EVALUATION OF DYNAMIC RESPONSE PROPERTIES OF EXISTING GEOTECHNICAL WORKS USING MICRO-EARTHQUAKES

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SUMMARY:
We propose micro-earthquake array observation as an easy, efficient and economic method for evaluating the dynamic response properties of geotechnical works in earthquake-prone regions. The purpose of this paper is to demonstrate the efficiency of the method based on the observation of small irrigation earth dams conducted immediately after an earthquake swarm beginning from December 17, 2009 in Izu Peninsula, Japan. We performed a two-day earthquake observation simultaneously on two valley-type irrigation dams, placing vibration sensors on the crest of the two dams and on the surface of outcropping bedrock. As a result, the horizontal bedrock-to-crest transfer functions of seismic motions based on analyses of six earthquake records almost uniquely specified. Accordingly, we could demonstrate the validity of the proposed method. In addition, spectral ratio of crest to bedrock of microtremor, or ambient vibration, is very similar to the transfer functions of micro-earthquakes.

Keywords: dam, dynamic property, geotechnical works, microearthquake, natural frequency

1. INTRODUCTION

We propose herein micro-earthquake array observation of geotechnical works as a method of evaluating dynamic response characteristics of them. This paper demonstrates, in the aspect of seismic response properties, the efficiency of the proposed method based on a two-day observation of micro-earthquakes on twin small earth irrigation dams during an earthquake swarm in 2009.

Earth dam for irrigation pond, which is called “Tame-ike” in Japanese, is one of the oldest geotechnical works in the history of human being. Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF (2012)) is quoted as reporting that there are approximately 210 thousands irrigation-pond dams in Japan, and that approximately 75% of the dams was constructed in or before the Edo-era corresponding to the period from1603 to1868; i.e. they are some 150-years old or older. Such irrigation dams have historically experienced disaster caused by earthquakes and heavy rains; such that approximately 1,200 dams suffered in 1995 Kobe Earthquake (Tani and Hori (1998)). Most of damaged dams are small-size earth-type. Hence, earthquake-induced irrigation-pond hazard mitigation should be convincingly recognized as an essential measure against risk to vulnerable communities in gradually urbanized farming areas in Japan.

Basic mechanisms of seismic damage to geotechnical works, such as earth dams, can be classified to (1) collapse of the main bodies of the geotechnical works due to inertial force, (2) large deformation of the main bodies due to liquefaction of the main bodies, their base ground or both, and (3) breakage of the main body due to crossing of seismic surface faulting. The first two mechanisms are dominated by seismic response characteristics of a coupled system of the main body and its base ground. Thus, for evaluation of seismic vulnerability of existing geotechnical works, it is necessary to evaluate the seismic response properties of the coupled system which dominates seismic actions on the existing geotechnical works. Hence, easy, efficient and economic evaluation methods are highly expected.

2. TRANSFER FUNCTION APPROACH USING MICRO-EARTHQUAKE OBSERVATION

2.1 Basic concept

We had thought that microtremor measurement and earthquake observation can be efficient methodologies for evaluating seismic response properties of geotechnical works, and so have been applying them to irrigation ponds (Mori and Furukawa (2010a), Furukawa and Mori (2010)). The wave field of earthquake is relatively clear, while that of microtremor or ambient vibration is understood to be a complex of the body and surface waves caused by human activities, weather circumstances, or both. Thus, earthquake observation is very effective for the evaluation but has been only applied to large dams as reported by Masukawa et al. (2002), and then it is too expensive to be utilized for small earth dams. In fact, the high initial cost for introduction of observation system seems to be the reason why there is no literature dealing with application of earthquake observation to small dams. If so, it would be cost effective for us to temporarily use highly-sensitive and portable vibration-sensors for a short period in order to evaluate seismic response properties of a small dam. Furthermore, if occurrence of earthquake is very frequent, we could obtain micro-earthquake motions on dams and their surrounding ground.

The Gutenberg-Richter law says that the number of earthquakes of magnitude M is proportional to 10^{-bM}, where the value of b seems to vary from area to area but worldwide it seems to be around b=1. Taking the G-R law into account, the number of earthquakes is expected to be ten times as much as that of earthquakes with one greater magnitude. Comparing with the number of large earthquakes (M≥7), which are generally expected to be observed in strong motion observation, the number of small earthquakes (5>M>3) is expected to be 100 to 10,000 times and that of micro-earthquakes (3>M>1) is expected to 10,000 to 1,000,000 times. These multiplying factors imply being equivalent to the efficiency of earthquake observation in economic and practical aspects.

2.2 Transfer function approach for evaluation of seismic response characteristics

Seismic response of a geotechnical work is represented by its dynamic motion responding to incident earthquake wave entering bedrock underlying both a base layer and the geotechnical work. Fig. 1 shows a valley-type irrigation-pond dam as an example of geotechnical work in the field of vertically propagating incident wave for comprehending the transfer function approach.

