A SEISMIC ANALYSIS OF NUCLEAR POWER PLANT COMPONENTS SUBJECTED TO MULTI-EXCITATIONS OF EARTHQUAKES

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SUMMARY

In the case of analyzing the seismic responses of Reactor Pressure Vessel and Reactor Core Internals including Fuel Assemblies, these components have been carried out using the coupled model with Reactor Building and soil. And the soil-structure interaction between Reactor Building base mat and soil has been represented by some appropriate spring constants. Recently, however, if the analysis of soil-structure interaction is carried out in more detail, it is necessary to analyze separately these components from the soil-structure model in order to facilitate the soil-structure interaction analysis by decreasing the degree of freedom. In this case, the analysis of the soil-structure interaction model is carried out first of all, and then these separated components are analyzed by using the analytical results of the soil-structure model.

Furthermore, when the nonlinear characteristics of nuclear power plant such as soil-structure interaction and reinforced concrete structures are taken into consideration, it is also necessary to analyze separately such components as Reactor Core Internals from these structures.

Moreover, the total weight of such components as Reactor Pressure Vessel and Reactor Internals is extremely lighter than that of Reactor Building. So, it is considered that the seismic responses of Reactor Building are not influenced by the responses of such components as Reactor Internals. Under these conditions, we have tried to study the theory that analyzes the seismic responses of components subjected to multi-excitations of earthquakes from these supports. In this analysis, the modal analysis methods are used to determine the seismic responses of structural systems instead of the direct integration method.

And we have compared these results with some kinds of other analytical methods, and investigated the accuracy of numerical results of these analysis, applying to such components as Reactor Pressure Vessel and Reactor Internals of an acual plant.

The results of this method of analysis are summerized as follows:

(1) One of the seismic analysis methods concerning systems subjected to multi-excitations of earthquakes has been presented to the conference of JSME. Although the analytical theory presented to that conference is correct, it has a serious problem about the accuracy of numerical results. This computer program and theory cannot be used practically due to the time necessary to calculate. However, the method described in this paper overcomes those serious problems stated above and has no problem about the computer time and precision. So, it is possible to apply this method to the seismic design of an actual nuclear power plant practically.

(2) The feed back effects of the seismic responses of Reactor Internals to Reactor Building are considered so small that we can separate the model of Reactor Internals from Reactor Building.

(3) The results of seismic response of Reactor Internals are fairly consistent with those obtained from the model coupled with Reactor Building.

(4) We can extend this analysis method described in this paper to the model of Reactor Internals subjected to more than two random excitations of earthquakes.

(5) It is possible that this analysis method is also applied to the seismic analysis of such three-dimensional systems as piping systems subjected to multi-excitations of earthquakes.

1. Introduction

Recently, the analytical theory and technique of seismic analysis have been remarkably developed mainly due to the advancement of the computer systems.

And these developments and advancements have been making the non-linear analysis of Reactor Building including Soil Spring and detailed Soil-Structure Interaction analysis (such as F.E.M.) of nuclear power plant possible.

In this paper, we take note of the method of response analysis of such components as Reactor Pressure Vessel and Reactor Internals, when the advanced analytical techniques described above have been conducted.

So far, we have been investigated the analytical methods in the case of such components as RPV and Reactor Internals subjected to multi-input excitations (Ref. 1,4). Furthermore, we have investigated and developed new analytical theory mainly based on the method described in Ref. 1, and have got some interesting results.

So we introduce this analytical method and present these analytical results applied to actual nuclear power plants in this paper.

2. Analytical method of components subjected to multi-excitations

2.1 Equation of motion of coupled system

In the case of components, which have more than two supporting points to Reactor Building, are coupled with Reactor Building in the analytical model, the equation of motion of this coupled system can be represented as follow,

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{U\}\ddot{y}_0 \qquad (1)$$

where [M], [C] and [K] are mass, damping and stiffness matrix respectively, {U} is vector associated with $\ddot{y}_0$, and $\ddot{y}_0$ is external excitation.

