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ON-SITE EXPERIMENTAL DYNAMIC ANALYSIS TO ASSESS THE SEISMIC BEHAVIOUR OF THE ITALIAN PEC FAST REACTOR BUILDING TAKING INTO ACCOUNT THE SOIL-STRUCTURE INTERACTION EFFECT

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SUMMARY

The paper describes the on-site dynamic tests carried out by ISMES on behalf of ENEA on the PEC fast reactor building, using various excitation methods (two eccentric back-rotating-mass mechanical vibrator, blasting in bore-hole, hydraulic actuators at the building foundations). It points out the purposes of the four tests campaigns performed at various construction stages and reports the main experimental results with concern both the design safety margins and the data for the validation of the three-dimensional numerical model of the reactor building, including soil-structure interaction phenomena.

INTRODUCTION

The numerical and experimental studies, performed in the years 1981-1982 to verify the adequacy of the PEC reactor-block design, demonstrated the need of design modifications in order to improve the core behaviour in an earthquake.
The adequacy of the new design solution adopted was demonstrated in the case that the first natural frequency of the reactor building corresponds to about 10 Hz, as evaluated in the building design analysis with a lumped-mass model.
However, due to the non-negligible uncertainties by which such simplified design analysis could be affected, it was decided to perform a detailed study on the reactor building dynamic response to check the design analysis and evaluate safety margins. This study consisted in on-site tests and the development and application of a three-dimensional numerical model of the reactor building, taking into account soil-structure interaction.
This paper deals with the experimental part of the work, which allowed the structural response to be directly characterized and also provided the data for the validation and calibration of the numerical model discussed in Ref. 1.

IN SITU CAMPAIGNS AND EXCITATION METHODS

The tests have been carried out in three construction stages and by using various excitation methods. The first tests were performed in 1983 and 1984 by use of a 100 kN two eccentric back-rotating-mass mechanical vibrator (shown in Photo 1), located on two different floors in various positions and directions (Ref. 2). In 1983 the fuel transfer cell was not constructed yet, while in 1984

it was about 80% constructed: both measurements and numerical analysis demonstrated the strong effects of this structural part on the building response.
Thus, the final tests were carried out on the complete structure, in March 1985 by use of vibrations generated by blasting in bore hole (the test took advantage of a geophysical investigation programme performed in the neighborhood of the site), and in December 1985 again with the cited mechanical vibrator in various positions and directions, and also by means of hydraulic actuators (flat jacks) located between the foundations of the reactor building and those of the adjacent fuel element handling building (see Photo 2 and Fig. 1). These actuators applied sinusoidal forces of up to 2500 kN. Fig. 2 shows, as an example, dynamic responses obtained by a mechanical shaker in several positions (Fig. 3) during the three testing campaigns carried out.
In the final experimental tests, the dynamic response of the reactor building was measured by means of a 55 unit transducers network (some positions are shown in Fig. 3); furthermore, the dynamic behaviour of the structures which are located around the reactor building was studied by means of 24 further measuring positions. The frequency range 1-18 Hz was analyzed.

EXPERIMENTAL TRANSFER FUNCTIONS AND SUBSEQUENT ANALYSIS

<u>General comments on the results</u> Basing on the analysis of the recorded data, the following considerations may be drawn:

- investigations carried out have indicated the possibility of getting reliable measurements of transfer functions, using an exciting equipment made of a mechanical vibrator and measuring the response by transducers of marked sensitivity.
  The excitation at the foundations by means of hydraulic actuators first of all have provided the possibility of using such dynamic loads to measure the transfer functions of the building. This type of excitation tools, if installed permanently, could be used to test, for verification purposes, the behaviour of specific components, restraints, anchors, supports after their installation;

- structural responses resulted to be considerably different (both in terms of natural frequencies and amplifications) in the three successive periods in which the structure was tested. Indeed, while in 1983 pours were being completed up to the working area level, in 1984 the fuel transfer cell was poured (concrete structure sited above the aforementioned elevation) and in December 1985 all the casts inside the reactor building as well as inside the adjacent structures were finished. According to both the experimental data and the numerical evaluations, the fuel transfer cell has a remarkable effect on the dynamic response of the building;

- the analysis of collected functions (Fig. 2) shows first amplification peaks in the range included between 14 and 15 Hz in 1983, between 12,5 and 13,5 Hz in 1984, and between 9,0 and 9,2 Hz in December 1985;

- the vibrations induced by explosions have been recorded at different locations in the building, at the surface free field conditions and in depth at the site (Ref. 2).

