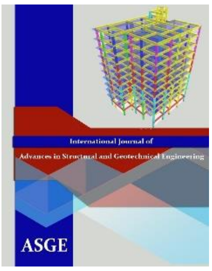



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# Comparative Study between 2D and 3D Analysis for Deep Excavation Case History

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## ABSTRACT

The design of deep excavation problems is considered a huge challenge for the designers. Both 2D and 3D modelling are usually considered in the analysis and design. The results of the straining actions including bending moments, shear forces and normal forces as well as forces in lateral supports may differ in case of 2D and 3D analysis. The wall deformation as well as the subsidence profile may also differ in case of 2D and 3D analysis. In this study, PLAXIS 2D and 3D shall be used to assess the adequacy of the software in predicting the site measurements for a case history. The variations in results between both the 2D and 3D analysis shall be also discussed.

***Keywords:*** *Deep excavation, Sheet pile wall, Pre-stressed ground anchors, Plaxis 2D, Plaxis 3D, Case study.*

## INTRODUCTION

Correct modeling of deep excavation problems is always considered a challenge. Case study is selected to evaluate the adequacy of the Plaxis software to predict the settlement profile near deep excavation, wall deformations as well as forces in lateral supports. A description of the general parameters, such as the evaluated soil parameters, pore pressures, the geometry of the excavation and the SPW and anchor characteristics can be found. The input and calculation conditions for the different calculation methods and material models used in this model are also described. The results are obtained from calculations using both Plaxis 2D and Plaxis 3D and compared with the site measurements. Both Mohr coulomb model and hardening soil model shall be adopted in the study.

## CASE HISTORY

The SPW was installed during the construction of the southernmost tunnel face of Götatunneln in central Gothenburg; see the area marked by an ellipse in Figure 1.

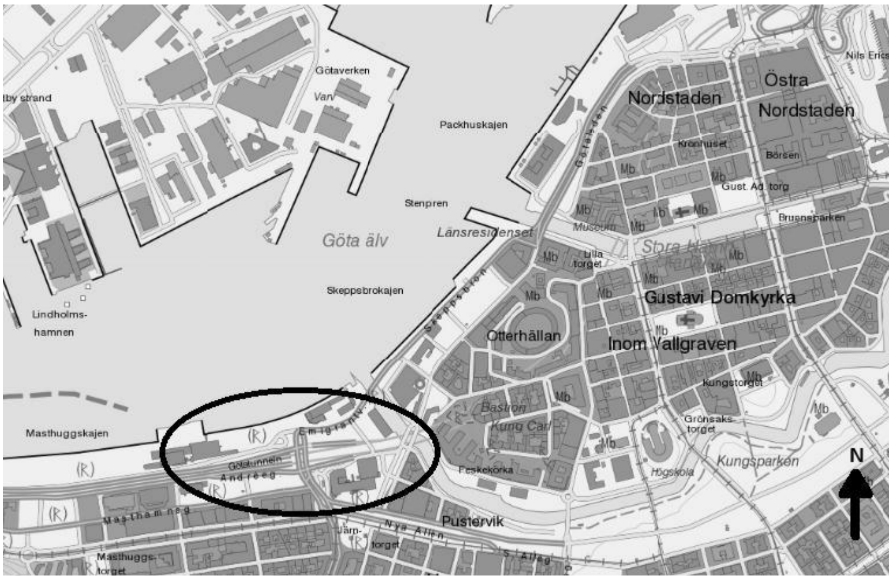


Figure 1: Location of the excavation shaft (VISS, 2014).

The studied part of the SPW is located between two buildings, see Figure 2. The surrounding buildings are located approximately 20 meters from the studied cross-section and it is therefore assumed that they do not affect the SPW. The excavation might affect the surrounding buildings by causing settlements in the area, but such impacts on the surrounding buildings are not considered in this study.

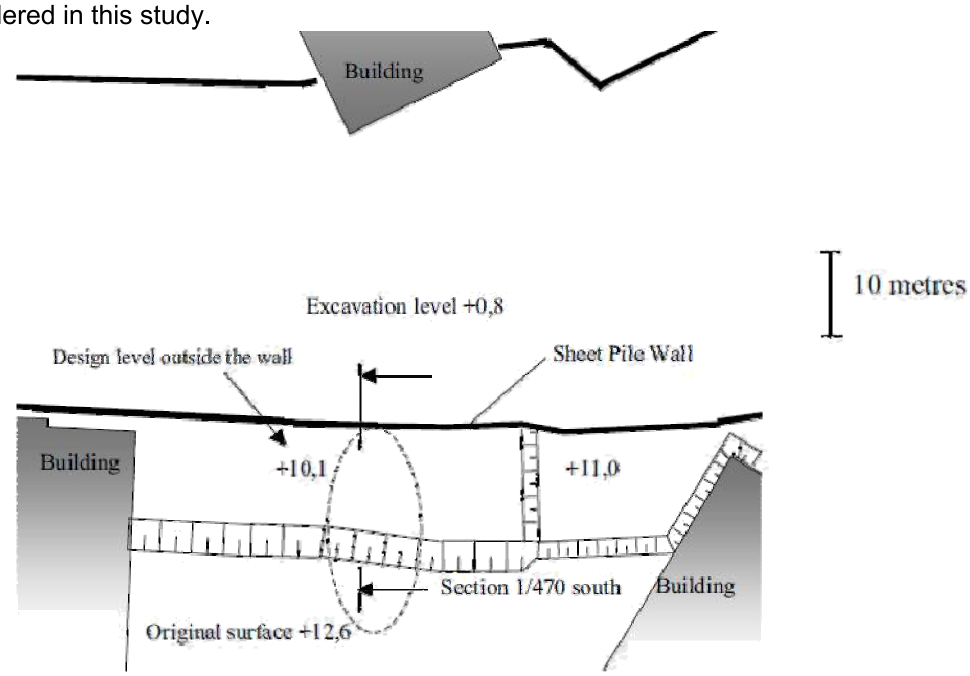


Figure 2: Plan of the excavation shaft with the studied SPW marked as a section (Kullingsjö, 2007, p. 107).

