SEISMIC RESPONSE ANALYSIS OF NUCLEAR REACTOR BUILDINGS UNDER CONSIDERATION OF SOIL-STRUCTURE INTERACTION WITH TORSIONAL BEHAVIOUR

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SUMMARY

This paper is the further report of the previous SMIRT-3 Paper K 3/2 in which an approximate explanation is presented in regard to the experimental and analytical studies of No. 1 reactor building (BWR) of Hamaoka Nuclear Power Station. In this paper, the seismic response analysis is described in detail for estimating the soil-structure interaction effects with the torsional behaviour.

The analytical method is firstly shown for estimating the stiffness of reactor building by the bending-shear and torsion theory of the thin wall sections in regard to the behaviour of structure. The three-dimensional behaviour of structure can be obtained more briefly and simply by the proposed method.

Secondly, the dynamical soil-foundation coefficient for estimating the dissipation of vibrational energy on the ground is derived by H. Tajimi's theory which is based on a solution of the propagation of seismic waves caused by point excitation on the surface of the elastic half-space medium. The above results give the vibrational impedances of the soil-foundation corresponding to the static soil coefficient, which is defined to the excitation force in the frequency domain.

In order to analyze to the equivalues of reactor building, the authors thirdly attempt to approximate the dynamic soil-foundation coefficient as the frequency transfer function of displacement. The complex damping is used for more suitably estimating the elastic structural damping effects of structure.

The regression analysis of many degrees of freedom is fourthly attempted for estimating the natural periods and equivalent viscous damping ratios directly from the experimental results by the forced vibrational test performed in 1974.

The analytical results are finally shown for simulating and comparing with the abovementioned experimental results.

Through these studies, it is concluded that the radiation damping effects are remarkable in the reactor building and the proposed seismic response analysis is reasonable for estimating the soil-structure interaction with the torsional behaviour of structure.

1. Introduction

The most important problem for dynamical analysis of structures is to select a suitable design earthquake motion and employ a suitable mathematical model according to the dynamical characteristics of a structure. It is well known that many damping effects in soil-structure interaction are observed in building with a short fundamental period such as a nuclear reactor building, by the dissipation, to the ground, of energy vibration through the foundation.

This report is in addition to the previously written SMIRT-3 Paper K3/2[1] in which an approximate explanation as regarding the experimental and analytical studies of No. 1 Reactor Building (BWR, 540 MWe) at Hamaoka Nuclear Power Station in Japan will be written, the power plant being located at Hamaoka-cho about 50 km to the south of Shizuoka City and 50 km to the east of Hamamatsu City (See Fig. 1).

Japan has undergone devastating earthquakes throughout her history and many historical records on earthquakes are available. This is why the design of Hamaoka Nuclear Power Plant has been made taking into account the possibility of future earthquakes which may register as much as 8 on the Richter scale.

Maximum acceleration of 3G was adopted in the design probabilistic earthquakes ground motion based on the above earthquakes records. A new structural type termed COMBINED TYPE was adopted to accomplish the following two results: (1) specifically protect the reactor building from the overturning moment and 3G design ground motions, and (2) expect a radiation damping effect by a dynamical soil-structure interaction. Therefore, Reactor Building, Radioactive Waste Disposal Building and Control Building were set on a 64 square meter and 4 meter deep concrete foundation mat placed directly on a firm mudstone layer.

Fig. 2 shows the experimental damping ratios between the fundamental periods in bridge foundation and nuclear reactor buildings in Japan derived from the dimensionless frequency $\omega_1\sqrt{A}/Vs$, where ω_1, A and Vs are foundamental circular frequency, foundation area and soil shear velocity, respectively. It is apparent that the damping ratios between the fundamental periods, in structures are equal to the dimensionless frequency $\omega_1\sqrt{A}/Vs$ in structure.

Therefore, 10% was employed as a fundamental period damping ratio to make the aseismic design of No. 1 Reactor Building, Hamaoka Nuclear Power Station.

In 1974, the authors performed a forced vibration test at No. 1 Reactor Building, although the authors already reported the experimental and analytical results in the previous SMIRT-3.

