INTRODUCTION

The Telleda Tunnel is located in Sant Celoni (Barcelona) and is part of the Sant Celoni - Riells sub-section of the new high-speed railway line between Barcelona and the French border; designed so that passenger trains can travel at up to 300 km/h.

This tunnel has a length of 209 m, but its uniqueness lies in its scant cover over the vault, which is at most 28 m above the tunnel axis, and the steep transversal gradient of the land.

The combination of these two circumstances converted the selection of the method for construction of this tunnel into a very delicate matter. If an open cut was considered, then the height of one of the side slopes would easily surpass 60 m, with the consequent problems of stability as the excavation would be in soft ground of the Miocene Period, and with an important occupation on the exterior surface which has a high landscape value.

On the other hand, underground construction of this tunnel posed serious problems due to the severe stress dissymmetry of the ground to be excavated and the substantial excavation cross-section, since the tunnel was to have a free section of 87.2 m².

This paper presents the activities carried out to define the method for constructing the Telleda Tunnel and the construction thereof.

The Design and Control of the construction of the Sant Celoni to Riells sub-section was commissioned by the Administrador de Infraestructuras Ferroviarias (ADIF) to a Consortium formed by the engineering firms AYESA and GEOCONTROL; whilst the construction of this sub-section was awarded to the Consortium formed by COPCISA and AZVI.

DESIGN OF THE TELLEDA TUNNEL

The procedure followed for the Telleda Tunnel project was that of Active Structural Design (A.S.D.), which complements the deterministic method used in the definition of the typical cross-sections with the observational method during the construction of the tunnel.

This combination of different methods in the project and work control phase is highly convenient for minimizing the risk involved in the site characterization, especially in the case of tunnels built in soft rock.
The design in the planning phase is based on characterizing the ground with the greatest possible precision and in dimensioning the supports used in all the constructive phases by means of strain-stress calculations that allow convergence that can be measured in each phase of the construction to be defined accurately.

During the work, besides the geomechanical site characterization in each excavation pass to confirm the type of section to apply, if the convergence measured is substantially bigger than the calculated value for each Type Section, it is necessary to make new calculations to define the strengthening of the support.

The A.S.D procedure, as is illustrated in Figure 1, includes the phases of GROUND CHARACTERIZATION, CALCULATION OF THE TYPE SECTIONS and CONFIRMATION DURING CONSTRUCTION, in such a way that construction risks can be effectively minimized.

The most representative characteristics in the Telleda Tunnel project are explained in the following paragraphs.

Figure 1. Chart flow for applying the Active Structural Design (A.S.D).
2.1 Geomechanical site characterization

The Sant Celoni to Riells sub-section was to be built in a terrain of the Miocene Period constituted by a compact granular matrix, integrated by levels of clays, silts and sands which include gravels and granitic boulders.

The effective geomechanical characterization of this kind of terrain is a very delicate task since, on one hand, the granular matrix is quickly degraded by the action of the water which is habitually used in the boring surveys and, on the other, the presence of gravels and boulders makes it practically impossible to obtain representative samples of the terrain for testing in the laboratory by conventional procedures.

For this reason, in this case, it was considered that the most appropriate methods for characterizing this type of material were "in situ" tests, particularly the pressuremeter tests.

Also, back analyses of the stability of various natural slopes existing in the area where the Telleda Tunnel was to be built proved highly useful.

As a result of the survey work carried out, the geological profile of the tunnel was established, which is shown in Figure 2. In it, the typical materials that appear are basically clays, silts, sands and gravels with little cohesion.

In Table 1 are shown the mechanical characteristics that are considered representative of the stress-strain behavior of these terrains.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific weight (MN/m³)</th>
<th>Qu (MPa)</th>
<th>E (MPa)</th>
<th>ν</th>
<th>C (MPa)</th>
<th>Φ  (º)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays and silts</td>
<td>21.8</td>
<td>0.49</td>
<td>213.9</td>
<td>0.35</td>
<td>0.07</td>
<td>23</td>
</tr>
<tr>
<td>Clays and silts</td>
<td>21.6</td>
<td>0.27</td>
<td>268.5</td>
<td>0.30</td>
<td>0.06</td>
<td>34</td>
</tr>
<tr>
<td>Gravels</td>
<td>21.4</td>
<td>0.09</td>
<td>220.9</td>
<td>0.30</td>
<td>0.02</td>
<td>40</td>
</tr>
</tbody>
</table>

The terrain has practically the characteristics of compact soils; although its cohesion and, above all, its modulus of deformation determined by means of pressuremeter tests is quite high.

