J. Labudkova et alii, Frattura ed Integrità Strutturale, 39 (2017) 47-55; DOI: 10.3221/IGF-ESIS.39.06

Focussed on Modelling in Mechanics

Numerical analyses of interaction of steel-fibre reinforced concrete slab model with subsoil

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ABSTRACT. Numerical analyses of contact task were made with FEM. The test sample for the task was a steel-fibre reinforced concrete foundation slab model loaded during experimental loading test. Application of inhomogeneous half-space was used in FEM analyses. Results of FEM analyses were also confronted with the values measured during the experiment.

KEYWORDS. Foundation structure; Subsoil–structure interaction; FEM; Steel-fibre reinforced concrete.

Citation: Labudkova, J., Cajka, R., Numerical analyses of interaction of steel-fibre reinforced concrete slab model with subsoil, Frattura ed Integrità Strutturale, 39 (2017) 47-55.

Received: 20.07.2016
Accepted: 19.09.2016
Published: 01.01.2017

INTRODUCTION

Foundation structure and subsoil are interdependent, and therefore the effect of the foundation soil loaded with the topside structure cannot be neglected. The analysis must take the interaction of the foundation structure with subsoil into account. The main effort of solving of the foundation-subsoil interaction is to find a computational model that would represent the true foundation conditions.

Characterization of the interaction of the foundation structure and subsoil is a current problem that involves a series of diverse determining factors (type of foundation structure, its dimensions, material, character of subsoil, character of load etc.). Foundation structures, compared with other types of structures, are also unique in that under static calculation greater simplification occurs due to less accuracy of the input soil data. Soil is in fact a natural material and to conclusively describe its properties is rather difficult. Furthermore, this interaction system is of significantly spatial and non-linear character, which is very difficult to objectively describe using simplified plane theories. The variability of subsoil additionally contributes to the complexity of the entire system.

There is currently no universally valid model to reflect the interaction of the foundation structure with the subsoil and to determine the appropriate distribution of the contact stresses and deformations in the footing bottom and the distribution of stresses and deformations in the deeper layers of subsoil under the footing bottom itself. Therefore the results also differ depending on the choice of the subsoil model.

CURRENT STATE OF ART

In order to refine the methods of calculation of subsidence, surveys and experimental measurements are still being conducted. The mentioned research project took eight years, conducted by Stavební geologie, n.p. The progress, results and conclusions from this research have been published by several authors – Feda, Havlíček and others in [6, 8].

Measurements of soil subsidence and contact stress on models during load tests in-situ takes place in the present as well. In 2013, Huang, Liang, X., Liang, M., Deng, Zhu, Xu, Wang, and Li from the Department of Civil Engineering of University of Architecture and Technology in China published an article [9] about study of interaction of two-way reinforced slab, gradually loaded with uniformly distributed load. Deformations and internal forces on the slab calculated based on the theory of elasticity were compared with the experimental results of an in-situ test. The development of cracks in the slabs was monitored and the diagram of work was drawn, showing the dependence of deformations on increasing loads.

Interaction of foundations and subsoil has been the research subject at the University of Greenwich, UK for many years. In 2012, Alani and Aboutalebi published article [2] about observation of the effect of the rigidity of the foundation base on the mechanical behaviour of concrete slabs. This analysis was conducted on slab model with dimensions 3.0 x 3.0 x 0.2 m. Alani and Aboutalebi presented their results of another experimental measurement also in 2014, in article [1]. The research mentioned in this article contributes to a better understanding of the behaviour of foundation slabs from reinforced concrete and fibre-reinforced concrete for various types of loads. In 2012, Alani in cooperation with Beckett and Khosrowshahi published article [3], which focuses on design of concrete foundation slabs with special emphasis on use of steel and synthetic fibres and alternative to reinforcing.

