STRUCTURAL HEALTH MONITORING OF AN AGED ARCH DAM USING LONG-TERM CONTINUOUS OBSERVATION OF AMBIENT VIBRATION/SEISMIC MOTION

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Abstract

Structural health monitoring technique was applied to an aged arch dam, where long-term continuous observation of ambient vibration/seismic motion was performed over a span of three years and a half and where the predominant frequency variation along time was detected, the variation during ambient vibration/seismic motion. As the result, the following was made clear;

1) The predominant frequency of the observed arch dam perpendicular to the dam axis varies with a period of one year, correlating highly with the dam surface temperature, that is, basically high in summer and low in winter. The predominant frequency of the dam in winter tends to be lower as the compressive stress is inferred to become lower caused by the contraction of the dam concrete due to the dam temperature drop.
2) The reservoir water level also affects the predominant frequency of the dam. The predominant frequency becomes lower as the reservoir water level becomes higher when the water level is higher than a certain level due to the effect of added mass. On the other hand, when the water level is lower than a certain level, the predominant frequency tends to be higher as the water level becomes higher as the joints between the dam concrete blocks close due to the water pressure increase.
3) During the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake, the observed record with very large maximum acceleration of about 630 gal was obtained at the crest of the dam. The duration of the seismic motion of the main shock ranged about three minutes.
4) Spectral analyses of the main shock record of the 2011 Off the Pacific Coast of Tohoku Earthquake and of the ambient vibration records before/after the main shock 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 during the ambient vibration after the main shock returned back to the one before the main shock, on the whole.
5) Thus, the following important matters were made clear, which are significant from the viewpoint of the structural health monitoring;
   a) The structural health of an aged arch dam can be evaluated through the monitoring of the predominant frequency variation which is detected as the result of the long-term continuous observation of ambient vibration/seismic motion and its data analysis.
   b) It was shown objectively by the numerical value of the predominant frequency that the structural health of the observed aged arch dam was maintained even after the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake, and also lots of its large-scale aftershocks.
   c) It was confirmed that the structural health of the observed arch dam was maintained and also that the seismic load unchanges through the fact that the predominant frequency of the observed arch dam unchanged before and after the large-scale earthquakes, which shows that the seismic back-check on the observed aged arch dam is unnecessary even after suffering from large-scale earthquakes.

Keywords: *structural health monitoring; long-term continuous observation; predominant frequency variation; 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 References [1, 2] and so on. Under the above-mentioned circumstances, our research project aimed

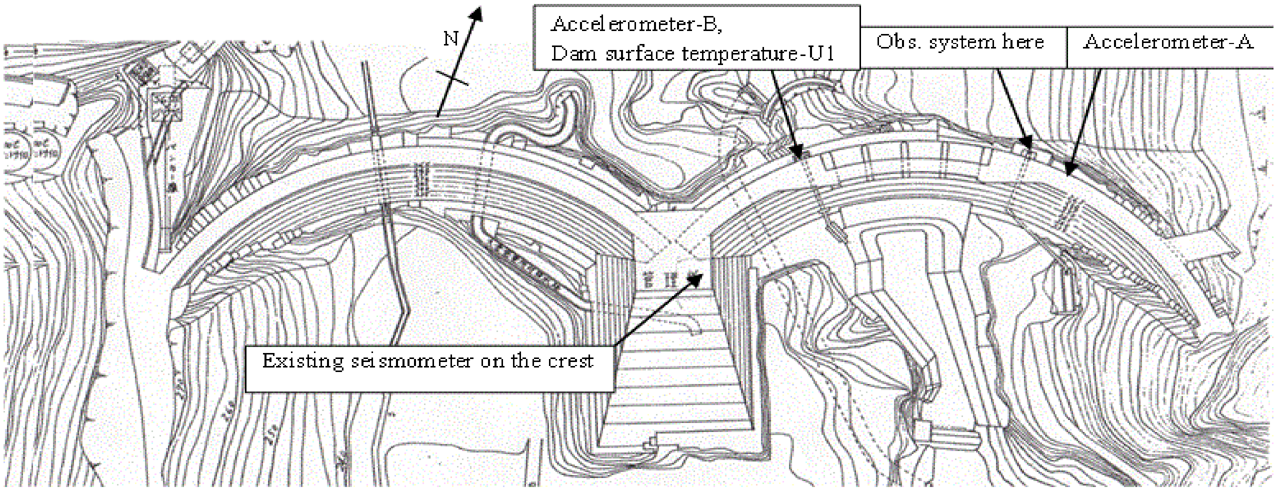


Fig. 1 – Plan of the observed dam, accelerometer layout for long-term continuous observation of ambient vibration/seismic motion and sensor location for dam surface temperature observation

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 of our system. Reference [5] is referred to on the plan of the observed dam and the information on the existing seismic observation system.

at obtaining basic data to develop a method to evaluate structural health of dams utilizing vibration observation. In our project, research items included high-density observation of ambient vibration [3], where many seismometers were arranged on the dam crest and simultaneous observation of ambient vibration at many observation stations was performed to obtain predominant 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 predominant frequency variation and/or the one during and/or after seismic events [4]. Using long-term continuous observation, it is considered possible to identify dynamic characteristics of the observed structure as well as to detect predominant frequency variation under the usual state of usage, which offer basic data for structural health monitoring/diagnosis. In our project, it was also performed to use FEM to analyze dynamic characteristics of the dam as well as to evaluate structural health [3].

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, predominant frequency variation over a span of about three years and a half is examined from the viewpoint of structural health monitoring. In addition, the results of the analyses using recorded data at the dam crest during the 2011 Off the Pacific Coast of Tohoku Earthquake, during large-scale aftershocks, and during the ambient vibration before/after such seismic events are reported. In this paper, "structural health" means that there is no structural damage and/or deterioration which affects the rigidity of the whole of the observed structure.