In accordance with the geological profile presented in Figure 2, it was foreseen that the upper half of the section of the Telleda Tunnel would be excavated in sandy and silty levels, while in the lower half of the section, the excavation would be carried out in clayey and silty layers.

Consequently with the mechanical characteristics determined for these materials, taking into account the overburden over the tunnel, the normal calculations revealed appreciable problems with instability in the heading if the construction of the tunnel was carried out by conventional underground methods.

Figure 2. Geological profile of the Telleda Tunnel.
2.2 Construction process

The election of the construction process for the Telleda Tunnel, in accordance with the foregoing, had to guarantee two specific objectives:

1. Minimize the open cut excavation.
2. Assure the face stability, if the excavation was to do in underground.

The open cut construction of this tunnel required provisional slopes to be dug, the height of which was nearly 60 m, which led to this construction procedure being discarded due to the high environmental impact involved.

Clearly the use of tunnel-boring machines was not feasible due to the short length of the tunnel and for this reason the possibility was explored of using underground construction methods that allowed good control of the stability of the heading. In short, the application of the Traditional Madrid Method was studied, the ADECO-RS method, carrying out the excavation in ADVANCE and BENCHING, under a protective umbrella of jet-grouting and the method of subdivision of the section into several galleries.

The Traditional Madrid Method was discarded being a method requiring much skill and the intensive employment of very specialized manpower difficult to find in the area where the Telleda Tunnel was to be built.

The ADECO-RS and ADVANCE and BENCHING methods, under the protection of a heavy umbrella, resolved the problem of face instability well, but the construction costs were very high.

Finally, the method of subdividing the section into several galleries was rejected because the severe stress dissymmetry existing in the terrain made it very problematic to guarantee the stability of the temporary partitions for separation between the galleries into which the section had to be divided.

Since the methods studied did not offer sufficient guarantee of a safe and cost-effective construction of this tunnel, a mixed cut and cover / underground solution was considered that was constituted by three main phases:

1. Open-cut excavation to the level of the tunnel vault.
2. Construction of the tunnel walls by means of individual pile walls and the vault of the tunnel, concreting against the excavated ground.
3. Excavation underground of the tunnel section, under the protection of the pile walls and the vault concreted "in situ".

With this solution, which is illustrated in Figure 3, it was possible to minimize the environmental impact of the tunnel construction and proceed with the underground excavation in total safety sheltered by the pile walls and the vault of reinforced concrete.

2.3 Dimensioning the slopes and the tunnel structure

For the proposed method to be competitive it was essential for the slopes of the open cut excavation to have the greatest possible dip and the structure of the tunnel, formed by the pile wall and the vault of reinforced concrete, could properly withstand the stress dissymmetry they were subjected to. In the following sections the most pertinent aspects are presented regarding the dimensioning of the lateral slopes and the tunnel structure.

2.3.1 Dimensioning the excavation tunnels

The design of the excavation slopes for the construction of the Telleda Tunnel was planned leaving a working platform of 16 m in width, and giving priority to the minimization of the left slope which was the highest, being unnecessary to use any means of support in its stabilization.

To study the stability of the left side slope, a parametrized finite element model was prepared for the purpose of studying geometries with slope heights of 36, 34, 32 and 30 m, in which were included the different materials that constituted the ground: gravels, sands and clays. Also included in the model was the structure of the tunnel and the backfill of the excavation, the object being to be able to analyze all construction phases. In Figure 4 is shown the model prepared for the calculations, which were carried out with the FLAC 4.00 program, using the mechanical properties indicated in Table 1 and analyzing the fol-
ollowing constructive phases.

1. Excavation of the trench to the level of the tunnel vault leaving an esplanade of 16 m in width.
2. Construction of the sides by means of two pile walls and the tunnel vault, concreted against the ground.
3. Excavation of the tunnel in underground.

As the criterion for selecting the most appropriate slope geometry it was considered that the calculated stability coefficient should be as near as possible to 1.3. This value was considered reasonable because it concerned a provisional slope and whose hypothetical instability would not affect people or buildings.

After carrying out the calculations, it was verified that if the left slope was dug with a slope of 1 (H): 1.5 (V), equivalent to 56.3°, the safety coefficient obtained was 1.34, and so this geometry was accepted.

In Figure 5 is shown the distribution of the shear strains, calculated for the selected geometry. It can be appreciated how the maximum values are grouped following the hypothetical rupture surface that would materialize in the event of the slope becoming unstable.

2.3.2 Dimensioning the structure of the tunnel

Once the construction solution had been chosen, the dimensions of the walls, vault and floor of the tunnel were obtained by calculating the strain-stress conditions for the final phase of construction using the geomechanical model described in section 2.3.1., which were also solved with the FLAC 4.00 code.

