Hazard mapping of earthquake-induced landslides for three scenario earthquakes by using Lidar DEM and airborne resistivity data

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ABSTRACT
Shikoku Island which is located in southwest Japan, has been threatened by great earthquakes occurred along the Nankai Trough and the Median Tectonic Line. We proposed a method to estimate the landslide susceptible slopes by combining estimated looseness of the bedrocks and topographical effect of amplifying seismic wave. It is named as Index of susceptibility for earthquake-induced landslides (ISEL). We have applied this method to natural slopes along the Median Tectonic Line in northeast Shikoku. Three susceptibility maps for earthquake-induced landslides are provided 150 gals for the Nankai Earthquake of magnitude 8, 300gal for the Nankai Trough Earthquake of magnitude 9 and 600 gal for the Median Tectonic Line Earthquake of magnitude 8. These earthquake-induced landslide hazard maps are useful for estimating damages and risk management for future great earthquake.

1. INTRODUCTION

Asia has been the site of several giant earthquakes within a decade, including the 1999 Chi-Chi earthquake in Taiwan, the 2005 Kashmir earthquake in Pakistan, the 2008 Wenchuan earthquake in China, the 2011 Tohoku earthquake and the 2016 Kumamoto earthquake. In mountainous areas, landslides induced by earthquakes cause substantial damage to the lives, infrastructure, environment, and economies.

Shikoku Island which is located in southwest Japan, has been threatened by great earthquakes occurred along the Nankai Trough and the Median Tectonic Line. Estimated magnitude of the Nankai Earthquakes is 8.4 and the largest magnitude along the Nankai Trough is estimated 9.0. Estimated magnitude of the Median Tectonic Line Earthquakes in northeastern part of Shikoku is 8.0 or more.

In order to estimate the susceptibility of a landslide, indicators of looseness are useful. Surface morphology and topographic characteristics are useful information for finding loosened slopes (Tabor 1971; Chigira 1992; Chigira and Kiho 1994). Nonomura and Hasegawa (2013) proposed an algorithm for automatically extracting flexural toppled slopes using digital elevation model (DEM) with 10m resolution. This algorithm is useful for finding earthquake-induced deep-seated landslide susceptible zones, but it is difficult to use it directly for estimating susceptible zones to landslides due to earthquakes.

Core drilling and ground-based geophysical surveys provide high-resolution subsurface data, such as geological structure and looseness, but these methods are not applicable to regional research due to its cost, especially in mountainous regions. On the other hand, airborne geophysical surveys can be utilized as a faster method compared ground-based geophysical surveys. One of the major airborne geophysical prospecting methods is helicopter-borne electromagnetic resistivity survey (HEM). Since the resistivity data is related several geological factors, such as water content, clay mineral, lithology and looseness of bedrocks, HEM data have been used to extrapolate data of field geological survey (Supper et al., 2013; Baroň et al., 2013; Schamper et al., 2014). To estimate the distribution of specific geological parameters from resistivity data, it needs to exclude the influence from other factors and extract the information related to only the target parameter.

In areas with wide coverage and limited accessibility, airborne survey is only approach to compensate the shortage of in-situ data. In order to estimate the loosened rock mass from airborne resistivity distribution, Nonomura et al. (2016) proposed a method for regionally mapping of gravitationally deformed and loosened slopes by using localized distribution of the relative resistivity, which is called the "average ruggedness of resistivity" to be an index of looseness.

To identify slopes susceptible to earthquake-induced landslide, both looseness of rock mass and topographical effect of amplifying seismic wave need to be considered. In this study, we propose a method to estimate susceptible zones to earthquake induced landslides by combining estimated looseness from the "average ruggedness of resistivity" data (Nonomura et al., 2016) and topographic effect which is quantified by using Digital Elevation Model (Uchida et al., 2004). Index of susceptibility for earthquake-induced landslide (ISEL) is proposed by combining looseness of rock mass and topographic effect. Then, we have prepared three susceptibility maps in Shikoku mountain range for earthquake-induced landslides 150 gals for the Nankai Earthquake of magnitude 8, 300gal for the Nankai Trough Earthquake of magni-tude 9 and 600 gal for the Median Tectonic Line Earthquake of magnitude 8.

