Passage of a precast segmental lining tunnel through an active fault - Special segments and details -Thessaloniki metro

P. Lunardi, G. Cassani, A. Canzoneri
Rocksoil, Milan, Italy.

F. Carriero
Astaldi former Rocksoil, Rome, Italy.

G. Bomben
FAMA, Pordenone, Italy.

ABSTRACT: along the track of Thessaloniki Metro, the two precast segmental lining tunnels pass through an active fault named “Philaya”. According to the available data from scientific bibliography, (most important: Pitilakis and associates, 2014 expertise report), the fault plane is assumed to cross the longitudinal tunnel axis perpendicularly, under a dip angle of 60° or 70°. The potential coseismic displacement is evaluated as 15 cm for the Operational Design Earthquake (ODE) and 25 cm for the Maximum Credible Earthquake (MCE). ODE corresponds to a seismic event that is expected to occur during the lifetime of the structure. MCE corresponds to a quite severe earthquake scenario of higher return period. In these severe conditions, a special set of segments and connection details have been designed, produced and installed. The aim was allowing and controlling tunnel deformation, to guarantee the full service of the line after the earthquake.

1 INTRODUCTION

The Thessaloniki (see Figure 1) metro project is an important underground project with 13 stations and 9.5 km of total length.

Figure 1. Geographical location of Thessaloniki city.

Most of the track is double tube, with the following characteristics:
- two running tunnels 7700 x 2 meters long
- precast segmental lining (universal ring)
- external diameter: 6.19 m
- segments thickness: 30 cm
- overburden: 5 ÷ 28 m

The figure 2 shows (in red) the alignment of the metro line, along the sea.

Figure 2. Metro alignment.

The whole track is under water table, in sandy-silty clays and clays deposits.

Near Voulgari Station, the double tube tunnels have to pass through a fault, named Pylaia. This is the most critical point under a geotechnical point of view (see Figure 2).

The main issue is that the fault is classified as active: it is expected that, in case of earthquake, an important dislocation can occur between the two plates; so, the tunnel must be constructed as a flexible structure, in order to accommodate the deformation without increasing the stresses.

The paper discusses a smart solution to this issue, based on the use of special connection details, which reached the required performance with minimal changes to the formwork of the segments and without using special steel segments or, even, a widening of the TBM tunnel (originally proposed solution).

2 GEOLOGY AND GEOMETRY OF THE FAULT ZONE

2.1 *Geology and geotechnics*

The geological evaluation of the soils in the fault area came out from total of 19 boreholes and several geotechnical campaigns. It consists of the following geological formations, starting from the more recent and moving to the ancient ones:

- Man Made Deposits / Archaeological Layer;
- Quaternary Deposits: Unit A1 (Unit A1c);
- Neogene Deposits: Sandstone – Marl Series Unit B (Unit B2, B3 and B4).

"Pylaia" active fault represents a discontinuity between Quaternary and Neogene deposits; in fact, it causes a clear contact between Unit A1 and Sandstone-Marl Series formation (see Figure 3).

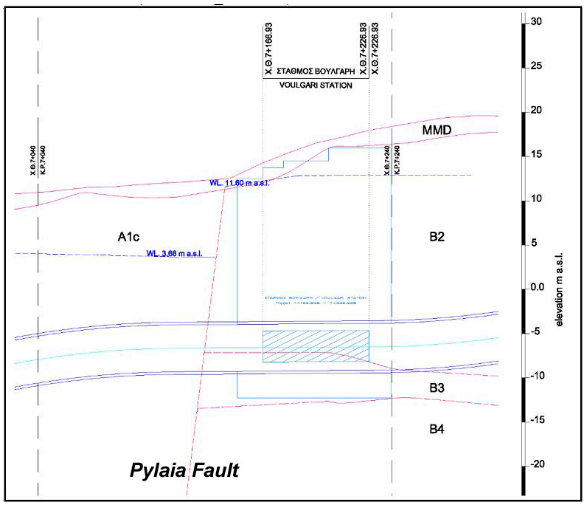


Figure 3. Pylaia fault zone geology.

In the first part of the stretch, before "Pylaia" active fault, the Man Made Deposits overlie the Quaternary deposits (Unit A1c); after "Pylaia" active fault, the MMD overlies the Neogene Sandstone – Marl Series (Unit B).

The following Table 1 summarizes the design parameters for the considered stretch, according to the statistical examination of the whole dataset of field and laboratory tests. They have been applied for the main soil types, representative of the different recognized geomaterials.

Table 1. Geotechnical parameters table.

Layer	γ (kN/m³)	c' (kPa)	φ' (°)	E (MPa)	E_s (MPa)	K (m/s)
MMD	19.5	5	27	4	5	--
A1c	21	15	26	19	25	$1x10^{-7}$
B2	18	50	26	63	85	$1x10^{-7}$
B3	21	20	31	45	60	$1x10^{-7}$
B4	20	60	25	80	110	$1x10^{-7}$

The symbols listed in Table 1 represent the following parameters: γ is the soil weight, c' is the drained cohesion, ϕ' is the drained friction angle, E is the Young module, E_s is the Young module at low strain and K is the coefficient of permeability.

