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The response of buildings to movements induced by deep excavations

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ABSTRACT: Deep excavations and tunnelling can cause ground movements that affect buildings within their influence zone. The current approach for building damage assessment is based on tensile strains estimated from the deflection ratio and the horizontal strains at the building foundation. For tunnelling-induced deformations, Potts & Addenbrooke (1997) suggested a method to estimate the building response from greenfield conditions using the relative building stiffness. However, there is not much guidance for building response to excavation-induced movements. This paper presents a numerical study on the response of buildings to movements caused by deep excavations in soft clays, and proposes design guidance to estimate the deflection ratio and the horizontal strains of the building from the building stiffness.

1 INTRODUCTION

Activities associated with deep excavations and tunnelling can cause ground movements that affect buildings within their zone of influence. The current approach for building damage assessment is based on the maximum tensile strains estimated from the deflection ratio and the horizontal strains at the foundation level (Mair et al, 1996). Potts & Addenbrooke (1997) proposed the modification factor and relative stiffness approach to incorporate the influence of building stiffness for predicting building response to tunnelling-induced movements. This has since been updated by Franzius et al (2006). However, there is not much guidance on how building stiffness can be included to estimate building response to movements induced by deep excavations.

A preliminary numerical study on the influence of building stiffness and the building's deformation response to excavation-induced movements was presented by Goh & Mair (2008). Using the Plaxis finite element software, a total stress analysis was carried out for a 20 m deep excavation in soft clay where the building was modelled as an elastic beam with axial and bending stiffness properties. In general, a building with low axial and bending stiffness is flexible and would follow the ground deformations in the greenfield condition, while a stiff building with high axial and bending stiffness would tend to rotate and move as a rigid body. Specifically, the preliminary study showed that the modification factor for horizontal strains induced in the building depends just on its axial stiffness, whilst the modification factor for deflection ratio depends on both the axial and bending stiffness. However, when the axial stiffness is high enough and in the range corresponding to actual buildings, the modification factor for deflection ratio depends mainly on the bending stiffness of the building.

A detailed numerical study was since completed to investigate the response of buildings to movements caused by deep excavations in soft clays, using the finite element software Abaqus. In this investigation, more parameters related to the building and excavation characteristics were varied, including the building length, building location, excavation depth, consolidation effects, etc. This paper presents the findings of the detailed study, and the development of design guidance to include building stiffness when estimating the building's deflection ratio and horizontal strains from the greenfield response.

2 INFLUENCE OF STRUCTURAL STIFFNESS AND GEOMETRY

2.1 *Finite element modelling*

To understand building behaviour under the influence of excavation-induced movements, a 2D finite element study was conducted using Abaqus. The building was modelled as a weightless, elastic beam with axial and bending stiffness properties—this is similar to the elastic beam simplification used in Potts & Addenbrooke's study of buildings under the influence of tunnelling-induced deformations. The excavation is done in soft clay, undrained, and is supported using a multi-propped earth retaining wall with adequate toe embedment into stiff clay. A soil-structure interface was modelled between the soil and the building and between the soil and the wall, so that slipping will occur when the shear stress at the interface exceeds a maximum value of 20 kPa. Figure 1 shows the key elements and parameters in the base model of the analysis, where a 20 m deep excavation was simulated in a 20 m thick deposit of soft clay. The building's length and its location behind the excavation were varied—together with various combinations of axial and bending stiffness—to investigate the influence of structural stiffness and geometry on the building response to excavation-induced deformations.

Following the findings from the preliminary study (Goh & Mair, 2008), the stiffness values of the elastic beam were chosen to reflect realistic combinations in actual buildings so that the axial stiffness is not too low in comparison to the bending stiffness. Table 1 shows the combinations of bending and axial stiffness generally assumed in the study, although additional stiffness combinations were sometimes included to refine the results.

Furthermore, Potts & Addenbrooke's approach of using the building modification factors to describe the deformation behaviour in buildings is also used in this paper. Essentially, the modification factors of deflection ratio (M^{DRsag}; M^{DRhog})

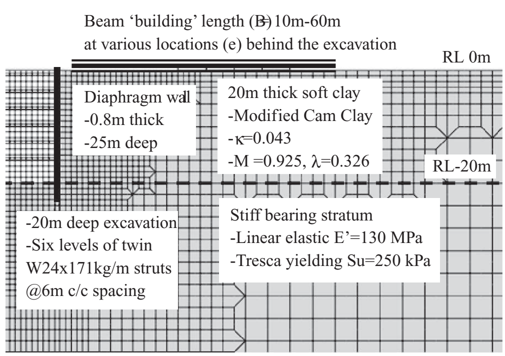


Figure 1. Key elements and parameters in excavation model.

