Hazard mapping of earthquake-induced deep-seated catastrophic landslide using Helicopter-borne electromagnetic (HEM) data

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Abstract

Asia has been the site of several giant earthquakes within a few decades. Although it is impossible to stop large-scale landslides that might be induced by the next earthquake, the damage can be mitigated by determining landslide-susceptible areas and estimating the hazard beforehand. Large number of articles is proposing many different methods of landslide-susceptibility estimation. Topographical approaches are commonly used. Topographical features can be used for roughly estimating distribution of large-scale landslide, but these are not directly related to the subsurface geological conditions. On the other hand, geophysical surveys are useful techniques for estimation of regional bedrock conditions. One of the geophysical parameters, resistivity can be available to estimate subsurface features, although resistivity tends to be affected by several compositional characteristics of bedrocks, such as lithology, mineralogy, and water content.

The aim of this study is to develop an algorithm to predict the susceptible slopes to earthquake induced large-scale landslide using Helicopter-borne electromagnetic (HEM) data. The algorithm was developed and applied to slopes along roads to estimate the situation of catastrophic deep-seated landslide after huge earthquake.

Keywords: resistivity, deep-seated catastrophic landslide, disaster risk management

1. Introduction

Asia has been the site of several giant earthquakes within a decade, the 1999 Chi-Chi earthquake in Taiwan, the 2005 Kashmir earthquake in Pakistan, the 2008 Iwate-Miyagi Nairiku earthquake in Japan, the 2008 Wenchuan earthquake in China and the 2011 Tohoku earthquake (Shou and Wang 2003; Chigira and Yagi 2006; Sato et al. 2007; Wang et al., 2003; Chigira et al. 2010; Maeda et al., 2011). In mountainous areas, landslides induced by earthquakes cause substantial damage to the lives, infrastructure, environment, and economies. Although it is impossible to completely stop large-scale landslides that might be induced by the next earthquake, the damage can be mitigated by determining landslide-susceptible areas, estimating the hazard, and preparing it beforehand.

Huge earthquakes have triggered several thousand landslides. Most landslides were small and middle scale shallow landslide. Deep-seated large-scale landslides are few (less than 10%), but the damage of each landslide was serious. Deep-seated landslide occurred on the surfaces of rupture or at loosened rock mass.

In geological studies, several geophysical methods are used to investigate the subsurface geological condition. Airborne geophysical surveys are useful techniques for estimation of regional bedrock conditions. Those can be completed much faster than ground-based soundings, without topographically limitation even in the steep slopes. Since resistivity tends to be affected by several compositional characteristics of bedrocks, it needs to be estimated the distribution of loosened zones from the resistivity data.

To identify slopes susceptible to earthquake-induced deep-seated catastrophic landslide, both looseness of rock mass and topographical effect of amplifying seismic wave needs to be considered. Hasegawa et al. (2015) proposed the index of susceptibility for earthquake-induced deep-seated catastrophic landslides (ISEDCL) by combining looseness of rock mass and topographic effect of earthquake induced landslide. Looseness of rock mass is estimated by using resistivity and topographical effect of amplifying seismic wave is quantified by using Digital Elevation Model.

In this study, the ISEDCL is applied to slopes along the crucial national road for emergent transportation just after the huge Nankai Earthquake. ISEDCL was proposed as an index for quantifying looseness of rock mass by using resistivity data. Since the resistivity is influenced by several factors, such as mineralogy, looseness, lithology, and water content, the usefulness need to be investigated under several different geological condition.

2. Data and method

2.1 Resistivity

Resistivity data have been commonly used to determine landslide susceptibility, where main factors of landslides are the presence of water, production of clay minerals, and the existence of a slip surface, which are indicated as lower resistivity areas (Lebourg et al., 2010). Airborne electromagnetic survey data provide information about the distribution of subsurface resistivity (Huang and Fraser, 1996; Beard, 2000). The method is based on the propagation of electromagnetic fields, which induce currents in the subsurface. 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 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. In order to predict the distribution of loosened rock mass, “ruggedness of resistivity” index was developed (Nonomura et al., 2012). The unsaturated fractured bedrocks would have relatively higher resistivity (Sass, 2006). Loosened beds situated above the water table in highly fractured and permeable condition show higher resistivity than sound bedrocks in the same lithology. At the same time, resistivity tends to be affected by several other compositional characteristics of bedrocks, such as lithology, mineralogy, and particle size. In order to investigate the distribution of the loosened zones and exclude lithological impact from the resistivity data, “ruggedness of resistivity” was proposed (Nonomura et al., 2012). The index is available to differentiate fractured bedrock from sound bedrock using shallow layer (140 kHz returns data for depths of 5–30 m). In this study, we investigate the availability of this method by applying it to the study area with different lithological condition.

