Geological unpredictability in tunnels

Design and construction difficulties during construction of the "Pale" tunnel for the new SS 77 state road of "Val di Chienti"

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Abstract

The article shows how the ADECO-RS approach used during the construction of around 20x2 km of double-bore 13 m diameter tunnels (as part of the "Quadrilatero" project passing through the Umbria-Marches Apennines) safely and successfully overcame unpredictable geological difficulties, and guaranteed the completion of the work within the times and costs of the detailed design.

Keywords: *tunnel, geological accident, industrialization, ADECO-RS.*

1. Introduction

One of the most important construction works currently being completed in Italy is without doubt the new SS 77 Val di Chienti, Maxi allotment no. 1 of the "Marches-Umbria Road Axis and internal penetration Quadrilatero" road system. The work is a variation of the current state road SS 77 for a stretch of about 35 Km connecting Foligno (Umbria) to Pontelatrave (Marches) (Fig. 1). According to Italian classifications, it is a Category B "main extra-urban road" with separate carriageways, each made up of two 3.75 m lanes, and is a rectification of the old SS 77, which was excessively winding. Choosing a new path, passing through the Umbria-Marches Apennines, made necessary the construction of 13 double-bore tunnels (D=13 m) for a total of 20x2 km in underground.
For the construction of these tunnels, considering the geological complexity of the Apennine deposits to be bored, the ADECO-RS approach (Lunardi 2008) was chosen; which uses the most advanced technologies available today to achieve a high degree of tunnelling industrialization in any terrain and stress-strain condition.
Fig. 2 overviews the entire route's project.

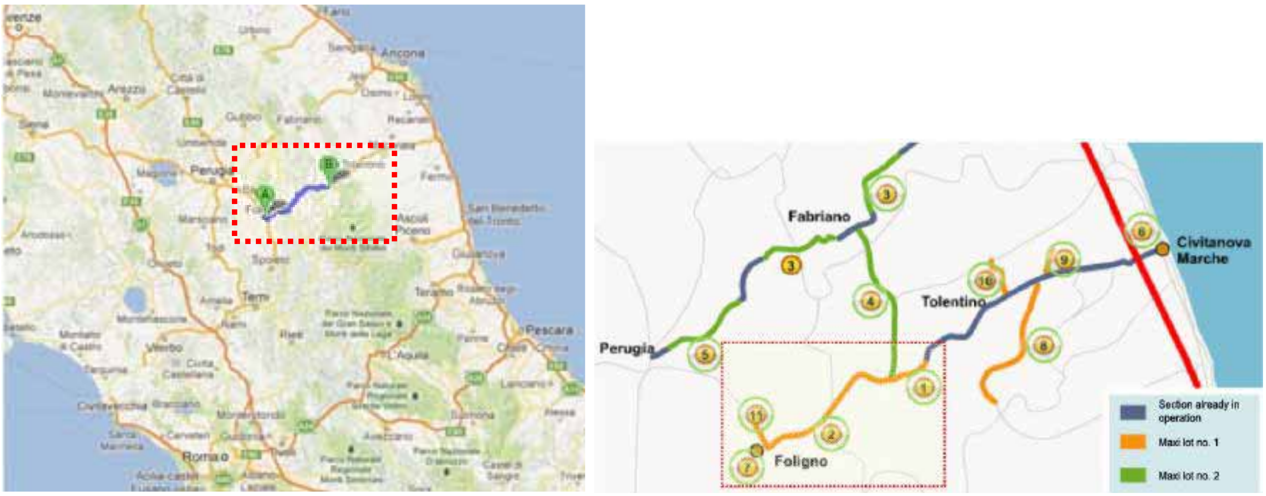


Fig. 1 *Localization of works*

Many difficult situations were faced during the excavation process, all of which were overcome thanks the above-mentioned approach.
Below, one of the most complex will be described in detail: during the excavation of the "Pale" tunnel, due to a sudden and unforeseeable geological situation, a tunnel variation had to be designed while the work was underway.

2. The "Pale" tunnel near the portal facing Foligno

The "Pale" tunnel is a 2.3x2 km twin tunnel (Fig. 2).
Near the portal opening facing Foligno, the tunnel passes under the SS 77 with minimum coverage of about 15 m (Pic. 1).
According to the Detailed Design, which had been drawn out following a survey phase based on the findings of an intense geognostic campaign, the two bores of the tunnel on this route were supposed to pass through a lapideous mass of limestone and stratified marly limestone belonging to the Maiolica Formation (Ma), and possessing good geomechanical characteristics. Consequently, the designed section types were those of a typical rock advancement (Fig. 3).

