Investigation of installation effects in diaphragm wall construction

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Abstract: Parametric studies have been carried out to compare predictions of installation effects of diaphragm walls using empirical methods, 2D and 3D finite element analyses (FEM) using PLAXIS with measurements taken in the field. The aim of the work was to better understand the effects of installation and identify the most sensitive modelling parameters and activities within the process. The FEM modelling and measurements in the field highlighted a number of important factors; different types of panel (primary, secondary or continuous panel) experience varying installation effects, the elevation of support fluid has the greatest impact on stability than any other factor and the accuracy of predictions were most affected by 3D effects and small strain stiffness. The study showed that approximately 50% of the horizontal movements can be recovered during concreting but perhaps more importantly was the fact that installation difficulties can easily quadruple the size of horizontal movements measured in the field thus should never be overlooked. The findings of the study have been used to provide to some suggested guidelines on the appropriate method of prediction for a given project with regard to the sensitivity of the surroundings and likelihood of installation difficulties.

1.0 INTRODUCTION

1.1 Background

Diaphragm wall techniques are most commonly used to enable deep excavations for buildings and infrastructure projects within urban environments. Their use internationally dates back over 50 years however experience in Sweden is limited. Temporary diaphragm walls have been used in two infrastructure projects in Sweden, the Citytunnel project in Malmö in stiff competent soil/rock and the Götaleden project in Gothenburg where soil consists of soft clay. This paper primarily presents findings from a research project funded by SBUF (Svenska Byggbranschens Utvecklingsfond), NCC Construction Sverige AB and Chalmers Tekniska Högskola based on comparisons of field measurements and numerical analyses for the Citytunnel project, full details of the work can be found in [1]. The aims of the research work which forms the basis of this paper was as follows:

- Identify any relevant published cases of movements etc. from other countries
- Identify which factors affect the stability of the diaphragm wall excavation most
- Provide some guidelines on how one should measure and predict installation effects
- Identify what degree of "accuracy" should be used in prediction of movements

1.2 Are installation effects important?

Installation effects of diaphragm walls are often assumed to be negligible. When an excavation is to be carried out the impact of the works is most commonly assessed by use of some sort of numerical analysis. The proposed wall and support works are normally "wished in place" thus only provide information on the effects of the planned excavation sequence and not the works as a whole. The significance of this "assumption" depends entirely on the surroundings.

For the geotechnical engineer the degree of sensitivity in the surroundings is normally indicated by the specified movement criteria. In the project considered horizontal movement criteria's were between 5mm (close proximity to sensitive buildings) and 30mm (no buildings).

The work will show that when relatively tight movement criteria's are specified installation effects form a significant part of the overall impact of geotechnical works. Even projects which tolerate larger movements can have significant installation effects if installation "difficulties" occur.

2.0 CITYTUNNEL PROJECT E101, MALMÖ

2.1 Ground conditions

The soil conditions and characteristic geotechnical parameters used in the FEM analyses are summarised in Figure 1. Limestone was modelled as a homogeneous "soil", in reality the material was highly structured and anisotropic with flint bands up to 1m thick, these issues aside it was judged that strains within the competent rock would be so small that effects on the overall results would be negligible.

