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FLOOR RESPONSE SPECTRA FOR SEISMIC QUALIFICATION OF KOZLODUY VVER 440-230 NPP*

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ABSTRACT

In this paper the floor response spectra generation methodology for Kozloduy NPP, Unit 1-2 of VVER 440-230 is presented. The 2D coupled soil-structure interaction models are used combined with a simplified correction of the final results for accounting of torsional effects. Both time history and direct approach for in-structure spectra generation are used and discussion of results is made.

1 INTRODUCTION

The Kozloduy NPP is located in the North-West part of Bulgaria on the Danube river. The plant consists of four units of 440 MW and two units of 1000 MW. In the last 15 years there have been three strong, intermediate depth earthquakes in the Vrancea seismic zone (1977, 1986, 1990) which have affected the NPP site. The Vrancea zone is located approximately 300 km northeast of the plant. It is known for the generation of strong, long-period seismic motions.

In 1990 an intensive work program for qualification of the plant according to the international standards (IAEA 1991; IAEA 1992) was initiated. The work started by a project for site confirmation. As a result, new design seismic characteristics were obtained. A Review Level Earthquake is defined by a maximum acceleration of 0.2 g and a response spectrum shown in Fig. 1. The generation of the in-structure spectra is the second step of the qualification of the NPP for seismic events. The work started by generation of the floor response spectra for Unit 1-2. This paper describes the methodology used in the floor response spectra generation.

2 DESCRIPTION OF THE STRUCTURES

The Unit 1-2 of VVER 440-230 have been operated for more than 20 years according to the Russian criteria for design and safety (USDOE Team 1989). The main building of Unit 1 and 2 consist of four parts: the reactor building, the turbine building, the intermediate building, and the auxiliary building. A layout of the main building is shown in Fig. 2. All buildings are

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reinforced concrete cast-in-place structures. The reactor building is a rigid structure 39 m × 126 m in plan, characterized by massive concrete walls up to an elevation of 10.4 m. In that part of the structure are located the reactor and the primary circuit equipment. From that level up to the roof there is a frame structure. The height of the reactor building is 35 m.

The turbine hall - 39 m × 252 m in plan, placed next to the reactor building, is formed by very flexible frames both in the longitudinal and transversal directions. The connection between the reactor building and the turbine hall is the intermediate building. Because of the different stiffness of the reactor and the turbine building, an intensive torsional interaction is expected. The torsional response is considered especially important for outer column row of the turbine hall.

The main part of the critical equipment, for which floor response should be computed, is located in the reactor and in the intermediate building. For these structures the influence of the torsional response is considered as not very intensive.

The building complex is presented by plane models both in the transversal and longitudinal directions. The models are coupled with the soil - it means the direct soil-structure interaction analysis scheme is used. For the importance of the torsional modes a complete 3D model of the structure is made and subsequently a 3D seismic response analysis is performed in order to modify some of the results.

3 LOCAL GEOLOGY MODEL

The local geology is characterized by deep alternating layers of loess, sand, clay and a mixture of the former soils. Up to a depth of 250 m there is no evidence of rock formation. The soil characteristics of a generalized soil profile are given in Table 1.

A comprehensive soil column study is performed first. The goals are to determine the dynamic characteristics of the local soil system; to assess the depth needed for the coupled soil-structure interaction model; to investigate the role and the importance of the shear strength degradation in soil and the amount of energy dissipated by material damping.

Six different soil models are investigated. A profile with a depth of 48 m is selected for further soil-structure model generation. Criteria for that selection are the change of the maximum acceleration in depth, the amount of the stiffness degradation and damping increase in soil.

4 SOIL-STRUCTURE INTERACTION ANALYSES

The soil-structure interaction analysis is performed using the computer programs FLUSH (Lysmer, 1975) and PLUSH (Romo-Organista, 1979). Two FE models are developed respectively in the transversal and longitudinal directions. The models are presented in Figs. 3 and 4. Soil is modeled by rectangular and triangular plane elements with two translational degrees of freedom per node. The same elements are used for modeling the footings and the massive concrete in the reactor building. Frames are modeled by beam elements with two translational and one rotational degree of freedom per node.

