THE REINFORCEMENT OF AN ASR AFFECTED INTAKE TOWER USING POST-TENSIONED TENDONS

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Abstract

One intake tower in Japan's Hokuriku district with a height of 62.7m was constructed between 1977 and 1979 for power generation and agricultural use. 20 years after the construction, an inclination with concomitant expansion of the structure was found due to the clearance of 40mm between the top of the intake tower and the connecting bridge. As a result of the investigation of the concrete, it was revealed that deformation had occurred as a consequence of ASR expansion of the intake tower concrete, and the inclination (horizontal displacement) from the vertical line reached 90mm after 10 more years. 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. This paper presents the overview of the investigation and the method of the reinforcement including the effect of the countermeasure.

Keywords: ASR, Reinforcement, Deformation

1 INTRODUCTION

In order to clarify the influence on structures caused by ASR expansion, measurements of ASR expansion related pressure were conducted [1,2]. 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 [3,4,5].

In this paper we will present the investigation of ASR-caused deformities to a water intake tower and the attempts to reinforce the tower using post-tensioned tendons [6]. Concerning the reinforcement, laboratory test results indicated that a small binding force of 0.2～0.3N/mm^2 could decrease the ASR expansion, and this was the basis for the determination of the initial stress [7]. The construction was carried out in 2011, and in 2012 after applying this 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 [8].

2 OVERVIEW OF THE INVESTIGATION

2.1 History of the intake tower

This intake tower is located at a dam in the upstream region of a river in Japan's Hokuriku District. Figure 1 shows the actual site. 74m^3/s of water can pass through the intake tower and 400 thousand 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.

20 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.

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2.2 Displacement measurement

Distance from vertical line to both the interior wall and the exterior wall were measured at each elevation. Figure 2 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 13 shows the horizontal change in distant over time at the top of the tower, and Figure 14 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 86mm, 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.

2.3 Cause of the inclination

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. 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.

In April the lake level is at its lowest, so 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 towers increasing inclination in the direction of the lake. Figure 3 is a summary outline of the primary causes of the ASR.

2.4 Alkali-Silica Reactivity of volcanic river aggregates

Hokuriku district river sand and gravel from one river in the region was used in the intake tower. This aggregate is considered to be the most reactive in Japan. Figure 4 shows the result of chemical test according to JIS A 1145. The outcome of the aggregate classification was 'deleterious,' indicating that the alkali-silica reactivity of both the fine and coarse river aggregates is similar when their soluble silica content (Sc) is more than 100 mmol/l. Furthermore, Figure 5 shows the result of the accelerated mortar bar test for a specimen using the river gravel according to JIS A 1146. As shown in this figure, the specimen expanded significantly with curing. In this manner, we confirmed that this gravel was deleterious.

We estimated that the alkali amount of the intake tower concrete was about 2.3kg/m^3. This calculation was based on the fact that the unit content of cement was 290kg/m^3, and the alkali content of cement was 0.8%, which was in keeping with cement factory production at that time.

Although, the alkali amount of the intake tower concrete was not so high, it is assumed that ASR developed in the intake tower concrete due to the combination of the high reactivity of the aggregate and the severe conditions to which the concrete was subjected.

3 THE METHOD OF THE REINFORCEMENT

3.1 Countermeasures to ASR

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.

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

Table 1 shows the applicability of normal repairs and reinforcement for this intake tower given the ASR situation. 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.

3.3 The reinforcement using post-tensioned tendons

Concerning the specifications of the PC steel wire, the tension-adjustable SEEE anchor A type, 360TA (19× Φ12.7mm, yield point load of 2964kN, drilling diameter of Φ165mm), which was the maximum size available, was adopted. Figure 6 shows the insertion work status of the anchor. Figure 7 shows the construction location plan view, and Figure 8 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 $\pm$ 0.5 °. Figure 9 shows the track record for the 12 drilling geometries. 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 /mm^2). Incidentally, when the tension in the longitudinal direction is introduced, there is a possibility that deformation will proceed in the transverse direction [9], so follow-up measurements and visual inspections of the structure's appearance become increasingly important.

4 TESTING OF THE BORING CORE CONCRETE

4.1 Overview of the core

Using the drilling core taken during test construction, core observation and testing was carried out. Although signs of alkali-silica reaction were confirmed in all core samples and there were some minor, partial cracks observed at the levels of cross-sectional changes in the structure, the continuous core samples collected confirmed overall soundness.

