DeepEX 2D and 3D FEM Verification Part 1

Salsburg braced excavation - Schweiger et al (2009)

This example involves the analysis of a deep excavation project carried out in clayey silt in Salzburg. The excavation was stabilized using a diaphragm wall, a jet grout panel, and three levels of struts to ensure structural support and safety during construction as illustrated in Figure 8.6.1. The dimensions of the excavation are approximately square, measuring 19 meters by 20 meters.

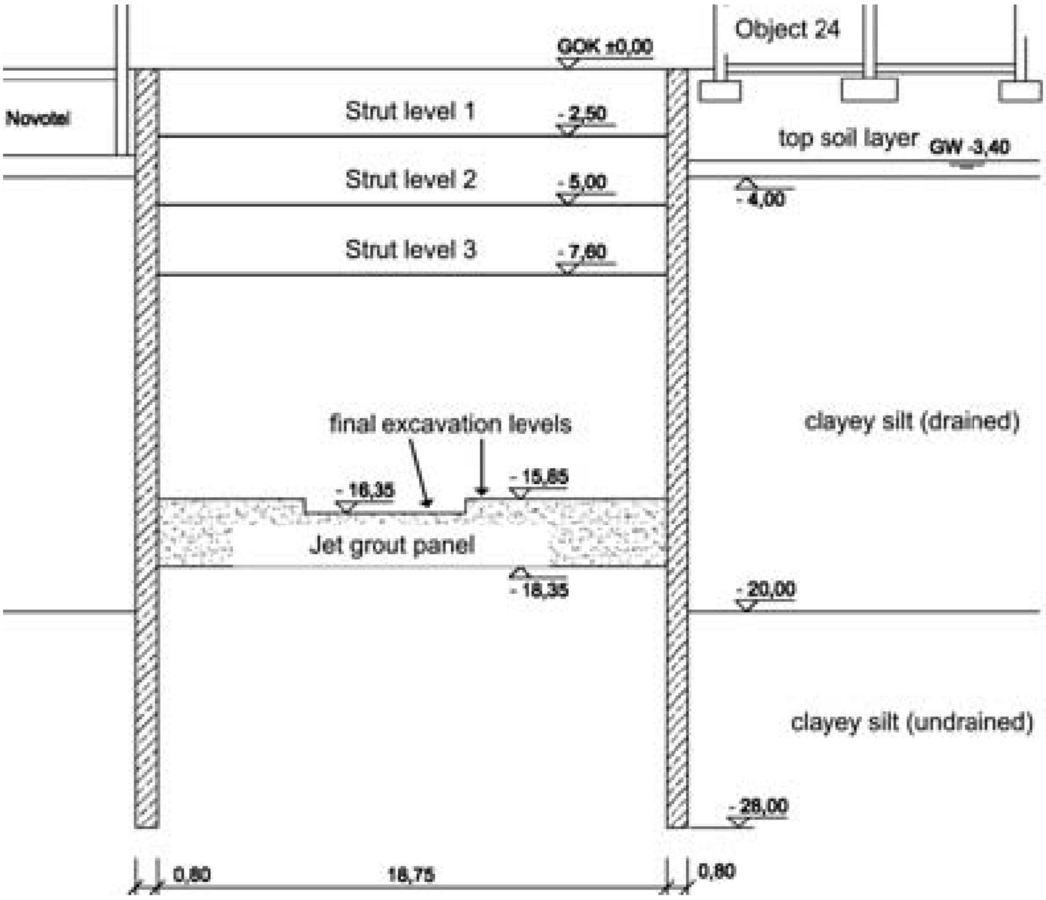

Figure 1: Salsburg braced excavation as presented in [Schweiger et al 2009]

Beginning with the initial stress state and accounting for the loads from the foundations of adjacent buildings, the diaphragm wall and jet grout panel were introduced using a wish-in-place approach. Following this, excavation stages, groundwater variations, and the installation of struts were modelled through a step-by-step analysis to simulate the progressive nature of the construction process. In terms of soil behaviour, it was assumed that below a depth of −20 meters, the soil behaves as undrained due to its predominantly cohesive nature. Above −20 meters, the presence of thin sandy layers prompted the assumption of drained conditions, reflecting the more permeable characteristics of the upper soil layers. This distinction between drained and undrained behaviour is crucial for accurately capturing the soil-structure interaction and predicting the overall performance of the excavation system as stated in [Schweiger et al 2009].