Table 1. Bending stiffness and axial stiffness of building model.

EI (kNm²/m)	10^3	10^4	10^5	10^6	10^7	10^8	10^9
EA (kN/m)	10^3	10^4	10^5	10^6	10^7	10^8	10^9

and the modification factors of horizontal strains ($M^{\varepsilon hc}$; $M^{\varepsilon ht}$) are defined as follow:-

$$M^{DRsag} = \frac{(\Delta/L)_{sag,Bldg}}{(\Delta/L)_{sag,GF}} \quad (1)$$

$$M^{DRhog} = \frac{(\Delta/L)_{hog,Bldg}}{(\Delta/L)_{hog,GF}} \quad (2)$$

$$M^{\varepsilon hc} = \frac{\varepsilon_{hc,Bldg}}{\varepsilon_{hc,GF}} \quad (3)$$

$$M^{\varepsilon ht} = \frac{\varepsilon_{ht,Bldg}}{\varepsilon_{ht,GF}} \quad (4)$$

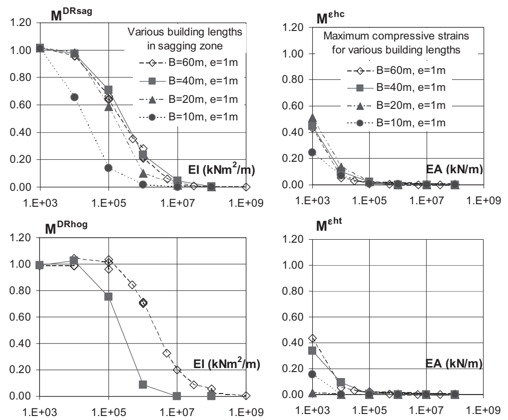
where $(\Delta/L)_{sag}$ and $(\Delta/L)_{hog}$ are the sagging and hogging deflection ratios, ε_{hc} and ε_{ht} are the maximum compressive and tensile horizontal strains, and the subscripts refer to the Building (Bldg) and the GreenField condition (GF).

2.2 *Effect of building length*

The length of a building is an important parameter affecting its stiffness. This is analogous to beam behaviour where a longer beam would deflect more than a shorter beam under the same loading and support conditions. To investigate this, the length of a building—the nearest edge of which is 1 m behind the excavation—was varied from 10 m to 60 m in the finite element analysis. In the base excavation model (model UD_A), the sagging trough is 20 m long—this was found by interrogating for the point of inflexion on the surface settlement curve. Thus, the 10 m and 20 m long buildings would be completely within the sagging zone of the greenfield settlement trough, whilst the 40 m and 60 m long buildings would show both sagging and hogging deformation.

Figure 2 plots the modification factors for deflection ratio and horizontal strain against the bending stiffness and axial stiffness, for various building lengths. In terms of deflection ratio, it is observed that a shorter building would have a lower modification factor compared to a longer building with the same bending stiffness. In terms of horizontal strains, a shorter building also appears to have a lower modification factor than a longer building, when the axial stiffness is low.

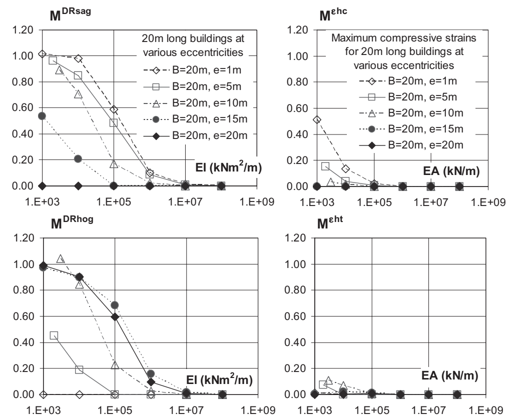
Moreover, it is noted that the horizontal strain modification factor is close to zero when the axial stiffness is sufficiently high, i.e. when axial stiffness is of the order 10^5 kN/m. This threshold is below the axial stiffness of actual buildings. For example, a 100 mm thick reinforced concrete slab will have an axial stiffness that is in the order of 10^6 kN/m.