2.2 *Seismic and geometry*

The Pylaia (complete name is Pylaia-Panorama) fault is located in the Eastern part of the city and is normal with E-W direction, total length of 9 km, extended up to the region of Pylaia Municipality. Zervopoulou and Pavlides (2008) characterized this fault as active according to the seismotectonic data.

Based on empirical relationships (Wells and Coppersmith, 1994) the mean expected earthquake in case of a surface rupture of 6 km length is $M_w = 6.0$. In case of activation of each individual segment of length 3 km, which is considered the most likely, the mean expected magnitude of earthquake is $M_w = 5.6$.

The same earthquake intensity has been predicted by Caputo et al. (2012), which also gives a preliminary estimation of 0.35 m for the maximum presumed fault displacement using the empirical relationship of rupture area versus magnitude (Wells and Coppersmith, 1994) and inverting the seismic moment equation, keeping constant rigidity ($3.5x10^{10}$ Pa) and resolving for the slip.

The potential fault plane (discontinuity) has been defined in terms of slope, dip and geometry by Prof. Pitilakis and associates in the expertise report dated October 2014 "*Evaluation of the spatial distribution of the permanent ground displacements at the level of the twin tunnels due to potential fault crossing*".

According to the available data from previous reports (Anastasopuolos et al. 2007; Gerolymos et al. 2007; Pavlidis et al., 2004; Pitilakis expertise report, 2008), the fault plane is assumed to cross the longitudinal tunnel axis perpendicularly, under a dip angle of 60° or 70°. The potential coseismic displacement is 15 cm for the operational design earthquake (ODE) and 25 cm for the maximum credible earthquake (MCE). ODE corresponds to a seismic event that is expected to occur during the lifetime of the structure. MCE corresponds to a quite severe earthquake scenario of higher return period.

It should be emphasized, according to the established knowledge of faults tectonics, these displacements correspond to the estimated average slip of the fault and that the offset at the ground surface may be much lower and in some cases it may be not visible at all.

In Greece there are several cases where the slip at the fault has not manifested at the surface (see for example the 1995 Kozani earthquake, Hatzefeld et al., 1997).

3 DESIGN ALTERNATIVES AND FINAL SOLUTION

Based on these data, designers and contractors studied several possible solutions to give to the tunnel enough flexibility to face this kind of deformation.

The first solution was to enlarge the TBM tunnel with a traditional excavation; construction steps would be the following:

- passage through the fault with the TBM, laying the standard precast segments lining;
- at the end of the excavation, go back in place and operate a widening of the tunnel with traditional excavation;
- cast in situ a reinforced concrete lining made into short rings, to reach a sufficient longitudinal deformability; this solution would have had a strong impact on time and cost of the whole project.

The second solution was to produce special steel segments, used in the fault zone (about 80 meters), which could stand much greater stresses and deformations, compared with standard concrete segments. This solution would be feasible, but it would take a large metal carpentry work and a very complex geometric study of all the joints. Then, the very tight schedule of the project drove designers to study a solution with the least possible changes from the standard lining.

The third solution, the final one, is based on the observation of the tunnel deformations induced by the dislocation of the fault (see Figure 4). The phenomenon will be described in more detail below the article, but it can be anticipated that the tunnel undergoes a vertical double inflection and is stressed mainly in traction (due to the fault slip direction). The design could go in direction to have a stiff transverse section and to allow the opening of the joints in a controlled manner, in the longitudinal direction (to follow the elongation with a small longitudinal tension increase). After a long calculation step, the designers understood the feasibility of a solution based on standard precast segment lining (with very small changes) and a complete set of connection details, with considerable savings in time and cost.

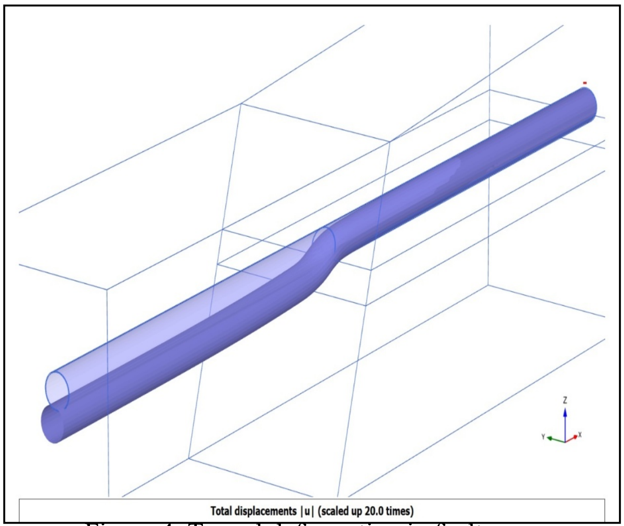


Figure 4. Tunnel deformation in fault zone.

4 3D CALCULATION – NUMERICAL RESULTS

The study of the interaction between tunnel and soil, due to fault movement, is developed in three-dimensional condition, by Plaxis 3D 2012 software.