An exhaustive list of the construction stages is presented below:

Stage GF: Greenfield conditions (Ko based imposed stress field)
Stage Prior Project: activation of adjacent building foundations with building loads
Stage 0 Wish in place activation of concrete diaphragm walls
Stage 1: Wish in place activation of jet grout panel
Stage 2: excavation at level -2.5m
Stage 3: activation of 1st level bracing system
Stage 4: excavation and dewatering at -5m
Stage 5: activation of 2nd level bracing system
Stage 6: excavation and dewatering at -7.5m
Stage 7: activation of 3rd level bracing system
Stage 8: final excavation at level -15.6m

2D Finite Element Model and Verification

The majority of the necessary properties for the construction of the 2D finite element model are presented within the paper. The soil hardening law is utilized in the simulation of all the soil layers. The exact stiffness and strength properties presented in the paper are illustrated respectively in the table 1 and 2 of Figure 2. A Mohr Coulomb constitutive law is selected for the simulation of the foundations and jet grout panel with a friction of angle ϕ=40° and cohesion calibrated to match the unconfined compression strength of the concrete. The selected stiffness and strength properties are illustrated in table 4. Due to the lack of sufficient data regarding the material properties of the jet grout panel, the stiffness of the panel was treated as a variable in the analysis presented in the paper and eventually recalibrated to match the monitored behavior of the walls.

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: Model properties as presented in [Schweiger et al 2009]

Finally strut level stiffness and spacing was presented in table 3 of the studied paper as illustrated in Figure 8.6.2. The exact location and horizontal dimensions of the Novotel foundation (building located at the left of the excavation) and strip foundation of object 24 (building located at the right of the excavation) was not included in the paper, however was approximately extracted from the 2D and 3D analysis Figures included in the paper. The final stage of the 2D finite element model in Deepex is illustrated in Figure 3.

