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The Problematics of Tunnels Safety - The Rehabilitation of the Montemor Tunnel

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Abstract

A tunnel is an underground passage allowing the overcoming of natural barriers and making easier communication routes (roads, railways, etc). Its use became current and its relevance, both environmental and economical, has increased exponentially. All of this combined with the consequences of the accidents occurred in the last 30 years, lead to the consideration of problems associated with the operation of a tunnel, which where behind the implementation and creation of the Directive 2004/54/CE.

In Portugal, based on the Directive, it was implemented the Decree Law no. 75/2006, taking into account, different tunnel safety requirements for tunnels with more than 500m (the Directive covered only the tunnels integrated on the European roads network).

The aim of this paper is, using as an example, the Rehabilitation Project of the Montemor Tunnel, to address the different variables associated with the theme of tunnels safety, as well as the evaluation of the tunnel fire resistance, analyzing both all the geotechnical-geologic and structural characteristics involved in a structural evaluation of a tunnel.

1. Main Characteristics of the Montemor Tunnel

The Montemor Tunnel was built in 1994, has two completely independent tubes, with about 130m² of cross section each, and near 740m of overall length. The tubes with concrete structure were built using NATM technology, except the zones continuous to the portals, which were built using the cut and cover method. The vertical minimum gabarit is 4,7m. Each tube has three uni-directional traffic lanes with 3,75m width each, as well as a left berm with 1m and a right berm with 4m width (slow traffic side). The transversal gradient is constant with a value of 2,5% and the average longitudinal gradient is about 5,3%, corresponding to near 38m of differential levels between opposite portals. The average daily traffic is about 13,550 vehicles, corresponding to approximately 3% to heavy goods over 3,5t.

From the geological point of view, the tunnel intersects a scenario composed by rocky layers of a clayed and green marls complex (SW side), as well as on a complex of sandstones, including weathered sandstones, soft marls and clays (NE side), with an average inclination of about 15º to SE.

Based on this geological characterization, the tunnel can be divided in three main sections, associated with the marls complex, the sandstone complex and a fault area, as seen in Figure 2.

Its Hydrogeological conditions, as a result of a location in the base of some hills, close to two small water streams and a maximum cover of about 30m, are of a
permeability co-related with the more weathered materials, which leads to the existence of a ground water table located above the Tunnel base, especially after strong raining periods.

In order to confirm the different assumptions related to the hydrogeological characterization there were installed nine piezometers in three cross sections. Its location is connected with the three main geological sections.

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The evaluation made, led to the installation of new geodrains, in order to assure the location of the ground water table below the Tunnel base, respecting the initial Project assumptions, as well as the implementation of a monitoring and survey plan, in order to assure the permanent location of the ground water table below the Tunnel base.

The tunnel structural conditions, according to the original project, can be divided as following:

- Reinforced concrete cross section, built using the cut and cover method: 41m, at the SW side, and 5m, at the NE side, including both portals.
- Plain concrete cross section, built using the NATM method with a minimum thickness of 0,30m, final lining, over initial lining. The initial lining, dependent from the geological conditions, comprised the following elements: shotcrete, steel ribs, radial and umbrella arch nailing.

In order to confirm this information, as well as to assess the effective structural resistance, several nondestructive or slightly destructive diagnostic tests were performed:

- Detection of the internal reinforcing steel cover (pacometer).
- Detection of the reinforcing steel corrosion.
- Detection of the concrete carbonation.
- Detection of the clorets percentage at various depths at the concrete.
- Concrete resistance and deformability (UCS).
- Detection of the steel reinforcing and profiles using georadar devices (800MHz and 1,6MHz).

The results obtained confirmed, in a general way, the main information stated at the Tunnel original Project.

2. **Structural Fire Resistance**

2.7- Structural Fire Resistance - The main structure of all the tunnels in which the local collapse of the structure may have catastrophic consequences, for example underwater tunnels or tunnels that can generate the collapse of social important structures and infrastructures located at the surface, has to have a sufficient level of fire resistance.

