A compact design for shaft-tunnel junction adopted for Greater Cairo Metro Line 3. Design aspects and use of advanced numerical methods.

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Summary

The design of shaft-tunnel junctions on the Greater Cairo metro system has evolved over time. The geological conditions in Cairo are challenging, with alternated layers of sands and clays and the existence of a water table. Initially for former metro line 2, the junction between rectangular shafts and the bored tunnel was achieved by excavating the cross-passages in artificially frozen ground. Later for the new line 3, the technique of artificial freezing was replaced by a ground improvement approach using plastic concrete. More recently, a new concept was introduced whereby no ground improvement and no connecting galleries are necessary. The principle lies in driving the TBM to partially intercept an unexcavated circular slurry wall. The shaft can then be excavated in several stages, allowing for the construction of the upper part and the lower part of a reinforced concrete portal aimed at strengthening the opening created by the TBM in the shaft slurry wall. While this approach entails savings in both the cost of soil treatment, and in the construction time of the cross-passage, it requires adequate detailing of the reinforcement in the slurry wall panels and the dimensioning of the shear connectors between the panels of the shaft, the segmental lining of the tunnel and the concrete elements of the portal. Advanced 3D numerical modelling is thus used to assess structural forces on which the detailing is based. The complex geometry of the junction associated with the non-linear behaviour of the ground and of the inter-panel joints as well as the impact of the construction sequence led to adopt advanced numerical methods. It is only recently that finite element software with sufficient capabilities and user-friendliness are available to model such a 3D configuration in a realistic way and within a timeframe compatible with project requirements. This example illustrates how advances in construction methods can be stimulated through improvements in the analytical tools.

Keywords: shaft, junction, compact, portal, design, numerical analysis, 3D

1. Introduction

In tunnelling works, annex structure construction is always a challenging part of the project. As opposed to standard tunnel boring which is a repetitive mechanized work, annex structures are singular points: firstly, they are generally excavated by the conventional method in unstable ground which requires preliminary soil treatments; secondly, bored tunnel lining needs to be supported prior to opening; finally, the excavation of the connecting gallery induces an increase of the forces in the neighbouring structures (in the shaft walls, for instance).

The design adopted for the annexed structures belonging to Phase 2 of the construction of Cairo metro Line 3, as developed by the site and the design managing team based on the experience gained during the construction of previous metro lines in Cairo, reduces significantly the difficulties mentioned here-above. The principle of this concept lies in driving the TBM to partially intercept an unexcavated circular slurry wall. The main advantage of this method is that no ground improvement and no connecting galleries are then necessary.

Advanced 3D numerical modelling was very helpful firstly to validate the feasibility of such a concept and secondly to assess structural forces in all components of this complex geometry.

2. Greater Cairo Metro Line 3

2.1 Project phase 2

The new Line 3 is split in four phases, see Fig.1. To date, phase 1 is close to completion and phase 2 is under progress. The other phases 3 and 4 are planned.

Phase 2 is going from Abbasia station to Haroun El Racheed station. This phase includes:

- Five underground stations: the tunnel route starts from Abbasia station (KP 18.574), already completed in Phase 1, ends at Haroun El Racheed station and passes through Cairo Fair station (KP 16.421), Stadium station (KP 14.701), Kolleyet El Banat station (KP 13.032) and Al Ahram station (KP 12.093), from South to North. The length of each station is about 150m.
- The Underground Tunnel which extends from Abbasia station to Haroun El Racheed station and which will be executed by Tunnel Boring Machines (TBM). The tunnel is circular in shape with an internal diameter of 8.35m.
- Seven shafts directly connected to the bored tunnel: five ventilation and fire brigade access shafts located at KP 17.801537 (annex 11A), at KP 17.115320 (annex 11B), at KP15.733477 (annex 13A), at KP 13.801769 (annex 15A) and at KP 11.36423 (annex 19A), one ventilation shaft located at KP 12.481660 (annex 17A) and one fire brigade access shaft located at KP 15.1514796 (annex 13B)