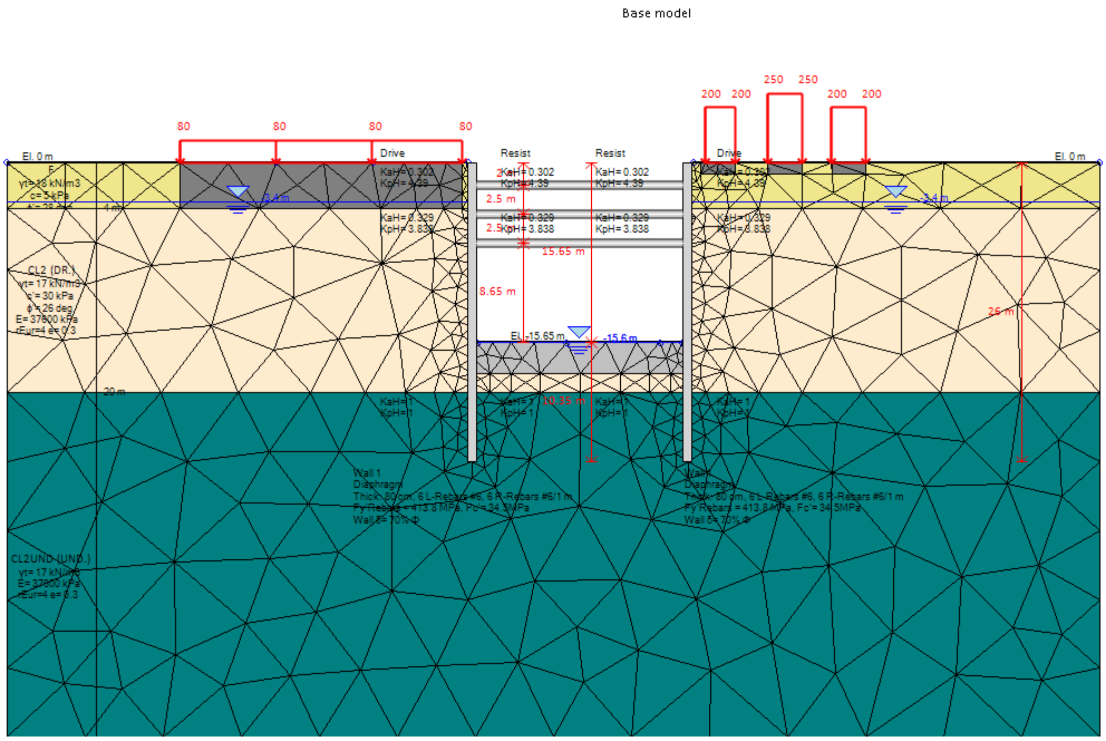

Figure 3: 2D model constructed in DeepEX

As outlined by Schweiger et al. (2009), several variations of the model were developed to account for different stiffness and strength parameters of the diaphragm wall and jet grout panel. The initial approach V1 assumes an elastic diaphragm wall, and stiffness and strength of the jet grout panel in accordance with table 4 of Figure 2. The lateral displacement results of the left and right diaphragm wall are illustrated in Figure 44 for the DeepEX 2D model, the Plaxis 2D results presented in [Schweiger et al 2009] and the actual measured displacement of the walls.

Three additional model variations were considered in the aforementioned paper, including: (a) simulating the diaphragm wall using an elastic-perfectly plastic material, (b) increasing the stiffness of the jet grout panel by a factor of three, and (c) doubling the tension cut-off in the diaphragm wall. These different assumptions had minimal impact on the results for the upper section of the wall, as deformations in this area were primarily controlled by the struts. The results for the right wall align well with measurements in the upper section; however, this is not the case for the left wall. In the lower section, adjusting the initial stiffness of the jet grout panel was crucial for achieving a reasonable match with the measured displacements. A comparison of the lateral displacement of the two walls for the final V4 variation is illustrated in Figure 5.

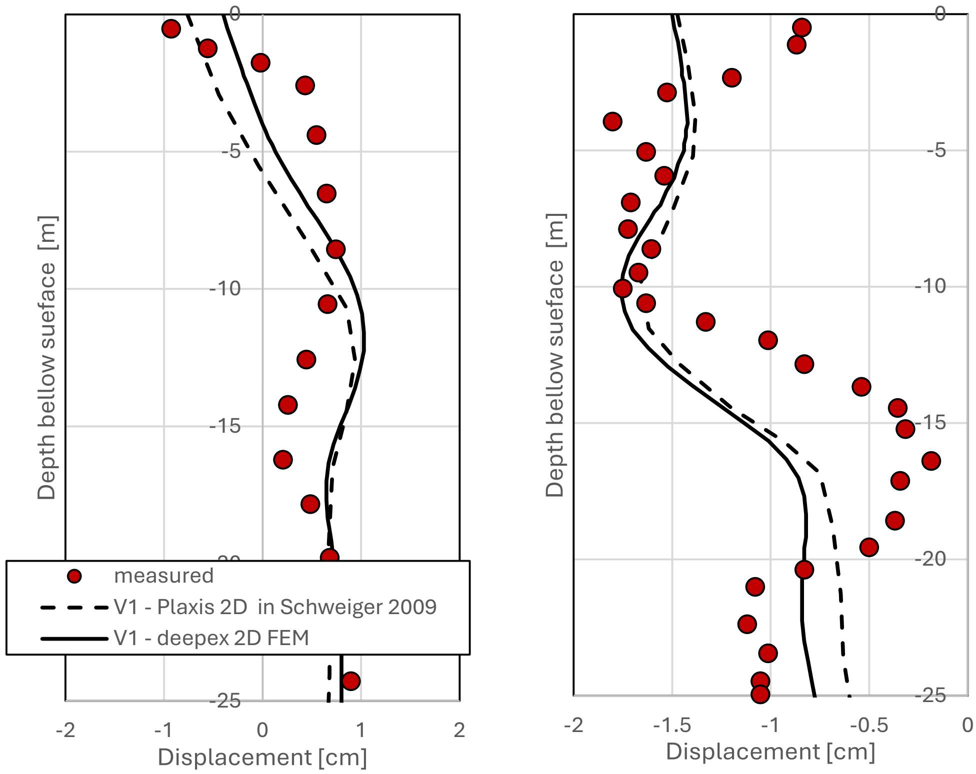

Figure 4: Variation V1 2D FEM models a) left and b) right diaphragm wall lateral displacement