The finite element mesh for soil is defined by 10-nodes tetrahedrons; tunnel is described by *plate* elements, 6-nodes triangular elements, which model precast segments; *interface* elements are described by 12-nodes triangular elements (6 couple of close nodes). Analyses are carried out assuming that soil deformations are developed in drained conditions.

The finite element domain is 200mx40mx55m (XxYxZ); elevation are between +18 m a.s.l. (maximum ground level) and -43.5 m a.s.l.(about 30 m below the top pf B4 unit); Z axis origin coincides with absolute elevation of 0 m a.s.l.. Figure 5 shows a geometrical sketch of the finite element model. Model includes only one tunnel, being Z axis of symmetry of the model; tunnel axis is at Y=6.5 m and represent alignment track 2. A fault slope of 70° (the worst realistic case) has been modelled.

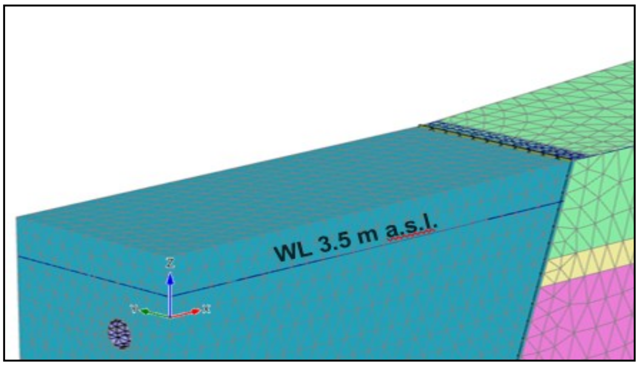


Figure 5. Finite element model (Plaxis 3D).

The fault slope has been modelled imposing a movement to the left part of the model (see Figure 6); the value of the movement is 15 cm for the operational design earthquake (ODE) and 25 cm for the max. credible earthquake (MCE).

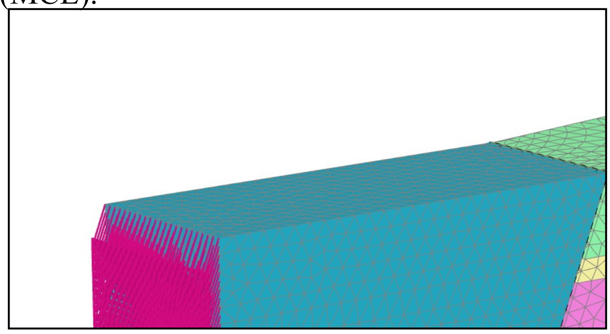


Figure 6. Imposed displacement.

A lot of sensitivity analyses have been carried out, to verify the impact of the slip surface, the lining/soil interface, the lining stiffness on the final deformation of the tunnel and the lining stress level. In particular, the presence of the deformable longitudinal joints is represented, in the model, with a reduction of the longitudinal Young modulus of the lining. Four different stiffness reductions have been analysed, applying the E_1/E_2 ratio going from 1 to 1/1000, where E_1 is the Young module in longitudinal direction of tunnels and E_2 is the Young module of the transversal sections.

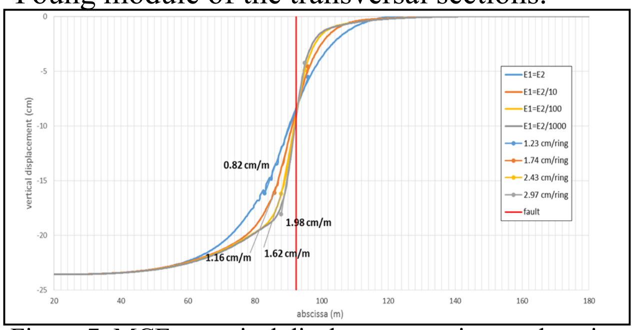


Figure 7. MCE – vertical displacement at invert elevation, along the track

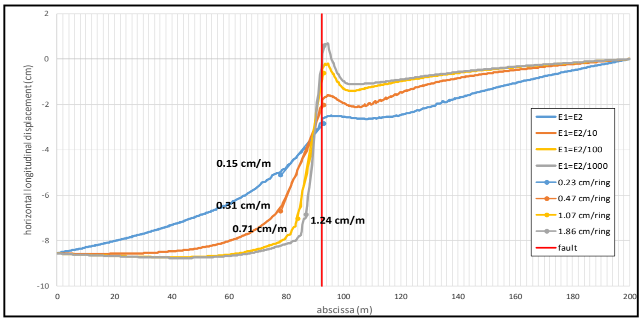


Figure 8. MCE – horizontal displacement at invert elevation, along the track

Comparing displacements of tunnels with different stiffness, it results that maximum displacements increase with the decrease of stiffness, but the zone of tunnel affected from the fault activation decreases with the decrease of stiffness; this is more evident for horizontal displacements. The length of tunnel mostly affected from the fault movements is around 20 m (about from x=85 to x=106).

