On the seismic response in a large deep-seated landslide in southwest Japan
-with special focus on the topographic and geological effects-
西南日本における大規模深層地すべりの地震応答に関する研究
−地形および地質構造の影響−

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論文要約

Chapter 1 Introduction

In recent years, several strong earthquakes have triggered numerous landslides, resulting in significant human and economic losses. Although a lots of post-earthquake field investigations of landslides provide a basis for understanding the phenomena of landslides triggered by earthquakes and for classifying the types of landslides, to prevent, or to at least mitigate, the possible damages resulting from coseismic landslides, a better understanding on the mechanism of the interactions between the slope and seismic waves and the influence of the earthquake on the parameters controlling the stability of a slope is of great importance. Therefore, several studies based on field seismic monitoring, numerical experiments, and laboratory tests were conducted to analyze the mechanisms of seismically induced landslides from the point of seismic site response properties of slopes with respect to landslide risk assessments. As one of the significant seismic site responses, the amplification resulting from the resonance can result in slope failure or the reactivation of a landslide even at unexpectedly large distances from the earthquake epicentre. Many studies analyzed the reasons for the amplification effects on the slope in different views and the relationship between the amplification and slope stability have been examined. Nevertheless, our understanding on the seismic site response related to the structure of landslide is still poor. Especially for the deep-seated landslides, the geological and topographical conditions can be very complicated, the researches on the seismic site response within the landslide body of the deep-seated landslide had been rarely performed.

As well known, Japan is frequently affected by strong earthquakes. There are many potential deep-seated landslides in Japan’s accretionary prism mountains. It is deemed that the Nankai and/or Tonankai megathrust trench will cause a very strong earthquake in the coming years, and these landslides could be reactivated by the coming mega earthquakes.

Therefore, according to the long-term in-situ monitoring on a targeted deep-seated landslide, this research was conducted to analyze and interpret: 1) features of the seismic site response (e.g. amplification and polarization effect) on different areas of the landslide and various strata within landslide body; 2) the mechanism of the seismic site response of the deep-seated landslide; 3) the potential movements and their influence factors of different strata within the landslide body. The findings obtained in this research may provide some new ideas for understanding the seismic behaviours and the possible failure pattern of the deep-seated landslide under earthquakes.

Chapter 2 Background of research area

The research area, Kisawa village is located on Naka District, Tokushima Prefecture, Japan. With the strong relief and steep chutes, the geomorphology of this area is characterized by deep river valleys with steep slopes. Most of the liner depressions on the mountaintop and the settlements are located on gentle slopes formed by past landslides. The seismic activity indicates that the Nankai megathrust will cause a very strong earthquake, with a probability more than 80% of occurring in the coming 30 years and the high potential strong shaking intensity may result in the reactivation of many deep-seated landslides in this area.

Due to the rainstorm caused by the Typhoon Namtheum in 2004, many catastrophic landslides were triggered. As one of the giant deep-seated landslides in this area, Azue landslide was selected as the research field for conducting the long-term seismic monitoring. After the landslide in 2004, three sub-landslide blocks were found and identified on the slope above the main scarp, due to the occurrence of cracks and continued movement of these unstable sub-blocks, the Japanese government immediately put efforts to investigate and mitigate the landslide risk.

For the geological setting of the Azue landslide area, the bedrock outcropping in the landslide area is composed mainly of Paleozoic greenstone (Kurosegawa terrane), which represents pillow lava, pillow breccia and pyroclastic rock. Jurassic sandstone (about 20 m thick), sandwiched in the greenstone, outcrops on the middle upper slope areas of the valley. Mixed rock appears in the lower portion of the source area and on the top of the ridge. Limestone (about 50 to 80 m thick) outcrops along the river bank extending to the middle upper part of the valley. In addition, A fault without crushed zone (strike of N52°W~ N60°W and dip of about 30°~62° to S) passes through the landslide. The topography of the landslide area is characterized by deep river valleys with steep slopes, and in 2004 a landslide occurred on a steep chute near the ridge of the hill slope. In general, the elevation difference from the river bank to the ridge is about 500 m. Most of the landside areas are steep slope, especially for the source area and landslide sub-blocks.

Geological drilling revealed that these sub-landslide blocks have thicknesses ranging from 20 to 50 m. The geotechnical context mainly consists of three strata: superficial gravelly soil, strongly weathered greenstone (fractured greenstone) and weakly weathered greenstone. The current sliding surfaces are developed in the strongly weathered greenstone and the maximum depth reaches approximately 50 m. There are also potential landslide surfaces inferred to be located between the superficial gravelly soil and strongly weathered greenstone strata, approximately with a maximum depth of 30 m.