In the transversal direction the model dimensions are about 48 m in depth and 222 m in width. The transmitting boundaries are at 60 m from the structure to the left and right.

In the longitudinal direction the soil model dimensions are 48 m in depth and 170 m in width. A transmitting boundary is placed at the right side, the left side is a symmetry axis.

The element dimensions are selected according to the requirements for the highest frequency of analyses - 25 Hz. Three variants of the soil characteristics are analyzed - mean values, two time the average - and one-half of the average soil characteristics. Damping in the structure is considered generally 6%, 4% for the massive concrete of the reactor shaft, 7% for the girders in the intermediate building.

The control motion is specified at the free field by means of response spectrum and/or artificially accelerograms generated by using SIMQKE techniques (SIMQKE, 1976). There are no differences in the models used for the computer programs FLUSH and PLUSH. The only difference is the presentation of the seismic excitation - FLUSH is using a time history and PLUSH is using a spectrum (response spectrum or PSD). The assumption in PLUSH concerning the seismic excitation is that it is a Gaussian noise. The first passage problem is solved there on the base of the Vanmarke's formulations (Vanmarke, 1976). Because of that, results with different levels of confidence could be computed. In the case investigated the confidence level needed is estimated by comparison of the results from the direct approach and from the time history approach. The criterion used is - the generated spectra by the direct approach should envelope the spectra generated by the time history approach. On that basis a level of confidence of 97% is estimated.

The procedure for generation of the in-structure spectra is in compliance with the USNRC RG 1.122 (USNRC RG-1.122, 1976). It consists of the following main steps:

1. Investigation of the transversal models both for horizontal and vertical excitation.
2. Combination of the co-directional response according to SRSS rule.
3. Investigation of the longitudinal models both for horizontal and vertical excitation.
4. Combination of the co-directional response according to SRSS rule.
5. Combination of the horizontal response from the transversal and longitudinal models according to SRSS rule.
6. Enveloping the vertical response from the longitudinal and transversal models.
7. Enveloping the response from the model variations - three different sets of soil characteristics and two models with structural variations are used.
8. Smoothening and broadening of the response spectra.
9. Correction of the response spectra for the torsional effects.

Note that the girders in the intermediate building are assumed to be connected to the support columns in two ways: hinge joint and rigid connection. In such way two models of the structural variations are considered.

5 SPACE MODELING

In order to assess the torsional effects, a 3D model is constructed and analyzed by the computer program STARDYNE (see Fig. 5). To assure compatibility of the results, the seismic excitation for the 3D model at foundation level is determined from the coupled 2D models. The correction factor for torsional response is determined by comparison of the maximum acceleration computed by 2D and 3D analysis at the locations where spectra are specified. The results from the comparisons are given in Table 3. The correction factor of 1.25 is applied on the whole frequency range of the spectral values at locations in the intermediate building.

6 DISCUSSION OF RESULTS

The final FRS consists of a horizontal and a vertical floor response spectra for various damping values at the locations specified. The pertinent information of the 5% damping horizontal and vertical floor spectra at various levels of the intermediate equipment building is summarized in Table 3.

The final horizontal spectra at the elevation of 28.4 m of the intermediate building is shown in Fig. 6. The spectra mainly contain five structural frequency peaks at 1.4 Hz, 2.5 Hz, 5.5 Hz, 8 Hz and 11 Hz. The frequency at 1.4 Hz belongs to the fundamental mode of the main building in the longitudinal direction. The frequency of 2.5 Hz is the dominant mode of the main building in the transversal direction. The 5.5 Hz may belong to the higher mode in the longitudinal direction. The mode at 8 Hz belongs to the higher mode in the transverse direction. The mode at the frequency of 11 Hz is believed to be the mode of the rigid reactor building.

