



GeoStudio Example File Braced Deep Excavations in Soft Ground

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Introduction

Halim and Wong (2005) presented a paper titled “Evaluation of Modified Cam Clay Parameters for Deep Excavation Analysis” in a publication called Underground Singapore 2005. The deflections measured in shoring walls during construction were presented for six case histories. Each of the cases was analyzed with the software SAGE CRISP. The objective was to determine if the Cam Clay constitutive model could be used to numerically model the behavior of the excavation shoring walls. In this example, GeoStudio is used to analyze one of the six case histories to demonstrate the workflow for analyzing braced excavations and to determine if GeoStudio can produce similar patterns of wall displacement.

Numerical Simulation

Figure 1 presents the geometry and stratigraphy for the Lavender MRT station in Singapore. In ascending order, the geology comprises a clayey silt, silty sand (split into two units), a lower and upper marine clay, and a fill material. The analysis takes advantage of symmetry, modeling a 12 m width of excavation to a depth of 15.5 m. The left edge of the domain was chosen to be sufficiently far-field as to not impose an influence on the stress-strain response around the excavation.

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Color	Name	Material Model	Initial Void Ratio	Unit Weight (kN/m ³)	O.C. Ratio	Lambda	Kappa	Effective Elastic Modulus (kPa)	Effective Poisson's Ratio	Cohesion (kPa)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Vol. WC. Function	K-Function
	Dense silty sand	Mohr-Coulomb	0.5	20				88,000	0.33		0	45	Silty Sand	Sand
	Fill	Tresca	0.5	18				21,000	0.33	80			Silty Sand	Sand
	Lower marine clay	Modified Cam Clay	1.18	16	1.5	0.2637	0.0527		0.33			26.2	Clay	Clay
	Medium dense silty sand	Mohr-Coulomb	0.5	20				60,000	0.33		0	43	Silty Sand	Sand
	Upper marine clay	Modified Cam Clay	1.18	16	2.15	0.3223	0.0644		0.33			25	Clay	Clay
	Very dense clayey silt	Tresca	0.5	20				100,000	0.33	800			Silty Sand	Sand

