Comparison of Methods for the Seismic Response of Nuclear Power Plant Buildings

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ABTRACT

Five methods have been used to compute the response of reactor buildings :

1/ The Square Root of Sum of Squares.

2/ The Complete Quadratic Combination.

3/ The Sum of Absolute Values.

4/ A modal time-historic analysis.

5/ A modal synthesis method of soil-structure interaction.

Two types of reactor building are proposed :

1/ A fast reactor building modelized by a bi-dimensional beam-elements model, including a foundation on elastomer pads.

2/ A P.W.R. reactor building modelized with a classical stick model and soil stiffness or soil impedance matrix.

Results of accelerations displacements and forces are compared in several tables.

1. Introduction

With the assumption of linear behaviour, we have compared four different methods of seismic analysis in order to compute the response of two different reactor buildings. Some of the results are presented in this paper.

The usual method to compute the response of a structure to an earthquake loading is the Square Root of Sum of Squares method (SRSS). It is well known that in the case of modes close to each other, this method can lead to significant errors.

In order to improve it, DER KIUREGHIAN has proposed the Complete Quadratic Combination, based on a statistic approach of the problem [1].

It is also possible to carry out a time-historic analysis of the response of the structure ; in the present paper we propose a semi-analytical modal analysis.

The last method we used has been proposed by LUCO and WUONG [3] ; it is a modal synthesis method, applied in the computer program CLASSI.

The first model we studied is a bi-dimensional model of a Fast Reactor Building, including quite sophisticated foundations, the second one is a stick model of reactor building with a soil stiffness.

2. The computing methods

2.1 The SRSS method

This method is well known and we do not think it is necessary to expose it once more. We just focus on the basic assumption of this method : the responses of the modes of the structure are independant random variables.

2.2 The CQC method

In a recent paper [1], DER KIUREGHIAN studied the response of a viscously damped, linear structure to a stationary excitation. Assuming a white noise input, he could exhibit approximate expressions of the three first spectral moments of the response.

Then, being interested in the statistic of peak response, he could obtain a very simple approximate expression of the mean of peak response which is written :

$$\overline{R} = [\sum_i \sum_j \rho_{ij} \overline{R}_i \overline{R}_j]^{1/2}$$

where :

R_i is the maximum modal response of the i-th mode of the structure.

ρ_{ij} is a coefficient, the expression of which is :

$$\rho_{ij} = \frac{2\sqrt{\xi_i \xi_j}\,[(\omega_i+\omega_j)^2(\xi_i+\xi_j) + (\omega_i^2-\omega_j^2)\,(\xi_i-\xi_j)]}{4(\omega_i-\omega_j)^2 + (\omega_i+\omega_j)^2\,(\xi_i+\xi_j)^2}$$

where ω_i and ξ_i are the frequency and the damping coefficient of the i-th mode of the structure.

So a new response spectrum method is formulated which has been named the complete combination method.

Then, verifying that "the strong phase of earthquake-induced ground motion is usually nearly stationary", and that the wide band assumption is acceptable, this method has been proposed in seismic analysis of structures [2].

2.3 The time-historic method

We assume that the modal damping matrix is diagonal so as to get an uncoupled system of equations and we compute the response of each mode by a semi-analytical method as follows.

Each modal equation can be written :

$$\begin{cases} \ddot{q}(t) + 2\xi\omega\,\dot{q}(t) + \omega^2 q(t) = p(t) \\ q(o) = q_o,\ \dot{q}(o) = \dot{q}_o \end{cases}$$

We name $q_1(t)$ and $q_2(t)$ the solutions of the homogeneous equation and we introduce $a_1(t)$ and $a_2(t)$ so that :

$$q(t) = a_1(t)\,q_1(t) + a_1(t)\,q_2(t)$$

It can be shown that $\dot{a}_1(t)$ and $\dot{a}_2(t)$ are the solutions of the system :

$$\begin{vmatrix} q_1 & q_2 \\ \dot{q}_1 & \dot{q}_2 \end{vmatrix} \begin{vmatrix} \dot{a}_1 \\ \dot{a}_2 \end{vmatrix} = \begin{vmatrix} 0 \\ p \end{vmatrix}$$

So we are able to obtain the analytical expressions of $\dot{a}_1(t)$ and $\dot{a}_2(t)$ versus $p(t)$. Then we have $a_1(t)$ and $a_2(t)$ by integration :

$$a_1(t) = a_1(o) + \int_o^t \dot{a}_1(s)\,ds$$

$a_1(t)$ et $a_1(o)$ are functions of q_o et $\dot{q}_o$ and the integral is computed by the trapezoides method.

