Design and excavation for the widening of a railway tunnel: the case of the Castellano tunnel in Italy

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Conventional Tunnelling Methods in Development and Use

The paper describes the works carried out to widen the tunnel Castellano along the existing railway line "Adriatic" between Bologna and Lecce. The work is a part of a more extensive adaptation program to the European new geometric standards for railway, in which this railway dorsal is included. In particular, the paper illustrates the consolidation system of the surrounding the tunnel soil needed to demolish safely the existing lining and to excavate the surrounding soil to create the new cavity.
To control the reactions of the soil during the excavation, an intensive monitoring system was installed. Some results of this monitoring system are here illustrated and analyzed.
The effectiveness here shown suggests the use of this method for similar contexts.

Keywords: *Widening, Gabarit C, Italian approach, Monitoring, Construction Site*

1. Introduction

The railway line Bologna – Lecce is one of the strategic infrastructure connecting the North to the South of Italy and constitutes an integral part of the freight corridor system of European interest named "Rete Terfn". In such context during last years numerous interventions were planned to increase the capability of the line and to adequate the railway to the European standards in terms of dimensions by the wagons.
Along the railway dorsal some tunnels are not suitable in terms of internal dimensions with respect to the minimum required by the current international standards. Infact, the international standard referred to the shape and dimension of the wagons (Gabarit) is fixed from the Uic (Union International Chemin de Fer). The Gabarit that has been adopted for the European basic railway line is the so-called "Gabarit C".
One of the tunnel along the above-mentioned line is the **Castellano tunnel**. It is an old tunnel built in the **XIX century.** The existing lining is made with brick elements with a typical "horseshoe shape". The horizontal dimension is about 4.1 m while the height is about 7.0 m. As aforementioned, these dimensions are not suitable for the transit of the "Gabarit C", and so a design for a widening of the tunnel was executed. This enlargement involved both the existing lining, which was completed demolished, and the surrounding soil.
The soil is a typical Apennine soil and it is constituted mainly by silt and clay with saturated sand lenses and thin layers.
In the following chapters a descriptions of the planned works, i.e. the way in which the tunnel has been widened and made suitable for the transit of the wagons belonging to the Gabarit C shape, is illustrated.
The works interested both the portal sections and the current underground sections by the use of different constructions methods.
The paper deals especially about the underground part.
All activities were controlled by an intense monitoring program to follow the real response of the soil during to the excavation, according to the Italian approach for tunnelling.
Further characteristics of this project concerned the specific arrangement of the construction site, due to the small working spaces, the interference with several works and, finally, the reduced time-schedules to complete the widening of the tunnel in order to minimize the interruption of the railway traffic.

2. The existing Tunnel: short description

The existing Castellano tunnel ("existing" is referred to the tunnel status before the enlargment) is located between the chainage km 206+821 (Northern portal – Ancona side) and km 208+390 (Southern portal – Varano side) of the railway Bologna – Lecce, Ancona – Varano section (in the Central Italy).
The tunnel was a single track tunnel and had a total length of 1569 m along a curved route with a longitudinal slope of 1%.
The overburden increases quickly from the Ancona side up to reach the maximum value of 70 m after 350 m. Then the cover decreases gently until it becomes very small (approx. 1 diameter of tunnel) after 430 m from the Varano side and it stays so up to the southern portal.
The tunnel was built in the middle of the XIX century and it represents a pioneering engineering work in the Central part of Italy for the period and the specific conditions of the site.
In the past some sections of the old tunnel were submitted to different interventions to keep safely the railway traffic through the tunnel: rehabilitation of the brick lining up to full reconstruction of the tunnel section, stabilization measures by grouting injections behind the lining and by the use of tiebacks anchored on the lining, re-profiling of the cross section.
The original tunnel section had a horseshoe cross section with an inner length of 4.10 m and the lining was composed by brick masonry elements. The restored sections of the tunnel had a horseshoe shape but the inner length was 5.50 m.
Fig. 1 shows a typical cross section and an image of the old Castellano tunnel, respectively. Fig. 2 shows a detail of the existent lining in masonry before the rehabilitation works.

