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The fixed link over the Strait of Messina: final design of the underground works

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ABSTRACT: A brief description is given of the final design for the fixed link over the Strait of Messina. After a short history of the design procedures, a description is given of the infrastructures planned, the main geological and geotechnical characteristics of the area and, in particular, the criteria used in the final design of the road and railway infrastructures on the Sicilian and Calabrian sides of the fixed link are reported.

1 Introduction

The history of a permanent connection between Sicily and the continent is relatively recent. Ideas and proposals for a permanent connection have circulated since the end of the nineteenth century, but the first specific studies date back to 1965 when ANAS (the Italian state-owned company for the construction and maintenance of motorways and highways) in co-operation with the State Railways held a "Competition of Ideas", in which 143 competitors participated. Twelve designs were chosen, of which nine were aerial projects, two were seabed projects and one a proposal below the seabed. The first prize was awarded jointly to six designs, comprising three suspension bridges, a cable stayed bridge with several spans, a single span tensile structure and a submerged tunnel (floating). In 1971, the Italian government declared the national interest for the work and decided to establish a company for the design, construction and operation of the work. In 1981 the *Società Stretto di Messina*, *Concessionaria di Stato* [Strait of Messina, State Concessionary Company] was formed in accordance with the procedures and objectives of Italian government. The company commenced its activities in 1983 and in 1985 granted a concession for the study, design, construction and rail operation and it signed an agreement with the contractors ANAS and State Railways for the formulation of a Conceptual Design for the connection.

The first step in the design procedures concerned the feasibility of the project and its nature, whether underground, in the sea or the air. At the end of 1986, the company Stretto di Messina submitted a feasibility study with designs for the three options and it gave its opinion on feasibility and costs for each solution.

Between February and December 1987, first the State Railways, then the *Consiglio Superiore dei LL. PP.* (authority responsible for the supervision of public works) and finally ANAS examined the feasibility studies and gave a technical opinion in favour of an aerial solution. In April 1988 they confirmed the opinion already given. The Conceptual Design of a suspension bridge therefore began.

Finally in 1992 Stretto di Messina completed and submitted the Conceptual Design, accompanied by detailed technical reports which identified, amongst other things, the expected cost for the construction of the bridge and the relative connections as well as the time required for construction.

On the basis of the Conceptual Design, in December 2002 a Preliminary Design was drawn up and submitted which included a railway and a motorway connection for the project. With Resolution No. 66/2003, the CIPE (Inter-ministerial committee for economic programming) approved it and in 2004 the company Stretto di Messina held an international competition for the design and construction of the bridge, which was won in 2005 by the EUROLINK consortium. The contract was signed in March

2006. Political motives halted the progress of the project again until the Spring of 2009, when the EUROLINK consortium was given the go-ahead to start the works. The final design was finally submitted in April 2011.

On 29th July 2011, the Board of Directors of Stretto di Messina approved the Final Design for the bridge over the Strait of Messina and for the approximately 70 kilometres of road and rail connections ashore. The total forecast investment was updated to €8.5 billion.

Rocksoil's work on the final design for the project included all the geological and hydrogeological studies, the design of the excavations for the construction of the foundations and anchor blocks for the bridge and also the design of all the underground works consisting of about 50 km of tunnels. The pages that follow describe the design for the railway and motorway tunnels.

Figure 1. The Main Works

2 General description of the works

2.1 The tunnels for the road connections

2.1.1 Road connections in Calabria

The configuration of the access (Messina direction) and exit (north and Reggio Calabria direction) routes for the bridge (see Table 1) involve various motorway connections and almost 4 km of tunnels (named Ramp A, Ramp B, Ramp C and Ramp D).

Table 1. Scheme of roads connections in Calabria

Road connections in Calabria	km	9.9
In tunnels	%	41
On the surface	%	53
On viaducts	%	16

2.1.2 Road connections in Sicily

The road works that form part of the infrastructures for the construction of the bridge run through Sicily for a considerable length (see Table 2) and pass through three tunnels (Faro Superiore, Balena and Le Fosse) with different geological and geomorphological conditions.