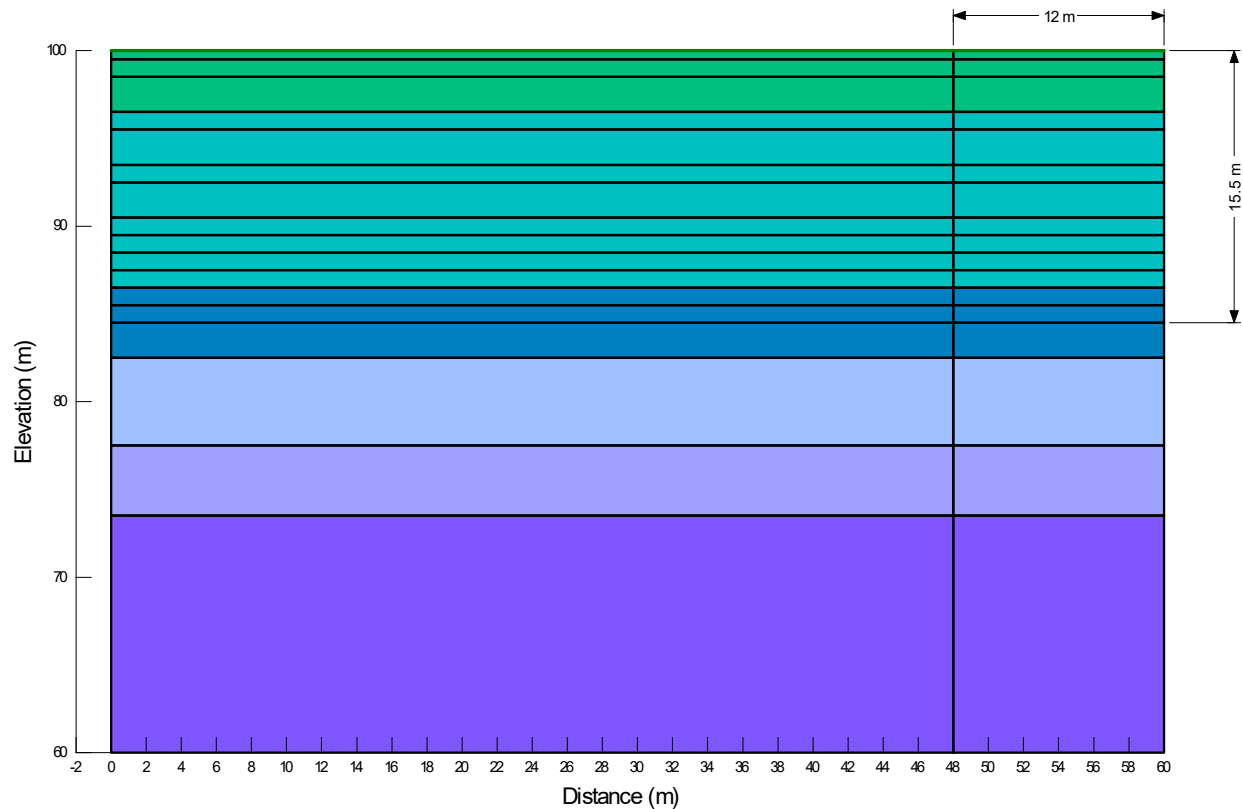


Figure 1. Geometry and stratigraphy for the Lavendar MRT station analysis.

Figure 2 presents the Analysis Tree for the GeoStudio Project. An *In Situ* analysis was conducted using the K0 procedure to establish the initial stresses and pore-water pressures in the ground. This approach is required because the marine clay units are defined using the Modified Cam Clay model. The size of the yield surface is governed by the OCR and normally consolidated K0 value because the soil was normally compressed during deposition. However, the initial stresses must be defined by the over-consolidated K0 value because the soil was unloaded in the vertical direction, producing a K0 and OCR greater than 1.0.

The subsequent fourteen analyses in the tree capture the construction history for the MRT station. Each construction stage is modeled using a Consolidation analysis to capture the stress-strain and pore-water pressure response of the system. The time duration for each analysis is arbitrarily set to 1 day to minimize pore-water pressure dissipation in the analysis. The construction sequence starts with the application of a 10 kPa stress boundary condition. The chronology then follows a pattern of excavation and installation of a strut. Each analysis forms the Parent for the subsequent Child analysis, establishing the initial stress and pore-water pressure conditions.

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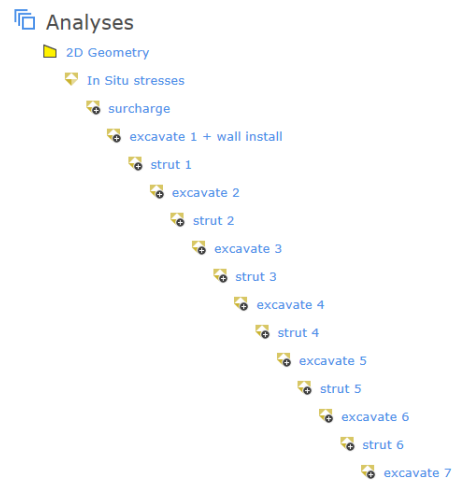


Figure 2. Analysis tree in the GeoStudio project.

Figure 3 presents the boundary conditions and strut locations for the model domain after the seventh excavation. The left and right vertical edges are constrained in the x-direction, while the lower boundary is fixed in the x and y directions. The struts are pinned on the right edge. The excavation stages are modeled by deactivating a region. Material deactivation involves determining the reaction forces acting on boundaries of regions that are to be deactivated (excavated). When a region becomes deactivated, opposing reaction forces are applied as boundary conditions to the adjacent active region boundaries. The stresses/forces from the Parent analysis (i.e. initial conditions) are used to determine the reaction forces.

