Effects of the structure-soil-structure interaction on the seismic behaviour of a nuclear power plant

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1 INTRODUCTION

In the calculation of the dynamic response of structures subjected to seismic excitation, the interaction between each structure and the soil is considered. But in the case of closely spaced structures, it may be necessary to also consider the interaction between adjacent structures through the soil.

Usually, the seismic analysis of a nuclear power plant in France is performed without taking account of the through-the-soil coupling effects ; each building is studied in "isolated configuration".

In this paper, the seismic analysis of a twin 900 MW nuclear power plant is presented. In a first time, all the buildings are considered isolated, in a second time, the through-the-soil coupling effects are taken into account. The buildings are resting on an intermediate soil characterized by a shear wave velocity of Vs = 583 m/s.

The layout and the dimensions of the rafts are illustrated in fig. 1.

The free-field motion is characterized by the EDF spectrum shown in fig. 2, with zero period acceleration normalized to 0.1 g in the horizontal direction and 0.067 g in the vertical direction.

The seismic excitation is represented by 2 vertically incident SH waves and one vertically incident P waves. The three excitations correspond to three artificial accelerograms of twenty seconds duration, compatible with the EDF spectrum.

The study is performed with the computer code CLASSI (Continuum Linear Analysis for Soil Structure Interaction) presented by Luco (1980).

The linear three dimensionnal soil-structure interaction problem is treated by using a substructure approach, which requires the solution of two basic problems involving the foundation and the soil. The first basic problem corresponds to the calculation of the dynamic force-displacement relationship at the interface between the foundation and the soil. The resulting relation is embodied in the impedance (dynamic stiffness) matrix. The second basic problem corresponds to the calculation of the dynamic response of the foundation, in absence of the super structure, when subjected to seismic excitation in the form of elastic waves. The resulting response of the foundation is called "foundation input motion".

The effects introduced by the presence of the superstructures and by the mass of the foundation are easily accounted for when once the two basic problems have been solved.

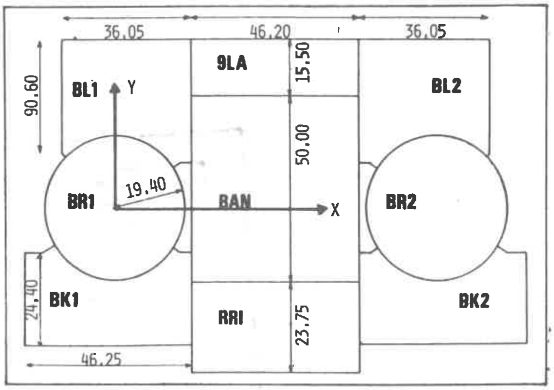

Figure 1. Layout of the foundations

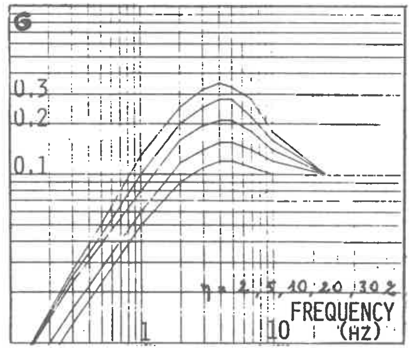

Figure 2. EDF spectrum

2 BASIC EQUATIONS FOR SOIL-STRUCTURE INTERACTION

The approach used in the computer code CLASSI to study the soil-structure interaction is well known :

- Analysis in the frequency domain.
- Substructure decomposition. Soil, foundation and superstructures.
- Decomposition in several basic problems.

This approach is illustrated in fig. 3 in the case of one structure, but is unchanged in the case of N structures.

The foundations are assumed to be perfectly rigid, resting on the soil surface (no embedment).

The seismic excitation, in a first step, is in the form of elastic waves with harmonic time dependance $e^{i\omega t}$. Thus the response of the N foundations and the N structures are also in the form $\{Uo\}\, e^{i\omega t}$.

The response to the free field excitation defined by an accelerogram is then obtained by means of a Fourier and inverse Fourier transform.

