Soil-structure interaction effects on modal parameters of office buildings with different number of stories

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Abstract. The paper summarizes the results of a numerical investigation designed to study the soil-structure interaction effects on modal parameters of three office buildings. The reinforced-concrete 4-storey, 8-storey, and 12-storey office buildings, each with additional two levels of embedded basements, represent low, medium, and high-rise structures, respectively. In order to conduct this research, detailed finite-element structure models were prepared. Soil-foundation flexibility was represented with the use of spring-based solutions, incorporating foundation springs and dashpots. The influence of diverse soil conditions (represented by their average effective profile velocities and shear moduli) on the dynamic characteristics of the analyzed three office buildings (e.g. fundamental vibration periods) was investigated and discussed.

1 Introduction and motivation

Structural response of a building subjected to various dynamic excitations, such as earthquake ground motions, mining-induced tremors, impact loads, or jumping crowd loads, may be affected by many different factors including base isolation (see, for example, [1,2]), structural dampers (see, for example, [3-5]), pounding effects (see, for example, [6-11]) etc. Among a number of factors, which may considerably modify the dynamic characteristics, and thus alter the seismic response of a structure, the interaction between the structure foundation and the underlying soil is considered to be one of the most important contributors (see, for example, [12-16]). Even though the soil-foundation flexibility may have a significant impact on dynamic behaviour, many studies either do not incorporate soil-structure interaction, which may result in misrepresentation of the actual building's response, or are performed for simplified stick models, according to which buildings are idealized as multi-degree-of-freedom systems (see, for example, [17-19]), which, on the other hand, may not be fully appropriate for irregular structures.

Motivated by the preceding discussion, the present study was designed to investigate the soil-structure interaction effects on modal parameters of three reinforced-concrete office buildings. The 4-storey, 8-storey, and 12-storey office buildings represent low, medium, and high-rise structures, respectively. In order to conduct this research, detailed finite-

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element structure models were firstly prepared. In the next step, the soil-foundation flexibility was represented with the use of spring-based solutions, incorporating foundation springs and dashpots, as it is the most commonly adopted approach for idealizing the soil-foundation interface in current engineering practice. The influence of diverse soil conditions (represented by their average effective profile velocities and shear moduli) on the modal characteristics of the analyzed structures (e.g. fundamental vibration periods) was investigated and discussed.

2 Numerical models

Three office buildings considered in the present study are irregular reinforced-concrete structures made in a slab-column system with an interior shear wall core. The 4-storey, 8-storey, and 12-storey structures have the same floor plans, meaning that only the total number of stories is different. Additionally, each building has two levels of fully embedded basements with total height of 2×4.35 m. The height of the typical above-grade storey is 3.75 m, whereas the height of the emergency exit located at the rooftop is 2.5 m. Accordingly, the overall heights of the 4-storey, 8-storey, and 12-storey structures are 26.2 m, 41.2 m, and 56.2 m, respectively. The plan dimensions of each structure are 27 m wide by 42 m long, whereas the gross dimensions of the foundation mat are 28 m wide by 43 m long. Reinforced-concrete exterior basement walls, interior staircase walls, floor slabs, and mat foundations were developed using 4-node shell elements, whereas reinforced-concrete columns were modelled with the use of beam elements available in an educational version of Autodesk Robot Structural Analysis Professional 2017. As an example, the numerical model of the 12-storey office building is presented in Fig. 1.

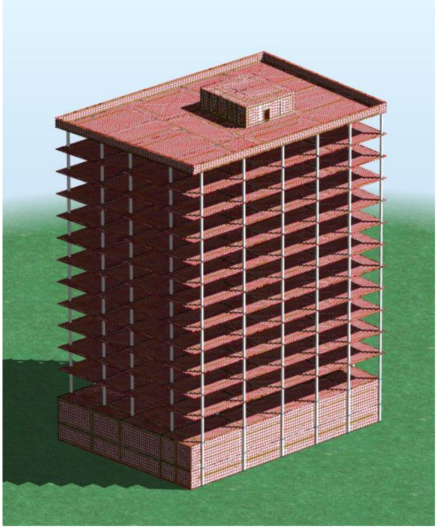


Fig. 1. Numerical model of the 12-storey office building.

3 Soil characteristics

Detailed description of soil conditions is an important component in every dynamic analysis incorporating soil-structure flexibility (see, for example, [20-22]). More specific procedures and guidelines for estimation of shear wave velocities (including calculation of overburden-corrected shear wave velocities) may be found, for example, in [23,24]. In order to investigate the soil-structure interaction effects on the modal parameters of the office buildings considered in the present study, three different site conditions were utilized. Soil properties were assumed in accordance to [25]. Geotechnical data represented by shear wave velocities, mass densities, and Poisson's ratios are briefly summarized in Table 1.

Table 1. Characteristics of the soil types considered in the study.