The geometry used in the calculations is based on Kullingsjö (2007, p. 108). The shaft is approximately 11 meters deep, the SPW is installed down to and attached to the bedrock and has wales and anchors at three different levels, as can be seen in Figure 3.
The installation procedure for the SPW and anchors is illustrated in Figure 3 and is as follows (Kullingsjö, 2007, p. 109):

a) Installation of the SPW.
b) Excavation to a depth of 2 meters on both sides of the SPW.
c) Excavation to a depth of 4 meters in front of the SPW.

d) Installation of wales and anchors at a depth of 3.5 meters.
e) Excavation to a depth of 6.5 meters in front of the SPW and 8.5 meters just beside the SPW.
f) Installation of wales and anchors at a depth of 7.5 meters.
g) Excavation to a depth of 9 meters in front of the SPW and 11.5 meters just beside the SPW.
h) Installation of wales and anchors at a depth of 10.5 meters.
i) Excavation to a depth of 11.7 meters in front of the SPW.

This information is used to model the calculation phases for this case

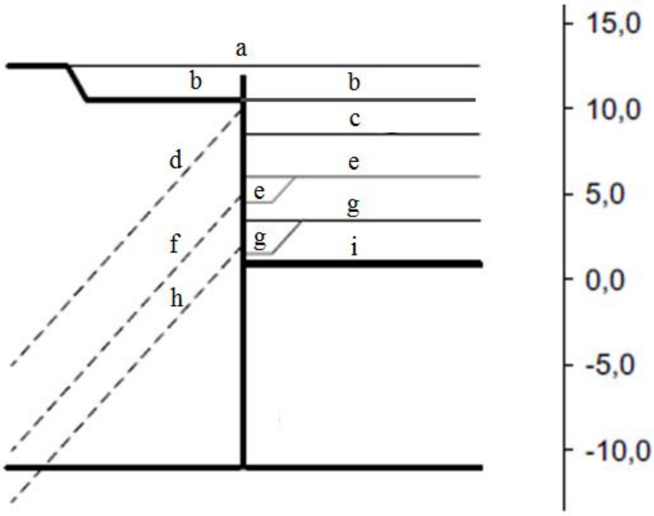


Figure 3: Schematic figure of the geometry of the excavation shaft (Kullingsjö, 2007, p. 108), .modified by authors

## SOIL DATA

The soil consists of 3 meters of fill on top of 19 meters of slightly overconsolidated clay. Beneath that there is approximately 1.5 meters of sand and then there is bedrock, see Figure 4.

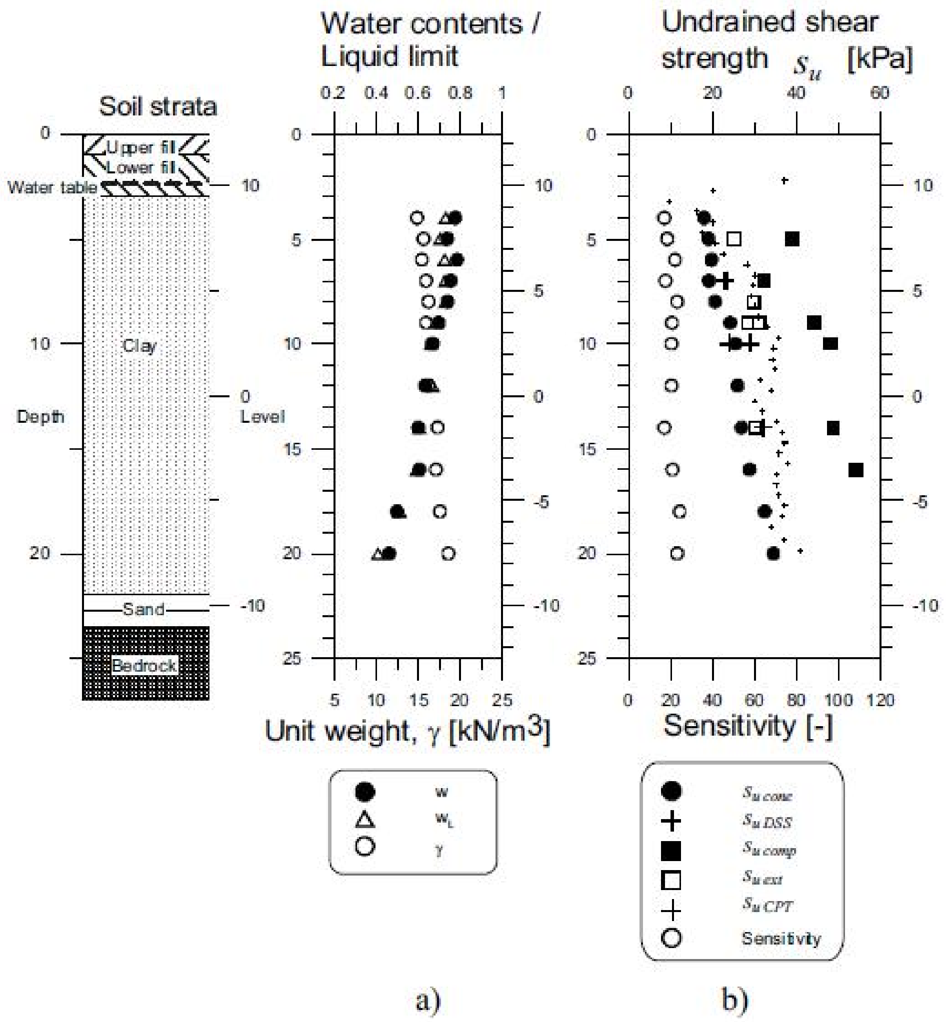


Figure 4: Soil strata and evaluated soil parameters for the analysed area (Kullingsjö, 2007, p. 136)

