

Analysis of the Soil-Structure Interaction for a High Rise Building Adjacent to Deep Excavation

N. Yeganeh ¹, A. Akhtarpour ^{*2}, J. Bolouri Bazaz ³, M. S. Baradaran ⁴

Abstract

The process in which the response of soil influenced by the motion of structure and the response of structure influenced by the motion of soil, is referred to as soil-structure interaction. Soil-structure interaction is an interdisciplinary field of endeavour which lies at the intersection of soil and structural mechanics and dynamics, earthquake engineering, geophysics, geomechanics, computational-numerical methods and technical disciplines. This is especially and significantly important for large and heavy structures such as nuclear power plants, dams, offshore platforms, bridges and high rise buildings built on soft soil. Excavation adjacent to buildings can intensify the soil-structure interaction effects. In this study, in addition to soil-structure interaction model and building-excavation interaction model, the fixed-based model was defined as well based on the finite difference method in FLAC. Modified mohr-coulomb model is used for soil medium and with the help of programming feature of the software, the stress-dependent stiffness and the material unloading behavior are applied. A fundamental stage in numerical modeling is the validation, verification and comparison of model results with field data. Validation of the numerical model is based on data extracted from tiltmeter installed on the column of a building adjacent to the excavation and some load cells placed on anchors against the excavated area wall. Analysis results studied in two separate parts of structural frame and retaining structure of excavation was studied, suggest that due to the high rigidity of retaining structure, the excavation practice does not affect the values of internal forces of adjacent structural frame. However, there was a significant difference in the values of the internal forces between the fixed-based model and the interactional models. Moreover, type of modeling of structure adjacent to the excavation as an overload or structural frame, only influences the vertical deformation of existing building foundation during the excavation.

Keywords: Excavation, Structural Frame, Soil-Structure Interaction, Instruments, Verification, FLAC2D.

¹ Ph.D. in Civil Engineering, Geotechnics, University of Technology, Sydney, Australia

² Associate Professor, Department of Civil Engineering, Ferdowsi University of Mashhad. akhtarpour@um.ac.ir

³ Associate Professor, Department of Civil Engineering, Ferdowsi University of Mashhad.

⁴ Research Assistant, Department of Civil Engineering, Ferdowsi University of Mashhad.

* **Corresponding Author**

1. Introduction

The study explores soil-structure interaction, focusing on the impact of excavation near buildings. Initial theories date back to 1936, and while general soil-structure interaction is well-studied, the specific effects of excavation are less explored (Baradaran et al., 2023, 2024). This research examines two modelling methods: frame and surcharge, using the Mashhad International Financial Centre as a case study. The project was selected due to its complex conditions, including the presence of a 17-story tower, monitoring equipment, and a retaining system with post-tensioned anchors. The study aims to provide insights into accurate modelling techniques for buildings adjacent to deep excavations.

2. Materials and methods

This research explores soil-structure interaction (SSI) analysis methods, focusing on direct and substructure approaches (Akhtarpour and Mortezaee, 2019). In the direct method, the entire structure-foundation-soil system is modeled and analysed simultaneously, accommodating nonlinear behaviour and complex geometries. The substructure method divides the SSI problem into simpler sub-problems, combining results using the superposition principle. The geotechnical properties of the subsurface layers are classified into coarse-grained and fine-grained units using the Unified Soil Classification System (Luo et al., 2016, 2007). The study area consists of approximately 79% coarse-grained soils in the upper section and 47% fine-grained soils in the lower section (Table 1). Parameters such as the elastic modulus and Poisson's ratio are derived, with specific values determined through empirical relationships and test data. The unloading-reloading modulus (K_{ur}) is found to be higher than the initial loading modulus.

Table 1. Soil geotechnical parameters

Layer	Thickness (m)	Soil Type	Specific Gravity (γ_s)	Internal Friction (Degree)	Cohesion (c)
1	9.6	Coarse	20	34	0.20
2	3	Fine	19.7	28	0.25
3	8	Coarse	20	36	0.20
4	6	Fine	19.5	20	0.25
5	4.5	Coarse	18	35	0.20
6	11	Fine	19.5	24	0.25
7	1.5	Coarse	20	39	0.20
8	4	Fine	19.5	28	0.25
9	2.5	Coarse	18.5	26	0.20
10	1.5	Fine	19.5	28	0.25

The selection of a suitable soil behavioural model is crucial, particularly for simulating unloading behaviour and the increase in stiffness with stress. The modified Mohr-Coulomb model is employed, and FLAC software is used for numerical modeling. The study highlights the need for accurate modeling techniques to address the complexities of soil behaviour near excavations, ensuring structural stability and safety (Pournoori et al., 2024).

