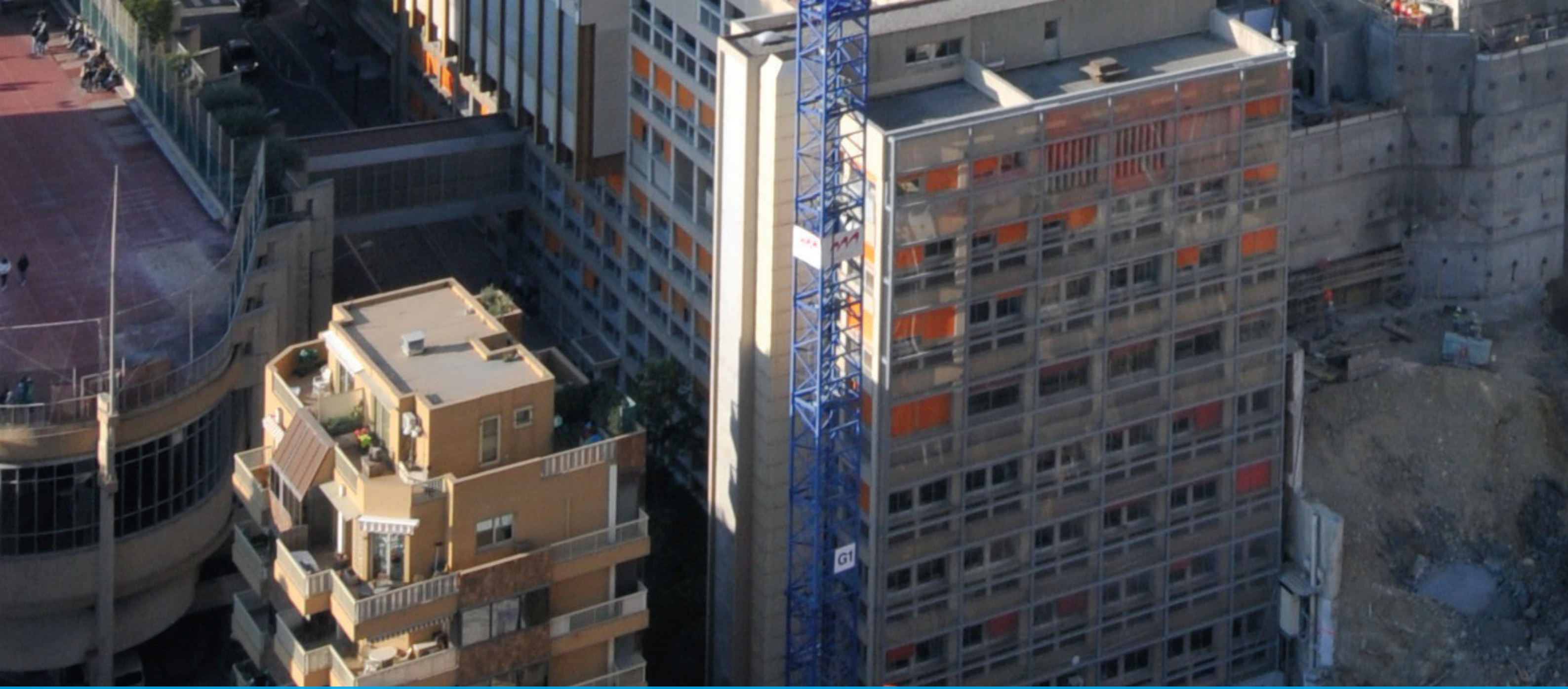

3D Finite Element Analysis of a Deep Excavation in Monaco

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The Odéon tower project in Monaco is exceptional, both by its height, 160m, the tallest building in Monaco, and the depth of the excavation required, planned to reach about 70m. TERRASOL was entrusted with geotechnical consultancy on the soil testing, foundations, etc, but also and mostly with the implementation of a 3D finite elements model to analyze notably the influence of excavations on the surrounding buildings.