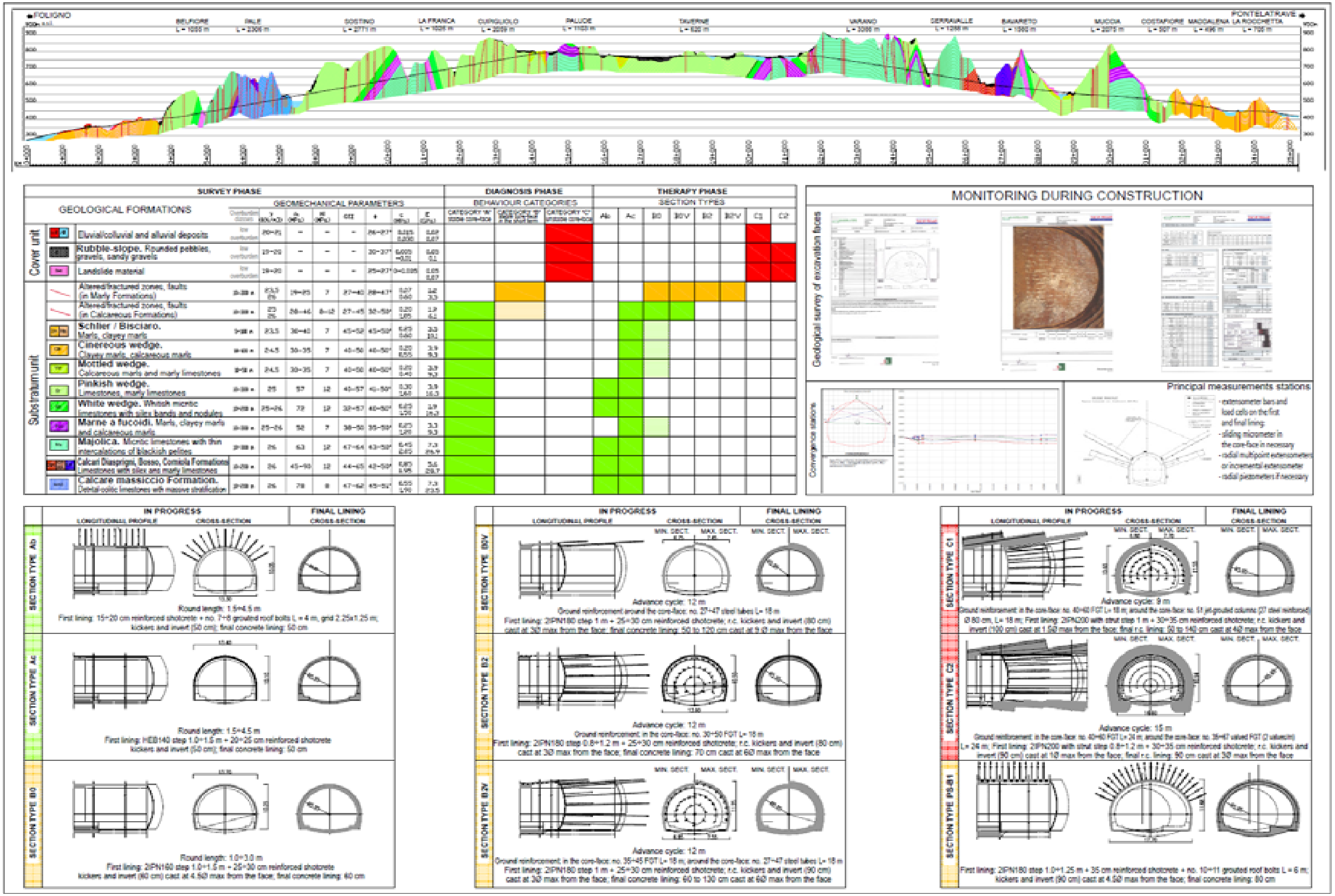


Fig. 2 *"Quadrilatero" project, Maxi allotment no. 1 overview.*

Pic. 1 *The "Pale" tunnel. Portal facing Foligno*

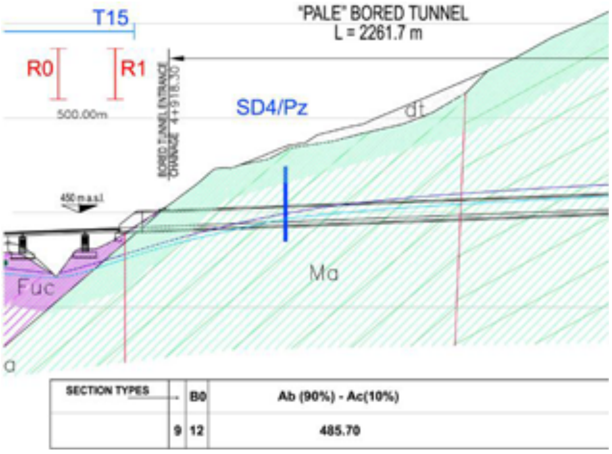


Fig. 3 *Geology and section types according to Detailed Design (North tunnel tube)*

These predictions were apparently confirmed both by the results of the preparatory earthworks for the portal bulkheads, which had brought to light the lithoid mass (Pic. 2a, 2b, 2c), and by the excavation of the first 15 m of the north bore, which had constantly faced a lithoid mass belonging to the Maiolica formation, possessing good geomechanical characteristics (Pic. 3).

Pic. 2a *Maiolica in the bulkhead head beam*

Pic. 2b *Maiolica at the base of the bulkhead*

Pic. 2c *Outcrop of Maiolica near the bulkhead*

Pic. 3 *Rock face at the pk. 4+933 of the Northern bore*

Everything was proceeding according to the design expectations when, suddenly, during the excavation of the northern tube, on the 11/03/2011, and having just placed the steel rib at around pk (chainage) 4+935 – therefore after 16.70 m from the portal and only 2 m after the survey pk 4+933, which had highlighted an entirely rock face (Pic. 3), arid material started to collapse from the top of the crown. Shotcrete was promptly pumped to contain the situation. However, the instability was rapidly and unexpectedly evolving. A patchwork of totally loose light-brown material, from fine sand to coarse gravel with cobbles, started to flow constantly and rapidly through a fissure of little more than 1 m in width that had opened on the cavity at the crown key, causing a sort of hourglass effect. The violence of the effect, which had developed in the absence of water, made it necessary to rapidly retreat all machines and operators, while the imbalance continued for minutes and only stopped once the accumulated material had completely covered the face and closed the crown (Pic. 4).

Pic. 4 *Material flowed into the tunnel*

Due to the modest overburden (about 15 m), the crumbling of material into the tunnel left on the ground, vertically to the face, a wide gap intercepting the slope downstream the SS 77 (Pic. 5a and 5b).

Pic. 5a *Overground gap, downstream the SS 77 (detail)*

Pic. 5b *Overground gap, downstream the SS 77 (general view)*

The necessary precautions were immediately taken, such as re-directing the traffic of the SS 77 onto a single alternating one-way carriageway (the upstream one) and by protecting the safety of the face with great amounts of cement and shotcrete.
The authorities decided to interrupt traffic on the SS 77 as a safety precaution and to allow the necessary operations to restore the carriageway. On that same day of the 11th March, the cavity was filled with lightened cement; the following days – always starting from the SS 77 – ground improvement operations were implemented, vertically on the North track, with metallic tube-rods and valved fibreglass tubes. During these actions, it was noted how the mix was heavily absorbed, proof of the high permeability of the material. Following these procedures, the traffic of the SS 77 was reactivated exclusively for the upstream carriageway. In the meanwhile, injections with valved fibreglass tubes were carried out from a specifically created emplacement on the slope, in order to improve the collapsed material, and then radial bolting to the slope was carried out in order to stitch the cavity cement filling to the surrounding mass. At the end of these operations, the travel area had been restored (Fig. 5) and traffic on the SS 77 state road was reopened on both lanes.

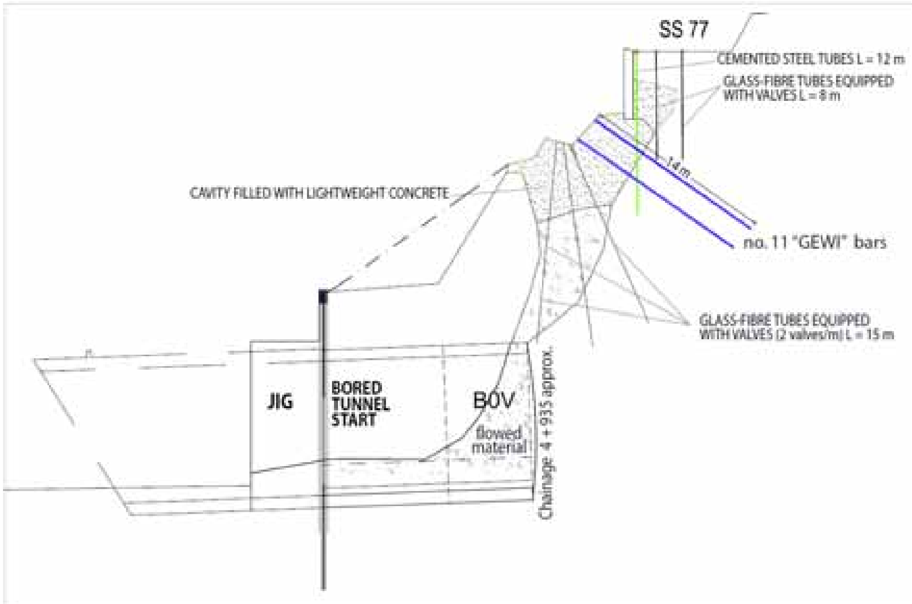


Fig. 4 *Ground improvement operations of the road area.*

Obviously, the tunnel advance works had to be suspended while expecting the development of a new tunnel design that would take into account the unexpected situation at hand. The face of the north bore was at pk 4+935, while excavation hadn't even begun at the south bore, where the face had stopped at the portal bulkhead (pk 4+946).
Topographic monitoring - which hadn't highlighted significant deformations in the tunnel, but registered a quickly depleting subsidence of a few centimetres in the road area (Fig. 10) - was of comfort as regards the stability of the works.

2.1 The new tunnel design

Following the events described, a new tunnel design for geological accident was developed in order to define all the operations necessary in order to resume excavation and guarantee the required safety margins.

2.1.1 The survey phase

Fig. 5 reports the planimetry of the performed geognostic surveys. As mentioned previously, the Detailed Design's surveys (in red in Fig. 5) had indicated, wherever the accessibility of the locations allowed (and in accordance with the geological analysis of the outcrops), the presence of a lithic mass possessing good geomechanical characteristicss (Maiolica formation).
An integrative geognostic campaign was implemented for the new tunnel design, and a specific emplacement was placed over the portal bulkhead of the north bore, allowing 5 total core recovery boreholes, 1 exploratory well and 9 seismic refraction lines. All supported by an overground geological-geomorphological survey.

