INVESTIGATION OF SAFETY MARGIN FOR TURBINE GENERATOR FOUNDATION AFFECTED BY ALKALI-SILICA REACTION BASED ON NON-LINEAR STRUCTURAL ANALYSIS

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ABSTRACT
A turbine generator foundation is a reinforced concrete structure having a table deck and columns to support equipments. After operation of the plant, the expansion of the table deck in turbine longitudinal axis has been observed. By investigation of concrete material properties, it was found that the expansion has been caused by alkali-silica reaction. This study has been performed to evaluate the safety allowance of strength capacity of the turbine generator foundation by nonlinear analysis using beam element model with elongation, rebar strain and material properties data which have been measured for almost 30 years in actual foundation.

Keywords: Alkali-silica reaction, Turbine generator foundation, In-situ tests, Non-linear analysis, Safety allowance of strength capacity

1. INTRODUCTION
A turbine generator foundation (TG foundation) is a reinforced concrete structure having a table deck and columns to support equipments. The structure has been designed to sustain dead load, operating load of machines and seismic loads.

After operation of the plant, the expansion of the table deck in turbine longitudinal axis has been observed. By investigation of concrete material properties, it was found that the expansion has been caused by alkali-silica reaction (ASR).

By the continuous observation of the actual TG foundation, it was found that the expansion was limited to the area of table deck portion and was steady for last 10 years and maximum elongation value of the expansion was around 1000 μ.

This study has been performed to evaluate the safety allowance of strength capacity of the ASR structure by nonlinear analysis using beam element model with elongation, rebar strain and material properties data which have been measured for almost 30 years in actual foundation.
2. ANALYTICAL METHOD

The analysis is a static analysis using multi purpose structural analysis computer code ABAQUS which can treat the expansion of the concrete due to ASR as one due to temperature rise and handle the nonlinear properties of the material.

2.1 Modeling

The three dimensional frame model with beam elements indicated in Fig.1 was adopted to analyze the TG foundation by the points of following view,

① To consider the difference of the elongations between sea side and mountain side of the table deck and consider nonsymmetrical mechanical loads,

② To model over all TG foundation structure in order to evaluate the stresses of columns and intermediate beams properly.

The beam element indicated in Fig.2, to which the material properties of concrete and rebar could be assigned individually, has been also used to simulate the stress states of the reinforced concrete due to the expansion by ASR.

2.2 Material properties

Following concrete material properties from the investigation of the core specimens taken from the actual foundation were used in the analysis.

- Sound area: Fc: 30.4 N/mm²  
  Ec: 2.49x10⁴N/mm²
- ASR area: Fc: 28.8N/mm²  
  Ec: 1.67x10⁴N/mm²

The material properties of rebar of σy: 409N/mm², Es: 2.04x10⁵N/mm² were used based on the data obtained from tensile tests of the rebar taken from the actual foundation.

The stress-strain curve of the concrete and the rebar used in the analysis are as indicated in Fig.3.

2.3 Loads and Load combination

Dead load, operating load (placement load, equipment load, and so on), seismic loads and short circuit load have been considered for this study.

And the expansion due to ASR in the axis direction of table deck was determined, as indicated in Fig.4, 50mm for sea side and 34mm for mountain side including thermal expansion (10mm) based on the continuous observation. The expansion in the perpendicular direction was assumed to be 6.7mm for generator side and 9.7mm for turbine side considering that the strain (840μ) equivalent to the average elongation (42mm) in the axis direction should also occur in the perpendicular direction.

Fig.1 Analytical model
2.4 Evaluation methods

For performing the evaluation of safety allowance of strength capacity of the structure, the material strengths of rebar and concrete assured by the tests were considered to determine the referenced values for the allowance evaluation (the standard value for allowance evaluation).

Following values were adopted as each standard value for allowance evaluation.

• Rebar and concrete
  - Rebar: Yield Strength (409N/mm²) 
    (The result of sampling tests of tensile strength)
  - Concrete: Compressive Strength
    - ASR portion: 28.8 N/mm²
    - Sound concrete: 30.4 N/mm² 
    (The results of core specimens taken from the actual foundation)

• Evaluation of shear strength
  For the calculation of shear strength capacity, the Ono • Arakawa lower bound equation, which is an original equation used to establish a design equation adopted in the standard of the Architectural Institute of Japan and by which shear strength capacity could be evaluated in safer side, has been used.

In the evaluation of shear strength capacity affection of twisting moment was considered by following equation.

\[
\left(\frac{Q}{Q_0}\right)^2 + \left(\frac{T}{T_0}\right)^2 \leq 1
\]

where

- Q: Working shear force
- Q₀: shear strength capacity
- T: Working twisting moment
- T₀: Twisting moment capacity

3. RESULT OF THE ANALYSIS

3.1 Analytical conditions

The list of analytical conditions to evaluate the safety allowance of strength capacity is indicated in Table 1.

