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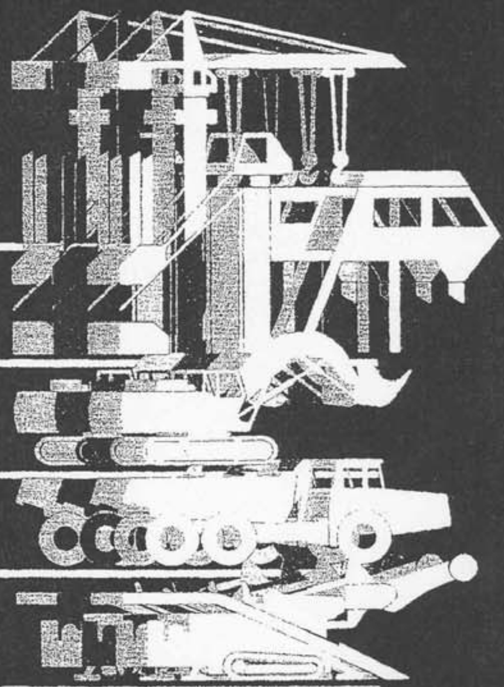

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Modern Tunnelling in Italy for High Speed Railway Line

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1. General Background

The Florence to Castello section of the new route completes the Bologna-Florence line and connects with the works scheduled for the Florence junction. The final detailed design specifications for the Conferenza dei Servizi (Local Autorities Conference) and the Atto Integrativo (Additional Contract) to the agreement between TAV S.p.A. and the General contractor FIAT S.p.a. took account of the experience acquired on other construction projects for the Italian High Speed Network. These final design specifications are finely detailed in all parts and were drawn working closely with all parties concerned in order to obtain rapid approval.

From a design viewpoint these underground works follow the same lines as those already under construction and are based on experience already acquired. However some new innovative elements have been introduced, particularly on the Via Gramsci Underpass and the Service tunnel, driven with a full face continuous TBM.

2. Geological and Geotechnical conditions

From chainage km 71 +500 (from the North) the tunnels on the Castello section of the line run through the Monte Morello and the Sillano Formations and the alluvial deposits of the Florence basin. The geological characterisation was performed on the basis of experience acquired during construction of the Vaglia Tunnel from the Carlone access tunnel in the direction of Florence which also runs through the Monte Morello Formation and on the basis of surveys aimed at ascertaining the lithology and stratigraphy of the formation and the main contacts with the Sillano Formation and with the sediments of the Florence Basin (Fig.1).

From a Geological viewpoint, the ground belonging to the Monte Morello and Sillano Formations consists of marine turbidity deposits belonging to the exterior Ligure domain and more specifically to the Supergruppo of the Calvana. This ground consists of medium fine, terrigenous, marine sediments The "Deposits of the Florence Basin" consist of recent fluvial-lacustrian deposits that make up the broad Florence Basin.

On a regional scale the Monte Morello Formation is characterised by a squashed syncline with its upperside on its side running from NNE to SSW. The core of the structure consists of marly-argillite facies that alternate with banks of marly limestone.

The succession of sedimentary strata can be summed up as follows:

- **The Sillano Formation (SSi)** consists of multicoloured argillites with irregular interbedding of quartzy-limy sandstones and calcarenites in fine strata, of marls and marly limestones, light grey in colour. The presence of micro fossils in the limestone and marl levels dates the formation between the lower part of the Upper Cretaceous and the Palaeocene periods. The argilites are prevalent in the more common facies. The configuration of the formation can not always be