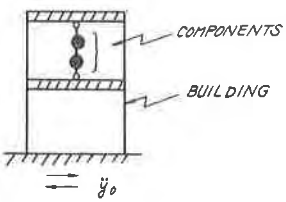

Fig. 1 Mathematical model

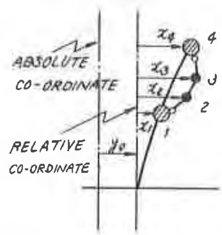

Fig. 2 Co.ordinate system of coupled model

2.2 Equation of motion of components seperated from main structure (building)

If the weights of components are so small compared with building, it is considered that the dynamic responses of building are not influenced by the responses of these components. Then, we can seperate these models of components from the model of Reactor Building, and also can analyze these components which are subjected to multi-input excitations. Fig. 1 and Fig. 2 show a mathematical model and Co-ordinate system of coupled model respectively in order to lead equation of motion of components. As we can obtain the response values of supported point 1 and 4 in Fig. 2, we seperate eq.(1) with known and unknown items by using the technique of matrix partition method.

$$\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{x}_b \end{Bmatrix} + \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{x}_b \end{Bmatrix} + \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix}\begin{Bmatrix} x \\ x_b \end{Bmatrix} = -\begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\{1\}\ddot{y}_0 \quad (2)$$

where $\{x\}$ and $\{x_b\}$ are displacement of components and supporting points respectively. Then, we part eq.(2) to such two equations as,

$$[m_{11}]\{\ddot{x}\} + [C_{11}]\{\dot{x}\} + [K_{11}]\{x\}$$
$$= -[m_{12}]\{\ddot{x}_b\} - [C_{12}]\{\dot{x}_b\} - [K_{12}]\{x_b\} - [m_{11}m_{12}]\{1\}\ddot{y}_0 \quad (3)$$

$$[m_{21}]\{\ddot{x}\} + [C_{21}]\{\dot{x}\} + [K_{21}]\{x\}$$
$$= -[m_{22}]\{\ddot{x}_b\} - [C_{22}]\{\dot{x}_b\} - [K_{22}]\{x_b\} - [m_{21}m_{22}]\{1\}\ddot{y}_0 \quad (4)$$

As the all items of right side of eq.(3) are known values, we can obtain the response values of components by solving eq.(3). But $[m_{12}]$ and $[m_{21}]$ in eq.(4) have the meaning of the off-diagonal mass matrix of Reactor Building, and these are generally zero. So, eq.(4) is used only to calculate the reaction forces of supported portion.

3. Modal analysis method of components subjected to multi-excitations from their supporting points

3.1 Basic equation of motion

As we discussed in Chap. 2, the equation of motion of components, subjected to multi-excitations from their supporting points, is represented by eq.(3).

Here, considering the total displacements $\{x\}$ are made up of two seperated parts, the quasi-static displacements $\{x_s\}$ plus the displacements due to dynamic inertia force $\{x_d\}$, we can write $\{x\}$ in the partitioned form (Ref. 1),

$$\{x\} = \{x_s\} + \{x_d\} \quad (5)$$

The quasi-static displacement $\{x_s\}$ can be written,

$$\{x_s\} = -[K_{11}]^{-1}[K_{12}]\{x_b\} \quad (6)$$

Substituting eq.(6) to eq.(3), we can get,

$$[m_{11}]\{\ddot{x}_d\} + [C_{11}]\{\dot{x}_d\} + [K_{11}]\{x_d\}$$
$$= \left[[m_{11}]\,[K_{11}]^{-1}[K_{12}] - [m_{12}]\right]\{\ddot{x}_b\} - [m_{11}][m_{12}]\{1\}\ddot{y}_0 \quad (7)$$

when we get eq.(7), the item of $\{\dot{x}_b\}$ is neglected because it scarcely has influence on the responses of components.