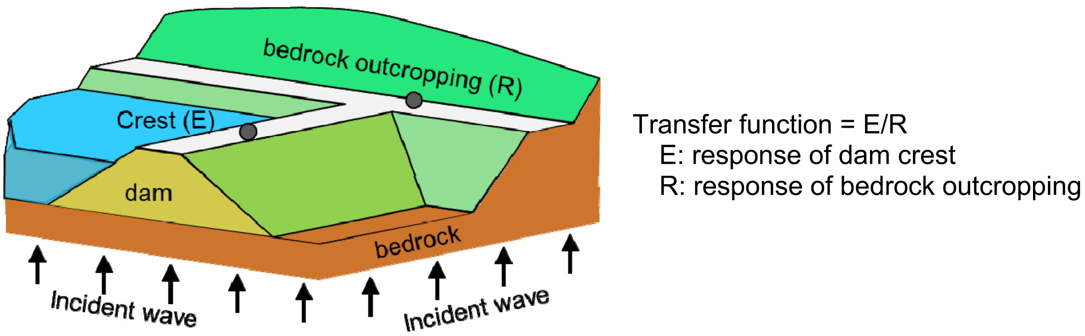


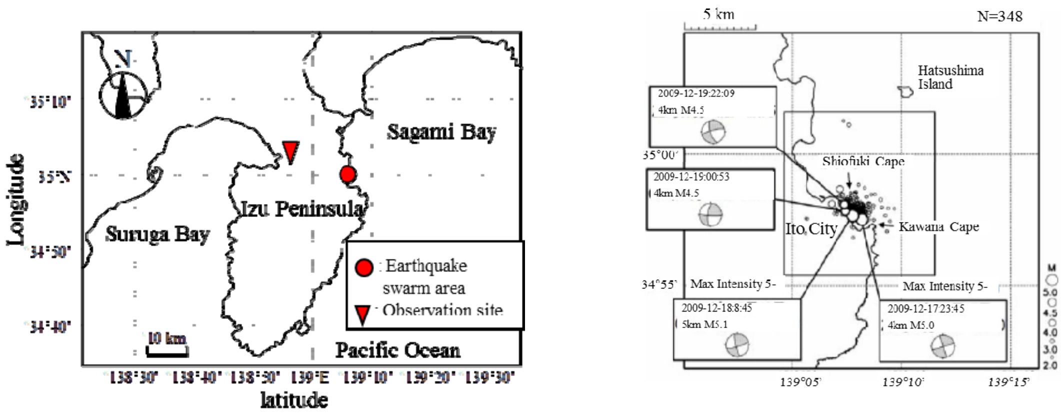
Figure 1. A valley-type irrigation-pond dam as an example of geotechnical work in the field of vertically propagating incident wave for comprehending the transfer function approach

A transfer function from a bedrock outcropping motion to a motion at arbitrary location of the geotechnical work can represent seismic response characteristics. Calculated by an appropriate numerical model responding to presumed input earthquake motion entering the bedrock, the transfer function can easily evaluate the seismic response of the system, especially in a case of linear elastic system. Assuming the input earthquake motion as shear wave vertically propagating both in the bedrock and in the geotechnical work overlying the base layer, the spectral ratio of the geotechnical work to the bedrock outcropping can be regarded as an observationally-evaluated transfer function. Therefore, evaluation of the seismic response of the geotechnical work can be easily conducted using the transfer function obtained in earthquake observation.

3. TEMPORARY EARTHQUAKE OBSERVATION AT IRRIGATION DAMS

3.1 Earthquake swarm

There was an earthquake swarm beginning on December 17, 2009 in the east coast of Izu Peninsula, Japan. An M5.0 earthquake occurrence at 23:45 on the day was reported as an emergent TV news according to Japan Meteorological Agency (JMA (2009a)), which reminded one of the authors a possible opportunity of effective micro-earthquake observation. As a result, aiming at verifying the feasibility of the micro-earthquake observation method, we performed a two-day earthquake observation simultaneously on two valley-type irrigation dams, placing vibration sensors on the crests of the dams and on the surface of bedrock outcropping around the dams (Mori and Furukawa (2010a). Fig. 2 shows (a) the region of the earthquake swarm and the location of our earthquake observation site, and (b) detailed distribution map of earthquakes. The observation site is located in the northern west of Izu Peninsula, and then is an approximately 17 km distance from the earthquake swarm region.



