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The Strengthening of an ASR-Affected Water Intake Tower in a Hydro-Electric Dam by Using Post-tensioned Tendons and the Long-term Monitoring of the Tower

Kazuyuki Torii^{1*}, Tetsuji Kubo², Chikao Sannoh³ and Maki Kanitani⁴

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Abstract

In the Hokuriku district in Japan, large numbers of concrete structures have been suffering from damage caused by alkali silica reaction (ASR). Some huge volcanoes are located within this district, and the headwaters of main rivers prompt the outflow and spreading of volcanic rocks such as andesite, rhyolite and tuff stones, which are the main volcanic reactive stones causing the serious damage of ASR in the entire area. To solve this problem effective countermeasures such as repair and strengthening methods should be established.

One intake tower in this area had deteriorated due to ASR, and deformation had occurred as a consequence of ASR expansion of the concrete. Countermeasures were carefully considered by academic experts, and post-tensioned tendons were inserted into the intake tower concrete (vertically oriented) so that the power station can continue to operate safely in the future. This is thought to be the first challenge of its type anywhere in the world for which the deformation of a real structure caused by ASR expansion must be controlled.

In this paper, the results obtained from laboratory tests using reactive aggregate and the overview of the investigation and the method of the reinforcement including the effect of the countermeasures will be discussed.

1. Introduction

In the Hokuriku district in Japan, large numbers of RC (Reinforced Concrete) and PC (Pre-stressed Concrete) bridges have been suffering from the damage caused by alkali silica reaction (ASR) (Torii 2010; Torii *et al.* 2012; Nomura *et al.* 2012). Some huge volcanoes are located within this district, and the headwaters of main rivers prompt the outflow and spreading of volcanic rocks such as andesite, rhyolite and tuff stones, which are the main volcanic reactive stones causing the serious damage of ASR in the entire area. **Figure 1** shows typical features of seriously deteriorated bridge piers as a result of ASR, where cracking, deformation and ASR gel extrusion occurred at the same time, and in the most serious cases, the steel reinforcements also were ruptured at their point of bending.

In order to clarify the influence on structures caused by ASR expansion, measurements of ASR expansion related pressure were conducted (Diamond 1989; Kawamura *et al.* 2004; Binal 2004; Multon *et al.* 2006). However, the actual amount of deformation on actual

structures has been indeterminate, and a method of control has not been confirmed. Furthermore, while there have been reports of structural deformities, methods for relieving the pressure have been employed, but methods of controlling the deformity as of yet have not been confirmed (Shayan *et al.*, 2000).



Fig. 1 Typical features of seriously ASR-deteriorated bridge piers.

¹Professor, Kanazawa University, Kanazawa, Japan.

*Corresponding author, *E-mail*: torii@t.kanazawa-u.ac.jp

²Manager, Hokuriku Electric Power Company Co. Ltd, Ushijima-machi, Toyama, Japan.

³Assistant manager, Hokuriku Electric Power Company Co. Ltd, Ushijima-machi, Toyama, Japan.

⁴Hokuriku Electric Power Company Co. Ltd, Ushijima-machi, Toyama, Japan.

Table 1 Results of chemical method according to JIS A1145 and accelerated mortar bar method according to ASTM C1260.

Name of river	Chemical method (JIS A1145)				Mortar bar method (ASTM C1260)	
	Sc ^{*1}	Rc ^{*2}	Sc/Rc	ASR Reactivity	Expansion at 14day(%)	ASR Reactivity
Kurobe	22	37	0.59	Innocuous	0.137	Innocuous or Deleterious(Unclear)
Jouganji	242	72	3.36	Not Innocuous	0.720	Deleterious
Jinzu	27	41	0.66	Innocuous	0.306	Deleterious
Shou	26	54	0.48	Innocuous	0.139	Innocuous or Deleterious(Unclear)

*1: Amount of Dissolved Silica (m mol/l), *2: Amount of Alkalinity Reduction (m mol/l)

This paper discusses an assessment of alkali-silica reactivity in volcanic gravel from Jouganji River in the Hokuriku district, which is considered to be the most reactive in Japan. Secondly we will present the investigation of ASR-caused deformities to a water intake tower which was constructed by using river aggregates produced from Jouganji river and the attempts to reinforce the tower using post-tensioned tendons (Bianchi *et al.* 1992). Concerning the reinforcements, laboratory test results indicated that a small restraining stress of 0.2~0.3N/mm² could decrease the ASR expansion, and this was the basis for the determination of the initial stress (Torii *et al.* 2000; Ishii *et al.* 2005). The construction was carried out in 2011, and in 2012 after applying the tension, it was determined that the deformity had been effectively controlled. This case does not only concern the use of post-tensioned tendons for large scale structural reinforcement and controlling of deformity, but also has provided a model for the understanding of ASR deformity in other hydro-engineering structures, and as such has proven to be very useful (Silveira *et al.* 1996; Cavalcanti *et al.* 1996; Blaikie *et al.* 1996; Huang *et al.* 1996; Seignol *et al.* 2009; Sellier *et al.* 2009; Pan *et al.* 2013).

2. Mineralogical properties and Alkali-Silica reactivity of volcanic river aggregates

Mineralogical properties and alkali-silica reactivity of volcanic river aggregates which had been used in Toyama prefecture are presented in this chapter. **Table 1** shows the results of the chemical method (JIS A1145) and the mortar bar method (ASTM C1260) used on river gravel produced in the river of Toyama prefecture. As shown in this table, gravel of Jouganji river which was used in the intake tower described in later chapter is the most reactive one. It is necessary to grasp the characteristics of each type of river gravel, because the ASR reactivity for each type is different.

Incidentally, in this region, the ASR suppressing effect of locally produced fly ash has been confirmed and the ASR control measures by fly ash have been recommended in recent years (Sannoh *et al.* 2008; Hashimoto *et al.* 2013; Torii *et al.* 2016).