The maximum spectral acceleration varies from 0.75 g at a level of 6.3 m above the ground surface to 1.9 g at the level of 28.4 m. The maximum floor acceleration is 0.42 g at a level of 28.4 m.

The vertical floor spectra have a distinct structural frequency peak at 11 Hz. This mode is the fundamental vertical vibration mode of the floor beams of the intermediate building. The maximum spectral acceleration is 1.9 g at a level of 28.4 m. Note that the vertical spectral acceleration is relatively high. This is attributed to the code limitation in absence of the transmitting boundary in bottom of the SSI model for vertical excitation. Table 4 contains a summary of the floor response spectra at other locations.

7 2D LUMPED MASS FRAME MODEL WITH SOIL SPRINGS AND DAMPERS

An independent analysis is carried out on a 2D lumped parameter model shown in Fig. 7 using the computer code FLUSTR-ANL at Argonne National Laboratory. The model was developed for the USDOE's Team Analysis of VVER plants in 1987 (Ma et al. 1989). The structure is assumed to be rested on a rigid ground slab. The shear wave velocity is assumed to be 305 m/s (1000 ft/s). It is close to one-half of the average site shear wave velocity used in the 2D FE models. The soil is represented by frequency-independent soil springs and dampers. A time history analysis is carred out.

Figure 8 shows the computed horizontal spectrum of 5% damping at the level of 28.5 m of the intermediate building under 0.2 g Review Level Earthquake. As can be seen, the dominant mode in the transverse direction is 2.5 Hz with a spectral acceleration of 1.5 g. The higher mode occurs around 8 Hz. The ZPA of the spectrum is about 0.3 g. Those values agree well with the 5% damping spectrum shown in Fig. 6. Note that the spectral values of Fig. 6 have been corrected by a factor of 1.25 for torsional effects. This good agreement provides some assurance that the FLUSH/PLUSH analyses have been properly performed.

8 CONCLUSIONS

The results presented allow the following conclusions:

1. The FLUSH/PLUSH programs are efficient tools for computation of in-structure spectra of the frame buildings. There is generally very good agreement between the results of both of the programs.
2. Although the main part of the seismic energy is radiating in the horizontal direction, the absence of an absorbing boundary at the model bottom leads to conservative results, especially for vertical excitations. It seems reasonably an increased material damping to be used in that case.
3. A reliable assessment of the influence of torsional motion on spectra generated by plane models may not be easy. The response of the construction edges is dominated usually by that motion. If important equipment is located at such places, a direct generation of the response spectra from a 3D model could be advantageous.
4. The structure-equipment interaction is very important, especially in the case where the building structure is a relatively light and flexible frame. The interaction between the turbine hall, the intermediate building and the deaerator structure is an example of such an interaction.

5. The 2D lumped mass frame provides an effective way for understanding the complicated structural response and for upgrading the structures.

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Table 1. Local soil profile

No.	Layer Thickness (m)	Depth from Surface (m)	Density [t/m^{-3}]	Shear Wave Velocity (m/s)	Type
1	3.00	3.0	1.86	290	loess
2	10.50	13.5	2.00	450	loess
3	17.50	31.0	2.10	500	sand gravel
4	11.00	42.0	2.05	430	clay
5	42.50	84.5	1.90	520	sand
6	19.50	104.0	2.00	550	clayey sand
7	29.00	133.0	2.00	450	sandy clay
8	20.00	153.0	2.00	540	dense clay
9	22.00	175.0	2.00	580	dense clay
10	30.00	205.0	2.00	530	dense clay
11	17.00	222.0	2.00	630	dense clay
12	-	-	2.00	680	stiff clay

Table 2. Comparison of maximum accelerations calculated from 2D and 3D models at levels 28.4 m and 21.85 m of the intermediate building