The total response of the foundations $\{Uo\}$ is decomposed in :

(1) $\{Uo\} = \{Uo^*\} + \{Us\}$

$\{Uo^*\}$ is the 6N generalized foundation input motion vector, which corresponds to the response of the foundations to seismic excitation in absence of external forces (massless foundation, no superstructure). $\{Uo^*\}$ includes 3N translational and 3N rotational components. For seismic excitation propagating vertically and foundations resting on the surface, the rotational components are zero and the translational components are equal to those of $\{Ug\}$, 3N vector characterizing the free field motion on the ground surface.

$\{Us\}$ is the 6N vector which corresponds to the response of the rigid foundations when sujected to the 6N generalised force $\{Fs\}$ issued from the structures (foundations + superstructures) in absence of seismic excitation.

(2) $\{Us\} = [C(\omega)]\{Fs\}$ where $[C(\omega)]$ is the 6N x 6N compliance matrix, and $[K(\omega)] = [C(\omega)]^{-1}$ is the impedance matrix.

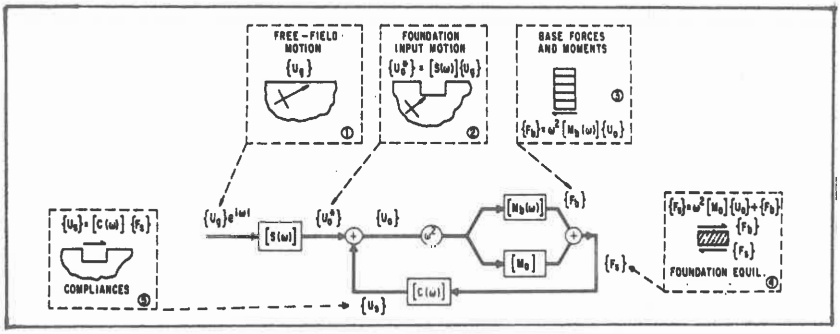

Figure 3. Decomposition of the interaction problem.

The equilibrium of the foundation of mass Mo is written :

$$(3) \quad \{Fs\} = \omega^2 \, [Mo] \, \{Uo\} + \{Fb\}$$

$[Mo]$ 6N x 6N mass matrix of the rigid foundations
$\{Fb\}$ 6N generalized force vector, applied by the superstructures on the foundations. This force $\{Fb\}$ can be written, by means of the equivalent mass matrix of the superstructures, in the form :

$$(4) \quad \{Fb\} = \omega^2 \, [M_b(\omega)] \, \{Uo\}$$

The elimination of $\{Fb\}$, $\{Fs\}$ and $\{Us\}$ in (1), (2), (3), (4) leads to :

$$(5) \quad \{Uo\} = \left([I] - \omega^2 \, [C(\omega)] \, \left([Mo] + [Mb(\omega)]\right)\right)^{-1} \{Uo^*\}$$

The equation (5) points out the through-the-soil interaction effects between the different structures - the scattering effects of the seismic waves by the foundations, in the term $\{Uo^*\}$; in this study (surface foundation, vertically propagating waves), these effects are non-existent - The radiating effects, in the term $[C(\omega)]\left([Mo]+[Mb(\omega)]\right)$

3 CHARACTERISTICS OF THE MODEL

- Superstructures

A French twin 900 MW nuclear power plant is composed of two Reactor buildings (BR), two Electrical and connecting buildings (BL), two Fuel buildings (BK), and three buildings common to units one and two ; electrical building (9LA) and Nuclear Auxiliary building (BAN and RRI), as illustrated in fig. 1. In the computer code CLASSI, the structures are defined by their fixed base modal characteristics and the associated damping ratios. The eigen frequencies and eigen vectors are issued from beam elements modelling, and the damping ratios are equal to 7 per cent for reinforced concrete structures and 5 per cent for prestressed structures (Reactor building containment). The principal characteristics of the 3 structures, BR, BK, BAN are provided in table 1.

- Foundations

They are rigid, weighty, resting on the surface. The layout is illustrated in fig. 1.