Table 2. Scheme of roads connections in Sicily

Road connections in Sicily	***km***	***10.4***
In tunnels	%	71
On the surface	%	23
On viaducts	%	6

2.2 The tunnels for the railway connections

2.2.1 Rail connections in Calabria

The existing railway interested by the project on the Calabrian side is a section of the Tirrenica Rosarno-Reggio Calabria line.

The new infrastructural configuration requires the insertion of a connection to the bridge from the end section of the High Capacity Line. The connection of the railway from the bridge to the High Capacity Railway Line will also requires ramps in the direction of both Salerno and Reggio Calabria.

Details of the connection works are summarised in Table 3.

The alignment of the railway route runs almost entirely underground through four tunnels named: Ramp 1, Ramp 2, Ramp 5 and Ramp 6.

Table 3. Scheme of rail connections in Calabria

Rail connections in Calabria	**km**	**2.7**
In tunnels	%	84
On the surface	%	14
On viaducts	%	2

2.2.2 Rail connections in Sicily

The alignment starts from the axis of the piers of the bridge on the Sicilian side, corresponding to design chainage km 0+000. The connection runs mainly underground (see Table 4) running through two twin-bore tunnels (Santa Agata and Santa Cecilia). These tunnels have an inner radius of 4.40 m. and a total length of approximately 15.500 m.

Table 4. Scheme of rail connections in Sicily

Rail connections in Sicily	***km***	***17.5***
In tunnels	%	93
On the surface	%	5
On viaducts	%	2

3 The design of the underground works

The design of the tunnels was performed according to the ADECO-RS method, a well-known and established approach to the design and construction of tunnels developed by Rocksoil S.p.A. of Milanunder guide of *Prof.* Pietro Lunardi starting at the end of the 1970s.

The main feature of the ADECO-RS approach (an acronym for the Analysis of Controlled Deformation in Rocks and Soils) is that the design engineer focuses his attention, in the construction of an underground work, on assessing the deformation response of the medium (the ground) to the action of excavation. All three components of this response (extrusion, preconvergence and convergence) are predicted and analysed beforehand and then controlled by means of appropriate stabilisation methods.

The innovative features of the ADECO-RS approach are that excavation can be performed in any type of ground and under any stress-strain conditions. It is always full face and the control of the deformation response is performed ahead of the face with preconfinement action and not just downstream from it with simple not very effective confinement action, as occurs in the case of partial excavation.

More specifically, preconfinement action is exerted by using the core of ground ahead of the face (reinforced, when necessary, with adequate stabilisation action) as a structural element to stabilise the tunnel when excavation is carried out and the tunnel is lined.

When the ADECO-RS approach is used, the design of underground works is carried out completely before excavation commences. The design comprises the prediction of risks and variations (even in terms of stress-strain) which might be encountered during the construction stage with respect to the design predictions, for which it provides the necessary counter measures. It is possible to industrialise tunnel excavation in this manner and to construct with quality certification and to budget and on schedule.

The design stage according to the ADECO-RS approach proceeds and is completed as follows:

- a survey phase;
- a diagnosis phase;
- a therapy phase.

The design stage is followed by the construction stage, which consists of the following.

- an operational phase for the construction of the tunnel;
- a phase to monitor the work and fine tune the design.

During the last stage, the deformation response of the rock mass during tunnel advance is measured (measurement of extrusion at the core-face and convergence measured from the surface and in the cavity), interpreted and monitored and stabilisation operations are balanced as a consequence between the face and the perimeter of the excavation, in accordance with the design and the possible variation of the interventions, as specified in the design.

3.1 Survey phase

The survey phase using the ADECO-RS approach is the phase in which the existing natural equilibriums are analysed and the geology and geomechanics of the medium to be excavated are fully characterised.

3.1.1 Geology of the Strait of Messina area

The geology of the Strait of Messina area was defined as a result of studies and surveys carried out as part of the Final Design and by reading the relative literature. The latter in particular has seen, since 2003, the publication of both papers and geological maps as well as the production of considerable data already made available as part of the Preliminary Design.

The Strait of Messina is located at the southern end of the *Arco Calabro-Peloritano*, characterised by the *Unità Kabilo-Calabridi* termed *Calabridi* for short, which are a segment of the *Orogene Appenninico-Maghrebide*.

