

RESPONSES OF 3D EXCAVATION AND ADJACENT BUILDINGS IN SAGGING AND HOGGING ZONES USING DECOUPLED ANALYSIS METHOD

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ABSTRACT

Deep excavation in metropolitan regions must take account of the safety of the construction site and the serviceability of the nearby buildings. This evaluation is rarely comprehensive because of the complication of the structure-excavation system especially if the three-dimensional (3D) nature is considered. This paper studies 3D deformation characteristics for excavation and the responses of adjacent buildings located in different settlement zones. The adjacent building that is studied is a typical low-rise school building supported by spread footings. A robust decoupled analysis method (DAM) that considers nonlinear soil behavior and inelastic structural responses is developed. Different scenarios for the wall deflections, building settlements, plastic hinges of the structure and member forces of the tie beam are studied for an adjacent building that is positioned in sagging, transition and hogging zones. The analytical results show that building settlement can differ significantly from greenfield settlement, depending on the location of the building. A building in a sagging zone is more prone to damage because it experiences larger angular distortion and plastic hinge formation than buildings at other locations. However, a building in a transition or a hogging zone exhibits tension in the tie beam because of the differential horizontal movement of the footings. The engineering implications of the results of this study are discussed in this paper.

Key words: Excavation, ground settlement, soil-structure interaction, 3D simulation, building damage, decoupled analysis method.

1. INTRODUCTION

Deep excavation in relatively soft alluvial soil deposits in close vicinity to surrounding buildings is a common geotechnical engineering problem in Taiwan. Significant progress has been made both in the engineering and the academic sectors. However, this kind of construction activity remains challenging and has high risks. If the excavation is not well analyzed in advance, there can be severe consequences in surrounding areas or structures. In particular, a spread-footing structure is more vulnerable to differential settlement than structures with other foundation types. Therefore, this study focuses on 3D excavation behavior

and an assessment of excavation-induced responses of a low-rise framed building that is supported by spread footings.

The prediction and assessment of an adjacent building's responses, induced by nearby deep excavation, is an important engineering issue. It is current engineering practice that an evaluation is conducted based on greenfield ground settlement results, without considering any excavation-structure interaction. Apparently, there is much room for improvement. Some studies have tried to improve predictions by simplifying the adjacent building to a beam and using 2D finite element analysis. Significant effects are observed on the ground settlement profile due to adjacent building (Potts and Addenbrooke 1997; Dang *et al.* 2011; Dang *et al.* 2012; Lin *et al.* 2014; Lin *et al.* 2015). However, this type of analysis cannot provide information about an adjacent building's responses. Recent development of 3D finite element computer programs such as PLAIX3D has provided better tools to analyze the excavation-building interaction problem. However, the inelastic behavior of an adjacent building cannot be modeled because of the limitations of the software (Truong 2013). More versatile computer programs, such as ABAQUS, simulate nonlinear soil behavior and inelastic structural responses due to deep excavation. However, the analysis is often too complicated for practical application. Therefore, there is a need to develop a more suitable alternative. In this paper a new analytical technique, called the Decoupled Analysis Method (DAM), is proposed for the evaluation of the interactions between a braced-excavation and an adjacent building.

The Decoupled Analysis Method is firstly developed. A robust and comprehensive decoupled analytical procedure is estab-

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lished. A well-documented excavation case is then analyzed as the baseline case in this study. A nearby building is then added to the excavation model and this scenario is analyzed using the proposed DAM. The results for the excavation and the building are then verified. Finally, to demonstrate the potential applicability of the DAM, the responses of a 3D excavation and an adjacent building in zones with sagging and hogging ground settlement profiles are studied using this DAM.

2. THE DECOUPLED ANALYSIS METHOD

The Decoupled Analysis Method (DAM) simulates an excavation with an adjacent building and considers nonlinear soil behavior, building loads and inelastic structural behavior. A very complicated three-dimensional excavation-structure problem is divided into two simpler problems: (1) an excavation problem with loadings at the foundation locations and (2) a structural response problem with prescribed displacements at the foundation. The general concept is illustrated in Fig. 1. In this study, PLAXIS 3D is used to simulate the excavation and the nearby building is simulated using SAP2000. These two computer programs are widely used in the engineering sector. The DAM takes advantage of the modeling capability of PLAXIS 3D in geotechnical engineering and of SAP2000 in structural response. To correlate the results of the excavation and the building analyses, a robust and comprehensive iterative procedure must be developed. The excavation model, the building model and the iterative procedure are described in detail in the subsequent sections.

2.1 Modeling of Excavation

The Taipei National Enterprise Center (TNEC) is a well-documented excavation case history (Ou *et al.* 1998) and is used as the baseline case in this study. Firstly, the excavation is simulated in 3D greenfield condition, to confirm the input parameters by comparing the results with field measurements. An adjacent building is then added to the numerical model and analyzed using the proposed decoupled analysis method. In particular, the building studied is a reinforced concrete type on spread footings. The rationale and details are discussed in the next section.

The TNEC case is a deep excavation for an 18-story building with five basement levels to a depth of 19.7 m. The excavation is supported by a diaphragm wall that is 0.9 m thick and 35 m deep. The top-down method was used for construction, with slabs that are 0.15 m thick. Two levels of struts (at 2 m and at 16.5 m below ground level) were installed and respectively preloaded to 784.8 kN and 1177 kN, in order to provide additional support for the wall. The horizontal spacing of the struts is 8 m (for the upper strut) and 3 m (for the lower strut). Seven excavation stages were required to reach the final excavation depth. The excavation profile and the soil profile are shown in Fig. 2.

The sand layers are modeled using the Mohr-Coulomb (MC) model, with effective stress drained analysis. The input parameters for these layers are shown in Table 1. The Hardening Soil (HS) model with effective stress undrained analysis is used for the clay layers. All parameters for the HS model are shown in Table 2.