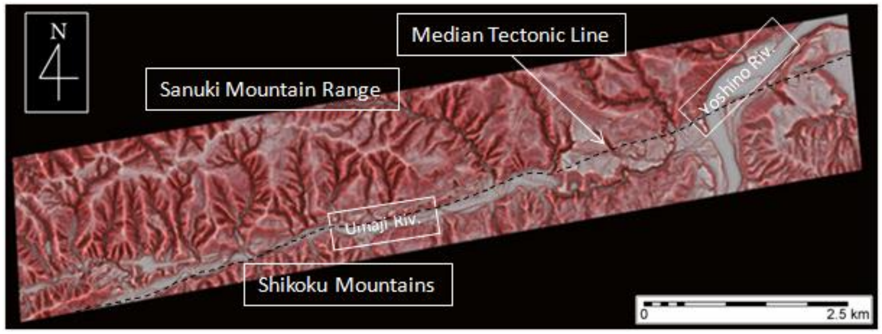
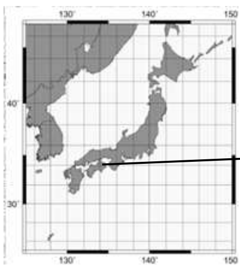


Figure1. Topography of the study area

2 STUDY AREA



...ed in northern part of Shikoku. T... e Median Tectonic Line active fa... the northern Sanuki. Mountain R... hikoku Mountains (Figure 1). ...ange is underlain by the Upper C... which consists mostly of a... andstone and shale. The S... rocks are distributed in the s... ns, and are mainly composed of pelitic schist and green schist. The Umaji River, which is a branch river of the Yoshino River flows eastward along the valley between the Sanuki Mountain Range and Shikoku Mountain Range. The Yoshino River flows northward from Shikoku Mountains and changes the flow direction toward east at the junction of the Umaji River.

3 METHODOLOGY

3.1. Concept of index of susceptibility for earthquake-induced landslides (ISEL)

In this study, we proposed a method to estimate landslide susceptibility by combining quantitative information related to topographic effect of amplifying seismic vibrations and looseness of bedrock (Figure 2).

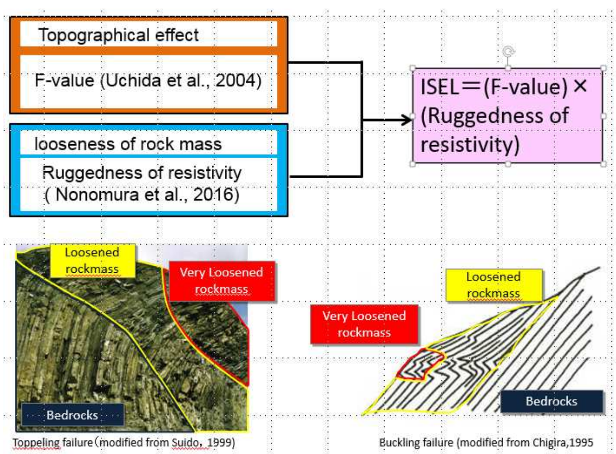


Figure2. Concept of index of susceptibility for earthquake-induced landslides (ISEL)

Figure 3 shows the flow of the analysis.