<u>Modal analysis</u> A detailed analysis of the transfer functions obtained during the final tests allowed the natural frequencies and the modal shapes of the first modes of the structure to be determined. Comparing the response at the various monitored elevations, we come to the conclusion that these amplifications correspond to structural deformation modes of the building that

are not solely ascribable to rigid body movements on the foundation soil.
The dynamic response in the two orthogonal planes seems to be enough similar as far as the first two amplifications peaks are concerned, 9,1 Hz in N-S plane and 9,2 Hz in E-W plane, while it is considerably different for the upper amplification peaks which lie at about 16.7 Hz in the plane N-S, and at about 21.0 and 21.7 Hz in the plane E-W, respectively (Fig. 2).
The fundamental frequencies and the modal shapes of the soil-structure system, were compared with the computed values in order to calibrate the numerical model of the reactor building (Ref. 1).
The experimental results also enabled the first natural frequencies of the adjacent buildings to be determined and the building-to-building interaction to be classified.

Direct determination of the floor response spectra on the basis of the experimental results For the direct evaluation of the seismic reactor building response, the transfer matrix $[R(f)]$, which connects the absolute response $\{\ddot{Q}_A(f)\}$ of the structure to the free-field earthquake $\{a(f)\}$ by the equation:

$$\{\ddot{Q}_A(f)\} = [R(f)]\ \{a(f)\}, \tag{1}$$

must be defined and determined.
In particular $\{\ddot{Q}_A(f)\}$ represents the absolute accelerations of the nine lumped masses - at which correspond the mass-matrix $[M_S]$ - by which the reactor building has been described.
These lumped masses have been obtained by defining structure layers separated by horizontal planes and assuming that these layers behave as rigid bodies.
The transfer matrix $[R(f)]$ can be evaluated from the results of the final experimental tests, according to the following procedure:

- the structure is considered as an elastic, linear system;
- said $[H_R(f)]$ the fixed base structural matrix which relates the relative accelerations $\{\ddot{Q}_R(f)\}$ of the reactor building to the column matrix $\{\ddot{X}_f(f)\}$ of the six independent movements of the foundation (considered as a rigid body), the following equation can be written:

$$\{\ddot{Q}_A(f)\} = [H_R(f)]\ \{\ddot{X}_f(f)\} + [T]\ \{\ddot{X}_f(f)\} \tag{2}$$

- the six independent seismic movements of the reactor building foundation are given from the next expression:

$$\{\ddot{X}_f(f)\} = \{a(f)\} + [\bar{Z}(f)]^{-1}\ (-[T]^T[M_S]\ \{\ddot{Q}_A(f)\}) \tag{3}$$

(where: $[\bar{Z}(f)]^{-1} = -\ (2\pi f)^2\ [Z(f)]^{-1}$) is the experimental soil-impedance matrix);

- on the basis of the equations (2) and (3), the correlation between the transfer matrix $[R(f)]$ and the remaining typical system matrices, can be defined:

$$[R(f)] = ([I] + ([H_R(f)] + [T])[\bar{Z}(f)]^{-1}\ [T]^T[M_S])^{-1}\ ([H_R(f)]+[T]) \tag{4}$$

(where $[I]$ is the unit matrix).

While the soil-impedance matrix has been evaluated solely by means of the experimental data, the assessment of the fixed base structural matrix required the use of an experimental-numerical methodology.
The experimental impedance functions reproducing stiffness and damping properties of the rock foundation, were taken into account for including soil-

structure interaction phenomena into the numerical model of the reactor building.