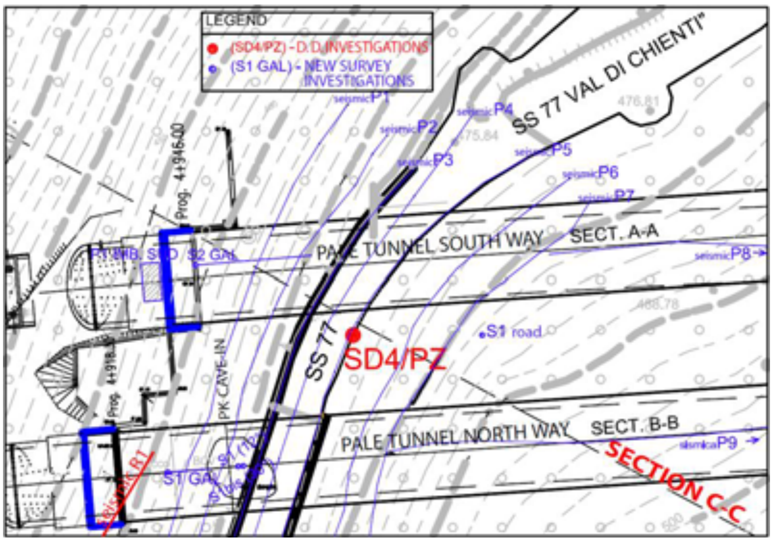


Fig. 5 *Geological surveys.*

The result was the highlight of important, albeit contained, masses of debris placed on an intensely fractured rock substrate near the "Pale" tunnel portal and under the SS 77, and belonging to the Maiolica formation. These debris deposits interfered significantly with the initial section (about 50 m) of the tunnels in construction; and the rock-debris contact was represented by a downstream slanted plane, which effectively denoted a potentially unstable situation (Fig. 6).
These deposits were delimited to a very small area, between the portal bulkhead and the SS 77, and for this reason hadn't been intercepted by the D.D. surveys, despite being very close to each other (distance from seismic R01 – carried out near the portal of the north bore – and the borehole SD4PZ – carried out on the SS 77 between the two bores – is only about 35 m), but unfortunately exactly at the margins of the deposits themselves (Fig. 7).

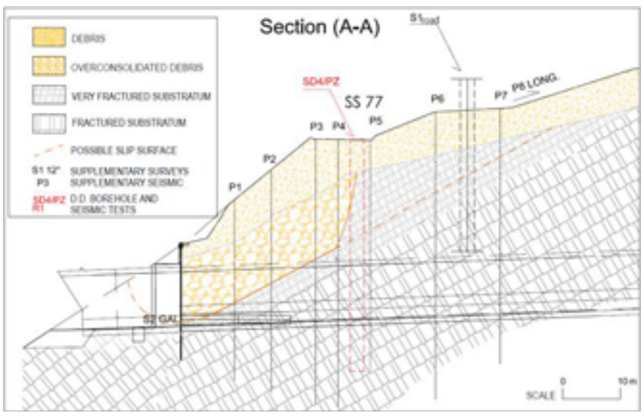


Fig. 6a *South tunnel tube longitudinal section.*

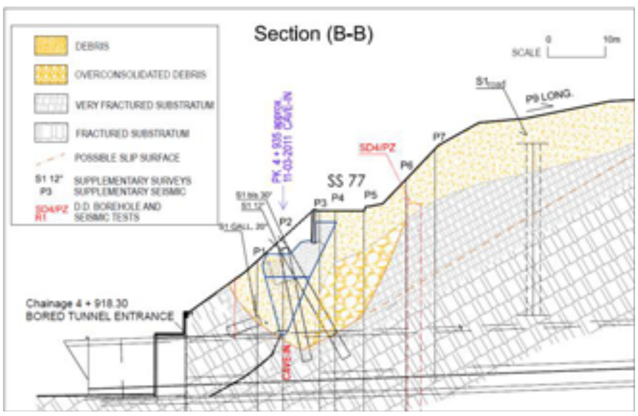


Fig. 6b *North tunnel tube longitudinal section.*

This new geological situation, which had only been discovered during the works themselves and following the integrative surveys, could never have been forecast during the detailed designing and was therefore an unpredictable geological surprise.
As regards the genesis of these relevant debris masses, they seem to have been caused by the colluvium filling of a pre-existing recess in the rock substrate, caused by fluvial erosion. The brusque subsiding of the substrate and consequent increase in the debris' thickness, was therefore caused by the presence of a paleo river bed of the ancient course of the Lane Trench, in the nearby area. This "valley", incised inside the rock substrate and subsequently filled with colluvium, was indeed characterized by a certain continuity, with a direction that transversally cut the path of the tunnels (Fig. 7); it was observable both at the north carriageway, about near the face of pk 4+936 (affected by the release phenomenon), and at the face of the south carriageway (around pk 4+946 ca.). The seismic survey indicated its presence between the two bores as well; as can be evinced by observing the P1 seismic line (Fig. 8), which presented an in-depth analysis of the seismic stratigraphy characterized by a low level of propagation of seismic waves, compatible with the presence of debris.

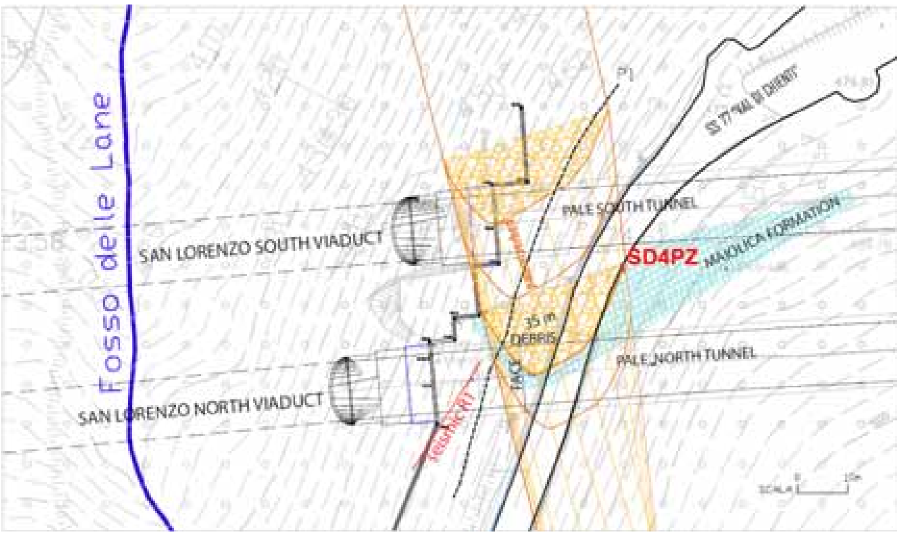


Fig. 7 *Illustrative chart of the geometry of the paleo river bed filled with colluvium.*

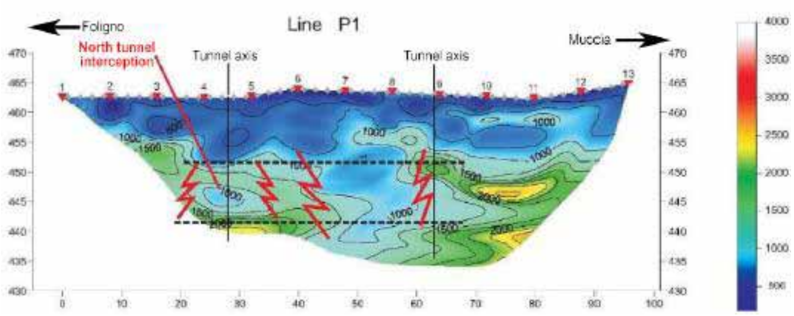


Fig. 8 *The tomographic seismic section P1.*

The lateral walls of the paleo river bed were characterized, on the side of the valley, by vertical slopes, in which the rock substrate, once eroded, had become more stable due to the anti-dip slope attitude of the layers; while on the side of the mountain, the layers had slid down the slopes due to the dip slope attitude and to the presence of inter-layer pelithic levels (see Fig. 6).

On the basis of the results of the seismic surveys, supported by the in situ boreholes and surveys, the debris area resulted (barring local variations) to be made up of loose material on the surface and denser, more cemented (or perhaps including blocks or layer relics) material in depth.

<u>Geotechnical-geomechanical characterization</u>
The geotechnical-geomechanical characterization of the masses interfering with the excavation of the bored tunnel was defined on the base of the analysis of the results of the geognostic survey and seismic integrative campaigns (Table 1).

Table 1 *Geotechnical-geomechanical characterization.*

Formation	**GSI RMR**	γ [kN/m³]	**c** [kPa]	**φ** [°]	**E** [MPa]
Debris		20	0÷10	32÷36	50÷100
Densed debris		20	25÷50	35-37	300÷600
Heavily fractured rock substrate with presence of karstic phenomena	GSI= 29-36 RMR_b= 29-41	26	100÷150	36÷48	1500-2800

2.1.2 The diagnosis phase

During the diagnosis phase the criticalities affecting the work were identified and quantified according to the following analyses:

1) Evaluation of the *ante operam* stability conditions of the slope.
2) Definition of the excavation behaviour categories of the surrounding mass.

