Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Experimental and analytical investigation of Paks NPP building structures

Tamás Katona & László Turi
Nuclear Power Plant Paks Ltd, Hungary

Andrés Halbritter & Norbert J. Krutzik
Siemens AG, Power Generation Group (KWU), Offenbach, Germany

ABSTRACT: The dynamic characteristics of VVER-440 NPP building structures were experimentally investigated using explosive techniques. The same characteristics were calculated analytically. The comparison of experimental and analytical results shows the adequacy of the modeling of the structures and soil-structure interaction.

1 INTRODUCTION

There are four VVER-440 units in operation at the PAKS NPP site. The units are of the V-213 type, i.e. they represent the new design, approaching in many respects the current, demanding western standards. The reliability of the units shown over 26 years of reactor operation has been fairly satisfactory. The cumulative load factor is 84.3 % (as of end of 1991).

The V-213 version of the VVER-440 units has a number of advantageous properties. E.g. the power density of the core is low, and there is a huge water inventory in the primary and secondary circuits for mitigating any possible LOCAs. The hermetic reactor box, analogous to the containment, is also dimensioned to bear a LOCA event.

The V-213 design also has some deficiencies, e.g. practically no impacts of outside events such as earthquake, airplane crash, etc., had been taken into consideration.

At the time of site selection the current site was decided to be suitable, taking into consideration the historical seismic activity data: the seismic hazard was characterized by an intensity level of V (MSK-64) at an annual frequency of 10^{-3} and with these values no special seismic dimensioning was needed.

The recent probabilistic seismic hazard assessment calculations show that the safe shutdown earthquake with an annual probability of 1 in 10000 has an MSK intensity VIII with a peak horizontal acceleration of about 3.3 ms^{-2}.

As a consequence, a comprehensive seismic safety program has been started to determine the actual seismic strength of the plant and work out the necessary reconstructions. As the NPP in question is a plant in operation which is not designed for seismicity, we decided to use in parallel several methods for its qualification, decreasing by this the conservatism of analyses. Therefore, in parallel with the computational analyses of the reactor building, we also performed dynamic experiments. The present paper reports on these dynamic measurements, gives their results and presents a comparison of measuerd data with the computed ones.

2 DESCRIPTION OF MEASUREMENTS

2.1 Object of studies

The object of the studies was the reactor building and we intended to determine its primary dynamic characteristics, eigenfunctions and forms as well as damping to the extent allowed by the restrictions imposed by the measuring conditions. As the reactor building is located on a relatively loose ground, the soil-structure interaction cannot be neglected. Therefore, prior to giving a short description of the reactor building we quote the characteristics of the site itself.

2.1.1 Characteristics of site

The Paks NPP site is located in the central region of the Pannonian Basin. The ground level at the site is about 97 m above sea level. The region in the vicinity of Paks generally consists of wind-blown Loess deposits dating from the Pleistocene Age.

The Danube has cut a wide flood plain through the Loess deposits into the Pannonian deposits. The flood plain consists of recent Holocene deposits. The deep boreholes beneath the Paks site show that the Pannonian deposits extend down to 600 meters. Below this is limestone dating from the Badenlain Age and then older rocks. The shallow borings show about 26-30 meters of alluvial silts, sands and gravels. Their density varies from loose to medium in the upper 12 meters, becoming dense below 16 meters. Below 26 meters there are very dense Pannonian silts and sands.

The relatively dense layer, with high propagation velocity of transversal waves, is covered by a loose layer with lower velocity of transversal waves. This gives the possibility for surface waves (Love) to be formed.