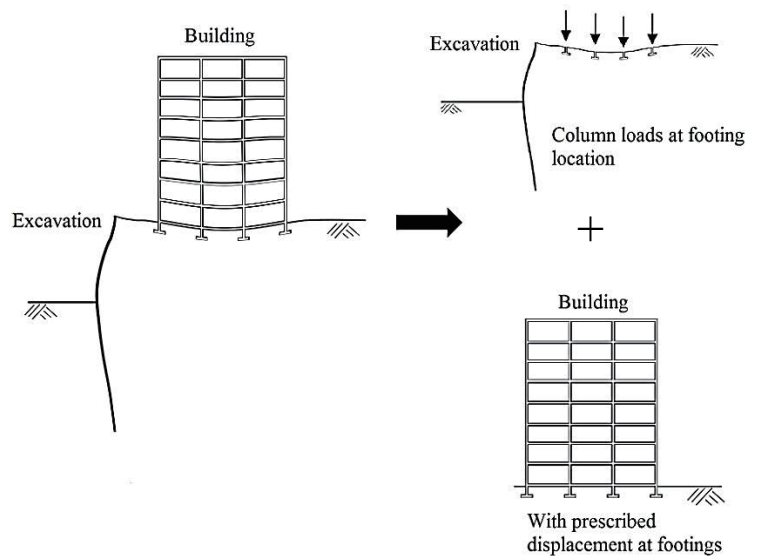


Fig. 1 General concept of Decoupled Analysis Method

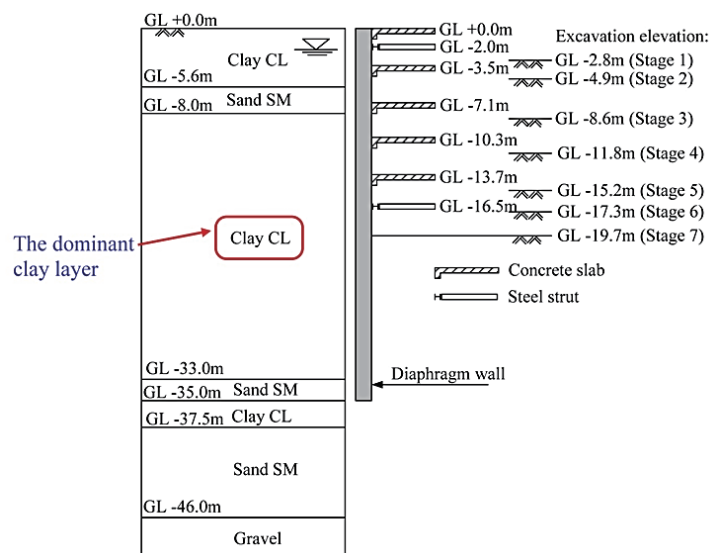


Fig. 2 Excavation and soil profiles

Table 1 Input parameters for sand layers

Depth (m)	Description	γ (kN/m ³)	Relative Density	ϕ'_p (°)	ϕ'_i (°)	c' (kN/m ²)	E' (kN/m ²)	ν'
5.6 ~ 8	SM1	18.93	Loose	30	28	0.001	76111	0.3
33 ~ 35	SM2	19.62	Medium	33	31	0.001	260430	0.3
37.5 ~ 46	SM3	19.62	Dense	35	33	0.001	271799	0.3

Note: for all sand layers, $R_{inter} = 1.0$, Dilatancy angle, $\psi = 0^\circ$

Table 2 Input parameters for clay layers

Depth (m)	Description	γ (kN/m ³)	ϕ'_p (°)	ϕ'_i (°)	c' (kN/m ²)	E'_{ur}^{ef} (kN/m ²)	E'_{50}^{ef} (kN/m ²)	E'_{oed}^{ef} (kN/m ²)
0 ~ 5.6	CL1	18.25	30	29	0.001	19996	6665	4666
8 ~ 16.5	CL2-1	18.15	29	28	0.001	22678	7559	5292
16.5 ~ 33	CL2-2	18.15	29	28	0.001	21025	7008	4906
35 ~ 37.5	CL3	19.13	30	29	0.001	18017	6006	4204

Note: for all clay layers, $R_{inter} = 1.0$, $m = 0.67$, $\nu'_{ur} = 0.2$

To apply the building loads, the footings of the building are modeled in the excavation model at the same location as they occur in the building. The modeling considers the horizontal footing reaction and the side wall resistance between the footing and the surrounding soil. However, tie beams are excluded, since their effects are accounted for in the structural analysis.

The PLAXIS 3D excavation model is shown in Fig. 3. To simplify the simulation, an excavation area of 21.5 m by 105 m is used. To ensure insignificant boundary effect, the boundary used is 5 times the excavation depth. Therefore, the length and width of the numerical model used in this analysis is 305 m by 120 m. The excavation is first modeled in PLAXIS 3D, with all soil layers and the required structural components. The footings of the nearby structure are also modeled at an appropriate location.

The purpose of the footings is to transfer the loadings from the structure onto the soil. The vertical load is a result of the vertical displacement that is induced by the excavation, the dead load and the live load of the structure. A study by Ou *et al.* (2000) showed that the soil behind the retaining wall of an excavation settles down and also moves horizontally. This study also showed that similarly to vertical ground settlement, the amount

of horizontal soil displacement varies with the distance from the wall. Therefore, the horizontal forces that are obtained from the building model in SAP2000, which are the result of the horizontal displacements that are induced by the excavation, are also used in the excavation model.

2.2 Modeling of Building

The building to be added to the excavation is a reinforced-concrete type with spread footings. The building is a typical Taiwanese school-like structure. As shown in Figs. 4 and 5, it has five stories that are 3.6 m height. It also consists of two bays and ten spans. The bays have different widths of 3 m and 9 m and the spans, which are perpendicular to the longest side of the excavation, are each 4.5 m long. Therefore, the total length of the building is 45 m in the longitudinal direction and the width is 12 m. The sizes of beams and columns are determined according to the reference values in the database, as shown in Table 3. The footings that are connected by a tie-beam system are embedded 1.5 m in the ground and are 0.5 m thick.

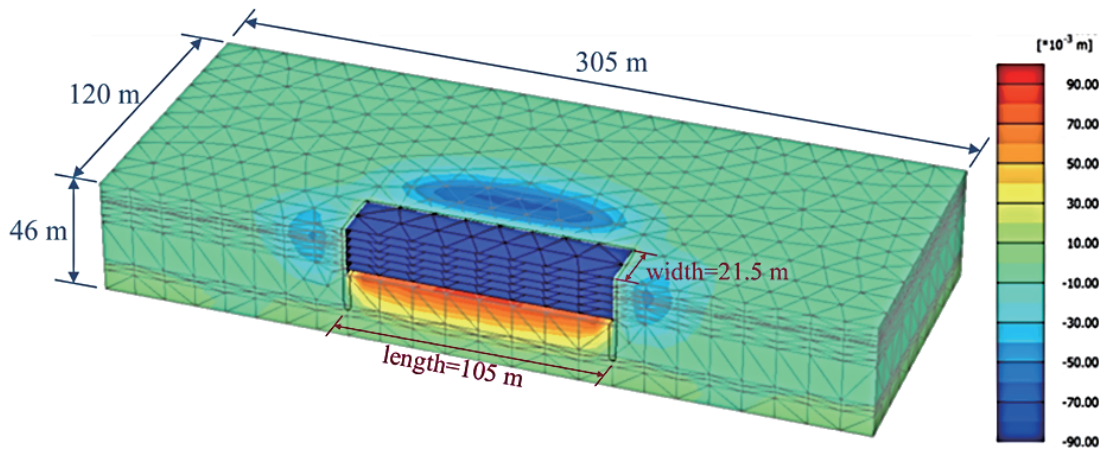


Fig. 3 Screenshots showing the excavation model and settlement contour at final excavation stage in PLAXIS 3D

