Numerical Analysis of Subsoil-Reinforced Concrete Slab Interaction

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Abstract. *This article presents the numerical modeling of interaction between a reinforced concrete slab and subsoil using ABAQUS. Subsoil was simulated as both homogeneous half-space and inhomogeneous half-space. Reinforcement bars in the concrete slab were accurately modelled allowing capturing a precise deformation profile of the slab in interaction with subsoil. Input data for numerical analysis were adopted from a published work. Results of the study were verified on the basis of comparison with those of the previous study.*

Keywords

Deformation, finite element method, interaction models, numerical models, reinforced concrete slab, subsoil-structure interaction.

1. Introduction

Researches on subsoil-structure interaction have been intensively done over recent years. Those studies have covered many aspects of the interaction [1], [2], [3], [4], [5], [6] and [7]. For instance, R. Cajka 2013 presented a method of determination of friction parameters for soil-structure interaction [5]. Stress strain analysis of elastic half-space using Gauss numerical integration and Jacobean of transformation was conducted by R. Cajka in 2013 [6] and results were further analyzed by R. Cajka and J. Labudkova in 2015 [7].

In addition, experimental measurements of stress and subsidence in subsoil were also carried out by many researchers such as G.X. Mei et al. 2005 [8], Cajka et al. 2014 [9] and [10]. M. Mohyla et al. 2017 [11] analyzed stress under foundation slab with a physical surface interface between foundation slab and the subsoil by experimental measurement. Measurements from site tests and experiments allow having a better understanding about behaviors of both subsoil and structure as well as their interaction.

Unfortunately, in-situ tests and site experiments are usually expensive and time consuming. As a result, numerical analysis of subsoil-structure interaction has become a current trend. Researchers and experts are improving and developing the analysis of subsoil-structure interaction based on finite element methods (FEM) or based on the combination of both experimental measurements and FEM. For example, R. Cajka 2014 [12] made a comparison of calculated values of settlement and stress state of concrete slab on subsoil and those values got from experiments. In 2014, R. Cajka and J. Labudkova [13] described how calculated deformations depend on parameters of soil environment modeled by 3D finite elements. Deformation and contact stress of the slab and subsidence of the subsoil were calculated by using two FEM programs, Scia Engineer [14] and Mkpinter (a non-commercial software created by Cajka R., co-author of this paper), in [15]. Numerical interaction model of reinforced concrete (RC) slab and subsoil was also modelled in ANSYS [16] with application of inhomogeneous half-space to get better subsoil behavior [17]. This model was also applied to simulate the interaction between subsoil and steel-fibre reinforced concrete slab in [18].

This research aimed at the analysis of the interaction between subsoil and RC slab under the scheme of FEM. The study can be considered as a continuing development of the work of [17] on which ABAQUS [19] is used instead of ANSYS and reinforcement bars in the concrete slab are modelled with more realistic 3D body. In addition, this work took into account of the influence of friction between the subsoil and the slab which was neglected in [17]. Furthermore, the non-linear material model of Mohr Coulomb was employed instead of Drucker-Prager model had been used in [17]. Using this model, it is assumed that the compressive strength far exceeds the tensile strength. To facilitate the comparison between results of this work and those of [17], input parameters (geological profile, dimensions of the subsoil and slab, boundary conditions of the subsoil and results from experimental loading test) of [17] were adopted here. Outcomes of parametric study were compared with those of [17].

2. Numerical modeling in Abaqus

It is necessary to underline that ANSYS was chosen to facilitate the work of [17]. Both ANSYS and ABAQUS have lots of things in common and they both can solve such a work of the research. However, ABAQUS was intentionally exploited here as an occasion of comparing analysis results from both programs to a specific subsoil-structure interaction problem.

Like ANSYS, ABAQUS is one of the powerful tools for non-linear finite element modeling and analysis of almost engineering problems. The main principle of ABAQUS is to use the Newton-Raphson algorithm to calculate and automatically adjust increments to give results. This program was selected as a simulation tool for the research due to its wide material modeling and metaphysics capabilities. The software also helps in solving the contact between subsoil and concrete slab in this work via 3D elements.

In this study, 3D finite elements in ABAQUS 2017 were used to create models for both subsoil and the slab as well as the interaction between them. As above mentioned, all input parameters of [17] were re-applied in these simulations.