2.1.2 Description of reactor building

The Paks NPP consists of so-called twin units. The primary building of two units is located on a common monolith basement block of 2 m thickness. The main buildings are connected by two, in a symmetrical layout. The bottom of the base block is set at the elevation of -8.5 m. The twin units consist of a foundation of 145 m length, 52 m width and 18.9 m height, with a dilatation separation at the middle. On this foundation there are two condensing towers having a base surface of 42 x 24 m^2, and emerging up to 50 m elevation. The studied reactor building is a structure designed to bear a 2.5 bar pressure generated by a LOCA. Above the 18.9 m elevation there is a hall serving for reactor maintenance and reloading. The reactor building not only houses the process equipment of the first category but is also the third safety barrier in the way of radioactive materials. The floor and wall thicknesses vary from 0.6 to 1.5 m, complying with structural and radiation shielding demands. Besides the generally used standard concrete with a density of 2100 kg/m^3, here and there also heavy concrete of 3600 kg/m^3 is used for biological protection.

The overall volume of a building belonging to a unit amounts to 47,000 m^3.

On the eastern side there is a NW oriented gallery building of 12 m width and the turbine hall of 39 m span attached to the reactor building. Both are constructed of steel. On the southern side there is also a gallery building attached to the reactor building supported partly by reinforced concrete pillars and by the reactor building wall and oriented WE.

2.2 The methods of studies

The studies consisted of getting the buildings to move using distant explosion, with subsequent measuring of the acceleration response of the structure. By analysis of acceleration signals the characteristic eigenfrequencies and forms of the reactor building have been identified.

2.2.1 The excitation

The dynamic study of the buildings was performed with the help of a series of explosions generated far from the buildings, at a distance of 2.5-4.5 km. The maximum quantity of explosives blown at the same time amounted to 500 kg. The loads were located in 20 m deep boreholes, 50 kg in each. The form of the building is an elongated rectangle with the main axis oriented NW, therefore we made explosions in the directions of both axes, i.e. both east and south of the building.

The distances of explosion points and the masses of explosive were determined during a set of preliminary experiments. At the same time we had to take into account the allowed vibration speed limits for the buildings on site and in its neighborhood and the level of the reactor building response necessary for a reliable measurement. The results of these preliminary experiments showed more reasonable blowing up higher explosive quantities (500 kg) at higher distances (2-5km), because in this case the exciting signal contains the lower frequencies in the range of eigenfrequencies of the building.

After the preliminary measurements we carried out two series of experiments.

In the first series the points of explosion were located south of the plant at distances of 2.5 and 4.5 km. At 2.5 km the quantities of explosive amounted to 50, 100 and 200 kg, while at 4.5 km the quantities were 200 and 500 kg.

In the second series of experiments at the eastern point at 2 km distance one load of 100 kg and two loads of 300 kg, while at southern point at 2.6 km 2 loads of 450 kg were detonated.

2.2.2 Array of detectors

In the forementioned two series of experiments the location patterns of the acceleration sensors were slightly different.

In the first series the sensors were located at a number of points of the floors at the elevations of -6.50, 0.00, 18.90, 38 and 49.80 meters so that the form of motion of the floors could be identified. In addition, we had free field measuring points at 5 and 100 meters from the building, in the direction of the explosions.

The detector layout for the 2nd series of measurements is shown in Fig. 1.

At every measuring point triaxial sensors were used. In the free field boreholes the sensors were located at 0, -5, -10, -15 and -20 m depth in a dense sludge ensuring coupling to the ground. (Sorry to say, a significant number of these sensors were damaged during the experiments, and so the data are incomplete.)

During the test explosion and the first series it turned out that the sensors inside the building measured strong local vibrations; therefore for the subsequent explosions we put sensors only on the places representing the building motions. The detector positions F, G and H were located at the elevations -6.5 m, 18.9 m and 38 m, respectively; position P was on the top of the condensing tower at 48.9 m. The positions I, J, K and L monitored 4 points of a frame element of the steel structure of the turbine hall at the elevations -6.50, 18.90, 18.90 and 0.00 m, respectively.

The detector positions M, N and O were at elevations -3.60, 9.60 m and 19 m of the gallery building beside the reactor building.

