ANALYSIS OF SOIL-STRUCTURE INTERACTION EFFECTS OF NPP STRUCTURES ON NONHOMOGENEOUS SUBSOIL

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Abstract. *This paper describes the soil-structure interaction (SSI) effects to the Nuclear Power Plant (NPP) structure with reactor VVER-1200. The simplified 1D and numerical 3D FE models of the nonhomogeneous subsoil are investigated. The methodology of the calculation of the frequency dependent complex functions of the soil stiffness and damping is presented.*

Keywords

Nuclear Power Plant, Impedance functions, SSI, FEM, ANSYS.

1. Introduction

After the accident of nuclear power plant (NPP) in Fukushima the IAEA in Vienna adopted a large-scale project "Stress Tests of NPP", which defines new requirements for the verification of the safety and reliability of NPP. Based on the recommendations of the ASCE standard [1] and IAEA in Vienna [11, 12], the effective seismic resistance of objects is assessed in PGA sites up to 0,3g according to the "Seismic Margin Assessment" methodology (SMA) [6].

The required methodology was based on a reference earthquake (RLE) or a "Seismic Margin Earthquake" (SME) earthquake, which is an earthquake with seismological parameters of a given site and response spectrum at the free terrain level corresponding to 84.1% probability of non-elevation (median overs), including Peak Ground Acceleration (PGA) for a given acceptable annual occurrence probability (typically 10^{-4} /year). During the last couple of decades, it has been well recognized that the soil on which a structure is constructed may interact dynamically with the structure during earthquakes, especially when the soil is relatively soft and the structure is stiff [2-5, 7-10, 13-33]. This kind of dynamic soil-structure interaction can sometimes modify significantly the stresses and deflections of the whole structural system from the values that could have been developed if the structure were constructed on a rigid foundation [7, 27, 31- 33]. Two important characteristics that distinguish the dynamic soil-structure interaction system from other general dynamic structural systems are the unbounded nature and the nonlinearity of the soil medium [9, 14, 20, 23, 31, 33]. Generally, when establishing numerical dynamic soil-structure interaction models [12], the following problems should be considered:

- Radiation of dynamic energy into the unbounded soil;
- The hysteretic nature of soil damping;
- Separation of the soil from the structural model;
- Possibility of soil liquefaction under seismic loads;
- Other inherent nonlinearities of the SSI model.

However, due to the complexity of dynamic soil-structure interaction, numerical modelling of this phenomenon remains a challenge. There still exist many difficulties to cover in one model all the problems listed above.

The recommendations for the simplified NPP calculation model and the calculation methods are based on recommendation of ASCE 4/98 [1] and refer to standard approaches to dynamic calculations using finite element method with a sufficiently precise spatial model of structures [4, 20-22, 29, 31-33].

A complete analysis of seismic soil–structure interaction should include the following steps:

- Site response analysis;
- Foundation scattering analysis;
- Foundation impedance analysis;
- Structural modelling;
- Analysis of the coupled system interaction response.

2. Stiffness and damping soil parameters in the subsoil

Dynamic soil characteristics are obtained with sufficient accuracy from the refractive and reflexive survey of a given site [2, 10, 27, 31-33]. Depending on the propagation rates of the longitudinal and transverse waves in the soil, we can determine its physical characteristics. For each sublayer layer in the depth of foundation direction, the velocity propagation velocities between the two wells are determined.

The basic rigid parameter characterizing the earth body for dynamic calculations is the dynamic G_{dyn} (or Young's elastic modulus modulus)

$$G_{dyn} = v_s^2 \rho\,, \quad E_{dyn} = v_s^2.\rho.2\left(1+\nu_{dyn}\right),$$
$$\nu_{dyn} = \left(v_p^2 - 2v_s^2\right) / \left[2\left(v_p^2 - v_s^2\right)\right] \qquad (1)$$

where ρ is the density, v_s - the velocity of the shear waves propagation in the respective earth (layer), v_p is the velocity of the longitudinal waves.

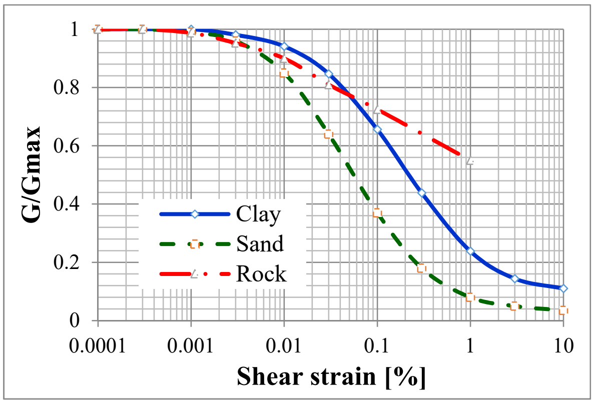

Fig. 1: Shear modulus dependence on the shear strain.