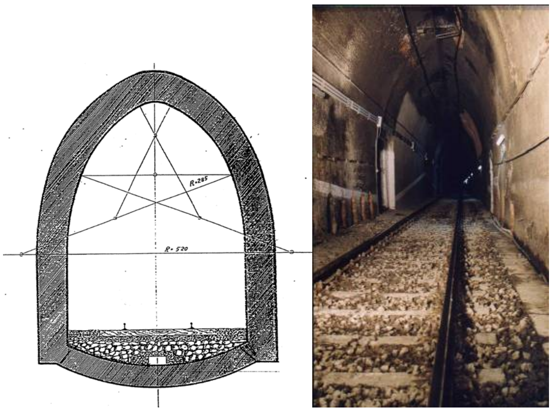


Fig. 1 *Old Castellano tunnel: Typical cross section (at the left), image taken from inside of tunnel (at the right)*

Fig. 2 *Old Castellano tunnel: Detail of the lining in masonry elements*

The existent tunnel has been investigated as a geognostic campaign through field tests directly performed on the lining. Flat jacks to measure the state of stress on lining (and secondly to evaluate the elastic modulus) and boreholes to measure the local thickness of lining have been executed on three cross sections dislocated along the tunnel. For each section a total of 4 flat jackets were performed located on sidewalls and archs and n.2 boreholes at the sidewalls. The results of these tests have shown that the masonry lining has a measured thickness between 65 and 87 cm (average 75 cm) and is subject to appreciable values of stress up to 2.5 MPa. The average value of stress along the section is approx. 1.70 MPa and this trend is similar among the three investigated sections. The elastic modulus obtained from flat jacks have average values ranging 5000-5500 MPa.

3. Geological and geotechnical assessment of site

3.1 Geological conditions

The tunnel was excavated for the most part within of the clayey marls belonging to the "Marne di Monte dei Corvi" Formation. These marls have a rock consistency with plastic levels and fractured parts.
In detail, the geotechnical-geomechanical units crossed by the tunnel starting from the southern portal are:

- Unit A1: eluvial-colluvial deposits composed by sandy silts and clays. This unit is crossed for approx. 410 m within the cut and cover tunnel section of the Varano side;
- Unit C1: the upper part of the Marne di Monte dei Corvi Formation, mainly composed by hard silts and clays deposits with sandy-silty interbedded. This unit is crossed for approx. 200 m;
- Unit M1: it is mainly composed by very hard silts and clays deposits. They are overconsolidated and fractured, in some zones with marly parts. Saturated sandy interbedded are present. This is the most crossed unit by the tunnel for approx. 980 m;
- Unit F1: it is an accumulation of landslide composed by deposits belonging to the units C1 and M1. These deposits are destructured. This unit is crossed for a short section of approx. 50 m within the underground section and then by the cut and cover tunnel section of the Ancona side.

The whole track of the tunnel is located above the water table.
The distribution of the geological formations crossed by the tunnel is shown in the geological-geotechnical profile of Fig. 3.

