Analysing Allowable Horizontal Displacements of Retaining Wall Based on Limited Settlements of Adjacent Building

Quoc Thien Huynh[1], Huu Thoi Tra[1], Lindung Zalbuin Mase[2], Nhat Hoang Vo[3 and 4], and Van Qui Lai[3 and 4]
[1]*Institute of Research and Development, Duy Tan University, Danang, Vietnam*
[2]*Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Bengkulu, Indonesia*
[3]*Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), 268 Ly Thuong Kiet, District 10, Ho Chi Minh City, Vietnam*
[4]*Vietnam National University Ho Chi Minh City (VNU-HCM), Linh Trung Ward, Thu Duc District, Ho Chi Minh City, Vietnam*
E-mail: lvqui@hcmut.edu.vn

ABSTRACT: This paper proposed and validated allowable horizontal displacements of retaining wall based on limited settlements of adjacent building with shallow foundation. The Finite Element Analysis (FEA) by Hardening Soil (HS) model was employed to verify horizontal displacements of retaining wall (δ_{max}) and settlements of adjacent building (U_y) from seven well-documented excavation cases in Ho Chi Minh (HCM) city, Vietnam. Following the comparisons between the FEA results and field observations, a close correlation between δ_{max}/H and U_y was proposed to $\delta_{max}/H = -\alpha U_y$, in which α was unit coefficient varying according to excavation depth H(m). Another case of deep excavation in Ha Noi city, Vietnam was used as a practical application to confirm the obtained results.

KEYWORDS: Deep excavation, Adjacent building, Limited settlement, Allowable displacement.

1. INTRODUCTION

The design and construction of deep excavations in urban areas are always huge challenges because of high damage risks. Along with ensuring the stability of deep excavation, minimizing the damage impact on adjacent building is also an extremely important task. Specially, adjacent buildings on shallow foundations or melaleuca piles are highly sensitive to forced movements caused by ground deformation. However, the ground deformation is surely occurred in excavation process through the horizontal displacement of retaining wall (R-wall). Ou (2014) argued that factors causing the displacement of R-wall certainly induce the settlement of surrounding ground surface. This probably results in the subsidence of adjacent buildings on the ground surface. In several damage cases, the adjacent buildings are seriously lost functionality or serviceability or their structures can be completely damaged. Thus, during the construction process of deep excavation in urban areas, the settlement of adjacent buildings must be in limited controls on damage criteria. In another way, the limited settlement of adjacent buildings is a key parameter that is needed to be carefully examined in deep excavation designs. It would be really a useful guideline if the allowable lateral displacement of R-wall is proposed based on damage considerations of adjacent building induced by the limited settlement.

In previous studies, many issues due to deep excavation works were investigated, such as lateral displacement of retaining walls (Hsiung, 2009; Yong and Oh, 2016; Huynh et al., 2020a, 2020b), deformation of ground surface around deep excavation (Hsieh and Ou, 1998; Hsiung and Dao, 2014), internal force of supporting structure (Goldberg et al., 1976; Tan and Chow, 2008), input parameters of deep excavation model (Khoiri and Ou, 2013; Moormann, 2004; Lai et al., 2020), damage of adjacent building near deep excavation (Schuster et al., 2009; Huynh et al., 2021). Hung and Phienwej (2016) stated that it needs to specify the allowable levels of R-wall displacement and ground settlement that could induce cracks or tilts on the adjacent building to quantify the design parameters of deep excavation. Mana and Clough (1981), Ou et al. (1993), Hsieh and Ou (1998) and Moormann (2004) studied correlations between ground settlement (δ_{vmax}) and R-wall's horizontal displacement (δ_{max}). However, the settlement of adjacent building is different from the ground surface due to the stiffness of adjacent building, distribution of surcharge load and depth of foundation surface (Tang and Kung, 2012; Lin et al., 2016). To the authors' best knowledge, there is still a gap in considering relationships between adjacent buildings' settlement and R-wall's horizontal displacement.

Based on the above ideas, seven urban excavation cases in HCM city, Vietnam were used for modelling and analysis. The FEA software, Plaxis 2D 2019, was employed to perform the excavation stages and adjacent buildings. Based on FEA results and comparisons with field observation, a close correlation between δ_{max}/H and U_y was proposed. New allowable values of R-wall's lateral displacement were suggested in detail from the resulting correlation and the limited settlement values of adjacent building.

2. DESCRIPTIONS OF STUDIED CASES

Seven excavation cases, namely Madison (Case A), Lancaster Lincoln (Case B), Golden Star (Case C), Lakeside Tower (Case D), Rivergate Residence (Case E), E. Town Central (Case F) and Tresor (Case G), were located in HCM city, Vietnam. The projects locations are shown in Figure 1. The excavation depth varied from 6.20 m below ground level (BGL) to 18.8 m BGL, and the number of basements was in the range of 2 to 5 floors. The excavations were carried out according to different construction methods, which were top-down, semi top-down and bottom-up techniques. Different R-wall types, including the Diaphragm wall (DW), Sheet pile wall (SPW) and Bored pile wall (BPW), were used as supporting structures for the deep excavations. The adjacent buildings around the excavations were 1-3-story buildings founded on shallow foundations or melaleuca piles and observed their settlement and tilt during the construction process. Table 1 and Table 2 summarize the main details of the projects including construction methods, types of retaining wall and bracing, types of soil, soil tests, adjacent buildings, monitoring items, damage effects on adjacent buildings.

Semi-top-down or top-down construction techniques and reinforced concrete diaphragm walls with thicknesses of 800 to 1000 mm were employed for excavation cases deeper than 14 m BGL. The observed lateral displacement of DWs in the studied cases was in the range of 0.14% to 0.3% of excavation depth (H). These field outcomes were totally consistent with the 0.2-0.5%H range found in the excavation study of Ou et al. (1993) and the 0.15-0.6%H range for historical excavation cases in HCM city of Hung and Phienwej (2016). Two excavation cases, namely C and D, which had excavation depth lower than 7 m BGL in soft soil, were done by bottom-up construction method. SPWs and BPWs with a length of 18 m were used as R-walls for excavation works. The observed lateral displacement of these R-walls was in the range between 0.92%H and 1.81%H. This result was similar to the study of Hung and Phienwej (2016) for past excavation cases retained by SPW and BPW. They indicated that in cases of the low bracing stiffness of the steel struts and bending stiffness of SPW or BPW, the observed displacement of R-walls was approximately in the range of 1%H to 2.4%H.

