Excavation-induced ground settlements and responses of adjacent building at various positions using 3D decoupled analysis method

H. D. Lin, H. C. Liao, K. J. Lin, Y. M. Hsieh, C. C. Chen

Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taiwan, hdlin@mail.ntust.edu.tw

ABSTRACT: Deep excavation in metropolitan regions surrounded by adjacent buildings is an important geotechnical problem in Taiwan. Past studies of this issue are relatively limited because of the complexity and the three dimensional nature of the excavation-structure system. This paper studies the 3D deformation characteristic of an excavation and the responses of adjacent buildings at different orientations and locations, such as the sagging, the transition and the hogging zones of the ground settlement profile. The type of adjacent building studied is a typical low-rise school building supported by spread footings. A robust Decoupled Analysis Method (DAM) developed by the authors that can consider nonlinear soil behavior and inelastic structure responses is adopted in this study. The excavation-induced ground settlements and the deformations in the adjacent buildings are studied for eight scenarios whereby the adjacent buildings are located in 4 positions and 2 orientations. The results show that ground settlement and building response can differ significantly from the greenfield condition, depending on the location and the orientation of the building. Findings and their engineering implications are discussed in this paper.

RÉSUMÉ: Le creusage profond dans les zones métropolitaines entourées de bâtiments adjacents est un problème géotechnique important à Taïwan. En outre, les études antérieures pertinentes à ce sujet sont relativement limitées en raison de la complexité et de la nature 3D du système d'excavation-structure. Cet article étudie les caractéristiques de déformation 3D de l'excavation et les réponses du bâtiment adjacent de différentes orientation et emplacement. Le bâtiment voisin étudié est un bâtiment typique de faible hauteur soutenu par la fondation de pied. Une méthode robuste d'analyse découplée (DAM) développée par les auteurs qui peut prendre en compte le comportement non linéaire du sol et les réponses de la structure inélastique est adoptée dans cette étude. Les réponses induites par l'excavation sont étudiées pour huit scénarios où les bâtiments adjacents sont situés en 4 positions et 2 orientations. Les résultats analytiques montrent que l'affaissement du sol et la réponse du bâtiment peuvent différer considérablement de l'état de champ libre en fonction de l'emplacement et de l'orientation du bâtiment. Les conclusions et leurs implications techniques seront discutées dans cet article.

KEYWORDS: excavation, decoupled analysis method, ground settlement, building deformation.

1 INTRODUCTION

Deep excavation in relatively soft alluvial soil deposits in close vicinity to surrounding buildings is an important geotechnical engineering problem in Taiwan (Dang et al. 2011). In general, deep excavation is a three-dimensional problem (Finno et al. 2007). This study focuses on the 3D excavation behavior and the excavation-induced responses of a low-rise framed building that is supported by spread footings.

The Decoupled Analysis Method (DAM) is adopted in this study. This method divides a very complicated three-dimensional excavation-structure problem into two simpler problems. One of which is an excavation problem with building loadings at the foundation locations, and the other is a structural response problem with prescribed displacements induced by excavation at the foundations. The general concept is illustrated in Figure 1. In this study, the nonlinear soil behavior induced by the excavation is simulated using PLAXIS 3D and the inelastic structural behavior of a nearby building is simulated using SAP2000. These two computer programs are widely used in the engineering sector. The DAM takes the advantage of the modeling capability of PLAXIS 3D in geotechnical engineering and SAP2000 for structural response. To correlate the results of the excavation and the building analyses, a comprehensive iterative procedure is required. The building is analyzed prior to excavation using SAP2000. Only the self-weight and the live load are considered. The reaction loadings at footings obtained are the inputs for the PLAXIS 3D excavation analysis. The outputs are the vertical and the horizontal displacements at the footing positions. The building model is again analyzed using prescribed displacements that are generated from the excavation model. The footing reactions are again obtained and used as the inputs for the subsequent round of excavation analysis. This iterative procedure has been proven to be robust and efficient. In general, a convergence tolerance of ±5% can be reached within a few iterations (Lin et al. 2015, Lin et al. 2016).

