The soil structure interaction for 3D irregular problem

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Abstract. As we are going through advancements in construction field and the imperatives of reliability requirements of the structure, soil always have an important role as a material that supports the whole structures, the Soil structure interaction is one of the most vital arts, nowadays and with the new technologies of soil testing and as we get closer for a better understanding of soil behaviour, we have the chance to model and anticipate the real behaviour of the structures resting on the soil. In this study, the effect of soil as a supporting material will be revealed and carefully studied to clarify and dye out the importance of Soil structure Interaction, and its effect on the governing efforts that are used in design of the structural elements. Soil structure interaction it is not just about the coupling of the soil and the structure, but also studying the effect of construction phase change between the adjacent buildings. The elastic settlements are going to be calculated using analytical solution, Boussinesq iterative solution, and elastic solution of Abaqus finite element model, then will be coupled as springs that model soil elastic half space (EHS) to check the impact of SSI.

1. Structure and lithology material properties
In this study, the differences of the straining actions of a 3D irregular problem is going to be shown as the boundary condition of the structure varies from fixed supports, using the analytical solution, Boussinesq solution and comparing the results with Abaqus linear elastic solution.

The structure is supported on a sandy lithology with 14000 kN/m² young’s modulus, 0.25 Poisson’s ratio, angle of internal friction \( \Phi = 40.00^\circ \), and cohesion \( C = 0 \) kPa.

The structure is made of C40/50 concrete class which has 3500000 kN/m² young’s modulus, 0.2 Poisson’s ratio, and 2500 kG/m³ density.

2. Structure and lithology geometric properties
The structure is a 10-story building, the height of the first floor is 3.40m and the height of the typical floors is 3.00m, this study will take place for fixed base structure and mat foundation of the structure rest on sand soil.

The thickness of the foundation mat is 0.8m, while the thickness is 0.22m for the typical floor slabs, and 0.30m for the core walls. The sections of the columns and beams are unified for purpose of simplicity where columns have 0.65m x 0.65m section and 0.50m x 0.60m for beams.

Figure 1, Figure 2, Figure 3, and Figure 4 show the 3D model, SAP2000 finite element model, typical floor layout, and the foundation layout.
The soil has been represented in Pdisp software for iterative Boussinesq solution of soil coupling and for the elastic analysis in Abaqus software, the dimensions of the lithology are 250m x 200m x 100m where the soil depth is 100m.

**Figure 1.** The structure 3D model.

**Figure 2.** The structure SAP2000 finite element model.

**Figure 3.** The structure typical floor layout.
3. The applied loads and load combinations.
The loads that have been taken into considerations are the own weight of the structure, 2.50 kN/m$^2$ of floors covering and finishing described as dead loads, 5.00 kN/m$^2$ of live loads, 1.6 kN/m$^2$ of the snow loads applied on the last floor of the building, and finally wind loads have been automatically applied on the structure as the structure has a closed façade, the wind basic speed is 1.05 m/s calculated automatically using SAP2000 software and according to the Eurocode 1-2005 with exposure coefficient of 0.80 for direct pressure exposure and 0.50 for suction exposure.

The load combinations of the Eurocode EN1990. The governing loads combination which produces the maximum pressure on the ground was $\text{ULS3} = 1.35 \text{ Dead load} + 1.5 \text{ Live load} + 1.05 \text{ Snow load} + 1.05 \text{ Wind in +Y Dir.}$

4. Soil structure coupling used methods
Thanks to the British physicist Robert Hooke’s work back to the 17th century, we can predict the elastic settlements of any material under a set of assumptions, since he assumed that the material is perfectly elastic, isotropic, and homogenous in the direction of loading the specimen.

Hooke represented the behavior of the elastic material as a linearly elastic spring, in Figure 5 we can see the different types of springs such that Spring (b) is representing Hooke’s solution. Spring (a) is a hard spring, where is noticeable as the applied forces are increasing, the settlement is merely increasing, on the other hand, spring (b) is linearly elastic, where the applied forces is linearly proportional with the settlement, in construction field, spring (b) is the most used. Spring (c) is a mild or week spring as it undergoes significant settlement with a very humble applied force.

Then by calculating the elastic settlement of the lithology due to the applied load from the structure, coupling between the structure and the soil can be achieved. In this research, assessing the settlement will be studied using different approaches.

After acquiring the soil subgrade reactions, it will be applied to the finite element model since the behavior of the structure can be observed and compared between the different types of coupling and the case of solving the structure in fixed boundary conditions.
4.1. The analytical solution of elastic settlement (DAS, 2009)

The analytical solution of calculating the elastic settlement is derived from the equations of the theory of elasticity, the analytical solution for the elastic settlement.

\[ S_e = \Delta \sigma \cdot \alpha \beta \frac{1-\nu^2}{E} \cdot I_s \cdot I_f \]  

Where \( \Delta \sigma \) is the effective induced stresses including foundation weight, \( \nu \) is Poisson’s ratio, \( E \) is the young’s modulus, \( I_s \) is the shape factor derived by Steinbrenner in 1934, \( I_f \) is the depth factor and is a function of the ratio between the foundation level and the width of the foundation, and the ratio between the length and the width of the foundation. The shape factor is derived by Fox in 1948, and for the foundation resting on the ground surface \( I_f = 1 \).