2. Outline of the observed dam, observation system and analysis method

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. The high water level of the observed dam is EL.270.60 m. 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.

Fig.1 [5] 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, the acceleration and the dam surface temperature were observed, all of which were on the dam crest. In the acceleration observation, totally three components of accelerations, that is, horizontally two-directional and vertical components from seismic motion to ambient vibration level were observed per an 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 [6], 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. In this paper, the direction perpendicular to the axis of the dam crest-line 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 10th to 50th degree at the interval of ten degrees, and final identification result was taken from 20th degree where the identified predominant frequencies and peak amplitudes were comparatively stable, taking account of all the trials over the whole period where the long-term continuous observation was performed. An example of system identification result is shown in Fig.2.

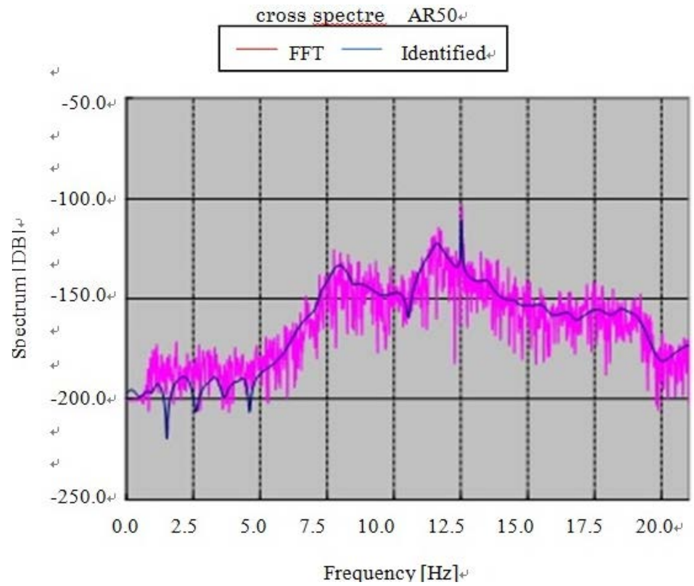


Fig. 2 – Example of dynamic characteristics identification from long-term continuous observation record of ambient vibration : Cross spectre between observation station -A and -B (AR50)

In Fig.2, there are two marked peaks observed. One is at around 8 Hz, and the other around 11.5 Hz. The mode shape corresponding to the first peak obtained from high-density ambient vibration observation [3] is antisymmetric first mode, and that of the second peak is symmetric second mode, both of which prove to be the principal modes in the evaluation of structural health. So, in this paper, the former one is called "mode-1" and the latter "mode-2", hereafter.

In Fig.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.

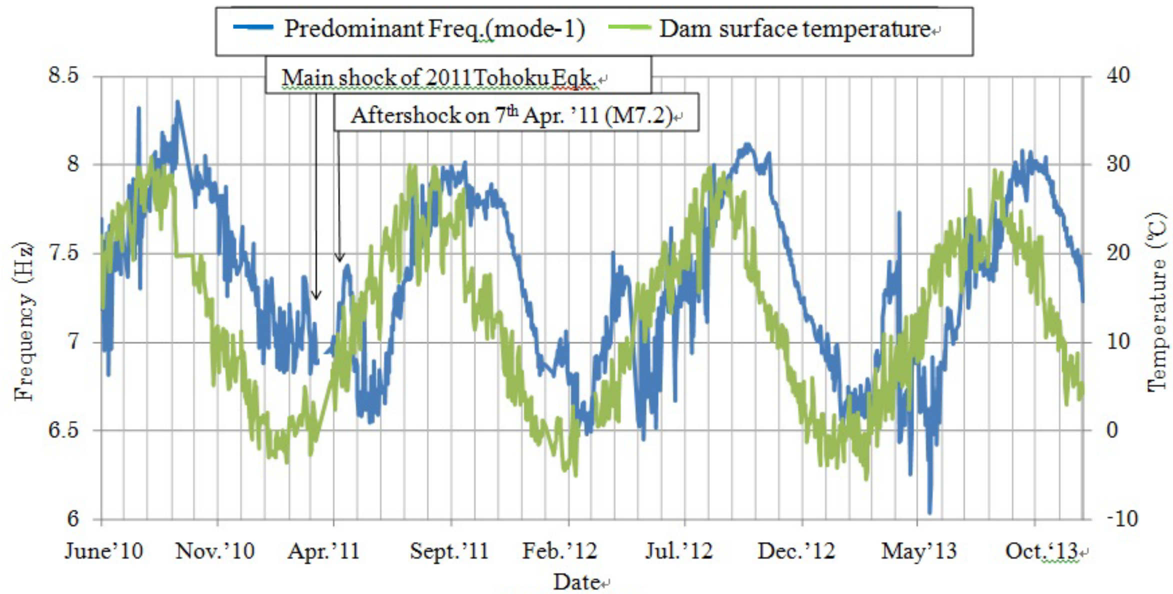
3. Predominant frequency variation of the observed dam over time during ambient vibration and its correlation with dam surface temperature, reservoir water level

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. In this section, predominant frequency variation of the observed dam over time during ambient vibration is described as well as its correlation with dam surface temperature and/or reservoir water level.

