System Identification, Detection of Proper Frequency Variation of an Aged Arch Dam and Its Dynamic Behavior during the 2011 Great East Japan Earthquake

T. Ueshima & M. Shibuya
Miyagi University, Japan

K. Kanazawa
Central Research Institute of Electric Power Industry, Japan

H. Shiojiri & M. Nakamura
Nihon University, Japan

SUMMARY:
In order to grasp proper frequencies and their variations over time, including the ones during and/or before/after seismic events, long-term continuous observation of ambient vibration/seismic motion was undertaken at the crest of an aged arch dam, which, up to now, revealed the following; 1) The identified proper frequencies of the dam using ambient vibration data during about five months from summer to winter became lower together with the dam surface temperature. 2) During the main shock of the 2011 East Japan Earthquake, observed record with a very large maximum acceleration of about 630 gal was obtained at the dam crest, of which the duration ranged for about three minutes. 3) The predominant frequency during the Event became remarkably lower than the one from the ambient vibration before the Event, and the one from the ambient vibration after the Event, on the whole, returned back to pre-main shock level.

Keywords: proper frequency variation, ambient vibration, The Great East Japan Earthquake, aged arch dam

1. INTRODUCTION

In Japan, aged dams are increasing of which completions of construction were nearly fifty years ago. So, the importance of maintenance is increasing. Methods to evaluate structural health of dams are expected to be developed. Methods to evaluate structural health utilizing vibration observation are to utilize variation of dynamic characteristics before/after structures are damaged. Researches to develop such methods are recently active with civil and/or architectural structures as research objects. But such researches with dams are not so many, except Proulx, J. et al. (2001), Darbre, G. R. et al. (2002), Okuma, N. et al. (2008) and so on. Under the above-mentioned circumstances, our research project aims at obtaining basic data to develop a method to evaluate structural health of dams utilizing vibration observation. In our project, research items include high-density observation of ambient vibration, where many seismometers are arranged on the dam crest and simultaneous observation of ambient vibration at many observation stations is performed to obtain proper frequencies and mode shapes of the dam, and long-term continuous observation of ambient vibration/seismic motion to obtain dynamic characteristics of the dam by means of system identification, and to detect proper frequency variation and/or the one during and/or after seismic events. Using long-term continuous observation, it is considered possible to identify dynamic characteristics of the observed structure as well as to detect proper frequency variation under the usual state of usage, which offer basic data for structural health monitoring/diagnosis. In our project, it is also scheduled to use FEM to analyze dynamic characteristics of the dam, to evaluate structural health as well as to detect damages during seismic events by means of reverse analysis.
In this paper, dynamic characteristics of the dam are identified first using data obtained by means of long-term continuous observation of ambient vibration, and then, proper frequency variation over about five months is examined. In addition, the result of the analyses using recorded data at the dam crest during the 2011 Great East Japan Earthquake, during a large-scale aftershock, and ambient vibration records before/after such seismic events is reported. The observed main shock record has a large maximum acceleration with very long duration time, which is considered very precious.

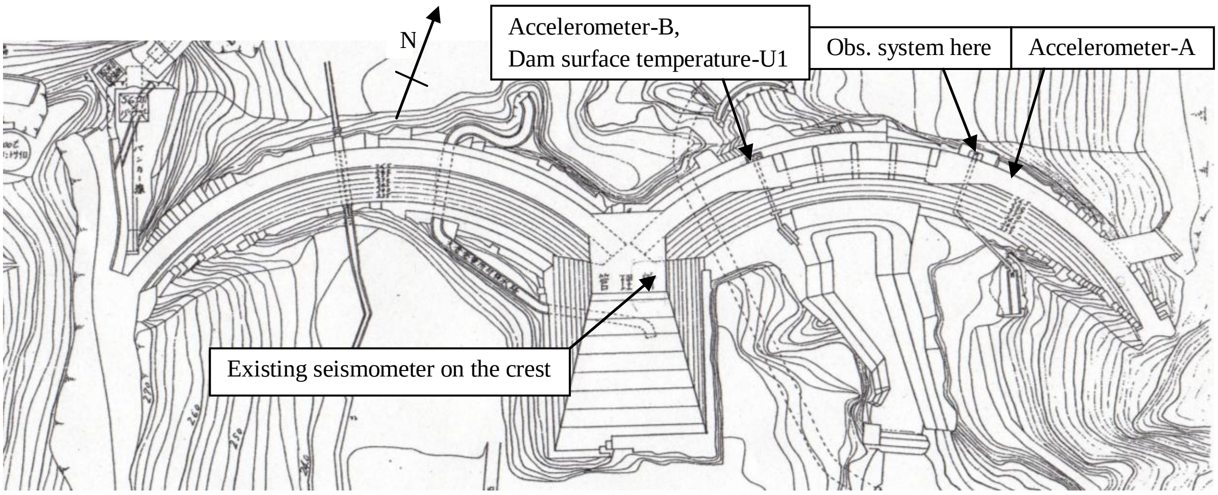

Figure 1. Plan of the observed dam, accelerometer layout for long-term continuous observation of ambient vibration/ seismic motion and location for dam surface temperature observation

Footnote : Just such observation stations are shown in this figure as are used in this paper. "Existing seismometer" means that it is a part of seismic observation system set up beforehand independent from our system.

2. OUTLINE OF THE OBSERVED DAM, ON ANALYSIS METHOD AND SYSTEM IDENTIFICATION

The observed dam is Ohkura Dam in Miyagi Prefecture, Japan, of which the construction was completed about fifty years ago. The dam has the height of 82.0 m, with the length of the top of the dam 323.0 m, the total storage capacity 28,000,000 m^3, and the dam volume 226,000 m^3. It is a concrete dam with two arches in a row, that is, a double-arch type concrete dam, which is the only one in Japan. There is a gate for discharging water at almost the center of the left bank side arch, and the dam crest is used as an ordinary road with 4.4 m wide.