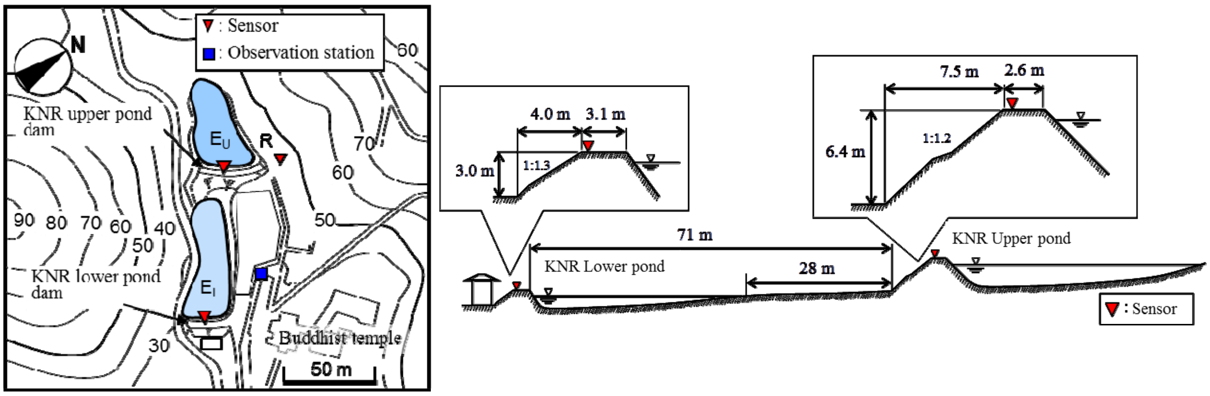
(a) Location of earthquake swarm and observation site (b) Detailed distribution map of earthquakes

Figure 2. Locations of earthquake swarm and our earthquake observation site

The earthquake swarm activity began at noon of December 17 and continued for four days from 17th to 20th, especially high activity for only first 48 hours. This earthquake swarm concentrated within a 4-km radius and many of the earthquakes have similar mechanism of right-lateral strike-slip faulting. Therefore, earthquake motions recorded by us are regarded as motions caused by earthquakes that have same mechanism, same propagating path, and different magnitudes.

3.2 Observation site and irrigation-pond dams

Irrigation-pond earth dams for micro-earthquake observation are twin dams (KNR dams) chosen as the closest ones to the earthquake swarm region. Plan and longitudinal section views of observed irrigation dams with sensor arrangement are shown in Fig. 3. The twin irrigation ponds were constructed up and down along a valley between hills with relative elevations of around 30 and 60 meters. Accordingly, these earth-dams are classified to valley-type dam. It was a very quiet situation in the aspect of vibration measurement since KNR dams is located in sparsely-populated area. Since all the sensors are located within 40-m radius, the observed points are regarded to be in the same incident earthquake wave field. The upper dam is 45 m long, 6.4 m high, and 2.6 m wide at crest. The lower dam is 23 m long, 3.0 m high, and 3.1 m wide at crest. Both dams are quite small. The age of the dams is less well-known, but they were reportedly constructed before Meiji-era (1868-1912) and not to be renovated yet.



(a) Topography around observed irrigation ponds and sensor

(b) Longitudinal section view of the twin ponds and embankments with dimensions, and locations of sensors

Figure 3. Plan and longitudinal section views of observed irrigation dams with sensor arrangement

3.3 Observation

Data acquisition system for observation is GEODAS-12-USB-24ch, which is consisting of amplifier, AD converter, and recorder. Sensors for observation are three sets of CR4.5-2S, which is three-component moving-coil type velocity sensor using pendulum of 4.5 Hz natural frequency with modification of gain to be flat between 0.5 Hz and 23 Hz by condenser regulation. Placing three sensors at the crests of upper and lower dams (E_U and E_L), and on the surface of bedrock outcropping (R), we conducted microtremor measurement and micro-earthquake observation. A horizontal component of each sensor was directed along the longitudinal axis of dam and another component in the transverse direction. The longitudinal axes of the two dams are approximately parallel to each other. Thus horizontal components of three sensors were placed in the same direction.

Sampling frequency was 100 Hz, duration time of a record was 600 seconds. Continuous recording had been conducted through the observation of two periods; first period of 160 minutes from 5 to 8 p.m. on December 19, and the second period of 440 minutes from 4 to 12 a.m. on December 20. For the first period of observation, seamless occurrence of micro-earthquakes was recognized from the beginning of the observation. For the second period of observation after resting for a while, seismic activity was considerably reduced. Finally more than 100 micro-earthquakes including a felt quake were recorded.

