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A simulation on rainfall-earthquake induced landslide over wide area using the limit equilibrium method

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In this study, we conduct a slope stability analysis in a wide area considering two effects of rainfall and earthquake. The event of interest is the earthquake that occurred in Cianjur, Indonesia on November 21, 2022. Three-dimensional slope stability analysis was performed using the Hovland method, which is a type of limit equilibrium method, in consideration of rainfall, topography, and geological information. The result shows that due to seismic force, the safety factor decreases over the entire slope.

Key Words : *earthquake, Hovland, landslide, , rainfall*

1. INTRODUCTION

Landslide is a common type of natural disaster, and it frequently occurs in Indonesia as well as in the Asia-Pacific Region. During a decade period from 2009 to 2018, 5129 landslides occurred in Indonesia. These landslides claimed the lives of 5920 people, injured 2164 people, and more than thousands of houses were displaced.

Rainfall and earthquakes are two most prevalent natural causes of landslides. In the area which characterized as a seismically active zones, earthquake played as a solely role in triggering most of the pre-existing landslide. It significantly increased their magnitude and frequency and finally exacerbated their likelihood and destruction capability. Post-earthquake landslide types are mainly rock and soil slides with shallow or moderate thickness. At the same time, the earthquake made many slopes unstable and produced abundant loose sediments and deposits, which are likely to be transformed into landslides or debris flow under subsequent intense rainfall.

Around 90% of all landslides occur during periods of heavy rainfall, making rainfall one of the most important causes of landslide occurrences. Rainfall has a negative impact on slope stability because it not only makes rock masses more saturated, which reduces their shear strength, but it also results in increased pore water pressure [1)].

There are two types of methods in landslide risk assessment, the first one is a statistical method, based on causal factors, and the second is a numerical analysis method that requires dynamic calculation. As an example of statistical methods, Rasyid [2)] discusses the relationship between multiple factors and slope failure by frequency ratio and logistic regression.

Regarding the numerical analysis method, a simple alternative method based on dynamic theory. Methods based on limit equilibrium theory are widely used for the evaluation of slope stability, but their accuracy and performance for actual phenomena, especially under three-dimensional conditions, have not been sufficiently verified. Therefore, in this study the

3D Hovland [3] method was applied to real terrain where there was a lot of collapse due to heavy rains and earthquakes.

2. METHOD

(1) Groundwater Condition

In this study, the groundwater conditions were set as conditions in which the surface layer was completely saturated. Drawdown of an external water level is usually impairing the stability of slope. Rapid variations in the water level may result in pore pressure gaps and an increased hydraulic gradient. Reduced slope stability may result from such pore-pressure gaps and a diminished or absent sustaining water load[4].

(2) Factor of Safety Calculation

Slope stability is extremely important consideration in the desigh and contruction of earth dams. In this study the factor of safety (FoS) was calculated using the Hovland method which is a three-dimensional slope stability analysis method based on the limit equilibrium method. A single column element and the forces acting on it are shown in Figure 1[5]. T_{ij}, N_{ij} and W_{ij} are respectively the shear force, the total normal force and the weight on the base of the column element, and Q_{ij} is the summation of intercolumn forces acting on the sides of the column element. The directions of the applied force of T_{ij}, N_{ij} and W_{ij} are given below by the following unit vector (t_{ij}, n_{ij} and eg).

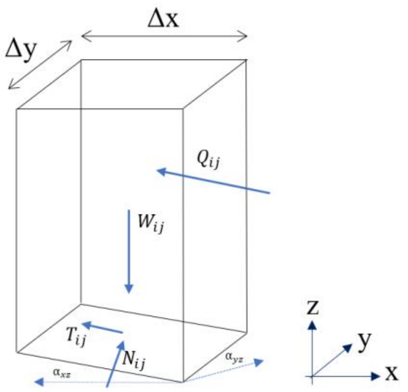

Figure. 1 Force acting on a divided column

$$n_{ij} = \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix},\ t_{ij} = \begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix},\ eg = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \tag{1}$$

(2.1) Hovland method

The Hovland method ignores the internal forces acting between the soil columns[6]. In Hovland method, Q_{ij} is assumed to be zero, which mean there are no side force. The formula for the Hovland method is shown below[7]:

$$FoS = \frac{\sum_i \sum_j \left\{cA + \left(W_{ij} n_{ij} - u_{ij} A n_{ij}^2\right) tan\phi\right\}}{W_{ij}\mathrm{ij}} \tag{2}$$

where c is cohesion, A is bottom area of the soil and ϕ is internal friction angle.