3.2 Eigenvalue analysis

In order to obtain natural frequencies, vibration modes, etc, the equation of eigenvalue analysis is represented as follow,

$$\left[[K_{11}] - \lambda[m_{11}]\right]\{x\} = \{0\} \quad (8)$$

where λ is eigenvalue, $\{X\}$ is eigen vector.

3.3 Modal damping analysis

The modal damping of each mode, which we used in our analysis, can be obtained from eq.(9). (Ref. 3)

$$h_j = \sum_{i=1}^{n} h_i W_{ei} \Big/ \sum_{i=1}^{n} W_{ei} \tag{9}$$

where W_{ei}, h_i are strain energy and damping factor of i-th element respectively, h_j is modal damping factor of j-th mode.

3.4 Response analysis by modal analysis method

The equation of response analysis of components subjected to multi-random excitation is represented in eq.(7). In order to solve eq.(7) by mean of modal analysis method, we dissolve $\{x_d\}$ to some independent vibration modes $\{Xn\}$,

$$\{x_d\} = \sum_{j=1}^{n} q_{dj} \{X_j\} \tag{10}$$

Using eq.(10), we can write eq.(7) as the form of eq.(11),

$$\ddot{q}_{dj} + 2h_j W_j \dot{q}_{dj} + W_j^2 q_{dj} = \ddot{x}_b \beta_j^* - \ddot{y}_o \beta_j^{**} \tag{11}$$

where

$$\beta_j^* = \{X_j\}^T \Big[[K_{11}]^{-1} [K_{12}] - [m_{11}]^{-1} [m_{12}] \Big] \{1\} \Big/ \{X_j\}^T [m_{11}] \{X_j\},$$

$$\beta_j^{**} = \{X_j\}^T [m_{12}] \{1\} \Big/ \{X_j\}^T [m_{11}] \{X_j\}.$$

Solving eq.(11), and using eq. (5) and eq.(6), we can get the response values of components which are subjected to multi-random excitations from their supporting points.

4. Application for Nuclear Power Plant

We tried to apply this analytical method described in Chap. 3, for actual nuclear power plant. We present two numerical examples, one is the comparisons of response values of components of uncoupled model with coupled model, and the other is the analysis of uncoupled system using the results of non-linear analysis of Soil-Structure Interaction.

4.1 Comparisons of response values of components of uncoupled model with coupled model

Fig. 3 shows the mathematical model of RPV and Reactor Internals coupled with Reactor Building. Fig. 4 shows the mathematical model of RPV and Reactor Internals separated from Reactor Building. Table 1 shows the results of natural periods and modal damping of each mode, and comparison of results of uncoupled model with coupled model. Fig. 5 shows the vibrational modes of coupled and uncoupled systems. Fig. 6 and Fig. 7 show the comparison of results of response values of RPV and Fuel Assemblies respectively.

From these results, we can say that the results obtained from our analytical procedures described in this paper, are fairly agree with those obtained from normal coupled system analysis method.

TABLE I

COMPARISON OF THE RESULTS OF EIGEN VALUE ANALYSIS
BETWEEN COUPLED MODEL AND UNCOUPLED MODE.

COUPLED MODEL			UNCOUPLED MODEL		
MODE	NATURAL PERIOD	MODAL DAMPING	MODE	NATURAL PERIOD	MODAL DAMPING
	sec	%		sec	%
1st	0.261	6.6	1st	0.261	6.6
2nd	0.228	5.0			
3rd	0.194	3.5	2nd	0.194	3.5
4th	0.150	1.4	3rd	0.150	1.4

4.2 Analysis of uncoupled system using the results of non-linear analysis of Soil-Structure Interaction

Fig. 8 shows the vertical section of Improved Type of Mark-I BWR nuclear power plant. Fig. 9 shows the vertical section of Reactor Internals including Fuel Assemblies. Fig. 10 and Fig. 11 show respectively the mathematical models of Reactor Building of this Improved Mark-I. Fig. 12 and Fig. 13 show the nonlinearity of Soil-Structure Interaction when we consider the effect of uplift between Reactor Building Base Mat and Soil during earthquake.