(a) Modification factor for sagging and hogging deflection ratios (M^{DRsag}, M^{DRhog})

(b) Modification factor for maximum horizontal strains ($M^{\varepsilon hc}$, $M^{\varepsilon ht}$)

Figure 2. Modification factors for various building lengths (nearest edge at 1 m behind excavation).



(a) Modification factor for sagging and hogging deflection ratios (M^{DRsag}, M^{DRhog})

(b) Modification factor for maximum horizontal strains ($M^{\varepsilon hc}$, $M^{\varepsilon ht}$)

Figure 3. Modification factors for 20 m long building at various distances (e) behind the excavation.

This implies that the horizontal strains in most buildings on continuous foundations would be negligible.

However when the axial stiffness is low, the horizontal strain modification factor is near to 0.5. This is due to the effect of a slipping interface modelled between the soil and the building. If an interface without slipping is modelled (i.e. where the soil nodes are rigidly connected to the building nodes), the horizontal strain modification factor would be near to unity when the axial stiffness is low.

2.3 *Effect of building location*

To investigate the influence of building location, the distance of the nearest edge of a 20 m long building to the excavation—defined as building eccentricity in this paper—is varied from 1 m to 20 m. The modification factors are shown in Figure 3. In the sagging zone, the deflection ratio modification factor for a building nearer to the excavation is higher than that of a building further away from the excavation. The converse is true in the hogging zone, as the deflection ratio modification factor of a building nearer to the excavation is lower than that of a building further away from the excavation. In terms of horizontal strains, there is a similar observation that the modification factors are near to zero when the axial stiffness is sufficiently high and of the order 10^5 kN/m.

2.4 *Relative bending stiffness of building*

Further finite element analyses were completed for buildings that are 40 m and 60 m long and at various eccentricities behind the same excavation (model UD_A). The deflection ratio modification factors for all the buildings are plotted against the bending stiffness in Figure 4. There is a wide spectrum in the modification factors between different buildings with the same bending stiffness. This implies that the deflection ratio in a building depends on factors other than simply its stiffness.

Since the modification factor is a measure of building response relative to the greenfield response, a parameter that gives the flexural stiffness of the building with respect to the soil can be similarly defined. Such a relative bending stiffness parameter should include the factors affecting the settlement behaviour of the building, such as its bending stiffness, its length, and its eccentricity, and possibly the excavation depth. Other than soil stiffness, a geometric parameter influenced by these factors is the sagging (and hogging) length of the building. Hence, it is proposed to define a new dimensionless relative bending stiffness factor (ρ_{sag} and ρ_{hog}) as

$$\rho_{sag} = \frac{EI}{E_S * L_{sag}^3} \tag{5}$$

$$\rho_{hog} = \frac{EI}{E_S * L_{hog}^3} \tag{6}$$

where EI (in kNm²/m run) is the bending stiffness of the building, E_s (in kN/m²) is a representative elastic stiffness of the soil defined as the weighted average of the soil stiffness above the excavation level, and L_{sag} and L_{hog} (in m) are the sagging and hogging lengths of the building in the greenfield condition.

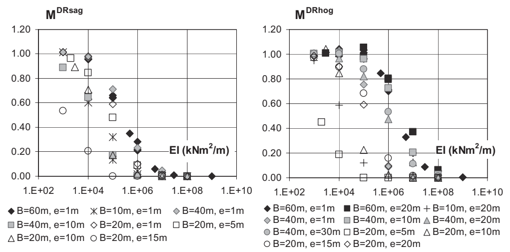


Figure 4. Deflection ratio modification factors for different building bending stiffness values.

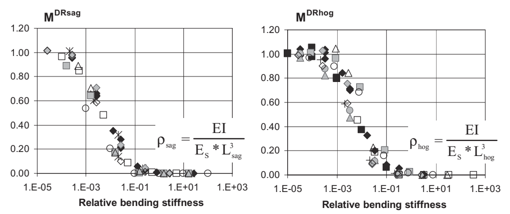


Figure 5. Deflection ratio modification factors for the new relative bending stiffness values.

When the deflection ratio modification factors are re-plotted against the new relative bending stiffness as shown in Figure 5, the data points converge into a narrow band. This suggests that the newly defined relative bending stiffness is a more useful parameter to describe the deflection behaviour of a building, compared to just using its bending stiffness.

