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SEISMIC RESPONSE OF A STRUCTURE UNDER VARIOUS SUBSOIL MODELS

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Abstract. *This paper describes three types of methodologies for modelling the soil - structure interaction of a building under seismic load. An example of a real building is used to demonstrate differences in the dynamic response results in the calculation of internal forces and displacements. The response of the structure was calculated by decomposing the seismic load into natural vibration modes. A 3D calculation model for the RC building was set up, and variant options of the soil models were considered for a dynamic analysis of the calculation model. In calculation model A, the soil was modelled using equivalent stiffness values of the soil, stemming from the theory of a rigid circular disc on an elastic homogeneous half-space. Non-uniformly modelled vertical stiffness of the soil according to the Boussinesq model was used for model B. Model C was used for modelling the soil according to its actual composition, with subsequent additional calculation of the Winkler-Pasternak constants of the soil.*

Models A and B, where homogeneous "averaged" soil is considered using the equivalent stiffness model (spring constants), both show almost no serious differences among the dynamic response results. Model C, where the actual layered soil is considered on the basis of Winkler-Pasternak theory, has an effect on the increase in the dynamic displacements, particularly in the vertical direction, given that the soil layers below the foundation structure are modelled more accurately than for the "averaged" soil of models A and B. However, the internal forces of model C are considerably lower than for the other models. As a rule, the dynamic response of calculation models operating with "averaged" values of the subsoil for a structure embedded on alternating rigid and soft soil layers is markedly shifted to the conservative side (smaller values). The internal forces are considerably lower in these models A and B. The response of the structure in dynamic displacements is the opposite, and the dynamic displacements are significantly higher for the Winkler-Pasternak model C. than for models A and B.

1 INTRODUCTION

Considering the current level of knowledge, two procedures are available for analysing potential ways for modeling the structure - subsoil interaction:

a) Assuming a rigid foundation structure, the behavior of the subsoil can be modeled using equivalent stiffness values of the subsoil (classical model A, and improved Boussinesq model B). This procedure is derived from the theory of a rigid disc oscillating on the elastic half-space of the subsoil, with the actual layered subsoil being equivalent to the simplified homogeneous subsoil.

b) Modelling the subsoil while taking into account its layered nature and the mechanical properties of all the subsoil layers on which the building structure is founded (model C). Not only the vertical load of the subsoil, but also the distribution of the load in directions horizontal to the surroundings of the foundation structure, and the co-action of this part of the subsoil with the building structure itself, can be taken into account in this subsoil - structure system model.

In order to recommend a suitable modeling procedure for the soil - structure interaction, the concrete building of an NPP was chosen (for variant calculations), and selected soil modeling procedures were subsequently applied to it successively.

Basic variants for modeling the support of nuclear structures upon seismic load were adapted from the standard ASCE 4-98 [2] and Report UCRL-15910 [5]. The principles of Eurocode EN 1998-1 [1] were also considered, including its National Annexes, as well as other classical publications, including the publications of E. Reissner, G. W. Housner, J. Lysmer, F. E. Richart and R. W. Whitman. A complex treatment of this issue can be found in [7], [8] and [9].

2 COMPUTATIONAL MODEL

2.1 Calculation model of the structure

The structure is designed as a three-storey building with plan dimensions 16.6 × 54.8 m (Figure 1). The building is placed on a monolithic base plate 800 mm in thickness. The basement floor is constructed from monolithic plates and walls. The baseplate is 800 mm in thickness, the ceiling plates are 600 mm and 200 mm in thickness, and the walls are 600 mm, 400 mm, 300 mm and 200 mm in thickness.