Analyzing the seismic responses of Reactor Building including the non-linearity of Soil Spring, we took out the response time histories of the Base Mat and the supporting portion of components (nodal point 4). Then, we carried out the multi-input analysis of Inside P.C.V. components including Fuel Assemblies.

The typical response values are shown in Fig. 15 for RPV, and Fig. 16 for Fuel Assemblies.
Concerning the Soil-Structure Interaction analysis, the same analytical procedure can also be applied for the case of analyzing the Soil-Structure Interaction in more detail (using F.E.M. etc.), as shown in Fig. 14.

5. Conclusion

The results of this method of analysis are summerized as follow.

(1) The method described in this paper has no problem about the computer time and precision. So, it is possible to apply this method to the seismic design of an actual nuclear power plant practically.

(2) The interaction effects of the seismic responses of Reactor Internals to Reactor Building are considered so small that we can seperate the model of Reactor Internals from Reactor Building.

(3) The results of seismic response of Reactor Internals are fairly agree with those obtained from the model coupled with Reactor Building.

(4) We can apply to the model of Reactor Internals subjected to more than two random excitations of earthquakes.

(5) The method described in chap. 4-2. of this paper can be also applied to the analysis of Reactor Internals using the results of response values of nonlinear analysis of Reactor Building and using the results of response values of more detailed Soil-Structure Interaction analysis, for example, such methods as FEM.

(6) It is possible that this analytical method is also applied to the seismic analysis of such three dimensional systems as piping systems subjected to multi-excitations of earthquakes.

References

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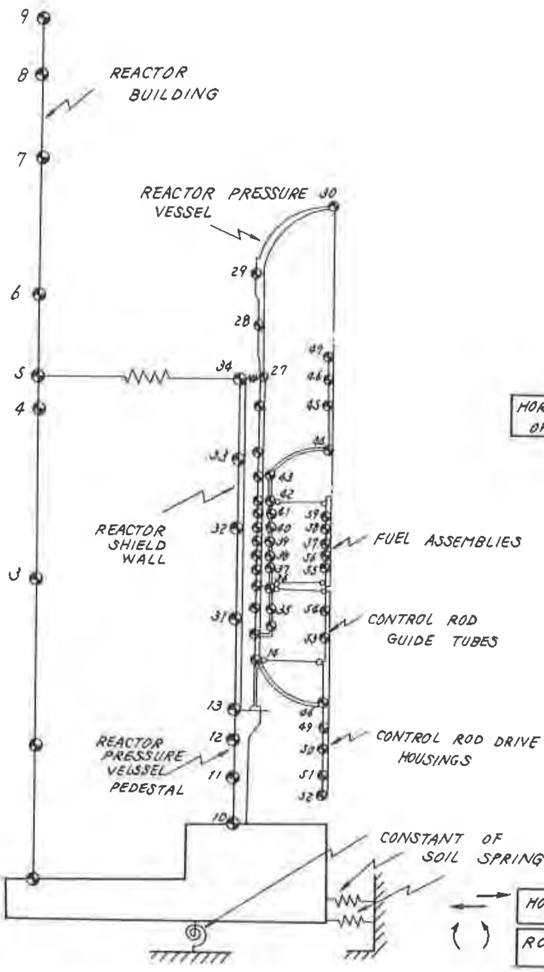


Fig. 3 MATHEMATICAL MODEL OF REACTOR INTERNALS (COUPLED MODEL)