Figure 1 shows the observed dam plan, and at the same time, the location of the observation stations for long-term continuous observation. In the long-term continuous observation, acceleration and dam surface temperature are observed, all of which are on the dam crest. In acceleration observation, totally three components of accelerations, that is, horizontally two-directional and vertical components from seismic motion to ambient vibration level are observed per a observation station. After dividing all the observed data into small sample data at an interval of five minutes each so that they do not overlap each other, the dynamic characteristics of the observed dam were identified toward each small sample data, applying cross spectrum method (Kanazawa, K. et al. (2005), which is called "ARMA method" hereafter).

In the application of ARMA method, the component from 0.0 Hz to 21.0 Hz in the observed data was extracted using band-pass filter with trapezoidal shape.

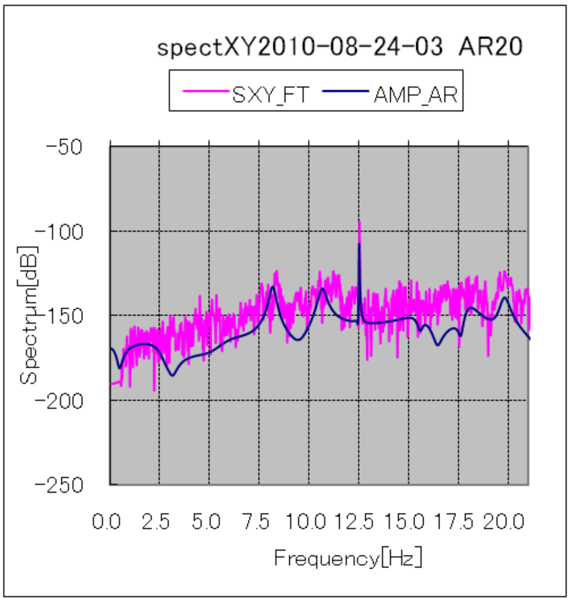

Figure 2. Example of dynamic characteristics identification from long-term continuous observation record of ambient vibration : Cross spectre between observation station-A and -B (AR20) SXY_FT:FFT from the observed, AMP_AR:Identified

Table 1. Example of dynamic characteristics identification from long-term continuous observation record of ambient vibration : Cross spectre between observation station-A and -B (AR20)

No.	Proper frequency [Hz]	Damping const. [%]
1	8.3	5.1
2	10.8	5.3
3	18.2	3.4
4	20.0	2.6

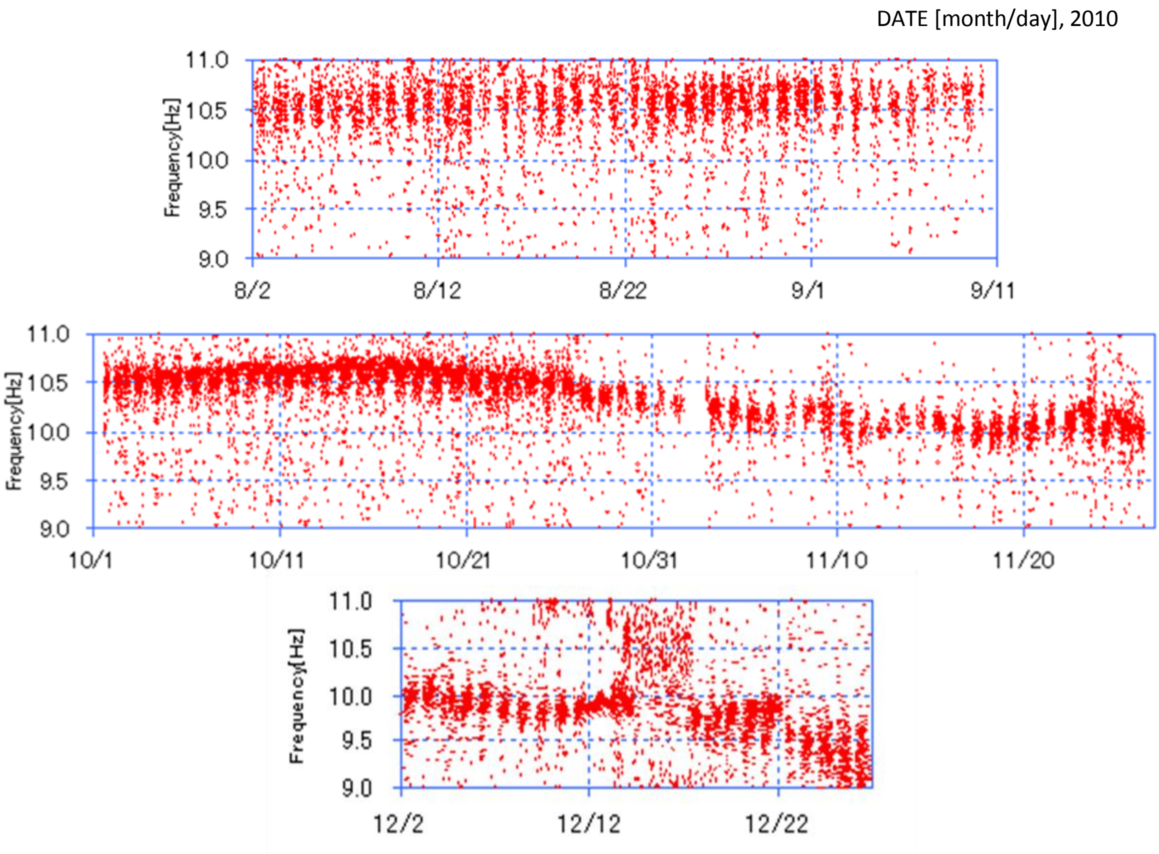

Figure 3. Example of proper frequency variation over time identified from cross spectre between Observation Station-A & -B : Proper frequencies within the frequency range from 9 to 11Hz are in the figure.