The *calabro-peloritano* structure is composed of a stack of thrust faults, characterised by a crystalline basement with an inversion of the metamorphic grade (i.e. increasing towards the surface) from semi-metamorphic grades to high grade units. Only the structurally most elevated fault outcrops, which is the *Unità dell'Aspromonte*, consisting of high grade metamorphic rocks. This unit forms the substrate on which the overlying Miocene and plio-quaternary strata rest. It outcrops along the *peloritana* ridge and in the northern tip of Calabria, where it also includes plutonites with a grainy-diorite composition. The prevailing opinion in the literature is that the faults in the area of the Strait are of a distensive nature. The structural picture for the Strait is the result of a period of collision between the continental crust and the edge of the African plate. This collisional period only occurred in the central western part of the Island, while to the east of the Milazzo area, the continental crust came up against the Ionic oceanic crust which was still in subduction.

On the Calabrian side various formations are foundrelated to a cenozoic-quaternary sedimentary succession, overlying a paleozoic crystalline-metamorphic substrate.

The area on the Sicilian side of the bridge includes the eastern portion of the Monti Peloritani ridge and the Ganzirri peninsula. The *Calabridi* outcrop in the *Monti Peloritani* and represent the Sicilian segment of the *Orogene Appenninico-Maghrebide* but, however, only the structurally highest layer, which is the *Unità dell'Aspromonte*, consisting of gneiss and mica schist rocks with pegmatitic-aplitic strata. This unit forms the substrate, on which the overlying Miocene and plio-quaternary strata rest. The smaller edges lie within the city of Messina. However, the *Sabbie e Ghiaie di Messina*, marine terraced Pleistocene deposits and holocene beach deposits dominate in the Ganzirri peninsula.

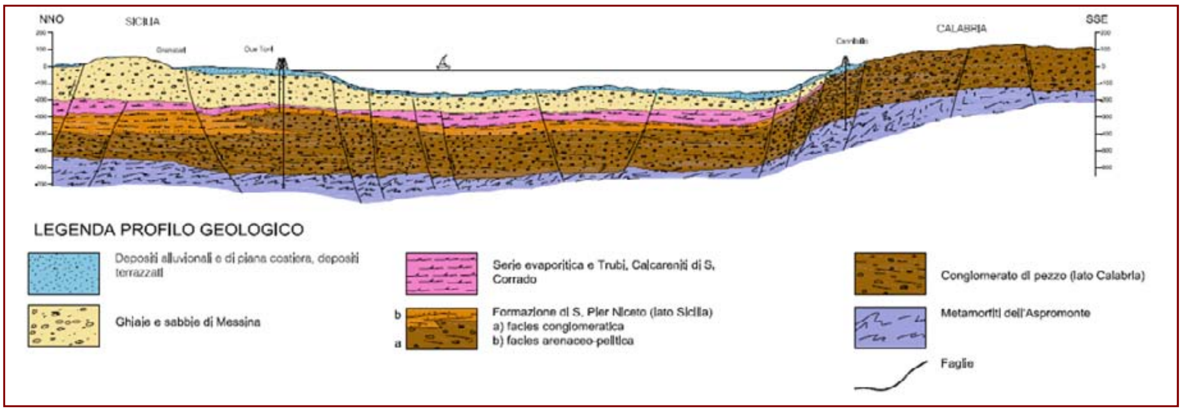

Figure 2. Geological profile at the site of the bridge

3.1.2 Geotechnical characterisation

An in-depth and extensive survey campaign was carried out for the Final Design to characterise the geotechnics of the geological formations involved in the works. In order to reconstruct the geological and geotechnical profiles for the bridge and along the road and rail alignments of the most significant sections, use was also made of the abundant data available from previous surveys carried out since 1984 in a number of stages. It was used and interpreted on the basis of the surveys carried out in the current design stage and for the different geographical position of the infrastructures.