The Tongji University in China conducted tests and comparison of two foundation slabs. The test results are described in the 2004 article by Chen [10]. For reinforcement of the fibre-steel concrete slabs, two types of steel fibres were used, with fibre content 20 and 30 kg/m^3. The effect of the steel fibre reinforced concrete (SFRC) foundation slab on the bending rigidity has been found and published. The common conclusion of all these scientific research works by many authors was determination and confirmation of significant difference between the test results and values obtained using calculation models, numerical models and available standards.

EXPERIMENTAL LOADING TEST OF REINFORCED FIBRE-CONCRETE SLABS

In late 2014, an experimental load test of reinforced fibre-concrete slab has been conducted. During the experimental load tests, the stress-strain relations of the foundation structure and subsoil during their interaction were monitored. The load test was carried out using the testing facilities at the Faculty of Civil Engineering, VŠB - TU Ostrava [4]. From a geological aspect these are simple foundation conditions. The top subsoil layer is formed by loess loam consistency with class F4 consistency, and its thickness is approx. 5 m. The soil was described by the following properties – weight density $\gamma = 18.5$ kN.m^{-3}, Poisson coefficient $\mu = 0.35$, modulus of deformability $E_{def} = 23.7$ MPa.

The fibre-concrete slab had dimensions 2.00 x 2.00 x 0.17 m. The concrete class C25/30 was used for casting. The concrete was reinforced with fibre reinforcement. The reinforcement consisted of steel fibres of type 3D DRAMIX 65/60B6 – 25 kg.m^{-3}.

During the test, the fibre-concrete slab was loaded in the centre by pressure exerted by hydraulic press (Fig. 1). The dimensions of the loaded area were 200 x 200 mm. During the load test of the fibre-concrete slab, the load cycle was set to 50 kN / 30 min. With this method of loading the slab breach occurred in the 6-th cycle, or at load of 280 kN.

The slab failed by being pushed through. The slab was raised then in such a way so that development of the crack could be investigated – the crack had developed at the lower part of the slab which was in contact with the soil. Fig. 2 shows the cracks at the lower surface of the failed fibre-concrete slab.

The testing facilities are used also for other experimental measurements of subsoil-structure interaction - the process, results and conclusions of other loading test are described in detail in [11].

Figure 1: Casting and loading test of fibre-concrete slab.

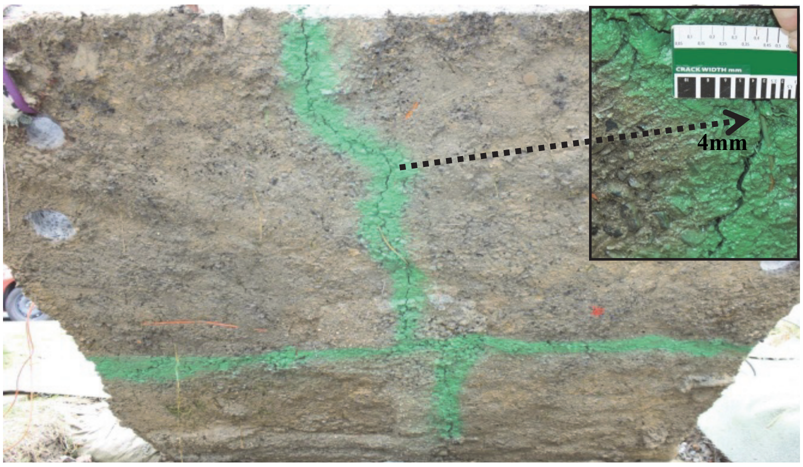

Figure 2: Cracks at the lower surface of the failed slab.

APPLICATION OF THE ELASTIC HALF-SPACE THEORY

To solve the interaction between foundation structures and subsoil, the finite element method was used. The subsoil model represents the spatial numerical model of an elastic half-space using finite elements. To detect stress caused by load of structures on the foundation soil, we can replace the real subsoil by its idealized and simplified model, so-called elastic half-space. Subsoil can be thus modelled also as a spatial (3D) model of the soil massive, which allows detailed monitoring of the processes within the subsoil. The half-space can be modelled discreetly or as a continuum (Fig. 3). Continuum can be modelled as viscous, plastic, elastic, linear, nonlinear etc. (Fig. 3) [7].

