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VIBRATION MEASUREMENT AND SIMULATION ANALYSIS ON A REINFORCED CONCRETE STRUCTURE WITH ALKALI-SILICA REACTION

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ABSTRACT

This paper discusses vibration test and measurement of elastic wave velocity, and simulation analyses on the vibration test concerning the turbine generator foundation of the Ikata nuclear power station unit #1, Japan, where expansion produced by alkali-silica reaction (ASR) has been observed.

Under the vibration test, vertical excitation test of the beams and microtremor measurement were conducted to estimate eigen frequency/mode and examine time-dependent change of the stiffness of the foundation by comparing with the results in the previous test done in the same way. Elastic wave velocity was measured to observe the difference of material properties among places of the foundation. Simulation analyses on the vibration test were done to estimate the elastic modulus of the members where ASR is induced.

We obtained the following conclusions: (1) The time-dependant change of the stiffness and ASR have very low effect on the entire structure of the unit #1 (2) It is estimated that ASR has not developed since 1989 because the reduction of the eigen frequencies of the foundation is small. (3) The reduction of the elastic modulus of the table-deck stands out by comparison of the elastic modulus of the unit #1 and #2 from the measurement of elastic wave velocity. (4) The elastic modulus ratio of the members with ASR to the members without ASR is estimated from 0.5 to 0.6 by the simulation analyses.

Keywords: alkali-silica reaction, elastic modulus, vibration measurement, simulation analysis

1. INTRODUCTION

Expansion produced by alkali-silica reaction (ASR), has been observed in the turbine generator foundation of the Ikata nuclear power station unit #1, Japan. It is a PWR station whose commencement of commercial operation was in 1977. The foundation is a reinforced concrete structure supporting turbines and generator. A series of investigations and experiments has been carried out to verify the structural reliability of the foundation, which has length of 50 m, width of 15 m, and height of 18.7 m. The purpose of this study is to observe time-dependent change of the stiffness of the foundation and to estimate the present elastic modulus of the concrete of the members where ASR is induced.

Vibration test, measurement of elastic wave velocity, and simulation analyses on the vibration test were done on the foundation of the unit #1, where the ASR was found. The same test, measurement, and analysis were done also on the foundation of the unit #2 that has the same structure and dimension as the unit #1 for comparison, though it has not shown indication of ASR such as hair crack.

Under the vibration test, eigen frequency/mode was investigated and the test results were compared, to study variations in years, with the results of previous tests done in a similar way. Velocity of elastic wave was measured, with logging method and transmission method, on the foundation of the unit #1 and #2, to study the difference of material properties among places of the foundation. Simulation analyses on the eigen frequency/mode obtained from the vibration test were done to estimate constraint with surrounding structures and the elastic modulus of the foundation.

2. VIBRATION TEST

2.1 PURPOSE

The vibration tests were conducted during periodic inspection to investigate eigen frequency/mode of the foundation of the unite #1 and unit #2. Table 1 indicates the vibration tests performed after the completion.

Table 1 Vibration tests performed after completion

	unit #1			unit #2
No. of times	1	2	3	1
Time	Jan., 1986	Jun., 1989	Feb., 1993	Apr., 1991
Condition	Normal Operation	Suspension	Normal Operation	Suspension
Purpose	Investigate the influence to the foundation of the unit #1, #2 of blasting vibration by the construction of the unit #3 and obtain data concerning stable operation of generator.	Estimate time-dependant change from the variation of vibration characteristics	Obtain data to investigate the cause which makes more vibration amplitude on the side of mountain	Investigate initial value in time-dependant change and compare the results of the unit #1
Content	Vibration measurement under normal operation	Microtremor measurement Vertical excitation test of beam Vibration measurement on startup	Vibration measurement under normal operation	Microtremor measurement

2.2 VERTICAL EXCITATION TEST OF BEAM

2.2.1 PROCEDURE

The sweep excitation test by an electromotive exciter (maximum excitation force: 4900N) was conducted to investigate vertical eigen frequency/mode of the beams of the foundation.

The excitation and measurement were done at each of five beams on the table-deck and on the first floor of both the unit #1 and unit #2. Figure 1 shows an example of them. The frequency range of excitation and measurement was from 5 to 128Hz out of consideration of the test results in 1989 and the target of excitation force was 880N.

