Earthquake-induced landslide susceptibility evaluation using a regression equation of seismic residual displacement over a wide area

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ABSTRACT

This study describes the evaluation of earthquake-induced landslide susceptibility over a wide area. An index of landslide susceptibility is the seismic residual displacement calculated from a regression equation using a simple slope model. A method for creating a data file for estimating landslide susceptibility is discussed. The data file for the seismic residual displacement calculation would include parameters pertaining to the center, slope inclination, azimuth, geology, unit weight, and strength in each grid in the target region. Thirty-two directions are studied to determine the predominant direction of slope failure. Using this data file, regional landslide susceptibility maps can be created using the classified seismic residual displacement. To validate the proposed method, the created regional landslide susceptibility map is compared to the landslide inventory map of the 2004 mid-Niigata Prefecture earthquake.

Keywords: slope; landslide susceptibility; seismic residual displacement

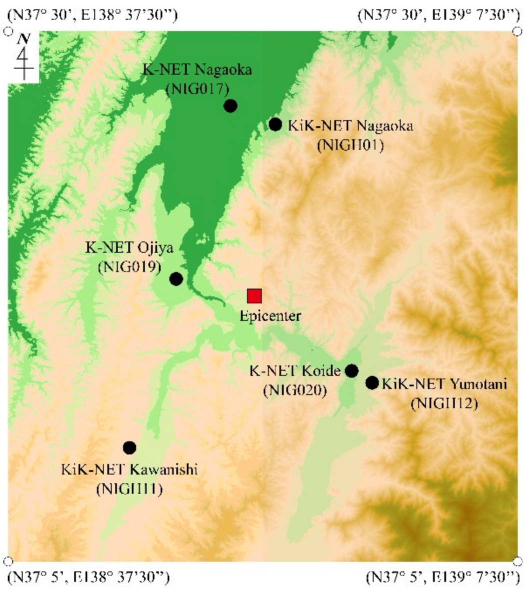
1 INTRODUCTION

Japan is one of the nations that is most susceptible to earthquakes. When a large earthquake occurs, many houses, buildings, and infrastructures collapse, and many landslides occur. Recently, numerous buildings and civil engineering structures were damaged owing to the Kumamoto earthquake that occurred on April 16, 2016, and many natural slopes collapsed. In particular, as shown in Fig. 1, the Aso Bridge collapsed as a result of a large deep-seated landslide in the Tateno district of Minamiaso village. The scale of the deep-seated landslide was estimated to be approximately 700 and 200 m in collapse length and width, respectively, with approximately 500,000 m^3 of collapsed soil. It is not realistic to use structural measures to prevent the occurrence of all slope failures caused by earthquakes. Non-structural measures are important to reduce the extent of damage and to assist evacuation prior to the disaster.

Fig. 1. Deep-seated landslide due to the 2016 Kumamoto earthquake in the Tateno distinct of Minamiaso village. This photograph was taken by Asia Air Survey Co., Ltd.

2 OBJECTIVES

The United State Geological Survey (USGS) produces landslide susceptibility maps that describe the relative likelihood of future landsliding based solely on the intrinsic properties of a locale or site. This research proposes a method for creating an earthquake-induced landslide susceptibility map with an index of seismic residual displacement, using an observed seismic record obtained after the earthquake. In this research, a method for creating an earthquake-induced landslide susceptibility map is proposed based on a method using the regression equation of the Newmark method adopted in the California Geological Survey of the US. To verify the validity of the proposed method, it was applied to landslides triggered by the mid-Niigata Prefecture earthquake in 2004, and compared with the actual inventory map created after the earthquake. The proposed regional landslide susceptibility map will be useful for understanding potential slope failure locations and magnitudes of damage, as well as for planning field investigations and to prevent secondary disasters immediately after earthquakes.