In Figures 6a to 6c are shown the distributions of the axial forces, bending moments and shear forces that are acting on the vault and the walls of the tunnel, in the final phase of construction.
The reinforcement was calculated for the walls and vault with the maximum values obtained in the calculations and applying the criteria of the spanish standard EHE-98.

3 CONSTRUCTION OF THE TELLEDA TUNNEL

In the following sections the most representative details in the construction of the Telleda Tunnel are presented.

3.1 Excavation of the trench

The excavation of the trench necessary to build the Telleda Tunnel began in September 2004 with the construction of the perimeter gutter to prevent runoff water entering the excavation.

The excavation works were carried out by normal mechanical means with no problems of any type appearing and were concluded at the vault level by mid-November 2004. This signified that the 12600 m$^3$ corresponding to the trench were removed in two months, at a rate of 2500-3000 m$^3$/day.

A general view of the trench is shown in Figure 7, in the final phase of the excavation, while Figure 8 shows a detail of the highest slope of the trench.

3.2 Construction of the pile walls and the vault.

Once the excavation of the trench reached the upper level of the vault, was started the construction of the walls for the tunnel sides, constituted by reinforced piles of 0.85 m in diameter with a spacing of 1.1 m
between centers.

Figure 9 shows a moment in the construction of these piles when, in the deepest part of many of them, the use of a trepan was required due to the need to traverse very resistant boulders.

The construction of the pile walls began in December 2004 and was completed in April 2005.

After construction of the pile walls excavation was started for building the vault, as can be seen in Figure 10.

The construction of the vault began in the month of May 2005 and was completed in June of the same year.

3.3 Excavation underground

Before beginning the underground excavation the construction began on the Barcelona portal side, a task which signified digging the portal slopes to the definitive excavation, as can be seen in Figure 11.

The underground excavation began in September 2005, using a conventional backhoe to load the waste onto trucks; as can be seen in Figure 12.

This operation, which was performed without difficulty due to the excellent behavior of the pile walls, was completed in 48 days, which signified an average rate of excavation of 4.4 m of tunnel per working day.

The conclusion of the excavation underground was made to coincide in time with the end of construction of the portal on the French side, as can be seen in Figure 13.
3.4 \textit{Finishing the tunnel}

Once the portals were built and the construction of the tunnel concluded, the waterproofing of the walls was carried out using PVC sheeting, and the concreting of the definitive walls which constituted the lining of the tunnel, as can be seen in Figure 14.

The construction of the tunnel concluded with laying the floor that was to allow the emplacement of the tracks, as illustrated in Figure 15.

4 \hspace{0.2cm} \textsc{MONITORING THE STABILITY}

The critical point in the construction of the Telleda Tunnel was constituted by the stability of the left lateral slope, which had to be excavated with a 56.3" and have a maximum height of 32 m.

To monitor the stability of this slope during the excavation process, benchmarks were placed on the crest which were leveled periodically.

In Figure 16 the evolution is shown of the movements of the six topographical benchmarks located in the highest part in the bank; that was the most critical area in the slope.

In this figure it can be appreciated that as the excavation proceeded the settlement of the control landmarks occurred, reaching a maximum value of 17 mm when the excavation arrived at the deviation of the tunnel vault.

This value practically coincided with that foreseen in the calculations, which signified the confirmation of the forecasts made.

Starting from the maximum settlements, the following level readings indicated the stabilization of the movements and even the recovery of the movement produced in the benchmarks located in the highest part in the bank.

During the excavation underground, no movements took place in the trench banks, as was foreseen from the calculations carried out.
5 CONCLUSIONS

The Telleda Tunnel, in spite of having a length of only 214 m, proved highly difficult to design due to the steep of the existing natural slope, transversal to the tunnel, in which it was to be dug and to the significant ecological value that the external surface covering the tunnel had.

During the preparation of the project several alternative construction procedures were analyzed and finally a mixed method was chosen, cut and cover and underground, which permitted the external ground surface affected by the construction to be minimized.

The ground to be excavated was constituted by a compact granular matrix, made up of layers of clays, silts and sands which included gravels and granitic boulders.

This terrain, which was considered to be a compact soil or a very soft rock, presented small, but significant cohesions, which allowed excavation slopes to be planned with gradients of 56.3° and a maximum height of 32 m.

Once the open cut excavation had been carried out the pile walls were built which would later constitute the tunnel sides, and the tunnel vault was accomplished.

After building the pile walls and the vault, the excavation of the tunnel started underground, using conventional machinery, to complete the tunnel.

The construction method planned proved highly satisfactory as no geotechnical problems arose during the work, which, together with a careful executed construction, allowed this tunnel to be built in a very safe and efficient manner.