Deep-seated Landslide Assessment by Using Hemi-sphere Slope Stability Coupled with Hydrological model in Kii peninsula in 2011

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1. INTRODUCTION

The sensitivity of landslides to climate change may depend on their type, especially on the size and depth of the landslide. As shallow landslides are generally governed by shorter-duration rainfall, they may be more influenced by evolution, such as changes in rainfall intensity. In contrast, deep-seated landslides may be affected by long-term hydrometeorological evolutions, such as changes in the weekly rainfall or groundwater flow. Few studies have proposed the deep-seated landslide model. Jeong. S et al. (2018) proposed infinite slope stability to shallow and deep-seated landslides, but the result of the deep-seated landslide was overestimated. Hence, the previous deep-seated landslide model did not consider the hydrological model, and the infinite slope model was not suitable for deep-seated landslides of the shape of the failure plane.

In September 2011, typhoon Talas brought heavy rain and caused landslides and floods in the Kii Peninsula, Japan. Especially the extensive sediment-related disasters are deep-seated landslides, which have occurred in the southern Nara and Wakayama prefectures after 700-800 mm of rainfall fell in 48 hours with at least 900-1,000 mm of total rainfall. This study aims to analyze deep-seated landslides using developed slope stability and hydrological model at the Akatani landslide in the Kii Peninsula (2011).

2. STUDY AREA

The study area is the Kii peninsula in Japan, where landslides caused by Typhoon Talas and deep-seated landslides were induced by heavy rainfall, as shown in **Fig 1**. Arai and Chigira (2017) reported the geological structure of 14 landslides. From that, the Akatani landslide has been selected to investigate by Arai and Chigira (2017), and the Kawarabi thrust has controlled the mechanism of failure. The Kawarabi thrust dips high-angle faults, and joints cut a 34-degree downslope along one or both sides of each landslide body. The Akatani landslide is located on the right bank of the Akatani river. Arai and Chigira (2017) investigate the soil parameters and topography at the Akatani landslide by the direct shear tests of the Kawarabi thrust gouge, as **shown in Table 1**.

3. METHODOLOGY

To model deep-seated landslide failure induced by rainfall, the model is divided into two main parts that are used to describe the relationship among rainfall infiltration and groundwater recharge and slope stability.

3.1 Rainfall infiltration and groundwater table calculation

This study uses the Green-Ampt model to calculate the amount of rainfall that infiltrates into the hillslope. The Green-Ampt model is a simplified infiltration model that assumes a homogeneous soil profile and a uniform initial distribution of water content. Moreover, the suction head at the wetting front the coefficient of hydraulic conductivity are constant. Mountainous areas are characterized by sloping terrain. Then, this study uses the Green Ampt model for a sloping surface as proposed by Chen and Young. Equation 1 shows the infiltration rate and equation 2 shows cumulative infiltration.

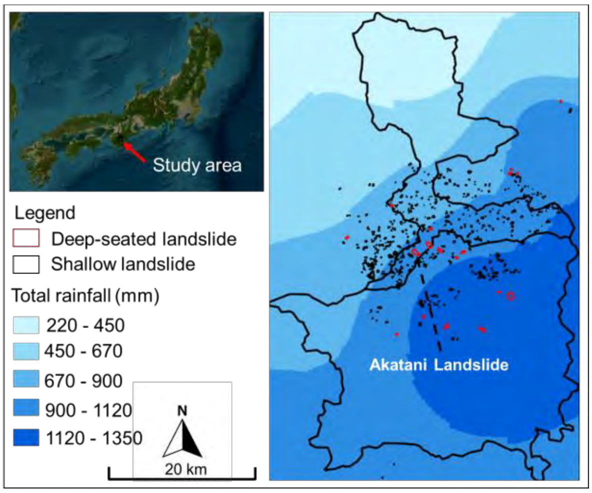

Fig.1. Distribution of landslides and cumulative rainfall between 31 August and 4 September 2011.

Table 1 Parameters used for the slope stability analysis.

Properties, symbol, unit	Value
Total rock unit weight, γ_t, kN/m^3	23.5
Saturated rock unit weight, γ_{sat}, kN/m^3	23.5
Cohesion, C, kPa	4.60
Friction angle, φ' , degree	36.3
Depth of slip surface, r, m	32
Gradient of slope, β, degree	25-35

$$i_t = K(\frac{\psi\Delta\theta}{I_t} + cos\beta) \qquad 1)$$

$$I_{t+\Delta t} - I_t - \frac{\psi\Delta\theta}{cos\beta}\ln[\frac{I_{t+\Delta t}cos\beta+\psi\Delta\theta}{I_t cos\beta+\psi\Delta\theta}] = Kcos\beta\Delta t \quad 2)$$

where i_t is the infiltration rate at time t, I_t is the cumulative infiltration at time t, ψ is the matric suction head along with the wetting front, $\Delta\theta$ is deficit water content, K is the coefficient of hydraulic conductivity and β is the slope angle.

$$Zw = \frac{I_t}{\Delta\theta} \qquad 3)$$

where Zw is wetting front depth on unsaturated soil zone, which induced by rainfall. The groundwater discharge is based on Darcy's law, Rosso et al. (2006) proposed a groundwater index that is ratio between the depth of the

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groundwater table and the depth of unsaturated soil, and can be expressed as follows:

$$\Delta Hw = \frac{i}{i^*} z \left[1 - \exp\left(-\frac{1}{A_l}\frac{i^*}{z}t\right)\right] \qquad 4)$$

with,

$$i^* = \frac{Tbsin\beta}{a} \qquad 5)$$

with,

$$A_l = \frac{e}{1+e} * (1 - Sr) \qquad 6)$$

where $\omega = \Delta Hw/Z$ is the groundwater index, ΔHw is the depth of the groundwater table in unsaturated zone, z is the depth of unsaturated zone, i is the infiltration rate, T is the hydralic tranmissimiivity, b is the width of channel flow, a is the upslope contributing area, e is the void ratio, Sr is the degree of saturation, and t is rainfall duration. The hydrological model.

