



3D Finite Element Analysis of a Complex Excavation

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This article describes the development of a comprehensive three-dimensional finite element model for the Stata Center basement excavation (Cambridge, USA) using PLAXIS 3D 2012. The project involved a complex sequence of berms, access ramps and phased construction of the concrete mat foundation. Lateral wall movements and building settlements were closely monitored throughout construction, while photos from a network of webcams located around the open-plan site provided a detailed time history of the construction processes. The analyses highlight the effects of the 3D excavation and support geometry on wall deflections and show a good agreement with the measured response assuming undrained conditions using the Mohr-Coulomb soil model.

➤ The Ray and Maria Stata Center building at MIT (Massachusetts Institute of Technology) was designed with a basement for underground parking requiring a 12.8m deep excavation. The excavation was supported by a perimeter diaphragm wall that formed part of the permanent structure and extended 14 m into a deep layer of underlying Boston Blue clay. The diaphragm wall was braced by a combination of prestressed tieback anchors, preloaded raker and corner bracing support elements. The control of ground movements was a critical aspect of the subsurface design due to the close proximity of the excavation to the historical MIT Alumni swimming pool building (a meter away from the edge of the excavation).

The complexity of the excavation process and structural supports presented a significant modeling challenge that exceeded the computational capabilities of finite element codes available at the time of construction (in 2001). The predictions of performance were limited to simplified 2D finite element models (plane strain, half sections) that were assumed to generate worst-case scenarios for wall deflections and ground deformations.

The measured performance during the actual excavation exceeded the allowable wall deformations (38mm) prescribed at the start of the project with maximum lateral movements

that ranged from 51mm to 89mm and maximum settlements exceeding 50mm. Fortunately, these movements did not cause any noticeable damage to adjacent structures and were eventually deemed acceptable. Nonetheless, the magnitude of these unforeseen movements could have potentially caused more problems.

More comprehensive three-dimensional finite element analyses of the Stata Center basement excavation have been enabled by the recent advances in PLAXIS 3D software including the efficient multicore iterative solving capabilities and geometric data import from CAD files. These analyses showed a good agreement with the measured response assuming undrained

conditions in clay and highlighted the effects of the 3D excavation and support geometry on wall deflections.

Project Description

The site for the MIT Stata Center has a very large rectangular plan area (approx. 100m x 119m), which abuts an existing building along its southern edge (Figure 2). A floating mat foundation system was designed so that the weight of the building is balanced against the weight of the soil extracted from the site. The excavation support system comprises a reinforced 76 cm thick concrete diaphragm wall that is supported through the use of:

1. three levels of tiebacks on the west, south, and

Layer	Soil Model	Top Elevation, m	γ , kN/m ³	S_u , kPa	ϕ'_{ps}	G/σ'_{vs}	ν'	K_s
Fill	MC (D)*	6.4	18.9	-	35°	75	0.3	0.5
Organics	MC (UD)	3.0	15.7	48	-	150	0.3	0.5
Sand	MC (D)	1.2	20.4	-	37°	230	0.3	0.5
BBC (Upper)	MC (UD)	-3.0	18.4	68 - 61	-	75	0.3	0.8
BBC (Lower)	MC (UD)	-17.0	19.3	61 - 93	-	75	0.3	0.6
Glacial Till	MC (D)	-29.0	22.0	-	43°	385	0.3	1.0

Table 1: Soil properties (*D = drained, UD = undrained)