4.2 Compressive strength and static modulus of elasticity

Figure 10 shows the test results for the compressive strength of a core sample from the tower, and Figure 11 shows the test results for static modulus of elasticity. The compressive strength results were on average higher than the planned average standard strength(σ28:24N/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.

4.3 Observation of the thin section by the polarized 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. 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.

4.4 DRI method

The observation based on the DRI method was carried out (this item is shown Table 2) by the visual observation of the coarse aggregate at the side of the cores (Φ165mm, extension 45.75m), and the numbers corresponding to the items were counted every 1m, then the number was weighted. This number has been discussed with respect to the progress of the ASR [10]. Figure 12 shows the evaluation result. As a result, the phenomenon caused by the ASR has been confirmed across the intake tower. In addition, near EL1090m there is a section that is not submerged, and the compressive strength was large and the evaluation index for that location was low. However, for other sections the evaluation index varied, but there was no apparent association with compressive strength, so a static elastic modulus was not found. The reason there was no clear tendency is that this evaluation was made using only observations of coarse aggregate. However, the fine aggregate also exhibited significant reactions as revealed by the polarizing microscope observations, so it is not possible to draw final conclusions until the factors from all kinds of aggregate are taken into consideration.

5 EFFECT OF THE COUNTERMEASURE

5.1 The measurement of the displacement

Figure 13 shows the horizontal change in distant over time at the top of the tower, and Figure 14 shows the vertical change over time at the top of the tower, including after the countermeasure was implemented. Changes to the top of the intake tower after the countermeasure was implemented have decreased. Therefore, the effect of the countermeasure has been confirmed.

5.2 Monitoring of the tension of the tendons.

Figure 15 shows changes of tension over time that were measured by a load cell. As shown in the figure, although some variation over a year's time was seen, drastic load change was not seen. Therefore, we have confirmed that tensions had been stably controlled.

6 CONCLUSIONS

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.

The observation under the polarized microscope and the evaluation using the DRI method of the cores has confirmed that ASR occurred in both the fine aggregate and coarse aggregate. Additionally, ASR was observed in the entire interior of the intake tower.

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 ~ 0.3N/mm^2.

7 Acknowledgment

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TABLE 1: Applicability of normal repairs and reinforcement.

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

TABLE 2: Items Observed Using the DRI Method.

Items observed	Weighting factor
a. Cracks in coarse aggregate	Number ×0.75
b. Cracks in coarse aggregate filled with ASR gel	Number ×2.0
c. Open Cracks in coarse aggregate	Number ×4.0
d. Coarse aggregate de-bonded	Number ×3.0
e. Reaction rims	Number ×0.5

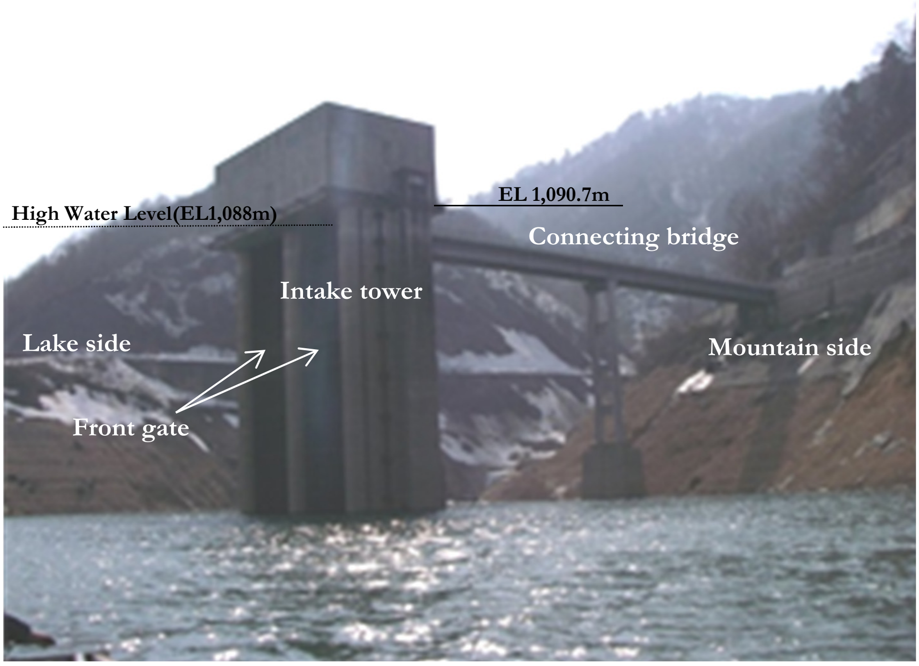

FIGURE 1: Actual site of the intake tower.