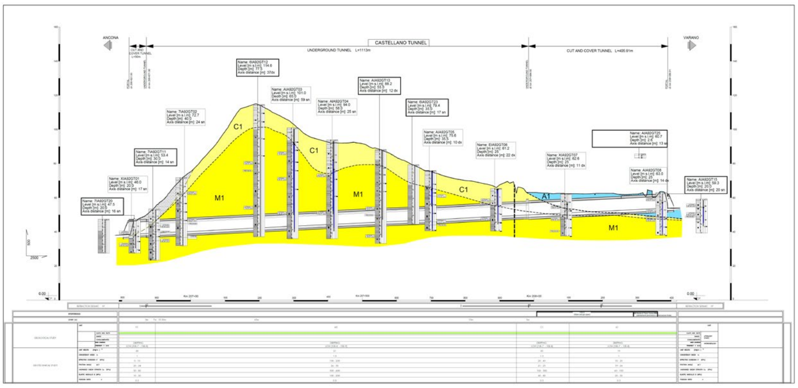


Fig. 3 *Geotechnical profile of Castellano tunnel*

3.2 Geotechnical conditions

An intense investigation program both field and laboratory tests has allowed evaluating the mechanical properties of the soils crossed by the tunnel.
A total of 20 boreholes, drilled up depth of 78 m, were performed along the track. Field tests were SPT tests, pressuremeter and Lefranc permeability tests, Cross-hole seismic tests. Some boreholes were equipped with piezometers to monitor the groundwater conditions, more with inclinometers to monitor the response of the slope on the Ancona side. Seismic refraction surveying complete the field investigation campaign.
The laboratory tests have included tests to evaluate both physical and mechanical properties (especially, triaxial tests CIU and UU, direct shear, oedometer tests). A special kind of lab tests that were performed are triaxial extrusion cells. These tests have allowed to study the face extrusion due to the excavation within cohesive soils and to have an estimate of the confinement pressure required to stabilise the tunnel face. These tests shown a pseudo-elastic behaviour (usually this is considered the border to evaluate tunnel face supports using this approach) for the investigated

samples until confinement pressures of 350 kPa.
The laboratory tests integrated with the field tests have allowed to define the geotechnical parameters for the soils encountered during the excavation. The range of these parameters are summarized in Table 1.

Table 1 *Summary of the geotechnical parameters for the Castellano tunnel*

Material	Unit weight (kN/m³)	Undrained shear strength parameter (kPa)	Effective cohesion (kPa)	Effective friction angle (°)	Effective elastic modulus (MPa)
A1	19	60÷100	10÷20	19÷24	25÷50
C1	20	100÷300	20÷40	21÷25	40÷80
M1	21	300÷600	100÷200	26÷30	100÷200
F1	20	50÷80	0÷10	20÷24	10÷30

4. Description of the project

The Castellano tunnel was subjected to an adjustment to the Gabarit C shape. It has involved the implementation of the new cross section through the dismantling of the existent lining, the later widening and the reconstruction of all structural elements. The cross section is designed for a single track. The planning of the route (plan and altimetry) is left as the same of the old tunnel.
The new tunnel is arranged as follows:

1. Cut and cover tunnel Varano side for length 406 m;
2. Underground tunnel has length 1113 m;
3. Cut and cover tunnel Ancona side for length only 50 m.

1. The cut and cover Varano side (406 m) was built as the "top-down method" for the first and the last section (135 m and 166 m respectively). The middle section was built as the "bottom-up method" (105 m). The sections as top-down method consist of bored piles (ϕ1200 m spaced 1.30 m) at the sides of the old tunnel, the cast in situ of the top reinforced slab to connect the head of piles and then the excavation takes place under the roof. A definitive earth backfilling as the original ground level has completed the construction. The bottom-up, instead, kept the same inner shape of the underground tunnel (polycentric type) but the sidewalls are vertical. This section was built within an excavated trench and the concrete structure was constructed in it. An earth refill above the structure has completed the design solution and has allowed to preserve the original ground conditions.
2. The underground tunnel was performed through the widening of old tunnel and reconstruction of a new lining as polycentric shape. Due to peculiarity of the adopted solution, the detailed description of the sequence of the operations is given below.
3. The cut and cover Ancona side was built as the "top-down method" as the same characteristics of the two parts belonging to the Varano side.

The new tunnel has the same length of the old tunnel (1569 m) with the addition of two portals each one has length 17.4 m to properly manage the water runoff in the inlet and outlet zones of tunnel.
The new chainages of the tunnel have become: 206+803.6 (Northern portal) and 208+407.31 (Southern portal).
The works have been included the arrangement of safety devices along the tunnel:

- Safety niches for safety of operations personnel. They are placed at regular intervals (each 25 m) both underground and cut and over tunnel sections.
- Plant niches to house equipment. They are placed each 250 m only in the underground section of tunnel.

Both types of niches were built on right side of the cross section (also called "sea side") towards

Ancona that is the same side where were placed the niches in the old tunnel.
The tunnel widening resulted in the total interruption of the railway traffic in tunnel during the whole duration of the works. The temporary traffic was moved on a new and near tunnel, the Vallemiano tunnel, that is a single track tunnel and was still arranged for the Gabarit C wagons.