The stability analyses of the slope were carried out by referring to the geological section along the greatest dip (Fig. 9a), using the "*shear strength reduction (SSR)*" technique (Fig. 9b, 9c).
For maximum safety, the calculations simulated the presence of a layer of metric thickness in contact between the debris and the rock (Maiolica) with cohesion equal to none, so as to take into account the presence of any possible sliding.
Finally, in reference to the indications given by the piezometer installed in borehole SD4PZ, the water table was considered absent.
The calculation parameters used in the analyses are reported in Table 2.

Table 2 *Calculation parameters used in stability tests.*

Material	**γ**	**c'**	**φ'**	**E**
Debris	20 KN/m3	20 KPa	36°	300 MPa
Debris (higher than reduced resistance of metric thickness)	20 KN/m3	0	36°	300 MPa
Maoilica	26 KN/m3	120 kPa	36	2100 MPa

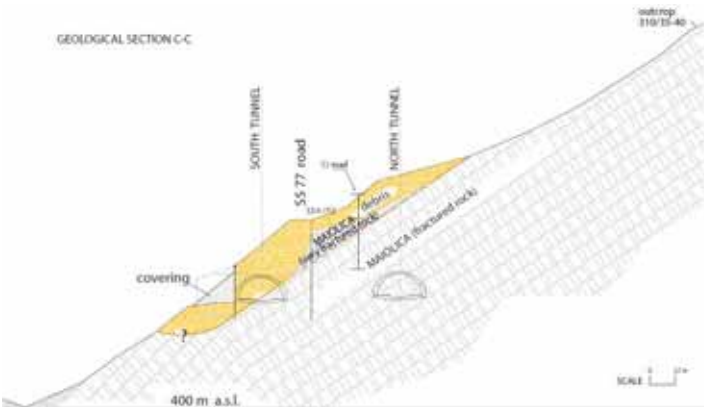
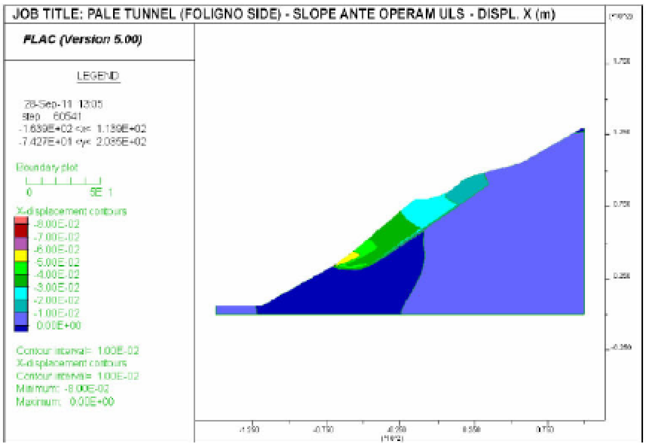


Fig. 9a *Geological section along the greatest dip.*



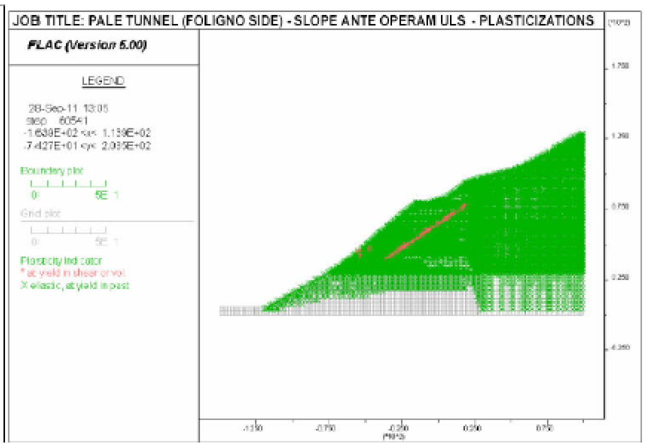
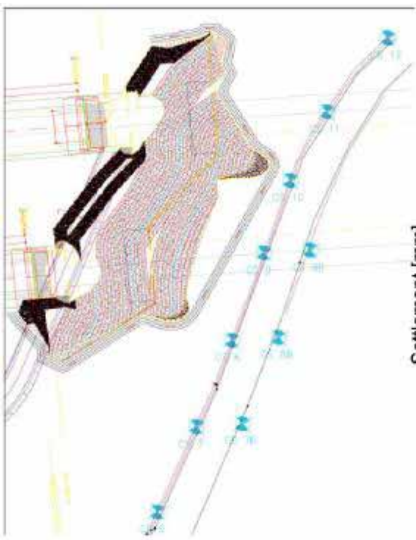


Fig. 9b Ante-operam *analysis of the slope stability (displ.)* ***Fig. 9c*** Ante-operam *analysis of the slope stability (plast.)*

The safety factor of the slope in ante-operam conditions resulted equal to F=1.25.

This value was also confirmed by the results of the monitoring carried out through plane-altimetric and precision levelling topographic measurements on topographic targets positioned on the edge of the SS 77 (Fig. 10a, 10b) and also by the information received from the ANAS, according to which, at least in the last years, no significant cracking events had taken place along the SS 77 state road.



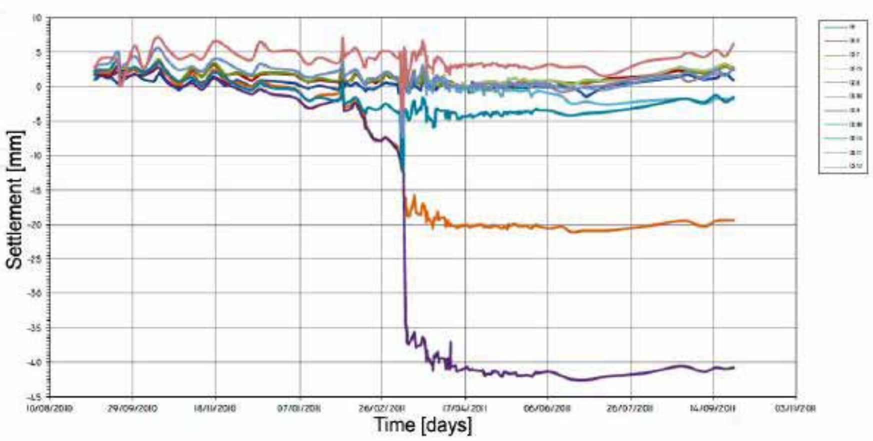


Fig. 10a *Monitoring points plan.* ***Fig. 10b*** *Subsidence vs. time, max = 42 mm.*

Propaedeutic stabilizing operations at the base of the slope were therefore deemed unnecessary. Considering the conditions of shallow overburden, included in the interval of about 5 ÷ 25 m, the Tamez method (Tamez 1984) was used to foresee the excavation behaviour of the ground mass. This method evaluates said behaviour by considering the limit-equilibrium of the prism of potentially unstable ground near the excavation. The Tamez method doesn’t offer information of the deformation behaviour, however the author associates a different type of excavation face behaviour to each SF value interval (calculated safety factor), as can be seen in the following Table 3.

Table 3 *Tamez method: Safety Factors and excavation face behaviour*

SF	**Excavation face behaviour**
>2,0	Elastic behaviour (Category A behaviour, stable core-face)
1,5 – 2,0	Elastic plastic behaviour: normally acceptable subsidence (Category B behaviour, short term stable core-face)
1,0 - 1,5	Elastic-plastic behaviour: important subsidence (Category B behaviour, short-term stable core-face)
<1,0	Failure (Category C behaviour, unstable core-face)di tipo C, nucleo-fronte instabile)

The results of the performed analyses for the “Pale” tunnel are reported in Table 4.

