3D Slope Stability Analysis for Slope Failure Probability in Sangun mountainous, Fukuoka Prefecture, Japan

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Abstract

On July, 2003, following a short duration of heavy rainfall, a slope failure disaster occurred in the Sangun Mountain area, Fukuoka Prefecture, Japan. This disaster was triggered by a landslide. In order to assess the slope failure hazard potential in the future, the study of probability of slope failure is critical.

This paper presents the integrating of deterministic and statistical approach to assess the performance of the predicted results based on a factor of safety (FS) of whole slope units. Therefore, the spatial probabilistic modeling of slope failures using a combined Geographic Information System (GIS), 3D slope stability analysis, and a Monte Carlo simulation approach is applied in the slope failures-prone area of Sangun mountain area, Fukuoka Prefecture. Morphological aspects (elevation, slope aspect, slope gradient) are extracted from airborne laser survey data (LiDAR data) in each 5 m-grid that provided by local governments in Japan were assumed ground elevation to create a digital terrain model (DTM); a range of soil properties has been reported in adjacent basins with similar geological and geomorphologic condition.

The overall performance achieved by the Frequency Ratio (FR) analysis was assessed by comparison between the expected results of the 3D slope stability analysis and an independent dataset extrapolated from the slope failure inventory. As result, the validation of this model has shown enough, which the samples classified to slope failure occurrence, 70% corresponds to area where slope failure phenomena have actually occurred. In addition, the consideration of FR analysis is presented that the hydrological characteristics as a causal factor in determining the occurrence and distribution of slope failure probability in Sangun mountain area.

Keywords: 3D Slope stability, Frequency Ratio, GIS, Slope failure

1. Introduction

The prediction of the location, intensity and time or periodicity of landslides is the primary goal of the landslide hazard assessment (Ondrasik. R., 2002). The prediction of localities with landslides potential or probability is the simpler case. Analyze the relationship between landslides and the various factors causing landslides not only provides an insight to understand landslide mechanisms, but also can form a basis for predicting future landslides and assessing the landslide hazard. Chunxiang.W.et.al (2006), summarized that in areas with the similar Geotechnical conditions, researchers generally make two fundamental assumptions. Such as, the one hand, landslides will occur in the same geological, geomorphological, hydrogeological and climatic conditions as in the past. On the other hand, the properties and types of landslides will also be the same. Therefore, the study of the mechanisms and properties of past landslide is a valuable reference for assessing the future landslide hazard in its adjacent or geotechnically similar area.

Here, we demonstrated the implementation of the 3D slope stability modelling to assess the factor of safety (FS) of the whole slope units based on sub catchment and produce a reasonable cohesion values. The critical 3D slope stability simulation gave the results about the relationship on between morphological aspect and Geotechnical parameters. The Factor of Safety (FS) values has become important to explain the susceptibility of landslide. In this analysis is concern for two parts of FS value ranges, such as FS≤1.0, and FS≤1.2.

Furthermore, the observation of relationships between the distribution of slope failures in the past and probability of the occurrence slope failure based on 3D slope stability analysis is carried out by determining the best-fit model for each Geotechnical parameter value. In this study, the frequency ratio (FR) model is used, furthermore, the reasonable value obtained. Moreover, the effect of cohesion values was analyzed to obtain more knowledge about hydrology control in slope failure susceptibility.

2. Study Area and Slope Failure Historical

The catchment is located in the mountain region in northern Kyushu, Japan, the Sangun mountain massif (Fig.1). The geology consists mainly of Mesozoic granitic rock. Paleozoic and Mesozoic metamorphic rocks can be also observed on some valley slopes as roof pendants, but they are limited.