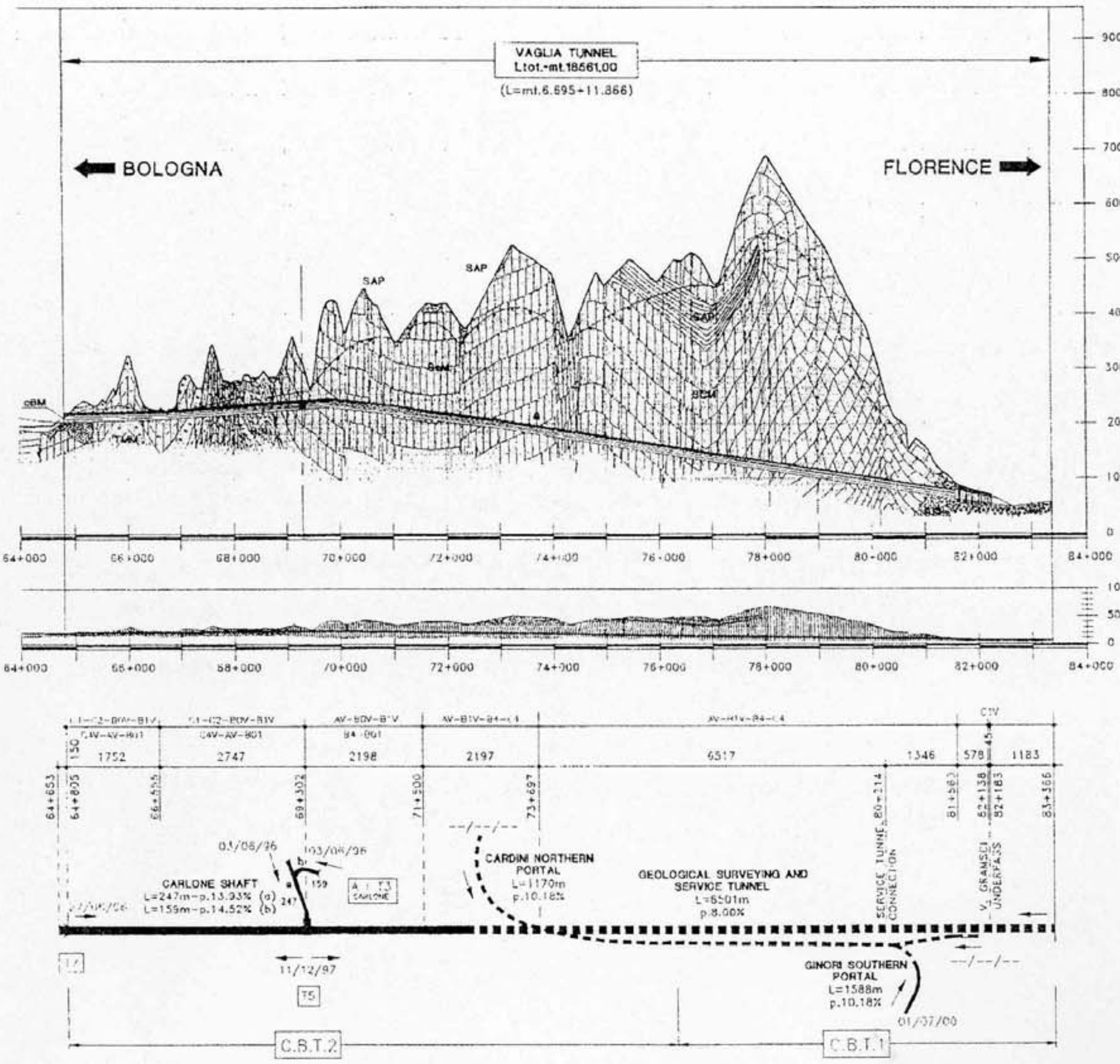

Figure 1 – Vaglia Tunnel: geological profile

identified because it is very disturbed tectonically and is consequently very similar to the Complesso Caotico. Other quite common facies contain greater quantities of sandstones, with densely alternating strata of grey argillites with or without interbedded marly limestones and marls. The Sillano Formation may also contain, in the roof, large lentils of quartzy-limy sandstones resulting from marine turbidity and of argillites that make up the Pietforte Formation.

- **The Monte Morello Formation (ScM)** (alternatively "Alberese Formation"), of turbidity deposits, consists mainly of marly limestones and limy marls, whitish or yellowish in colour, in large banks occasionally with thin levels of calcarenites. These are separated by zones of densely alternating brown grey limy sandstones and argillites. The maximum thickness of this sequence is approximately 700-800 m. The presence of micro fauna (foraminifers) and of nannoplankton dates the formation at between the Palaeocene and middle and lower Eocene periods. Ground belonging to the Pescina (SAP) Formation, of the middle to lower Eocene period, very similar to the Sillano Formation is found only in the Monte Morello zone in the roof of the formation. The lithological contents of the "Alberese", in accord with what was already known from the literature and from previous surveys, are as follows (Fig. 2):

- limestones and limy sandstones
- marly limestones
- marls
- argillites.

The variation in the percentage of the clay component results in a transition through the terms described from limestones to marly limestones to marls and from marls to clayey marls and finally to argillites. In percentage terms the intermediate lithotypes (marls and marly limestones) are clearly more predominant while the purer components are less frequent.