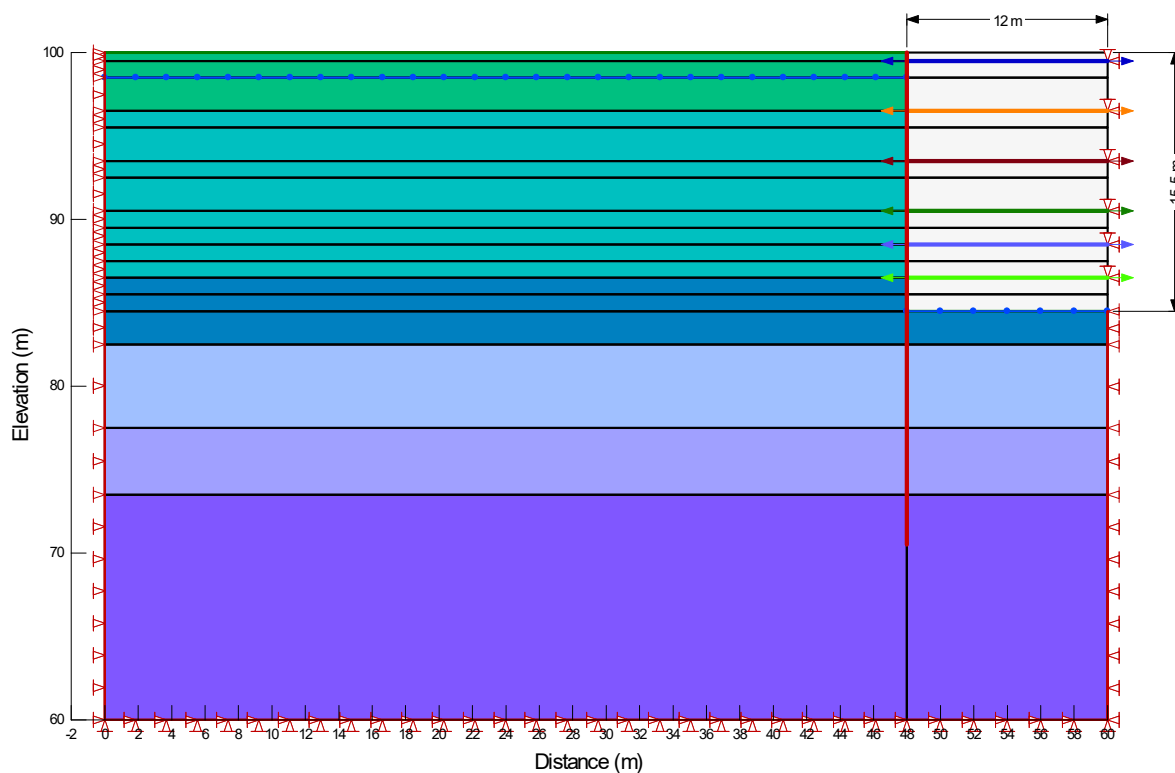


Figure 3. Boundary conditions and strut locations after excavation 7.

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The analyses are based on the assumption that drainage will not occur behind the wall during the excavation phase. A pore-water pressure of 0 kPa is therefore applied to the line at elevation 98.5 m to maintain a constant total head. Dewatering of the excavation is modeled by applying a zero pore-water pressure condition at the base of the excavation. An impervious barrier was applied to the line representing the diaphragm wall, indicating that the wall will restrict groundwater discharge into the excavation.

Strut installation is modeled independently from the excavation stage because each strut is pre-stressed after installation. Defining a pre-axial force (i.e., a pre-stress) for a structural bar automatically produces a force boundary condition applied to the end-points of the structure.

