Structural Monitoring Test For An Aged Large Arch Dam Based On Ambient Vibration Measurement

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SUMMARY
The long-term continuous ambient vibration test has been conducted at two aged large arch dams for 5 years. We have already presented the results on the first 1 year monitoring conducted at Hitotsuse arch dam [1]. These results show that the seasonal changes in natural frequency is correlated to the reservoir water level and temperature changes besides due to deteriorations or damages. However, from only 1 years' data, it cannot be specified that the seasonal changes of natural frequency of arch dam are strongly correlated to the reservoir water level and temperature changes. In this paper, we have confirmed that the reproducibility of the seasonal changes in the natural frequency due to the reservoir water level and temperature changes from 5 years' data measured at the same dam.

Keywords: arch dam, ambient vibration, natural frequency

1. INTRODUCTION

In Japan, the number of large concrete dams which were constructed more than 50 years ago has been increasing. It is extremely important to evaluate structural safety of such dams against age-related deterioration as well as large earthquakes. In current state of safety management on dams, although the water leakage and displacement of the dams are usually monitored and visual inspection is usually conducted daily or after large-scale earthquakes in order to evaluate the integrity of the dams. However, most of dams are too huge to observe damages in details. And also if damages develop on upstream side under water level, or on the contact part between the dam and foundation rock, it is difficult to observe them directly. The monitoring of natural frequency based on the ambient vibration measuring is one of the effective solutions. This is because decreasing rate of rigidity of the dam due to the damage can be detected from the change of the natural frequencies.
Based on the background described above, we have been conducted the long-term continuous ambient vibration test at two large arch dams for 5 years. We have already presented the results on the first 1 year monitoring conducted at Hitotsuse arch dam shown in Figure 1[1]. In these results, it shows that

Figure 1. Hitotsuse arch dam

the seasonal changes in natural frequency of the arch dam are correlated to the reservoir water level and temperature changes besides due to deteriorations or damages. However, from only 1 years' data, it cannot be specified that the seasonal changes of natural frequency of arch dam are strongly correlated to the reservoir water level and temperature changes. In this paper, we have confirmed that the reproducibility of the seasonal changes in the natural frequency due to the reservoir water level and temperature changes from 5 years' data measured at the Hitotsuse arch dam.

2. OUTLINE OF HITOTSUSE ARCH DAM

Hitotsuse arch dam was constructed in Kyushu region, south part of Japan in 1963 (aged 49 years). As shown in Figure 2, the height and crest length of the dam are 130.0m and 418.0m. The crest and base thickness are 4.0m and 22.3m, and the dam has four inspection catwalks on the downstream surface. The water level varies from 170.0m to 200.0m above the sea level.

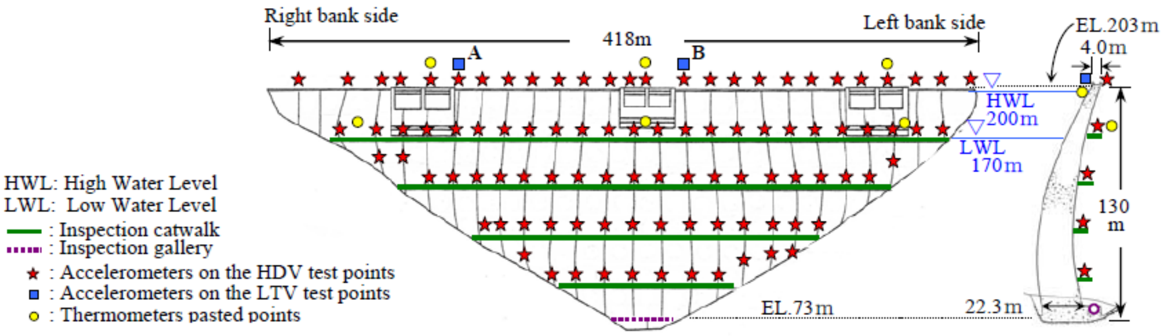


Figure 2. Downstream view and measuring points of Hitotsuse arch dam

3. MEASUREMENT POINT AND PROCEDURE

We have conducted two kinds of ambient vibration tests as follows.