Table 4 *The “Pale” bored tunnel. DIAGNOSIS PHASE: results of the Tamez method analyses*

Geomechanical Formation	Lithology	Analysis	H (overburden)	$R_{average}$	$H/D_{average}$	$D_{excavation}$	$H_{excavation}$	Parametri geomeccanici di riferimento			Safety factor	BEHAVIOUR CATEGORY
								γ_{nat}	φ	c		
			[m]	[m]	[m]	[m]	[m]	[KN/m^3]	[°]	[kPa]		
Detr	Debris	DETR_5	5	7,10	0,4	14,20	11,00	20	35	5	**0,1**	**C**
Detr		DETR_10	10	7,10	0,7	14,20	11,00	20	35	5	**0,1**	**C**
Detr		MAI_C_7\ detrito 4-15	15	7,10	1,1	14,20	11,00	20	35	5	**0,6**	**C**
Ma fratt-Detr	Debris / Very fractured Maiolica with karst phenomena	MAI_C_11-10\ detrito 10	20-30	7,10	1,4-2,1	14,20	11,00	26-20	39-35	100-5	**1,2**	**B**
Ma fratt-Detr		MAI_C_11-15\ detrito 10	25-35	7,10	1,8-2,5	14,20	11,00	26-20	39-35	100-5	**1,2**	**B**

In particular, a Category “C” excavation behaviour (unstable core-face) was observed where the debris mass affected the excavation face, with much lower safety factors (in absence of ground improvement operations) than the unit. Where the face was entirely within the Maiolica Formation but heavily fractured and affected by karstic phenomena, reduced SF values were observed in absence of operations, identifiable with a Category “B” excavation behaviour (“short term stable core-face”).

The therapy phase

During the therapy phase, the necessary stabilization operations were developed – in terms of pre-confinement/confinement actions, excavation characteristics and face advancement speed, section types, etc. – necessary to be adopted in order to resume the excavation in safety.
To this aim, it must be stressed that all operations here to be described had already been foreseen by the Detailed Design in a global work view, therefore the New Design consisted mostly in a specific-case contextualization, which was quite quick and easy to set up.
Due to the heterogeneous and incoherent nature of the debris material (Category "C" excavation behaviour, "unstable core-face") and the unfortunate attitude of the rock-debris contact, the tunnel sections examined were particularly delicate.
In the above-described context, the triggering of any unstable situation – even a local one – during advance could have caused significant slope instability, and risked affecting the SS 77 state road which passes over the two tubes of the tunnel just in the section under consideration, with an overburden of about 15÷20m.
It was therefore necessary, during design and execution of the works, to set up all operations required to limit the negative effects of the excavation on the slope, through the use of sufficiently cautionary section types.

<u>The design solutions</u>
Considering the potential instability of the contact zone between the layer of debris and the rock substrate - placed on a plane subject to landslide at the same inclination of the slope and positioned above the excavation profile - a systematic operation of sewing and redeveloping the profile through the use of valved fibreglass tubes ahead of the tunnel profile had to be set into place, so as to intercept the potentially sliding strip (Fig. 11).

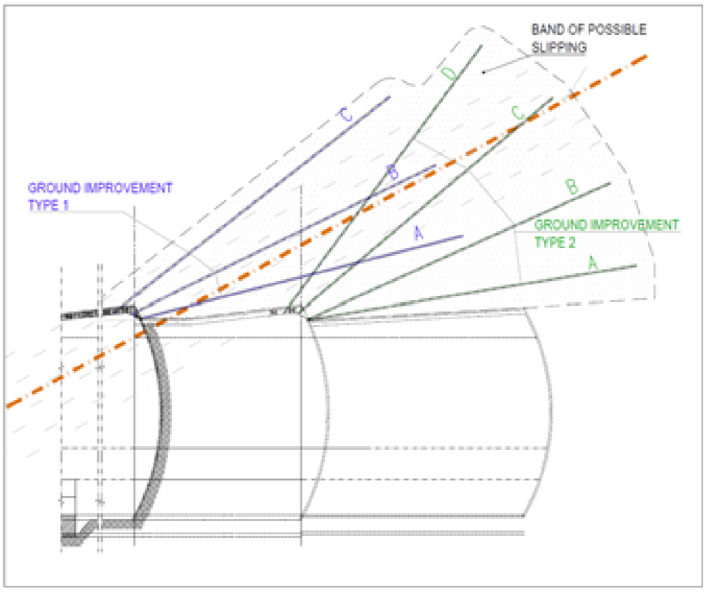


Fig. 11 *Improvement operations in the potentially sliding strip.*

In those tunnel sections which are completely or partially inside the layer of debris, presenting a Category "C" excavation behaviour (unstable core-face), a section type called C1P, was applied; this section involved the installation, previous to the excavation, of intense reinforcement operations in the core face (using valved fibreglass structures) and protection of the same core-face (using reinforced jet grouting around it), as well as sufficiently rigid primarily (steel-rib and invert strut) and final linings (Fig. 12).

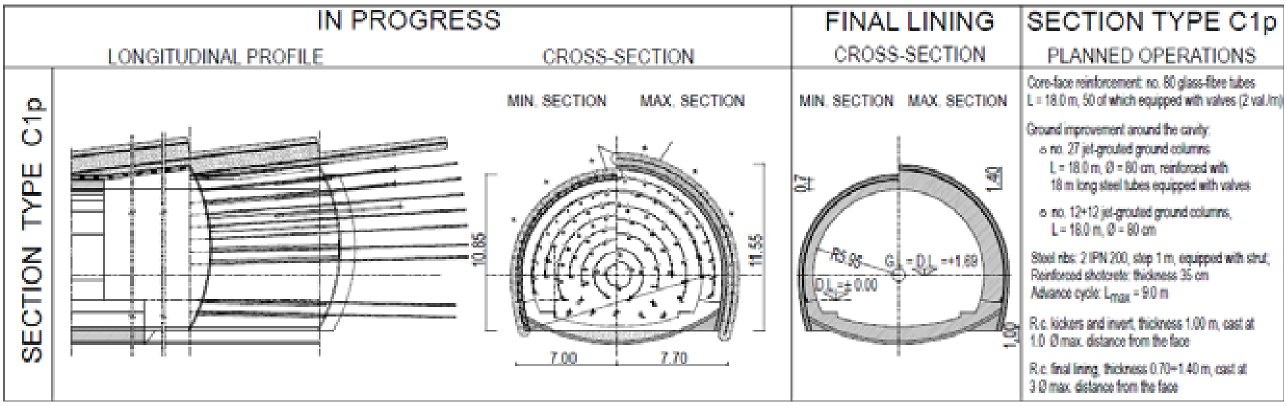


Fig. 12 *Characteristics of section type C1P.*

For the first advance fields localized inside the Maiolica Formation (very fractured and locally karstified), yet still nearby the delicate contact zone between debris and rock substrate, the decision was made to use excavation section types, named B2VP and B0VP, which – as well as reinforcing and protecting the core-face – gave the possibility to also execute injections capable of restructuring and filling the cavities found, according to the entity of the karstic phenomena and the relative fracturing degree (Fig. 13).

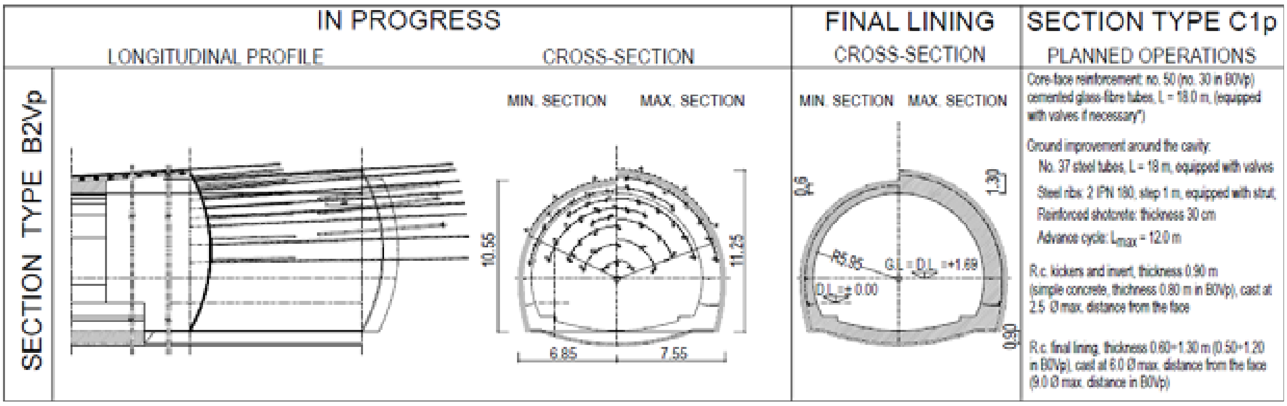


Fig. 13 *Characteristics of section type B2VP.*

The adopted distribution of the section types is reported in the planimetry of Fig. 14 and in the longitudinal sections of Fig. 15.

