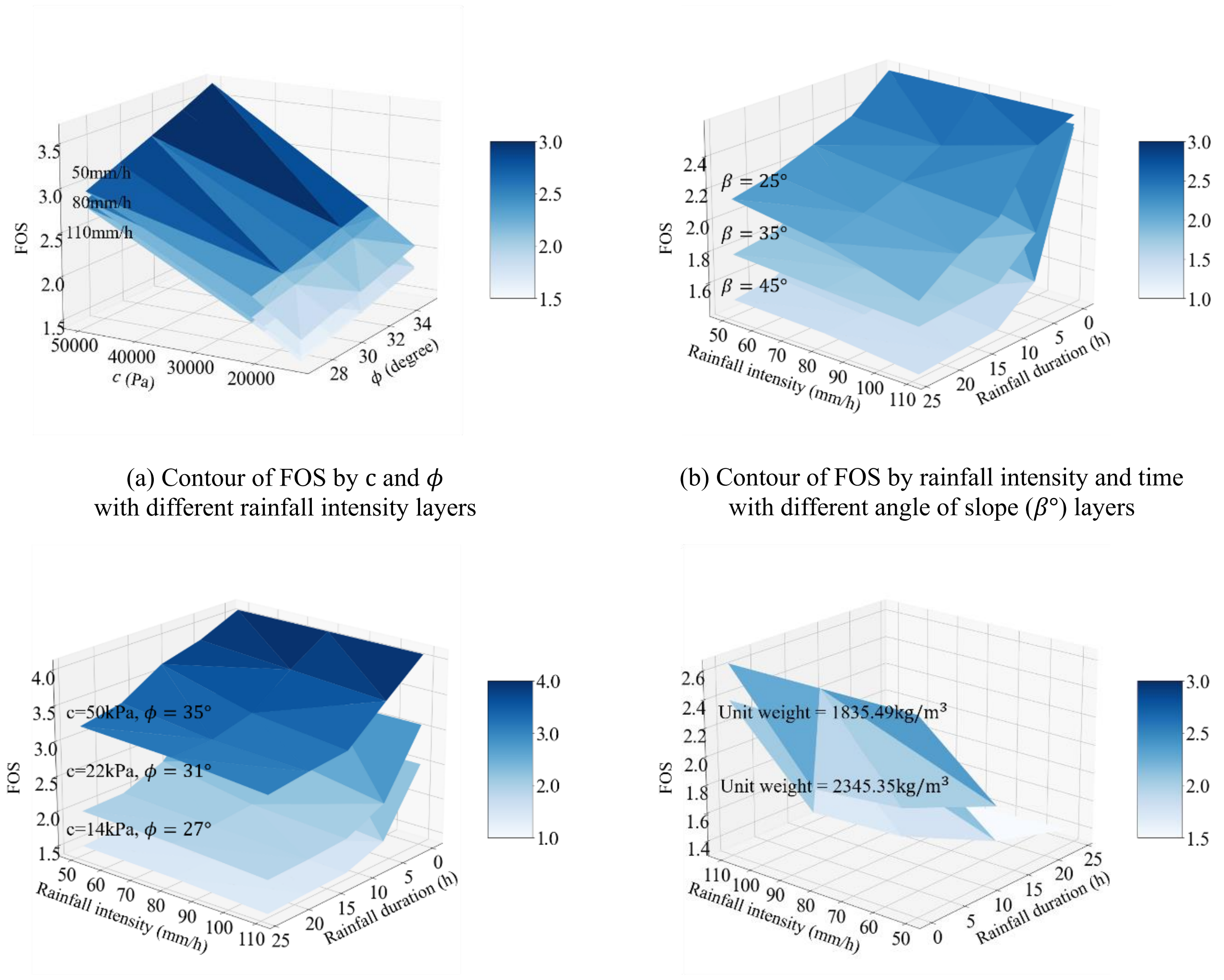
Based on the results of the slope displacement analysis, the maximum horizontal displacement of the slope face is 0.05 m and the maximum vertical displacement in the slope face is 0.19 m (see Fig. 6). This is the displacement when the slope is stable with the 1.84 of FOS.

4. Effects of variables and sensitivity analysis

4.1 Assumptions for analysis

4.1.1 Model

In the entire study, the model size is kept the same and only the angle of the slope is varied. The slope is 50 m of the length of the base including the slope face (from crest to toe) and 10 m in height, and the angle of the slope is denoted as β°, as shown in Fig. 7. Because the software for the slope stability analysis is for three-dimensional (3D) modeling, the thickness of the Seep/W model is set as 1 m in FLAC3D as well. And the zone in the thickness direction is set to be a single block which means there is no difference in this direction since it is assumed as



(a) Contour of FOS by c and ϕ with different rainfall intensity layers

(b) Contour of FOS by rainfall intensity and time with different angle of slope (β°) layers

(c) Contour of FOS by rainfall intensity and time with different c and ϕ

(d) Contour of FOS by rainfall intensity and time with different unit weights

Fig. 8 FOS with variables of loamy sand (SM based on USDA) (common specific variables are in same layers)

homogeneous. Additionally, the results were shown on one side while the other side's results are the same because of the same boundary condition.

4.1.2 Material properties

The material properties in the different analysis steps are varied because the seepage analysis needs hydraulic properties of the soil, whereas the slope stability analysis requires mechanical parameters. Therefore, in this study, the core assumption about the material properties is the soil type since the soil type is one of the intuitive understandings in the field. Particularly, the hydraulic properties are fixed according to the soil type, whereas the mechanical parameters are varied because of the uncertainty in soil mechanics. The soil type is classified by the United States Department of Agriculture (USDA) Soil Classification System (hereafter referred to as USDA) was used, as the hydraulic properties of the soil type are classified similarly by the USDA. The parameters are listed in Tables 1 and 2. The data was collected with the division of soil type both in hydraulic properties and mechanical parameters. Therefore, the references that offer the possible mechanical parameters in range according to the soil type were used.