SPATIAL NUMERICAL MODEL – FEM

For the interactive role of subsoil and fibre-concrete slab, which was also subjected to experimental measurements, spatial numerical models using 3D finite elements were created. The computational model was created using the SHELL 181 (2D) element for the concrete slab, and the SOLID 45 (3D) element for the subsoil model. Additionally the slab thickness was defined for the planar element SHELL 181. The subsoil model was created both as homogeneous and as inhomogeneous half-space. When creating spatial model using 3D elements, it is particularly problematic to correctly determine the size of the modelled area representing the subsoil, to choose boundary conditions and the size of the finite element network. Given that the soil is patchy substance and its properties differ from the idealized linear elastic, isotropic and homogeneous material, the calculated subsidence values do not correspond to the actual values, measured on specific structures or during the experiments. This can be partially solved by using inhomogeneous elastic half-space. In an inhomogeneous half-space, the vertical stress concentrations along the axis of the foundation are different than in the homogeneous half-space. The modulus of deformability changes continuously with depth. The concentration factor ν is entered in the calculations.

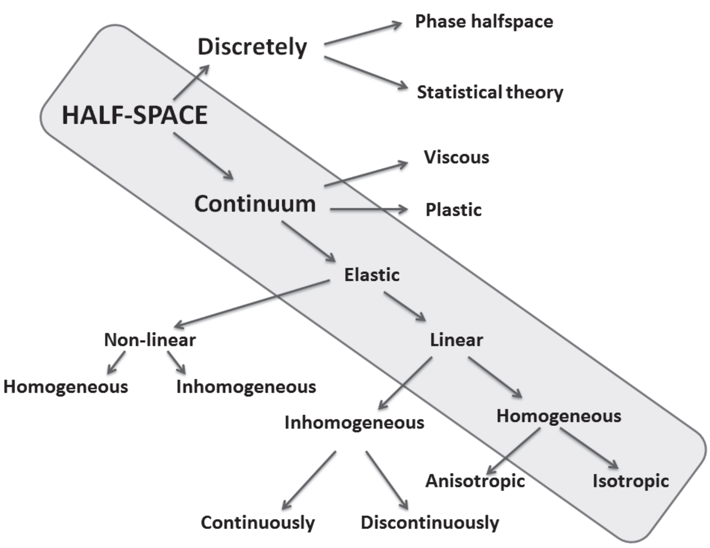

Figure 3: Types of half-space and their classification.

According to the Frölich formula in [7], a relation is proposed based on the condition of minimum deformation work. If ν = 3 it is an elastic isotropic half-space (E = const.) and if ν = 4 it is a half-space whose modulus of deformability increases linearly with depth depending on E_0 - the modulus at the surface, z-coordinate (depth) and coefficient m dependent on Poisson coefficient μ. Modulus of deformability increases linearly with depth according to Eq. (1) shown in [7]:

$$E_{def} = E_0(z+1)^m \quad \text{(see Tab.1)} \tag{1}$$

$$m = \frac{1}{\mu} - 2 = \frac{1}{0.35} - 2 = \underline{\underline{0.875}} \tag{2}$$

Fig. 4 and Tab. 1 shows a model of an inhomogeneous half-space, in which the deformability module increases with increasing depth of the subsoil model (in layers).

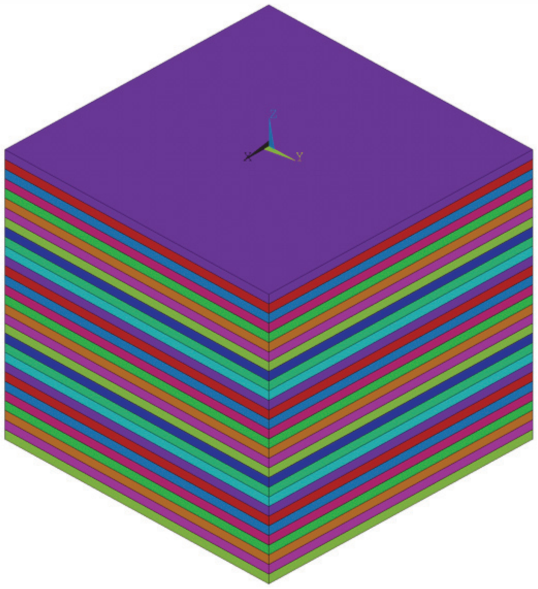

Figure 4: Inhomogeneous half-space.