From a geomechancal viewpoint, the results of laboratory and in situ tests show four distinct groups:

- group 1, consisting mainly of limestones, with the presence also of limy sandstones, marly limestones and marls in strata or banks of several metres to around one metre in thickness;
- group 2, consisting of dense alternations of marly limestones, marls and argillites with the percentage of marls higher than in the previous facies;
- group 3A consisting of limestones, marly limestones, and marls with a high percentage of cataclastites and fractured limestones;
- group 3B, consisting mainly of marls and argillites in strata or banks of from several metres to around one metre in thickness.

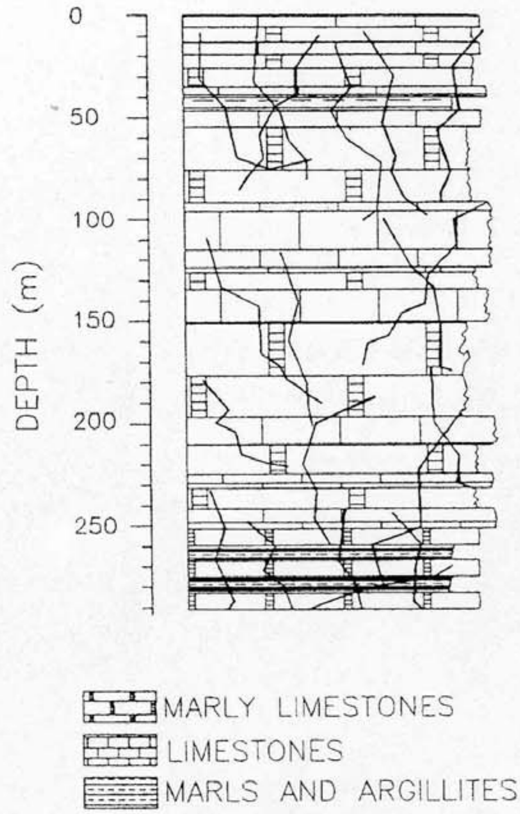

Figure 2 – Sratigraphic column

The geomechanical properties are given in table 1.

Monte Morello Formation ScM	γ kN/m³	c_{picco} MPa	$c_{res.}$ MPa	ϕ_{picco} °	$\phi_{res.}$ °	E GPa	ν	Group
Mainly limestones/ limy sandstones	25	1.0-1.4	0.6-0.9	42-45	38-40	7.0-15.0	0,2	1
Marly limestones/ Marls	25	0.4-0.7	0.25-0.40	38-41	35-38	4.0-9.0	0,2	2
Marly limestones/ Marls (Fractured)	24	0.24-0.3	0.15-0.20	33-37	30-34	3.0-6.0	0,25	3A
Marls and Argillites	24	0.15-0.2	0.10-0.12	27-31	24-27	2.0-8.0	0,25	3B

Tabella 1: Geomechanical Characteristics of the Monte Morello Formation

- **The Florence Basin (BF - Bacino di Firenze)** consists of recent fluvial-lacustrian deposits of the late Pliocene period that formed by the filling of a tectonically created depression caused by stretching of the earth's crust that occurred in the area of Tuscany. They consist of silty sandstones and sandy silts with a varying clay content and the presence of lithic elements varying in size from a few millimetres to some centimetres and varying in shape from almost sharp and angled to almost round.

2.1 Hydrogeolgy

Existing information would seem to confirm the presence of a sloping water table, where the hydrodynamic model has been well identified in order to know the effects on surface of the dewatering operated by the tunnel. Water flow is by secondary permeability, through the fractures in the rock and the direction and quantity of flow is presumably regulated by aquiclude (thick strata of compact limestones, packs of impermeable argillites) and saturated levels (fractured zones of tectonic origin, belts of cataclastites).

More intense water flow may occur through micro-Karstic zones (caused by the limestone dissolving along the fractures) or by genuine underground Karst systems, the presence of which is not to be excluded.

The circulation of underground water is closely connected with the lithology, stratigraphy and the structure of the sedimentary units described above.

The permeability of the rock masses was investigated by in situ Lugeon tests and water rise in piezometer tubes. The result allowed average permeability along the route of the tunnel to be estimated as follows:

- for the Monte Morello Formation consisting mainly of alternating limestones, marly limestones and marls and some argillites permeability was estimated at between 10^{-7} and 10^{-8} m/sec.;
- for the Sillano Formation, consisting mainly of argillites, permeability was estimated at 10^{-8} m/sec.;
- for the Florence Basin deposits on the end section of the route average permeability was estimated at 10^{-6} m/sec..