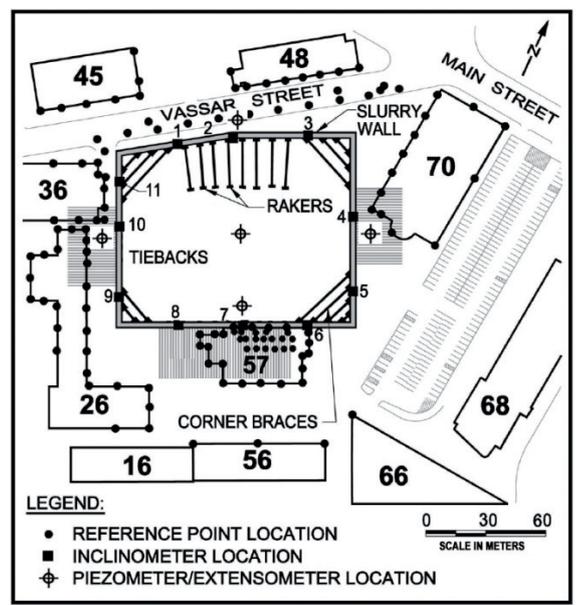


Figure 1: Excavation support plan and site view

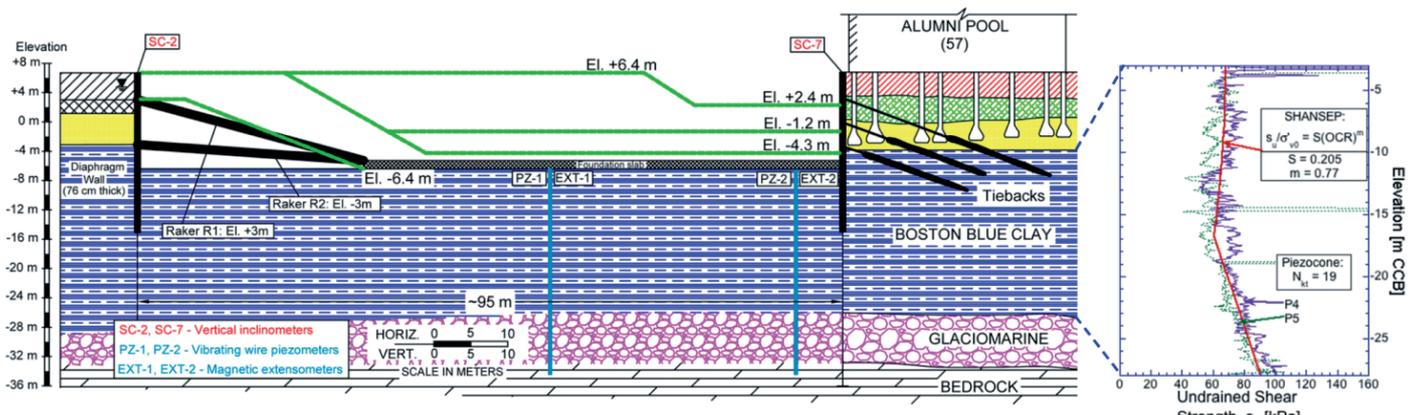


Figure 2: Subsurface conditions

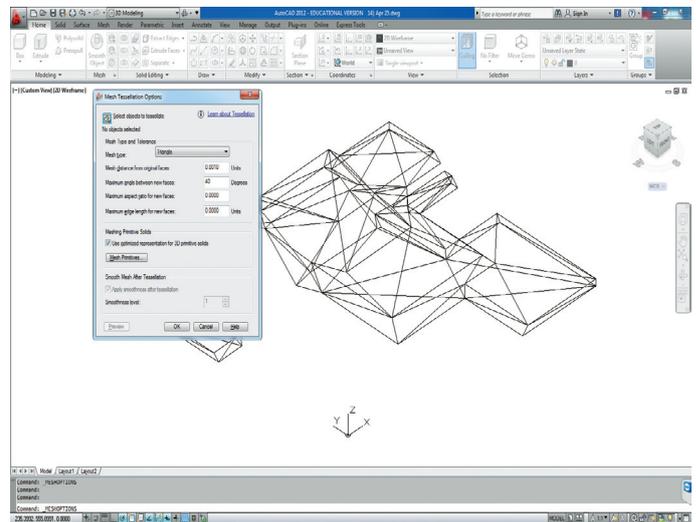
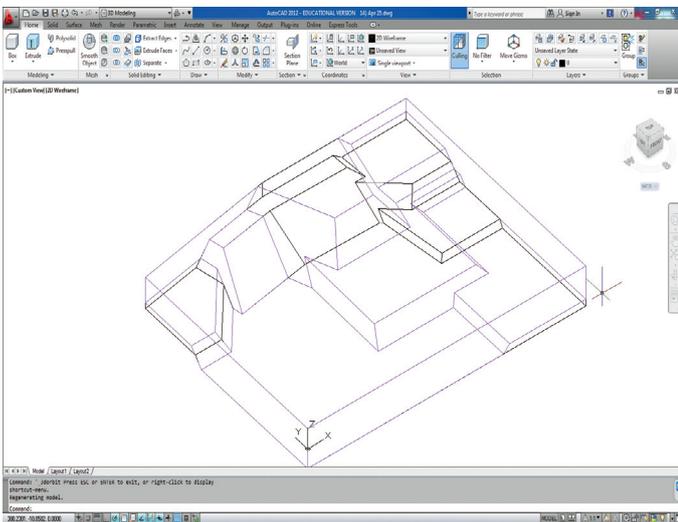
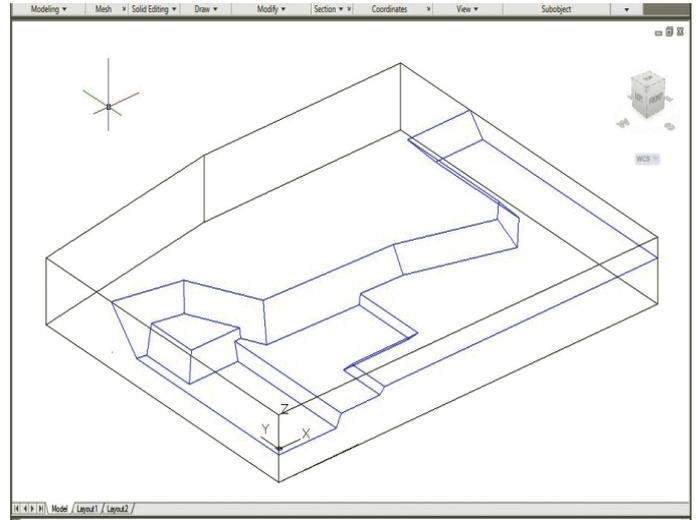


Figure 3: Design of soil clusters to be excavated in several PLAXIS phases

- east sides,
 - 2. two levels of corner bracing, and
 - 3. two levels of raker supports on the north side.
- Tiebacks were installed at an angle of 20 degrees from the horizontal at El. 3 m, El. -0.3 m, and El. -3 m and preloaded from 498 to 569 kN. Two levels of corner bracing consisting of 91-cm-diameter pipe struts were installed at El. 3 and El. -3 m.

The City of Cambridge prohibited the installation of tiebacks beneath the Vassar Street such that two levels of inclined raker bracing (at El. 3 and El. -3 m) were used along the North side of the excavation. The raker bracing consisted of 91 cm in diameter pipe struts extending from embedded plates in the diaphragm wall to kicker blocks embedded in the concrete mat foundation (Figure 1).

Site Characterization and Soil Properties

The site is located at the eastern part of the MIT campus in Cambridge, Massachusetts. The ground surface is approximately level at El. +6 m, and the groundwater table is in the overlying fill

at the depth of 1.8 m. A typical subsurface profile underlying the Stata Center in the middle of the site would consist of 3.4 m of fill, 1.8 m of organics, 4.3 m of sand, 26 m of clay, and 4.6 m of glacial till (Figure 2). The principal stratum is the marine clay (Boston Blue Clay), which can be sub-divided into an upper overconsolidated clay crust and a lower lightly-overconsolidated unit. The clay has low hydraulic conductivity and is modeled as an Undrained Elastic - Perfectly Plastic (EPP) material with the undrained shear strength that ranges from a minimum value, $s_u = 60\text{kPa}$ at El. -16m to a maximum, $s_u \approx 90\text{kPa}$ at the base of the clay. The other layers are also represented by the EPP (Mohr-Coulomb) model. Table 1 illustrates soil properties based on the subsurface exploration program.