3.1. High-density Vibration Array Test (the HDV test)

The HDV test was carried out on 21-22 February 2007 in order to confirm the relation between natural frequency of the dam and the mode shapes on whole of the dam. Figure 2 also shows the vibration measuring points on the downstream-sides of the dam. In the HDV test, 97 array points are set on the downstream surface of the dam, and ambient vibration was repetitively measured with replacing eight portable accelerometers. The measuring time at each point is fixed to 10 minutes. Final modal identification results are synthesized by combining the mode shapes estimated from the all repetitive tests, where the records at two fixed sensors in the long-term vibration measuring test (the LTV test) are used for adjusting the amplitude and phase angle of each modal result obtained at different time.

3.2. Long-term Vibration Measuring Test (the LTV test)

The LTV test has been conducted since 14 August 2006 to evaluate the seasonal changes of the natural frequencies, where the modal property varies with temperature or reservoir water level. For this test, two tri-axial accelerometers are installed on the right-hand-side (sensor A) and the centre (sensor B) of the dam as shown in Figure 2, to avoid nodes as ‘zero’ displacement points, and to obtain the cross-spectrum of the responses among the two measuring points. The measurement system was configured to record continuously with the sampling rate of 200 Hz and the measuring data is stored in every one hour. Six thermometers are also set on the upstream and downstream surfaces of these dams respectively, as shown in Figure 2.

4. RESULTS

The natural frequency and its mode shape of these dams were identified from the HDV test data, and changes in the natural frequency are evaluated from the LTV test data observed for about 5 years.

4.1. Identification of Mode Shapes (the HDV test results)

Figure 3 shows an example of the auto power spectral density function (PSD) estimated from the records on the sensors A and B (measuring on the LTV test) at the day as the HDV test on Hitotsuse arch dam. As applied the cross spectrum based-identification method to the HDV test data [2] [3], three lower mode shapes can be identified. The resonance peak in the three mode shapes are marked as lower triangles in Figure 3. Figure 4 illustrates these identified mode shapes. As shown in each mode shape, the deformation shapes on the every height of the dams was similar to one another, but their amplitudes increased with the upper height. These latest mode shapes were quite similar to the past mode shapes obtained by the forced vibration tests conducted just after the completion of each dam [4]. The fact indicates that the mode shapes did not change at all for about fifty years, and the ambient vibration measurement gives the accurate mode shapes comparable to the results by the forced vibration test.