3. The rail underground tunnel

3.1 Cavity stress-strain behaviour forecasts

The geological and geomechanical characterisation of the ground along the route was used to make forecasts of the stress-strain behaviour of the tunnel resulting from the effects of the stress

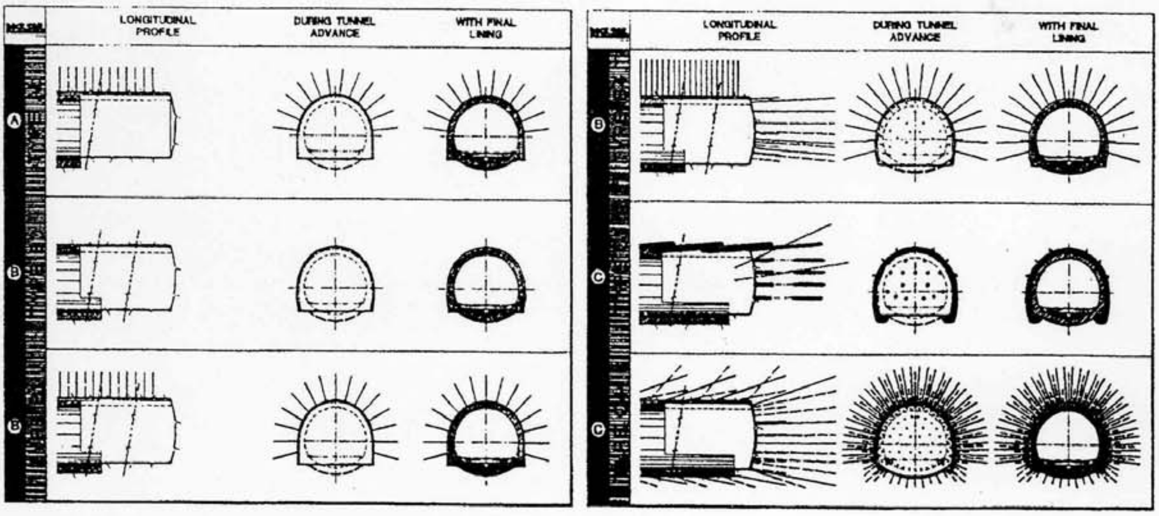

Figure 3 – Tunnel section type

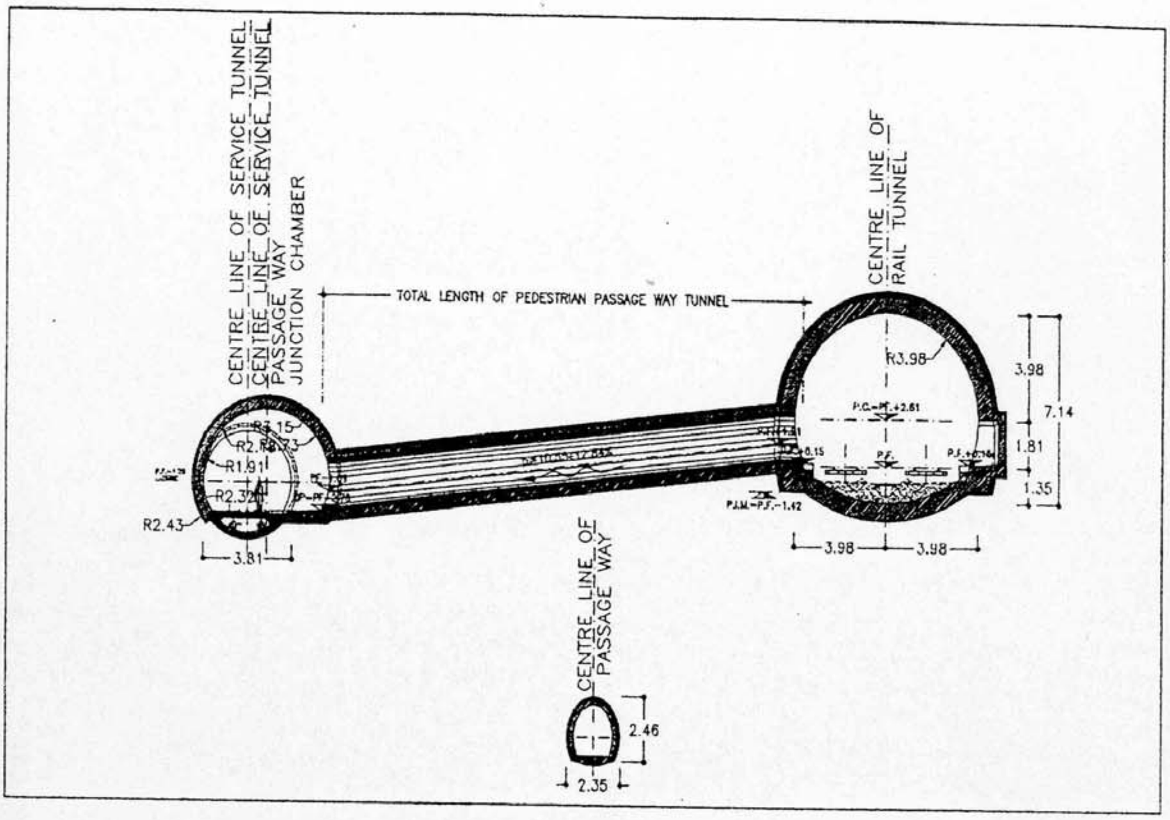

Figure 4 – Tunnel section types at passage way tunnels

states induced around the cavity and of the hydrostatic heads present during excavation. The forecasts were made using the ADECO-RS approach which was employed for all tunnel design on the Florence to Bologna section. Mathematical analysis showed that the tunnel stress-strain behaviour through the Monte Morello section would be conditioned by the lithological and mechanical characteristics of the rock mass. Table 1 gives the geomechanical characteristics classified in groups. The sections of tunnel belonging to group 1 can be mainly assigned to stress-strain behaviour category A, while for those falling within groups 2 and 3A the behaviour is between A and B depending on the size of the overburden and behaviour category C is predicted for ground in group 3B. The stress-strain behaviour category forecast in the Sillano Formation is mainly B with some C in the more tectonised parts. Information acquired during construction of the Vaglia tunnel between chainage km 68+100 and 68+900 was also used to make the forecast. The passage through the ground of the Florence Basin will require careful monitoring of the deformation response to tunnel advance due to the poor quality of the ground and the intense urbanisation of the area.

3.2 Proposed advance methods

The prediction made for the northern section already driven through the Monte Morello formation were again confirmed here, while the types of tunnel section selected for the Sillano stretch take account of experience acquired while tunnelling through the same formation just a few kilometres to the North (Fig. 3). The same innovative elements introduced to the design in the section up to chainage km 71+500 were again employed on this section. Precise expected deformation ranges were associated with each tunnel section type and criteria were specified for making variations to stabilisation operations and for changing from one to another of the specified section types. The design also involved water proofing and drainage of the tunnel with the aim of reducing the permeability of the of the rock as much as possible. The objective was to achieve controlled drainage around the tunnel in order to reduce water pressure to admissible values for the linings.

