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ANALYSIS OF THE IMPEDANCE FUNCTIONS USING 3D FINITE ELEMENT MODEL OF SUBSOIL

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Abstract: *This paper describes the soil-structure interaction effects in the case of the NPP main buildings with reactor VVER-1200/491 PWR. The simplified 1D and numerical 3D FE models of the subsoil are presented. The main reason of this methodology is proposed the frequency dependent complex function or as a spring-dashpot system, with the spring becoming negative for certain frequencies, which cannot be directly implemented in standard structural analysis codes. The methodology of the calculation of the impedance functions due to dynamic excitation are considered.*

Keywords: nuclear power plant, impedance functions, SSI, FEM, ANSYS

1. Introduction

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 (Chen, 2003, Králik, 2009). 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 (Gazetas, 1991). 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 (Chen, 2003, Kralik, 2009, Park, 2013, Werkle, 2014). Generally, when establishing numerical dynamic soil-structure interaction models (ISO, 2014), the following problems should be taken into account:

1. Radiation of dynamic energy into the unbounded soil;
2. The hysteretic nature of soil damping;
3. Separation of the soil from the structure;
4. Possibility of soil Liquefaction under seismic loads; and
5. Other inherent nonlinearities of the soil and the structure.

The investigation of the SSI effects to the resistance of structures is especially important from the point to arrange the safety of nuclear power plants (NPP). The recommendations for the NPP calculation models and methods are based on the recommendation of ASCE 4/98 (ASCE, 2000) and IAEA (IAEA, 1992, 2008).

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 (IAEA, 1992, Chen, 2003). Depending on the propagation rates of the longitudinal and transverse waves in the soil, we can determine its physical characteristics (Gazetas, 1991, Wilson, 1989,

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Wolf, 1994). 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)

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

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

In the case of the homogenous subsoil under NPP buildings the simplified methods to set the equivalent dynamic soil stiffness and damping can be used.

If we have the layered subsoil with the various material properties, the SSI must be investigated using the 3D soil model.

This paper presents the investigation of the SSI effects in case of the NPP main building with reactor VVER1200. The geology profile under NPP was variable and complicated in plane and in depth. The geology profile was determined from the 12 surveys (see Fig. 1).

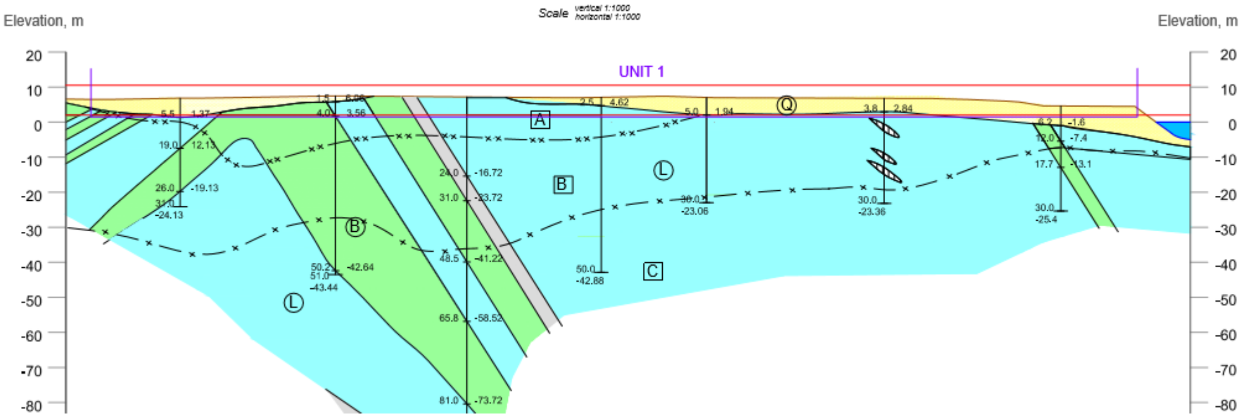

Fig. 1: Engineering geological cross-section under NPP main building.

3. Impedance of foundation using FE Model

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 pilot-based substructure must be considered for all structures (Chen, 2003, Gazetas, 1991, Kralik, 2009) using direct integration methods or the method of impedance functions. 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. In particular, the six steps can be implemented using the finite element (FE) method (Coronado, 2016, Chen, 2003, Kralik, 2009). The static soil stiffness ($K = P_o/U_o$) 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

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.

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 $\left[U(t) = U_o e^{i\omega t + i\phi}\ or\ \theta(t) = \theta_o e^{i\omega t + i\phi}\right]$ of the foundation 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 $K(\omega)$ is defined as the ratio between the harmonic force acting on the foundation and its vibration amplitude. It must be noted that this is a frequency dependent complex quantity.

$$K(\omega) = P(t)/U(t) = P_o e^{i\omega t} / \left(U_o e^{i\omega t + i\phi}\right) = P_o e^{-i\phi} / U_o \qquad (2)$$

5. In soil dynamics, it is customary to express the complex dynamic impedance as shown in Eq. (2). 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:

$$K(\omega) = k_1 + i\omega k_2, \qquad (3)$$

$$k_1(\omega) = Re\left(K(\omega)\right) = \left(P_o/U_o\right)cos(\phi), \qquad k_2(\omega) = Im\left(K(\omega)\right)/\omega = -\left(P_o/U_o\right)sin(\phi)/\omega$$

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

4. Calculation of impedance function on 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 83.8 m × 78 m in plane and 74.9 m in high. The dynamic characteristics (velocity of the shear and longitudinal waves) were defined from the 9 borehole in this area. 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 v_s < 1000 m/s.