2.2.3 Data acquisition

The signals of the accelerations sensors were recorded at every sensing point in the frequency range of 0.2-33 Hz by a local digital data acquisition system. The data were sent to a central data acquisition system (IBM286PC) through optical cables.

The explosions time signal triggered the data acquisition process so that the correct phase of signals coming from different measuring places was ensured.

2.3 The measuring process

The explosions of higher quantity explosives were always preceded by trial explosions of minor quantities (100 kg). These were intended to convince us that the explosions would not do any harm, and to demonstrate the same to the authorities. On the other hand, we had to determine the expected vibration amplitudes for setting the measuring equipment ranges.

3 RESULTS OF MEASUREMENTS

Fig. 2 shows the x component of the acceleration time signal measured in the free field at measuring position 3A with an explosion in the eastern direction. The outer excitation acceleration time signal has characteristic sections.

The first section can be identified as the arrival of the longitudinal wave having a relatively high frequency content (8-13Hz). Its propagation velocity determined by time of arrival is 1900 m/s. The velocity of the surface wave package arriving a little later is in the range 270-380 m/s depending on the frequency showing the characteristic dispersion of surface waves.

The response measured in the building follows the peculiarities of the excitation as it can be seen in Fig. 3 showing the response time signal measured on the top of the condensing tower at position 5P.

3.2 Short time interval spectra

The time evolution of the frequency content of the excitation was also analyzed using the frequency spectra formed from short sections of the measured acceleration signal. The short range spectra were made on records of a length of 1.28 s using Hannings window. The window was moved along the time axis with a spacing of 0.25 s. Fig. 4 shows the section beginning at 4 s of the processed time signal measured at the free-field position 2A. One can clearly see the arrival of different phases of the exciting waves.

3.3 Evaluation of results

3.3.1 Free field

Fig. 5 shows the PSD of the acceleration signal measured at the free field position 2A after an southern explosion. As it can be seen, the excitation signal is characterized by several well separated lines between 1.8 and 4.3 Hz such as e.g. that of 2.0, 2.3-2.4, 2.5-2.6, 2.83, 3.0, 4.1 - 4.3 Hz.

The longitudinal and transversal waves did not excite the lowest eigenfrequencies of the building but after their decrease the excitation effect of the subsequent surface waves could be measured. The frequencies measured in the free field are very close to the lowest eigenfrequencies of the building, but they are not identical.

The acceleration response spectra at point 3A due to explosion in south direction are presented in Fig. 6. They were obtained considering the measured time histories up 6 seconds eliminating partially the high frequency content of the excitation.

3.3.2 Structure

The acceleration response of the structure was measured at the positions indicated in

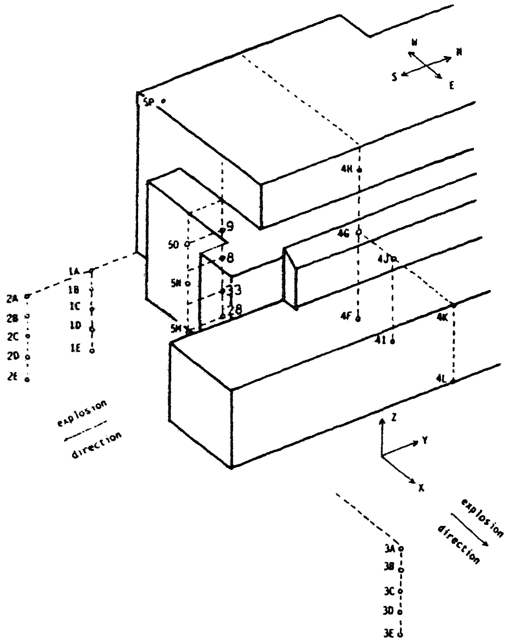

Figure 1. PAKS NPP site. Explosion and measuring point positions.