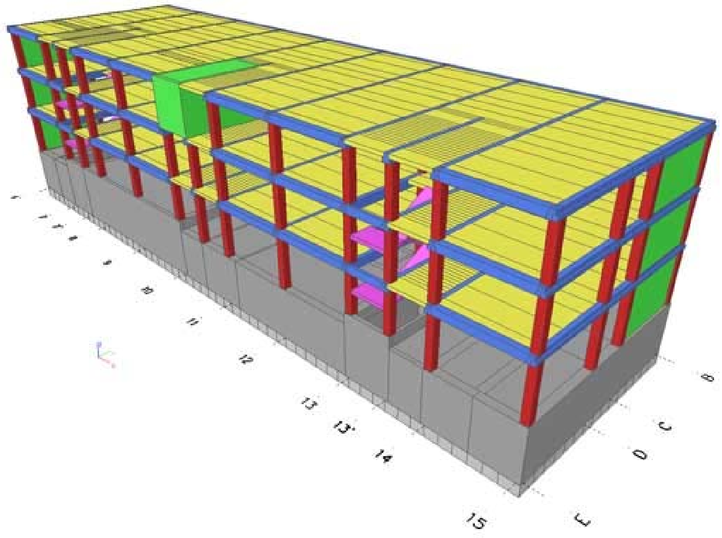

Figure 1: Calculation model, north-west view

The main above-ground part of the building is designed as a three-storey prefabricated reinforced concrete building with modules 6.0 + 3.0 + 6.0 m in depth of the building, 9 × 6.0 m in length, and 3.6 m in structural height. The cross sections of the columns and beams are rectangular 500 × 500 mm. Prestressed ceiling panels are used 240 mm in height and 590 mm, 740 mm, 950 mm, 1090 mm, 1190 mm, 1550 mm and 1790 mm in panel width. The structure is braced with stiffening side walls 140 mm in thickness and interior stiffening walls 240 mm in thickness, with added reinforcing concrete wall 350 mm in thickness. The external cladding is designed from Siporex panels 300 mm in thickness.

The calculation was done using the finite element method to divide the structure into elements (element mesh) with maximum beam length or with maximum dimensions of the plane elements 0.5 m. A soil element dimension equal to 0.5 m was used for the calculation model C. SCIA software [10], based on the deformation variant of FEM, was used.

2.2 Soil structure

Soil model A

If the effective stiffness of the foundation structure is high in comparison with the soil stiffness, the stiffness characteristics of the building structure can be considered on the level of the foundation joint, using the equivalent stiffnesses (spring constants), which correspond to the vibration of the rigid structure on the soil. This methodology has been derived from the vibration of a rigid round disc on an elastic homogeneous half-space [4], [8] and [9]. The derivation of the equivalent stiffnesses corresponds to the vibration of a system with 6 degrees of freedom. This is a conservative procedure, which takes into account an equivalent homogeneous and linear-elastic soil beneath the whole foundation. Soil composition below the baseplate of the building:

Clay loams with an admixture of tuffs ... layer thickness from 16 m to 18 m,
Sandy clay ... layer thickness 40 m,
Andesites and andesite agglomerates ... layer thickness over 500 m.

Characteristics of a simplified homogeneous soil medium (averaged values for clay loams and sandy clay):

Poisson ratio ... $\nu = 0.4$, mass density ... $\rho = 2000\ \text{kg/m}^3$
velocity of the shear wave propagation ... $v_S = 255$ m/s
shear modulus of elasticity ... $G = \rho \cdot v_S^2 = 130.1$ MPa

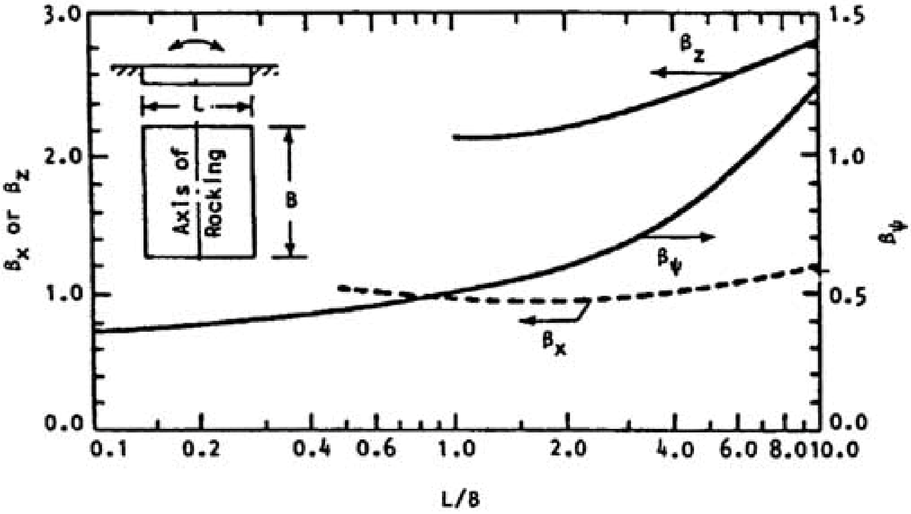

Figure 2: Constants for determining the soil stiffness [2]