Figure 5 shows the following insitu/lab test results and selected parameters, which are summarized as follows.

- Variation of OCR with depth as per the insitu conditions.
- The undrained shear strength, which used in the model is evaluated from a compilation of several different tests,
- The parameter $\varphi'_{cv}$ which is used for the clay layers in all models and evaluated from triaxial tests.
- The undrained Young's modulus, $E_u$, is also evaluated from triaxial tests.

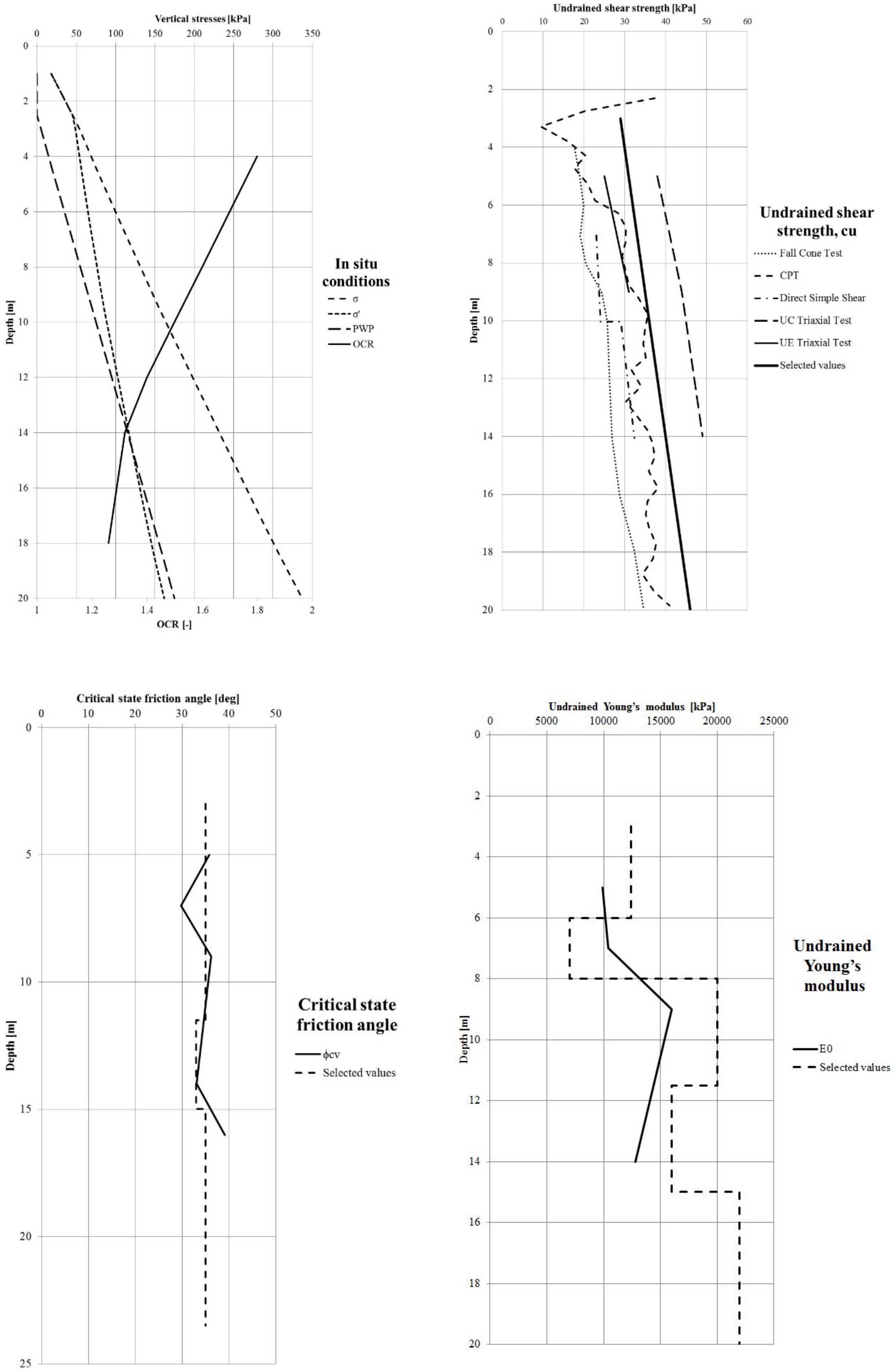


Figure 5: the insitu/lab test results and selected parameters

## PORE WATER PRESSURE

The PWP is based on measurements performed during the construction of the SPW, which are presented by Kullingsjö (2007). These measurements show that the groundwater surface is at approximately 2 meters below the ground surface and that the hydraulic head measured at different depths vary between approximately 2-2.5 meters beneath the ground surface.
For simplified use in the models it is assumed that the groundwater surface is 2 meters below the ground surface and that the PWP is hydrostatic.