Model Description

The excavation for the Stata Center has a complex geometry and variety of structural support systems which makes the project challenging to model. However, the uniqueness of this project is that the excavation process was very well

documented - it was constantly photographed, monitored, and described in daily field logs, as well as recorded on webcams located around the construction site. Using these data, it was possible to create a full three-dimensional numerical model of the actual excavation with respect to the time frame of construction sequence.

Olsen (2001) developed a series of 3D geometric models to represent the construction process by reconciling daily field reports, photographs and time-lapse of the project. Figure 4 illustrates the process of converting the geometric information into Phases used in the development of the 3D finite element model. Project data from project drawings were initially used to construct a CAD model of the support system. This information was then used to create a base case model within PLAXIS 3D. The excavated surface geometry is obtained from the models reported by Olsen (2001) that are converted into a set of tetrahedral elements using mesh tessellation operators in the CAD program. These are then imported into Plaxis 3D as soil clusters that represent the excavation

process as a series of 36 “staged construction” steps in the finite element model. Figure 5 shows that the resulting finite element model represents a close approximation to the original geometric model.

The overall finite element model extends laterally beyond the footprint of the excavation to a distance of 150-170m in all directions and vertically to the base of the glacial till. The model represents the soil mass using approximately 11200 tetrahedral elements (10-noded) with the second order interpolation of displacements. The calculation time lasted less than 20 hours on an Intel Core i7-3960X Extreme Edition CPU overclocked to 4.0 GHz with 16 GB RAM on a SSD hard drive.

The diaphragm wall is represented by three-dimensional elastic plate elements. The toe of the diaphragm wall does not extend into the underlying rock; therefore, it is free to move within the soil mass. The mat foundation was also modeled using elastic plate elements; tiebacks and corner bracers were represented

as prestressed node-to-node anchors. The free lengths of tiebacks were modeled using node-to-node anchors, and the embedded pile elements represented the grouted part. Each raker comprises a 91 cm diameter steel pipe strut (prestressed node-to-node anchors) that supports the wall and is inclined downward to a kicker block cast into the foundation slab.

The Boston Blue Clay has been modeled assuming undrained conditions using the Mohr-Coulomb model. The layer is subdivided into two units, each with undrained shear strength varying linearly with elevation (i.e., matching the undrained strength profile shown in Figure 2). Since the site surface is assumed to be mainly horizontal, the initial stresses are defined by K0 conditions, and hydrostatic pore pressures, with groundwater table at El. 4.6m. The boundary conditions used in the model are the Plaxis standard boundary conditions with fixity in the horizontal plane at the basal boundary and zero prescribed lateral displacements along the corresponding axes at the borders.

Results

A general pattern of measured movements at the center of a wall typically correspond to an initial cantilever movement of approximately 10-20 mm during the excavation to the first tieback support level, as well as 32 mm before the first level of raker support. The movement was fully recovered (except the North Wall) and the wall moved back during pre-stressing the first level of bracing. After the installation of the first level support, the wall rotated at the brace during the excavation progress. At the subsequent bracing, the wall kept moving laterally below the brace location. The maximum movements (June, 2001) measured in the inclinometers range from 51-64 mm at SC-02 (North), SC-04 (East), and SC-10 (West) to about 82 mm at SC-07 (South). The greatest movements were observed within the middle of a tieback supported wall while the smallest movements were recorded by the inclinometers located closer to the corners. In contrast, the North wall, supported by the raker support, showed an opposite pattern with the smallest movements occurring at the center due to the fact that the plan geometry of the North wall consisted of two