The photomicrograph of reactive minerals and other materials in the Jouganji river gravel is presented in **Fig. 2**. In the petrographic survey on mineralogical properties of the river gravel, it was found that they were mainly

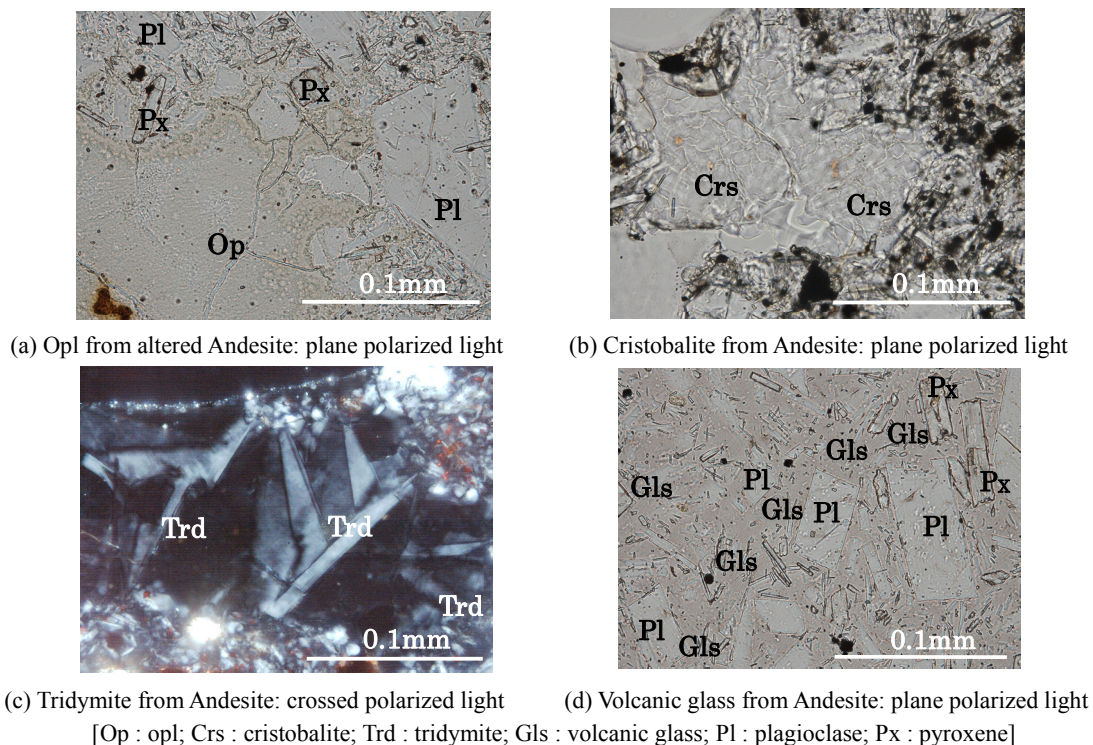


Fig. 2 Photomicrographs of reactive minerals and non-reactive minerals in the river gravel used in the intake tower taken with a polarizing microscope observation.

Table 2 Lithology of the Jouganji gravel determined by petrographic observation.

Rock type		Vol. %	Main constituents
Rock fragment	Granitic rocks	39	Plagioclase, Quartz, Hornblende, Biotite, Alkali feldspar, Chlorite, Epidote, Sphene, Prehnite, Opaque mineral, Pyroxene
	Andesite	36	Plagioclase, Cristobalite, Tridymite, Volcanic glass, Pyroxene, Opaque mineral, Quartz, Opal, Smectite, Biotite, Hornblende, Olivine, Apatite
	Basalt	2	Plagioclase, Pyroxene, Volcanic glass, Opaque mineral, Cristobalite
Mineral fragment		23	Plagioclase, Quartz, Alkali feldspar, Biotite, Pyroxene, Hornblende, Chlorite

constituted of granitic rocks and volcanic stones, in which the reactive minerals in typical andesite stones were cristobalite and/or tridymite, op1, and small amounts of volcanic glass, as shown in **Table 2**. The composition ratio of 30% andesite stones was roughly equivalent to the most pessimistic results gained by the mortar bar or concrete bar test of andesite stones in the river. Thus, it has become very clear that the reactive river sand and river gravel contain reactive minerals, especially op1, the most reactive mineral, and that its amount may be near the most pessimistic volume. A recent survey shows that in the bridges and buildings using this river sand and gravel, a severe ASR has still occurred after 2010 even in the case of total alkali content of 2 kg/m³ and less, which is considerably smaller than the JIS A5308 required value of less than 3 kg/m³.

3. Overview of the investigation

3.1 History of the intake tower

This intake tower is located at a dam in the upstream region of Jouganji river in Hokuriku District. **Figure 3** shows the actual site. 74m³/s of water can pass through the intake tower and 400 thousands kW can be generated by using this water at 3 power stations located downstream of the tower. This electricity corresponds approximately to the power needs of about 130 thousand households. Thus, this intake tower is a critical structure for the area and the company.

The intake tower is a SRC structure. **Figure 4** shows a cross-sectional view and a side view of the intake tower. The water level of the dam varies depending on the

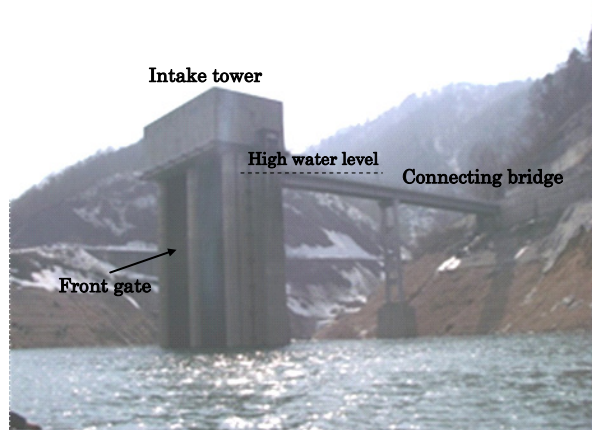


Fig. 3 Overview of actual site of the intake tower.

power demand. Usually it reaches the highest level around May, and decreases to about 1070m in the summer months. Then it decreases further to about 1060m in the winter (February - March), returning to the highest water level due to snowmelt in the spring. Temperatures during the summer rise to about 25 degrees, and in winter they fall to about minus 10 degrees. In the winter, there is snow cover of about 5m. Therefore, between November and April it is not possible to go to the site area.

Twenty years after the construction of the tower, an inclination with concomitant expansion of the structure was discovered due to the formation of a clearance of 40mm between the top of the intake tower and the connecting bridge. After the detection of this separation, investigations were conducted to find the cause.

3.2 Displacement measurement

Distance from vertical line to both the interior wall and the exterior wall were measured at each elevation. **Figure 5** shows the results of the investigation of the interior wall and the exterior wall. Measured distance shows the average of measured values on the interior wall and the exterior wall. With the bottom of the tower's base located at 1,045 meters above sea level, we noted that from about an elevation of 1,065 meters the intake tower wall began to exhibit an inclination in the direction of the lake. At the top of the tower (elevation 1,090.7 meters above sea level), there was a deviation from the vertical of 80mm. It was not clear at the time of construction how accurately the vertical orientation of the tower wall was, so it is unclear exactly to what degree the wall's configuration has deformed.