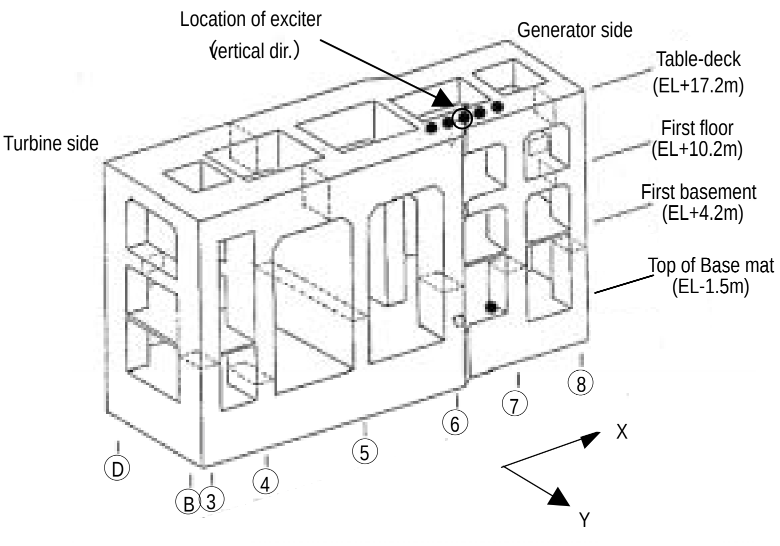
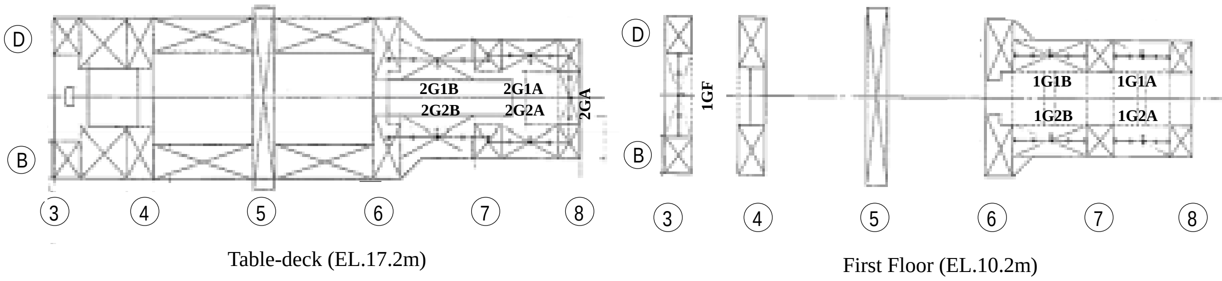


Fig.1 Location of exciter and measurement points at the unit #1



NOTE: The texts such as 2GA represent names of the beams

Fig.2 Location of the beams where the test was conducted at the unit #1

Vibration sensors were set at 5 places on the beam and 2 places on the top of base mat (or the first basement level) and at the vibrator so that the acceleration at each place was measured. Figure 2 shows the location of the beams where the test was conducted at the unit #1.

2.2.2 TEST RESULTS

The modal analysis was conducted using the transfer functions measured at 7 places (5 places on a beam and 2 places on the base mat or the first basement level) to the excitation force so that eigen frequency/mode was estimated. Figure 3 shows the results in the center point on the beam 2GA as an example of curve fitting in the modal analysis. We chose eigen frequency on the following condition: (1) It is the minimum frequency where phase lag is about $\pi/2$ in the transfer function to excitation force. (2) It is the frequency where the amplitude of vibration in the center of a beam has clear peak and the entire beam vibrates in the first mode.

Table 2 shows the comparison of the natural frequency estimated in this test and the previous test and Fig. 4 shows an example of the vibration modes obtained by the modal analysis. The eigen frequencies of the unit #1 are 0.88 – 095 times compared with those of the unit #2 and the average of the unit #1 is 10 % lower than that of unit #2. This reduction of the eigen frequency includes the difference by the effect of relative density of the concrete. Because the stiffness as well as the mass of a concrete structure depends on relative density and the relative density of the concrete of the unit #1 is 5% lower than that of the unit #2. The difference between the unit #1 and #2 is estimated 3% according to AIJ standard calculation of reinforced concrete structures. Assuming that the unit #1 foundation equated with the unit #2 foundation structurally and the unit #2 foundation is in sound state (without ASR), it is likely that the reduction (about 7%) of the eigen frequency results from time-dependant change of the stiffness or ASR. The beams on the table-deck have more reduction in the frequency than those on the first floor. This cause is estimated to be the difference of the degree of ASR.

Table 2 Eigen frequency of each beam obtained by modal analysis

unit Hz (ratio)

story	direction of beam	name of beam	unit #1 1989	unit #1 2003	unit #2 2003
table-deck	, w	2G1A	-	24.36 (0.92)	26.42 (1.00)
		2G1B	-	28.00 (0.88)	31.87 (1.00)
		2G2A	-	24.31 (0.93)	26.05 (1.00)
		2G2B	30.08 (0.93)	28.59 (0.89)	32.20 (1.00)
	, x	2GA	33.84 (0.96)	32.65 (0.93)	35.19 (1.00)
first floor	, w	1G1A	58.03 (0.97)	55.32 (0.93)	59.57 (1.00)
		1G1B	39.63 (0.96)	37.70 (0.91)	41.34 (1.00)
		1G2A	49.11 (0.92)	48.93 (0.91)	53.51 (1.00)
		1G2B	39.69 (0.94)	38.60 (0.92)	42.04 (1.00)
	, x	1GF	46.39 (0.95)	46.06 (0.95)	48.68 (1.00)