Fig. 14 *Planimetry, including description of operations.*

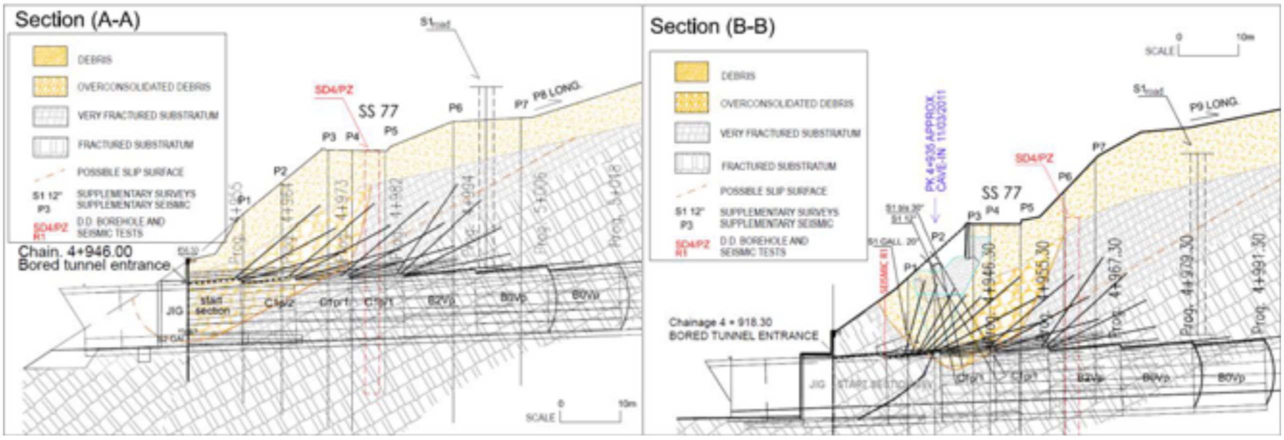


Fig.15a *South tube longitudinal section with operations* ***Fig.15b*** *North tube longitudinal section with operations*

In order to maintain the safety of the tunnel and of the road area, additional operations were enacted upon the North tube, during the excavation of which the above-described cave-in phenomenon took place, by improving the detensioned mass in those segments that were directly affected by the cave-in phenomenon (Fig. 16).

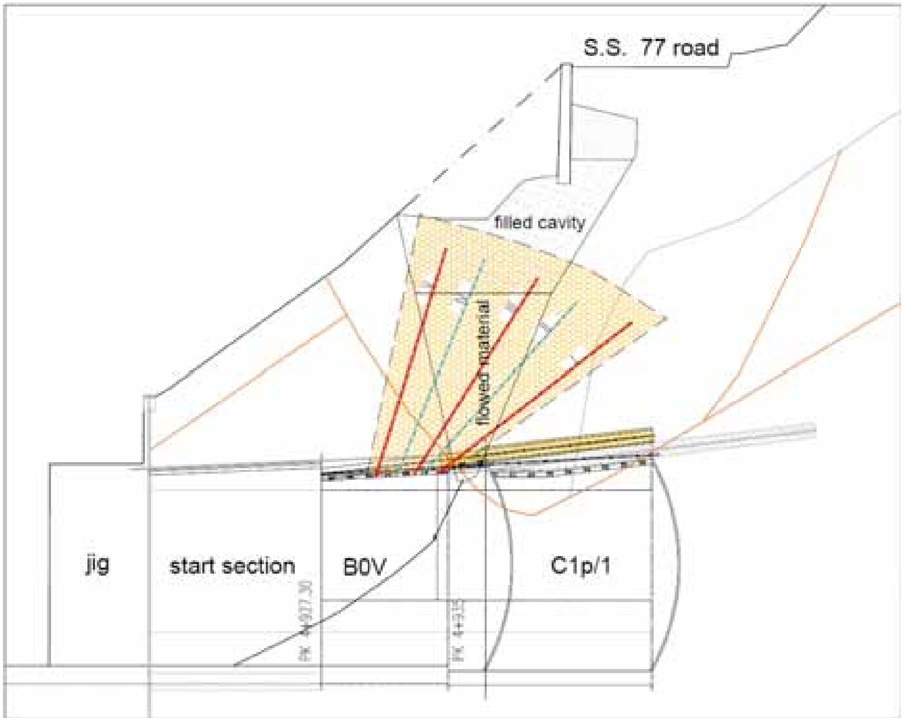


Fig. 16 *Improvement of the ground mass affected by the cave-in*

Due the delicate geological context, in order to avoid an overlap of disturbance effects on the mass caused by the excavation of the two tunnel tubes side by side, it was decided to keep the advance faces of the North and South carriageways at a distance of about 3 excavation diameters. In this manner, the excavation of the delayed tunnel could take place having already installed kickers and invert in the earlier tunnel.

<u>Dimensioning</u>

The dimensioning of the operations was carried out first by using the Tamez method, with the goal of meeting the necessary safety margins (SF >= 2) in terms of core-face stability (Table 5).

Table 5 *THERAPY PHASE: result of Tamez method analyses*

Geomechanical Formation	Lithology	Analysis	H (overburden) [m]	$R_{average}$ [m]	$H/D_{average}$ [m]	$D_{excavation}$ [m]	$H_{excavation}$ [m]	Relative geomechanical parameters γ_{nat} [KN/m^3]	φ [°]	c [kPa]	Safety factor	BEHAVIOUR CATEGORY	Therapy Section types	Safety factor with stabilization measures
Detr	Debris	DETR_5	5	7,10	0,4	14,20	11,00	20	35	5	**0,1**	**C**	Start section	4,8
Detr		DETR_10	10	7,10	0,7	14,20	11,00	20	35	5	**0,1**	**C**	C1P-2	3,3
Detr		MAI_C_7\ detrito 4-15	15	7,10	1,1	14,20	11,00	20	35	5	**0,6**	**C**	C1P-1	2,0
Ma fratt-Detr	Debris / Very fractured Maiolica with karst phenomena	MAI_C_11-10\ detrito 10	20-30	7,10	1,4-2,1	14,20	11,00	26-20	39-35	100-5	**1,2**	**B**	B2VP	2,1
Ma fratt-Detr		MAI_C_11-15\ detrito 10	25-35	7,10	1,8-2,5	14,20	11,00	26-20	39-35	100-5	**1,2**	**B**	B0VP	1,9

The finite differences FLAC calculation code was used for the final analysis of the first phase ground improvement operations designed in the different section types.

In particular, the following aspects were analysed:

1. Dimensioning and analysis of the C1P (South carriageway) and B2VP (North carriageway) section types, simulating the construction phases of the two tunnel tubes side by side. In the analysed section (section. C-C in fig. 14 and fig. 17), despite having reconstructed the geometry of the slope at its section of maximum dip, it was decided to consider the minimum interaxis of the tunnel tubes present in the transversal section so as to evaluate, through the use of a precautionary schematization, not only the influence of the excavation in terms of stress state modification of the slope on its own stability conditions, but also the interference of the excavations of the two carriageways.