The recommended equivalent stiffness values (spring constants) for a rectangular foundation are provided in ASCE 4-98 [2] for the whole foundation area and, in parenthesis, for foundation finite element dimensions 1 m × 1 m:

Stiffness in the horizontal direction x, and for rocking ψ:

$$k_x = 2\cdot(1+\nu)\cdot G\cdot\beta_x\cdot\sqrt{B_x\cdot L_x} = 9\ 845\ \text{MN/m} \quad (12.2\ \text{MN/m})$$

$$k_{\psi\cdot x} = \frac{G}{1-\nu}\cdot\beta_{\psi\cdot x}\cdot B_x\cdot L_x^2 = 7\ 110\ 484\ \text{MNm/rad} \quad (1\ 365.5\ \text{MNm/rad})$$

Stiffness in the horizontal direction y, and for rocking ψ:

$$k_y = 2\cdot(1+\nu)\cdot G\cdot\beta_y\cdot\sqrt{B_y\cdot L_y} = 10\ 364\ \text{MN/m} \quad (12.8\ \text{MN/m})$$

$$k_{\psi\cdot y} = \frac{G}{1-\nu}\cdot\beta_{\psi\cdot y}\cdot B_y\cdot L_y^2 = 1\ 106\ 075\ \text{MNm/rad} \quad (8\ 778.4\ \text{MNm/rad})$$

Stiffness in the vertical direction z, and for rotation t:

$$k_z = \frac{G}{1-\nu}\cdot\beta_z\cdot\sqrt{B_z\cdot L_z} = 14\ 805\ \text{MN/m} \quad (18.3\ \text{MN/m})$$

$$k_{t\cdot z} = \frac{16\cdot G\cdot R^3}{3} = 4\ 884\ 251\ \text{MNm/rad} \quad (6\ 029.9\ \text{MNm/rad})$$

where

G ... is shear modulus of elasticity, ρ ... is soil mass density, v_s ... is propagation velocity of shear waves, ν ... is Poisson ratio of soil, L_x, L_y, L_z ... are dimensions of the foundation structure (in plan and high), R ... is radius of the circumcircle of the foundation structure, β_x, β_y, $\beta_{\psi x}$, $\beta_{\psi y}$ ... are constants according to Figure 2;

B_x, B_y, B_z ... are dimensions of the foundation structure in perpendicular direction to the translation or rotation plane (see the scheme in Figure 2 below).

Soil model B

Higher accuracy of soil modeling using equivalent stiffnesses - spring constants can be achieved using the Boussinesq soil model, the principle of which is described in [4], [7], [8] and [9]. The same simplified homogeneous soil medium as in model A was used for calculating the soil characteristics. The Boussinesq soil model assumes that the stiffness distribution below a rigid foundation structure is not linear but rather shows extremes under the rigid edges of the foundation structure. The course of the load distribution between the rigid foundation and the soil is approximately parabolic. However, in the simplified calculation the vertical stiffness distribution is modeled as step-by-step linear below the foundation slab, by the half value in the middle part of the foundation slab, and by the 1.5 multiple at the edges of the foundation slab. The horizontal stiffness shows a constant distribution over the entire area of the foundation slab. The vertical stiffness values were unequally divided; the value 0.5 k_z was used in the central part of the foundation slab, and on the boundaries of the foundation slab the value 1.5 k_z was used. In the calculation model, the vertical stiffness was entered as a piecewise constant function with the step 3 m, and the horizontal stiffness was entered as an invariable:

vertical stiffness for circumferential bands ... k_z = 30.5 MN/m,
vertical stiffness for the central band (in the centre of the span) ... k_z = 21.0 MN/m,
vertical stiffness for the internal bands ... k_z = 10.5 MN/m,
horizontal stiffness in both horizontal directions for all bands ... $k_x = k_y$ = 15 MN/m,
horizontal rocking stiffness: $k_{\psi\cdot x}$ = 1 618 MNm/rad, $k_{\psi\cdot y}$ = 10 200 MNm/rad.

Soil model C

In order to perform a seismic analysis of the structure, it is recommended [2] to consider using the two-parameter Winkler-Pasternak model for soil modeling to use the two-parameter Winkler-Pasternak model. The 3D model of the soil-structure-interaction has to include:

- Mechanical characteristics of individual soil layers, including the ground water level and/or the level of the incompressible (rock) soil;
- Combinations of static (and/or quasi-static) load states to be considered in the calculation of the soil parameters as additional loading of the foundation structure [3].