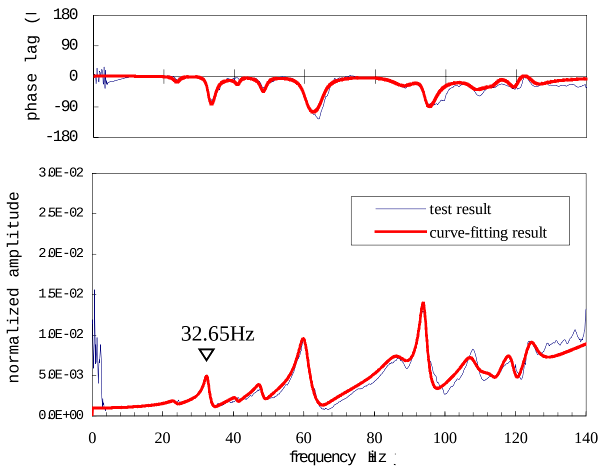


Fig.3 Curve fitting of transfer function of the beam 2GA at the unit #1

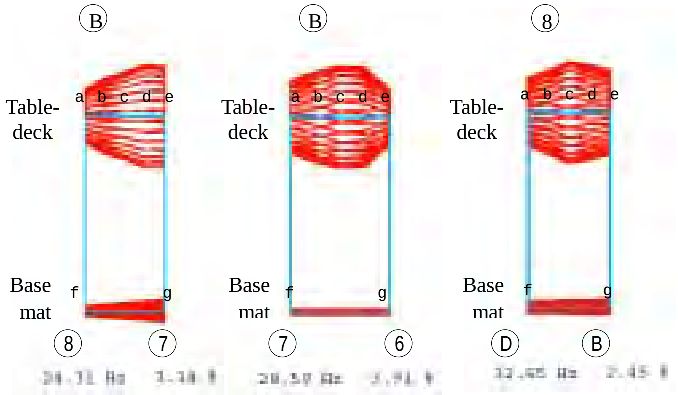


Fig.4 Mode shape of each beam on table-deck at the unit #1

2.3 MICROTREMOR MEASUREMENT

2.3.1 PROCEDURE

Microtremor measurement was conducted to investigate eigen frequency/mode of sway and rocking vibration of the entire foundation. Five sets of microtremor measurements were done for the unit #1 and #2, where each set consisted of simultaneous measurements at 12 places. Three sets were for measurements in three directions on the table deck; the other two sets were for measurements on sway and rocking vibration. The simultaneous measurement of displacement was done during 25 minutes on each case on and after 17 o'clock, when it was in relatively calm state. Figure 5 shows the measurement points of the microtremor at the unit #1.

2.3.2 MEASUREMENT RESULTS

Fig.6 shows the maximum displacement distribution on the generator side at the unit #1. According to the figure, the displacement distribution is the first mode shape, in which the higher floor has more amplitude, however the amplification of displacement between the base mat and the first basement level is small. The same results are obtained in the X-direction and the Y-direction in each unit. Though the foundation and the surrounding structures are separated structurally on the first floor and the table-deck level, the slab on the first basement level is continued between them and the concrete structure contacts partially under the slab. It suggests that the constraint on the first basement level (EL. 4.2m) is the effect of the surrounding structures in the case of the vibration amplitude level of microtremor.

The modal analysis using the transfer functions on the basis of the measurement point on the base mat was conducted to evaluate eigen frequency/mode and damping factor. Table 3 shows the eigen frequencies of the foundation evaluated by the modal analysis, compared with the results in the previous test. For the unit # 2, the ratios of the eigen frequencies in 1991 to those in 2003 are about 1.0 in the X-direction and the Y-direction on the generator side and the turbine side except the result in the Y-direction on the turbine side. It suggests approximately no variations in the eigen frequency in the unit #2 foundation.

On the basis of the result in 2003 of the unit #2 foundation, the frequency ratios are form 0.81 to 0.95 and there is more reduction in the Y-direction on the turbine side. The reduction of the frequency by the ASR is estimated to be from 2.5% to 8.5% in the consideration that the effect of the relative density of the concrete is reduction of frequency of 3%. The horizontal vibration mode of the foundation showed in Fig.7 also has the constraint on the level of EL.4.2m as is the case of the maximum displacement distribution.

2.4 SUMMARY OF VIBRATION TEST

The reduction of the eigen frequency of the unit # 1 is less than 10% compared with that of the unit #2. Consequently the effect of the ASR and the time-dependant change of the eigen frequency on the vibration characteristics of the entire foundation is estimated small. The result of the vibration test also suggests that there is no time-dependant change and development of the ASR as the reduction of the frequency in the duration of 14 years, from 1989 to 2003, is small.

