Parametric study of input parameters of soil-structure interaction based on elastic half-space theory

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Abstract: - Foundations are necessary elements of all constructions. Over the years, a variety of foundation design procedures have been developed. This article deals with one of these methods, numerical modeling. Finite element method was used and has an advantage that allows us to simulate a real behavior of various phenomena and predict them. Currently there is no clear definition of the procedure that would be able to simulate the soil-structure-interaction with the sufficient precision. One of the reasons is that the input parameters directly affect the results. Understanding this phenomenon is crucial to maximizing the potential of this method. A parametric study that examines the effect of boundary conditions and the model size on the resulting deformation of soil-structure deformation was done. Series of numerical models with same parameters and variable of boundary conditions and dimensions based on the elastic half – space theory were constructed in Ansys to observe this problematic. The study proves that the influence of boundary conditions as well as dimensions affect the resulting deformation. the emphasis was put on examining the behavior of individual influences and their separation. Besides this the necessary size of the model is examined in this article.

Key-Words: - Finite Element Method, geomechanics, concrete, foundation, contact task, numerical model, soil-structure interaction, boundary value problematics

1 Introduction

Along with the development of computer technologies, computer simulations have been used to predict various phenomena. There are number of methods to perform simulations these include method of boundary elements, discrete elements, finite difference, finite element method, which was used in this work. One of the phenomenon that are being pursued by scientists around the world is problematic of foundation in contact with subsoil [1], [2].

Numerical models are used to simulate this problematic in every way. Scientists create models of concrete and calculate estimated maximum capacity of elements [3], [4], predicting punching [5], crack spreading [6], soil deformations [7], composites [4], [6], [8] etc.

Calculating an estimated deformation with computer has an advantage, that even large problems with complicated geometry can be solved relatively easily with comparison to analytical calculations which are suitable mainly for simple shapes of foundations whereby the upper structure is expressed by loading. However, the problem is that although the computational models are constantly developed the optimal procedure is still don't known to provide sufficiently accurate results that works under all conditions. Hence it is necessarily to explore behavior on simple models before proceeding to a large scale modeling. Therefore, this topic is still relevant and is under research by many scientists all over the world. Together with the numerical models laboratory and experimental tests [9-11] are realized to supplement and support the research and verify the numerical results.

2 Methods

2.1 Experiment

One of the universities studying this problematic is The Faculty of Civil Engineering on VŠB - Technical University in Ostrava in the Czech Republic [9-11]. Since they have been dealing with this issue for a long time the testing device was developed and constructed to allow confirming and comparing numerical results with realistic values. The testing device (Fig.1) was specially designed to examine the contact task as well as soil behavior [12]. First tests purpose was to try and prove the proper function of the device, after this series of tests on concrete slabs was performed. All slabs had same dimensions (2000 x 2000 x 150 mm) and were placed on same subsoil

Fig.1 Typical concrete slab with dimensions 2 x 2 m during testing

with same parameters. The main difference was in the method of concrete reinforcing. All slabs were loaded with force up to 1000 kN, which is the device limit, or until the concrete was destroyed. Slab no. D10-G01 was selected as a reference for this paper. Slab was made of plain concrete with no reinforcements with a compressive strength class C25/30.

Together with the slab, few samples were produced together and tested in the laboratory. From these measurements following characteristics was evaluated:

- average compressive strength of concrete (cube test) $f_{c,cube} = 25.11$ MPa
- average compressive strength of concrete (cylinder test) $f_{c,cyl} = 20.03$ MPa
- average tensile strength $f_t = 2.10$ MPa
- average elastic modulus $E = 17\,000$ MPa

2.2 Numerical simulation

Based on the performed experiment, the numerical model was created so that the model preserves the main parts of the experiment.

Ansys APDL was used as a calculation program. This program has been chosen and preferred for its wide range of applications, even though the large number of programs that are specially adapted to the soil or concrete calculations exists.

Another advantage of this program is that the calculation can be adapted for supercomputer use enabling larger – scale tasks and also reducing computer time requirements. The use of the supercomputer being considered in the future.

3 Numerical model set up

3.1 Numerical model theory

One way of modelling the subsoil is theory of elastic half-space. Theory based on Boussinesq´s method for stress distribution under the vertical concentrated load was assumed in this paper.