Figure 1 The projects location in Ho Chi Minh city, Vietnam

Adjacent buildings around the excavations were carefully surveyed before excavation works. They were low-rise building from 1 to 3 stories founded on shallow foundations, which placed in a distance of two times of the excavation depth (2H) from R-wall's edge. The observation of adjacent buildings' behaviours during excavation process was completely carried out by monitoring points including settlement and tilt measurements. The field measurements showed that the maximum settlement was approximately 50-60 mm in Case C and D, which the excavated area was retained the SPW, BPW, and steel struts. In these cases, the most damaging influence of R-walls' horizontal deflection on the adjacent buildings was in Case C. The damage level was moderate to severe, in that, an adjacent building must be renovated. In Case D, the level was only light damages, which only needed to be repaired by normal decorations, despite the large lateral R-wall displacement. In the other cases (A, B, E, F, G), their adjacent buildings had low settlement between 20 m and 40 mm. The damage influence on adjacent buildings was from very light to light, only several fine cracks appeared in the external brickwork, masonry and plaster ceiling, which were easily repaired by using normal decorations to cover the light cracks. Excepted for case B, which was damaged in the moderate to severe level, several adjacent buildings must be evacuated to ensure life safety for nearby residents in excavation process. And some of them must be rebuilt after finishing the basement construction completely. These things are briefly summarized in Table 2.

Table 1 Basic data of 7 excavation projects in Ho Chi Minh City

Case	Method	Type of retained/ bracing	No. of bracing	Type of soil	Adjacent buildings	H_w	H	δ_{max}	δ_{max}/H
						m	m	mm	%
A	Semi-Topdown	DW/ Slab	4	Soft soil, stiff clay to dense sand	3 floors	37	15.5	32.9	0.22
B	Semi-Topdown	DW/Slab	3	Soft soil, stiff clay to dense sand	1-3 floors	32	14.7	45.2	0.30
C	Bottom-Up	SPW/Shoring	2	Soft soil, stiff clay	1-3 floors	18	6.5	129.1	1.81
D	Bottom-Up	BPW/Shoring	2	Soft soil, stiff clay	2 floors	18	6.5	57.2	0.92
E	Topdown	DW/ Slab	4	Soft soil, stiff clay to dense sand	2-3 floors	30	14.8	20.9	0.14
F	Semi-Topdown	DW/Slab	5	Soft soil, stiff clay to dense sand	2-3 floors	42	18.8	45.7	0.24
G	Topdown	DW/Slab	4	Soft soil, stiff clay to dense sand	2-3 floors	30	14.8	25.1	0.17

Notes: H_w is length of R-wall; H is excavation depth, δ_{max} is lateral displacement of R-wall

Table 2 Summary of soil tests, monitoring and effects on adjacent buildings

Case	Type of Soil Tests		Monitoring Items	Damage to the adjacent buildings
	Lab Tests	Field Tests		
A	CU, UU, DS, OED	SPT, VST	In, GS, BS, T, MW, SG	Light damage, cracks width 0.2-0.7 mm, cracks length 30-83 cm
B	CU, UU, DS, OED	SPT, VST, PMT	In, GS, BS, T, Pz, Cr	Moderate to severe damage, relocated Several buildings
C	CU, OED, DS	SPT, VST	In, GS, BS, T, Cr, SG	Moderate to severe damage, renovated one building
D	DS, OED	SPT, VST	In, GS, BS, T, SG	Light damage, repair by using normal decoration
E	CU, UU, DS, QC	SPT, PT	In, GS, BS, T, MW	Light damage, several buildings exceed the allowable settlement
F	CU, UU, DS, OED, QC	SPT, VST, PT	In, GS, BS, T, Pz, MW	Light damage, several buildings exceed the allowable settlement
G	DS, QC	SPT, VST, PT	In, GS, BS, T, Pz, MW	Very light damage

Notes: CU is consolidated undrained triaxial test, UU is unconsolidated undrained triaxial test, UC is unconfined test, OED is oedometer test, DS is direct shear test, QC is quick compression test. SPT is standard penetration test, VST is vane shear test, PT is pump test. In is Inclinometer measurement, GS is ground settlement measurement, BS is building settlement measurement, T is building tilt measurement, Pz is piezometer measurement, MW is monitoring well.

3. ANALYZING DISPLACEMENT OF R-WALL AND SETTLEMENT OF ADJACENT BUILDING BY FINITE ELEMENT ANALYSIS

The settlement of adjacent buildings around deep excavations is dependent on numerous factors, including the horizontal displacement of R-wall, groundwater pumping inside excavation, stiffness of retaining structures, stiffness and foundation type of adjacent buildings. Besides, geological conditions and distance to the excavation also significantly affect the settlement of adjacent buildings. Thus, calculating their settlement by analytical formulas is very complicated and impossible to consider all the above factors. In that case, FEA is more optimal in solving all of these factors simultaneously. FEA is a highly accurate method, but it heavily depends on input parameters.

In this study, the FEA software, Plaxis 2D 2019, with Hardening Soil (HS) model was employed to simulate the soil behaviors. The HS model is an advanced soil model for the simulation of different behaviors of soil based on isotropic hardening (Schanz et al. 1999). It assumes stress-dependent stiffness obeying the power law as presented in Equation 1 and considers plastic straining due to primary deviatoric loading (E_{50}) and primary compression (E_{oed}). The elastic un/reloading (E_{ur} and ν_{ur}), dilatancy effect and failure are according to the Morh-Coulomb criterion, which limiting states of stress are described by means of the friction angle φ, the cohesion c and the dilatancy angle ψ. Soil stiffness is described much more accurately by defining three different stiffnesses. The triaxial loading stiffness E_{50}^{ref}, the triaxial unloading stiffness E_{ur}^{ref}, and the oedometer loading stiffness E_{oed}^{ref} at a reference stress level P_{ref}.

$$E_{50} = E_{50}^{ref}\left(\frac{c'\cos\varphi' + \sigma_3 \sin\varphi'}{c'\cos\varphi' + P_{ref}\sin\varphi'}\right)^m \tag{1}$$

In the HS model, most soil stiffness parameters are commonly determined from laboratory tests, including the Consolidated-Drained Triaxial Test (CD) and Oedometer Test (OED). However, FEA predictions based on these parameters may not agree well with field observations because the soil stiffness obtained from these tests may be lower than in their field due to the disturbance of soil samples. Hence, empirical formulas from the back analysis of past projects, which were determined from the soil module modification based on correlations with soil strength parameters, are widely used in design practice. The soil strength parameters could be determined from Direct Shear Test (DST), Standard Penetration Test (SPT), the Vane Shear Test (VST).

For the clayey layers, the total stress undrained analysis with undrained internal friction angle $\varphi_u=0$ and undrained shear strength cu=Su was adopted in the computation. The Su value could be taken from the VST or DST. The secant modulus for clayey layers was computed from semi-empirical equations suggested in previous studies. (Lim et al. ,2010; Khoiri and Ou, 2013; Likitlersuang et al., 2013; Hsiung and Dao, 2014; Hsiung et al., 2016; Yong and Oh, 2016; Huynh et al., 2020). Specifically, the E_{50} value was in the range of 300Su to 500Su, as shown in Table 3.