Figure 6 shows the horizontal change in distant over time at the top of the tower, and **Fig. 7** shows the vertical change over time at the top of the tower, which horizontal and vertical measurements were both conducted from 22 years after construction. During the 8-year period of 22 to 30 years following construction the rate of horizontal change at the top of the tower was 5.6mm per year. Assuming that the average rate of change was the same prior to the commencement of measurements and taking into account the currently measured change of 80mm, we estimate that the beginning of this deformation started about 15 years following construction. During the same 8-year period, the rate of vertical change was calculated to be 2.1mm per year. Thus, assuming that the deformation along the vertical axis of the tower also began 15 years after construction and assuming that the rate of deformation was uniform over time, we estimate that the

overall height of the tower at its top has increased by 33mm on the side of the connecting bridge.

3.3 Results of the residual expansion test

Figure 8 shows the results of the residual expansion test according to the JCI DD2 method. Each core was taken from the side of the tower at the heights of El 1070m and

El 1060m after 30 years of the construction. As shown in Figure 8, a slightly expansive tendency was observed at the heights of El 1070m and El 1060m.

Therefore, it has been determined that it will be necessary to watch for the future expansion.

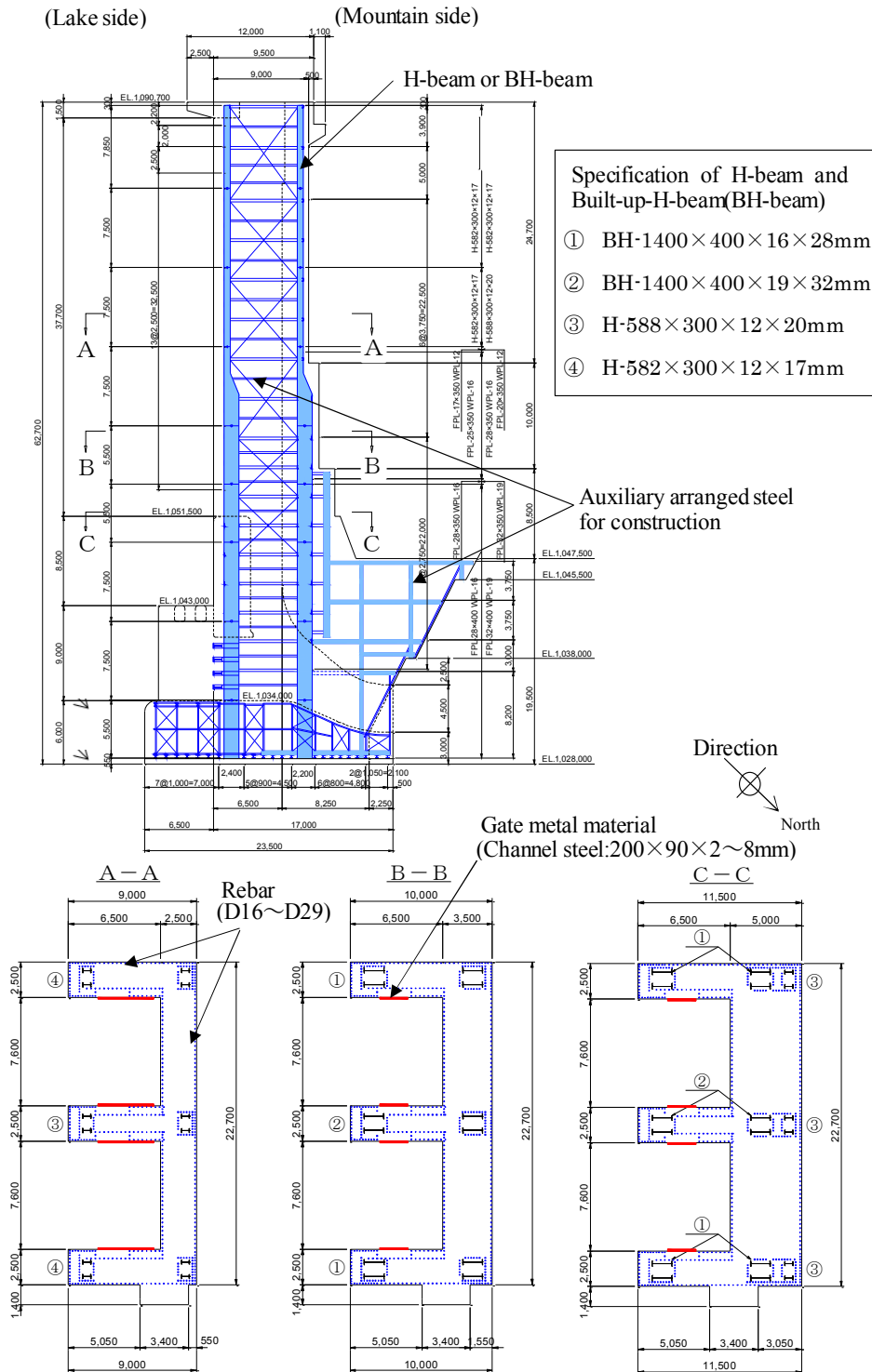


Fig. 4 Cross-sectional view and side view of the intake tower.

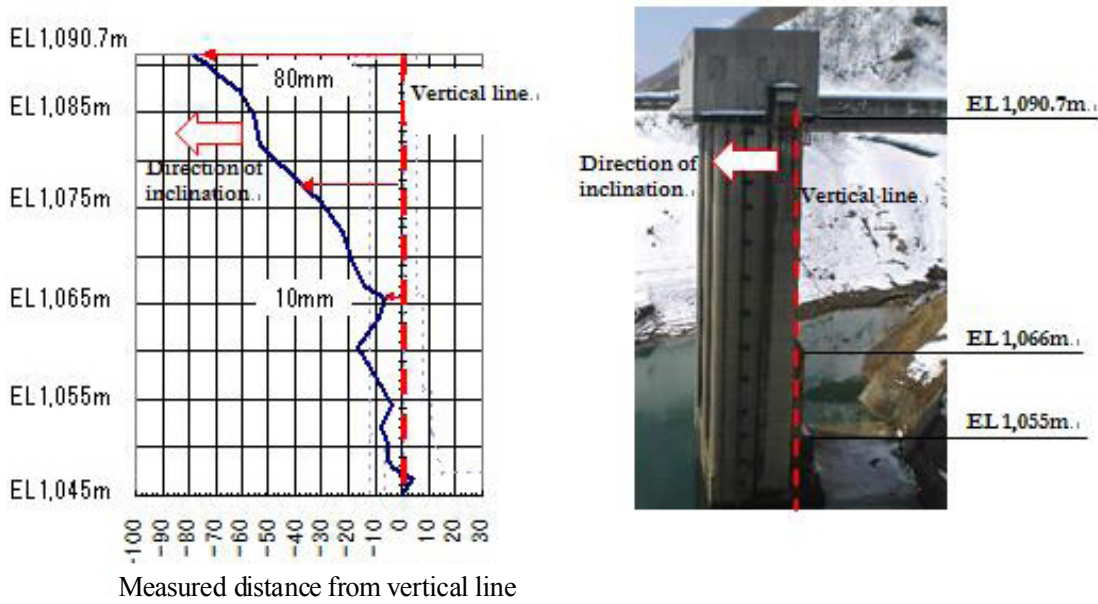


Fig. 5 Investigation of the interior wall and exterior wall.