The assumptions of the Boussinesq theory are:

- the soil mass is:
  - elastic
  - isotropic
  - homogeneous
  - semi-infinite
  - weightless
- the applied load is vertical, concentrated acting on the surface
- the Hook´s Low is applied, that means that the ratio between stress and strain is constant

The soil model based on this theory was made in this paper and was designed as a cube/block with finite dimensions. Since one of the premises was necessity of semi-infinite subsoil, main goal is to inspect whether it is possible to replace half-space by cube/block with finite dimensions if the modeled area is large enough and also find minimum necessary dimensions of the soil

3.2 Input parameters

To satisfy the premise related to loading concrete slab was omitted in the numerical model and force was applied directly to the soil through the spreading area of 400 x 400 mm according to the test. Other assumptions were preserved so that the results obtained were clear. This theory can be verified by manual calculation for simple tasks that provides advantage for determining the validity of model design and calculations. This is useful because creating a correct model can be problematic due to higher amount of inputs which can directly affect results. Such input data includes choice of boundary conditions, dimensions of finite element cube and size of the finite element. That means if we have two same models with minor change in the boundary conditions it will affect the results.

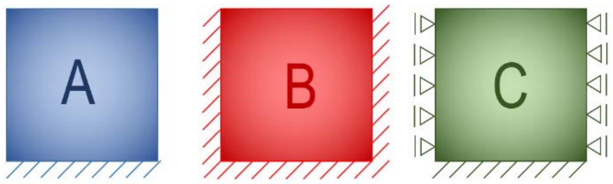

Fig.2 Assumed variants of boundary conditions

To prove this assumption, three types of boundary conditions were used (Fig.2):

- First boundary condition (A) is represented by the fixed support applied to the bottom surface of the soil while all other surfaces were left free.
- Second type (B) was created by applying fixed support to the all surfaces of the soil except the top one, which was left free.
- In the third condition (C) were selected the same surfaces as in the B variant, but in this case they were pinned against the movement only in the perpendicular direction to the plane of the surface and the bottom surface was supported by the fixed support.

3.3 Soil model

Solid 45 was used for three dimensional modeling of soil. This element is defined by 8 nodes having three degrees of freedom at each node (translation in the x, y and z direction). All volumes were divided by finite element mesh with size of 1m. Behavior of the soil model was characterized by modulus of elasticity and Poisson coefficient. Based on the Boussinesq´s assumptions the self - weight was neglected.

Soil characteristics entering the model are:

- Modulus of elasticity E = 35 MPa
- Poisson coefficient $\mu = 0.25$
- Applied force F = 350 kN

3.4 Soil dimensions

Dimensions of the cube representing soil were chosen firmly to 10 m in the axis x and y (Fig.4). The dimension in the axis z – height was defined variable with 2 m increment starting at 2 m with maximum of 20 m.

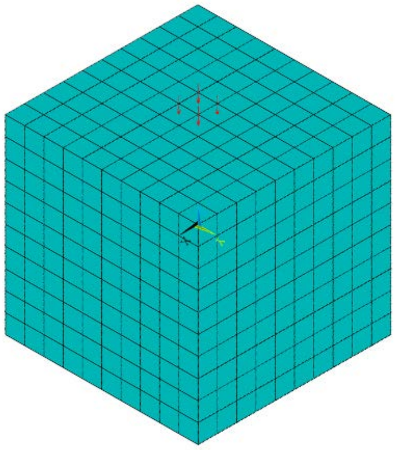

Fig.3 Typical numerical model layout. Cube with dimensions of 10 x 10 x 10 m with finite element size 1m

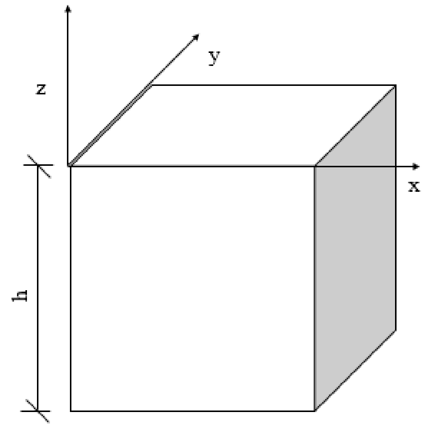

Fig.4 Coordinate system

4 Results and discussion

To achieve described goal, set of models were made and compared. Totally 90 models with different dimensions and boundary conditions were computed. The model setup was prepared as described (Fig.3), the rest variables were defined identical for all models. All numerical results were evaluated into the Table I, III and V. One example of graphical result can be seen on Fig.5.