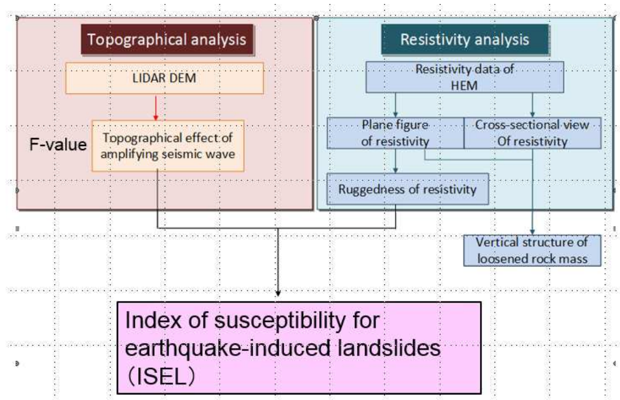


Figure3. Flow of estimating index of susceptibility for earthquake-induced landslide

3.2. A method to estimate topographic effect of amplifying seismic vibrations

Several researches noted that extremely high seismic accelerations were found at sites located on topographic ridges (e.g., Miles and Keefer 2000). Many models exist for assessing the stability of slopes during earthquakes. Traditionally, landslide potential has been analyzed by applying deterministic and static stability models. Both intrinsic and extrinsic parameters are used for analysis. Extrinsic variables are site specific and possess a temporal distribution, and the intrinsic parameters used in analysis usually have many restrictions to collect; such as bedrock geology, geomorphology, soil depth, soil type, slope gradient, slope aspect, slope curvature, elevation, engineering properties of the slope material, land use patterns, and drainage patterns. To overcome this issue, Uchida et al. (2004) statistically quantified the topographical effect on earthquake-induced shallow landslide susceptibility using slope and mean curvature calculated with 10m resolution DEM based on extensive study of 1995 Hanshin-Awaji Earthquake (Kobe earthquake) in the Rokko mountain range underlain by granite and covering weathered sandy soils (Equation 1).

F=0.075 × Slope-8.9 × Mean curvature+0.0056 × Maximum Acceleration-3.2 (1)

When F value is smaller than zero, it means that there is no possibility to occur shallow landslide. Larger F value shows higher probability of the landslide occurrence. It has been noted that seismic wave tend to be amplified at ridge with steep slope. The Equation 1 is applicable to areas even with different lithology. The applicability of F-value was confirmed in the areas damaged by the 2008 Chuetsu-oki earthquake underlain by Pleistocene and Pliocene sedimentary rocks which are different lithology from Rokko mountain range (Hasegawa et al. 2009). However, F-value is not applicable to deep-seated landslide at 2004 Chuetsu earthquake (Uchida et al., 2006). This is probably because susceptibility of shallow landslides is sensitive to the topography. On the other hand, the susceptibility of deep-seated landslide should be largely related to the subsurface ground condition, such as looseness of slopes and pre-existing sliding surface.

3.3. A method to estimate looseness

In this study, we focus on the looseness of slopes. Airborne geophysics measurement is the only remote-sensing method to survey both near surface parameters and subsurface geological structures below the ground surface down to several tens to hundreds of meters. One of the major airborne geophysical prospecting methods is helicopter-borne electromagnetic resistivity survey (HEM). Because of helicopter-borne observation, it can be applicable even in steep alpine terrains where accessible routes are limited. In the several research projects, airborne geophysical measurement was used for mapping landslide mass and the applicability was evaluated. (Schrott and Sass, 2008; Supper et al., 2008; Nakazato and Konishi, 2005; Tofani et al., 2013).

Although the HEM has recently evolved into a promising method of widely investigating subsurface properties, the applicability to landslide detection and mapping has some limitations. Since the resistivity is influenced by several factors; not only loosened bedrock but also water content and clay mineral, it is difficult to estimate the amount or degree of each parameter. The resistivity includes water and air content information. Several researches have focused on the relative changes in resistivity to indicate the bedrock features, such as heavily fractured or sound bedrock (Leucci and Giorgi, 2005; Steelman et al., 2015). It is known that higher resistivity zones are corresponding to fractured rock mass under relatively dry condition because fractured rocks are filled with air (Palacky, 2008; Leucci and Giorgi, 2005). In Nonomura et al. (2016), “ruggedness of resistivity” was proposed as an index to estimate looseness of bedrock.

