Responses of adjacent ground and building induced by excavation using 3D decoupled simulation

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ABSTRACT

This paper presents a study on excavation-induced deformation characteristics of ground and adjacent building using three-dimensional (3D) decoupled simulations. A decoupled analytical technique is proposed to enhance the consideration of both the 3D nonlinear soil behavior and the inelastic structure responses. The excavation effects and the adjacent structure’s responses are decoupled and simulated by two separate programs: PLAXIS 3D for excavation and SAP 2000 for structure. Two models are bridged by a simple iteration scheme. A well-documented excavation case history and low-rise framed building are used for demonstration. The obtained results exhibit that the decoupled analytical method is feasible to incorporate properly the 3D nonlinear soil behavior and the inelastic structure responses. It also seems practical to use since the numerical outcomes often converge within several iterations. The analytical results show that the lateral and vertical movements of the structure are significantly different from those of the greenfield ground. In addition, more in-depth inelastic structure responses can be investigated such as where the plastic hinge may occur in the structure. This is a significant advancement as it provides additional insights on assessing the building’s potential damage and serviceability.

Keywords: excavation, soil-structure interaction, decoupled analysis, building damage potential

1 INTRODUCTION

With the rapid infrastructural development in urban cities, the need for space makes it necessary to conduct deep excavations. The movements caused by such excavations can cause damage on nearby buildings, especially for the low-rise buildings founded on spread footings. It is because this kind of structure may be vulnerable to the differential settlements induced by the excavation. Therefore, it is important to predict those movements and take precautionary measures in order to prevent these damages.

Numerical analysis has been a useful tool in predicting the behavior of excavations. Even though great achievements have been made, the behavior of excavations with buildings nearby is hard to predict with the current approaches since most of the simulations are simply done in the plane strain condition or without considering the adjacent building. In some cases, the building is considered but its geometry is usually simplified and structural properties are limited within linear elastic range.

In a recent study, the authors (Lin et al. 2014) presented a 3D simulation procedure of the excavation problem with building consideration that can take into account the nonlinear soil behavior and the inelastic building behavior. In this pilot study, the excavation and the adjacent building were decoupled and simulated by two separate programs that are specified for the excavation and the structure. The preliminary results are very promising and warrant further study. Therefore, this decoupled analytical procedure is enhanced in this paper in a more comprehensive manner. The developed technique will be demonstrated with a well-documented excavation case history. The 3D greenfield excavation model is firstly considered. The nearby building is then taken into account. The responses of the excavation and the adjacent building are studied. The effects of the building existence on the excavation behavior are also examined.

2 DECOUPLED ANALYSIS PROCEDURE

The primary concept of the decoupled analysis procedure is to decouple the excavation-structure system into two individual problems of excavation and structure. In particular, the excavation and building are modeled respectively by PLAXIS 3D and SAP 2000 as illustrated in Figure 1. Detailed dimensions of the excavation and the adjacent building are omitted here.
but will be described in Section 3. The existence of the adjacent building in the excavation model is simply represented by the footings with their reaction forces. These decoupled simulations can take advantages of the modeling capability of PLAXIS 3D in geotechnical engineering and SAP 2000 in structural application.

The key issue of the decoupled analysis procedure is how to bridge the two problems with a robust and efficient iteration process. Figure 2 shows the proposed iteration scheme to link the excavation and structure simulations together. In the initial step, the building is analyzed in SAP 2000 prior to the excavation activity i.e. only the self-weight and live loads are considered, and no excavation-induced movements exist. The outputs are vertical and lateral reactions at the footings. The forces obtained from the above structural analysis are in turn used as input in the PLAXIS 3D excavation model (as shown in Figure 1a). The outputs are the vertical and horizontal displacements at the footing positions. These displacements are then adopted as the prescribed conditions in the subsequent structural analysis. In other words, after the initial step the building analysis is conducted with the excavation induced movements. This procedure is iterated until the difference in the outputs of reaction forces and displacements from two successive steps are less than a specified tolerance such as 5%.