The Odeon project consists in the construction of a high-rise building (160 m) in Monaco, with approximately 10 basement levels, located on a steep slope hillside (from 130 NGM to 67.5 NGM). The ground level is assumed to be placed at 67 NGM. The retaining structures to be built around the excavation are the following:

- A 15 m high soldier-micropile wall (from 114 NGM to approximately 94 NGM);
- A 20 m high soldier-pile wall (from 94 NGM to approximately 74 NGM);
- A 38 m deep diaphragm wall, used for the basement excavation, from 74 NGM to approximately 36 NGM.

The soldier-micropile and the soldier-pile walls are temporary structures, whereas the diaphragm wall is permanent. The diaphragm wall will be supported by the parking floors (construction based on the "up and down" method). The superstructure will be resting on the peripheral diaphragm wall (including buttresses) and on localized diaphragm walls inside the excavation.

Several buildings already exist around the excavation, one of them being a middle school located nearby the diaphragm wall and associated to older retaining structures (an anchored wall).

The aim of our work was to determine the horizontal and vertical displacements of the various retaining walls around the middle school (the existing anchored wall of the school and the

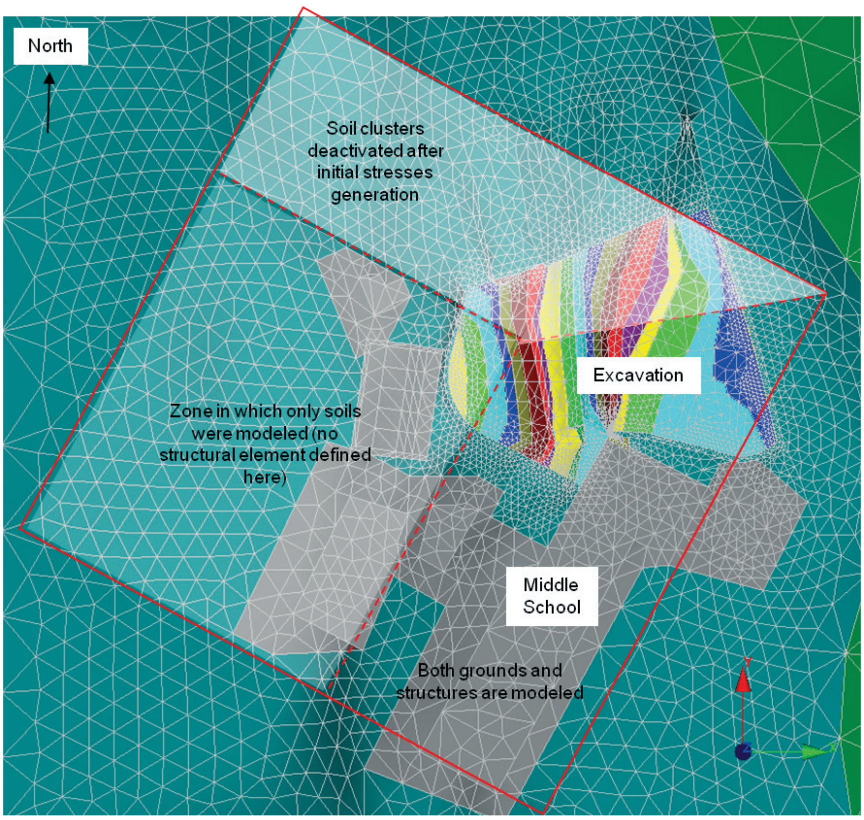

Figure 1: Top view of the modeled area

Loading	γ_{unsat} (kN/m3)	E(kPa)	ν	c'(kPa)	ϕ (°)	ψ (°)
Screes	20	0.101E6	0.30	10	30	0
MCM	24	1.218E6	0.30	30	32	0
Limestone	24	1.600E6	0.30	70	38	0
Unloading	γ_{unsat} (kN/m3)	E(kPa)	ν	c'(kPa)	ϕ (°)	ψ (°)
Screes	20	0.111E6	0.43	10	30	0
MCM	24	1.336E6	0.43	30	32	0
Limestone	24	1.816E6	0.30	70	38	0

Table 1: Soil properties

new retaining walls built during the works) and to describe the general behavior of the school structure. PLAXIS 3D 2010 has been used for this calculation.

