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3D finite element analysis of a deep excavation and comparison with in situ measurements

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ABSTRACT: The paper describes the analysis of a deep excavation project in clayey silt in Salzburg. The excavation was supported by a diaphragm wall, a jet grout panel and three levels of struts. Because of insufficient information on the material properties of the jet grout panel the stiffness of it was varied in a parametric study. The effect of taking into account the stiffness of a cracked diaphragm wall on the deformations was also investigated. In some of the 3D calculations a non-perfect contact between diaphragm wall and strut was simulated by means of a non-linear behaviour of the strut. The evaluation of the results and comparison with in situ measurements showed that analyses which took into account the reduced stiffness of the diaphragm wall due to cracking achieved the best agreement with the measurements. Furthermore settlements of buildings could be best reproduced by the three-dimensional model.

1 INTRODUCTION

Soft subsoil deposits in Austria are mainly fresh water deposits, sedimented in the post-glacial lakes after the boulder periods. These deposits are known as lacustrine clays on the foothills of the Alps. One example for a widespread lacustrine clay deposit is the basin of Salzburg, where the city of Salzburg is situated on subsoil sediments, which partly show a thickness up to 70 m, called "Salzburger Seeton", which can be classified as clayey silt.

In the design stage of deep excavations in such problematic soils finite element calculations are a useful tool to obtain reasonably realistic predictions of deformations expected. In practical engineering 2D-models are still prevailing, but 3D-model become increasingly attractive. It will be shown, and this is the main purpose of this paper, that the best overall match with in situ measurements, in particular with respect to surface displacements behind the wall, is achieved with 3D-models. If only wall deflection is considered also 2D analyses show reasonable agreement. The mechanical behaviour of the soil is modelled with an elasto-plastic constitutive model, namely the Hardening Soil model as implemented in the finite element code Plaxis (Brinkgreve 2002). For the project the "class A" 2D analysis predicted the overall deformation behaviour with sufficient accuracy from a practical point of view, but a more detailed comparison with in situ measurements has been made after construction involving 3D finite element analyses. Furthermore some details with respect to the strutting have been changed during construction which have not been taken into account in the original analysis.

The input parameters for the constitutive model have been determined not solely from site investigations but also from previous experience of finite element analyses under similar conditions (see e.g. Schweiger & Breymann 2005).

In the following a brief description of the problem will be provided together with the material parameter used. The different assumptions with respect to modelling the diaphragm wall and the jet grout panel are discussed. Finally results from various 2D and 3D analyses are compared with in situ measurements of wall deflection and surface displacements.

2 PROBLEM DESCRIPTION AND MATERIAL PARAMETERS

2.1 *Project description*

A cross section of the excavation with strut levels and final excavation depth is shown in Figure 1. In plan the excavation is roughly square, approximately

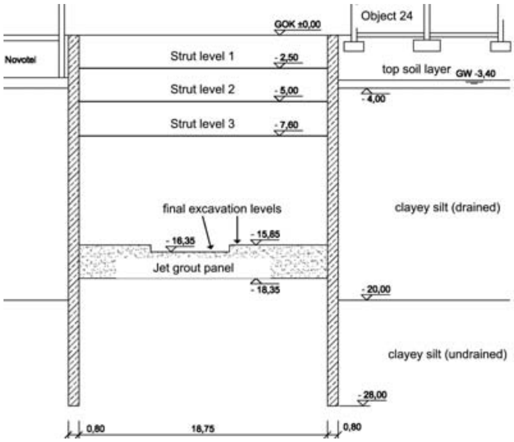

Figure 1. Cross section of excavation and strut levels.

19 × 20 m, which of course must raise doubts whether a 2D analysis is at all appropriate in this case. Attention is paid to the fact that a jet grout panel just below the final excavation level has been constructed to act as lateral support. This has been constructed before the start of the excavation and allowed excavation without installing a fourth strut level. Groundwater lowering inside the excavation was achieved by vacuum wells (commonly used in Salzburg) which extended below the excavation level in order to reduce uplift.

The construction sequence is closely reflected in the analysis. Starting from the initial stress state ($K_0 = 0.55$ for all layers) and the loads of the foundations of the neighbouring buildings (80 kN/m^2 for the Novotel, 200 and 250 kN/m^2 for the strip footings of Object 24) the wall and jet grout panel have been introduced wish-in-place. Then excavation steps, groundwater changes and installation of struts have been modelled in a step by step analysis. Soil behaviour below −20 m is assumed to be undrained, above −20 m, due to the presence of thin sandy layers, as drained.