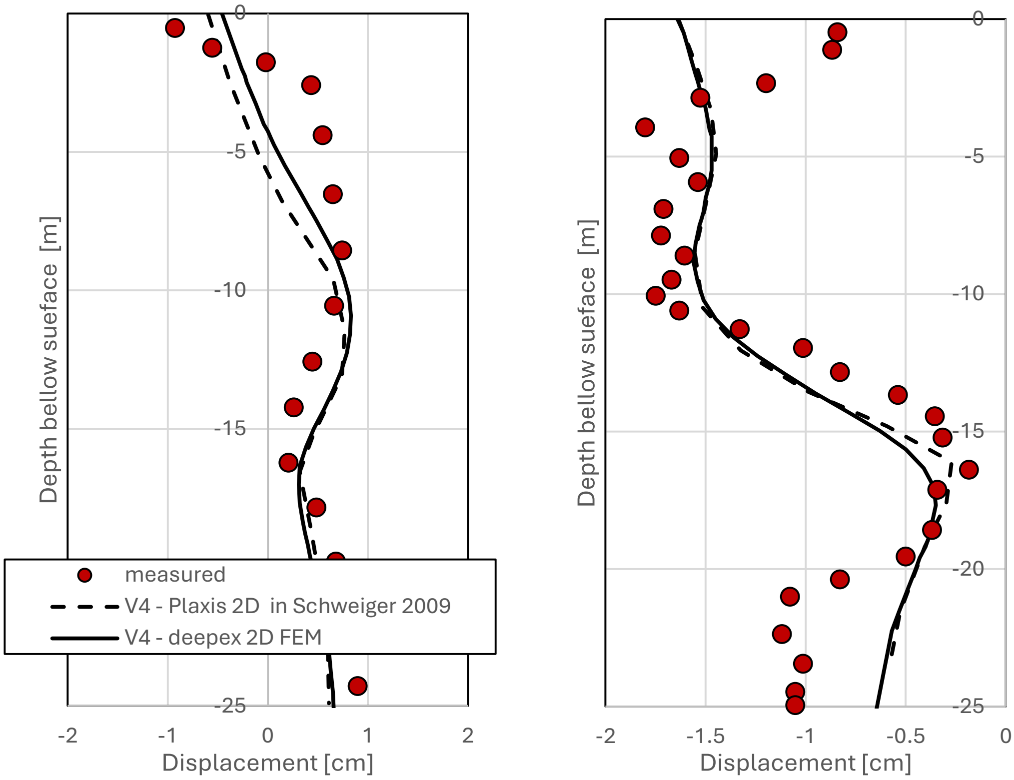

Figure 5: Variation V4 2D FEM models a) left and b) right diaphragm wall lateral displacement

3D Finite Element Model and Verification

As the final step in this example evaluation process of DeepEX, a 3D finite element model (FEM) has been developed to simulate the excavation. The need for the 3D analysis arises due to the excavation geometry (square shaped) and the inclusion of specific elements of the bracing system, such as struts placed diagonally across the corners. These structural features cannot be accurately modelled under plane strain conditions, necessitating a more sophisticated approach. The constructed 3D FEM model is illustrated in Figure 6.

