Earthquake Response Analysis of NPP Buildings with Reactor WWER 440 Including Site Effects

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ABSTRACT

This paper gives the results of earthquake response analysis of nuclear power plant buildings with reactor VVER 440 including soil-structures interaction effects. Earthquake resisting of all the important buildings was considered taking a dynamic effect on soil-structures interaction into account. The different soil models (springs, 3D FE and IFE) are presented. The foundation stiffness at the dominant frequencies of the soil-structure system was represented by equivalent springs and damping values. The impedance functions were calculated from CLASSI program. The strain-dependent shear modul and material damping of layered soil model were performed with SHAKE program. The results of dynamic transient analyses for different soil models are compared.

INTRODUCTION

The earthquake resistance analysis of NPP buildings in Jaslovské Bohunice was based on the recommends of international organization IAEA in Vienna [1, 5, 8, 9, 11, 15] to get international safety level of nuclear power plants.

The review level earthquake (RLE) based on the Jaslovské Bohunice site specific hazard study, original seismic design ground motion, and established standard response spectra should be defined according to the requirements provided in [1, 4, 5, 11, 15].

The earthquake input must be specified in terms of free-field ground motion accelerograms for time-history dynamic analyses.

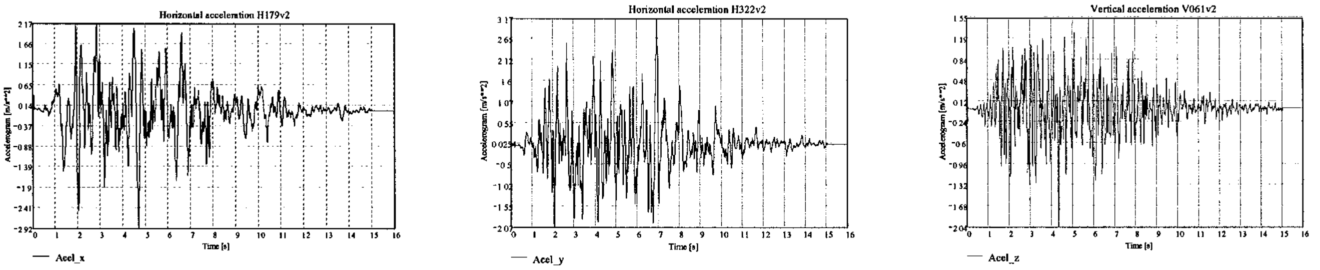


Fig.1 3D spectrum compatible design accelerograms H179v2, H322v2 a V061v2

The foundation of the reactor building embedded into the soil. This embedment has two effects on the dynamic analysis of the building:

➲ In comparison to a surface foundation the dynamic behavior of the foundation is different. The impedance analysis results in stiffness parameters and damping ratios for the foundation soil system, which are higher than those for a surface foundation. This leads to slightly higher global frequencies and a higher damping capacity of building soil system.

➲ The second effect is that the acceleration time histories at foundation level are different from the control motions specified at the surface of the free field.

In the case where structure and soil are idealized in only one Finite Element system or a consistent substructuring analysis the control motion is specified at the top of the surface and the effect of the embedment on both impedance and free field motion are automatically taken into account.

SOIL - STRUCTURE INTERACTION

Soil-structure interaction (SSI) is one of the most widely studied phenomena in earthquake engineering [1, 2, 4, 6, 7, 9, 10, 12, 14, and 16]. It is important because the vibration behavior of structures during earthquakes can be influenced significantly by the properties of soil and the structure. SSI analysis methods have been developed to account for rocking behavior, torsion effects, different support motions, nonlinear behavior and many other complex phenomena. Various substructure methods, hybrid methods, and volume methods have been implemented for one, two and three-dimensional analysis using finite element and continuum based procedures.