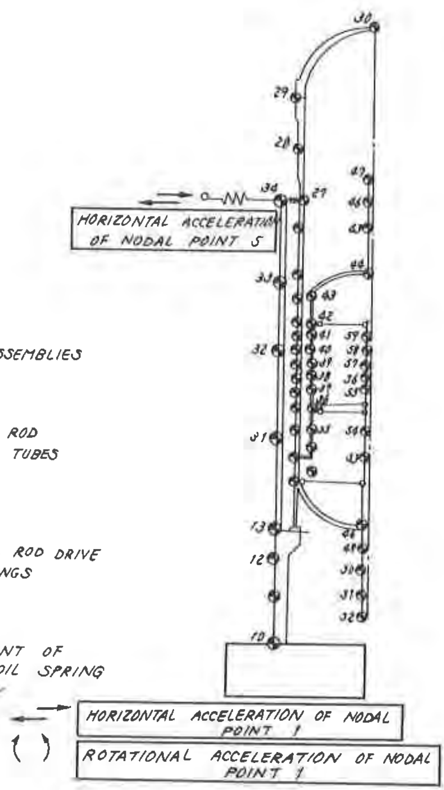


Fig. 4 MATHEMATICAL MODEL OF REACTOR INTERNALS (UNCOUPLED MODEL)