Period : The figure at the highest row from August 2 to September 11, the figure at the middle row from October 2 to November 26 (+alpha), and the figure at the lowest row from December 2 to December 27. All within the year 2010.

In this paper, the direction perpendicular to the axis of the dam crestline is expressed as "NS-direction" and the one parallel to the dam axis as "EW-direction" respectively, for the sake of simplicity. Dynamic characteristics of the dam were identified using cross spectra of NS-directional components of observation station-A and -B. As to the degree of ARMA model, trial calculation was performed from 10^{th} to 50^{th} degree at the interval of ten degrees, and final identification result was taken from 20^{th} degree where peak was comparatively stable. An example of system identification result is shown in Figure 2 and Table 1. In Figure 2, a sharp peak is recognized at 12.5 Hz, but the damping constant of the peak is extremely small around the extent of 0.01 %, which offers the reason for not judging the mode as that of dam body itself. So, the mode was not looked upon as the object of consideration in this paper.

3. EXAMPLE OF PROPER FREQUENCY VARIATION OVER TIME AT THE DAM

Each of the dynamic characteristics of the observed dam identified every five minutes applying ARMA method is the one at a time section. Long-term continuous observation is performed with the objective of examining how the dynamic characteristics identified in such a way vary over time. This process is first to place in a row in time direction the identified dynamic characteristics at each time section, then to examine/evaluate the variation of the dynamic characteristics over time.

Figure 3 shows an example of placing in a row the proper frequencies variation over time. In Figure 3, proper frequency variation over time from 9 to 11 Hz is shown. As to the period, the summer (in the highest row), the fall (in the middle row) and the winter (in the lowest row) are shown, each of which picks up the period of 1 to 2 months. Figure 3 shows the clear tendency of proper frequency decrease from summer toward winter.

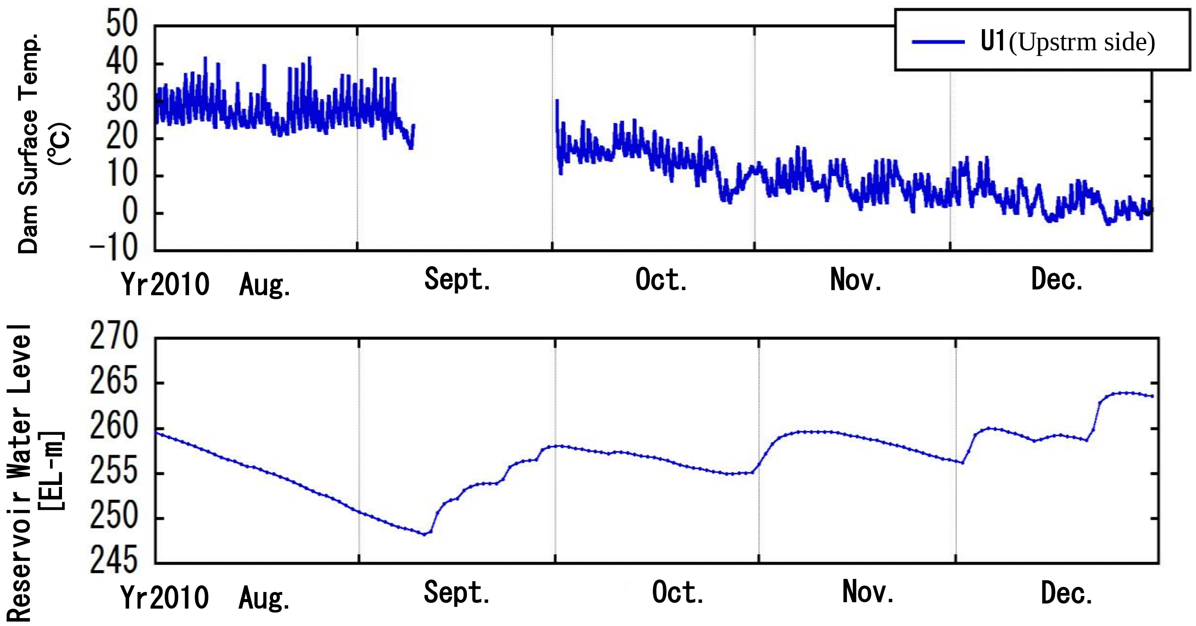

Figure 4. Variation of dam surface temperature and reservoir water level over time from Aug. to Dec., 2010

On the other hand, Figure 4 shows the variation of the dam surface temperature (at the upstream side) and of the reservoir water level over time from August to December, 2010. Comparing the variation of the proper frequency over time with that of the dam surface temperature, it is shown that both parameters decrease together over time.

The mechanism of the proper frequency decrease following the dam surface temperature decrease is inferred as follows; following the dam body temperature decrease, the dam shrinks, arch effect is lost, the compressive stress of the dam body concrete decreases and as the result, Young's modulus decreases. Or the proper frequency decrease is inferred to be caused by the joint rigidity decrease following the compressive stress decrease. Moreover, Figure 3 also shows that the proper frequency variation as the environmental change ranges considerably wide, and that there may be a case where the identified proper frequencies vary wide even for the same mode when the periods to be identified are far different each other.