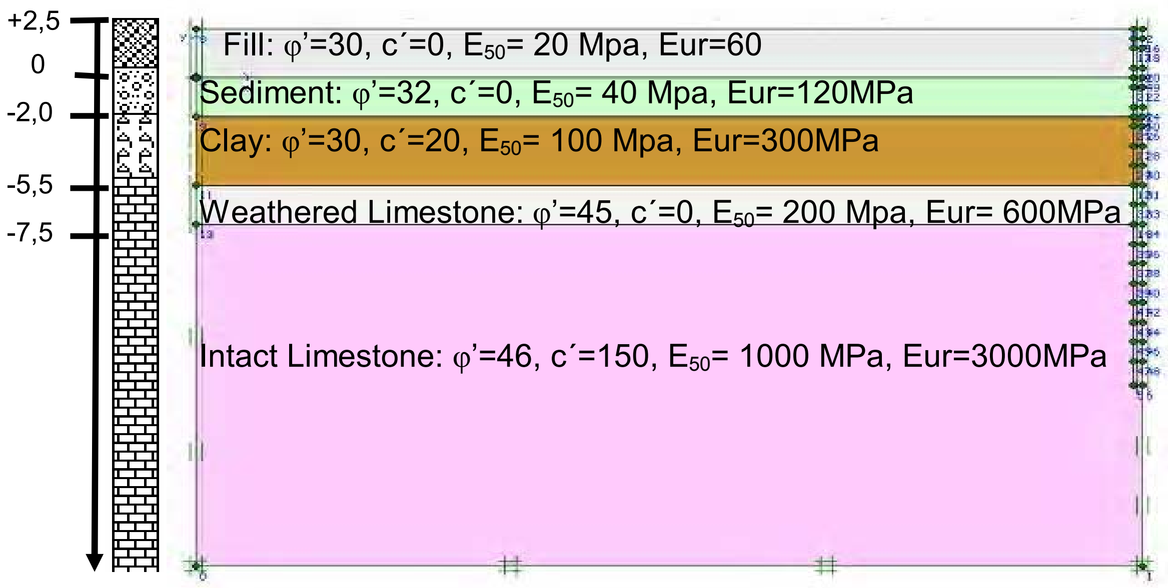


Figure 1: A typical 2D PLAXIS model showing site ground conditions and preliminary soil parameters used for the Citytunnel project

2.2 Construction of diaphragm walls for the Citytunnel project

The method of diaphragm wall construction for the Citytunnel project consisted of use of a "grab" down to competent soil/rock in one to three "bites" depending on the panel size followed by use of a "mill" while the excavation was supported by bentonite slurry. The method of installation is described in full detail in [1] and is briefly summarised in Figure 2. Where particularly "hard" digging was met the use of a chisel was also implemented to increase production rates/reduce wear on the mill. The tools used on site influence the installation effects greatly, particularly in the case of dynamic loads imparted by chiselling which are difficult to analyse numerically.

Both the measurements on site and analyses with 3D FEM show that the type of panel (primary, secondary or continuous) installed can have a significant effect on the horizontal movement profile thus requires some definition. A primary panel is the first panel to be installed and includes installation of a "stop end" at both ends to which adjacent panels are later connected, see Figure 2, sequence 1-3. A secondary panel is a panel for which the panels on either side are already installed as shown in Figure 2, sequence 4. A continuous panel is a panel which connects to a previously installed panel on one side but where there is no other adjoining panel. In general the piling contractor on the project preferred to install "continuous" panels where possible to achieve maximum overall productivity however only primary and secondary panels were used adjacent to sensitive structures in an attempt to reduce movements in these areas.

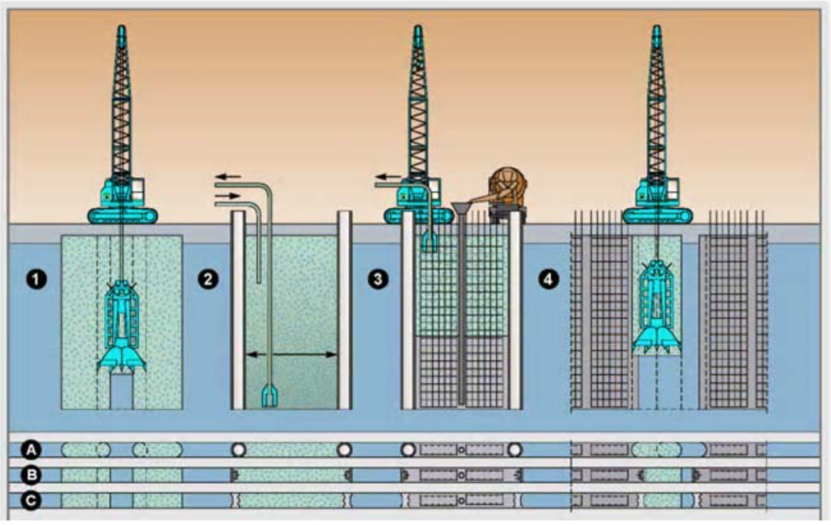
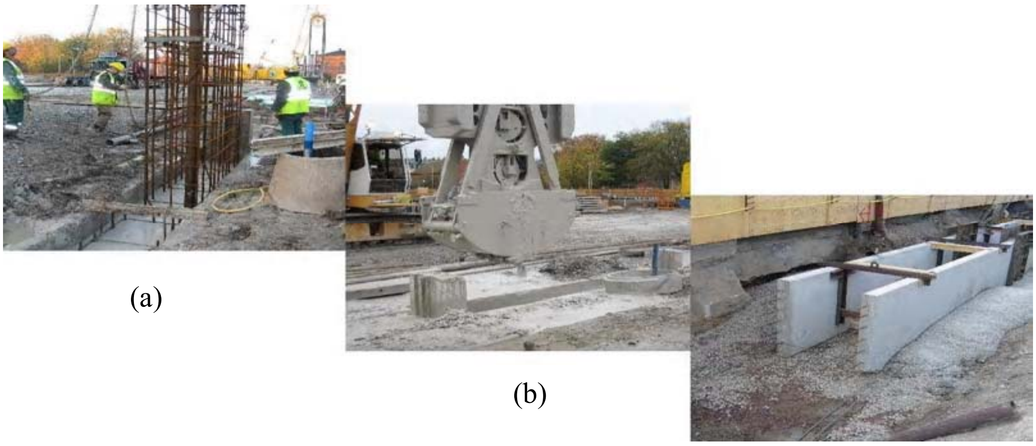