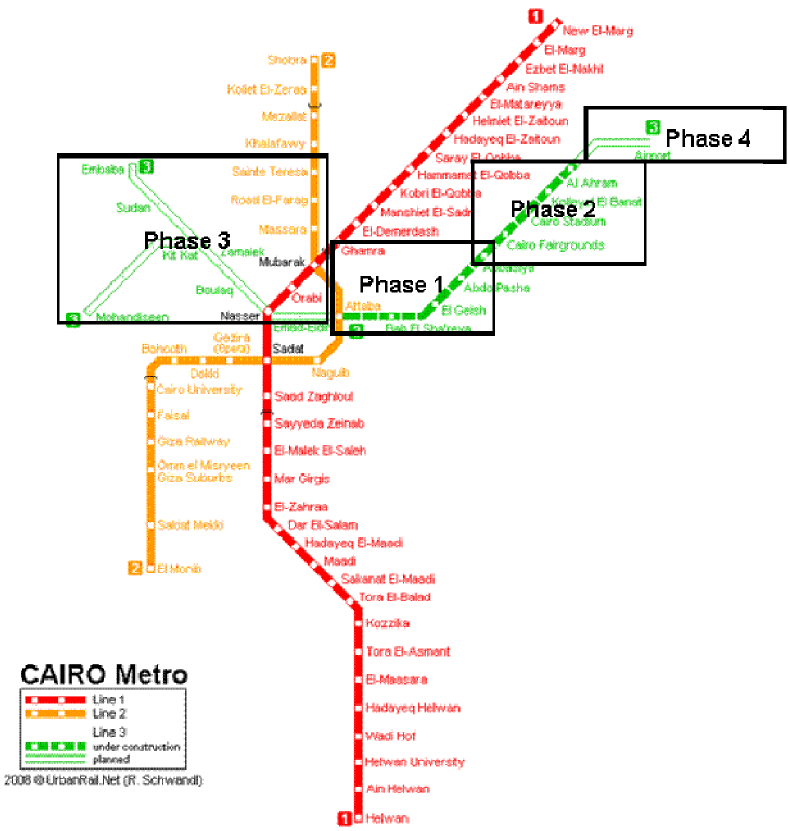


Fig.1 View of existing Line1 and Line2 and of the future Line 3

2.1.1 Tunnel route

The tunnel route passes under the densely built city of Cairo. When possible the tunnel route follows large avenues and streets but sometimes passes under existing structures, especially between Abbasia station and Cairo Fair station. This section includes many challenging points: deep foundations of some bridges at immediate proximity of the tunnel, buildings up to six floors high just above or at close proximity of the tunnel, sewage pipes passing close to tunnel crown.

2.1.2 Tunnel Boring Machines

The particularity of phase 2 of the Line 3 is that two different TBMs are used to complete the excavation mainly due to the changes in hydrological conditions along the tunnel route: the tunnel starts at Abbasia station crossing saturated sands and clay below water table, then from Cairo Fair station the water table level is lower and the tunnel crosses partially to totally dry sands and clays.

Thus, the boring starts between Abbasia station and Cairo Fair station with an Herrenketch slurry TBM. The tunnel face is supported by a total slurry pressure, varying from 60 kPa to 180 kPa at crown, and mostly above 120 kPa.

Then a NFM earth pressure balanced TBM is used from Cairo Fair station to Haroun El Racheed station. The tunnel face is supported by a total pressure, varying from 50 kPa to 150 kPa at crown, and mostly below 100 kPa. Face support pressures have been adjusted not only to ensure stability of the face but also to control induced settlements when passing below existing buildings and surface structures. Both TBMs have an excavation diameter of 9.41m.