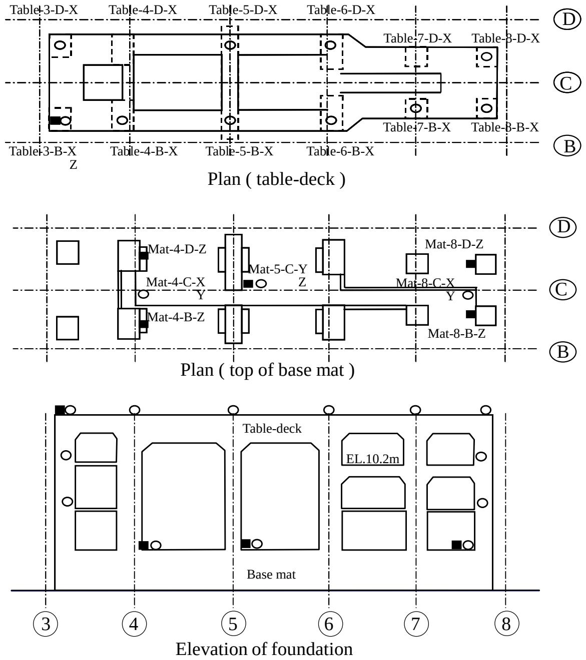


Fig.5 Measurement points of microtremor at the unit #1

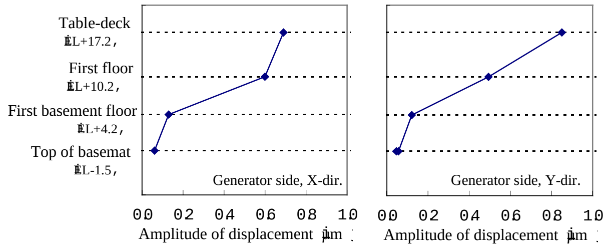
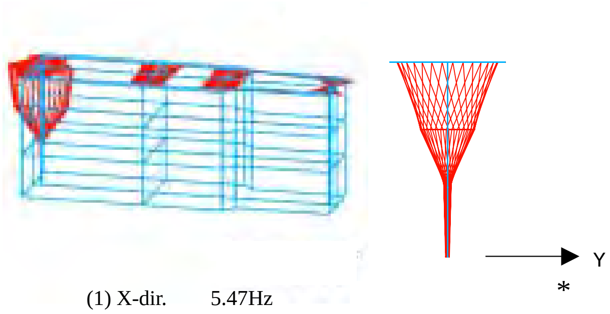


Fig.6 Maximum displacement distribution on generator side at the unit #1

Table 3 Eigen frequency obtained by modal analysis of microtremor

unit Hz (ratio)

Dir.	Location	unit #1		unit #2	
		1989	2003	1991	2003
, w	generator side	5.45 (0.93)	5.26 (0.90)	5.71 (0.98)	5.83 (1.00)
	turbine side	5.28 (0.91)	5.47 (0.94)	5.71 (0.98)	5.83 (1.00)
, x	generator side	7.11 (0.88)	7.61 (0.95)	8.14 (1.01)	8.05 (1.00)
	turbine side	7.95 (0.81)	8.65 (0.89)	8.86 (0.91)	9.77 (1.00)



*: The figure (2) shows the mode which was estimated from only the data of measurement points in the turbine side, because a good curve-fitting was not obtained from the data of the entire structure. The frequency indicates what is estimated from the data of the entire structure.

Fig.7 Mode shape obtained by modal analysis of microtremor (unit #1)

3. MEASUREMENT OF ELASTIC WAVE VELOCITY

3.1 PURPOSE

Velocity of elastic wave was measured on the foundation of the unit #1 and #2, so that the difference of material properties among places of the foundation was investigated. The surface condition of the concrete-cores taken in the measurement also was examined.

3.2 MEASUREMENT PROCEDURE

Measurement was done, with logging method and transmission method. Figure 8 shows the illustration of the measurement.

Logging method: a drill hole, which diameter is 65mm, is bored in the concrete, the velocity of elastic wave, which was generated at the surface near the drill hole by a hit of a hammer, was calculated from the measurement with acceleration sensors set in the hole.

Transmission method: acceleration sensors were set on the surface opposite from the side where elastic wave was generated by a hit of a hammer, so that the wave velocity could be calculated from the arrival time of the wave and the thickness of the concrete member.

In the unit #2, the measurements, both the logging and transmission method, were conducted at five points. In the unit #1 the logging method and the transmission method were done at five points (No.1 - No.5) and the transmission method were done only at seven points (No.6 - No.12). Figure 9 shows the measurement points in the unit #1.

3.3 MEASUREMENT RESULTS

Fig.10 shows the measurement results of the unit #1 with those of the unit #2. The elastic moduli obtained by the logging method (No.2 - No.4) in the unit #1 and #2 are approximately close value. The ones obtained in the unit #1 and #2 by the transmission method (No.7 - No.12) are also close. However, the elastic modulus of No.1 point by the logging method and No.1, No.6 points by the transmission method, which are located in the table-deck at the unit #1, is more reduced value than those of the other points.