The Table 2 summarized the results of these calculations under a deformation point of view, which transforms the continuous calculated deformation in a GAP+OFFSET between two consecutive rings.

Table 2. Maximum Gap and Offset for MCE and ODE.

	ODE [mm/ring]	MCE [mm/ring]
GAP	10	18,5
OFFSET	15	30

These values, together with the relative tensile/compressive levels in the lining models, represent the starting point for the study of the special connection details between the rings, which Rocksoil developed together with the specialist details supplier FAMA.

5 DESCRIPTION OF THE SPECIAL JOINTS

First, it is necessary to summarize the results of the analyses above: it is possible to realize a precast segments lining (using the same moulds of the standard segments) that can withstand the stresses due to the fault dislocation, with the following conditions:

- in transversal direction it is possible to maintain the ring rigid (to ensure that the train clearance is respected);
- in longitudinal direction, it is necessary to make the lining deformable, to avoid an

unwonted, and unsustainable, increase of stresses;
- it is necessary to realize deformable joints able to control deformations and to withstand a relative distancing of the segments (GAP) up to 18.5 mm and a relative vertical movement between two rings (OFFSET) up to 30 mm (values for the Maximum Credible Earthquake - MCE); at the end it is necessary to verify that the stresses transmitted from the joints (bolts) to the segments are coherent with the calculation model;
- the joints should be able to transmit the shear forces after the displacements of GAP and OFFESET, accordingly to the calculation model.

The set of special details developed to comply with these conditions is described below. It includes:
- a ductile tensioner linked to a four springs system that bear the tension longitudinal stress allowing the design displacements of the joints foreseen in ODE and MCE (Deformable longitudinal bolt);
- a seismic shear connector that allows the shear stress transition between two rings, without interferences with the displacements of the seismic devices with springs.
- a centering pin that reduces the installation mistakes and doesn't bear any kind of stress in seismic and static conditions.

The following figures 9 and 10 show the position of these details; it must be remembered that they are ring-ring connectors: the transversal connections remain standard.

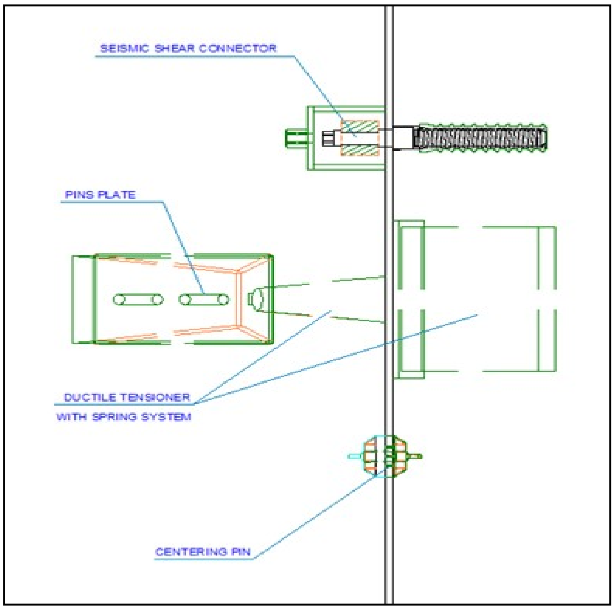


Figure 9. Special details, plan view

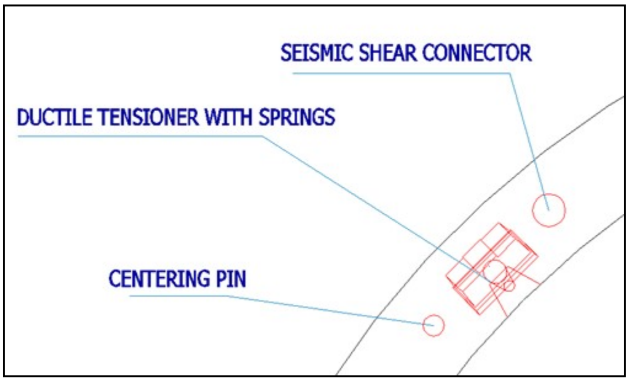


Figure 10. Special details, longitudinal view

5.1 *Deformable longitudinal bolt/spring system*

This device, developed by FAMA with Rocksoil support, is the most important of the set and the most innovative one; the following Figures 11 and 12 show how it is made.

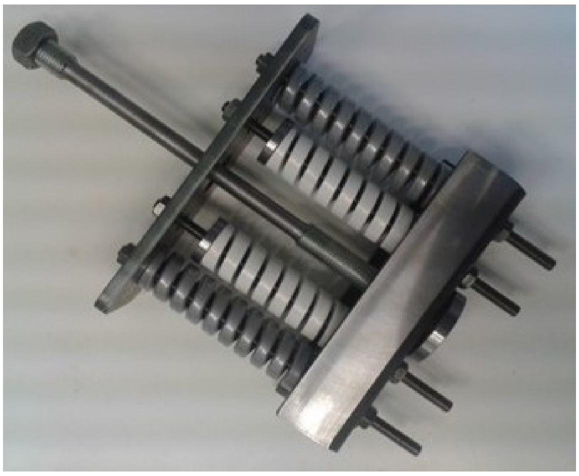


Figure 11. Deformable longitudinal bolt system- photo.