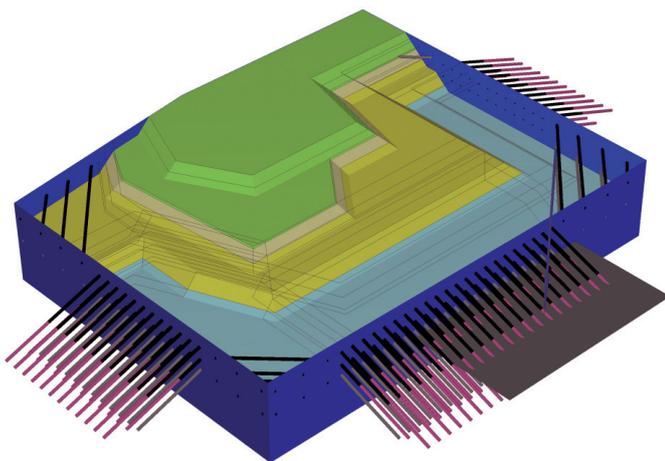


Figure 4: Staged construction mode and output example

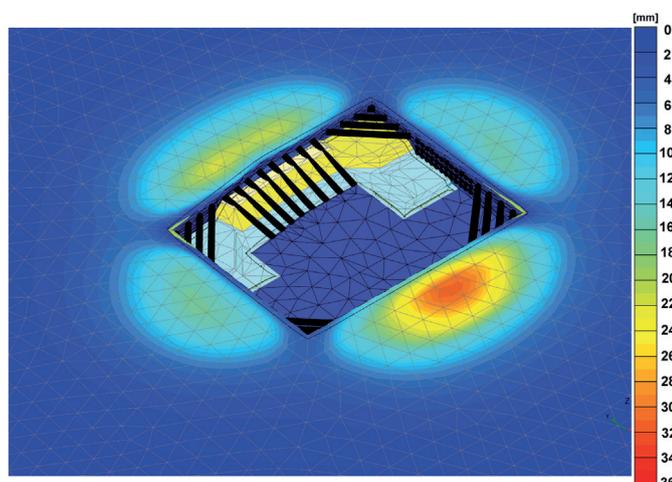
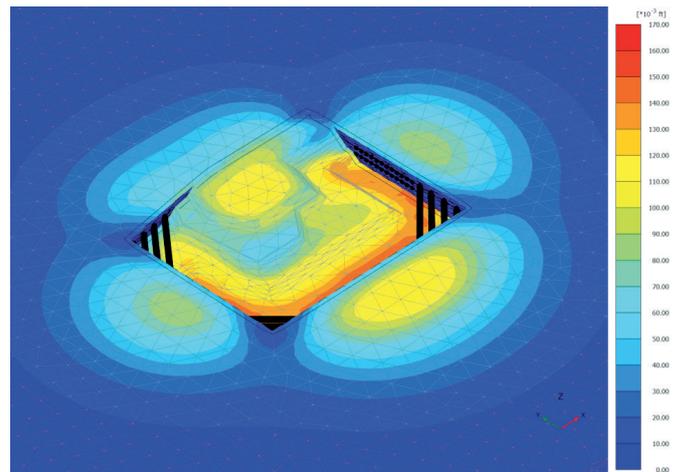
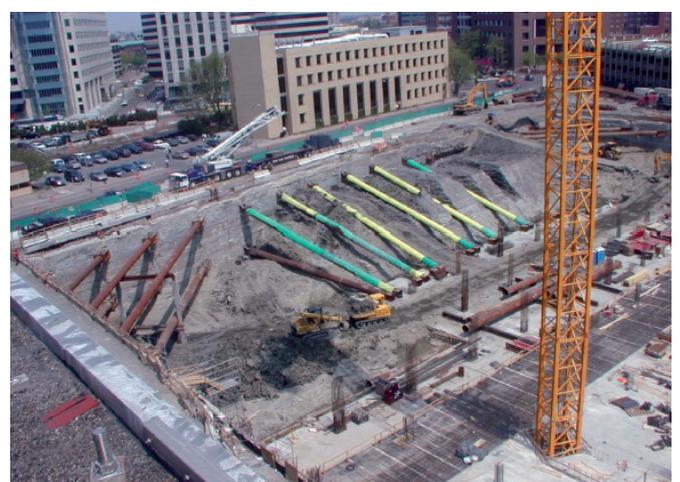