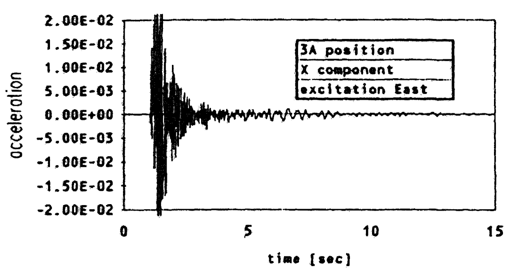

Figure 2. Free-field acceleration signal measured at point 3A.

Fig. 1. The predominant frequencies of the reactor building obtained from the tests are 1.9 - 2.1, 2.25, 2.45 Hz and they match very well with the analytical results (2.12, 2.38 Hz). For the reactor hall the experimental and analytical frequencies compare also satisfactory (1.6-1.9 and 1.84 Hz respectively). Near frequencies were obtained for the turbine hall and for the galleries. The response spectra obtained from the measured time histories and calculated using a complete 3D finite element model including the soil-structure interaction are plotted for some points (Fig. 7). The finite element model was excited using the measured free field acceleration time histories. The comparison

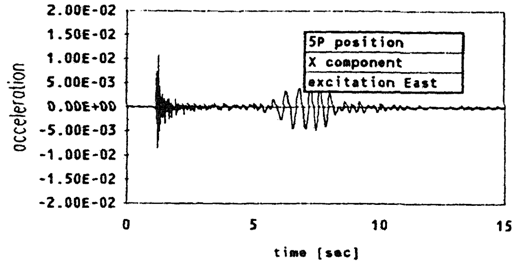

Figure 3. Acceleration response signal measured at point 5P.

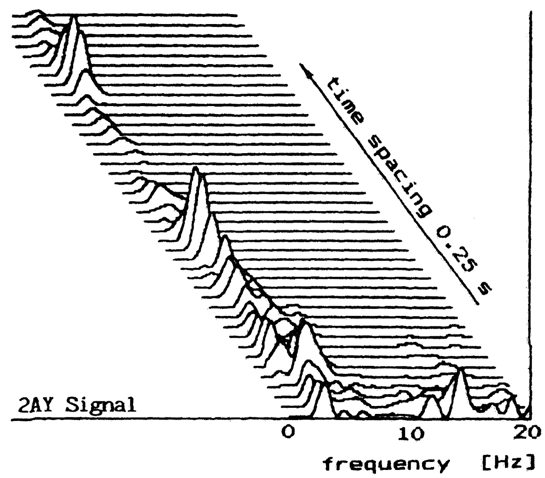

Figure 4. Short time PSD of the 2A signal

of the structural responses obtained using both methodologies is satisfactory.

3.4 Determination of damping

Using the trailing edge of the acceleration function measured on the reactor building the global damping value characterizing the current state can be determined provided that the building after excitation is supposed to be a freely vibrating system. This damping can be evaluated by fitting the expression

$$a(t)=c_4\exp(-c_1t)\ \sin\ (c_2t+c_3)+c_5$$

to the trailing edge of the low frequency vibrations. The damping can be defined as the ratio

$$\beta = c_1/c_2$$

This approximation is quite acceptable because in the decaying section the time signal is shaped out practically in all cases by a single predominant frequency.