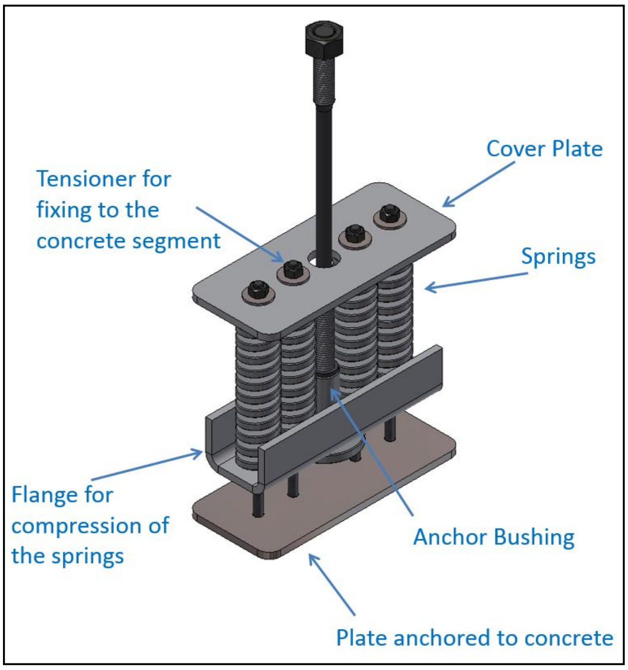


Figure 12. Deformable longitudinal bolt system - scheme.

Before the execution of tests each element of the devices has been checked, under the design stresses, by F.E. analysis (see Figure 13).

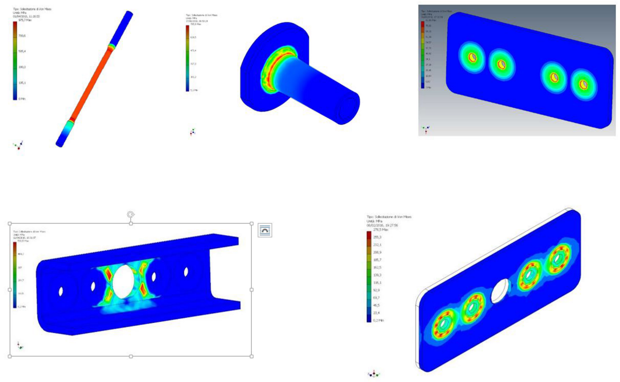


Figure 13. F.E. analysis of device element

The aim of the device is to comply with design forecasts in terms of load-displacement, for standard operational situation (in this condition the bolt has to tighten the gasket), ODE (Operational design Earthquake) and MCE (Maximum Credible Earthquake); see the results of the tests executed in Figure 14.

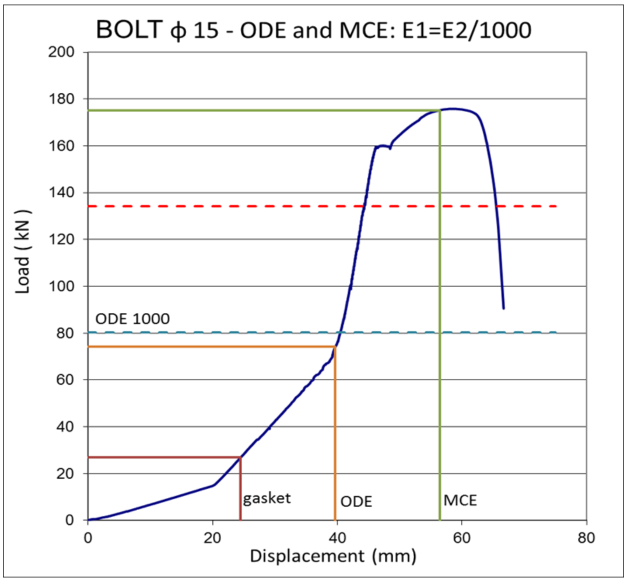


Figure 14. Load - displacement curve.

It is possible to notice that the curve has a variable gradient:

- the first stretch is linked to the stiffness of the first pair of springs,
- in the second portion also the second pair of springs begins to work;
- in the third section the springs reach their limit, and stiffness of the system is related to the axial stiffness of the bolt;
- finally, in correspondence of MCE the bolt is enervated: this feature is necessary to prevent the stress on the segments continue to increase.

The important goal reached by this system is the elastic behaviour in ODE conditions, with reversibility of internal forces, and ductile behaviour of the system in MCE conditions.

The following Figures 15 and 16 show the device respectively in standard operational position and in the extreme position that be reached after a MCE; it is clear the very high value of Offset and Gap that the device allows.

