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Maintenance Management of Turbine Generator Foundation Affected by Alkali–Silica Reaction

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Abstract

A change in distance between the generator rotor axis and the bearing of the table deck in the turbine generator (TG) foundation of Unit #1 of the Ikata nuclear power plant was observed during an inspection in 1979 after the start of operation. This led to measurements of the structure expansion (from 1981), the cracking condition (from 1982), and core sampling of the concrete member (from 1986), based on which deformation and cracking was determined to be the result of an alkali–silica reaction (ASR). However, as the strength of the TG foundation was still in excess of its design value, ASR was not considered to have affected its ability to support equipment. Subsequent analysis of the structural stability of the TG foundation found no change in deformation or concrete strength over a period of continued monitoring, and hence, the TG foundation has been used up to the present time. The aim of this paper is to establish a maintenance management method for similar structures exhibiting cracks caused by ASR.

1. Introduction

Concrete degradation by an alkali–silica reaction (ASR) has been reported in recent years at nuclear power plants such as the Gentilly facility in Canada and Seabrook facility in the United States (Chénier et al. 2012). In Japan, the rupture of reinforcing bars by expansive forces has also been reported in outdoor structures affected by ASR, such as piers and abutments of bridges (Minato and Torii 2010). As long-term-service is essential to major infrastructure, there has been an increasing need for maintenance management plans for structures affected by ASR.

This paper discusses the maintenance management method that has been implemented for the turbine generator (TG) foundation of Unit #1 of the Ikata nuclear power plant, in which concrete cracks caused by ASR have been observed. This approach includes an evaluation of the current and long-term soundness of the structure, and is aimed at establishing a method that can be used to manage the cracks caused by ASR in any major structure.

2. Overview of turbine generator foundation

The TG foundation of Unit #1 was constructed in 1975 to provide a supporting structure for the turbine and generator, and has been in commercial operation since 1977. This reinforced concrete (RC) structure consists of a table deck, columns, walls and a foundation mat measuring $50 \times 15 \times 18.7$ m in length, width, and height, respectively. The dimensions of this structure and the materials used in its construction are shown in Fig. 1. Part of the top surface of the table deck is covered by plastic tiles, while the rest of the concrete surface is exposed.

As the TG foundation is located within the turbine building, it is not exposed to direct sunlight, wind, or rain. Furthermore, no moisture is supplied by any of the other equipment in the building. However, the table deck is in an atmosphere that is affected by the heat of the turbine. From environmental measurements taken in 2003–2011, it is known that the annual average temperature and relative humidity around the TG foundation during operation is approximately $35^\circ$C and 30%, respectively.

3. Maintenance management

3.1 Concept

The current condition of the TG foundation was assessed (to understand the extent of ASR) through measurements of its deformation, the mechanical properties of the RC member, and a structural analysis. These results have suggested that its support function can be maintained; however, a long-term evaluation has also been implemented that will continue these measurements so as to predict the future should any change in the ASR process occur (Table 1, Fig. 2).
3.2 History
A change in the distance between the generator rotor axis and bearing was discovered in the table deck during an equipment overhaul in 1979, but no abnormality was found in the axis vibration and the deformation was able to be corrected by adjusting the equipment. Cracks later appeared on the lateral surface of the beam of the table deck in 1982, and it is thought that these may have been caused by deformation of the concrete resulting in the change in the distance between the generator rotor axis and bearing. Observation of these cracks and measurement of the deformation of the table deck therefore commenced. In order to clarify this, strain gauges were installed on the TG foundation in 1986 to measure the strain in the reinforcing bars. Concrete core samples were also taken and subjected to compressive strength testing. These studies concluded that the deformation of the TG foundation was caused by ASR based on the