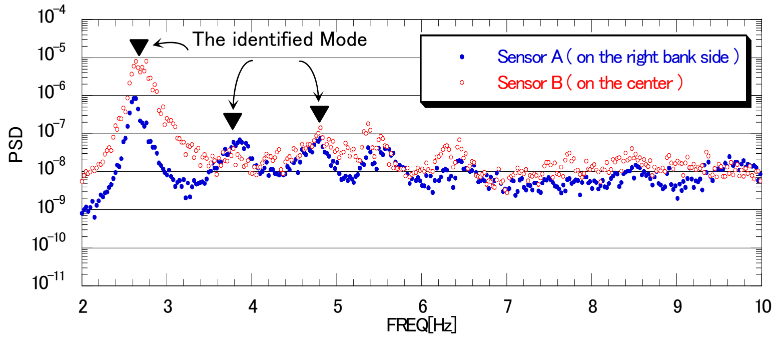
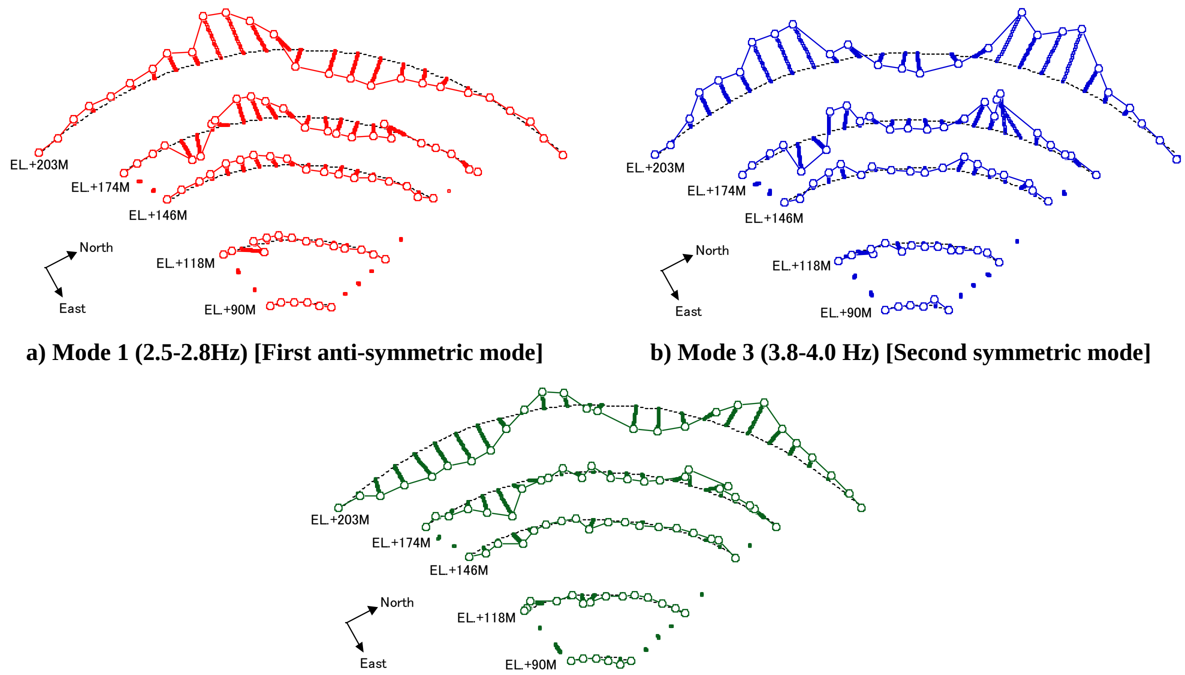


Figure 3. Power spectrum density on the day of the HDV test at Hitotsuse arch dam



a) Mode 1 (2.5-2.8Hz) [First anti-symmetric mode]

b) Mode 3 (3.8-4.0 Hz) [Second symmetric mode]

c) Mode 4 (4.6-4.8 Hz) [Second anti-symmetric mode]

Figure 4. Power spectrum density on the day of the HDV test at Hitotsuse arch dam

4.2. The LTV Test Results

We have conducted seasonal change in natural frequencies of Hitotsuse arch dam from 5 years measuring data. The natural frequencies are identified for every 5 minutes by applying the identification method based on ARMA model [5], and the median filter (window band width: 24 hours) is applied to these identification results. Figure 5 shows the time histories of natural frequencies of Mode 3 and Mode 4, with the reservoir water level, dam surface temperature for about 5 years (Aug 2006 – September 2011). To compare the natural frequency of Mode 3 and Mode 4, although these are different in the band of frequency, they show the same behaviour in through the period. In warm season, we found the relation of inverse proportion between water level and natural frequencies. For example, from May to July 2010, the natural frequencies of Mode 3 and Mode 4 rapidly increase with decreasing the water level, and also rapidly decrease with increasing the water level. Similarly, in cold season, we found the relation of proportion between dam surface temperature and natural frequencies. For example, in every winter season (from November to March), although the change in dam water level is various at every year, the natural frequencies of Mode 3 and Mode 4 gradually decrease with decreasing the dam surface temperature gradually, and vice versa. As mentioned above, the natural frequency shows the strong dependence against the water level and the dam surface temperature according to the season.