4.2 Tendency of FOS according to variables with rainfall in loamy sand

Detecting outliers is important because the number of data is greater than 3,000. In addition, the validity of the coupling analysis method designed in this study needs to be verified based on the consistency of the results. Moreover, grouping the variables is important to monitor the approximate tendency, because this study is focused on predicting the FOS as the range. The FOS variations with variables are shown in a 3D coordinate system in Fig. 8.

4.2.1 Assumption for analyzing tendency of FOS in loamy sand

The selected soil type in this analysis is loamy sand (SM

Table 1 Hydraulic properties by soil type

	Fredlund and Xing (Sillers 1997)				Saturated hydraulic conductivity (m/s) (Carsel *et al.* 1988)
Soil Type	a (kPa)	n	m	θ_s	
Loamy sand (SM in USDA)	6.68	3.398	0.874	0.365	4.05E−5
Silt loam (ML in USDA)	63.14	2.188	0.665	0.444	1.25E−4
Sand (SW, SP in USDA)	17.27	6.357	4.428	0.38	8.25E−5

Table 2 Mechanical parameters by soil type (Obrzud and Truty 2012, Kezdi 1974, Prat *et al*. 1995, NAVFAC 1986, VVS; Cater and Bentley 1991, Peck 1974, Minnesota Department of Transportation 2007, Mok *et al*. 2016, Bowles 1968)

Mohr–Coulomb model parameters by range					
Soil Type	Dry unit weight (kg/m^3)	Young's Modulus (Pa)	Poisson's ratio	Cohesion, c (Pa)	Friction angle, ϕ
Loamy sand (SM in USDA)	1835.49-2345.35	7E6-30E6	0.27-0.47	14000, 22000, 50000	27-35
Silt loam (ML in USDA)	1280	1.5E6-80E6	0.48-0.5	7000, 22000, 67000	18-40
Sand (SW, SP in USDA)	1784.50-2294.36	10E6-320E6	0.3-0.4	0	29-43

in the USDA). The used rainfall intensities are 50 mm/h, 80 mm/h, and 110 mm/h because the highest rainfall per hour in Seoul was approximately 113 mm in 2011. The properties and parameters are selected in the available ranges of loamy sand (see Table 2). After the seepage analysis using the values in Table 2, the pore water pressure value of each grid point is input into the slope stability analysis in which the observation times are 0 h, 6 h, 12 h, and 24 h for each rainfall intensity.

4.2.2 Tendency of FOS with loamy sand

Fig. 8(a) shows that the FOS tends to increase with increasing c and ϕ. In addition, the lower rainfall intensities are located higher than the higher rainfall intensities, i.e., a low rainfall intensity implies a high FOS. In Fig. 8(b), as the angle of the slope decreases, the FOS increases; it decreases when the rainfall duration increases. For Fig. 8(c), c and ϕ are randomly selected, but still, it means the minimum, median, maximum range of each parameter. If c and ϕ are in the range between the layers, the FOS curved plane will be located in their gap. In addition, the FOS decreases with the increase of rainfall duration. Fig. 8(d) shows that a low dry unit weight implies a high FOS.

Summarizing, based on the tendencies of the FOS versus the variables considering loamy sand, the FOS is high with a low rainfall intensity, small angle of the slope, large c and ϕ, low dry unit weight, and short rainfall duration. However, the variables that contribute the most to the FOS cannot be determined still.

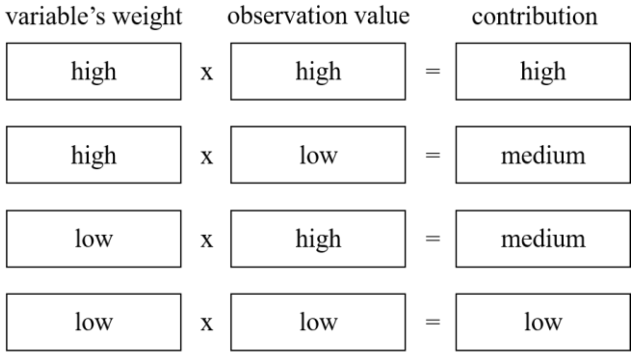


Fig. 9 Contribution according to weight and observation value of variable

5. Sensitivity analysis of effects of variables

To determine the variables that strongly affect the FOS, sensitivity analysis is performed before predict how to suggesting the range of the FOS. The high-impact factors are the main variables when suggesting the range. The variables considered in this study are rainfall intensity, rainfall duration, angle of the slope, strength parameters, and unit weight. With the sensitivity analysis, the contribution of each variable can be determined.

5.1 Theory of sensitivity analysis

The purpose of sensitivity analysis is to check the stability of a model by modifying the input variables. It is not for the defining function but for recognizing the importance of each variable. In this study, to evaluate the importance of each variable, a linear regression sensitivity analysis is conducted to analyze the contribution of each variable in each observation. For the multivariate, multiple linear regression determines the most influential input variables according to how much each input variable reduces the residual sum of squares. The form of the regression equation is shown in Eq. (8). (Mohanty and Codell 2002) The variable importance (model weight) represents the relative importance of each variable in the unit of a suitable model based on all observations. This was expressed as the regression coefficient in Eq. (8). It can be used to analyze the specific weight (how much a variable contributes to the predicted values of a model). The predicted values can be varied by the specific weights of the variables of the model and the values of the variables in each observation (see Fig. 9). To consider each observation, when calculating the regression coefficient for specific independent variables, the other regression coefficients are assumed as 0 (see Eq. (8)).

$$y = m_1 x_x + m_2 x_2 + \cdots + m_n x_n + b \quad (8)$$

* y: dependent variable; x_i: independent variables; m_i: regression coefficients; b: intercept.