Figure 1 displays the constitutive model and parameterization used for each material in the domain. The two sand layers, fill material, and clayey silt were defined using the Mohr-Coulomb model. The Modified Cam Clay model was used for the lower and upper marine clay. The response type (drained/undrained) of all materials is ignored in a Consolidation analysis because all materials are assumed to participate in groundwater flow. The hydraulic properties were defined using the estimation routine in GeoStudio.

The diaphragm wall and struts are modeled using a structural beam and structural bars, respectively. Halim, D. and Wong K.S. (2005) do not provide details on the structural stiffness properties. A typical modulus for a concrete diaphragm wall was assumed ($1\text{e}7$ kPa). The cross sectional area and moment of inertia equal are set to 1 m^2 and 0.083 m^4 , respectively. All of the struts have a modulus of $1\text{e}8$ kPa and a cross-sectional area of 0.01 m^2 . The pre-axial force in the six struts varies from 190 kN to 390 kN. The pre-axial forces are positive to model compression and therefore a lateral load acting against the wall. The spacing of the struts in the out-of-plane direction was assumed to be 1 m based on the units presented by the authors.

Results and Discussion

Figure 4 present the groundwater flow regime and total head contours after the third excavation. Figure 5 presents profiles of pore-water pressure along the right edge. Groundwater flow occurs downward on the left side of the wall, underneath the wall, and then upward toward the excavation. Unloading of the marine clay produces a tendency for volumetric expansion, which is restricted until water flows toward the clay. This drop in pore-water pressure within the clay causes downward groundwater flow from the base of the excavation at the onset of unloading.

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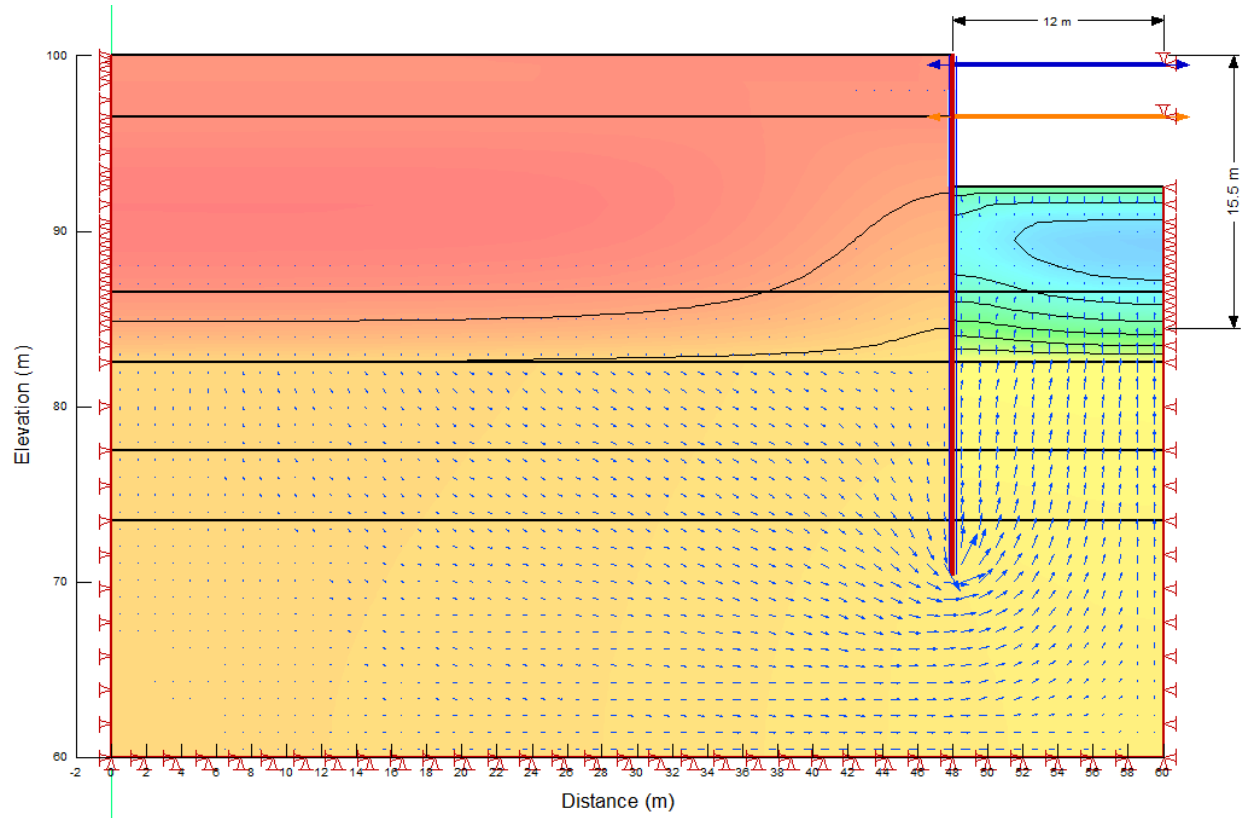