2.1.3 Bored tunnel and annexed structures

The tunnel lining has an inner diameter of 8.35m. The lining segments are 0.40m thick and are made of concrete with a cube strength of 42.5 MPa. The lining is made of tapered precast segments, of 1.50m mean width. A ring is made of five typical segments, two counter key segments and one key element. Concrete faces are equipped with bolted connections: two bolts of 25/22 diameter are installed per segment face between ring and between segments. For watertightness, segments are equipped with a sealing gasket at extrados plus an hydrophilic gasket placed in addition at intrados.

At the junctions with annexed structures, special rings are used: they are similar to the standard rings but each ring face is equipped with polyamide dowels which increase the shear capacity between each ring, see Fig. 2

The annexed structures are made of near circular shafts of internal diameter 8.87m or 10.27m. The slurry wall panels are 1.0m or 0.80m thick. The temporary and also final shafts lining is made of 14 adjacent slurry walls panels. These panels are not structurally connected between each other, see Fig. 3.

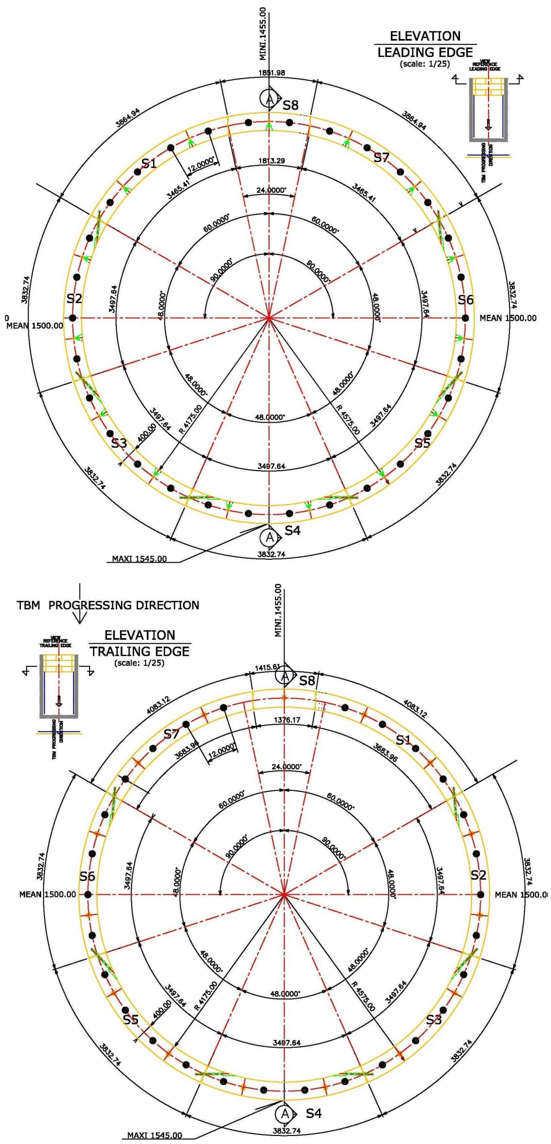


Fig.2.Tunnel lining – Special rings

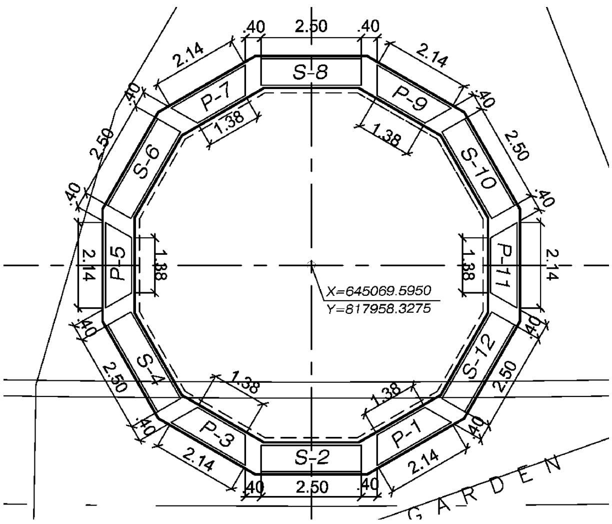


Fig. 3 Shaft - Slurry walls cages location

Slurry panels are reinforced in order to support earth and water pressures and also all forces induced by the bored tunnel intersection. Reinforcement is achieved by FRB bars in the part planned to be intersected by the TBM machine.