| Purpose                                | Measurement for understand the extent of ASR | Structural analytical evaluation |
|----------------------------------------|--------------------------------------------|---------------------------------|
|                                        | Deformation                                 | Concrete core sampling tests    |
|                                        | Mechanical properties                       | • Compressive strength and      |
|                                        |                                             | static elastic modulus          |
|                                        |                                             | • Reactivity of the aggregate   |
|                                        |                                             | (Observation of cut surface     |
|                                        |                                             | of concrete core)               |
|                                        |                                             | • Accelerated expansion test    |
|                                        |                                             | • The rebound hardness measure-|
|                                        |                                             | ment of concrete                |
| The soundness                          | • The measurement of the expansion of        | • Structural analysis          |
| evaluation                               | of the table deck                            |                                |
|                                        | • Visual inspection of concrete cracks      |                                |
|                                        | • The measurement of the internal tempera-  |                                |
|                                        | ture of the concrete                         |                                |
|                                        | • The measurement of reinforcing bar strain |                                |
|                                        | • The measurement of the axis vibration     |                                |
|                                        | level                                       |                                |
|                                        | • The column inclination measurement        |                                |
|                                        | • The investigation for reinforcing bar      |                                |
|                                        | rupture                                     |                                |
| The long-term                          | • Continuation of the above measurement     | • Structural analysis based on  |
| soundness evaluation                   |                                            | an assumption of ASR recommen-  |
|                                        |                                            | ding                              |

Fig. 1 Schematic of turbine generators and their foundation.

Table 1 Classification of TG foundation maintenance items.

| Purpose                                | Measurement for understand the extent of ASR | Structural analytical evaluation |
|----------------------------------------|--------------------------------------------|---------------------------------|
|                                        | Deformation                                 | Concrete core sampling tests    |
|                                        | Mechanical properties                       | • Compressive strength and      |
|                                        |                                             | static elastic modulus          |
|                                        |                                             | • Reactivity of the aggregate   |
|                                        |                                             | (Observation of cut surface     |
|                                        |                                             | of concrete core)               |
|                                        |                                             | • Accelerated expansion test    |
|                                        |                                             | • The rebound hardness measure-|
|                                        |                                             | ment of concrete                |
|                                        |                                             | • Structural analysis          |
|                                        |                                             |                                |
|                                        |                                             |                                |
|                                        |                                             |                                |
|                                        |                                             |                                |

Concrete
• Specified Strength : 20.6 N/mm² (210 kg/cm²)
• Cement : moderate heat portland cement
• Fine Aggregate : washed sea sand
• Coarse Aggregate : crushed stone
• Cement : moderate heat portland cement
• Fine Aggregate : washed sea sand
• Coarse Aggregate : crushed stone

Reinforcing bar
• Deformed bar SD345 (Former JIS SD 35)
• Specified Strength : 20.6 N/mm² (210 kg/cm²)

Unit : m
• Length : 50.0 m
• Width (Turbine Side) : 15.0 m
• Width (Generator Side) : 11.0 m
• Height (from top of foundation mat) : 18.7 m

Fig. 1 Schematic of turbine generators and their foundation.
developing table deck expansion, distribution of concrete cracks with directionality along the main reinforcement direction, a decrease in the static elastic modulus, and the fact that andesite containing silicate mineral was used as a coarse aggregate. A gelled substance extracted from the surface of the core samples was identified as alkaline silica gel, with the alkali content of the concrete as much as 9 kg/m³. Despite this, it was concluded that there was no problem in terms of the TG foundation providing sufficient support, as there was no induced vibration that might affect its operation. Furthermore, the compressive strength of the concrete has remained in excess of its design strength and ongoing structural analysis commenced in 1988 showed enough supporting function.

