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In situ full scale testing of the 1000 MW unit of the nuclear power plant Kozloduy

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ABSTRACT: The main purpose of the test was definition of the dynamic properties of the structure: resonant frequencies, mode shapes, damping capacity and soil-structure interaction, as a basis for development of more sophisticated mathematical model which could be used for earthquake response prediction not only for the considered structure, but also for similar ones. The experimental investigations presented in this paper are only an excerpt from the ample study "Investigations for Increase of the Seismic Safety of the Nuclear Power Plant Kozloduy" jointly realized by the Institute of Earthquake Engineering and Engineering Seismology, Skopje, Republic of Macedonia and the Institute of Geophysics at the Bulgarian Academy of Sciences, Sofia, Bulgaria. The subject of this paper is full-scale dynamic testing of the reactor building (V-th Block) of the nuclear power plant "Kozloduy". The dynamic characteristics such as resonant frequencies, mode shapes, damping capacity and soil-structure interaction have been defined for both orthogonal directions. According to the testing program, two different methods have been applied: ambient and forced vibration method. The test results are separately presented below.

1 INTRODUCTION

The dynamic behavior of a structure subjected to an earthquake depends both of the characteristics of the motion and the dynamic properties of the structure. There are a number of analytical procedures which can be successfully used for definition of the dynamic properties of a structure, but still the most reliable approach is the experimental study by means of full-scale testing. There are many reasons for accurate definition of these parameters: 1.) From the mathematical point of view, the mode shapes and the natural frequencies of a system are eigen values of its dynamic matrix which consists of mass and stiffness matrices and any change of either the mass or the stiffness of the structure yields certain modification of the dynamic properties. 2.) No matter which kind of mathematical model is used in the design, it always involves a number of more or less rough assumptions and approximations and each of them reflects certain difference between the actual and the calculated dynamic properties. Thus, the experimentally defined mode shapes and natural frequencies can be used for control of the applied design procedure.

2 DESCRIPTION OF THE TESTED STRUCTURE

The tested structure consist of two structural units: central unit-reactor building housing the reactor and the accessory equipment and auxiliary building around the reactor building, Fig. 1. The reactor building is constructed as a reinforced-concrete cylinder, with a reinforced-concrete dome on the top. The dome is supported on the walls of the cylinder trough a massive prestressed ring. These two structures, the reactor and the auxiliary building, are vertically separated by an expansion joint along the whole height of the reactor building, while in the lower part, at level 13.20, by a massive reinforced-concrete slab and both structures become one unity.

Within of the tested structure, to the east side, is the machine building which represents a structure separated by an expansion joint from the reactor building and the auxiliary building. The reactor and the auxiliary building are founded trough a reinforced-concrete slab at level -7.0.

At the time of the experimental tests reactor and turbogenerator were completely turned off.

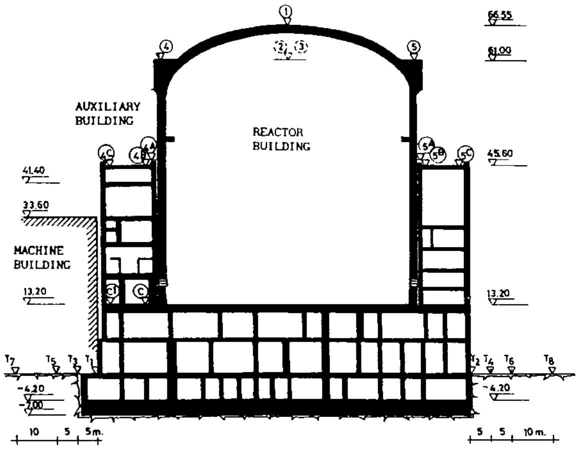


Fig. 1. Cross Section of the Reactor Building

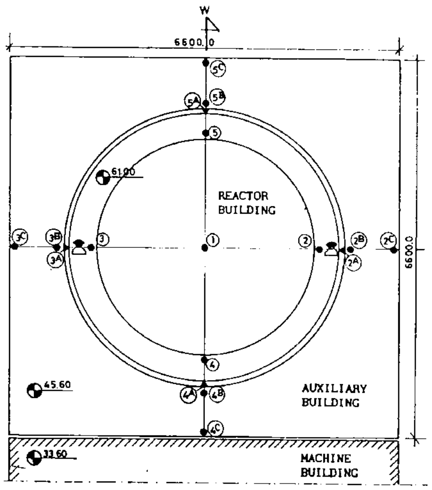


Fig.2. Disposition of the Equipment and Instrumentation

3 TEST EQUIPMENT AND APPLIED PROCEDURE

For dynamic testing of the reactor building two different methods have been applied: ambient and force vibration methods.

