ZONATION OF FAILURE PROBABILITY FOR LANDSLIDES INDUCED BY EARTHQUAKE IN KITAKYUSHU CITY USING GIS

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ABSTRACT

We calculate failure probability of earthquake-induced landslides throughout Kitakyushu City based on Monte Carlo simulation (minimizing the uncertainty of slope parameters) and Newmark stability analysis (estimating factors of safety). Meanwhile, hazard maps of earthquake-induced landslides in Kitakyushu city are produced according to the results of failure probability by using the geographical information system (GIS) with different peak ground accelerations (PGAs) and seismic occurrence periods at both conditions of $m = 0$ and $m = 1$.

On the hazard maps, it is evident that the districts of Kokura Minami, Moji, Kokura Kita, Yahata Higashi and Yahata Nishi in Kitakyushu City would suffer the disaster of landslide severely. In the lower cases of PGA, the Southwest of Kokura Minami, the borders between Moji and Kokura Kita, and the borders between Yahata Higashi and Yahata Nishi are the major areas impacted by extremely serious hazard of earthquake-induced landslides. As PGA, seismic occurrence period or/and water factor increases, critical hazard of landslide has an extensive area, covering Wakamatsu. Nevertheless, Tobata, the only one of fortunate district throughout Kitakyushu City, is in safety all the time.

Keywords: Landslide, Earthquake, Hazard map, Kitakyushu city, GIS.

1. INTRODUCTION

Landslide is a widespread hazard as well as a major geomorphic process affecting landscape evolution in mountainous regions around the world (Aleotti 1999, Guzzetti 1999, Dai 2002, Roering 2005). The hazard causes not only considerable financial losses but also major ecological and environmental problems (Hovius 1997, Chigira 2006, Claessens 2007). Each year landslides cause more than 100,000 deaths and injuries, with damage costing more than 1 billion USD (Schuster 1996). In many countries, the economic losses and casualties caused by the hazard of landslide are greater than commonly recognized, and this kind of hazard generates a yearly loss of property larger than that from any other natural disaster including earthquakes, floods and windstorms (Garcia-Rodriguez 2008).

Kitakyushu is a city located in Fukuoka Prefecture, Kyushu, Japan. The weather of Kitakyushu City is temperate and the rainfall is averagely 1,265 mm per year. The City, furthermore, is situated in a hill area. Thus, Kitakyushu City suffers the hazard of landslide induced by rainfall critically. On March 20, 2005, a great earthquake with a magnitude of VII on the Richter scale hit Fukuoka area. The earthquake induced very serious slope disasters in the around areas, including the Kitakyushu City. It is necessary, therefore, to understand the potential disaster of earthquake-induced landslides throughout Kitakyushu City. Unfortunately, it is the beginning yet to understand the issue of hazard caused by landslides associated with earthquake although many scientists and engineers take much effort on the cases of rainfall.

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Zonation, which is an effective method to understand the hazard of landslides by macro view, has been applied in many concerned mountain areas of the world. The authors assess the landslide susceptibility induced by earthquake in Kitakyushu City using GIS, applying the Monte Carlo simulation and Newmark stability analysis for theoretical computation of failure probability. Here the former minimizes the uncertainty of strength parameters by applying huge numbers of physical parameters of geological slopes while the latter estimates the factors of safety of earthquake-induced landslides, considering the influence of rainfall on the stability of slopes.

2. METHODOLOGY

2.1. Physical and Geometrical Parameters of Geological Slopes

According to a new geology map, there are mainly four types of soils in Kitakyushu City, which are weathered respectively from granite, sedimentary rock, igneous rock and hydrogenous rock.

Through analyzing the frequency characteristics of three physical parameters, i.e. γ (unit weight), c (cohesion strength) and φ (internal friction angle), for the four types of soils, the distribution functions for each parameter are obtained based on the laboratory data. On the other hand, the geometrical parameters of landslides, θ (slope angle) and H (thickness of sliding layer), are accepted as dependent to the logarithmic and normal distributions. After generating 3,000 random numbers, furthermore, the corresponding statistical values of physical and geometrical parameters of geological slopes, 3,000 numbers for each one, are calculated by their distribution functions.