Table 2. Maximum acceleration and its occurrence time for each component of each observation station

Obs.St.-comp.	Maximum acceleration (gal)	Occurrence time of maximum acceleration (h:mm:ss)
A-UD	121.8	14:46:26
A-NS	395.8	14:46:24
A-EW	113.0	14:46:24
B-UD	125.6	14:46:23
B-NS	626.2	14:46:23
B-EW	135.2	14:46:25

Footnote : PC used in the observation has time lag from UTC. The times in the table include such error.

As for the effect of the reservoir water level on the proper frequency variation, whereas there is a period where the reservoir water level changes suddenly from decrease to increase (Figure 4), the proper frequency decreases gradually throughout the period from summer to winter (Figure 3). Based on the observed data up to now on the relationship between proper frequency and reservoir water level, it is reported that proper frequency increases as reservoir water level decreases when reservoir water level is high enough, whereas proper frequency decreases as reservoir water level decreases when reservoir water level becomes lower than a certain level (Ueda, M. et al. (2000), Okuma, N. et al. (2008)). Referring such observed data up to now, it is inferred that the effect of the reservoir water level change on the proper frequency variation over time is not so large. More detailed investigation on it will be the next subject.

4. DYNAMIC BEHAVIOR OF THE OBSERVED DAM DURING THE 2011 GREAT EAST JAPAN EARTHQUAKE, AND THE LARGE-SCALE AFTERSHOCK

When the 2011 Great East Japan Earthquake*1) occurred at around 14:46 of March 11, 2011, our long-term continuous observation system was at work, and acceleration time history records were obtained as shown in Figure 5. Two seismometers were installed on the dam crest, where the epicentral distance was about 189 km. In Figure 5, acceleration time history records of totally six components, that is, NS-directional, EW-directional and vertical components of observation station -A and -B, are shown in the same scale (gal/plot mm). Table 2 shows maximum acceleration and its occurrence time of each component at each observation station.

*1) According to the quick report by National Research Institute for Earth Science and Disaster Prevention (NIED hereafter, for short), the magnitude of the Earthquake was 9.0, the epicenter was located at Sanriku-Oki and the maximum seismic intensity was 7. (http://www.bosai.go.jp/saigai/2010/images/20110323_01.pdf)

Our observation system also recorded ambient vibrations before/after the main shock. Spectral analyses of both the main shock record and ambient vibration records before/after the main shock revealed the following;

1) The duration of the acceleration time history records of the main shock of the 2011 Great East Japan Earthquake obtained by our observation system was so long, ranging for about three minutes. At both observation stations, the acceleration amplitude of NS-component (which is perpendicular to the axis of the dam crestline) was the largest in three components, and the recorded maximum acceleration reached about 630 gal at observation station-B(NS).

   As for the records obtained by the existing seismic observation system, the maximum acceleration at the dam crest was 185 gal and the one on the base rock which is 40.5 m lower than the crest level was 87 gal, both of which were recorded in NS-directional component. The occurrence time when the maximum acceleration was recorded was 14:47:40.00*2).

   *2) The existing seismic observation system is independent from our long-term continuous observation system, and so, for example, as for time, what is described in the footnote of Table 2 does not apply here to the existing system.

2) The observed acceleration time history records consist of plural wave groups and the maximum acceleration was recorded in the second wave group which arrived 40 to 50 seconds later than the first wave group. This feature is common to most strong motion records in Miyagi Prefecture (http://www.bosai.go.jp/saigai/2010/20110316_01.html), which is considered that the feature of the fault mechanism of the 2011 Great East Japan Earthquake emerged to the seismic records at the observed dam crest.

3) Spectral analyses of the main shock acceleration record brought the predominant frequency of 5.7 Hz at the observation station-A(NS), and 5.9 Hz at -B(NS) respectively (Figure 6), whereas the ones of the same observation stations (component) from the ambient vibration records before/after the main shock range from 6.6 to 7.1 Hz (Figure 7, 8), which showed clearly that the predominant frequency during the main shock was remarkably lower than the ones from the ambient vibration records.

   As for the sharp peak at 12.5 Hz with very small damping constant in the spectra from ambient vibration records (Figure 7, 8), it was not looked upon as the object of consideration in this paper as was written in chapter 2, but a comment is added here, that is, the peak at 12.5 Hz is almost irrecognizable in the spectre from the main shock, following the increase of the vibration amplitude at all the frequency range, including at the predominant frequency of a little less than 6 Hz, which is another evidence that the mode is not that of the dam body itself.

4) Examination on the predominant frequency variation before and after the main shock using midnight ambient vibration records brought that the one after the main shock, on the whole, can be looked upon as returning back to the one before the main shock, taking account of the remarkable decrease of the predominant frequency during the main shock compared with the ones from the ambient vibrations before/after the main shock (Figure 7, 8).

5) It was also examined whether or not the phenomena mentioned in the above 3) and 4) reappeared during a large-scale aftershock. Here in this paper, the aftershock was examined which occurred at the midnight of April 7, 2011*3). The epicentral distance of the observed dam was about 113 km and the maximum acceleration at the dam crest was about 430 gal (at the observation station-B(NS)). Spectral analyses of the aftershock also brought that the predominant frequency during the aftershock remarkably decreased when compared to the one from the ambient vibration