Figure 4. Groundwater flow system after excavation #3.

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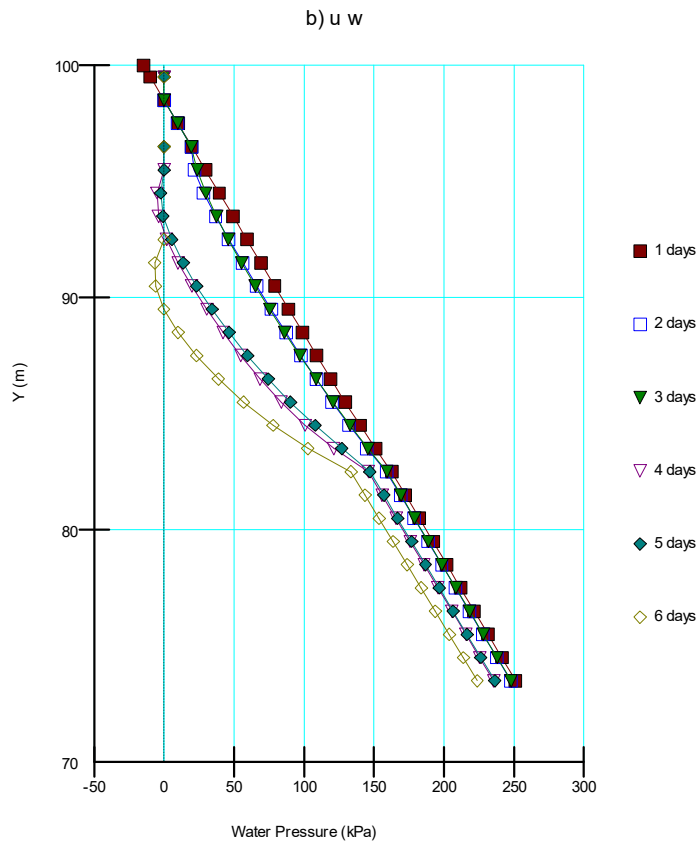


Figure 5. Pore-water pressure profiles on right edge.

The measured and computed wall deflection profiles at the end of construction are presented in Figure 6. The GeoStudio computed lateral wall deflections are in good agreement with the field measured values, capturing both the magnitude and patterns presented by the authors. A review of the profiles from analysis-to-analysis reveals that the strut pre-stressing has a significant effect on the displacement pattern and magnitudes. For example, excavation #3 produced about 9 cm of lateral displacement toward the excavation, while the installation of strut #3 returned the wall about 8 cm inward. It is important to realize that the wall only displaced by about -38 mm – that is, 3.8 cm or 0.032 m – over an excavation depth of 15.5 m, which is relatively infinitesimal.