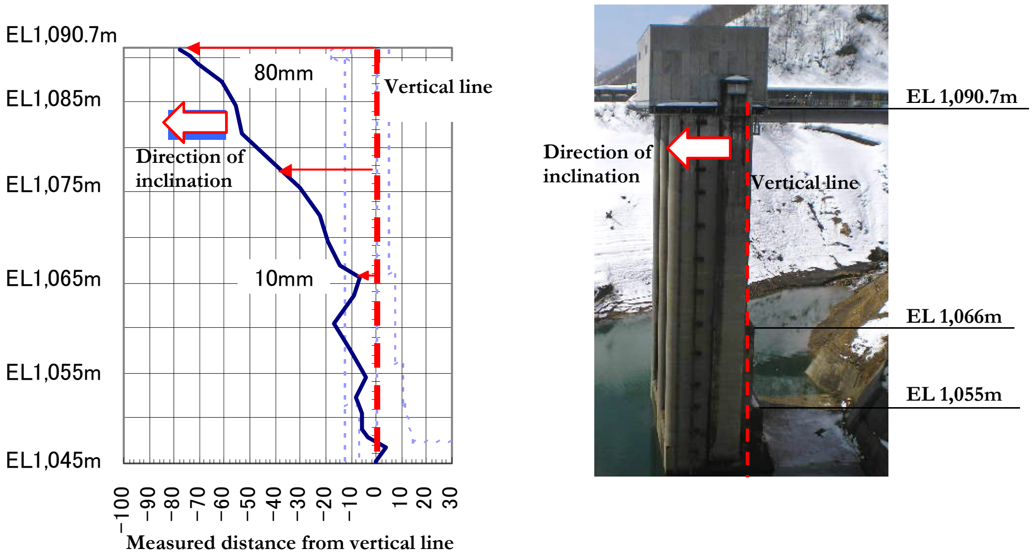

FIGURE 2: Investigation of the interior wall and exterior wall.

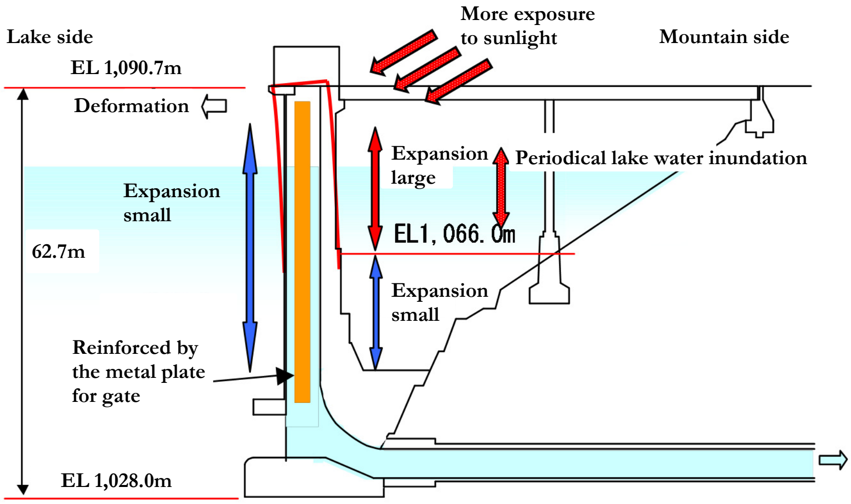

FIGURE 3: Summary outline of the primary causes of the ASR.