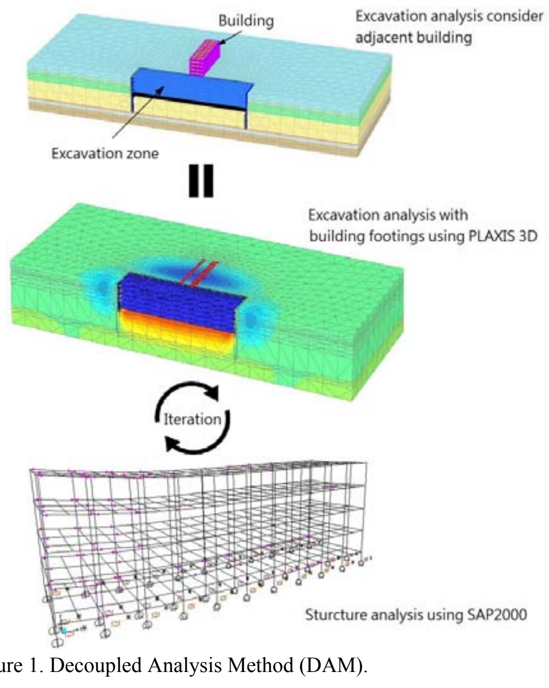
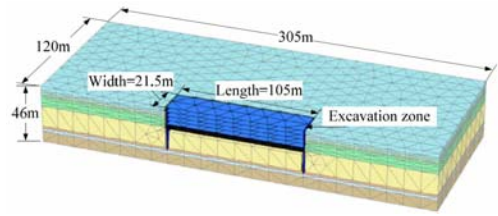


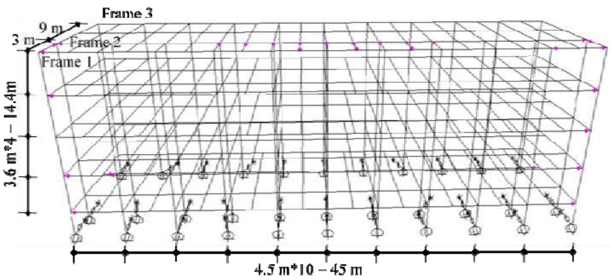
Figure 1. Decoupled Analysis Method (DAM).

2 ANALYTICAL MODELING

This study uses a well-documented TNEC excavation case history (Ou et al. 1998, Ou et al. 2000) as the greenfield excavation model. The excavation area is 21.5m by 105m and the numerical model is 305m by 120m, as shown in Figure 2(a). A low-rise framed building that is supported by spread footings is then added to the vicinity of the excavation, as shown as in Figure 2(b). This study uses eight scenarios, whereby the adjacent buildings are located in 4 positions and 2 orientations, as shown in Figure 3. When the long axis of the building is in the direction normal to the excavation's length (along the settlement trough) is defined as orientation A. For buildings of orientation B, the long axis is perpendicular to orientation A. Four building positions are studied for each direction. The building is located in three zones along the settlement trough at the center of the excavation and in one zone at the corner of the excavation. These three zones are the sagging zone (1m away from the excavation), the transition zone (18m away from the excavation), and the hogging zone (35m away from the excavation).

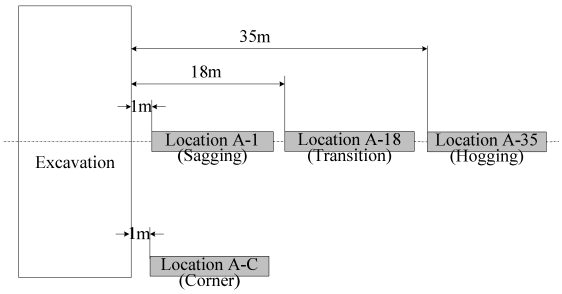


(a) 3D greenfield excavation model.

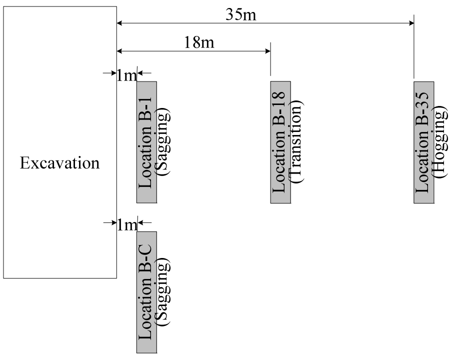


(b) 3D building modeling.

Figure 2. Analytical models.



(a) Building orientation A.