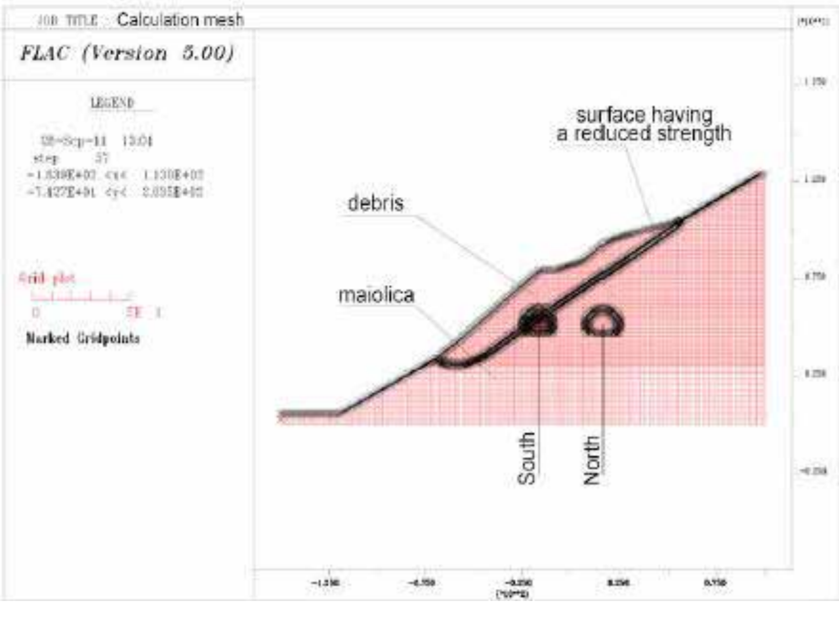


Fig. 17 *Calculation section.*

The improvement of the ground mass due to the improvement operatons allowed the expected deformation response in the tunnel (centimetric displacements) and therefore also the stresses in the linings, always contained within the regulation limits (Pic. 18a, 18b).

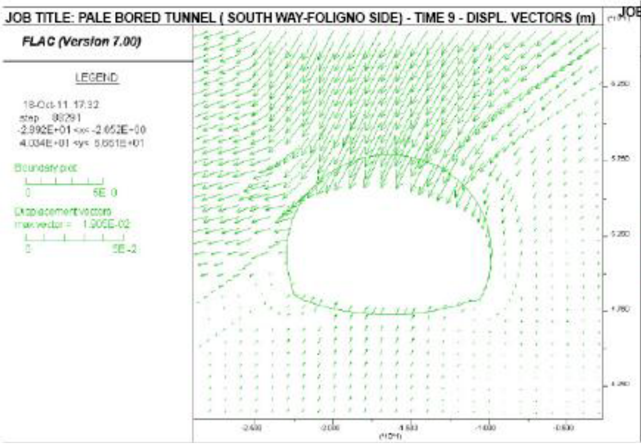


Fig. 18a *Results of calculation analyses (expected displacements)*

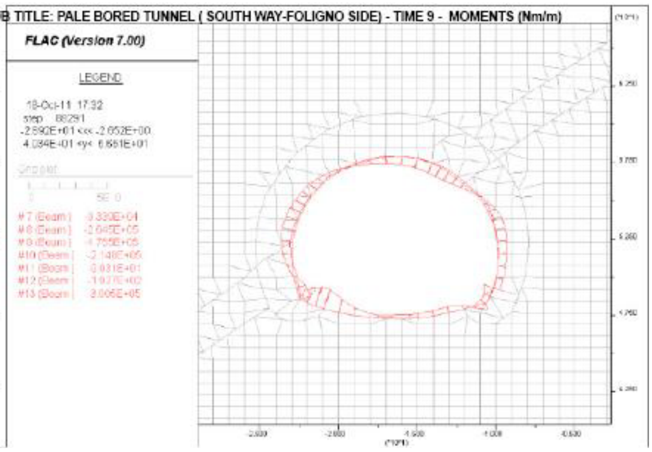


Fig. 18b *Results of calcul. analysis (expected stress in the linings)*

2. Stability of the slope following tunnel construction, according to the "*shear strength reduction (SSR)*" technique, iteratively reducing the value of the friction angle on a sliding surface until convergence of the numerical solution. The post-operam safety factor does not substantially modify itself when compared to the ante-operam conditions. This indicates that the excavation works of the tunnels, which used section types capable of reducing the disturbance effects on the slope, didn't alter the stability conditions of the same when compared to the *ante operam* conditions (Fig. 19a, 19b).

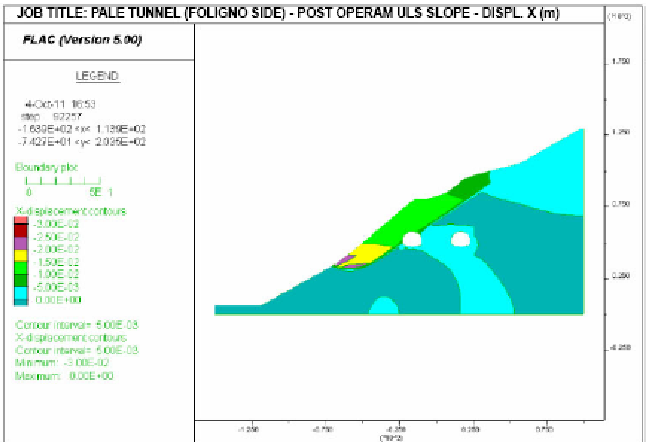


Fig. 19a Post-operam *analysis of the slope stability (displ.)*

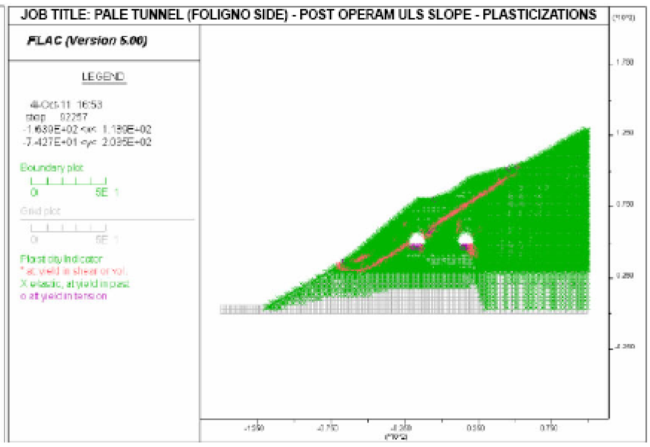


Fig. 19b Post-operam *analysis of the slope stability (plasticizations)*

3. Effects caused by the excavation of the two tunnel tube on the SS 77 state road. As a function of the expected deformation response in the tunnel (of centimetric order), analyses have foreseen downstream displacements of the slope and ground subsidence of 2-3 cm, such as to cause distortions upon the road area equal to less than 0.5% - a negligible damage class (Fig. 20).

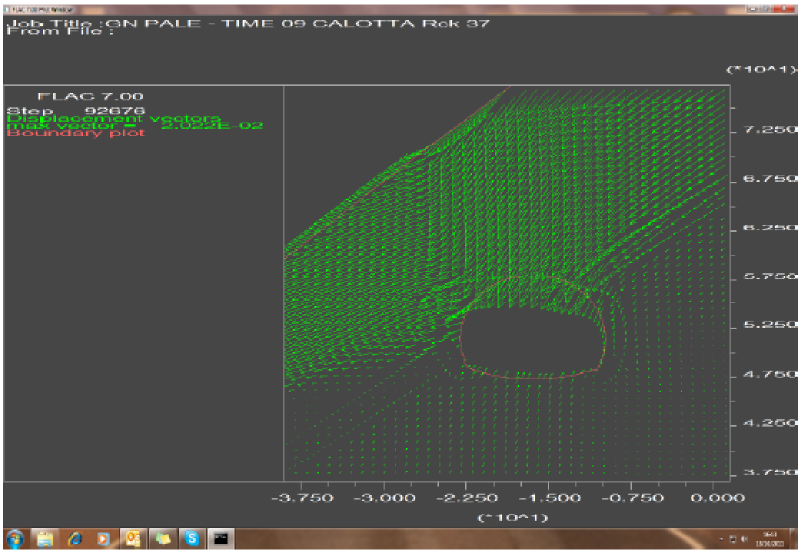


Fig. 20 *Calculated settlements caused on the slope by the excavation.*

The detailed analysis has allowed survey of the stress and deformation state in the surrounding structures and mass, in each construction phase of the section types, up to completion of works and therefore allowing the evaluation of the evolution of the work's behaviour in the short, middle and long term. In particular, due to the reduced distance between the two tubes, analyses were carried out by taking into account the interference effects caused by the advance of the two adjacent faces.
From the point of view of the loads acting upon the linings, particularly difficult conditions were caused by the following reasons:

- The presence of a possible sliding surface at the contact point between the debris in which part of the tunnel was excavated, and the Maiolica base formation.
- Dissymmetric load conditions at a significantly parietal tunnel track.