2.2 *Material parameters*

The soil parameters used in the analysis for the top soil layer (0–4 m below surface) and the clayey silt are summarized in Tables 1 and 2. As mentioned previously, parameter determination is not only based on site investigations and laboratory experiments but also from experience of back analyses of other deep excavations in Salzburg. Therfeore soil parameters have not been varied in this study. In Table 1 E_{50}, E_{oed} and E_{ur} are the reference stiffness in primary loading (for deviatoric and oedometric stress paths) and unloading/reloading respectively.

The axial stiffness of the struts (Table 3) differs for the three levels, the material behaviour is assumed to be linear elastic. Table 4 lists the basic set of parameters used for diaphragm wall, jet grout panel and the foundation structures of Novotel and Object 24. In the 2D analyses a Mohr-Coulomb failure criterion has been used for wall and jet grout panel whereas the cohesion was chosen in such a way to obtain the uniaxial compressive strength (UCS) as listed in Table 4, assuming $\varphi' = 45°$. Tension cut-off was set to UCS/10. R_{inter} denotes the reduction of soil strength to model wall friction. In the 3D analyses the wall was elastic and stiffness was either assumed to correspond to “uncracked conditions” or “cracked conditions”. The stiffness properties of the jet grout panel have been varied because of the significant uncertainty in obtaining reliable values for the in situ stiffness of such panels.

Table 1. Stiffness parameters for soil layers.

	E_{50} (MPa)	E_{oed} (MPa)	E_{ur} (MPa)	m –	p_{ref} (kPa)	ν_{ur} –
Soil layer (0–4 m)	3	3	12	0.0	40	0.2
Clayey silt	37.6	37.6	150.4	0.30	100	0.2

Table 2. Strength parameters for soil layers.

	c (kPa)	φ (°)	ψ (°)
Soil layer (0–4 m)	5	28	0
Clayey silt 1	30	26	0

Table 3. Axial stiffness of struts.

	EA (kN)	spacing (m)
Strut level 1	3.234E6	3
Strut level 2	1.067E7	3
Strut level 3	5.334E6	3

Table 4. Parameters for wall, jet grout panel and foundations.

	E (kN/m^2)	ν –	R_{inter} –	UCS (N/mm^2)
Diaphragm wall	2.9E7	0.2	0.7	18.8
Jet grout panel	5.0E5	0.2	0.7	2.25
Foundations	3.0E7	0.2	0.7	–

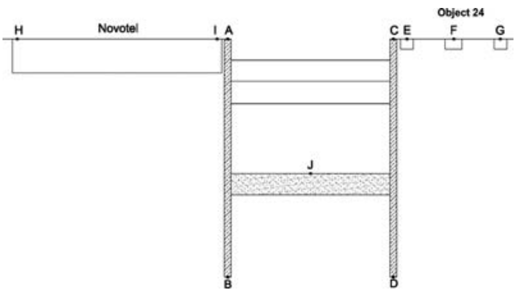

Figure 2. Location of points used for comparison.

3 IN SITU MEASUREMENT PROGRAMME

The existence of structures in the close vicinity of the excavation required a careful observation of deformations during construction. Therefore, about 30 settlement gauges were installed to monitor the settlements outside the excavation, in particular of the adjacent buildings. In addition, four inclinometers were installed in the diaphragm walls in order to measure the horizontal deflection of the wall in all construction stages. Two of them were located approximately in the cross section chosen for the 2D analysis, i.e. along the centre line of the excavation. Figure 2 depicts the points chosen for the comparison of measurement and analysis for settlements.

4 NUMERICAL MODELS

As mentioned previously 2D and 3D analyses have been performed using Plaxis 2D and Plaxis 3D Foundations. The 2D model consists of approximately 2,300 15-noded elements (Figure 3) and the 3D model of approximately 11,000 15-noded wedge elements (Figure 4). Lateral boundaries are fixed in horizontal direction and the bottom boundary in vertical and horizontal direction in both models. It can be seen that the 3D mesh is much coarser as compared to the 2D mesh but studies performed on the 3D model showed that a mesh with more than 20,000 elements resulted in only marginal differences in displacements. However, bending moments are more sensitive to discretisation and a stability analysis would certainly not yield correct results with the mesh adopted for the 3D analyses.