The stiffness parameters of sand soil are comparatively difficult to be determined from laboratory tests because sand samples are easily disturbed during sampling. The modulus of sand E' is significantly influenced by physical properties, field sample density and interactive force of the sand gains, which are mainly impacted by the sample disturbance (Mase et al., 2019). Instead of soil sampling, the SPT is commonly employed in practice engineering for calculating the sand E' value. Tan and Chow (2008), Hsiung (2009) and Hsiung et al. (2016) proposed the E' value of 2000N for the FEA simulations of deep excavations in Taiwan and Malaysia based on a series of back analyses of field observation data. Japan (2001) recommended using the E equal to 2800N in common practice. Huynh et al. (2020) used the E_{50} value of 2000N to 2800N to conduct FEA modeling of excavation cases in sand soil in Ho Chi Minh city, Vietnam. From this reviewed literature about semi-empirical equations, the sand E value in the range of 2000N to 2800N was employed for the FEA in this study. For other stiffness parameters, the E_{ur} and E_{oed} values were taken equal to $3E_{50}$ and E_{50}, respectively, as proposed by previous researches (Schanz et al., 1999; Tan and Chow, 2008; Schweiger, 2009; Teo and Wong, 2012). Table 3 presents input parameters of all soil layers for all cases.

In two-dimensional (2D) simulation, the adjacent building was simulated such as a flat framed structure including floor, beams and columns, foundations. This adoption was successfully applied in several studies about the adjacent buildings' behavior (Cording et al., 2010; Sabzi and Fakher, 2015; Zhang et al., 2018; Huynh et al., 2020). The flat frame was demonstrated by plate element with flexural stiffness EI (kN/m^2/m) and axial stiffness EA (kN/m). The 2D frame stiffness equal to the total stiffness of the floor and beams was divided by corresponding spacing length ($L_{spacing}$) as expressed in Equation 2 (Huynh et al., 2020, 2022a, 2022b):

$$EI_{1m} = \frac{EI_{floor} + EI_{beams}}{L_{spacing}};\; EA_{1m} = \frac{EA_{floor} + EA_{beams}}{L_{spacing}} \tag{2}$$

In which: EI_{floor} and EI_{beams} are the flexural stiffness of floor and beams, respectively. EA_{floor} and EA_{beams} are the axial stiffness of floor and beams, respectively. $L_{spacing}$ is the length of spacing.

Table 3 Input parameters for soil layers

Soil layers	Cases	Depth (m)	N value	φ' (deg)	c' (kPa)	S_u (kPa)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	m
Soft clay (1)	A, E, F, G	1-10	0-1	-	-	20-40	$300S_u$	~ E_{50}^{ref}	~$3E_{50}^{ref}$	1
Soft clay (2)	B, C, D	1-25	0-1	-	-	15-50	$300S_u$			1
Stiff clay (1)	A, E, F, G	5-14	6-13	-	-	45-80	$500S_u$			0.75
Stiff clay (2)	B, C, D	17-36	10-23			70-115	$500S_u$			0.75
Dense sand (1)	A, E, F, G	7-40	9-22	28-31	5-10	-	(2000-2800)N			0.5
Dense sand (2)	B, C, D	32-50	20-35	30-33	4-6	-	(2000-2800)N			0.5

For the discussion purpose, Case A, namely Madison, located at 15 Thi Sach Street, District 1, HCM city, Vietnam was typically investigated by FEA simulation. The project consisted of 17 stories and 3 basements was built on an area of 2360 m^2. The rectangular excavation was 65 m long and 37 m wide. The retaining structure was made of diaphragm wall with the thickness of 800 m and the length of 37 m. The excavation was done by the semi top-down technique with four levels of slab bracing and four excavation stages. The maximum excavation depth was 15.5 m BGL in the final stage. Figure 2 illustrates the cross section, surcharge load, geological conditions, construction process, bracing systems and excavation levels. Furthermore, Figure 3 presents the plan of construction site and the arrangement of monitoring points. More detailed information on the construction sequences is summarized in Table 4.

The adjacent buildings located next to deep excavation were low-rise buildings founded on shallow foundations. Their frame structures were investigated in the pre-construction stage. Figure 4 shows the geometric dimension of the building plan. Investigated geometric dimensions of building structures were 100 mm of floor thickness, 200×300 mm of beam width and height, 200×200 mm of column width and height, 1.2×1.2 m of shallow foundation width and length, and the spacing of 4.0 m ($L_{spacing}$ = 4.0 m). 2D frame stiffness was computed per 1 m unit in the plane strain model as expressed in Equation 2 and presented in Table 5. To control the damage level of adjacent buildings, several points observing their settlement were installed and monitored during the excavation process.

Table 4 Construction sequences of case A

Construction sequences		Finishing date
1	1st excavation to -3.8 m BGL, and install B1 slab and L1 slab.	31/03/2017 (Cycle 24)
2	2nd excavation to -7.3 m BGL, and install B2 slab.	26/04/2017 (Cycle 38)
3	3rd excavation to -11.8 m BGL, install H400 steel struts at -10.3 m BGL	25/05/2017 (Cycle 57)
4	4th excavation to the bottom levels of foundation (-15.55 m BGL)	27/06/2017 (Cycle 82)

Table 5 Input parameters for 2D frame structure (Case A)

Parameters	EA (kN/m)	EI (kNm^2/m)	w (kN/m/m)	ν
Floor+beam	3,105,000	5,287	6.00	0.15
Column	270,000	900	0.25	0.15
Foundation	6,500,000	350,000	5.60	0.15