The main advantage of this method is that we are led to a very low cost because the integration does not need a small time-step. Nevertheless this method cannot be applied for a non-linear system.

2.4 The method of CLASSI

Inthis modal synthesis method, for the soil-structure interaction, the foundation of the building is assumed to be rigid.

Firstly, we have to know the foundation input motion U_o which is defined as the harmonic response of the centroide of the rigid, massless foundation, without structure, to a seismic harmonic wave.

Then we have to know the soil motion U_s on the lower face of the foundation, versus the forces F_s due to the foundation, what is written :

$$U_s = C(\omega)\,F_s$$

where $C(\omega)$ is the complex admittance soil matrix.

We also need the relation between the actual motion U of the foundation and the forces F induced by the structures, which is written :

$$F = \omega^2 M(\omega) U$$

where $M(\omega)$ is complex and called the "equivalent mass matrix".

Then, the synthesis consists of writting the equilibrium of the foundation, what enables us to write :

$$U = \{I - \omega^2 C(\omega) [M_0 + M(\omega)]\}^{-1} U_0$$

where M_0 is the mass matrix of the foundation.

An inverse FOURIER transformation gives us the time-historic solution for a given accelerogram and a given type of wave.

3. Presentation of models and results

Two models of Nuclear Power Plants are shown, corresponding to two different branches. Results about displacements, accelerations and forces are shown in tables.

3.1 Fast Reactor Building

The fast reactor building includes a foundation sheme which incorporates two rafts separated by reinforced elastomer pads so as to isolate the structure from the effects of strong horizontal seismic motions. The hearth is placed on a suspension system.

The model is bi-dimensional, composed of classical beam elements (Fig. 1). The soil-structure interation consists of spring constants, estimated by DELEUZE's theory [4].

The horizontal and the vertical seismic directions are foreseen. Some results are shown in the Tables 1.1 and 1.2. On the Fig. 1 are given the main participating frequencies for each direction.

The study is carried out with the NRC spectrum and with the Long-Beach (North-South) accelerogram.

3.2 PWR reactor building

3.2.1 First modelling

This analysis is carried out with a bi-dimensional study. The modelling consists of classical beam elements (two modes, each with three degrees of freedom).

The sketch of the building shows a rigid raft surmounted by three masts, clamped at the same point of the raft (stick-model), which represent the outside limit, the inside limit and the inner structures (Fig. 2.1).

The ground is represented by springs calculated according to DELEUZE's method [4]. This first model is used for the SRSS and CQC methods and for the time-historic analysis. The considered spectrum is the NRC spectrum and the accelerogram is the one of Long-Beach earthquake (North-South).

3.2.2 Second modelling

This study has been carried out with the program CLASSI on the same reactor building and with the same ground.

The single difference between this study and the upper one is that we take into account the soil-structure interaction with the aid of impedance functions depending on frequency (Fig. 2.2).

The stick-model of the structure is unchanged ; its modes and frequencies are computed with clamped basis (instead of soil-stiffness), as requiered by CLASSI.

The seisme wave considered is a volume wave with vertical propagation. The accelerogram is the same as for the time-historic analysis.

The results for the PWR building are shown in the table 2.

4. Comments on results and conclusions

On these results, we can see that the classical time-historic analysis and the modal synthesis method of CLASSI lead to very close results and we can conclude that DELEUZE's method for soil stiffness is once more validated here.

For the SRSS and the CQC methods, they give the same results, on the model, for the horizontal componant of the earthquake ; and, of course, that is expected because of the distance of the frequencies of the participating modes.

For the vertical componant of the earthquake, we have not really closed frequencies but the hight level of damping gives extra-diagonal coefficients ρ_{ij} that are not small ; consequently the results are not the same with the two methods, and we can see that the CQC results are closer to the transient analysis results. We do not exhibit results of accelerations for the CQC method because it seemed to us that the correlation matrix ρ was just usable for displacements and forces and that further studies have to be carried out in order to obtain a correlation matrix for accelerations.

So as to give one comparison more, we also present in the tables the results of the sum of absolute values method ; and of course this method widely overestimates the responses of the structures.