Level (m)	Column Axis	3D Maximum Acceleration (g)	2D Maximum Acceleration (g)	3D/2D
28.4	13	0.349	0.339	1.029
28.4	14	0.418	0.339	1.233
28.4	15	0.418	0.339	1.233
28.4	16	0.415	0.339	1.224
28.4	17	0.426	0.339	1.256
28.4	18	0.464	0.339	1.368
			average	1.223
21.85	13	0.289	0.293	0.986
21.85	14	0.309	0.293	1.054
21.85	15	0.309	0.293	1.054
21.85	16	0.352	0.293	1.201
21.85	17	0.358	0.293	1.221
21.85	18	0.382	0.293	1.303
			average	1.136

Table 3. Horizontal and vertical floor spectra (5% damping) of the intermediate building

	Horizontal Spectra		Vertical Spectra	
Level Above Ground (meter)	ZPA of Floor Spectra (g)	Major Peak Frequencies and Spectral Acceleration	ZPA of Floor Spectra (g)	Major Peak Frequencies and Spectral Acceleration
28.4 meters (node 276)*	0.42 g	1.9 g at 1.4 Hz 1.6 g at 5.5 Hz 1.4 g at 2.5 Hz	0.3 g	1.9 g at 11 Hz
21.8 meters (node 278)	0.375 g	1.3 g at 11 Hz 1.1 g at 1.4 Hz 1.1 g at 2.5 Hz	0.25 g	1.3 g at 11 Hz
14.5 meters (node 280)	0.35 g	1.1 g at 11 Hz 1.0 g at 2.5 Hz	0.25 g	1.25 g at 11 Hz
10.5 meters (node 282)	0.35 g	1 g at 11 Hz 1 g at 2.5 Hz	0.35 g	1.5 g at 11 Hz
6.30 meters (node 284)	0.34 g	0.75 g at 11 Hz	0.25 g	1.25 g at 11 Hz

*Node number of FLUSH/PLUSH model.

Table 4. Summary of horizontal and vertical floor response spectra (5% equipment damping) at various locations

	Horizontal Spectra	Vertical Spectra
Location	Frequency Peak and Spectral Acceleration	Frequency Peak and Spectral Acceleration
turbine foundation 9.6 above ground	3 g at 5.5 Hz	insignificant, peak spectral acceleration less than 0.3 g
deaerator support 6 m above ground	2.5 g at 11 Hz	insignificant, peak spectral acceleration less than 0.3 g
reactor block 10.5 m above ground	1 g at 11 Hz	insignificant, peak spectral acceleration less than 0.5 g
boron injection recirculation pump 9 m below ground	insignificant, peak spectral acceleration less than 0.5 g	insignificant, peak spectral acceleration less than 0.5 g
control room 10.5 m above ground	0.6 g at 2.4 Hz	0.6 g at 16 Hz

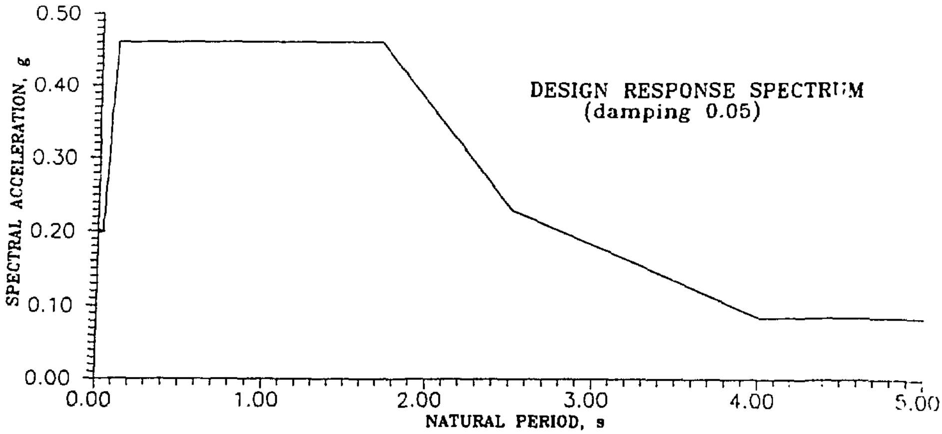

Fig. 1 Site Ground Spectrum (5% damping)