3 INFLUENCE OF UNDRAINED EXCAVATION CHARACTERISTIC

3.1 *Depth of excavation*

To investigate the influence of excavation depth on building response, additional analyses were completed where the soil profiles were varied and final excavation depths changed. Table 2 summarises the excavation configurations varied in the study. For each excavation, the point of inflexion was found by interrogating for the point of maximum slope in the surface settlement curve. It is observed that the inflexion point which defines the length of the sagging trough may be different even though the excavation depth is the same. For example, the sagging trough in model UD_B is wider than in base model UD_A although the excavation depths are the same, and this is due to the thicker soft clay layer. This is because ground deformation in a multi-propped excavation is usually controlled by deep-rooted movements near the excavation level. The sagging length would give a better sense of the size and characteristics of induced ground deformations, as compared to the excavation depth. Although the elastic modulus of the soil—defined as the weighted average of the Young's modulus above the excavation level—does not describe the non-linear stiffness of soil exactly, it is noted that the different relative stiffnesses between buildings are in the orders of magnitude and such approximations on soil stiffness would be acceptable.

For a 60 m long building with the nearest edge at 1 m behind each of the different excavation depths, the modification factors for deflection ratio are plotted against the bending stiffness of the building in Figure 6a, and against the newly defined relative bending stiffness in Figure 6b. The spread in the modification factors is reduced when they are plotted against the relative bending stiffness. This shows that the sagging (and hogging) length for the greenfield condition is a suitable parameter to normalise the effects of excavation depth on building stiffness.

3.2 *Design guidance on modification factors for deflection ratio*

As with the base model, the buildings behind each of the excavation models were also varied in terms of the lengths (B = 10 m–60 m) and the locations (e = 1 m–30 m). The deflection ratio modification factors from all the models in Table 2 are plotted against the relative bending stiffness in Figure 7.

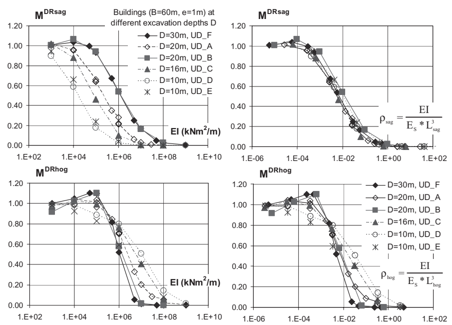
The modification factors for both sagging and hogging deflection fall into a narrow band. When the relative bending stiffness is less than 10^{-4}, the modification factor is close to unity and the flexible building would have a deflection ratio similar to that of the greenfield. When the relative bending stiffness is more than 10^0, the modification factor is close to zero and the stiff building would have zero deflection. Between the two values, the modification factor decreases rapidly from unity to zero, and this can be defined approximately using two curves—a mean curve for the best estimate response and an upper bound curve for the most flexible response. These two curves are the same for sagging deflection and hogging deflection modification factors. This can be used as a design guidance to estimate the modification factors and hence the deflection ratio in buildings adjacent to deep excavations in soft clay.

3.3 *Relative axial stiffness of building*

Earlier, it was pointed out that the horizontal strain modification factors depend mostly on the

Table 2. Excavation configurations varied in the study.

	Base UD_A	Model UD_B	Model UD_C	Model UD_D	Model UD_E	Model UD_F
Excavation depth	20 m	20 m	16 m	10 m	10 m	30 m
Soft clay thickness	20 m	30 m	16 m	12 m	12 m	32 m
Wall depth	25 m	35 m	20 m	15 m	15 m	40 m
Thickness of wall	0.8 m	1.0 m	0.6 m	0.6 m	0.6 m	1.0 m
No. of props	6 nos.	6 nos.	5 nos.	3 nos.	3 nos.	10nos.
1st activity	Excavate to RL-1.0 m				Prop at RL-0 m	
2nd activity	Excavate to RL-0.5 m				Prop at RL-3 m	
Location of inflexion pt.	21 m	29 m	17 m	11 m	11 m	30 m
Soil elastic modulus Es (kPa)	4709	4709	3767	2355	2355	7064



(a) Modification factors plotted against the bending stiffness of building

(b) Modification factors plotted against the relative bending stiffness

Figure 6. Effect of excavation depth on modification factors for deflection ratio.

