Influence of foundation deformation on seismic response of PWR reactor building

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ABSTRACT

Seismic analysis of a PWR reactor building has been performed with different hypothesis for the soil structure interaction ; the model was an axisymmetric finite element one.
- A first calculation with springs and dampers for the SSI, applied on a circle has shown a great deformation of the basemat.
- Then a stiffness matrix, equivalent to the SSI was established and introduced in the axisymmetric model.

The paper will describe calculation methodology of this impedance matrix and results of modal analysis.

1 INTRODUCTION

Seismic analysis of a PWR reactor building was performed with an axisymmetric model described in reference 1. The soil is homogeneous with Young modulus equal to 300 MPa, Poisson ratio, ν, equal to 0.4, volumic mass = 1800 kg/m^3. SSI was modelised by springs and dampers, calculated by usual formulas (ref. 2-3), located on the external circle of the basemat (i.e., on one node of the finite element model).

The modal analysis shows a great influence of the foundation deformation which is not coherent with the spring calculation, made with rigid foundation hypothesis:
- the first vertical mode frequency varies from 3.5 to 2 Hz if the location of the spring is modified and is equal to 5.8 Hz if the basemat is supposed rigid ;
- the horizontal floor response spectra is very sensitive to the basemat stiffness (see figure 1 where floor response spectrum, calculated at the internals highest level for different modelisation, are compared).

For the first horizontal or vertical mode which are global motion modes, it could be possible to have a simplified method to take into account the basemat and soil stiffnesses.

For higher modes, the basemat flexibility must be taken into account, especially for opposite phase motions of internals and containment (ref. 4).

So, impedance matrix of SSI was calculated and introduced in the axisymmetric model.

2 IMPEDANCE MATRIX CALCULATION

2.1 Method

The impedance matrix calculation is based on G. Deleuze works (ref. 5) which give the analytical response in any place of a semi infinite homogeneous medium due to an harmonic excitation applied on a circular surface. This analytical response is calculated by solution of Navier equation. The various steps of the calculation made by Sophonie computer code are the following:

- division of the basemat into circles of equal size,
- calculation of each circle motion, U_i , due to harmonic forces, F_j applied on itself and on other circles.
  This gives a matrix A such as:

$$U = A\ F$$

- calculation of impedance matrix, K_c, for rigid body motion, U'_i, of zones composed of one or more circles

$$U = P\ U' \qquad F' = K_c\ U'$$

$$\Longrightarrow$$

$$F' = P^T\ F \qquad K_c = P^T\ A^{-1} P$$

  F'_j is the force applied on zone j; K_c is complex and frequency dependent and can be written as addition of stiffness and viscous matrices

$$K_c = K + i\omega C$$

2.2 Comparison to usual formulas

The basemat was divided into 91 circles in an hexagonal mesh due to computer time calculation (see figure 1). The distance between adjoining circle centers is 4.768 m, such as the mean distance of circle centers is equal to the mean distance, d, of nodes in a circle $d = 128\ R/45\ \pi$, where R is the basemat radius (= 25.675 m) and each radius circle, r_o, is equal to 2.69 m such as $\Sigma\ \pi\ r_o^2 = S_{TOT} = \pi R^2$. If we consider only one zone the spring, K, can be compared, for low frequency to usual formulas, K' for the various rigid body motions;

- vertical : $K_V = 1.57 \times 10^{11}$ N/m $K'_V = 1.83 \times 10^{11}$ N/m.
- horizontal: $K_H = 1.26 \times 10^{11}$ N/m $K'_H = 1.39 \times 10^{11}$ N/m.
- rocking : $K_\phi = 5.78 \times 10^{13}$ N-m $K'_\phi = 8.06 \times 10^{13}$ N-m.

The discrepancy between Sophonie results and usual formulas is 16%, 9% and 28% for the various motions. This can be explained mainly by the mesh which is not circular in Sophonie calculation.

2.3 Application to PWR reactor building

For application to the building, the basemat was represented by 91 circles and 5 concentric zones in the same hexagonal mesh. The impedance matrix is a 5x5 terms for vertical excitation and 10x10 terms for horizontal excitation as no hypothesis was made about coupling terms between displacement and rotation.