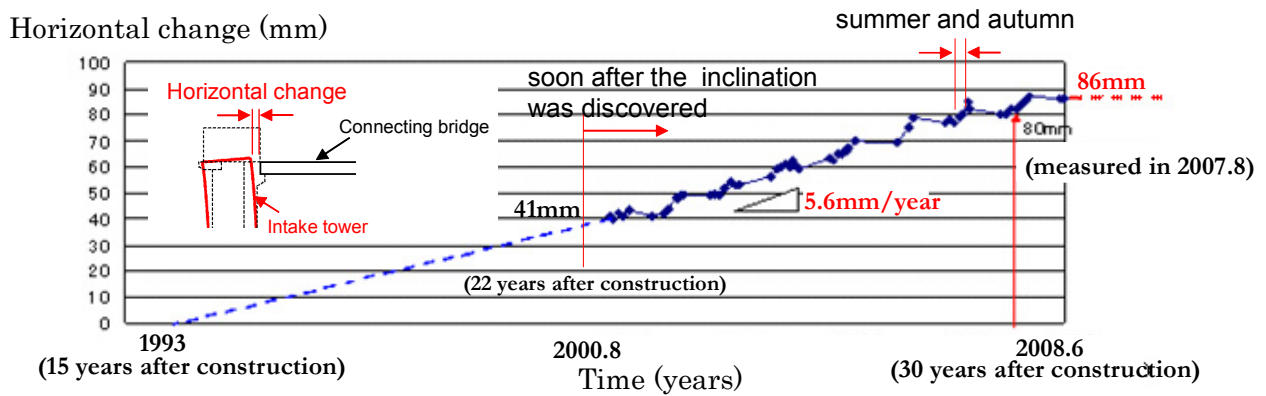


Fig. 6 Horizontal change in the position of the top of the tower over time.

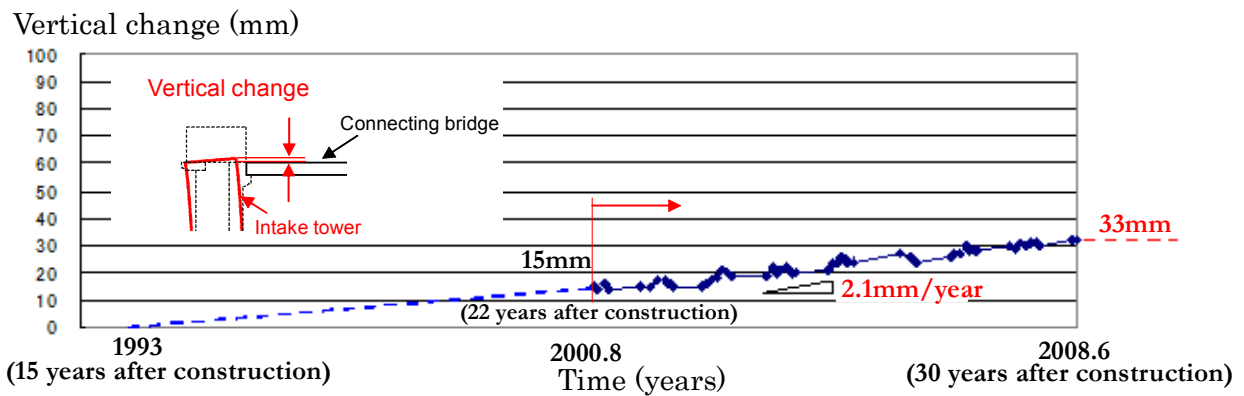


Fig. 7 Vertical change in the position of the top of the tower over time.

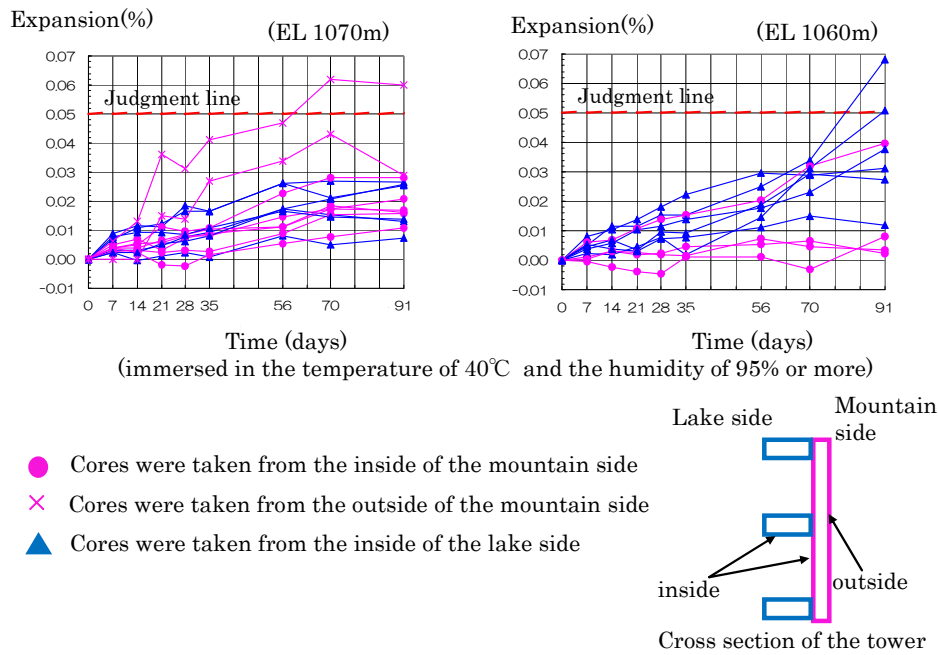


Fig. 8 Result of the residual expansion test according to JCI DD2.

3.4 Cause of the inclination

Figure 9 shows the condition of the surface of the intake tower's exterior wall. On the surfaces of the exterior and interior walls extensive mapping cracks were observed. The cracks were approximately 0.2mm in width at 20 to 30 cm intervals and were not severe.

The intake tower concrete (at the levels of EL1035, 1047, 1060, 1070, and 1087) was investigated using an SEM-EDS. Figure 10 shows an example of an image at the level of EL1060. This investigation discovered ASR gel in all samples taken from all locations.