In the case of the nuclear power plants, the two acceptable methods of SSI (soil-structure integration) analyses are the impedance function or substructure approach and the direct method. The first method divides the SSI problem into a series of simpler problems, solves each independently, and superposes the results. The direct methods solve SSI problem in one step for linear material and geometric properties or in more steps for nonlinear material and geometric properties [2, 4].

The nonlinear behavior of soil shall be considered and may be approximated by equivalent linear material properties. Elementary, viscous, or transmitting boundaries may be used in the direct method. Under severe earthquake ground motions, the response of buildings may be influenced, if not dominated by nonlinear behavior.

EQUIVALENT LINEAR SOLUTION

Dynamic stiffness characteristics depend on soil material properties and shape foundations. The foundation configuration under Power Plant EBO V2 is very complicated. The foundation plate (75,0/70,0m) under building is on level -8.9m. The foundation plate (39,5m/27,0m) under babbler tower is on level -8.9m too.

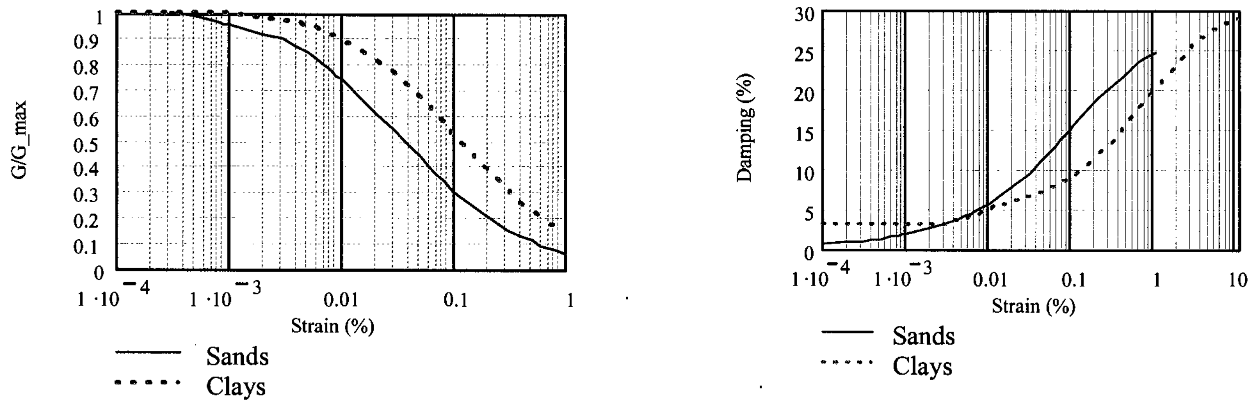


Fig.2 Typical Shear modulus and Damping vs Strain Degradation Curves

Dynamic modulus is determined of geophysical experiments [6, 8, 9, 11] in local site Jaslovské Bohunice. Foundation is embedded on soft clays or sands and gravels.

Table 1 Geophysical experimental results

Soil	v_p [m/s]	ρ [t/m^3]
soft clays	330 - 650	1,6 - 1,8
sands + gravels	1600 - 1800	1,8 - 2,1
Consolidated clays (neogén)	2500 - 2900	2,1 - 2,4

The unbounded soil can be represented [2, 7, 8, 9, 14, and 16] by more simple physical models. Use of the simple physical models leads to some loss off precision, but that is more than compensated by their many advantages. With a few springs, dashpot, and masses with frequency-independent coefficients, the unbounded soil can be represented by the same type of dynamic model as the structure enabling the same structural dynamics program to be applied. The lumped-parameter model can be conceptionally constructed from cones by assembling their exact discrete-element models in parallel and by calibrating with rigorous solutions.

Dynamic spring and dashpot soil characteristics were calculated by more methods.