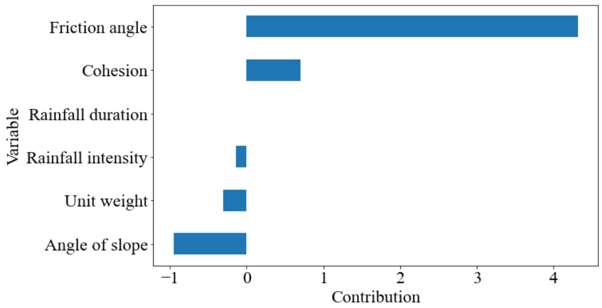


Fig. 10 Loamy sand (SM in USDA)

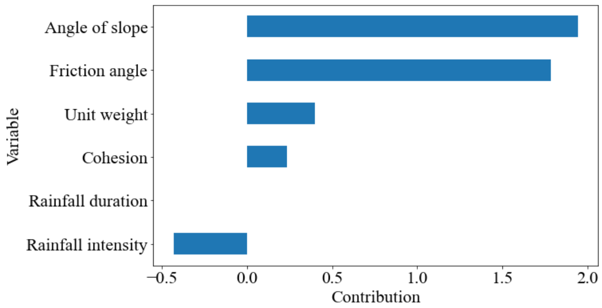


Fig. 11 Silt loam (ML in USDA)

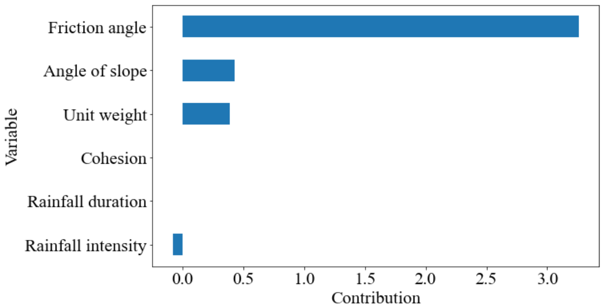


Fig. 12 Sand (SW or SP in USDA)

5.2 Results of sensitivity analysis

The y in Eq. (8) is FOS and the x_i in Eq. (8) is the friction angle, cohesion, rainfall duration, rainfall intensity, angle of slope, and unit weight. The results of the sensitivity of each variables vary according to the soil type (see Figs. 10-12). Loamy sand is highly affected by the friction angle. For silt loam, the effect of the friction angle is still high. However, the variable with the largest contribution is the angle of the slope. According to Matías *et al.* (2022), granitic residual soil, which is silty sand in the USDA, is most sensitive to the angle of the slope (among the height of the slope, cohesion, friction angle, and unit weight). Additionally, the relationship (positive or negative) between the angle of slope and FOS can be different by the soil type because of the difference in seepage velocity and flow velocity. (Chae *et al*. 2007) The contribution of cohesion in the sand (SW or SP in the USDA) is 0, because the cohesion is 0 kPa. In contrast, for loamy sand and silt loam, positive values of contributions are obtained.

The results show that the sensitivity of each variable selected in this study varies with the soil type; therefore, all these variables should be considered, unless there is the sensitivity analysis for many cases that can be leaded to consider the variables' contribution. In addition, although the rainfall intensity is included, its contribution was considerably smaller than those of the other variables. Therefore, considering all the mechanical parameters including the strength parameters by the soil type is necessary. Also, the tendency can be varied because the variables present positive or negative contributions according to the soil type.

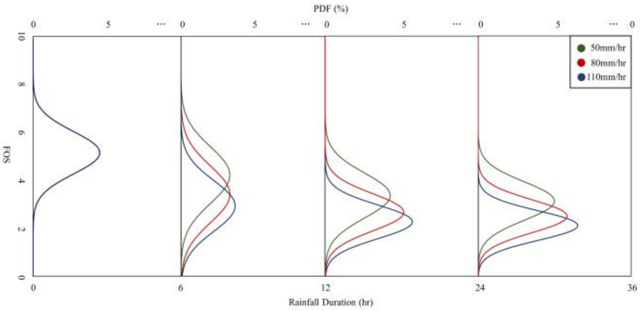
6. Correlations between variables related to slope during rainfall and FOS

6.1 Correlations by the rainfall intensities

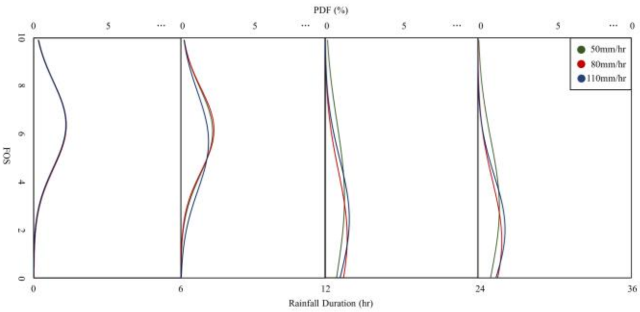
For loamy sand, the maximum and minimum FOS values with 50 mm/h of rainfall under the initial condition (when the rainfall duration is 0 h, i.e., without rainfall) are 7.30 and 3.44, respectively. The FOS at the peak of the probability density function (PDF) is 5.2. The FOS is maximum when the unit weight is the lowest and the cohesion and the friction angle are the highest. The FOS is minimum when the angle of the slope and the unit weight are the highest and the cohesion and the friction angle are the lowest. As the rainfall duration increases, the maximum and minimum FOS values decreases, and the FOS at the peak of the PDF decreases to 4.2, 3.4, and 3.1 as the rainfall duration increases. And the tendency of FOS according to the variables is changed. It's the same for the unit weight and the friction angle but the maximum and minimum FOS's angle of slopes is 35 degrees, the lowest cohesion has the maximum FOS, and the highest cohesion has the minimum FOS.