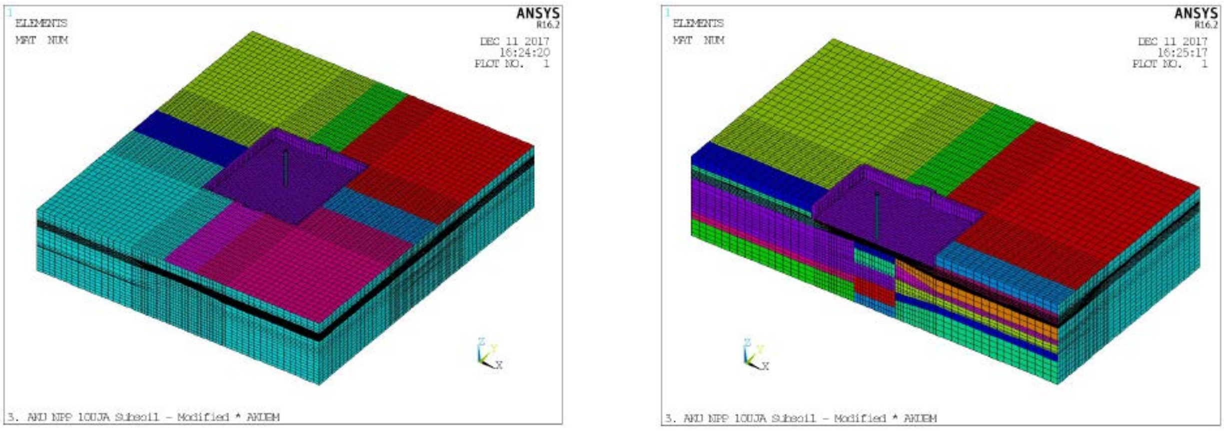

Fig. 2: FE model of the subsoil under NPP main building (231226 elements, 91 materials).

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.

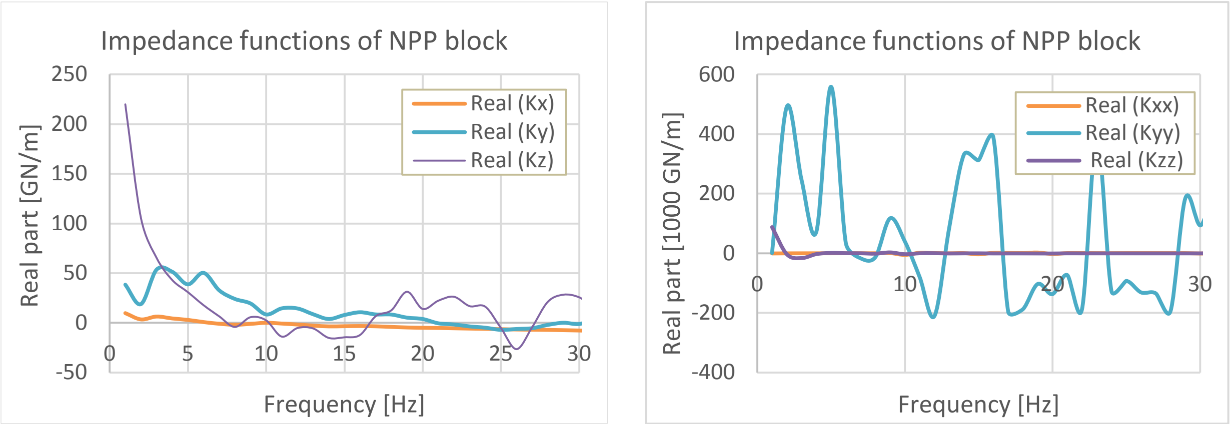

Fig. 3: Real part of the impedance functions for translation and rotation.

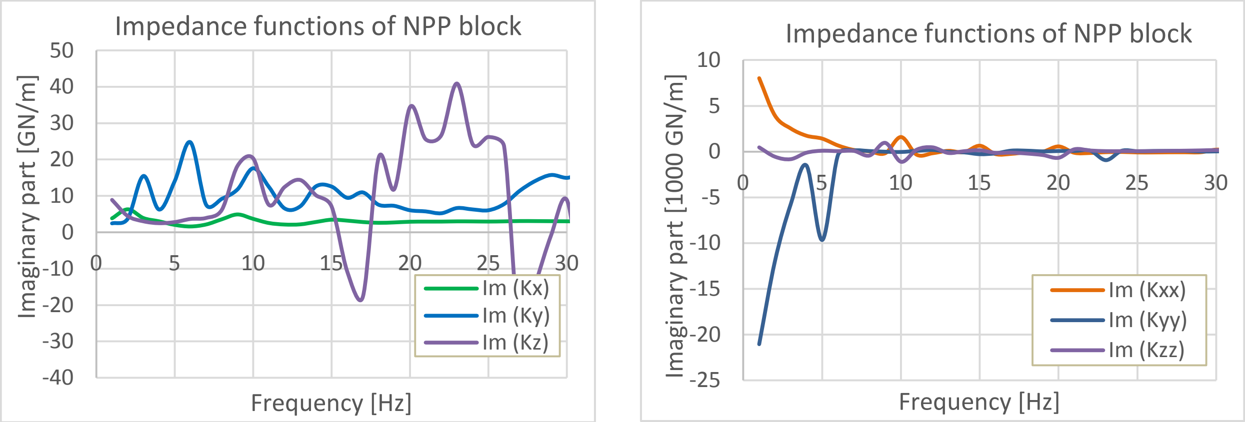

Fig. 4: Imaginary part of the impedance functions for translation and rotation.

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 in 12 boreholes were calculated on FE model in software ANSYS.

5. 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. 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 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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