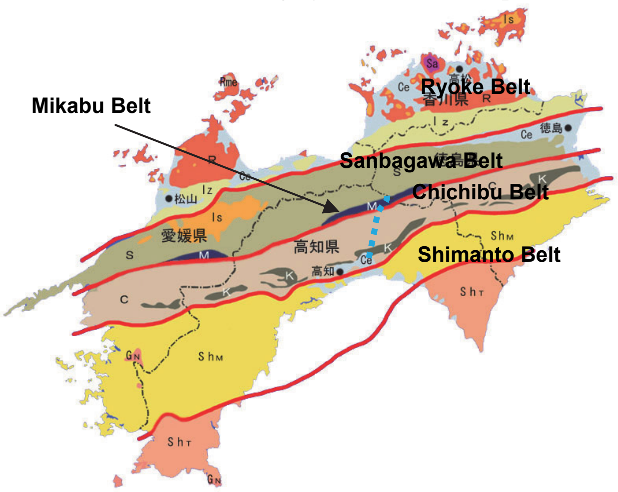

Fig. 1 The geology of Shikoku (after Geological Survey Enterprises Association Shikoku HP). The blue dot line shows the study area.

2.2 Index of susceptibility for earthquake-induced deep-seated catastrophic landslides (ISEDCL)

Deep-seated catastrophic landslides tend to occur at loosened zones with topo-graphical effect of amplifying seismic wave. The topographic effects on earth-quake ground motion have been well documented. It has been noted that slope and average curvature are very important parameters for quantifying the topographical potential of earthquake-induced landslide. Uchida et al. (2004) quantified the topographical effect on earthquake-induced shallow landslide susceptibility and proposed a parameter, which is called ‘F-value’ to estimate the landslide susceptibility by extensively studying landslide damage in the Rokko mountain range (granitic terrain) after the Hanshin-Awaji Earthquake (Kobe earthquake) of 1995 (Equation 1).

$$F = 0.075\times\text{Slope} - 8.9\times\text{Meancurvature} + 0.0056\times\text{peak ground accerelation} - 3.2 \quad (1)$$

The applicability of F-value was shown in the 2008 Chuetsu-oki earthquake (Hasegawa et al., 2009). In this research, F-value was utilized to estimate the distribution of topographical effect of amplifying seismic wave. If F-value is larger than zero, there is some possibility to amplify seismic wave and occur shallow landslide.

Index of susceptibility for earthquake-induced deep-seated catastrophic land-slides (ISEDCL) is defined by multiplying F-value and ruggedness of resistivity. Ruggedness of resistivity is a parameter for estimating looseness of rock mass and F-value is used to quantify the possibility to amplifying seismic wave.

3. Study area

The study area is located at Shikoku mountains located between 33°50'26”N and 33°37'37”N latitude and between 135°38'00”E and 135°47'25”E longitude (Fig. 1). The Shikoku Island is located in the western

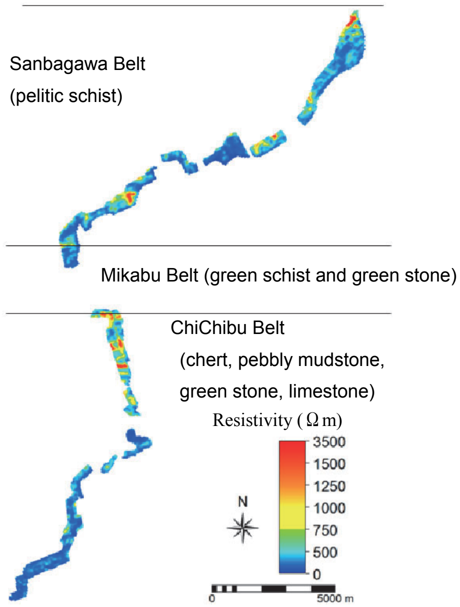

Fig. 2 Resistivity distribution in the three different geological belts.

part of Japan, and it can be roughly divided into five geological zones: Ryoke Belt, Sanbagawa Belt, Mikabu Belt, Chichibu Belt, and Shimanto Belt. The study area is located over Sanbagawa Belt, Mikabu Belt and Chichibu Belt. The Sanbagawa Belt is mainly composed of pelitic schist. Mikabu Belt is mainly composed of green schist and green stone. Chichibu Belt is composed of chert, siliceous mudstone, acid tuff, and limestone.