In Table I the results from models with width of 10 meters and variable height were evaluated. We can observe that the results with the soil depth of 2 m are approximately the same for all three boundary conditions but with the decreasing depth the difference increases. This phenomenon is caused by the boundary conditions itself. In the small depth the boundary condition on the sides of the cube are not activated so only variable influencing the results is the height of the subsoil. Once the depth increases the influence of the boundary conditions of the sides of the cube becomes more significant.

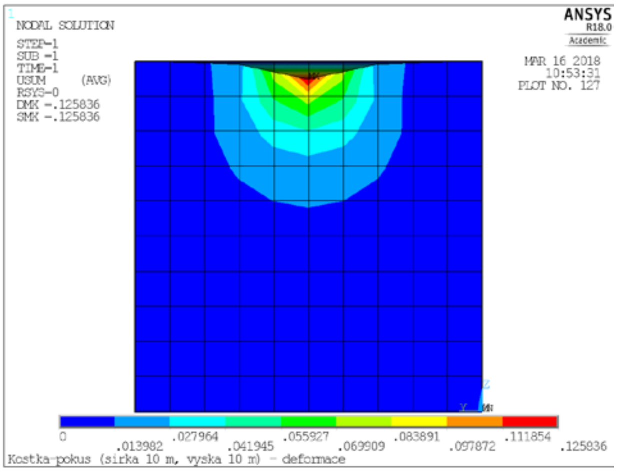

Fig.5 Ansys model (10 x 10 x 10 m) with boundary conditions type B in the middle cross section of the cube with graphical inscription of deformation.

Table I. Surface deformation for different height of the cube for cube with width 10 meters

Heigth of the soil [m]	Deformation z [mm]		
Boundary condition	***A***	***B***	***C***
2	-3.85	-3.85	-3.85
4	-4.68	-4.66	-4.66
6	-5.05	-4.92	-4.95
8	-5.31	-5.01	-5.13
10	-5.53	-5.03	-5.30
12	-5.73	-5.04	-5.47
14	-5.94	-5.05	-5.64
16	-6.14	-5.05	-5.80
18	-6.34	-5.05	-5.97
20	-6.54	-5.05	-6.14

Table II. Displacement increment per depth increment for data from Table I.

Height of the cube [m]	Displacement increment per depth increment		
Boundary condition	***A***	***B***	***C***
4	-0.417	-0.406	-0.407
6	-0.184	-0.129	-0.143
8	-0.127	-0.043	-0.092
10	-0.110	-0.014	-0.084
12	-0.104	-0.005	-0.083
14	-0.101	-0.002	-0.083
16	-0.100	0.000	-0.083
18	-0.100	0.000	-0.083
20	-0.100	0.000	-0.083

Table III. Surface deformation for different width of the cube with height 10 meters

Width of the soil [m]	Deformation z [mm]		
Boundary condition	***A***	***B***	***C***
2	-24.84	-3.31	-20.83
4	-9.18	-4.17	-7.96
6	-6.60	-4.66	-6.02
8	-5.83	-4.90	-5.48
10	-5.53	-5.03	-5.30
12	-5.39	-5.11	-5.24
14	-5.32	-5.16	-5.22
16	-5.29	-5.19	-5.22
18	-5.27	-5.21	-5.22
20	-5.26	-5.22	-5.23

The curve of boundary condition B is parallel to the x axis since the additional deformation is prevented by input values. The curve of boundary type A is more steep than the type C because the soil is not prevented from bulging to the sides.

We can observe different behavior at the sides of the model in the Table I. Since the width of the soil model is constant where the assumption was that the soil in this distance should be untouched. That means that the displacement values at the boarder are null. But the only case where the displacement is zero is boundary condition type B, where these values are fixed. In case of boundary conditions type A and C the value of the vertical deformation at boarder is non-zero.

