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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 convered 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 130m^2 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.

Figure 1- View of the tunnel portals

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.

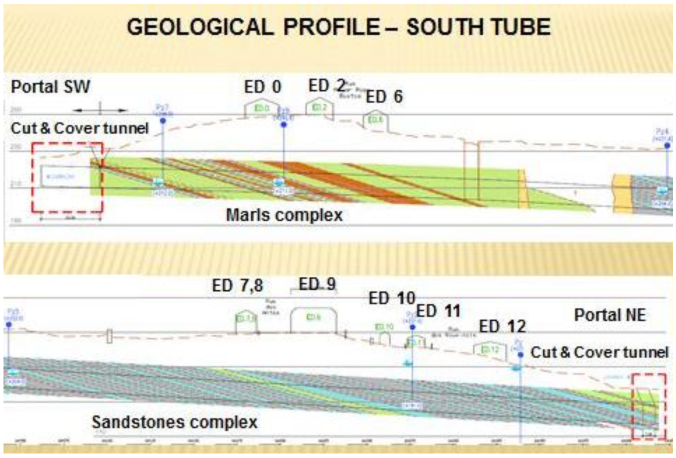


Figure 2 Geological longitudinal profile

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.

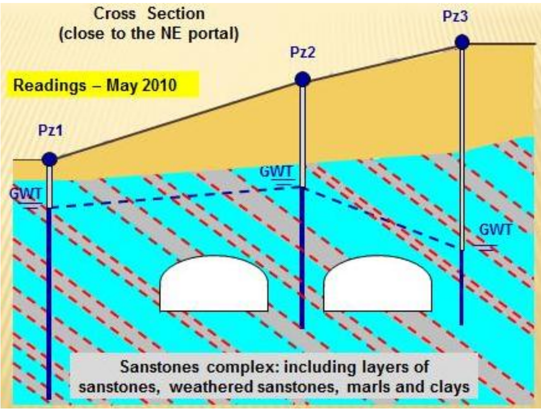


Figure 3- Hydrogeological cross section

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).

Figure 4- Tunnel structural evaluation [6]

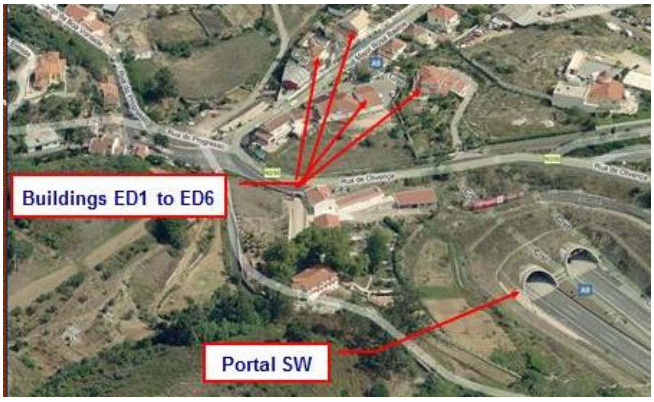
The results obtained confirmed, in a general way, the main information stated at the Tunnel original Project.

2. <u>Structural Fire Resistance</u>

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.



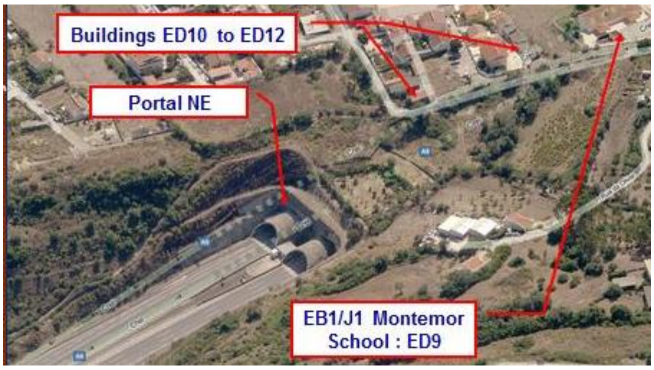


Figure 5- Surface conditions

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).