Table 2 Dynamic soil springs

Author	k_x[MPa/m]	k_y[MPa/m]	k_z[MPa/m]
STN 730036	15	15	30
PN-80/B-03040	24	24	35
ASCE 4/86	41,5	41,5	56,1
Gazetas	17,2	17,2	35,3
Lysmer, Bycroft	44,7	44,7	57,4
Pais, Kausel	43,6	44,1	57,8
Mean modulus	21,2	21,2	41,5

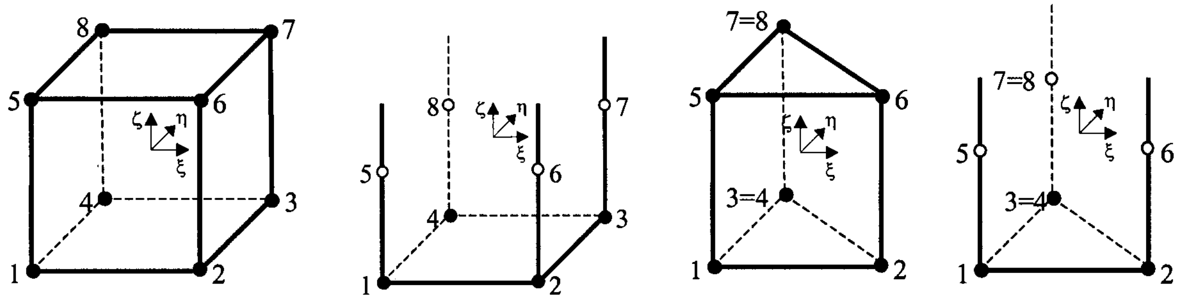
Differences in stiffness characteristics are the results of calculus model variance. The radiation of energy of the propagating waves away from the structure will result in an increase of the effective damping of the final dynamic system.

For a soil site consisting of a shallow layer resting on rigid rock, it is possible that no waves propagate away from the structure (if the frequencies of the excited waves lie below the so-called cut-off frequency of the layer, which is equal to its fundamental frequency). In this case, only the material damping of the soil will act, and no beneficial effect on the seismic response is to be excepted. In any soil-structure interaction, analysis it is very important to determine whether the loss of energy by radiation of waves (radiation damping) can actually take place.

The uncertainties in the SSI analysis shall be considered. In view of a probabilistic evaluation of uncertainties, an acceptable method to account for uncertainty in SSI analysis is to vary the soil shear modulus. Soil shear modulus shall be varied between the best estimate value times (1+ C_v) and the best estimate value divided by (1+ C_v), where C_v is a factor that accounts for uncertainties in the SSI analysis and soil properties. The minimum value of C_v shall be 0,5.

SOIL MODELING BY INFINITE SOLID ELEMENTS

The nuclear power plant foundation plate lies on a soil body. This unbounded soil body is modeled by infinite solid elements. Only the simplest infinite elements are used in the structure – soil modeling. These elements are derived from 8-node solid element (Fig. 1).



A B

Fig. 3 A – 8-node finite element and 4-node infinite superparametric element derived
B – 6-node finite element and 3-node infinite superparametric element derived

The ANSYS system is not containing structural infinite elements. But in the ANSYS element library is existing element for user defined stiffness, damping and mass matrix (MATRIX27). For modeling unbounded soil body software INFINITE8 was developed by authors [7, 9]. During structural analysis in ANSYS system, the separated parts of stiffness matrix are connected again. A diagonal damping matrix for infinite elements is derived from stiffness matrix. The stiffness matrix diagonal items are multiply by different coefficients for x,y,z directions. The damping matrix is included into ANSYS by the similar way as stiffness matrix.

IMPEDANCE SSI ANALYSIS

SSI analysis by the *impedance function or substructure approach* [1, 6, 14, and 16] shall consist of the following steps:

- Determine the input motion to the massless foundation,
- Determine the foundation impedance functions or foundation stiffness,
- Analyze coupled soil-structure system by solving equation of motion.

On the basis of the impedance functions, an iterative procedure can be used to determine a set of frequency-independent soil springs and dampers for modal analyses of the coupled systems.

Equivalent springs and damping values are frequency-independent data representing the foundation stiffness at the dominant frequencies of the soil-structure system. They can be read from the impedance functions.