Underground Construction

Our calculation focused on a local model (only part of the entire project) including the different new retaining structures set up near the middle school. Thus we restricted the model to the neighborhood of the new retaining wall, including the existing wall and the new wall, the middle school, and a part of the excavation pit.
The soils located uphill the middle school and the excavation were taken into account for initial stresses calculation, without modelling the other existing buildings. The soils located uphill the excavation were deactivated afterward to shorten the calculation time (cf. Figure 1).

Geotechnical profile

The three soil layers encountered on the construction site are the following: superficial colluviums lying over Marls and Calcareous Marls, with a local Limestone layer located downhill the model. All these layers are tilted.
Given the complexity of the different layers, the definition of 28 boreholes was necessary to fully describe the soil model. We used the Mohr-Coulomb model for all soil layers: as a previous model of the excavation was realized using the Mohr-Coulomb model, which is accetable when dealing with rock, we kept using it to be able to compare the results of both models. The soil properties are described in Table 1.

Structural Elements

The model includes the existing retaining structures, which are:

- The old 16 m high anchored wall (from 87 NGM to 71 NGM) associated to the middle school, made of reinforced concrete;
- The T-shaped reinforced concrete walls of the existing terraces uphill the school;

The model also includes the walls of the new retaining structures, which are:

- A soldier-pile wall with 10 piles (Ø 1000 mm) of variable height (26 m to 14 m, from max. 100 NGM to min. 74 NGM), made of shotcrete and reinforced concrete;
- A soldier-micropile wall with 4 micropiles (Ø 280 mm) approximately 9 m high (from 87 NGM to min. 78 NGM), made of shotcrete;
- A 48 m deep diaphragm wall (from 74 NGM to 26.4 NGM), with 10 m embedment below the raft of the underground structures.

Those retaining structures include piles, micropiles, shotcrete and reinforced concrete, and prestressed anchors with various inclinations. Besides, the floors of the tower basements are built while the excavation goes on, from 73 NGM to 36.8 NGM.

Some structural simplifications were necessary while building the model. The three main simplifications are the following:

- The main simplification was that only a part of the excavation has been introduced in our model. In order to take into account the interaction with the other part, a surface of zero prescribed displacements was defined in the center of the excavation, and only the South half of the excavation and the floors was modeled (using the project symmetry).
- The middle school building structure was not modeled: only the building load was taken into account. Besides, the foundations (piles) of the middle school were not modeled but the building load was applied at the piles tip level (64 NGM).
- The existing wall of the middle school (M1) consists of an anchored wall. Only the anchors placed near the excavation (approximately 30 m) were modeled. The wall part most distant from the excavation pit (which does not have much influence on the works) was modeled by a plate with prescribed displacements.

Finally, the structural elements used in the model (cf. Figure 2 and Figure 3, page 12) are the following: 6 existing (anchored) walls, 2 new soldier pile walls, the diaphragm wall around the excavation, 13 floors inside the excavation, 15 piles and 140 anchors.

The material properties for the structural elements are presented in Table 2 to Table 4.

Model and mesh properties
The final model dimensions are the following:

- 165 m long in the East-West direction;
- 130 m wide in the North-South direction;
- Levels from 130 NGM to 10 NGM.

It includes approximately 137,700 elements with an average size of 5 m, and approximately 198,740 nodes (cf. Figure 4).

