Vibration characteristics and earthquake response of a fill dam having a semi-circular dam axis

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ABSTRACT :

Shin-Yamamoto dam located in the near field of 2004 Niigata-ken Chuetsu Earthquake sustained serious damage such as large settlement and liquefaction. It is 42.4m high fill dam having a semi-circular dam axis, constructed in 1990. This study aims to find vibration characteristics of the dam and to estimate the cause of the damage. For these purposes, micro-tremor measurements and 3-D numerical simulations were conducted. The H/V spectral ratios, often used to estimate ground motion characteristics from micro-tremor data, indicated the vibration periods in the directions normal and parallel to dam axis were slightly different. A 3-D dynamic analysis was conducted to estimate response of the dam to the main shock. The result showed that earthquake response of the right half side of the dam was supposedly stronger in the dam-axis direction than in the normal direction, but that it was reversed on the left half side. Frequency response functions derived from numerical analysis had similar characteristics from the micro-tremor measurements. Finally, a high correlation was found between the earthquake response intensity in the normal direction and the earthquake-induced settlement.

KEYWORDS: 2004 Niigata-ken Chuetsu Earthquake, micro-tremor, finite element method, peak period, earthquake response

1. INTRODUCTION

1.1. Background and Purpose

Shin-Yamamoto dam located in the near field of 2004 Niigata-ken Chuetsu earthquake (Mj6.8) sustained serious damage such as large settlement and liquefaction. The location of the epicenter and Shin-Yamamoto dam are shown in Figure 1. Figure 2 shows a plan of the dam and observation points of micro-tremor measurements (OHMACHI et al 2007). This dam is a zoned fill dam having a semi-circular dam axis.
Generally, earthquake response of fill dams having semi-circular dam axes have been little studied before, much less than that of fill dams having straight dam axes (Japan Society of Civil Engineering 1989, OKAMOTO 1984). Thus, vibration characteristics of Shin-Yamamoto dam was investigated first by micro-tremor measurement and a 3-D numerical simulation. Next, response of the dam to the main shock was estimated to discuss causes of the earthquake damage.

1.2.Outline of Shin-Yamamoto dam

Shin-Yamamoto dam is on the hillside of Yamamoto Mountain in Niigata prefecture and was built for hydroelectric power generation in 1990. It is a zoned fill dam with a semi-circular dam axis. Its maximum height and crest length are 42.4m and 1392m, respectively. The height change along to dam axis is shown in Figure 3.

1.3.Damage to Shin-Yamamoto Dam

As it was located about 5km distant from the epicenter, Shin-Yamamoto dam must have experienced very strong earthquake shaking during the main shock. Unfortunately, however, main shock records at the dam were overwritten by aftershock records and lost. In its neighborhood, strong motion accelerometers at JMA OJIYA

about 5km distant form the dam registered peak acceleration of 780gal.
Reportedly (OHMACHI et al 2007, KOJIMA el al 2008), the crest was displaced upstream about 20~40cm on the left half side of the dam, while downstream about 3~10cm on the right half side. Settlement of the crest was about 10~40cm on the right half side, while it was about 50~85cm on the left half side. Due to the large settlement, top of an H-shaped steel beam which was embedded to protect monitoring cables from the bottom to the top of the filter zone was observed protruding about 30cm from the asphalt pavement, as shown in Figure 4. On the upstream side near the left end, boiled sand was found at several places on the riprap surface and nearby deposit as shown in Figure 5.
The broken line Figure 3 shows settlement along the crest, which was revealed by a post-earthquake survey. Maximum settlement was about 85cm at the observation point No.17, about 2% of the dam height.