These complex frequency-dependent functions represent the dynamic behavior of the foundation. The real parts of these functions represent the frequency-dependent stiffness; the imaginary parts the amount of damping in the soil-foundation system.

The impedance functions was calculated using CLASSI (SASSI) computer code for flat (embedded) foundation. This program solves the foundation-soil-interaction problem using the continuum approach for the unbounded soil medium. We have taken the impedance function for NPP foundation plate [8], which real and imaginary part is presented on fig.4, 5.

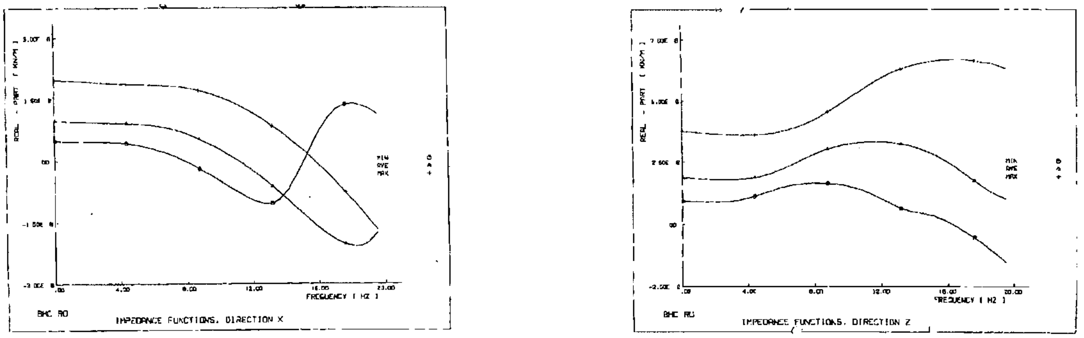


Fig.4 Real part of impedance function for horizontal (X) and vertical (Z) direction

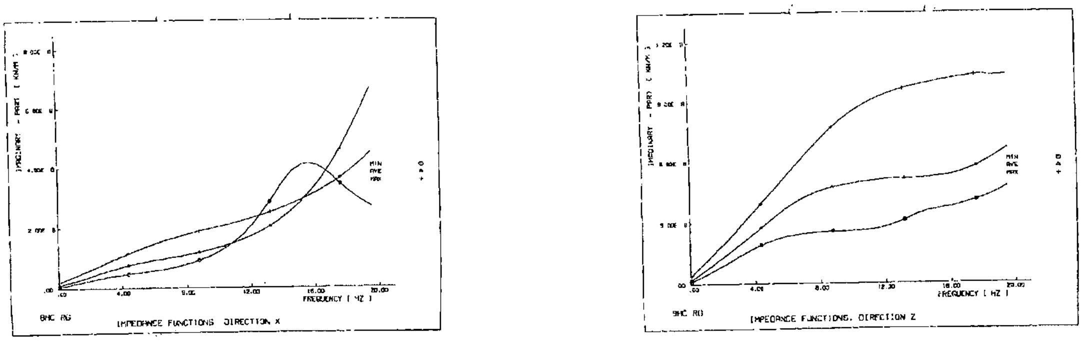


Fig.5 Imaginary part of impedance function for horizontal (X) and vertical (Z) direction

The stresses between soil and rigid slab is assumed to be constant over defined subregions. Equivalent springs and damping values are frequency-independent data representing the foundation stiffness at the dominant frequencies of the soil-structure system. They can be read from the impedance functions. In case of modal analysis some iterations may be necessary to obtain the final stiffness and damping.

The primary disadvantages of frequency domain analysis are that it cannot solve true nonlinear soil and structure problems and it is computationally inefficient for the solution of three-dimensional problems.

DIRECT SSI ANALYSIS

SSI analysis by the *direct method* [1, 2, 4] must be consist of the following steps

- Locate the bottom and lateral boundaries of the soil-structure model,
- Establish input motion to be applied at the boundaries,
- Establish soil model, properties, and layer boundaries to be used for the foundation,
- Perform SSI analysis in one or two steps, using structural finite element models.