In this paper, the authors report the further results in regard to estimating the three dimensional behaviour in analytical study and the vibration characteristics in experimental study. The former is a new method in which a thin walled beam theory with torsional behaviour is applied and the latter is a regression analysis on the degree of freedom for evaluating the eigenvalues and eigenvectors from experimental results.

2. Analytical Study

2.1 General

It is one of the important aseismic design problem to estimate the damping effects of a structure with a short fundamental period such as a nuclear reactor building, as shown in Fig. 1.

Generally speaking, the damping effect of an elastic structure may be considered as a structural damping mechanics of which damping factor or logarithmic damping ratio is free of the disturbing force frequencies and the eigenvalues of the structure. On the other hand, the damping effect in soil-structure interaction may be approximately equal to the viscous damping effect. The authors made an attempt to estimate the structural damping effect and the radiational damping effect as follows:

1) Application of a complex stiffness for estimating damping effect on the structure in the elastic range.
2) Application of the dynamical soil-foundation stiffness based on a solution of the propagation of seismic waves on the surface of the elastic half-space medium for estimating the radiation damping effect.

The above problems were already discussed in the previous report,[1] 30 in this report the authors are proposing to apply the thin walled beam theory for estimating briefly and simply the three dimensional behaviour with torsional one of reactor building.

Concept on Complex Damping

The authors propose the following simplest mathematical model using complex numbers to express the structural damping effect. A spring constant can be expressed as:

$k = k_o \exp(i\,\mathrm{sgn}\omega\phi)$, where $\phi = \sin^{-1}h$ and h is an assumed damping ratio (1)

sgn ω is necessary to obtain a pair of conjugate values, when the response values in the time domain are transformed in those in the frequency domain by Fourier's Transformation (References [1], [3]).

Dynamical Soil-Foundation Stiffness

The authors propose the dynamical soil-foundation stiffness by W. Tajimi's theory based on the vibrational impedance of soil-foundation defined as the excitation force on the surface of the elastic half space medium in the frequency domain. The authors have also extended the above theory to a rectangular foundation, although the above theory is limited to the simplified representations of foundation geometry, soil material properties and loading conditions. In order to analyze the eigenvalues and eigenvectors of a vibrational system, the authors attempted to approximate the dynamical soil-foundation stiffness in frequency domain with the linear or quadratic function of the eigenvalue of vibrational system as follows:

$$K_R(\omega) + {}_iK_I(\omega) = (k_{RO} + i\,\mathrm{sgn}\omega k_{IO}) + \lambda(k_{RI} + i\,\mathrm{sgn}\omega K_{I1}) + \lambda^2(k_{R2} + i\,\mathrm{sgn}\omega k_{I2}),$$ where λ = eigenvalue of vibrational system. (3)

(Reference [1]).

2.2 Application of Thin Walled Beam Theory

Nuclear reactor buildings are in general forced to be of wall arrangements spatially complex, and stress analysis and modelization are often difficult compared with ordinary structures.

With regard to the above problem, one of the authors previously proposed the three dimensional analysis by finite element method (F. E. M.) in SMIRT-1, 1971 [4]. Although F. E. M. is an effective and useful method for estimating the behaviour of reactor building, it is very difficult to control a large number of input and output data, thus needing a long time in computation to obtain the results.

In this report, the authors propose another new method [5] for estimating the behaviour of reactor building by application of "Thin Walled Beam Theory", which is used recently as an effective means of analysis by the aircraft, seacraft and automobile industries to enable economical design.