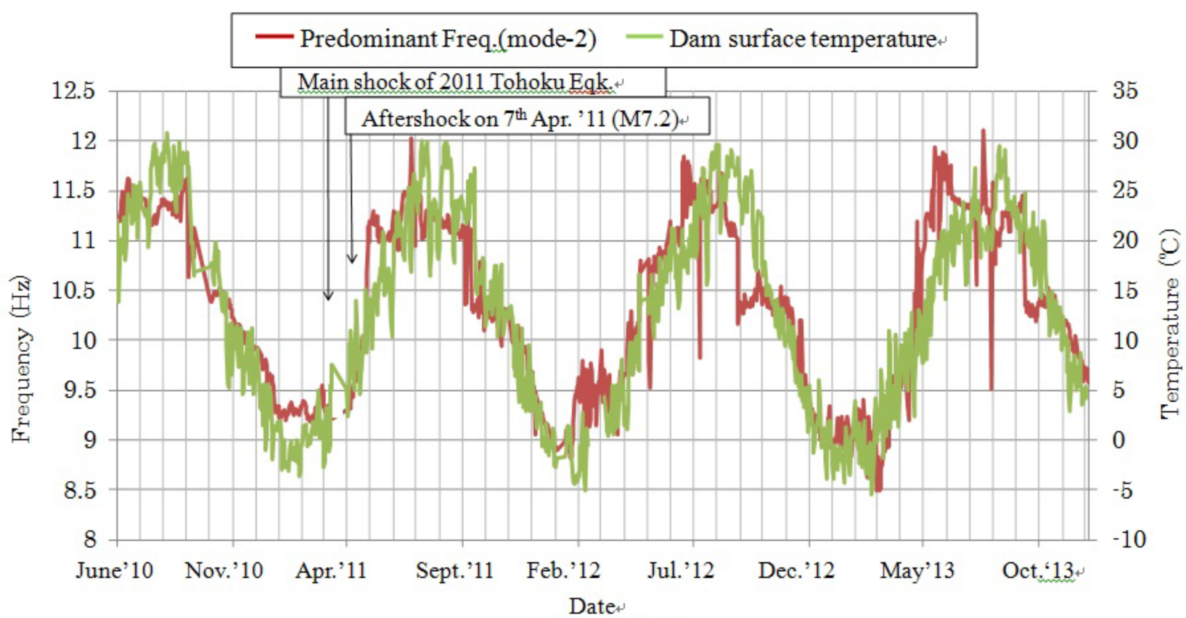
3.1 Predominant frequency variation of the observed dam over time during ambient vibration and its correlation with dam surface temperature

Fig.3 shows the predominant frequency variation of the observed dam during ambient vibration over a span of three years and a half corresponding to mode-1 in blue and to mode-2 in brown respectively, together with the dam surface temperature in greenish-yellow. In expressing the long-term variation, one day average is taken for the predominant frequency which is obtained every five minutes to remove daily variation, and also for the dam surface temperature [5] which is obtained every hour. The following was made clear from the long-term continuous observation of ambient vibration at the aged dam crest and its analysis to obtain the predominant frequency variation over a long period, and also from its correlation with dam surface temperature;

(1) The predominant frequencies of the observed dam both for mode-1 and -2 have high correlation with the dam surface temperature where they vary with a period of one year, that is, high in summer and low in winter. As for the predominant frequency seasonal variation width, it becomes up to about 2.5 Hz in mode-1 and up to about 3.5 Hz in mode-2. The predominant frequency seasonal variation obtained from the long-term continuous observation of the ambient vibration at the observed dam crest is proved to be considerably wide, when taking account that the variation of the one obtained from the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake against the one from the ambient vibration which occurred just before the



(1) Mode-1



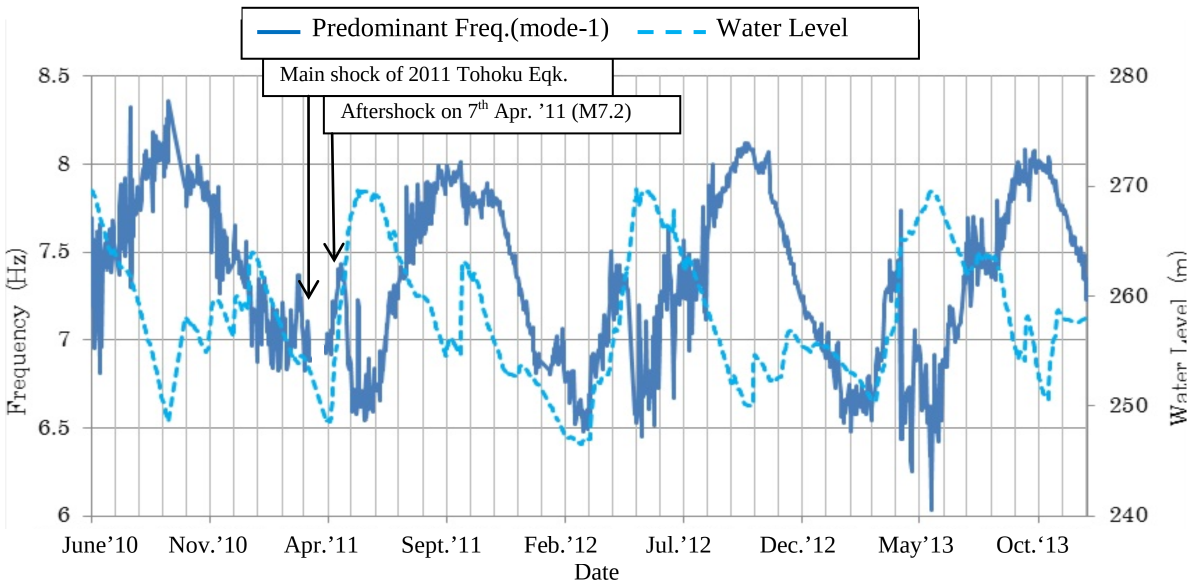
(2) Mode-2

Fig. 3 – Predominant frequency variation over a span of three years and a half identified from cross spectre between Observation Station-A & -B and correlation with dam surface temperature