Table 5. Scheme of foreseen investigations

Core drilling and in situ tests		Calabria	Sicily	Bridge	Total
Core drillings	number	39	87	50	176
Total length	ml	2318	4787	3660	10765
Cross-hole	number	240	280	1780	2060
Down-hole	number	358	359	-	717
SPT	number	302	1195	200	1697
LPT	ml	-	-	760	760
Pressure meter and dilatometer	number	45	58	20	123
Permeability	number	81	141	10	232
Piezometer holes	number	18	46	10	74
Inclinometer holes	number	3	11	-	14
Frozen samples	number	-	-	70	70

In accordance with the design specifications, three distinct types of material were identified from the viewpoint of the geotechnical characterisation criteria:
- more or less cemented course grain materials (more or less silty sands and gravels);
- fine grain materials(more or less sandy-gravelly silts and clays);
- rocks (sandstones, siltites, marly, limestones, limey marls, marls and argillites).

The distribution along the alignments of the different formations is as follows:

Table 6. Calabria – Geological formationsalong the alignments

Conglomerato di Pezzo	59%
Plutonites	31%
Sands and Gravels of Messina	6%
Terraced marine deposits	3%
Coastal beach deposits	<1%
Trubi	<1%
Slope deposits	<1%
Alluvial deposits	<1%
Calcareniti di S..Corrado	<1%
Le Masse Formation	<1%

Table 7. Sicily – Geological formations along the alignments

Messina Gravels	*(72% road, 44% rail)*
San Pier Niceto	*(16% road, 21% rail)*
Chalkey-sulphurous series	*(3% road, 13% rail)*
Alluvial and coastal deposits	*(8% road, 10% rail)*
Metamorphites	*(7% rail)*
Trubi	*(3% rail)*
Slope deposits	(<1%)
San Corrado and Arenazzolo Calcarenites	(<1%)

As it is clear, the prevalent formation on the Calabrian side is the *Conglomerato di Pezzo*, while that on the Sicilian side is clearly the Sands and Gravels of Messina, loose or weakly cemented materials.

3.2 Diagnosis phase

As performed according to the ADECO-RS approach [Lunardi, 2006], the diagnosis phase is that in which the deformation response of the medium to the action of excavation is analysed in the absence of stabilisation intervention. The underground alignment is then divided into uniform stress-strain behaviour categories on the basis of that analysis according to the stability conditions predicted at the face (core-face stable, stable in the short term or unstable).

No section of the tunnels designed was found belonging to the behaviour category A (stable face) in the diagnosis phase.

However, sections classified as belonging to behaviour category B (core-face stable in the short term) were as follows: approximately 15% of the alignments of the road tunnels on the Sicilian side, approximately 85% of the alignments of the tunnels on the Calabrian side, 100% of the alignments of the rail tunnels on the Calabrian side.

Finally, sections classified as belonging to behaviour category C (core-face unstable) were as follows: approximately 85% of the alignments of the road tunnels on the Sicilian side and approximately 15% of the alignments of the road tunnels on the Calabrian side.

3.3 Therapy phase

As performed according to the ADECO-RS approach, the therapy phase is that in which the control of the deformation response is designed through the selection of appropriate excavation and stabilisation methods.

3.3.1 Tunnels to be driven using conventional excavation

In consideration of the length of the alignments, the partially urban context and the excavation in non-homogeneous grounds, full-face conventional excavation was chosen for all the road tunnels and for the rail tunnels on the Calabrian side.

More specifically, sections of excavation which involve the more or less intense reinforcement of the core-face with fibre-glass structural elements were chosen for the sections of tunnel classified in behaviour category B (core-face stable in the short term). Figure 4 gives an example of tunnel section type B2.

On the other hand, sections of excavation were designed for stretches belonging to behaviour category C, which involved intervention to protect and reinforce the core-face with fibre glass structural elements cemented and injected both into the face and around it. The protective intervention for sections in loose materials was performed by means of sub horizontal jet-grouting as illustrated in Fig. 5 (tunnel section type C1A).
A special technique of sub-horizontal jet grouting injections with drilling and simultaneous injection ahead of the face was chosen to get an effective control of volume loss for those stretches of tunnel affecting buildings on the Sicilian side, where it appeared very important to control deformation. In this case reinforcement of the core-face was performed using a micro-jet technique with fibre glass tube reinforcement. As an alternative, micro-jet was used in advance with the simultaneous insertion of fibre glass tubes. This obtained.