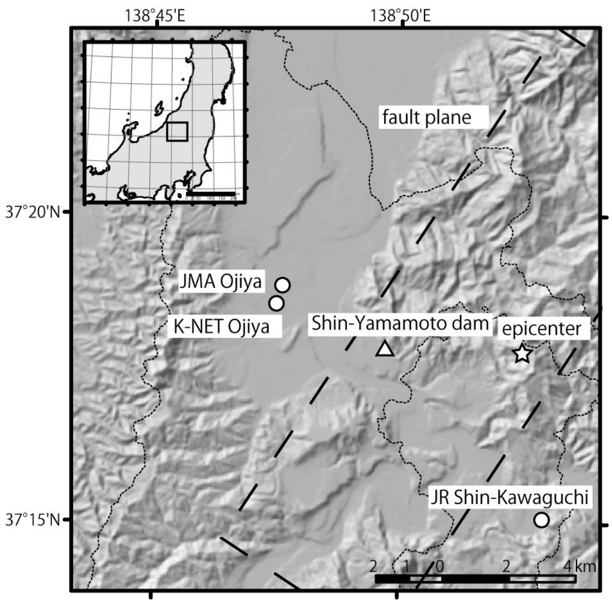


Figure 1 Location Map

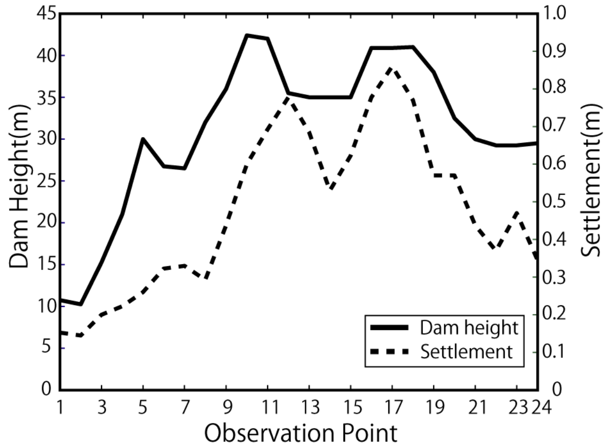


Figure 3 Dam Height and Settlement

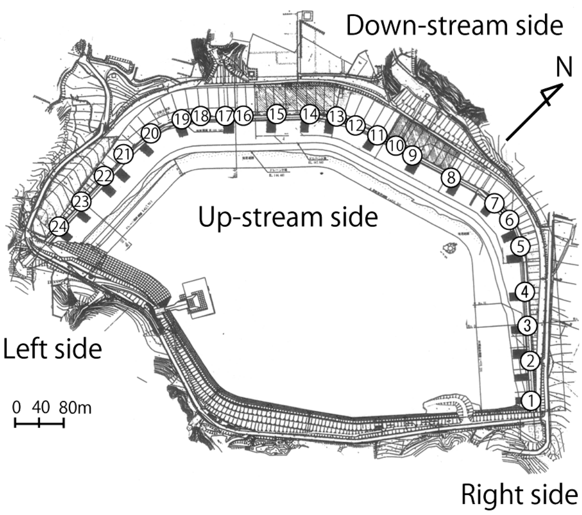


Figure 2 Plan of Shin-Yamamoto Dam and Location of Measurement Points


Figure 4 H-beam's Top indicating Settlement


Figure 5 Boiled Sand indicating Liquefaction

2.VIBRATION CHARACTERISTICS FROM MICRO-TREMOR MEASUREMENTS

2.1.Micro-tremor Measurements

Micro-tremor measurements were conducted three times. The first was in November, 2004, immediately after the earthquake damage, the second in November, 2005, at the final stage of the restoration work, and the third was August, 2006, after filling the reservoir with water. The measurements were done at the same 24 points along the crest shown with numbered circles in Figure 2. In this paper, 2005 measurement is introduced, mainly because of little noise from reservoir filling.

At each measurement point on the dam crest, three-component micro-tremor in terms of velocity was observed with a sampling rate of 100Hz. The three components were two horizontal ones, that is; in the directions normal and parallel to dam axis, and vertical one.

2.2.Result from Micro-tremor Measurements

From the observed time histories, the Fourier spectra and the H/V spectral ratios, which are often used to estimate ground motion characteristics from micro-tremor data, were calculated to find vibration characteristics of the dam. As shown in Figures 6 and 7, the Fourier spectra and the H/V spectral ratios indicate some peaks between 0.15s and 0.40s, and it is difficult to find vibration periods of the dam from the Fourier spectra and the H/V spectral ratios at one observation point only.

To cope with the difficulty, the Fourier spectra and the H/V spectral ratios at all the observation points are arranged in numeric order from No.1 through No.24, which are tentatively called the Fourier spectra contour map and the H/V ratio contour map, respectively. As shown in Figures 8 and 9, a peak at around 0.4s in the Fourier spectra contour map disappeared in the H/V ratio contour map. While peaks changing between 0.15~0.20s which are not seen in the Fourier spectra contour map, appear in the H/V ratio contour map.