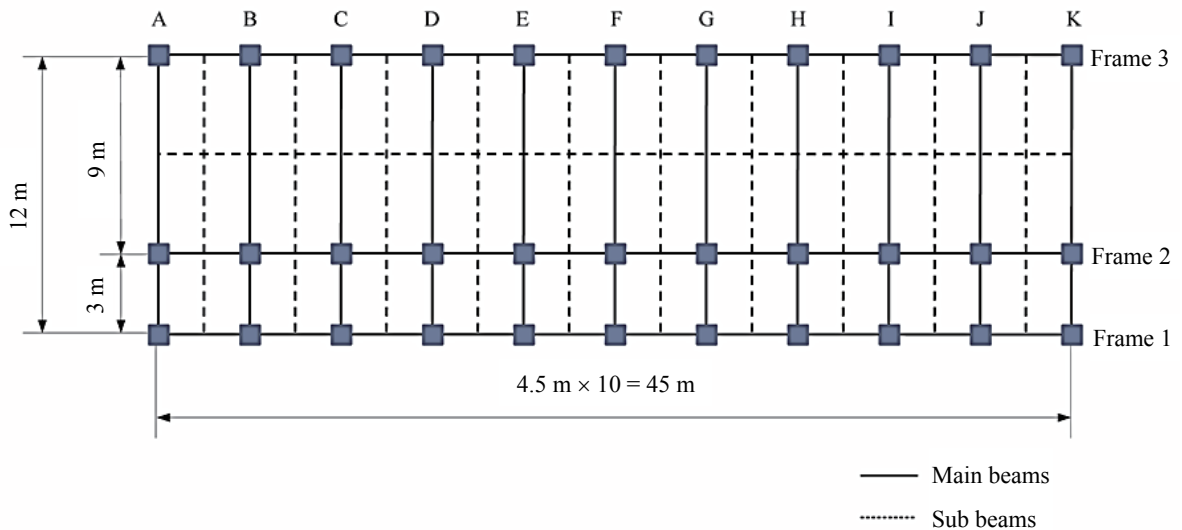


Fig. 4 Plan view of the building's floor

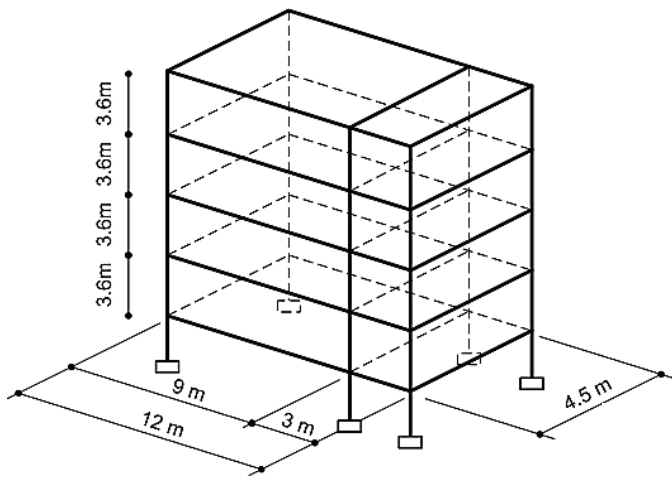


Fig. 5 Typical geometry of one single span of the building

Table 3 Structure member dimensions

Structure member	Name	Dimension (cm)
Main beam	B4060	40 × 60
Sub beam	B3050	30 × 50
Column	C4560	45 × 60
Slab	S	15

The building is simulated as a three-dimensional frame with beams and columns. The building analysis has two stages. Firstly, the building is analyzed considering all required loads, including the self-weight, the live load and the earthquake load, for the proper design of the steel reinforcement. This simulates the constructed state of the building. The second stage structural analysis involves analyzing the building’s responses to displacements at the footings that are induced by nearby excavation. Two types of loading are used in the excavation-induced building analysis: the dead load and the live load. The magnitude of the load is determined based on Taiwan’s building design code. The average dead load is 1.2 t/m² and the live load is 0.3 t/m². It is noted that only 50% of the live load is used because of the temporary nature of the live load.

A very important aspect of the simulation of the building is the modeling of the footing. In the building model, the real dimensions of the footing are not modeled. They are represented by a joint at the end of the column. These joints are designed to enable the reasonable application of vertical and horizontal displacements. Figure 6 shows the application of horizontal and vertical displacements, δ_h and δ_v , respectively, on a footing. The vertical displacements that are obtained from the excavation analysis are applied directly to the footings. However, the horizontal displacements are applied using an additional horizontal soil spring that connects the column joint and the surrounding soil mass. The nonlinear horizontal soil springs are simulated according to the force-displacement behavior of the footings and the surrounding soils analyzed using PLAXIS 3D.

The horizontal soil spring enables reasonable simulation of the soil-footing interaction (Sang 2014). When compression occurs in the soil spring, the soil on the spring-side of the footing is

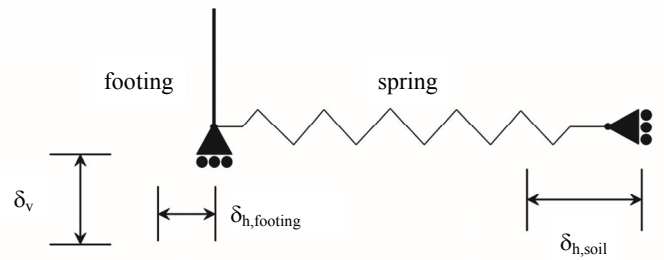


Fig. 6 Model for application of horizontal displacement on footing through a spring

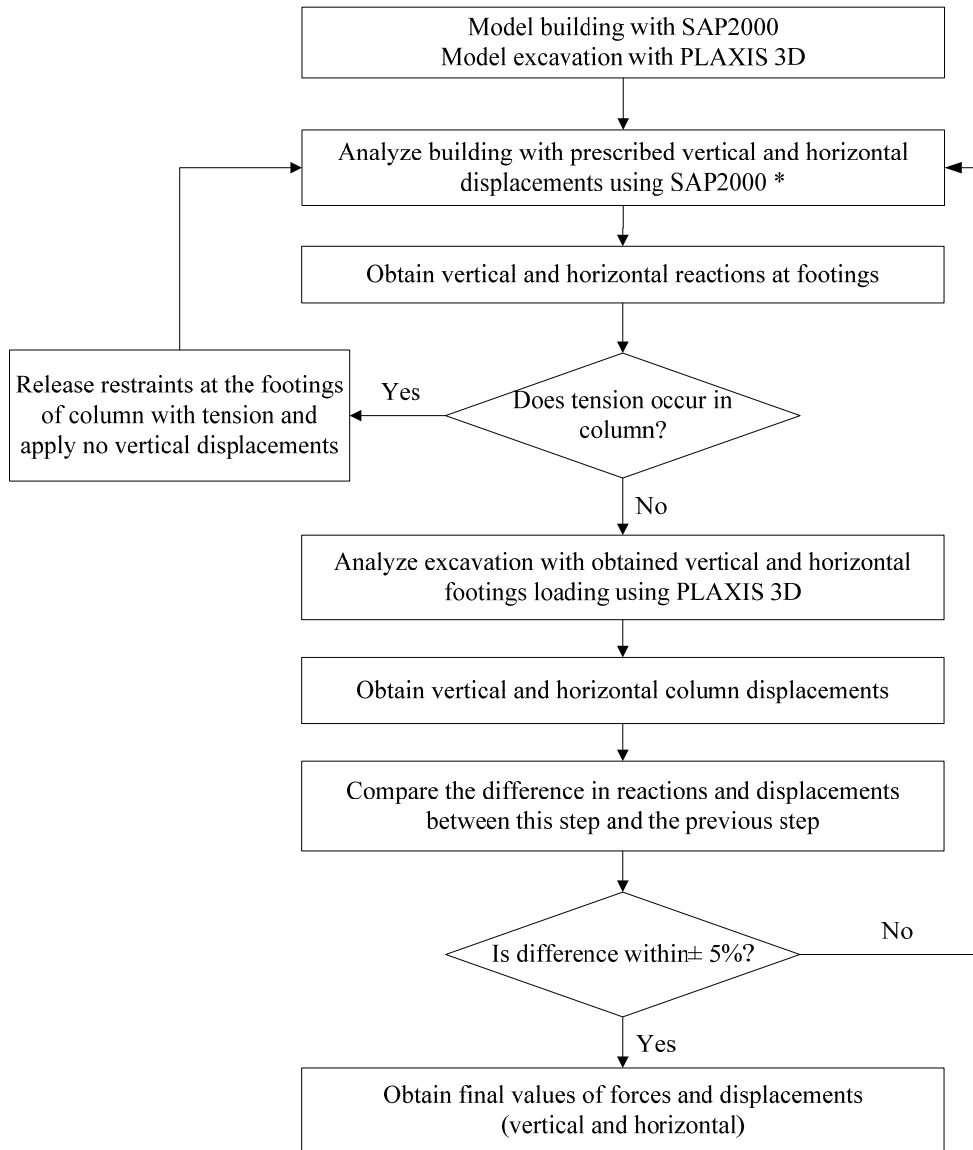
resisting movement and is therefore compressed. Tension means that the soil on the other side of the footing is resisting movement. This is because soil does not take tension, so tension on a soil spring at a footing implies that there is separation between the soil and the footing.