The ambient vibration test was performed for preliminary checking the resonant frequencies of the structural system in two orthogonal horizontal direction within the frequency range of 0-25 Hz. The equipment for this test was consisting of three Ranger seismometers, model SS - 1, Kinemetrix - USA production, signal conditioner, type SC-1, Fourier frequency analyzer, model 3582A, Hellwet Packard production-USA. Five measurement points for installation of the seismometers were selected on the tested structure (point 1 on the top of the reactor building, points 2 and 3 on the reactor ring and points 2^C and 3^C at the level of the auxiliary building terrace), Fig. 2.

The time history records have been transformed in frequency domain using two channels frequency analyzer obtaining Fourier amplitude spectra. The peak values of the spectra correspond to the resonant frequencies of the tested structure. The processing of the signals was performed on the site by plotting the records on x-y plotter.

The forced vibration test was performed for more precisely definition of the resonant frequencies (preliminary defined by ambient vibration method) as well for definition of horizontal and vertical modes shapes. In this case two rotational mass force generators GSV-101 (manufactured by Geotronix, USA) were placed radially on the ring of the reactor building. The magnitude of the resulting force depends on the load in the baskets and the square of the rotation frequency, which can be controlled within the range of 0.5 to 9.0 Hz, and its maximum amplitude is limited to 22.7 kN per generator. The rotational velocity is controlled by a pair of special electronic control units, one for each of the generators. The synchronization device provides both frequency control (up to one thousandth part of a Hz) and in-phase operation of the generators (within several degrees). A contra phase function (phase angle of 180 degrees) of the generators can be also selected to produce a torsional moment, instead of the lateral force which is produced during the in-phase operation. The resonant frequency curves were obtained by changing the frequency in small steps and measuring the structural response by accelerometers. For the determined resonance frequencies, defined were the corresponding horizontal mode shapes at the level of the reactor building ring and at the level of the terrace. Special attention was paid to the definition of the vertical mode shapes of the structure for both orthogonal directions, with measurement of both the horizontal and the vertical component for the respective excitation at each point. These measurements were performed at the level of the ring and the terrace of the reactor building, as well as at level 13.20 of the platform. In determination of the vertical mode shapes, the soil-structure interaction, measurements were conducted also at free-field points at various distance from the excited structure.

4 TEST RESULTS

The main objective of the ambient vibration test was to estimate the dominant frequencies of the structure as preliminary information, which are of particular interest when the forced vibration method is applied. The sensors (Ranger seismometers) have been distributed on the roof of the cylindrical reactor unit, as well as on the auxiliary building. The Fourier amplitude spectra of the records are shown in Fig. 3.

To obtain more accurate information on the dynamic behavior of the structure, forced vibration tests have been performed. A set of frequency response curves has been obtained by measuring of the structural response at the selected points on the roof of the reactor and the auxiliary building, Fig. 4. To obtain spatial presentation of the structural vibration under dynamic excitation, the horizontal and vertical profiles have been measured in the selected points.

Fig. 5. show the horizontal mode shapes in N-S and E-W direction as well as mode shape for torsional vibration. All horizontal profiles were located on the roof of the reactor building as well as on the auxiliary building.