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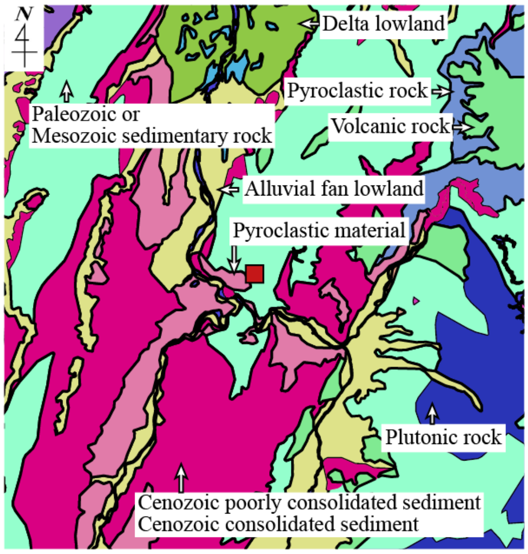

Fig. 3. Geological map of the target region; the map was created from part of the seamless data used in the land conservation map (1:200,000) produced by the Ministry of Land, Infrastructure, Transport and Tourism.

3 CREATION METHOD OF EARTHQUAKE-INDUCED LANDSLIDE SUSCEPTIBILITY MAP

The following are essential to evaluate the earthquake-landslide susceptibility: a discrete elevation model (DEM), topographical information, and geotechnical information such as the geotechnical strength parameters according to its geology of the target region. Along with this information, earthquake information, such as acceleration time history at multiple observation stations in the vicinity of the epicenter, should be obtained. Based on this information, the seismic residual displacement can be calculated as an index, and landslide susceptibility can be visually mapped to predict future landslide risk.

3.1 Study area

The study area of the earthquake-induced landslide susceptibility created by the proposed method was set to a range of 46,243 m in length and 44,457 m in width, centered at the epicenter of the mid-Niigata Prefecture earthquake, as shown in Fig. 2. This is based on the basic geographic data from the Geographical Survey Institute of Japan. Based on this 10-m DEM data, triangle elements were created by bisecting all of the grids, and the slope and direction of the plane constituted by the triangles were calculated and assigned to the barycentric coordinates. In this study, to calculate the residual displacement at the time of the earthquake for each slope direction, the azimuth of the slope was set to 32 azimuths.

3.2 Geological and geotechnical data

For the geological map of the study area, part of the seamless data used in the land conservation map (1:200,000) produced by the Ministry of Land, Infrastructure, Transport and Tourism was used. Fig. 3 shows the geological map of the study area. Concerning the test results of Takahashi et al. (2004) and Abe et al. (2006), the friction angle and cohesion of the bedding plane were set at 35° and 0 kPa, respectively. Commonly adopted values were used for the unit weight and strength parameters. Table 1 shows the unit weight and strength parameters used in this study.

Table 1. Geomaterial properties.

Geology	Unit weight (kN/m^3)	Friction angle (°)	Cohesion (kPa)
Delta lowland	15.49	30	0
Alluvial lowland	15.49	30	0
Cenozoic poorly consolidated sediment Cenozoic consolidated sediment	16.67	35	0
Bedding plane of sedimentary rock	20.00	35	0
Pyroclastic material	20.00	35	0
Bedding plane of pyroclastic rock	20.00	35	0
Bedding plane of volcanic rock	20.00	35	0
Bedding plane of plutonic rock	20.00	35	0

3.3 Estimation of the time history of acceleration at a specific location

A time history of acceleration at a specific location can be estimated from the record of the observatory near the epicenter. To estimate the time history of acceleration at the specific location, it is necessary to determine the maximum acceleration and the shape of the waveform. In this study, the maximum acceleration was estimated using the inverse distance weighting method and the acceleration record of the observatory near the epicenter. Moreover, the waveform was used with referring to that of the nearest observation station.

3.4 Slope model and yield acceleration

A simple infinite slope model was used to evaluate the landslide susceptibility in a wide area. This slope model is a common model that is often used in evaluating landslide susceptibility. Kieffer et al. (2006) reported in the field investigation after the mid-Niigata Prefecture earthquake that shallow collapse of a layer thickness of 1 to 2 m occurred parallel to the slope on most slopes. From this observation, the landslide susceptibility was evaluated with a constant sliding mass thickness of 2 m.

The slope yield acceleration can be calculated as the acceleration with a seismic safety factor of 1.0 during shaking, as follows:

$$a_c = \frac{c(1+\tan^2\alpha)}{\gamma h(1+\tan\alpha\cdot\tan\phi)} - \tan(\alpha-\phi) \qquad (1)$$

where a_c is the horizontal seismic yield coefficient, h is the depth of the sliding mass, α is the slope inclination, γ is the unit weight of the sliding mass, ϕ is the friction angle of the sliding mass, c is the cohesion of the sliding mass.