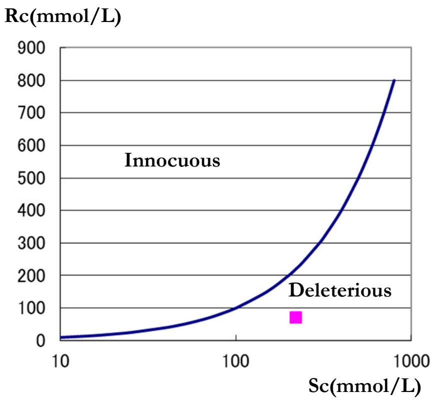

FIGURE 4: Result of chemical test.(JIS A1145)

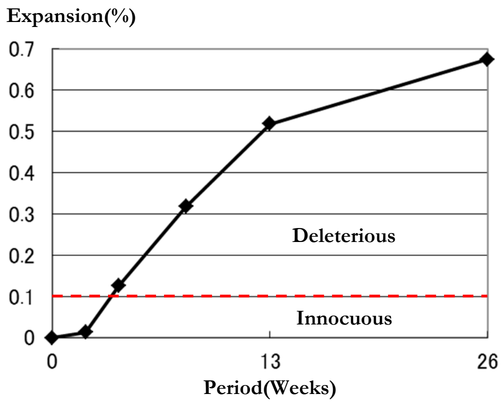

FIGURE 5: Result of the mortar bar test.(JIS A1146)

FIGURE 6: Insertion work status of the anchor.

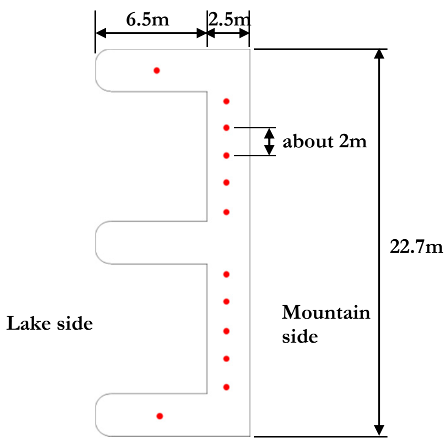

FIGURE 7: Construction location plan view.

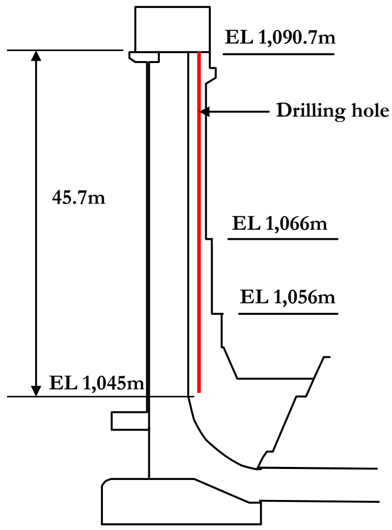

FIGURE 8: Drilling depth view.

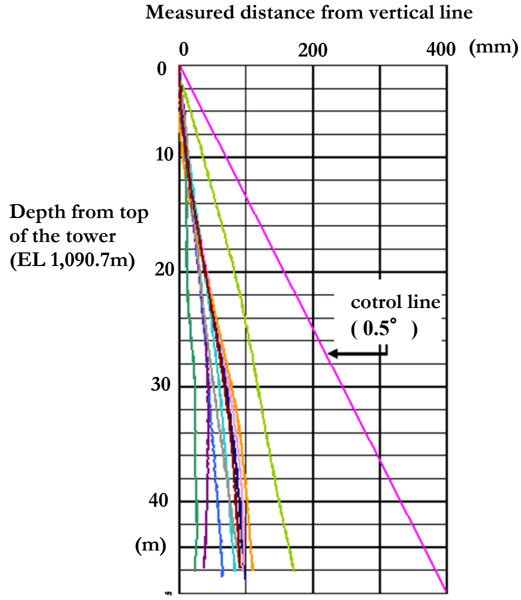

FIGURE 9: Track record for the 12 drilling geometries.

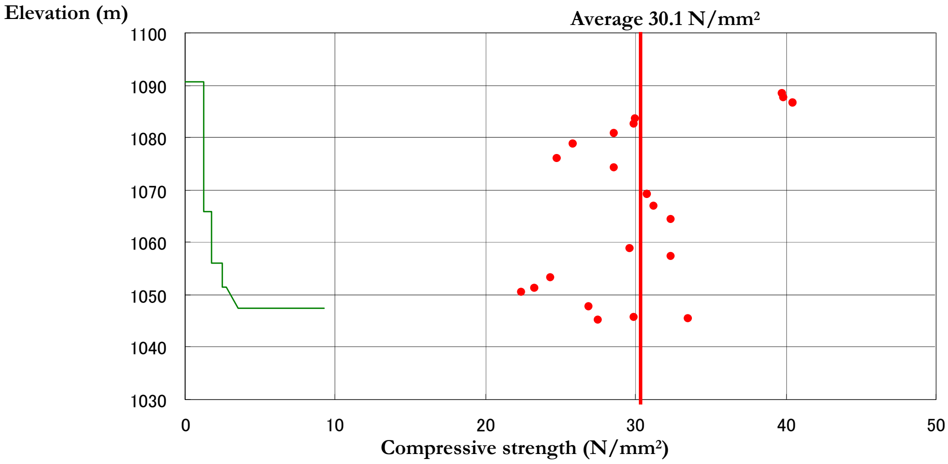

FIGURE 10: Compressive strength of the cores.

