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Prediction of Concrete Frost Damage of The Nagawado Dam Based on The Standardized Freezing and Thawing Cycle Method

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ABSTRACT:
The Nagawado dam is a concrete arch dam located in a cold highland district in the central Japan. The dam was developed in 1960's. 44 years have already passed since commencement of the dam operation. Because of its climatic location, the dam surface is subject to cold ambient air and frequent cycles of freezing and thawing in the winter. The safety management of the dam includes inspections, surveys and investigations of the dam concrete surface. Some deterioration of the concrete was observed at the concrete surface due to the frost damage in recent years. Concrete core samples were collected from the downstream surface in order to evaluate depth of the frost damage. Distribution of relative dynamic elastic modulus was examined by measurements of ultrasonic wave propagation velocity for each core sample. We confirmed the deterioration is very limited less than 1cm depth from the downstream surface. Furthermore, thermometers were newly installed 1cm depth from the surface in order to monitor temperature history through a winter season. Thermal distribution in the concrete depth and its time history were evaluated by an unsteady heat conduction analysis and the monitoring data of the new and existing thermometers. The frost damage in future was predicted based on the standardized freezing and thawing cycle method. We judged the dam concrete will be sound and stable in the long term considering the reliability limit interval of the prediction.

Keywords: Frost damage, dynamic elastic modulus, standardized freezing and thawing cycle method, prediction of future deterioration.

1. INTRODUCTION

The Azusa River is the primary tributary of the Sai River, which consists of the upstream of the Shinano River system. The upstream area is well known for cold climate, and snowfall. The Azusa Hydropower Development Project was started in 1964 aiming for construction of 3 major dams and hydropower stations along the river. The Nagawado dam is located uppermost among the Project where the dam foundation has an elevation of 830m. After approximately 5-year construction period, the Nagawado dam started its operation in 1969. Table 1 shows specification of the dam. It is severe climate condition from December to March. Especially, the monthly mean temperatures are below 0 degree Celsius from December to February. The dam surface is subject to frequent cycles of freezing and thawing. The ambient temperature at the dam site becomes below 0 degree Celsius at night thorough the winter season, while the temperature in the daytime becomes usually 0 degree Celsius or over. This study is aimed to evaluate the dam concrete soundness at the present and in future from the standpoint of material engineering.

Table 1. Specification of the Nagawado dam

Item	Specification		
Name of River	The Azusa Rive, a tributary of the Shinano River		
Elevations	Crest	:	EL. 985.0 m
	Foundation	:	EL. 830.0 m
Dam	Type	:	Concrete arch dam
	Height	:	155.0 m
	Length of crest	:	355.5 m
	Volume	:	660,000 m^3
Completion	Completion of the dam body in 1968, start power generation in 1969		

Table 2. Concrete Mix Proportions

G_{max}	Mix Proportion(%)		s/a	Unit Content (kg/m^3)					AE	Slump	Air
(mm)	W/(C+F)	F/(C+F)	(%)	W	C	F	S	G	(cc)	(cm)	(%)
150	50	25	21	100	150	50	440	1681	54	3±1	3±1

2. OBSERVATIONS THROUGH INSPECTIONS AND SURVEYS

The dam is inspected monthly and engineers take high resolution photos of the dam from control points during the inspection. The concrete damage map was drawn from the photos in order to evaluate the deterioration progress as shown in Fig.1. The deteriorations are more distinct in the following areas.

- The dam concrete around the abutments where it is exposed to rain or snow.
- The dam concrete where water leaks are observed.

The typical deteriorations observed are exposed aggregates, cracking and scaling. The cracks propagate diagonally around the abutments and vertically around the center area. The scaling is confirmed widely around abutments. Photo 1 shows characteristics of the frost damages.