*Decree Law no. 75/2006*
At the surface, over the tunnel, are located different medium and small size buildings. It can be point out a social important building: EB1/J1 Montemor School, which is located in a small distance to the tunnel entrance in the Loures side. All the buildings were identified (ED1 to ED12) and in this context it was possible to analyse a need for a structural safety analyses, taking into account the tunnel stability in face of a fire.

For this purpose and according to the collected information, the Tunnel standard fire resistance was previously classified with the criteria R180 (the load bearing function is maintained during 180 minutes of fire exposure, according to the EN1992-1-2).

The structural fire resistance was evaluated using the standard temperature – time curve, stated at the EN1991-1-2, as well as the relations between the evolution of the temperature with the concrete depth and also the variation of resistance with the temperature for slabs, proposed at the EN1992-1-2 (Figures 6 and 7).

Considering the results of both calculations and diagnostic tests, at the cut and cover sections there was a need to increase the fire resistance protection level of the tunnel. So for that purpose, it was proposed the adoption of a layer of insulating material at the internal surfaces, acting as a passive thermal barrier. This fire protection layer, with a minimum thickness of 25mm, was formed by sprayed inorganic vermiculite cement, with the following advantages:

- Slowing down the increase of temperature at the Tunnel structure, compatible with the R180 classification, as well as indirectly with the safety of the surface structures and infrastructures;
- Vermiculite cements are inorganic materials which do not burn, produce smoke or release toxic gases under high temperature conditions;
- Compatible with the Tunnel minimum gabarit;
– Allows sprayed application and the coating final surface to be suitable for painting and good finishing, as well as easy to repair.

There was another measure needed to take in order to comply with the R180 classification, so it was proposed the execution of new dilatation joints, at each 25m at the concrete Tunnel final lining, with 50mm width of gap (Figure 8).

![Tunnel Cross Section - Plan](image)

Figure 8- Detail of dilatation joint [5]

Combined with all of this structural measures, all of the tunnel equipment will be designed to have a minimum level of fire resistance, keeping the necessary safety functions during fire.

3. Risk Analysis

A risk analysis on the tunnel was carried out in order to evaluate the tunnel overall safety level and to define risk reduction measures. A risk analysis is one of the main tools in an integrated safety evaluation approach of a tunnel. Beyond all the prescriptive measures present in the DL, it recognises the different risk analysis methodologies as an important tool to evaluate the tunnel safety.

The adopted methodology for the risk analysis took into account all the design factors and traffic conditions that could affect the tunnel safety. The different traffic characteristics and type needed for the base of the safety evaluation, were limited by the lack of experience and information regarding the Portuguese tunnels. In this scenario and as reference, the experience of other European countries on a multi criteria approach was considered (Figure 9), in order to assess whether additional safety measures and/or supplementary equipment that would be necessary in order to compensate the lack of fulfillment of all the minimum requirements and, as consequence, to ensure a level of safety not lesser than the one existing at the same A9 motorway, but outside the Tunnel.

![Risk Assessment Process](image)

Figure 9- Risk assessment process [adap. 2]

The risk analysis carried out for the Montemor Tunnel was based on a systematic analysis of all the minimum requirements stated in the Decree Law no. 75/2006. Overall the different safety issues, whether strucutral, ventilation or circulation options,.., there was attributed a factor/value to each, considering that they were independent and equivalent. Each factor was defined with the aim to take into account the improvement or the aggravation of the different characteristics of the tunnel when compared with the minimum requirements, which means that when a:

- Factor is equal to 1,0, the existent situation or the adoption of additional measures is according to the Directive minimum requirements.
- Factor is lesser than 1,0, the existent situation is not according to the Directive minimum requirements.

For example:

**Minimum requirement:** longitudinal gradient of 3%

**Montemor Tunnel:** longitudinal gradient of 5,3%

Considering the number of fires (N) proporcional to the number of accidents (N₀) and the longitudinal gradient (s), it is possible to adopt the following correlative model:

\[ N = N_0 \left(1 + 0.1s\right) \]
\[ N^{3\%} = N_0 (1 + 0.1 \times 3) \]
\[ N^{5.3\%} = N_0 (1 + 0.1 \times 5.3) \]

\[ \text{Factor} = \frac{N_0 (1 + 0.1 \times 3)}{N_0 (1 + 0.1 \times 5.3)} = \frac{1.3}{1.53} \approx 0.85 \]

- Factor is bigger than 1.0, the existent situation or the adoption of additional measures exceeds the Directive minimum requirements (ex: 2 tubes and a number of vehicles / day lesser than 4,500 per lane without a duplication forecast in the next 15 years, comparing with the minimum requirement value of 10,000, lead to a factor of about 2.0).