With the increase in the rainfall intensity (to 80 mm/h and 110 mm/h), the FOS in the initial condition and the FOS peak of the PDF remain the same. Thus, the maximum and minimum FOS are constant. The maximum and minimum values of the FOS with increasing rainfall duration and intensity, decrease. In Fig. 13(a), the FOSs when the PDF values are at the peak vary according to the above tendencies.

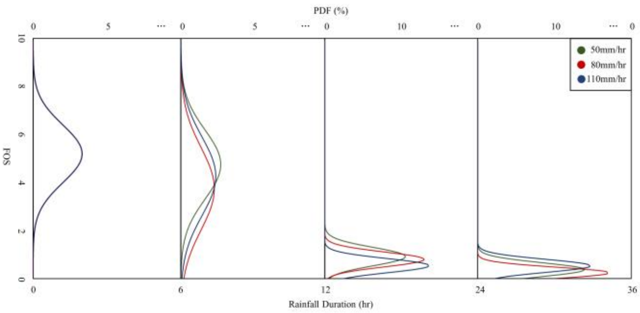
For silt loam, the maximum and minimum FOS values with 50 mm/h of rainfall under the initial condition are 9.28 and 3.24, respectively. The FOS at the peak of the PDF is 6.4. The FOS is maximum when the angle of the slope and the friction angle is the highest. The FOS is minimum when the angle of the slope is the highest and the cohesion and the friction angle are the lowest. However, as the rainfall duration increases, the maximum and minimum FOS values are not constant. The FOS at the peak of the PDF decreases to 6.1, 3.3, and 2.9 as the rainfall duration increases. And the FOS became 0 since the duration is 12 h in the slope with 25 degrees of angle of slope. Also, the cohesion affects differently by the duration increasing. From 12 h, the maximum FOS has the maximum cohesion. Besides, it has a higher FOS (9.96) compared to the previous duration and then decreases when the cumulated amount of rainfall is high which means since the silt loam is one of the cohesive soils, the higher cohesion increases the safety of slope



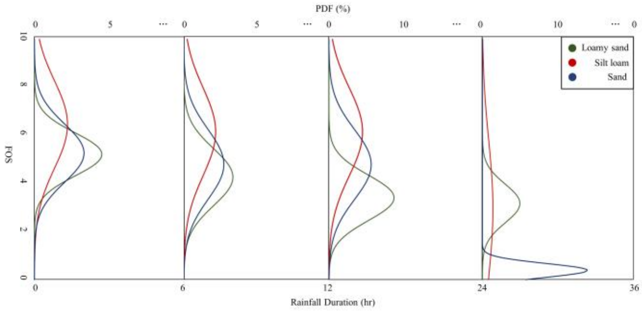
(a) Loamy sand



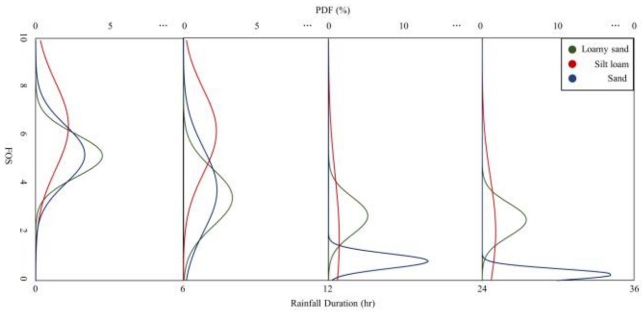
(b) Silt loam



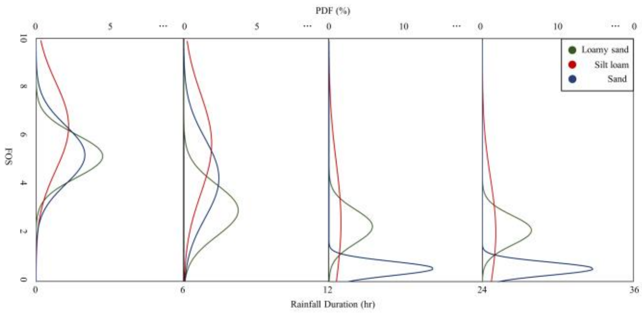
(c) Sand



(d) 50mm/h



(e) 80mm/h



(f) 110mm/h

Fig. 13 (a)-(c) PDF by FOS for different rainfall intensities and durations according to the soil types; (d)-(f) PDF by FOS for different soil types and durations according to the rainfall intensities

strongly compared to other variables.

With increasing rainfall intensity (80 mm/h and 110 mm/h), the FOS values under the initial condition and at the peak of the PDF remain unchanged. However, the tendencies of the maximum and minimum FOS values vary. For example, the maximum FOS has the highest angle of the slope and the minimum FOS has the lowest one. Fig. 13 (b) shows that when the PDF values are at the peaks, the FOS shifts according to the above tendency. The sensitivity analysis of silt loam (see Fig. 11) shows that the FOS is proportional to the angle of the slope.