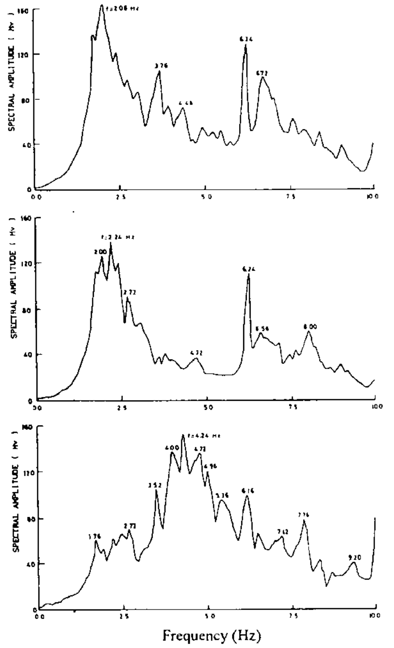


Fig.3. Fourier Amplitude Spectra

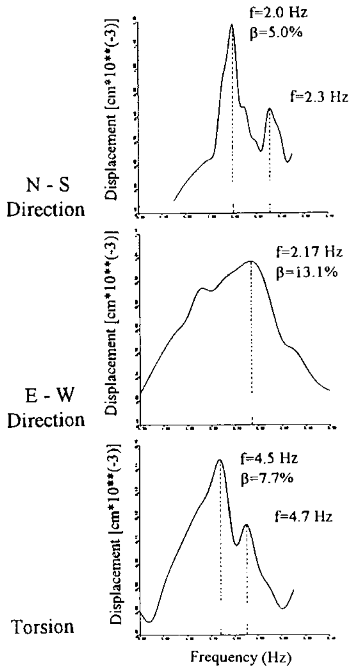


Fig.4. Frequency Response Curves

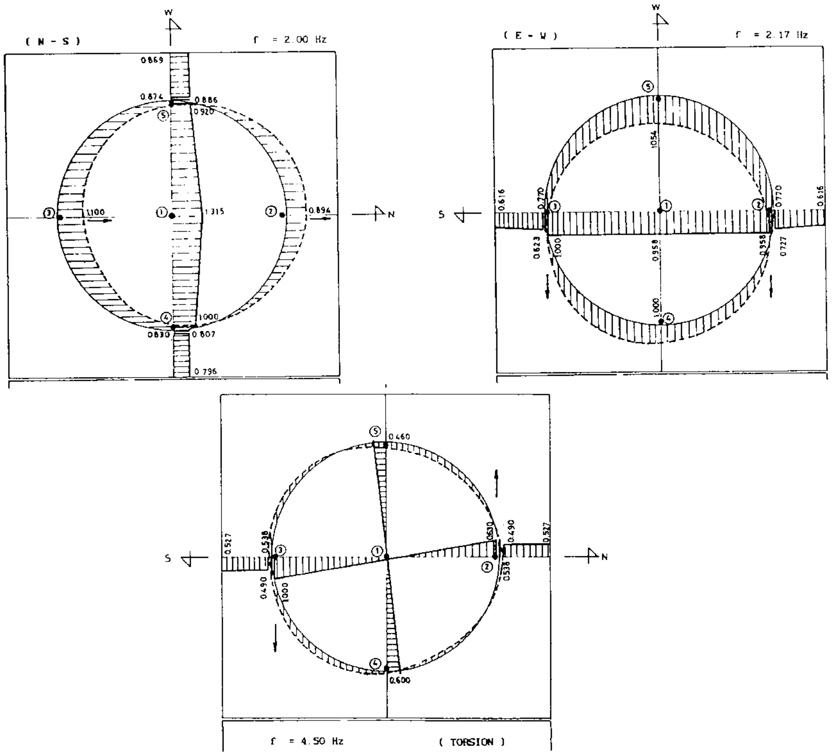
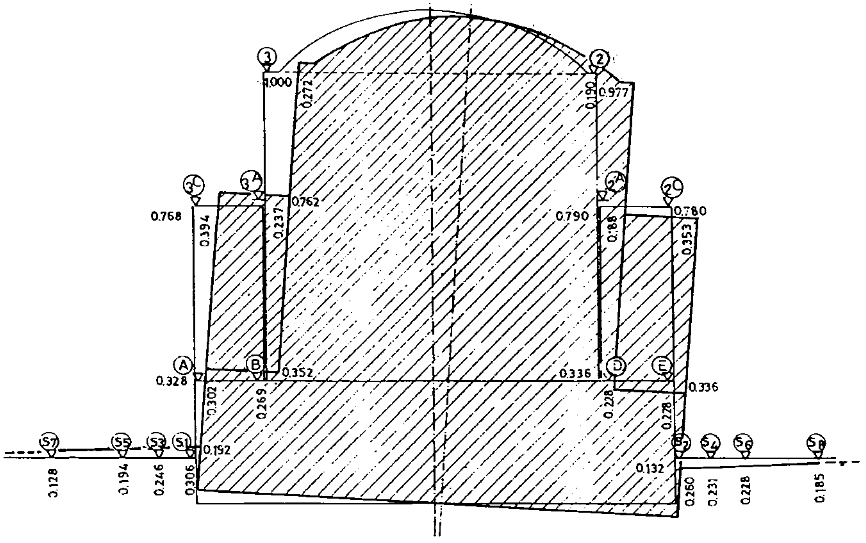