As a rule of thumb, the fundamental period of a rock fill dam is empirically given by T=H/200, where T and H are the period in the second and the dam height in m, respectively (OKAMOTO 1984). When H=42.4m for Shin-Yamamoto dam is substituted in this equation, the period of the dam is estimated to be T=0.21s. Thus, the peak at around 0.40s in the Fourier spectra contour map seems to be associated with a coupled vibration of the dam-foundation system.

As the vibration period of a fill dam is roughly proportional to the dam height, it seems reasonable to draw a continuous line connecting peaks in the H/V ratio contour map shown in Figure 9. A dotted line drawn in Figure 9 a) shows two peaks at No.11 and No.18, and the longest peak period in the direction normal to dam axis is found to be about 0.24s at these points. The change in the peak period over entire dam length appears similar to the change in the dam height shown in Figure 3. On the other hand, the peak period in the dam axis direction shown in Figure 9 b) does not seemingly change in direct proportion to the dam height.

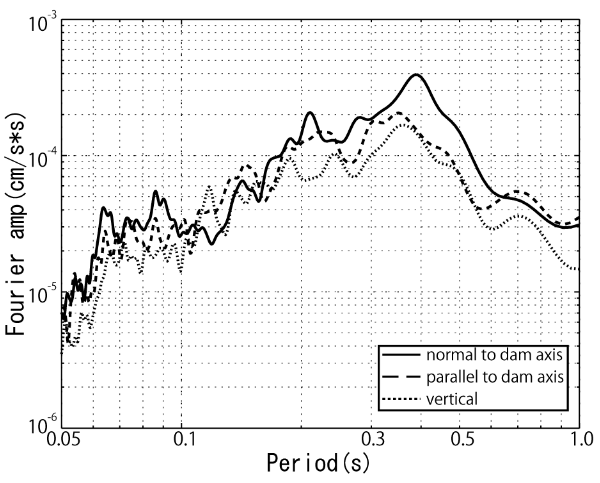


Figure 6 Fourier Spectra at No.17

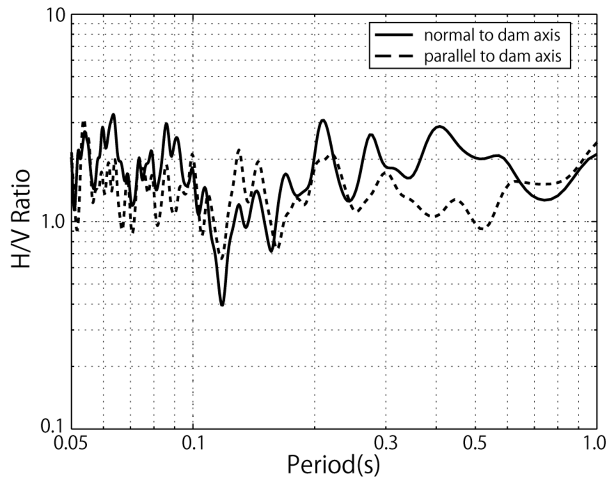
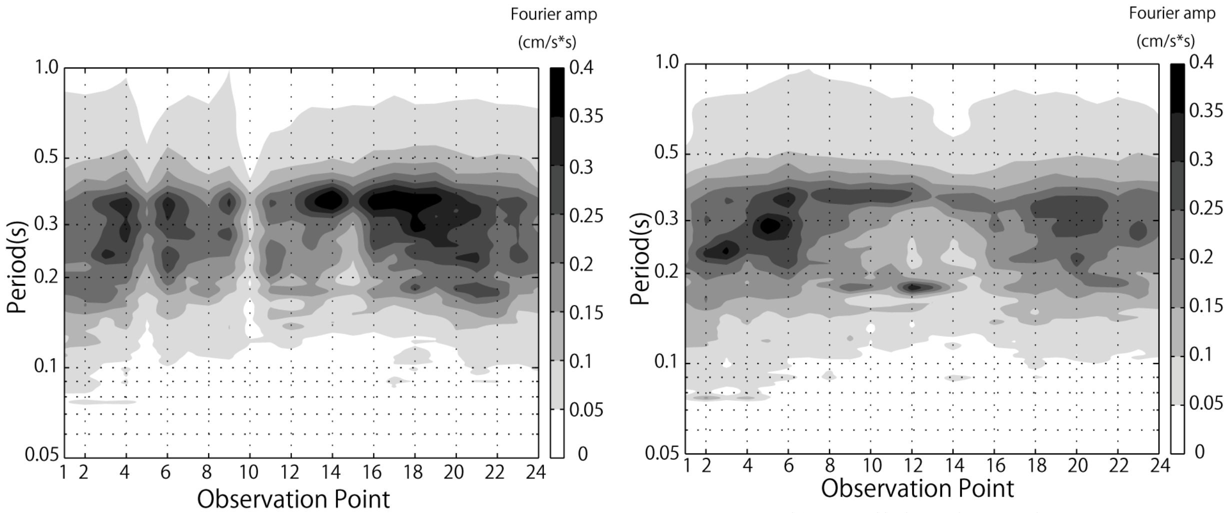
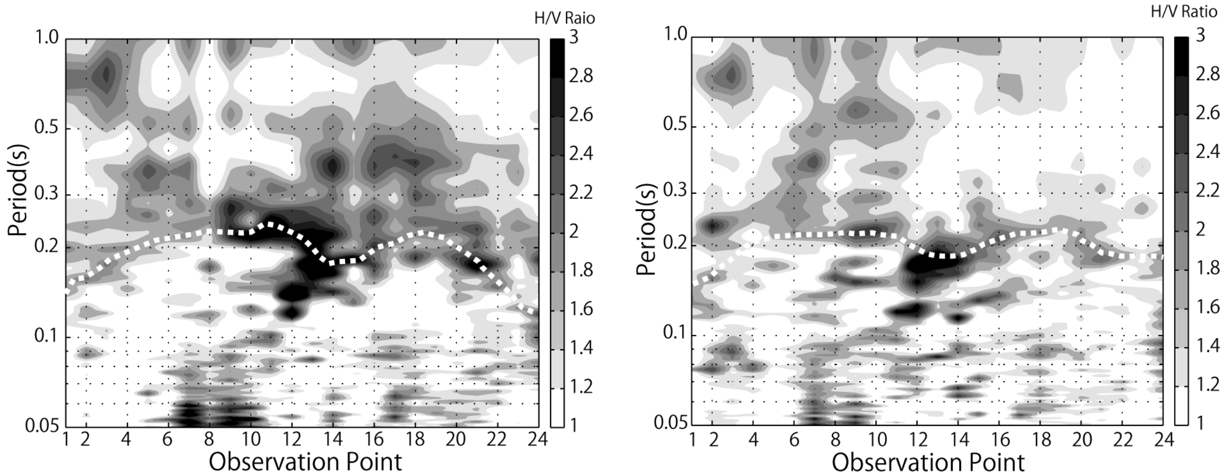


Figure 7 H/V Spectral Ratio at No.17



a) Normal to dam axis b) Parallel to dam axis

Figure 8 Fourier Spectra Contour Map



a) Normal to dam axis b) Parallel to dam axis

Figure 9 H/V Ratio Contour Map

3.VIBRATION CHARACTERISTICS FROM 3-D FINITE ELEMENT ANALYSIS

3.1.3-D FE Model

A 3-D FE model of the dam was made as shown in Figure 10, adjusting the height at 24 observation points. The number of finite elements and nodes are 10,304 and are 18,505, respectively.

Properties of the dam materials were determined so as to give the same peak periods between the micro-tremor measurement and 2-D FE analysis at 4 cross sections shown in Figure 10. Table 1 shows the parameters used for the 3-D analysis in which the dam was assumed uniform. Validity of the parameters was checked by comparing the vibration periods from the 2-D analyses of zoned models and uniform models. As the right and left ends of the dam are plunged into the mountain rock, boundary conditions at both ends were fixed in three directions.

Under these material and boundary conditions, a series of 3-D modal analysis and earthquake response analysis were conducted. In the latter analysis, earthquake ground was input at the basement of the dam model, and resulting response acceleration was output at the before-mentioned 24 points on the crest. From the Fourier spectra of the output divided by those of the input, a frequency response function at each point was calculated for two directions normal and parallel to the dam axis, respectively.