The mountainous catchment, especially in the Sangun region is hazardous areas for sediment disasters. On July 18-19, 2003, a short duration, high-intensity rainfall event impacted the city of Sangun area in Fukuoka Prefecture, Japan (Fig.1). The rainfall triggered many landslides and debris flows (Hanamura et.al., 2004). The slope failure and resultant debris flow in a Sangun area in Fukuoka was the largest and most damaging of these disasters. A moderate-size, 1-8 m deep debris avalanche triggered the debris flow about 0.5 km at the upslope of where the casualties occurred. The rainfall intensity that plunging into the village of Sangun area was estimated about 315 mm / day, and the density of slope failure were estimated about 48 points/km2. Based on the aerial map and field investigation, the number of slope failure in the study area was about 278 points.

3. Data sets and Methods

3.1 Data sets

The following Geo-spatial data were prepared for the slope stability analysis: (1) geology map, scale 1: 200.000 obtained from the Geological Survey of Japan, AIST 2005 and (2) airborne laser survey data (LiDAR data), provided by local government in Japan. The LiDAR data were a point cloud with only attributes of x, y and z values. In this study, minimum-z-values in each 5 m-grid were assumed as ground elevations to create a DTM. Geotechnical data, including cohesion, friction angle, and unit weight, were derived from the laboratory test of previous studies conducted in the area and literature review. In this study, slope failures location map is prepared based on the previous researches conducted in the area and aerial photographs. In addition, field work has been carried out to map recent landslides. The instability factors were chosen based on the above-mentioned studies which were carried out from literatures and field investigations.

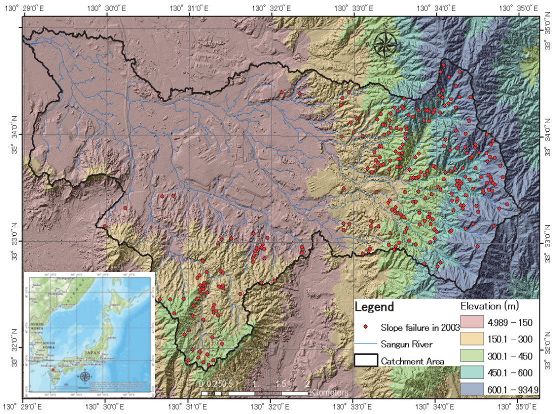

Fig.1 Study area map and distribution of slope failures

3.2 Methods

The availability of the geographical information system (GIS) can facilitate the use of a deterministic or a probabilistic Geotechnical approach as part of a method of assessment of slope failure hazard. Regarding the attributing factors, the assessment of slope failure susceptibility is carried out by using the Slope Failure Analysis System (SFAS) GIS. Based on the model of slope stability analysis and Monte Carlo simulation, the critical slip surface and minimum 3D safety factor can be obtained for each slope unit (Xie. M, et al., 2003).

(1) Slope units

For the landslide-hazard assessment of a large mountainous area with complex geometry and geological conditions, a key problem is how to extract the appropriate slope unit for potential sliding-surface identification and minimum 3D safety-factor calculation. Slope unit, namely, the portion of the land surface delimited by watershed divides and the channel has similar topographic and geological characteristics. The suitability of the slope units for landslide-hazard assessment and other landrated study has been recognized by several authors (Hansen, 1984; Xie. M et al., 2003; Dymond et al., 1995). To improve the results related to the distribution of slope unit, the eliminate tool has been used in the feature of GIS data.

(2) Analysis of mechanical parameters

In this study, we assume the flat area is the slope value at less than 4^0. Based on the field slope failure survey in July, 2013, the depth of slope failure was described, such as 3 to 30 meters. The geological map was described that the Sangun mountainous is most of granite rock. The engineering geological report of this area provides the initial value of mechanical parameters, such as cohesion (c) 12,3 kN/m^2; friction angle (ϕ) 20^0; unit weight (γ) 40 kN/m^3.