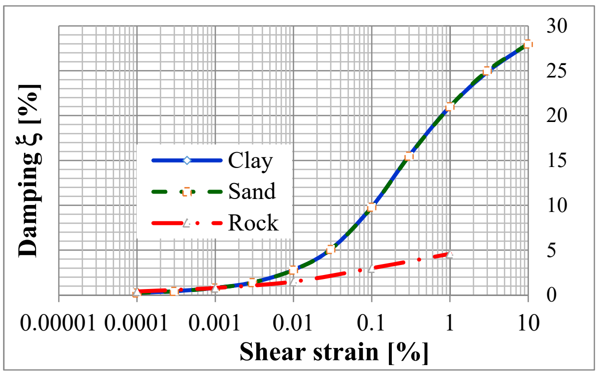

Fig. 2: Proportional attenuation on the shear strain.

In the case of earthquakes, there is a large movement of the soil, and because of plastic deformation, the value of the dynamic soil module also drops. According to the recommendations of international standards, this reduction will maximally reach 65% of the dynamic module measured for small seismic events. The process of the shear modulus can be seen in Fig. 1 depending on the shear strain [2, 7]. The damping is proportional to the attenuation on the shear strain (see Fig. 2).

Depending on the level of seismic stress, both the stiffness and the attenuation characteristics of the subsoil change according to Eurocode 8 recommendations. The typical range of the longitudinal (P) and shear (S) wave velocities for different subsoil conditions [2].

Tab.1: The ratio of dynamic to static modulus of elasticity [26].

Soil	E_{dyn}/E_{stat}	E_{stat} [MPa]
No cohesive soil	2.5 ÷ 4.0	30 ÷ 120
Cohesive soil	4.0 ÷ 10.0	6 ÷ 30
Rigid soil. rock	6.0 ÷ 60.0	60 ÷ 700

3. Geophysical characteristics of the heterogeneous subsoil

Three types of the site are defined by IAEA NSG 3.6 [12] standard in dependency on value of v_s:

- Type 1 sites: v_s > 1100 m/s;
- Type 2 sites: 1100 m/s > v_s > 300 m/s;
- Type 3 sites: 300 m/s > v_s;

The geology profile under NPP main building is variable and complicated in plane and in depth. The geology profile was determined from 12 surveys (see Fig. 3).

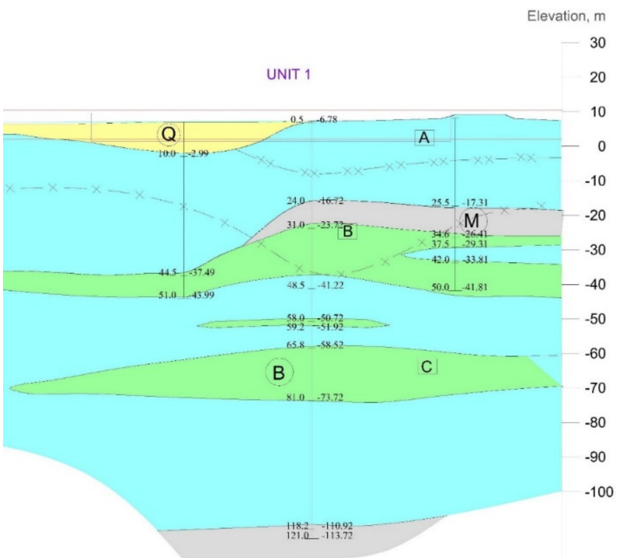

Fig. 3: Engineering geological cross-section under NPP main building.

Tab.2: The comparison of the $v_{s,30}$ values defined by the various methodology [31].

Bore hole	Abs. elevation of borehole [m]	$v_{s,30}$ [m/s]			
		PS logging	Micro-tremor Array	Down-hole	ReMi/ MASW
Center	7.28	707	1200	1470	1050
Edges	7.79	820		1370	

The average shear wave $v_{s.30}$ can be determined by various experimental methods (see Tab. 2) or numerically in accordance with the Eurocode 8 in following form:

$$v_{s.30} = 30 \Big/ \left(\sum_{i=1,N} h_i / v_i \right), \quad (2)$$

where h_i and v_i denote the thickness (in meters) and shear-wave velocity (at a shear strain level of 10^{-5} or less) of the i-th formation or layer, in a total of N, existing in the top 30m.