<u>Analysis of the results</u> Basing on the design free-field time histories in the case of Safe Shutdown Earthquake and by use of the eq. (1), the absolute accelerations at several elevations of the reactor building have been calculated.
The structure has been simultaneously excited along the three considered directions (N-S, E-W, and vertical) and the resulting floor response spectra have been evaluated.
The floor response spectra obtained by the experimental results for the horizontal and vertical directions at the foundation level (-12,75 m), at the vessel supporting floor (0,00 m) and at the working level (+5,50 m) are compared in Fig. 4 with the corresponding design spectra calculated by ANSALDO using a beam model of the building (the N-S design value at the foundation level was not calculated).
The horizontal response spectra are in general larger in design analysis, at least for frequencies relevant to the reactor block seismic behaviour (characterized by natural frequencies of 5-6 Hz).
Higher experimental values in the vertical direction generally correspond to rocking effects neglected in the design analysis that represents the building response on the reactor axis.

CONCLUSIONS

The detailed on-site experimental program carried out on the PEC fast reactor building has been described, together with the method adopted for directly estimating the floor response spectra of the structure.
All the excitation techniques employed led to coherent results. The use of hydraulic jacks at the reactor building foundations showed to be a very promising technique, especially if the possibility of such excitation type is foreseen in the reactor design phase.
A large number of transducers was necessary: the number adopted was correct in order to describe the structure response with the due detail.
The natural frequencies measured after reactor building completion are in good agreement with the values calculated in the design analysis: this confirms the adequacy of the adopted reactor-block design solutions.
The floor response spectra directly determined on the basis of the experimental results have been compared with the design values.
The combination between experimental tests and numerical analysis allowed the setting up of a calibrated model of the reactor building in which the experimentally determined soil properties were introduced.

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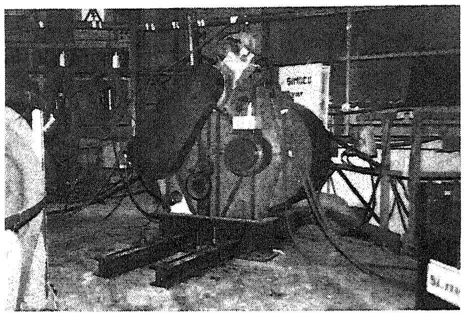

Photo 1 Two eccentric back-rotating mass mechanical vibrator

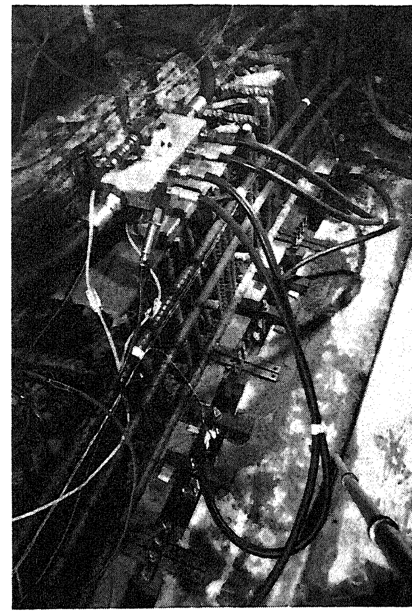

Photo 2 Installation of the hydraulic actuators

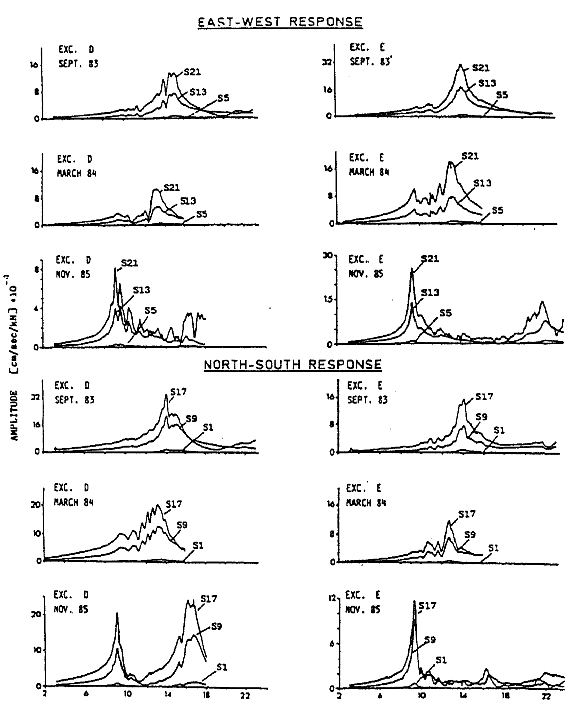

Fig. 2 Examples of transfer functions measured during the three in-situ tests by a mechanical exciter