The lower boundary shall be located far enough from the structure that the seismic response at points of interest is not significantly affected. The lower boundaries need not be placed more then 3 times the maximum foundation dimension below the foundation. The lower boundary may be assumed to be rigid. The location and type of lateral boundaries may be selected so as not significantly affect the structural response at points of interest. Elementary, viscous, or transmitting boundaries may be used.

NONLINEAR SOLUTION

Under severe earthquake ground motions, the response of buildings may be influenced, if not dominated by nonlinear behavior [2, 4, 6, and 9]. Thus, to estimate the dynamic response of a structure subjected to a severe earthquake, a nonlinear dynamic response analysis is necessary. The nonlinear strategies for one dimensional soil profile models can be used in simplified SSI models. Various nonlinear analysis programs perform direct numerical integration of the equilibrium equations two- and three- dimensional structural models using various numerical solution strategies.

We cannot to use more complicated soil model, because the FEM model of nuclear power plants has a lot of DOF and following solution process would be expensive. System ANSYS includes nonlinear spring elements with nonlinear damping, which we can effectively to use.

For nonlinear systems, which utilize an iteration strategy, the stiffness matrix **K** may vary over the time step and this equation for mean static error is no longer valid. However, by using an effective stiffness matrix, $\mathbf{K}_{\mathrm{eff}}$ based on the element states at the beginning and end of the time step, the mean equilibrium error of the system can be approximated by replacing $\mathbf{K}_{\mathrm{eff}} = \mathbf{K}\,(\mathbf{G}_{\mathrm{eff}})$. Effective shear modulus is determined from Lysmer courves G/Gmax and γ_{eff} (fig.1).

This method can be applicable for problems with local nonlinearities at the foundation level such as structural uplift of soil nonlinearity near the soil-structure interface.

MODELLING OF SYSTEM

The NPP (Power Block) building was discretized [8, 9] by the 3D finite elements model to obtain realistic behavior of structure. The model consists of 21 791 elements with 62 977 degrees of freedom. The drawbars are modeled by bilinear elements and contact between bubbler tower and air-conditioning center by gap elements.

The seismic loading was considered by spectrum compatible 3D accelerograms at foundation level to obtain time response. The structure - soil interaction was modeled with consideration of active area mass by Newmark and Barkan springs and viscous boundary elements.

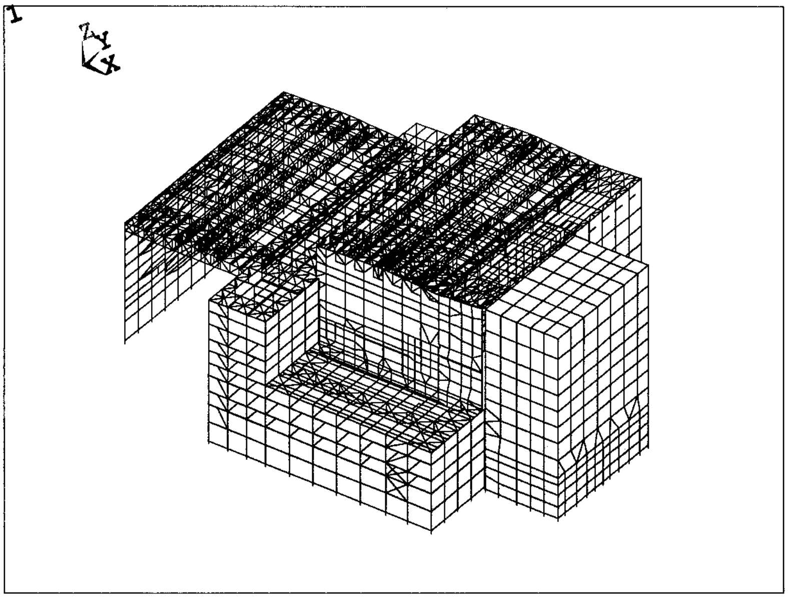


Fig.6 FEM model of NPP building

The material damping occurring in the soil and the structure mainly involves a frictional loss of energy. The damping forces, which are independent of frequency, are proportional to the displacements, but are in phase with the velocities.