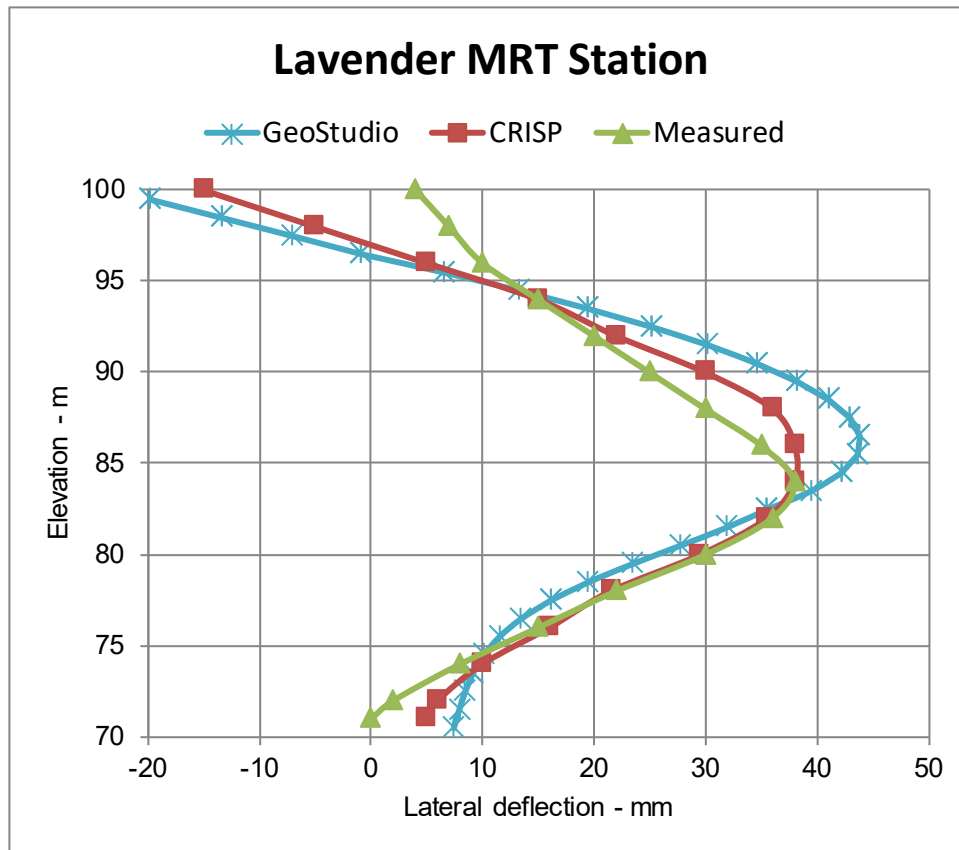


Figure 6. Deflection profiles with 100% strut pre-stress.

Figure 7 presents the bending moments in the diaphragm wall for each stage of construction. The maximum bending moment is just over 1200 kN*m. A change in sign (+/-) occurs near the base of the excavation. In the case of design, a sensitivity analysis could be conducted to determine the possible range of bending moment values for different input parameters, such as wall/strut stiffness, strut spacing, and other soil properties.