2.3 The Iterative Procedure

When the building and the excavation are modeled, a robust and efficient iterative procedure is developed to combine the results of the excavation and the building analyses. The iterative procedure is shown in Fig. 7. In the initial step, the building is analyzed prior to the excavation activity, using SAP2000. Therefore, only the self-weight and the live load are considered and no excavation-induced movements exist. The reactions at footings are obtained. If there is tension in the column, the restraint at the footing supporting that column is released. No prescribed vertical displacement is applied at that footing. The reaction loadings at footings that are obtained using this structural analysis are the input for the PLAXIS 3D excavation model. The outputs are the vertical and horizontal displacements at the footing positions. The building model is analyzed again, using the displacement values that are generated from the excavation model. This is when the building begins to ‘feel the presence’ of the excavation. The footing reactions are again obtained and used as the input for the subsequent round of excavation analysis. This procedure is iterated until the difference between the reaction forces and the displacements for two successive cycles are less than an allowable tolerance. In this study, a tolerance of ±5% is allowed.

In order to reduce the number of iterations that are required for convergence, the average values of the newly obtained forces and the preceding forces are used as the input for the next iteration in PLAXIS 3D. This technique has been proven to significantly enhance the computing efficiency. The horizontal forces attain convergence much faster, so this averaging technique is not used. It should be noted that the building is assumed to be in balance with the surrounding ground before the excavation. In the analysis, the building settlement prior to the excavation is reset to zero. However, the stress that is induced in the soil remains and can have a subsequent effect.

Based on the results in the following sections the DAM is deemed robust because the analytical procedure is logical, systematic and repeatable, as shown in the flowchart of Fig. 7. The DAM is also efficient for practical application because the convergence of the iterative procedure is fast and good. For all of the scenarios studied, the number of iterations that are required for convergence is less than 5 cycles, with a tolerance of ±5% in reaction forces and displacements from two successive cycles.



* At the first step, prescribed displacement = 0

Fig. 7 Iterative procedure of decoupled analysis

3. VALIDATION OF THE DECOUPLED ANALYSIS METHOD

3.1 Verification of Soil Input Parameters

A well-documented TNEC excavation case history was used to verify the reasonability of the soil input parameters. The numerical model and input parameters are summarized in Section 2.1. The ground settlement contour that is obtained from PLAXIS 3D analysis of the greenfield condition after the final excavation is shown in Fig. 3. The overall settlement pattern is reasonable. It shows that ground settlement along the excavation length is greater than ground settlement along the width. The maximum settlement along the excavation’s length occurs at the center. Same trend is observed along the excavation’s width. This is due to the corner effect, which was noted by Ou (2006) and Finno *et al.* (2007).

Figure 8 compares the ground settlements perpendicular to the excavation length at the center section for the 3D simulation with the field measurements. In general, the results are similar throughout the excavation stages. The predictions for the maximum wall deflection for the 3D simulation match very well with the measured value of 10.6 cm at the final excavation stage. However, the ground settlements are slightly underestimated. The measured maximum ground settlement is 7.8 cm, but 6.0 cm is estimated by the simulation. This difference can be attributed to the fact that the soil models that are used in the simulation do not consider the small strain effect. The overall ground settlement profiles are in reasonable agreement with the measured results, so the soil models used and their parameters are satisfactory for this study. The nearby building is also considered in the simulation, using the DAM technique.

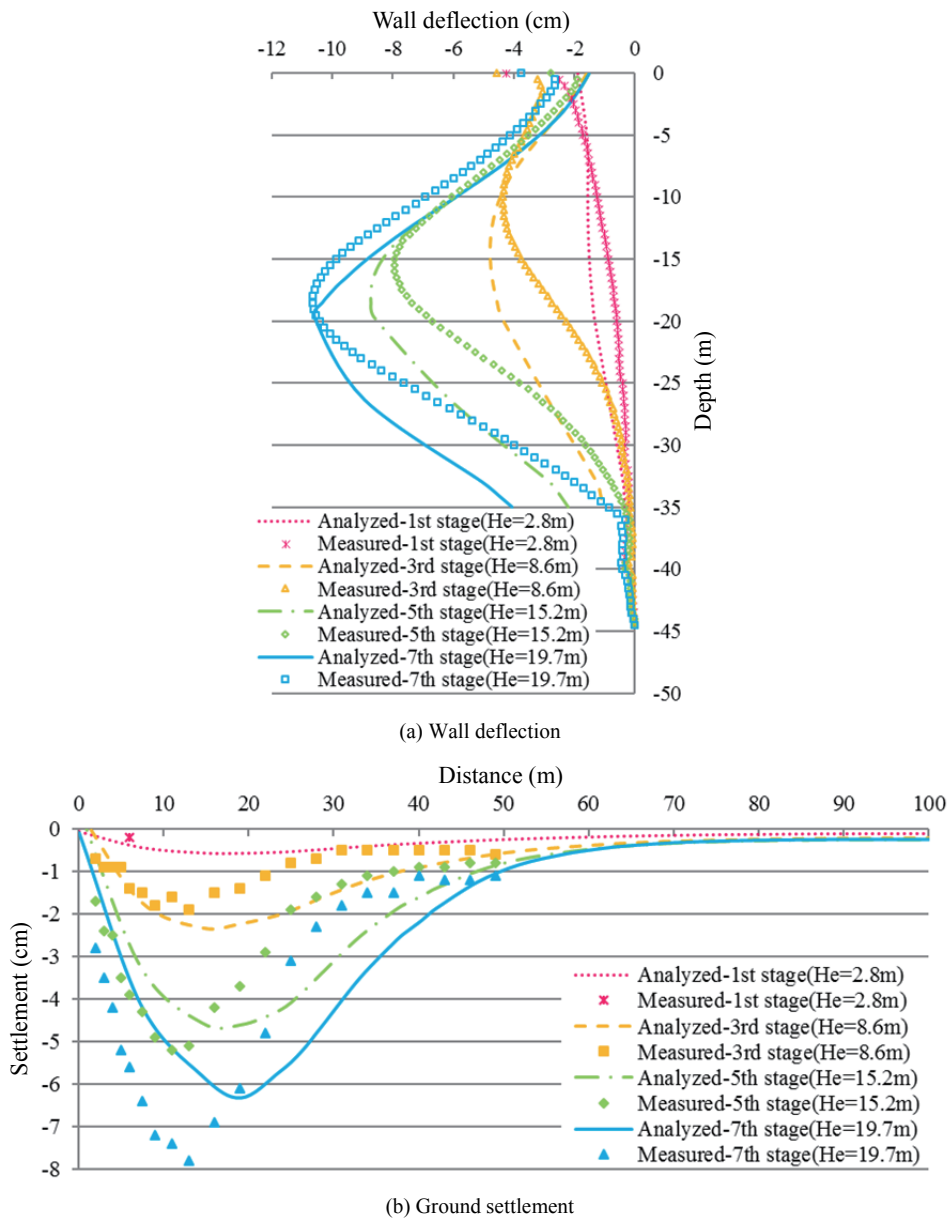


Fig. 8 Comparison of wall deflection and ground settlement between simulation and observation