Masses in ton		Dimensions in metre	Frequencies of the main fixed-base modes in Hz				
				Containment		Internal structures	
BR	57 400	Ø = 38.80 H = 56.00	X Y	4.086	15.21	5.69	14.03
BK	33 200	Lxl = 46.25x22 H = 46.50	X Y	5.68 3.56	16.43 7.92	 18.40	
BAN	57 430	Lxl = 46.20x50 H = 27.30	X Y	9.20 13.45	 27.4		

Table 1. Main characteristics of structures.

To obtain the compliance matrix, each foundation has been divided into smaller subregions over which the tractions are considered to be constant.

- Soil

The soil is modelled as a uniform viscoelastic half-space characterized by a shear wave velocity of Vs = 583 m/s, density ρs = 2.1 Ton/m³, Poisson's ratio ν= 0.4 and material damping constant ξs = 0.05.

4 RESPONSES OF THE STRUCTURES

4.1 Transfer functions

As a first step in the study of the interaction effects, it is interesting to consider the transfer functions for the various buildings. In fig. 4, 5, 6, and 7, for the BR, BK and BAN, are given the frequency dependent transfer functions $Z_B(\omega)$ and $Z_\theta(\omega)$ for the base of foundations, and transfer functions $Z_T(\omega)$ for the top of structures, in the cases with, and without, the through-the-soil coupling effects.
The transfer function Z_B corresponds to the ratio of the horizontal motion at the base of the foundation of the structure to the free field motion Ug. The transfer function Z_θ corresponds to the ratio of the rotation of the base (multiplied by the length one) to the free field motion Ug. The transfer function Z_T corresponds to the ratio of the horizontal motion at the top of the structure to the free field motion Ug.
The results in fig. 4a, b, c show no modification in the frequency of the main peak (f = 2.3 Hz) for the Reactor building. In other respects, Fig. 4d shows a decrease of the frequency of the main peak for the vertical translation.
The results in Fig. 5 for the Nuclear Auxiliary Building show large modifications in transfer functions and more particulary the emergence of a peak at about 2.3 Hz which is precisely the fundamental frequency of the Reactor building. In figure 5a and 5c, for the translation transfer function Z_{BX} and Z_{BY}, the 2.3 Hz peak is one of the highest peaks but in fig. 5b and 5d for the rocking transfer function $Z_{\theta X}$ and $Z_{\theta Y}$, the 2.3 Hz peak is not substantial and the main peak is increased in frequency in comparison to the case without the through-the-soil coupling effect.
The results shown in Fig. 6 for the Fuel building are similar to those

of Fig. 5. It must be noticed that for the rocking transfer functions, Z_{θ_X} and Z_{θ_Y}, the main peak is again notably increased in frequency (see fig. 6d for Z_{θ_X}). The results in Fig. 6b for the vertical translation are similar to those of fig. 4d, with a decrease of the frequency of the main peak which becomes about 2.6 Hz.

The results in Fig. 7a and 7b show very slight modification for the translational transfer functions at the top of the reactor building, except for the second peak in fig. 7b (Reactor building internal structures) which is much lower in amplitude. This second peak corresponds to the first frequency of the fixed base internal structures.

In Fig. 7c and 7d, for the Nuclear auxiliary building, the results show amplification and deamplification, but above all an increase of the frequency of the main peak.

In Fig. 7e and 7f, for the Fuel building, the results show no modification of the frequency of the main peak, but a decrease of the amplitude.

To explain the differences between 7c and d on the one hand and 7e and f on the other hand, it must be noticed that the Nuclear auxiliary building is "rigid" and the Fuel building is "flexible" (in his upper part).

In conclusion, the results in Fig. 4, 5, 6 and 7 allow us to say that
- the two Reactor buildings, the heaviests of the nuclear island, carry along the foundation of the other buildings during their movement,
- the presence of a heavy building close to one another, in a manner constitutes a fixed base which increase the rocking frequency of the foundation. It is the case for the Nuclear auxiliary building flanked by the two Reactor buildings, and for the Fuel building close to the Reactor building and the Nuclear auxiliary buildings BAN and RRI.
- this increase of base rigidity have more less influence on the response of the top of the building than this building is more flexible,
- in the vertical direction, there is a carry along effect for all the buildings, which gives a marked decrease in the fundamental frequency of this movement.

