A Simple Method for Producing Probabilistic Seismic Shallow Landslide Hazard Maps

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Abstract

To develope a method for assessing the potential of shallow landslides during earthquakes, we analyzed the shallow landslide data caused by the 1995 Hyogo-ken Nanbu earthquake. We developed a simple method to map the potential of shallow landslides during earthquakes using Digital Elevation Model and potential earthquake wave data. In the developed method, slope gradient, mean curvature and peak ground acceleration were used to evaluate the relative potential of shallow landslides. We examined the applicability of the method to other past earthquake (2000 Kozushima earthquakes). The analyses showed that the developed method is a useful tool for assessing the relative potential of shallow landslides during earthquakes. In 2004, Niigataken Chuetsu Earthquake occurred. This earthquake triggered a lot of shallow and deep-sheeted landslides. So, we examined the applicability of our method to Niigataken Chuetsu Earthquake, 2004. The analyses showed that the proposed method is also the useful tool for assessing the relative potential of shallow landslides triggered by Niigataken Chuetsu Earthquake, although the proposed method is not effective to predict the location of deep-sheeted landslide during earthquake.

Keywords: shallow landslide, earthquake, potentail of shallow landslide, evaluation system

1. Introduction

Landslides are one of the most damaging collateral hazards associated with earthquakes. Indeed, damage from seismically triggered landslides and other ground failures has sometimes exceeded damage directly related to strong shaking and fault rupture. Seismically triggered landslides damage and destroy homes and other structures, block roads, sever pipelines and other utility lifelines, and block stream drainages. Predicting where and in what shaking conditions earthquakes are likely to trigger landslides is a key element in regional seismic hazard assessment (Jibson et al., 2000; Keefer, 2002).

Methods of predicting the seismic landslide susceptibility that have been proposed are broadly categorized in three types:

(1) Physically-based numerical simulation, such as three-dimensional dynamic shaking analysis (e.g., Ashford et. al. 1997, Mizuyama et al., 2002)

(2) Simple conceptual slope displacement analysis, such as the Newmark method (e.g., Wilson and Keefer, 1985; Jibson et. al. 2000)

(3) Empirical methods based on the relationships between topographical and geological factors and the seismic landslide susceptibility during the past earthquakes (e.g. Caplongo et al., 2002; Carro et al., 2003)

Methods in group 1 have a powerful potential for use in regions where there have been no past earthquake disaster data and as a way to evaluate the probability of slopes failure triggered by earthquake which has wave motion with differing characteristics, because these methods are relatively based on physical mechnism. However, several practical challenges, such as the problem of computation time and the ability to obtain adequate underground information, including soil mechanical and geophysical parameters, have to be overcome.

Methods in group 2 are relativley simple, so computation time is much shorter than that of group 1. However, the problem of the ability to obtain adequate underground information is still remained. According to difficaluties of data correction, in most cases it can be thought that the use of simple, empirical model

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approaches, such as groups 1 and 2, is more prcatical methods, compare with the use of a fully distributed, physically model with a large number of model parameters.

While, if the the seismic landslide susceptibility can be empirically evaluated by surface topography, it can be thought that methods in group 3 are highly applicable owing to recent progress in GIS technologies and knowledge about the relationships between topography and seismic landslide susceptibility (e.g., Nishida et al., 1997). To develop general empirical hazard modeling equations, however, it is necessary to test the applicability of the empirical relationship prepared based on the data of the previous earthquake to other regions and/or other earthquakes which have different wave characteristics. An applicability of the empirical equation for a variety of region and earthquake has not been examined.