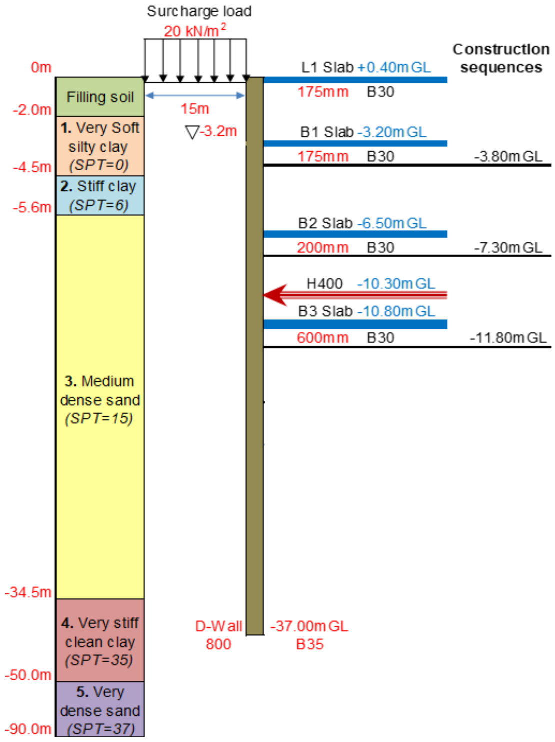


Figure 2 Construction section and soil profile of Case A

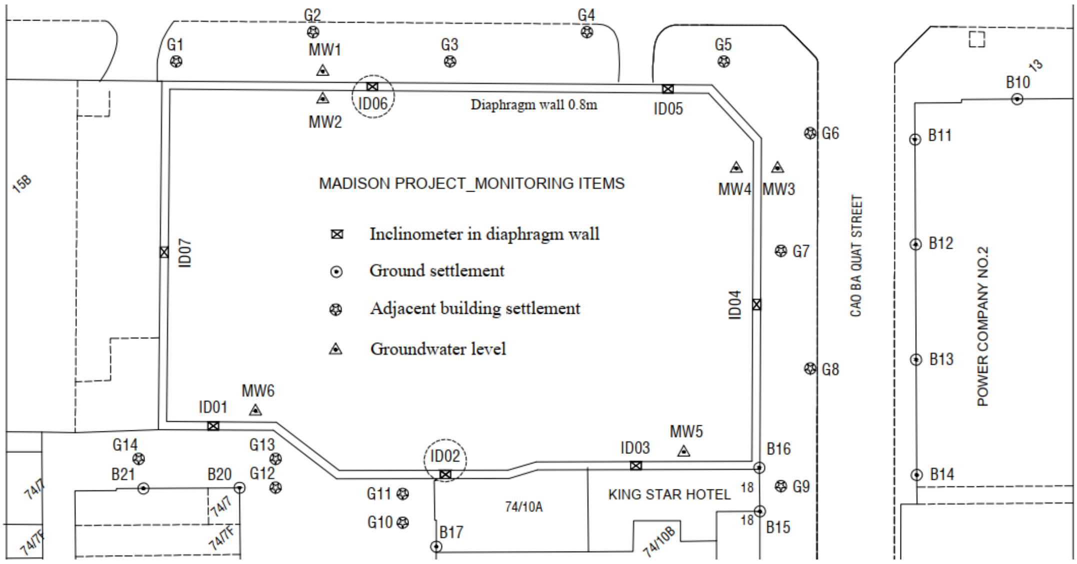


Figure 3 Arrangement of monitoring points (Case A)

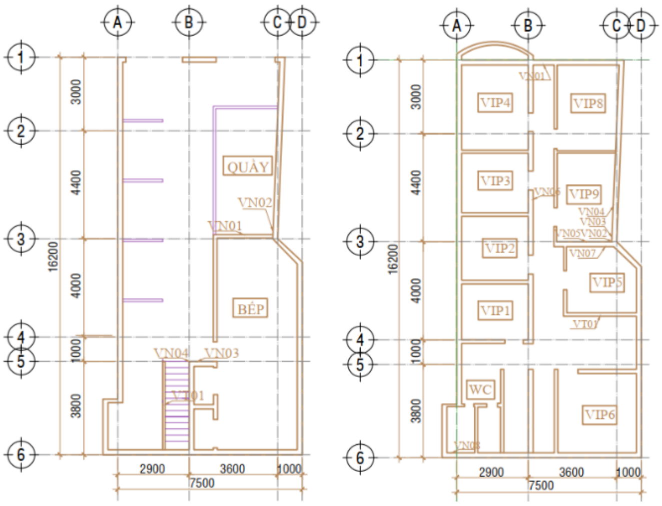


Figure 4 Structural plan of adjacent building (Case A)

Based on all the summarized information, the modelling and mesh generation of FEA of Case A is adopted in Figure 5. The length of the cross-section of the domain was 40 m. The lateral and bottom boundaries were set at 80 m horizontal and 80 m depth, respectively, according to the suggestion of Plaxis (2019) and the range of ground concave surface settlement (Hsieh and Ou, 1998; Clough, 1990). Figure 6 demonstrates the comparisons between the FEA results and field observation of the R-wall's horizontal displacement and the adjacent building's settlement at the ID02 monitoring point. The results indicated that the predicted FEA agree well with the measured values in all excavation stages. The observed displacements were 12.9 mm, 32.9 mm, 6.0 mm at the top, middle, toe of R-wall, respectively. The corresponding predicted displacements by FEA were 12.5 mm, 33.5 mm, 6.5 mm. The errors between prediction and observation were less than 5% over the whole length of R-wall. Moreover, the settlement of FEA was in good agreement with that of observation. At the final stage, excavation to 15.5 m BGL, the FEA and observation settlement were 20.3 mm and 19.7 mm, respectively.

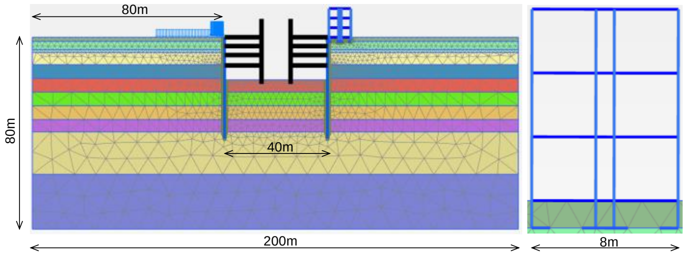


Figure 5 Two-dimensional FEA model of case A

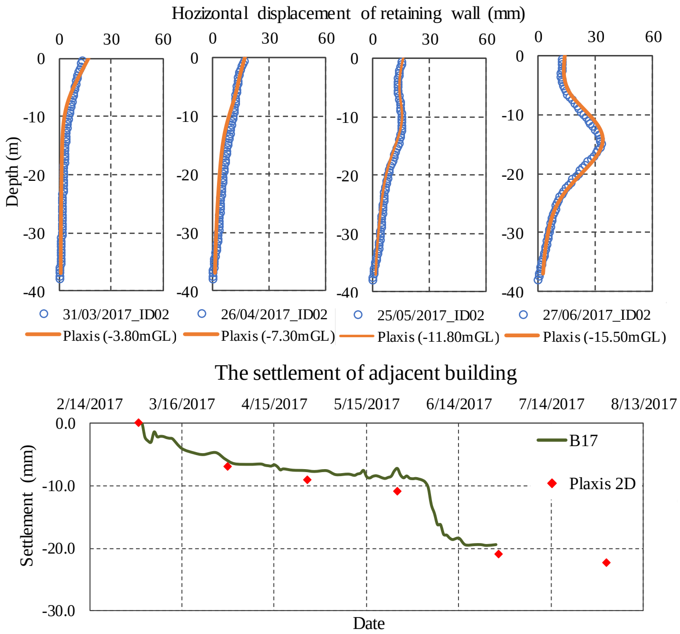


Figure 6 Analysis results of case A

For the other cases, similar procedures as for Case A were conducted. Comparisons between the FEA results and field observation of the R-wall's horizontal displacement and the adjacent building's settlement are showed from Figure 7 to Figure 12. In the deepest excavation stage, R-wall's horizontal displacements and excavation depths were 45.2 mm and 14.7 m (Case B), 129.1 mm and 6.45 m (case C), 57.2 mm and 6.15 m (case D), 20.9 mm and 14.75 m (case E), 45.7 mm and 18.8 m (case F), 25.1 mm and 14.75 m (case G), respectively. In terms of the cantilever excavation stage, these values were 5 mm and 1.0 m (case B), 32 mm and 1.3 m (case C), 23 mm and 1.4 m (case D), 14 mm and 3.55 m (case E), 13 mm and 2.35 m (case F), 10.5 mm and 3.55 m (case G). For the adjacent building's settlement, in final excavation stages, the FEA results were 33.3 mm, 61.2 mm, 49.5 mm, 20.2 mm, 31.5 mm, 28.6 mm of Case B, C, D, F, F, G, respectively. While the field measurements were 35.0 mm, 61.7 mm, 49.3 mm, 20.0 mm, 28.0 mm, 31.3 mm of Case B, C, D, F, F, G, respectively. The other values are presented and compared in Figures 7 - 12. The predicted results showed perfectly similar behaviors with observed values in each excavation stage of all the studied cases. This means that the soil parameters using for FEA models were perfectly accurate and reliable for simulation of deep excavations in HCM city, Vietnam.