Fig. 2. Iteration procedure for decoupled analysis

3 ANALYTICAL MODELS

This paper adopts a well-documented excavation case history, namely Taipei National Enterprise Center (TNEC), presented by Ou et al. (1998). TNEC constructed by top-down construction method had the diaphragm wall with thickness of 0.9 m and depth of 35 m. There were totally 7 excavation stages. The excavation geometry was 43 m wide and 105 m long. The largest excavation depth was 19.7 m. The soil strata were alternating layers of sand and clay from the ground surface to 46 m deep. There was a thick clay layer from 8 m to 33 m deep that had dominant influence on the excavation behavior. In the simulation, the hardening soil and Mohr-Coulomb models are used for clay and sand, respectively. The 3D TNEC excavation model is shown in Figure 1a. The excavation is firstly simulated in greenfield condition in order to verify the reasonableness of the excavation model. Then the nearby building is considered using the decouple analysis procedure.

The building is a typical school-like structure in Taiwan. It has four stories as shown in Figure 1b. The height of each story is 3.6 m. There are 10 equal spans
with total length of 45 m in the longitudinal direction and the width is 12 m. The footing is connected by a tie-beam system. The sizes of beams, columns are determined according to the reference values in the collected database. Since the building settlement induced by a nearby excavation is mainly examined, for simplicity the loading considered includes two types: dead load and live load. The load magnitude is determined based on Taiwan’s building design code. In specific, the average dead load is 1.2 t/m$^2$; and the live load is 0.3 t/m$^2$. It is noted that only 50% of the live load is used due to the temporary nature of the live load.

In the simulation, the building can be positioned at any place surrounding the excavation such as at the center or near the corner zones. Herein, for simplicity only a scenario of building at the center section is demonstrated as illustrated in Figure 1a.

4 RESULTS AND ENGINEERING IMPLICATIONS

4.1 Ground response

It is found that the predicted wall and ground movements under greenfield condition are close to the field measurements. In other words, the excavation model is proven to be reasonable. When the building is included in the simulation, the comparisons in the vertical and horizontal movements of the building and the greenfield ground are shown in Figure 3.

4.2 Building response due to nearby excavation

The excavation-induced building responses are shown in Figure 4 in terms of axial forces and plastic formation. These two factors are essential to examine the building performance. Figure 4a indicates that tensile force can be found in tie beams at the far spans. This is because the maximum horizontal movement in the building takes place in the middle span. It gives a push towards the excavation causing compression and a pull on the members on the other side causing tension. Normally, a concrete member is relatively vulnerable to the tensile force. Therefore, this observation is valuable especially for the structural design to avoid damage or severe crack in the beams.

Moreover, plastic deformation is found in the building as demonstrated Figure 4b. It occurs on the beam at the beam-column joints and concentrates on the top floors at spans near the excavation zone. The plastic deformation implies that the member forces are significant comparing to the bearing capacity and the member may have high potential of damage. Therefore, the plastic hinge can provide insights on where potential damage may occur.

To estimate overall building performance, the
angular distortion and lateral strain are adopted based on previous works. Son and Cording (2005) proposed an evaluation chart to assess the building serviceability as shown in Figure 5. The results from the decoupled analysis are also plotted in Figure 5. In this study, the lateral strains are calculated at the level of footing location. Figure 5 shows that the first spans suffer more from angular distortion while the spans farther away from the excavation show greater lateral strain. The lateral strain characteristic agrees with the tension observed in spans 7-10 (Figure 4a). Meanwhile, the angular distortion is also consistent with the plastic hinge locations (Figure 4b).

**Fig. 5. Building damage evaluation on the chart proposed by Son and Cording (2005)**

### 5 CONCLUSIONS

This paper presents a decoupled analytical procedure and demonstrates its applicability in analyzing the 3D excavation-structure system. Nonlinear excavation behavior and inelastic structure responses can be simulated separately with well accepted computer programs in geotechnical and structure engineering. A robust iteration procedure is developed to bridge the results from the decoupled analyses. This decoupled procedure is proven to be relatively simple, efficient, and exhibits high potential for practical application.

The analytical results of the responses of the adjacent ground and building induced by excavation using 3D decoupled simulation shows that the building settlement is larger than the greenfield ground settlement at the same position. The horizontal movement of the building is more uniform than that of the greenfield ground. The relative footing movements due to the nearby excavation may cause tensile strains in the tie beam connecting the footings. In addition, plastic hinges may occur in the building. The calculated lateral strain and angular distortion are also consistent with locations of the tensile force and the plastic hinge formation in the building. These observations provide valuable insights on how and where the damage may occur.

### ACKNOWLEDGEMENTS

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