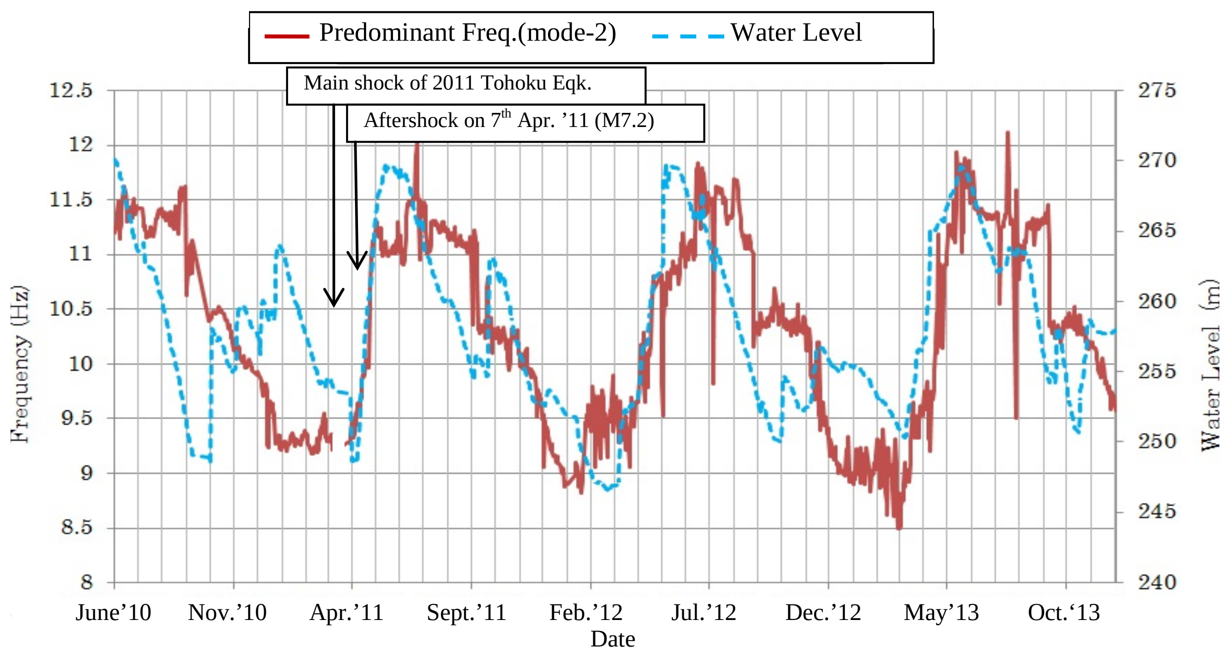
Footnote: One day average is taken both for predominant frequency and dam surface temperature. Predominant frequency variation curves both for mode-1 and -2 break off for about three weeks just after the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake. Observation data could not be obtained during the period due to power failure.

Earthquake, was about 1 Hz. Such characteristics of the predominant frequency seasonal variation of the dam is inferred to be caused as follows, that is, the predominant frequency of the dam body becomes lower in winter due to its contraction, which causes the loss of arch action affected by the opening of joints and the decrease of equivalent stiffness of the dam body.

(2) In mode-1, there is the phase lag between the predominant frequency variation over time and the dam surface temperature, that is, the phase of the predominant frequency is about 1-3 months later than that of the dam surface temperature. On the other hand, in mode-2, there is almost no phase lag between the predominant frequency and the dam surface temperature. As the result, the correlation coefficient for mode-2 is larger than that for mode-1. As for the reason why the difference between in mode-1 and -2 occurred, the reservoir



(1) Mode-1



(2) Mode-2

Fig. 4 – Predominant frequency variation over a span of three years and a half identified from cross spectre between Observation Station-A & -B and correlation with reservoir water level

Footnote: Mostly the same as the one for Fig.3. Reference [5] is referred to on the records of the reservoir water level.

water level may possibly affect the phenomenon. The problem is considered later on again.

(3) As far as considering the long-term variation of the predominant frequency and the temperature in terms of one day average, significant difference is not identified whether taking the dam surface temperature or the atmosphere temperature as reference temperature. A research result is shown that concrete stiffness increases as structure surface temperature difference appears, and as the result, natural frequency of the structure increases [7]. In this research project, temperatures both at dam surface and atmosphere, and both at upstream and downstream are observed, and so, it is a future research subject how surface temperature difference affects predominant frequency variation.

3.2 Effect of dam surface temperature and/or reservoir water level on predominant frequency variation of the observed dam over time during ambient vibration

In this subsection, firstly the effect of the reservoir water level [5] on the predominant frequency variation over time is considered, then summarizing this section, the effects of the dam surface temperature and/or the water level on the predominant frequency variation of the observed dam over time during ambient vibration are considered.

In Fig.4, the predominant frequency variation of the observed dam over a span of three years and a half during ambient vibration for mode-1in blue solid line and -2 in brown solid line respectively is shown together with the reservoir water level variation in light blue dashed line. Following the former subsection, in expressing long-term variation, one day average is taken for the predominant frequency which is obtained every five minutes to remove daily variation. As for the reservoir water level, original data is taken once a day. In addition, the correlation between the predominant frequency and the reservoir water level is shown in Fig.5 for each mode.