Table.1. Mechanical parameters values on 3D Slope Stability simulation

No	Cohesion (kN/m^2)	Friction angle (^{0})	Unit weight (kN/m^3)
1	10	20	40
2	12.3	20	40
3	15	20	40
4	20	20	40
5	25	20	40
6	30	20	40

Based on the history of slope failure, the occurred slope failure was due to rainfall. Therefore, in this study the assessment is concerned the influence of cohesion value in the simulation. Furthermore, the several pairs of mechanical parameters with different values of unit weight are calculated (Table 1).

In order to determine of the 3D safety factor of the sliding surface, using the slope units feature, topographic information, and the GIS-based 3D limit-equilibrium models (Hovland model) (Xie et al. 2003; Xie and Esaki, 2005) are being used in the simulation. By inputting these parameters into the model of slope stability, the value of a safety factor or failure can be obtained. Based on Hovland's (1977) model, the 3D safety factor can be expressed as follows equation:

$$F_{3D} = \frac{\sum_J \sum_I (cA + W\cos\theta\tan\phi)}{\sum_J \sum_I W\sin\theta} \qquad (1)$$

Where, F_{3D}: the 3D slope safety factor; W: the weight of one column; A : the area of the slip surface; c : the cohesion: ϕ : the friction angle; θ : the normal angle of slip surface: and J,I: the amount of row and column of the pixel in the range of slope failure.

To quantitatively assess the stability of a slope in engineering geology, a parameter F_{3D} known as factor of safety is introduced. A value $F_{3D} > 1$ indicates stability, whereas $F_{3D} < 1$ implies instability. Thus, the transition between stability to collapse may be envisaged mathematically as a decrease in the factor of safety to values below unity.

(3) Performance of the 3D Slope Stability analysis

Spatial effectiveness of the susceptibility map will be checked by the highest percentage of the actual slope failure by comparing the predicted unstable site.

The relationship between number of slope failure occurrence and number of slope unit by 3D slope stability analysis based on Factor of Safety (FS) criteria are the assumption that be used in the performance task. The frequency ratio is the ratio of the slope unit where slope failure occurred in the total slope unit in the study area, and also, is the ratio of probability of slope failure occurrence of a non-occurrence for a given factor's attribute.

4. Results

4.1 Slope failures characteristic in the catchment

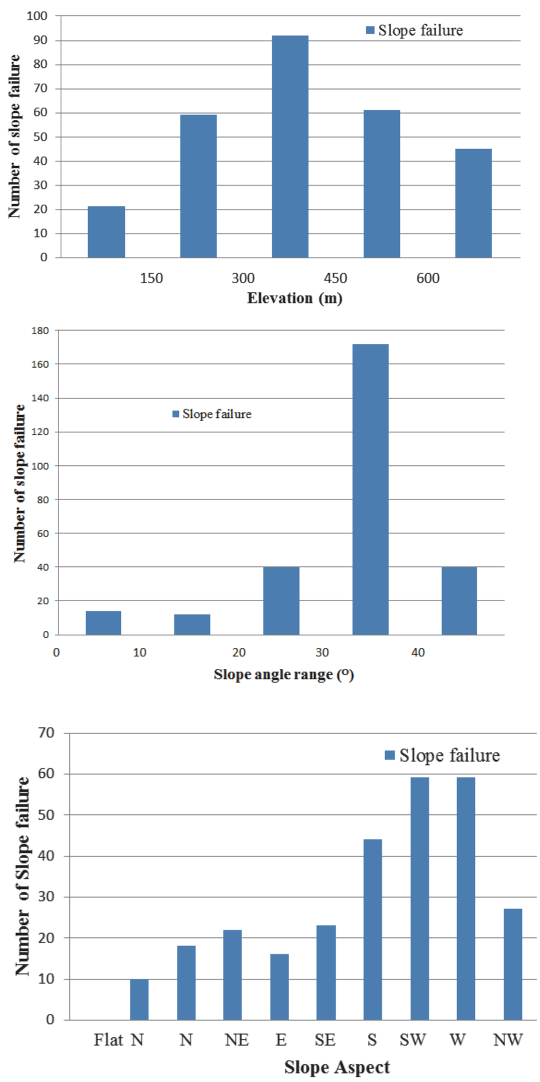

Fig.2 Slope failure characteristic in the Sangun basin

Table 2 Results of the 3D Slope stability simulation by using the varying of cohesion values