Loads and Boundary Conditions

Initial stresses
The stresses initialization is performed during the initial calculation phase, using gravity loading with all soil clusters activated.

In the next phase, once the initial stresses state was reached, the soils located uphill and North to the excavation were deactivated to enable the staged construction calculations.

Applied overloads
A structural overload of 150 kPa is applied at the base of the school piles (at 64 NGM), which corresponds to a distributed load of 15 kPa by floor for a building composed of a ground floor and 9 floors (cf. Figure 5).

Hydraulic conditions
We considered for the present calculation that drains are introduced behind the retaining structures: thus the water level was assumed to be lowered below the structures and was therefore not considered in the current model.

Boundary conditions: displacements
During the initial phase, the boundary conditions are the Plaxis standard boundary conditions:

- Zero prescribed displacements along the x axe on the yz borders;
- Zero prescribed displacements along the y axe on the xz borders;
- Zero prescribed displacements along the x, y and z axes on the model base.

During the calculation, after deactivation of the soil clusters located uphill and North to the excavation, additional surfaces of prescribed displacements have been defined:

- Zero prescribed displacements along the y-axis on the East-West plan placed uphill the middle school, to retain the grounds;
- Zero prescribed displacements along the x-axis on the North-South plan uphill the excavation, to retain the grounds to be excavated;
- Zero prescribed displacements along the x, y and z axis on the plan oriented North East-South West, placed at the center of the excavation, enforcing symmetry conditions.

Staged Construction

To model the whole construction process, 43 calculation phases were necessary: the initial phase (0) to calculate the initial stresses, phase 1 to deactivate some of the soil clusters, and after that, two calculation phases for each excavation phase (one to deactivate the excavated grounds, and one to activate the retaining structures).

Main Results

The whole project lasted 2 month. We needed 7 weeks to create the definitive model and to define all the calculation phases, 2 weeks to

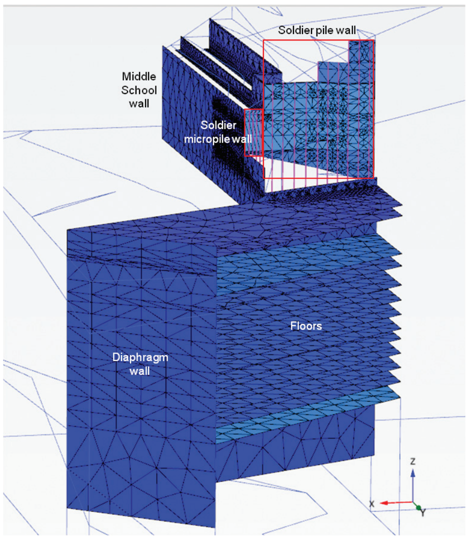

Figure 2: Global view of all the plates

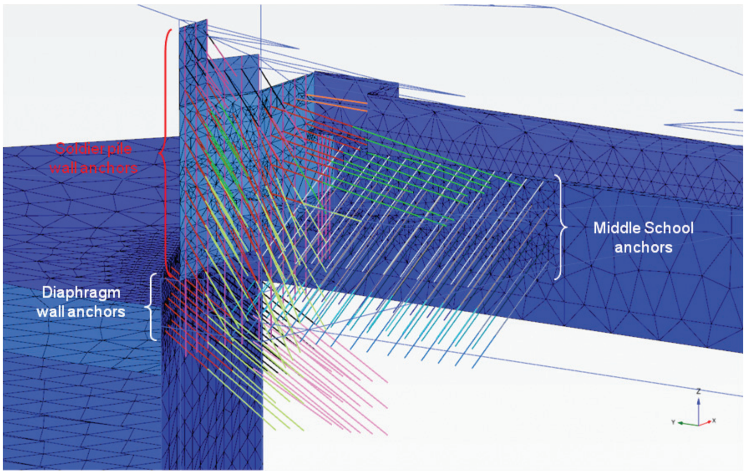

Figure 3: Global view of all the anchors

Plates	e (m)	γ(kN/m³)	E (kPa)	ν
Middle School (M1)	0.60	25	20E6	0.25
M6_wall	0.30*	25	20E6	0.25
M6_foot	0.40*	25	20E6	0.25
Shotcrete	0.20	24	25E6	0.25
Reinforced concrete	0.40	25	25E6	0.25
Diaphragm wall	0.82	25	30E6	0.25
Floors	*Variable*	25	35E6	0.25