3.2 The Iterations for Decoupled Analysis

To demonstrate the efficient convergence of the proposed iterative procedure, a building is added 1 m away from the diaphragm wall, near the center zone of the excavation, with its longitudinal axis perpendicular to the wall. To properly simulate the interaction between the footing and the surrounding soil one horizontal plate element and four vertical plate elements are used. The variation in the column loads through the iterations of the decoupled analysis is shown in Fig. 9. F0 is the column load obtained from the initial analysis of the building, with no consideration of displacements, and F4 is the load after the fourth iteration. It is seen that after four iterations, the values converge very well. The horizontal forces on the footings are included in the iterations in this study and their variation through the iterations is small. Convergence is reached after three iterations. These results are for the columns of frame 2, which are defined in Fig. 4. The results for other frames also show a fast convergence within a few cycles. More promisingly, the results for buildings at differ-

ent locations are the same. The fast convergence ensures good computing efficiency for the decoupled method and certainly demonstrates its feasibility for practical application.

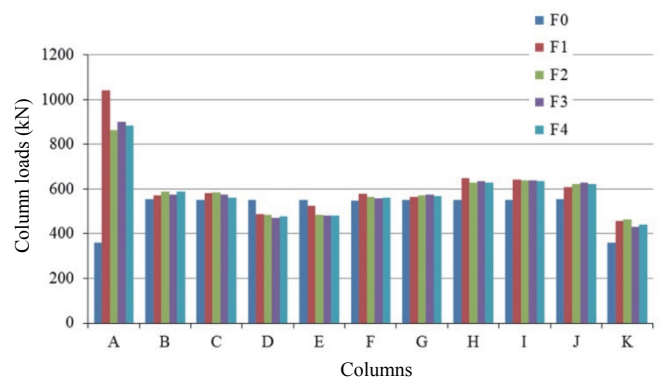


Fig. 9 Variation of vertical column loads at various iteration steps

In addition to the column loads at the footing, ground movements are also carefully studied throughout the iteration process. The results show that vertical ground movements converge quickly. The change is very slight between successive iterative runs, even for the first two iterations. However, it should be noted that a slight change in displacement results in a significant change in the structural member force, so the ground settlement is included in the iterative process. Horizontal ground movements also show a similar tendency.

3.3 The Deformation Behavior for the Excavation and the Building

Figure 10 compares the greenfield ground settlement with the building settlement upon completion of the final excavation. The footing settlement pattern is similar to the greenfield ground settlement. This is reasonable, since footings are relatively flexible foundations. However, the building settlement is about 1.3 times the greenfield settlement, mainly due to the building load. The wall deflection for the building, as shown in Fig. 11, is also slightly greater than the greenfield wall deflection. The wall deflection increases by 1.1 cm when the building is considered. These observations are consistent with the results of a previous study by Dang *et al.* (2012).

The horizontal displacement behavior is very different to that of the vertical displacement. Figure 12 also compares the horizontal ground movement in the greenfield condition with that of the building. It shows that the footings move more evenly in the horizontal direction than the ground in the greenfield condition. Tie beams between footings apparently provide lateral rigidity and hold the footing together. Since the horizontal ground movements are applied to the building through soil springs, as described in Section 2.2.1, the interaction behavior is of interest. A comparison of the horizontal ground movement and the actual horizontal footing movement is shown in Fig. 12. The difference that is shown in Fig. 12 shows the effect of the spring on the building's response and that even when the building is considered, the horizontal movement of the ground still varies more than the footings. The overall structural responses, including the balance between the applied loads and the reaction forces, the pattern of member axial forces, the distribution of shear forces, the distribution of bending moment, were also checked by one of the authors, who is an experienced structure engineer.

These comparisons demonstrate the applicability of the proposed decoupled analysis method. The numerical results would be even more convincing if they could be verified with good field measured results for an excavation with an adjacent building. Unfortunately, at present this information is not available. The authors have attempted verification by conducting a fully coupled analysis, using ABAQUS. The preliminary results are very promising but they are not included in this paper in the interests of brevity.

4. EXCAVATION BEHAVIOR AND THE RESPONSE OF AN ADJACENT BUILDING

Since the decoupled analytical technique has been demonstrated to give satisfactory results it is used to study the effect of a building's location on both the excavation and the building's response. In this study, the location of the building varies in the direction normal to the excavation's length (along the settlement trough), as shown in Fig. 13. It is located in three zones of the settlement trough. The three zones are the sagging zone (1 m

away from the excavation), the transition zone (18 m from the excavation) and the hogging zone (35 m from the excavation). Note that the building is 45 m long, so there is overlap between successive building locations. Therefore, the sketch in Fig. 13 is not drawn to scale. Except for the location of the building, the excavation model, the structure model and the input parameters are the same as those described in the previous sections.

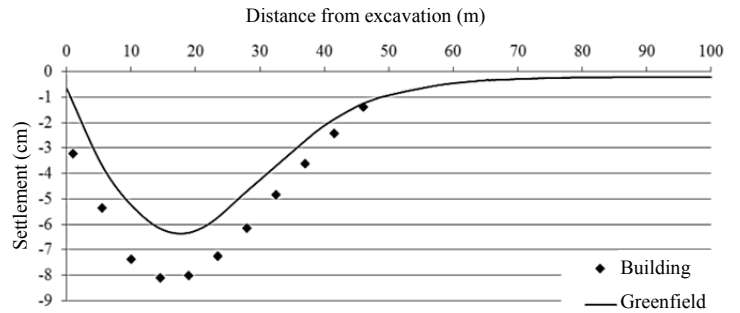


Fig. 10 Comparison of greenfield ground and building settlements

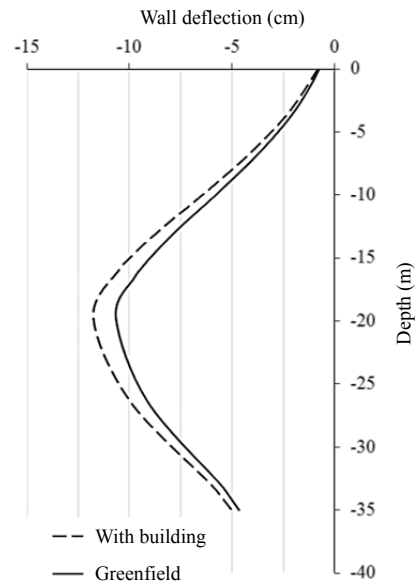


Fig. 11 Comparison of wall deflection in greenfield condition and with building consideration