3.4 Data analysis

In this study, only horizontal components are analyzed for verification of transfer function approach in micro-earthquake observation. The procedure of analysis is described hereafter. A segment of 20.48 seconds involving some seconds of microtremor before a P-wave arrival, main motion including P- and S-wave arrivals, and S-wave coda is extracted. After drift correction, a Fourier spectrum is calculated using the corrected time history, and then a Fourier spectral ratio of a dam crest to the bedrock outcropping (HH ratio) is also calculated using a couple of corrected time histories at the two locations. For easily identifying predominant frequencies in Fourier spectra or spectral ratios, Parzen window of 0.5-Hz bandwidth was used. As mentioned before, the Fourier spectral ratio can be regarded as a transfer function from the bedrock outcropping to a dam crest. In the same manner, the predominant frequency in the Fourier spectral ratio can be regarded as the natural frequency of a coupled system of a dam overlying a base layer on bedrock. For analysis of microtremor, the same way was adopted. Exceptionally, the entire segment of the time history is used for the drift correction.

For identifying earthquakes, we used the list of earthquake sources provided by JMA through their website (JMA (2009b) and the list of earthquake sources calculated by JMA provided by National Institute of Earth Science and Disaster Prevention (NIED (2009)) through their website.

4. RESULTS OF MICRO-EARTHQUAKE OBSERVATION AND DISCUSSIONS

4.1 Situation of recorded earthquake swarm

This five-minute period is one of the most seismically active time portions among our observed dataset. The unit of velocity in this paper is micro-meter per second (μm/s). Comparing with microtremor of which maximum amplitude is 2 μm/s, twelve portions where amplitude suddenly grows up and gradually attenuates as time passes can be clearly recognized in the five minutes. These portions having a shape of trumpet mouth correspond to micro-earthquakes. All the twelve portions have two numbers each in the graph; one is a peak amplitude value shown above the abscissa and the other is an earthquake magnitude shown below. During this period, no running vehicle, no pedestrians, no breeze was recognized. It is necessary to note that wave forms amplitudes greater than 100 in "Large" micro-earthquake are not drawn in Fig. 4.

Compared peak amplitudes at the three different locations in same micro-earthquakes with each other,

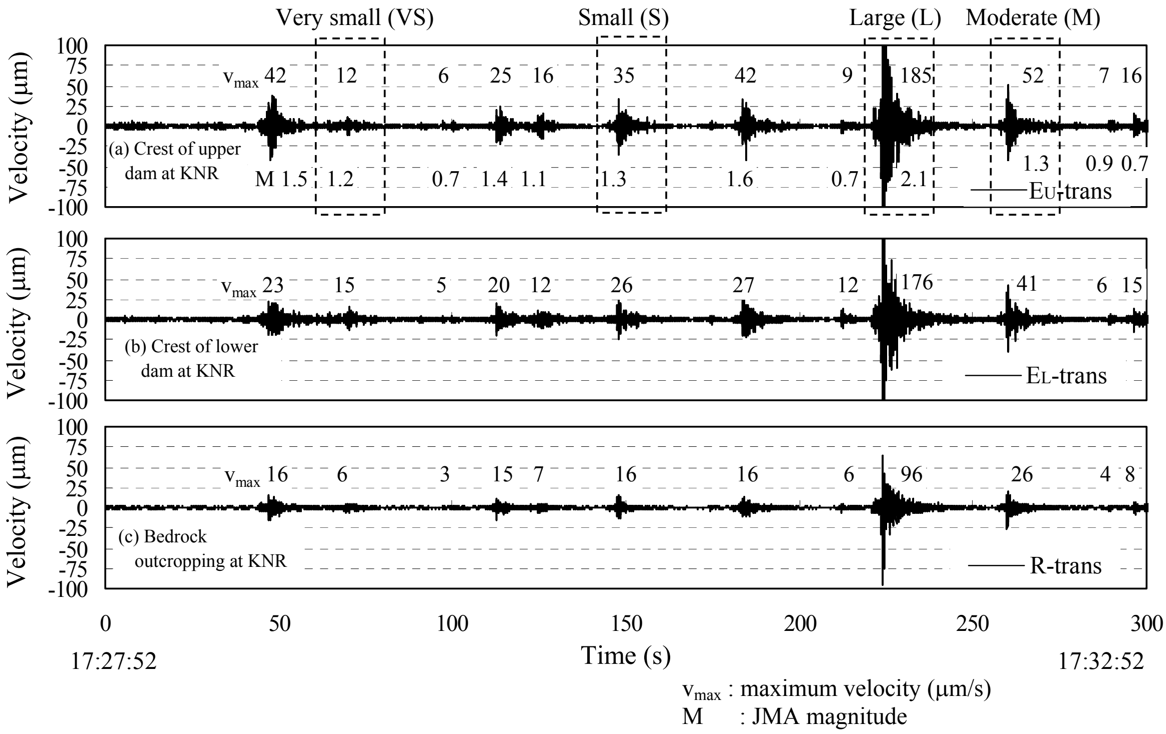
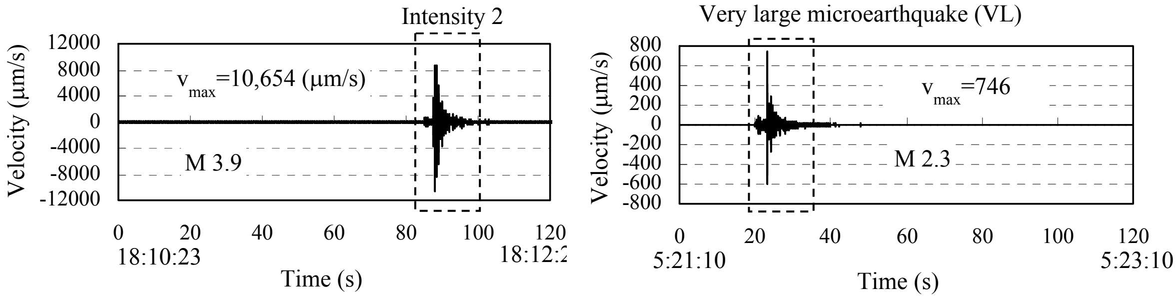