Table III contains the results with the height of 10 meters with a variable width. Unlike Table I, Table III expose largest difference in the results in the smallest width. This is caused by differential boundary conditions behavior. That means that boundary conditions A and C are free in movement in *z* axes and the final deformation depends only on the area multiplied by the modulus of elasticity. Different from it boundary conditions type C allows only vertical deformations as big as fixed ends allows. From this reason results from boundary conditions A and C with increasing width of the model decreases and the results B grows. This phenomenon becomes less visible with the width of 10 meters and above.

Table V combines both previous concepts and includes results when both the width and the height are variables. From the results we can observe combination of the both described phenomenon but not so visible. The results from variant A and C can be described as uniaxial deflection behavior so with increasing length and area, the deformation increases as well.

Tables II, IV and VI were created where displacement increment per depth increment was calculated for all boundary conditions for better observation. This increment was calculated as difference of deformation *z* [mm] in two adjacent steps divided by the difference of increment of height of soil *h* [m] in two adjacent steps.

The Tables II and IV represent the influence of boundary conditions and their development. We can see that the behavior of all three boundary conditions is similar. At the beginning the change between individual steps is very steep but it stabilizes in a few steps and after this it is constant. This course is graphically described in the appendix in Fig.6 and Fig.7. Since the Table VI combines both curves, so the resulting shape is not linear but hyperbolic (Fig.8 - appendix).

Table IV. Dicplacement increment per depth increment for data from Table III.

Width of the cube [m]	**Displacement increment per depth increment**		
Boundary condition type	***A***	***B***	***C***
4	7.832	-0.429	6.435
6	1.291	-0.242	0.973
8	0.385	-0.120	0.267
10	0.150	-0.069	0.090
12	0.068	-0.041	0.032
14	0.034	-0.025	0.009
16	0.018	-0.015	0.001
18	0.010	-0.009	-0.002
20	0.006	-0.005	-0.002

Table V. Surface deformation for different width of the cube with height same as width

Heigth and width of the soil [m]	**Deformation z [mm]**		
Boundary condition type	***A***	***B***	***C***
2	-4.89	-3.31	-4.17
4	-5.41	-4.15	-4.84
6	-5.47	-4.64	-5.09
8	-5.50	-4.88	-5.22
10	-5.53	-5.03	-5.30
12	-5.54	-5.13	-5.36
14	-5.55	-5.20	-5.40
16	-5.56	-5.26	-5.42
18	-5.57	-5.30	-5.45
20	-5.58	-5.33	-5.47

Similar parametric study was made before, but the results were not clear due to the size area of model that was limited by calculation time [13]. Due to this limitation study stops at dimensions of cube 8 m. Also amount of produced models were limited with regard to effort and time required. It can be said that this process was inefficient and exploring area was not large enough to answer all questions. The biggest issue was insufficient amount of models. After comparison the deformation values with increasing dimensions cannot be predicted.

This study eliminates the lack of variability of previous work [13] on dimensions of the model and understanding of the influence of selected boundary conditions to them. Although selected models are not sophisticated enough and do not take real behavior into account well, the maximum simplification of the

Table VI. Dicplacement increment per depth increment for data from table V.

Heigth and width of the cube [m]	**Displacement increment per depth increment**		
Boundary condition type	***A***	***B***	***C***
4	-0.264	-0.421	-0.336
6	-0.028	-0.243	-0.126
8	-0.017	-0.124	-0.065
10	-0.011	-0.075	-0.040
12	-0.008	-0.050	-0.027
14	-0.006	-0.036	-0.019
16	-0.005	-0.027	-0.015
18	-0.004	-0.021	-0.011
20	-0.003	-0.017	-0.009

task contributes to the clarification and separation of individual influences. Now the influence of the model dimensions and the boundary conditions is clarified, and in future works the detected influences can be taken into account when evaluating the results.

4 Conclusion

Aim of this parametric study was to investigate the dependence of the boundary conditions as well as dimensions of numerical model of subsoil to the calculated deformation. In this study three series of calculations were created. One of them has constant height of 10 m of the subsoil with variable width. Second has constant width of 10 m with variable height. And the third combines both previous so it has variable height and width. When the one of the dimensions is fixed, the influence of the other can be revealed.