2.2. Factor of Safety and Failure Probability

The authors calculate the factors of safety for the estimation of theoretical failure probability of earthquake-induced landslides by the equation (1) and equation (2), meanwhile considering the influence of rainfall on the stability of the landslides.

$$Z = \frac{g}{a'}\left(\frac{c_m}{\gamma H} + \cos\theta \tan\varphi_m - \sin\theta\right) \tag{1}$$

$$Z = \frac{g}{a'}\left[\frac{c_m}{\gamma_{sat} H} + \left(1 - \frac{\gamma_w}{\gamma_{sat}}\right)\cos\theta \tan\varphi_m - \sin\theta\right] \tag{2}$$

Here equation (1) is applied to calculate factors of safety at the condition of only earthquake whereas equation (2) is for coupling cases of earthquake and rainfall. As the PGA is zero equation (1) and equation (2) would not be available to calculate the factor of safety. For those 0 gal PGA cases, the traditional formula of Newmark stability analysis is applied, which has the following form.

$$FS = \frac{c_m + \left[(1-m)\gamma + m\gamma'\right]H\cos\theta\tan\varphi_m}{\left[(1-m)\gamma + m\gamma_{sat}\right]H\sin\theta} \tag{3}$$

As mentioned above, the authors apply Monte Carlo simulation and Newmark stability analysis in the process to calculate factors of safety of earthquake-induced landslides. Furthermore, for computation of theoretical failure probability, the following definition is applied.

$$P_F = \frac{Numbers\left(FS < 1\right)}{3000} \tag{4}$$

2.3. Meshes of Geology and Elevation Maps

For producing the hazard maps of earthquake-induced landslides, it is an essential step to divide geology and elevation maps into small dimension meshes, each of which has a unique number and the information about the slope angle, soil types and areas.

A specifically meshed tool generates the meshes for geology and elevation maps in GIS, where the dimension is 100m*100m for each one. The information of meshes such as slope angle, soil types and areas are obtained by the spatial analysis approach of GIS. Based on these thoughts, the meshed work of maps is completed and some basic information associated with the meshed results is shown in Table 1.

Table 1 Basic information of meshed maps.

Numbers of soils	Meshes		Soil types	Area	
	Numbers	Total		km^2	Percent (%)
1	30,175	45,166	I	40.144	8.925
2	11,982		II	181.257	40.300
3	873		III	45.354	10.084
4	34		IV	183.020	40.691
None	2,102		Total	449.775	100.000

2.4. Zonation of Failure Probability for Landslides

Firstly, it is essential to calculate the actual failure probability for each mesh based on the meshed information mentioned above. In this process, there could be always two cases to consider due to the numbers of soils in one mesh as follows.

1) When the mesh has only has one kind of soil, a simple interpolating method is applied to obtain the actual value for failure probability. The method could be expressed as the following equation,

$$P_{Fi} = P_{Fj} + \left(P_{Fk} - P_{Fj}\right) \cdot \left(i - j\right) \tag{5}$$

Where P_{Fi} is the failure probability of each mesh with actual slope angle of i, a real number ; both P_{Fj} and P_{Fk} are theoretical failure probability associated with the actual slope angle, in which j is the integer of i, and as a integer number also, $k = j + 1$.

2) When more than one soils exist in the mesh (e.g. Table 1.), a weighted average of failure probability is calculated for the mesh by the equation below.

$$P_{Fi}^{WA} = \frac{P_{Fi}^{1} \cdot A_1 + P_{Fi}^{2} \cdot A_2 + \cdots + P_{Fi}^{n} \cdot A_n}{A_1 + A_2 + \cdots + A_n} \tag{6}$$

Where n is the numbers of different types of soils; P_{Fi}^{n} is the actual failure probability for different types of soils in one mesh and A_n denotes the corresponding area.

Secondly, it is necessary to import the actual failure probability completely into each mesh by the authors with a Fortran program. Then GIS could provide a color automatically for each mesh due to the level of probability value, and in this case, the color ranges from green to red, representing a low-level and high-level of landslide failure respectively. This is the final step to produce hazard maps.

3. RESULTS AND DISCUSSION

3.1. Hazard Maps

Applying the zonation approach of earthquake-induced landslides mentioned above, we produces 28 hazard maps using GIS for different PGAs and seismic occurrence periods of years both at the conditions of $m=0$ and $m=1$. The detailed information of those hazard maps throughout Kitakyushu City could be found in Table 2.

Table 2 Hazard maps produced by this thesis.