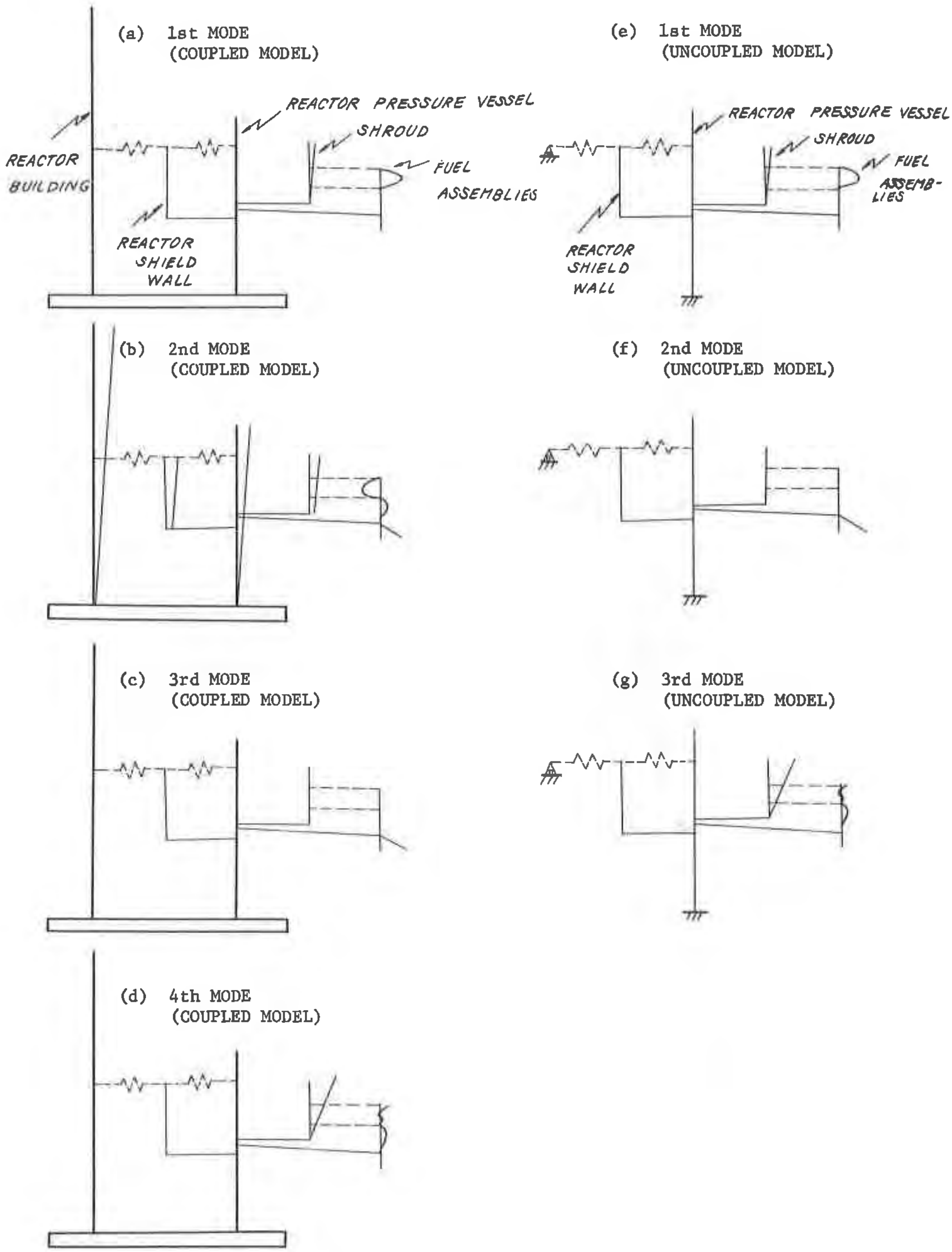
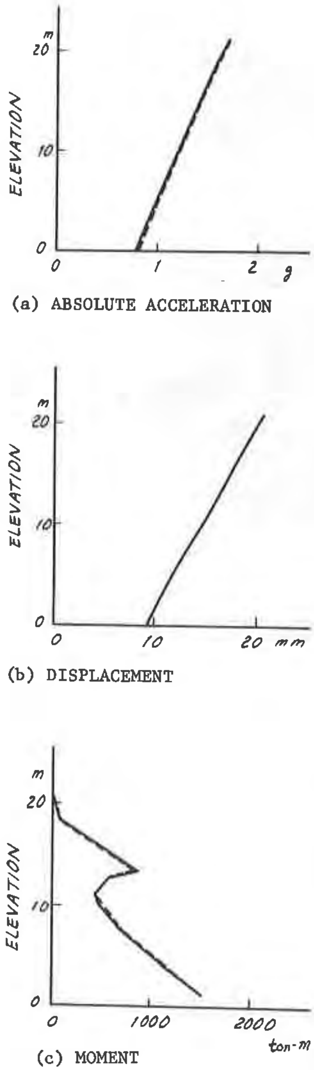
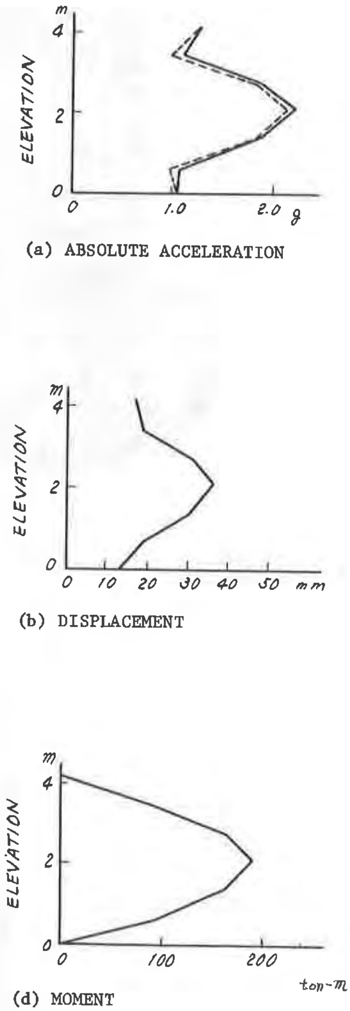


Fig. 5 VIBRATIONAL MODES





——— RESPONSE VALUES OF UNCOUPLED MODEL

------- RESPONSE VALUES OF COUPLED MODEL

Fig. 6 MAXIMUM RESPONSE VALUES OF REACTOR PRESSURE VESSEL EXCITED BY TAFT 1952EW (MAX. 300 GAL)

Fig. 7 MAXIMUM RESPONSE VALUES OF FUEL ASSEMBLIES EXCITED BY TAFT 1952EW (MAX. 300 GAL)