4.2 Results of the time-history analysis

A second way of analysing the interaction effects results for considering the floor response spectra, and the differential displacements.

4.2.1 Floor response spectra

The floor response spectra at the top of buildings are given in figures 8, 9, 10 for the Reactor building, Nuclear auxiliary building and Fuel building. It can be observed that taking account of the through-the-soil coupling effects gives no important differences and more often the differences are a decrease of the accelerations.

Fig. 8, for the Reactor building, shows no modification for the containment in X direction and a decrease for the internal structures and for the containment in Y direction.

Fig. 9, for the Nuclear Auxiliary building, shows - for the horizontal direction X and Y, a little shift towards the high frequencies - for the vertical direction Z, a little shift towards the low frequencies.

Fig. 10, for the fuel building, shows - for the horizontal direction X and Y, no modification in frequency (this is due to the flexibility of the building) - for the vertical direction Z, a shift towards the low frequencies.

All this results are in agreement with the observations made previou-

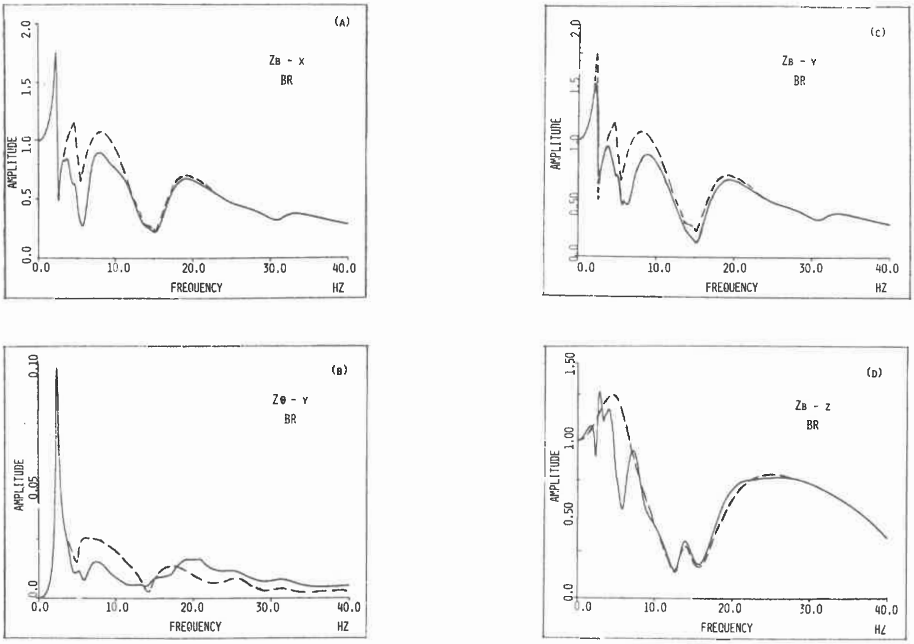

Figure 4 : Amplitudes of the translational Z and rocking Z transfer functions for the base of the Reactor building. The segmented line repre-sents the amplitude of the corresponding transfer functions for the foundations without the through the soil coupling effects.