Layer description	Thickness [m]	Modulus of deformation E_{def} [MN/m^3]	Poisson ratio ν	Mass density [t/m^3]
gravel fill	0.5	100	0.20	2.00
clay loam	16 to 18	5.6	0.40	1.95
sandy clay	40	9.3	0.40	2.00
andesites	more than 500	incompressible stone base		

Table 1: Soil characteristics

The ground water level is deeper than the foundation level, and therefore the water - bearing soil was not used in the model. The calculation software cannot be used to calculate the horizontal stiffness values from the parameters of the layers that were entered. The horizontal stiffness of the soil was thus entered similarly as in model A.

For calculating the Winkler-Pasternak soil constants, the following soil layers (Table 1) were used. The calculation software (using an iterative method) gradually increases the accuracy of Winkler-Pasternak parameters C_1 and C_2 (Figure 3) that are being investigated for the selected structural elements (which are in contact with the soil) until the required accuracy is achieved.

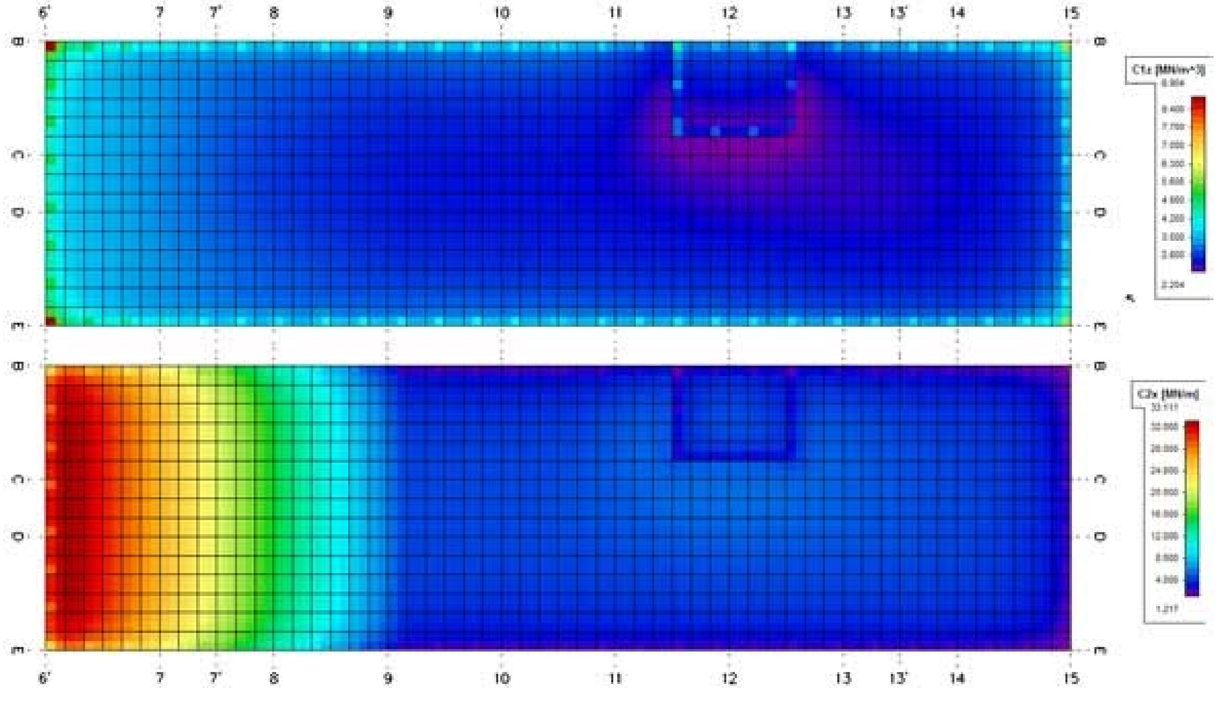

Figure 3: Winkler-Pasternak parameters C_1 and C_2; C_{1z} (above), C_{2x} (below)

2.3 Seismic load and response calculation

The maximum calculation earthquake load was used (SL-2). For this type of seismic load, the peak ground acceleration in horizontal direction was 0.15 g, the peak ground acceleration in vertical direction was 0.10 g, and the ground response spectra according to Figure 4 for a return period of 10 thousand years.