2.4 Analysis of impedance matrix

For vertical displacement of the basemat, the stiffness matrix to introduce shows important coupling terms between adjacent zones and bigger terms for the external zones (see table 1). Similar remarks can be done for horizontal or rocking motion.

Table 1

$$\begin{bmatrix} 0.57 & & & & \\ -0.46 & 1.4 & & \text{Symmetry} & \\ -0.014 & -0.79 & 2.1 & & \\ -0.034 & -0.013 & -1.12 & 2.8 & \\ -0.033 & -0.077 & -0.076 & -1.48 & 2.32 \end{bmatrix}$$

Stiffness matrix, $\bar{K}$, for vertical excitation

$$K = k\bar{K} \qquad (\Sigma \Sigma K_{ij} = 1), \qquad k = 1.57 \times 10^{11} \text{ N/m.}$$

3 MODAL ANALYSIS

The modal analysis of the building has been performed with the axisymmetric model and impedance SSI matrix, successively for vertical and horizontal excitation.

3.1 Vertical excitation

The first mode, at 5.4 Hz, is predominant for the seismic response and no basemat deformation is observed (see table 2).

We can notice that this mode is similar to the mode calculated with a rigid basemat assumption if we correct the frequency by the coefficient $\sqrt{K'_v/K_v}$ of § 2.

Table 2. Modal analysis results

Vertical excitation		Horizontal excitation	
frequency	modal mass	frequency	modal mass
5.37	106.3	2.16	61.3
8.38	0.4	3.25	0
8.70	0.7	5.1	18.1
10.42	1.5	8.0	25.9
		8.7	1.0
		11.8	1.0

Two additional calculations were performed with simplified impedance matrices that is to say diagonal matrices (table 3).

- If the diagonal terms are supposed proportional to the zone area, Winkler model, the predominant mode at 5 Hz shows an important deformation of basemat.
- If the diagonal terms are calculated by summation of complete matrix terms ($\overline{K_i} = \sum_{j=1,5} K_{ij}$), the result is similar to the calculation with the complete matrix.

In fact when looking the two diagonal matrix, one can observe that the Winkler model gives terms too stiff in the internal zone.

Table 3

Winkler model

$$\begin{bmatrix} 0.077 & & & & \\ & 0.13 & & \text{Symmetry} & \\ & & 0.19 & & \\ 0 & & & 0.26 & \\ & & & & 0.33 \end{bmatrix}$$

Second diagonal matrix

$$\begin{bmatrix} 0.026 & & & & \\ & 0.056 & & \text{Symmetry} & \\ & & 0.100 & & \\ & 0 & & 0.156 & \\ & & & & 0.656 \end{bmatrix}$$

Diagonal stiffness matrices, $\overline{K}$, ($\overline{K_i} = k\, K_i$, $k = 1.57\ 10^{11}$ N/m

3.2 Horizontal excitation

The modal shapes of the first modes show (see figure 2):

- first a rocking mode with global motion of the building,
- a second mode with no motion of the internals, the two containments have opposite sign motion,
- the third mode is mainly an internal mode.

The first mode frequency, if corrected by the coefficient $\sqrt{K'_\psi / K_\psi}$, is similar to the rigid basemat calculation.

The third mode, which must be less sensitive to the previous coefficient because it involves basemat deformation in addition to soil

springs, has a frequency 5.1 Hz, lower than calculated with rigid basemat 6.2 Hz (or with beam model 6.9 Hz).

4 CONCLUSION

The Sophonie code allows to calculate impedance matrix which was introduced in axisymmetric finite element model of the building.

The main vertical mode and the first horizontal mode, which are global motion modes (vertical or rocking) on the soil stiffness, could have been calculated with rigid body model of the basemat.

The third mode excited by horizontal excitation is sensitive to the basemat deformation and needs a correct calculation of the impedance matrix.

In addition calculations, made for vertical excitation with simplified diagonal impedance matrix, show that springs, proportional to the surface area where it is applied, does not give the correct mode as the springs are not stiff enough in the basemat external area.