Here we propose simple practical method for predicting the seismic landslide susceptibility based on the analysis of the data of Hyogo-ken Nambu Earthquake occurred in 1995. Then, we test the applicability of the proposed empirical equation for predicting the seismic landslide susceptibility during other recent earthquakes

2. Hazard modelling equation for Rokko Mountains

2.1. Data and materails

We developed and calibrated the methodology in Rokko Moutains. This mountains lies just a few kilometers north of the Hyogo-ken Nambu Earthquake epicenter and contains dense concentrations of landslides. Hyogo-ken Nambu Earthquake occureed in January 17, 1995. Most of Rokko Mountains is underlained by graite and covered by forest vegetaions. We used datasets developed by the Rokko Sabo Office, Ministry of Construction (now Ministry of Land, Infrastructure and Trasportaion). These datasets include (1) a comprehensive inventory of triggered landslides, (2) polygon data of landslide, (3) detailed geologic mapping of the region, and (4) high-resolution (10 m mesh grid data) digital elevation models of the topography.

2.2. Developing hazard modeling equation

Previous research by Nishida et al. (1997) indicated that topographic factors contributing to earthquake triggered shallow landslide were both the slope gradient and the slope curvature. As indices representing the slope curvature, we computed six indices from the digital elevation model (DEM) and examined applicability to predict seismic landslide susceptibility: overground divergence angle, underground divergence angle, average curvature, curvature along slope direction, curvature orthogonal to the slope direction and Laplacian. Also, we examined effects of effective length for calculation (dx and dy in eq. 1) of slope curvature indices, as shown in Fig. 1. Average curvature of effective length 20 m was the most correlated with seismic landslide susceptibility, although differences between the indices representing the slope curvature had little impact on the results of prediction of seismic landslide susceptibility. the average curvature of slope (H) was calculated by following equations.

$$H = \frac{h_{xx}(1+h_y^2) + h_{yy}(1+h_x^2) - 2h_x h_y h_{xy}}{2(1+h_x^2+h_y^2)^{\frac{3}{2}}} \tag{1}$$

where $h_x = \dfrac{\partial h}{\partial x}, h_y = \dfrac{\partial h}{\partial y}, h_{xx} = \dfrac{\partial^2 h}{\partial x^2}, h_{yy} = \dfrac{\partial^2 h}{\partial y^2}, h_{xy} = \dfrac{\partial^2 h}{\partial x \partial y}, h$ is elevation.

Number of papers reported that the seismic landslide susceptibility was affected by both moment magnitude of earthquakes and distance from the epicenter (please see review by Keefer (2002), indicating that the degree of ground motion strongly affects on the seismic landslide occurrence. Several indices proposed as explanatory variable of seismic landslide susceptibility, including Arias intensity (e.g., Wilson and Keefer, 1985), the peak ground acceleration (Jibson and Keefer, 1993) and so on. We examined applicability of peak ground acceleration and peak ground velocity as indices representing the ground motion. Thus, we found

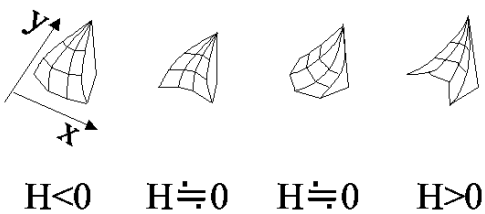

Fig. 1. Schematic illustration of average curvature (after Nishida et al. (1997))

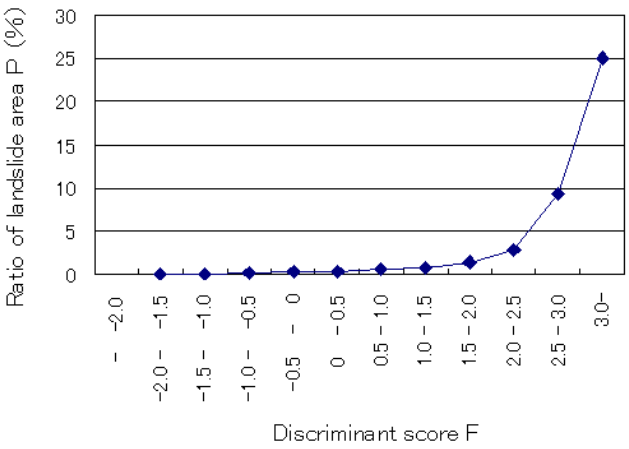

Fig. 2. Relationship between the discriminant score F_R and percentage of landslide occurrence area P