To investigate the subsurface geological condition of the landslide materials in different areas, the geophysical surveys were carried out on landslide block and deposit area, including multichannel analysis of surface waves (MASW) and electrical resistivity tomography (ERT). The distributions of Shear-wave velocity (Vs) and electrical resistivity (ER) were obtained on the two areas.

Chapter 3 Research approach and analysis method

For in-situ seismic monitoring, five seismic stations (P1 to P5) were installed at different locations in the landslide area. In detail, Station P1 (300 m in elevation) is placed on the bedrock (greenstone) outside of the landslide area served as a reference site; Station P2 (311 m in elevation) is located on the ancient landslide deposit near the river; Station P3 (682 m in elevation) is located on the middle part of landslide sub-block A; Station P4 (723 m in elevation) is on a local ridge of the hill slope with sharp topography and close to the boundary of block-A; Station P5 (713 m in elevation) is placed on the bedrock exposed by the construction of a new road on the top of the hill slope.

Dense ambient noise observation was also performed to study the spatial variation of the site response and its correlation with the landslide characteristics. The observation array which includes a total of 61 single stations were arranged zonally along the extending direction of landslide sub-blocks. The array size in block-A is a length of 150 m and a width of 80 m; and has a length of 280 m and a width of 90 m is deemed as the array size for block-B. Moreover, the array ranges from 710 m to 760 m in elevation.

For evaluating the amplification effects and the resonance frequency of the landslide, the most prevalent and effective method named Standard Spectral Ratio (SSR) and the horizontal-to-vertical component spectral ratio (HVSR) were applied to analyze the seismic and noise records in the frequency domain. In addition, the method named horizontal vector rotation was also applied to examine the specific directivity of the site responses on different landslide area.

In order to examine the vibration feature of the landslide, this study employed the polarization analysis for the observation recordings. A method named time-frequency polarization analysis (TFPA) based on complex polarization analysis (CPA) and continuous wavelet transform (CWT) was applied to examine the shape (linear or elliptical polarization), vibration direction (strike and dip) of the ground motion on different landslide area.

Chapter 4 Amplification effects on landslide area by earthquake observation

Through the continuous recording, the seismometers have obtained a substantial amount of earthquake data. The high quality of these recordings with a signal-to-noise ratio (SNR) greater than 3 was picked for analysis. After being pre-processed, the selected raw data of three-component waveforms were divided into the S-phase and coda wave, respectively. After the HVSR calculation, the features of the HVSR curve on the different seismic station are drawn as follows:

1) For Station P1, the HVSR curves have no predominant peak in the frequency bands, and the average HVSR peak amplitudes are less than 2 in both S-phase and coda waves. It can be concluded that there is no, or very weak (if any), amplification effect. For Station P5, the HVSR curves show a predominant peak at a frequency of around 2.4 Hz, with the HVSR peak amplitude less than 4 in both S-phase and coda waves.

2) Both in S-phase and coda waves, the HVSR curves on Station P2 shows the greatest peak values approximately around 6.4 Hz and the average HVSR peak amplitude is approximately 10, with some individual amplifications even greater than 20.

3) In landslide block, the HVSR curves for Station P3 and P4 have multiple predominant peaks. For P3 in S-phase, the two peaks occur at about 2.4 Hz and 7.2 Hz, respectively; in coda waves, three peak at 2.1, 9.3 and 17.4 Hz, respectively. Station P4 shows the two peak amplitudes at 2.6 Hz and 14.2 Hz, respectively, in S-phase. In coda waves, the peaks occur at 2.4 and 14.8 Hz, respectively, In addition, the average HVSR peak amplitude of 2–5 for P3 and P4.

In addition, the results from the method of SSR were also analyzed and compared with those from the HVSR method. In general, the resonance frequencies of the spectral ratio curves from two methods present good consistence in frequency bands less than 10 Hz for station P2, P3 and P4 in both S-phase and coda waves. However, a clear difference occurs in the frequency bands greater than 10 Hz in coda waves. For the peak amplitudes, the values from the SSR method are 1.5-3 times greater than those from the HVSR method.

Chapter 5 Seismic site response on landslide sub-block by ambient noise observation

In order to examine the resonance phenomenon distributed on the landslide sub-blocks, the HVSR technique was also employed and the resonance patterns were classified into three groups.