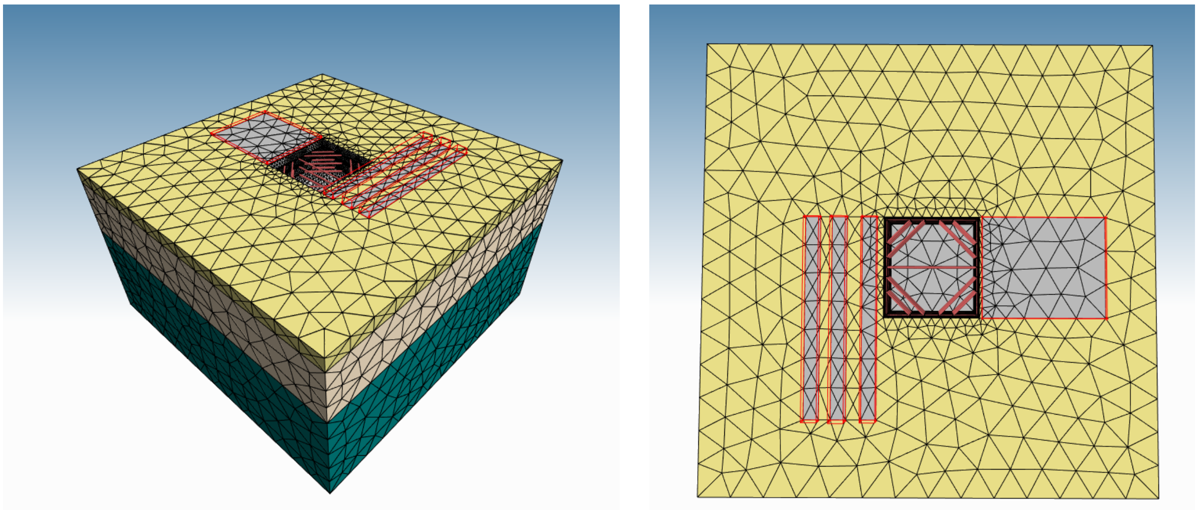

Figure 6: 3D model constructed in DeepEX

In the first series of analyses presented in Schweiger et al 2009, particular attention has been given to the deflection of the upper portion of the wall. Three distinct calculations have been carried out to assess the wall's behaviour under different stiffness assumptions in the paper (a. elastic, b. equivalent cracked concrete and c. inelastic behaviour). Additionally, along the lines of the V4 variation, an increase of the stiffness of the jet grout panel by a factor of three is also assumed as a closer approximation of the grout soil panel properties. A comparison of the lateral displacement of the two walls for the Z1 variation indicated in the paper (elastic behaviour of the wall) is illustrated in Figure 7. As illustrated in the results, displacement of the lower part of both walls (near the resisting soil grouting panel) is adequately captures by the 3D numerical models. However, a lack of accuracy is mainly illustrated in the upper portion of the wall where the struts are located. As indicated in the paper wall stiffness sensitivity study, in this particular location variation of the wall stiffness from the two extreme conditions of fully cracked to cracked has little to no influence as the strut supports govern the behaviour there. The aforementioned divergence between measurements and numerical models is explained in the paper. More specifically, it is indicated in Schweiger et al 2009 that, following some discussions with the designer, an additional analysis was carried out under the assumption of a non-ideal connection between the struts and the wall. Specifically, it was assumed that an imperfection exists, preventing the full mobilization of the strut's support from the outset. This was modeled using a nonlinear approach for the strut in variation 7 (V7), which results in a 0.25 mm/m “gap” to be closed before the full support is activated.