that the peak ground acceleration is strongly correlated with seismic landslide susceptibility, rather than the peak ground velocity. Further, if we consider the rupture directivity effect in near-fault strong ground motion to calcurate the peak ground accelation, the correlation between the peak ground accelation and the seismic landslide susceptibility became large. Thus, we used an empirical equations describe the relationship between distance from the surface projection of the updip edge of the fault plane and the peak ground acceleration proposed by Fukushima (2002), who consider the rupture directivity effect.

According to these preliminarily analyses, we decided three explanatory variables: slope gradient, average slope curvature and the peak ground acceleration. To determine weighting factors of explanatory variables, we did linear discriminant analysis. Thus, we derived the equation 2 (hereafter refer to "Rokko Equation").

$$F_R = 0.075I - 8.9H + 0.0056a - 3.2 \tag{2}$$

where F_R is discriminant score calculated by Rokko Equation, I is gradient, H is averaged curvature and a is peak acceleration of ground motion.

2.3. Results of prediction of landslide susceptibility in Rokko Mountains

In this study, we assumed that the discriminant score F_R represents seismic landslide susceptibility. Thus, we test the relationship between F_R and percentage of landslide occurrence P (Figure 2). In this study, if there was a collapse polygon in the center of a 10m mesh, this mesh was treated as a collapse mesh to calcurate P. There is a strong correlation between F_R and P. For example, the collapse probability of the slope with discriminant score from -0.5 to 0.5 is 0.25%, on a slope with discriminant score of 3 or more, it is approximately 25% or more, indicating that on a slope with a discriminant score of 3 or more, the probability of collapse during an earthquake is more than 100 times that of a slope with discriminant score of 0. This means that the value of F can express the probability of seismic landslide occurrence in Rokko Mountain during Hyogo-ken Nambu Earthquake.

3. Testing the applicability of proposed eqaution to other erathquakes

3.1. Data and materails

We examined the applicability of the methodology in Kozushima Island and Niigata-ken Chuetsu region.

In Kozushima Island, 1526 of shallow landslide occurred by large earthquake (M = 6.5) in July 1, 2000. Kozushima Island is underlain by predominantly tuff and covered by forest. We used dataset produced by Public Works Research Institute, Japan. The landslide size was relatively larger than that of Rokko Mountains (Figure 3). These datasets include (1) a comprehensive inventory of triggered landslides, (2) polygon data of landslide, and (3) high-resolution (1 m mesh grid data) digital elevation models of the topography.

While, in Niigata-ken Chuetsu region, the Niigata-ken Chuetsu Earthquake of October 23, 2004 caused many mountain slopes to collapse and triggered many landslides, resulting in extensive damage. An investigation performed by National Institute for Land, Infrastructure and Management, Japan has shown that the slope