In this analysis procedure, it is assumed that the reactor building consists of a pair of thin walled beam of open and/or closed section between the top and bottom floors as shown in Fig. 3. Assumed displacements and force-resultants of thin wall elements in the cross sections are shown in Fig. 4, in which the axes X and Y denote the principal axes of cross-sectional area. The basic equations in relation to stress and strain are as shown below on elastic theorem.

$$\sigma_z = \frac{E}{1-\nu^2}\frac{\partial w}{\partial z},\ \sigma_s = \frac{\nu E}{1-\nu^2}\frac{\partial w}{\partial z} \text{ and } \tau_s = G\left(\frac{\partial w}{\partial s} + \frac{\partial \chi}{\partial s}\frac{\partial u}{\partial z} + \frac{\partial y}{\partial s}\frac{\partial v}{\partial z}\right), \qquad (4)$$

where: σ_z, σ_s and τ_s denote the stresses acting on the thin wall surface of the element in the direction of the local coordinate axes (s, n, z).

Displacements are also defined as shown below on the elastic beam theory.

$$u_p = u_{sc} - (y_p - y_{sc})\theta_z,\ v_p = v_{sc} + (x_p - x_{sc})\theta_z,$$
$$w_p = w_c - x_p\theta_Y - y_p\theta_X + \alpha_x\omega_x + \alpha_Y\omega_Y, \qquad (5)$$

where: the suffixes p, sc denote certain points on the thin wall, the shear center and the centroid of cross section respectively and θ_X, θ_Y are the angles of rotation about X and Y axes which are the function of Z only and independent of both X and Y. θ_Z is the angle of torsion at the distance from the origin. $\alpha_x\omega_x$ and $\alpha_Y\omega_Y$ are the additional symbols of displacement due to the shear stress in which α_X and α_Y are defined separately in the direction of the principal axes X and Y. Therefore, α_x and α_Y are determined by the following equations taking into consideration the continuation of warping and the zero axial force of thin wall cross sections by shear strain as follows:

$$\alpha_\xi = \int^s \frac{ds}{t}\int^s \xi t\,sd - C_\xi\,\xi,\quad C_\xi = \oint \xi t\,ds \int^s \frac{ds}{t}\int^s \xi t\,ds \Big/ \oint \xi^2 t\,ds, (\xi = X, Y) \qquad (6)$$

On the one hand, the rotations by shear stress are defined as:

$$\phi_X = \frac{du}{dz} - \theta_Y, \quad \phi_Y = \frac{dv}{dz} - \theta_X \tag{7}$$

Considering the total bending moment and shear force of cross section, one obtains:

$$M_\xi = -\oint \sigma_z \xi t ds = \frac{E}{1-\nu^2} \oint \frac{\partial w_p}{\partial z} \xi t ds = \frac{EI_{\xi\xi}}{1-\nu^2} \frac{d\phi}{dz}, \tag{8}$$

$$S_\xi = \oint \tau_s \frac{d\xi}{ds} t ds = G[J_\xi \phi_\xi + (I_{\xi\xi} + C_\xi J_\xi)\omega_\xi], \ (\xi = x, y), \tag{9}$$

where:

$$I_{\xi\xi} = \oint \xi^2 t ds \text{ and } J_\xi = \oint \left(\frac{d\xi}{ds}\right)^2 t ds .$$

From eq. (8) one obtains:

$$\phi_\xi = \frac{1-\nu^2}{EI_{\xi\xi}} \int M_\xi dz + A_o, \ (\xi = x, y), \tag{10}$$

and A_o may be obtained from the edge condition of beam.

From eq. (9) one obtains:

$$\omega_\xi = (J_\xi - \frac{S_\xi}{G})/(I_{\xi\xi} + C_\xi J_\xi), \ (\xi = x, y), \tag{11}$$

Substituting eqs. (10) and (11) into eqs. (4) and applying the principle of minimum potential energy, one obtains the following important equation:

$$\frac{E}{1-\nu^2} \frac{J_\xi C_{bs\xi}}{I_{\xi\xi}+C_\xi J_\xi} \frac{d^2\phi_\xi}{dz^2} + GI_{\xi\xi}\phi_\xi = - C_\xi S_\xi + \frac{E}{1-\nu^2} \frac{C_{bs\xi}}{G(I_{\xi\xi}+C_\xi J_\xi)} \frac{d^2\phi_\xi}{dz^2} ,$$

$$(\xi = x, y), \tag{12}$$

where:

$$C_{bs\xi} = \oint \alpha_\xi^2 t ds.$$

Applying eq. (12) to the beam on which ends the concentrated load acts, the solution of eq. (12) is :

$$\phi_\xi = A_1 e^{\alpha z} + A_2 e^{-\alpha z} - C_\xi Q_\xi / GI_{\xi\xi} , \tag{13}$$

where:

$$\alpha^2 = -(1-\nu^2)(I_{\xi\xi}+C_\xi J_\xi) GI_{\xi\xi}/EA_{\xi\xi}C_{bs\xi}. \tag{14}$$