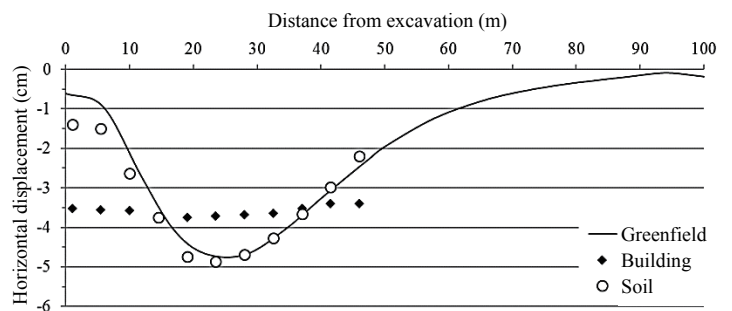


Fig. 12 Comparison of horizontal ground and footing movements

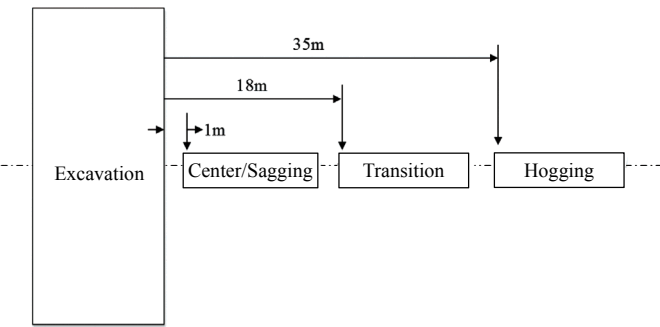


Fig. 13 Sketch showing the excavation and different building locations

4.1 Excavation Behavior

Wall Deflection

The wall deflection profiles after the final excavation stage for buildings located in the sagging, transition and hogging zones are shown in Fig. 14. The maximum wall deflection is greatest when the building is located 1 m from the wall, followed by 18 m, and then 35 m, which is very close to the greenfield condition. A similar trend was observed by Dang (2009). This phenomenon is reflected in the movement of the soil mass. A screen shot from the PLAXIS 3D for the sagging case that shows the direction and the magnitude of soil movement is shown in Fig. 15. The greatest movement, both horizontally and vertically, occurs within a distance that is less than the entire length of the building (i.e. from 1 m to 45 m away from the wall). Since the movement of the wall mostly depends on the amount of movement in that soil zone, a building that is located in this region increases the overburden pressure and the lateral pressure on the wall, which causes it to deflect more.

The maximum wall deflection for each case is normalized by the maximum wall deflection in the greenfield excavation and plotted against the distance from the wall in Fig. 16. The figure shows that the effect of the building on the wall decreases gradually until it reaches a certain value. Extending the line further to a ratio of 1.0, a location where there would probably be no influence is at about 40 m, which is very close to the location of the primary influence zone (PIZ) (Ou 2006). The PIZ is at about 39.4 m.

Ground Settlement

Figure 17 shows the effect of building proximity on the ground settlement pattern by comparing ground settlement curves for different building locations with the greenfield scenario. The maximum ground settlement is observed when the building is located in the sagging zone because its location is right at the trough of the settlement curve, so its weight impacts the maximum settlement more than in other cases. However, for the hogging case the maximum ground settlement is slightly less than the greenfield curve. This is reasonable because more settlement occurs below the building (about 30 m to 70 m away from the wall). Notice that the total volume of the settlement trough is still slightly larger than that for the greenfield case. The behavior for the transition case is between the behavior for these two scenarios.

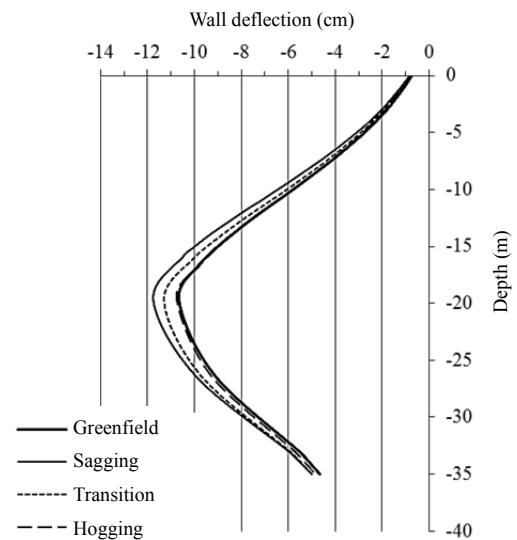
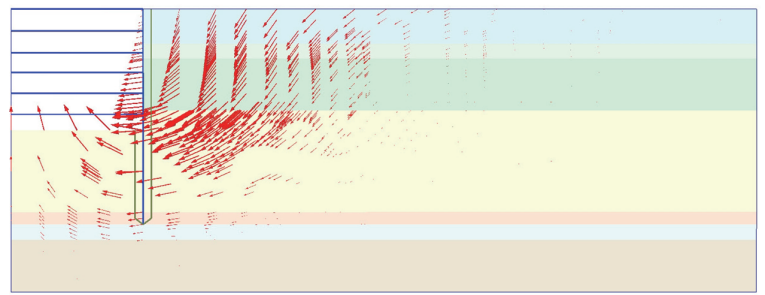


Fig. 14 Wall deflection with building location varied along settlement trough



Total displacements |u| (scaled up 50.0 times)
Maximum value = 0.1112 m

Fig. 15 A screen shot from PLAXIS 3D of the sagging case showing soil movement

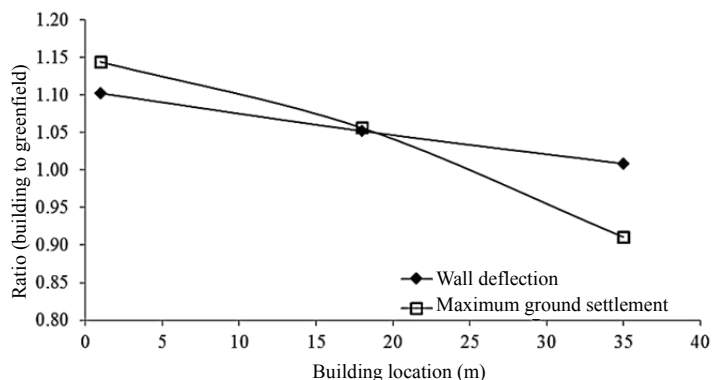


Fig. 16 The ratio of wall deflection and maximum ground settlement at various building locations