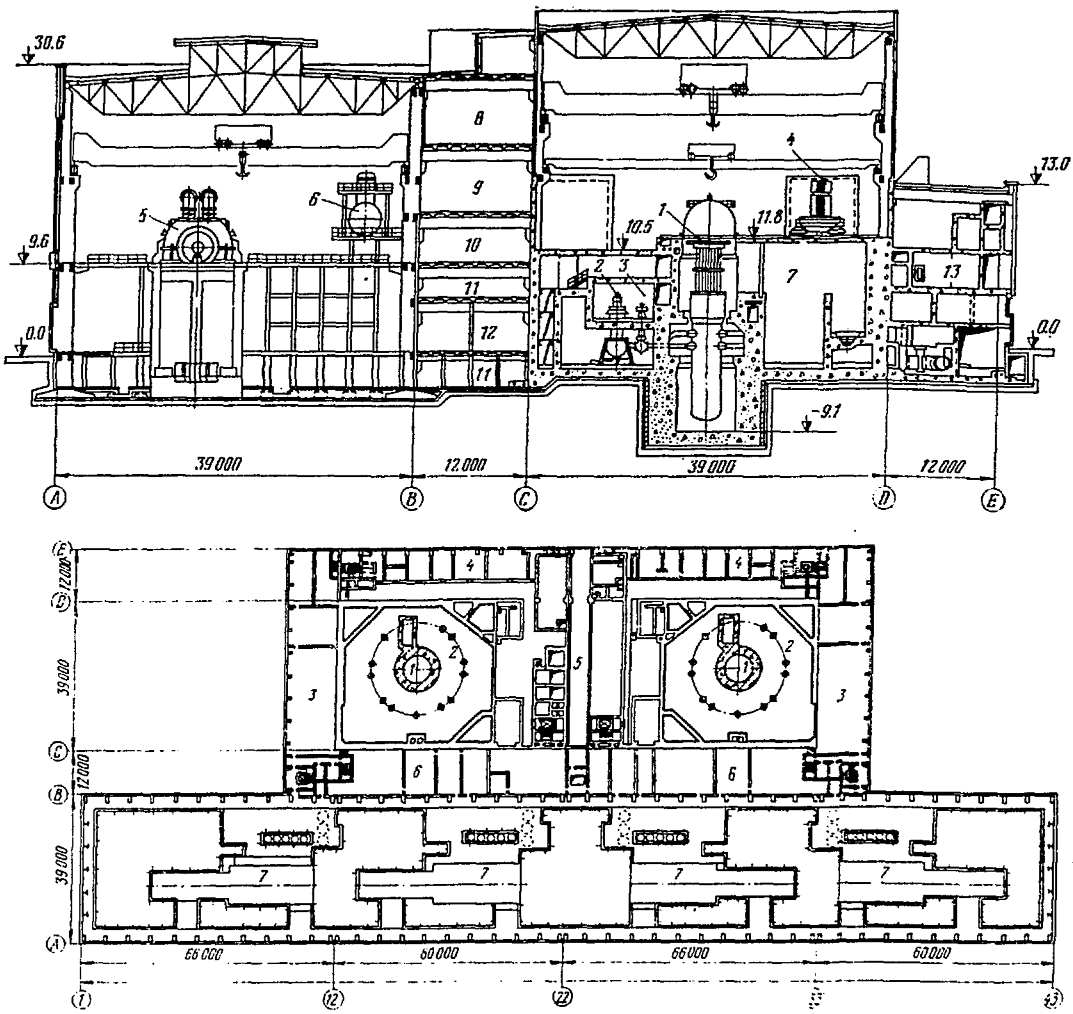

Fig. 2 Elevation and Plan Views of the Main Building

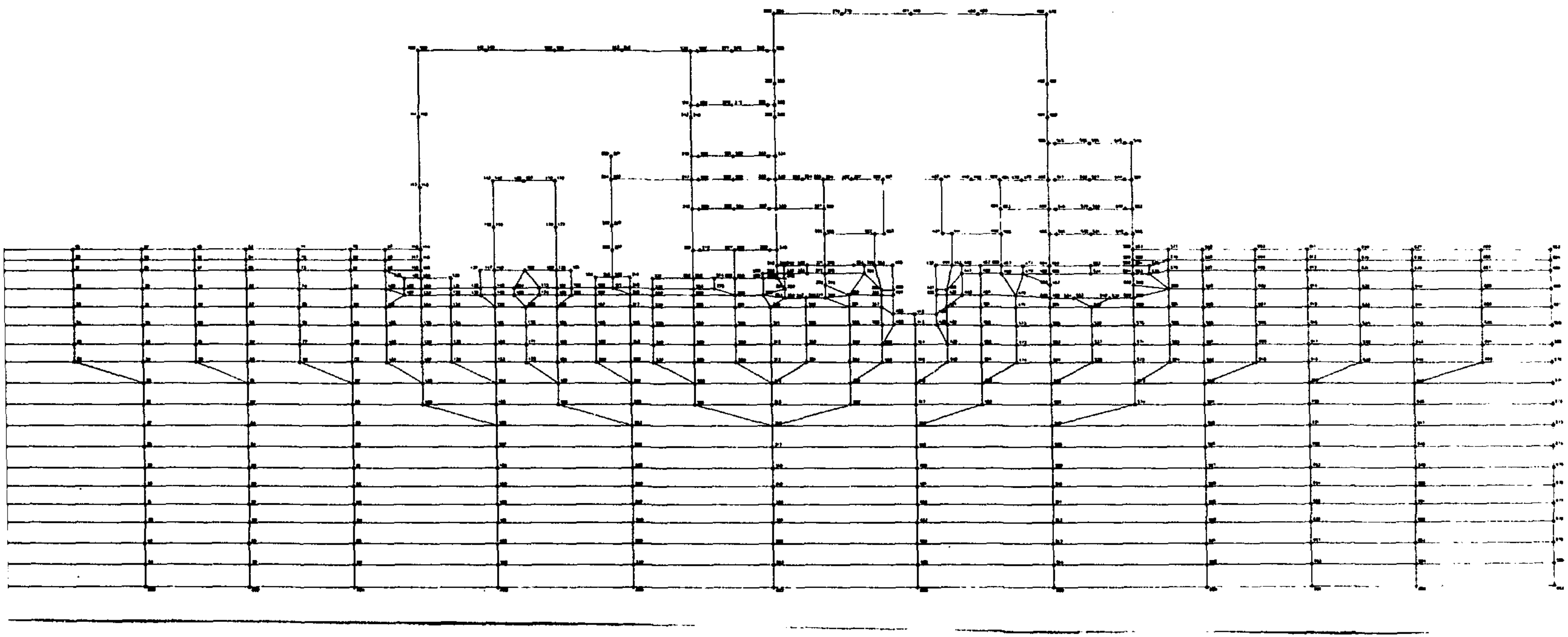

Fig. 3 Transversal SSI Model