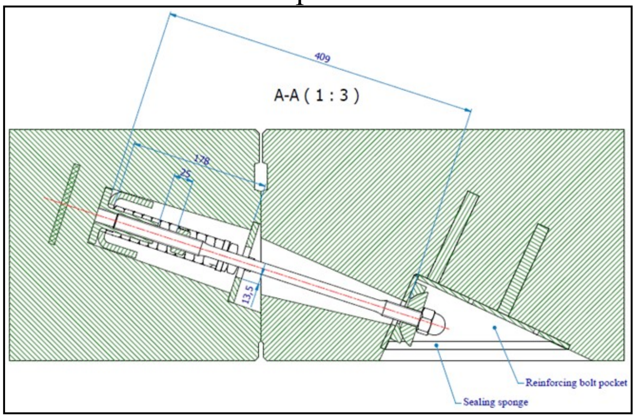


Figure 15. Device in standard position

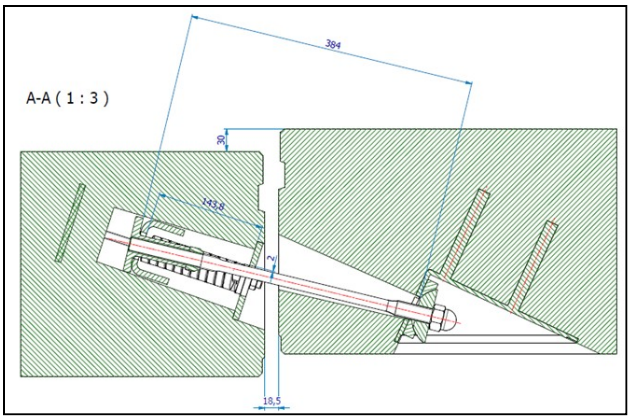


Figure 16. Device after MCE (maximum offset and gap).

5.2 *Shear connectors*

The deformable longitudinal bolts descripted above solve completely the longitudinal stresses issue, but cannot resist to the shear forces; so it was needed to design a specific device with the following features:

- let two consecutive rings free to move relatively, up to the deformation related to MCE;
- prevent further relative shear displacement, to ensure the train clearance;
- avoid any longitudinal stress.

The shear connector, invented by FAMA with Rocksoil support, is made up of a steel bolt with a cut destruction pin and a cylindrical steel plate where it is free to move in (see Figure 17).

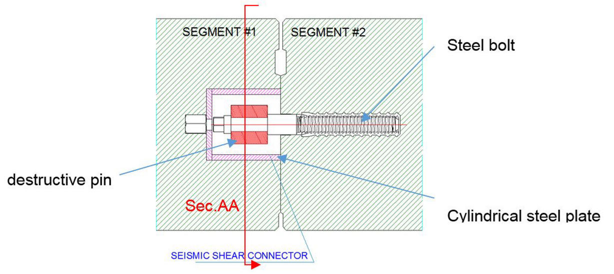


Figure 17. Shear connector

Once that in ODE condition the displacement has occurred, the rings have relatively moved their selves and consequentially the pin connector is in contact with the steel cylindrical plate. The pin is strong enough to transfer the radial shear force between the two rings without breaking. Figure 18 shows the geometry of the shear connector, just before reaching the limit position (in red you can see a sacrificial bushing).

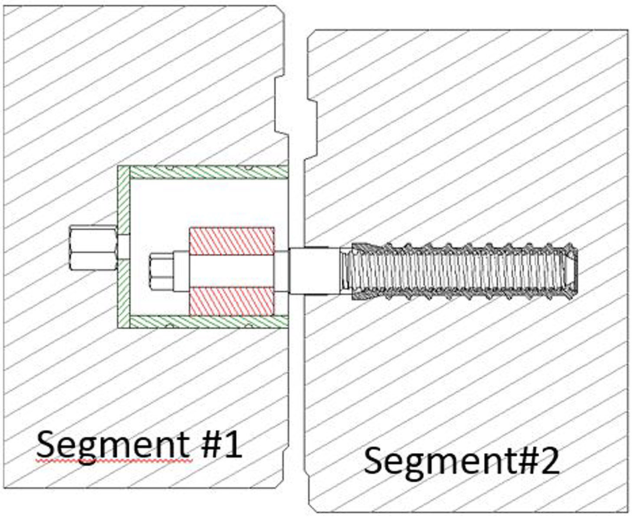


Figure 18. Shear connector just before ODE

In MCE condition a higher value of gap and offset between two rings are requested therefore a part (the red in previous Figure) of the pin of the shear connector breaks allowing the transferring of the shear radial force between them.

5.3 *Centering pins*

This device has been introduced in the design to avoid that an assembling mistake could add to offset and gap due to the earthquake: the aim is to realize an assembling almost without offset.

The other feature of the pin is no interference with the other devices (no tensile strength, very low shear resistance).

These features can be easily reached with a simple plastic pin (see Figure 19).