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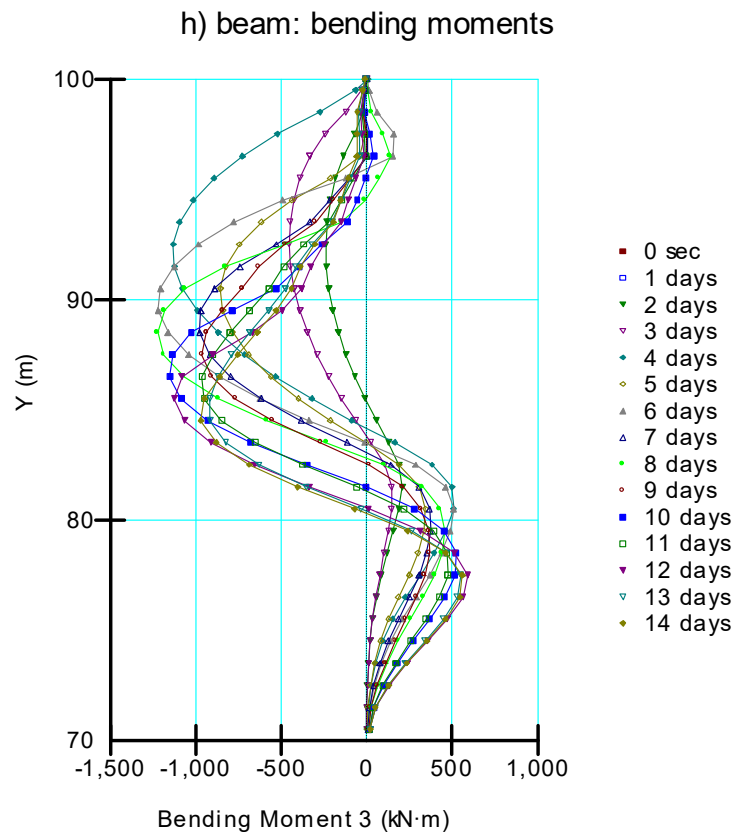


Figure 7. Bending moments at each stage of construction.

The maximum settlement takes place some distance behind the wall and not immediately behind the wall (Figure 8). The overall displacement pattern is downward and toward the excavation. The pore-water pressure decreases with each subsequent excavation, causing an increase in mean effective stress and therefore settlement. The top of the wall rotates counterclockwise about the base of the excavation, causing the ground surface to heave upwards directly adjacent to the wall. The struts amplify this heave as the soil is compressed after each strut installation.

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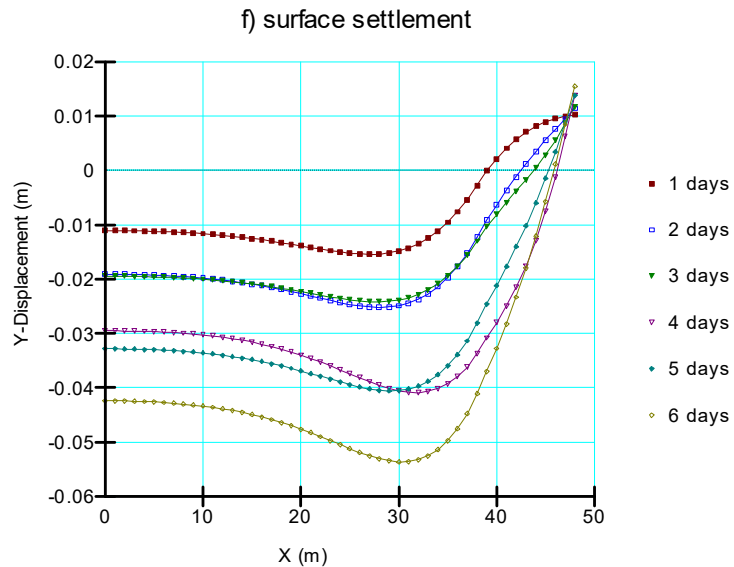


Figure 8. Surface settlement profiles.

Summary and Conclusions

The analysis of the Lavender MRT case study demonstrates that GeoStudio can be used to model the behavior of deep shored excavations in soft ground. More importantly, the case study reveals the importance of conducting sensitivity analyses at the design stage of this type of project. To arrive at a reasonable approximation of field behaviour, it is important to correctly parameterize the soil/rock and structural material models. The numerical analysis can reveal the importance of strut pre-stressing, the effect of soil and structure stiffness on deflections and bending moments, and the role of pore-water pressure on the performance of the system.

References

Halim, D. and Wong K.S. (2005). *Evaluation of Modified Cam Clay Parameters for Deep Excavations Analysis*, Underground Singapore 2005, pp. 188 – 199.