For sand, the maximum and minimum FOS values with 50 mm/h rainfall under the initial condition are 7.38 and 3.33, respectively. The FOS at the peak of the PDF is 5.2. The FOS is maximum when the angle of the slope and the unit weight are the lowest and the friction angle is the highest. The FOS is the minimum when the unit weight and the angle of the slope are the highest and the friction angle is the lowest. As the rainfall duration increases, the maximum and minimum FOS values vary. As the rainfall duration decreases, the FOS at the peak of the PDF decreases to 4.7, 0.9 and 0.4.

With the change in the rainfall intensity (80 mm/h and 110 mm/h), the FOS under the initial condition and the FOS at the peak of the PDF are the same. However, the maximum and minimum FOS values vary. The minimum and maximum values of the FOS decrease mostly as the rainfall intensity and rainfall increase. In Fig. 13(c), the FOS at the peak PDF values are not constant.

With variation in the rainfall duration and rainfall intensity, the tendencies related to the angle of the slope, unit weight and cohesion are not constant. Based on the sensitivity analysis, contributions of the angle of slope and unit weight are completely opposite compared to those for loamy sand. Therefore, cases in which the tendencies of FOS varied not limited to the angle of the slope, cohesion and the unit weight vary can exist. Thus, analyzing the variance of the FOS according to the variables should not be limited to the minimum or maximum case because the various variables can affect to the FOS simultaneously.

6.2 Correlations by the soil types

To observe the difference in FOS between the soil types, the PDFs were analyzed and divided by them (see Fig. 13(d)-13(f)). For most of the soil types, the FOS decreases with the increment of the rainfall duration. With 0 h and 6 h of rainfall duration, the silt loam has the highest FOS, and the loamy sand has the lowest FOS. As the increasing of the rainfall duration, the sand becomes the one which has the lowest FOS rapidly. That means the velocity of decreasing is higher than the loamy sand. Besides, the silt loam's FOS with the higher rainfall duration (12 h and 24 h) and intensity (80mm/h and 110mm/h) are smaller than the ones of loamy sand. Therefore, loamy sand is the soil that is less sensitive to rainfall. Also, the soil type that is the most sensitive to the amount of total rainfall is sand. It means if the amount of sand is contained a lot in the slope, then, it needs careful observation in the aspect of the rainfall. Also, it contains the meaning that the decreasing velocity of FOS is different by the soil type, also in the aspect of rainfall duration and rainfall intensity.

7. Correlations between variables related to slope during rainfall and displacement

7.1 Correlations by the rainfall intensities

The variations in the maximum horizontal (toward the outside of the slope surface) and vertical (toward gravity direction) displacements of loamy sand with the rainfall duration and intensity are shown in Figs. 14(a) and 14(d). Based on the PDF, the distributions of the displacements in both directions in the initial condition are widened This suggests that the displacement varies by an external factor in the same soil type.

If the decreasing velocity of FOS is low, then the changes of displacement by the rainfall are insignificant. Accordingly, the PDF of displacements is almost the same. However, with the increment of the rainfall duration, the displacement increases in both directions.

The results for silt loam are shown in Figs. 14(b) and 14(e). Based on the PDF, without rainfall, the range of the displacement is in a small-value area compared to the loamy sand. This suggests that the displacements of the silt loam are not sensitive to the variables. However, the FOS of silt loam is higher than that of loamy sand with a short rainfall duration. The changes in the displacement according to the rainfall duration and rainfall intensity are significant in the horizontal direction. However, the displacement of 80 mm/h and 110 mm/h are almost the same since the peak values' difference of PDF in 12 h and 24 h of rainfall duration has 0.001 m. As the rainfall duration increases, the displacement increases or same in both directions.

The results for sand are shown in Figs. 14(c) and 14(f). Based on the PDF, the range of the displacement lies in the small-value area compared to the other soil types. As the rainfall duration increases, the horizontal displacement at the peak of the PDF increases. Also, the differences that come from the rainfall intensity are significant. However, for vertical displacement, there's less difference compared to horizontal one.

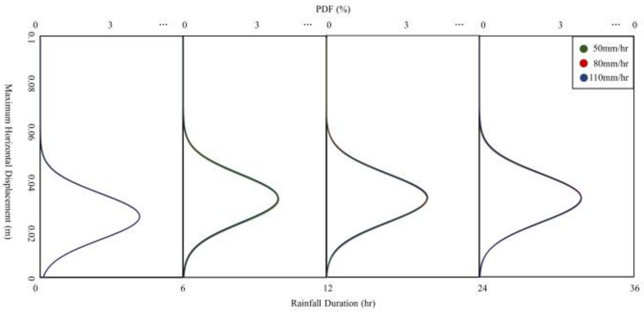
7.2 Correlations by the soil types

In Fig 15, the horizontal and vertical displacements are shown by the soil types. In both directions, the soil type which has the highest values when the rainfall duration is under 24 h, is the loamy sand. And the silt loam is following, the sand has the lowest displacements in the horizontal direction. In some vertical direction cases, it is the opposite between the silt loam and sand. However, with the rapidly increasing velocity, the sand has the highest displacement even if it cannot be converged because of the enlarged deformation. Therefore, it means that the sand shows a high deformation velocity to rainfall compared to the other soil type like the changes in FOS.