3.2. Results from 3-D FE Analysis.

The lowest 4 mode shapes and vectors were obtained from the modal analysis as shown in Figure 11, in which vibration vectors in two horizontal directions were calculated from the mode shapes shown on the left column and plotted on the right column.
According to Figure 11, the 1st and 2nd modes represent displacement mainly in the direction parallel to dam axis, and the 3rd and 4th modes mainly deform in normal direction. In the 1st and 2nd modes, the middle part of the dam (No.8~No.21) displaces together. In addition, No.14 is a node for the 2nd mode, and both side of this point displace in the opposite direction. While, in the 3rd the portion between No.9 and No.12 displaces, the portion between No.15 and No.19 displaces in the 4th mode. The portions of the large displacement in the 3rd and 4th modes are almost the same as those of large height as shown in Figure 3. As a whole, the displacement in the direction normal to the dam axis in the 3rd and 4th modes takes place in a limited portion when it is compared with the displacement in the dam axis direction in the 1st and 2nd modes.
The frequency response functions calculated for the 24 observation points are arranged in a numeric order in Figures 12 and 13, each of which is tentatively called a contour map of frequency response function. The contour map for the normal direction shown in Figure 12 has a single peak at No.11, while that for the parallel direction shown in Figure 13 has double peaks at No.11 and No.17. These peaks appear at the points where the dam has largest cross sections as shown in Figure 3. In the middle portion of the dam (between No.9 and No.20), the peak period is almost kept constant, and the peak value is small at around No.14 where the node in the 2nd mode is observed as shown in Figure 11.
When the H/V ratio contour map from micro-tremor measurements shown in Figure 9 is compared with the contour map of the frequency response function shown in Figures 11 and 12, both peak periods in the normal direction have common features; that is, two peaks in the middle of the dam as well as similar peak periods. The peak period of the vibration in the dam axis direction shown in Figure 13 does not show such similarity with Figure 9. Although it is difficult to compare in detail the H/V ratio contour map and the frequency response function in the dam axis direction, the peak periods are almost common.
In summary, even for a dam having a semi-circular dam axis like Shin-Yamamoto dam, principal directions for the dam vibration is normal and parallel to the dam axis, and the peak periods in the two directions are slightly different. In the normal direction, a smaller portion along the dam crest is likely to displace in phase, while in the dam axis direction a larger portion along the dam crest is likely to displace in phase.

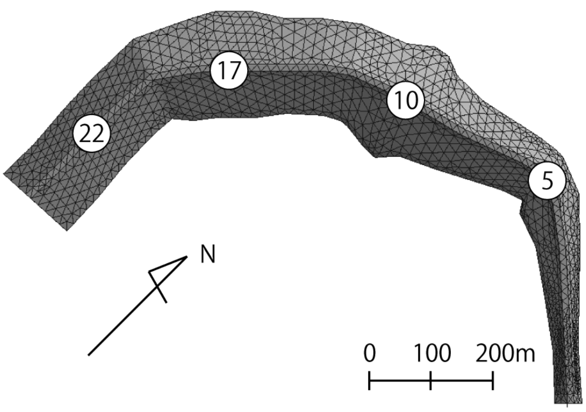


Figure 10 3-D FE Model

Table 1 parameters of the dam materials

Young's modulus(kN/m²)	Poisson's ratio	Density(kg/m³)	V_s(m/s)
1350000	0.32	2242.6	475

