A Simple Parametric Numerical Model to Assist the Design of Repair Works and Maintenance of Tunnels

A simple parametric numerical model to assist the design of repair works and maintenance of tunnels

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Abstract. Tunnels are resilient infrastructures whose service life is generally much higher than the designed nominal one, thus increasing the number of existing tunnels still in operation with an average service life of more than 50 years. From a more Italian perspective, Italy's complex morphology has made it necessary to excavate a considerable number of tunnels to develop the nowadays railway and motorway traffic lines. However, recent cases of tunnel lining local collapses have highlighted that some existing Italian tunnels have almost reached the end of their service life, revealing their maintenance, refurbishment and/or upgrading works to be an urgent need. Taking advantage of the tunnel refurbishment plan ongoing in Italy, the aim of this study is to support the design of temporary maintenance works by means of simple numerical modelling. In such a way it is possible to consider fundamental geotechnical parameters that can play a key role in the effectiveness and in the applicability of the studied maintenance solutions. The attention is here devoted to interventions with suspended steel ribs to prevent local instabilities of the aged concrete.

Keywords: Tunnel ageing, Existing tunnels, Tunnel refurbishment, Maintenance work, Numerical modelling

1 Status quo of existing tunnels in Italy

Tunnels are resilient infrastructures whose service life is generally much higher than the designed nominal one, thus increasing the number of existing tunnels still in operation with an average service life of more than 50 years [1].

Coping with tunnels ageing consists in the process of ensuring the continuation of service in safe conditions. For this purpose, different strategies can be considered:

- Maintenance works: minor works aimed at guaranteeing the tunnel designed service life, e.g., repair work for preventing local blocks detachment (see Fig. 1-a).
- Rehabilitation works: major works aimed at extending the tunnel designed service life, e.g., complete replacement of the tunnel vault after experiencing severe cracks formation and water income (see Fig. 1-b).

- Upgrading works: major works aimed at changing the tunnel designed use by upgrading it, e.g., tunnel enlargement to host more lines or tracks (see Fig. 1-c).
- Disposal: reusing old tunnels changing their designed use by downgrading them, e.g., hosting art exhibitions or bicycle ways (see Fig. 1-d).

a b

c d

Fig. 1. Examples of strategies throughout coping with tunnel ageing in Italy: a) Provenzale tunnel, Genoa, b) San Fermo tunnel, Como, c) Nazzano tunnel, Rome [2] and d) "Le Gallerie", Trento.

Concerning Italy, due to its complex morphology, its railways and motorways need a great number of tunnels to guarantee safe and fast pathways. It is no coincidence that Italy is one of the first countries in the world for number and length of existing tunnels (see Fig. 2). However, despite the resilience of this kind of underground infrastructures, many Italian existing tunnels have almost reached the end of their service life.

Accordingly, this study is intended to provide a support in the design of maintenance works by means of simple numerical modelling, that allows to further consider fundamental geotechnical parameters which can play a key role in the effectiveness and in the applicability of the maintenance solutions.

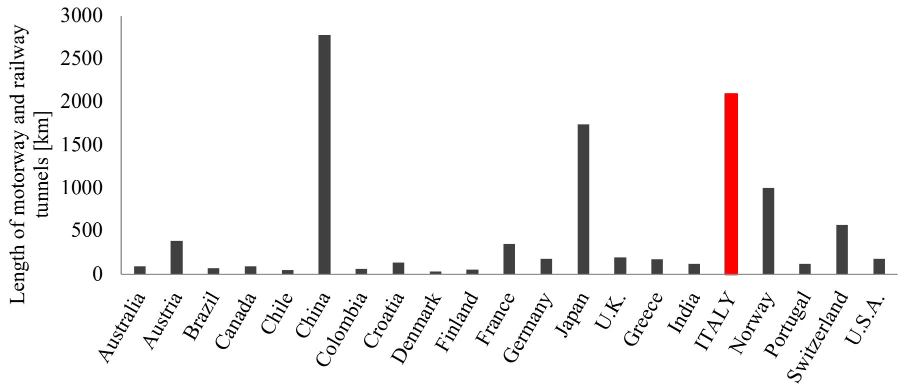

Fig. 2. Length of motorway and railway tunnels among several countries around the world (modified from [1]).