Slurry walls panels have varying depths depending on bored tunnel levels and have various embedment lengths depending on encountered water conditions.

3. Design of annexed structures of phase 2

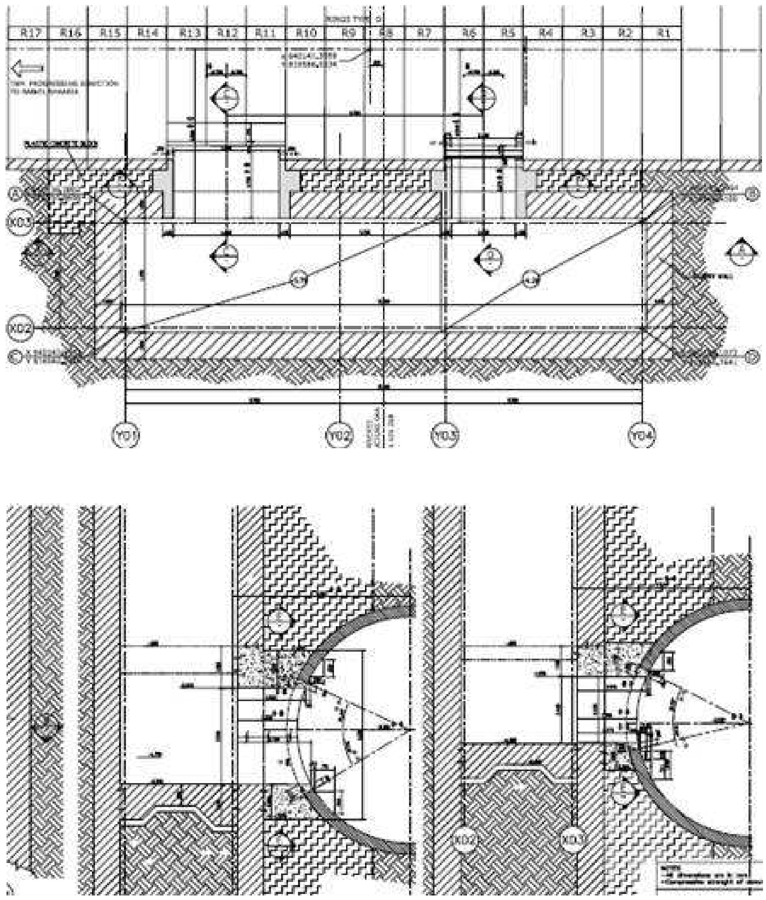


Fig. 4 Phase 1 – Configuration of annexed structures Plan view and sections

Experience gained with the annexed structures of phase 1 revealed the difficulties pertaining to the construction of connecting galleries of very limited length (only 1.0 to 1.5m long) to be excavated from a shaft of very limited dimensions (only 3.0m wide) in which space was further reduced by a massive strutting system.

Moreover, excavation in sand below water required expensive soil improvement (soil freezing was adopted for Line2 and plastic concrete substitution was adopted for the Line3 phase1). See Fig. 4.

For phase 2, the choice made by the design managing team to adopt a circular shape for the shafts made the standard shaft strutting system inapplicable and made a larger work space available inside the shaft. The choice to drive the TBM to partially intercept the unexcavated shaft wall implied that no ground improvement and no connecting gallery were necessary. This meant that no manual underground excavation works were required.