5 RESULTS OF 2D MODEL

Four different analyses have been performed with the 2D model:

Variation 1 (V1): Wall and jet grout panel elastic with elastic properties according to Table 4.

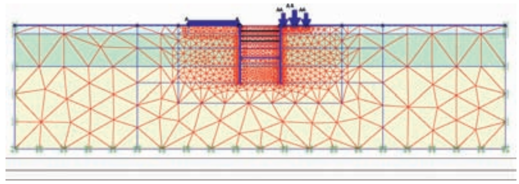

Figure 3. 2D finite element mesh.

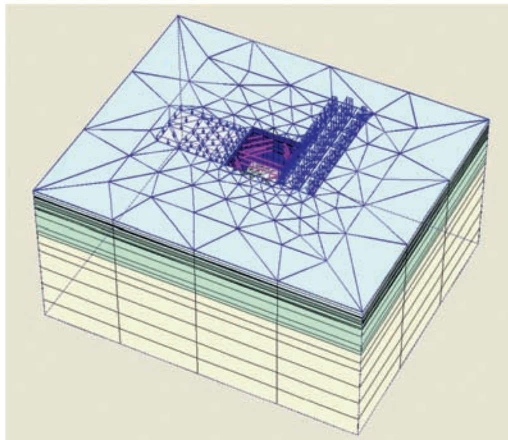

Figure 4. 3D finite element mesh.

Variation 2 (V2): Diaphragm wall modelled as elastic-perfectly plastic material with UCS as given in Table 4.

Variation 3 (V3): V2 and increase of stiffness of jet grout panel by a factor of 3.

Variation 4 (V4): V3 and increase of tension cut-off in diaphragm wall by a factor of 2.

Figures 5 and 6 compare the deflection of the wall for the final construction stage for all four analyses with the measurements obtained from the inclinometers.

It follows that the different assumptions made have little influence on the results in the upper part of the wall because in this part the deformations are governed by the struts. Results for the right wall compare well with measurements in the upper part, for the left wall this is not the case. For the lower part only V3 and V4 produce a reasonably match and it turned out that it is difficult to obtain the wall curvature as measured at the location of the jet grout panel.

Figures 7 to 9 show a comparison of calculated and measured vertical displacements at various points on the ground surface. The two sets of squares in each diagram represent pairs of settlement gauges which are in close distance to the points picked from the numerical analysis at various stages of construction (the dates are given within the diagram, the axis represents calculation steps, representing the progress of construction

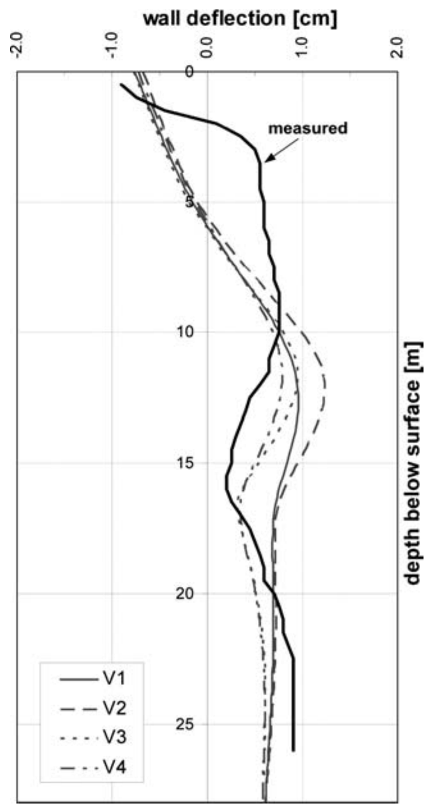

Figure 5. 2D analysis: wall deflection – left wall.

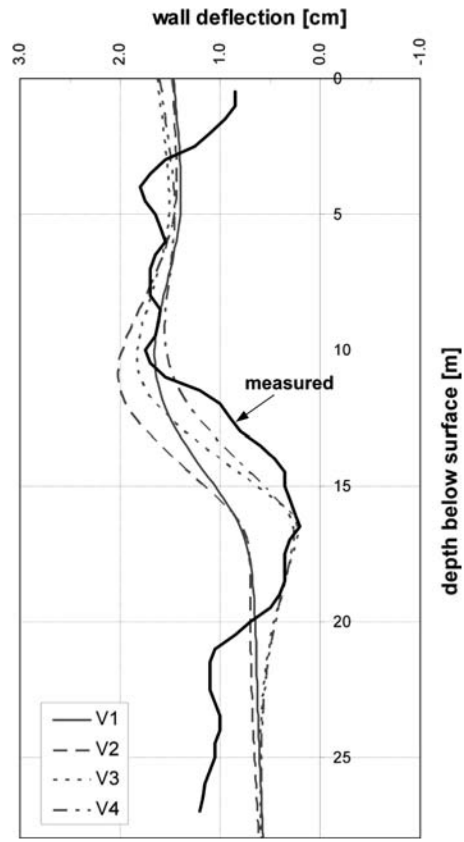

Figure 6. 2D analysis: wall deflection – right wall.