4. Result

4.1 Resistivity distribution

The resistivity distribution of 140 kHz electromagnetic wave shows strong contrast (Fig.2). Higher resistivity is found in Sanbagawa Belt with pelitic schist and in northern part of Chichibu Belt with chert. Lower resistivity is found in Mikabu Belt with green-schist and northern part of Chichibu belt with pebbly mudstone and green stones. The distribution of resistivity is influenced by the lithology.

In previous research (Nonomura et al., 2012), ISEDCL was developed as an index for quantifying looseness of rock mass for estimating loosened zones with less influence of lithology; higher resistivity zones correspond to loosened zones and lower resistivity zones correspond to less loosened zones within the radial distance. The test site was a small area under one type of lithology, alternation of sandstone and mudstone. In order to develop versatility of the ISEDCL, the capacity needs to be examined under several geological conditions.

4.2 Ruggedness of resistivity

In order to localize distribution of resistivity, the concept of openness is applied to resistivity data, instead of to DEM, and the distribution of relatively higher resistivity is estimated. It is called “ruggedness of resistivity”. To calculate ruggedness of resistivity, the zenith angle and the nadir angle from the point of nterest is calculated within a radial distance (L) along all eight azimuthal directions.

The radial distance L is one of key factors to define the range of area for calculating relative distribution of resistivity. In order to operationally estimate the