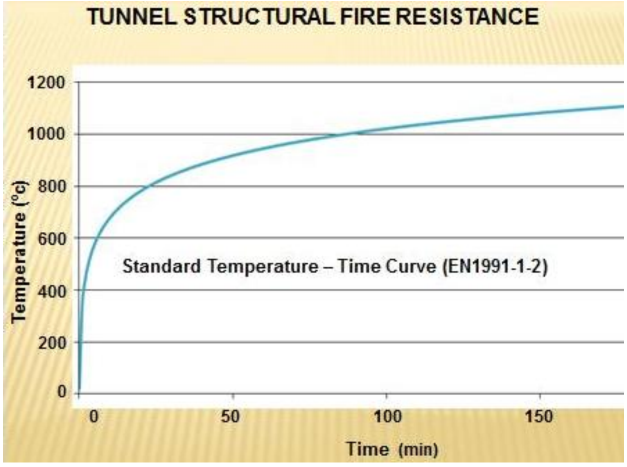


Figure 6- Standard temperature – time curve [6]

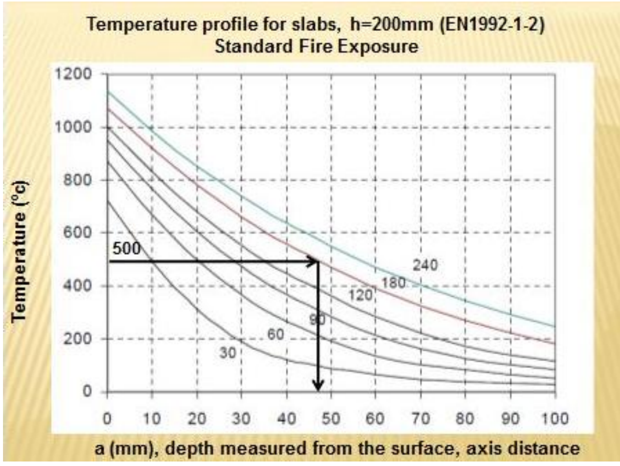


Figure 7- Temperature evolution with depth for concrete elements (500 ºC isotherm) [6]

Considerating 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 porpose, 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).

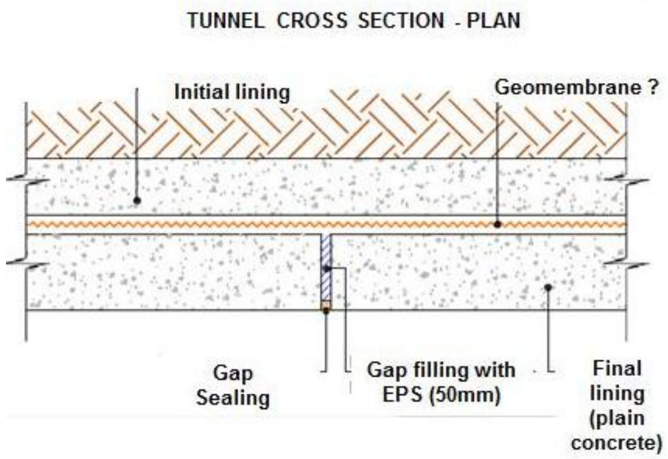


Figure 8- Detail of dilatation joint [5]

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 redution measures. A risk analysis is one of the main tools in an integrated safety evaluation approuch of a tunnel. Beyond all the prescritive measures present in the DL, it recognises the diferent risk analysis methodologies as an important tool to evaluate the tunnel safety.

The adopted methodology for the risk analysis took into acount 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.

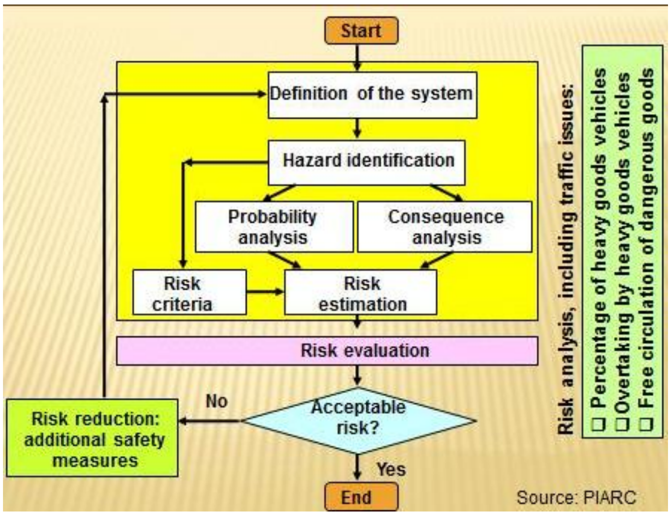


Figure 9- Risk assessment process [adap. 2]

The risk analysis carried out for the Montemor Tunnel was based on a sistematic analysis of all the minimum requirements staded in the Decree Law no. 75/2006. Overall the diferent safety issues, whether strutural, ventilation or circulation options,.., there was atributed 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 agravation of the diferent 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 Tunel: longitudinal gradient of 5,3%