3.1 Geological and hydrological context for annex structure 17A

The geology consists of fill layer overlaying sand intermixed locally with gravel, silt and interlayer of clay with a limited thickness. A decrease of the presence of thick hard clay band is observed. The sand formation is more frequent than other tunnel drives. Water table is at about rail level.

3.2 Geometry of shaft-tunnel junction at annex structure 17A

The final open space in the connecting gallery is rectangular with a height of 3.84m and a width of 4.5m (for other annex structures, the width can reach 6.0m).

At the junction, the stability of the bored tunnel lining during construction stages as well as in final stage is ensured thanks to a concrete portal located in the shaft and made of:

- an upper beam located at the top of the intersection between the tunnel lining and the slurry-walls,
- a lower beam located at the bottom of the intersection between the tunnel lining and the slurry-walls,
- two side walls connecting the two elements previously mentioned, Fig. 5

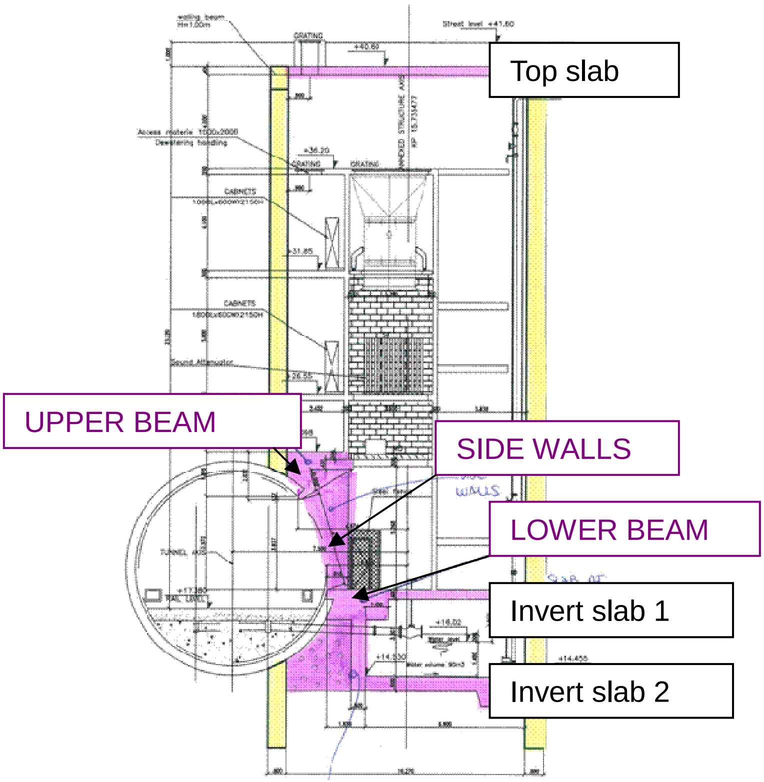


Fig. 5 Major structural elements

All these elements are connected to the slurry walls while only the upper and lower beams are connected to the bored tunnel lining through sealed reinforced bars. Invert slabs bring an additional stiffness to the supporting system, while other structures are present to support the internal equipments.

3.3 Construction methods and technology

Construction stages are presented here-below :

- first the slurry walls of the shaft are installed in the ground,
- then the TBM passes and cuts the slurry walls in the shape of two cylinders partially intersected,
- temporary support in the tunnel is placed,
- the excavation of the shaft can proceed from surface level down to the bottom level of the upper beam,
- when the excavation reaches this level, connecting bars between the upper beam and the tunnel lining and between the upper beam and the slurry walls are sealed; then the beam can be concreted, thus creating the first support for the tunnel lining,
- excavation of the shaft can can continue down to the bottom level of the lower beam ; at this point, connecting bars between the lower beam and the tunnel lining are sealed as well as the connecting bars between the lower beam/side walls and the slurry walls; then the side walls and the lower beam are concreted, thus completing the temporary and final support for the tunnel lining,
- excavation is completed down to invert level; then invert slab, invert wall and slab at tunnel level are concreted,
- at the last stage, tunnel lining is fully supported and can be opened to create the final passage from the shaft to the tunnel.