Figure 2: Diaphragm wall, general construction sequence

The diaphragm walls used at Citytunnel E101 were 0.8m thick and installed to depths of between 14m to 24m, the depth of the main excavation was generally 2m above the toe of the wall. Panel sizes varied from 2,8m (adjacent to sensitive structures) to 10,5m and were connected by prefabricated concrete "stop ends" with built in water bar as can be seen in Figure 3(b). In total 11,700 m2 of walls were installed on the project supported at full excavated depth by around 700 temporary rock anchors. The stages of installation of the diaphragm walls consisted of the following:

- installation of concrete guide walls, installed to a depth of 1m, Figure 3(c)
- excavation under bentonite slurry of density ρ=10.4 kN/m^3 and elevation 1.3m above ground water level with a "grab" tool to competent rock at ca 9m, Figure 3(b)
- excavation (under bentonite) from approximately 9m to final depth with the "mill"
- cleaning of the bentonite suspension (often a pause overnight)
- installation of reinforcement cages, Figure 3(a)
- concreting using tremmie pipes from the bottom up



(a)

(b)

(c)

Figure 3: Illustration of some of the phases of panel installation at the Citytunnel project (a) installation of reinforcement (b) excavation with "grab" (c) guide wall installation

2.3 Field Measurements

During installation of diaphragm walls at the Citytunnel project measurements of horizontal movements in the ground were taken to study effects of the installation process. Measurements were taken from 11 inclinometers in 7 different areas around the site, see Figure 4. The "research" area was located in the works area known as etapp 2 where no buildings were present immediately behind the wall at the time of diaphragm wall installation. Four inclinometers were installed in the "research" area, whereas other inclinometers were installed and monitored as part of the contract works. The layout of inclinometers in the "research" area are indicated in figure 5, the geometry and ground conditions for diaphragm wall panels 2-12 (closed panel) and 2-16 (continuous panel) and their adjacent panels were used as the basis for both 2D and 3D FEM analyses.