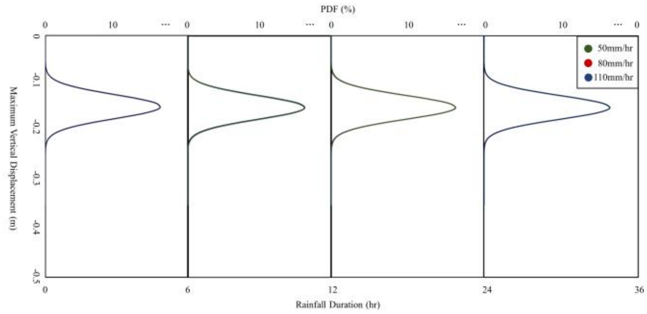
Additionally, the FOS and displacement do not show an absolute relationship, if the soil type shows higher FOS compared to the others, then the displacement would be lower or higher. Although the FOS of loamy sand is the lowest when the rainfall duration is 0 h and 6 h and the FOS of silt loam has the highest, while the loamy sand has the highest displacement in both directions, the silt loam does not show the lowest displacement. Therefore, to define the relationship between the FOS and displacement, the division of the soil types should be considered with earlier studies.

7.3 Correlations between variables and displacement

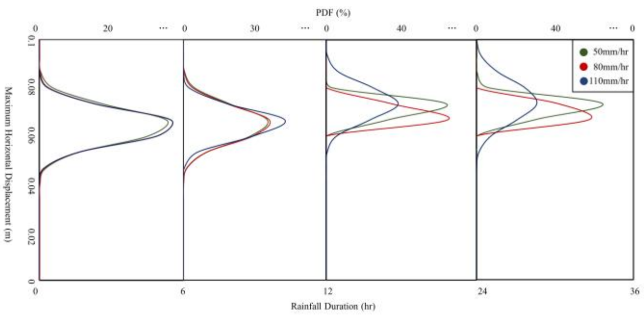
To define the correlations between the variables and displacement, the following analysis was conducted with the obtained data. According to the soil type, the changes related to the variables show the common aspect in a positive or negative relationship. The positive relationship means that if the value of variables increases, the displacement increases. For the negative relationship, it is vice versa. The comparing case is consisted of two different displacements but only with the difference in the specific



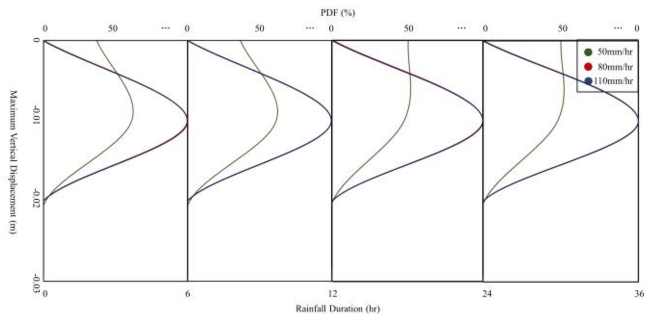
(a) Horizontal displacement of loamy sand



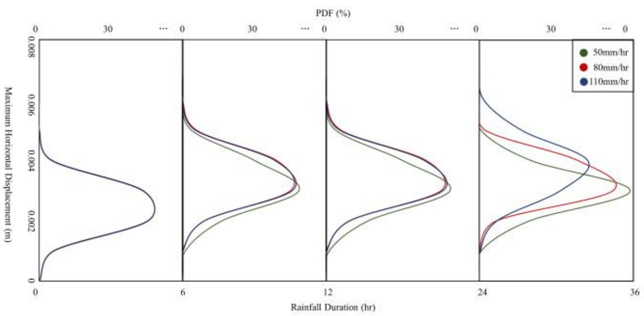
(d) Vertical displacement of loamy sand



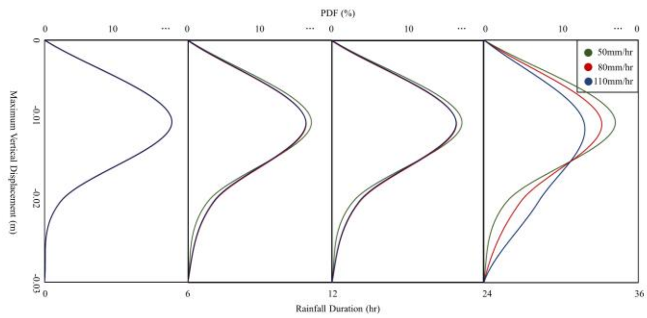
(b) Horizontal displacement of silt loam



(e) Vertical displacement of silt loam



(c) Horizontal displacement of sand



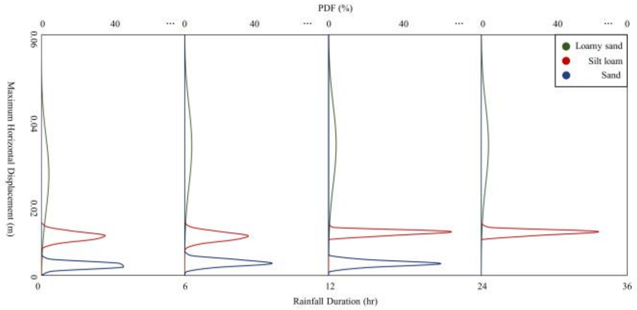
(f) Vertical displacement of sand

Fig. 14 Maximum horizontal (toward the outside of slope surface) and vertical (toward gravity direction) displacements of slope in PDF for different rainfall intensities and durations

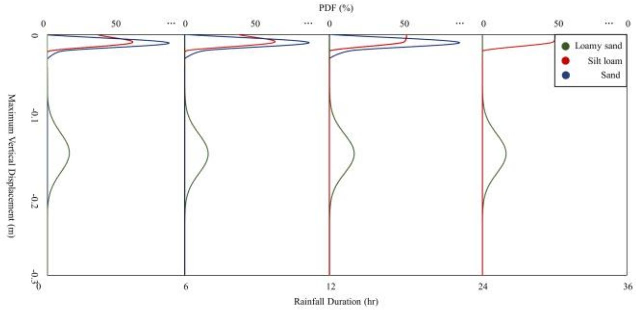
variable while the rest of them are the same. For example, if the focused variable is friction angle, then the rest of the variables such as cohesion, unit weight, angle of slope, rainfall duration, and rainfall intensity are the same. The total comparing cases were counted in the same soil type and the ones not showing the same relationship compared to the other cases, were assumed as the error and the reason was found. For the rainfall duration and rainfall intensity, they have a positive relationship according to Fig. 14 and Fig. 15. Therefore, the number of comparing cases and errors were not counted in this section.