The details were explained in Nonomura et al (2016), but it is briefly explained in the followings. Result of calculating the localized distribution of 140 kHz resistivity data within a radial distance in one direction is called “ruggedness of resistivity”. A positive value of ruggedness of resistivity means relatively higher resistivity at the focal pixel, and the larger values indicate much higher than that of surrounding pixels (Figure 4). Ruggedness along all eight azimuthal directions is averaged, called the “average ruggedness of resistivity”, is useful to emphasize the localized relative resistivity distribution within a radial distance. The index was validated by comparing with the field observed rock mass structural data. In this study, looseness of the bedrock is estimated by using “average ruggedness of resistivity”.

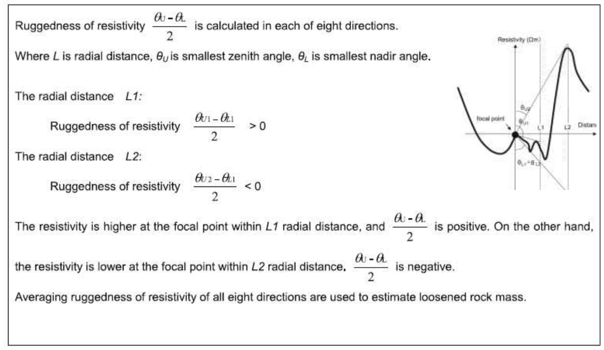


Figure 4. Ruggedness of resistivity is available to differentiate fractured bedrock from sound bedrock using shallow layer (140 kHz returns data for depths of 5–30 m). (Nonomura et al., 2106)

3.3 A method to estimate landslide susceptibility

Landslides tend to occur at slopes of loosened bedrocks influenced by strong vibrations during earthquakes. Index of susceptibility for earthquake-induced landslides (ISEL) is proposed by multiplying F-value and “average ruggedness of resistivity” as the estimated looseness from airborne resistivity data.

ISEL = F-value × average ruggedness of resistivity (2)

In the F-value equation, the magnitude of the earthquake can be included as the peak ground acceleration (Equation 1). F-value is used as the seismic wave amplifying topography index. Pixels in which the F-values with less than 0 are excluded because the topographically amplification influence is estimated to be small. Positive value of average ruggedness of resistivity means that resistivity is larger than that of surrounding areas, and it can be regarded to be loosened slopes. Therefore, pixel in which the average ruggedness of resistivity with larger than zero is estimated to be a part of loosened zones. High ISEL values show loosened zones with largely amplifying topography, namely, highly susceptible to landslides.

4 RESULTS

4.1 TOPOGRAPHIC ANALISYS

Figure 5 shows the distribution of F-value of three scenario earthquakes. Estimated PGA are 150gal for a small-scale Nankai Trough Earthquake, 300gal for a large-scale Nankai Trough Earthquake and 600gal for a

Median Tectonic Line Earthquake. Although F-value increases according to increases of PGA, we cannot identify susceptible slopes individually.

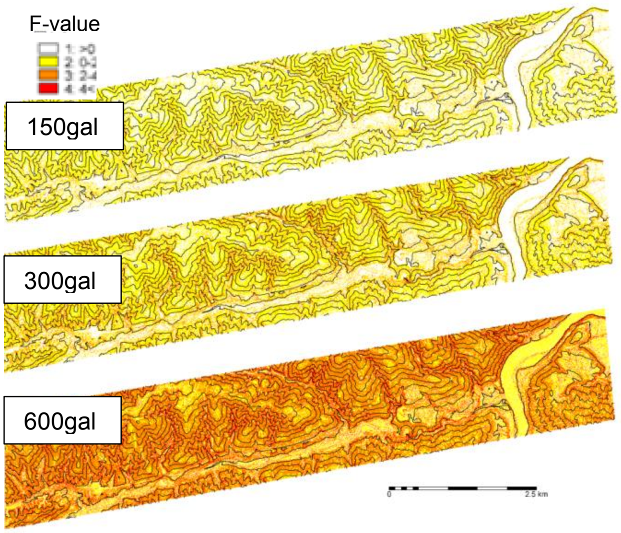


Figure 5 F-value for three scenario earthquakes.