Map	PGA (gal)	Map	PGA (gal)	m	Map	PGA (gal)	Map	PGA (gal)	m
No. 1	0	No. 8	700	0	No. 11	0	No. 18	700	1
No. 2	100	No. 9	800		No. 12	100	No. 19	800	
No. 3	200	No. 10	900		No. 13	200	No. 20	900	
No. 4	300	No. 21	Per year		No. 14	300	No. 25	Per year	
No. 5	400	No. 22	10 years		No. 15	400	No. 26	10 years	
No. 6	500	No. 23	30 years		No. 16	500	No. 27	30 years	
No. 7	600	No. 24	50 years		No. 17	600	No. 28	50 years	

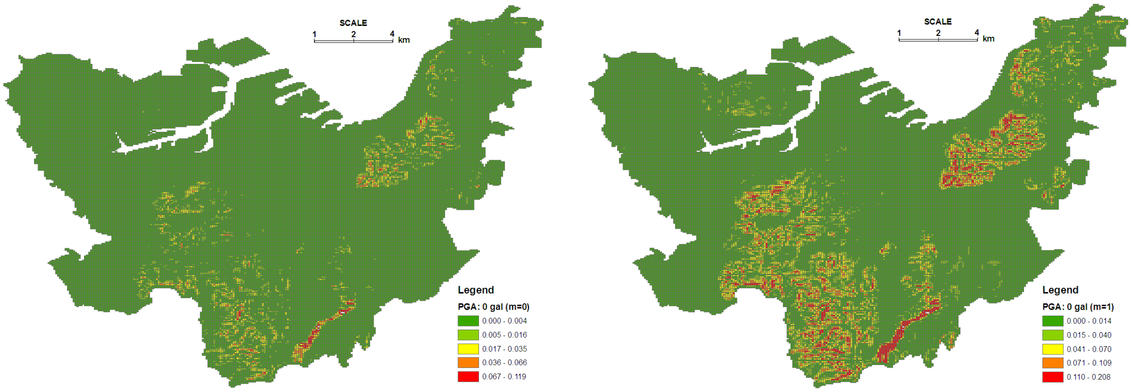
3.2. Failure Characteristics of Landslides

Some particular hazard maps of earthquake-induced landslides throughout Kitakyushu City are shown as Figures 1.~3. In order to reduce the pages, other maps are not displayed here. However, this has no distinctly negative impacts on analysis results of failure possibility and distributional characteristics of landslide disaster respectively caused by earthquake or coupling case of earthquake and rainfall.

The hazard maps of No. 1 and No. 11 draw the outline of the critical areas suffered by earthquake-induced landslides (Figure 1.). In the two cases, the PGAs are both 0 gal while water factors are 0 and 1 respectively. As the PGA reaches 900 gal, those critical areas in hazard map of No. 20 become the severest, where the failure probability is the highest level as a whole (Figure 2.). Meanwhile, hazard regions could be extensive. Some other areas without disaster at first begin tending to bear a moderate-level or low-level failure possibility caused by earthquake or coupling condition of earthquake and rainfall. These are the common characteristics of hazard maps for earthquake-induced landslides in Kitakyushu City.

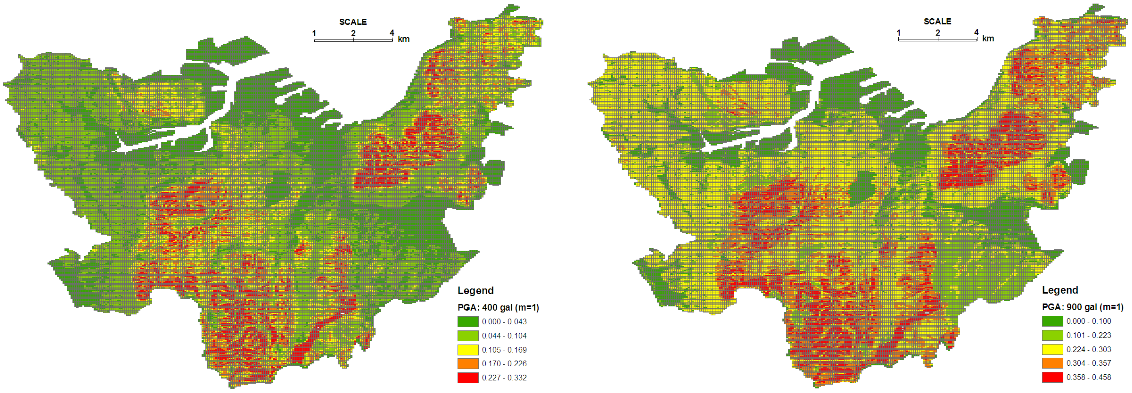
By the definition of calculation for failure probability with different periods of seismic occurrence, it is easy to understand that these hazard maps with seismic occurrence period of years may reduce the low-level features of failure probability, which appear visibly when PGA becomes greater than 400 gal. One interesting example is the comparison between hazard maps of No. 20 and No. 28. The latter has a higher maximum critical-level of failure probability, but it is much clearer than the former that has many areas with the low-level probability of landslide failure.