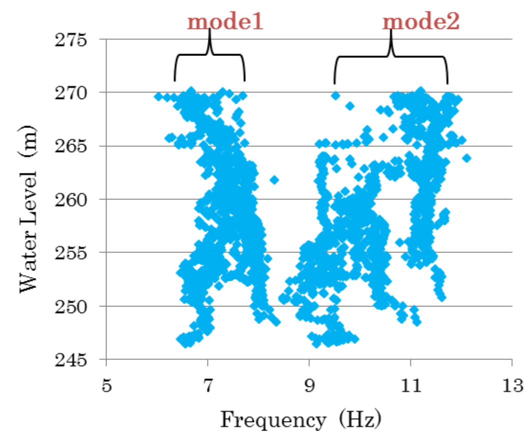


Fig. 5 – Correration between predominant frequency and reservoir water level during ambient vibration

The observed arch dam in this project is double arch which is the only one in Japan, and both the valley shape and the structural form are complicated. So, the above-mentioned effects are considered to appear characteristically. Summarizing this section, the following can be pointed out as for the effect of the dam surface temperature and/or the reservoir water level on the predominant frequency of the dam during ambient vibration;

(1) In mode-1, the correlation between the predominant frequency and the reservoir water level during ambient vibration in this research showed similar to the ones in the preceding researches [2, 8], that is, the predominant frequency becomes lower as the water level becomes higher when the water level is higher than around El. 260 m, maybe due to the effect of added mass. On the other hand, however, when the water level is lower than around El. 260 m, the predominant frequency becomes higher, in some cases, as the water level becomes higher, as the joints of dam concrete blocks are inferred to close due to water pressure increase, though there is clearly a different tendency when the water level is lower than around El. 260 m (Fig.5). It can be seen that there is the phase lag between the predominant frequency variation and the temperature change over time, and, on the other hand, the predominant frequency becomes high or low respectively when the water level is low or high on the whole (Fig.3(1), 4(1)). The added mass effect is inferred, on the whole, to excel the joint closure effect in this mode.

(2) On the other hand, in mode-2, the phases of the predominant frequency variation and the temperature change over time agree each other, and appreciable predominant frequency decrease could not be recognized even when the water level becomes higher (Fig.3(2), 4(2)). In other words, the predominant frequency becomes higher as the water level becomes higher, on the whole, though varying widely (Fig.5). So, the joint closure effect is inferred to be superior to the added mass effect in this mode.

(3) Biregression analysis was performed based on the condition that both the dam surface temperature and the reservoir water level are influential on the predominant frequency variation. In mode-1, the correlation coefficient of the temperature to the predominant frequency was 0.541, that of the water level was 0.201, and the bicorrelation coefficient of the temperature and the water level to the predominant frequency was 0.736. As for the reason why the correlation coefficient of the water level is small, it is considered that the different effects of added mass and joint closure cancel each other. On the other hand, in mode-2, the correlation coefficient of the temperature to the predominant frequency was 0.863, that of the water level was 0.605, and the bicorrelation coefficient of the temperature and the water level to the predominant frequency was 0.917. As the result, it was proved that there is strong or very strong correlation between the predominant frequency and the dam surface temperature and/or the reservoir water level.

(4) It was shown in this section that both the dam surface temperature and the reservoir water level affect the predominant frequency variation of the dam body over time during ambient vibration with getting mutually involved. It is important to separate the influence of the temperature on the predominant frequency variation from that of the water level also from the viewpoint of structural health monitoring, which is a future subject.

4. Dynamic behavior of the observed dam during the 2011 Off the Pacific Coast of Tohoku Earthquake and its large-scale aftershocks

When the 2011 Off the Pacific Coast of Tohoku Earthquake[*1)] occurred at around 14:46 of 11th March, 2011, our long-term continuous observation system was at work, and acceleration time history records were obtained as shown in Fig.6. Two seismometers were installed on the dam crest, where the epicentral distance was about 189 km. In Fig.6, the 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 1 shows the maximum acceleration and its occurrence time of each component at each observation station.

*1) The magnitude of the Earthquake was 9.0, the epicenter was located at Sanriku-Oki and the maximum seismic intensity was 7 [9].

In addition to the main shock record, preshock records and numerous succeeding aftershock records were obtained, together with the ambient vibration records before/after such big seismic events. Spectral analyses of both the main shock/aftershock records and the ambient vibration records before/after the big seismic events revealed the following;

(1) The duration of the acceleration time history records of the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake obtained using our observation system was so long, ranging about three minutes. At each of two observation stations, the acceleration

Table 1 – Maximum acceleration and its occurrence time of each component at 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 the exact Japan time. The times in the table include such error.

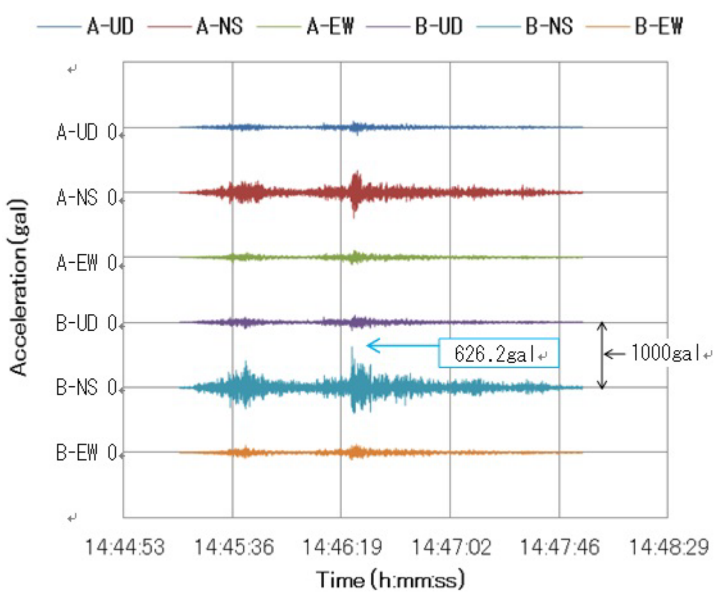


Fig. 6 – Acceleration time history records obtained at the observed dam crest during the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake

Footnote: 1) Y-axis: The name of the observation station - component.
2) PC used in the observation has time lag from the exact Japan time. The times in the figure include such error.

amplitude of NS-component (which is perpendicular to the dam axis) was the largest in three components (Fig.6, Table 1), 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 [5], 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, of which the records are from Reference [5], is independent of our long-term continuous observation 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 (Fig.6). This feature is common to most strong motion records in Miyagi Prefecture [9], which is considered that the feature of the fault rupture mechanism of the 2011 Tohoku 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, whereas the ones of the same observation stations (component) from the ambient vibration records before/after the main shock ranged from 6.6 to 7.1 Hz, which showed clearly that the predominant frequency during the main shock was remarkably lower than the ones from the ambient vibration records (Fig.7).