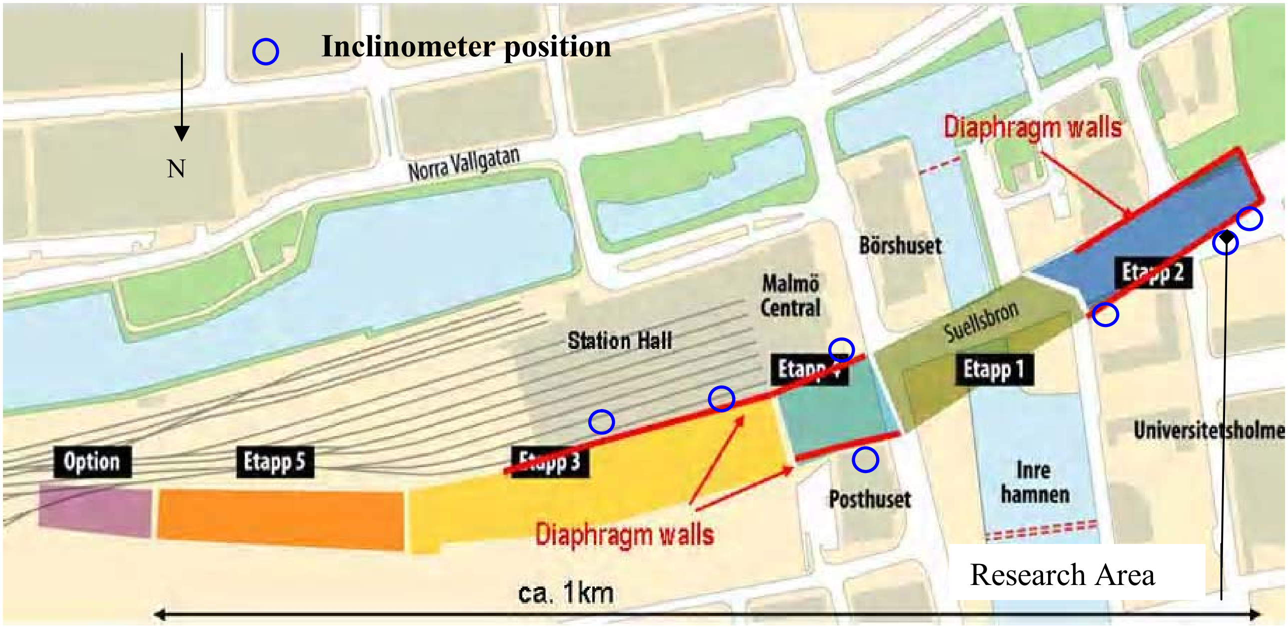


Figure 4: Areas of diaphragm walls and position of inclinometers at the Citytunnel project

Inclinometers in the research area were monitored closely with all measurements taken manually after each stage of the installation according to section 2.2, in addition a final measurement was taken one to two days after completion of the panel. A typical result is shown in figure 6 (a) for selected stages; movements are positive inwards (towards the centre of the wall). One can clearly see movements are greatest at full depth with approximately 50% recovery when the surrounding soil is "reloaded" during concreting followed by a small degree of creep movement. The effects of excavation depth were found to be insignificant at a distance of 4m away from the wall.

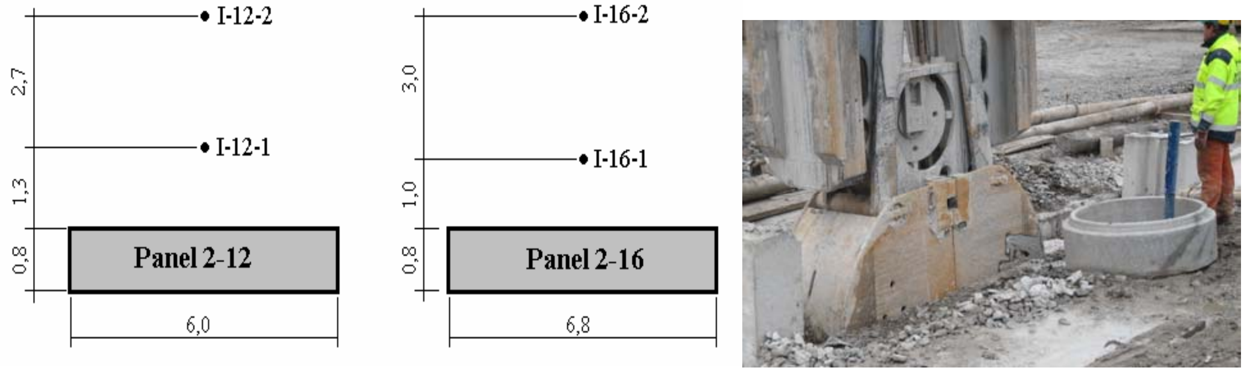
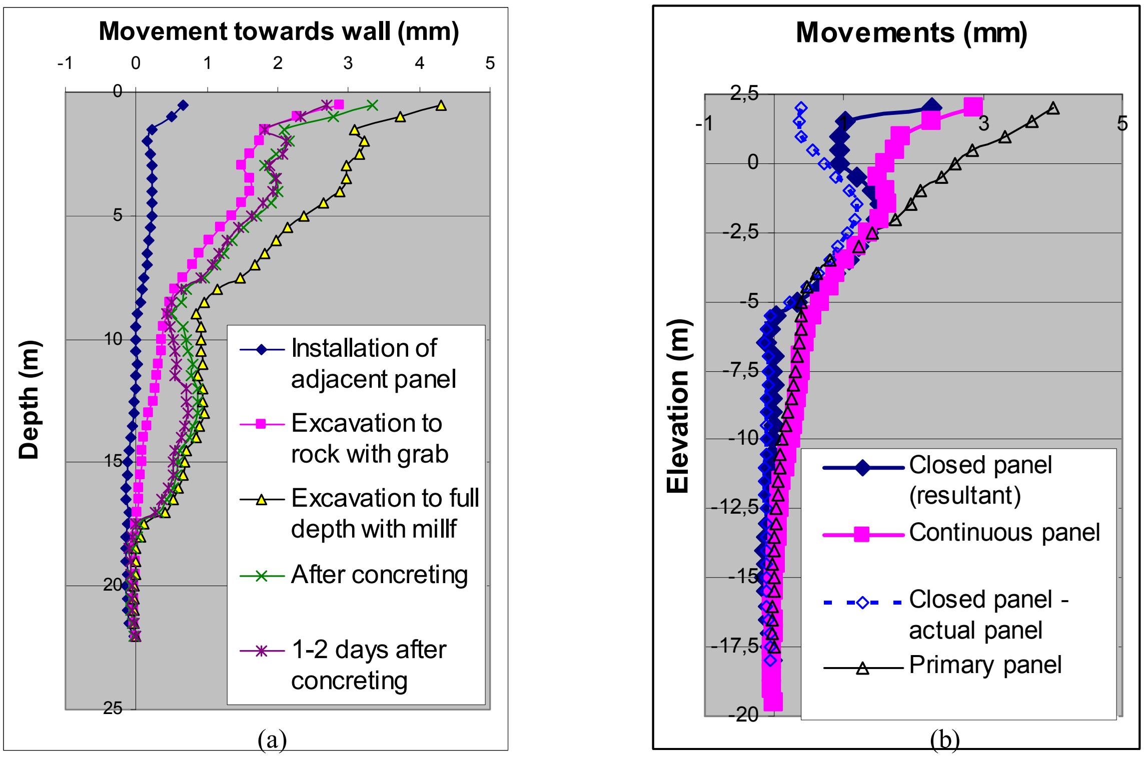