3.2 Deep-seated landslide slope stability model

The failure mechanism of deep-seated landslide is rotational or translational failure and failure plane is more than 10 meters depth. The general mechanism of rainfall-induced deep-seated landslide, which affected both of wetting front and the ground-water recharge. From those issues, the deep-seated landslide model applies from hydrological model and slope stability model. The hydrological model is based on wetting front and groundwater recharge from Eq. 3 and Eq. 4. The slope stability can be developed from infinite slope stability based on rotational failure, which apply hemi-sphere shape as Eq.7 to 8. The factor of safety is ratio of resisting force (τ_r) and driving force (τ_d), the slope collapsed by FS is less than 1.

$$\tau_r = [c * (2\pi r^2)] + \Bigg[\Bigg(\Bigg(\Bigg(\gamma_{sat}\Bigg(\Bigg(\pi {H_w}^2\left(r - \tfrac{H_w}{3}\right)\Bigg) + \Bigg(\left(\tfrac{2\pi r^3}{3}\right) - \Bigg(\pi(r - Z_w)^2\left(r - \tfrac{r-Z_w}{3}\right)\Bigg)\Bigg)\Bigg)\Bigg) + \Bigg(\gamma_t\Bigg(\Bigg(\pi(r - Z_w)^2\left(r - \tfrac{r-Z_w}{3}\right)\Bigg) - \Bigg(\pi {H_w}^2\left(r - \tfrac{H_w}{3}\right)\Bigg)\Bigg)\Bigg)\Bigg)cos\beta\Bigg) - \Bigg(\gamma_w\Bigg(\Bigg(\pi {H_w}^2\left(r - \tfrac{H_w}{3}\right)\Bigg) + \Bigg(\left(\tfrac{2\pi r^3}{3}\right) - \Bigg(\pi(r - Z_w)^2\left(r - \tfrac{r-Z_w}{3}\right)\Bigg)\Bigg)\Bigg)cos\beta\Bigg)\Bigg] tan\varphi' \qquad 7)$$

$$\tau_d = \Bigg[\Bigg(\Bigg(\gamma_{sat}\Bigg(\Bigg(\pi {H_w}^2\left(r - \tfrac{H_w}{3}\right)\Bigg) + \Bigg(\left(\tfrac{2\pi r^3}{3}\right) - \Bigg(\pi(r - Z_w)^2\left(r - \tfrac{r-Z_w}{3}\right)\Bigg)\Bigg)\Bigg)\Bigg) + \Bigg(\gamma_t\Bigg(\Bigg(\pi(r - Z_w)^2\left(r - \tfrac{r-Z_w}{3}\right)\Bigg) - \Bigg(\pi {H_w}^2\left(r - \tfrac{H_w}{3}\right)\Bigg)\Bigg)\Bigg)\Bigg] sin\beta \qquad 8)$$

4. RESULTS AND DISCUSSION

Fig. 2 shows the landslide analysis with rainfall intensity and duration. The landslide analysis selected individual landslides in those events to determine potential failure by a factor of safety with rainfall intensity. As a result, the factor of safety is decreased gradually with increasing rainfall intensity and duration of Typhoon talas. The groundwater level rose approximately 1.5 meters by the groundwater model during rainfall when the factor of safety was less than 1.0. The gradient slope's potential collapse ranges from 30 – 35 degrees due to the Kawabari thrust dip angle. Hence, the Modified Hemi sphere landslide model is based on a deep-seated landslide mechanism with Mohr coulomb theory and can be applied to deep-seated landslide in Kii landslide event. The rainfall intensity and duration might affect the mechanism of failure. The failure mechanism of deep-seated landslide gradually collapsed when the groundwater rose and the wetting front increment. However, this model has to be developed and verified with others case studies.

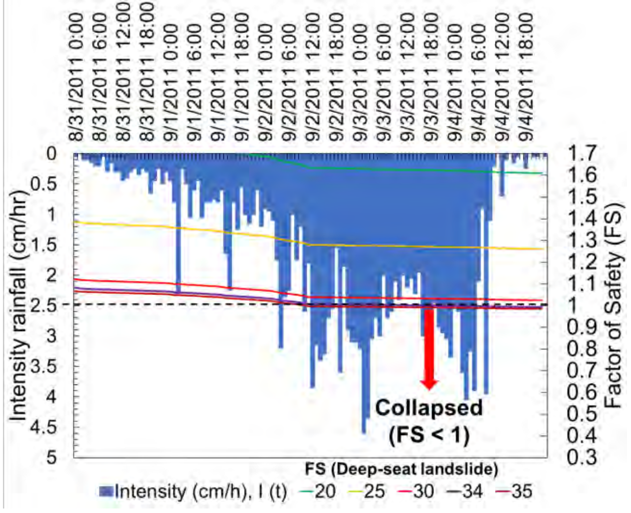

Fig.2. The relation between rainfall intensity and FS of Akatani landslide at Kii Peninsula, 2011.

5. CONCLUSIONS

From the result, the deep-seated landslide failure mechanism in the Kii peninsula has been controlled by the geological condition (Kawarabi Thrust, faults, etc.), and rainfall intensity and duration. As obtained by this proposed slope stability model, a large amount of rainwater possibly caused a pore pressure buildup, which triggered the deep-seated landslide.

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