Figure 5: Output of the phase “April 25, 2001” in PLAXIS3D (vertical displacements) and corresponding photo of the construction site



planes that intersect at the wall center (Figure 7).

Figure 6 presents comparisons between the computed and measured wall deflections for the 11 inclinometers located around the perimeter (Figure 1) at 4 stages of construction (spanning the period from mid-January to June 2001). The inclinometers can be sub-divided into sections where the wall is supported by tieback anchors (SC-10, SC-08, SC-07, and SC-04), corner bracing (SC-11, SC-09, SC-06, SC-05 and SC-03) and raker supports (SC-02, SC-01).

In general, the patterns of measured wall deflections are very well described by the base case finite element model. The results are within 5-10mm of the measured maximum and toe deflections of the diaphragm wall at the end of construction (Phase 35), with the noted exception of conditions at the NW and NE corners of the site (SC-11, SC-01 and SC-03), where measured maximum wall deflections are 20mm higher than the numerical predictions. The most likely causes influencing the results are the ground loss during construction of the wall panels and lack of preloading of the 2nd level corner bracing prior to final excavation of berms in the NE

corner. Nevertheless, the base case results are in particularly good agreement with wall deflections along the tieback-supported South wall and in close agreement with maximum deflections at the center of the raker-supported North wall.

Conclusions

The application of a full 3D analysis in PLAXIS 3D 2012 to the Stata Center excavation project has been demonstrated. In order to capture the 3D effects of soil and support system responses from a non-uniform excavation process, complex shapes of soil volumes were extruded based on the photographs and excavation plans using CAD. The non-uniform soil excavation resulted in the three-dimensional effects which were well-captured by the 3D model predictions. The analysis results show a good agreement with the measured data and provide keys to explain many features of the observed performance including the differences in diaphragm wall deformations associated with sections supported by tieback anchors, raker beams and corner bracing. The usage of a relatively simple constitutive soil model (within the undrained conditions) was sufficient due to the overconsolidated state of the marine clay. The study has shown that the full 3D finite

element analysis can be effectively used for such complex excavation projects.