First of all, 3D subsoil model was simulated as a half-space in two cases: linear elastic homogeneous isotropic half-space and linear elastic inhomogeneous isotropic half-space. The former has constant value of modulus of deformability throughout its 6 m thick one-layer body while the latter includes 30 equal thickness soil layers of which values of deformability modulus varies by depth. The case of linear elastic inhomogeneous isotropic half-space is to take into account of the heterogeneity of subsoil material. This choice allows a better description of subsoil behavior than the homogeneous one [17] and [18]. The 3D element, SOLID C3D8R, was selected to simulate the subsoil. It is an eight-node linear brick element with reduced integration (1 integration point). This only integration point is located in the middle of the element. One of the important parameters of subsoil is modulus of deformability. It can be determined by oedometer tests, laboratory tests or tests in situ as discussed in literatures [20] and [21]. In this research, calculation of modulus of deformability is inherited from formulas presented in [17] with minor revision as follows:

$$E_{def,z} = E_0(1 + z^m), \quad (1)$$

where $E_{def,z}$ is the modulus of deformability (MPa) of the subsoil at z depth, E_0 is the modulus of deformability (MPa) at the surface of subsoil, z is the coordinate of considered layer of subsoil (m) in z direction (depth), m is a coefficient depending on Poisson coefficient, v.

$$m = \frac{1}{v} - 2, \quad (2)$$

Input parameters of the subsoil model are summarized in table 1.

Tab. 1: Input parameters of the subsoil model.

Parameters	Unit	Value
Dimensions of subsoil	m	6 x 6 x 6
Mesh size used in the subsoil model	m	0.2 x 0.2
Thickness of each layer in inhomogeneous half-space, z_i	m	0.2
Poisson coefficient, v	-	0.35
Modulus of deformability at the surface of subsoil, E_0	MPa	33.1

Tab. 2: Input parameters of the slab.

Parameters	Unit	Value / Description
Dimensions of slab	m	2 x 2 x 0.12
Cover thickness	m	0.02
Mesh size used in the slab model	m	0.2 x 0.2
Poisson coefficient, v - without crack - with crack	 - -	 0.2 0
Strength class of concrete	class	C25/30
Modulus of elasticity: - without crack, E_c - with crack, E_c^{II}	GPa	 27.5 7.3
Reinforcement bars	pcs	38 bars of 1.9 m long and 8mm diameter, Mesh size 0.1 x 0.1 m
Elastic modulus of reinforcement	GPa	210
Poisson coefficient of reinforcement	-	0.3

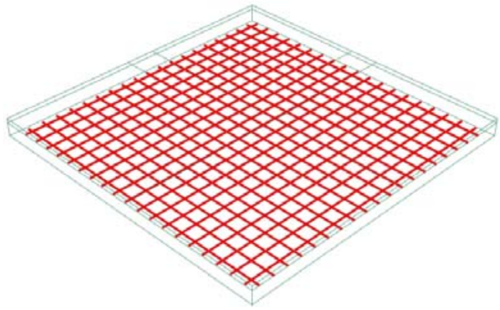
Three variants of boundary conditions were adopted from [17], include:

- Variant A: vertical and horizontal shifts in the lower base of the subsoil model were hindered, node shifts of 4 peripheral walls of the subsoil model were not hindered,
- Variant B: vertical and horizontal shifts in the lower base of the subsoil model were hindered, horizontal node shifts of 4 peripheral walls of the subsoil model were hindered,
- Variant C: vertical and horizontal shifts in the

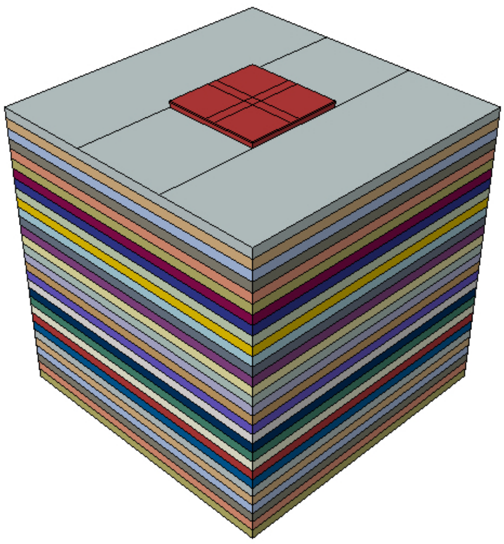
lower base and in the 4 peripheral walls of the subsoil model were hindered.