Figure 5: Plan of inclinometers installed behind panel 2-12 and 2-16 and "on site" conditions

When analysing inclinometer measurements it is important to consider the significance of panel type. Figure 6 (b) presents the profiles for all three panel types, the measurements show that not only are 3D effects significantly different for panels which are geometrically very similar but also the influence of the guide wall increases with increasing 3D effects, inducing a more S-shaped profile in the top half of the wall This effect is also evident in results from numerical analyses when the guide wall is modelled as a "wished in place" elastic beam. Movements were greatest during installation of a primary panel with almost double the amount of horizontal movement in comparison with a secondary panel, with a continuous panel lying in between.

Figure 6 (b) presents the horizontal movements for the secondary panel (I12-1) both in terms of movements specific to panel 2-12 and resultant movements which includes the effects from adjacent panels. There is clearly a difference between the two over the top 8m of the wall although perhaps not sinificant from a practical point of view this difference would have a substantial impact on the size of reported movements, particulary when softer soils are present. Given this fact it is vitally important to know both when reference measurements have been taken, what activites on site have occured since calibration and from what level calibration has taken place, it should be outside the area of influence of diahragm wall construction.



(a) (b)

Figure 6: Horizontal movements measured during wall installation (a) during selected stages of installation for a contiguous panel (I16-1), (b) After completion of installation for different panel types at 1m behind the diaphragm wall

Measurements taken using the contract inclinometers around the site were only taken before and after panel installation as determined by the control program due to severe production constraints. The area known as Etapp 3 was immediately adjacent to the piled station hall built around 1912 founded on piles installed to the top of the weathered limestone rock. In some areas replacement piles were installed prior to installation of the diaphragm wall due to fears that the existing piles would clash thus risked damaging the Station Hall. Etapp 4 had sensitive structures on both sides of the excavation (Posthus and Malmö Central) these buildings were founded on traditional strip footings on either the clay moraine or sand/silt sediment above the clay. Measurements from all 11 inclinometers have been normalised by panel depth and are presented in Figure 7. The movements were generally as expected (3-5mm) except at the midpont of the station hall in Etapp3. In this area a horizontal movement of 12mm was measured (allowable horisontal movement < 5mm) with 5mm settlement in the station halls northen fasad and some severe tilting (33mm at roof level). Prior to diahragm wall installation the building was not highlighted as sensative due to the fact it was piled, the investigation that followed and explanation of why excessive movements occured is discussed in

2.4 Prediction of installation effects

After a study of published literature it was concluded that little relevant data was available however guidelines given in ref [3] were used to provide an approximate upper and lower bound empirical prediction, see Figure 8. Static calculations for both internal and external stability were carried out and checked against results from numerical analyses, they were found to give very similar factors of safety. The comparisons showed that installation effects reduced significantly with increased factors of safety (safeguarded by the elevation and density of the support fluid). To better understand the installation process further work focused on the use of FEM analyses. These analyses can be divided into three groups:

- Simulations carried out prior to diaphragm wall installation. These included a parameter study using plain strain 2D PLAXIS models looking at the impact of different soil parameters, soil models, variations in support fluid and even variations in the actual installation process such as extended hold periods etc., full details are given in ref [1]. For clarity only results for the "ground model" are given here using the hardening soil model, see Figure 7, also given is a tentative trend line which can used for approximate estimates of installation effects of diaphragm walls for similar projects.
- Simulations carried out with 3D PLAXIS TUNNEL using both parameters from the 2D ground model and a model which accounted for small strain stiffness. Analyses were carried out when actual movements were known however no conscious attempt was made to "refine" parameters. The effects of installation of adjacent panels are included with each panel being excavated in three bites thus replicating the site sequence.
- Simulations carried out with 2D PLAXIS adjacent to the piled station hall. These analyses were carried out to try and explain why excessive movements of the train hall's northern façade had occurred. A parametric study looked at 10 different cases which replicated the installation sequence used on site to try and reproduce measurements taken in the field both in terms of movements in the ground and pile caps.

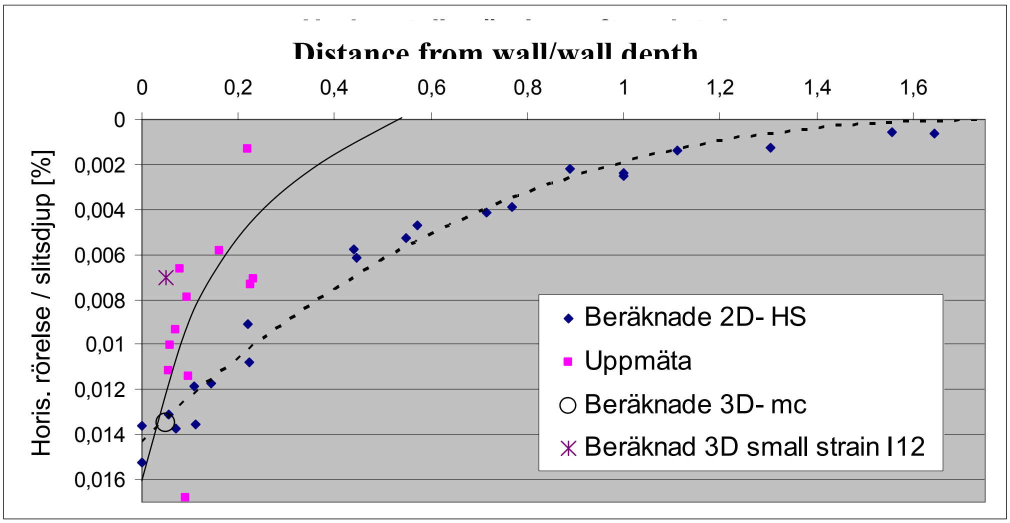


Figure 7: Normalised resultant horisontal movements after diaphragm wall installation measured in the field and predicted with 2D & 3d FEM

Results of the large parametric study with 2D FEM analyses can be found in ref. [1]; they indicate that the two most influential parameters are soil stiffness and elevation of the support fluid during excavation. A simple Mohr Coulomb model using the E_{50} stiffness modulus grossly over estimated movements (400%) whereas use of a hardening soil model overestimated movements by approximately 100%, see Figures 8. The work concluded that both 3D effects and small strain stiffness have a significant effect on the accuracy of the predictions. A comparison of 2D FEM analyses (ground model) for different wall depths and measured movements on site after panel completion (not the maximum values during excavation of panel) are presented in figure 7 and can be used to obtain empirical predictions of horizontal movements for similar ground conditions.

The issues of small strain and 3D effects were investigated further using the 3D FEM program PLAXIS 3D TUNNEL. Comparison of results from simulations of Panel 2-12 are presented in figure 8. It was found that extremely accurate predictions could be made providing that there were no excavation difficulties and that accurate soil parameters could be determined, i.e. good quality soil investigation data was available.