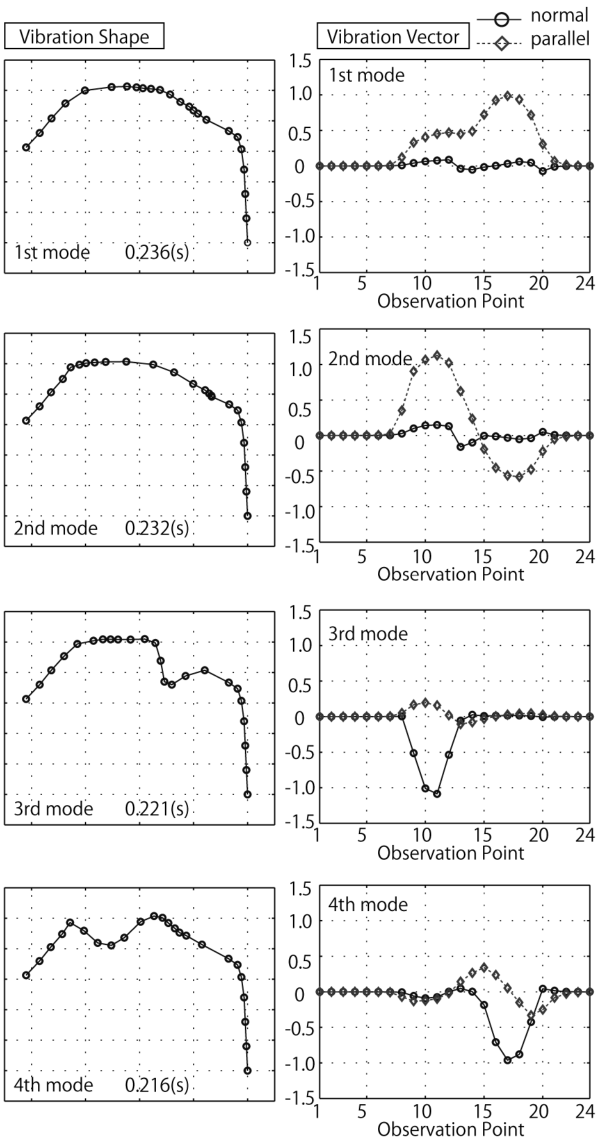


Figure 11 Vibration Mode Shapes and Vectors

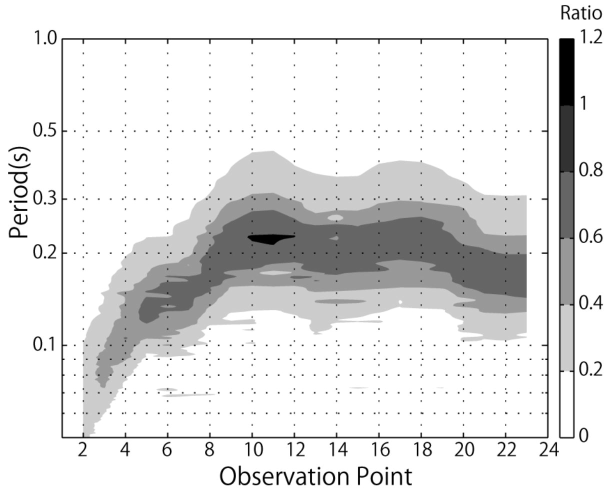


Figure 12 Contour Map of Frequency Response Function (in normal)

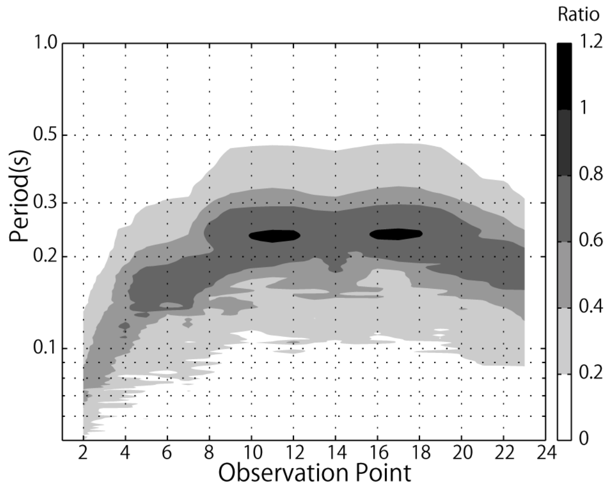


Figure 13 Contour Map of Frequency Response Function (in parallel)

4.EARTHQUAKE RESPONSE

4.1.Input Strong Motion

Earthquake response analysis was conducted to estimate the response of the dam to the main shock. As for the input motion, a best for the analysis is to use observation records at the dam foundation. But, as main shock records at the dam were lost, the strong motion of the dam was estimated from seismic records at JMA OJIYA located about 5km from the dam (see Figure 1) based on boring data, with a result shown in Figure 14.