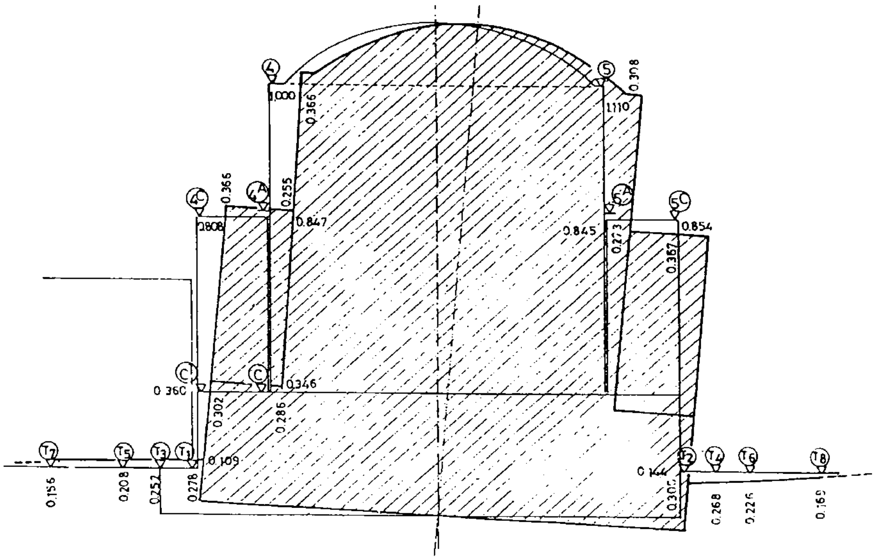
Fig.5. Horizontal Mode shapes in N-S, E-W and Torsional Direction

The vertical mode shapes are shown in Figs.6. and 7., for N-S and E-W direction, respectively. Both horizontal and vertical mode shapes correspond to the fundamental modes of the structure. The amplitudes of the mode shapes are normalized to the reference point, the amplitude of which is assumed as unity.



f = 2.00 Hz
a_3 = 0.19 $\cdot$ 10^{-3}g
δ_3 = 11.8 μ

Fig.6. Vertical Mode Shape in N-S Direction, f = 2.00 Hz



f = 2.17 Hz
a_4 = 0.15 $\cdot$ 10^{-3}g
δ_4 = 8.1 μ

Fig.7. Vertical Mode Shape in E-W Direction, f = 2.17 Hz

5 CONCLUSIONS

Based on the given results a general impression is that the tested structure is very rigid, so that its dynamic model could be assumed as a rigid body system supported on a flexible base. Because of the frequency range limitation of the used vibration generators, only the fundamental resonant frequencies in N-S and E-W direction and torsion have been defined within the range of 0.5-9.0 Hz. The horizontal and vertical mode shapes show rather simple dynamic behavior of the structure. Comparative measurements performed on the reactor and the auxiliary building show that both buildings vibrate together, always in phase, and could be assumed as a unique system. The frequencies response curves are characterized by a wide frequency band resonance, which indicated large damping capacity. The torsional fundamental frequency (f=4.50 Hz) is much higher than the translation frequencies in N-S (f=2.00 Hz) and E-W (f=2.17 Hz) direction, possibly because of the high torsional rigidity of the structure. The damping coefficient determined by the frequency response curves has a value within the range of 4-13 % of critical damping. Comparing the damping capacity obtained for the reactor building and the auxiliary building, it is concluded that the damping coefficients related to the reactor building are almost twice higher than those of the auxiliary building. The measurement of soil-structure interaction gives a clear picture of the typical type of vibration of the structure in resonance conditions showing considerably influence of rotational effect, which should be considered in the dynamic response analysis.

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