Considering the number of fires (N) proporcional to the number of acidents (N_0) and the longitudinal gradient (s), it is possible to adopt the folowing correlative model:

$$N = N_0\ (1 + 0{,}1s)$$

$$
\left|\begin{array}{l} N^{3\%} = N_0\,(1 + 0{,}1 \times 3) \\[1em] N^{5{,}3\%} = N_0\,(1 + 0{,}1 \times 5{,}3) \end{array}\right.
$$

$$\downarrow$$

$$
\boldsymbol{Factor} = \frac{N_0\,(1 + 0{,}1 \times 3)}{N_0\,(1 + 0{,}1 \times 5{,}3)} = \frac{1{,}3}{1{,}53} \approx \mathbf{0{,}85}
$$

- 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.

Summary of Minimum Requirements according to Directive 2004/54/EC EP

● Mandatory for all tunnels
* Mandatory with exceptions
O Not mandatory

Vehicles/day (V/D) >2000
Tunnel length: 500 to 1000m

Existent tunnel

		Chapter		Factor	Comments
Structural measures	2 tubes or more	2.1	-	2,0	V/D half Directive
	Gradient < 5%	2.1	*	0,85	V/D half Directive
	Emerg. walkways	2.3.1	*	>1,0	Exceed Directive
	Emerg. exits at least every 500m	2.3.3-2.3.9	*	0,7	Could be 1, as it is an existent tunnel
	Cross connections at least each 1500m	2.4.1	O	1,0	Not applicable to a tunnel with 750m
	Lay-bys at least each 1000m	2.5	O	1,5	Continuous emergency lane
	Drainage of flammable and toxic liquids	2.6	*	1,0	Designed according to the Directive
	Fire resistance of structures	2.7	●	1,0	According to the Directive
Lighting	Normal lighting	2.8.1	●	1,0	According Dir.
	Safety lighting	2.8.1	●	1,0	According Dir.
	Evacuation light.	2.8.1	●	1,0	According Dir.
Ventilation	Mechanical vent.	2.9	O	>1,5	Both tubes
Emergency stations	At least every 150m	2.10	*	1,0	According to the Directive
Water supply	At least every 250m	2.11	●	1,0	According to the Directive
Road signs		2.12	●	1,0	According Dir.
Control centre		2.13	O	1,4	Exceed the Directive
Monitoring systems	Video	2.14	O	>2,0	Over the Directive
	Automatic incident / fire detection	2.14	●	>1,0	3 systems (CO, visibility and video)
Communication systems	Radio emergency	2.16.1	O	1,0	According Dir.
	Emergency Radio messages for users	2.16.2	●	1,0	According Dir.
	Loudspeakers	2.16.3	●	1,0	According Dir.
Emergency power supply		2.17	●	1,0	According Dir.
Fire resistance of equipment		2.18	●	1,0	According Dir.
Partial Multiplied Factor				7,5	Structures and equipment well above Directive requirements
Other traffic requirements					
Heavy goods percentage		1.3.2		5,0	3% against 15%
Heavy goods overtaken		3.8		<0,25 to>0,1	Statistical Risk
Dangerous goods circulation		3.7		1,0	Return period >1000 years
Final Multiplied Factor				>3,7	Overall conditions above Directive requirements

Figure 10- Risk analysis methodology [adap. 4]

Regarding the <u>emergency and evacuation signing</u> in the overall length of the tunnel the preventive safety signing was upgraded, acording to the Decree Law. It will include the following main situations: tunnel sign and classification, as well as, for instance: emergency exits (nearest exits 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.

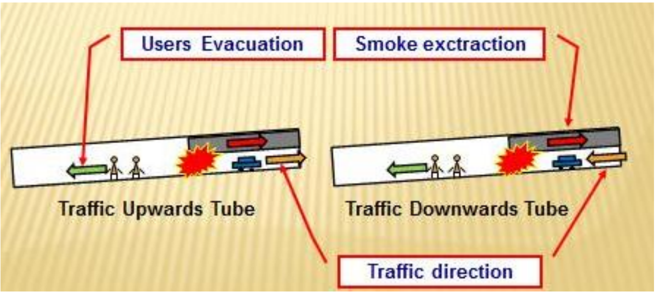


Figure 11- Mechanical Infrastructures: Fire Situation

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 the exception of 4 reversible 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 constrution fases in the final efforts, as well as the stress-strain behaviour.