Table 2: Plate properties

Anchors		Free part		
Structure	Type	E (GN/m²)	A (mm²)	EA (kN)
Soldier pile wall	Dywidag ϕ 36mm	194	1018	197.47E³
	7T15	194	980	190.12E3
	9T15	194	1260	244.44E3
Middle school existing wall M1	7T13	194	651	126.29E3
	10T13	194	950	180.42E3
	12T13	194	1116	216.50E3
	13T13	194	1209	234.55E3

	Anchored part				
Type	E(GN/m²)	γ(kN/m³)	A(mm²)	d(m)	T_{skin}(kN/m)
7T15Eb	194E6	70	980	0.035	70
7T15MMC	194E6	70	980	0.035	112
9T15Eb	194E6	70	1260	0.040	70
9T15MMC	194E6	70	1260	0.040	112
7T13MMC	194E6	70	651	0.029	112
10T13MMC	194E6	70	930	0.034	112
12T13MMC	194E6	70	116	0.038	112
13T13MMC	194E6	70	1209	0.039	112

Table 3: Anchor properties

Beams	d_{for} (m)	A_{tot} (m²)	d_{ext} (m)	d_{int} (m)	A_a (m²)	A_b (m²)	γ(kN/m³)	E (kPa)	E (m⁴)
Micropiles	0.28	0.062	0.22	0.17	0.0137	0.048	70	194E6	6.7E-5
Piles	1.00	0.785	-	-	-	-	25	30.0E6	4.9E-2

Table 4: Beam properties

achieve the calculations, and 1 week to analyze the model results. Given the high number of elements and calculation phases, the whole calculation required almost 12 hours to be completed.

The model results show that the new retaining structures should guarantee the stability of the excavation as well as the one of the school building. The total displacements of the new retaining structures do not exceed 5 mm in the present simulation. The Figure 6 shows a model global view with total displacements.

Conclusion

Comparing the final results with those of the previous model, the displacements were similar. This demonstrates that the simplifications which have been made for this local model were acceptable. The PLAXIS results also showed that the total displacements were acceptable for the structures: according to the calculations, the new retaining structures have been safely designed. These results will be used during construction works to check that the in-situ displacements do not exceed the maximum calculated ones.

This project required a 3D model with high geometrical complexity and many calculation phases. However, the model construction has been relatively easy (given the various structural elements that had to be modeled): once we got familiar with all PLAXIS 3D commands, especially creating copies of a selection, it became quite fast to define the various structural elements. The most time consuming operations were those related to mesh generation due to the complexity of the model.

The final results were totally satisfying, and our conclusion about using PLAXIS 3D 2010 is very positive. Using the command line feature proved to be a highly useful tool: we could not have achieved the whole meshing and the calculations as quickly as we did without that tool.

The results post-processing in terms of displacements and loads has been achieved rather rapidly thanks to the Output tools (many display options and ability to select part of the structures only).