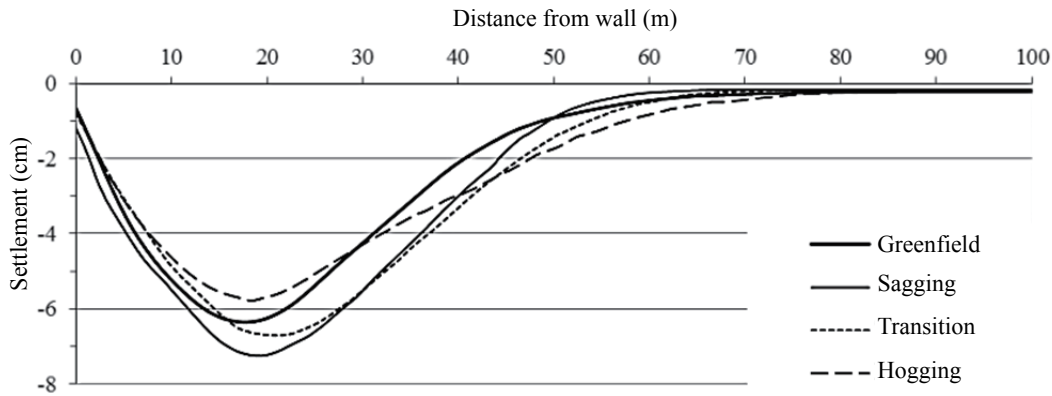


Fig. 17 Ground settlement with building at different locations

In Fig. 16, the ratio of maximum ground settlement with a building to that for the greenfield condition is plotted against the distance from the excavation. Clearly, the effect of the building on the maximum ground settlement decreases farther from the excavation, and settlements are slightly greater than those for the greenfield condition until a certain value is reached (about 25 m away). It should be noted that the location at which this change occurs can depend on many factors, such as the building's weight, the support system, or the soil conditions.

4.2 The Building's Response

Building Deformation

Figure 18 shows the greenfield ground settlement compared to the building settlement. All three buildings tend to follow the increasing and decreasing patterns of the greenfield settlement curve, depending on their location. They also generally settle more than greenfield ground, especially around the trough of the greenfield settlement. However, the magnitudes differ from the greenfield values. At the greatest settlement, the building in the sagging zone settles about 1.3 times more than the greenfield settlement. In the hogging and the transition cases, the effect is similar but less significant. Therefore, the differential settlement and so the angular distortion among footings can be greater than that for the greenfield case. In other words, the potential damage to a building may be underestimated if the greenfield settlement curve is used. This result has a very important engineering implication. Further discussion about the potential damage evaluation for an adjacent building is included in the next section.

Horizontal footing displacements and horizontal greenfield displacements for different building locations are shown in Fig. 19. The horizontal displacements of the footings differ significantly from the greenfield horizontal displacements. They are more evenly distributed. The difference is most significant if the building is located in the sagging zone. This behavior occurs mainly because of the greater horizontal rigidity that is provided when there are tie beams between footings.

Damage Evaluation

Bjerrum (1963) was the first to study structural damage by relating building performance with the corresponding angular distortion. Yen and Chang (1991) studied several excavation cases in Taipei and suggested some allowable settlements for different soil and foundation types. More recent studies have

shown that additional damage evaluation parameters, such as lateral strain and horizontal strain, may be used to give a better assessment of the structural performance (Son and Cording 2005; Schuster *et al.* 2009; Juang *et al.* 2011). Therefore, all of the structure responses that are induced by nearby excavation are of interest. The DAM provides a numerical tool for this purpose. Some interesting results are discussed as follows.

Figure 20 shows the deformed shape of the building frame with plastic hinges that are formed in the sagging and hogging zones. It shows that for a building in the sagging zone, plastic hinges are formed more on the spans nearest to the excavation and at the upper floors than in buildings at other locations. In other words, a building in the sagging zone is most vulnerable to excavation. This result is expected, since for the sagging case, the building is closest and the difference in ground settlement is also the greatest. The hogging case shows a more even distribution of plastic hinges, with less likelihood of occurrence.

For the building that is located in the sagging zone, the tie-beam is seen to exhibit some tension in the rear spans of the building. However, there is compression in the spans that are closer to the excavation. This is because the soil, and so the footings at the middle of the building move towards the excavation more than the rest, which exerts a pull on the footings behind and a push on those in front and produces tension and compression. The tie-beams in the buildings that are located in the transition zone experience tension throughout all of the spans and are in greater danger of cracking than the building in the sagging zone, as shown in Fig. 21.

The chart by Son and Cording (2005) is used to evaluate building damage due to angular distortion and lateral strain, as shown in Fig. 22. The lateral strain is calculated at the footing level by dividing the difference in the horizontal displacement of the two footings by the distance between them. A comparison of the potential damage to the three buildings shows that the building that is closest to the excavation (the sagging case) is exposed to the greatest potential damage (with up to moderate to severe damage zone). In this case the potential damage is mainly due to the angular distortion, as marked in Fig. 22. The lateral strain is of little significance. For the buildings that are located in the transition and the hogging zones, most of the results show less than the slight damage. However, it is interesting to note that some spans have a greater lateral strain and exhibit higher damage potential.