The first partial multiplied factor results from the multiplication of all factors due to the structure and infrastructure factors, leading to a value much bigger than 1.0 (7.5). Furthermore, it was also possible to consider the extra risk due to the other traffic requirements, mainly the heavy goods vehicles overtaken. The multiplication of those factors with the previous partial value led to value of 3.7, bigger than 1.0, ensuring, as consequence, a safety level bigger than the one existing at the same A9 motorway, but outside the Tunnel.

Taking into account this analysis, the following hypothesis and measures were adopted and proposed:

- Maximum fire heat release rate of 30MW, correspondent to a heavy goods vehicle.
- Ventilation solution (sanitary and safety) based on a minimum consumption approach.
- In case of fire, an evacuation and smoke control solution allowing the smoke flow always upwards, on both tubes, and, in consequence, the evacuation of users always downwards.
- The free circulation of heavy and heavy dangerous goods vehicles, including the overtaking.

In the risk analysis developed it can be pointed that there must be a pre-establish maximum factor when considering the beneficial factors in order to control some of the subjectivity in the analysis. This means that if the tunnel presents a safety level superior to the minimum imposed, the factor that translates this must be limited.

<table>
<thead>
<tr>
<th>Summary of Minimum Requirements according to Directive</th>
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<tbody>
<tr>
<td>Mandatory for all tunnels</td>
</tr>
<tr>
<td>Vehicles/day (VDF) &gt;2000</td>
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<tr>
<td>Chapter</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td>Structural measures</td>
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<tr>
<td>Gradient &lt; 5%</td>
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<tr>
<td>Emerg. exits at least every 500m</td>
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<tr>
<td>Crossconnections at least every 1500m</td>
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<tr>
<td>Lay-bys at least each 1000m</td>
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<tr>
<td>Drainage of flammable and toxic liquids</td>
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<tr>
<td>Fire resistance of structures</td>
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<tr>
<td>Lighting</td>
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<tr>
<td>Safety lighting</td>
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<tr>
<td>Evacuation light</td>
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<tr>
<td>Ventilation</td>
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<td>Emergency stations</td>
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<td>Water supply</td>
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<td>Road signs</td>
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<td>Control centre</td>
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<td>Monitoring systems</td>
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<td>Communication systems</td>
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<tr>
<td>Emergency/Radio messages for users</td>
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<tr>
<td>Loudspeakers</td>
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<tr>
<td>Emergency power supply</td>
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<td>Fire resistance of equipment</td>
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<tr>
<td>Partial Multiplied Factor</td>
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<td>Other traffic requirements</td>
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<tr>
<td>Heavy goods overtaken</td>
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<tr>
<td>Danger goods circulation</td>
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<tr>
<td>Final Multiplied Factor</td>
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</tbody>
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Figure 10: Risk analysis methodology [adap. 4]
distances on the side walls), emergency stations (fire extinguishers, SOS) and panels with lane signals (including open and close lanes).

Analyzing the mechanical infrastructures, considering the fire situation there was a base philosophy in its design. The mechanical active systems intend to guarantee the smoke control in order to prevent it from affecting large tunnel sections before extraction, improving the speed and effectiveness of fire – fighters activities, as well as the speed of users evacuation.

The philosophy stated was that in fire situations the smoke flow will be done always upwards, facilitating user’s evacuation on the opposite downward direction. This option can be justified by the following issues [7]:

- Tunnel tubes big cross section, about 130m².
- Tunnel small length, about 740m, equivalent to approximately 38 hydraulic diameters.
- Only about 3% of heavy goods traffic over 3,5 t.
- -Existence of 3 traffic lanes, in each tube, with 3,5m wide and a continuous berm on the slow traffic side with 4m wide.
- In spite of the Tunnel overall length is lesser than 3,000m, the existence of a Control Centre allowing the Tunnel technical active management.
- Auto evacuation could be performed always downwards, decreasing, at least 3 times the evacuation time (for the same distances), comparing with the same operation upwards. This strategy is according with the common practice for upwards direction traffic. For the downwards direction, the increase of risk is compensated by the specific measures considered, as demonstrated through the risk analysis (Figure 11).