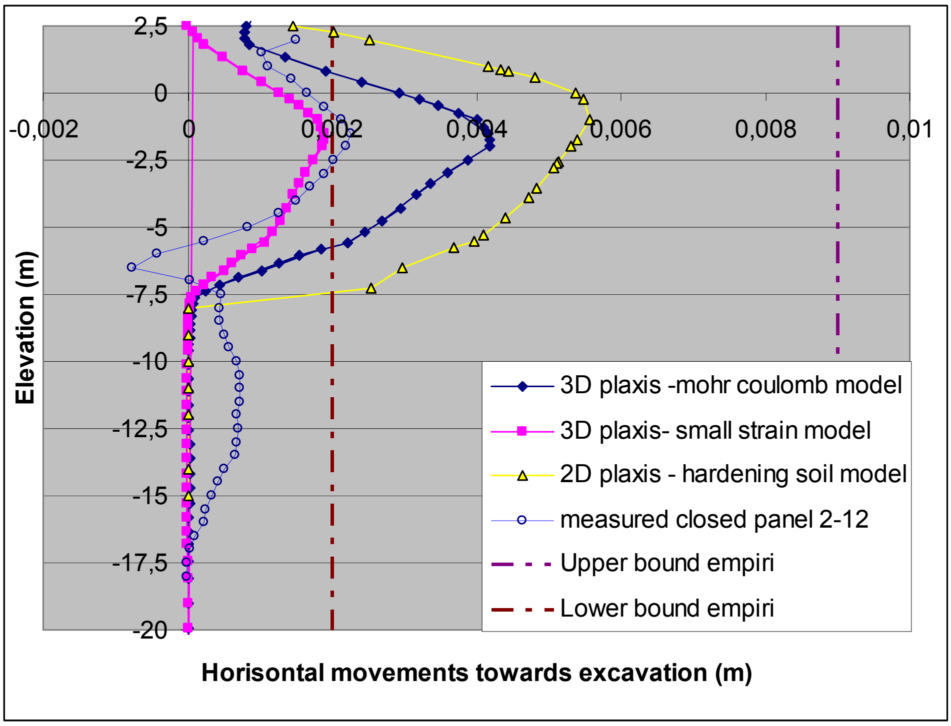


Figure 8: Comparison of predicted movements from empirical methods, 2D, 3D and field measurements for a "closed" panel (20m deep) after installation of the diaphragm wall.

2.5 When installation "difficulties" occur….

Horizontal movements behind the diaphragm wall during installation were generally small (3-5mm) however a number of installation "difficulties" led to larger movements. The "difficulties ranged from rapid loss of support fluid (70m^3) and rapid loss of concrete (80 $m^{3)}$ to breakdown of the piling rig due to "hard" digging of flint bands and siliceous limestone. Installation difficulties were most prevalent in an area adjacent to the station hall where horizontal movements of up to 12mm were measured in the ground and 33mm in the station hall facade such that temporary shoring had to be provided. A total of 10 different scenarios were considered as part of the investigation into the movements with the help of 2D FEM looking at effects of everything from reduction in the soil parameter properties to loss of support fluid and simulation of excavation of a "boulder" (0.5m x 1.0m) from the side of the excavated wall. The scenario which best described movements in the field considered simulation of boulder removal in addition of reduced soil properties within the weathered limestone.

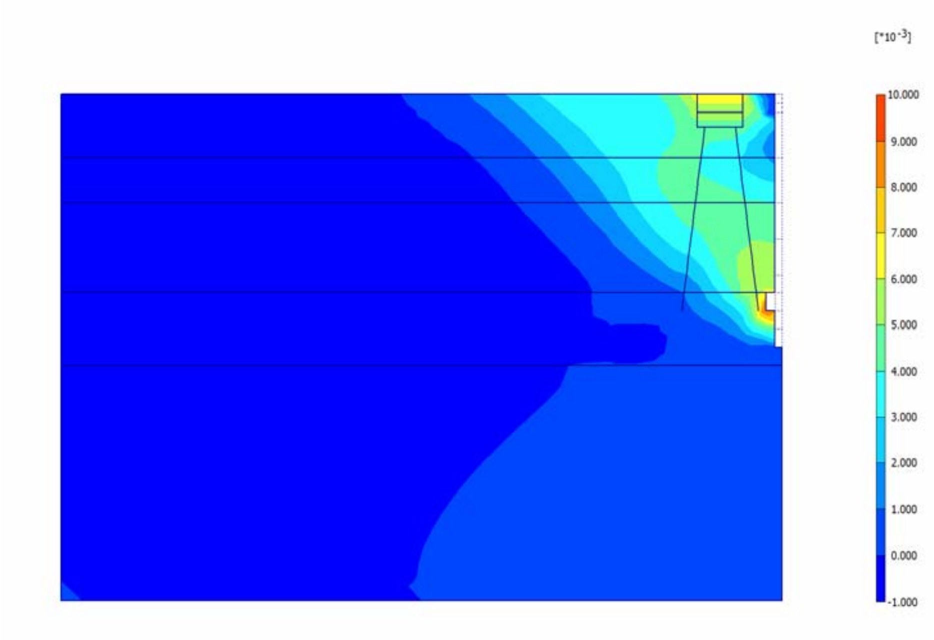


Figure 9: Total movements (10mm) adjacent to Station Hall after simulation of inst. difficulties