3.4 OBSERVATION OF CONCRETE-CORE

Figure 11 shows the results obtained from the observation of surface condition of the concrete-core taken in the measurement points of from No.1 to No.5. The results are summarized as follows:

The gelatinous substance was observed in the surface of the No.1 core

The results of observational classification of the aggregates in the cross section suggest the indication of ASR in all cores (from No.1 to No.5) is confirmed, however the rate of deterioration of the aggregates in No.1 point is remarkable and the aggregate in the cores taken under the table-deck has low rate of deterioration or damage.

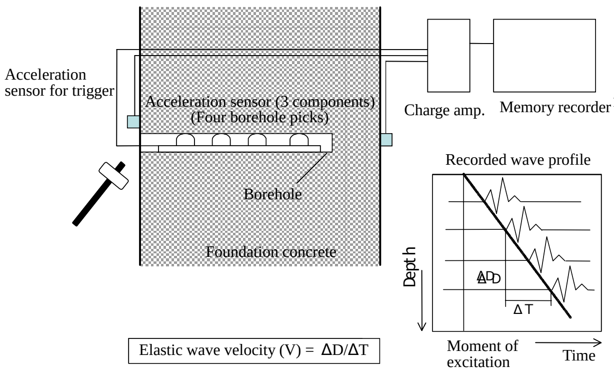


Fig.8 Illustration of measurement of elastic wave velocity

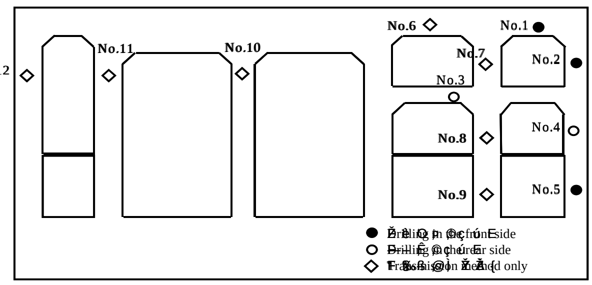


Fig.9 Measurement points at the unit #1

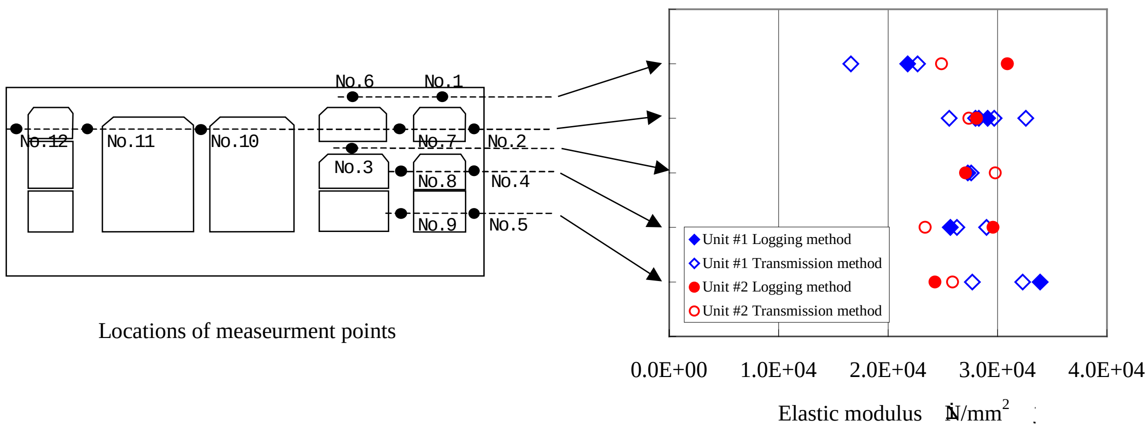
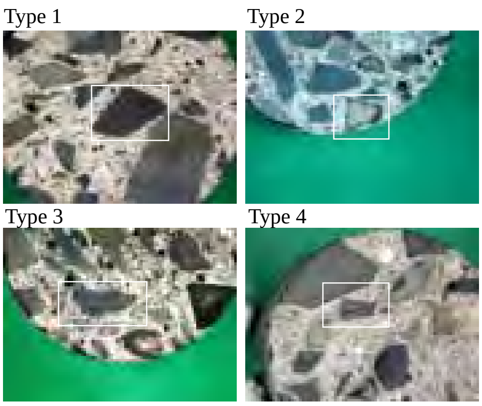


Fig.10 Evaluation result of elastic modulus

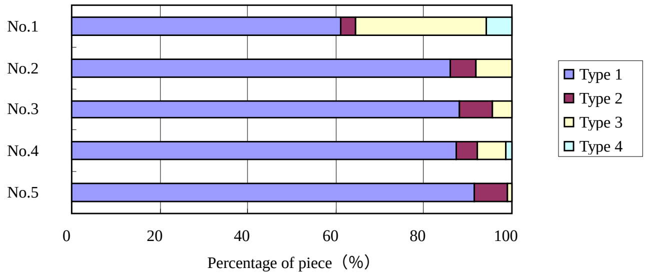
3.5 SUMMARY OF MEASUREMENT

The results of the measurement of elastic wave velocity and the observation of aggregates of the cores taken suggests the reduction of the elastic modulus in the table-deck of the unit #1 is outstanding, however the reduction of that in the part under the table-deck is small.