The response to the seismic load was calculated by decomposing the seismic load into natural vibration modes. A value of 5% as the modal damping ratio was considered for all the modes. The ductility reserves of the structure under seismic load [6] were not considered in this case, in order to avoid falsifying the response results.

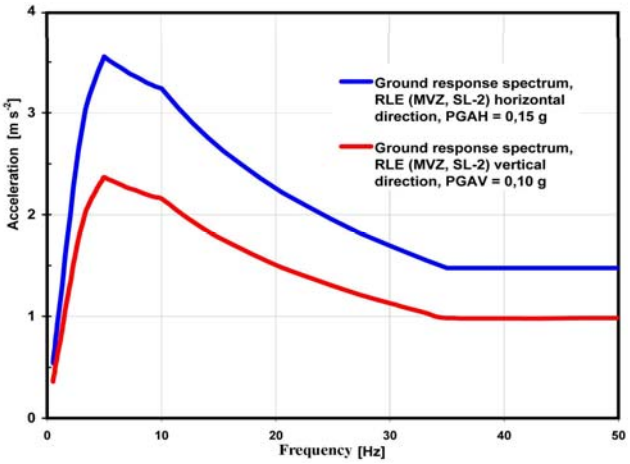

Figure 4: Ground response spectra

3 NATURAL VIBRATIONS

In total, 200 natural modes were used, covering the frequency interval up to 20 Hz of structure vibration.

Natural frequency	Model A	Model B	Natural mode description	Model C	Natural mode description
$f_{(1)}$	3.40	3.36	structure bending in longitudinal direction	1.53	structure rotation about the longitudinal axis
$f_{(2)}$	3.82	3.76	structure bending in transversal direction	2.46	structure rotation about the transversal axis
$f_{(3)}$	4.14	4.11	rotation about the vertical axis	2.91	structure vertical translation, bending of the floor slabs
$f_{(4)}$	6.37	6.21	bending of the floor slabs	3.37	structure rotation about the vertical axis
$f_{(5)}$	6.77	6.69	bending of the floor slabs, higher mode	4.19	bending in longitudinal direction, bending of the floor slabs
$f_{(6)}$	7.15	7.11	bending of the floor slabs, higher mode	5.34	bending of the floor slabs

Table 3: The lowest calculated natural vibration frequencies [Hz]