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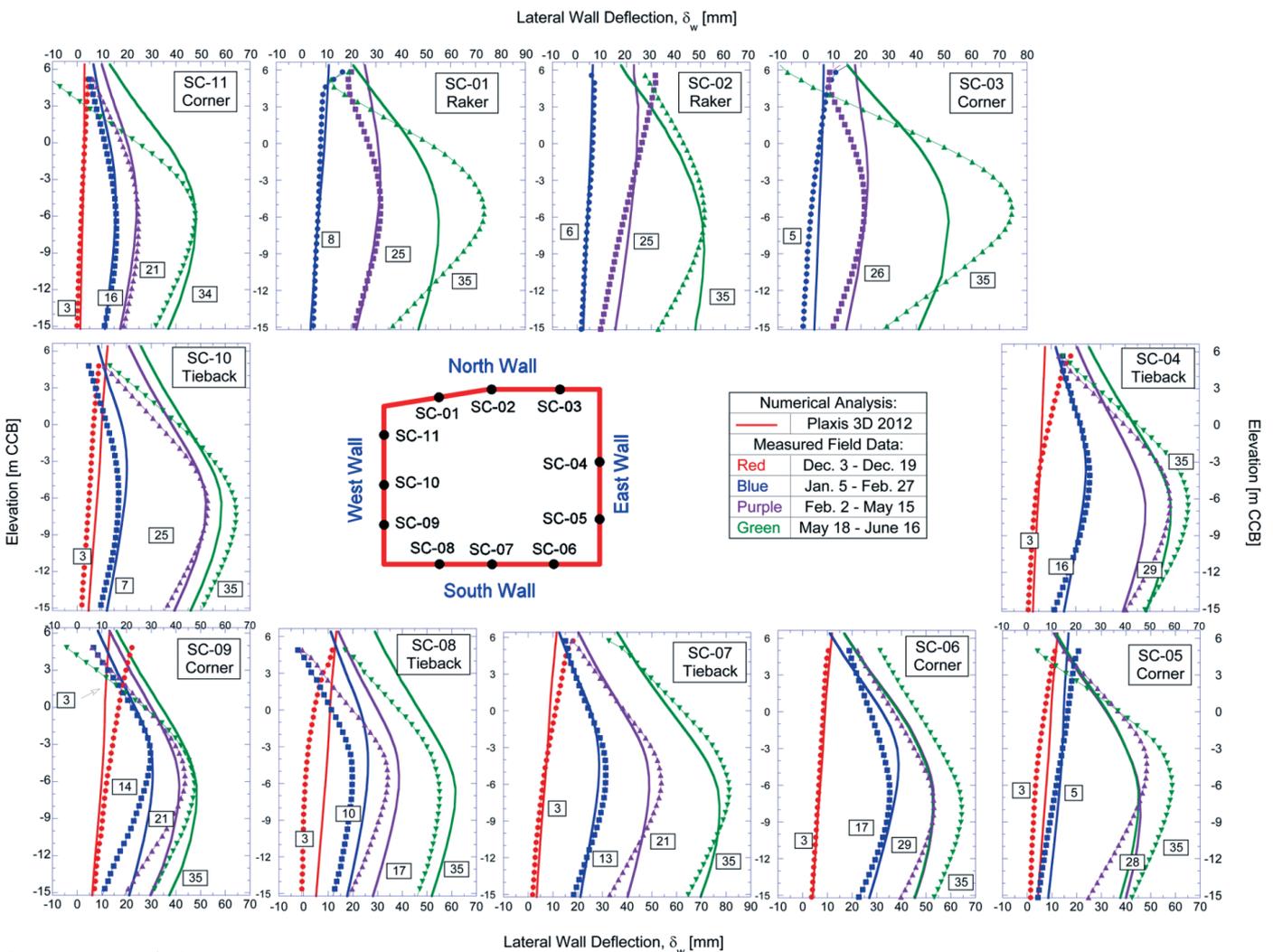