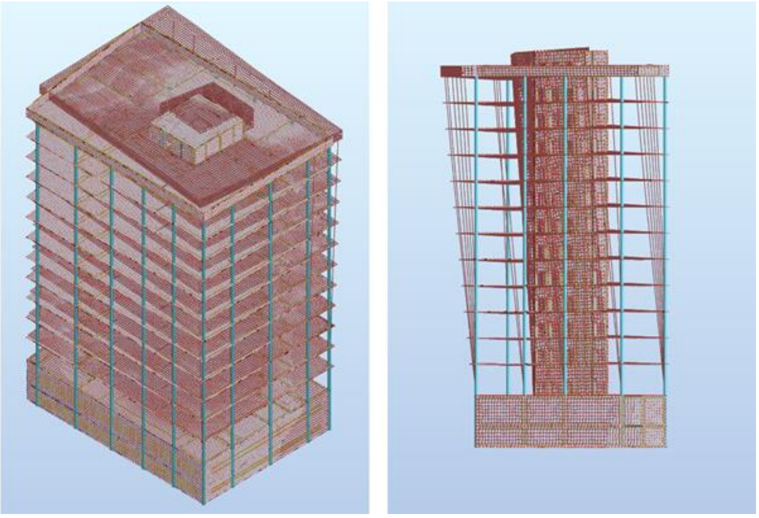
Soil type	Shear wave velocity (m/s)	Mass density (kN/m^3)	Poisson's ratio (-)
Dense soil	500	20	0.40
Stiff soil	300	18	0.35
Soft soil	150	16	0.30

4 Soil-structure flexibility

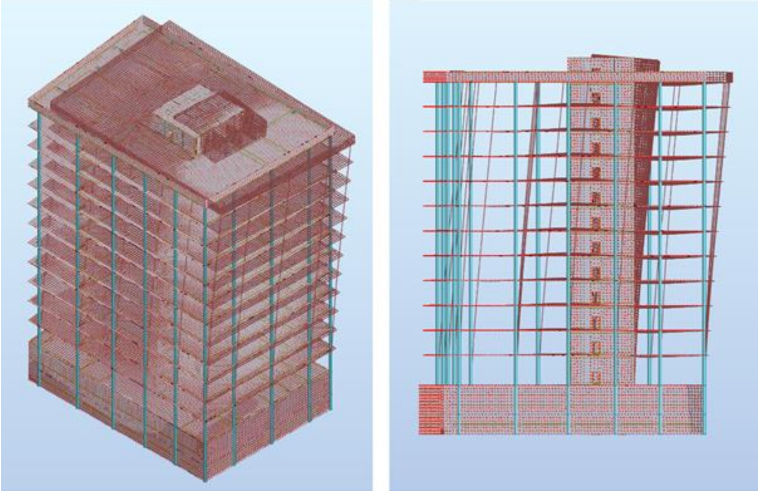
Soil-structure interaction may be implemented into numerical analysis through many different approaches, either by incorporating foundation springs and dashpots or modelling the soil beneath the structure as a solid continuum with finite elements (see, for example, [26-28]). In the present study soil-foundation flexibility was implemented using spring-based solutions proposed in [29], which are identified among the most commonly adopted equations in current engineering practice. This approach includes calculations of soil springs to capture translational and rotational degrees of freedom, and dashpots to address soil damping effects. For each site condition considered in this study, characteristics of springs and dashpots were developed by calculating translational (k_x, k_y) and rotational (k_{xx}, k_{yy}) stiffnesses for rectangular rigid foundation as well as dashpot coefficients (c_x, c_y, c_{xx}, c_{yy}). The foundation stiffness was calculated using the static stiffness as well as the embedment correction factors η. The base spring stiffness was subtracted from the overall horizontal stiffness to determine the portion of the horizontal stiffness attributed to passive pressure resistance against basement walls (total translational stiffness is larger due to embedment). Vertical springs and dashpots were distributed over the footprint of the foundation, allowing the foundation to deform in a natural manner. Edge intensities were adjusted to match the overall rocking stiffness values, as the vertical soil reaction is not uniform, and tends to increase near the edges of the foundation. Correction factors were determined using the equations presented in [30]. Corner intensities ware calculated as the average of edge intensities in both directions. It should be also underlined that both horizontal and vertical springs are elastic with no compression capacity limit and zero tension capacity.