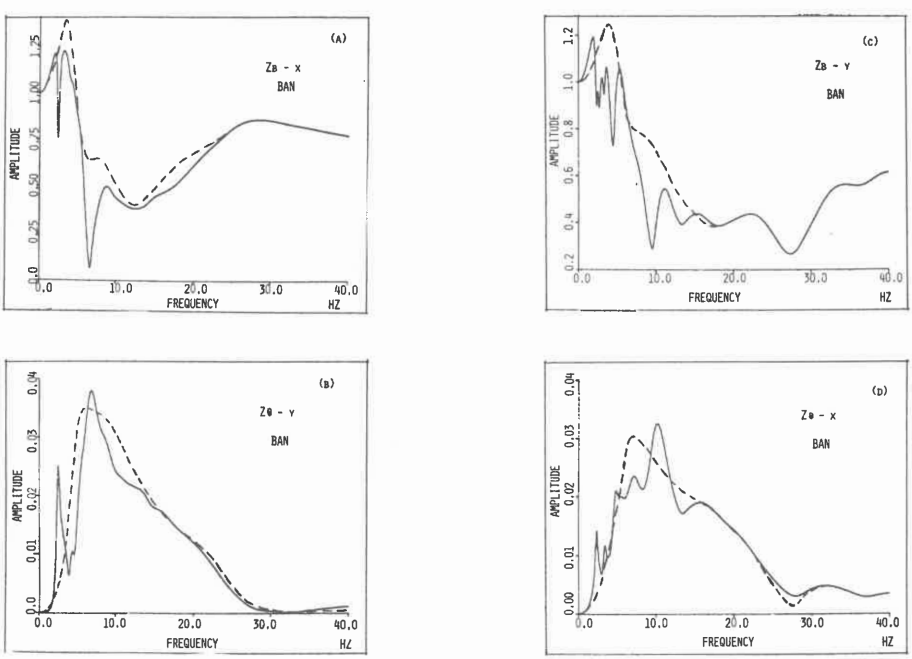

Figure 5 : Amplitudes of the translational Z and rocking Z transfer functions for the base of the Nuçlear Auxiliary building.

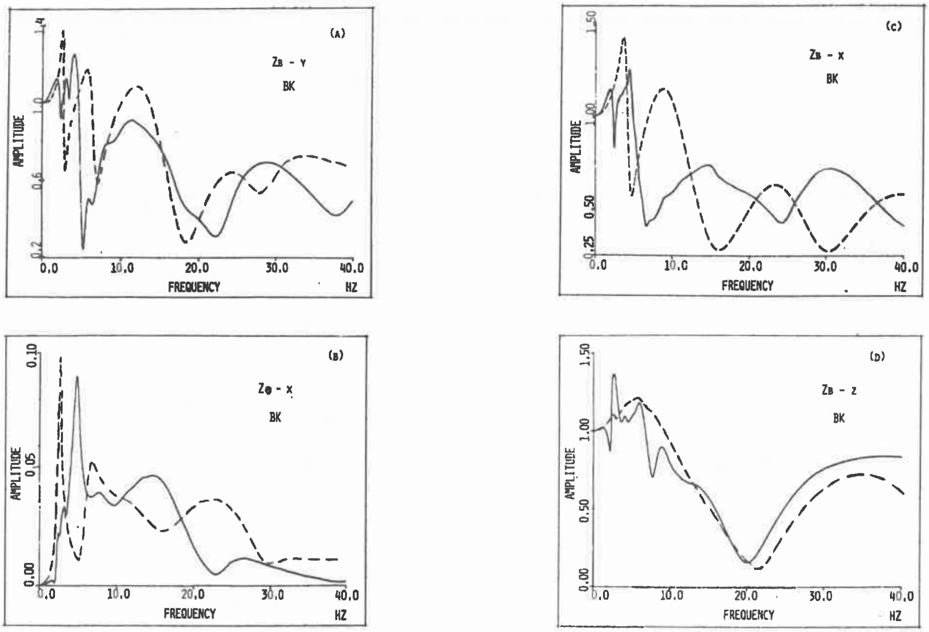

Figure 6 : Amplitude of the translational Z and rocking Z transfer functions for the base of the Fuel building.