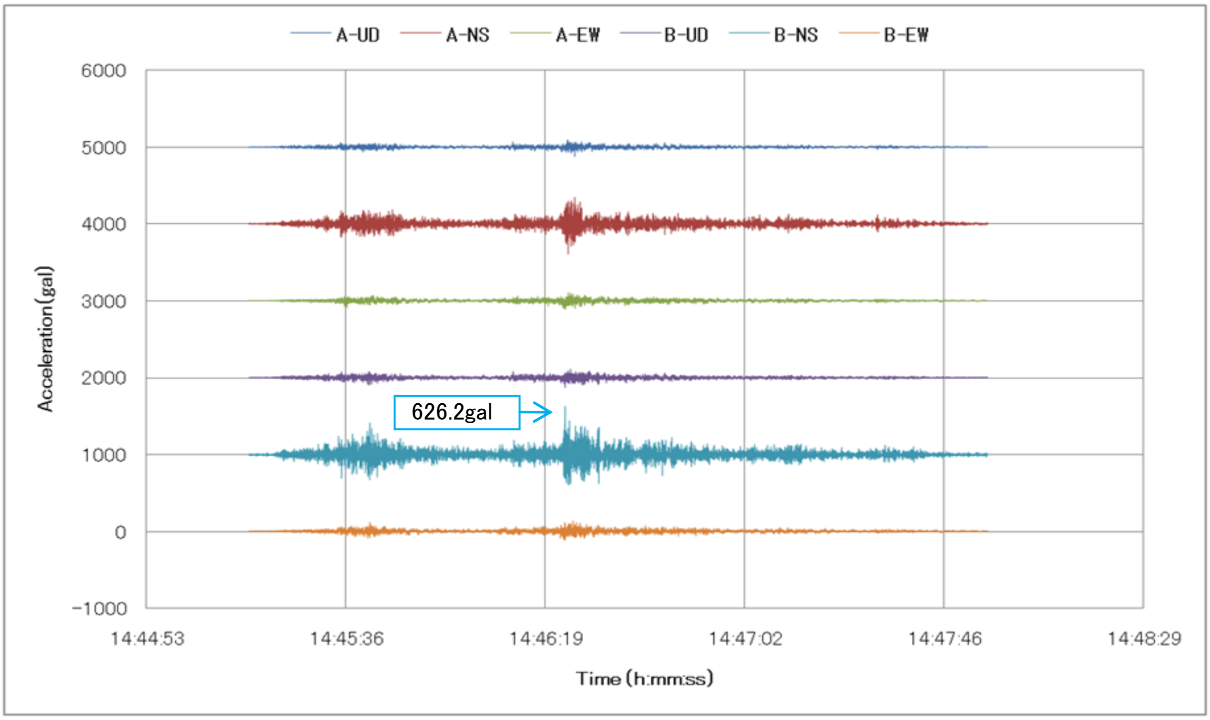

Figure 5. Acceleration time history record observed at the dam crest during the main shock of the 2011 Great East Japan Earthquake : From the highest row, A(UD), A(NS), A(EW), B(UD), B(NS), B(EW), respectively, where the way of expression is the name of the observation station (component).

Footnote : PC used in the observation has time lag from UTC. The times in the figure include such error.

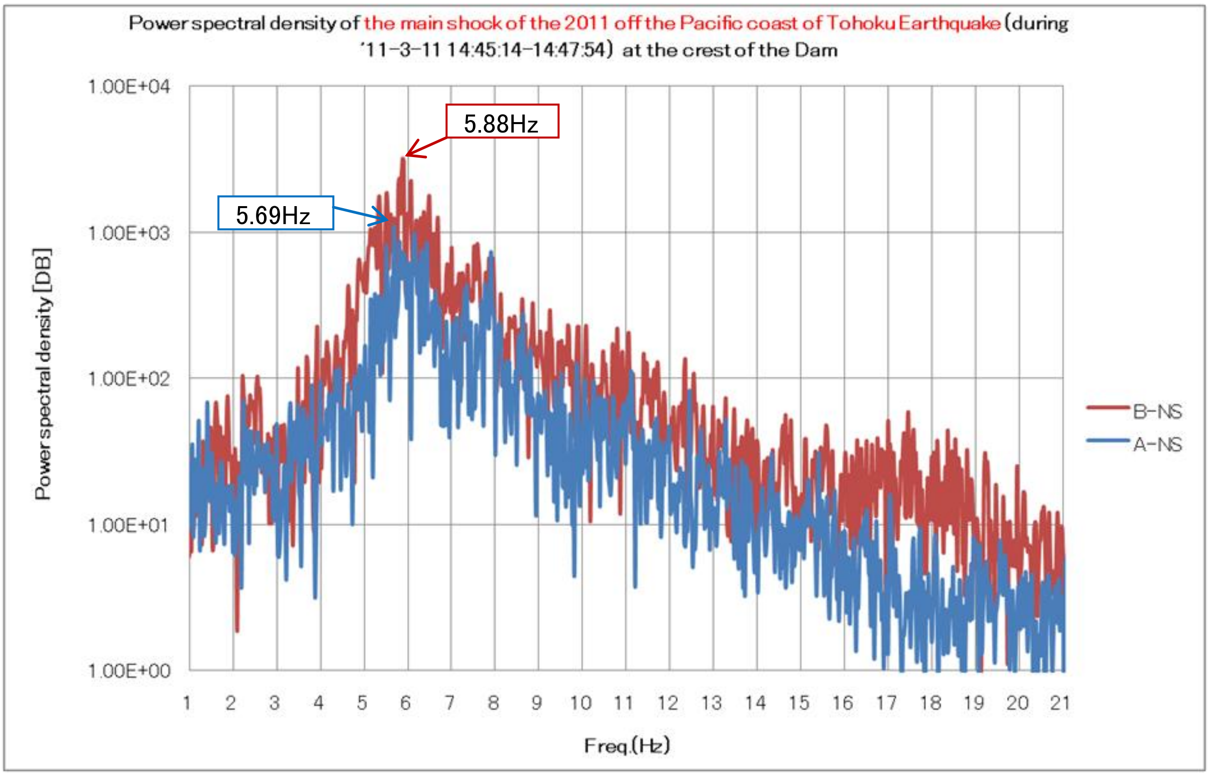

Figure 6. Power spectral density of the main shock acceleration record of the 2011 Great East Japan Earthquake at the dam crest for observation stations -A(NS) and -B(NS)

Footnote : PC used in the observation has time lag from UTC. The times in the figure include such error.