5 Modal analysis

In the final step of the current numerical investigation, modal analysis was conducted to investigate the influence of soil-structure flexibility (i.e. represented by three soil conditions presented in Section 3) on modal parameters of the analyzed office buildings. The results obtained for the 4-storey, 8-storey, and 12-storey office buildings were compared with those obtained for fixed-base conditions. As an example, fundamental modes of vibration, in both transverse and longitudinal directions, of the 12-storey fixed-base building are presented in Fig. 2. Results obtained for all site conditions considered in the study are briefly summarized in Table 2 and also presented in Fig. 3.



a)

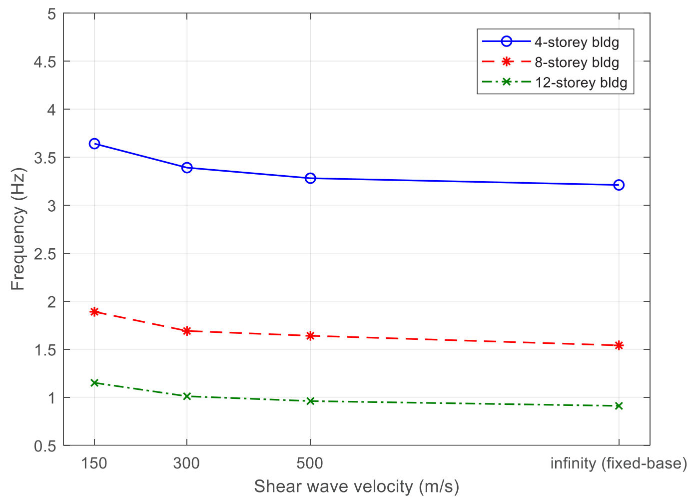


b)

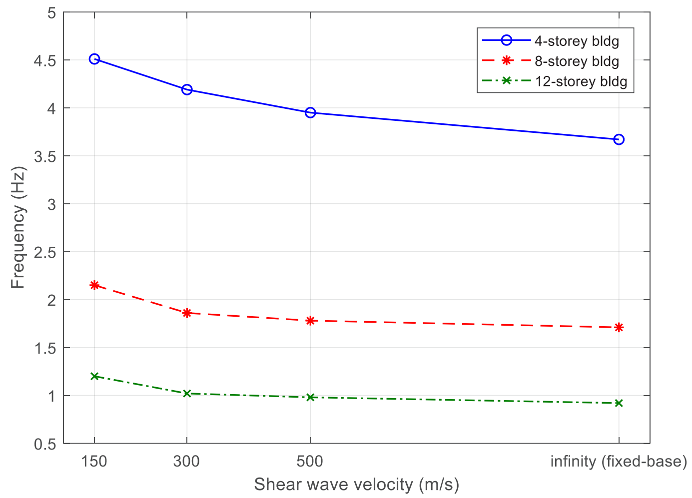
Fig. 2. Transverse: (**a**) and longitudinal, (**b**) modes of vibrations for the fixed-base 12-storey office building.

Table 2. Results of modal analysis.

Site conditions	**Frequency (Hz)**					
	4-storey building		**8-storey building**		**12-storey building**	
	Transverse mode of vibration	Longitudinal mode of vibration	Transverse mode of vibration	Longitudinal mode of vibration	Transverse mode of vibration	Longitudinal mode of vibration
Fixed-base	3.64	4.51	1.89	2.15	1.15	1.20
Dense soil	3.39	4.19	1.69	1.86	1.01	1.02
Stiff soil	3.28	3.95	1.64	1.78	0.96	0.98
Soft soil	3.21	3.67	1.54	1.71	0.91	0.92



a)



b)

Fig. 3. Frequencies for transverse: (**a**) and longitudinal, (**b**) modes of vibration for the analyzed buildings.

5 Results and conclusions

The present study was designed to examine the soil-structure interaction effects on the modal parameters of reinforced-concrete office buildings with different number of stories. Three different site conditions were utilized into numerical analysis to investigate the importance of the soil flexibility. Next, the results were compared with those obtained for the fixed-base structures. The numerical investigation resulted in the following conclusions:

1. Close inspection of Table 2 and Fig. 3 clearly shows that soil flexibility can considerably modify the modal parameters of the building structure by lengthening its fundamental period (the lower the fundamental frequency, the longer the fundamental period of vibration). As expected, the effects of soil-foundation flexibility become

more significant as the stiffness of the underlying soil decreases. The present investigation confirmed that for stiff and dense soils modal parameters were only modestly affected. For the soft soil the reduction levels in the fundamental frequencies in transverse direction for the 4-storey, 8-storey, and 12-storey buildings are 11.8%, 18.5%, and 20.8%, respectively, when compared to the fixed-base models. The reduction levels in the fundamental frequencies in longitudinal direction for the 4-storey, 8-storey, and 12-storey buildings are 18.6%, 20.4%, and 23.3%, respectively, when compared to fixed-base models.

2. Results obtained exhibits that the soil-structure interaction effects seem more profound for taller buildings as the reduction levels in fundamental frequencies in both transverse and longitudinal directions are the highest for the 12-storey building.

Conducted numerical investigation, even though utilizing simple engineering approach of incorporating the soil-foundation flexibility with springs and dashpots, clearly demonstrates the significance of soil-structure interaction. Ignoring the site conditions, especially in case of soft soils, may not provide accurate results in dynamic analysis.

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