Figure 4. Velocity time histories of transverse components of earthquake motions at all the three points during the period from 17:27'52" to 17:32'52" on December 19, 2009

amplification from the surface of bedrock outcropping to the crests of dams in the aspect of peak velocity is easily evaluated. The amplification factor for the upper dam ranges from 1.7 to 2.6 and averages 2.1, and for the lower dam it ranges from 1.3 to 2.5 and averages 1.7. Accordingly, it is understood that these amplification factors can be used in seismic response evaluation of the dams to presumed input bedrock motion, and that the upper dam has averagely 1.2 times amplification as much as the lower dam in the aspect of seismic vulnerability evaluation. Hence, such easily understanding is very useful for seismic risk assessment and risk communication among owners, engineers and community peoples.

4.2 Spectral analysis of representative records

We will herein demonstrate the difference and similarity of spectral characteristics of earthquake motions among different levels of motions. Six different levels of earthquake motions were chosen as representative motions for spectral analysis as shown in Table 2 compiling information of recorded



(a) 2009-12-19 18:10:23 ~2009-12-19 18:12:23 (b) 2009-12-20 5:21:10 ~2009-12-20 5:23:10

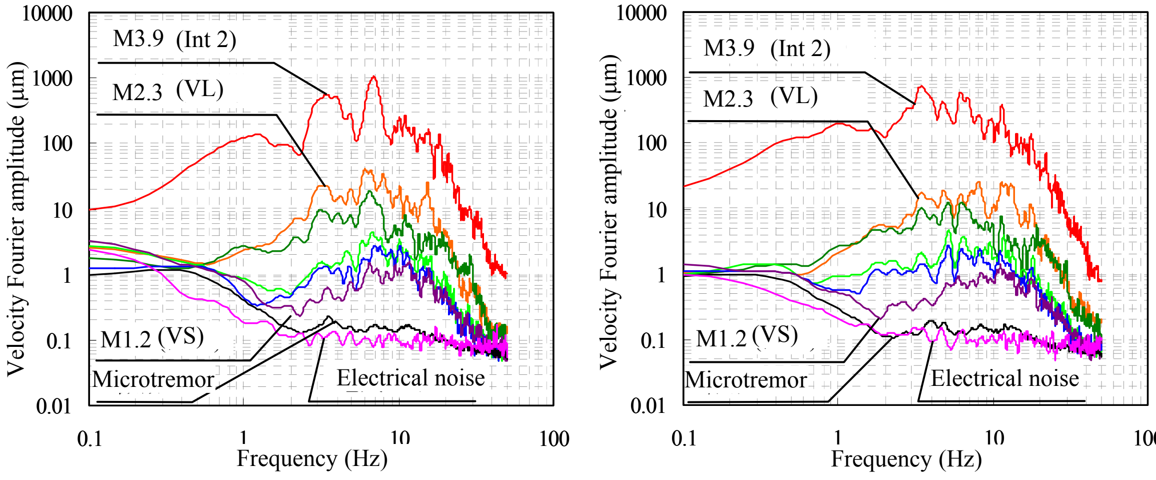
Figure 5. Velocity time histories of transverse components of a very large micro-earthquake motion (VL) and a seismic intensity of 2 motion (Int2)

earthquakes and observed peak velocities. Very small (VS), Small (S), Moderate (M), and Large (L) micro-earthquake motions are shown in Fig.4 with indications of their abbreviated names. On the other hand, large amplitudes of motions were selected from other observation periods: Very large micro-earthquake motion (VL) is represented by the motion recorded between 5:21'10" and 5:23'10" on December 20 which is shown in Fig.5 (a). Seismic intensity 2 small earthquake motion (Int2), of which amplitude is actually the maximum among all recorded motions, represents the motions of felt earthquakes. The Int2 motion, which is shown in Fig.5 (b), was recorded between 18:10'23" and 18:12'23" on December 19. This earthquake motion with a seismic intensity of 2 at the observation site was caused by a M3.9 earthquake with a focal depth of 4 km resulting seismic intensity of 3 in Ito City.