Figure 6 shows the results of the elastic settlements according to the analytical solution across the mat.

4.2. Boussinesq solution of elastic settlement (Olson, 1989)

Boussinesq is a French mathematician, physicist, and a scientist that has many contributions in hydrodynamics, bodies vibrations. In 1885 he derived a solution for stresses and displacements for a
load acting on an elastic space, where using his solution, settlements at different points at the surface of the elastic half space could be predicted, his solution gave a quite accurate solution for the adjacent structures. Boussinesq assumed the elastic half space mean as isotropic, homogenous, and derived his solution for a load acting just on the surface of the EHS to find the settlements at any certain point inside the EHS, the settlement equation derived by Boussinesq is as following.

$$w_{x,y,z} = \frac{P(1 + \nu)}{2\pi E} \left[ \frac{z^2}{R^3} + \frac{2(1 - \nu)}{R} \right]$$  \hspace{1cm} (4.2)

Where, $w_{x,y,z}$ is the displacement at any point in the Cartesian coordinates $(x,y,z)$, $P$ is the applied load, $\nu$ is Poisson’s ratio, $E$ is soil young’s modulus, $G$ is soil shear modulus, $r$ is the perpendicular distance between the point of load and the point $(x,y)$ and equals $\sqrt{x^2 + y^2}$, $R$ is the perpendicular distance between the point of load and the point $(x,y,z)$ and equals $\sqrt{r^2 + z^2}$. Figure 7 shows a point load applied on elastic half space.

**Figure 7.** Point Load Applied On EHS.

The iterations have been processed by assuming initial subgrade reaction under the footing and by exporting the stresses to the elastic half space in Pdisp software to calculate the elastic settlement using Boussinesq solution, transform the settlements into subgrade reactions and by updating the FE model, new values of the subgrade reactions are born, and by keeping the iterations the solution converges and the difference between the subgrade reactions from the iterations are diminished to the minimum. Figure 8 shows the numerical model of the soil in Pdisp software, while Figure 9 shows part of the used iterations, while Figure 10 shows the elastic settlement of the foundation due to Boussinesq solution.

**Figure 8.** Soil numerical model represented in Pdisp software.
4.3. *Abaqus solution of elastic settlement*

By exporting the fixed structure reactions from the SAP2000 model to Abaqus FE solver and modelling the raft and the lithology as shown in Figure 11 we can see the soil and the raft numerical model, the values of the settlements have been acquired as shown in Figure 12.
The differences between the solutions can be shown in Figure 13 where the difference between the Boussinesq solution and Abaqus solution are the minimum, however proving that the analytical solution cannot be used as SSI technique since the analytical solution cannot take into considerations the stiffness of the footings.

Figure 12. Abaqus elastic settlement solution.

Figure 13. Elastic settlements comparison between the different solutions.

Figure 14 and Figure 15 show the difference of the axial forces between the SSI Boussinesq solution and the fixed model, while Figure 16 and Figure 17 show the difference of the shear forces between the SSI Boussinesq solution and the fixed model, moreover Figure 18 and Figure 19 show the difference of the bending moments between the SSI Boussinesq solution and the fixed model.
Figure 14. Max Axial Force in Fixed Model 7414.19 kN.

Figure 15. Max Axial Force in Fixed Model 5328.75 kN.

Figure 16. Max Shear Force in Fixed Model 229.08 kN.

Figure 17. Max Shear Force in Fixed Model 431.2 kN.

Figure 18. Max Bending Moment in Fixed Model 301.93 kN.m.

Figure 19. Max Bending Moment in Fixed Model 929.39 kN.m.

Conclusion

The difference between Boussinesq settlement solution and Abaqus settlement solution were 2.89% while the difference between the analytical settlement solution and Abaqus settlement solution were 21.5% in which it proves that the analytical solution cannot be used as a solution for SSI. The differences of the internal efforts in the structure varied as well between the fixed model and the other different SSI solutions which prove a special attention should be paid for the structure to design through SSI process.
The analytical solution has many demerits concerning the calculation of the elastic settlements, in which it does not take into consideration the position of the load and it deals with the average vertical stresses on the soil, and this is a failure in terms of assessing mats displacements and it fits very well for just an isolated or strip footing or any uniform load.

Another point against the analytical solution in terms of foundation stiffness, in calculating the elastic settlements using the analytical solution, there’re no terms in the equations to contain the stiffness of the foundation which will reduce and modify the shape of settlements along the foundation, since if this modification has been incorporated in the settlement assessing equations, it will be suitable for soil structure coupling.

The analytical solution still does not take into consideration the irregularity in mats and foundations, since the analytical solution is valid just for the square and the rectangular foundations in which does not satisfy the complexity of nowadays foundations.

Boussinesq solution solves just for isotropic soil, where the reaction of the soil – specially strains – are expected to be the same in all directions, this assumption has many limits which it might be applicable in the coarse grained soil in its elastic zone of loading, and it is very blind to the anisotropic model where the soil reactions might differ from a direction to another as example in the soft grained soils or in the hardening terms of the coarse grained soil.

Eventually, the analytical solution cannot be used in soil structure interaction, while in the other hand Boussinesq solution can fit very well in soil structure interaction process but in just the elastic limits of the soil.

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