TRANSIENT RESPONSE BY TIME INTEGRATION

The differential equation of motion of finite element system under seismic motion of ground can be written [2, 4, and 16] in the well-know matrix form

$$\mathbf{M}\ddot{\mathbf{q}}+\mathbf{C}\dot{\mathbf{q}}_r+\mathbf{K}\mathbf{q}_r=\mathbf{F}(t) \tag{1}$$

where ***M***, ***C***, ***K*** are mass, damping and stiffness matrices respectively; ***F*** is the vector of external nodal forces; $\boldsymbol{q}$, $\boldsymbol{q}_r$ are absolute and relative vector of nodal displacements. We have

$$\mathbf{q}_r=\mathbf{q}+\mathbf{q}_b, \qquad \ddot{\mathbf{q}}_r=\ddot{\mathbf{q}}+\ddot{\mathbf{q}}_b \tag{2}$$

where $\boldsymbol{q}_b$ is ground vector of nodal displacements. Introducing eq. (2) into (1) the equilibrium equation leads to

$$\mathbf{M}\ddot{\mathbf{q}}_r+\mathbf{C}\dot{\mathbf{q}}_r+\mathbf{K}\mathbf{q}_r=\mathbf{F}(t)-\mathbf{M}\mathbf{q}_b \tag{3}$$

where right-sides terms of equation (3) associated seismic and external loads.

The transient analysis was realized by direct integration in time of dynamic equations (1) or (3) by Newmark. This method is move convenient for problem solution with necessity to wave character of action.

The Rayleigh damping is proportional to a combination of the mass and the stiffness matrices

$$\mathbf{C}=a_0\mathbf{M}+a_1\mathbf{K}+\sum_{j=1}^{nmat} b_j\mathbf{K}_j+\sum_{k=1}^{nel}\mathbf{C}_k\ , \tag{4}$$

where a_o is constant mass matrix multiplier, a_1 is constant stiffness matrix multiplier, b_j is constant stiffness matrix multiplier for material j, *nmat* - number of materials with material damping, *nel* - number of elements with specified damping.

For the structures where the different materials provide drastically differing energy loss mechanisms in various parts of the structure, the distribution of damping forces will not be similar to the distribution of the inertial and elastic forces. Moreover, the resulting damping will be non proportional. The most effective way to determine the non-proportional damping matrix is to first evaluate one or more proportional damping matrices.

The modal damping of the steel frame and reinforced concrete wall alone would be 7% of critical damping [5, 15]. The damping of soil is alone 10% of critical damping.

NUMERICAL SOLUTION

The NPP foundation plate was discretized [8, 9] by the 2D finite shell elements with various model of soil. We compared the static and dynamic behavior of foundation plate with 6 alternative soil model – springs and dashpot (Zdwc, Zdwp), finite 3D elements (Zdef, Zder), infinite 3D elements (Zdin, Zdir). Normal (Zdef, Zdin) and reduce soil stiffness were used.