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Fast Reactor Building Horizontal Earthquake (ox) NRC 0.1 G		SRSS	CQC	Σ | |	Classical Transient
Accelerations at the nodes ($m.s^{-2}$)	60	1.21		1.33	1.37
	14	1.32		1.51	1.42
	40	1.36		1.70	1.47
	109	1.35		1.61	1.45
Displacements at the nodes (10^{-3} m)	60	33.29	33.29	33.44	36.08
	14	36.13	36.13	36.35	39.12
	40	37.12	37.12	37.48	40.17
	109	37.15	37.15	37.65	40.18
Forces (10^4 N) Moments (10^4 Nm) at the first named node of the liaisons	56-20	Fx 3 977 Fy 7 758 Mz 50 541	Fx 3 977 Fy 7 750 Mz 50 500	Fx 4 060 Fy 8 537 Mz 53 500	4310 8410 55100
	60-99	Fx 1 186 Mz 2 533	Fx 1 186 Mz 2 534	Fx 1 419 Mz 2 969	
	60-32	Fx 4 546 Mz 45 916	Fx 4 542 Mz 45 875	Fx 4 721 Mz 48 417	4970 50000
	60-36	Fx 8 550 Mz 70 042	Fx 8 546 Mz 70 000	Fx 8 904 Mz 73 708	9410 76700

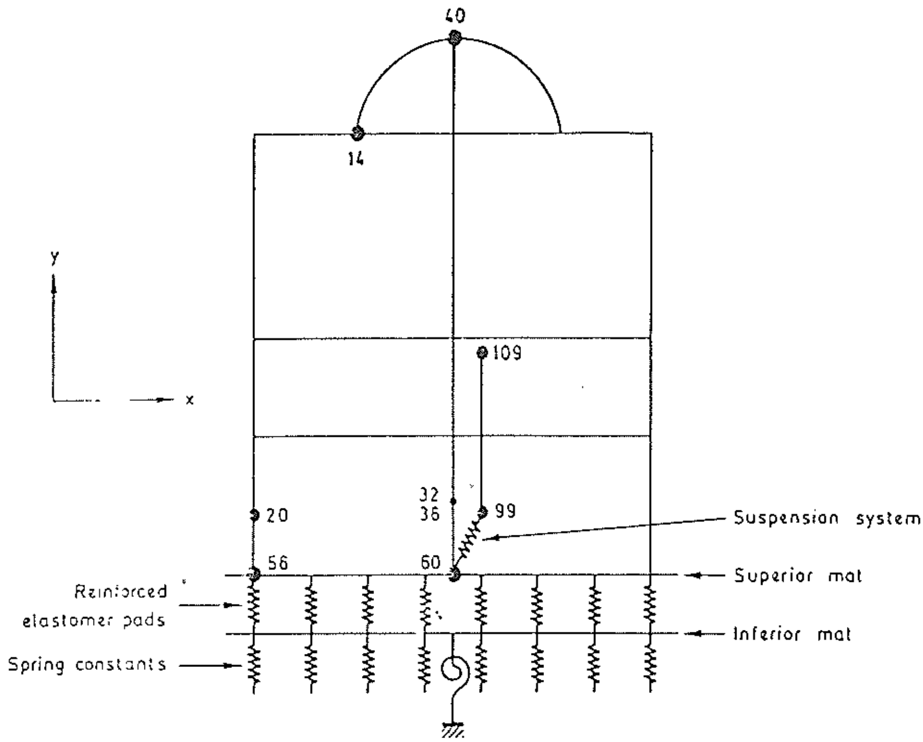
Table 1.1

Fast Reactor Building Vertical Earthquake (Oy) NRC 0.067 G		SRSS	CQC	Σ | |	Classical Transient
Accelerations at the nodes ($m.s^{-2}$)	60	0.60		0.97	0.94
	14	0.84		1.54	1.21
	40	0.87		1.68	1.24
	109	1.07		1.48	1.18
Displacements at the nodes (10^{-3} m)	60	0.24	0.33	0.39	0.33
	14	0.32	0.46	0.54	0.45
	40	0.34	0.47	0.55	0.46
	109	9.10	9.11	9.34	9.82
Forces (10^4 N) Moments (10^4 Nm) at the first named node of the liaisons	56-20	Fy 3 472 Mz 3 756	Fy 5 058 Mz 3 821	Fy 5 950 Mz 7 808	5119 4108
	60-99	Fy 2 132	Fy 2 129	Fy 2 270	
	60-32	Fy 1 834	Fy 2 388	Fy 2 740	2337
	60-36	Fy 3 062	Fy 3 957	Fy 4 592	3847