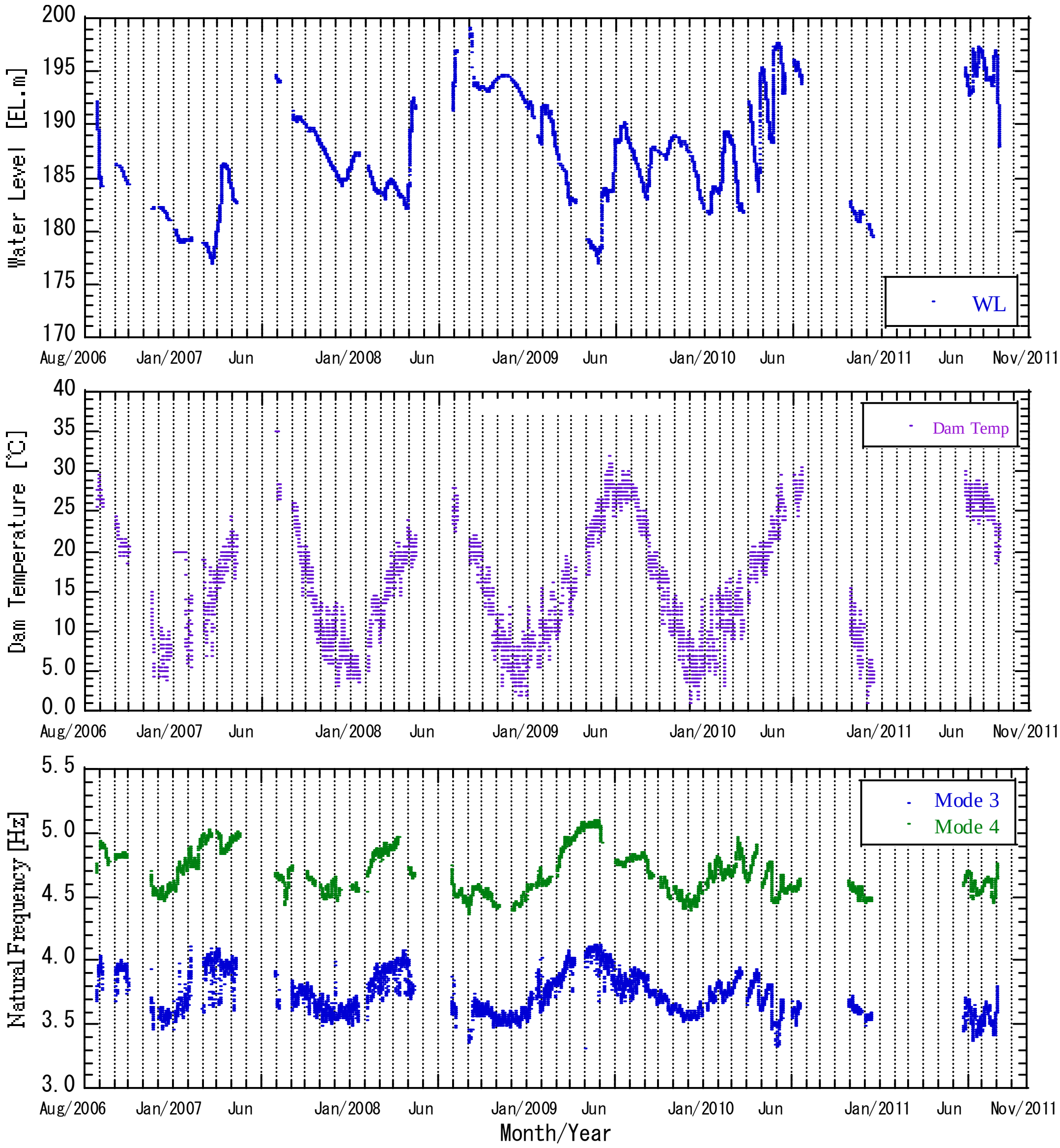


Figure 5. The time histories of natural frequencies, water level, and dam surface temperature for about 5 years