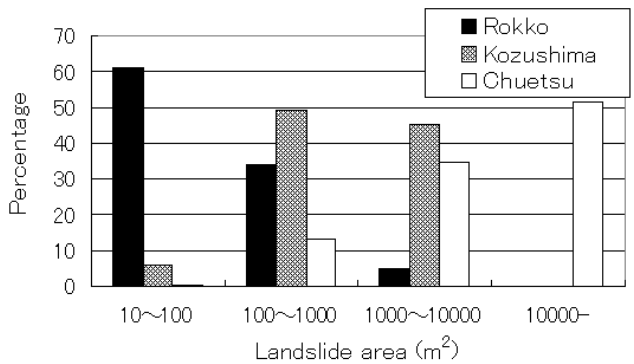

Fig. 3. Appearance percentage of landslide area

collapse area rate of the Niigata-ken Chuetsu Earthquake is about 1 order larger than the slope collapse area rate in the Rokko Mountains caused by the Hyogo-ken Nambu Earthquake (http://www.nilim.go.jp/lab/rbg/index.htm). Also, Niigata-ken Chuetsu triggered deep-seated (ca. depth > 10 m), large landslide (Figure 3). Niigata-ken Chuetsu region is underlain by Tertiary sedimentary rock and covered by forest and paddy field. We used datasets developed by the Yuzawa Sabo Office, Ministry of Land, Infrastructure and Trasportaion). These datasets include (1) a comprehensive inventory of triggered landslides (2) polygon data of landslide and (3) high-resolution (1 m mesh grid data) digital elevation models of the topography.

3.2. Methods for test of applicability of proposed method

We developed spatially distributed data (10m × 10m grid cells) about slope gradient and average curvature data based on the high-resolution DEMs. Also, we calculated peak ground acceleration of each 10m × 10m grid cell using the method proposed by Fukushima (2002). The locations of fault plan were referring to the results of survey by the Earthquake Survey Committee of the Earthquake Survey and Research Headquarters, Japan.

Moreover, since, in Chuetsu region, a number of deep-seated landslide occurred, landslides were classified into two based on the aerial photograph; one is more than 50% of the collapsed soil mass retained its original shape and remained inside the collapsed area (hereafter refer to deep-seated landslide) and the others (hereafter refer to shallow landslide). As a result, there were 831 shallow landslides and 47 deep-seated landslides.

To examine applicability of Rokko Equation, we calculated the relationship between F_R and P. Further, to validate coefficients for explanatory variables in Rokko Equation, we did linear discriminant analysis for Kozushima Island and Chuetsu region using the same explanatory variables. Consequently, equations 3 and 4 were derived thorough linear discriminant analysis for Kozushima Island and Chuetsu region, respectively (hereafter refer to "Kozushima Equation" and "Chuetsu Equation", respectively)

$$F_K = 0.045I - 59H + 0.007a - 3.1 \quad (3)$$

$$F_C = 0.079I - 35H + 0.018a - 7.3 \quad (4)$$

where F_k and F_C is discriminant score calculated by Kozushima and Chuetsu Equations, respectively.

3.3. Results

3.3.1. Kozushima Island

Positive relationship between F_R and P was obtained for both Kozushima Island, as similar to Rokko Mountains (Figure 4), indicating that we could predict the rekative dagerousness of seisimc landslide occurrence in Kozushima Island before the earthquake using Rokko Equations.

Also, the F_K is positively correlated with P. Moreover, Figure 4 shows that there is no significant difference in the F-P relationshipe between Rokko and Kozushima Equations

3.3.2. Chuets region

Figure 5 shows the F-P relationships as calculated based Rokko and Chuetsu Equation. As shown in Figure 5, there was almost no difference between in the F-P relationships calculated by Rokko Equation and by

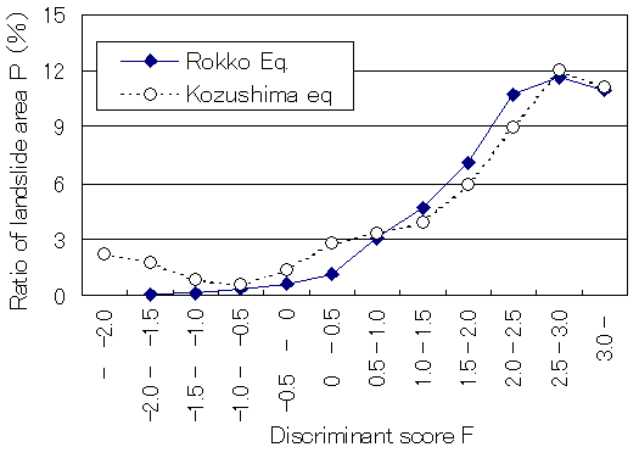

Fig. 4. Relationship between the discriminant score F and percentage of landslide occurrence area P in Kozushima Island