As a result of the research, ASR was observed in the entirety of the intake tower, causing expansion. Furthermore, from the elevation of 1065m, the tower was leaning towards the lake. The height of the tower is about 63m, and in the cross section of the tower the water intake gates are shown. Due to the gate there is less exposure to sunlight on the lake side. On the mountain side there is a solid wall. Compared to the lake side, the

mountain side wall has more exposure to sunlight which is believed to be a large influence on the ease of ASR development. What's more, on the mountain side in the vertical direction, the structure is not reinforced. Thus, it is believed that this permits a large ASR influence on this side of the tower.

The amount of ASR expansion is said to be affected by the percentage of the steel that constitutes the cross section. Table 3 shows the value of the cross-sectional area of the steel (steel, rebar, gate metal material) as a fraction of the cross-sectional area of the concrete. Comparing the mountain side wall to the lake side wall, the proportion of steel in the mountain side wall is small, thus it is presumed that the expansion of the mountain side is larger than that of the lake side. Comparing the fractional value of steel in each section, the value of the A-A section is small, thus it is presumed that the expansion of the upper portion is larger than that of the lower portion.

Furthermore, in March the lake level is at its lowest, so

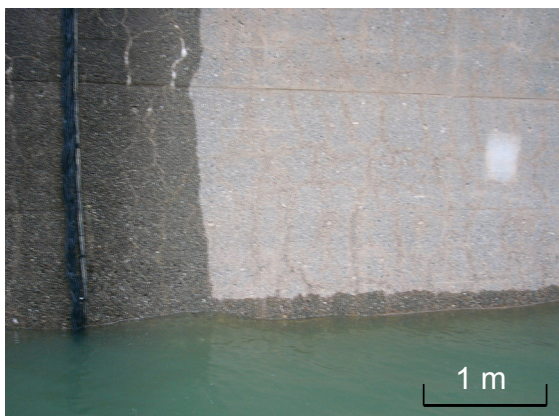


Fig. 9 Condition of the surface of the intake tower's exterior wall.

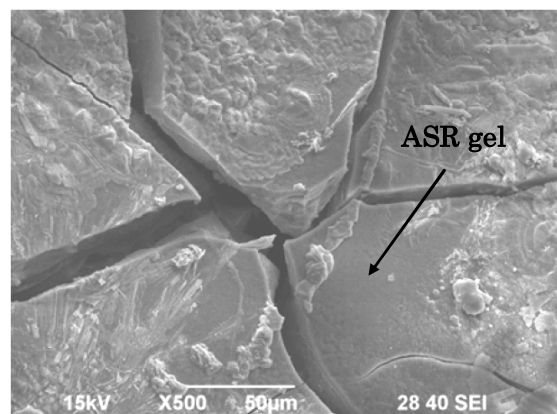


Fig. 10 Example of the observation of the concrete by SEM-EDS.

Table 3 Values of the steel as a fraction of the cross-sectional area of the concrete (%).

Section (See Fig. 4)	Values of the steel as a fraction of the cross-sectional area of the concrete (%)	
	Lake side wall	Mountain side wall
A-A	0.0065	0.0028
B-B	0.0079	0.0038
C-C	0.0079	0.0039

between May and August as the lake fills, the upper portion of the tower is exposed periodically to more sunlight followed by lake water inundation which we believe promotes the formation of ASR gel.

In this way the comparative differences between the concrete environments and the different degrees of reinforcement on the mountain side and lake side result in unequal amounts of ASR expansion on opposite sides of the tower. This is the fundamental cause of the tower’s increasing inclination in the direction of the lake. **Figure 11** is a graphic illustration of the primary causes of the ASR. Incidentally, this figure is obtained by charting the estimated, qualitative effects taking into account the basic mechanisms of the ASR (Larive,C., *et al.*, 2000).

4. The Method of the reinforcement

4.1 Countermeasures to ASR

There is an affect on the operability of the gate when the top of the tower has deformed horizontally by 1700mm. Therefore, even if there are further horizontal deformations of 5.6mm annually (the deformation rate based on previous measurements), there will be no problem for 300 years. However, if partial peeling between the gate attachment and concrete occurs due to the deformation, there may exist a risk that the gate will be rendered unusable that cannot be clearly predicted. If this were to happen, power generation would be stopped and there would likely be great difficulty in carrying out repairs. Thus, we decided to implement the countermeasures. Another potential problem that has been considered is

whether or not the connecting bridge might possibly drop. In fact, the stopper installed to prevent the such bridge collapses has already been repaired once due to the deformation of the tower.

As described above, concerning the overall usage of the intake tower, there have been no safety or usage problem up to now except repairing the bridge’s connecting members. Although after 30 years of ASR, the alkalinity and the residual expansion tests do not indicate the faster development of the tower inclination, in fact the intake tower change is continuing so we must consider that it may continue. If this occurs the concrete and metal gates could separate resulting in the gates being rendered unusable. Thus, even if there is little physical deformity or expansion, we believe ASR countermeasures are valid.

4.2 Chosen countermeasure

Usually measures to control ASR eliminate water source which is necessary for the reaction. However, being as this tower stands inside of the lake, its concrete surfaces are necessarily exposed to water as a matter of course. Due to this, it is necessary to effect a countermeasure for all of the interior and exterior surfaces, but it is impractical to effect a countermeasure completely in the limited time available. This is the difficulty we face concerning the elimination of the reaction’s water source. In the case of this structure, the ASR was discovered 15 years following its construction and close to 30 years later the reaction is gradually progressing. For now we need not consider urgent measures, and we must consider that the gradual halt of the ASR may be possible. With this in

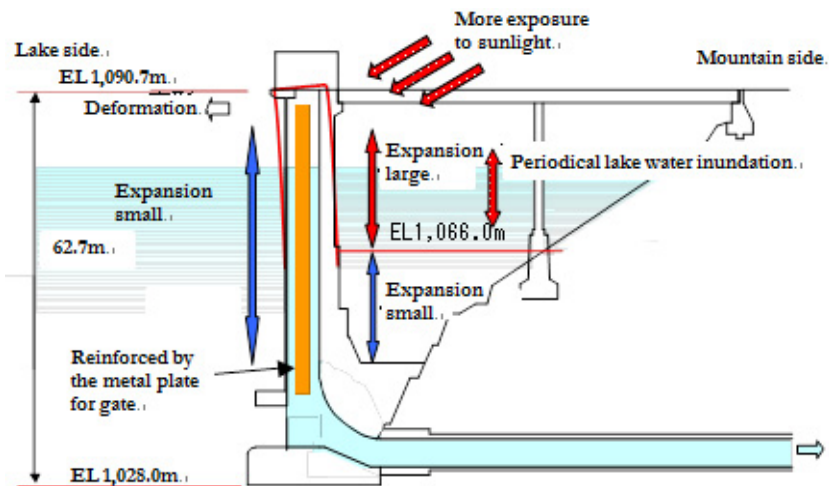


Fig. 11 Graphic illustration of the primary causes of the ASR.