The distributions of the HVSR curves along the extended direction of the blocks show that along with this horizontal profile, evident recurrent peaks of the HVSR curve at very low frequency bands of 0.2 to 0.5 Hz appear for the majority of stations with mean amplitudes of H/V ratio ranging 2-4 (if a peak is visible). The distribution of the peaks of the HVSR curve in frequency bands ranging from 1-10 Hz demonstrates the location-dependence of resonance in the landslide sub-blocks. With an increase in the distance, the peaks of the HVSR curve gradually appear, with the peak amplitude within 2-4. However, the amplitudes of the H/V ratio decrease gradually from the central part to the other boundary of the block (block-B). Also, the peaks of the HVSR curve disappear gradually. In addition, the distribution of the resonance in high frequency bands over 10 Hz covers the areas of the landslide sub-blocks more widely than the frequency bands of 1-10 Hz and the HVSR peak amplitude reaches 5-6. In general, the resonance phenomenon is diverse in the central part of the landslide sub-blocks where HVSR curve reaches multiple peaks, especially near the boundary between the block-A and B.

From the peaks of the HVSR curve, the distributions of the three clusters of the resonance frequency (HVR_f) are mapped on the landslide sub-blocks. The 1st cluster of HVR_f in the frequency bands within 0.2-0.5 Hz covers the major areas of the blocks approximately independent of the geological condition of the subsurface strata. The 2nd cluster of HVR_f in the narrow frequency bands of 4-10 Hz is concentrated near the boundary between block-A and B. On the contrary, the 3rd cluster of HVR_f is distributed on the major areas of the blocks with a broad frequency band of 10-30 Hz. In general, the values of the HVR_f exhibit stronger variations in higher frequency bands (over 10 Hz) than those in low frequency bands (below 10 Hz).

Chapter 6 Vibration features of the landslide sub-blocks

To further examine the vibration features of the landslide sub-blocks aroused by the resonance, a polarization analysis was carried out based on the recordings of the ambient noise observations. The parameters, including ellipticity PE (the extent of the polarization), ϕ (the strike of the maximum polarization in the horizontal plane) and δ (the dip of the direction of the maximum polarization) can be obtained to evaluate the polarization effect.

Considering that the polarization phenomena appear almost on the horizontal plane (dip (δ) is about 90°) in this study, statistical analysis on the strike (ϕ) of the polarization parameter was carried out to identify the pronounced vibration directions of the landslide sub-block. In low frequency bands less than 1 Hz, the vibration of the ground motion indicate a systematic tendency along two directions at approximately N25° (±15°) and N150° (±10°), respectively. It is also indicated that the consistent distribution for vibration directions of the ground motions in the frequency bands of 1-

10 Hz occur on both block A and B and the predominant polarization appears along N125° (±15°). Different from the ground motions vibration in the frequency bands of 1-10 Hz, the polarization patterns in 10-30 Hz vary significantly from station to station, without any systematic trend.

In addition, the extent of polarization (PE) distributed over the landslide sub-blocks shows that obvious polarization of the ground motion can be found in the central areas of the blocks. Block-A presents a more linear polarization (values of PE less than 0.2) than block-B, especially in the frequency bands greater than 1Hz.

Chapter 7 Discussion

Based on the analysis results of the data obtained from long-term seismic observation and large-scale ambient noise monitoring, the seismic site response on landslide will be discussed on different aspects in this chapter.

In view of the amplification phenomenon and its influence factor, it is inferred that the coda waves in an earthquake record can provide more information than S-phase on the occurrence of peaks of the H/V ratio, and thus can provide more evidence for understanding the features of ground motion. However, greater amplification effects occur in the S-phase than in the coda waves.

On the other hand, the vibration pattern caused by different factors were also identified. The directional vibrations resulting from a topography effect are approximately perpendicular to the ridge direction, with the HVSR peak amplitudes of 2 to 6. However, the vibration resulting from the geological effect are complicated. According to the comparison between the ranges of the resonance thickness where the HVR_f occurs and the geological boundary, it is found that the variation tendency of the resonance thickness at depths of less than 15 m is approximately consistent with the geological boundary line between the gravelly soil and strongly weathered greenstone stratum. Thus, the material contrast is considered the reason for the resonance. However, the variation tendency of the resonance thickness at depths greater than 15 m is obviously inconsistent with the geological boundary between the strongly and weakly weathered greenstone. In particular, the HVSR peak amplitudes occur in the weakly weathered greenstone stratum. This phenomenon may be caused by the feature of the structure of the landslide body (e.g. rock strength with different shear-wave velocity). This new finding may also account for the difference of the resonance thickness and the geological boundary between the strongly and weakly weathered greenstone and may be also considered as the mechanism of the seismic site response in such weathered rock strata deeply within the landslide.