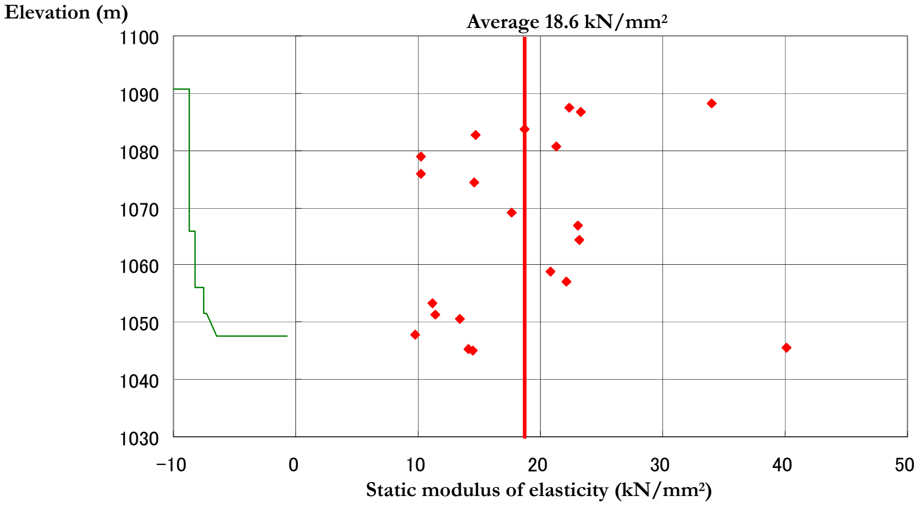

FIGURE 11: Static modulus of elasticity of the cores.

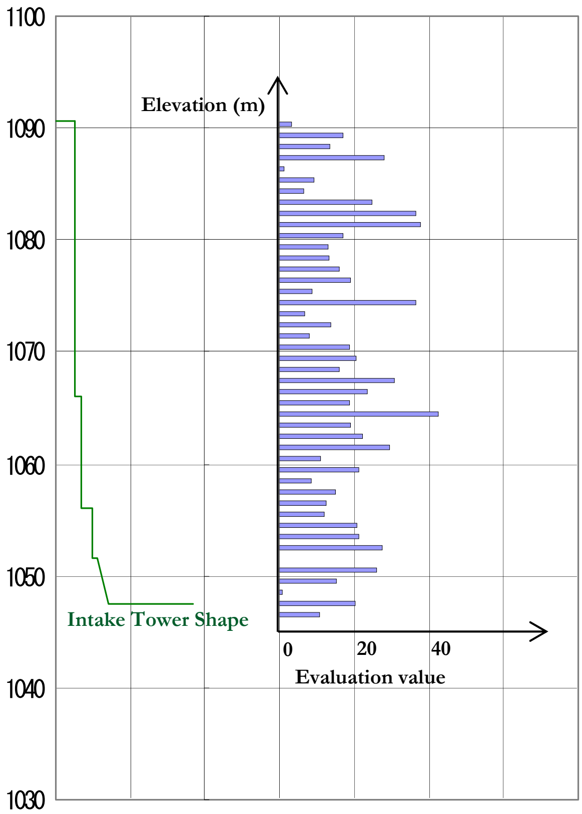

FIGURE 12: Evaluation result based on the DRI method.