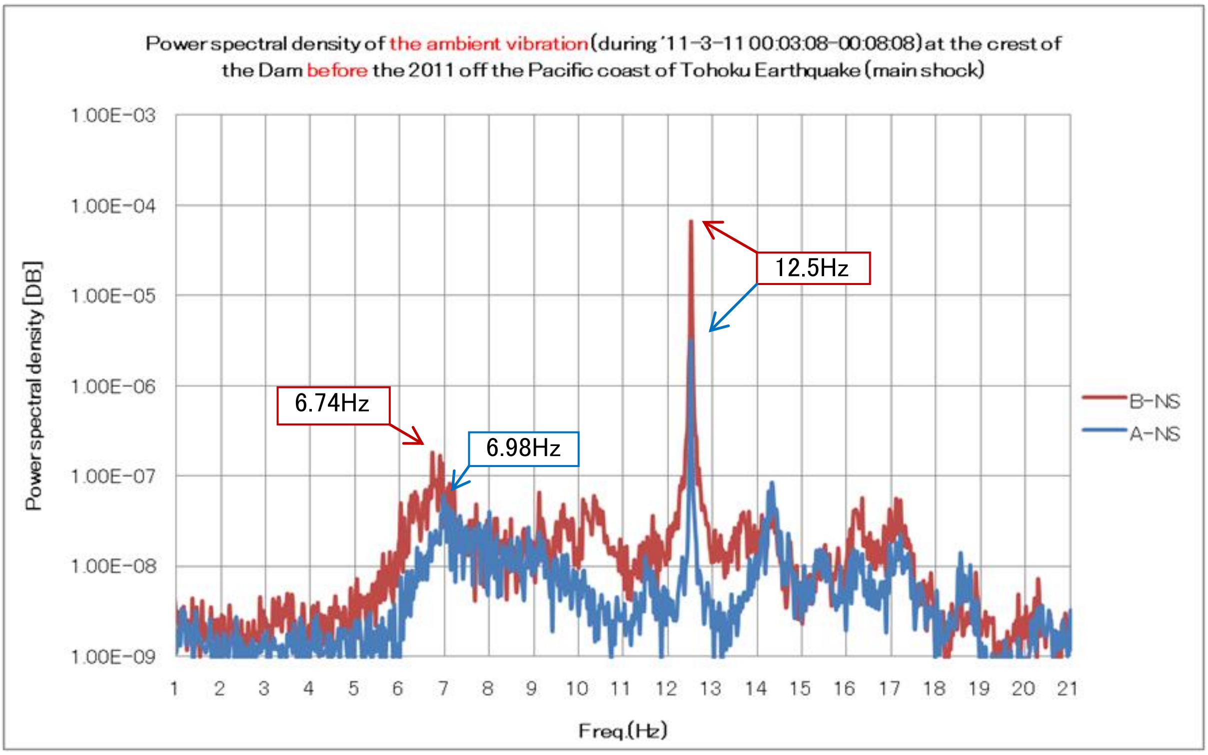

Figure 7. Power spectral density of the ambient vibration acceleration record at the dam crest before the main shock of the 2011 Great East Japan Earthquake for observation stations -A(NS) and -B(NS)

Footnote : PC used in the observation has time lag from UTC. The times in the figure include such error.