In the case 1 the analyses of the conditions under normal operation with 
1. Step 1: dead load + operating load and 
2. Step 2: expansion of the table deck, and adding to these load with 
3. Step 3: seismic load (design level) or 
4. load due to short circuit torque have been performed to assure stress states under design level loads.

In the case 2 the allowance capacity for seismic load has been evaluated by performing the analyses for gradually increasing seismic loads. The seismic loads for the evaluation of the safety allowance are considered simultaneously in vertical direction and horizontal direction.
Table 1  List of analytical conditions

<table>
<thead>
<tr>
<th>Case No. of analysis</th>
<th>Case1</th>
<th>Case2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>1-2</td>
<td>1-3</td>
</tr>
<tr>
<td>① dead + operating loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>② expansion of TD</td>
<td>X + Z direction</td>
<td></td>
</tr>
<tr>
<td>③ seismic load (static)</td>
<td>X Direction (Axial direction)</td>
<td>Plus</td>
</tr>
<tr>
<td></td>
<td>Minus</td>
<td>—</td>
</tr>
<tr>
<td>④ Z direction (Perpendicular to axis direction)</td>
<td>Plus</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Minus</td>
<td>—</td>
</tr>
<tr>
<td>⑤ Y direction (vertical direction)</td>
<td>upper</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>lower</td>
<td>—</td>
</tr>
<tr>
<td>⑥ short circuit torque</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*1 TD: Table Deck  
*2 Sc: seismic load equivalent to design level  
*3 T: short circuit torque

3.2 Result of the analysis

(1) Case 1

The results of each analytical case are shown in Fig.5. The figure shows ratios of working stress to the standard value for allowance evaluation as mentioned in 2.4. As major results of analytical cases, figures of deformation of step 2 of case 1-1 and case 1-3, crack propagation of step 2 of case 1-1 and member force distribution of step 2 of case 1-1 are shown in Fig.6.

By those figures followings are understood.
- In case 1-1 the maximum values are calculated at the intermediate beam (1G2A) for tensile stress of rebar, at the table deck (2G2A) for compressive stress of concrete and at A2 column top for shear stress. However those stresses have enough allowance to the standard values for allowance evaluation.
- In case 1-3 the maximum stresses are occurred at same locations to the case 1-1 and the value of tensile stress of rebar at intermediate beam (1G2A) is approximately 70% of the standard value for allowance evaluation.
- As understood by comparing the deformation between the case 1-1 and the case 1-3, ASR is more critical than seismic load for the structure.
- In Case 1-6 working stress are smaller than the above seismic cases and there are enough allowance to the standard value for allowance evaluation.

As a result of the evaluation mentioned above, followings are confirmed for the stress state under the loads equivalent to the design condition.
① The ratio of the maximum stress to the standard value for allowance evaluation is approximately 70%.
② The cause to induce critical stress is expansion due to ASR at the table deck.

(2) Case 2

As a list showing the result of each analytical case, the ratio of rebar yielding load, concrete compressive fracture load and shear fracture load under seismic loads gradually increased to design loads are indicated in Fig.7. As a representing data of the analysis result, the relation between calculated displacement and seismic loads of the case 2-3 is indicated in Fig.8.

By those figures followings are understood.
Fig. 6-1 Deformation

Case 1-1 (Step 2: ASR Expansion)

Case 1-3 (Step 3: ASR + seismic load)

Fig. 6-2 Crack Propagation (Case 1-1 (Step 2))

Fig. 6-3 Stress • Deformation • Moment • Shear Force
As understood by the relation of the ratio of applied seismic load to design seismic load and displacement, shear failure of the intermediate beam 1G2A at 4.7 times of the design seismic load, rebar yielding of the column B1 EL4.2m at 5.8 times, concrete compressive failure of the column B1 EL4.2m at 6.8 times have been occurred progressively. The similar progressive failure has been observed in other cases.

By the application of seismic load in the horizontal direction (+), \(\sigma_y\) of sea side E2 column EL 4.2 m reached at approximately 5 times of the design seismic load. By the application in the horizontal direction (-), \(Q_u\) of sea side intermediate beam (1G2A) reached at approximately 4.7 times of the design seismic load. Also it was found that the influence by vertical seismic load is insignificant.

As a result of the calculations it has been found that the minimum allowance capacity to the seismic load is approximately 4.7 times of design seismic load.

4. CONCLUSION
The safety allowance of TG foundation affected by ASR has been studied using analytical methods. As a result it was assured that there was enough allowance for design condition and seismic load beyond the design condition.