5. Design stage

The underground section was organized through the implementation of a construction sequence that includes, broadly, the dismantling of the existent masonry lining, the excavation to widen the section and finally the reconstruction of all structural elements.
The excavation approach here adopted and very often used in Italy, here is called ISET – Italian System for Excavation of Tunnels. In its application it ranges from competent rock masses to "not self supporting" soils [1]. According to ISET principles, three conceptual excavation behaviour and correspondent tunnel support classes (named "A", "B" and "C") can be adopted [2].
For the Castellano tunnel two sections type were designed. The first support section – Section type 1 is provided for low covers and has an excavation response of C type (unstable materials). The second support section – Section type 2 is instead provided for high covers within the Unit M1 and has an excavation response intermediate between B (short time stability) and C (unstability) types.
Globally, the section type 1 was applied for a length of approx. 210 m while the section type 2 for a length of approx. 900 m.

5.1 Section type 1

The excavation sequence of interventions can be so summarized:

- Pre-support measures around the tunnel through the implementation of valved fiberglass elements. They have a length of 7 m and longitudinal spacing of 1.5 m. The fiberglass elements are grouted and then injected for each valve under high pressure. N.11+12 elements radially arranged are used in crown and sidewalls, while in the zone under the invert n.4+4 elements are used;
- Excavation to widen the cross section, included the invert portion, with rounds of 1.5 m;
- Installation of the primary support composed by steel ribs 2IPN200 spaced 1.5 m embedded in shotcrete fiber-reinforced thick 25 cm. This support is also immediately installed in the invert portion (to have a closed section) with the same characteristics;
- Cast in place of the reinforced concrete lining in the invert thick 90 cm;
- Installation of the drainage and waterproofing system;
- Cast in place of the final lining (reinforced concrete lining shell) thick 80 cm in crown and sidewalls.

5.2 Section type 2

Section type 2 is similar to Section type 1 (same types of support). The difference is due to the primary support that is not applied in the invert and to the different distances for the cast of the final linings from the face (that are more stringent for the Section type 1). Two sections type adopted are shown in Fig. 4 and Fig. 5.

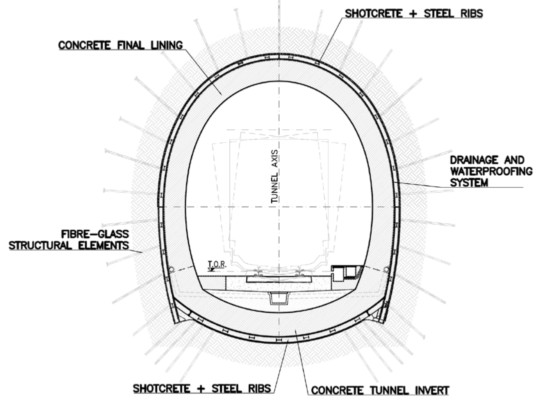


***Fig. 4** New Castellano tunnel: Section type 1*

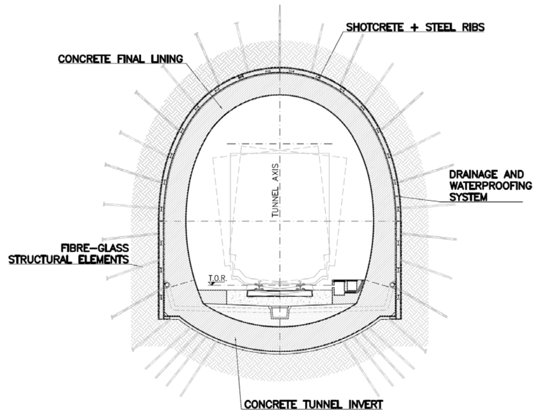


Fig. 5 *New Castellano tunnel: Section type 2*

6. Construction stage

The excavation was carried on by hydraulic hammer both to dismantle the existent lining and to widen the section.
Fig. 6 shows the real construction sequence adopted during the tunnel widening that is very consistent with the design stage.
Fig. 7 shows some phases during the execution of the widening. It allows to point out the differences between the old and new cross section of tunnel as well as the small working spaces inside of tunnel.