A microtremor record is also analyzed in the same manner for comparison. Analyzed microtremor was observed in the last observation period when seismic activity was very low or the situation of microtremor seemed to be usual there. The peak amplitude of VS motion is 12 μm/s and microtremor 2.7 μm/s. Moreover, it is confirmed that the SN ratio in an earthquake motion due to an earthquake with a magnitude greater than 1.3 is at least more than ten. In the cases of earthquake motions greater than S motion, both the timings of P-wave and S-wave arrival are easily visible, PS times are almost the same, and similar attenuation of S-wave codas is also recognized in a trumpet-mouth-like shape. Such features seem to mean that these earthquakes have a similar focal mechanism, a similar focal depth, and almost the same hypocentral distance. Consequently, the micro-earthquake motions of the dams can be regarded as convincing seismic response to incident wave into the bedrock. Since even micro-earthquakes have typical features of felt earthquakes, the method can be an effective tool for seismic evaluation of geotechnical works.

4.3 Fourier spectra of bedrock outcropping motions

In this section, we will study the features of Fourier spectra of bedrock outcropping motions of the six earthquakes and the microtremor records. Fourier spectra of transverse components (a) and longitudinal components (b) of the bedrock outcropping motions are shown in Fig.6. This figure also shows a Fourier spectrum based on an electrical noise record, which was obtained by constraining the movement of the pendulum of a certain component in the sensor used in the micro-earthquake observation and analyzed in the same manner. Comparison of motion record with the electrical noise provides information on the quality of the record in terms of SN ratio. The electrical noise has the features indicating that the property in the frequency lower than 2 Hz shows a typical 1/f noise due to electrical circuit, and that the slope of gain becomes relatively gentle in the frequency range higher than 2 Hz. In the microtremor record, SN varies from 1 to 2 only in the frequency range from 3 to 15 Hz. Thus this frequency range is only effective for analysis of the dynamic responses of dams in the case of the microtremor. In the cases of micro-earthquake motions, the spectral amplitudes in a wide frequency range increase with the increase of peak velocity. Convex shapes are seen in the spectra and such convex heave grows in amplitude and the peak of the heave shifts lower in frequency with the



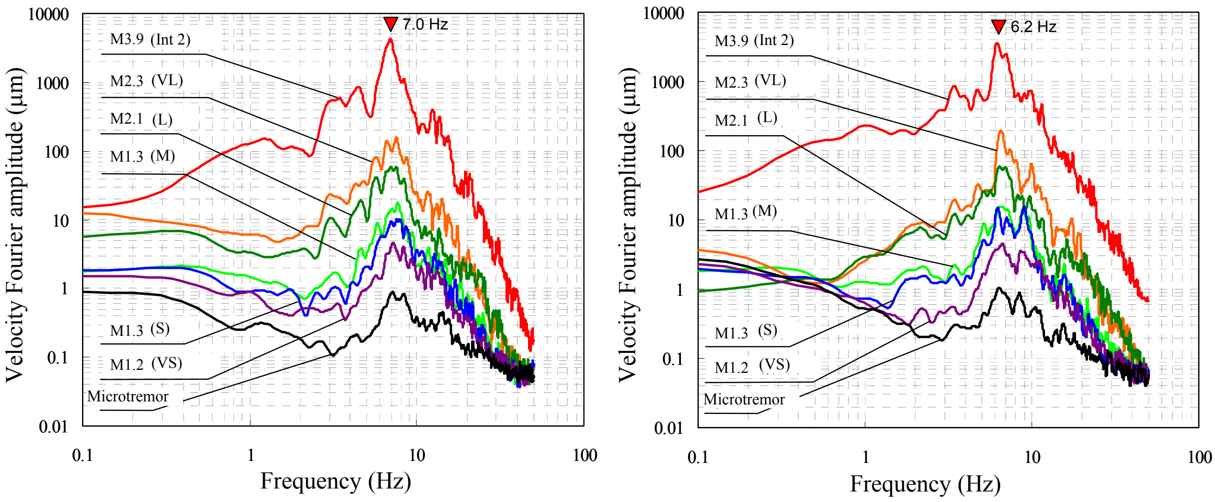
(a) Transverse components (b) Longitudinal components