As ASR is a progressive process, it is necessary to evaluate the long-term soundness of the TG foundation based on the measurements that have been taken up to the present time. In 2002, the development of ASR was verified to have settled based on the fact that table deck expansion stopped around 1991, no new cracks indica-
tive of ASR were observed, and that the rate of remaining expansion had been decreasing since 1989. The structure was therefore considered to have a low possibility of expansion in the future (Takakura and Ishikawa et al. 2005). Also in 2005, structural analysis by a three-dimensional frame model of the TG foundation deformation that took into account the mechanical properties of its concrete verified that its supporting function would be maintained. Structural analysis assuming redevelopment of ASR was carried out to show enough supporting function in future. Since then, no major changes in the deformation conditions or compressive strength of the concrete that would indicate a change in ASR conditions have been observed through ongoing column inclination measurements, rebound hardness tests and reinforcing bar rupture investigations. As a result of this verification of the current and long-term soundness of the TG foundation, it has remained in continuous use up to the present time.

Chapter 4 presents the main measurement results used to understand the current ASR conditions and determine whether they had settled, as well as the results of a subsequent structural analysis. Chapter 5 outlines the state monitoring that has been continued or added since determining that the ASR conditions had settled.

4. Soundness evaluation

4.1 Analysis of ASR condition

4.1.1 Table deck expansion

Expansion of the table deck was measured to determine the extent of any deformation of the TG foundation after measuring the change of the distance between the generator rotor axis and its bearing. Ten benchmarks were set for this measurement on both the mountain side and sea side of the TG foundation, as shown in Fig. 3. Starting in December 1981, the distances between these benchmarks were measured using a micrometer and steel rod, and the total of these distances was used to determine the displacement. As shown in Fig. 4, expansion in
the axial direction due to ASR increased up until the early 1980s, but appears to have stopped around 1991. Since then, the expansion has remained at the same level as the benchmark measurement, which fluctuates by approximately 10 mm as a result of temperature variations due to seasonal change and turbine generator operation.

4.1.2 Crack conditions
Visual inspection of concrete cracks in the TG foundation has been undertaken since 1982 to monitor the deformation of the TG foundation. In 2002, major cracks were observed in the main reinforcing bar direction on the mountain side surface of the TG foundation (Fig. 5), and these were accompanied by cracks developed in a perpendicular direction to the reinforcing bar at the lower portion of the turbine support beams. The maximum local crack width was approximately 3.0 mm. As only a few cracks were observed in the main reinforcing bar direction and top of the column during the early stage of crack monitoring (1982), these later cracks are assumed to have developed as a result of expansion of the TG foundation. Once ASR was determined to have settled, and crack repair work was carried out, no new cracks have been observed.

4.1.3 Concrete core sampling
Concrete core sampling of the TG foundation was carried in order to determine if it could still provide a supporting function, and to better understand the extent of ASR and the expansion rate. The compressive strength of the concrete, its static elastic modulus, observations of the cut surface of the cores and the results of accelerated expansion tests carried out up until 2002 are all presented here.

(1) Compressive strength and static elastic modulus
The locations on the TG foundation from which concrete core was sampled are shown in Fig. 6, and the compressive strength of these cores is shown in Fig. 7. This reveals that the actual compressive strength of the table
(2) Cut surface of core samples

Reaction rims and/or cracks in the aggregate are known to occur when ASR develops, and so preliminary observation of cores taken from different sections was carried out to clarify the extent of ASR in each area. The core samples were cut into 2 cm-thick disks, the surfaces of which were polished for more detailed observation using a stereomicroscope. Through this analysis of six surface points per core sampling point, the surface crack and reaction rim condition was classified into one of four categories, and number of reaction rims and/or cracks was counted (Fig. 10). When compared to other areas of the TG foundation, the table deck had more Type 2 (with reaction rims) and Type 4 (with reaction rims and cracks) features, which clearly indicates that this area was affected by ASR (Japan Association for Building Research Promotion 2006, Takakura and Watanabe et al. 2005). This would also explain why cracks were more conspicuous in this area in Fig. 5.

(3) Accelerated expansion tests

The time-dependent behavior of the concrete cores obtained through accelerated expansion testing using the JCI-DD2 method proposed by the Japan Concrete Institute (JCI) is shown in Fig. 11. This method uses cylindrical cores (100 mmØ × 250 mm) kept at 20°C and 95% relative humidity to measure the released expansion, and these are subsequently exposed to an environment of 40°C and >95% relative humidity to measure the residual expansion.