4. CORRELATION BETWEEN THE SETTLEMENT OF ADJACENT BUILDING AND THE HORIZONTAL DISPLACEMENT OF R-WALL

The suggestion of the allowable horizontal displacement of R-wall based on the limited settlement of adjacent building must carefully consider all factors which can affect the relationship between the displacement of R-wall and settlement of the adjacent building. In that, excavation stages or excavation depth H(m), which determine the working condition of the R-wall as a cantilever or continuous beam, is one of the most important parameters.

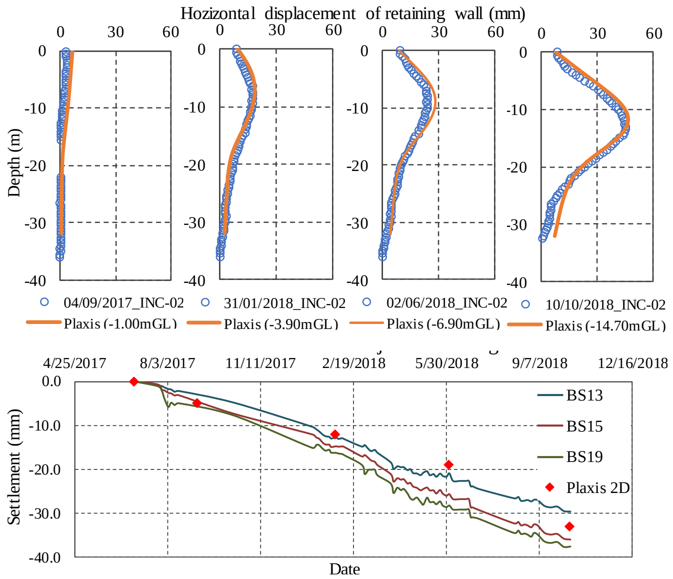


Figure 7 Analysis results of case B

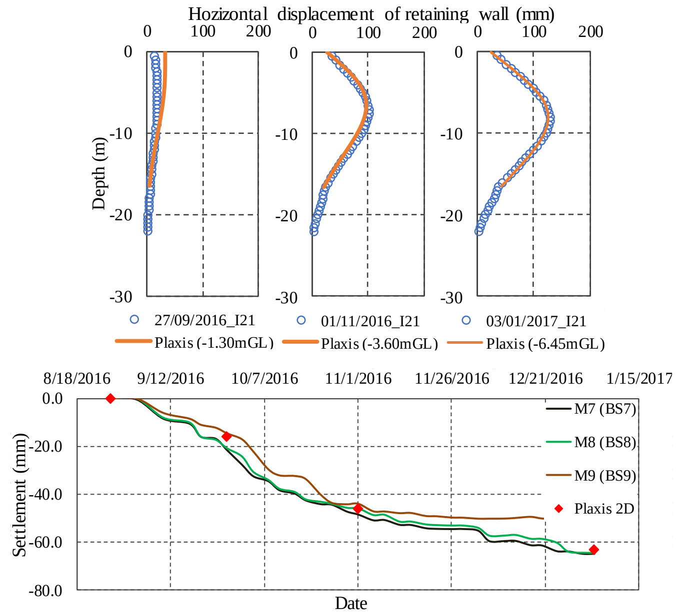


Figure 8 Analysis results of case C

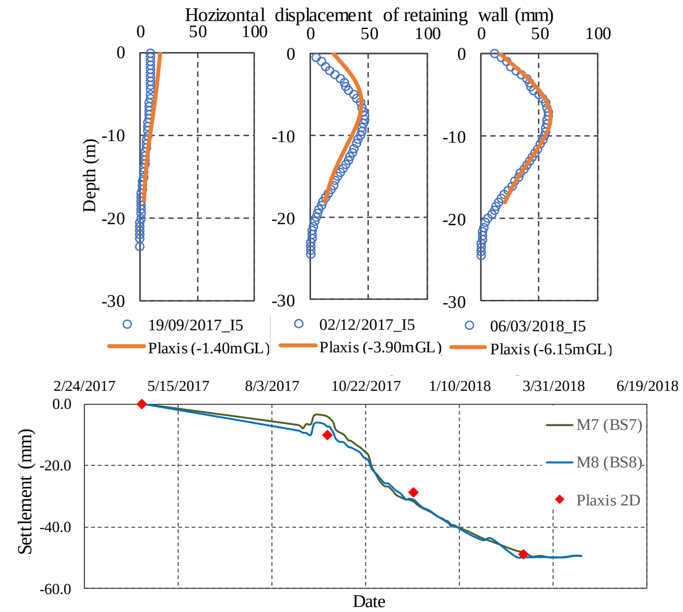


Figure 9 Analysis results of case D

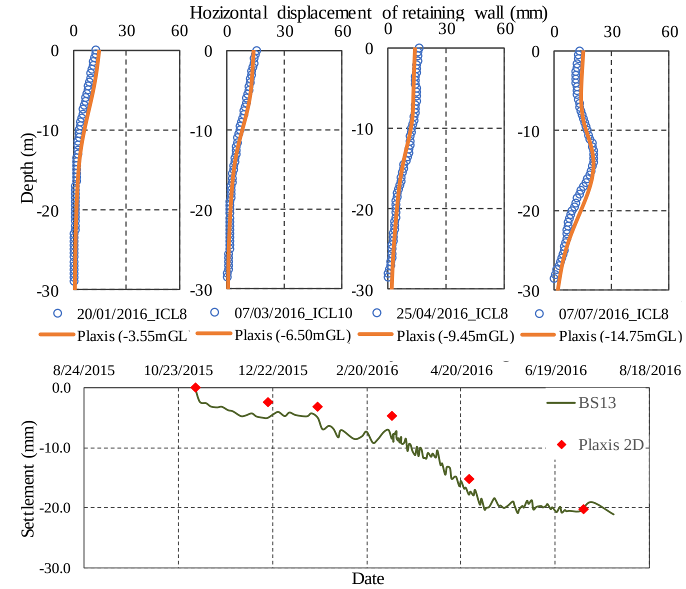


Figure 10 Analysis results of case E

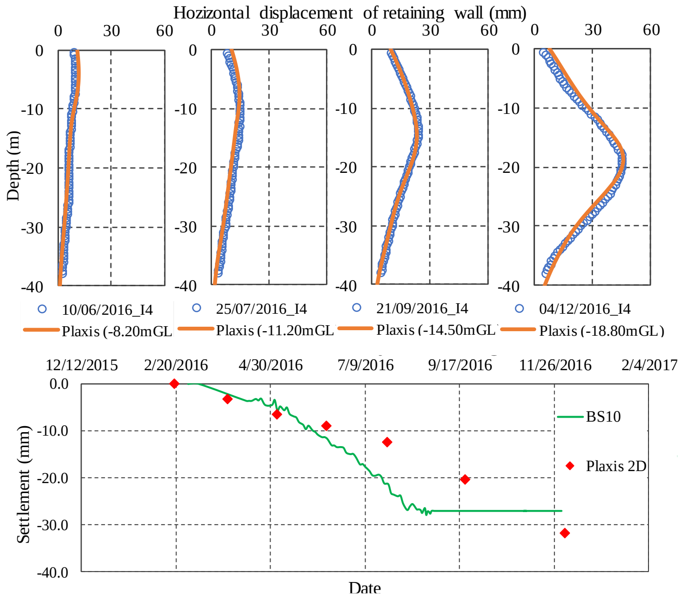


Figure 11 Analysis results of case F

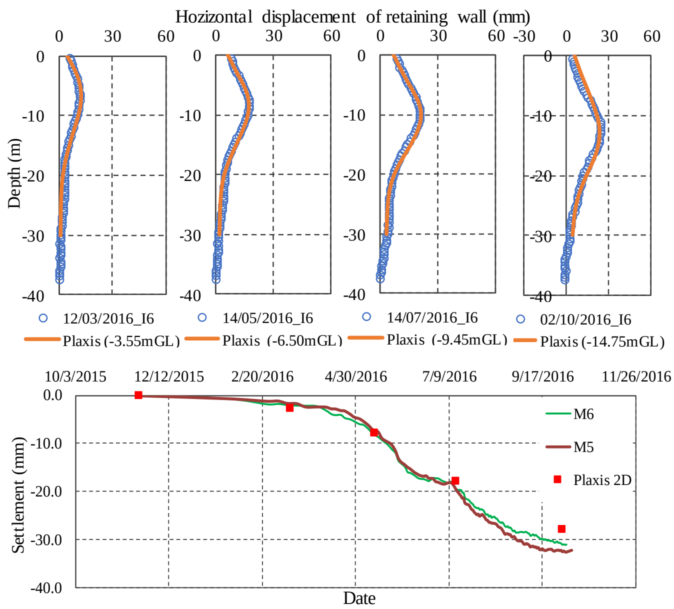


Figure 12 Analysis results of case G

For this deep verification, the relationships between the δ_{max}/H values and the excavation depths H(m) (excavation stages) was reviewed from the reliable field data of past studies, including 63 historical cases of deep excavations in soft to stiff clays of Goldberg et al. (1976), 18 deep excavations in soft clays in HCM city of Hung and Phienwej (2016) and more than 30 excavation projects in both cases with and without adjacent building in weak geological condition in Vietnam, which the author collected from Hoa Binh Construction Group. Figure 13 demonstrates the δ_{max}/H values according the excavation depths H(m) from the summarized data. Note that, the excavation depths corresponded to excavation stages from seven studied cases are summarized in Table 6. The result indicated that the δ_{max}/H value decreases according to the excavation stage or excavation depth H(m). Specifically, in the excavation cantilever phases (Exc. Cantilever), when the excavation depth is lower than 3 m BGL and the R-wall is in supporting the earth pressure, the δ_{max}/H value ranges between 0.5% and 2.5%. This result is similar to most of the excavation cases of Hung and Phienwej (2016). Furthermore, the δ_{max}/H value ranges from 0.1% to 1.5% when excavate to B1, B2, B3 (Exc. B1, B2, B3), which the excavation depth of B1 is in a range of 3 m to 5 m, B2 in a range of 5 m to 8 m and B3 in a range between 8 m and 12 m. In terms of the excavation of B4, B5 and B6 (Exc. B4, B5, B6), which is in the 12-17 m range of excavation depth B4, 17-23 m of excavation depth B5 and larger than 23 m of excavation depth B6, the δ_{max}/H value is in the 0.1- 0.5% range. Comparing to the δ_{max}/H values of previous researches, which ones were not considered based on excavation stage or excavation depth H(m), the δ_{max}/H values in this