Cohesion (KN/m2)	FS Criteria	Number of slope unit by 3D slope stability calculation (A)	D (%)	Number of slope failure occurrence (B)	E (%)	C=A-B
10	FS≤1	394	31.88	200	71.94	194
	FS≤1.2	515	41.67	239	85.97	276
12.3	FS≤1	386	31.23	198	71.22	188
	FS≤1.2	507	41.02	236	84.89	271
15	FS≤1	386	31.23	195	70.14	191
	FS≤1.2	495	40.05	235	84.53	260
20	FS≤1	352	28.48	182	65.47	170
	FS≤1.2	496	40.13	234	84.17	262
25	FS≤1	325	26.29	162	58.27	163
	FS≤1.2	473	38.27	233	83.81	240
30	FS≤1	285	23.06	144	51.80	141
	FS≤1.2	456	36.89	228	82.01	228

FS: Factor of safety; Total number of slope unit (ΣnSU)=1,236 units; Total number of slope failure occurrence (ΣnSF) = 278 points; D: A / ΣnSU x 100%; E: B / ΣnSF x 100%; C: the difference of the number of slope unit by 3D Slope stability analysis and number of slope failure occurrence, D: the percentages of the number of slope unit by 3D Slope stability calculation (A) and total of number of slope unit (ΣnSU); E: The percentages of the number of slope failure occurrence by intersection with 3D slope stability calculation (B) and total of number of slope unit (ΣnSF).

A slope failure inventory map shows the location, morphology characteristic of slope failures (Fig.1). However, no detailed slope failure inventory map existed in the study area. The locations of landslide scars are determined and mapped by a field survey in 2003. The relationships between morphology aspect and slope failure distribution is presented in this study (Fig.2). The distributions of slope failure are used in this analysis. The morphology aspect are elevation, slope angle, and slope aspect.

Elevation is classified into five categories such as., <150 m, 150-300 m, 300-450 m, 450-600 m, and >600 m. It is found that the majority of the area failures in the category of 300-450 m followed by 150-300 m, >600 m, 150 -300 m, and <150 m. From the calculation of frequency ratio, class interval of 300-450 m is the highest with 92 slope failures each out of 278 failures which are 33.09 %.

Slope angle is classified into five categories such as, $<10^0$, $10\text{-}20^0$, $20\text{-}30^0$, $30\text{-}40^0$, and $>40^0$. Majority of slope failures (172 units) in the area have been occurring within a slope angle of $30 - 40^0$ followed by $<40^0$, $20\text{-}30^0$, $<10^0$, and $10\text{-}20^0$. The amount of slope failure show increase with the increasing of slope angle values in the range $10 -40^0$ (Fig.2b).

Slope aspect is classified into eight categories such as., North ($0\text{-}22.5^0$, $337.5\text{-}360^0$), Northeast ($22.5\text{-}67.5^0$), East ($67.5\text{-}112.5^0$), Southeast ($112.5\text{-}157.5^0$), South ($157.5\text{-}202.5^0$), Southwest ($202.5\text{-} 247.5^0$), West ($247.5\text{-}292.5^0$), and Northwest ($292.5\text{-}337.5^0$). Majority of slope failure in the area have been occurring within the slope aspect of the Southwest and West which are 59 units. In the Figure 2c, the graph shows the direction of slope aspect which N=North, NE=Northeast, E=East, SE=Southeast, S=South, SW=Southwest, W=West, and NW=Northwest. Figure 2c shows the slope failure increase with the direction of slope aspect of East to West.