On the hazard maps, it is generally evident that the districts of Kokura Minami, Moji, Kokura Kita, Yahata Higashi and Yahata Nishi would suffer any disaster of landslide severely (Figures 1.~3.). In the lower cases of PGAs, the Southwest of Kokura Minami, the borders between Moji and Kokura Kita, and the borders between Yahata Higashi and Yahata Nishi are the major areas impacted by an extremely serious hazard of earthquake-induced landslides. As PGA, seismic occurrence period or/and water factor increases, a critical hazard of landslide has an extensive area, covering Wakamatsu. Nevertheless, Tobata, the only one of fortunate district in the City, is in safety all the time.



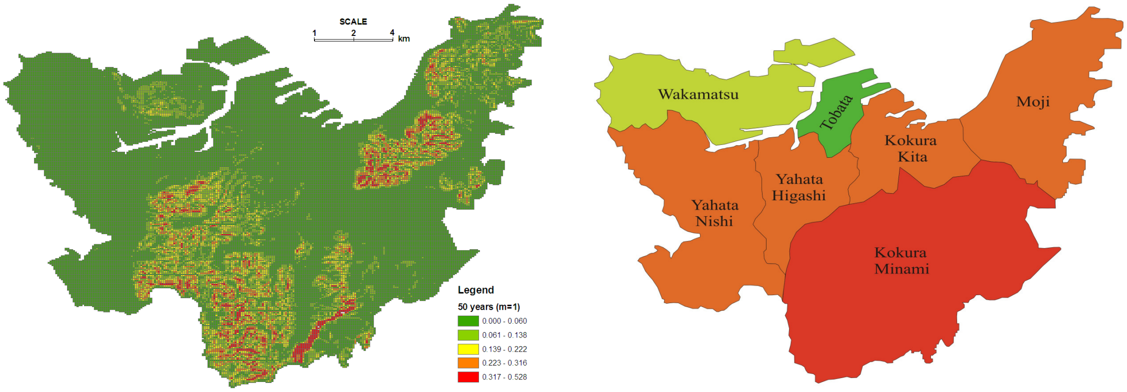
(a) (b)

Figure 1 Hazard maps of No. 1 and No. 11.



(a) (b)

Figure 2 Hazard maps of No. 15 and No. 20.



(a) (b)

Figure 3 Hazard map of No. 28 and districts of Kitakyushu City.

4. CONCLUSIONS

For the actual cases, the geological slopes are in the stable conditions because of the equilibrium between soil strength and slope angle. As the external factors such as earthquake or rainfall are involved into the equilibrium, the slope may fail. By this mechanism, it is better to understand that, for a certain case of geological slope, either greater PGA or shallower water table would make the slope softer. Consequently, even the angle is lower; the slope would not be that stable all the same.

The districts of Kokura Minami, Moji, Kokura Kita, Yahata Higashi and Yahata Nishi would suffer the disaster of landslide severely. In the lower cases of PGA, the Southwest of Kokura Minami, the borders between Moji and Kokura Kita, and the borders between Yahata Higashi and Yahata Nishi are the major areas impacted by an extremely serious hazard of earthquake-induced landslides. As PGA, seismic occurrence period or/and water factor increases, a critical hazard of landslide has an extensive area, covering Wakamatsu. Nevertheless, Tobata, the only one of fortunate district in Kitakyushu City, is in safety all the time.

Those hazard maps with different periods of seismic occurrence may reduce the low-level feature of failure probability. The hazard map of seismic occurrence period within 50 years has a higher maximum critical-level of failure probability whereas the map is much clearer than another at the PGA of 900 gal that has many areas with moderate-level possibility of landslide failure. For the cases of $m = 0$, a longer occurrence period of years has a greater area percent of failure probability in the high-level hazard than a shorter one. This is more visible at the condition of $m = 1$, corresponding an obvious reduction of area percent with low-level probability of landslide failure.

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