## SHEET PILE WALL AND ANCHORS

The SPW is an anchored Z-section AZ36 SPW. The characteristics of the SPW are presented in Table 1. The SPW is installed down to the bedrock, at 23.5 m depth (Kullingsjö, 2007, p. 106). The following table summarizes the characteristics of AZ36 SPW (ArcelorMittal, n.d.).

Table 1: AZ-36 SPW material properties

| Parameter | Value | Unit |
|---|---|---|
| Weight, w | 1.90 | $kN/m^2$ |
| Young's modulus, E | $2.1 * 10^8$ | kPa |
| Moment of inertia, I | $8.28 * 10^{-4}$ | $m^4/m$ |
| Normal stiffness, EA | $5.19 * 10^6$ | kN/m |
| Flexural rigidity, EI | $1.74 * 10^5$ | $kNm^2/m$ |

The anchors used are cable anchors which are installed with an angle of 45° and anchored in bedrock. The anchors are installed in three rows, symbolized by the arrows in Figure 3.3, at depths 3.5, 7.5 and 10.5 meters (Kullingsjö, 2007, pp. 110-116). The input parameters, c-c distance and the pre-stress applied to the different anchors can be seen in Table 2.

Table 2: Pre-stressed anchors parameters

| Parameter | Row 1 | Row 2 | Row 3 | Unit |
|---|---|---|---|---|
| Length | 28.3 | 22.6 | 18.4 | m |
| Number of strands | 12 | 12 | 12 | - |
| Young's modulus, E | 1.95 * 108 | 1.95 * 108 | 1.95 * 108 | kPa |
| Normal stiffness, EA | 4.88 * 105 | 4.88 * 105 | 4.88 * 105 | kN/m |
| C-C distance | 5.9 | 2.2 | 2.1 | m |
| Pre-stress | 170 | 523 | 548 | kN/m |

## SOIL PARAMETERS

The soil parameters had been concluded based on the site investigation data, tests results as well the following correlations. Both Mohr coulomb model and hardening soil model are used in the analysis. Undrained A method had been considered which involves the use of drained parameters with undrained drainage type.

- Undrained parameters: Based on site investigation and test results (Emil Johansson 2014).
- Drained parameters: Based on the following equations.

  Equation 1: $C' = 0.1\ C_u$ (Danish code) Equation 2: $E_u = 3\ E_d / (2*(1+ \nu'))$

- Hardening soil model parameters: Based on the following equations: (The hardening soil model-a practical guidebook, z soil.pc 100701 report.)

Equation 3: $$E_{50} = E_{50}^{ref}\left(\frac{c\cos\phi - \sigma_3'\sin\phi}{c\cos\phi + p^{ref}\sin\phi}\right)^m$$

Equation 4: $$E_{oed} = E_{50}\left(\frac{1-\nu}{(1+\nu)(1-2\nu)}\right)$$

Equation 5: $$E_{oed} = E_{oed}^{ref}\left(\frac{c\cos\phi - \sigma_1'\sin\phi}{c\cos\phi + p^{ref}\sin\phi}\right)^m$$

The adopted soil profile and parameters can be summarized as per the following table.

Table 3: summary of adopted soil profile and parameters

| Level | | Undrained parameters | | Drained parameters | | | Hardening soil model parameters | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Top | Bottom | $C_u$ (kPa) | Eu (MPa) | $C_d$ (MPa) | $\phi_d$ | Ed (MPa) | E50 ref (MPa) | Eoed ref (MPa) | Eur ref (MPa) | m |
| 0.00 | -3.00 | --- | 50 | --- | 30 | 43 | 117 | 111 | 351 | 0.5 |
| -3.00 | -6.00 | 30 | 12.4 | 3 | 35 | 10.7 | 25.4 | 23.3 | 64.8 | 0.8 |
| -6.00 | -8.00 | 33 | 7 | 3.3 | 35 | 6 | 12.6 | 10.8 | 31.5 | 0.8 |
| -8.00 | -11.50 | 36 | 20 | 3.6 | 35 | 17 | 30.4 | 26 | 76.1 | 0.8 |
| -11.50 | -15.00 | 39 | 16 | 3.9 | 33 | 14 | 21.6 | 17.9 | 53.9 | 0.8 |
| -15.00 | -23.50 | 45 | 22 | 4.5 | 35 | 19 | 23.8 | 18.5 | 59.6 | 0.8 |

## ANALYSIS USING PLAXIS 2D AND PLAXIS 3D

The aim of analysis is to assess the site readings taken in the short term condition during the construction period using 2D and 3D analysis. Both Mohr coulomb soil model and hardening soil model had been used. Undrained analysis had been considered in the analysis, as the undrained represents the short term behavior during the construction.

The construction sequence in the Plaxis followed the following 9 phases which can be summarized as per the following table

Table 4: The construction sequence in Plaxis

| Phase No. | Description |
|---|---|
| Phase 1 | Install the sheet pile walls |
| Phase 2 | Excavate till depth 2 meters at both sides of the wall |
| Phase 3 | Excavate till depth 4 meters |
| Phase 4 | Install row 1 of anchors at depth 3.5 meters and adjust pre-stressing force |
| Phase 5 | Excavate till depth 8 meters |
| Phase 6 | Install row 2 of anchors at depth 7.5 meters and adjust pre-stressing force |
| Phase 7 | Excavate till depth 11 meters |
| Phase 8 | Install row 3 of anchors at depth 10.5 meters and adjust pre-stressing force |
| Phase 9 | Excavate till depth 11.7 meters |

**Models Configurations**

The 2D and 3D models configurations are shown as per figures 6 and 7 respectively.