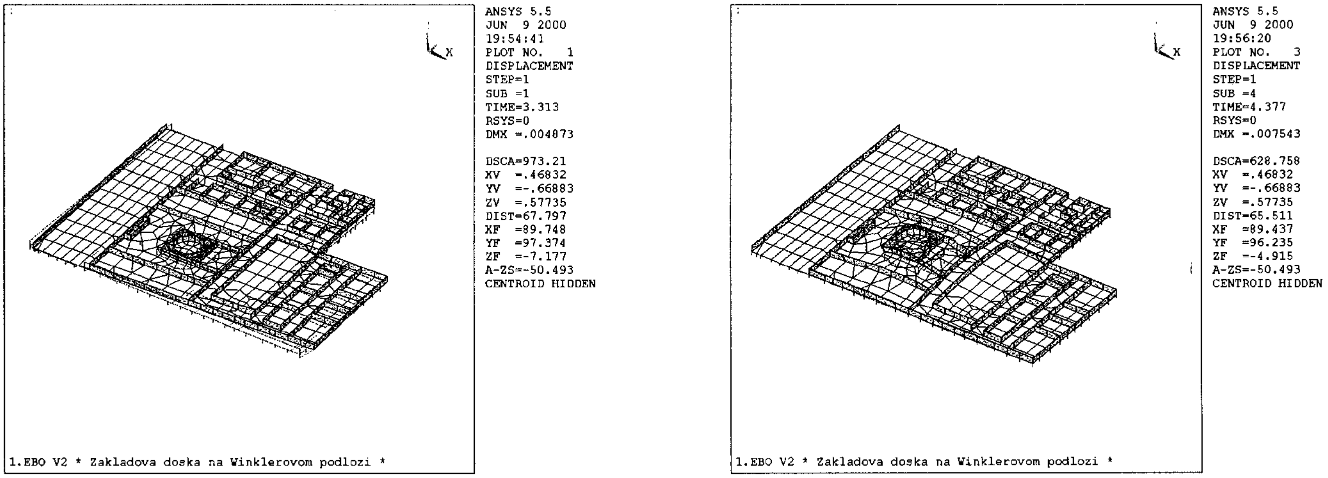


Fig.7 Dominant shape of foundation plate in horizontal and vertical direction.

Table 4 Comparison of frequencies of different soil model

	f[Hz]	%	f[Hz]	%	f[Hz]	%
Zdwc	3.660	99.0	3.272	65.0	5.102	25.3
Zdwp	3.634	99.0	3.314	57.8	4.380	24.4
Zdef	3.959	94.7	3.448	64.1	7.643	35.3
Zder	2.836	95.7	2.482	67.2	5.347	25.1
Zdif	6.669	94.3	5.882	47.8	11.223	15.0
Zdir	4.787	97.0	4.238	55.7	8.542	15.3
Zdiwf	4.800	98,6	4,360	60,4	7.390	24,8
Zdiwr	3,420	98,9	3,100	63,2	4,880	32,1