The ventilation system will be composed by unidirectional ventilators, with 2 rotational speeds, located in the central zone of each tube, in order to manage both sanitary and smoke control situations. All fresh air ventilators (sanitary ventilation) will be equipped and monitored through automation in order to allow the optimization of both ventilation and air opacity conditions, leading to safer driving conditions under minimum energy consumption.

4. Evaluation of Structural Safety

After the surface recognision there was a need to verify the structural safety beyond all the interventions due to fire safety in the tunnel. For that purpose there were considered two models. The main difference between the models was the consideration of the tunnel construction phases in the final efforts, as well as the stress-strain behaviour.

Model no.1

This model was based on the actions predetermined in the original project, considering strings to simulate the interaction between the structure and the surrounding soil.

Model no.2

Regarding this modelling there are two key aspects: it is more realistic to have a time gap between the construction of the first to the second tunnel, which penalizes the efforts on the structure of the first tunnel and the consideration of the nails deactivation due to question of durability, considering that it will be possible a section degradation due to the corrosion phenomenon.
1. Execution of the temporary lining and the anchors in the first tunnel
2. 1.ª Excavation phase in the first tunnel
3. 2.ª Excavation phase in the first tunnel
4. 3.ª Excavation phase in the first tunnel
5. 4.ª Excavation phase in the first tunnel
6. 5.ª Excavation phase in the first tunnel
7. Execution of the temporary lining and the anchors in the second tunnel
8. 1.ª Excavation phase in the second tunnel
9. 2.ª Excavation phase in the second tunnel
10. 3.ª Excavation phase in the second tunnel
11. 4.ª Excavation phase in the second tunnel
12. 5.ª Excavation phase in the second tunnel
13. Execution of the permanent lining
14. Deactivation of the anchors

Figure 13 - Construction phases considered in model 2 [6]
From the analysis of the two models, it was evident that the second model is a more realistic approach. The first model tends to be more conservative and the efforts obtained from it, lead to the non verification of the structural security in some of the different tunnel sections.

The using of the second model corroborates that there is a connection between the final efforts that the structure is subjected to and the consideration of the evolution of the different construction phases. The efforts obtained from this model were less severe and more realistic and allowed to show that the structural security of the tunnel is verified.

5. **Main conclusions**

The work developed intended to be a reflection on the problematics of the implementation of the Decree Law no. 75/2006 taking into account the Montemor Tunnel case study.

It was visible in the rehabilitation of the tunnel the need to control continuously different aspects of the tunnel, considering its maintenance and the reliability of its safety systems.

Being one of the tools of the Decree Law, the use of risk analysis is not easy in Portugal since it is a country that doesn’t have the statistic base or the experience to allow its realisation. There is no guidance or regulation to help and control the viability of the risk analysis. For future analysis to be developed, the process used on the risk analysis described in this paper represents a good starting base.

One of the principle thematic behind the Decree Law is the tunnels fire resistance. The image defined by the Montemor Tunnel which can be extrapolated to the Portuguese reality, is that at the level of equipment, cables and subsystems and means of security, the tunnel could be classified as not safe. The interventions taken place by the implementation of the Decree Law has a beneficial overall consequence on the country, but in an macro-economical context that it’s in, the deadlines imposed and the budget necessary to it’s concretisation becomes borderline almost impossible. It should be made a more flexible and progressive timetable for the implementation of the Decree Law no. 75/2006, considering the particularities of each tunnel and each country.

In the rehabilitation project developed it was patent that there is a difficulty at the characterisation of the geometrical and geological-geotechnical and hydrogeological scenario. There were complications in the confirmation of the tunnel structural characteristics, mainly in the confirmation of the tunnel initial lining.

The calculations that were made showed the correlation between the tunnel’s final efforts with the consideration of the different construction phases, mainly if the stress-strain analysis is performed.

6. **References**