4. Detailed design based on 3D numerical analysis

4.1 Aims of the analysis

An important consequence of adopting such a compact design is that the slurry wall panels of the shaft and the lining rings of the tunnel become integral parts of the load bearing structure at the junction. The construction sequence, the 3D effects and the interactions between these different structural parts and the ground are therefore key elements to the detailing of the reinforcement to be placed in the slurry walls and the lining rings.

The main aims of the finite element model presented below were to assess, during temporary construction stages and over the long term, the forces in the slurry wall panels, the forces in the shaft inner structures and the contact stresses at their interface. Based on these forces and contact stresses, reinforcement and shear connectors could be detailed for the slurry wall and the inner structures. A modified version of the model (not presented here) was used to check the lining rings and to design a temporary support system in the tunnel at the junction.

4.2 Model presentation

The ground layers, the tunnel lining, the slurry wall and the inner structures of the shaft were modelled in 3D in a single finite element model using the software midas GTS, which is dedicated to geotechnical and tunnel engineering analysis. The model representing the annexed structure 17A is presented in the following.

4.2.1 Ground layers

Seven horizontal ground layers made of fill, sand or clay are modelled with thicknesses ranging from 1.5 to 10 meters. The overall dimensions of the model are 100m x 100m in plane and 80m in depth. The ground layers are meshed with tetrahedron elements which allow easy mesh refinement where necessary and mesh coarsening towards the model boundaries, Fig. 6.

The material model adopted for all ground layers is Mohr-Coulomb perfect plasticity, see Table 1. The ground water table is assumed to intercept the tunnel close to its invert. The sand and fill layers are assumed to behave in a drained way. The clay layers are assumed to behave in an undrained way during the construction stages. For the long term computation stage, the clay layers are assumed to become drained.

Table 1 Long term material properties

Material	density [-]	E [MPa]	□ [-]	c [KPa]	□ [°]	K_0 [-]
Man-made fill	1.80	10	0.30	0	30	0.5
Upper sand	1.95	70	0.30	0	37	0.4
Middle sand	2.00	130	0.30	0	39	0.37
Upper clay	1.80	54	0.35	20	29	0.61

The insitu stresses are determined based on the equilibrium under self-weight and on normally consolidated K_0 ratios deduced from Jaky formula ($K_0 = 1-\sin\phi$).

4.2.2 Tunnel lining

The tunnel lining is modelled with triangular plate elements. Interface elements are inserted between the lining and the ground to model sliding and debonding. Since the model is primarily aimed at detailing the shaft structures, the exact geometry of the lining segments is not represented and the lining is assumed to behave as a continuous linear elastic shell.

4.2.3 Shaft slurry wall

The exact geometry of each slurry wall panel is modelled. The panels are meshed with triangular plate elements. Dedicated line interface elements are inserted between each panel to allow relative sliding, hinging and debonding. The slurry wall panels are assumed to behave linear elastically.

Two analysis cases are considered with varying assumption on the behaviour of the panel joints, Fig. 7. In the first analysis case, the joints are assumed perfectly sticking (i.e. continuous shell modelling). In the second analysis case, the joints are assumed perfectly sliding (no cohesion or friction) and with zero tensile strength. The variability of the actual properties of the inter-panel joints and the difficulty to anticipate which case will be the most adverse for the detailing of the panels led us to consider the two bounding cases and carry out the reinforcement detailing of the panels based on the envelop of both results.