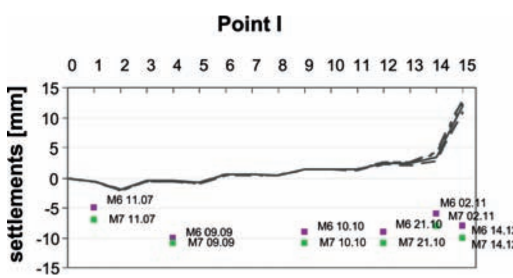

Figure 7. 2D analysis: surface displacements – Point I.

with time). Only for point H a reasonable agreement between calculation and measurements could be achieved, although one has to mention that absolute values are very small, with about 10 mm as maximum settlement. In point I the analysis predicts heave whereas settlements have been measured, but for point E settlements are overpredicted.

6 RESULTS OF 3D MODEL

In this section results from 3D analyses are presented. These analyses have been performed because the geometry of the excavation (approximately quadratic in plan view) and also part of the bracing system (struts across the corners of the excavation) cannot be adequately represented in plane strain conditions. In the first series of analyses emphasis has been put on the stiffness of the diaphragm wall and 3 different calculations have been performed: the first assumed linear elastic behaviour for the wall with a stiffness assigned representing "stiffness I" (uncracked conditions), the second one assumed "stiffness II" (cracked conditions) and the third one introduced a non-linear behaviour by means of a pre-defined curve relating allowable bending moments to the curvature of the wall. In Figures 10 and 11 these are denoted with Z1, Z2 and non-linear respectively. It has been observed already in the 2D analyses that the assumption for the stiffness of the jet grouted panel has – as expected – a significant influence on the curvature of the wall. The inclinometer measurements indicate that the lower value – obtained from laboratory experiments – seems to underestimate the support in situ. This has been confirmed also from

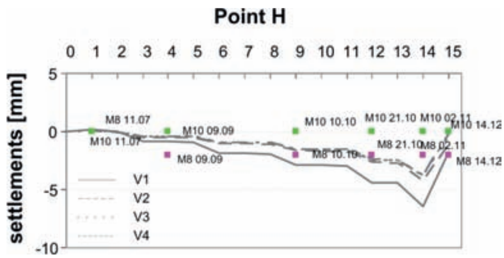

Figure 8. 2D analysis: surface displacements – Point H.

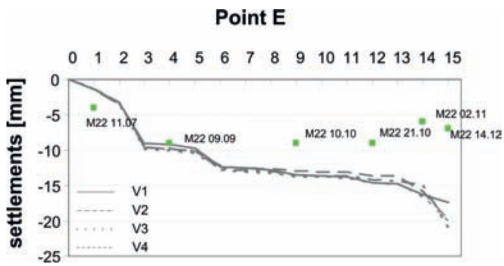

Figure 9. 2D analysis: surface displacements – Point E.

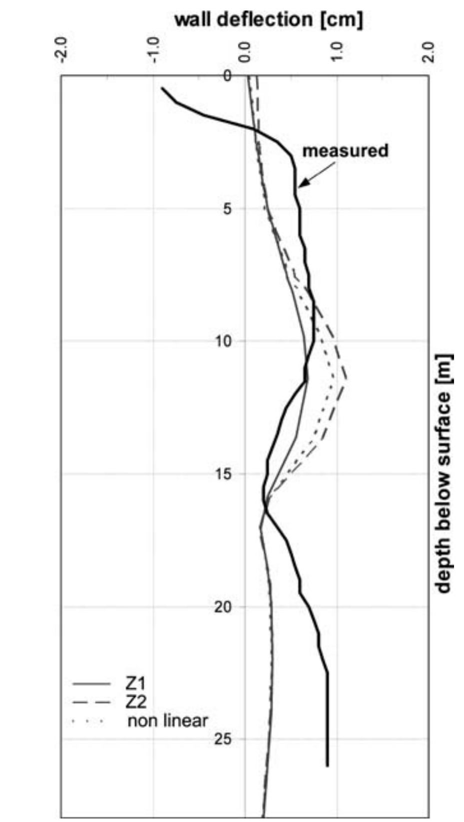

Figure 10. 3D analysis: wall deflection – left wall.