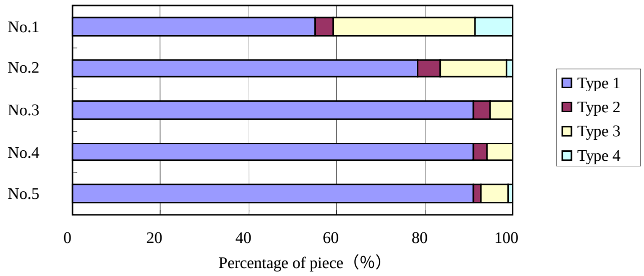
Observational classification
Type 1: no variation
Type 2: reactive rim (black fringe of aggregate) is observed
Type 3: crack is observed
Type 4: both reactive rim and crack are observed
(type 2 + type 3)



(a) Observational classification



(b) Observation result of the cores taken from the surface part of the member



(c) Observation result of the cores taken from the interior part the member

Fig.11 Observation result of the cores taken from the foundation

4. SIMULATION ANALYSIS ON VIBRATION TEST

4.1 PURPOSE

Simulation analysis on the eigen frequency/mode of the vibration test was done to estimate elastic modulus of the concrete members that the foundation consists of.

4.2 ANALYSIS MODEL

Three-dimensional FEM model was used to evaluate three-dimensional behavior, e.g. torsion. The model was made with beam and shell elements modeling column, beam, wall, slab in the extent of the top of the base mat (EL.-1.5m) to the table-deck (EL.17.2m). Each member was divided into several FEM elements in the consideration of the measurement points on the vibration test. Figure 12 shows the model used in the simulation analysis. The following values were used as the material properties of the reinforced concrete except elastic modulus. The relative density of reinforced concrete was determined by the cores taken in the measurement of elastic wave velocity.

Poisson's ratio: 0.2
Relative density of reinforced concrete: 23.1kN/m^3 (unit #1), 24.4kN/m^3 (unit #2)

4.3 EFFECT OF CONSTRAINT BY SURROUNDING STRUCTURES AT EL.4.2M

The foundation and the surrounding structures contacts partially at and under EL.4.2m and the mode, in which the displacement of the foundation is constrained at EL.4.2m, is obtained by the modal analysis on the microtremor measurement. Consequently, it is examined which boundary condition (No constraint, spring support, pinned support showed in Fig. 13) simulates the results of the vibration test best to investigate the degree of the constraint. This investigation was done for the unit #2 without ASR. Table 4 shows the results of eigen-value analysis on the three boundary conditions. The estimated elastic modulus in the table indicates the elastic modulus, by which the eigen-frequency of the analysis model agrees with the frequency of the vibration test. Fig.14 shows the detailed comparison of the normalized displacement distribution on the generator and turbine side in reference of the first mode shape (the X-direction mode)

The following is obtained from the figures and the table:

The estimated elastic modulus is remarkably large value in the case of no constraint.

Compared with the result of spring support and pinned support, the case of the spring support approximates the results of the vibration test better than that of the pinned support does.

We decided to use the spring support as the boundary condition at EL.4.2m on the ground of the above fact.

4.4 SIMULATION ANALYSIS ON VIBRATION TEST

4.4.1 SIMULATION ANALYSIS ON VERTICAL EXCITATION TEST

Stationary excitation analysis was conducted to estimate the elastic modulus, by which the analysis model simulates the eigen frequency, the vibration mode, the transfer function in the center of the beam of the vibration test. In the analysis of the unit #2, elastic modulus is evaluated giving a uniform value in the entire structure in each excitation case individually. The result that the elastic modulus in the table-deck is reduced outstandingly is obtained in the measurement of elastic wave velocity. Consequently it is assumed that ASR is induced in the members in the table-deck. In the analysis of the unit #1, elastic modulus is evaluated giving 0.5 (case 1), 0.8 (case 2) and 1.0 (case 3) as the ratio of elastic modulus of a member with ASR to a member without ASR in each excitation case individually. These values are determined according to the reference [1]〜[3].

Figure 16 shows the result of Beam 2G1A, case 1 as an example of stationary excitation analysis using the elastic modulus, which is adjusted so that eigen frequency in the analysis model agrees with that in the vibration test. The transfer functions by the analysis model and the vibration test agreed approximately including the peaks other than the eigen frequency which is adjusted till 50 Hz. Figure 17 shows the elastic modulus estimated in each case with the results of the section 4.4.2.