The average shear velocity $v_{s.30}$ for NPP foundation. obtained with the use of different methods are compared in Table 2.

The mean values of the subsoil geophysical characteristics under the reactor building center were determined from the experimental measurement (see Tab. 3).

Tab.3: Geophysical soil characteristics under reactor center.

v_s [m]	v_p [m]	z. [m]	ρ [g/cm3]	G_d [MPa]	μ [-]
382	1668	-7.5	2.685	392	0.47
439	1965	-10.5	2.685	517	0.47
673	2141	-12.0	2.685	1216	0.45
901	2978	-16.0	2.685	2180	0.45
1257	3660	-23.0	2.685	4242	0.43
1964	3984	-25.0	2.700	10415	0.34
1860	4256	-33.5	2.648	9161	0.38
2370	4335	-43.5	2.658	14930	0.29
2809	5254	-50.0	2.704	21336	0.30
2530	5318	-92.0	2.738	17526	0.35
3013	5738	-100	2.720	24693	0.31

4. General principles of structural-base interaction

For most common structures, the effect (SSI) of the structure-substrate interaction will be more advantageous as it reduces the effect of bending moments and shear forces on individual structural elements. The effect of the dynamic interaction of the soil-structure must be considered for all constructions [6, 11, 19, 33].

- Method of direct integration.
- Method of impedance functions.

The effect of foundation depth is considered when an object is laid at a depth greater than 6m.

The direct method of the design and substrate interaction consists of the solution of the following tasks:

- Localize the contact between the structure and the subsoil,
- Define the seismic load at the level of the base joint,
- Create the calculation model subsoil, its properties, soil layering under the foundation,
- Carry out the interaction in one or two steps,

If the direct method is considered, the stiffness and attenuation of the substrates can be modelled as a set of independent springs or, in more detail, based on the finite element method.

The impedance function method [30] consists of the following steps:

- Determine the seismic load assuming a rigid base,
- Determine impedance functions for given foundations,
- Analysis the interactions between the structure and the base.

The impedance functions define the dependence of stiffness and subtle stress on the substrate based on frequency. It is assumed that the harmonic force is applied to the rigid base deposited on the flexible half-frame. Such a computational model assuming linear behaviour, provides a better understanding of the properties of the underlying behaviour, depending on the actual frequencies of the structure itself.

In the case of a simple base model and substrate, the impedance functions are determined by the ratio of the harmonic force $P(t)$ acting on the rigid base to its displacement u(t) in the shape

$$K_{imp} = P(t)/u(t) = (k - m\omega^2) + ic\omega = k_1(\omega) + ik_2(\omega) \quad (3)$$

where k (resp. c) represent the stiffness (resp. attenuation) of the substrates, m is the mass of the base, ω is the circular frequency (see Fig. 4).

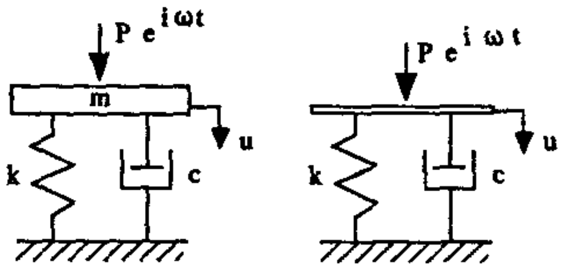

Fig. 4: Calculation model of base with mass m and without mass.

5. Impedance of foundation using FE Model

For complex foundation geometries or soil conditions, the dynamic soil impedance can be determined by dynamic analysis of a three-dimensional or two-dimensional continuum model of the soil-foundation system. The six steps can be implemented using the finite element (FE) method [3, 4, 9, 17, 19, 32, 33]. In this case, the soil is modelled as an elastic or viscoelastic material, which can be considered isotropic, anisotropic, homogeneous or nonhomogeneous. In a FE model, only a portion of the soil (i.e., a soil island) can be discretized; therefore, appropriate boundary conditions (non-reflective boundaries) must be applied where the soil is arbitrarily truncated. The response of a rigid foundation to static or dynamic load arises solely from the deformation of the supporting soil. The static soil stiffness (K = P/U) is used to model the soil-foundation response to static load. In an analogous manner, the dynamic soil impedance/stiffness (K = P(t)/U(t)) is used to model the soil-foundation response to dynamic loads. In particular, six dynamic impedances are required, three translational and three rotational, to formulate the dynamic equilibrium equation of a rigid foundation. These impedances are a function of the foundation geometry, the soil properties and vibration frequency of the dynamic loads (fm, ωm).