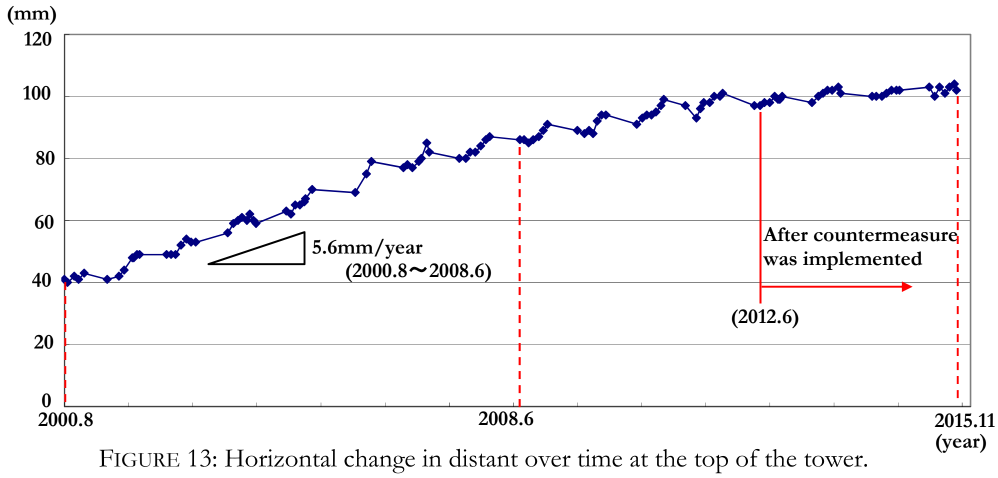

FIGURE 13: Horizontal change in distant over time at the top of the tower.

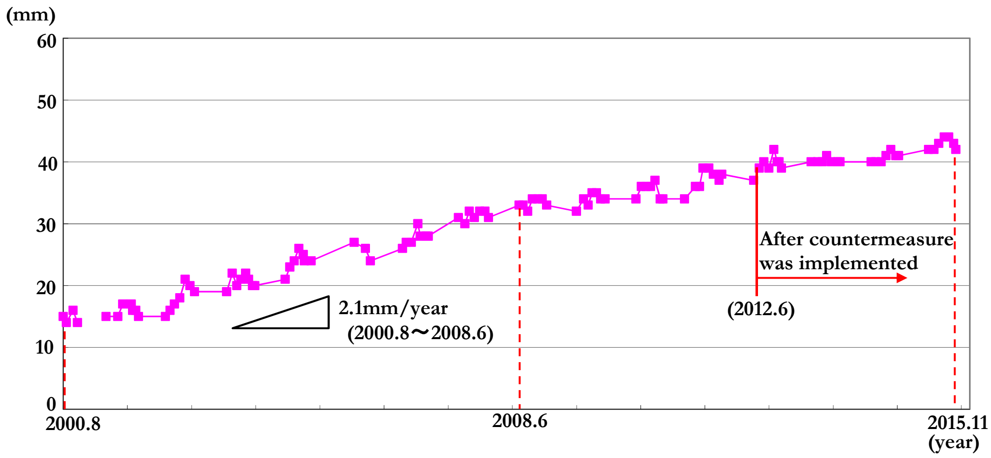

FIGURE14: Vertical change in distant over time at the top of the tower.

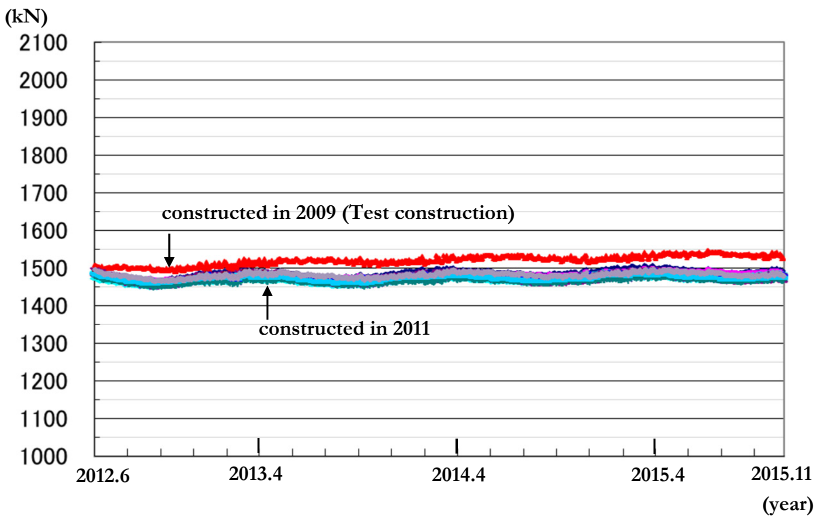

FIGURE 15: Changes of tension over time that were measured by a load cell.