Table 4 Applicability of normal repairs and reinforcement.

Aim	Example of Method
ASR Suppression	Paint application for moisture blocking Reinforcement using PC anchor
Controlling deformation caused by ASR	Bound by PC wire inside the precast concrete or the attachment of a steel plate to the concrete surface
Rebuilding	Complete or partial rebuilding

mind, we think it is proper to consider, even if just a little, the control of the ASR expansion and deformation.

Table 4 shows the applicability of normal repairs and reinforcement for this intake tower given the ASR situation (Torii *et al.* 2004; Kubo *et al.* 2004; Daidai *et al.* 2012). Generally, deformation bound by PC wire inside the precast concrete or the attachment of a steel plate to the concrete surface are the countermeasures of choice. However, as this intake tower has a complicated shape due to the gate on the front, restraining further deformation in the horizontal direction is difficult. Further to this, since the inclination of the intake tower is due to the vertical expansion of the ASR, this time it was decided to adopt a method for restraining the further vertical expansion using the PC steel wire. Of course, complete rebuilding of the structure would be the most reliable method. However, since such a construction project is exorbitantly large in scope and requires long-term shut-down of the power plant's operation, that option was not adopted.

4.3 The reinforcement using post-tensioned tendons

Concerning the specifications of the PC steel wire, the tension-adjustable SSEE anchor A type, 360TA (19×Φ12.7mm, yield point load of 2964kN, drilling diameter of Φ165mm), which was the maximum size available, was adopted. SSEE anchor is an anchor for PC

(Pre-stressed Concrete) developed by SSEE Corporation.

Figure 12 shows the cross-section of the hole after construction and Fig. 13 shows the situation of the construction. The anchors are inserted into the drilled holes. The anchor rods consist of 19 cables, which are each made from 7 PC steel wires. They have a diameter of 89mm and a length of 45.7m. The cable has a flexible structure. That is to say the cable (see cross sectional figure) is coated with anti-rust oil. This together with the polyethylene resin is inserted into the outer slide pipe. The lower parts of the rods are made from steel to fix the anchors at the bottoms of the holes. Throughout the holes cement milk is injected. First the upper parts of the rods

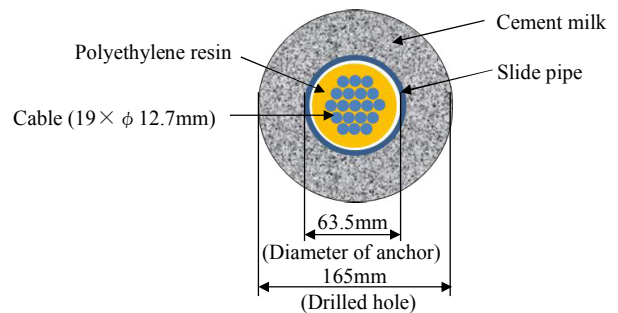
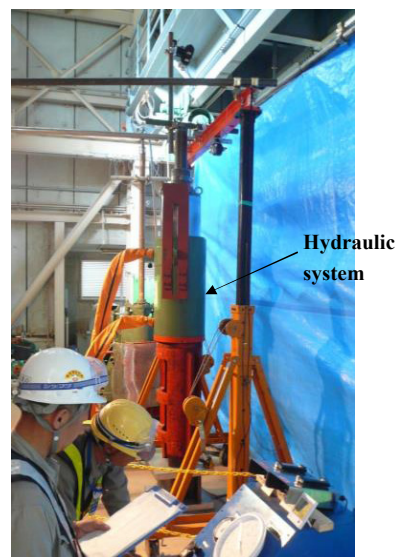


Fig. 12 Cross-section of the holes drilled for the post-tensioned tendons.



During the insertion of the anchor



During the tensioning work

Fig. 13 Photographs documenting the construction.

are hydraulically pulled, and then they are fixed in place with a nut. In other words, it is possible to create a compression force on the concrete by introducing a tensioning force to the rods. The anchors adopted this time have a screw on their tops. They are a type of anchor with adjustable tensioning force. Additionally, after considering margins corresponding to potential ASR development in the future, the largest anchor available in our country was adopted.

Figure 14 shows the construction location plan view, and Fig. 15 shows the drilling depth view. Drilling on the mountain side was, as much as possible, evenly spaced with 10 places, each place spaced at a distance of about 2m from the next. Furthermore, in order to balance the whole structure, two anchors were placed on the lake-side. The anchors' base positions of immobilization are set at near EL1045m close to the bottom portion of the tower structure, and in this way tension was applied to the entire structure. Thus, 45.7m drilling depth was needed.

Construction was first carried out for only one of the candidate locations in 2009. This was a test construction for the purpose of confirming the concrete properties and the workability of anchors in advance. Then, the remaining construction for the rest of the eleven locations was carried out in 2011. Drilling was accurate to within ± 0.5°. Tension work was carried out in the spring of 2012. The initially applied force was set at 1500kN (50% of the yield point load, 0.26N /mm²). The value of 0.26MPa was derived from the following calculation.

Tension per anchor : 1500kN

Total number : ten

The cross-sectional area of the intake tower's mountain side : $2.5 \times 22.7m = 56.75m^2$

Thus, $1500 \times 10 \div 56.75 = 0.26MPa$. In the history of

research to date concerning the expansive pressures of ASR gels and the required forces required to suppress that expansion there are reports about such topics. (e.g., Kawamura, M.)

According to some results of the investigations, pressure of 0.2 ~ 0.3MPa is said to be effective to suppress the expansion due to ASR (Torii *et al.* 2000; Ishii *et al.* 2005; Okuyama, *et al.* 2007; Ishii *et al.* 2008). However, the actual phenomena observed in the field have been much more complex. To this end we are conduct creep tests on cores taken from the intake tower by introducing a small, long-term load to the test sample in order to confirm the long-term influences of such loads on deformability(Torii *et al.* 2010).

Furthermore, the behavior of the actual structure is unclear. Thus, the monitoring is being continued, and, further to the behavior observed, we will adjust the anchors' introduced forces accordingly. Incidentally, when the tension in the longitudinal direction is introduced, there is a possibility that deformation will proceed in the transverse direction (Gravel *et al.* 2000), so follow-up measurements and visual inspections of the structure's appearance become increasingly important.