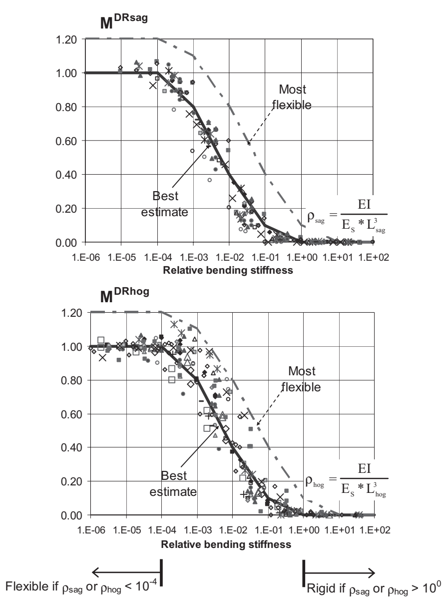


Figure 7. Deflection ratio modification factors for various buildings adjacent to different excavation depths.

axial stiffness of the building, but also depend (to a lesser extent) on the length of the building. In a similar way, a dimensionless relative axial stiffness (α) can be defined for buildings.

$$\alpha = \frac{EA}{E_S * B} \quad (7)$$

where EA (in kN/m run) is the axial stiffness of the building, Es (in kN/m^2) is the representative soil stiffness and B (in m) is the total length of the building.

Unlike deflection ratios where the modification factors between a building with slipping interface to the soil and a building without slipping interface were similar, the horizontal strains in the building can be influenced by the modelling of the soil-building interface. The maximum horizontal strains in the building were simulated using the most extreme situation where slippage is prevented at the soil-building interface. Figure 8 plots the horizontal strain modification factors against the relative axial stiffness using a non-slipping interface in the models under various excavation depths. An upper bound (shown on Fig. 8 as 'design estimate') can be used to estimate horizontal strain modification factors for buildings on continuous footings. Furthermore, for a 100 mm thick reinforced concrete slab that is 100 m long and continuous and for Es around 20 MPa, the relative axial stiffness is in the order of 10^0. This gives an indication on the range of the realistic axial stiffness of actual buildings, where the modification factor of horizontal strain would be near to zero as shown in the figure.

3.4 *Other parametric studies of the excavations in undrained conditions*

Other than excavation depths, parametric studies were also completed for other factors that would have an influence on the characteristics of the

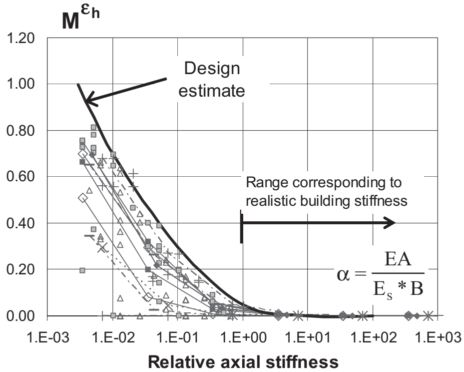


Figure 8. Horizontal strain modification factors for different relative axial stiffness values of buildings on continuous footings.

ground deformation caused by an adjacent deep excavation. These factors include:

- the stiffness of the excavation support system where the wall stiffness and prop spacing were varied in various excavation models,
- the effect of including building weight where a 40 kPa surcharge was placed on the 'beam' building with and without considering building stiffness,
- the effect of soil stiffness and constitutive modelling where the soft clay was modelled using a Strain Dependent Modified Cam-Clay model and then with a linear elastic, perfectly plastic Tresca model,
- the effect of composite soil profiles, where a thinner layer of firm soil was added into the otherwise homogeneous soft clay layer.

Full details of the procedures and results are given in Goh (2010). The soil stiffness and the composite soil profile studies showed that using the weighted average of soil stiffness above the final excavation level gives a reasonable estimate for the representative elastic stiffness of the soil. Furthermore, it was found that although ground and building deformation can be significantly influenced by the various factors in the parametric study, the building modification factors are much less affected when building behaviour is described using the proposed definition of relative stiffness. The design guidance shown in Figure 7 would still be applicable.

4 INFLUENCE OF CONSOLIDATION

4.1 *Effect on ground deformation*

Prior to this section, all the building responses were investigated during excavations in undrained condition. This is a reasonable approach only if the speed of excavation is quick relative to the time needed for pore water to flow in a low permeability soil so that consolidation is inhibited. However, there are many instances in published case histories where consolidation settlements are significant for excavations in soft clays (e.g. Nicholson, 1987, Wallace et al, 1993, Wen & Lin, 2002).