5 REFERENCES

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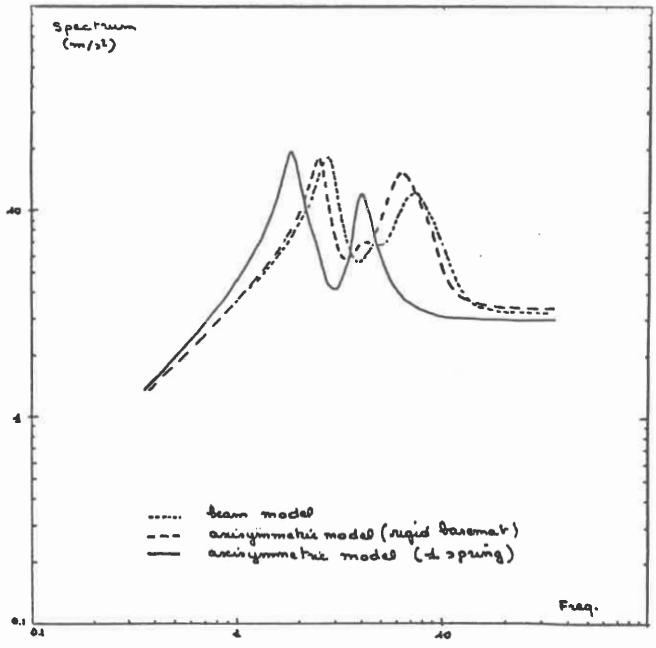

Fig. 1 - Horizontal floor response spectra at the top of internals.

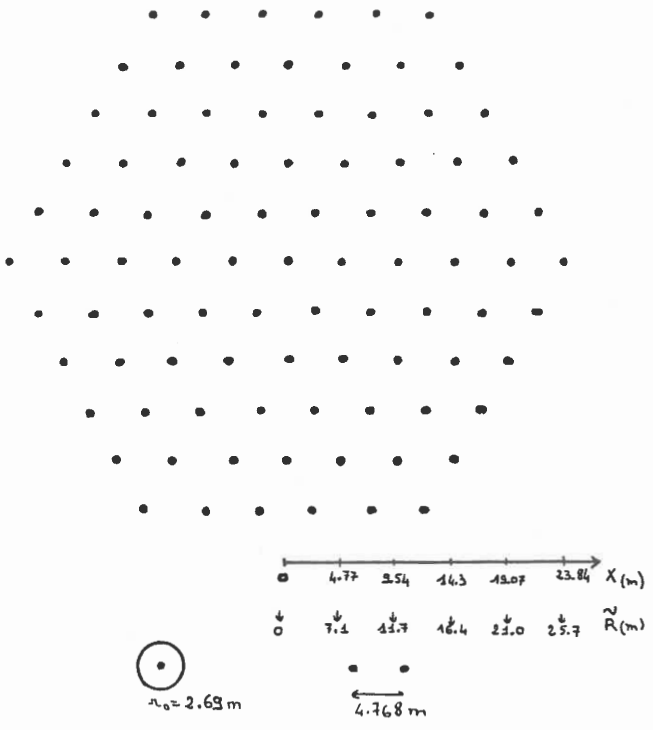

Fig. 2 - SOPHONIE computer code mesh for calculation of impedance matrix.

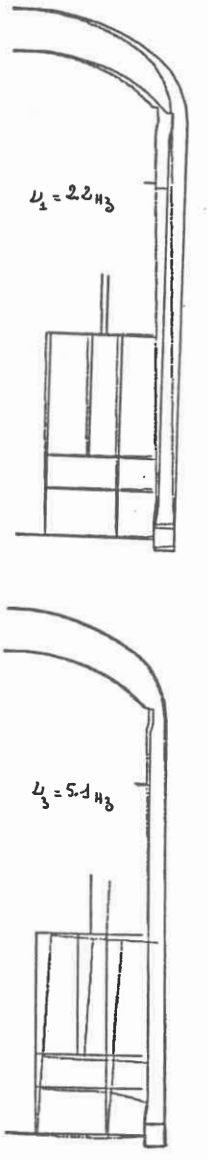

Fig. 3 - Mode shapes.