z [m]	E_{def} [MPa]	z [m]	E_{def} [MPa]
0.0	23.70	3.0	77.75
0.2	27.71	3.2	81.07
0.4	31.62	3.4	84.37
0.6	35.46	3.6	87.65
0.8	39.22	3.8	90.90
1.0	42.93	4.0	94.14
1.2	46.58	4.2	97.36
1.4	50.19	4.4	100.56
1.6	53.75	4.6	103.74
1.8	57.27	4.8	106.91
2.0	60.76	5.0	110.06
2.2	64.22	5.2	113.20
2.4	67.64	5.4	116.32
2.6	71.04	5.6	119.43
2.8	74.41	5.8	122.52
3.0	77.75	6.0	125.60

Table 1: Modulus of deformability of the subsoil modelled as inhomogeneous half-space.

The use of inhomogeneous half-space is also described by Fabrikant and Sankar in [5], and Zhou, Chen, Keer, Ai, Sawamiphakdi, Glaws, Wang in [12]. Fabrikant and Sankar in [5] introduce an equation for the shift in homogeneous half-space outside the loaded areas in relation to the offsets within the loaded area.

After creating the model and assigning various properties to the individual layers of subsoil model, which take into account the impact of increasing deformability modulus, a finite element network was created. The power load was defined in the nodes of the finite element network of the slab. Identically as the load, the load-bearing area corresponded to the actual load-bearing area of the experiment. Then the contact pair was created (TARGE 170 - CONTA 173) on the contact area, for which the influence of friction between the slab and the subsoil was neglected. To make contact, it was necessary to verify whether the normals of the two contacting surfaces face each other, or whether they had to be turned so that it was actually the case.

For such created numerical model the boundary conditions have been defined to prevent shifts of nodes of the external walls representing the subsoil model. The boundary conditions were processed in three variants (Fig. 5).

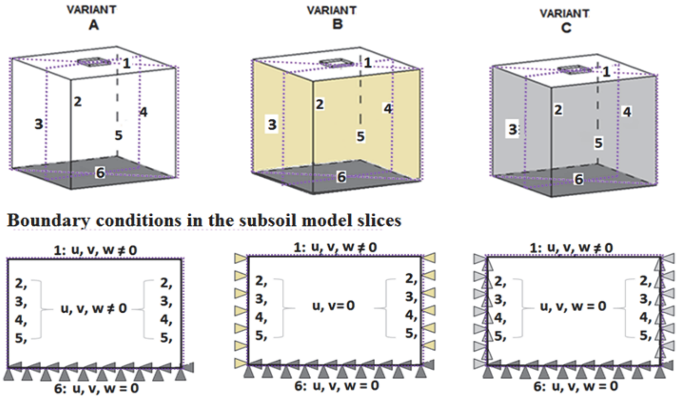

Figure 5: Boundary conditions.

PARAMETRIC STUDY

For the interactive task of fibre-concrete slab and subsoil, for which an experiment was also conducted, 72 spatial numerical models were created using the ANSYS software. These models differed in homogeneity or inhomogeneity of the subsoil model, size of the modelled area representing the subsoil and the boundary conditions (Fig. 5). Elastic half-space created as a homogeneous isotropic continuum was used in 36 models. Elastic half-space created as an inhomogeneous isotropic continuum was used also in 36 models.
The parametric study also includes the subsoil model, whose depth was determined according to EC 7 [13]: *„The depth of the compressible layer is determined as the depth at which the vertical effective stress induced by foundation load is 20 % of effective stress from overburden“.* The chart on Fig. 6 shows the depth of the deformation zone for the performed experiment. The depth of the deformation zone is 4.65 m.