5. Testing of the boring core concrete

5.1 Compressive strength and static modulus of elasticity

Figure 16 shows the test results for the compressive strength of a core sample from the tower, and Fig. 17 shows the test results for static modulus of elasticity. Please note that in Figs.16 and 17, the green outline of the tower on the left illustrates the relative locations in the tower structure where the various compressive strength measurements were taken. The compressive

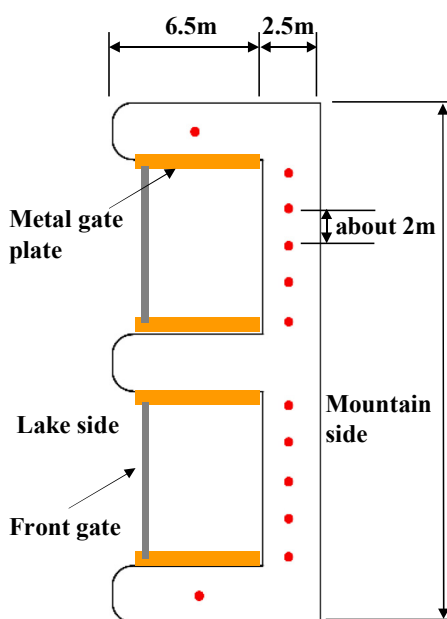


Fig. 14 Top view of the locations of the holes for the post-tensioned tendons (holes represented by red dots).

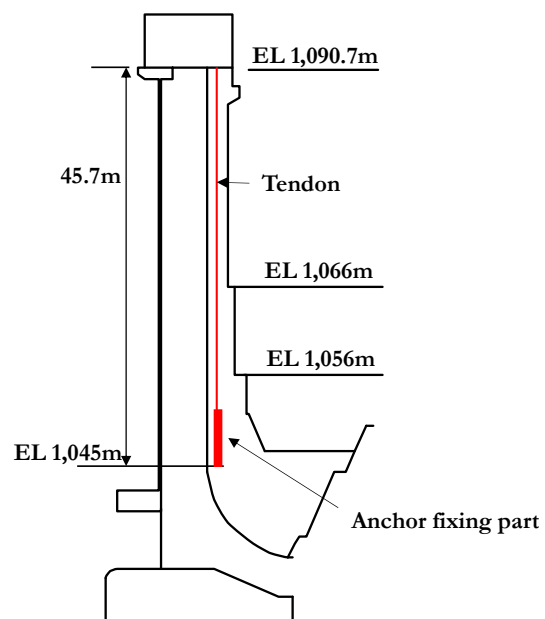


Fig. 15 Side view indicating the depth of the holes for the post-tensioned tendons.

strength results were on average higher than the planned average standard strength($\sigma_{28}:24\text{N/mm}^2$). Also, the results for compressive strength and static modulus of elasticity were both even higher at the 1,090 meter level. The compressive strength of the core from the intake tower's center showed a relatively high value. This is because the restraining force of the steel is stronger at the center of the tower.

Although variations of the compressive strength and the static modulus of the concrete in which ASR occurs tends to be large, the durability of the structure is believed to be no problem, because the actual concrete interior is bound with re-bars. In the lower part of the tower below 1066m, the fact that the static modulus of elasticity is reduced indicates that ASR should have progressed. However, the constraining conditions are significant, and we believe this is why not so much expansion was observed. Furthermore, it is believed that an additional reason why the progress of the ASR in the

lower part of the tower below 1066m differs from the upper part is the lower part is under water most of the year.

5.2 Observation of the thin section by the polarizing microscope

Some thin pieces made from cutting the core (40mm × 25mm) were observed under a polarizing microscope. These pieces were made one by one, each from the core in the vicinity of EL1086.5m, EL1080.6m, EL1076.1m, EL1071.3m, EL1068.4m, EL1061.9m, EL1057.1m, EL1052.4m, EL1050.5m and EL1046.4m. **Figure 18** shows an example of a micrograph (EL1061.9m). As a result, since cracks through the fine aggregate were observed in slices from all the elevations, it has become clear that ASR has occurred throughout the whole interior of the intake tower.

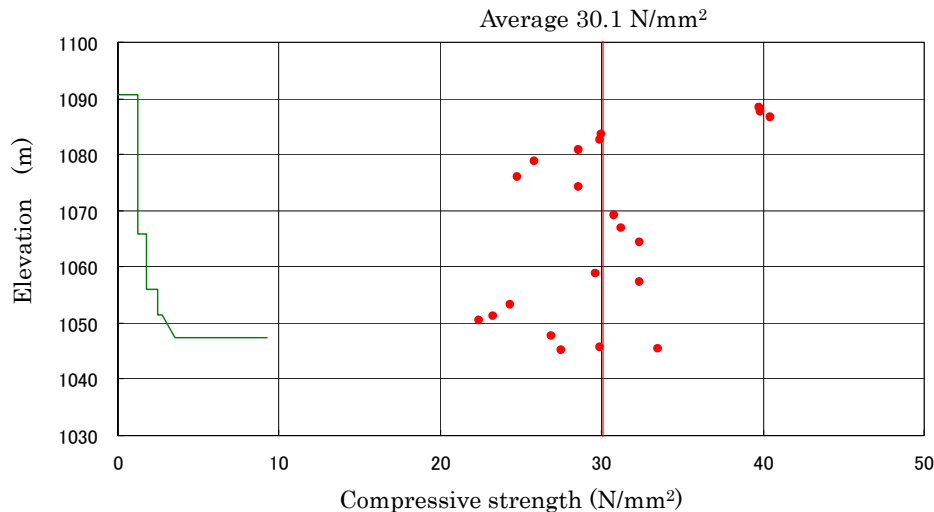


Fig. 16 Compressive strength measurements of the cores taken at various locations in the tower.

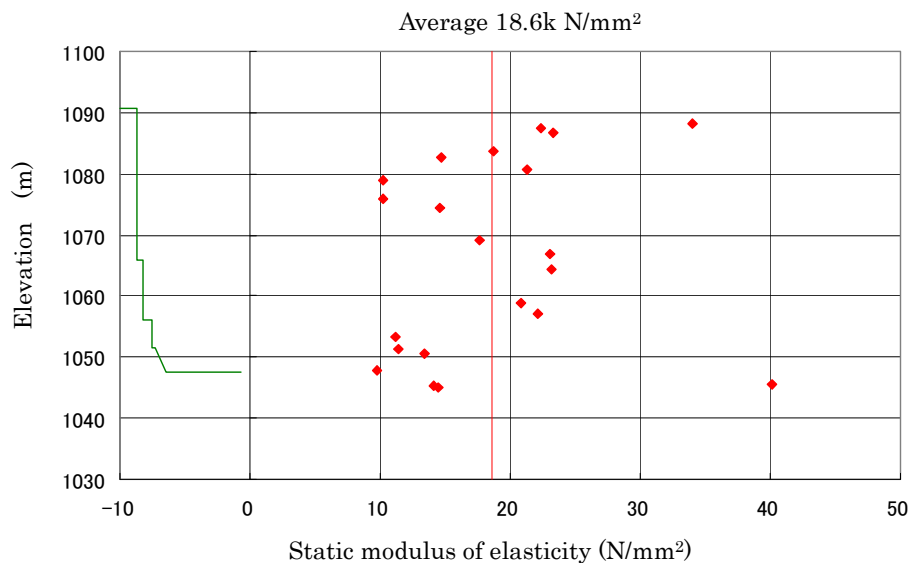


Fig. 17 Static modulus of elasticity measurements of the cores taken at various locations in the tower.