Figure 6: Lateral wall deflections results

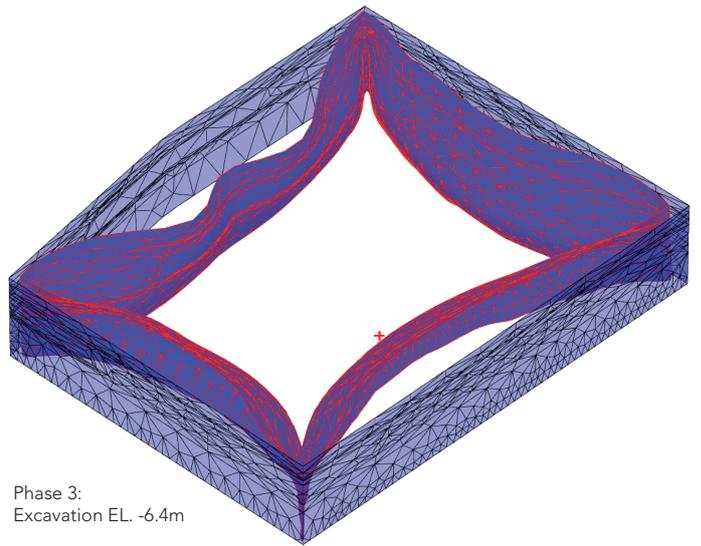
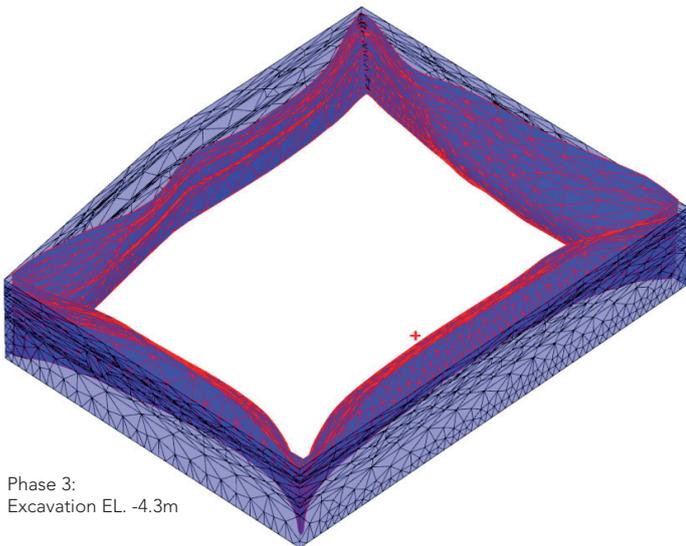
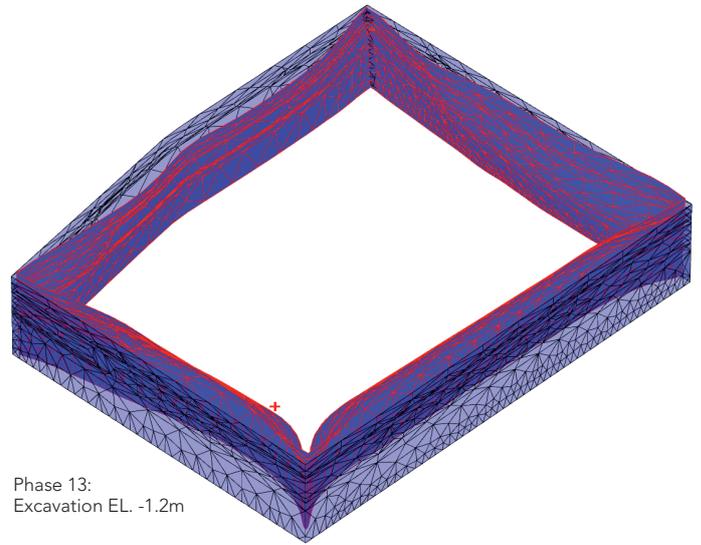
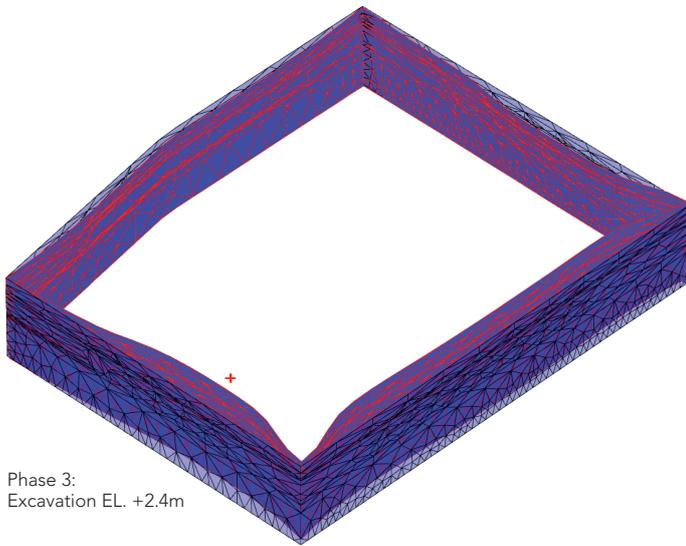


Figure 7: Three-dimensional diaphragm wall displacements