Table 1.2

P.W.R. Reactor Building Horizontal Earthquake (ox) NRC 0.1 G		SRSS	CQC	Σ	Classical Transient	CLASSI Transient
Accelerations at the nodes (in $m.s^{-2}$)	2	0.888		1.580	1.196	1.126
	6	2.999		3.676	2.704	2.454
	11	2.950		3.577	2.659	2.433
	15	1.273		1.924	1.484	1.470
	17	2.085		3.534	1.922	1.992
Displacements at the nodes (in 10^{-3}m)	2	2.15	2.25	2.27	2.39	1.96
	6	10.76	10.68	11.19	10.54	8.63
	11	10.57	10.49	10.97	10.36	8.40
	15	3.67	3.77	4.17	3.93	3.25
	17	6.01	6.10	6.90	6.25	5.21
Forces (10^4 N) Moments (10^4 N×m)	Liaison 2-3	T 3 490 M 149 800	T 3 450 M 144 800	T 4 212 M 181 100	T 3 464 M 135 500	T 2 967 M 122 000
	Liaison 2-8	T 6 510 M 267 900	T 6 423 M 257 900	T 7 760 M 321 600	T 6 488 M 243 400	T 5 386 M 213 500
	Liaison 2-13	T 4 645 M 86 890	T 4 768 M 81 620	T 7 174 141 300	T 4 926 M 81 430	T 4 927 M 82 500

Table 2



PARTICIPATING FREQUENCIES :

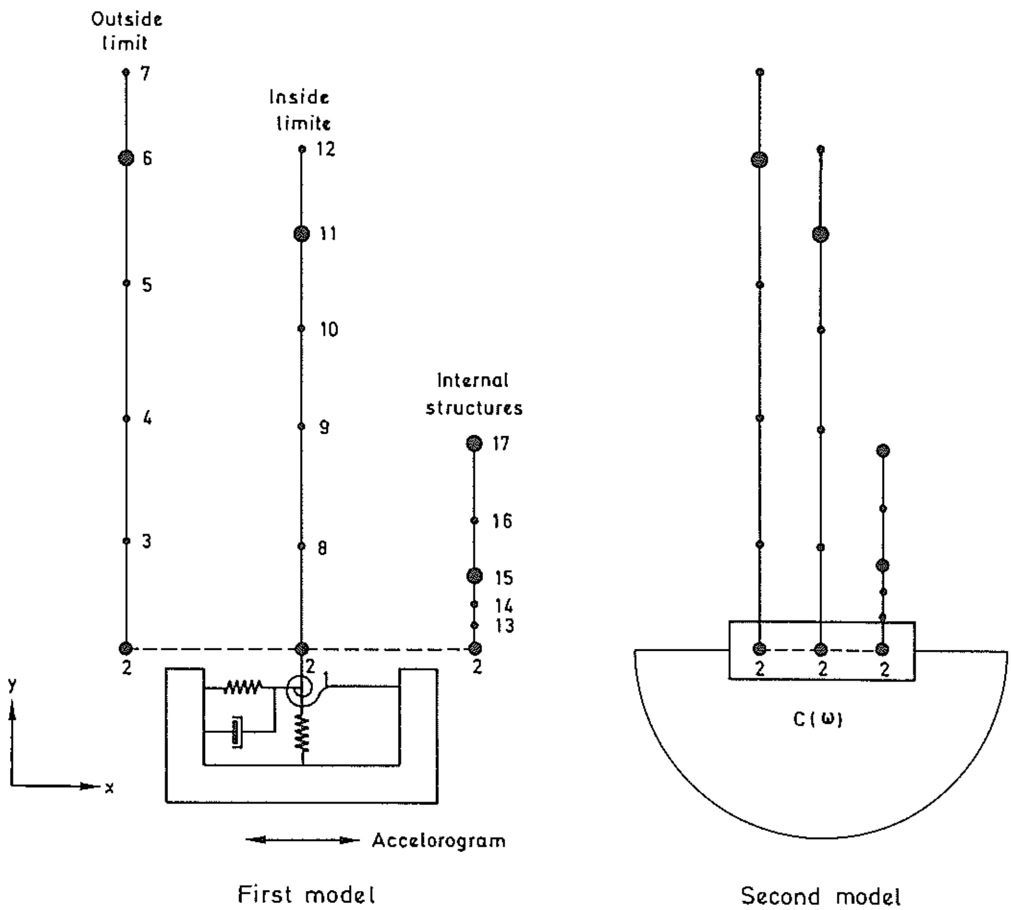
Horizontal direction

(Hz)		
Frequency	1.00	25.5
Modal damping	0.07	0.30
Modal mass	0.883	0.114

Vertical direction

(Hz)				
Frequency	1.73	5.78	7.78	8.76
Modal damping	0.124	0.076	0.183	0.246
Modal mass	0.096	0.030	0.444	0.403

Fig. 1



⊛ nodes where results are showns in Table 2.

Fig. 2