study were in the similar range. According to the research of Mana and Clough (1981), in soft clay using SPW for R-wall and a low FS heave, the δ_{max}/H might reach 2%. While using DW for R-wall, the δ_{max}/H might reduce to 0.5%. Long (2001) investigated 296 excavation cases in soft clay, in most cases of R-wall the normalized lateral displacement mostly ranged from 0.1% to 1% of excavation depth H(m). In some worse cases, the large lateral movement δ_{max}/H reaching 3.2% might occur in soft clays with low factor safety (FS). In another extensive empirical study was carried out by Moormann (2004), 530 case histories of deep excavation in soft clay (cu < 75 kPa) have been synthesized and analyzed. He found that δ_{max} varied from 0.5% to 1% of excavation depth H(m). In specifically, the δ_{max}/H was less than 0.9% in case of the DW used as a braced-wall support with H < 22 m, ranging from 0.1% to 0.75% for the one with H > 22 m, and could be exceed 1% for the sheet pile wall and soldier pile wall.

Following the above idea, the values of U_y and δ_{max}/H according to the excavation depths H(m) (excavation stages) of seven studied cases are summarized in Figure 14 and Table 7. It is noted that, the values of U_y and δ_{max}/H shown in Figure 14 are the FEA results, which were strictly evaluated by comparisons with field observations in section 3. The U_y value was the average of adjacent building's settlement. Figure 14 indicates markedly linear correlations between the δ_{max}/H values and the U_y values according to the excavation depth H(m). It is expressed in a linear function, $\delta_{max}/H=-\alpha U_y$, with high coefficient of determination, R^2. In which α (1/mm) is unit coefficient depended on the excavation depth H(m) (excavation stage). For example, in case of cantilever excavation, the α value is 12.8×10^{-2}. In other excavation stages, the α value ranges from 0.6×10^{-2} to 4.3×10^{-2}. The α value of cantilever excavation stage is quite large because the settlement of building is low but the horizontal movement is large. This is probably due to the ground surface deformation shape and the greatest lateral displacement at the top of R-wall. In this case, the adjacent building is unlikely to be damaged by settlement of ground, but it is harmed mainly due to horizontal movement of the surface ground. In the other excavation stages, this α value is significantly smaller than that of the cantilever excavation. The reason is probably that the bracing systems are installed to resist lateral earth pressures and along with the increase of excavation depth H(m), the δ_{max}/H value decreases as proved in Figure 13. The adjacent buildings are easily damaged due to large settlement of ground, which caused forced deformation on the buildings inducing the angular distortion β and lateral extension strain ε_L.