Exposed aggregate　Map Cracking　Scaling

Photo 1. Characteristics of the frost damage of the Nagawado dam

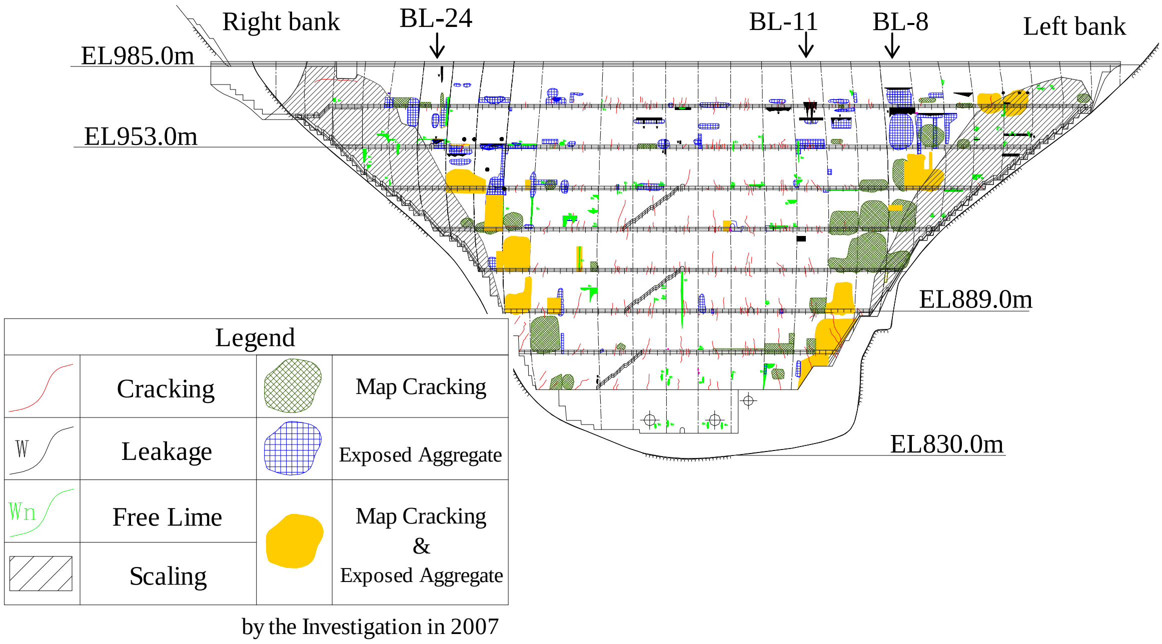


Figure 1. Damage map of the downstream surface of the Nagawado dam

3. EVALUATION OF THE FROST DAMAGE AT THE PRESENT

3.1. Frost damage index

'Relative dynamic elastic modulus' is generally applied as an index to evaluate frost damage of internal concrete. 'Relative dynamic elastic modulus' is defined as relative value of the dynamic elastic modulus to the non-degraded unit. It is known that dynamic elastic modulus of concrete is almost equivalent to the initial tangent elastic modulus of the material, and there is a close relationship between dynamic elastic modulus and the looseness of concrete pore structure caused by the frost damage (JCI Hokkaido, 2006). Concrete soundness is generally evaluated to be good against the frost damage when the relative dynamic elastic modulus is 60-80 % or over, according to the standard specification for concrete structures (JSCE, 2001) and Japanese Concrete Institute (JCI, 2008).

The previous study, Ishii et al in 1997, examined a relationship between relative dynamic elastic modulus and the degradation of the compressive strength of the Nagawado dam concrete. The study provided a formula to estimate the degraded compressive strength of the concrete. When the relative dynamic elastic modulus becomes 60 % of the non-degraded unit, the compressive strength of the concrete is estimated to be 28.8 N/mm^2 according to the formula. The estimated strength is still greater than the allowable compressive stress considered in the design stage which was determined with a safety factor of 4.

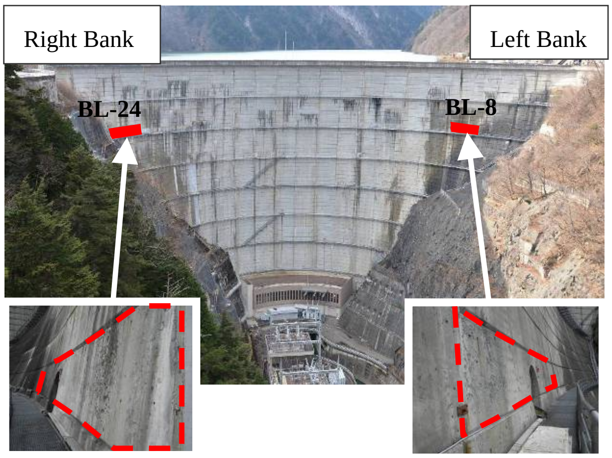
3.2. Core sampling and ultrasonic wave propagation velocity measurement