4.4.2 SIMULATION ANALYSIS ON MICROTREMOR MEASUREMENT

Eigen-value analysis was conducted to estimate elastic modulus, by which analysis model simulates the eigen frequency, the vibration mode of the vibration test. In the analysis of the unit #2, elastic modulus is evaluated giving a uniform value to the entire foundation in each excitation case individually. In the analysis of the unit #1, the same cases as the vertical excited test were examined.

Table 4 shows the mode shapes of the first mode, case 1 as an example of eigen-value analysis using the elastic modulus, which is adjusted so that the eigen frequency of the analysis model agrees with that of the microtremor measurement. In the modal analysis on the microtremor measurement, 3 blocks of records, which were recorded in different time, were treated to be recorded simultaneously. It is likely that a good curve-fitting was not obtained in the case of the unit #1 because of that. Consequently the elastic modulus was adjusted to focus on the behavior of the table-deck.

The modes shape in the analysis model and the measurement agree approximately. Figure 17 shows the estimated elastic modulus in each case with the results of the section 4.4.1.

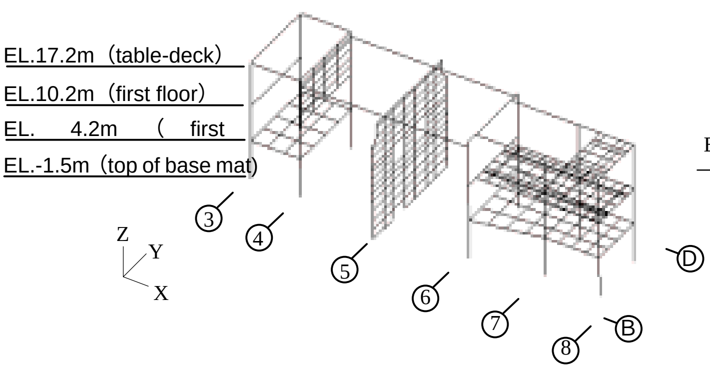


Fig.12 Analysis model (unit #1)

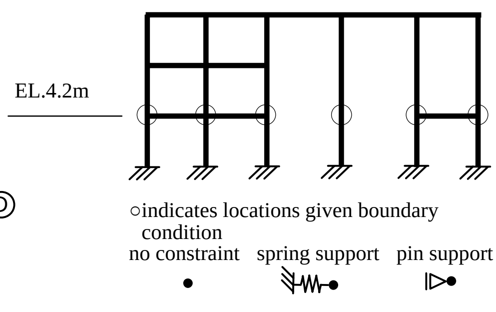
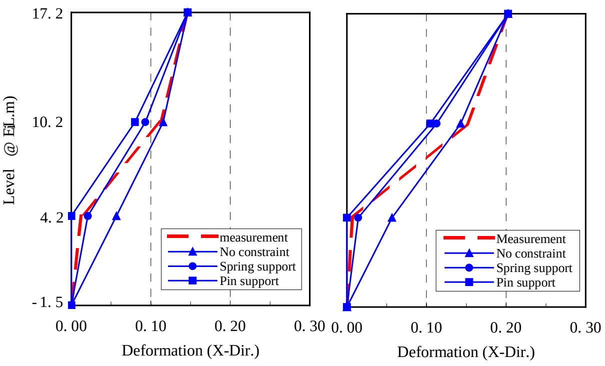


Fig.13 Boundary conditions

Table 4 Results of eigen value analysis

Boundary condition	No constraint		Spring support		Pin support	
Order	Eigen freq. (Hz)	Estimated elastic modulus (N/mm^2)	Eigen freq. (Hz)	Estimated elastic modulus (N/mm^2)	Eigen freq. (Hz)	Estimated elastic modulus (N/mm^2)
1	3.86	5.17E+04	5.30	2.75E+04	5.94	2.19E+04
2	5.58	4.72E+04	7.44	2.66E+04	8.16	2.21E+04
3	7.07	4.33E+04	8.65	2.89E+04	9.68	2.31E+04