Using the same base model for the undrained analysis (i.e. model UD_A as shown in Figure 1), a coupled consolidation analysis was performed for the finite element models by allowing pore water flow according to the boundary conditions and then allowing the soil elements to deform to the pore pressure changes (i.e. model CON_A). This is done by setting the time step to coincide with a realistic time required for each construction sequence. Apart from the first 1 m excavation and the first prop installation (which are assumed to be quick and undrained as before), consolidation was allowed with every metre of excavation taking 10 days and every prop installation taking 30 days. The total excavation duration is about 12 months (see Fig. 9).

Figure 10 compares the wall deflection, the surface settlement and the horizontal displacement profile at the ground surface in the undrained

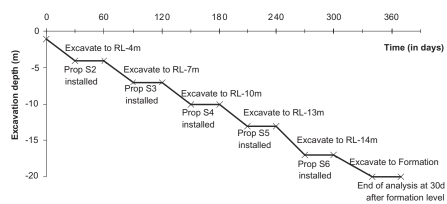


Figure 9. Excavation schedule for consolidation analysis.

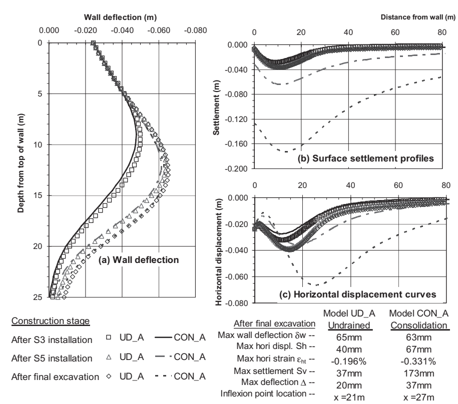


Figure 10. A comparison of wall and ground deformations between undrained (UD_A) and coupled consolidation (CON_A) analysis.

condition and with coupled consolidation. The wall deflection curves are similar between undrained and consolidation analysis at various stages of the excavation. However, the surface settlement and horizontal displacements increased substantially—and this can be up to four times the undrained deformations. The displacement troughs also became wider due to the effect of consolidation.

Figure 11 shows the change in groundwater pressure in the undrained excavation compared to the consolidation analysis, when the excavation has reached formation level. Arising from the significant reduction of vertical overburden within the excavation area, there is a reduction of water pressure across the bearing stratum below the compressible clay layer. This lowering of pore water pressure causes the soft clay layer to consolidate, and is similar to the field behaviour observed by Wen & Lin (2002) on the consolidation settlements being caused by under-drainage of the soft marine clay in Singapore. In comparison, the generation and dissipation of negative excess pore pressures directly behind the wall due to horizontal stress relief is much less dominant.

Additional analyses were also completed to investigate the factors that affect the extent of consolidation and ground deformation in the soil during excavation. These are detailed in Goh (2010), but can be summarised as follows:

- When the permeability of the wall was increased from being completely impermeable to 1×10^{-9} m/s, to simulate a leaking wall, there was an increased consolidation deformation which was more skewed towards the wall.
- When the total excavation period was shortened from 12 months to 6 months, the reduction in pore water pressure behind the wall and the resulting consolidation of the soft clay decreased.
- When the wall toe cut-off length was increased substantially from 5 m to 15 m in the stiff bearing stratum, there is some decrease in the consolidation movements.
- Reducing the permeability of the underlying bearing stratum from 1×10^{-7} m/s to 5×10^{-9} m/s significantly reduced the consolidation deformation so that the behaviour is near to the undrained deformation.
- Increasing the soft clay thickness from 20 m to 28 m resulted in a deeper excavation mechanism and increased the wall and ground movements, but also resulted in a longer drainage path that inhibited seepage in the bearing stratum and reduced consolidation in the overlying soft clay.