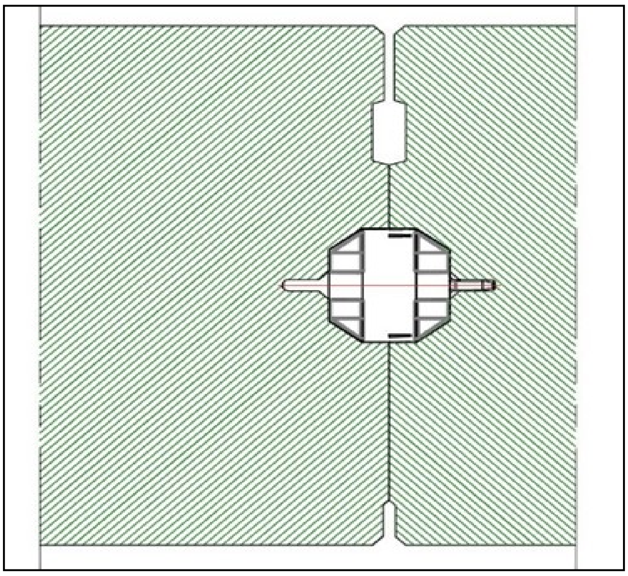


Figure 19. Centering pin.

5.4 *Special Gaskets*

Finally, we must mention another device designed for this particular situation: to prevent entry of water into the tunnel after the event of the earthquake (and therefore with very high values of gap), FAMA invented a gasket that can be "inflated "with a hardening resin working inside the tunnel (see Figure 20).

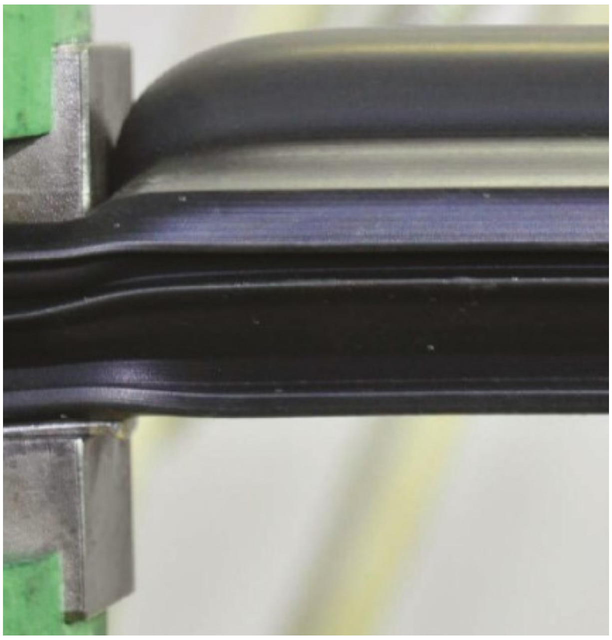


Figure 20. Inflated gasket.

This seal (the "embedded" type), has very good performance and could be proposed in other conditions. In this case the solution is not needed, because the land is very little permeable and therefore, a possible water input can be blocked with local injections.

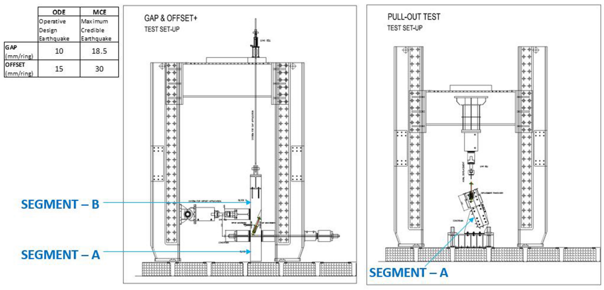
6 TESTS

Preliminary and final tests of the singular devices and of the complete system (device and TBM segments) have been developed, during the design, with the goal to fit the design assumptions. In detail:

- preliminary tests of the longitudinal system (see Figure 21). A lot of tests have been developed to find the best device able to fit the design assumptions. The results of the last test executed is showed in the previous paragraph 5.1.

Figure 21. Preliminary tests in Malignani Institute.

- test of shear connectors and centering pins, developed directly by FAMA with the device certified and validated before the execution.
- final test of the complete system (see Figure 22, 23 and 24). In Tor Vergata University followed by Prof. A. Meda, GAP/OFFSET tests and PULL OUT tests have been executed to be sure, particularly, that the steel bolts would collapse before the opening of cracks of the segments.



	ODE Operative Design Earthquake	MCE Maximum Credible Earthquake
GAP (mm/ring)	10	18.5
OFFSET (mm/ring)	15	30

Figure 22. Final Tests – Scheme.