4. The service tunnel

4.1 Geometry

The "Ginori" geological survey and service tunnel is 9,259 km in length and runs parallel to the "Vaglia" rail tunnel for 6,501 metres to which it is connected by small foot tunnels[1] every 250 m. (Fig. 4). The first section of 1,170 m. from Cava Ginori and the final section of 1,170 m. run down and up respectively with a gradient of 10.18%.

The service tunnel has an internal diameter of 5.6 m.. The purpose of this tunnel, both during construction and when it is in service, the construction criteria and its size definitely make it the most interesting part of the new Florence-Castello line.

The environmental constraint of driving the tunnel from one single portal (the Ginori portal), the need to construct it while controlling interference from underground water as much as possible and finally to keep construction times within acceptable limits led to the choice of a completely mechanised construction method.

4.2 Tunnel advance by TBM

The ground through which the "Ginori" tunnel passes all lies within the Monte Morello Formation, certainly a complex formation. The mechanical characteristics vary greatly, ranging from argillites to compact limestones. Consequently the designer of the TBM received considerable input from the tunnel consulting engineer. The result was an innovative machine fitted with advanced geological surveying systems and capable of adjusting the method of advance according to the different geomechanical conditions it encounters and, where necessary, of performing advance reinforcement both in the core and around it (Fig. 5). The ways in which it acquires cutter operating parameters and the criteria it employs to change the type of tunnel advance and to prepare the ground in ahead are explained in a document appended to the design specifications entitled "Guide Lines for performing surveys in advance, for selecting the appropriate operating methods and performing ground reinforcement operations". This document defines, right at the design stage, the criteria that the TBM operator and/or design engineer must adopt to:

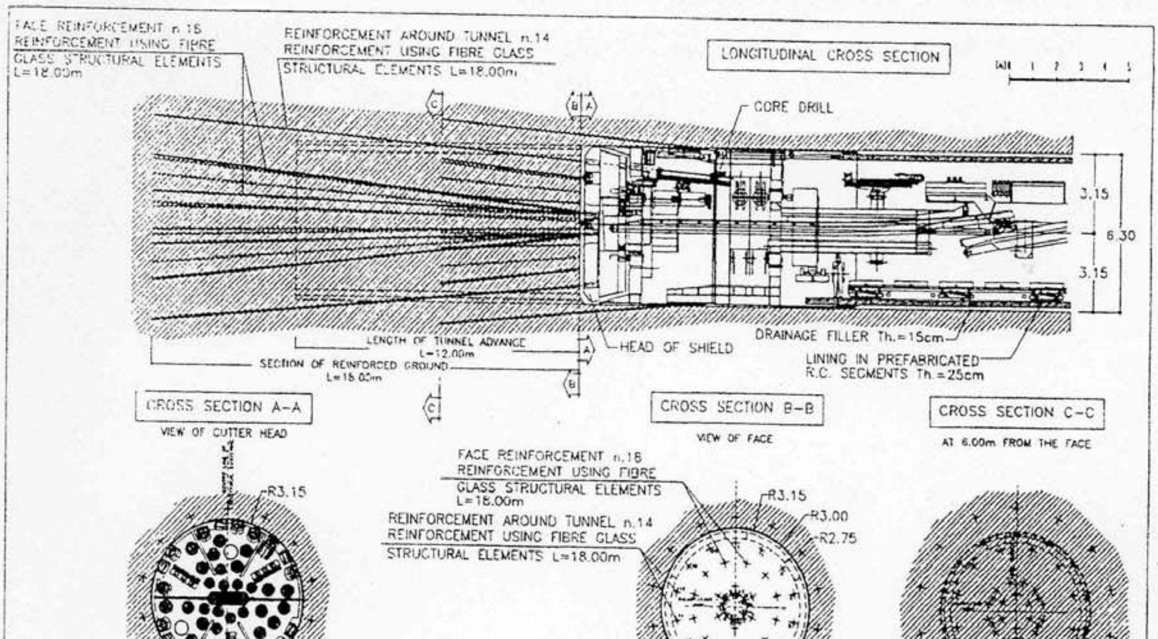

Figure 5 – Reinforcement operations performed by the TBM

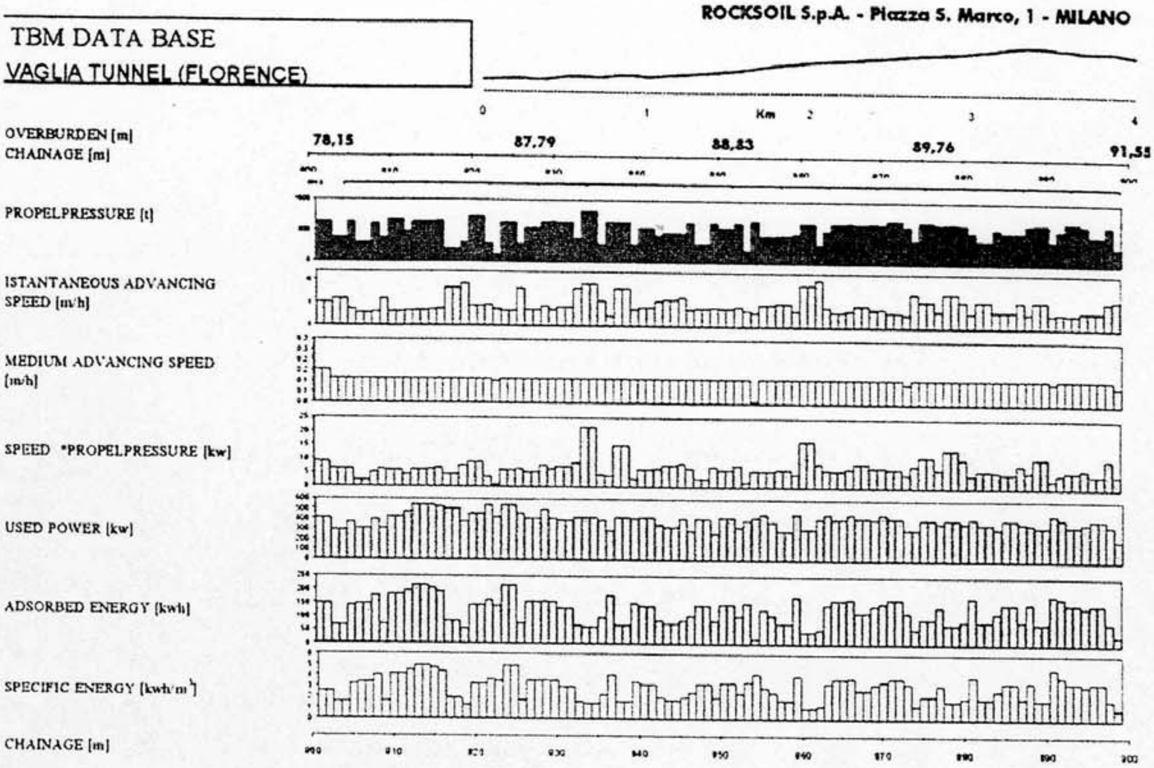

Figure 6 – TBM advance parameters

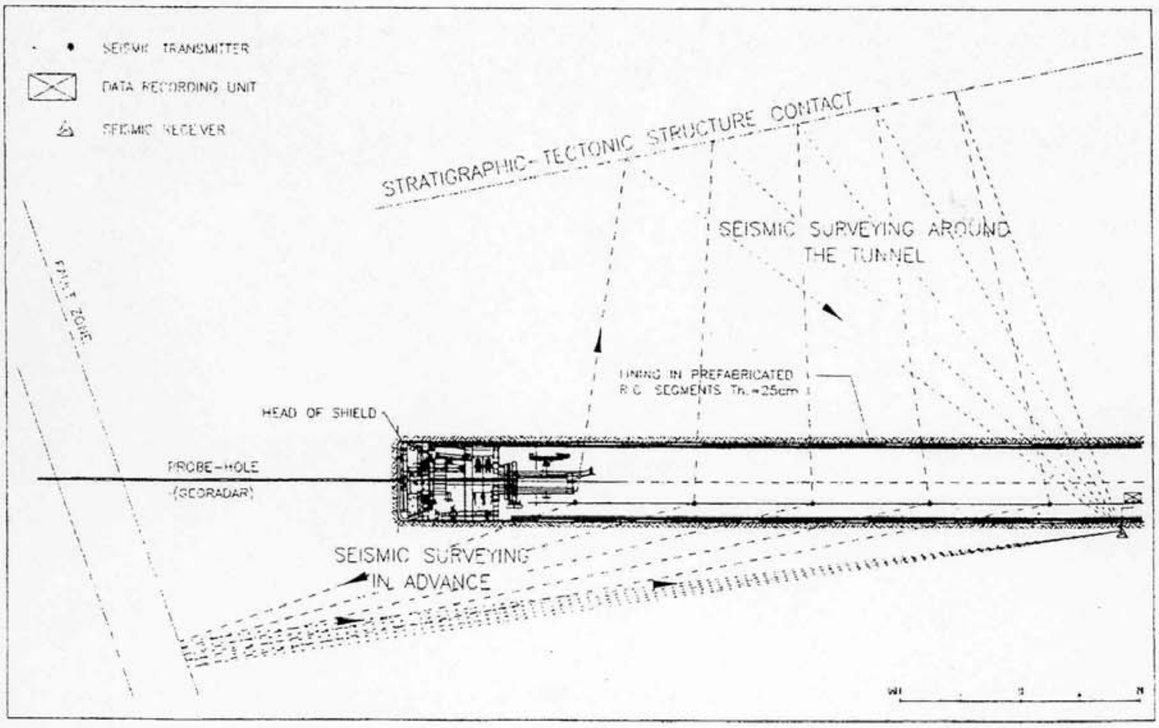

Figure 7 – Geological survey operations performed by the TBM

- confirm the current operating method;
- perform extra surveys to obtain a better understanding of the nature of the rock ahead of the face;
- change the operating method when different ground conditions are encountered;
- perform ground reinforcement operations that the machine is designed to do in the face and around the tunnel.

The "Guide Lines" therefore give the main parameters to be followed, with descriptions and quantities, and these are recorded during operations. The parameters are as follows:

- the TBM advance parameters that allow continuous and systematic monitoring of ground characteristics and its response to excavation (Fig. 6);
- the geological and geomechanical parameters acquired from systematic seismic surveying performed in advance. This information may be added to by georadar tests in probe holes drilled into the face (Fig. 7).

These parameters are associated with value ranges for normal functioning of the TBM. If the values actually measured differ substantially from those forecast as a result of particular local geomechanical conditions (tectonised zones, sudden lithological and structural changes, etc.), the TBM operator and/or the design engineer must take appropriate corrective or additional action as specified in the "Guide Lines". Specified action may include operational changes (e.g. overboring of the cutter head), locking of the telescope mechanism, activating the tail pistons, etc.) extra surveys (e.g. core drilling) or ground reinforcement design operations. If the conditions encountered do not correspond to any of those specified in the design, then other solutions must be considered (Fig. 8).