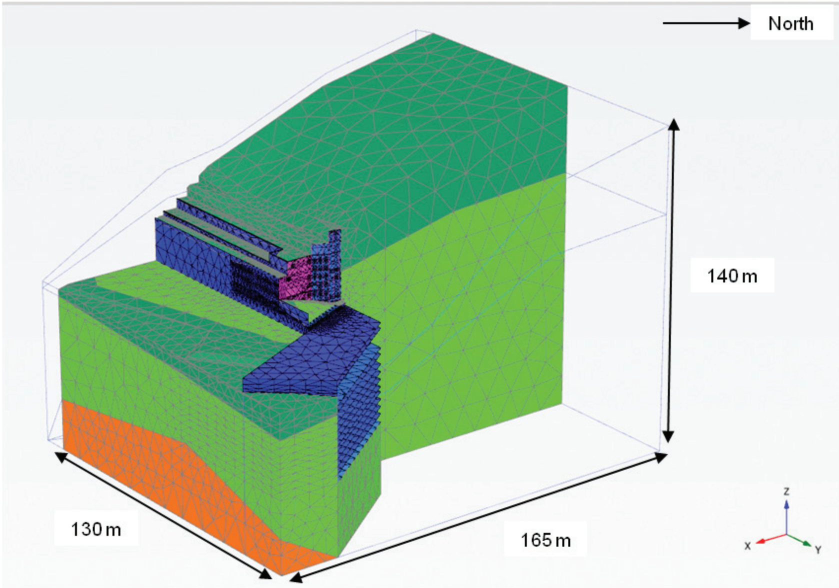

Figure 4: Global view of the final model

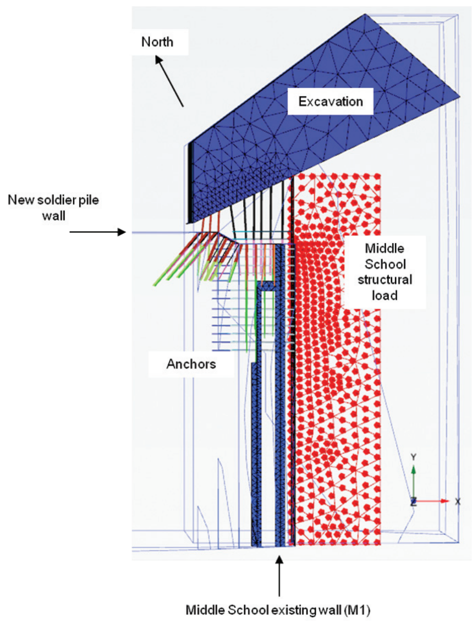

Figure 5: Top view of the middle school structural overload

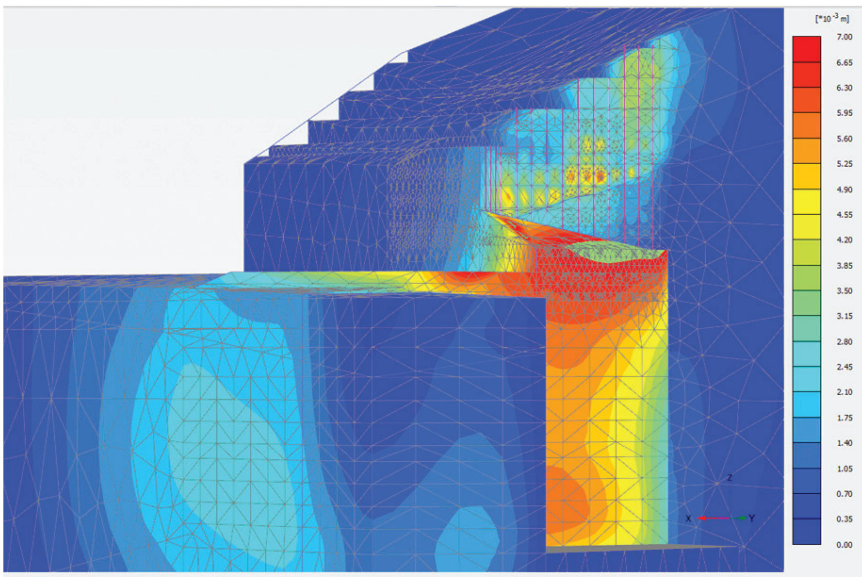

Figure 6: Global view of the final results (total displacement)