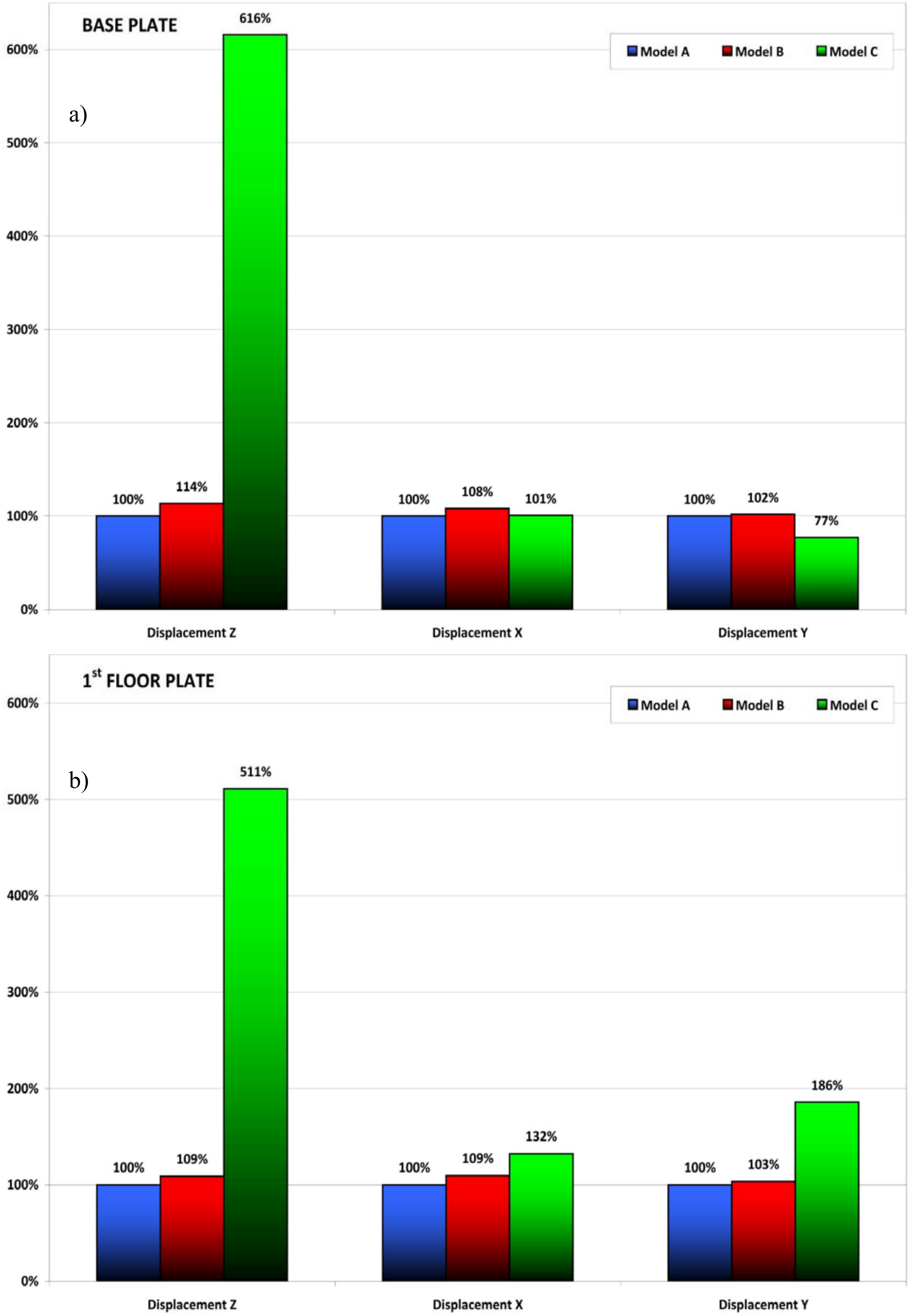

Figure 5: Displacement of the structure parts in the direction of the global axes, (a) baseplate, (b) floor plate