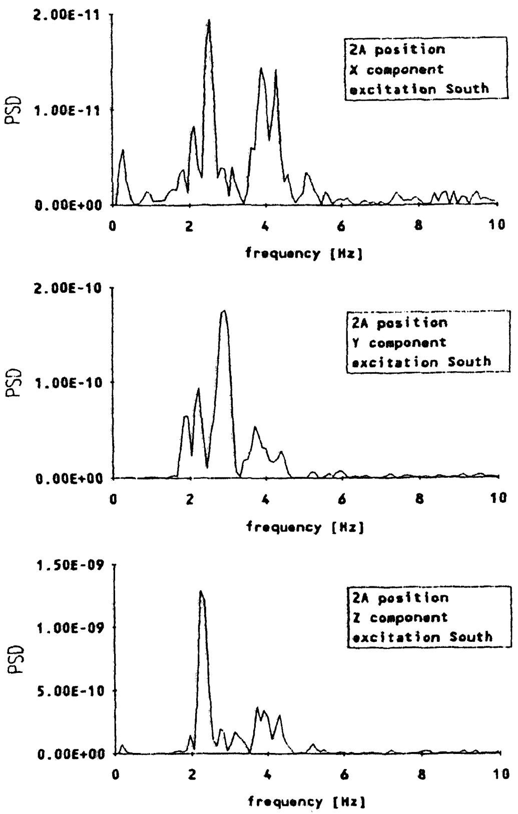

Figure 5. PSD of the free-field acceleration measured at point 2A, excitation "south"

The following values have been derived:

	For excitations from East		South		
	X	Y	X	Y	Z
Reactor building					
Pos.4G	6.9%	-		9.1%	10.1%
Pos.4H	7.5%	6.8%		8.7%	5.5%
Pos.5P	10.0%	7.7%	11.8%	10.4%	6.4%
Turbine hall					
Pos.4K	6.4%	-	9.8%	9.4%	8.1%
Gallery building					
Pos.50	6.1%	9.4%	8.4%	9.2%	14.8%

According to expectations, the values show some uncertainties. Both the values and the high dispersion are due to the very weak excitation.

Damping is strongly dependent from soil strain and consequently in case of earthquake higher damping ratios are expected. In the case of explosion excitation the amplitudes can be detected only by instruments, so the damping values

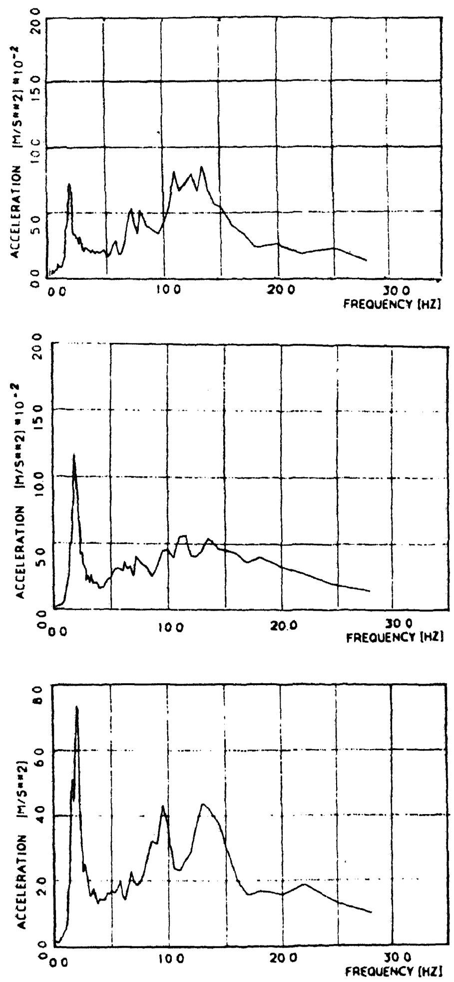

Figure 6. Response spectra of the free-field acceleration signal at point 2A/I excitation "south" (500 kg)

determined this way can be much less than those for an earthquake. The determined values can be taken as lower limits especially because the structure vibrating at its trailing edge is still subject to excitation, so that the decay is more prolonged than that for a freely oscillating system. Thus, for the calculations these values are low limits only.

4 CONCLUSIONS

A good approximation between the natural frequencies (determined experimentally and analytically) were verified.