<u>The monitoring program</u>

The monitoring designed the therapy phase and activated during the construction had been conceived for the following reasons:

- Guarantee safety of underground excavation works, as well as viability on the SS 77 state road.
- Optimize the intensity and distribution of the stabilizing operations in function of the real stress-strain behaviour of the mass following the progress of excavation.

To this end the following had been prepared:

- Daily monitoring of the tunnel with geo-structural surveys of the face and convergence measurements of the cavity.
- Daily plane-altimetric topographic monitoring using the reading of optic targets placed along the upstream and downstream edges of the SS 77 state road (according to Fig. 21).
- Daily visual and instrumental monitoring (using references placed above pre-existing cracks) of the integrity conditions of the SS 77 pavement.
- Daily plane-altimetric topographic monitoring, using the reading of optic targets placed on the bulkhead head beam.
- Weekly inclinometric monitoring installed on the "$S1_{Strada}$" borehole (Fig. 5), upstream the South bore (intensified according to the results of the topographic monitoring).

The designed measures guaranteed sufficient safety margins; despite this fact, both lanes of the road area were also equipped with a blinking traffic light linked to the faces of the tunnels beneath, thus allowing the workforce to block traffic on the SS 77 with a red light should the tunnel become unstable. This safety measure was defined in detail with the authorities.

2.1.3 Operational and monitoring phases

The evidence collected during the work progress fully confirmed the expectations, both in terms of deformation response of the ground mass and of the slope, and in terms of adequacy of the adopted section type.

Excavation started from the South tube (Pic. 6) which advanced for about 3 excavation diameters (about 40 m); successively, after having improved the ground mass affected by the cave-in (Fig. 14), advance proceeded from the face of the North tube. The interferences between the two tunnel tubes were thus contained.

Pic. 6 *Debris material at the face of South tube*

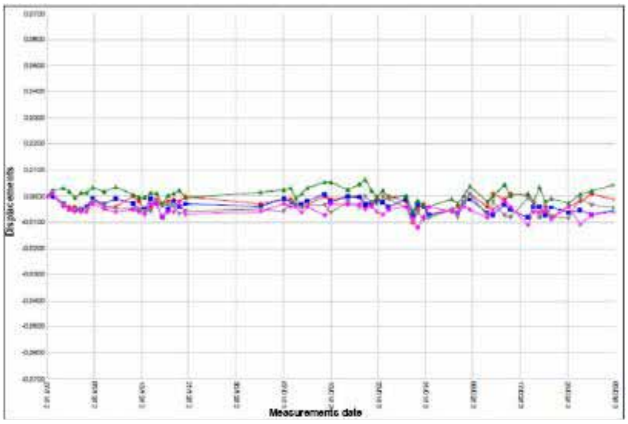


Fig. 22 *Deformation response of the cavity (displ. vs. time)*

The excavation face and the cavity profile have been kept in stable conditions thanks to the effect of the designed improvement operations (fibreglass in the core-face and steel-reinforced jet-grouting around the core).

The deformation response of the cavity, measured by convergence stations placed in every advance field, remained within the centimetric order, in line with expectations (Fig. 22).

Consequently, the topographic and inclinometric monitoring of the ground has shown contained subsidence and displacements, perfectly in line with the same expectations (Fig. 23 and Fig. 24).

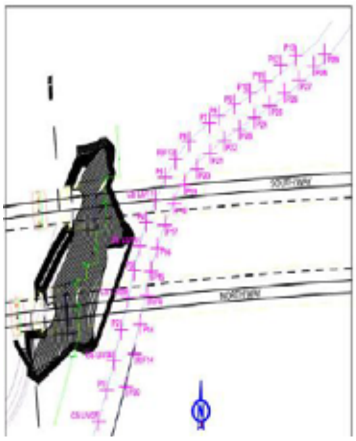


Fig. 21 *Monitoring points plan*

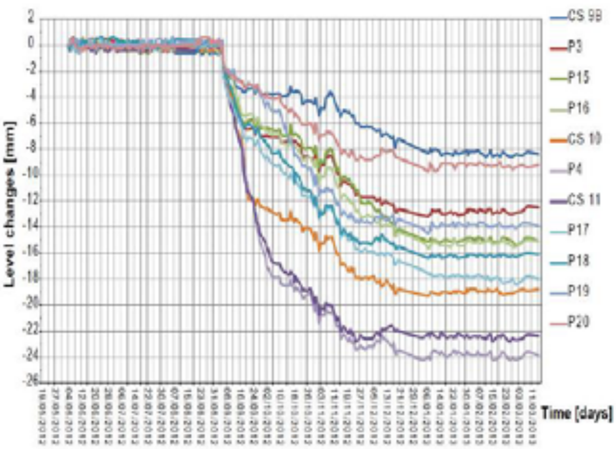


Fig. 23 *Subsidence/time (max. 24 mm)*

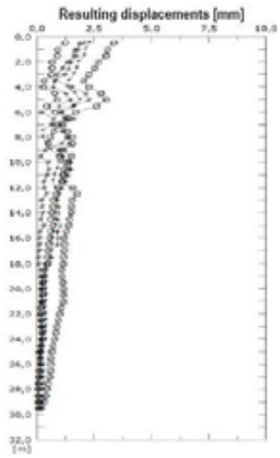


Fig. 24 *Inclinometer (max. 2.5 mm)*

The underpass of the SS 77 state road has therefore been completed in both bores, while keeping the traffic stable and without damage to the transportation infrastructures, with a constant production in the order of 0.7 ÷ 1.00 m/day of finished tunnel.
This has allowed the SS 77 state road to be under-passed by both tunnel tube without damaging the transportation infrastructure.

3. Final remarks

The new Val di Chienti SS 77 state road, Maxi allotment no. 1 of the Marches-Umbria Road Axis and internal penetration "Quadrilatero" road system, is currently one of the most significant Italian infrastructural works.
13 double-bore tunnels (D=13 m) have been constructed for the mentioned transport axis, for a total of 20x2 km in underground works. Despite the complexity of the Umbria-Marches Apennines, these works are today being completed after only 4 years of labour.
This has been made possible by the correct usage of the ADECO-RS design and construction approach, which is known for being greatly apt in facing problematic contexts, as it guarantees the industrialization of excavation, and respect of construction times and costs.
Thanks to this approach, problems such as that described above were able to be overcome quickly and successfully. In said situation, an unforeseeable geological situation was met during excavation at the portal facing Foligno of the "Pale" tunnel, due to the unexpected interception of a debris deposit – caused by an paleo river bed – which brought about a great flow of material from the crown area, and affecting the overground nearby the current path of the SS 77 state road.
The use of the correct section types (which had already been designed for the entire path, and just needed to be contextualized to the specific case), which projected ground improvement in advance through the use of fibreglass structures in the core-face and jet-grouting around it, made it possible for both tunnel bores to pass under the SS 77 state road, guaranteeing safety conditions to the works and no damage to the travel infrastructure, which remained open for as long as the works continued.
Daily production, in this delicate passage of about 50 -70 m nearby the portal, was equal to about 0.7 ÷ 1.00 m/day, which is more than acceptable considering the complexity and delicateness of the problems faced.
In conclusion, it may be of note that the total construction cost of all tunnels in the "Quadrilatero" project – 13 double bore tunnels, 130 m^2 of section and therefore a total 40 km of underground excavation in heterogeneous grounds and sometimes very difficult stress-deformation conditions – has been equal to about 600 million Euros in total, equal to about 15,000 euros/m of completed tunnel (complete of final lining). This is just another documented example which contradicts the words of those who gratuitously claim that the ADECO-RS approach costs more than other systems, which are furthermore incapable of meeting the same standards in production and safety.

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