To determine the constant values A_1 and A_2, it is necessary to use the boundary condition in regard to deflection, stress and $\phi\xi$ at both ends. Substituting eq. (14) into eqs. (4), (5), (8) and (9), one obtains the stress, deflection, bending moment and shear force of the thin walled beam.

Both St. Venant torsion and bending-torsional behaviour introduced by H. Wagner have been treated in the above procedure with the effect of shear lag. The authors applied the abovementioned method to obtain the total stiffness of reactor building. The authors' method is more simple and brief than F. E. M. to obtain the results, although it is difficult to solve the

complex stress in wall. Applying this method to Reactor Building, it took only two minutes in CPU time with the program "APPROX" developed by the authors at IBM 370/158. Fig. 5 shows some of the results calculated in regard to shear centers and principal axes in the cross sections of reactor building.

2.3 Analytical Results

The authors attempted to estimate the vibrational characteristics of Hamaoka No. 1 Reactor Building by the analytical method mentioned in paragraph 2.1 to 2.2. The assumed mathematical model in Table 1 is a spring-mass system with forty eight degrees of freedom by reason of the six components for individual mass points at a rate of one vertical and two horizontal displacement and three rotations. The assumed weights, and the moments of inertia of individual masses are shown in Table 1. The main resisting elements in reactor building are assumed to be reinforced concrete thin walls alone, of which Young's Modulus and Poisson's Ratio are 2.1×15^5 kg/cm^2 and 1/6 respectively. The dynamical soil-foundation stiffness is assumed to be the complex simple spring to six components in the exciting frequency domain, (see Reference [1]). The assumed stress distributed on the contact surface between soil and foundation is approximate to Boussinesq's stress distribution and the physical coefficients of soil are assumed as follows:

Density ρ = 2.01 t/m^3, Poisson's Ratio ν = 1/3 and

Velocity of shear wave Vs = 700 m/sec.

Some of the natural frequencies calculated and damping ratios of vibrational system are shown in Table II in relation to the superior compoments of modes. The resonance curves and phase for 1 ton exciting force calculated independent of exciting frequencies, are shown in Fig. 6 and 7.

3. Experimental Study

3.1 General

In March 1974, the authors conducted a forced vibrational test at the Hamaoka No. 1 Reactor Building to confirm the dynamical properties of a building. The two vibration exciters located on the fifth floor were designed and developed in Japan of which range of frequencies is 0.2 cps to 20.0 cps. (BCS A 200 types). The forced vibration test was performed with excitation applied to the building in both east-west and north-south directions. The exciting frequency was increased stepwise by 0.10 to 20 cps and the lateral motions of floors were recorded as the amplitude and phase of displacement at every frequency in a steady state. Measurements were taken using eight pairs of pick-ups located on the second basement, the first, the second, the third, the fourth, the fifth floors, and crane girder and roof by Takenaka's Forced Vibration Test System (FORVITT).

In order to estimate the exact properties of the building, the authors attemped to set the lateral motions in parallel to the exciting direction with regard to the calculated center of gravity of floors by separating the coupled resonance motions into two components, i.e., lateral and torsional

modes. The results relevant to some of the floors shown in Figs. 8 and 9 are the translated motions at the gravity center of floors of which values are transformed to the motions of the constant vibrational exciting force 98 tons independent of the exciting frequencies.

2.2 Regression Analysis of Many Degrees of Freedom for Estimating Experimental Results

When a structure is so large or heavily damped, the structure may have multiple modes at the exciting frequency. In cases where modal overlap is light, the resonance curves data can be considered to be in the vicinity of each modal resonance as if it were a single degree of freedom system. T. Hiromatsu proposed an approach to the analysis of forced vibration test by regression analysis of a single degree of freedom system (Reference [6]).