The procedure used to calculate the dynamic impedances of a rigid surface foundation can be summarized in the following steps:

1. The foundation can be modelled as massless and infinitely rigid; therefore, only the geometry of the area in contact with the soil is required. The use of a massless foundation is important since it avoids the need for recalculating the dynamic impedance every time that the foundation mass changes, which often happens during the design process.

2. A harmonic force or moment of frequency ω and of unit magnitude is applied to the rigid foundation $\left[e.g.\ P(t)=P_o e^{i\omega t}\ or\ M(t)=M_o e^{i\omega t}\right]$. Such force/moment generates stress waves that propagate into the underlying soil, which is modelled as a viscoelastic material.

3. The steady state vibration amplitude of the foundation $\left[U(t)=U_o e^{i\omega t+i\phi}\ or\ \theta(t)=\theta_o e^{i\omega t+i\phi}\right]$ under the harmonic force is obtained by keeping track of the reflections and refractions that take place every time that the stress waves reach a soil layer boundary.

4. The dynamic impedance is defined as the ratio between the harmonic force acting on the foundation and its vibration amplitude as shown in Eq. (4). It must be noted that this is a frequency dependent complex quantity.

$$K(\omega)=P(t)/U(t)=P_o e^{i\omega t}\Big/\left(U_o e^{i\omega t+i\phi}\right)=P_o e^{-i\phi}/U_o$$

5. In soil dynamics, it is customary to express the complex dynamic impedance defined below. In addition, the real and imaginary parts of the dynamic impedance are associated, by analogy, with a dynamic (frequency dependent) spring and dashpot as shown in following equations:

$$K(\omega)=k_1+i\omega k_2\,,$$

$$k_1(\omega)=Re\big(K(\omega)\big)=\left(P_o/U_o\right)cos(\phi)\,, \qquad (4)$$

$$k_2(\omega)=Im\big(K(\omega)\big)/\omega=-\left(P_o/U_o\right)sin(\phi)/\omega\,,$$

Steps 2 to 5 are repeated for each frequency of interest, until the range of vibration frequencies of the machine is covered.

6. Calculation FE model

The presented methodology was used for the analysis of the soil-structure interaction of the NPP main building with reactor VVER1200 which was situated in the complicated subsoil area. The dimension of the reactor building is 83.8m x 78m in plane and 74.9m in high. The simplified methods to specify of the stiffness and damping parameters based on the homogenization od the material properties of the subsoil are not representative in case of the soil layers with shear velocity vs < 1000m/s.

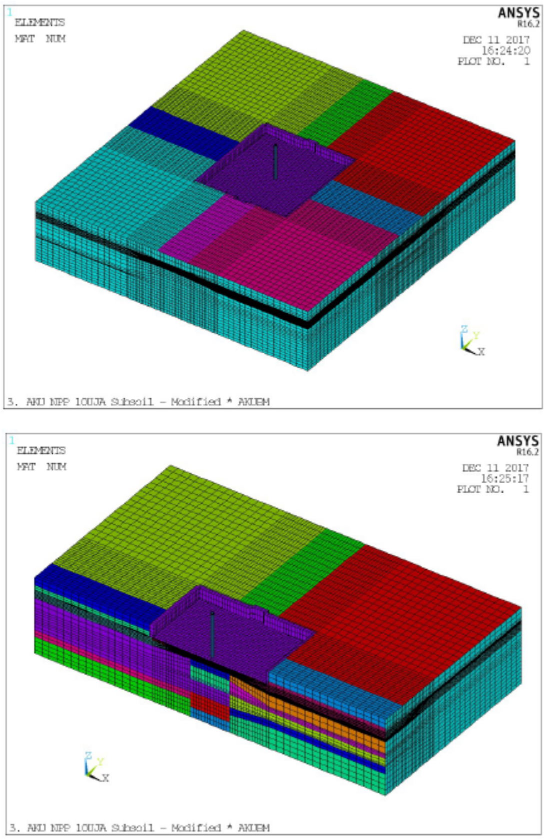

Fig. 5: FE model of the subsoil under NPP main building (231226 elements, 91 materials)

The subsoil around the NPP main building VVER-1200/491 PWR is modelled by solid elements SOLID185, the foundation plate by shell elements SHELL181 and surface around soil block by elements SURF154 in the software ANSYS (see Fig. 5).