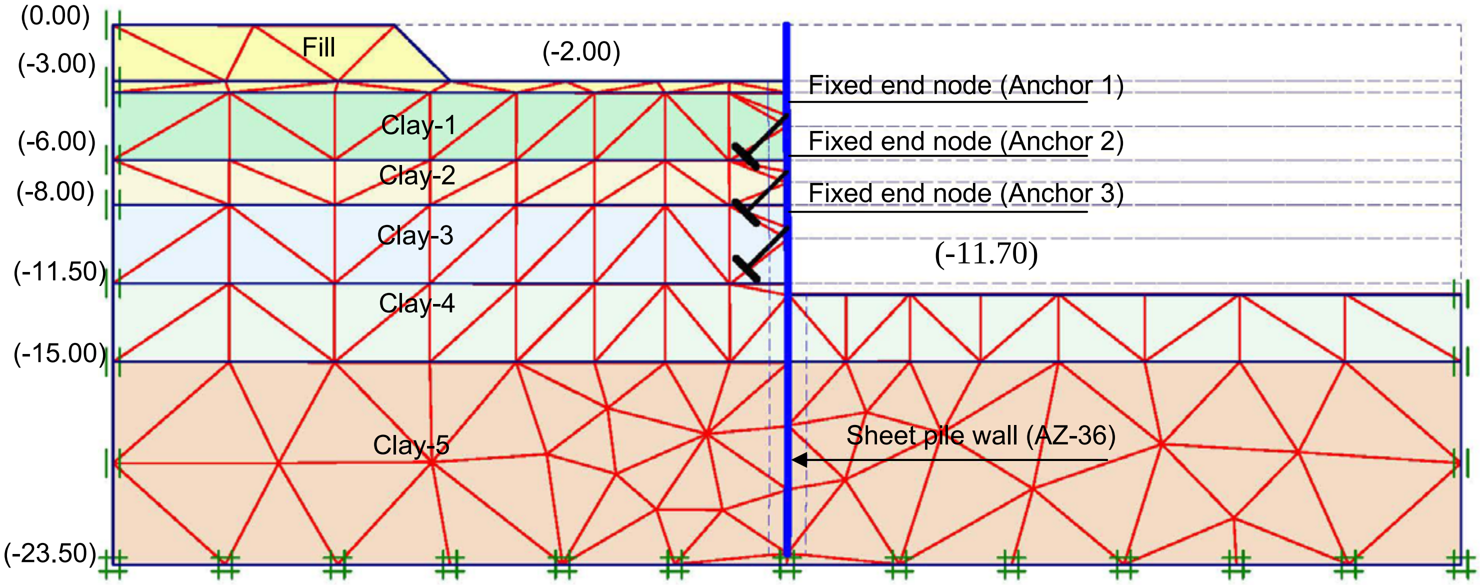


Figure 6: 3D Model general configuration during the last phase

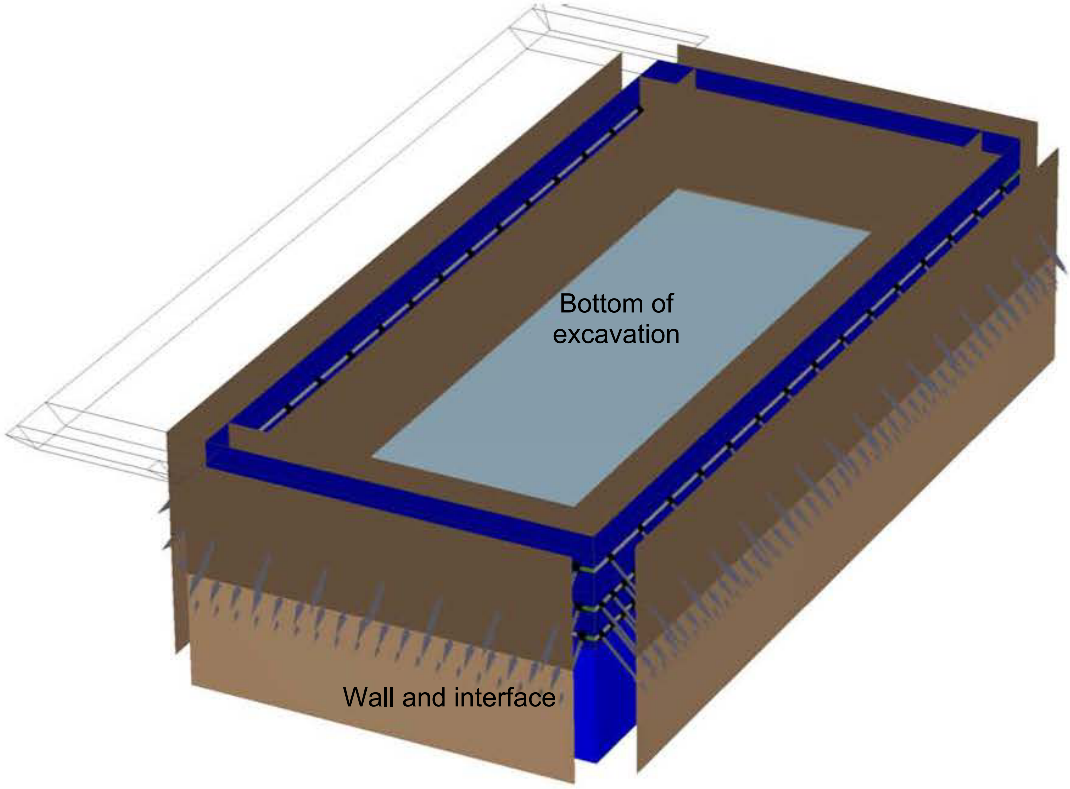


Figure 7: 3D Model general configuration during the last phase

**Results Of Analysis**

The resulting bending moment envelope for both 2D and 3D analysis can be summarized as per figure 8 and 9 for Mohr coulomb model and hardening soil model respectively.