3.5 Estimation of seismic residual displacement

Jibson (2007) proposed the following regression equation of seismic residual displacement calculated using the Newmark method with 2270 strong motion records measured in 30 earthquakes.

$$\log D_N = C_1 \log I_a + C_2 \log\frac{a_c}{a_{\max}} + C_3 \pm \varepsilon \qquad (2)$$

where D_N is the seismic residual displacement; a_{max} is the maximum acceleration at the ground; I_a is the Arias intensity; C_1, C_2, and C_3 are the parameters of the regression equation; and ε is the estimation error. Recently, Hsieh and Lee (2011) proposed another regression equation for seismic residual displacement.

$$\log D_N = C_1 \log I_a + C_2 a_c + C_3 a_c \log I_a + C_4 \pm \varepsilon \qquad (3)$$

where C_4 is a parameter of the regression equation. This study compared these two equations and selected one regression equation with a smaller estimation error.

To determine the parameters of the regression equations of Eqs. (2) and (3), it is necessary to select observation stations such that Ia is distributed over a wide range. In this study, K - NET Ojiya, K - NET Koide, and KiK - NET Nagaoka were selected; these are observatory stations close to the epicenter. The seismic yield coefficients in Eqs. (2) and (4) were set as 0.02, 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30, respectively, by changing the slope inclination while maintaining constant strength parameters and a constant sliding thickness of 2 m. Under this calculation condition, the seismic residual displacement was calculated using the Newmark method and was arranged for each seismic yield coefficients. The parameters were determined using Eqs. (2) and (4) to match the seismic residual displacement obtained using the Newmark method. The identification result is shown in Fig. 6, and the regression expression is given below.

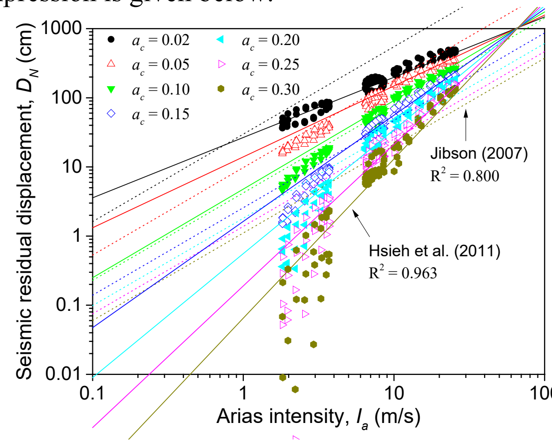

Fig. 4. Estimation of seismic residual displacement by the regression equation of seismic residual displacement calculated by the Newmark method.

$$\log D_N = 1.264 \log I_a - 1.216 \log\frac{a_c}{a_{\max}} - 0.592 \qquad (4)$$

$$\log D_N = 0.770 \log I_a - 9.333 a_c + 5.114 a_c \log I_a + 1.612 \qquad (5)$$

Fig. 4 shows that the seismic residual displacement can be estimated for a wide range of I_a. The R^2 values of Eqs. (5) and (6) were 0.800 and 0.963, respectively. Therefore, Eq. (6) is adopted as the regression equation of the Newmark method in this research.

3.6 Seismic residual displacement map and its verification

Fig. 5 shows the seismic residual displacement estimated using Eq. (6). In addition, it shows an inventory map consolidated from three inventory maps published by the Geographical Survey Institute. It can be seen that the location of slope collapse is where the seismic residual displacement is large. Here, to confirm the consistency between the inventory map and the estimated value of the seismic residual displacement, the prediction rate for failed slopes $PR_{failure} = n_1/(n_1+n_2)$, prediction rate for stable slopes $PR_{stable} = n_4/(n_3+n_4)$, and average prediction rate for failed and stable slopes $PR_{average} = (PR_{failure} + PR_{stable})/2$ were calculated with reference to Shinoda and Miyata (2017), where n_1 is the number of pixels of the predicted landslides in accordance with observed landslides, n_2 is the number of pixels of stable slopes in discordance with the observed landslides, n_3 is the number of pixels of predicted landslides in discordance with the stable slopes, n_4 is the number of pixels of stable slopes in accordance with the stable slopes.

These three parameters have upper and lower bound values such as one (perfect prediction) and zero (perfectly failed prediction), respectively.