On the other hand, when modal overlap is heavy, a single degree of freedom approach to modal parameter identification will not work. The parameters of the modes must be identified simultaneously.

In this report, the authors are attemping to estimate the modal parameters by regression analysis of many degrees of freedom.

Analysis Procedure

Motion X_i in one mass points i by the vibrational exciters will be expressed as:

$$X_i = \sum_{j=1}^{m} \left(\frac{U_{ij}\beta_{ij}}{\lambda j - i\omega} + \frac{\bar{U}_{ij}\bar{\beta}_{ij}}{\bar{\lambda} j - i\omega} \right) r\omega^2 e^{i\omega t}, \tag{15}$$

where: λ_j, $\bar{\lambda}_j$, U_{ij}, $\bar{U}_{ij}$ and β_{ij}, $\bar{\beta}_{ij}$ are eigenvalues, modes and participation factors respectively, which are complex and conjugate values. The term $r\omega^2$ is the acceleration of exciters and ω is circular frequency of exciting force. In order to apply the regression analysis, the authors establish the following regression model.

$$f_i = \sum_{j=1}^{m} \left(\frac{B}{\lambda j - i\omega} + \frac{\bar{B}}{\bar{\lambda} j - i\omega} \right) \omega^2 + \varepsilon i, \tag{16}$$

where: β_j, $\bar{\beta}_j$ and λ_j, $\bar{\lambda}_j$ are the parameters, ω is an observed value and f_1 is a predicted value. Eq. (16) is the intrinsically nonlinear model, so the parameters are unable to be denoted directly by linear function of parameters. Applying eq. (2) to the observed values Y, S the sum of square of deviation between the observed and predicted values are obtained as follows:

$$S = \sum_{k=1}^{N} \varepsilon_k^2 = \sum_{k=1}^{N} (Y - f_k)(\bar{Y}_k - \bar{f}_k). \tag{17}$$

where: Y is observed data at frequency ω, $\bar{Y}$ is conjugate value of Y,
f is predicted values, $\bar{f}$ is conjugate value of f, and
N is data block size.

When the linearization method is applied to eq. (17), the parameters will be obtained through a following two step processes.

1) First step to B_j and $\bar{B}_j$

where the eigenvalues λ_j and $\bar{\lambda}_j$ are taken to be constant values, eq. (16) will be reduced to:

$$f_{io} = \sum_{j=1}^{m} [(\frac{1}{\lambda_j - i\omega} + \frac{1}{\bar{\lambda}_j - i\omega})\, bR_j + i(\frac{1}{\lambda_j - i\omega} - \frac{1}{\bar{\lambda}_j - i\omega})bI_j]\omega^2 + \varepsilon i, \tag{18}$$

where: bR_j and bI_j are real and imaginary parts of β_j and $\bar{\beta}_j$ respectively. Similarly the conjugate value $\bar{f}_{oi}$ will be led to:

$$\bar{f}_{io} = \sum_{j=1}^{m} [(\frac{1}{\bar{\lambda}_j - i\omega} + \frac{1}{\lambda_j - i\omega})\, bR_j - i(\frac{1}{\bar{\lambda}_j - i\omega} - \frac{1}{\lambda_j - i\omega})bI_j]\omega^2 + \bar{\varepsilon} i, \tag{19}$$

It is very clear that eqs. (18) and (19) are the linear functions of the parameters bR_j and bI_j that eqs. (18) and (19) will be reduced to the following linear equations:

$$\begin{aligned} f_{io} &= b_1 X_2 + b_1 X_2 + \ldots + b_j X_j + \ldots + b_{2m} X_{2m} + \varepsilon i, \\ \bar{f}_{io} &= b_1 \bar{X}_2 + b_1 \bar{X}_2 + \ldots + b_j \bar{X}_j + \ldots + b_{2m} \bar{X}_{2m} + \bar{\varepsilon} i, \end{aligned} \tag{20}$$