Model no.1

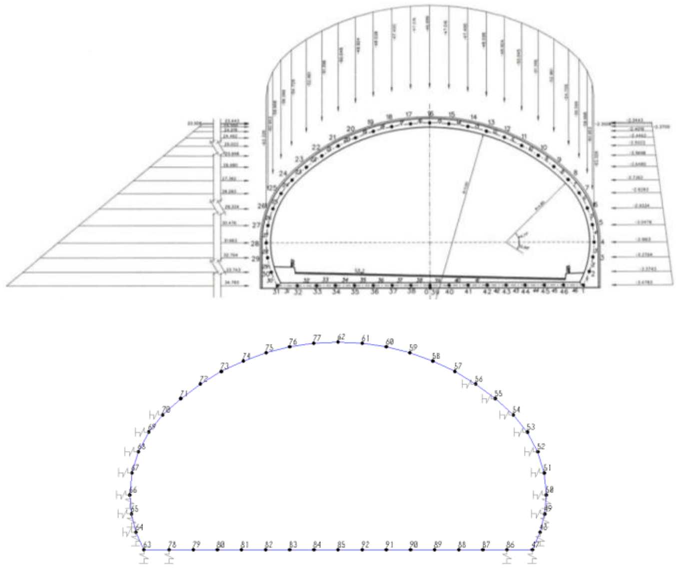


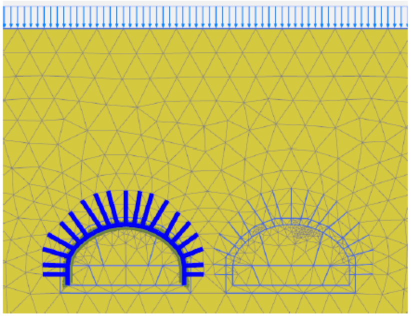
Figure 12- Actions and model considered in Model no.1 [6]

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.

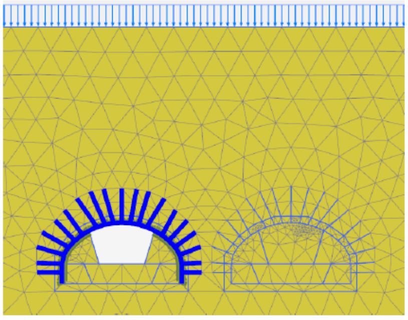
Model no.2

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

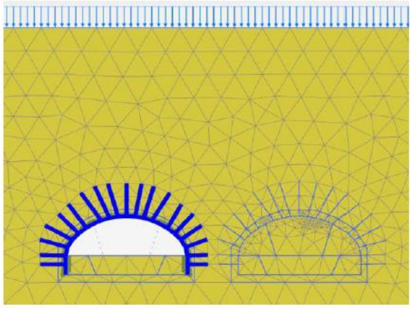
of durability, considering that it will be possible a section degradation due to the corrosion phenomenom.



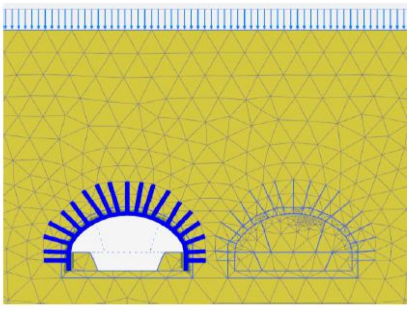
1. Execution of the temporary lining and the anchors in the first tunnel



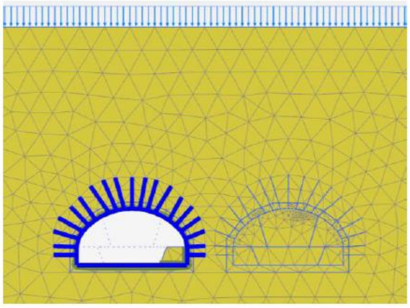
2. 1.ª Excavation phase in the first tunnel



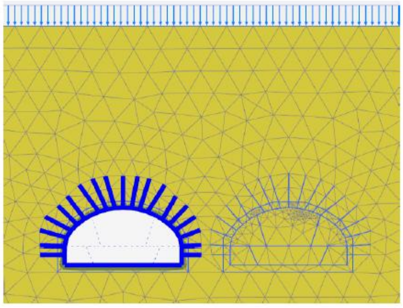
3. 2.ª Excavation phase in the first tunnel