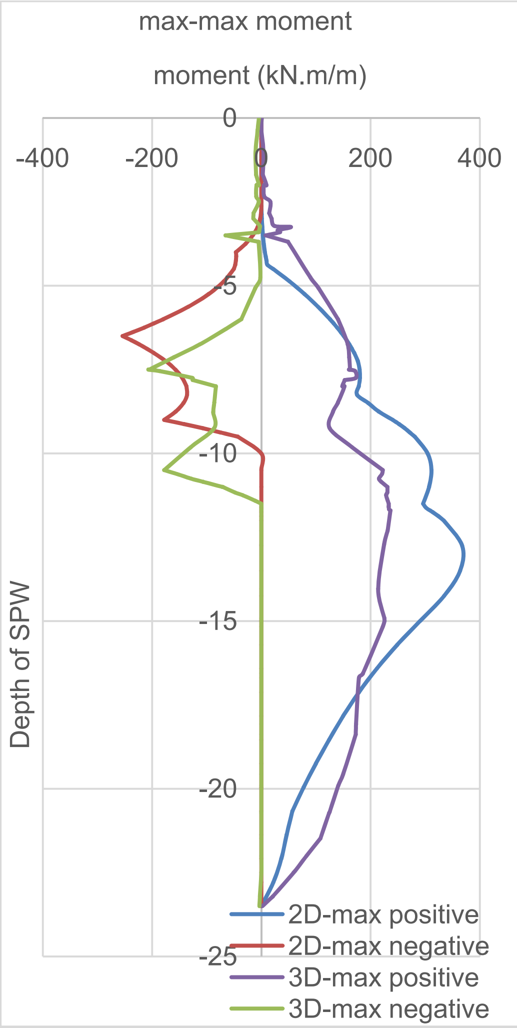


Figure 8: bending moment for Mohr coulomb model

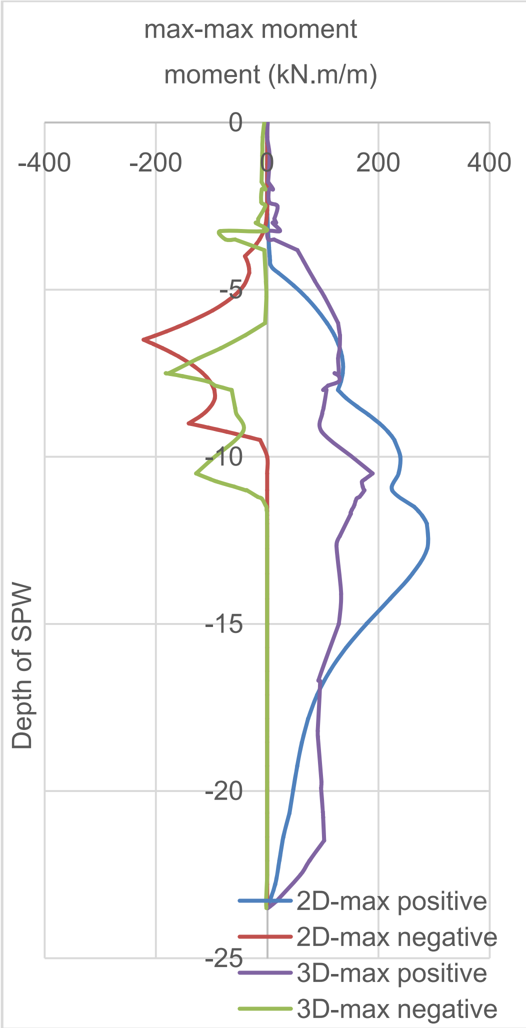


Figure 9: bending moment for Hardening soil model

The resulting anchors forces from the analysis are compared to the measured values during the project works. Figure 10 and 11 shows the anchor forces for Mohr coulomb models and hardening soil models respectively.