(4) Examination on the predominant frequency variation before and after the main shock using ambient vibration records revealed 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 vibration before/after the main shock (Fig.7).

(5) It was also examined whether or not the phenomena mentioned in the above (3) and

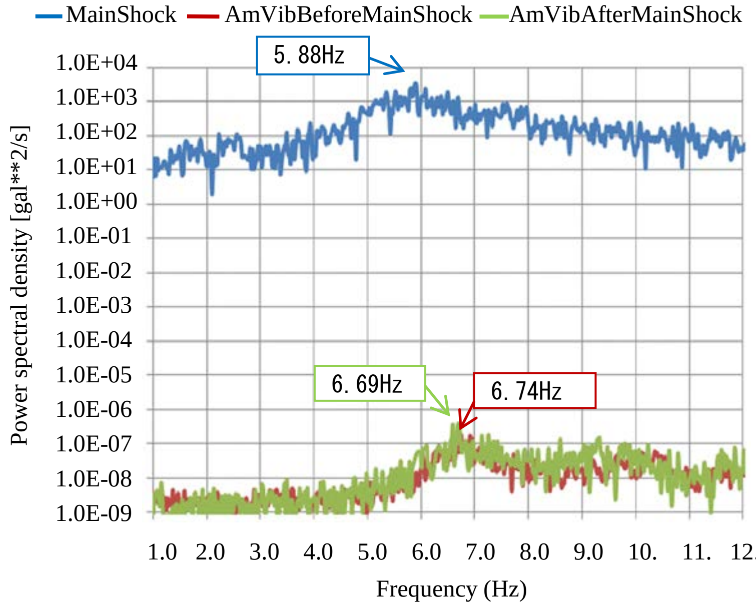


Fig. 7 – Spectra of the acceleration records at Obs. St. -B(NS) of 1) the main shock of the 2011 Tohoku Earthquake, 2) the ambient vibration before the main shock, 3) the ambient vibration after the main shock

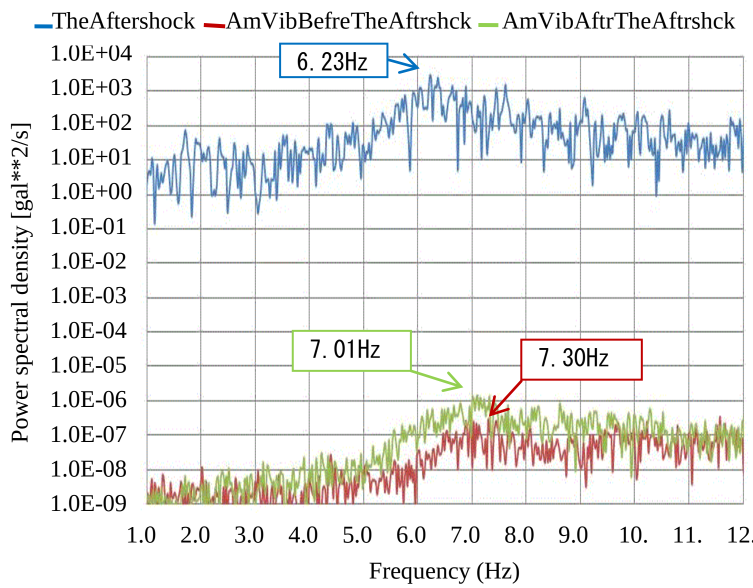


Fig. 8 – Spectra of the acceleration records at Obs. St. -B(NS) of 1) the aftershock of the Tohoku Earthquake occurred on 7th Apr. 2011, 2) the ambient vibration before the aftershock, 3) the ambient vibration after the aftershock

Footnote for Fig.7&8: 1) Note that the description in (3)-(5) in the text includes that on both observation stations -A & -B. On the other hand, Fig.7&8 are illustrated just on the data from the observation station-B.

2) The blue solid line is from the main shock of the Earthquake in Fig.7, and from the Aftershock in Fig.8. The brown solid lines in Fig.7&8 are from the ambient vibration records before the corresponding Events. The greenish yellow solid lines are from the ambient vibration records after the corresponding Events.

(4) reappeared during a large-scale aftershock. Here in this paper, the case of the aftershock was examined which occurred at the midnight of 7th April, 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 record also revealed that the predominant frequency during the aftershock remarkably decreased when compared with the one from the ambient vibration record before the aftershock, and that the one from the ambient vibration record after the aftershock almost returned back to the one before the aftershock, as shown in Fig.8. 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.

*3) According to Japan Meteorological Agency, the aftershock at the midnight of 7th April, 2011, occurred at around 23:32, with the magnitude of 7.2, the maximum seismic intensity of 6+ [10].

(6) Similar analyses were performed with what was mentioned above in (3)-(5) as for the ambient vibration/ seismic motion records from March, 2011 to December, 2012. As the result, it was shown that the predominant frequencies obtained from the seismic records were basically lower than the ones from the ambient vibration records before the seismic events, and that the predominant frequencies from the ambient vibration records after the seismic events returned back to the ones before the seismic events. However, there were not a few cases where the predominant frequency drops obtained from the seismic records could not be recognized.