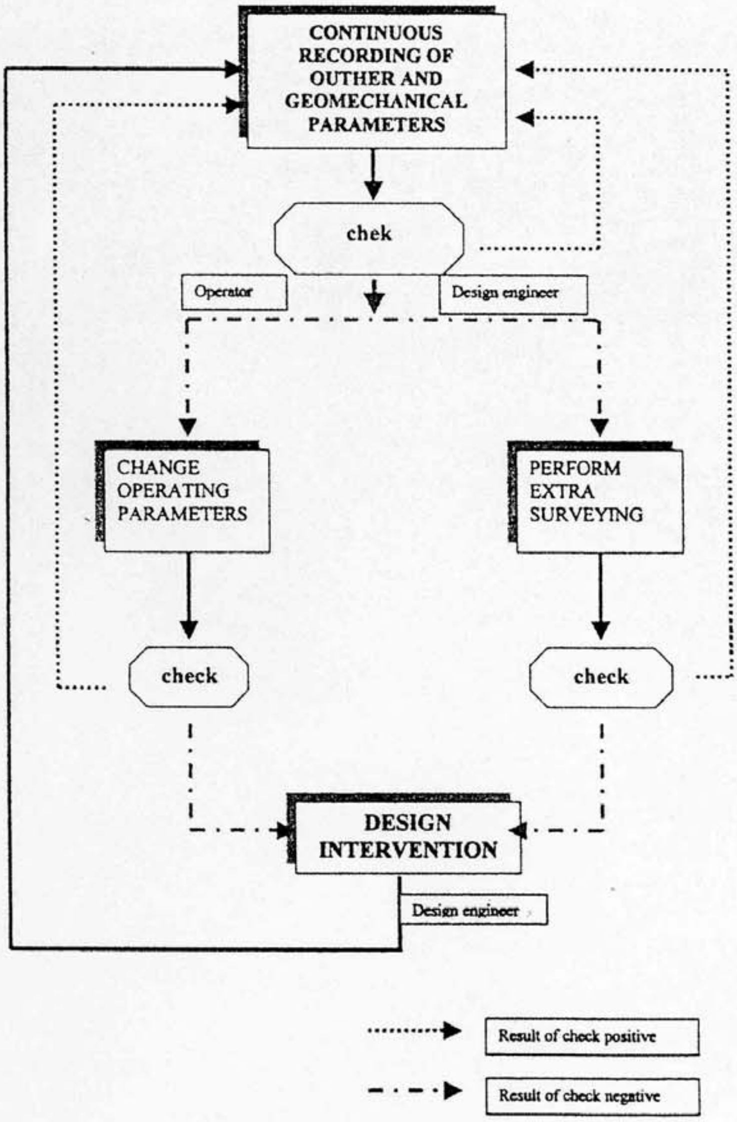

Figure 8 – TBM Guide Line

4.3 Tunnel lining

The lining of the Ginori tunnel is in prefabricated rc segments, 25 cm. thick. The ring consists of five segments plus a key segment. They are trapezoid in shape so they can be positioned in n different positions and thereby fit the theoretical profile of the tunnel better. The segments are only connected longitudinally. Transversally they just but together side by side. The floor for the road is made of specially designed prefabricated segments (Fig. 9).

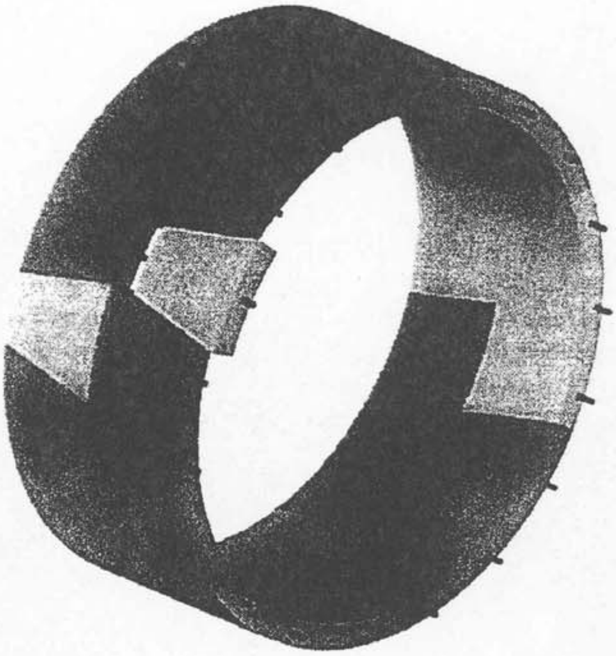

Figure 9 – Service tunnel: segment geometry