Figure 6. Fourier spectra of transverse and longitudinal components of the bedrock outcropping motions

increase of peak velocity. The peak shifts roughly from 11 Hz to 4 Hz. As a result, left declining slopes appear in the lower frequency side of the spectral heave and right declining slope due to the 1/f electrical noise in the noise spectrum appears in the frequency. A dip at the crossing point of the two reverse slopes is recognized in the spectra of every micro-earthquake motions. The dip appears at 1.9 Hz in VS motion, 1.4 Hz in S motion, 0.7 Hz in M motion, 0.6 Hz in L motion, and 0.6 Hz in VL motion. In the case of Int2 motion the amplitude of the earthquake motion is quite dominant rather than the noise, resulting no dip. The dip frequency is understood as the lower boundary frequency of effective vibration in terms of SN ratio. As mentioned before, the peak of envelope of the spectrum shifts roughly from 11 Hz to 4 Hz with the increase of magnitude from 1.2 to 3.9. This tendency seems to be harmonized with the omega square model (ω^{-2} model) with regard to corner frequency (Aki and Richards (1980)).

4.4 Fourier spectra of motions at dams

Fourier spectra of transverse components (a) and longitudinal components (b) of motions at the crest of the upper dam are shown in Fig. 7. The dip frequency varies from 3 Hz to 1.5 Hz in transverse component and from 3 Hz to 0.6 Hz in longitudinal component, depending on the amplitude of motion. Only the frequency range higher than the dip frequency should be evaluated in the aspect of seismic



(a) Transverse component (b) Longitudinal component

Figure 7. Fourier spectra of transverse and longitudinal components of motions at the crest of the upper dam at KNR site

response. Similarly to bedrock outcropping motion, the spectral amplitude increases with the increase of peak velocity. For example, comparing VL motion with M motion in transverse component, spectral amplitude of VL motion is 8 times large at 2 Hz, 15 times large at 6.5 Hz, and 8 times large at 7.6 Hz as much as M motion. Considering the ratio of peak velocity between the two components is approximately 10, the variation of spectral amplification seems to correspond to the amplification of peak value. In spite of change in peak frequency of spectrum envelope of motion at bedrock outcropping from 11 Hz to 4 Hz as described before, the peak frequencies of spectra of motions at dam crests are almost the same; 7.0 Hz in transverse component and 6.2 Hz in longitudinal component. This implies that the amplitude at the same frequency is always predominant responding to incident waves as bedrock motions with different levels and different spectral shapes.

On the other hand, the microtremor is compared with micro-earthquakes with regard to spectral characteristics of motions at the dam crest. The dip frequency of it is 3 Hz, which is equivalent to that of VS micro-earthquake. Local heave in the frequency range from 13 to 15 Hz seen in the spectra of earthquakes can be also recognized in the microtremor spectrum. The shape of spectrum in the range higher than predominant peak is proportional to each other among the micro-earthquakes and the microtremor. This finding leads us to understanding that microtremor on the surface of bedrock outcropping in a hill site has similar spectral characteristics with micro-earthquake motions.

4.5 Seismic response characteristics of dams

As mentioned before, the Fourier spectral ratio of a dam to a surface of bedrock outcropping can be regarded as the transfer function of the dam-bedrock system from the surface of bedrock outcropping to the dam. Considering the findings in the previous discussions, we will herein discuss the transfer function. Fig. 8 shows the Fourier spectral ratios of motions at dam crest to motions at surface of bedrock outcropping; transverse component in (a) and longitudinal component in (b). Reminding the previous finding that the boundary frequency (dip frequency) is approximately 3 Hz as a common number, the frequency range lower than 3 Hz should be out of consideration. As predominant frequencies of the dam are 7.0 or 6.2 Hz in Fourier spectra of motions at dam crests, Parzen window with 1.0 Hz bandwidth was adopted for easy observation of spectral ratio.

According to Fig. 8 (a), the spectral ratios of micro-earthquake motions are very similar to each other, having a similar shape, a common clear predominant frequency varying from 7.5 to 8.0 Hz, and a peak amplification factor of 6 to 10. In spite of different levels of motions varying from 10 to 10,000 μm/s, the spectral ratios based on the motions are definitely similar to each other. This fact verifies that the