Secondly, slab was also created by the 3D element SOLID C3D8R in 2 scenarios: without crack and with crack. Other parameters are depicted in table 2.

Furthermore, the subsoil-concrete slab model was loaded with a load force of 350 kN within the loaded area of 200 mm x 200 mm. It is important to be noted that friction between the slab and the subsoil was taken into account as a coefficient of 0.3 in this work. Surface-to-surface contact scheme was used to mediate the interaction between the subsoil and the slab. The 3D numerical models of the slab and the subsoil are illustrated in figure 1.



(a)



(b)

Fig. 1: 3D numerical models of the slab (a) and inhomogeneous subsoil (b).

3. Parametric study

Influence of inhomogeneity of the subsoil model was considered here through 9 different created 3D models (3 variants of boundary condition x 3 depths of the subsoil, 2m, 4m and 6m) of homogeneity half-space and another 9 different simulated 3D models of inhomogeneity half-space. Figure 2 depicts the slab deformations with variable depths of the homogeneity half-space and inhomogeneity half-space at three boundary conditions.

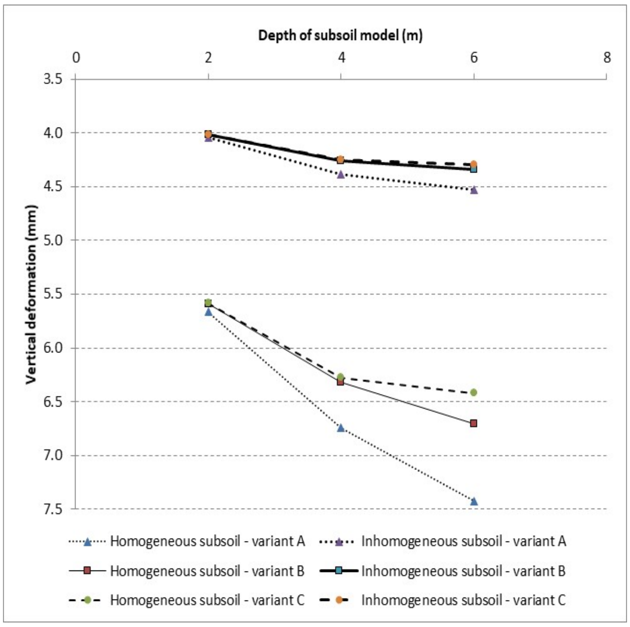


Fig. 2: Slab deformations in cases of homogeneity half-space and inhomogeneity half-space.

It is noticeable from figure 2 that slab deformations increase with the increase of subsoil depth. In addition, boundary conditions had major influence to final vertical deformations of the slab. Furthermore, resulting vertical deformations in case of homogeneous half-space are larger than those of inhomogeneous half-space. A closer look at figure 2 reveals that the difference in values of vertical deformation (between the largest and the smallest value) in the middle of the RC slab in homogeneous subsoil model is almost 4 times larger than those in inhomogeneous one. This indicates that homogeneity or inhomogeneity of the subsoil significantly impact the slab vertical deflections. All these results confirmed conclusions of [17]. Vertical deformations in the middle of the RC slab with boundary condition B in this study (using ABAQUS) were compared with those of [17] (using ANSYS) as shown in figure 3. Variant B was selected because it is considered to be most likely to occur in practice among the three variants.

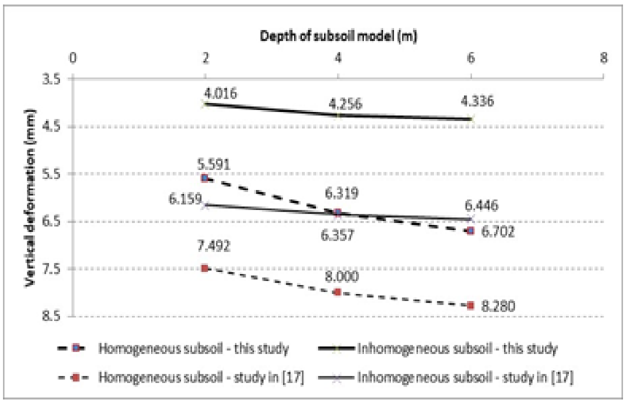


Fig. 3: Comparison of maximum slab deformations resulted from this work with those of [17].