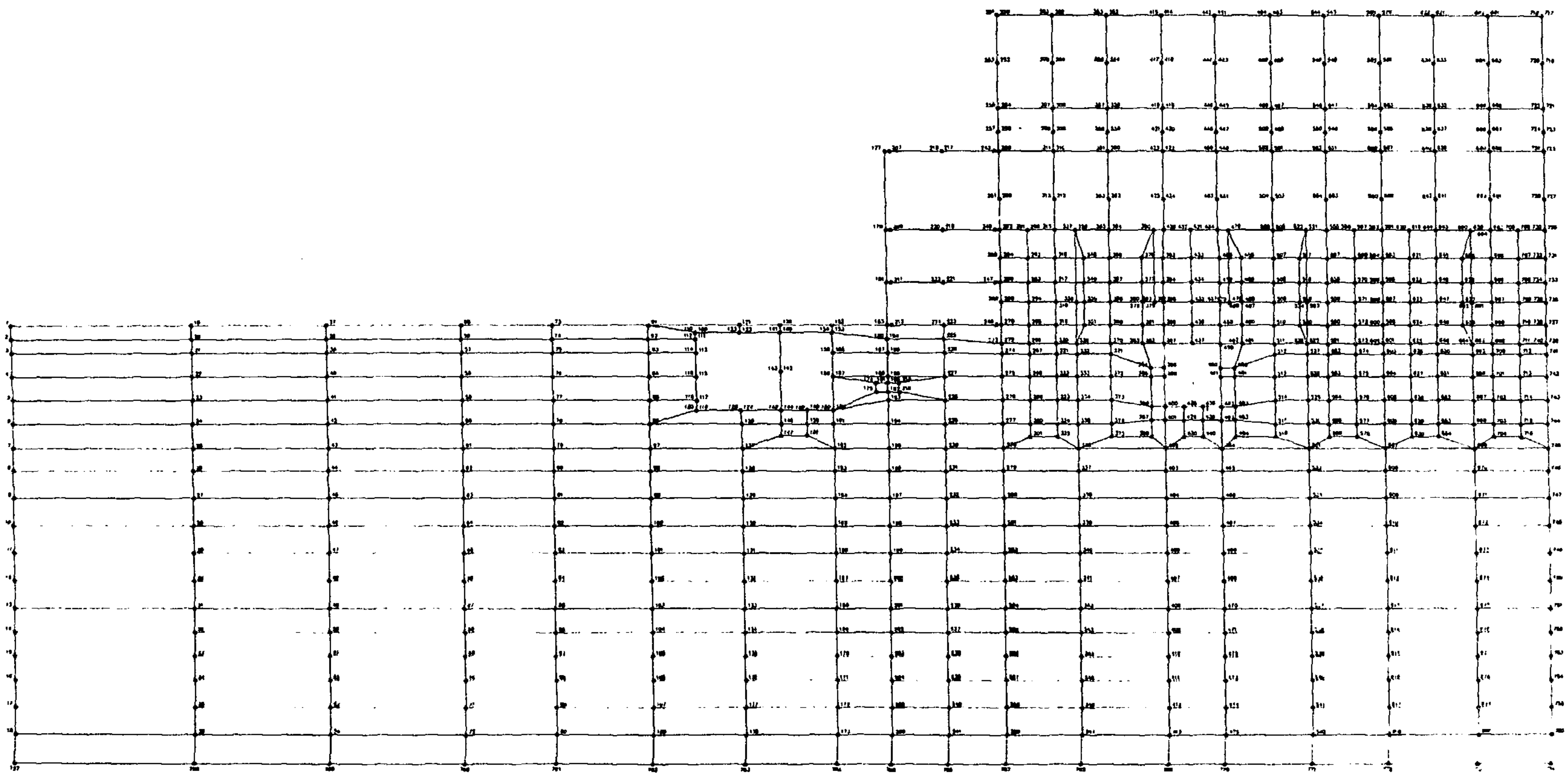

Fig. 4 Longitudinal SSI Model

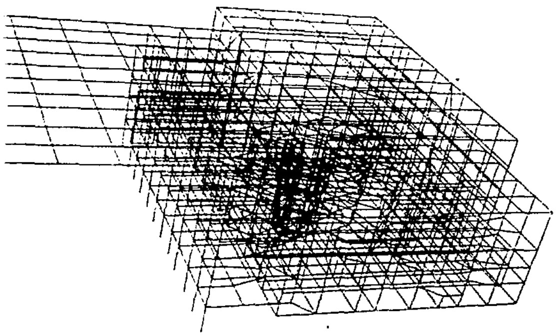

Fig. 5 3D Building Model