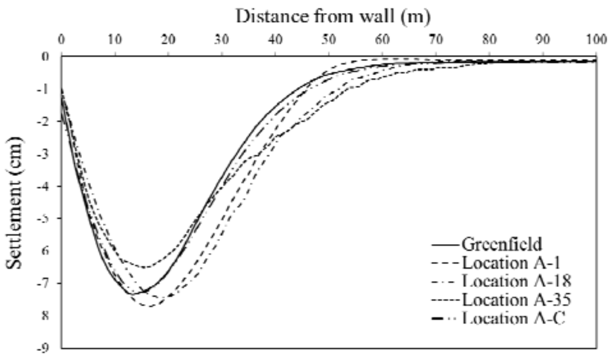
(b) Building orientation B.

Figure 3. Excavation and different building orientations and positions.

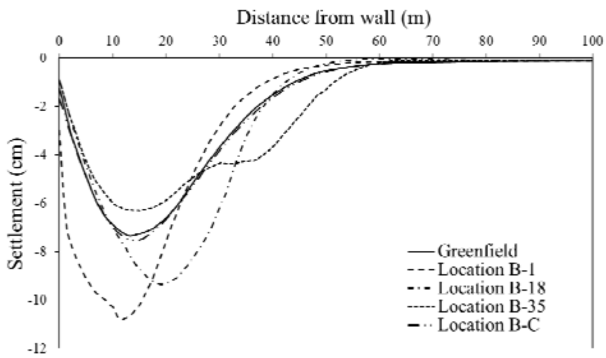
3 EXCAVATION BEHAVIOR AND THE ADJACENT BUILDING'S RESPONSE

3 .1 *Excavation behavior*

Figure 4 shows the excavation-induced ground settlement curves for different building positions and orientations and for the greenfield scenario. The maximum ground settlement is observed when the building is at location B-1. Because the building is 1m away from the excavation and parallel to the excavation length, its loads are concentrated within the trough of the settlement curve and magnify the maximum settlement. At a certain distance away from the excavation, the building has much less influence on the maximum ground settlement as well as the maximum diaphragm wall displacement. This distance has been shown to be very close to the Primary Influence Zone (PIZ) for buildings of orientation A (Lin et al. 2016). The results for orientation B are similar. However, building loads can still significantly increase soil displacements underneath the building. This phenomenon is clearly notable for location A-35 and location B-35, where the maximum ground settlement for buildings in the center section is about 3.6-4.7 times that for the building in the corner section.



(a) Building orientation A.



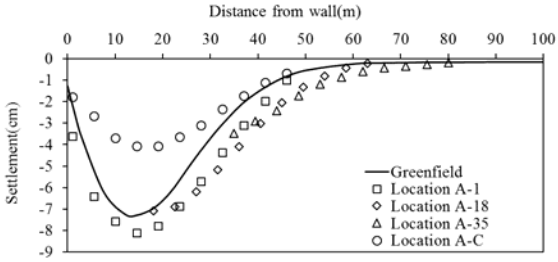
(b) Building orientation B.

Figure 4. Ground settlement for the greenfield scenario and for buildings at different locations.

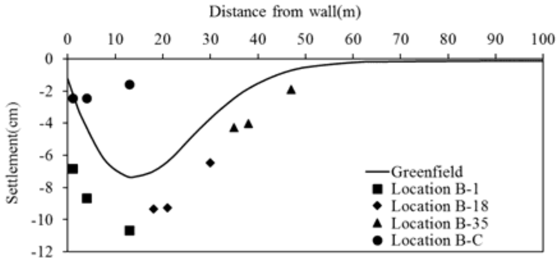
3 .2 *The adjacent building's responses*

Figure 5 shows the excavation-induced building foundation settlement pattern for different building positions and orientations, compared to the ground settlement curve for the greenfield scenario. All buildings show greater or lesser values than the greenfield settlement curve, depending on their location, but all follow the general pattern for settlement. They also generally settle more than greenfield ground, especially around the trough of the ground settlement. The building foundation settlements are 1.25-1.6 times that of the greenfield ground settlement. The maximum building foundation settlement is observed when the building is at location B-1, for the same reason as the ground settlement. Therefore, the differential settlement and the angular distortion between foundations is greater than that for the greenfield case. In other words, the potential damage to a building could be underestimated if the greenfield settlement curve were used.

Figure 6 shows the excavation-induced horizontal foundation displacement pattern for buildings at different positions and orientations, compared to the horizontal foundation displacement curve for the greenfield scenario. The results show that the horizontal foundation displacements are smaller than the foundation settlements and that the horizontal foundation displacements are more evenly distributed. The differential horizontal displacements for the building foundations are smaller than the differential foundation settlement. The differential horizontal displacements between Frame 1 and Frame 2 are smaller than those between Frame 2 and Frame 3 because the distance between Frame 1 and Frame 2 is smaller and the constraints for the tie beam between Frame 1 and Frame 2 are larger.