Damping ratios are a function of the deformation and for this reason the experimental values must be corrected in

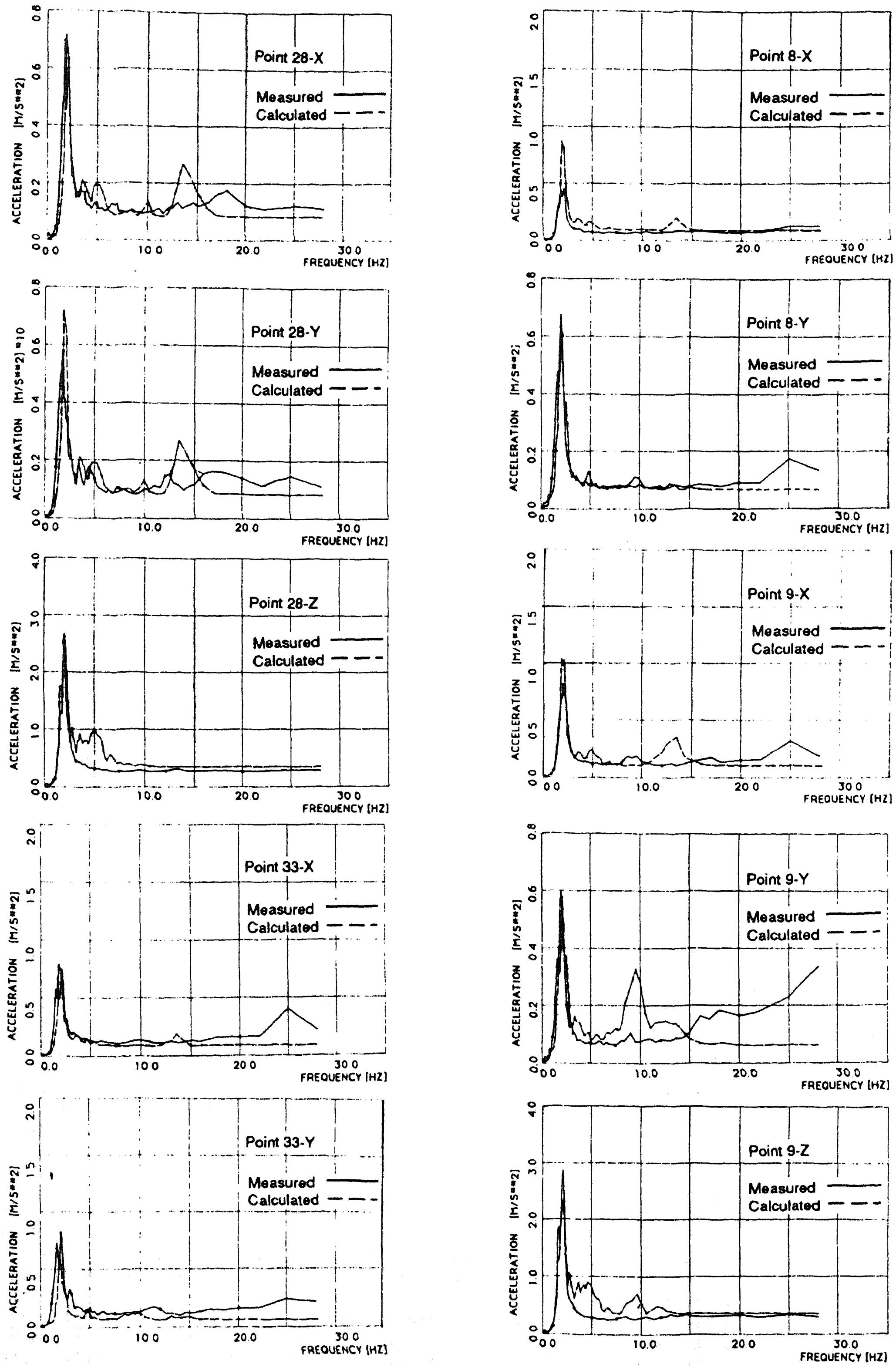

Figure 7 Comparison of FRS (D=2 %)

case of real earthquake. The comparison between the response spectra obtained using both approaches is reasonable. The experimental investigation here developed validates the analytical/numerical dynamic calculation of the PAKS NPP.