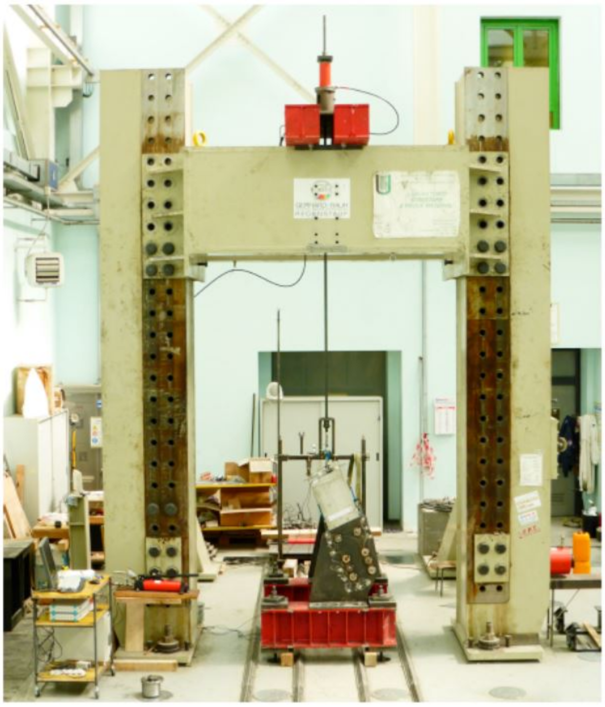


Figure 23. Final GAP/OFFSET Test.

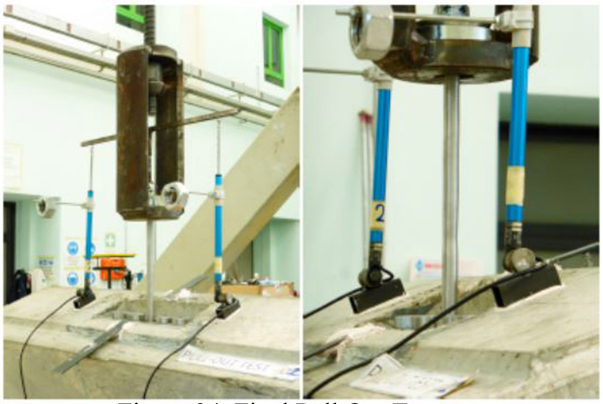


Figure 24. Final Pull Out Test.

7 STATUS OF THE WORK

The special segments, equipped with the devices described above, have been realized and installed in the tunnel, with no assembling problem neither in the segments factory and in the tunnel itself; the following photos show some of the details during assembly.

In particular, you can see in Figures 25÷28 some phases of the deformable bolts assembly and in the following figures 29÷30 other phases of the assembling process and the very small modifications to the moulds.

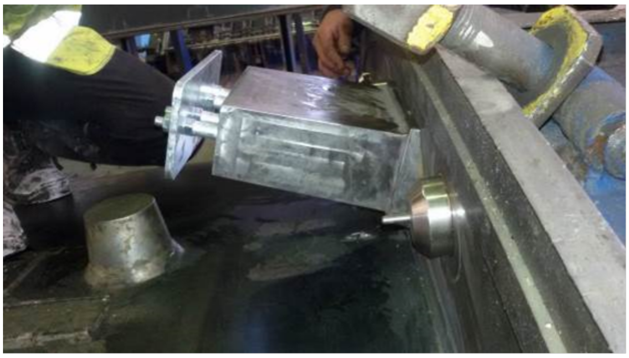


Figure 25. Ductile joint assembly – a)

Figure 26. Ductile joint assembly – b)

Figure 27. Ductile joint assembly – c)

Figure 28. Reinforcement cage

Figure 29. Local modifications to the moulds - a)

Figure 30. Local modifications to the moulds - b)

8 CONCLUSION

This paper refers to a specific critical passage along the Thessaloniki metro alignment: the passage of the precast segments tunnels though an active fault named Pylaia.

In particular, the paper discusses the adoption of special deformable joints between the rings. This solution allowed realizing the tunnel with very small changes to the moulds of the segments, avoiding special steel segments or tunnel enlargement in traditional excavation.

With the aim to obtain most realistic stress and displacement of the tunnel, starting from the previous study by prof. Kyriazis Pitilakis and Associates, complex three-dimensional numerical FEM analyses with Plaxis 3D 2012 software were carried out.

Some important aspects were investigated with several preliminary FEM analyses: the influence of the resistance to slip of the active fault plane, the influence of the interaction between tunnel and soil and the efficiency of a deformable backfill between tunnel and soil.

The tunnel has been modelled as a continuous pipe and, to take into account the presence of radial joint between two adjacent segments, a reduction of the thickness of the segments, as suggested by Wood (1975), has been applied. The reduction of the stiffness of tunnel in longitudinal direction, adopting an anisotropic model for plate, has been considered to take into account the presence of circumferential joint between two adjacent rings. In order to obtain a representative range of results, four different values for stiffness have been considered.

Results of these analyses had shown that the fault movement has effect in both predominant direction:

- a general increase of stresses in transversal direction for an extension of about 60 m across the discontinuity plane (increase that can be managed with a simple increase of reinforcement);
- an inflection of the longitudinal axis of the tunnel that produce mainly tensile and compressive axial force in longitudinal direction.

These results permitted to state that the realization of tunnel in precast segments through "Pylaia" active fault was feasible, but requested some modifications of segments; special segments connectors are foreseen from K.P. 7+093 to K.P. 7+153 (60 m – 40 rings).

The paper introduces the adopted solution.

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- Malignani Institute (Preliminary Tests)
- University of Tor Vergata - Prof. Alberto Meda (Final Tests)
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- People from Rocksoil SpA (Designer)

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