7. Impedance functions of NPP main building

On the base of the methodology presented in chap. 5 the impedance functions for the NPP main building VVER-1200/491 PWR considering the real layered subsoil properties determined by experimental testing of the subsoil were calculated on FE model in software ANSYS (see Fig. 5).

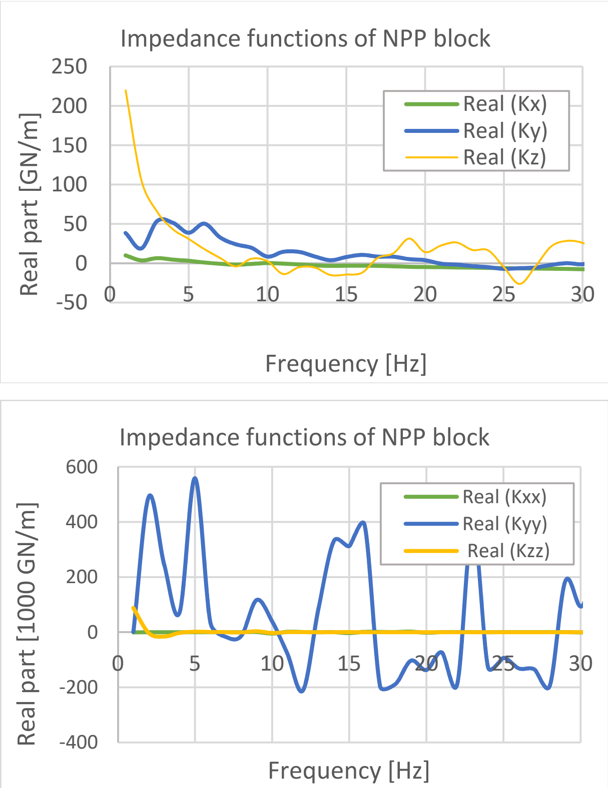

Fig. 6: Real part of the impedance functions for translation and rotation

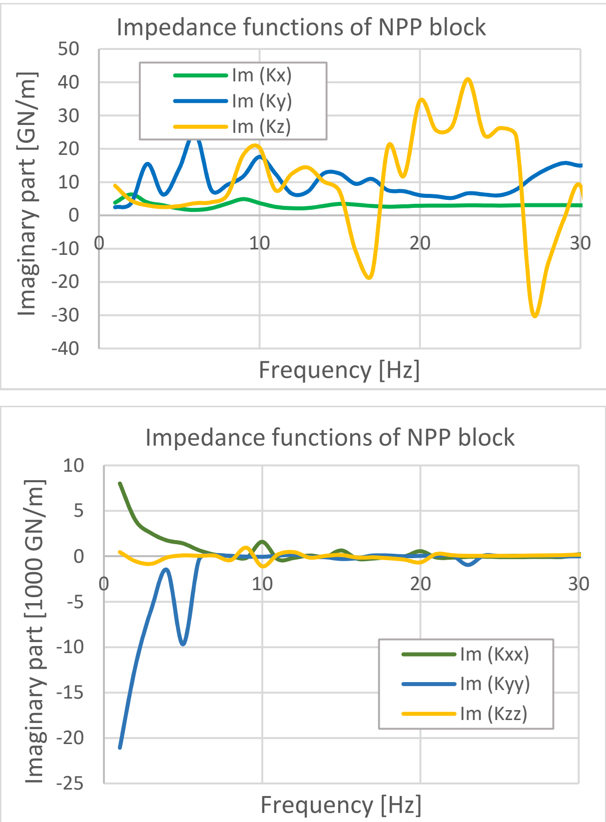

Fig. 7: Imaginary part of the impedance functions for translation and rotation

The impedance functions shape in figs. 6 and 7 are not simple and continuous functions as in the case of the analytical solutions of the impedance functions of the rigid plate on homogenous soil [31]. The layered properties of the soil under rigid plate and the discretisation of the subsoil using FE Model with the solid elements give us more detailed information's of the dynamic soil-structure interaction effects. The global stiffness and damping properties depend on the geometry and material properties of the soil under the rigid rectangular plate.

8. Conclusions

This paper describes the soil-structure interaction effects in the case of the NPP main buildings with reactor VVER-1200/491 PWR during earthquake excitation. The methodology of the calculation of the impedance functions were considered. The dynamic impedance is defined as the ratio between the harmonic force acting on the foundation and its vibration amplitude. The results from the 3D FE analysis show as that the impedance functions are not smooth functions in case of the layered subsoil with various material properties as in case of the homogeneous subsoil.

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