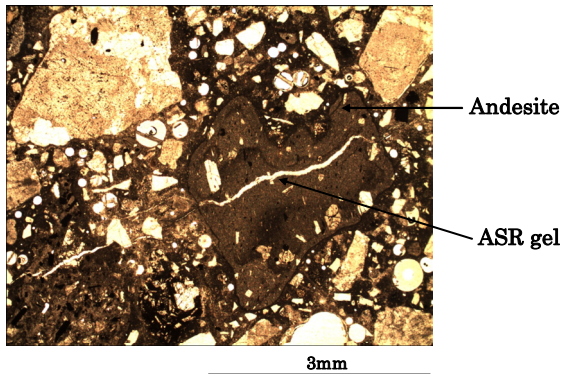


Fig. 18. Reactivity of Andesite in a micrograph (EL 1061.9m) : plane polarized light.

6. Effect of the countermeasure

6.1 The measurement of the displacement

Figure 19 shows the horizontal change in distant over time at the top of the tower, and Fig. 20 shows the vertical change over time at the top of the tower, including after the countermeasure was implemented. As described above, because of the severe environmental conditions at

sub-zero temperatures in winter, standard measuring devices cannot be used (Jensen 2000; Salles 2012; Zoilo 2012). Furthermore, due to the deep snow drifts in the area, it is not possible to go to the site in the winter. For this reason, measurements of displacement are conducted between spring and autumn.

In these figures, if the horizontal displacement had continued to progress in the same manner as had been shown through previous measurements between June 2012 and November 2015, it is estimated that the horizontal displacement at the top of the tower should have progressed an additional 16mm. However, after countermeasures, only 5mm of further progression in the horizontal displacement were observed. Thus, we confirmed that the suppression effect of the countermeasures was the reduction of further horizontal displacement by 11mm, which corresponds to 3mm per year. In brief, horizontal changes to the top of the intake tower after the countermeasure was implemented have decreased.

As described above, although the horizontal displacement greatly suppressed, the suppression of the vertical displacement appears to be less. Essentially the horizontal displacement is due to the difference between the vertical expansions on the mountain side and on the

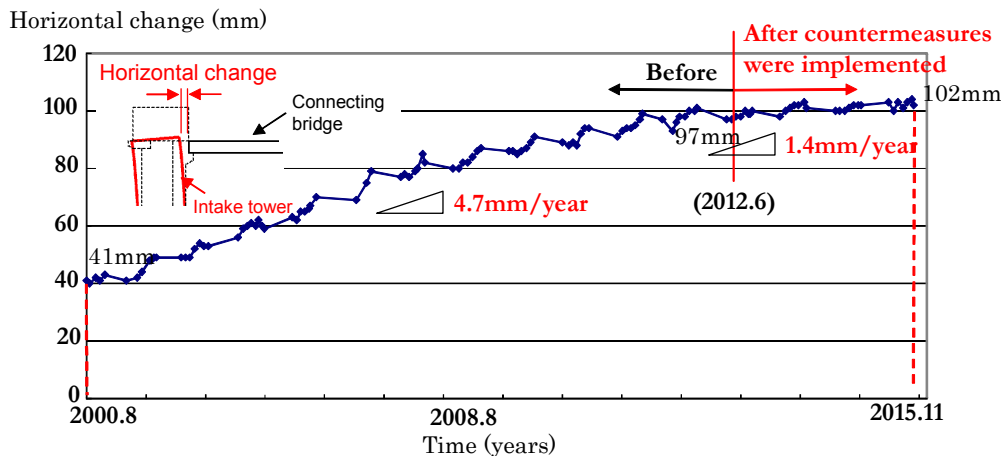


Fig. 19 Horizontal change in distant over time at the top of the tower.

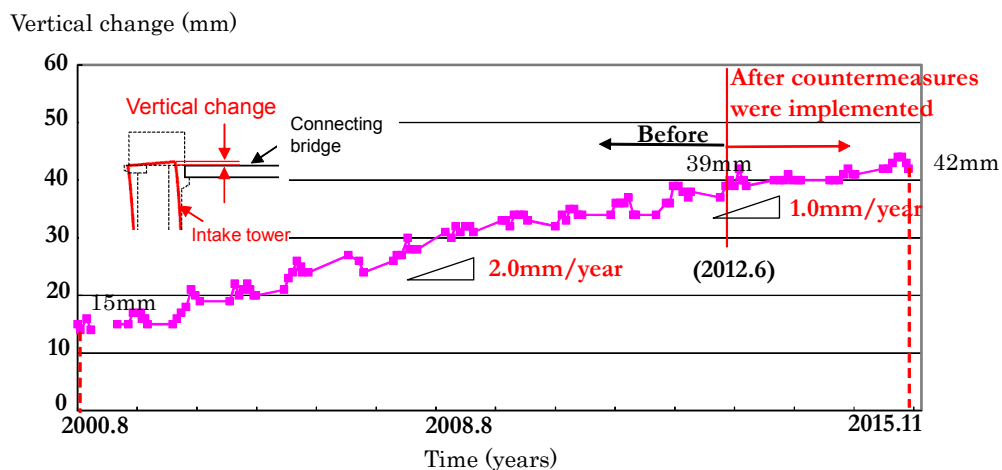


Fig. 20 Vertical change in distant over time at the top of the tower.

lake side of the tower. Although the results of this reinforcement have had a small inhibiting effect on the amount of vertical displacement, the difference in vertical expansion rate between the mountain side and the lake-side of the tower has been reduced, and this has effectively suppressed the horizontal displacement.

Please note that the primary purpose of the reinforcement is to suppress the horizontal deformation. Therefore, it can be said that the effect of the countermeasure has been confirmed.

7. Concluding remarks

In this paper the assessment of alkali-silica reactivity of volcanic gravel from Jouganji river in the Hokuriku district in Japan, which is considered to be the most reactive one in Japan, has been introduced. Secondly, the investigation of ASR-caused deformities to a water intake tower which was constructed by using river aggregates produced from Jouganji river and the attempts to reinforce the tower using post-tensioned tendons has been introduced. Although an inclination was confirmed on the intake tower, it has been shown that this is because of the difference in the ASR expansion due to the difference in environmental conditions and structural conditions. As a method for controlling the deformation of the intake tower caused by ASR, the method of using a PC anchor was adopted. Consequently it was possible to effectively suppress the deformation from the applied force of $0.2 \sim 0.3\text{N/mm}^2$.

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