2 Refurbishment plan for existing tunnels in Italy

To assist concessionaires and tunnels owners in the process of inspections, maintenance and renovation of existing tunnels, new methods and procedures have been studied, validated and released in the recent years [3-5]. The tunnel inspection manual envisages that, before applying any repair work, a deep fact-finding survey must be carried out, relying on both as-built documents and in-situ inspections. The aim of the inspections is to check the tunnel conditions by taking note of all the damages and defects. To this aim, supplementary target investigations are often needed (thermography, video-endoscopy, geo-radar, sample coring, laboratory tests, etc.).

Depending on the inspection outcome, the tunnel condition is assessed and an attention class is assigned. The next step is to identify appropriate and/or necessary interventions based on the quantity, the seriousness and the typology of the defects. Temporary interventions, with the aim of securing the tunnel in the short term (from three to ten years), are applied when mobility poses serious constraints to tunnel long closures or to allow getting further insights for defining a suitable rehabilitation intervention, while final interventions are designed where it is possible to make them straightaway.

To support the work of its designers to promptly solve the most common problems, the Italian motorway concessionaire Autostrade per l'Italia SpA who is undergoing an intensive tunnels refurbishment plan to renovate existing tunnels, developed a catalogue of typological prompt interventions. These temporary maintenance solutions change as a function of the harshness of the concrete lining deterioration and several other aspects like:

- the presence or not of the waterproofing system,
- the presence or not of water income,
- whether the tunnel has been excavated in rock or soil masses,
- the presence or not of a significant state of stress in the concrete lining.

With the aim to demonstrate the usefulness of resorting to simple numerical models to support the design of such temporary solutions, the attention in the following will be devoted to a specific temporary solution developed to face the deterioration of the aged concrete lining with the potential formation of unstable blocks with volumes higher than 1 m^3 and presence of water (see Fig. 3). Its realization envisages the implementation of suspended double rectangular profile steel ribs secured to the concrete lining by means of chemical anchors.

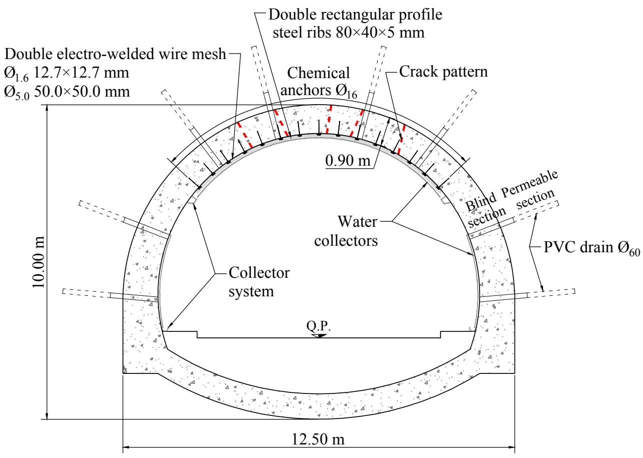

Fig. 3. Sketch of the temporary maintenance solution.

The use of numerical modelling, even kept at a very basic level, is of fundamental support in the design of temporary intervention that are designed for a variety of situations and not for a specific tunnel. Parametric analyses, as the ones that will be discussed in the following, may allow to consider the variability of the ground conditions, of the lining characteristics, of the geometrical aspects to allow for checking the availability of the interventions in a variety of situations. Fundamental aspects like the quality of the rock mass or the initial state of stress can be easily included in the computation and their role unraveled.

3 A simple effective numerical model

To explore the influence and the implications of some fundamental geotechnical parameters, a plane strain sensitivity analysis has been carried out by means of the software RS^2 [6]. This numerical investigation was meant to highlight if, whether in presence of a specific set of the above-mentioned geotechnical parameters, the chemical anchors slippage condition would have been possible or not. The anchoring resin at the interface between the concrete and the chemical anchors has been modelled through a joint element ruled by the Tresca failure criterion, whose cohesion (c') represents its strength. The latter has been varied arbitrarily during the analysis, depending on the case considered. The tunnel cross section shown in Fig. 3 was adopted.

The numerical analyses also investigated the role of:

- the earth thrust coefficient (K_0) between 0.5 and 2.0,
- the rock mass quality (GSI, Geological Strength Index [7]) between 20 and 80,
- the overburden of the tunnel(H) equal to 20.0 m and 40.0 m.

With the different parameters above, the sensitivity analysis was intended to investigate typical conditions for rock masses crossed by the Italian motorway network.

To this purpose two numerical models have been built to consider the different overburden. As shown in Fig. 4, for the sake of simplicity, the topographic surface has been considered horizontal.