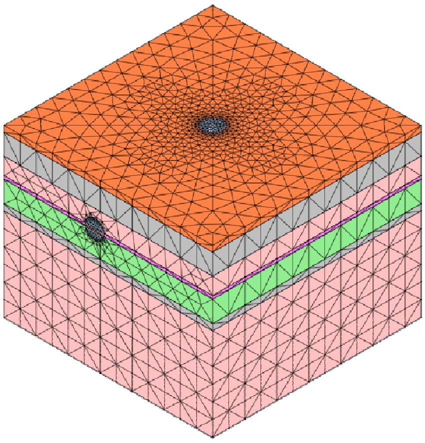
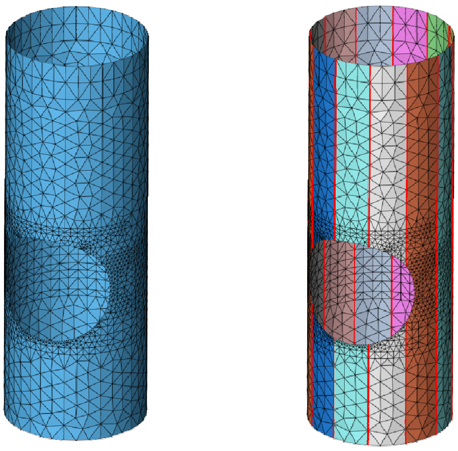


Fig. 6   Full model mesh (ground layers)



(a)   *(b)*

Fig. 7 Mesh of shaft slurry wall in case of continuous shell modelling (a) or sliding joint modelling (b)

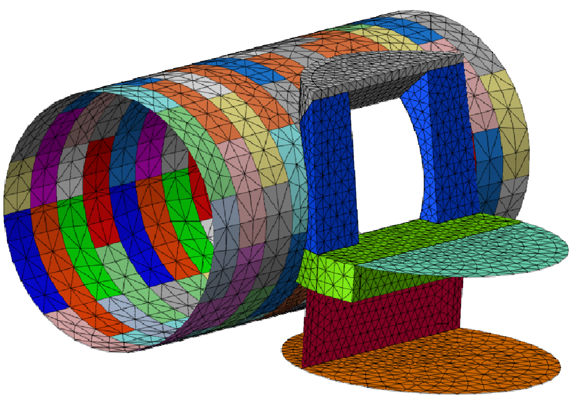


Fig. 8 Mesh of lining segments and inner structures (portal, slab and invert) at the junction.

4.2.4 Shaft inner structures

Sufficiently bulky inner structures of the shaft, including the portal and the upper beam, are modelled with solid tetrahedron elements. The invert slabs are modelled with triangular plate elements, Fig. 8. All shaft inner structures are assumed to behave linear elastically.

4.2.5 Construction stages

The non-linear analysis is carried out in 7 stages including stress initialization, shaft excavation stages, stages for the construction of elements of the inner structure, opening of the tunnel lining and eventually the long term behaviour including water level rise above the clay layer and uplift pressured applied on the raft.

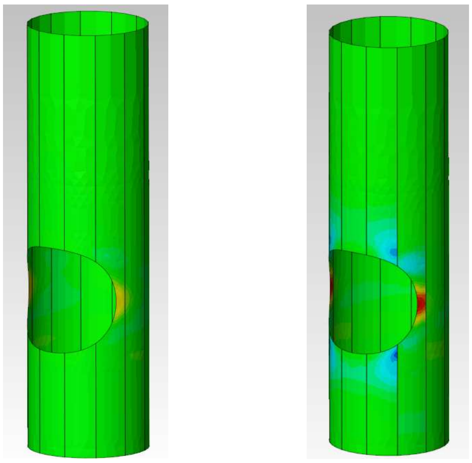
4.2.6 Model statistics

The model is made of 327 000 solid elements, 15 000 plate elements and 45 000 nodes. The seven construction stages run in 6 hours with the current capabilities of a standard desktop computer.