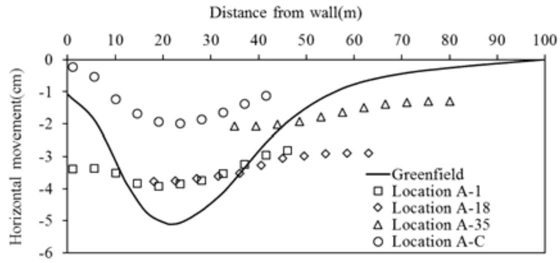


(a) Building orientation A.

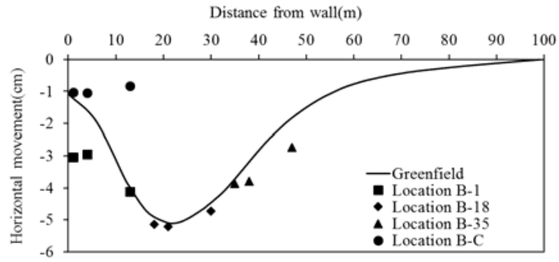


(b) Building orientation B.

Figure 5. Settlements of building foundations



(a) Building orientation A.



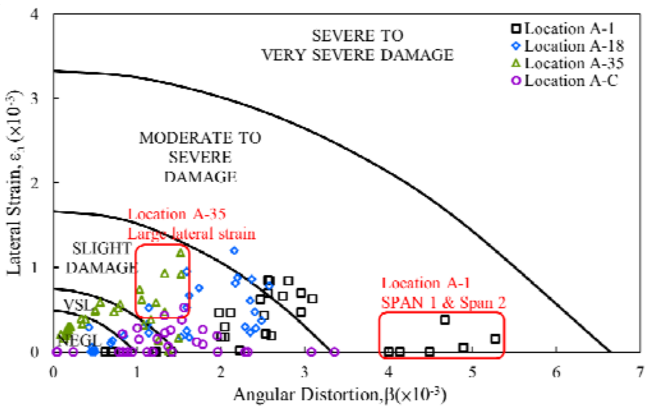
(b) Building orientation B.

Figure 6. Horizontal displacements for greenfield and building foundations.

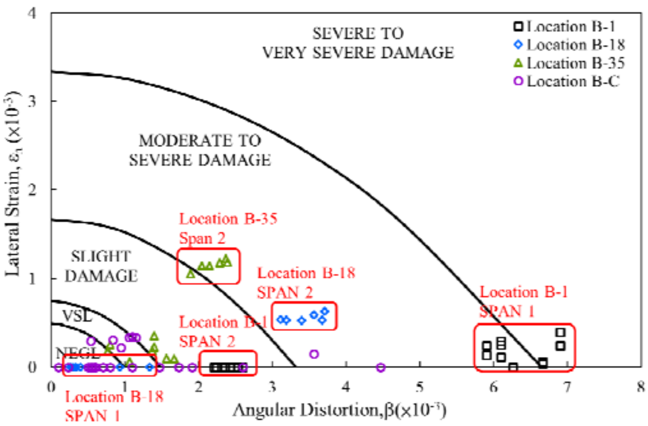
The results show that the maximum foundation settlement for a building in the center section is about 2.0-4.6 times that of the building in the corner section. The maximum horizontal foundation displacements for buildings in the center section is about 1.1-5.0 times that of the building in the corner section.

3.3 Building damage evaluation

Angular distortion is often used to evaluate the building damage potential (Bjerrum 1963, Yen and Chang 1991). Some recent studies have shown that additional damage evaluation parameters, such as lateral strain and horizontal strain, can be used to give a better assessment of the structural performance (Son and Cording 2005, Schuster et al. 2009 and Juang et al. 2011). In this study, the chart proposed by Son and Cording (2005) is used to evaluate building damage due to angular distortion and lateral strain, as shown in Figure 7. The lateral strain is calculated at the foundation level by dividing the differential horizontal displacement for two adjacent foundations by the distance that separates them. A comparison of the potential damage of all studied buildings shows that the building that is closest to the excavation (location A-1 and location B-1, in the sagging zone) has the greatest chance of incurring damage (moderate to very severe damage). In these two cases, the potential damage is mainly due to angular distortion. The maximum angular distortion for a building at location B-1 is 1.3 times that for a building at location A-1.