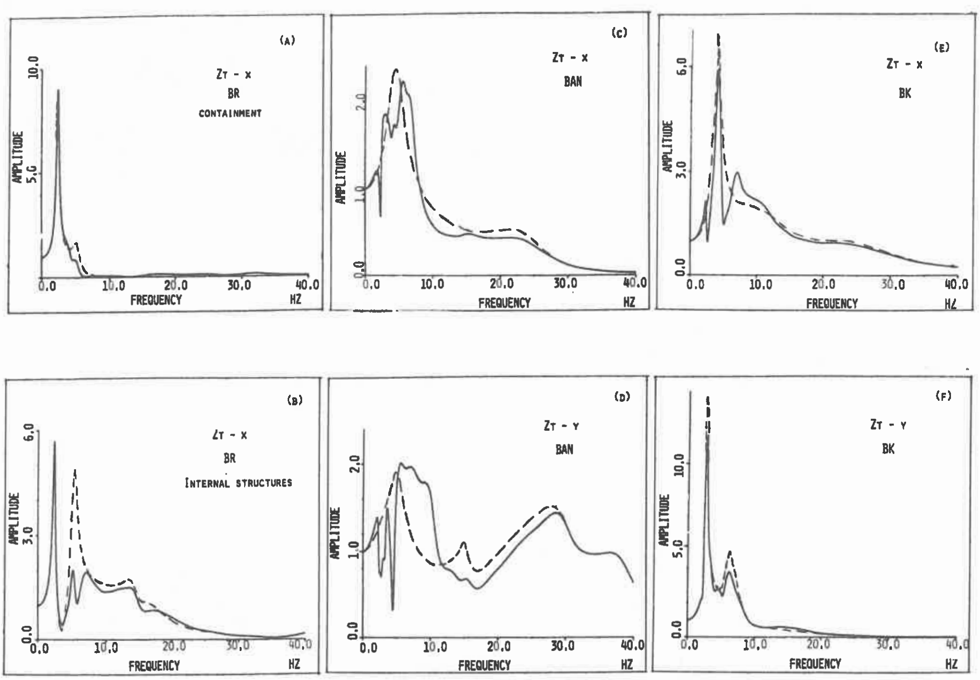

Figure 7 : Amplitude of the translational Z_T transfer functions for the top of the Reactor, Fuel and Nuclear Auxiliary buildings.

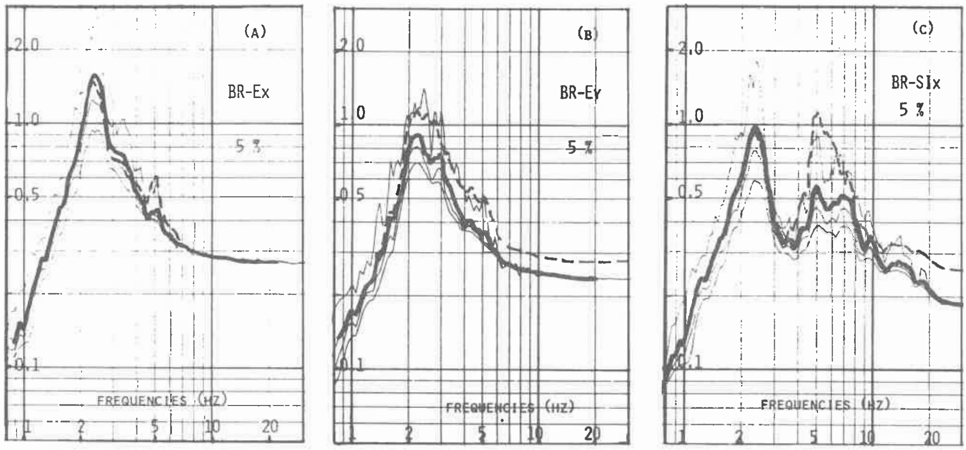

Figure 8. Horizontal floor response spectra at the top of the Reactor building.