4.2 Resistivity Analysis

4.2.1 Airborne electromagnetic survey

Airborne electromagnetic survey systems use pairs of transmitter and receiver coils. Oscillating primary magnetic field signals are generated by sinusoidal current flow through the transmitter coils at discrete frequencies to induce eddy currents in the subsurface, which are recorded by the receiver coils.

The system we used had transmitting and receiving coils with frequencies of 140 kHz, 31 kHz, 6.9 kHz, 3.3 kHz, 1.5 kHz, and 340 Hz inside a cylindrical container (the “bird”) that was suspended below the helicopter by 30-m-long wires and maintained at a height of about 35 m above the ground during data recording. The high frequencies record data from shallow layers (140 kHz returns data for depths of 5–30 m) is used. The study area was covered by 245 flight lines with 50-m interval.

Figure 6 shows the surface resistivity map (140kHz: 5-30m in depth) of the study area.

4.2.2 Ruggedness of resistivity

Figure 7 shows average ruggedness of resistivity map （Radial disatance:100m) of the study area. Area of positive value of average ruggedness of resistivity indicate the loosened zones of slopes. Figure 8 shows only the positive value of average ruggedness of resistivity map （Radial disatance:100m) of the study area.

4.3 Susceptibility maps for earthquake-induced landslides

We have prepared three susceptibility maps for earthquake-induced landslides 150 gals for the Nankai Earthquake of magnitude 8, 300gal for the Nankai Trough Earthquake of magnitude 9 and 600 gal for the Median Tectonic Line Earthquake of magnitude 8. Figure 10 shows distribution of index of susceptibility for earthquake-induced landslides (ISEL) of the study area. Susceptible slopes for earthquake-induced landslides are individually identified. As the PGA increase, highly susceptible slopes for earthquake-induced increase.

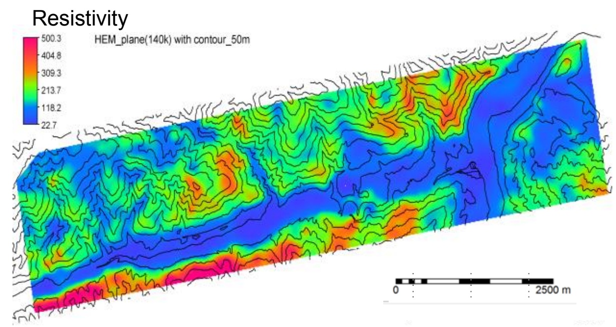


Figure 6. Surface resistivity map (140kHz: 5-30m in depth) of the study area.

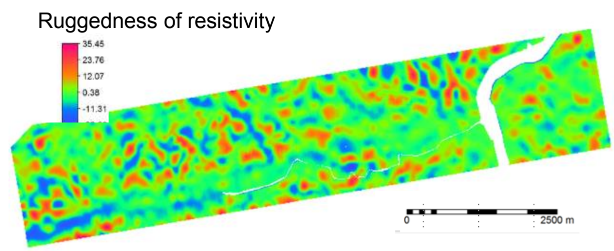


Figure 7. Average ruggedness of resistivity map（Radial disatance:100m) of the study area.

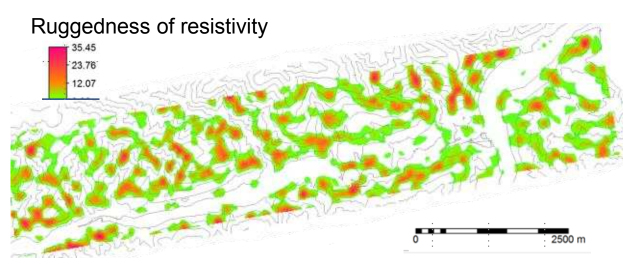


Figure 8. Positive value of average ruggedness of resistivity map （Radial disatance:100m) of the study area.

4.4 Field investigation of susceptibility slope for earthquake-induced landslides

Figure 11 shows a field investigation site of susceptibility slope for earthquake-induced landslides. Field observation of rockmass and borehole data of the slope indicate that the higher susceptible slope correspond to highly loosened rockamass of the slope (Figure 12).