Next, we describe the modeling of the effects of seismic ground motion. In this study, the horizontal seismic coefficient vector (k) is introduced as a horizontal vector on the xy plane, and the horizontal force is taken into account by multiplying it by the split column weight. The direction of the design horizontal seismic coefficient vector is assumed to be the entire slide.

$$FoS = \frac{\sum_i \sum_j \{cA + (W_{ij}(-e_g + k_I)n_{ij}) - u_{ij}A\,((-e_g + k_I)n_{ij})^2)tan\phi\}}{W_{ij}(e_g + k_I)t_3} \tag{3}$$

(3) Validation

This study uses ROC (Receiver Operating Characteristic) curves for quantitative comparative verification. The ROC is described and investigated by many authors [8)9)]. The ROC curve is widely used in the medical field, and it is a technique that has applications in the machine learning field. An outline of the evaluation procedure is described below.

First, multiple evaluation points are randomly set in the target area and classified into the following four categories.

- True Positive (TP) → Unstable cell within actual landslide. Predict landslide successfully
- False Positive (FP) → Unstable cell not within actual landslide. Predicts landslide unsuccessfully
- True Negative (TN) → Stable cell not within actual landslide. Predicts stable area successfully
- False Negative (FN) → Stable cell within actual landslide. Predicts stable area unsuccessfully

ROC is constructed by obtaining the sensitivity and specificity of the model at different classification thresholds. Sensitivity, or true positive rate, is given as the proportion of negatives correctly identified.

$$\text{Sensitivity} = \frac{TP}{TP+TN}$$

$$\text{Specificity} = \frac{TN}{TN+FP} \tag{4}$$

The global accuracy metric for a given model in an ROC curve is given by the area under the curve (AUC). ROC-AUC value ranges from 0 to 1. An AUC value 0.5, represented by a diagonal line, depicts a random classifier with no discrimination between classes. Curves plotted above the diagonal line (AUC > 0.5) would represent better classifiers, with improving discriminative power as AUC approaches 1.

3. NUMERICAL EXAMPLE

(1) Study Area

The study area is in Cianjur Regency, West Java Province, Indonesia, shown in Figure 2. On 21 November 2022 at 6:21:10 UTC (13:21:10 local time), an earthquake of 5.6 Magnitudes at a shallow depth of 10 km hit this region, triggering landslide and causing buildings to collapse. The actual location of the landslide is shown in red in Figure 2. The epicenter of the earthquake was on land, Long 107.05 E, Lat 6.84 S, about 9.65

km south-west of Cianjur. The Digital Elevation Model (DEM) was provided by Geospatial Information of Indonesia with spatial resolution 10 meter in the area 3 x 3 km.

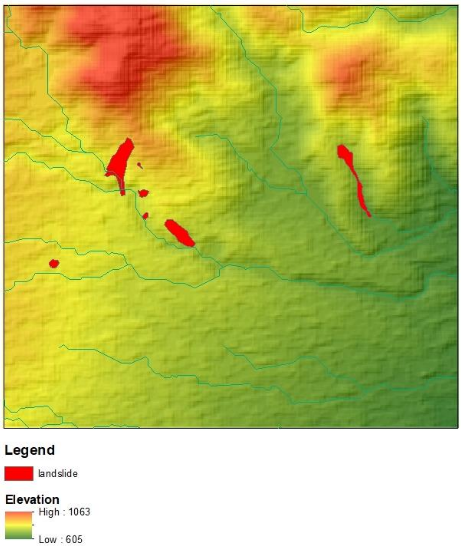

Fig. 2 Study area in Cianjur Regency, West Java, Indonesia

(2) Result and discussion

Parameters for soil properties were obtained through lab test results from soil samples in the study area (table 1). The size of the design horizontal seismic coefficient vector (*k*) calculated from the following formula[10]:

$$k = \frac{a_{max}}{g} \tag{5}$$

Where a_{max} is the peak ground acceleration (PGA) which equal to the maximum ground acceleration that occurred during earthquake. The PGA in Cugenang District, Cianjur Regency, West Java is 0.212 g (2.12 m/s2 or 212 gal). Then we get the maximum horizontal seismic coefficient k = 0.216. It is also assumed to be constant over the target area.