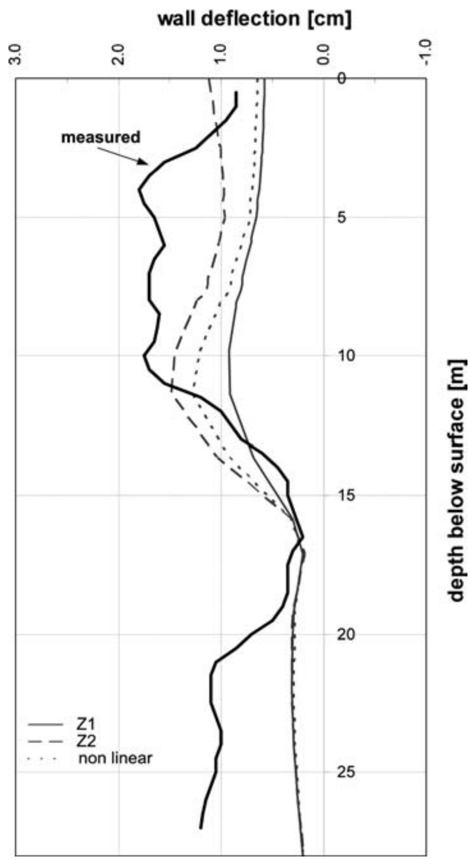

Figure 11. 3D analysis: wall deflection – right wall.

3D analyses and therefore only results assuming the high stiffness (1,500 MPa, as used in V3 and V4 of the 2D calculations) are presented in the following.

The comparison of horizontal displacements (Figures 10 and 11) clearly show the effect of varying the stiffness of the diaphragm wall in the unsupported zone whereas the assumption of "cracked stiffness" is closer to the measured curvature than the analysis with high wall stiffness, at least for the right wall. In the upper part the influence of varying wall stiffness is much less pronounced because the behaviour is dominated by the struts, however predicted horizontal displacements are less than measured. The non-linear model is, not surprisingly, between the two extreme cases.

Finally, after some discussion with the designer, an additional analysis was performed assuming a non-perfect connection of struts and wall, i.e. it was assumed that there is an imperfection before the full support of the strut can be mobilised. This has been achieved by a nonlinear model for the strut which

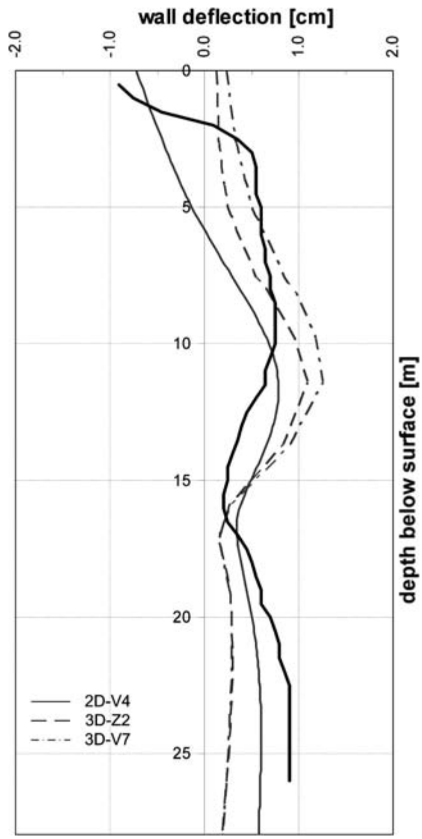

Figure 12. Comparison 2D-3D analysis – left wall.