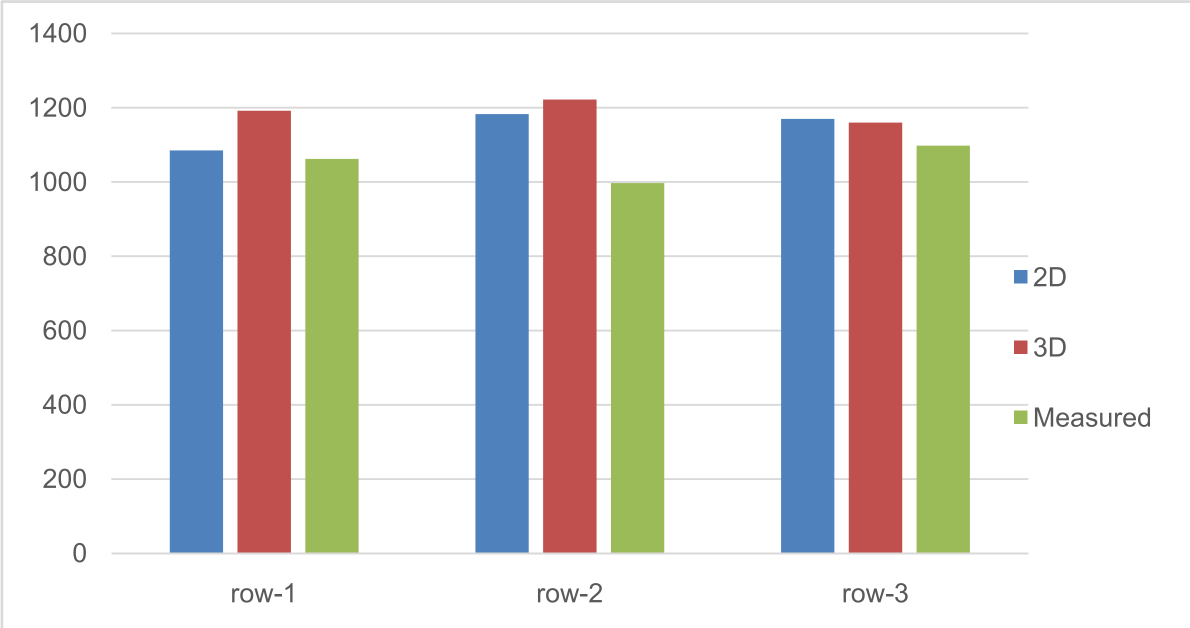


Figure 10: Forces in the ground anchors for Mohr coulomb model

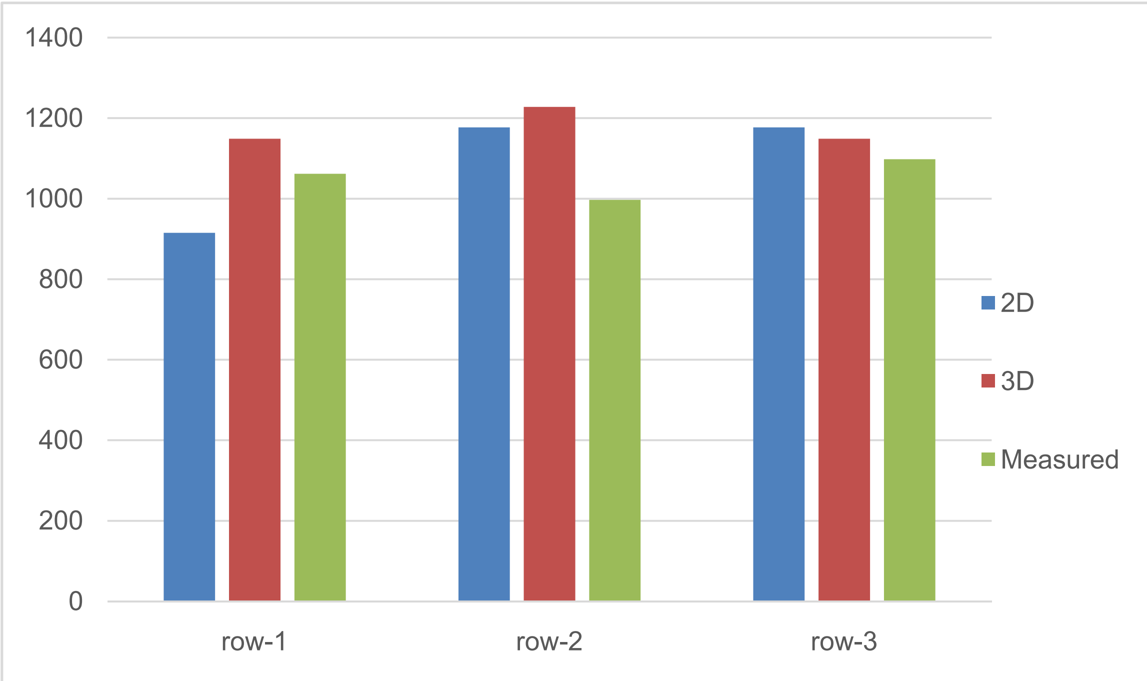


Figure 11: Forces in the ground anchors for Hardening soil model.

The deformations of the wall and the subsidence profile were also measured during the project works. Figures 12 and 13 shows the wall deformations for Plaxis 2D and 3D respectively, while figures 14 and 15 shows the subsidence profile for Plaxis 2D and 3D respectively.