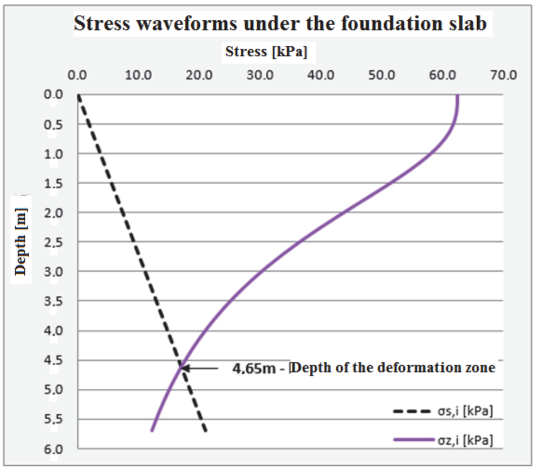

Figure 6: Depth of the deformation zone.

In the following charts and parts of the parametric study, the vertical deformations calculated in the subsoil models are also included, where subsoil depth exactly equals the depth of the deformation zone. On the chart on Fig. 7, based on the Tab. 2, it is possible to follow the effect and significance of the selected boundary conditions in connection with the resulting vertical deformations. The ground dimensions of the subsoil model have been maintained for all models (6.0 m x 6.0 m). Vertical deformations calculated in homogeneous half-space models are shown in light colours. Vertical deformations calculated in inhomogeneous half-space models are shown in dark colours.

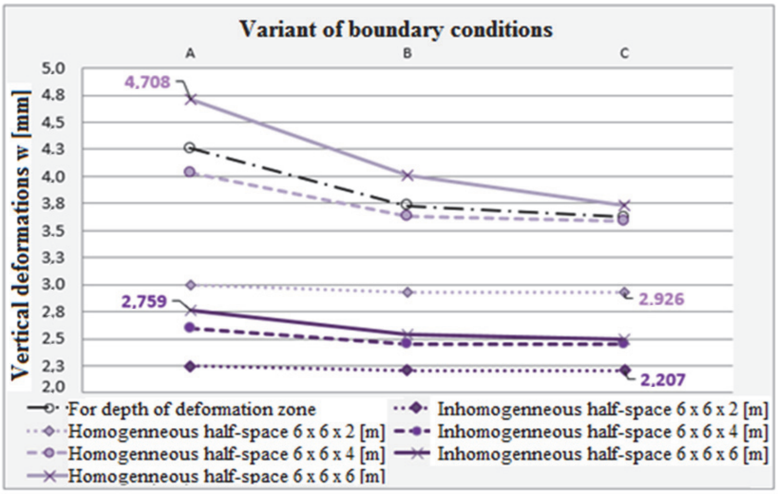

Figure 7: Dependency of the vertical deformation of the concrete slab on the selected boundary conditions with increasing depth of the subsoil model. The ground dimensions of the subsoil model are 6.0 × 6.0 m.

Model depth [m]	Inhomogeneous half-space Vertical deformations for variant of boundary conditions A	B	C
2.0	2.244	2.210	2.207
4.0	2.600	2.453	2.445
6.0	2.759	2.540	2.490

Model depth [m]	Homogeneous half-space Vertical deformations for variant of boundary conditions A	B	C
2.0	2.991	2.931	2.926
4.0	4.032	3.632	3.588
6.0	4.708	4.015	3.735

Table 2: Dependency of vertical deformation on the boundary conditions with increasing depth of the subsoil model.