(7) As the examination on the dependent characteristics of predominant frequency on vibration amplitude was considered also meaningful, and as many seismic records were obtained with maximum acceleration of several gal to about 630 gal from March 2011 to December 2012, the correlation between the predominant frequency and the maximum acceleration was examined from the 2011 Off the Pacific Coast of Tohoku Earthquake main shock and aftershocks at observation station -A(NS) (Fig.9). In illustrating Fig.9, the effects of the dam surface temperature and/or the reservoir water level was neglected. But the cases where the seismic events occurred when the water level was almost at the highest are illustrated in brown square mark so that they can be recognized easily, main extent of predominant frequency variation during ambient vibration in light blue solid arrow line, and that which occurred when the water level was almost at the highest in brown solid arrow line respectively in Fig.9. As the result, it was made clear that the predominant frequency could be looked upon as having tendency to decrease as the maximum acceleration amplitude increases, though varying widely, which might be caused due to neglecting the effects of the dam surface temperature and/or the water level. It was also made clear that the predominant frequencies obtained from the ambient vibration/seismic motion records which occurred

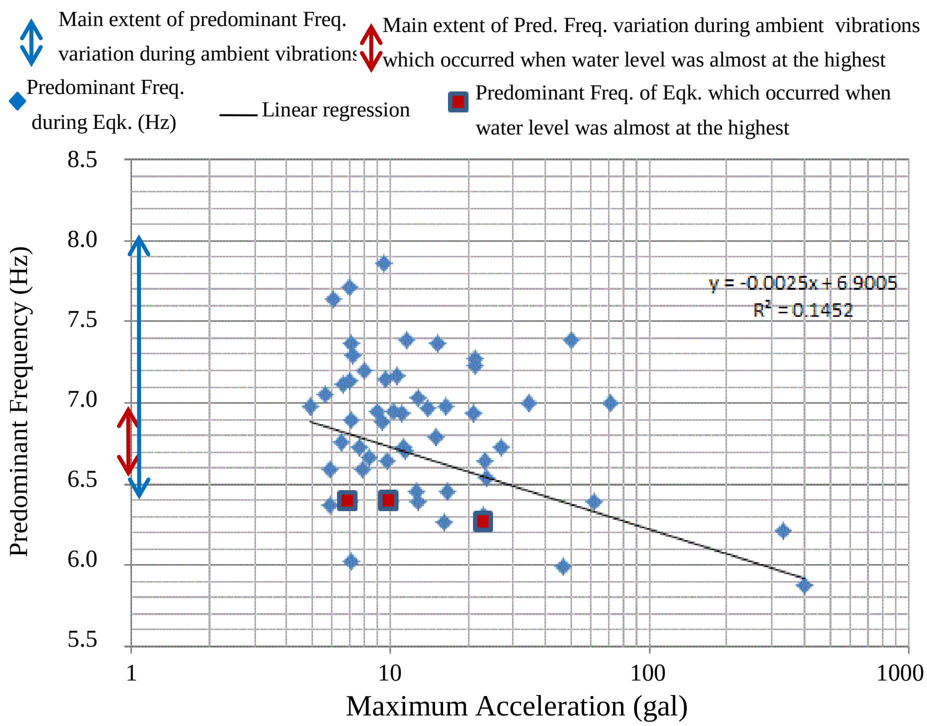


Fig. 9 – Correlation between predominant frequency and maximum acceleration: From the 2011 Off the Pacific Coast of Tohoku Earthquake main shock and aftershocks: Obs. St.-A(NS)

Footnote: Ambient vibration acceleration amplitude level of the observed dam crest is about 30 mgal or so. As for the plot of amplitude level for ambient vibration, it is not accurate in the figure above.

when the water level was almost at the highest are lower than others, showing the tendency to decrease, though a little, as the maximum acceleration amplitudes increase.

(8) Though the 2011 Off the Pacific Coast of Tohoku Earthquake and lots of its large-scale aftershocks occurred in the course of long-term continuous observation of ambient vibration/seismic motion, the remarkable variation of the predominant frequencies could not be recognized from the ambient vibration records before/after the above-mentioned big seismic events, referring to the figure showing long-term predominant frequency variation, which is considered to prove that no remarkable damage was generated during the period discussed in this paper.

(9) Thus, the following important matters were made clear, which are significant from the viewpoint of the structural health monitoring;

1) The structural health of an aged arch dam can be evaluated through the monitoring of the predominant frequency variation which is detected as the result of the long-term continuous observation of ambient vibration/seismic motion and its data analysis.
2) It was shown objectively by the numerical value of the predominant frequency that the structural health of the observed aged arch dam was maintained even after the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake, and also lots of its large-scale aftershocks.
3) It was confirmed that the structural health of the observed arch dam was maintained and also that the seismic load unchanges through the fact that the predominant frequency of the observed arch dam unchanged before and after the large-scale earthquakes, which shows that the seismic back-check on the observed aged arch dam is unnecessary even after suffering from large-scale earthquakes.

5. Conclusion

Long-term continuous observation of ambient vibration/seismic motion of an aged arch dam was performed, aiming at contributing to structural health monitoring. The observation system was at work when the 2011 Off the Pacific Coast of Tohoku Earthquake occurred, and, in addition to the main shock record, preshock records and lots of aftershock records were obtained together with the ambient vibration records before/after such seismic events. The above-mentioned long-term continuous observation was continued over a span of three years and a half. Analyzing these recorded data, the following was made clear;

(1) The dynamic characteristics such as the predominant frequency and the damping constant were identified using ambient vibration records. The observed dam was proved to have the predominant frequencies at around 8 Hz (mode-1, hereafter), 11.5 Hz (mode-2, hereafter), and so on.