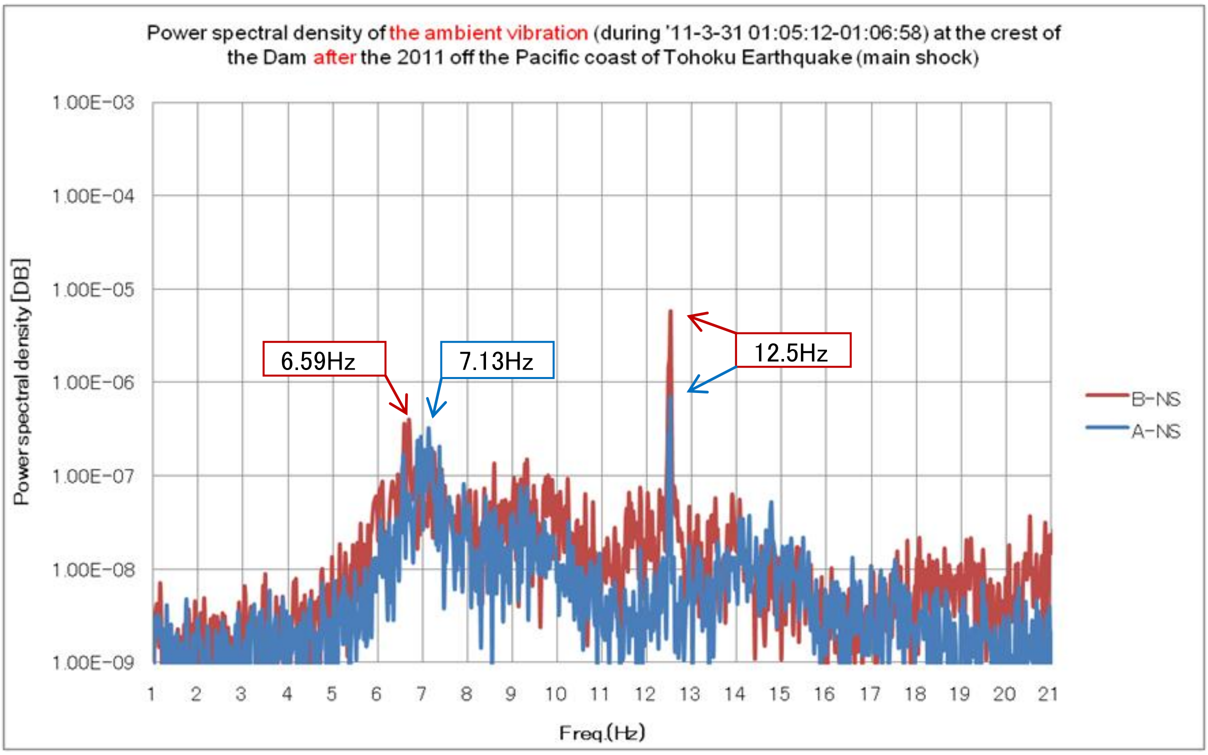

Figure 8. Power spectral density of the ambient vibration acceleration record at the dam crest after the main shock of the 2011 Great East Japan Earthquake for observation stations -A(NS) and -B(NS)

Footnote : PC used in the observation has time lag from UTC. The times in the figure include such error.

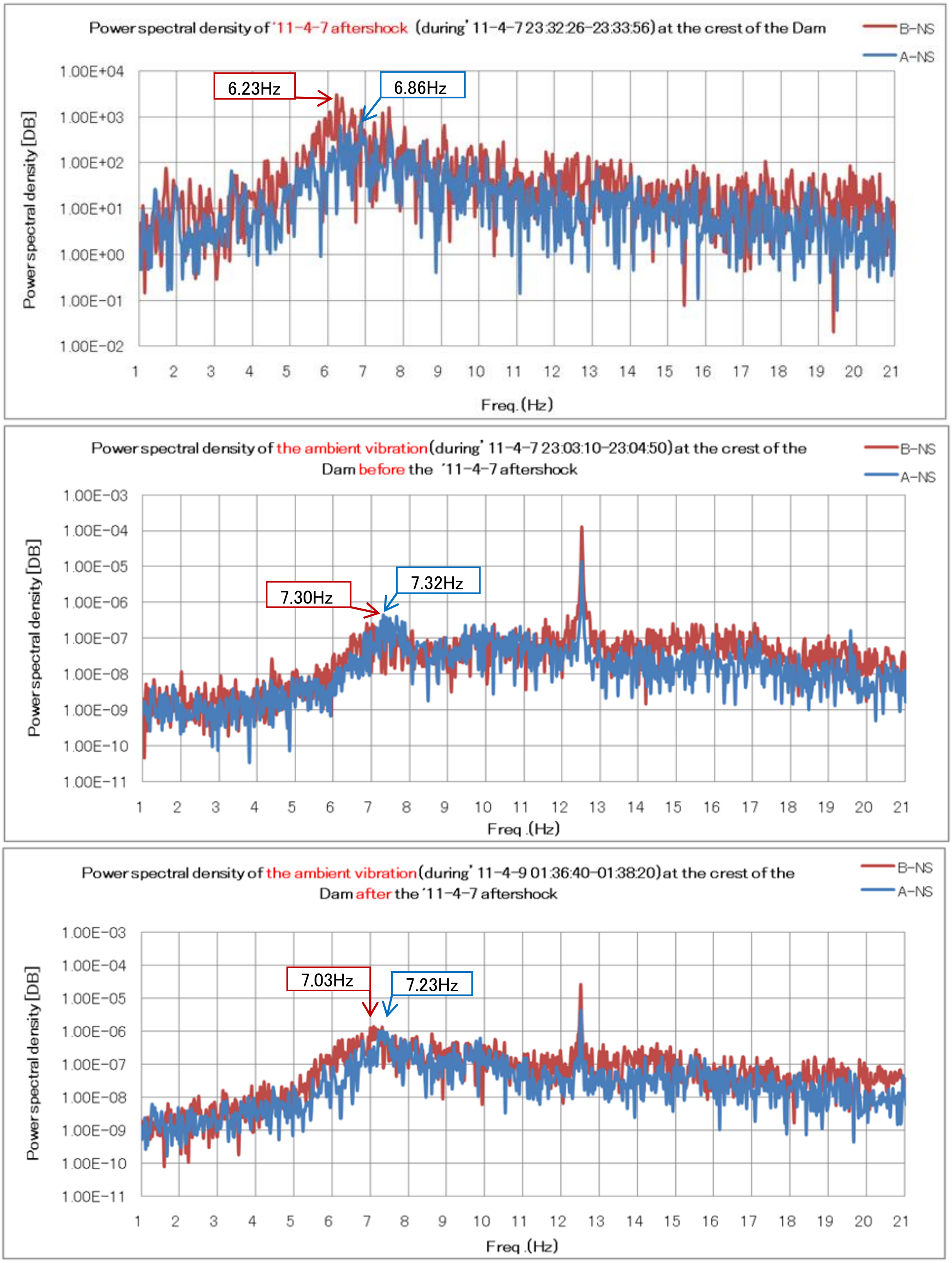

Figure 9. Power spectral density of the acceleration record of the aftershock occurred on April 7, 2010, and of ambient vibration before/after the aftershock at the dam crest for observation stations -A(NS) and -B(NS)

Footnote : The figure at the highest row is from the aftershock itself, in the middle row from the ambient vibration before the aftershock and at the lowest row from the ambient vibration after the aftershock. PC used in the observation has time lag from UTC. The times in the figures include such error.

record before the aftershock, and that the one from the ambient vibration after the aftershock almost returned back to the one before the aftershock, as shown in Figure 9. So, it was confirmed that the phenomena mentioned in the above 3) and 4) in the case of the main shock reappeared in this large-scale aftershock.