Both variants with one dimension fixed show the behavior that was assumed. The behavior of the third one with variables dimensions is not so obvious, even though we can observe here the same phenomenon as in two previous cases.

This paper establishes that assumption of replacing semi-infinite subsoil with a cube with large dimensions is not right. Because the results prove that larger subsoil does not lead necessary to the results with greater accuracy. Especially with the models behavior based on the Hook´s law. From the published results it is not possible to determine which model size is the right one.

Replacing the substructure with a cube is still possible, but it´s dimensions should be carefully selected in dependence on other input parameters as a material soil model and others. Determining appropriate size of modelling area is key step to obtain realistic values. If we can get realistic results from small numerical models like this and verify them by experimental tests successfully, it opens door to the future solving large tasks not only in the field of research but also to solve challenging numerical analyzes of civil engineering practice.

Research results in the following conclusions. The results of the numerical model analysis depend on:

- the selected boundary conditions
- the selected dimensions of the soil
- the subsoil model width to height ratio

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Appendix:

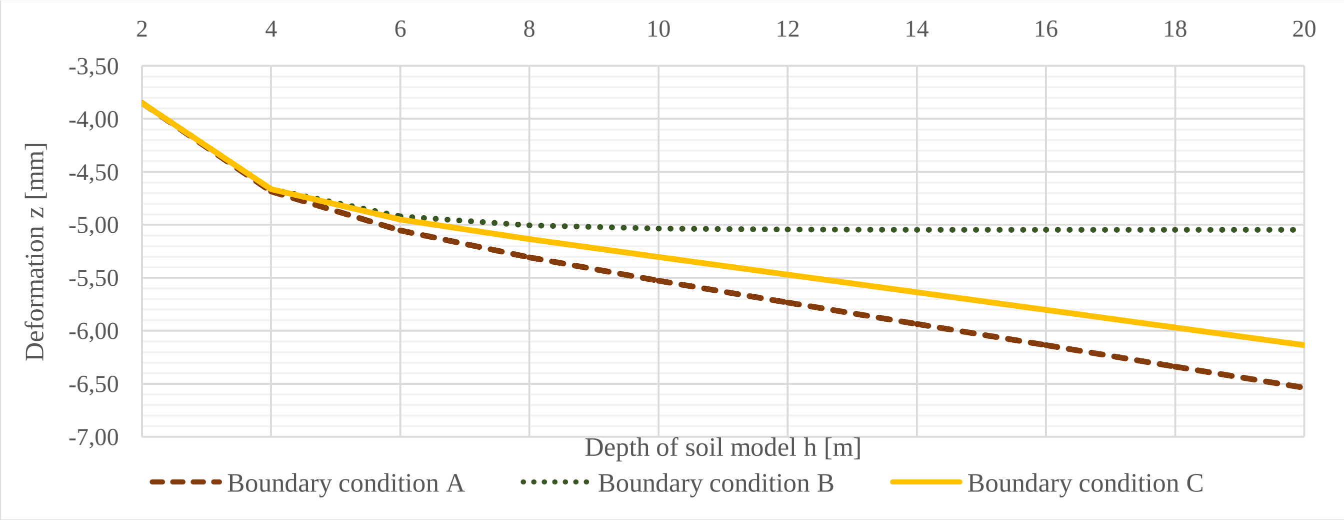

Fig.6 Total deformation from Table II – h=i, b= constant

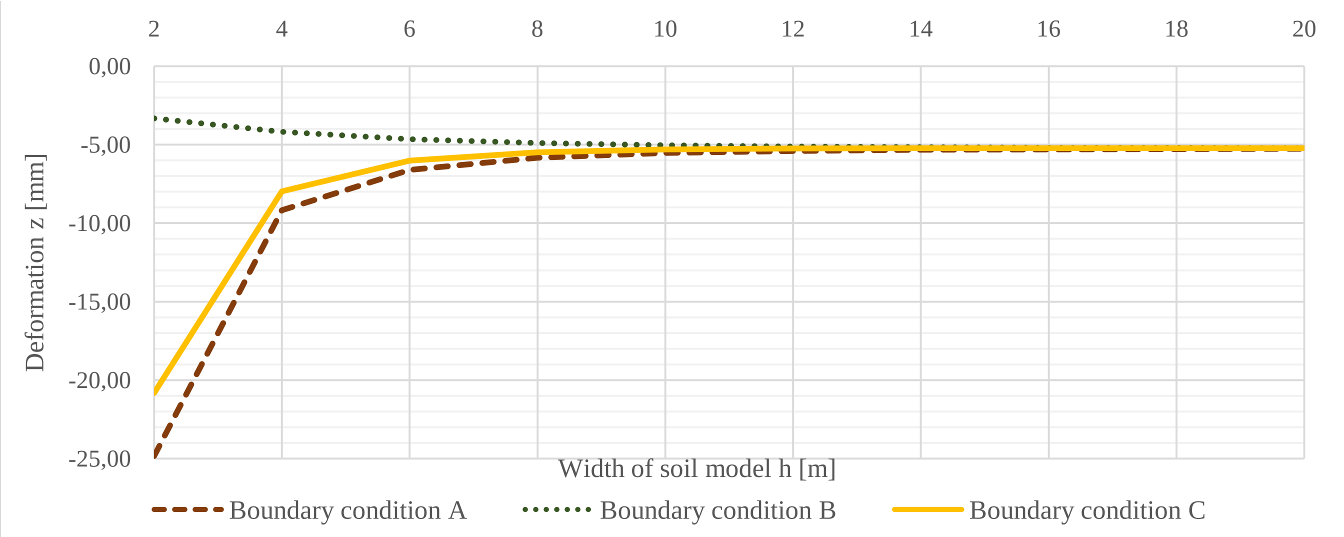

Fig.7 Total deformation from Table IV – b=i, h= constant

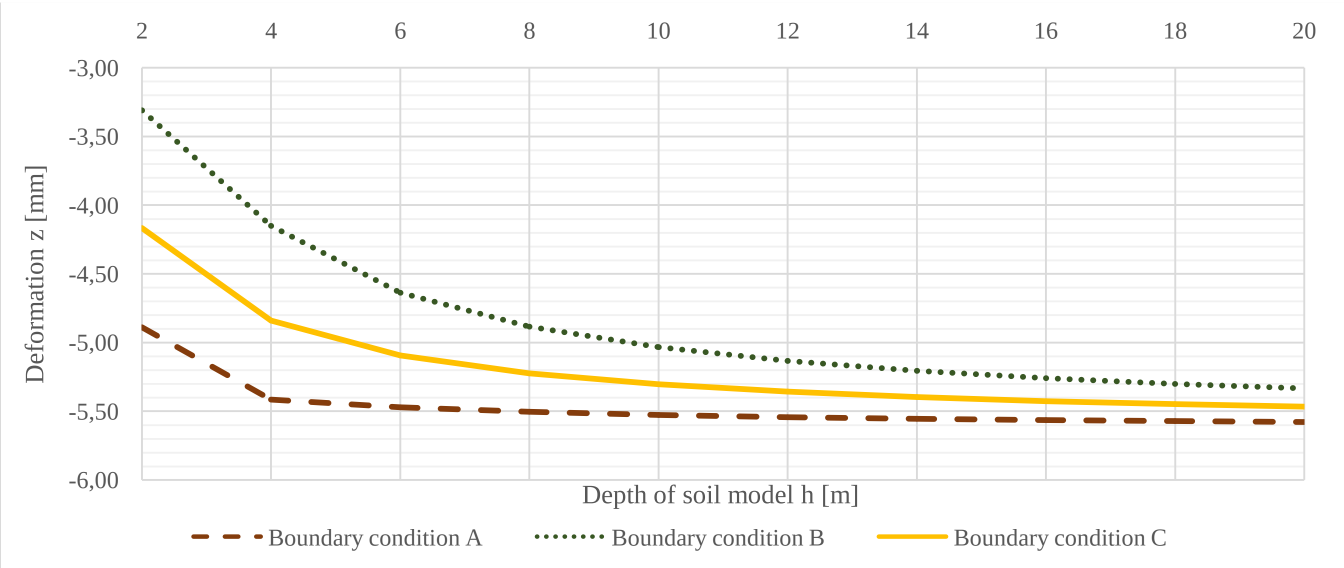

Fig.8 Total deformation from Table VI – b=i, h= i