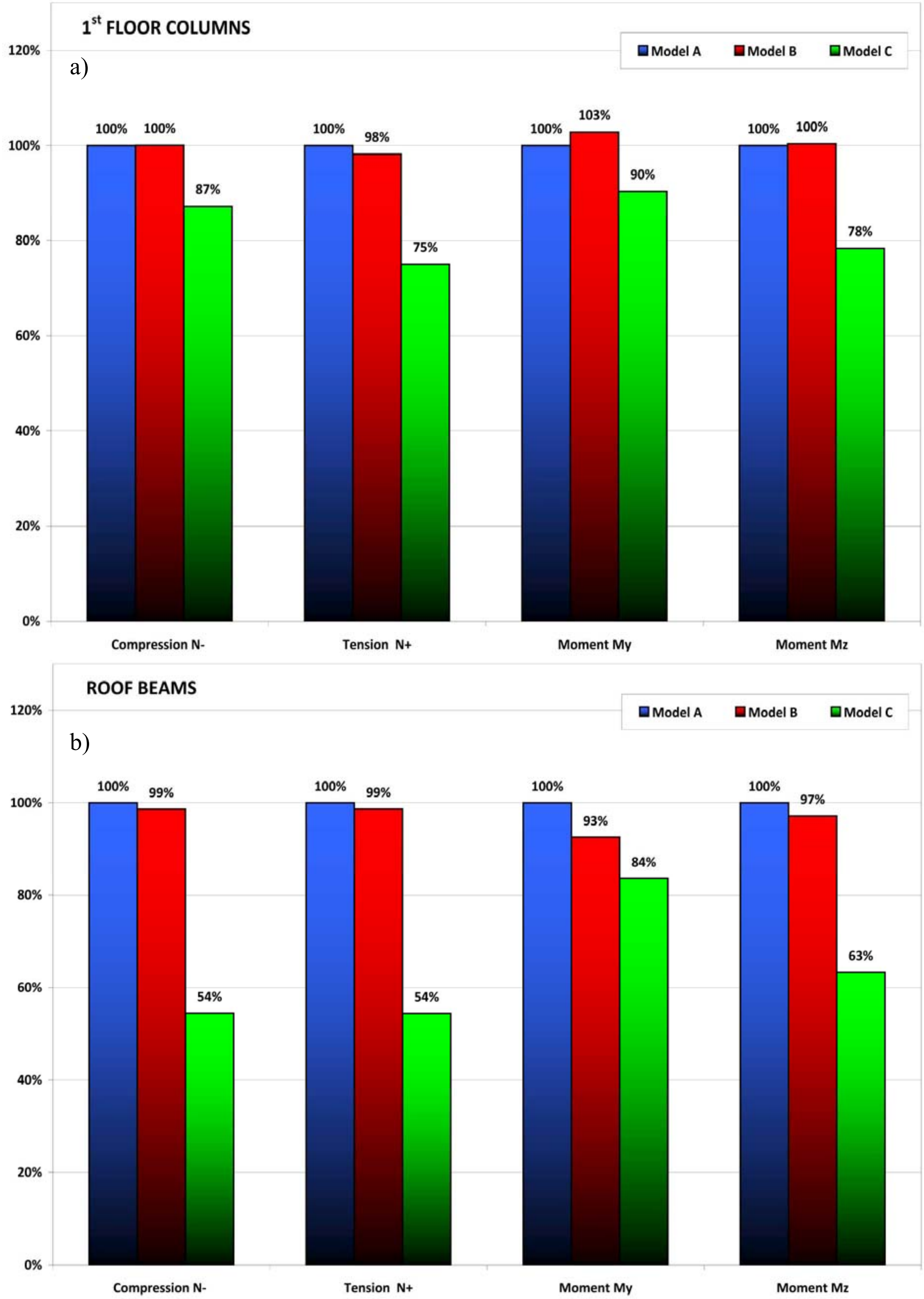

Figure 6: Internal forces of selected beams, (a) columns, (b) roof beams

A comparison of the lowest calculated natural frequencies and vibration modes reveals no marked differences between models A and B. The equivalent soil stiffness for both models is determined on the basis of the same methodology. The non-uniform input of the vertical stiffness (Boussinesq model) has no considerable effect on the values of the natural frequencies and the natural modes of vibration. Considering the much more pliable soil, model C has the lowest natural global modes of the whole structure vibration on the subsoil on the lowest frequencies. These vibration modes are different from the vibration modes of the other used models.

4 SEISMIC RESPONSE

The structure response was compared for the following envelope curve by combining the load conditions: Rc24 ... envelope of 24 seismic combinations of load states (dead load, cladding, roof, flooring, partition walls, part of live load, part of snow load, seismic load).

When we compare the values for the displacements and the internal forces of the structure according to various ways of considering the soil, it becomes apparent that soil models A and B, where homogeneous “averaged” soil is considered using equivalent stiffnesses (spring constants), show practically no difference. The effect of constant or variable vertical stiffness of the soil between models A and B has only an insignificant influence on the structure response results.

Model C, where the actual layered soil is considered, has an effect on the increase of the displacements, particularly in the vertical direction, given that the soil layers below the foundation structure show lower stiffness than the equivalent stiffness values of the “averaged” soil. However, the internal forces for model C are considerably lower than for the other models.

Both these trends are clearly shown in Figures 5 and 6. In summary, it can be noted that models A and B, which stem from the equivalent mass of the soil, are rather on the conservative side for the structure under study here, in terms of its safety (group I of limit states), while the opposite is true in terms of deformations (group II of limit states).

5 CONCLUSIONS

This paper has presented a proposed methodology for modeling the effect of the interaction between soil and building structure. Admissible ways of modeling the soil were analyzed for a chosen structure.

The principles for considering the soil - structure interaction were introduced mainly by the requirements of ASCE 4-98 [2], supplemented by the further requirements of Eurocode 8-1 [1] for seismic loading and by some published findings in quoted references.

A 3D calculation model for the building structure was set up, and variant options of the soil models were considered for the calculation model. In calculation models A and B, the soil was modeled using equivalent stiffness values of the soil, stemming from the theory of a rigid circular disc on an elastic homogeneous half-space.

Non-uniformly modeled vertical stiffness of the soil according to the Boussinesq model was used for model B. Model C was used for modeling the soil according to its actual composition, with subsequent additional calculation of the Winkler-Pasternak constants of the soil.

The example of this building was used to demonstrate that, when calculating the internal forces, calculation models operating with equivalent stiffness values of the soil for the purpose of interaction of the structure with soft soil are as a rule markedly shifted to the conservative side.

The internal forces are considerably lower in the calculation model that incorporates a realistic composition of the soil than in the models where the soil is simplified using global stiffness values. For deformations of the structure, the converse situation is found.

Both soil modeling methods are admissible, and the knowledge gained from this comparative calculation can be used when structures are to be reconstructed or rebuilt, and/or in cases where it is required to increase the load of a structure.

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