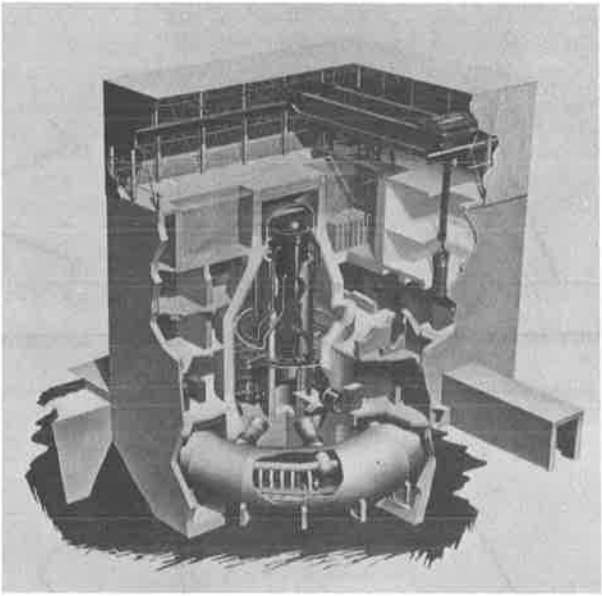


Fig. 8 VERTICAL SECTION OF MARK-I (IMPROVED) TYPE REACTOR BUILDING

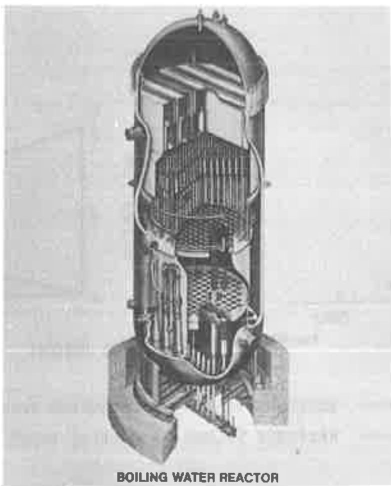


Fig. 9 VERTICAL SECTION OF REACTOR INTERNALS

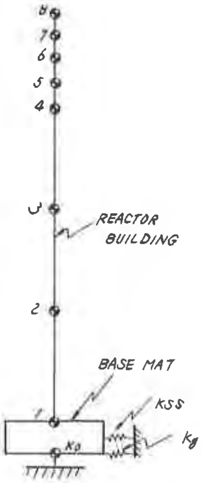


Fig. 10 MATHEMATICAL MODEL OF REACTOR BUILDING

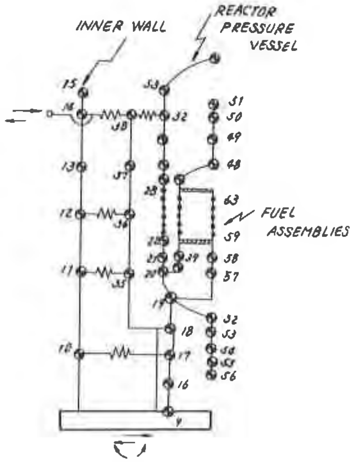


Fig. 11 MATHEMATICAL MODEL OF REACTOR INTERNALS

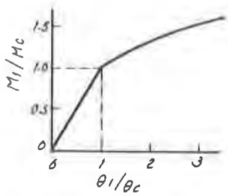


Fig. 12 OVERTURNING MOMENT FOR ROCKING ANGLE

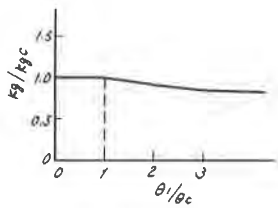
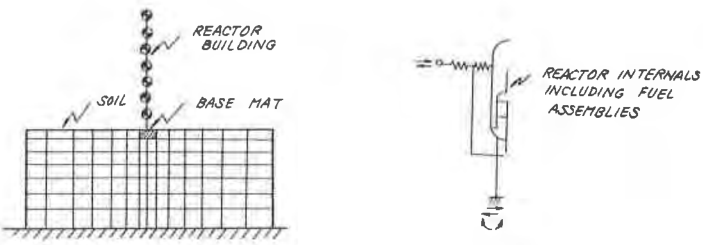