4.2.Results from Earthquake Response Analysis

The input motion and resulting response acceleration at 4 points are shown in Figure 15 in terms of particle orbits on a horizontal plane. Distribution of maximum response acceleration in two horizontal directions is shown in Figure 16 where distribution of settlement along the crest is also plotted. As shown in Figure 16, the earthquake response was supposedly stronger in the normal direction than in the dam axis direction on the left half side, while it is reversed on the right half side. Distribution of maximum response velocity is plotted and

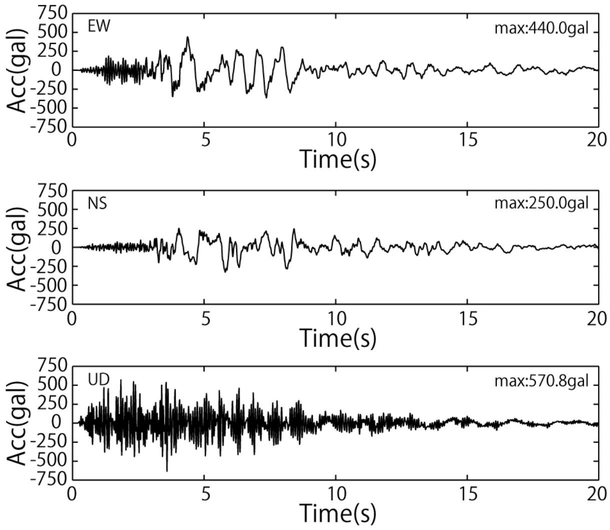


Figure 14 Input Strong Motions

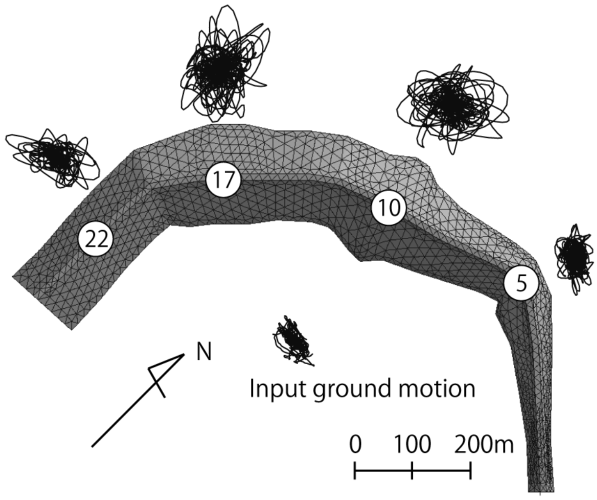


Figure 15 Orbit of Acceleration Response

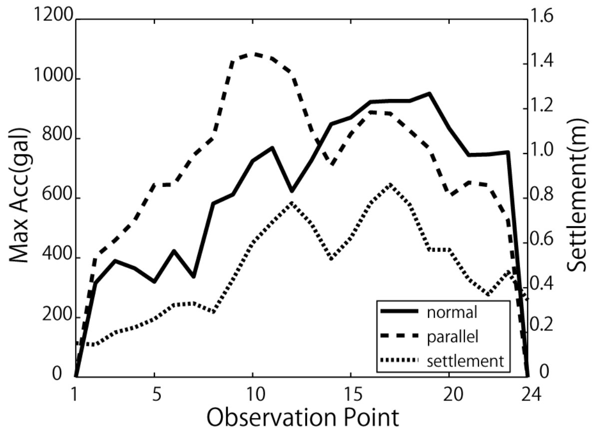


Figure 16 Distribution of Maximum Acceleration Compared with Settlement

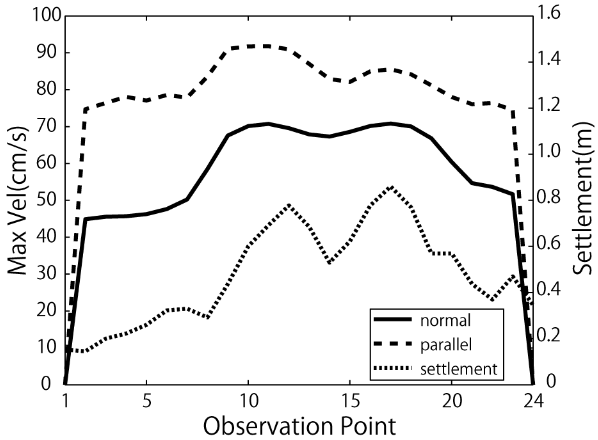


Figure17 Distribution of Maximum Velocity Compared with Settlement

compared with that of the settlement in Figure 17.