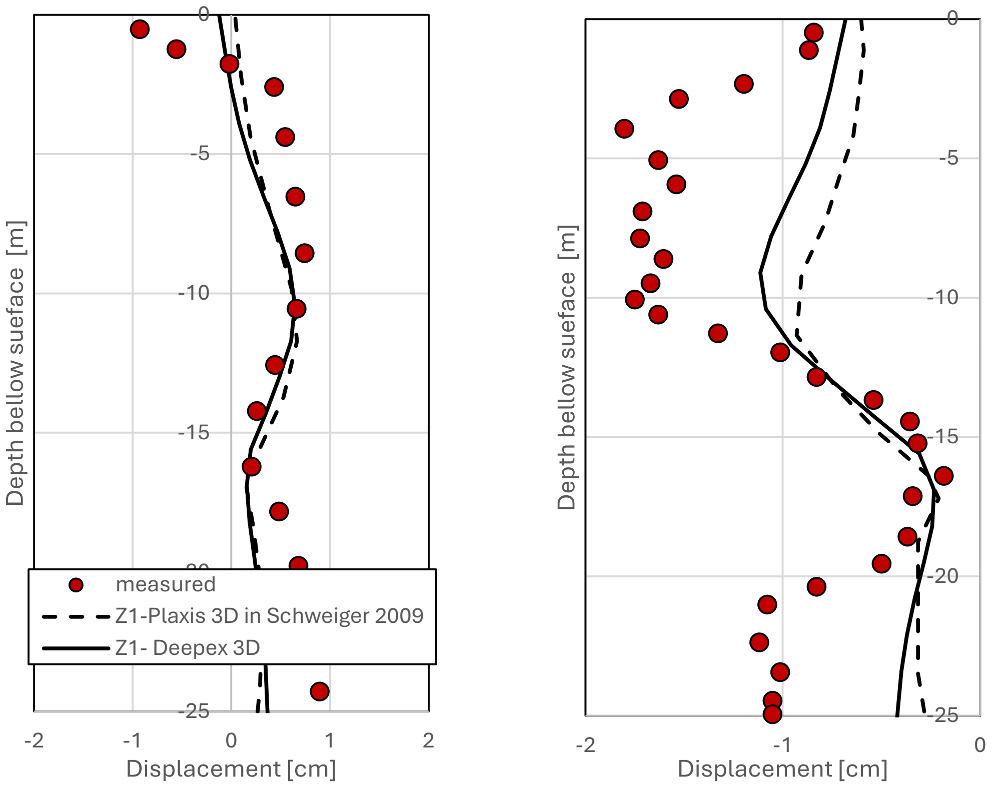

Figure 7: Variation Z1 3D FEM models a) left and b) right diaphragm wall lateral displacement

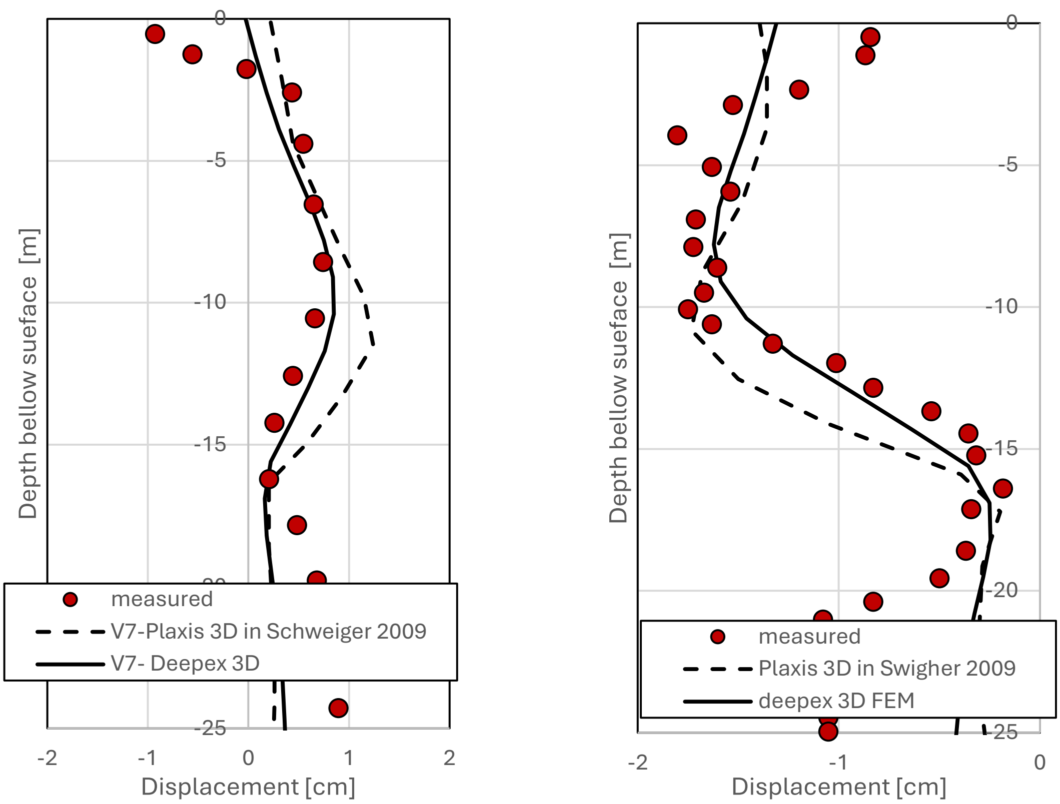

Figure 8: Variation V7 3D FEM models a) left and b) right diaphragm wall lateral displacement