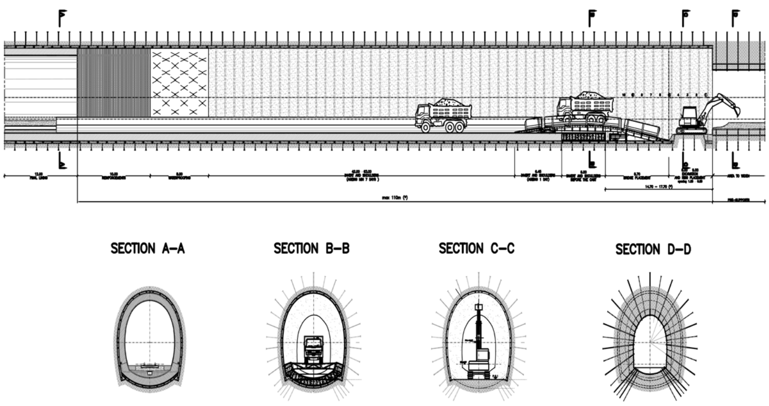


Fig. 6 *New Castellano tunnel: Construction sequence during works*

Fig. 7 New Castellano tunnel: Some images taken during the construction

The construction site was specifically arranged [3]. It is mainly due to different reasons:

- The small working spaces, as stated. This issue has obliged the construction company to adopt small vehicles and many than ordinary conditions.
- The interference with several works and other structures sub-surface, specifically in the cut and cover zones where the covers are low.
- The reduced time-schedules to complete the widening of the tunnel in order to minimize the interruption of the railway traffic.

The specific articulation of workings resulted in three different construction sites:

- Varano side for the construction of the cut and cover tunnel;
- Varano side to the widening of the old tunnel;
- Ancona side for the construction of the short cut and cover tunnel and for a section of the tunnel widening.

The total spoil extracted from the tunnel is equal to approx. 120.000 m^3: 100.000 m^3 of soil while 20.000 m^3 due to the existent lining.

7. Monitoring

During the execution of the works an extensive monitoring program was carried out and involved the use of:

- Convergences measurements stations each 15 m along the tunnel. The stations were installed to measure the 3D displacements on the primary support using 5 points set. The geological mapping of the tunnel walls each 10 m advance completed the data acquisition.
- Stress measurements stations on the primary supports. Each station is composed by n.2 load cells installed under the base of the steel ribs, n.5 strain gauges welded on the steel ribs wings and n.3 pressure cells installed between the joints plates of the ribs.
- Stress measurements stations for the final linings. Each stations is composed by n.8 pairs of strain gauges, of which n.3 installed in the invert, welded on the steel reinforcements before the cast.
- Settlements ground surface stations to control the subsidence settlements in the low covers zones.
- Inclinometers to measure the ground movements during the excavation at the Ancona side portal where was identified an accumulation of landslide.

The convergences measured were in general modest, with maximum values below the centimeter. This trend was observed along the whole tunnel and it can be considered as independent of the local cover. Fig. 8 shows typical convergences trend measured on low cover and high cover sections, respectively.

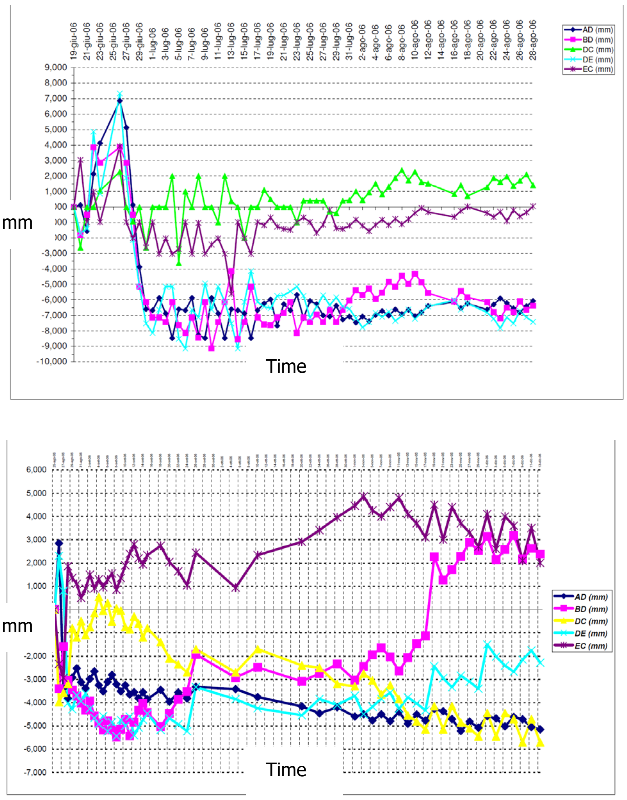
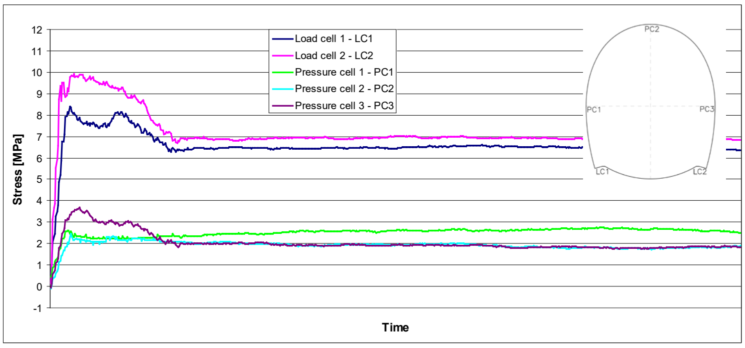