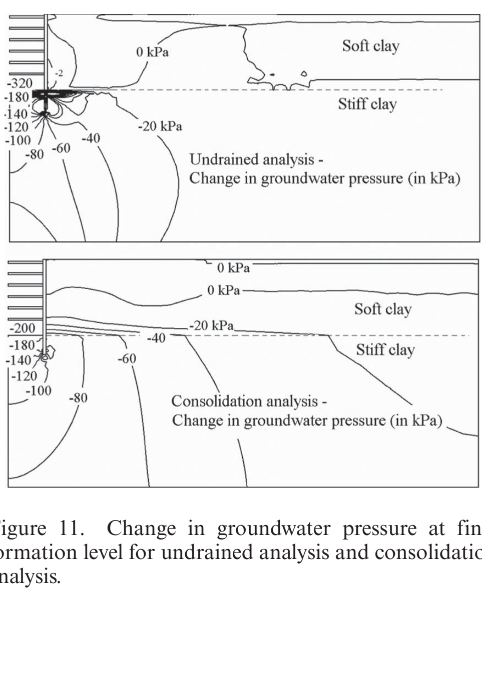


Figure 11. Change in groundwater pressure at final formation level for undrained analysis and consolidation analysis.

4.2 *Effect on building modification factors*

To investigate the influence of consolidation on the building modification factors, a few variations of the consolidation analysis were performed with a 60 m long building at 1 m behind the excavation. Table 3 shows the parameters that were varied in the consolidation analysis of the 20 m deep excavation.

The building stiffness values were varied in each of the consolidation models, and the modification factors of deflection ratio and horizontal strains are plotted against the relative building stiffness in Figure 12. Despite differences in the actual surface displacement profiles, the building modification factors from the consolidation analysis—plotted against the relative building stiffness—fall within the design guidance developed from the undrained analysis. Thus, the modification factor design curves can be used to estimate the response of a building from the deflection ratios and horizontal strains in the greenfield excavation, even when consolidation effects are significant.

Table 3. Variation of consolidation parameters.

	Permeability of wall	Excavation duration	Soft clay thickness
Model CON_A	Impermeable	12 months	20 m
Model CON_A1	10^{-9} m/s	12 months	20 m
Model CON_A2	Impermeable	6 months	20 m
Model CON_A3	Impermeable	12 months	28 m

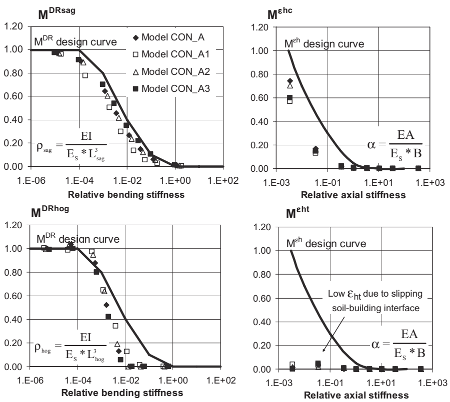


Figure 12. Building modification factors taking account of consolidation movements during excavation.

5 CONCLUSIONS

Using an elastic beam to model the building, it was observed that the deflection behaviour of the building depends mainly on its bending stiffness, while the horizontal displacement response depends on its axial stiffness. A building with higher bending and axial stiffness has a lower deflection ratio and horizontal strain. Therefore, by realistically including the influence of building stiffness to estimate deflection ratios and horizontal strains, the maximum tensile strains induced in the building can be reduced to result in a lower risk of building damage.

Other than bending stiffness, there are several factors related to the building and the excavation that would have an influence on the building deformation behaviour. For example, a shorter building will have a stiffer deflection response compared to a longer building with the same elastic stiffness in bending, and a building adjacent to a deeper excavation generally has a higher modification factor compared to another building with the same elastic and geometric properties adjacent to a shallower excavation.

Through a rigorous investigation of the parameters affecting ground deformations during a deep excavation, it has been found that there is a well-defined relationship between the building modification factors and the relative building stiffness. This makes it possible to use the modification factor and the relative stiffness approach to derive design guidance to estimate the influence of building stiffness on the actual deformation response of the building from the greenfield condition. As presented in this paper, a guidance to estimate the modification factors for buildings adjacent to deep excavations in soft clays has been proposed.

On a final note, it is likely that the proposed design guidance could be more dependent on the shape of the induced settlement trough, rather than on the construction process. In this study, the design curves were derived based on a concave settlement trough during a multi-propped excavation. For a convex settlement trough as observed during cantilever wall excavations, the different restraint conditions provided by the ground could well result in different design curves. On the other hand, a tunnelling-induced settlement curve that is similar to the concave settlement trough could have building modification design curves that are similar to the current study. These can be verified using findings from other research works.

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