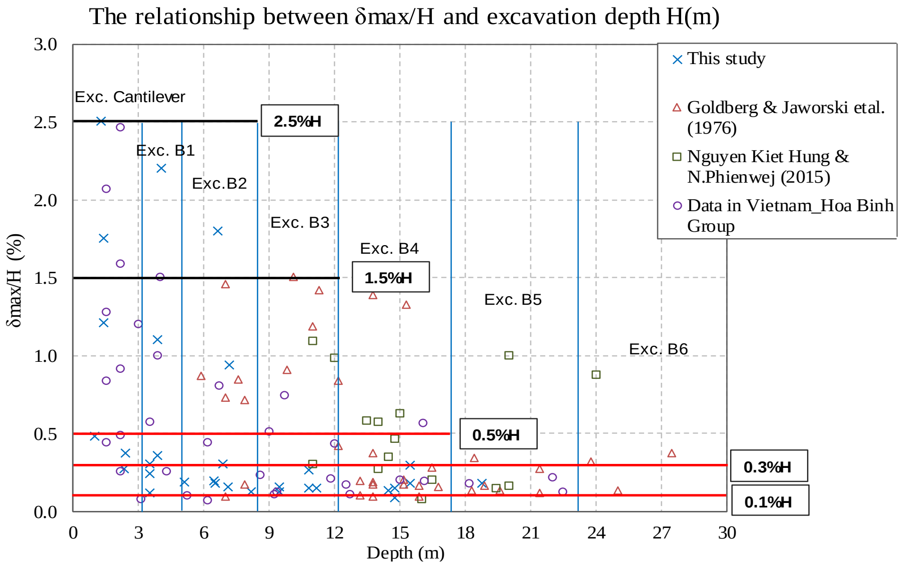
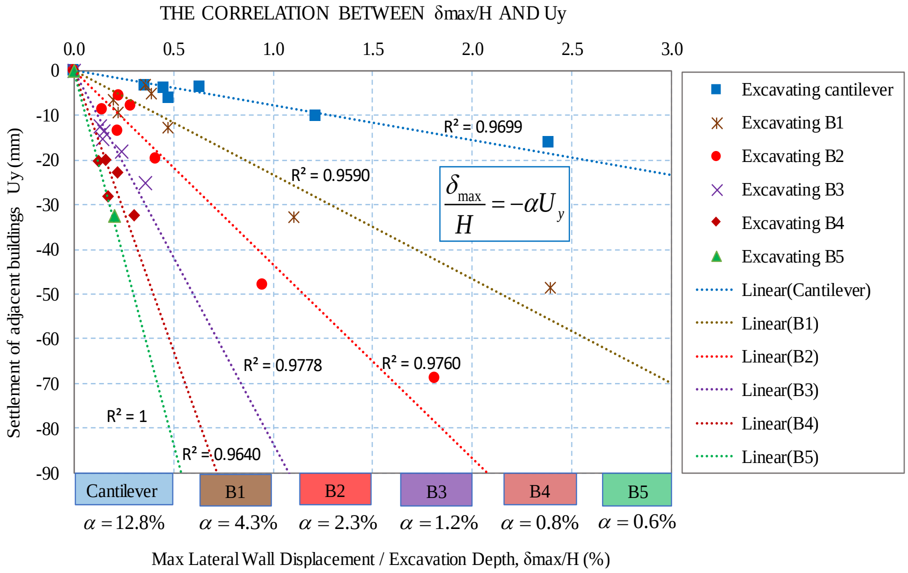


Figure 13 Relationship between δ_{max}/H and excavation depth H(m)



Note: α (1/mm) - unit coefficient depended on excavation depth H(m) (excavation stages), δ_{max}/H (%)

Figure 14 Correlation between δ_{max}/H and U_y

Table 6 Excavation depths corresponded to excavation stages from seven studied cases

Excavation stages	Cantilever	B1	B2	B3	B4	B5
Depth H(m)	0-3	3-5	5-8	8-12	12-17	17-23

Table 7 Correlation between δ_{max}/H (%) and U_y (mm) according to excavation depths H (m)

Excavation stages	Cantilever	B1	B2	B3	B4	B5
α (×10^{-2})	12.8	4.3	2.3	1.2	0.8	0.6

Note that, this study used the FEA results to make the correlation as shown in Table 7, because:

i. The settlement observation points on low-rise buildings are different from seven studied cases, and the adjacent buildings' settlement caused by the lateral displacement of R-wall is different at its isolating foundation locations. So, it is difficult to synthesize the settlement observation results without considering monitoring locations on the buildings. This problem can be solved by using the average settlement of observation points of adjacent building in FEA model and

ii. In the initial design, the model of excavation deep almost is implemented by FEA to predict the horizontal displacement of R-wall. It will be a good reference in predicting well the results of adjacent building's settlement from the FEA results, which were strictly validated with field measurements

5. ESTIMATING THE HORIZONTAL DISPLACEMENT OF R-WALL CONSIDERING THE ALLOWABLE SETTLEMENT OF ADJACENT BUILDING

The damage level of adjacent buildings is mainly assessed based on buildings' angular distortion β and lateral extension strain εL by a practical chart of strain state (Boscardin and Cording, 1989). Moreover, Schuster et al. (2009) first introduced a notion of damage potential index (DPI) to estimate damage potential of buildings adjacent. The damage levels were classified according to limited tensile strain levels ε_p, formed from the combination of the β and the ε_L (Boscardin and Cording, 1989). Additionally, it was also classified by visible damage repairs and crack width based on real damage observations by Burland (1977). It can be sure that the magnitude of building settlement is the main factor affecting the damage because the different settlement between isolated foundations certainly induces the β and ε_L on adjacent building. The accurate determination of the β and ε_L value is complicated in field measurement or observation. Hence, in some worse cases, we must limit the settlement of adjacent building to avoid or minimize unintended and uncontrolled damages. If the different settlement between isolated foundations of adjacent building is not occurred, the adjacent building will not be damaged in terms of its structure. Moreover, large settlements can cause aesthetic and functional influence on the building such as: service pipes may be fractured or disrupted, the building can be flooded due to building's ground elevation lower than the neighbourhood one. The water sewer line connected to the building can be broken, which impacts the building service. Limiting the building settlement to ensure the stability and service is an important task. However, the adjacent building's settlement closely relates to R-walls' lateral displacement.

Based on that view, various foundation design standards and researchers proposed the limited settlement to minimize the damages levels for adjacent buildings. According to the limited settlement S_{max}, Rankin (1988) classified the building damage levels into three categories, which was similar to the classification of Burland (1977). Eurocode 7 Geotechnical design proposed that normal structures with isolated foundations, the total settlements up to 50 mm are often acceptable. Larger settlements may be acceptable if the relative building rotations are maintained within acceptable limits and do not cause any damage to the building structure. Besides, numerous references also recommended the settlement for acceptable limits of building damages such as: TCVN 9362:2012, 80 mm was proposed for the limited settlement of functional damages of low-rise building. Sowers (1979) suggested two limited settlement ranges for masonry walled structures and framed structures damage. IS1904 divided the limited building settlement for isolated footing into two different types based on soil strata characteristics. Table 8 summarizes the limited settlement for building.