For Loamy sand, the correlations between variables and displacement were shown in Fig. 16(a). The number of comparing cases is 432 in friction angle, cohesion, and angle of slope and 324 in unit weight in both directions' displacement. Only the friction angle with vertical direction has the 2 error cases. There is no specific reason for other variables and the difference between the value is minimal. Therefore, it is assumed that the calculation error. However, in the aspect of the angle of slope, the tendency is different according to the angle of slope and other variables change.

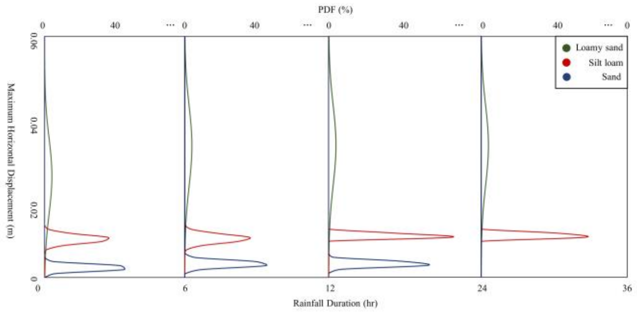
In both directions, if the unit weight and the angle of the



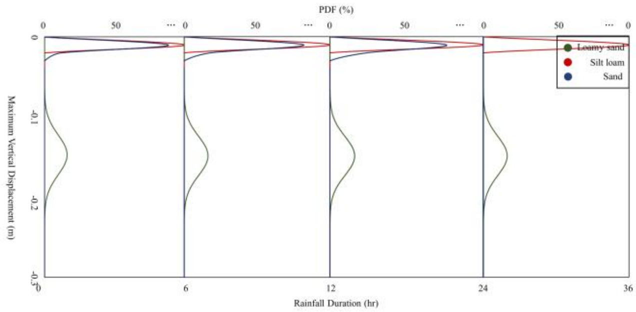
(a) Horizontal displacement of 50 mm/h



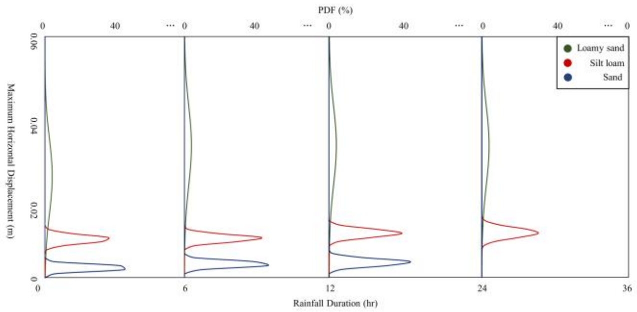
(d) Vertical displacement of 50 mm/h



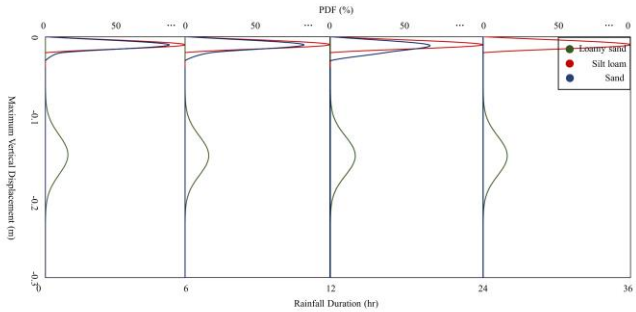
(b) Horizontal displacement of 80mm/h



(e) Vertical displacement of 80mm/h



(c) Horizontal displacement of 110 mm/h

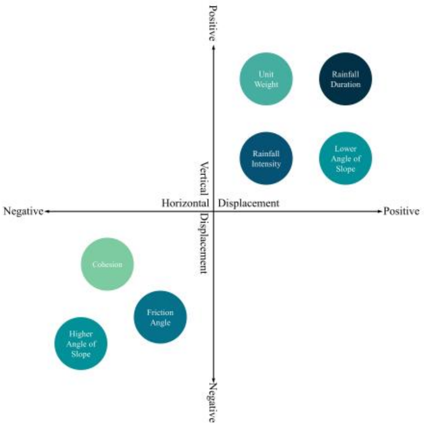


(f) Vertical displacement of 110 mm/h

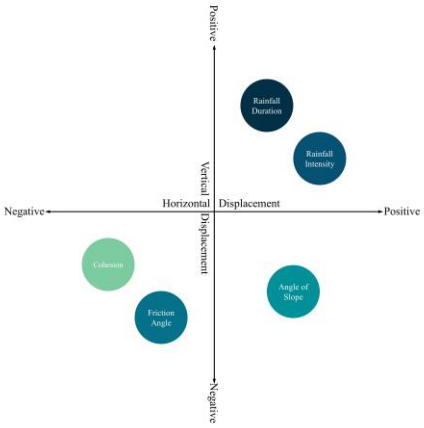
Fig. 15 Maximum horizontal (toward the outside of slope surface) and vertical (toward gravity direction) displacements of slope in PDF for different soil types and rainfall durations

slope are lower (comparing between 25 and 35 degrees) then it has a negative effect while it gets higher (comparing between 35 and 45 degrees) and becomes positive.