It can be seen for the individual types of boundary conditions how the deformations are growing with increasing depth. The largest vertical deformations were calculated under variant A, where the nodes of the peripheral wall of the modelled area may deform freely, which also confirmed the initial assumption. In variant B the horizontal deformations in nodes of the peripheral walls of the subsoil model are prevented, which is also reflected in the vertical deformations, which are smaller compared to variant A. The smallest vertical deformation occurred in variant C, in which the boundary conditions prevented all shifts of nodes of external walls representing the subsoil. The black dot-and-dash line in the chart on Fig. 7 shows the vertical deformations of the subsoil model, whose depth equals the depth of the deformation zone (4.65 m) calculated according to EC 7 [13].

In the second part of the parametric study (see Fig. 8 and Tab. 3) the dependence of deformations on the variable depth of the subsoil model has been monitored, while maintaining the same ground area of subsoil, which was 6.0 x 6.0 m. The depth always increases by 2.0 m. The subsoil models depths were therefore 2.0; 4.0; 6.0 m and 4.65 m, which is the calculated depth of the deformation zone according to EC7 [13].

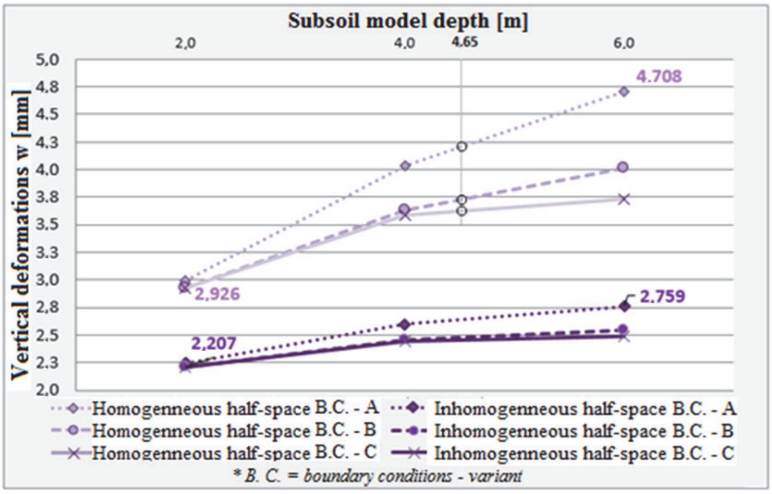

Figure 8: Dependency of vertical deformations of the concrete slab on the increasing depth of the subsoil model. The ground dimensions of the subsoil model are 6.0 × 6.0 m.

Model depth [m]	Inhomogeneous half-space Vertical deformations for variant of boundary conditions A	B	C
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Table 3: Dependency of vertical deformation on the increasing depth of the subsoil model according to boundary conditions.

From the chart on Fig. 8 it is clear that with increasing depth of the subsoil model, the difference between deformations calculated for individual variants of boundary conditions also increases. With increasing depth of the subsoil model, the choice of the boundary conditions therefore becomes a decisive factor influencing the resulting vertical deformation. Although this is true for both homogeneous and inhomogeneous half-space, the chart clearly shows that in terms of the effect of variable depth of the subsoil model on the vertical deformations, a model of an inhomogeneous half-space provides results that are not so heavily influenced by the chosen depth of the subsoil model, as was the case with the model of a homogeneous half-space.

In the last part of the parametric study (Fig. 9 alleging from Tab. 4) the dependence of vertical deformations on the variable size of the ground area of the subsoil model has been monitored, while maintaining the same depth of 6.0 m. The ground dimensions of the subsoil model were magnified in multiples of the width of the model of the foundation base. If the width of the foundation is designated as *b*, the boundary of the subsoil models was created in the distance of 0.5*b*; 1.0*b*; 1.5*b*; 2.0*b* from the foundation front. In the numerical model of the interaction of subsoil with fibre-concrete slab with width *b*=2.0 m, the subsoil models with dimensions 4.0x4.0 m, 6.0x6.0 m, 8.0x8.0 m, 10.0x10.0 m were then created.

The dependence of deformations on the variable dimensions of the ground area of subsoil indicates an important conclusion that the influence of boundary conditions diminishes with increasing footprint of the subsoil model. From the chart on Fig. 9 can be further concluded that given sufficient size of the ground dimensions of the subsoil model, the choice of boundary conditions does not matter.