4.2 Slope failure probability analysis by using a 3D Slope stability tool on Sangun mountainous

The calculations of Slope failure probability were performed by using 3DFAS and GIS tools. Geotechnical values were used to obtain the highest prediction accuracy for study area based on comparing the slope failure distribution. Table 1 shows the Geotechnical values based on the results of the small catchment analysis in a Sangun mountain area. The detail of a slip surface is uncertain because the lack information that obtained from a previous report.

To detect the 3D critical slip, the search is performed by means of a minimization of the 3D safety factor using the Monte Carlo simulation. Parts of study area (weathered granite zone) for the slope failure hazard assessment have been selected for priority assessment of safety factors of the slope where the most dangerous slope has also been identified by field investigation in the past.

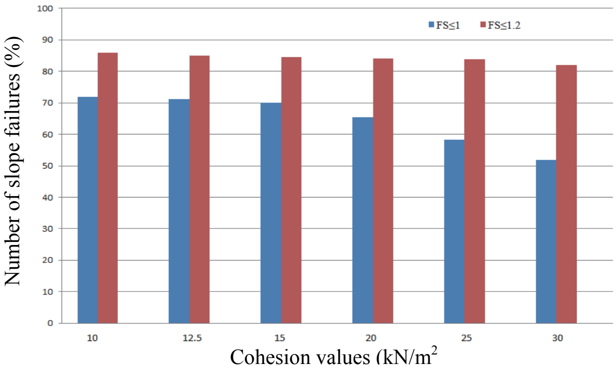

Fig.3. Relationships of cohesion values (c) and number of slope failures (%) based on the factor of safety (FS) of slope stability simulation.

For surface geological layer, the weathered granite parameters of cohesion (12.3 kN/m^2), friction angle (20^0) and unit of weight (40 kN/m^3). General geometrical parameters of the slopes have been investigated for assessing their probability geometrical calculation range value using Monte Carlo simulation. In this study, the geometrical calculation parameter range of depth (*c*) is 3 to 30 m, to simulate the critical sliding surface by Monte Carlo simulation.

Slope unit can be considered as the left or right part of a catchment. In this study, the total slope units are 1,236 units. Figure 3 shows the distribution of 3D safety factor calculated by GIS-based 3D slope stability analysis for specific dangerous slopes unit in the weathered granite area. Figure 3 also gives the detail comparative results in which dangerous slope was detected by field investigation of slope failure in the past. In the simulation, the cohesive values are considered to change and the range values of cohesion are 10 to 30 KN/m^2. The factor of safety results has been divided by fourth category, such as FS<1.00; 1.00<FS≤1.20; 1.20<FS≤1.50; and FS≥1.50.

Table 2 presents the results of 3D Slope stability simulation based on the varying of cohesion values. The criteria of safety factor were determined in two classes, such as FS≤1 and FS≤1.2.Number of slope unit by 3D slope stability calculation is decreased when the cohesion value increases. For the both of factor of safety classes, the percentages of the number of slope unit by 3D Slope stability calculation (A) and total of number of slope unit (ΣnSU), % (D), were calculated. Furthermore, intersection of slope unit distribution by 3D Slope stability calculation and inventory slope is in the boundary area provided detailing the variation of number of slope failure occurrence that based on the varying of cohesion values. In the simulation results, the number of slope failure occurrence has decreased when the cohesive value increases.

The percentages of the number of slope failure occurrence by intersection with 3D slope stability calculation (B) and total of number of slope unit (ΣnSF), % (E), have been calculated, too. The % (E) values were employed in this study to perform the highest percentage of the actual slope failure by comparing the predicted unstable site. On the other hand, the difference number of slope unit of calculation and intersection with slope failure, inventory, C value, which can be calculated from C = A-B, cautiously indicate how the good perform from simulation. The minimum values of C indicate a perfect result. In this study, C value shows decrease when the cohesion values increases, except the cohesion, 15, value.

5. Discussions

5.1 Evaluation the Slope failure probability map

New advanced technology has been used in this study, and results based on this simulation are obtained. The use of LiDAR in this study shows that the technique is very useful in the simulation process. With the help of the LiDAR was extracted the morphology of the study area.