Table 8 Various preferences of limited settlement of building

Category of damage/ Limiting Factor	Limited Settlement S_{max} (mm)	References
Aesthetic	10-50	Rankin (1988)
Functional	50-75	
Service-ability and structural	> 75	
Functional	50	Eurocode 7
Functional	80	TCVN standard
Masonry walled structure	25-50	Sowers, G. F (1979)
Framed structures	50-100	
Isolated footing on sand	40	IS1904 (1966)
Isolated footing on clay	65	

The displacement value of R-wall indirectly impacts the damage of adjacent building because the reduction of R-wall deflection will decrease the ground surface movement, resulting in the β and ε_L values being low (Boscardin and Cording 1989). Therefore, the most effective measure that can be taken to mitigate adjacent building's damages is to reduce R-wall displacement. The R-wall displacement plays a vital role in limiting the building damage. By combining obtained results from Figure 14 and limited settlement values for adjacent building from standards, this study proposed new allowable values of δ_{max} considering the limited settlement to minimize impacts and ensure safety for architecture and function of adjacent buildings. Following criteria values, 50 mm for ensuring safety about aesthetic damages and 80 mm for limiting no functional damages of low-rise building, the allowable values of δ_{max} were got and presented in Table 9. For instance, with the limited settlement of adjacent building of 50 mm, the allowable values of R-wall's lateral displacement are H/15 for cantilever excavation stage, and H/45, H/85, H/150, H/250, H/325 for B1, B2, B3, B4, B5 excavation stages, respectively. For case of S_{max} equal to 80 mm, the allowable values of δ_{max} should be less than H/10, H/30, H/55, H/100, H/150, H/200 for Cantilever, B1, B2, B3, B4, B5 excavation stages, respectively.

Table 9 Allowable values of R-wall's lateral displacement

Excavation stages	Cantilever	B1	B2	B3	B4	B5
U_y = -50 mm	H/15	H/45	H/85	H/150	H/250	H/325
U_y = -80 mm	H/10	H/30	H/55	H/100	H/150	H/200

6. VERIFICATION OF THE STUDIED RESULTS FOR A CASE STUDY

To confirm the studied results, a real project, namely H, located in Hanoi city, Vietnam was utilized. The project consisted of 27 stories and two basement levels located on an area of 10842 m^2. The deep excavation was done by bottom-up technique and retained by sheet pile walls with length of 12 m. The adjacent buildings were low-rise building (1-3 floors) and founded on shallow foundations. The construction section and field measurement of lateral displacement are showed in Figure 15. In excavation process, the observed maximum value of δ_{max} was 190 mm at the top of R-wall when cantilever excavation depth was reached to -4.5 m BGL (H = 4.5 m). The damage immediately affected the adjacent buildings, and settlements of adjacent buildings were measured as presented in Figure 16.

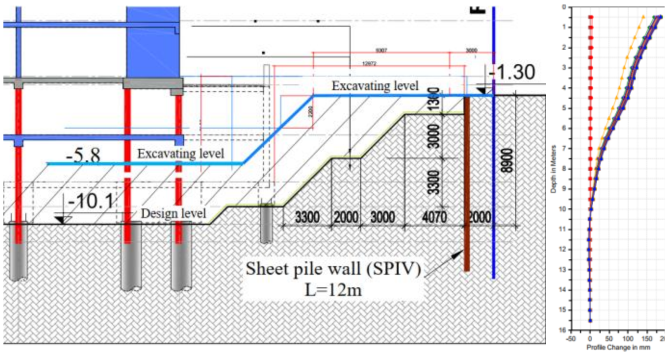


Figure 15 The real construction section and field data of lateral displacement of Case H

In terms of cantilever excavation, the α value in the equation $\delta_{max}/H = -\alpha U_y$ would be 12.8×10^{-2}. With the observed lateral displacement δ_{max} of 190 mm and excavation depth H of 4.5 m, the settlement of adjacent buildings U_y would be 32 mm. Comparing this estimated result to field measurement, a relative fit among these results was recorded and shown in Figure 16. In other words, the equation $\delta_{max}/H = -\alpha U_y$ can be successfully applied for predicting the settlement of adjacent buildings in this case.

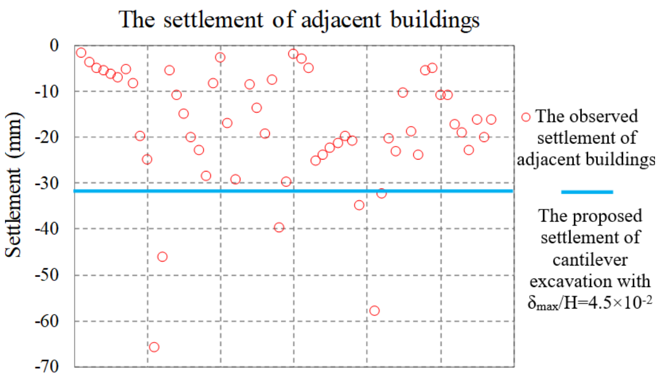


Figure 16 Comparison between observed and proposed settlement of Case H

7. CONCLUSIONS

The paper presents the FEA for the deep excavation cases in Vietnam. The close correlation between δ_{max}/H (%) and U_y (mm), and the δ_{max} value based on the limited settlement of adjacent building were proposed. Eight excavation cases were selected to model and analyze. The first seven cases were utilized for analyzed results by comparing the FEA simulations with the field measurement. The final case was used to confirm the accuracy of the proposed results. Several conclusions are summarized:

1) The predicted results of FEA simulations agree well with the field observations of R-wall's lateral displacement and the settlement of the adjacent building, when using the Hardening Soil model to analysis behaviours of deep excavation cases.
2) In cantilever excavation stage, the δ_{max}/H values range between 0.5% and 2.5%. These values range from 0.1% to 1.5% when excavating B1, B2, B3. In terms of the excavation stages of B4, B5 and B6, the δ_{max}/H values are in the 0.1%-0.5% range.
3) The correlation between δ_{max}/H (%) and U_y (mm) according to excavation depths H(m) (excavation stages) are proposed in terms of $\delta_{max}/H = -\alpha U_y$.
4) The allowable displacement values of R-wall to ensure safety about aesthetic damages (U_y = -50 mm) and limit no functional damages (U_y = -80 mm) of the adjacent building are proposed.

8. ACKNOWLEDGEMENTS

The authors are grateful to Hoa Binh Construction Group for their kind permission to use the observed field data of deep excavation cases in Ho Chi Minh city, Vietnam. We would like to thank Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for the support of time and facilities for this study.

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