Figure 6 shows the variations of the natural frequencies of Mode 4 versus the reservoir water level which were measured from August 2006 to November 2007. This figure is plotted every 5 minutes. Now, we will discuss about the natural frequencies effects on the reservoir water level, referring to the measurement result in Figure 6. When the reservoir water level rises from the lowest to a certain level (less than 180.00m), natural frequencies slightly increase with increasing the water level (denoted as "arrow A" in Figure 6). This behaviour can be attributed to the increase of the stiffness of the dam concrete due to the contraction along the construction joints under increasing hydrostatic pressure. After the water level reached above 180.00m or more, the added mass effect of the reservoir becomes dominant and the natural frequencies begin to decrease with increasing water level (denoted as "arrow B" in Figure 6). Moreover, we have already found the third path in the relation between frequency and water level, which denotes as "allow 3" in Figure 6. The third path seems to appear in low temperature. The third path might be caused by change in contact stiffness among the concrete blocks.
Figure 7 shows the variations of the natural frequencies of Mode 4 versus the reservoir water level for about 5 years (from August 2006 to September 2011). This figure is plotted by three colors according to the difference in dam surface temperature, and the median filter (window band width: 144 hours [6days]) is applied. This figure clearly shows that the relation between reservoir water level and natural frequency is inverse proportion which is different according to difference of dam surface temperature. And it also might be said that the change in natural frequency is affected by not the daily temperature change, but a change of certain period.

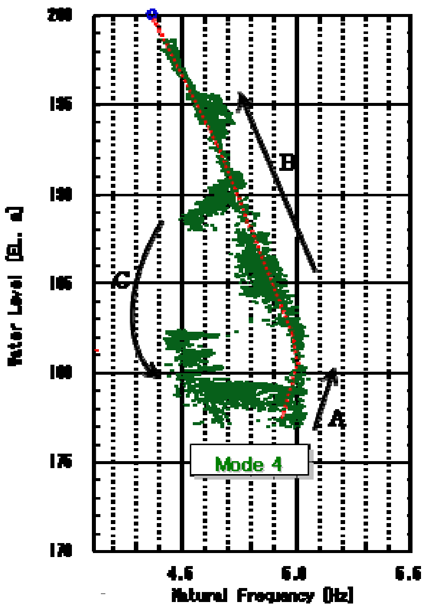


Figure 6. Effect of reservoir water level (Aug 2006 – Nov 2007)

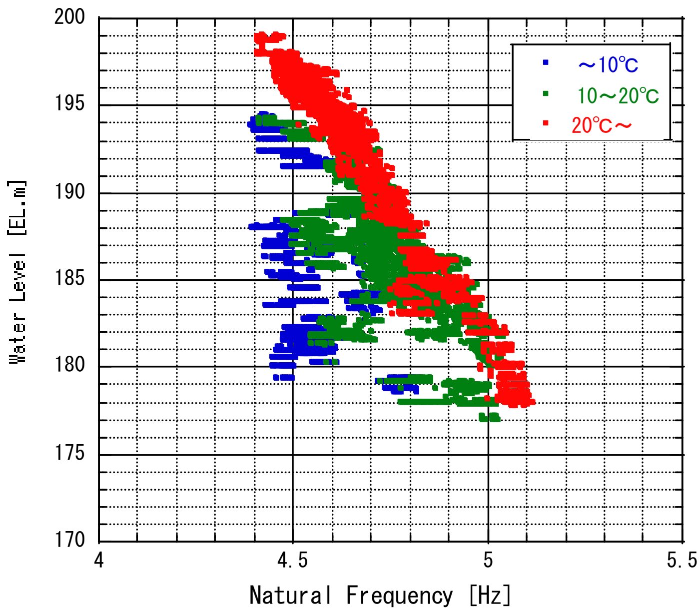


Figure 7. Effect of reservoir water level (Aug 2006 - Sep 2011)

5. CONCLUSIONS

The long-term continuous ambient vibration test has been conducted at Hitotsuse arch dam for 5 years. From about 5 years' data, we have confirmed that the seasonal changes of natural frequency of arch dam are strongly correlated to the reservoir water level and temperature changes. In addition, we have clarified that the relation between reservoir water level and natural frequency is inverse proportion which is different according to difference of dam surface temperature, and the change in natural frequency is affected by not the daily temperature change, but a change of certain period. These results have employed for developing structural damage detection technique based on ambient vibration test.

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