The possibility for future expansion of the table deck section is considered low because maximum expansion of the concrete was reached in 1989, and the expansion rate has remained low since then. Any alkali in the concrete has since been consumed by the production of silica gel due to aging, and so the expansion rate is less than that in 1986 and still below the reference value (<0.1% after 6 months) specified in JIS A1146 (mortar bar method). Expansion possibility of the concrete other than the table deck is considered to be small because its expansion rate has been smaller than that of the table deck since the measurement started.
4.2 Structural evaluation
The structural stability of the TG foundation then was verified in 2005 by an analytical evaluation that took into account the compressive strength and static elastic modulus values obtained from the table deck expansion and concrete core tests conducted once it was determined that ASR had settled. Although it is quite unlikely that ASR may reoccur in the future, this possibility was considered in order to fully examine the long-term soundness of the structure (Shimizu and Asai et al. 2005; Takakura et al. 2009).

4.2.1 Analysis model
A three-dimensional frame model with beam elements, as shown in Fig. 12, was adopted to analyze the TG foundation so as to

![Fig. 10 Classification of concrete core sample cut surface.](image1)

![Fig. 11 Time-dependent behavior of accelerated expansion tests.](image2)
(1) Take into account the difference in elongation between the sea side and mountain side of the table deck and the nonlinearity of some of the applied load.

(2) To model the entirety of the TG foundation structure above the basemat in order to properly evaluate the stresses in the columns and intermediate beams.

In the beam element shown in Fig. 12, the mechanical properties of the concrete and reinforcing bar were defined individually. This was then used to simulate the stress states in the reinforced concrete caused by expansion due to ASR. The expansion behavior of the concrete was simulated to fit the measured deformation on horizontal bidirection by applying a linear thermal expansion coefficient and an equivalent temperature increment. Here, it was assumed that the thermal expansion of concrete can be used to simulate expansion by ASR (Takakura and Shimizu et al. 2005).

4.2.2 Material properties

From previous studies of material properties obtained through investigations of core specimens taken from structures affected by ASR, it is known that the strength and static elastic modulus deteriorate greatly when compared to unaffected concrete (Kobayashi et al. 1991). However, it has also been reported that there is very little change in the stiffness and strength of concrete affected by ASR if it contains reinforcing bar restraints resulting in chemical prestress (Kobayashi 1986). The material properties of the table deck used in the analysis therefore took into account the material property reduction ratio, i.e., the ratio of the material properties of concrete affected by ASR to those of unaffected concrete. This ratio was defined on the basis of a literature review (Koyanagi et al. 1998, Tanahashi et al. 1996, Yamura et al. 1994), model testing (Murazumi and Watanabe et al. 2005, Murazumi and Hosokawa et al. 2005), vibration testing, measurements of elastic velocity (Takakura and Watanabe et al. 2005) and testing of core specimens taken from the actual TG foundation, as shown in Table 2. The relationship between the reinforcement ratio, compressive strength ratio and modulus ratio obtained using these methods is shown in Figs. 13 and 14.

The material properties used for analysis of the concrete were those obtained from core samples of the TG foundation based on an average value from five different methods, as shown in Table 2 (Shimizu and Watanabe et al. 2005). In order to simulate long-term forced deformation by elongation of the table deck section, the static elastic modulus in the sound section was reduced by 1/3 from that of the core sample (Takakura and Shimizu et al. 2005). The material properties of concrete were defined using these values for the uniformly sound section and ASR-affected section.

The material properties of the reinforcing bars were defined using average values for the uniformly obtained through tensile testing of reinforcing bars taken from the TG foundation (Table 3).