Fig. 8 Typical convergences trend measured: section with low covers (at the top), section with high cover (at the bottom)

The stress monitoring on the linings was performed for two sections: the section at ch. 207+070 (cover is 40 m) and at ch. 207+200 (where is the maximum cover of 70 m). Both sections are located within the geotechnical unit M1. The period of measurements was 1 month for each instrument, taken in different times during the construction.
The instrumentation installed on the primary lining shows a rapid increasing in the first days, probably due to proximity of the face, then a stabilization of the measured values (Fig. 9). The values measured in the highest cover section almost doubled the values obtained in the other instrumented section. In general, the primary supports appear low loaded and values are consistent with the expected design values. The stress measured by the load cells under the feet of steel ribs at the contact with soil foundation show higher values, till 18 MPa. These values seem in general high, but the presence of the closed invert immediately placed to the face has helped to adsorb the loads. The section 207+070 shows a certain symmetry for the load between two feet. The section 207+200 (max cover) shows that the right feet is more stressed than the left one, probably due to the ground surface position that is slopping from right to left.



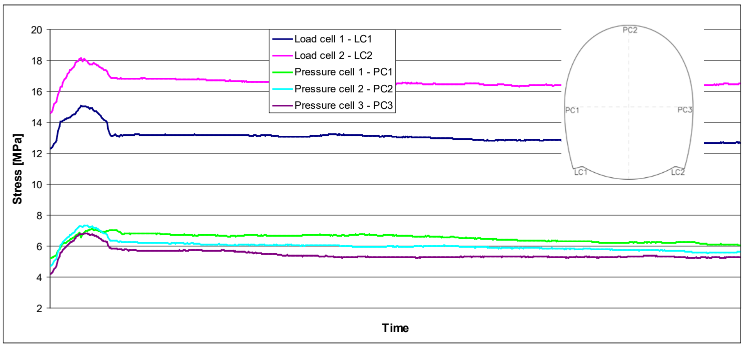


Fig. 9 *Measured stress on primary linings: section 207+080 (at the top), section 207+200 (at the bottom)*

The stress measured on the final linings show low values for the monitored period (Fig. 10 and Fig. 11). The values become stabilized after some days from the cast of the concrete, linked to rapid decreasing of the measured temperature within the cast. No creep effects were recorded within the monitored period.