In addition, as well as in the case of the main shock, the peak at 12.5 Hz is almost irrecognizable in the spectre from the large-scale aftershock, following the increase of the vibration amplitude at all the frequency range, though it clearly emerges in the spectra from the ambient vibration records before/after the aftershock (Figure 9).

*3) According to Japan Meteorological Agency, the aftershock at the midnight of April 7, 2011, occurred at around 23:32, with the magnitude of 7.2, the maximum seismic intensity of 6+. (The above-mentioned data on this large-scale aftershock mostly come from http://www.seisvol.kishou.go.jp/eq/sourceprocess/index.html).

In this chapter, the information and the knowledge were described as above obtained from the main shock records of the 2011 Great East Japan Earthquake, from the large-scale aftershock records and from their spectral analyses. But as for the ambient vibration records before/after the main shock/aftershock, they are just the result from the spectral analyses at just a time section each. In order to clarify, more precisely, proper frequency variations before/after the main shock/aftershocks, corresponding more precise analyses on the continuously obtained ambient vibration records are necessary.

5. CONCLUSIONS

In order to grasp the proper frequencies and their variations over time, including proper frequency variation during and/or before/after seismic events, long-term continuous observation of ambient vibration/seismic motion was undertaken at the crest of an aged arch dam. The 2011 Great East Japan Earthquake occurred in the course of this long-term continuous observation, and records were obtained for preshocks, the main shock, and numerous aftershocks. Ambient vibration records before/after the events were also obtained. Analyses of the observed records revealed the following:

1) Proper frequencies and damping constants were identified using ambient vibration records, which brought the proper frequencies of 8.3 Hz, 10.8 Hz and so on.
2) The proper frequency of the dam during about five months from summer to winter became lower together with the dam surface temperature, suggesting that both parameters are correlated positively with each other. On the other hand, as far as the data shown in this paper is concerned, it can be inferred that the change in the reservoir water level did not affect the above-mentioned proper frequency variation so much, but more detailed investigation on it will be the next subject.
3) During the main shock of the 2011 Great East Japan Earthquake, records were obtained with a very large maximum acceleration of about 630 gal at the dam crest. The duration of the seismic motion of the main shock ranged for about three minutes.
4) The observed acceleration time history records consist of plural wave groups and the maximum acceleration was recorded in the second wave group which arrived 40 to 50 seconds later than the first wave group. This feature is common to most strong motion records in Miyagi Prefecture, which is considered that the feature of the fault mechanism of the Event emerged to the seismic records at the observed dam crest.
5) Spectral analyses of the main shock and of ambient vibrations before and after revealed that the predominant frequency during the main shock became remarkably lower than the one from the ambient vibration before the main shock, and that the predominant frequency from the ambient vibration after the main shock, on the whole, returned back to pre-main shock level.
6) It was confirmed that the phenomena mentioned in the above 5) in the case of the main shock reappeared in the large-scale aftershock occurred in the midnight of April 7, 2011.

At the observed dam, as mentioned above, not only the main shock record of the 2011 Great East Japan Earthquake but also preshock records and the numerous aftershock records including April 7 event were obtained, together with ambient vibration records before/after such events, though there were some periods where continuous observation was not successful. Moreover, records from the existing seismic observation system will be available, where the seismometers are set not only at the crest but on the base rock of which the level is 40.5 m lower than the crest level. FEM analyses are also scheduled in our project. Further research on seismic safety, structural health and so on of aged dams will be performed utilizing such obtained data sets.

ACKNOWLEDGEMENT

In performing vibration observation at Ohkura Dam, the authors are supported financially (partly) by Tohoku Construction Association, the research field is offered from Sendai Dam Management Office, and, in addition, a part of the research is from Grants-in-Aid for Scientific Research by Japan Society for the Promotion of Science (Subject No. : 23560576). The authors wish to express their deep thanks to the Association, the Office and the Society as mentioned above.

REFERENCES

Ueda, M., Toyoda, Y., Shiojiri, H. and Satou, M. (2000). Resonant frequency of concrete arch dam evaluated from observational in-situ records and effects of construction joints on these features. *Journal of Structural Mechanics and Earthquake Engineering, JSCE, Japan.* **654, I-52**, 207-222

Proulx, J., Paultre, P., et al. (2001). An experimental investigation of water level effects on the dynamic behavior of a large arch dam. *Earthquake Engineering and Structural Dynamics.* **30**, 1147-1166.

Darbre, G. R. and Proulx, J. (2002). Continuous ambient-vibration monitoring of the arch dam of Mauvoisin. *Earthquake Engineering and Structural Dynamics.* **31**, 475-480.

Kanazawa, K. and Hirata, K. (2005). Parametric estimation of the cross-spectral density, *Journal of Sound and Vibration.* **282(1)**, 1-35.

Okuma, N., Etou, Y., Kanazawa, K. and Hirata K. (2008). Dynamic properties of a large arch dam after forty-four years of completion. *The 14th World Conference on Earthquake Engineering.* Paper No.0173

Ueshima, T., Kanazawa, K., Murakami, K., Nakamura, M., Shiojiri, H. and Ariga, Y. (2011). System identification, detection of proper frequency variation of aged arch dam and vibrational behavior during the 2011 off the Pacific Coast of Tohoku Earthquake by means of long-term continuous observation of ambient vibration/seismic motion. *The 31st Earthquake Engineering Symposium, JSCE, Japan.* 1-073 (8 pages).