For the stress-strain curve of the concrete and rein-
forcing bars, the non-linear curve shown in Fig. 15 was used so as to appropriately reflect the nonlinearity on compression side of the concrete, the cracks produced on the tensile side, and the yielding of the reinforcing bars. For structural analysis assuming the redevelopment of ASR, the compressive strength and static elastic modulus of the ASR-affected region were assumed to be 80 and 50% that of the respective sound portion of the structure. These values were considered the lower limit based on the study results shown in Figs. 13 and 14 (Shimizu and Watanabe et al. 2005).

4.2.3 Applied load and deformation
Dead load, operating load (live load, equipment load,
etc.), seismic load and short circuit torque load were all considered in this analysis (Japan Association for Building Research Promotion 2006; Shimizu and Asai et al. 2005). Expansion in the axial direction of the table deck due to ASR was assumed to be 50 mm on the sea side of the TG foundation and 34 mm on the mountain side. These values were determined by adding the displacement at the axial center of the turbine generator obtained from adjustment records of the turbine generator from the start of its operation until December 1982, at which point the expansion difference between the sea side and mountain side was 4 mm (Fig. 16).

Expansion in the perpendicular direction was assumed to be 6.7 mm for the generator side and 9.7 mm for the turbine side based on the notion that a strain (840 μ) equivalent to the average expansion (42 mm) in the axial direction should occur in the perpendicular direction. The average value for the expansion rate of the table deck in 2002 was determined to be 0.02% based on the accelerated expansion tests of core samples discussed in 4.1.3(3). The expansion value was assumed to be 10 mm (i.e., 0.02% of the total length of the table deck), which increased the length of expansion on the sea side from 50 to 60 mm. Thus, for structural evaluation assuming the redevelopment of ASR, the expansion value was set to 1.2 times the total value.

### 4.2.4 Evaluation methods

To evaluate the margin of safety with regards to the aseismic strength of the structure, the material strengths

| Table 4 List of analytical conditions. |
|----------------------------------------|
| ① dead + operating loads              |
| ② expansion of TD*¹                  |
| ③ seismic load (static)*²             |
| ④ short circuit torque*³              |
| X + Z direction                       |
| Constant expansion                    |
| Horizontal                            |
| X direction                           |
| (Axial direction)                     |
| +                                      |
| -                                      |
| -                                      |
| -                                      |
| +                                      |
| -                                      |
| -                                      |
| Z direction                           |
| (Perpendicular to axis direction)      |
| +                                      |
| -                                      |
| -                                      |
| -                                      |
| -                                      |
| Vertical                              |
| Y direction                           |
| +                                      |
| -                                      |
| -                                      |
| -                                      |
| -                                      |
| -                                      |
| T                                      |
| Local Condition                       |
| ① seismic load                        |
| ② expansion                          |
| ③ short circuit                      |
| ④ material strengths                 |

*¹ TD : Table Deck
*² Se : seismic load equivalent to design level
*³ Sc : gradually increasing seismic load

Load applied direction X direction (axial direction) : plus direction is from generator to turbine
Y direction (Vertical direction) : plus direction is from lower to upper
Z direction (perpendicular direction) : plus direction is from sea side to mountain side
*3 T : short circuit torque

![Fig. 14 Reinforcing bar ratio vs. elastic modulus of concrete.](image-url)
of the reinforcing bar and concrete obtained through testing were used to determine an appropriate reference (i.e., a standard value for margin evaluation). For this, the following values were adopted as standards:

- Reinforcing bar yield strength = 409 N/mm² (as determined by tensile strength testing)
- Concrete compressive strength (determined from core specimens taken in 2002)
  - ASR-affected region = 28.8 N/mm²
  - Unaffected concrete = 30.4 N/mm²

To calculate the shear strength capacity, the Ono–Arakawa lower bound equation was used to get conservative results, as outlined by the standards of the Architectural Institute of Japan (AIJ). The influence of twisting was taken into account by using an equation proposed by Article 22 of “AIJ Standard for Structural Calculation of Reinforced Concrete Structures”.