Concrete cores were collected from the downstream surface of the dam where the concrete was most deteriorated by the frost damage. The size of cores is 300 mm–long and 30 mm of diameter. The core locations are the BL-8 and the BL-24 where it has an elevation of

953 m as shown in Photo 2. Cracks and exposed aggregates are observed in the areas. Both areas are exposed to rain and snow. And the areas are also influenced by leaking water from the reservoir. Ultrasonic wave propagation method was applied to evaluate the dynamic elastic modulus of the concrete cores. Ultrasonic wave propagation velocities were measured cross direction to the core axe line through the core length. The applied method enables to evaluate the distribution of the dynamic elastic modulus. The measured velocities are 4.28 km/s on average at 26-30 cm depth from the surface, the deepest part of the cores. The values is almost same with the previous estimation. According to the estimation with the previous study’s assumption, the velocity will be 4.26 km/s when the Nagawado dam concrete is aged 44 years without marked frost damage.

The ultrasonic wave propagation is likely affected by existence of coarse aggregates. The ultrasonic wave propagates faster in aggregates or propagates slowly if there are gaps between aggregates and mortal. The measurement values which were affected by the coarse aggregates were excluded for evaluation of the dynamic elastic modulus. Both cores show almost equal values and similar distribution of the ultrasonic wave propagation velocities.

Relative values of the dynamic elastic modulus were calculated to the non-degraded unit. The relative values are smaller at the surface. The relative values at the dam surface are 74 % and 69 % in the BL-8 and the BL-24 respectively. The relative values are more than 80 % at 1 cm depth and a deeper part as shown in Fig.2. Those values exceed a criterion generally adopted for the concrete soundness against the frost damage, 60-80 %. This indicates the deterioration is minor and limited to the surface.



BL-24 BL-8

Core sampling locations

BL-24 BL-8

Collected cores

Photo 2. Location and collected cores

Photo 3. Measurement of ultrasonic wave propagation velocity

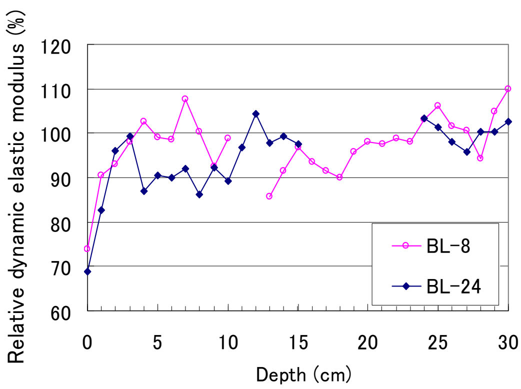


Figure 2. Distribution of relative dynamic elastic modulus

4. PREDICTION OF CONCRETE DETERIORATION IN THE FUTURE

4.1. Standardized freezing and thawing cycle method

The standardized freezing and thawing cycle method is applicable to predict the frost damage, Ishi et al in 1997. The concrete deterioration due to the frost damage could be predicted quantitatively considering accumulation of the standardized freezing and thawing forecasted.

As to the method, a freezing and thawing cycle is defined as a cycle that concrete temperature becomes above 0 degree Celsius after negative degree Celsius. Each cycle is converted into the standardized form of the freezing and thawing cycle. The conversion is made considering the water cement ratio of the concrete and the minimum concrete temperature for each cycle. Then, the degraded relative dynamic elastic modulus is predicted against sum of the standardized freezing and thawing cycles. The deterioration curve as Eq.1 is adopted for the prediction.

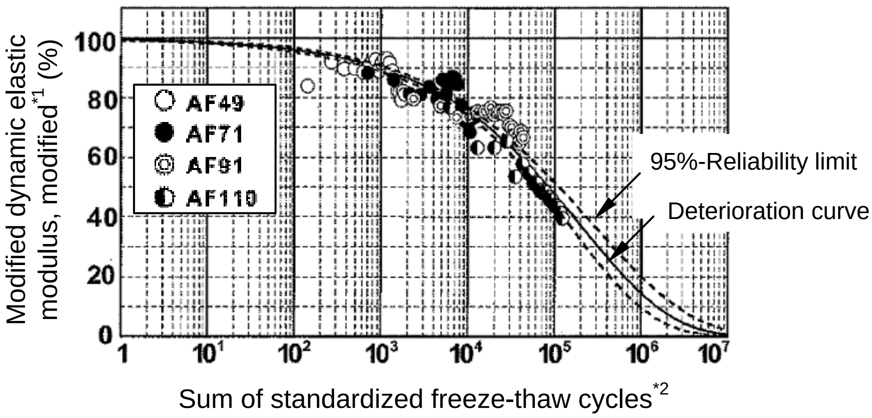
$$[\text{Relative dynamic elactic modulus}] = 100 \times \exp(-a \cdot N^{b}) \qquad (1)$$