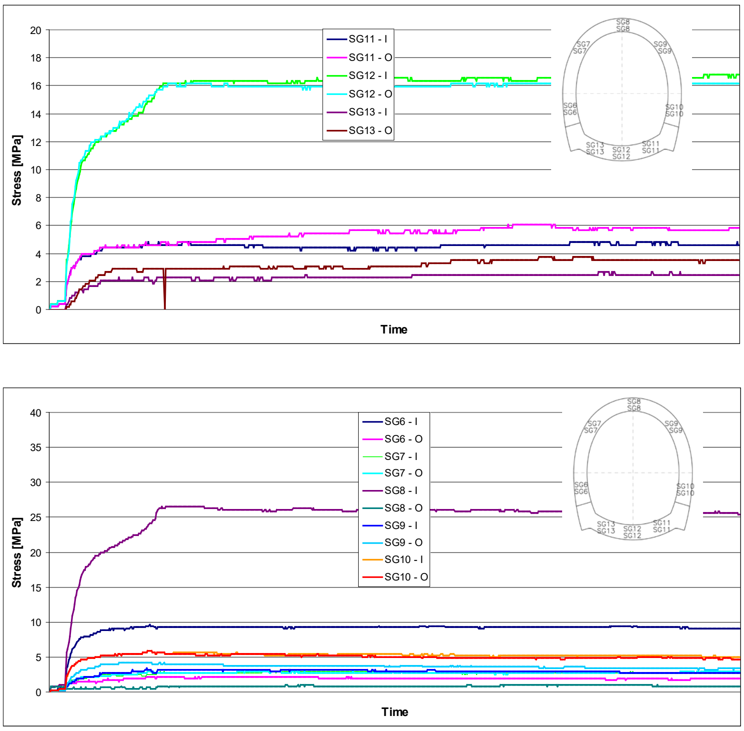


Fig. 10 *Measured stress on final linings at the section 207+080: stress in the invert (at the top), stress in the crown and sidewalls (at the bottom). I and O are respectively the inside and outside strain gauges*

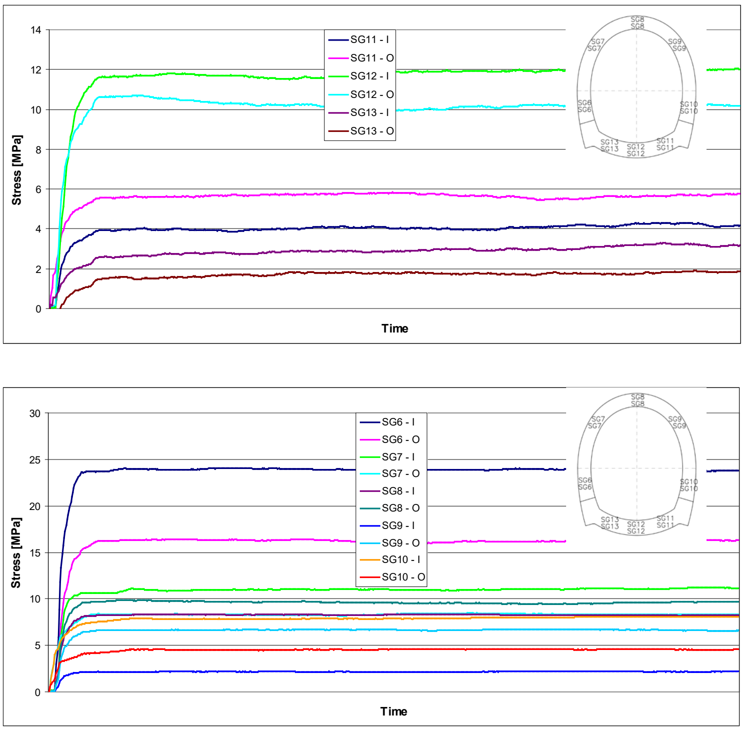


Fig. 11 *Measured stress on final linings at the section 207+200: stress in the invert (at the top), stress in the crown and sidewalls (at the bottom). I and O are respectively the inside and outside strain gauges*

8. Conclusions

The main conclusions from the experience of the works planned for the widening of the Castellano Tunnel, are the following:

- the combined system fiberglass elements and cement mortar injections, create a very efficient soil consolidated structure around existing lining so that, in spite of the frequent presence of saturated sandy lenses or layers, the excavation for the enlargement was realized safely without any instability problem;
- the measured convergences were limited to some millimetres showing a quasi-elastic behaviour of the consolidated ground and are consistent with the expected design values;
- the effectiveness of the consolidation system is also shown by looking to the loads on the primary and final linings. In both cases the loads were limited, due most probably to the optimal redistribution of the stress along the arch created by the consolidated system, and no creep effects were recorded for the monitored period;
- from the point of view of easy execution, the flexibility of the equipment, permitted to work inside to a very narrow space but also to industrialize the execution procedure so that the time to realize the interventions was limited to one year.

9. References

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