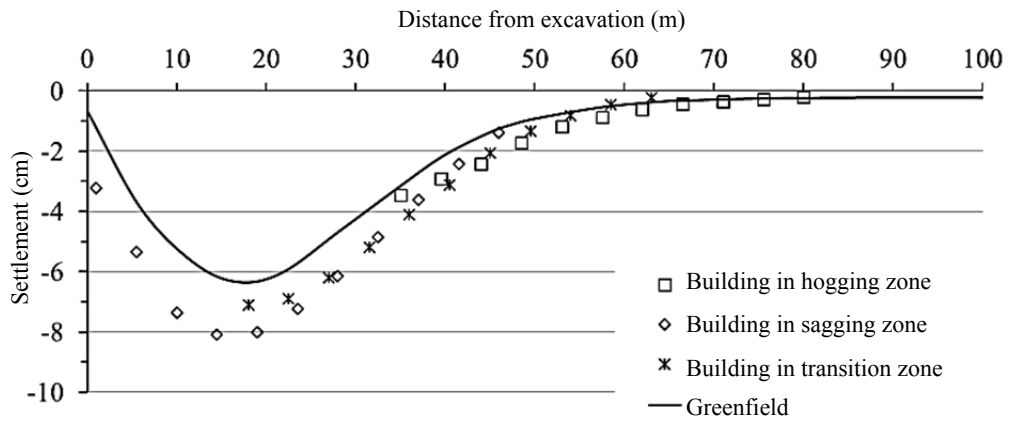


Fig. 18 Settlements for greenfield and building in different zones

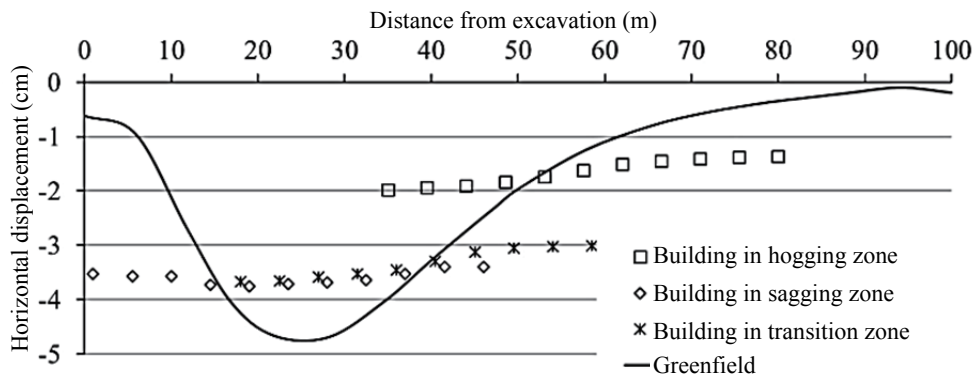


Fig. 19 Horizontal displacements for greenfield and building in different zones

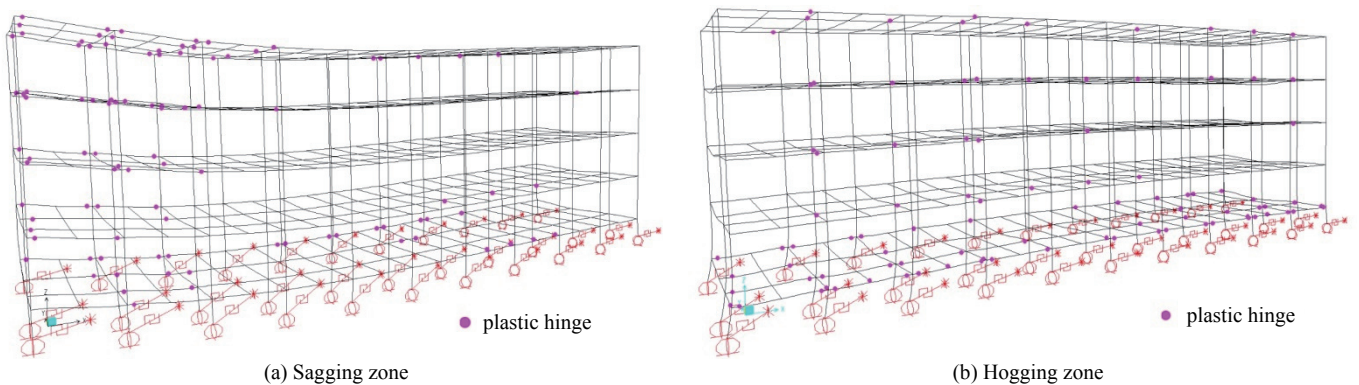


Fig. 20 The formation of plastic hinges for building in sagging and hogging zones

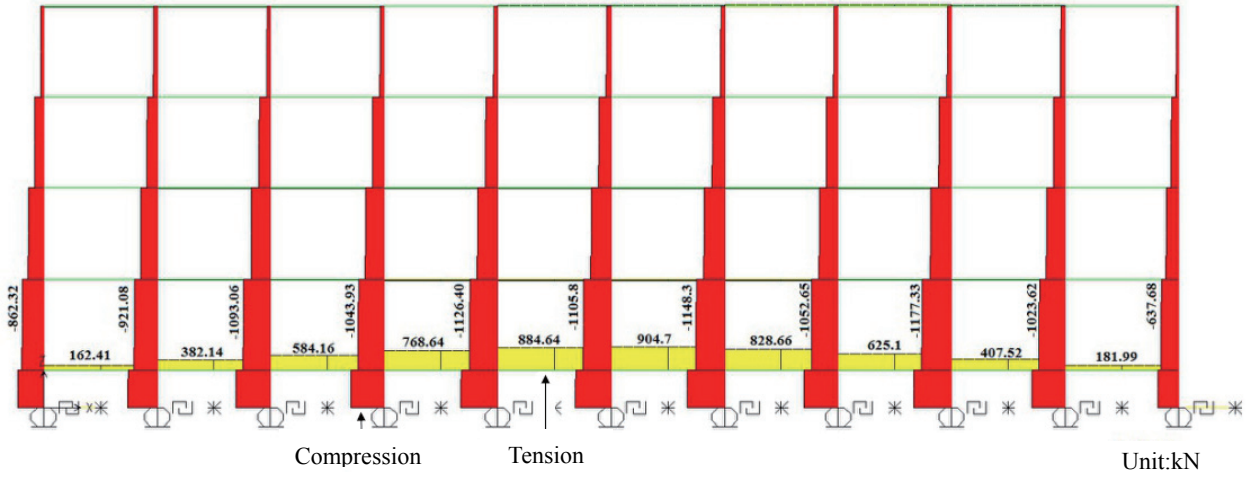


Fig. 21 Axial forces of building members with building in transition zone

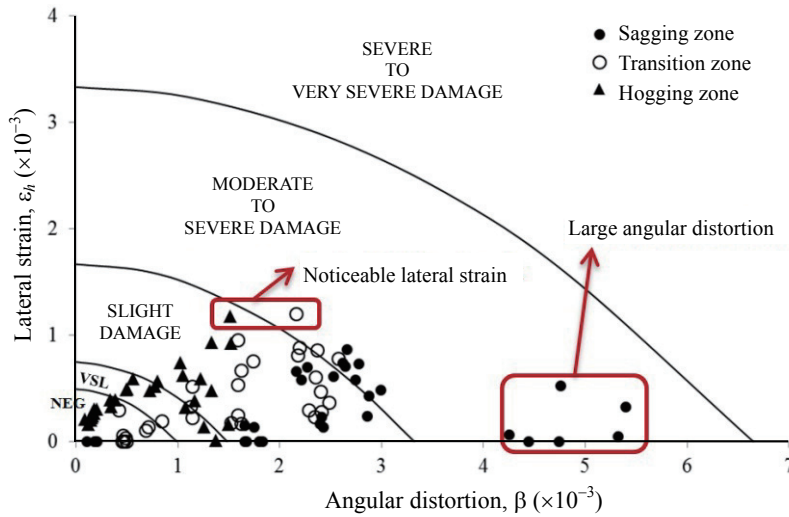


Fig. 22 Damage evaluation of building in different zones using Son and Cording chart

More detailed structural responses are possible using the decoupled analysis method that is proposed in this paper. In general, the overall results are reasonable and the lateral strain does provide an additional useful index for the assessment of potential building damage. However, the results show that the angular distortion remains the dominant index. This observation is somewhat different from the findings of Son and Cording (2005). In their study, most of the buildings were of a masonry structure and so were more vulnerable to lateral strain.

5. CONCLUSIONS

In this study, a Decoupled Analytical Method (DAM) is proposed 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 an adjacent building. The DAM is also robust and has many engineering applications. The DAM is used to assess the excavation and the responses of buildings in the sagging, the transition and the hogging zones. The results of this

study allow several conclusions to be drawn.

1. With a nearby building, the diaphragm wall deflects more when there is excavation. The degree of deflection depends on the distance of the building from the excavation. The closer the building, the greater is the wall deflection. At a certain distance away from the excavation, the building ceases to influence the wall deflection. This distance is very close to the Primary Influence Zone (PIZ).
2. The existence of a building near an excavation alters the ground and the footing settlement patterns. When the building is located in the sagging zone, 1 m away from the wall, the maximum footing settlement is about 1.3 times that of the greenfield value. The horizontal footing movements are more evenly distributed. Therefore, the interaction of the excavation and the building warrants proper consideration.
3. The DAM can provide many insights into the responses of a building that is adjacent to an excavation, such as the angular distortion, the lateral strain, the plastic hinge location or the tie beam forces. These insights allow a more accurate assessment of potential building damage.

4. A building that is located in the sagging zone and which is closest to the diaphragm wall is the most susceptible to excavation-induced damage. More plastic hinges and a larger angular distortion are observed for this case. Plastic points are likely to occur at beam-column joints, particularly at spans near the excavation zone.
5. Excavation can cause significant tensile strains in the tie beam that connects the footings, so cracks can occur in the concrete, which gives a greater potential for building damage I. This effect is more pronounced for buildings that are located in the transition and hogging zones.

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