Where:

N : Standardized teh freezing and thawing cycles

a, b : Constant coefficents

The previous study by Ishii evaluated the deterioration curve of the Nagawado dam concrete as shown in Fig.3. In the previous study, the deterioration curve was indentified by the accelerated laboratory tests and field exposure tests over 20 years. Test pieces/blocks were made of various mix concrete proportions including the Nagawado dam concrete design. The study concluded that the frost damage could be evaluated by the deterioration curve and the freezing and thawing cycles which should be convereted into the standardized form.



[*1] Modified dynamic elastic modulus was calculated as a relative value to the concrete strength with the subsequent strength increase.

[*2] The standardized freezing and thawing cycles were calculated based on W/C+F=49%, -6 degree C. of min.

Figure 3. Deterioration curve by laboratory test pieces

In this study, the method was applied to predict the dam concrete deterioration due to the frost damage. The deterioration curve, however, should be reviewed for accurate prediction with the following reasons. The deterioration curve by the previous study was based on the acceleration laboratory tests and field exposure tests. As to the field exposure tests, the concrete blocks were located in the reservoir area of the downstream dam. The concrete blocks were exposed to the reservoir environment, which was submerged sometimes in a year. Such exposed environment is different from the condition of the dam downstream surface and may affect the deterioration curve. Also, the previous study used resonant vibration method to measure the dynamic elastic modulus. The method is to evaluate the modulus of the mass block, while the modulus may be different by the concrete depth. And, the degrade surface may have smaller modulus. It indicates that the deterioration of the internal concrete may be overestimated in case the previous deterioration curve is adopted.

This study includes the concrete samplings as mentioned in chapter 3.2 in order to evaluate the present concrete and review the deterioration curve. The deterioration curve was indentified by a relation between the degraded dynamic elastic modulus of the concrete cores and the standardized freezing and thawing cycles at the measurement points. Thermal conduction analyses were also performed to identify the thermal distribution and the standardized freezing and thawing cycles. The method is applicable to predict the distribution of the deterioration in the concrete depth.

4.2.Evaluation of the future deterioration

4.2.1 Monitor the concrete temperature history through a winter season

There is a considerable difference of the solar radiation by place to place and time to time, since the Nagawado dam is a dome arch type located at the steep valley and it faces to the southeast. The right side of the dam gets into the shade all day, and the left side gets in the solar radiation for few hours per day in winter. It is necessary to consider such a condition difference to evaluate the concrete temperature history of the Nagawado dam. Photo 4 shows a state of the solar radiation in the daytime in winter.

Three thermometers were newly installed at the BL-8 and the BL-24 same as the core locations mentioned in chapter 3.2 and the BL-11 which was additionally selected for monitoring. The concrete temperature was monitored through a winter season from December 2012 to March 2013. The locations of the three thermometers are shown in Photo 4. The thermometers were installed at 1cm depth from the concrete surface, since the direct solar radiation to the thermometers should be avoided in order to evaluate the concrete temperature properly.

According to the monitoring records, the mean ambient temperature was below 0 degree Celsius from December to February. The new thermometer at 1cm depth at the left side monitored more freezing and thawing cycles during these months. The left side was exposed to sun in the daytime, which caused more frequent thawing in the daytime and freezing at night. In March, the mean ambient temperature became 0 degree Celsius or over. Less freezing and thawing cycles were monitored at the left side in March, since the concrete temperature at the left side was usually 0 degree Celsius or over all day. The sun condition gave differences of the concrete temperature between the left and right side of the dam as shown in Fig.4. The difference became larger on sunny day, and the maximum difference was observed in March.