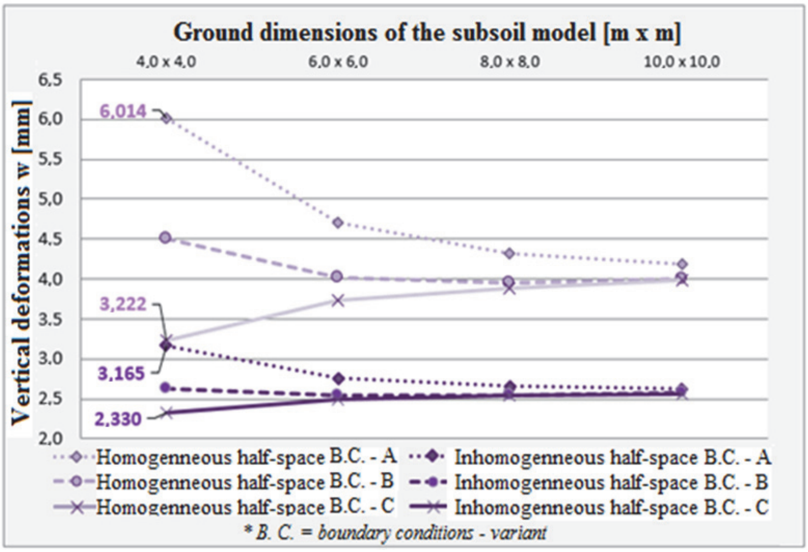

Figure 9: Dependency of vertical deformations of the concrete slab on the increasing ground dimensions of the subsoil model. The depth of the subsoil model is 6.0 m.

Inhomogeneous half-space				Homogeneous half-space			
Ground plan dimensions [m × m]	Vertical deformations for variant of boundary conditions			Ground plan dimensions [m × m]	Vertical deformations for variant of boundary conditions		
	A	B	C		A	B	C
4.0 × 4.0	3.165	2.621	2.330	4.0 × 4.0	6.014	4.489	3.222
6.0 × 6.0	2.759	2.540	2.490	6.0 × 6.0	4.708	4.015	3.735
8.0 × 8.0	2.655	2.545	2.543	8.0 × 8.0	4.313	3.951	3.891
10.0 × 10.0	2.619	2.570	2.565	10.0 × 10.0	4.184	4.000	3.977

Table 4: Dependency of vertical deformation on the increasing ground dimensions of the subsoil model according to boundary conditions.

CONCLUSION

The parametric study monitored and graphically evaluated the influence of individual parameters of the 3D numerical model of the interaction of fibre-concrete foundation slab and subsoil, in connection with vertical deformation. All the charts clearly show that the inhomogeneous continuum model generates smaller vertical deformations than the homogeneous continuum model. This is due to increase of the deformability modulus with depth. The chart also shows that compared to the model of homogeneous continuum model, the inhomogeneous continuum model is not as heavily dependent on the chosen geometric parameters of the subsoil model. The difference between the smallest and the largest resulting vertical deformation in the centre of the slab in the homogeneous subsoil model is 1.8 mm, while in the inhomogeneous subsoil model the difference between the minimum and maximum vertical deformation is only 0.5 mm. This is nearly four times less variance of values of geometrically identical models differing only in homogeneity or inhomogeneity of subsoil. From this it can be concluded that an inhomogeneous continuum provides more stable results that are less affected by the choice of the geometry and dimensions of the area representing the subsoil. During the experiment, the deformation measured in the centre of the slab was 2.83 mm. All the resulting deformations for the inhomogeneous half-space do not differ from the actual deformation by more than by 28 %, while the resulting deformations for the homogeneous half-space can differ even by 66 %.

ACKNOWLEDGMENTS

The work necessary for creating this article was supported by the Student Grant Competition of VŠB-Technical University of Ostrava. The project registration number is SP2016/140.

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