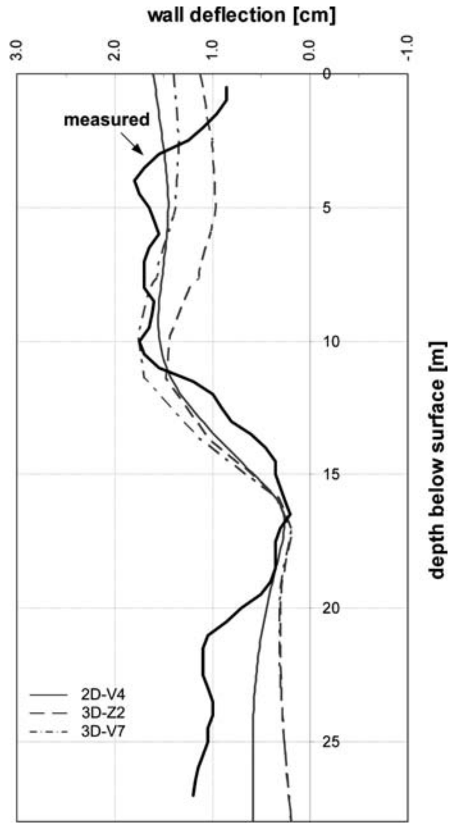

Figure 13. Comparison 2D-3D analysis – right wall.

results in a 0.25 mm/m "gap" to be closed before the full support is activated (this variation is denoted as V7 in the following diagrams). The consequence of this follows form Figures 12 and 13, in which results from the 2D analysis (Variation 4) are also plotted for comparison. For the left wall the curvature at the position of the grout panel is still not in full agreement with measurements but the upper part corresponds much better than in previous analyses. For the right wall the curvature and the upper part are now in reasonable good agreement with measurements (for the right wall the 2D analysis is also in good agreement). Figures 14 to 17 plot settlements at various observed points. It is immediately noticed that – in contrast to the 2D model – the 3D analysis predicts settlements also for Point I, although they are still slightly lower as compared to measured values. Point H corresponds in the sense that measured and calculated settlements are almost zero. Point E shows slightly higher settlements for later stages of construction than measured and the same holds for point G.

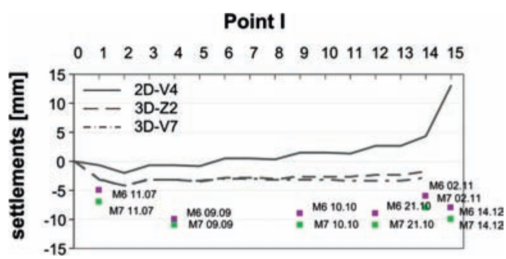

Figure 14. Comparison 2D-3D analysis: Point I.

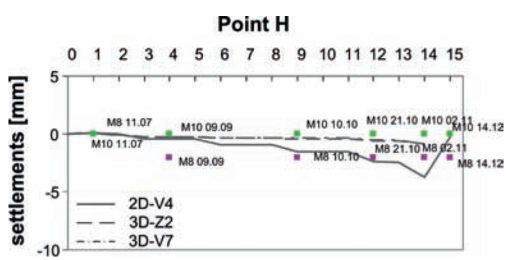

Figure 15. Comparison 2D-3D analysis: Point H.

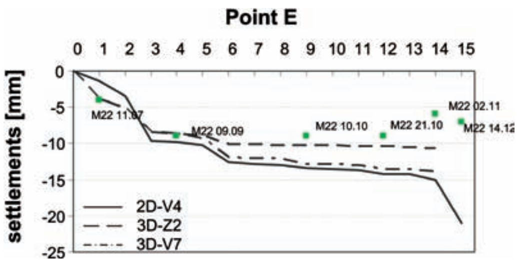

Figure 16. Comparison 2D-3D analysis: Point E.

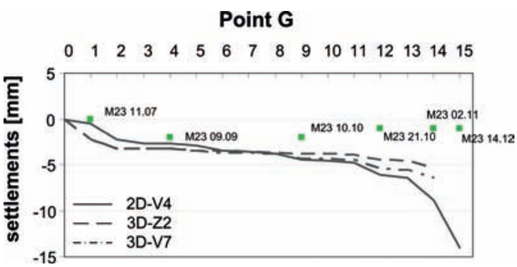

Figure 17. Comparison 2D-3D analysis: Point G.

7 CONCLUSIONS

Results form 2D and 3D finite element analyses of a deep excavation have been compared to in situ measurements. The excavation is supported by a diaphragm wall, 3 rows of struts and a jet grout panel located just below the final excavation depth. In a parametric study the stiffness of the diaphragm wall and the jet grout panel have been varied. The study showed that a 2D analysis would reasonably predict wall deflections (in particular for the right wall) but if both walls and vertical displacements of all surface points are considered the 3D analysis produces a somewhat better overall agreement with the measurements.

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