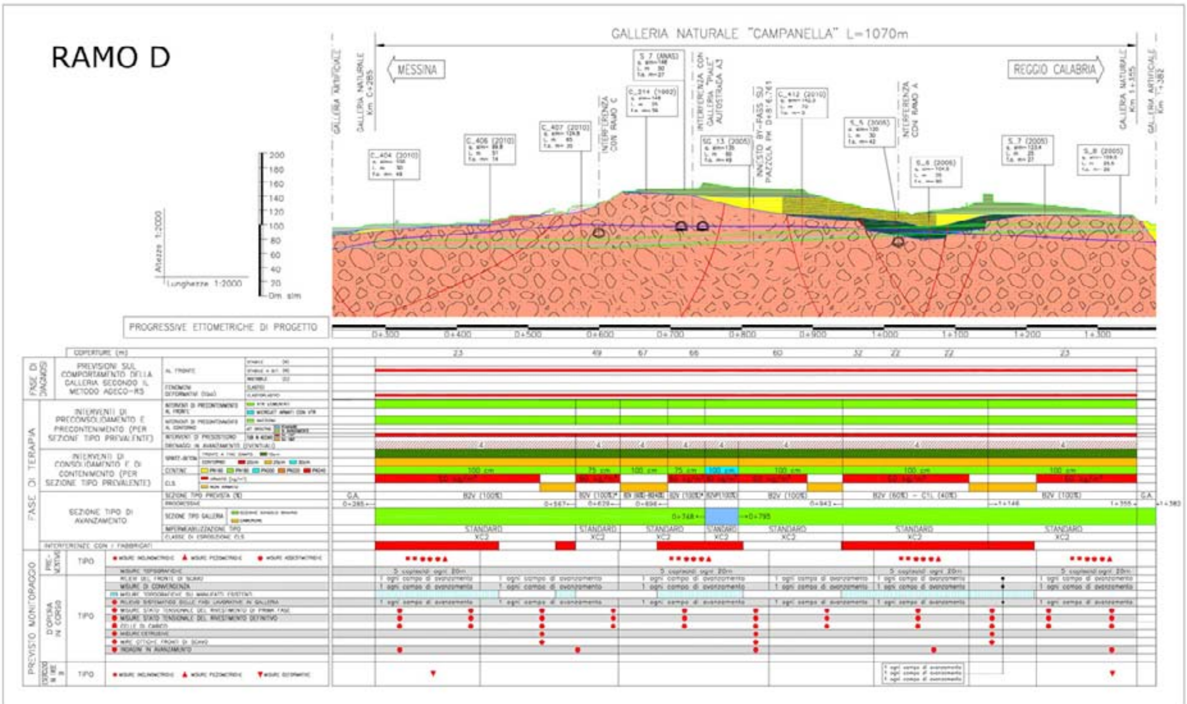

Figure 3. Example of the geomechanical profile

3.3.2 Mechanised excavation for the rail tunnels on the Sicilian side

In consideration of the length of the alignments, the urban context and excavation under the water table in prevalently loose ground, it was decided to use TBM tunnel advance for the rail tunnels on the Sicilian side.

The ground to be excavated for the S. Agata and S. Cecilia tunnels is extremely varied, because the alignment passes through different formations, each with totally different strength characteristics.

This non-homogeneity of the geological-geomechanical conditions, together with the widespread presence of surface interferences, made it difficult to select the type of machine to use for excavation.

In the end, since it was necessary to advance through both loose soils and rock and semi-rock masses and at the same time to always ensure continuous control over the core-face to prevent decompression with possible subsidence or worse, material falling into the tunnel. As a consequence, only two types of TBM technology were considered: EPB and hydroshield.

On an initial analysis, based solely on assessment of the granulometries present, it was decided to use EPB technology as most appropriate, although it requires preliminary ground improvement for it to be used successfully in all the grounds present along the alignment.