Based on this inference, the vibration patterns within landslide block were summarized. It is found that the obviously consistent vibration pattern with the HVSR peak amplitudes of 1 to 3 within the strongly weathered greenstone stratum. On the contrary, for the gravelly soil stratum, the vibration pattern showed inconsistency with the HVSR peak amplitudes of 3 to 5 and the vibration directions change site by site. In addition, the landslide deposit area shows the strongest vibration, with the HVSR peak amplitude greater than 8.

The relationship between the features of the resonance and vibration suggests that weak polarization and non-directional vibration (elliptical polarization with great ellipticity value) tends to be subjected to weak resonance, and strong resonance results in obvious polarization (linear polarization with small ellipticity value).

Based on these findings in this study, some practical significance can be obtained to understand the potential movement with different strata within landslide resulting from seismic site response.

The surficial stratum of the landslide body may be initiated along the direction of the local slope aspect and then result in shallow failures along the material boundary approximately. However, the deep stratum may slide along the boundary where the shear-wave velocities are different and the potential sliding direction may be controlled by the geological structure of the landslide area, such as the discontinuity. Especially, if the variation of the seismic boundary is continuous, the landslide materials in the deep stratum from neighbouring sliding blocks may slide together, although the evidence (such as opening cracks) on their ground surfaces may show that they could be different sub-blocks.

Chapter 8 Conclusion

In this study, seismic site responses on a large deep-seated landslide, which was reactivated by a rainstorm in 2004 accompanying Typhoon Namtheun in Naka Town, Tokushima Prefecture, Japan, were analyzed based on long term in-situ earthquake monitoring and dense ambient noise observation. Based on numerous seismic recordings obtained by 5 seismometers that were installed on different areas of the landslide, ambient noise recordings, and the results of geophysical and geological surveys, the seismic site response in different strata due to the factors of topography, material contrast and structure of the landslide body were analyzed. The main conclusions are drawn as follows:

1) Both the HVSR curves and SSR curves obtained from earthquake recordings show that different landslide areas have differing amplification features under S-phase and coda waves in seismic waves. It is made clear that the S-phase can result in stronger amplification phenomena in the landslide area than the coda waves, while coda waves make it possible to identify multiple amplifications. Weak amplification normally appears in bedrock areas, while strong amplifications appear in the landslide body areas.

2) The distribution of the HVSR curves on landslide blocks obtained from ambient noise indicates that the resonance phenomenon in the high frequency bands (greater than 10 Hz) exist in a wider range of the landslide body, however, this phenomenon in the low frequency bands (1-10 Hz) occurs obviously in the center area of the landslide body. In addition, in the high frequency bands, the variation tendency between the resonance with distance and the geological boundary is consistent. However, the variation tendency of the resonance with distance in the low frequency bands is not consistent with the geological boundary.

3) For the mechanisms of the seismic site response in the deep-seated landslide, the current research viewpoint may not account for the resonance phenomenon that can result in the amplification in the deep stratum (e.g. weathered rock stratum). However, this research provides the new finding that features of the structure within the landslide body, such as the difference in the rock strength, play a key role, resulting in resonance in the deep stratum. In general, the seismic site response of the surficial strata of the deep-seated landslide may be influenced by the material contrast near the geological boundary, however, the deep strata may be controlled by contrasts in the rock strength near the seismic boundary.

4) Seismic site response (amplification and vibration) resulting from the topography occurs predominantly on the upper part of the landslide body. The specific directivity is approximately perpendicular to the direction of elongation of the ridge of the hillslope. Furthermore, for the deep-seated landslide, the vibration direction of the surficial stratum is along the local slope aspect, however within the deep stratum, the vibration direction may be controlled by the local geological structure (e.g. discontinuity).

5) Through examining the relationship between the H/V ratio and polarization, it has been made clear that the vibration does not have pronounced directivity for low values of the H/V ratio. However, strong vibration directivity appears when the H/V ratio becomes stronger.

6) For potential failure of the deep-seated landslides resulting from seismic site response, the surficial stratum of the landslide body may develop shallow failures along the geological boundary approximately along the direction of the local slope aspect, however, a deep-seated failure may slide along a seismic boundary rather than the material boundary. In particular, if the variation of the seismic boundary is continuous, the landslide materials in the deep stratum from neighboring sliding blocks may slide together, although the evidence (such as opening cracks) on their ground surfaces may show that there could be different sub-blocks.

In general, based on the in-situ seismic observation on a target landslide, this research provides new findings to understand the mechanism of the seismic site response on a deep-seated landslide and the possible movement and failure of different strata within the deep-seated landslide. In particular, the influence of the structure of the landslide body was useful for interpreting the seismic site response within the deep stratum. In addition, this finding can be also used to detect the potential deep-seated landslide surface by means of the seismic observation, in particular using dense ambient noise observation.