It can be seen from figure 3 that the deformation line in case of homogeneous half-space in this research is almost parallel to that of [17]. The same situation also took place with case of inhomogeneous half-space. Resulted values of vertical deformation of this study are smaller than those of [17]. The difference in deformation values between this research and those of [17] are from 1.578 mm to 1.901 mm and from 2.101 mm to 2.143 mm in cases of homogeneity and inhomogeneity of the subsoil, respectively. Therefore, it can be inferred from the comparison that vertical deformation of the RC slab in considering interaction model analyzed by ANSYS is more conservative than that simulated by ABAQUS.

Influence of cracks in the slab to vertical deformations in the middle of the slab was also taken into account in this research. The main reason is that the cracks weaken rigidity of the slab and hence increase slab deformations. Only inhomogeneous half-space of the subsoil was considered here. Once again, results on slab deformations without and with cracks at boundary condition B are summarized in table 3.

Tab. 3: Maximum vertical deformations of the slab with inhomogeneous subsoil model and variant B.

Depth (m)	Maximum vertical deformations of the slab (mm)		Increase of deformation (%)
	Slab model without crack (a)	Slab model with cracks (b)	[(b) – (a)]/(a)
2	4.016	5.061	26.02
4	4.256	5.309	24.74
6	4.336	5.388	24.26

It is remarkable from table 3 that cracks increased vertical deformations in the middle of the slab at all three depths of subsoil model. This well agreed with the result of [17]. Amount of deformation increase was quite high, from 24.26 % to 26.02%. Figure 4 depicted the comparison between vertical deformations of the cracked and non-cracked slabs at boundary condition B in this study and those of [17].

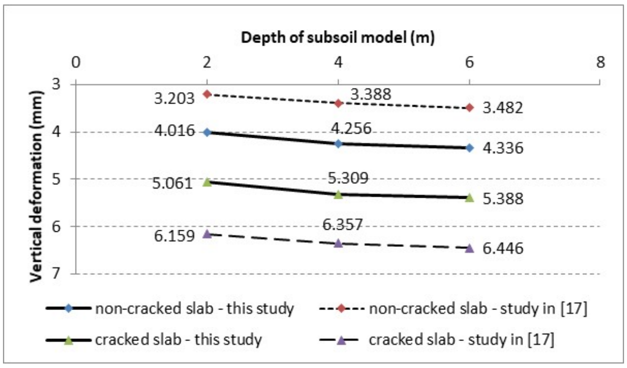


Fig. 4: Deformations of the cracked and non-cracked slabs of this work and those of [17].

It can be observed from figure 4 that deformation lines of the non-cracked and cracked slabs in this work and those of [17] have similar shape and they are likely to parallel to each other. Results from [17], however, demonstrated that cracks increased vertical deformations in the middle of the slab about 85 % to 92 % while the increasing amounts in this study were only 24 % to 26 %. This resulted from the fact that a friction coefficient of 0.3 between the subsoil and the slab was taken into account in this research.