This suggests that verification by the borehole data and field geological survey is usefull. Verification by real earthquakes is necessary for improvement of this method.

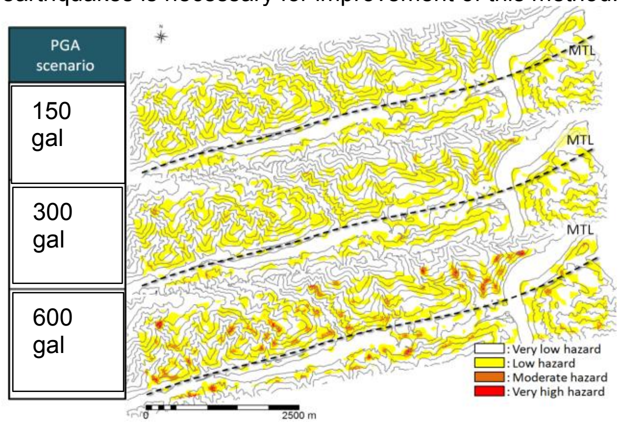


Figure 10 Index of susceptibility for earthquake-induced landslides (ISEL) for three scenario earthquakes of the study area

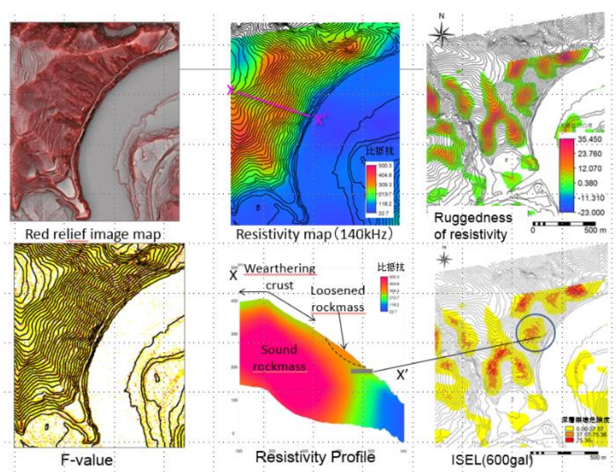


Figure 11 Field investigation site of susceptibility slope for earthquake-induced landslides.

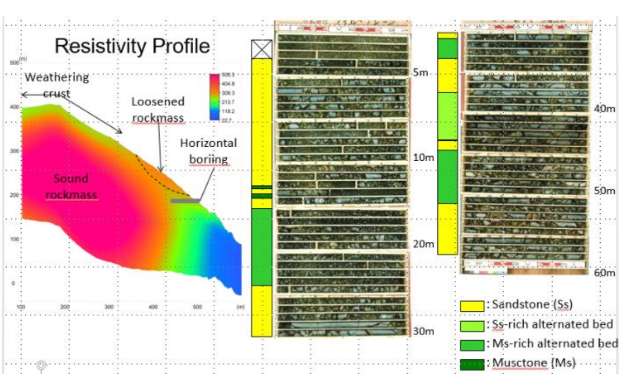


Figure 12 Borehole data of higher susceptible slope earthquake-induced landslides.

5 CONCLUSION

We have developed an effective method of hazard mapping for earthquake-induced landslides. Conclusions are summarized as follows:

1) Susceptible slopes for earthquake-induced landslides are extracted by evaluating both topographic effect of tremor and loosened rockmass.
2) Index of susceptibility for earthquake-induced landslides (ISEL) is proposed for estimating susceptibility to earthquake induced landslide by combining seismic wave amplifying topography index (F-value) and looseness index (ruggedness of resisitivity).
3) Three hazard maps for earthquake-induced landslides are proposed by using F-value and ruggedness of resistivity.
4) Risk of earthquake-induced landslides increase according to maximum acceleration.
5) Verification by the borehole data and field geological survey is usefull.
6) Verification by real earthquakes is necessary for improvement of this method.

Acknowledgment

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