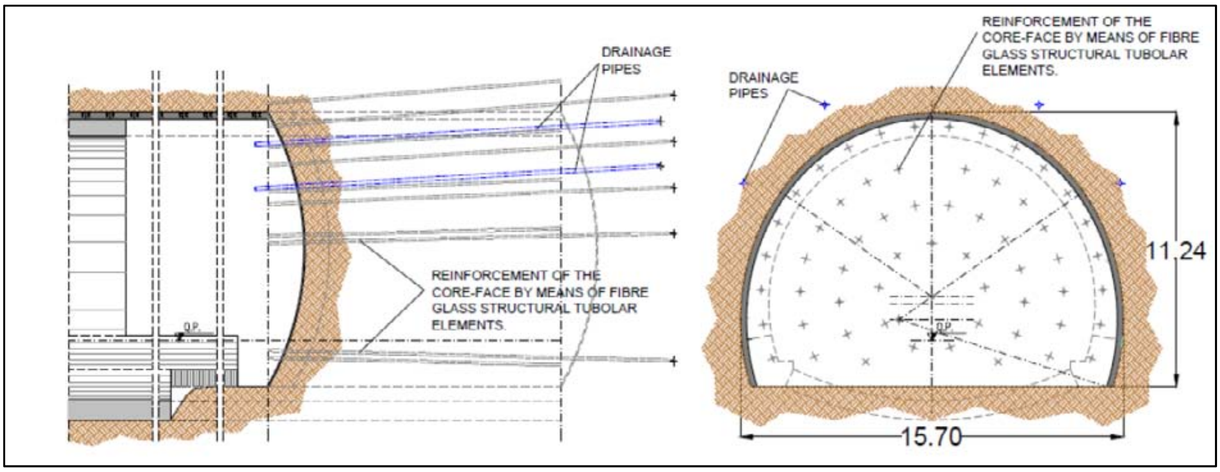

Figure 4. Tunnel section type B2 on the Sicilian side

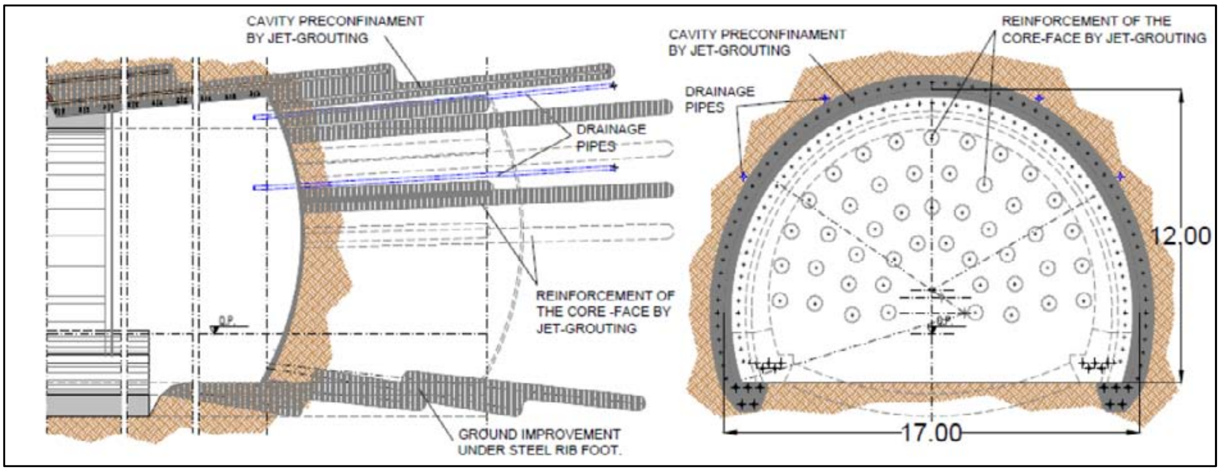

Figure 5. Tunnel section type C1A on the Sicilian side

3.4 Design of the variability

To be able to manage the project during construction with respect to time and cost control, ADECO – RS defines a possible variation of the different grouting and support interventions to be used during excavation. This variation refers to grouting measures (number and length of interventions, i.e. jet grouting columns or fibre glass elements); prelining (inter axis of the steel ribs) and distance of casting of the final lining from the face of excavation. This variation is governed according to the geotechnical conditions detected by the monitoring measures taken during tunnel advance. It is always possible to adapt the sections of excavation to the real necessities, avoiding any not useful intervention or cost. This way to proceed, at the end of the works, always guarantees a perfect control of time and cost of constructions.

4 Conclusion

Talking about the construction of a fixed link over the Strait of Messina, you immediately think of the bridge, which is the most visible and difficult work to design and build. The overall design of the fixed link, however, comprehends several additional works not less important, including 30 km of highway and railway tunnels. This paper has described the final design of them.

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