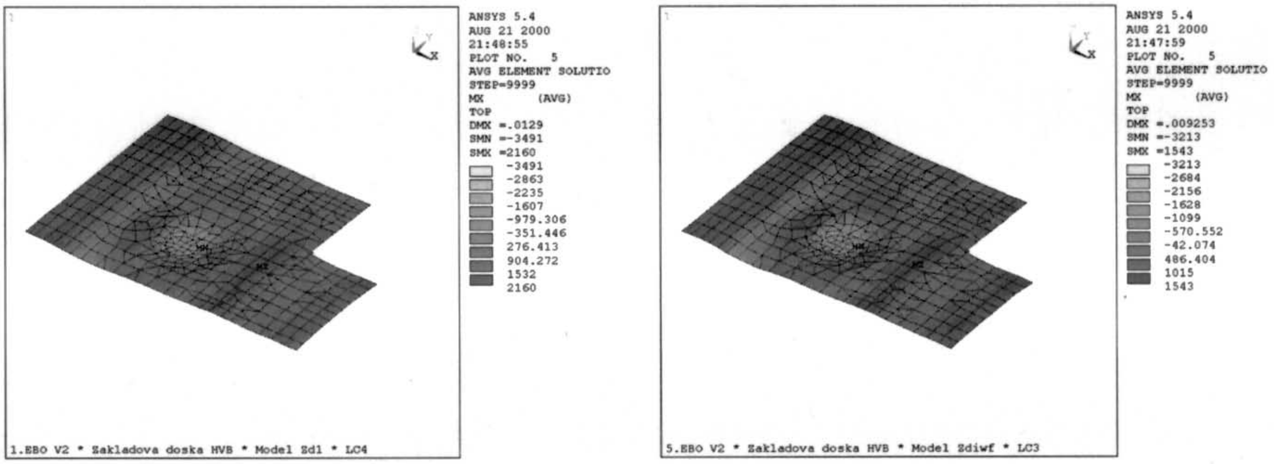


Fig.8 Comparison of bending moment extreme envelope on the model Zdwc and Zdiwf

Table 5 Comparison of bending moment on the foundation plate for different model

Extreme of Bending moment	Calculation model of foundation plate							
	Zdwc	Zdwp	Zdef	Zder	Zdin	Zdir	Zdiwf	Zdiwr
Max.m_x[MNm/m]	+2,30	+2,51	+3,14	+4,13	+1,37	+1,77	+2,26	+2,58
Min.m_x[MNm/m]	-3,82	-5,20	-2,47	-3,73	-1,78	-2,38	-3,50	-4,47
Max.m_y[MNm/m]	+2,12	+3,10	+3,33	+3,80	+1,29	+1,66	+2,17	+2,45
Min.m_y[MNm/m]	-4,19	-6,01	-3,92	-4,69	-2,01	-2,73	-4,12	-5,17

The solution – linear with nonproportional damping (ANSYS), linear with frequency dependent damping (SASSI) were calculated.

The realized seismic analyses of different soil model show the high influence soil model to modal and transient response results. The direct solution of soil-structure interaction using the finite elements has done better results than independent daspot-springs elements.

Presented results were considered as grant research VEGA 1/6306/99 on STU Bratislava [9].

CONCLUSIONS

In consideration of the works presented by more authors [1, 2, 4, 16], several recommendations regarding the earthquake analysis of buildings including site effects, as well as recommendations can be made:

- Structural engineers and designers should make every effort to obtain as much information as possible describing the properties of the site upon which a proposed structure is to be located. Useful site information includes site boring logs and soils test result, geophysical test results, and the results from ambient site vibration tests. The costs of obtaining this field data are easily justified when considered in light of the potentially devastating effect of site modification.

- The site properties should be used to build simple site models, which in turn can be provide a better definition of the input motions likely to develop at the base of the structure. The site properties should also be used to obtain the stiffness of massleas foundation springs for modeling the foundation flexibility,
- A well designed structure should have a minimum amount of torsion in the three-dimensional mode shapes associated with the lower frequencies of the structure, which are most likely to be excited by earthquake loading [12]. The principal directions of the structure qualitatively represent its most flexible directions. It is intuitive that a well designed structure should have equal stiffness in all lateral directions so that there is no tendency for the structure to be excited in any one particular direction,
- If an estimate of the ductility demands or the distribution of damage throughout a structure are required, two or three-dimensional nonlinear dynamic analysis can be conducted. SDOF nonlinear dynamic analysis procedures, based on the results of two or three/dimensional static collapse analysis are recommended as a simplified alternative to MDOF dynamic analysis,
- The idea that a well designed structure should have equal stiffness in all lateral directions can be extended to nonlinear response by recommending that the structure should also have equal strength in all lateral directions, precluding the development of a "weak" direction when the structure is subject to severe seismic loading. Clearly, this design objective would be difficult to achieve in practice,
- More work should be devoted to the implementation and verification of simplified nonlinear analysis methods. MDOF to SDOF transformation procedures should be evaluated for the approximate earthquake analyses of two and three-dimensional structures of various heights and configurations, designed using current seismic codes.

Three solutions - linear with nonproportional damping (ANSYS), linear with frequency dependent damping (SASSI) and nonlinear with nonlinear springs and damping (ANSYS) was calculated.

The realized seismic analyses with Siemens AG team and STU team [8, 9] proved good seismic resistance of NPP upgraded buildings in Jaslovské Bohunice. The building reconstruction plan was elaborated on the base of these analyses. In this plan, bubble tower and reactor hall and galeries steel structures must be fixed in lateral direction and in horizontal plane of roof.

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