A threshold of slope failure is a key parameter with which to calculate the prediction rates. In this study, the

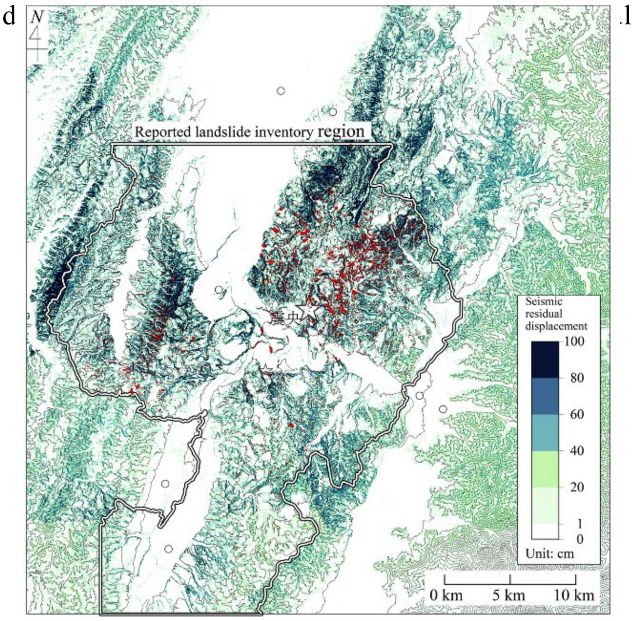

Fig. 5. Seismic residual displacement map of landslides triggered by the mid-Niigata Prefecture earthquake in 2004

displacement of greater than 5 cm calculated using the Newmark method. The prediction rates are calculated as follows: $PR_{failure}$ is 75%, PR_{stable} is 58%, and $PR_{average}$ is 67%. The estimation result of the seismic residual displacement is substantially in agreement with that of the observed landslides.

3.7 Earthquake-induced landslide susceptibility map

To facilitate easy understanding of landslide susceptibility and make it publicly available, it is considered useful to indicate the landslide susceptibility as a degree of susceptibility according to the value of seismic residual displacement. Therefore, this study classified the following four groups: susceptibility level I: $d < 5$ cm, level II: $5 \text{ cm} < d < 15$ cm, level III: $15 \text{ cm} < d < 30$ cm, and level IV: $30 \text{ cm} < d$. Here, d is the calculated seismic residual displacement. Fig. 8 shows the result of transforming the seismic residual displacement map shown in Fig. 7. In Fig. 8, the landslide susceptibility is divided into four groups, and it is possible to easily understand the regional landslide susceptibility.

4 CONCLUSION

This paper describes a method of creating a regional earthquake-induced landslide susceptibility map based on seismic residual displacement using a simple slope model. A regression equation was used to estimate the seismic residual displacement during the earthquake. The landslide susceptibility created by the proposed method is in good agreement with the actual inventory map created after the mid-Niigata Prefecture earthquake.

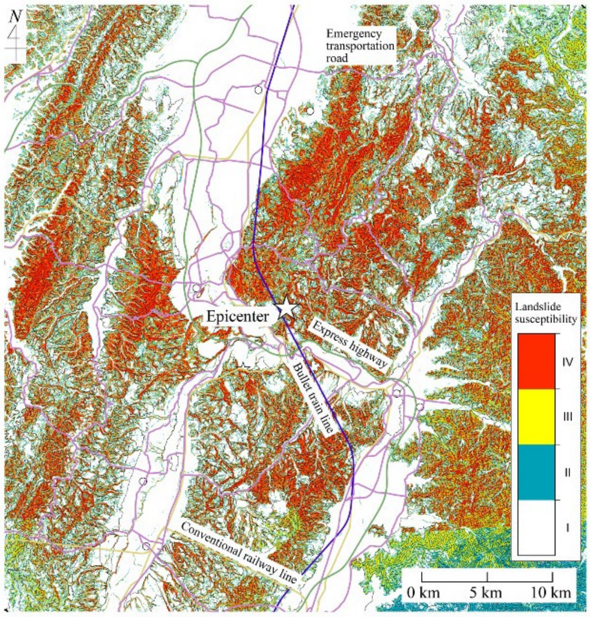

Fig. 6. Landslide susceptibility triggered by the mid-Niigata Prefecture earthquake in 2004.

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