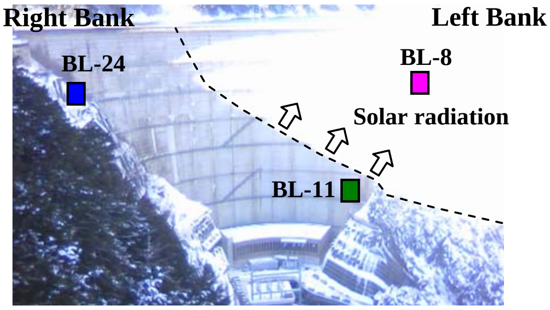


Photo 4. Thermometers on the surface

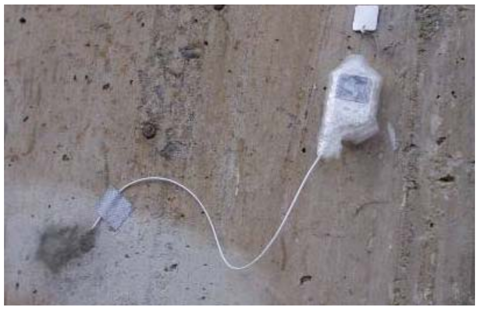


Photo 5. Thermometer

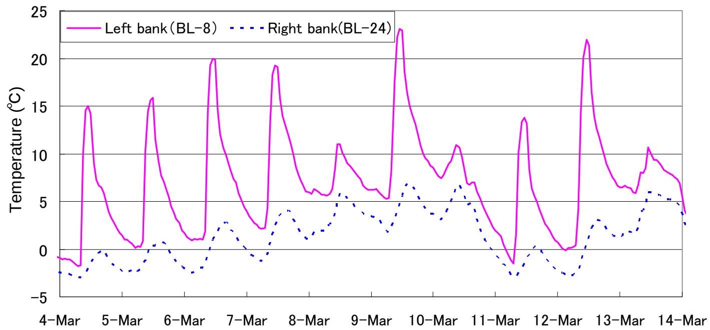


Figure 4. Monitoring the concrete temperature at 1cm depth

4.2.2 Thermal conduction analysis

At first, an unsteady heat one dimensional thermal conduction analysis was performed to evaluate the thermal distribution in the dam concrete. The analysis was performed for the deteriorated places, the BL-8 and BL-24 at EL.953 m and the BL-11 at EL.889 m. The analysis object period was set to the monitoring period of the new installation at the surface from December 2012 to March 2013. The monitored temperature data at the surface and the internal thermometers were applied for the analysis.

Secondly, the concrete time history series from the construction to the present were estimated by one dimensional thermal conduction analysis. Available data for the period is limited to the internal thermometers and ambient temperature. Therefore, the analysis was performed for the dam center where the internal thermometers was installed in the dam body. Fig.5 shows time histories of the internal concrete temperature by the analysis and the internal thermometer. Those values show reasonable matches. The physical properties applied are tabulated in Table 3.

Table 3. Physical properties

Thermal conductivity (W/m℃)	2.7
Density (kg/m^3)	2,390
Specific heat (kJ/kg℃)	1.16
Heat transfer coefficient (W/m^2℃)	13

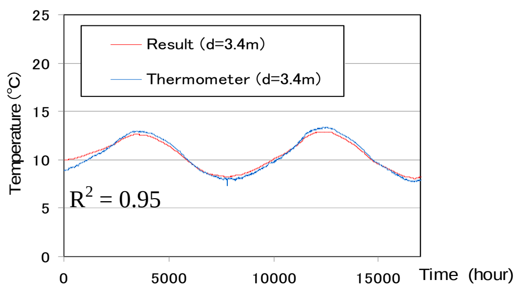


Figure 5. Internal concrete temperature

4.2.3 Freezing and thawing cycles from the construction

The standardized freezing and thawing cycles were examined for the representative point from the thermal conduction analysis as mentioned in chapter 4.2.1. The distribution of the cycles of each year is shown in Fig.6. The internal concrete has been experienced less freezing and thawing cycles from the construction to the present, and the frost depth is less than 80cm.

According to the period from December 2012 to March 2013, the thermal distribution at the BL-8, BL-24, BL-11 and the representative point are available by the analyses. Ratio of the standardized freezing and thawing cycles at each block to the representative point was indentified by comparison. The annual cycles at the BL-8, BL-24 and the BL-11 were examined applying the identified ratios to the representative point. The standardized freezing and thawing cycles for each location were obtained as shown in Fig.7.