(2) The predominant frequency of the observed dam perpendicular to the dam axis was shown to correlate highly with the dam surface temperature, varying periodically in about a year, that is, basically high in summer and low in winter. It was also shown that its difference between the maximum and the minimum in a year becomes up to about 2.5 Hz in mode-1 and up to about 3.5 Hz in mode-2. This variation width is larger than that when the observed dam was subjected to a strong earthquake like the 2011 Off the Pacific Coast of Tohoku Earthquake. The predominant frequency of the dam in winter tends to be lower as the compressive stress is inferred to become lower caused by the contraction of the dam concrete due to the dam temperature drop.

(3) The reservoir water level also affects the predominant frequency of the dam. In mode-1, the predominant frequency becomes lower as the reservoir water level becomes higher when the water level is higher than a certain level maybe due to the effect of added mass, but, on the other hand, when the water level is lower than a certain level, the predominant frequency tends to be higher as the water level becomes higher as the joints of the dam concrete blocks are inferred to close. On the other hand, in mode-2, the predominant frequency becomes higher as the water level becomes higher, on the whole, though varying widely. So, the joint closure effect is inferred to be superior to the added mass effect in this mode. It was also shown that both the dam surface temperature and the reservoir water level affect the predominant frequency of the dam body with getting mutually involved. It is important to separate the influence of the two parameters on the predominant frequency variation, also from the viewpoint of structural health monitoring, which is a future subject.

(4) During the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake, the observed record with very large maximum acceleration of about 630 gal was obtained at the crest of the dam. The duration of the seismic motion of the main shock ranged about three minutes. 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 rupture mechanism of the 2011 Off the Pacific Coast of Tohoku Earthquake emerged to the seismic records at the observed dam crest.

(5) Spectral analyses of the main shock acceleration record and/or the ambient vibration acceleration records before/after the main shock revealed the following;

1) The predominant frequency of the component perpendicular to the dam axis obtained from the main shock record was remarkably lower than the ones from the ambient vibration records.

2) Examining the predominant frequency variation before and after the main shock using the ambient vibration records, the one after the main shock, on the whole, can be looked upon as returning back to the one before the main shock.

(6) The aftershock was also examined which occurred at the midnight of 7th April, 2011. The epicentral distance of the observed dam was about 113 km and the maximum acceleration at the dam crest was about 430 gal. Spectral analyses of the aftershock also revealed that the predominant frequency during the aftershock remarkably decreased when compared to the one from the ambient vibration record before the aftershock, and that the one from the ambient vibration record after the aftershock almost returned back to the one before the aftershock. So, it was confirmed that the phenomena mentioned in (5) in the case of the main shock reappeared in this large-scale aftershock.

(7) Similar analyses with what was mentioned above in (5), (6) using the ambient vibration/seismic motion records from March, 2011 to December, 2012 showed that the predominant frequencies obtained from the seismic records were basically lower than the ones from the ambient vibration records before the seismic events, and that the predominant frequencies from the ambient vibration records after the seismic events returned back to the ones before the seismic events. However, there were not a few cases where the predominant frequency drops obtained from the seismic records could not be recognized. Though the 2011 Off the Pacific Coast of Tohoku Earthquake and lots of its large-scale aftershocks occurred in the course of long-term continuous observation of ambient vibration/seismic motion, the remarkable variation of the predominant frequencies could not be recognized from the ambient vibration records before/after the above-mentioned big seismic events, which is considered to prove that no remarkable damage was generated during the period discussed in this paper.

(8) The correlation between the predominant frequency and the maximum acceleration was also examined in view of the consideration that the examination on the dependent characteristics of predominant frequency on vibration amplitude is also meaningful, and that many seismic records were obtained with maximum acceleration of several gal to about 630 gal from March 2011 to December 2012. In the examination, the effects of the dam surface temperature and/or the reservoir water level were basically neglected. As the result, it was made clear that the predominant frequency could be looked upon as having tendency to decrease as the maximum acceleration amplitude increases, though varying widely, which might be caused due to neglecting the effects of the dam surface temperature and/or the water level, and that the predominant frequencies obtained from the ambient vibration/seismic motion records which occurred when the water level was almost at the highest are lower than others, showing the tendency to decrease, though a little, as the maximum acceleration amplitudes increase.

(9) Thus, the following important matters were made clear, which are significant from the viewpoint of the structural health monitoring;

1) The structural health of an aged arch dam can be evaluated through the monitoring of the predominant frequency variation which is detected as the result of the long-term continuous observation of ambient vibration/seismic motion and its data analysis.

2) It was shown objectively by the numerical value of the predominant frequency that the structural health of the observed aged arch dam was maintained even after the main shock of the 2011 Off the Pacific Coast of Tohoku Earthquake, and also lots of its large-scale aftershocks.

3) It was confirmed that the structural health of the observed arch dam was maintained and also that the seismic load unchanges through the fact that the predominant frequency of the observed arch dam unchanged before and after the large-scale earthquakes, which shows that the seismic back-check on the observed aged arch dam is unnecessary even after suffering from large-scale earthquakes.

At the observed dam, as mentioned above, basically ambient vibration records of observation stations over a span of about three years and a half were obtained as the result of long-term continuous observation. In addition, not only the main shock record of the 2011 Off the Pacific Coast of Tohoku Earthquake but also preshock records and numerous aftershock records including 7th April, 2011 event were obtained, together with the ambient vibration records before/after such seismic events. Moreover, the seismic records from the existing seismic observation system are 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 available in our project. Further researches on seismic safety, structural health and so on of aged dams will be performed utilizing such obtained data sets/analysis tools.

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