### 4.2.5 Results of analysis

Analytical evaluations of the TG foundation based on monitoring of its condition up until 2004, and assuming a recommencement of ASR, were undertaken for two separate cases. In Case 1, conditions under normal operation (a dead load + operating load and expansion of the table deck) were combined with seismic load or load due to short circuit torque to determine if the stress state remained within designed levels. In Case 2, the seismic load was gradually increased to determine the safe margin. A list of the analytical conditions used to evaluate the safety margin for strength in both cases is provided in Table 4.

(1) Evaluation of structure based on measurements

a) Case 1

The tensile stress of the reinforcing bar, compressive stress of the concrete, and occurrence of stress due to shear force are shown in Fig. 17 in relation to the stan-
A representative set of results for this analysis is given by the deformation mode of Case 1-1 and Case 1-3 shown in Fig. 18. Note that in Case 1-1, the maximum ratio of working stress to the standard value of tensile stress for the reinforcing bar is 60%, which provides a sufficient safety margin relative to the reference value (Fig. 17). In Case 1-3, this ratio increases to 70%, but this is still considered within an appropriate margin.

A comparison of the deformation between these two cases suggests that ASR was more critical than seismic load (Fig. 18).

b) Case 2

Figure 19 compares the seismic loads corresponding to yielding of the reinforcing bars, compressive fracture of the concrete and shear failure to the designed seismic

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Fig. 17 Results of analysis (Case 1: Analytical evaluation of structure based on measurements).

Fig. 18 Deformation (Case 1: Analytical evaluation of structure based on measurements).

Fig. 19 Results of analysis (Case 2: Analytical evaluation of structure based on measurements).
load. This reveals that the actual seismic load is within a suitable margin, being approximately 4.7 times of the designed load.

(2) Evaluation of structure with recommencing ASR

a) Case 1

An analysis similar to Case 1-3, where the ratio of the working stress to the standard value was maximum, was conducted based on an assumption of ASR recommencing using the measured conditions up to 2004 as a basis. The maximum ratio of the working stress to the standard value was found to increase in this case to 77%, but was still considered to provide a sufficient margin of safety.

b) Case 2

An analysis similar to Case 2-3, where member safety margin to seismic load was minimum, for the recommencement of ASR using the measured conditions up to 2004 found that the strength of the structure remained 4.4 times that of the gradually increasing seismic load, which was considered a sufficient margin.

5. Continuous monitoring

Continuous/additional monitoring for deformation in the TG foundation and of the compressive strength of its concrete has been used to verify that ASR has not recommenced after reaching a settled state of structural stability (Taniguchi et al. 2015). The column inclination has been measured along with any expansion of the table deck to determine deformation, while the concrete has been assessed by monitoring any cracking, its internal temperature and the strain in the reinforcing bars. This has verified that there has been no further development of ASR as of 2016, nor has there been any rupture of the reinforcing bars based on magnetic flux density measurements. Rebound hardness testing has also ascertained that there has been no major change in the compressive strength of the concrete.

5.1 Monitoring of deformation conditions

(1) Table deck expansion

The time-dependent behavior of the table deck expansion up until 2014 shown in Fig. 20 reveals that a gradual decrease in occurred in the expansion of both the sea and mountain side after about 2007. Following the cessation of operations in 2011, this decrease became much more pronounced, which is believed to be the result of the structure only being affected by the temperature of the atmosphere once heat generation in the steam pipe to the turbine stopped.

The expansion of unit between the benchmark distances of each section of the high- and low-pressure turbines and generator over time is shown in Fig. 21. Note that the unit expansion value used here represents the sum of the expansion values for each section divided by the set benchmark distance for each section. In the high-pressure turbine section, the internal temperature of the concrete during turbine operation in summer was
approximately 40°C on the sea side and approximately 45°C on the mountain side. These temperatures dropped by approximately 10°C during winter. A similar seasonal change was observed in other sections, but during regular inspection, the internal temperature was generally approximately 25°C all year. The positions at which the internal temperature was measured are shown in Fig. 22, while the time-dependent behavior of each section for a given temperature is shown in Fig. 23.