The more freezing and thawing cycles were monitored at the left side where the dam is exposed to more solar radiation in the daytime in winter. The number of the standardized freezing and thawing cycles were evaluated to be 35 cycles annually at 1cm depth at the BL-8. According to the BL-24 and the BL-11, the number of the cycles were smaller. Such difference is caused by the solar radiation conditions by places due to the dam site topography and the dome-arch shape. The number of the cycles and the frost depth at the BL-11 is far smaller due to its solar radiation condition.

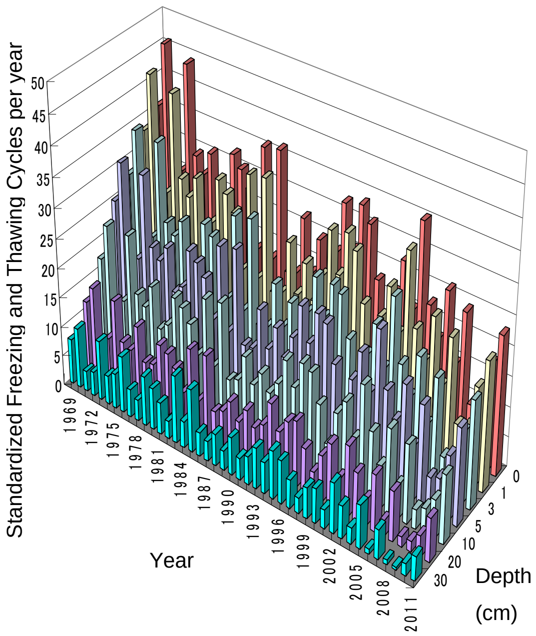


Figure 6. Freezing and thawing cycles, from the construction to the present

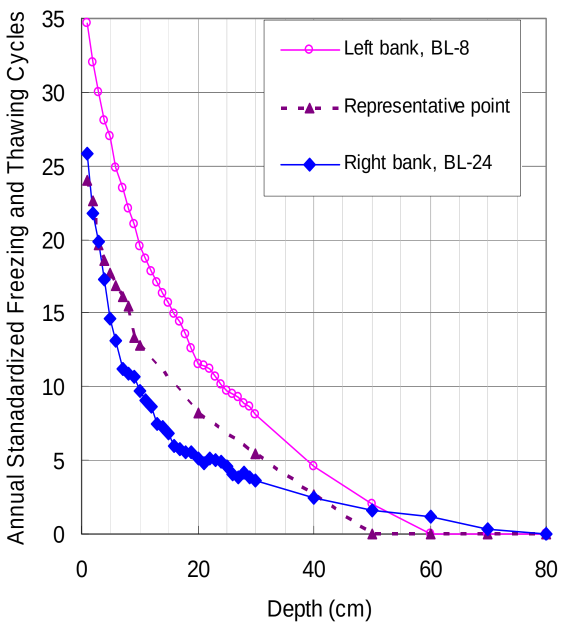


Figure 7. Annual standardized freezing and thawing cycles, BL-8, BL-24

4.2.4 Identification of the deterioration curve of the standardized freezing and thawing cycle method, and predict the future deterioration

In this study, the deterioration curve was reviewed based on the measured dynamic elastic modulus of the cores and the thermal conduction analysis. Fig.8 shows the data considered to indentify the deterioration curve. The measured dynamic elastic modulus shows degradation trend, although the data includes dispersion. The dispersion may be caused by the influence of the coarse aggregates in the cores. Eq.2 expresses the reviewed deterioration curve for the Nagawado dam concrete. The constant coefficients were indentified by a regression analysis. The 95%-reliability limit interval curve was also proposed as a conservative view point.

$$[\text{Relative dynamic elactic modulus}] = 100 \times \exp(-0.01 \cdot N^{0.21}) \qquad (2)$$

Where:

N : Standardized teh freezing and thawing cycles

Constant coefficents are $a = 0.01$, and $b = 0.21$ respectively.

The concrete deterioration could be predicted quantitatively with the deterioration curve and sum of the freezing and thawing cycles forecasted. The number of the standardized freezing and thawing cycles at 15 cm depth from the surface would be 16 cycles annually at the BL-8 where more freezing and thawing cycles were monitored by the thermometer.

Fig.9 shows prediction of the deterioration at 15 cm depth due to the frost damage. The relative dynamic elastic modulus will maintain approximately 90 % in 200 years according to the prediction curve. Even 95%-reliability limit interval considered, the relative dynamic elastic modulus will be more than 80 % in approximately 150 years. It was concluded that the dam concrete will be sound and stable in the long term.