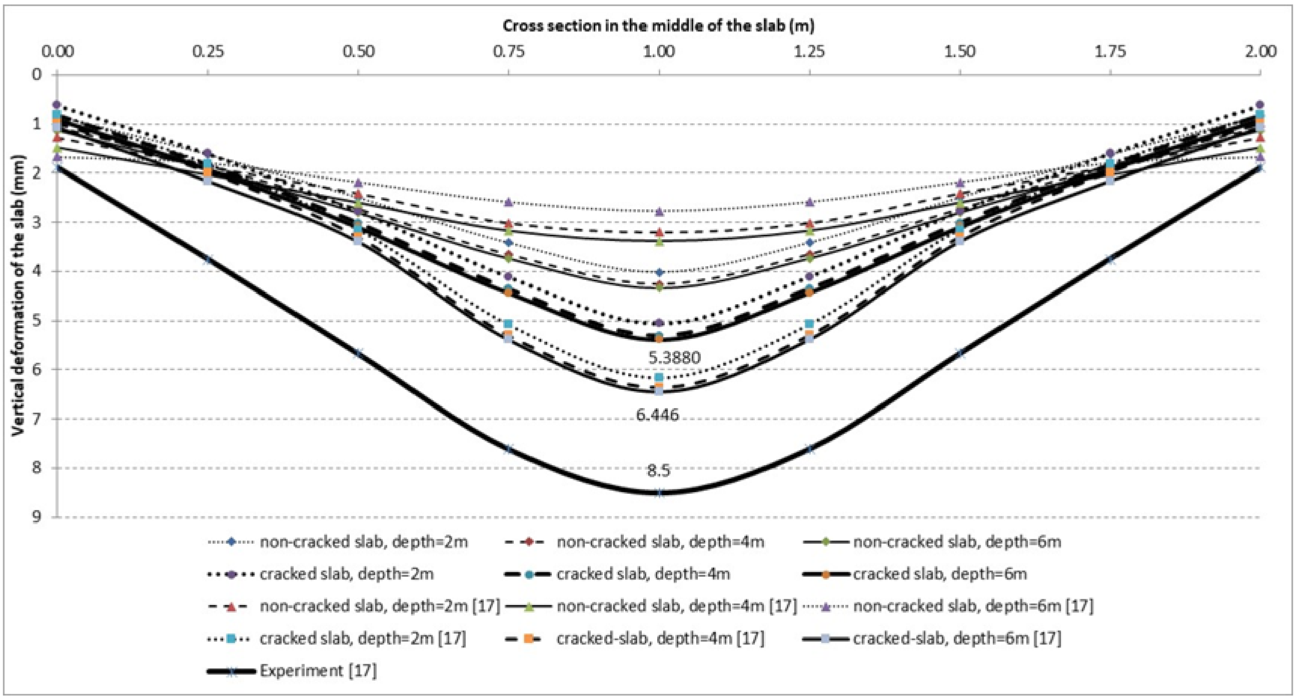


Fig. 5: Comparison of deformations of the cracked slab with the non-cracked slab.

In addition, results on vertical deformations in a cross-section in the middle of the slab (without and with cracks) at boundary condition B, obtained from ABAQUS are compared with accordingly results of [17]. The comparison is displayed in figure 5 included with the deformation curve of experiment adopted also from [17].

Please be kindly noted that all deformation curves in case of non-cracked slab were performed by light curves and the dark curves depicted deformation curves in case of cracked slab. It is quite clear from figure 5 that the closer the middle of the slab is, the larger difference of vertical deformation between non-cracked slab and cracked slab results. Maximum value of vertical deformation of cracked slab simulated by ABAQUS (this study) is 5.388 mm while that of cracked slab analyzed by ANSYS (study in [17]) is 6.446 mm. This minor deviation (1.058 mm, about 16.4 %) of vertical deformation can be explained firstly by the application of friction coefficient in the interactive model and secondly by the fact that reinforcement bars of the slab were accurately modeled in this study. It is also remarkable from figure 5 that the shape of deformation curves of cracked slab is quite similar to that of the deformation curve drew from site test by [17].

4. Summary and Conclusions

The interaction between a reinforced concrete slab and subsoil was analyzed using FEM by application of ABAQUS. Subsoil was modelled as both 3D homogeneous and inhomogeneous bodies to take into account of the influence of inhomogeneity of the subsoil to deformation of the slab. Two scenarios (without and with cracks) were integrated into the RC slab to consider impacts of cracks on deformation behavior of the slab. Reinforcement bars in the concrete slab were realistically simulated. Total of 36 interactive models were set up based on: variability of boundary conditions (3 variants), variation of depths of subsoil (3 different depths), homogeneity or inhomogeneity of the subsoil (2 options), cracked or non-cracked slab (2 scenarios). Friction between the slab and subsoil was also considered in the interaction. All input parameters were adopted from a literature (work in [17]).

Parameter study revealed that: (i) boundary conditions strong influenced to final vertical deformations of the slab; (ii) deformations of slab increased with the increase of subsoil depth; (iii) inhomogeneity of subsoil significantly impacted on slab resulted deformations; (iv) cracks weakened rigidity of the slab and increase slab deformations. These results confirmed conclusions of work in [17].

In addition, it can be inferred from the comparison between results from this research and those of [17] that vertical deformation of the slab would be reduced if friction between the slab and subsoil was taken into account in the analysis of interaction. Furthermore, lower vertical deformations of the slab (in comparison with those of [17]) would be observed if its reinforcement bars were realistically modelled.

It can also be concluded from this work that either ANSYS or ABAQUS can be efficiently employed in solving of subsoil-RC slab interaction problems.

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