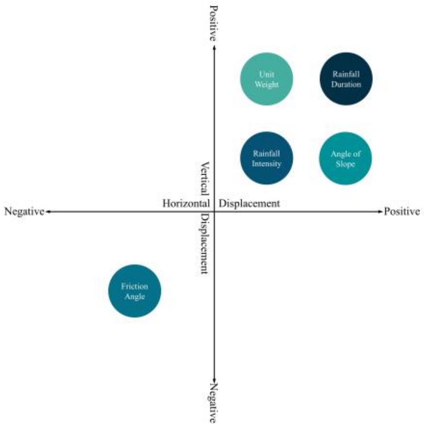
In the case of silt loam (see Fig. 16(b)), the comparing cases are 216 in friction angle, cohesion, and angle of slope. It has negative effect except the comparing vertical displacements with angle of slope. For friction angle, it has 4 error cases each in both direction because of the increase of the rainfall duration (over 12 h) and rainfall intensity (over 110 mm/h). And For cohesion, it has 25 errors with horizontal displacement and 19 errors with vertical displacement because of the same with friction angle which means the horizontal displacement is more sensitive to it (over 12 h of rainfall duration and 80 mm/h of rainfall intensity). In the comparison with the horizontal displacement with angle of slope has the 47 cases of error because of the increment of rainfall duration and intensity (between 35 and 45 degrees of angle of slope). When the rainfall duration is 24 h and the intensity is over 80 mm/h it is completely reversed. Besides, in the comparison with the vertical displacement, there are 36 cases of error because of the same reason (however between 25 and 35 degrees of



(a) Loamy sand



(b) Silt loam



(c) Sand

Fig. 16 Correlations between variables and displacement

angle of slope). When the rainfall duration is 24 h and the intensity is over 80 mm/h it comes back to the original tendency (which is the negative).

For sand in Fig. 16(c), the number of comparing cases for friction angle is 86 with 16 to 17 errors in horizontal and vertical direction each. It's 62 of total cases with 1 error (in vertical) for unit weight, and 90 for angle of slope. Relationship between horizontal displacement and the angle of slope has 24 error cases and 3 cases for vertical displacement which means it gets higher effect in horizontal direction. The friction angle has the negative effect like other types of soil and positive for the unit weight and angle of slope. However, the error is increasing in friction angle comparing while the rainfall duration and intensity are increasing. It means sand gets the larger influence on the amount of rainfall rather than strength parameter. For the error in the aspect of angle of slope, the error increases when the angle of slope and friction angle are increasing.

Overall, effect in negative or positive to the displacement are similar in most of the soil type in this study. However, the tendencies could be varied according to the other variables and the errors (that the ones have the different tendency with others) might be happened. Therefore, the correlations between the variables and displacement should be considered with all the parameters that was mentioned in this study.

8. Conclusions

Due to climate change, rainfall intensity and duration are getting increasing. Consequently, slope failure is also increasing. In addition, the uncertainty of rainfall is rising. In recent years, slope failure has accounted for over 50% natural disasters. Therefore, careful monitoring and research are required to manage this hazard.

In this study, a coupling analysis considering rainfall on a slope was designed to investigate seepage of rainfall and slope stability. In further, to develop the approach with the aim that evaluating the stability with the monitored displacements and finding the relationship between the FOS in real-time, the displacement analysis was conducted. As the fundamental research, the random variables (from the aspects of the geometry of slope, material properties, and meteorological factors) were applied to study the correlations with the FOS or displacement and decide which variables should be considered important.

• The designed process is semiautomated using macros between the Python and the numerical analysis software (FLAC3D) to utilize the output of seepage analysis software (Seep/W).
• The correlations between the variables—rainfall intensity, rainfall duration, angle of the slope, mechanical properties including the strength parameters based on the soil type, and FOS—are variable and dependent. Accordingly, the sensitivity (positive or negative and weights of the variables) differs by the soil type. Based on the PDFs (FOS by the rainfall intensity and the rainfall duration), the peak decreases with increasing rainfall duration at the same rainfall intensity.
• The loamy sand has the lowest FOS when the rainfall duration is 0 h and 6 h, the sand became the type that has the lowest FOS with the increase in the rainfall. Therefore, the decreasing velocity of FOS is highest in the sand, sensitively. Also, it does not show the constant velocity.
• The correlations between the variables and the displacement are not similar to those with the FOS. Based on the PDFs (displacement by the rainfall intensity and the rainfall duration). Therefore, the FOS and displacement do not have an absolute relationship in the values. It could be different by the soil type. However, if the FOS decreases rapidly, the displacement has the same aspect.
• The friction angle and cohesion are negative on the displacement while the rainfall duration, rainfall intensity and unit weight have are positive on the displacement. The influence of angle of slope on the displacement is varies by the soil type. Although the tendency of the effect is clear, there could be the cases because of the applying with other variables. Therefore, the consideration of the multi variables is necessary.
• Because the location of the maximum displacement of the slope varies according to the variables in this study, installing a sensor that can observe the critical point from the aspect of displacement should be considered in further

research.

• To address the uncertainty of the displacement and increase the reliability of the designed procedure, real-time measurement data should be obtained and compared with the designed analysis results.

Acknowledgments

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