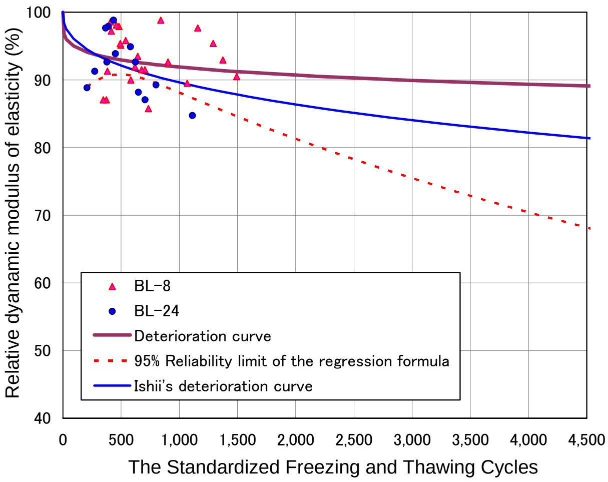


Figure 8. Relative dynamic modulus of elasticity vs. the standardized freezing & thawing cycles

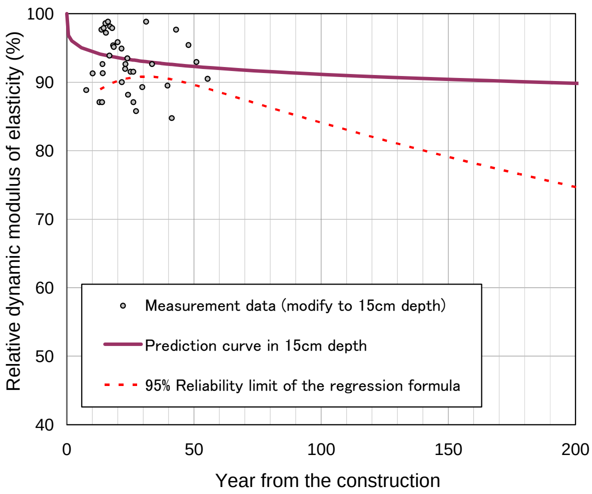


Figure 9. Prediction of the relative dynamic modulus of elasticity at 15cm depth at the BL-8

5. CONCLUSION

The concrete frost damages are observed at the 44-year aged Nagawado dam. The observed deteriorations are exposed aggregate, cracking and scaling on the dam surface. Two concrete cores were collected from the dam surface in order to evaluate the deterioration at the present. The core locations were selected where the concrete was most deteriorated by the frost damage. ‘Relative dynamic elastic modulus’ was applied as an index to evaluate the concrete deteriorations. The relative values are more than 80 % at 1 cm depth and a deeper part according to the core sampling. Those values exceed a criterion generally adopted for the concrete soundness against the frost damage, 60-80 %.

The standardized freezing and thawing cycle method is applicable to predict the frost damage. The concrete deterioration due to the frost damage could be predicted quantitatively considering sum of the freezing and thawing forecasted. A freezing and thawing cycle is defined as a cycle that concrete temperature becomes above 0 degree Celsius after negative degree Celsius. Each cycle is converted into the standardized freezing and thawing cycle form. The conversion is made considering the water cement ratio and the minimum concrete temperature for each cycle.

In this study, the deterioration curve of the Nagawado dam was reviewed for accurate prediction based on the measured dynamic elastic modulus of the cores and the thermal conduction analysis. Three thermometers were newly installed at 1cm depth from the dam surface in order to examine difference of the freezing and thawing by the dam places. The more freezing and thawing cycles were monitored at the left side where the dam is exposed to more solar radiation in the day time in winter. According to the thermal conduction analysis, number of freezing and thawing cycles are smaller in the internal concrete, and the frost depth of the Nagawado dam is less than 80 cm. The concrete future deterioration was predicted based on the reviewed deterioration curve. The relative dynamic elastic modulus will maintain approximately 90 % in 200 years. Even 95%-reliability limit interval considered, the relative dynamic elastic modulus will be more than 80 % in approximately 150 years. It was concluded that the dam concrete will be sound and stable in the long term, applying the standardized freezing and thawing cycle method and the reliability limit interval of the prediction.

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