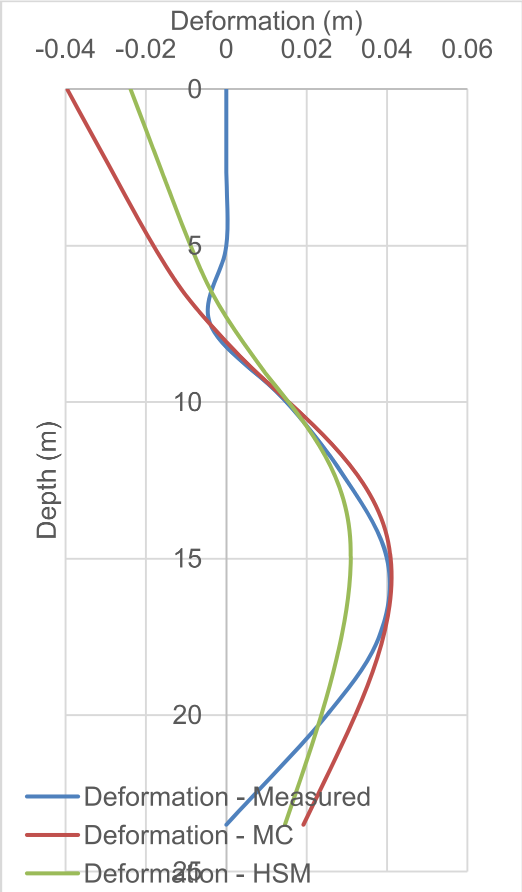


Figure 12: wall deformations for 2D analysis

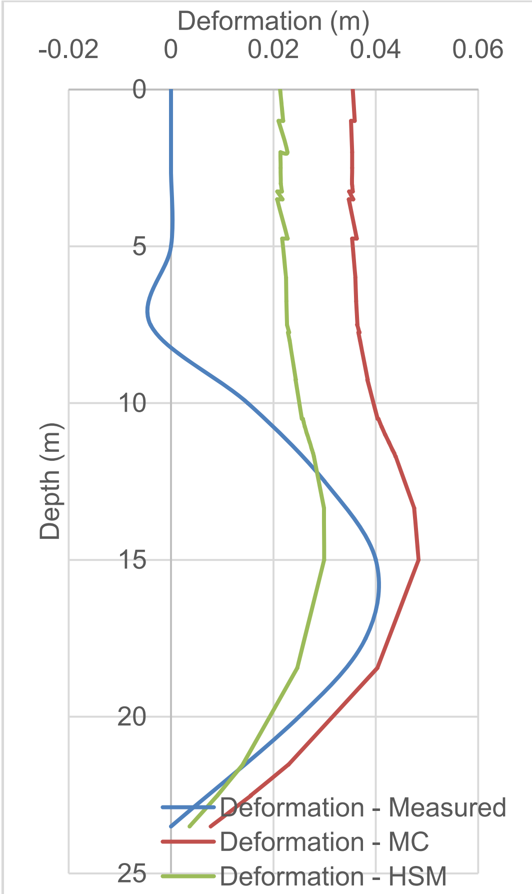


Figure 13: wall deformations for 3D analysis

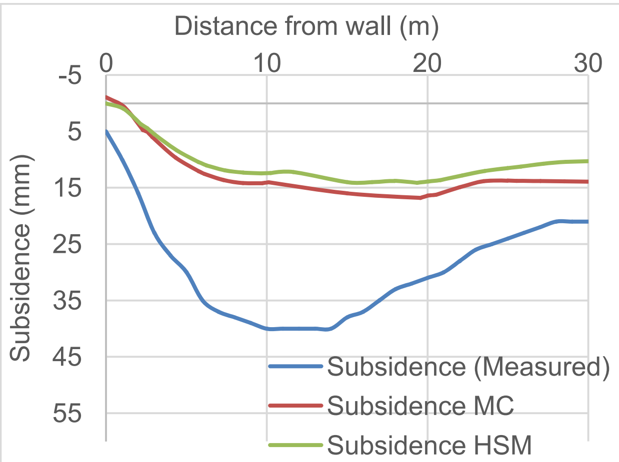


Figure 14: subsidence profile for 2D analysis

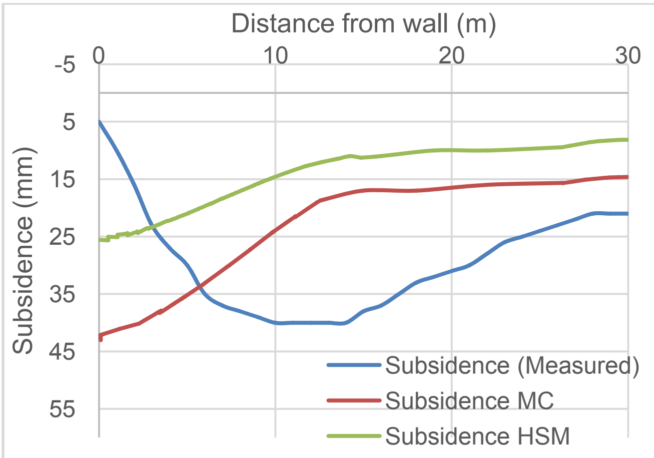


Figure 15: subsidence profile for 3D analysis

## CONSLUSIONS AND COMMENTS ON RESULTS

1- Anchors: The 2D and 3D analysis showed close results to the measured values during the project excavation works, the resulting anchor forces in the analysis is higher in most cases than the measured value, which is considered more conservative and more safe.

2- The wall deformations: The 2D and 3D analysis showed close results to the measured values during the project excavation works. The location and value of the maximum measured wall deformation is almost the same as the analysis results. The trend of the measured deformation is close to the analysis results. The measured deformation for the lower part of the wall was almost the same for both 2D and 3D analysis, while the measured deformation of the upper part of the wall was almost the average value between the 2D and 3D analysis.

3- The subsidence profile: The 2D and 3D analysis showed close results to the measured values during the project excavation works. The trend of the profile in case of 2D analysis was almost the same as the measure values. The trend of the profile in case of 3D analsyis was different until distance 10 meters away from the wall, and then it caught the measured trend from distance 10 meters to 30 meters away from the wall. It worth to mention that the maximum value is less than the measured one, as there might be partial drainage occurring in the area, which could cause consolidation settlements in the soil.

4- Bending moment of wall: The 2D and 3D showed close bending moments. The moment diagram as well as the maximum moment values were close. The maximum moments resulting from 3D analysis were mostly less than 2D analysis by about 30%, which is considered accepted range between 2D and 3D analysis.

5- For such problems with length of excavation pit much higher than width, the 2D analysis which considers plane strain simulation give close results in terms of straining actions and deformations. Accordingly, both 2D and 3D modelling are considered adequate for such deep excavation problems.

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