(a) Building orientation A.

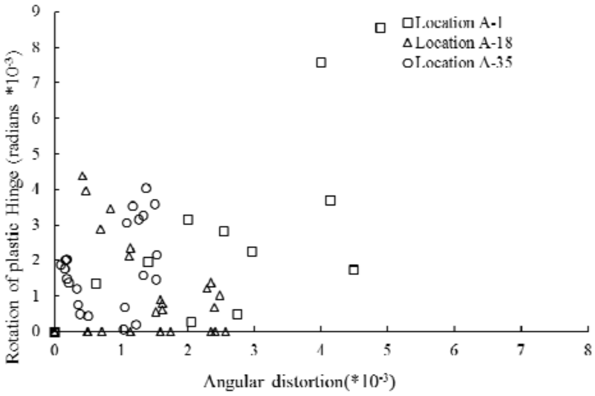


(b) Building orientation B.

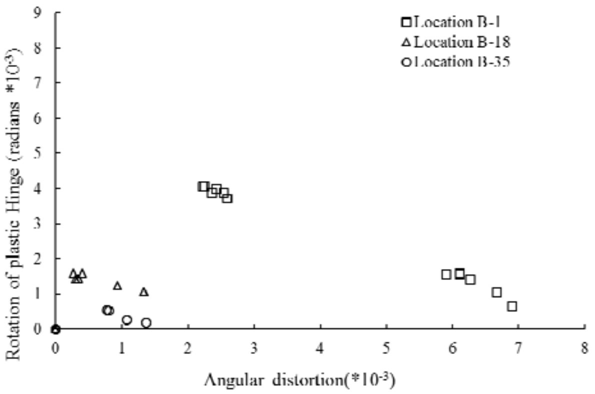
Figure 7. Damage evaluation for buildings in different zones.

A building that is far from the excavation (location A-35 and location B-35, in the hogging zone) is less likely to experience damage (slight to moderate damage zone). In these two cases, the potential damage is due to the combination of the lateral strain and the angular distortion. The maximum angular distortion for a building at location B-35 is 1.35 times that for a building at location A-35 and the maximum lateral strain is 1.2 times greater. The results show that when building damage occurs due to lateral strain, the tie beams experience tension and cracks. As a result, the structure is less able to withstand the bending moment and more plastic hinges occur.

Figure 8 shows the plastic hinge rotation and the angular distortion of the tie beam between building foundations. The results show that the building that is the closest to the excavation (location A-1 and location B-1, in the sagging zone) exhibits significant plastic hinge rotation and angular distortion. In addition, the potential damage for a building at orientation A is more severe than that for a building at orientation B.



(a) Building orientation A.



(b) Building orientation B.

Figure 8. Rotation of plastic hinge and angular distortion of foundation tie beam

4 CONCLUSIONS

This study uses a Decoupled Analytical Method (DAM) for the evaluation of the excavation-structural interaction problem. This DAM technique is demonstrated to give a comprehensive account of the nonlinear excavation behavior and the inelastic responses of the adjacent building. The following conclusions are drawn.

(1) The ground settlement is greater when the excavation involves a nearby building. The impact on the settlement depends on the position and the orientation of the building with respect to the excavation. The closer the building, the greater is the ground settlement. At a certain distance away from the excavation, the building has a smaller influence on the ground settlement. This distance is very close to the Primary Influence Zone (PIZ).

(2) The presence of a building near an excavation alters the ground and the foundation settlement patterns. When the building is located in the sagging zone, 1 m away from the wall, the maximum foundation settlement is about 1.25-1.6 times that of the greenfield value. The horizontal foundation displacements are more evenly distributed. Therefore, the interaction between the excavation and the building warrants proper consideration.

(3) The DAM provides valuable insights of the responses of a building adjacent to an excavation, such as the angular distortion, the lateral strain, the plastic hinge location and the tie beam forces. These insights allow a more accurate assessment of potential building damage.

(4) A building located in the sagging zone and the closest to the diaphragm wall is the most susceptible to the excavation-induced damage. Much significant angular distortion is observed.

(5) Excavation can cause significant tensile strains in the tie beam that connects the foundations, which causes cracks in the concrete and increases the potential for building damage. This effect is more pronounced for buildings that are located in the transition and hogging zones.

5 ACKNOWLEDGEMENTS

The authors would like to thank Ministry of Science and Technology of Taiwan for providing financial support for this study under grant number MOST 103-2221-E-011-072-MY2.

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