4.3.Relation between Damage and Earthquake Response by 3-D FE Analysis

According to Figures 16 and 17, earthquake response of the left side of the dam is not necessarily larger than that of the other portion. In addition, there was nothing particular in vibration characteristics o the left side of the dam from the micro-tremor measurements. Reportedly, deposit of fine particles was thick enough to cover the mouth of the drain layer located in the upstream side of the dam. Consequently, it seems reasonable to think that the thick sedimentation in front of the drain layer caused pore water pressure buildup under the strong shaking followed by the liquefaction. Results from the 3-D FE analysis are also consistent with statements in the report.

In Figure 18, the maximum response accelerations are compared with the settlement, and in Figure 19 the maximum response velocities are compared with the settlement. Apparently, the maximum response in the normal direction shows a higher correlation with the settlement. In particular, the maximum velocity in the normal direction shows the highest correlation with the settlement. Figures 18 and 19 imply that the settlement is likely to be produced when the maximum response at the crest exceeds 100gal in acceleration and 30cm/s in velocity. And the maximum response of the dam crest is estimated about 900gal in acceleration and about 70cm/s in velocity during the main shock.

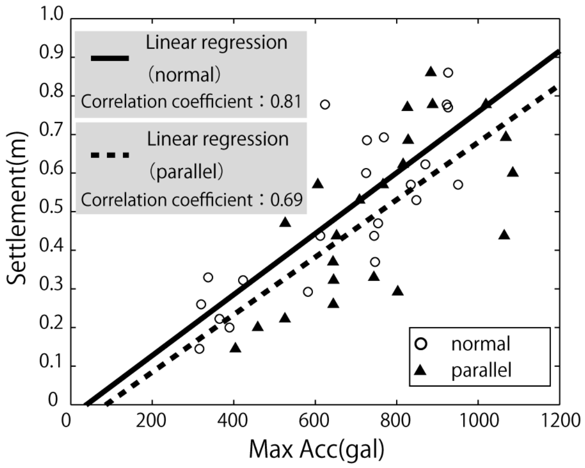


Figure 18 Maximum Acceleration plotted against Settlement

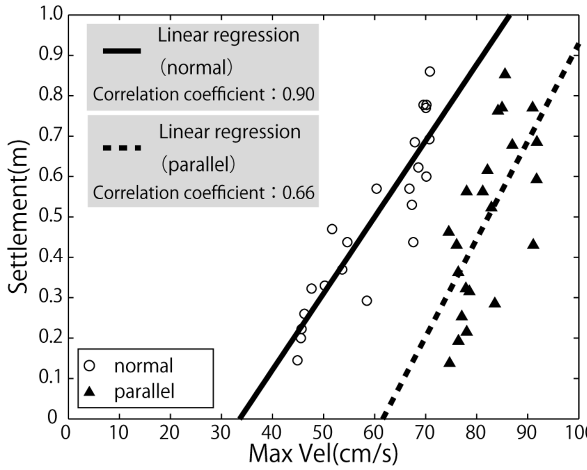


Figure 19 Maximum Velocity plotted against Settlement

5.CONCLUSION

Micro-tremor measurements and 3-D FE simulation were conducted to find vibration characteristics of Shin-Yamamoto dam and to estimate its response to the main shock. Findings from this study are listed below.

1. From the micro-tremor measurement, vibration periods of the dam were estimated. In the estimation, a contour map of the H/V spectral ratio has proved to be more helpful than the Fourier spectra.
2. The peak periods in the direction normal to the dam axis was found to change between 0.1 and 0.25s over the entire dam length in almost proportion to the height of each cross section. In the direction parallel to one, however, the peak period changes with less similarity between the height of each cross section.
3. The lowest two modes of the dam are associated with vibration in the dam axis direction, and the next two modes are in the normal direction. Thus, vibration in the dam axis direction induces displacement over a large portion along the crest, while vibration in the normal direction induces displacement of a limited portion.
4. Based on the strong motion records at JMA OJIYA, input earthquake motion was estimated for the 3-D response analysis of the dam during the main shock. The analytical result showed that the left side of the dam was shaken strongly in the normal direction, with a maximum response at the crest 900gal in acceleration and 70cm/s in velocity.
5. Finally, a good correlation was found between the maximum response velocity in the normal direction and the settlement of the dam crest.

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