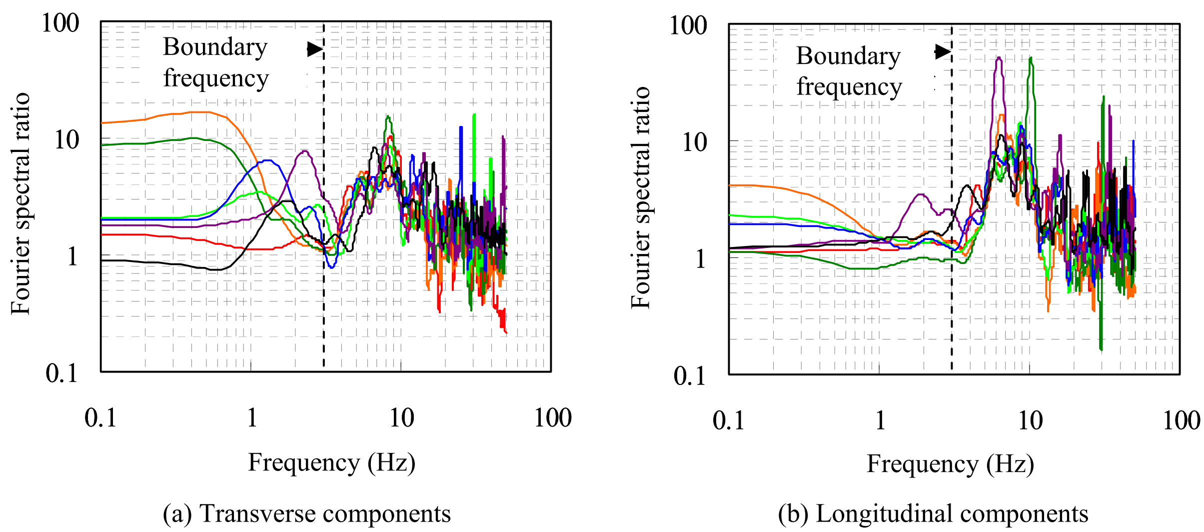


Figure 8. Fourier spectral ratios of motions at dam-crest to motions at surface of bedrock outcropping

spectral ratio between two different locations in the same incident wave field of an earthquake can be regarded as the transfer function in the case of geotechnical works overlying bedrock. In addition, the spectral ratio of the microtremor is also drawn in this graph. However, it is too similar to distinguish it from the micro-earthquakes. Hence, we can say that microtremor can be directly used for evaluation of seismic response characteristics.

In the case of longitudinal components as shown in Fig. 8 (b), similar discussions can be made. However, the shapes are different from transverse components. There are two peaks around 6.5Hz and 8.8 to 9.0 Hz in all spectral ratios. Detailed discussion will be made in future. The important finding is that the shapes and peaks of spectral ratios of micro-earthquakes and microtremor are very similar to each other even in the longitudinal components as well as the transverse.

5. CONCLUSIONS

In order to demonstrate the efficiency of the method of evaluating seismic response properties of geotechnical works by micro-earthquake observation, we conducted such observation at twin small irrigation earth dams immediately after an earthquake swarm beginning from December 17, 2009 in Izu Peninsula, Japan. Finally more than 100 micro-earthquakes including a felt quake were recorded. Based on the results of analyses for time histories and spectra of observed earthquake, the following conclusions are made:

(1) The amplification factor for the upper dam averages 2.1, and for the lower dam it averages 1.7. Accordingly, it is understood that these amplification factors can be used in seismic response evaluation of the dams to presumed input bedrock motion, and that the upper dam has averagely 1.2 times amplification as much as the lower dam in the aspect of seismic vulnerability evaluation.

(2) The SN ratio in an earthquake motion due to an earthquake with a magnitude greater than 1.3 is at least more than ten. In such earthquake motions, both the timings of P-wave and S-wave arrival are easily visible, PS times are almost the same, and similar attenuation of S-wave codas is also recognized in a trumpet-mouth-like shape. The lower boundary frequencies of SN-ratio-based effectiveness vary lower than approximately 2 Hz in bedrock outcropping motions. Since even micro-earthquakes have typical features of felt earthquakes, the method can be an effective tool for seismic evaluation of geotechnical works.

(3) In the bedrock outcropping motions, the peak of envelope of the spectrum shifts roughly from 11 Hz to 4 Hz with the increase of magnitude from 1.2 to 3.9. This tendency seems to be harmonized with the omega square model (ω^{-2} model) with regard to corner frequency.

(4) In spite of change in peak frequency of spectrum envelope of motion at bedrock outcropping from 11 Hz to 4 Hz, the peak frequencies of spectra of motions at dam crests are almost the same; 7.0 Hz in transverse component and 6.2 Hz in longitudinal component. This implies that the amplitude at the same frequency is always predominant responding to incident waves as bedrock motions with different levels and different spectral shapes.

(5) In spite of different levels of motions varying from 10 to 10,000 μm/s, the spectral ratios based on the motions are definitely similar to each other. This fact verifies that the spectral ratio between two different locations in the same incident wave field of an earthquake can be regarded as the transfer function in the case of geotechnical works overlying bedrock.

(6) The Fourier spectrum of microtremor on the surface of bedrock outcropping in a hill site is similar to that of very-small-amplitude micro-earthquake motions. Furthermore, the spectral ratio of the microtremor is definitely similar to that of each micro-earthquake. Hence, we can say that microtremor can be directly used for evaluation of seismic response characteristics.

Based upon the above-mentioned conclusions and satisfactory demonstrations, we propose micro-earthquake array observation as an easy, efficient and economic method for evaluating the dynamic response properties of geotechnical works in earthquake-prone regions.

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