3. Modeling in Flac2D

FLAC2D, a finite difference software with FISH programming for advanced modeling, was used for this study. Anchors were modeled with cable elements and specific prestress values, showing high accuracy with field data. Concrete piles were modeled considering their moment of inertia and shear behavior. Building frames were analyzed with adjustments for dead/live loads and structural forces, while foundations were modeled with detailed parameters. Mesh design aimed to minimize boundary effects, and model validation compared numerical results with field measurements, revealing high accuracy with minor deviations. The study introduced five numerical models, including scenarios with no surcharge, soil-structure interaction, building-excavation interaction, surcharge, and fixed support (Yazdi et al., 2024).

4. Results and Discussion

The soil-structure interaction (SSI) can either amplify or reduce the structural response, depending on the characteristics of the soil and structure (Matsagar, 2022). Key findings from models 1 to 5 are summarized below.

4.1. Frame Beam Bending Moments

Foundation settlement can alter load distribution, causing damage and changes in internal forces. Results for models 2, 3, and 5 show that interaction effects can increase bending moments by up to 2.2 times compared to a non-interaction model. Differences diminish above 35 meters, with model 5 maintaining negative bending moments throughout.

4.2. Excavation Wall Deformation

Retaining structures aim to limit displacement to protect adjacent structures. Models 1, 3, and 4 demonstrate minimal lateral displacement, with a maximum of 0.7 cm due to the stiffness of the retaining system. Pile deformation is consistent across models, with minor variations above the excavation level.

4.2.1. Pile Bending Moments and Axial Forces

The maximum bending moment occurs 2 meters from the top of the pile, with values of -21, -25, and -27 ton-m for models 1, 3, and 4, respectively. There is a noticeable discrepancy between calculated and actual axial forces, attributed to factors like wall displacement and poor soil conditions.

4.2.2. Vertical Deformation Profile

The type of adjacent structure modeling significantly affects the soil deformation under the foundation.

5. Conclusion

Asymmetric settlement significantly affects internal forces, necessitating accurate building modeling to avoid errors from ignoring soil-structure interaction. Excavation has minimal impact on static bending moments due to the retaining system's high stiffness. Bending moments are higher in interactive models for lower floors but are similar in upper floors compared to fixed base models, with impacts disappearing at the roof. In excavation retaining structures, lateral pile displacement is minimal due to high stiffness and prestressing, and the modeling approach (surcharge vs. building frame) does not greatly affect static analyses of wall deformation or pile

moments, though it does impact soil deformation. For static design, modeling the adjacent structure as a surcharge is usually sufficient, but for internal force analysis, a structural frame model is necessary.

References:

- Akhtarpour, A. and Mortezaee, M., 2019. Dynamic response of a tall building next to deep excavation considering soil–structure interaction. *Asian Journal of Civil Engineering*, 20(4), pp.479-502.
- Baradaran, M. S., Aftabi Sani, A., Abrishami, S. (2024). 'Application of Differential Transform Method for Solving Free-Surface Seepage Problem of One-Dimensional Porous Media', *Ferdowsi Civil Engineering*, 37(1), pp. 1-18.
- Baradaran, M.S., Qazanfari, R. and Baradaran, S., 2023. Study of soil reinforcement in the east of Mashhad using glass granule. *Materials Research Express*, 10(5), p.055202.
- Baradaran, S. and Ameri, M., 2023. Investigation of rutting failure in asphalt mixtures and its improvement strategies. *Road*, 31(114), pp.53-70.
- Baradaran, S., Rahimi, J., Ameri, M. and Maleki, A., 2024. Mechanical performance of asphalt mixture containing eco-friendly additive by recycling PET. *Case Studies in Construction Materials*, 20, p.e02740.
- Luo, C., Yang, X., Zhan, C., Jin, X. and Ding, Z., 2016. Nonlinear 3D finite element analysis of soil–pile–structure interaction system subjected to horizontal earthquake excitation. *Soil Dynamics and Earthquake Engineering*, 84, pp.145-156.
- Luo, W.L., Liu, C.W. and Han, X., 2007. Numerical simulation of behaviour of piled foundation influenced by tunneling. *Rock and Soil Mechanics*, 28(S1), pp.403-407.
- Matsagar, V., 2022. Earthquake Engineering and Technology. In *Theory and Practice in Earthquake Engineering and Technology* (pp. 1-53). Singapore: Springer Nature Singapore.
- Pournoori, P., Davarpanah TQ, A., Rajaei, A., Ghodrattnama, M., Abrishami, S. and Masoodi, A.R., 2024. Experimental exploration of fracture behavior (pure mode III) in eco-friendly steel fiber-reinforced self-compacting concrete with waste tempered glass as coarse aggregates. *Scientific Reports*, 14(1), p.9043.
- Yazdi, A.N., Akhtarpour, A., Abdalhusein, M.M. and Baradaran, M.S., 2024. Experimental investigation of the volume change of a swelling clay and its improvement. *Transportation Infrastructure Geotechnology*, 11(3), pp.1008-1031.