Substituting eqs. (20) into eq. (17), one obtains a normal equation by the partial derivative of S with respect to b_j as follows:

$$\frac{\partial S}{\partial b_j} = - X_j(\bar{Y}_i - \bar{f}_{oi}) - \bar{X}_j(Y_j - f_{oi}) = 0 \tag{21}$$

Expanding eq. (21) with the aid of eqs. (20), one obtains

$$\begin{aligned} &(X_j \bar{X}_i + \bar{X}_j X_i) b_1 + \ldots + (X_j \bar{X}_j + \bar{X}_j X_j) b_j + \ldots \\ &+ (X_j \bar{X}_{2m} + X_j X_{2m}) b_{2m} = X_j \bar{Y} + \bar{X}_j Y \end{aligned} \tag{22}$$

Thus, one obtains the following 2m kind of normal equation from the whole data:

$$[X\bar{X} + \bar{X}X]\{b\} = \{X\bar{Y} + \bar{X}Y\}, \tag{23}$$

where $[X\bar{X} + \bar{X}X]$ and $\{X\bar{Y} + \bar{X}Y\}$ are the symmetrical real matrix and real vector respectively.

2) Second Step to λ_j and $\bar{\lambda}_j$

Taylor's expansion may be useful and convenient for application in this case. When the parameters B_j and $\bar{B}_j$ are taken to be constant values, eq. (16) may be reduced to:

$$f_i = f_{io} - \sum_{j=1}^{m} [\frac{B_{jo}}{(\lambda_{jo} - i\omega)} \Delta\lambda_j + \frac{\bar{B}_{jo}}{(\bar{\lambda}_{jo} - i\omega)} \Delta\bar{\lambda}_j]\omega^2 + \varepsilon i, \tag{24}$$

where: $\Delta\lambda_j = \lambda_j - \lambda_{jo}$ and $\Delta\bar{\lambda}_j = \bar{\lambda}_j - \bar{\lambda}_{jo}$. Eq. (20) is also reduced to:

$$\begin{aligned} f_i = f_{io} - \Delta f_i = f_{io} - \sum_{j=1}^{m} [\{ &\frac{b_{jo}}{(\lambda_{jo} - i\omega)} + \frac{\bar{b}_{jo}}{(\bar{\lambda}_{jo} - i\omega)}\} \Delta\lambda R_j \\ + i\{&\frac{b_{jo}}{(\lambda_{jo} - i\omega)} - \frac{\bar{b}_{jo}}{(\bar{\lambda}_{jo} - i\omega)}\}\Delta\lambda I_j]\omega^2 + \varepsilon i, \end{aligned} \tag{25}$$

Similarly:

$$\bar{f}_i = \bar{f}_{io} - \Delta\bar{f}_i = \bar{f}_{io} - \sum_{j=1}^{m} [\{\frac{\bar{b}_{jo}}{(\bar{\lambda}_{jo}+i\omega)^2} + \frac{b_{jo}}{(\lambda_{jo}+i\omega)^2}\}\Delta\lambda R_j$$

$$- i\{\frac{\bar{b}_{jo}}{(\bar{\lambda}_{jo}+i\omega)^2} - \frac{b_{jo}}{(\lambda_{jo}+i\omega)^2}\}\Delta\lambda I_j]\omega^2 + \bar{\varepsilon}i, \qquad (26)$$

Eqs. (25) and (26) are so clearly the linear functions of $\Delta\lambda R_j$ and $\Delta\lambda I_j$ that they will be reduced to the following linear equations:

$$f_i = f_{io} - \Delta f_i = f_{io} - (\Delta\lambda_1 X_1 + \ldots + \Delta\lambda_j X_j + \ldots + \Delta\lambda_{2m} X_{2m}) + \varepsilon i,$$

$$\bar{f}_i = \bar{f}_{io} - \Delta\bar{f}_i = \bar{f}_{io} - (\Delta\lambda_1 \bar{X}_1 + \ldots + \Delta\lambda_j \bar{X}_j + \ldots + \Delta\lambda_{2m} \bar{X}_{2m}) + \bar{\varepsilon}i, \qquad (27)$$