From the relationship between the table deck expansion (Fig. 21) and internal temperature of the concrete (Fig. 23), it is evident that the internal temperature on the sea side was lower (maximum temperature of approximately 40°C) than on the mountain side, and that the unit expansion of the mountain side was greater. As the unit expansion on the mountain side was highest in areas of low internal concrete temperature (maximum temperature was approximately 40°C), the temperature most conducive to promoting ASR is considered to be in the vicinity of 40°C. The shrinkage observed in the table deck axial direction can also be explained by a decrease in the internal temperature of the concrete after operations were stopped.

(2) Reinforcing bar strain

The strain in the reinforcing bars has been measured since 1986 using meters that were installed following cutting of the main reinforcement of the columns and beams, where the initial strain at the cut-off was introduced to the meter. The measurement points are shown in Fig. 24 and the time-dependent behavior of the main reinforcing bar (M-1) in the sea side of the high-pressure turbine section is shown in Fig. 25. We see from this that there was a downward trend in the reinforcing bar strain following a peak in the early 1990s, which is consistent with the change in expansion behavior between the benchmarks.

(3) Column inclination

The column inclination has been monitored since 2008...
by measuring the difference between the displacement of the table deck relative to the position of the column base (a difference in height of approximately 11 m) using pendulums situated at each corner of the TG foundation. The measurement points and starting displacement is shown in Fig. 26, and the time-dependent behavior of the table deck displacement along its axis is shown in Fig. 27. Note that prior to 2011, the displacement on the mountain side varied between 56 and 62 mm depending on temperature, while the sea side displacement was between 50 and 56 mm. Once operations ceased, however, this displacement decreased owing to the decrease in the internal temperature of the concrete.

5.2 Compressive strength of concrete
In order to determine the compressive strength of the concrete, rebound hardness has been measured since 2008 near the portion where concrete cores were taken from the TG foundation in 2002. These tests have verified that there has been no major change in this time (Fig. 28).

5.3 Reinforcing bar rupture
The possibility of reinforcing bar rupture by ASR was considered to be low in the TG foundation because of its indoor environment. However, as reinforcing bars of similar diameter have ruptured in outdoor structures, the magnetic flux density of the bars has been measured at the corners of the columns and beams of the TG foundation since 2015. This has been achieved using a magnetizing unit based on a permanent magnet, with rupture being determined by whether the peak magnetic flux density exceeds a predetermined value obtained through a series of experiments (Hirose et al. 2012). No rupture has been detected since measurements began, with an example of the peak value for the magnetic flux density measured in the TG foundation provided in Fig. 29.

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Fig. 26 Location of column inclination measurement and starting displacement.

Fig. 27 Trend of column inclination.

Fig. 28 Trend of rebound hardness.
6. Conclusion

This paper has presented an overview of the maintenance management method that has been applied to the TG foundation of Unit #1 at the Ikata nuclear power plant ever since concrete cracks caused by ASR were first identified. This approach has included an evaluation of both the current and long-term soundness, and can be applied to other structures affected by ASR. The main conclusions drawn from this are as follows:

- The continued use of a structure subject to ASR is dependent on defining its required function and evaluating its current and long-term soundness. In the case of the TG foundation in this study, no problems were found in its ability to provide a support function because there was no induced vibration that might affect its operation.

- Outdoor structures such as piers and bridge abutments are more susceptible to ASR, as the surface of their concrete is more readily exposed to moisture and alkali, whereas the architectural structures are protected. However, the movement of water held within a concrete structure, and the heat generated within the structure, can affect the likelihood of ASR. There is therefore still a need to clarify the relationship between deformation caused by ASR and the surrounding environment in terms of the temperature, humidity, invasion of moisture, and others because these are not clarify.

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Fig. 29 Peak value of magnetic flux density distribution (example).
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