For Sangun mountain area the largest uncertainty is the Geotechnical parameters, since these are not measures in-situ. It is also a limited availability on representative literature data and knowledge of the actual slope conditions. Therefore the input parameters are assumed to have as good quality as possible. The input parameters are based on literature, this does clearly introducing some uncertainty. For all the figures that have been modeled in the 3D slope stability analysis has been measured with the influence of cohesion parameter.

Spatial effectiveness of the susceptibility map will be checked by the highest percentage of the actual slope failure by comparing the predicted unstable site. The rate graph will be created for variance of Geotechnical values, and their percentage will be calculated. The rate explains how well the model and controlling factors predict the landslide.

The model with the highest percentage is considered to be the best. Fig. 3 shows a representative the evaluation of slope failure predicted that produced by 3D slope stability analysis of variance of Geotechnical values for each factor of safety glasses. Therefore, the minimum of the number of cohesion values in each factor of safety classes gave a consideration performance in this evaluation.

In fact, the slope failure occurred in the FS≤1.0 value was higher than other values, where the calculated probability can be over 70 %. In order, the graph shows a highest of the actual slope failure occurred in cohesion values 10 KN/m2 for FS≤1.2 about 85.97%. The total number of slope failure is increasing, when the value of a factor of the safety increases. Due to the C values gave the similar values, therefore the cohesion value equal 10 KN/m^2 gave a very reasonable performance compare to similar C values performed by other cohesion values.

5.2 Effect of cohesion of granite in the Slope failure Probability analysis

Landslides tend to occur in topography hollow due to convergence of water and accumulation of colluvial soils in steep soil-mantled landscape that leads to a cycle of periodic filling and excavation by landsliding (Dietrich and Dunne, 1978).

If it increases weight and water pore pressure in granular granite, the rate at which water seeps into to the slope may also critical. When adding the cohesion in the 3D Slope stability tool does not allow us to model the water table to follow the infiltration networks, since normally this is the reality. This is also a weakness.

When the water is assumed to fill the pores within the rock, this will not be the case when modeling and the water will only affect the effective stresses within the slope as a whole. In our analysis of slope failure probability in Sangun mountainous area, we find that parameter combinations emphasizing topographic through low cohesion values provide the best results. In this study, the effect of water surface is equal the cohesion of soil value that used in the simulation of 3D Slope stability.

It is found that the number of slope failure based on FS≤1.00 is increasing with the cohesion value increase. Therefore, a ratio of slope failure in the past and slope failure probability shows more than 50% of all cohesion values for FS≤1.00 class. And the cohesion value 10 KN/m^2 is the best results in the simulation process, which the ratio shows more than 79%. Moreover, the ratios are increasing with the factor of safety classes is increasing, such as 28 – 50 % for FS≤1.2.

The relationship between slope failure probability and morphology aspect has been conducted that show the variety of distribution slope failure probability with slope angle aspect. The analysis showed that the slope angle within the greater than 30^0 indicates a high probability of slope failure occurrence. The ratio of slope failure occurrence was 0.89 and 0.9 in the range of 30 - 40^0 and greater than 40^0. During the fieldwork, few slope failures were observed in the areas presented by groundwater surface.

The occurrence of groundwater on the slope failure surface is indicated that the influence of hydrology aspect may consider the related cohesion value. Weathered granite shows a behavior as soil material.

6. Conclusions

The 3D Slope Stability tool has been provided the prediction of slope failure in the future in Sangun Mountainous. However, the performed of the results will be needed to get better results and the function of this tool.

Furthermore, the comparison results of the 3D slope stability simulation and slope failure evidence has better prediction accuracy for the study area. Therefore, in the future, the parameter values for unit weight (γ) and friction angle (ϕ) will be changed to simulate of the probability of critical failure in the Sangun catchment area.

Acknowledgements

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