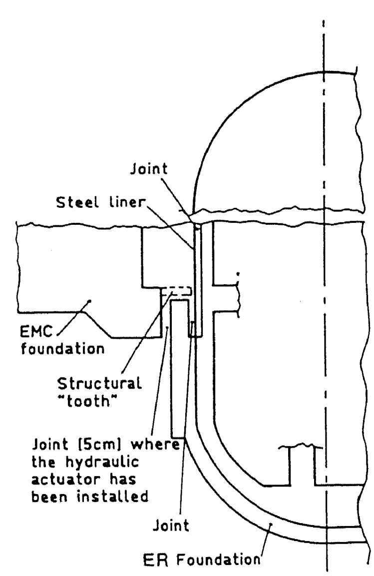

Fig. 1 Schematic representation of the Reactor Building (ER) and of the Fuel Element Handling Building (EMC) foundations of the excitation area

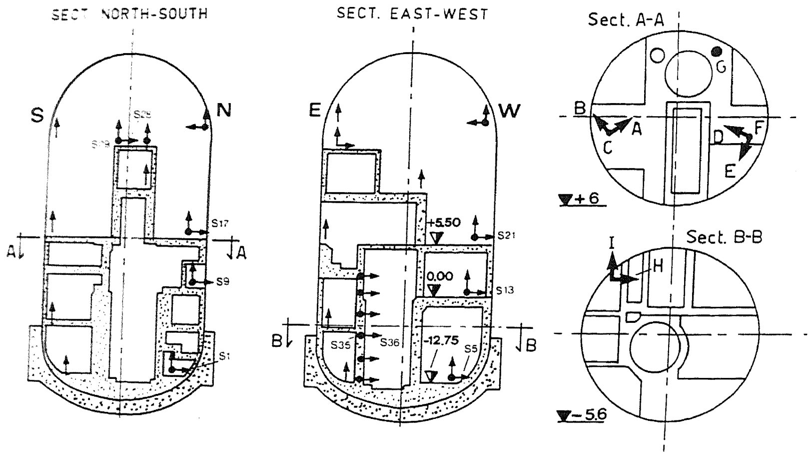

Fig. 3 Sketch of the PEC Reactor Building. Excitation positions and directions of mechanical shaker in the in-situ tests. Instrumentation axial positions

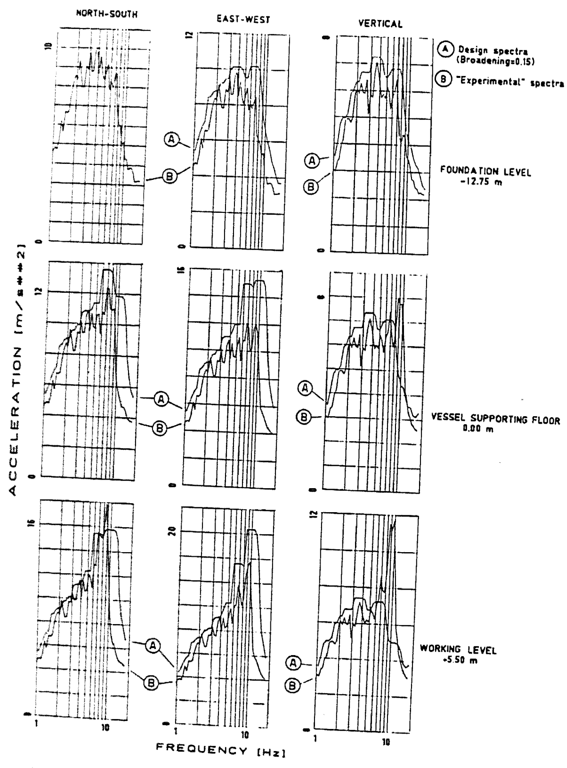

Fig. 4 Response spectra at the foundation level (-12,75 m), at the vessel supporting floor (0,00 m) and at the working level (+5,50 m) (damping ratio = 0,04)