(a) generator side (b) turbine side

Fig.14 Comparison of mode shapes

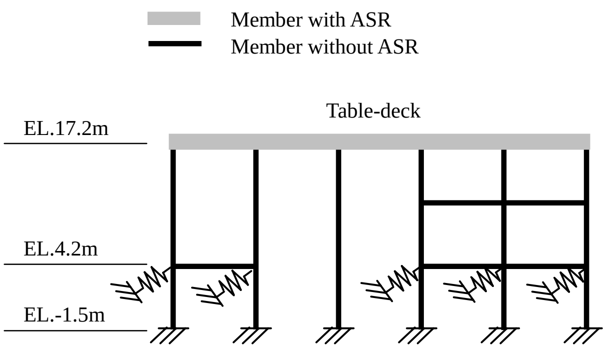


Fig.15 Assumption of members with ASR

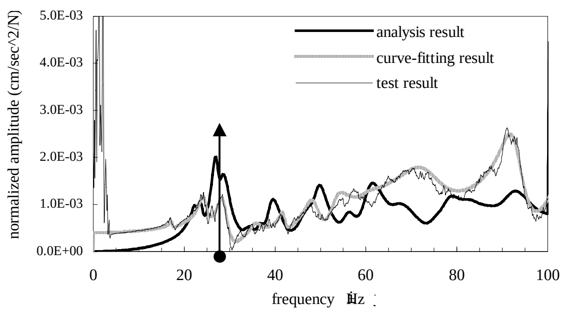
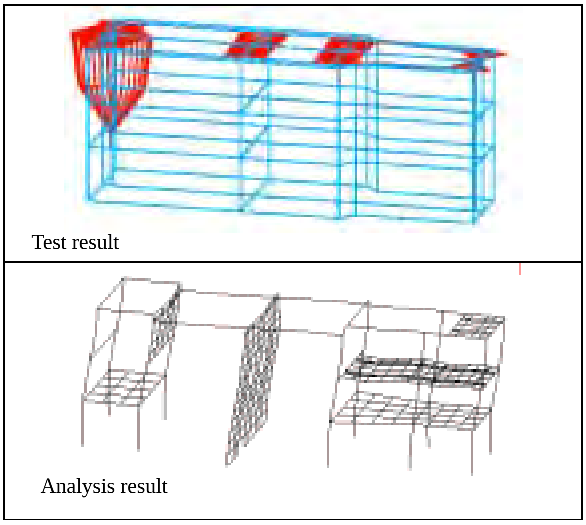


Fig.16 Comparison of transfer functions (beam 2G2B, case 1)

Table 5 Comparison of mode shapes (1st mode, case 1)



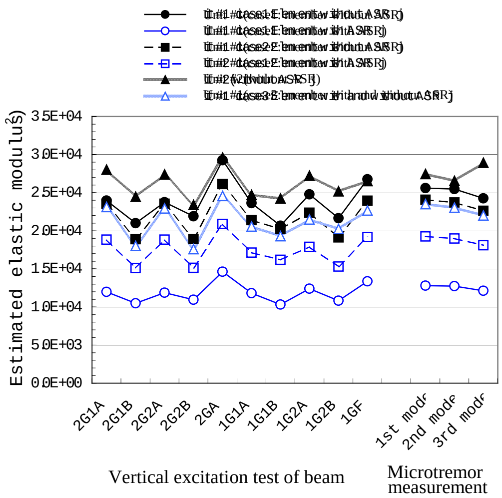


Fig.17 Estimated elastic modulus

4.5 SUMMARY ON SIMULATION ANALYSIS

Figure 18 shows the relationship of the ratio of elastic modulus of the member with ASR to that of the member without ASR and the ratio of elastic modulus of the unit #1 (the member with ASR and the member without ASR) to that of unit #2 with respect to the entire average of the elastic modulus estimated in the section 4.4.1 and 4.4.2.

The ratio of the elastic modulus of the unit #1 to the unit #2 is 0.9 in calculating it according to AIJ Standard for RC using the relative density of the concrete cores taken. The ratio of the element with the ASR to the element without the ASR is estimated to be from 0.5 to 0.6 if this value is applied to Fig.18.

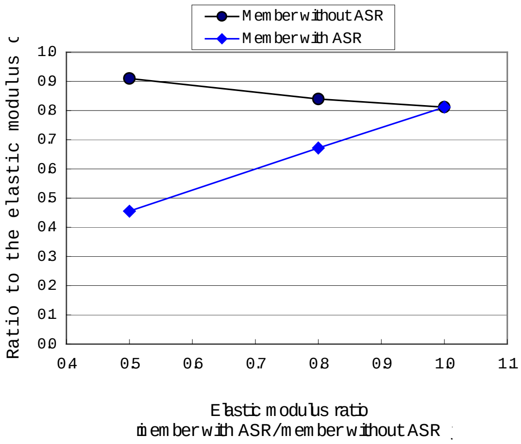


Fig.18 Summary of elastic modulus estimated by parametric study

5. CONCLUSIONS

We carried out the vibration test, the measurement of elastic wave velocity and the simulation analysis on the turbine generator foundations of the unit #1 and #2. We obtained the following conclusions:

Vibration test

(1) Constraint with the surroundings structures of the foundation was estimated on the eigen mode obtained from the vibration test

(2) The time-dependant change of the stiffness and the ASR have very low effect on the entire structure of the unit #1, though the eigen frequencies of the unit #1 declined compared with those of the unit #2 without ASR. It was estimated that the ASR has not developed since 1989 because the reduction of the eigen frequencies of the foundation is small.

Measurement of elastic wave velocity

(3) It is confirmed that the reduction of the elastic modulus of the table-deck stands out by comparison of the elastic modulus of the unit #1 and the unit #2 foundation and the reduction in the other parts is small.

Simulation analysis on the vibration test

(4) The simulation results approximate the test results in the case where spring support is used as the boundary condition at EL. 4.2m.

(5) The elastic modulus ratio of the members with ASR to the members without ASR is estimated from 0.5 to 0.6 by the simulation analysis.

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