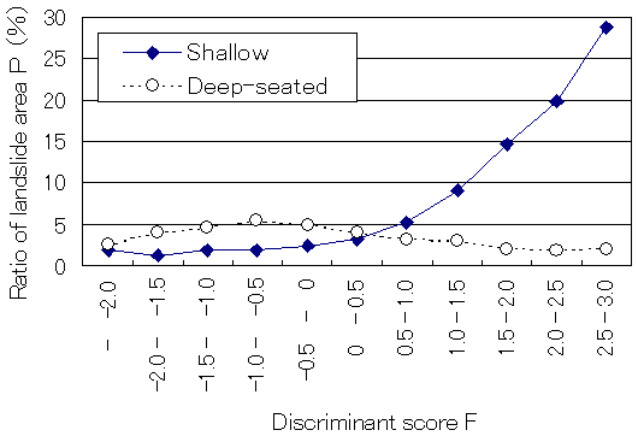

Fig. 5. Relationship between the discriminant score F and percentage of landslide occurrence area P in Chuetsu region

the Chuetsu Equation. In both cases, P tended to increase rapidly as F increased. In meshes with F from -1 to 0 for example, the collapse occurrence rate was about 7%, but if F was 2.5 or higher, the failure occurrence ratio was 20% or more. This shows that it is possible to evaluate relative degree of danger of landslide using both the Rokko Equation and the Chuetsu Equation.

If the F is smaller than 0, the values of P are relatively larger those of Rokko Mountain and Kozushima Island. So, next Figure 6 shows the result of using F calculated by Rokko Equation to calculate F and the percentage of shallow landslide meshes and the percentage of deep-seated landslide meshes. As shown by this figure, no remarkable correlation was found between F and the percentage of all meshes with each score that are deep-seated landslide meshes. And the percentage of shallow landslide meshes was 2% or less when F was -0.5 or less, but 29% of meshes when F was 2.5 or more.

4. Conclusion

A linear equation with the gradient, average curvature, and maximum acceleration as its explanatory variables was developed as a practical method of evaluating the probability of seismic shallow landslide occurrence using the dataset of Hyogo-ken Nambu earthquake. As a result of applying the linear discrimination equation to the Kozushima Island earthquake and Niigata-ken Chuetsu Earthquake, the discriminant score — landslide probability relationship varied according to the geology and the earthquake, but the ratio of landslide area tended to increase as the discriminant score rose. This means that it is concluded that the method proposed to evaluate the relative slope danger is highly versatile. Further, the precision was almost identical to that of the equation prepared based on the collapse distribution of the Kozushima and the Chuetsu Earth-

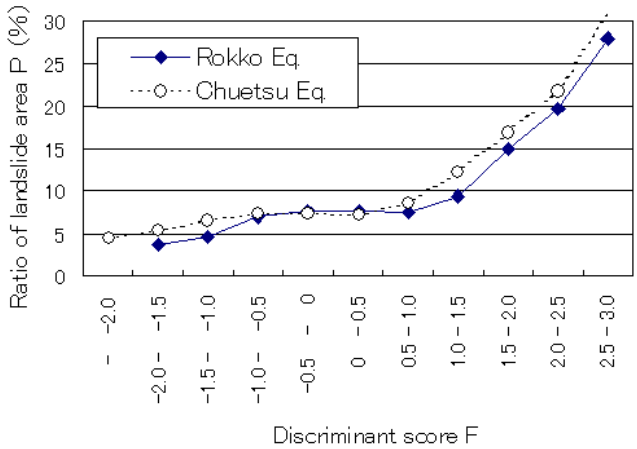

Fig. 6. Relationship between the discriminant score F and percentage of landslide occurrence area P of both seep-seated landslide and shallow landslide in Chuetsu region

quake, respectively. While, this study has shown that Rokko Equation cannot predict deep-seated landslide occurrence locations. That is, it can be thought that our proposed approach is highly applicable and practical to predict dangerous area of the seismic shallow landslide occurrence.

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