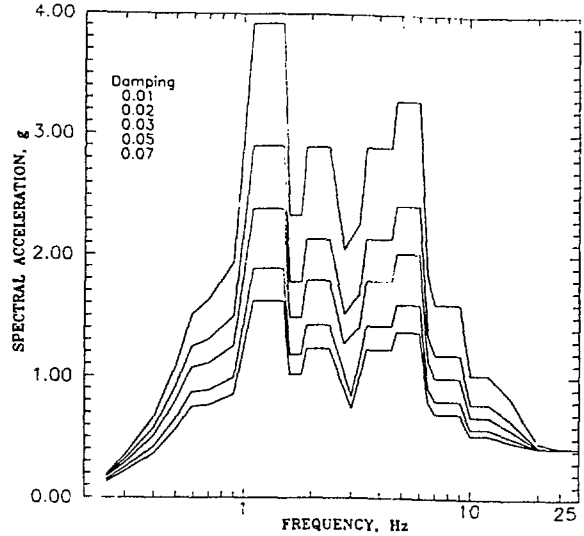

Fig. 6 Floor Spectrum at Level of 28.4 m of the Intermediate Building

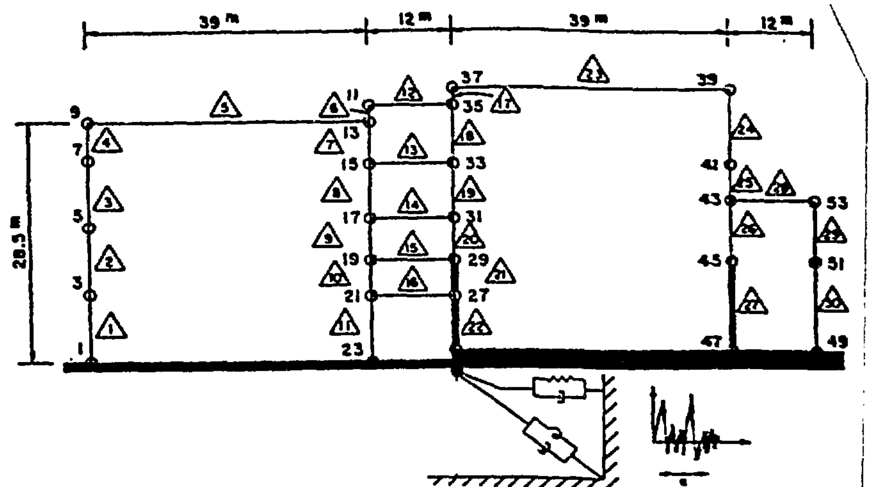