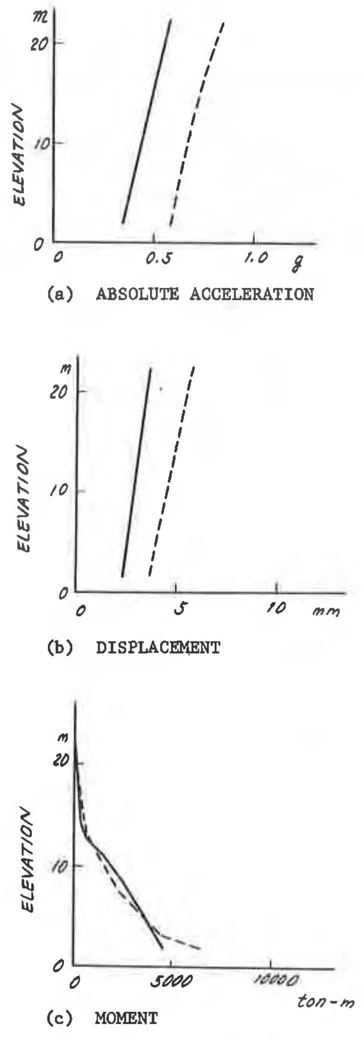
Fig. 13 HORIZONTAL SPRING CONSTANT FOR ROCKING ANGLE

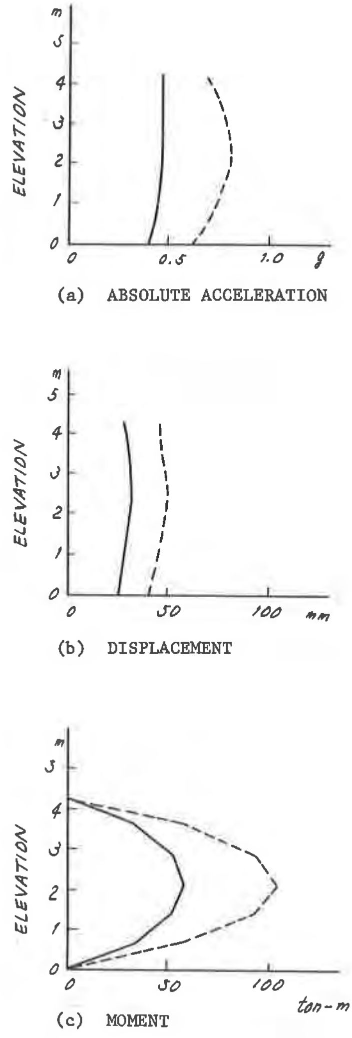


(a) MATHEMATICAL MODEL OF SOIL-STRUCTURE INTERACTION

(b) MATHEMATICAL MODEL OF REACTOR INTERNALS

Fig. 14 MATHEMATICAL MODEL OF NUCLEAR POWER PLANT IN CASE OF ANALYZING SOIL-STRUCTURE INTERACTION IN MORE DETAIL





——— RESPONSE VALUES EXCITED BY TAFT 1952 EW (MAX. 300 GAL) EARTHQUAKE

----- RESPONSE VALUES EXCITED BY EL CENTRO 1940NS (MAX.300 GAL) EARTHQUAKE

Fig. 15 MAXIMUM RESPONSE VALUES OF REACTOR PRESSURE VESSEL CONSIDERED THE NONLINEARITY OF SOIL-STRUCTURE INTERACTION

Fig. 16 MAXIMUM RESPONSE VALUES OF FUEL ASSEMBLIES CONSIDERED THE NON-LINEARITY OF SOIL-STRUCTURE INTERACTION