Table 1. soil properties at study area

Cohesion (kpa)	0.196133
Friction angle (degree)	32.7

Fig. 3 and 4 show the safety factor distribution during both normal and earthquake condition. Due to seismic force, the safety factor decreases over the entire slope, and the area at risk of collapse is widely distributed over entire slope, showing the same tendency as the actual collapse.

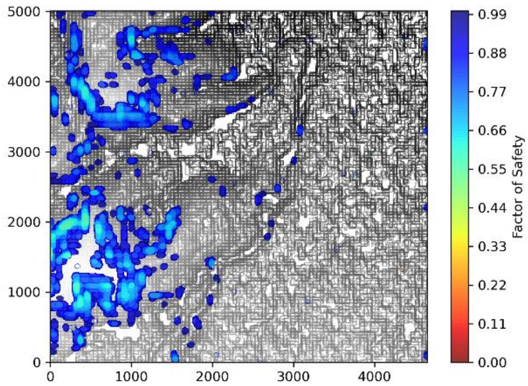

Fig. 3 Distribution of collapse in normal condition

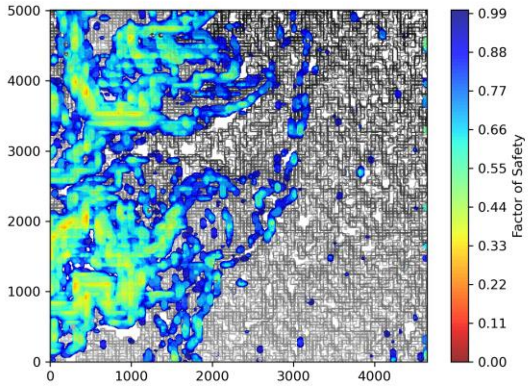

Fig. 4 Distribution of collapse in earthquake condition

On Fig.5 we can see the AUC value of target area is 0.701 and consistent with the actual landslide distribution to some extent. The analysis in Cugenang also assumes that the distribution of soil is uniform and seismic ground motions is also uniform, and it is possible that the assumptions regarding these calculation conditions affect the analysis results. Since areas below 1 can be found everywhere, it is thought that the Hovland method tends to overestimate.

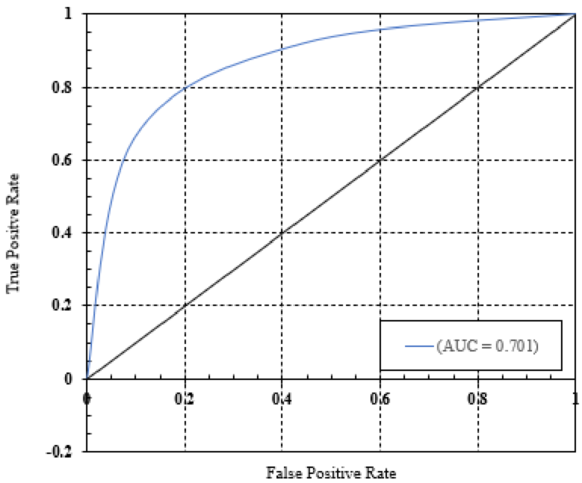

Fig. 5 ROC curve of slope stability result during an earthquake in Cianjur Regency

4. CONCLUSION

In this study, Cianjur Regency was affected by 5.6 M earthquake on 21 November 2022. Slope stability analysis in wide area was performed using 3D Hovland method, a limit equilibrium method, and comparison with the actual landslide. In this study, the groundwater condition is set as fully saturated condition. Soil parameter and seismic force used in the analysis are set as a spatial uniform condition. The result shows that due to seismic force, the safety factor decreases over the entire slope, and the area at risk of collapse is widely distributed over entire slope, showing the same tendency as the actual collapse. The groundwater condition is a critical factor for slope stability analysis. However, changes in groundwater level are affected by hydrogeological conditions, rainfall, and land cover. Future research should place an emphasis on groundwater data collection and groundwater modeling so that input data can more closely represent the actual groundwater condition

5. ACKNOWLEDGMENT

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