4.3 Results and detailing

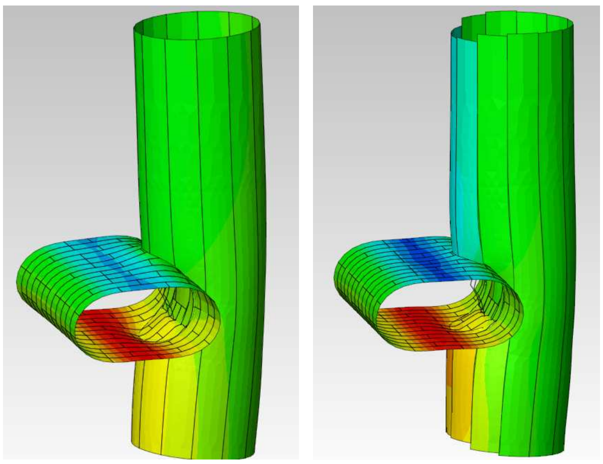
4.3.1 Forces in slurry wall panels

The model provides the distribution of axial and shear forces and of bending moments in the slurry wall panels for all construction stages, see for instance the bending moments in the last computation stage, Fig. 9. At any one point of the panels, the required reinforcement area is determined in each construction stage, for the short term and for the long term, for the continuous shell assumption and for the sliding joint assumption. Planned reinforcement detailing of the slurry wall panels is checked against the most adverse case.



(a) (b)

Fig. 9 Bending moments in the longitudinal direction of the panels in case of continuous shell modelling (a) or sliding joint modelling (b)



(a) (b)

Fig. 10 Displacement norm on deformed shape in case of continuous shell modelling (a) or sliding joint modelling (b)

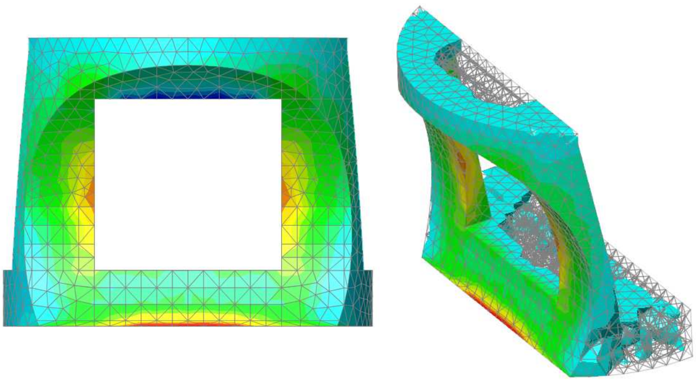


Fig. 11 Tensile zones in the portal structure

4.3.2 Displacements

Fig. 10 shows the deformed shape of the shaft slurry wall and of the tunnel lining at the final computation stage. It can be seen that, for both assumptions on the behaviour of panel joints, the tunnel lining ovalizes (i.e. flattens) with a vertical convergence reaching 18 to 20mm after opening of the junction door.

The tunnel ovalization induces the global “bending” of the shaft around the tunnel. With the modelling of sliding along panel joints, tunnel boring induces relative displacement of some of the panels of around 2 to 3 mm. However, once shaft excavation proceeds, no additional sliding appears as the hoop forces developing in the circular wall increase the shear capacity at the joints.

4.3.3 Detailing of the inner structures

The distributions of tensile stresses are obtained in the upper beam and in the portal elements. The values and the cross-sectional areas covered by these tensile stresses are used to assess the required reinforcement area to be implemented in the inner structure.

The contact between the inner structures and the slurry wall or the tunnel lining is modelled as fully bonded. The tensile contact stresses and the shear contact stresses are used to assess the required area of anchor bars to be implemented to ensure full connection between these different structural elements.

5. Conclusions

A new concept for shaft/tunnel junction was introduced whereby no ground improvement and no connecting galleries were necessary. 3D finite element analysis was successfully used firstly to validate the feasibility of such a concept and secondly to assess structural forces in all components of this complex geometry, which allowed detailing of the reinforcement and shear connectors. Induced displacements in the shaft and tunnel lining were shown to remain admissible.