This analysis gave a movement profile similar to that measured in the field but with a maximum movement of 10mm, see Figure 9. The analysis underestimated actual measurements slightly most likely due the failure to account for the dynamic effects of the grab and chiselin the analyses. It was concluded after further site investigations and the reults of the 2D FEM analyses that a shear zone existed within the limestone giving reduced strength properies and that excavation using the chisel and grab removed rock from beneath the existing piles effectively removing their toe support. Stability of the piled foundations affected by the installation of the diaphragm walls was reinstated by installation of injected ”titan” piles.

During the citytunnel project the principal installation difficulties were related to both the openness of the weathered limestone and the inclusion of large flint bands and sileaous limestone. Methods used to mitigate the effects of installation difficulties ranged from the use of small 2,8m panels adjacent to structues identified as sensitive (Posthus and Malmö Central) to the provision of a large slurry reservior that could quickly pump more support fluid to a panel under construction if rapid fluid loss occured. In the worst areas pre-grouting of the limestone with cement slurry prior to installation of the panels was carried out to reduce both the economic and environmental risk of large quantities of concrete and slurry suddenly being ”lost”. These measures worked to good effect but delays in production could have been mitigated if these issues had been investigated at project planning stage.

3.0 CONCLUSIONS AND RECOMMENDATIONS

Experiences from the Citytunnel E101 project illustrate that installation effects of diaphragm walls should not be ignored. In terms of horizontal movements the installation of the diaphragm walls caused horizontal movements of between 3-5 mm throughout the site providing no installation “difficulties” occurred with no clear difference between short panels (2,8m wide) and large panels (9,8m wide) after panel completion. These movements although small by most standards are significant with consideration of the sensitivity of the surroundings and specified tolerances. One can question if the specified movement tolerances of 5mm were reasonable but not the fact that installation effects represented a large part of the total movements caused by geotechnical works (50%) even without installation difficulties.

The most important factors that affect the impact of diaphragm wall installation are support fluid and soil stiffness assuming one has ensured internal stability. Empirical predictions based on relevant case studies give good approximations of upper and lower bound movements are an adequate method of prediction for the majority of projects where no tight movement restrictions are specified. Provision of a high factor of safety in static calculations will also ensure installation effects are small.

The author is a firm believer in the use of FEM calculations in the modelling of installation effects but these calculations are futile unless reliable soil parameters are present and specified movement tolerances are small (<10mm). When both these factors are present 3D analyses allowing for small strain stiffness can provide accurate predictions of movements (+10%), however time to carry out these analyses and verify the results can be significant.

The use of 2D FEM has been proved to be a powerful tool in terms of analysing the consequences of “unplanned” events and sensitivity of installation effects to variations in factors such as changes in support fluid or soil parameters at the Citytunne1 E101 project but over-predicts movements by approximately 100% when compared with the field. The discrepancy is explained by the failure of the analyses to take account of 3D effects and small strain stiffness. The author feels such analyses should be a “must” where tight movement tolerances are specified as a vital part of the geotechnical risk management process. The analyses can be fairly quickly undertaken and provide a much understanding of the overall influence of installation effects and soil-structure interaction.

When verifying installation effects on site one should always consider the following:

- Accurately monitor at least 2 two panel types which are similar geometrically, one primary panel and one closed panel to obtain the range of movements with depth.
- Check when the inclinometer was calibrated and how (which elevation) and protect it from construction traffic, see Figure 5.
- Measure movements for each key stage of the installation process according to 2.2 including activities prior to installation of the panel (guidewall, adjacent panels etc.)
- Keep detailed notes of the installation process (hold periods, change to digging method, support fluid density and elevation etc.) to assist with interpretation of results
- Remember movements in the ground adjacent to structures are often slightly smaller than the “green field” (no structures).

The work presented in this paper highlights a number of important factors; different types of panel exhibit different behaviour under installation, approximately 50% of the horizontal movements were recovered during concreting regardless of panel type, post installation effects were small but most importantly when in close proximity to sensitive structures one must not forget to investigate the effects of potential installation “difficulties”. In this respect the use of 2D FEM analyses can be a fantastic tool in the assessment of the effects of installation “difficulties”.

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