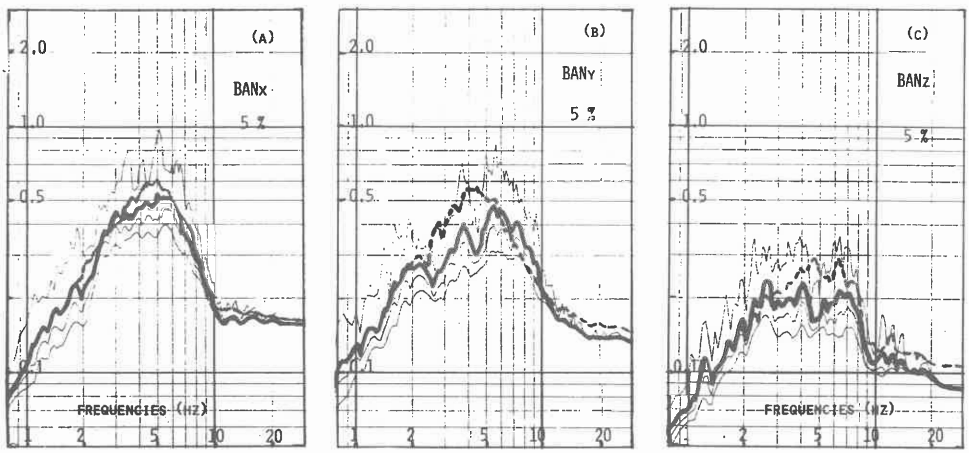

Figure 9. Floor response spectra at the top of the Nuclear Auxiliary building.

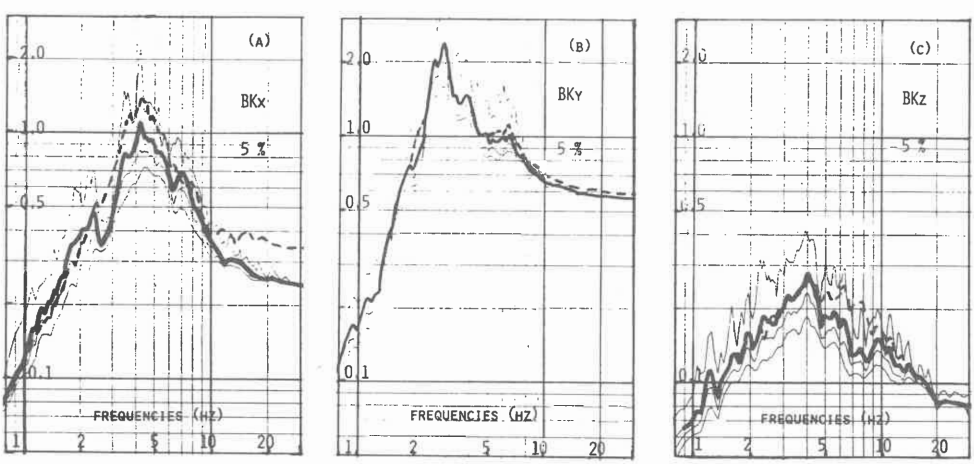

Figure 10. Floor response spectra at the top of the Fuel building.

sly on the transfer functions.

4.2.2 Differential displacements

The differentials displacements between the different buildings for the level of the raft, and for a higher level in the structure are presented in table 2, with and without the through-the-soil coupling effects.

The values are not very different, but table 2 clearly shows that :
- at the level of the rafts, the differential displacements are reduced by the interaction effects ;
- in the upper parts of the structures, the differential displacements are of the same order, but generally in increase in the direction defined by the two buildings and in decrease in the orthogonal direction.

This results can be easily explained by the interaction effects
- dragging along the rafts in translation,
- antagonism of the structures for the rocking around the axis orthogonal to the axis of the two buildings,
- dragging along the structures for the rocking around the axis of the two buildings.

	Raft		High level		
	X	Y	X	Y	Z
BR - BK	1.24 (1.72)	0.94 (1.94)	11.04 (13.08)	13.26 (12.17)	2.47 (4.19)
BR - BAN	1.33 (1.57)	1.04 (1.61)	5.73 (5.33)	3.64 (5.38)	

Table 2. Differential displacements (in millimeter)
1^{st} line (2^{nd} line) : with (without) the through-the-soil coupling effects.

CONCLUSIONS

We have pointed out the through-the-soil coupling effects on the seismic response of a twin 900 MW nuclear power plant resting on an intermediate soil (Vs = 583 m/s). The same study has been performed with a soft soil (Vs = 292 m/s) and we have obtained similar results, but a little more pronounced. We can conclude that the through-the-soil coupling does not sensibly modify the seismic response, such as floor response spectra or differential displacements, of such a nuclear power plant. Thus, it does not seem necessary to take into account the through-the-soil interaction between buildings in the design of a nuclear power plant.

REFERENCES

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