Fig. 7 2D Lumped Parameter Model

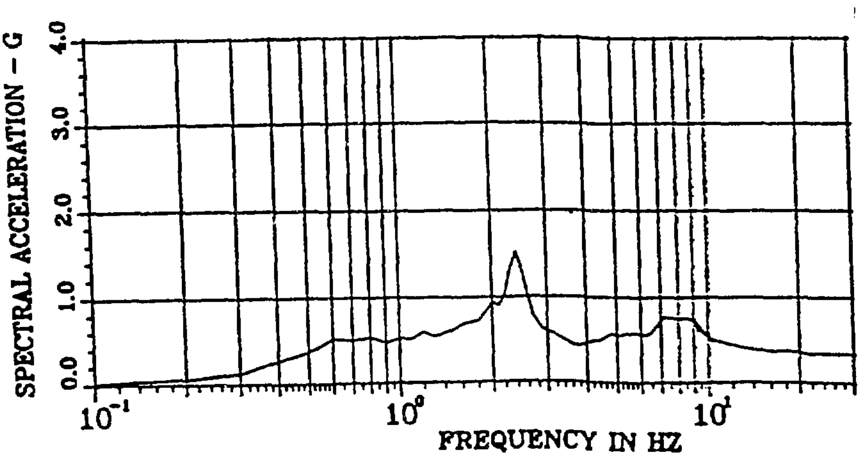

Fig. 8 Floor Spectrum (5% damping) at Level of 28.4 m of the Intermediate Building