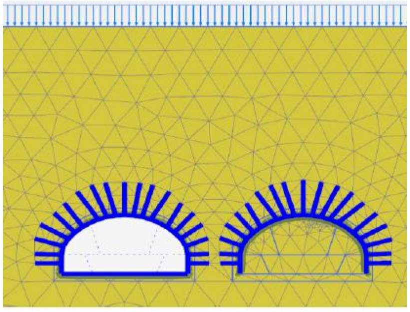
4. 3.ª Excavation phase in the first tunnel



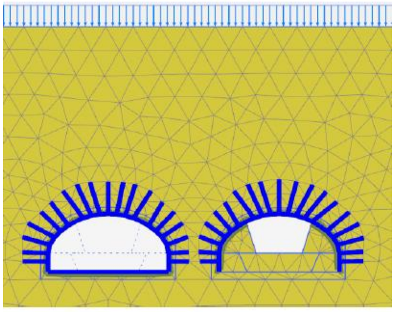
5. 4.ª Excavation phase in the first tunnel



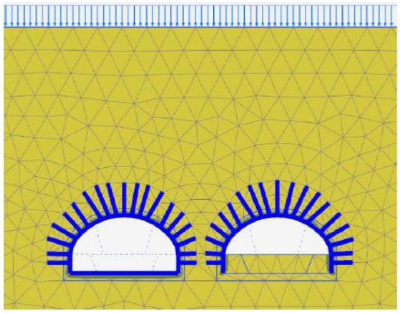
6. 5.ª Excavation phase in the first tunnel



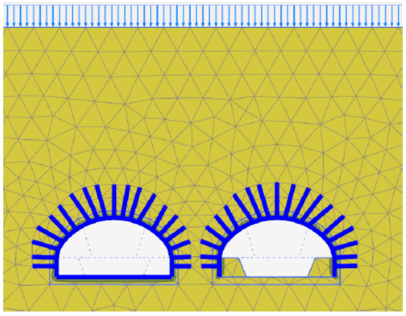
7. Execution of the temporary lining and the anchors in the second tunnel



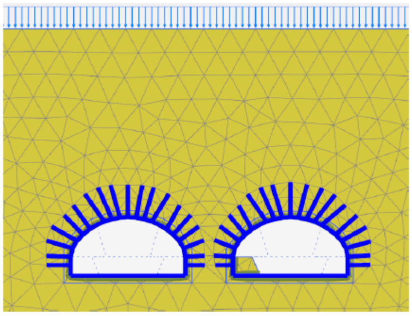
8. 1.ª Excavation phase in the second tunnel



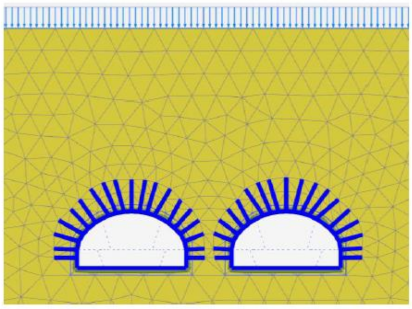
9. 2.ª Excavation phase in the second tunnel



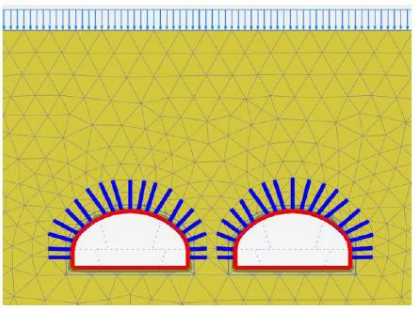
10. 3.ª Excavation phase in the second tunnel



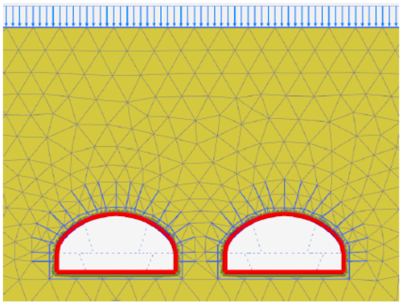
11. 4.ª Excavation phase in the second tunnel



12. 5.ª Excavation phase in the second tunnel



13. Execution of the permanent lining



14. Deactivation of the anchors

Figure 13 !- Constrution 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 obtain 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 conection between the final efforts that the structure is subjected to and the consideration of the evolution of the diferent constrution 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 constinuously diferent 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 viabilty os 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 thematics behind the Decree Law is the tunnels fire resistence. 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 budjet necessary to it´s concretisation becames 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 dificulty 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 linning.

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

6. References

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