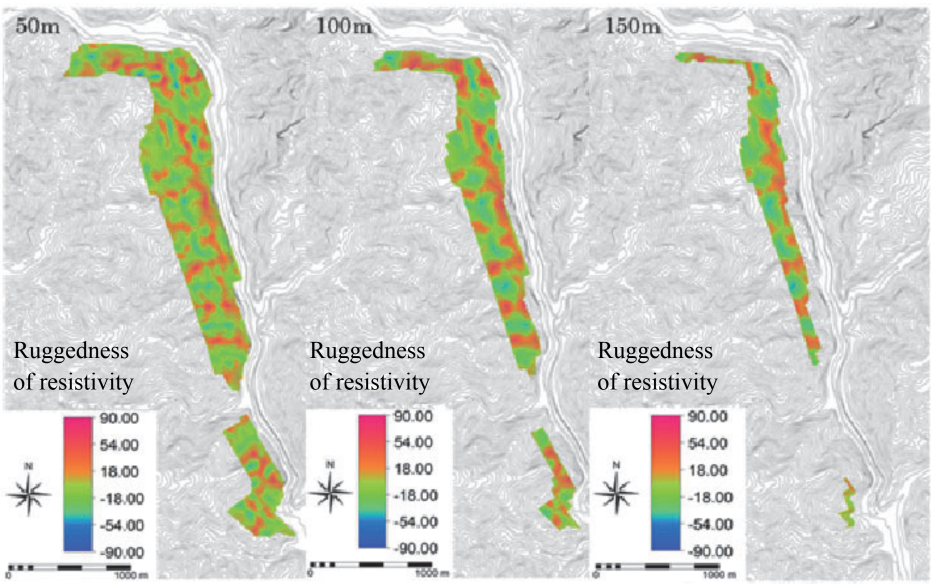

Fig. 3 Ruggedness of resistivity with different radial distance; 50m, 100m 150m

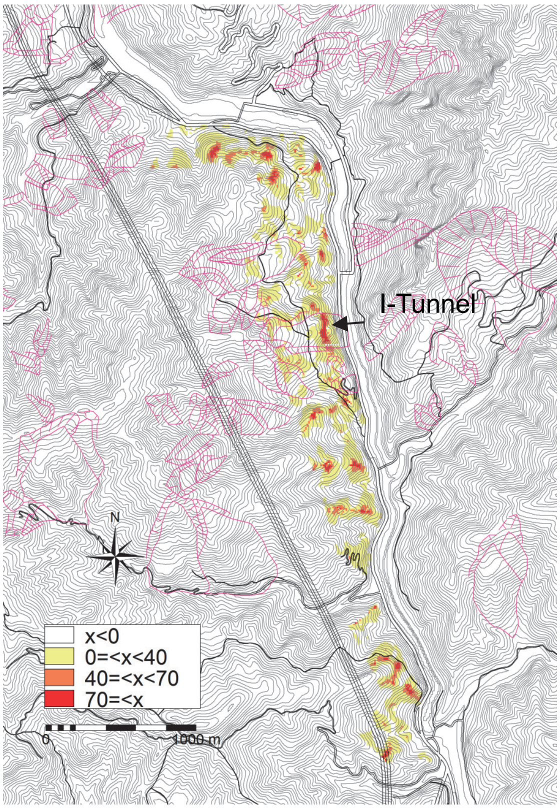

Fig. 4 ISEDCL estimated using the ruggedness of resistivity with 50 m radial distance and topographic effect of amplifying seismic wave, with peak ground acceleration (PGA) 400gal. ISEDCL is categorized into four levels

Fig. 5 Photos at I-Tunnel and slopes above the tunnel (a) Itagino tunnel (b) Rock mass with open crack above the tunnel (c) Toppled and fractured rock mass above the tunnel

looseness for deep-seated landslide susceptibility, appropriate radial distance is discussed.

Fig.3 show the ruggedness of resistivity with different L; L=50m, 100m, 150m. With longer radial distance, the ruggedness of resistivity shows more broad view of relative resistivity distribution. If the loosened is estimated with zones or some interval, longer radial distance is useful. If the looseness is estimated at each slope, localized relative distribution of resistivity is useful to identify the loosened slopes. In this study, looseness is estimated by using L=50 m in the slopes along the national road.

4.3 Validating ISEDCL in the field survey

ISEDCL is estimated using the ruggedness of resistivity with 50 m radial distance and topographic effect of amplifying seismic wave, F-value with peak ground acceleration (PGA) 400gal. The areas are categorized into four levels; very high hazard, high hazard, moderate, very low (Fig. 4). In the concentrated very high hazard zones along the road, the debris might damage the road and the road networks might be cut off.

In order to validate the estimated ISEDCL, the rock mass condition and the topographies were observed in the field (Fig. 5). Surrounding the I-Tunnel show the very high ISEDCL values. On the slopes above the tunnel, the rock mass fractured and loosened with many open cracks. Loosened rock masses bulge out with open cracks with 20 cm width. In this area, it was reported that the rock mass is gravitationally deformed and loosened due to toppling. Under strong rainfall, road section of Shikoku Regional Development Bureau office, which works on disaster risk management, close road to escape damage due to landslide.

The loss of the road network causes serious second damages. These earthquake-induced landslide hazard maps are useful for estimating damages and planning measures for future great earthquake and for planning bypass road to mitigate the damage as possible as we can.

5. Conclusions

Earthquake-induced landslide hazard maps are useful for estimating damages of the future great earthquake and planning measures to mitigate the damage as possible as. In this study, a method was developed to predict the susceptible slopes to earthquake induced large-scale landslide using Helicopter-borne electromagnetic (HEM) data and Digital Elevation Model (DEM). The method was applied to slopes along national roads which are expected to be emergency route when the great Nankai trough earthquake will occur.

The high frequencies record data of HEM indicate the geological information from shallow layers. In order to predict the distribution of loosened rock mass, “ruggedness of resistivity” index was developed (Nonomura et al., 2012). The unsaturated fractured bedrocks would have relatively higher resistivity (Sass, 2006). Loosened beds situated above the water table in highly fractured and permeable condition show higher resistivity than sound bedrocks in the same lithology. At the same time, resistivity tends to be affected by several other compositional characteristics of bedrocks, such as lithology, mineralogy, and particle size. In order to focus on the looseness, “ruggedness of resistivity” was proposed in the study area with several types of lithology.

Slopes above the I-Tunnel are estimated to be highly susceptible to landslide (high value of ISEDCL). By Shikoku Regional Development Bureau office, which works on disaster risk management, these slopes have been regarded to be hazardous slopes where the road will be closed to escape damage due to landslide under strong rainfall. ISEDCL is useful to estimate deep-seated landslide susceptibility.

Acknowledgements

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