Substituting eqs. (27) into eq. (17), one obtains a normal equation by the partial derivative of S with respect to $\Delta\lambda_j$ as follows:

$$\frac{\partial S}{\partial \Delta\lambda_j} = X_j\{(\bar{Y}_i - \bar{f}_{io}) + \Delta\bar{f}_i\} + \bar{X}_j\{(Y_i - f_{io}) + \Delta f_i\} \qquad (28)$$

Thus, one obtains the following 2m kinds of normal equations with the aid of eqs. (25) and (26):

$$[X\bar{X} + \bar{X}X]\{\Delta\lambda\} = -\{X(\bar{Y} - \bar{f}_o) + \bar{X}(Y - f_o)\}, \qquad (29)$$

where: $[X\bar{X} + \bar{X}X]$ and $\{X(\bar{Y} - \bar{f}_o) + \bar{X}(Y - f_o)\}$ are also the symmetrical real matrix and real vector respectively. Therefore, if the parameters λ_j, $\bar{\lambda}_j$ or β_j, $\bar{\beta}_j$ could be identified solving a set of simultaneous linear equations.

Estimation of Experimental Results

The authors apply the above mentioned regression analysis of many degrees of freedom to the experimental results of Hamaoka No. 1 Reactor Building. Table II shows the natural frequencies and damping ratios determined by this method with the analytical results. The predicted resonance curves are as shown in Figs. 8 and 9 with the experimental results.

4. Comparison between Experimental and Analytical Results

It is apparent that many damping effects are observed in the lower modes by the vibrational energy dissipation through the foundation into the ground as shown in Table II, the values of which are 22.9 % and 23.4 % in the east-west and north-south direction, respectively. They are certainly in excess of the 10% used in the design of the reactor building. The analytical values of damping ratio in the higher modes are more than the experimental results. This is the reason why the authors' analytical method in Section 2 is overestimated in the higher modes by approximating the dynamical soil-foundation stiffness with the linear or quadratic function of the exciting frequency to analyze the eigenvalues of vibration system. Although the analytical resonance curves shown in Figs. 6 and 7 are almost similar to the experimental

ones, some of the experimental natural frequencies are not simulated by the authors' analytical method. These unsimulated modes will be caused to occur by the effect of soil profile and/or the cross interaction between the reactor and turbine building, although it is difficult to evaluate their effects in the analytical results.

5. Conclusion

On this report, the authors give the analytical and experimental results about No. 1 Reactor Building, Hamaoka Nuclear Power Station. The analytical method is firstly shown for estimating the vibrational characteristics of reactor building with regard to the effects of structural damping and radiation damping. Especially the authors propose the thin walled beam theory for estimating briefly and simply the three dimensional behaviour of reactor building with torsion. Analytical results are shown in Table II, Figs. 6 and 7.

Secondarily the authors propose the regression analysis of many degrees of freedom for estimating the natural frequencies and damping ratios to directly obtain from the experimental results. The calculated values of Hamaoka No. 1 Reactor Building are shown in Table II and Figs. 8 and 9.

Through the above studies, the authors finally conclude as follows:

1) It is apparent that the damping effects are more remarkable in the lower modes.
2) The analytical results are approximately equal to the experimental ones in the lower modes by the authors' method.
3) Some of unsimulated modes will occur by the effect of soil profile and/or the cross interaction between the reactor and turbine buildings.

Acknowledgements

The authors wish to express their appreciation to Dr. Y. Ohsaki, Prof. of Tokyo Univ. and Dr. H. Tajimi, Prof. of Nihon Univ. for their guidance and helpful suggestions, and to Mr. N. Sugiyama a member of Chubu Electric Co. Ltd., and to Mr. J. Jido, Mr. T. Hiromatsu, Mr. T. Imazawa, Mr. Y. Sasaki and Mr. T. Shirai, members of Takenaka Technical Research Laboratory for their useful advices and work.

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