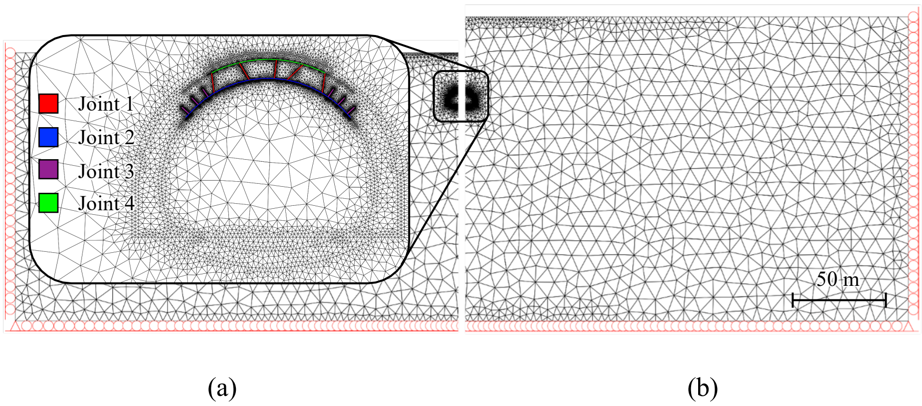

Fig. 4. Parametrical numerical models with two different overburdens: 20 m (a), 40 m (b) and detail of the joint elements adopted in the numerical model.

With respect to the tunnel cross section, a horseshoe shaped concrete lining with a variable thickness has been assumed, with the minimum ones being at the key and the invert (respectively of 0.90 m and 0.80 m) and the maximum one being at the springlines (1.40 m).

Finally, the steel ribs and the chemical anchors have been modelled explicitly through finite elements to assess their deformed setup and investigate the strength of the resin at the concrete-anchor interfaces.

The following stages have been considered to perform the sensitivity analysis:

1. geostatic stress state initialization,
2. head excavation with a relaxation factor of 30%,
3. temporary lining installation and bench excavation with a relaxation factor of 100%,
4. concrete final lining realization,
5. complete decay of the temporary lining,
6. concrete cracking and temporary maintenance work installation.

The last stage is supposed to let concrete wedges detach. To this aim, some joint elements have been adopted in the upper portion of the tunnel vault (see Fig. 4) to well represent the interaction between concrete blocks (joint 1) and between the concrete and the steel ribs (joint 2), the resin (joint 3) and the rock mass (joint 4). A proper parameterization of these elements (see Table 1), as a function of the original mechanical characteristics of each interacting entity, allowed to simulate a likely interaction between the above-mentioned concrete wedges and the maintenance work components. With reference to joint 4, it is noted that a variable GSI value implies different normal stiffnesses.

Table 1. Mechanical parameters of the joint elements adopted in the numerical model (Fig. 4).

	Joint 1	Joint 2	Joint 3	Joint 4
Normal stiffness [MPa/m]	270852	1135430	100000	141711 ÷ 334245
Shear stiffness [MPa/m]	0	0	10000	0
Friction angle [°]	30.0	20.0	0.0	13.4 ÷ 21.1
Cohesion [kPa]	0.0	0.0	100 ÷ 600	0.0
Tensile strength [kPa]	0.0	0.0	0.0	0.0

By way of example, the outcomes of two different analyses are shown in Fig. 5. The two images represent numerical analysis results with GSI = 50, K_0 = 1.0, H = 20.0 m and a cohesion, for joint 3, respectively, equal to c' = 240.0 kPa and c' = 175.0 kPa. A 30% decrease of c has brought to the slippage of the upper right chemical anchor.

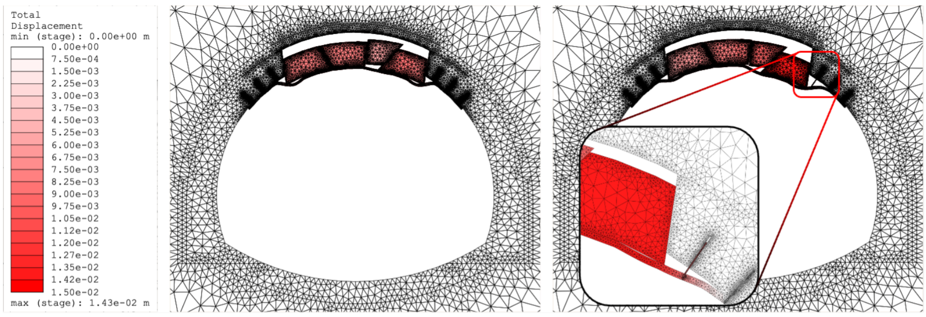

Fig. 5. Outcome of two different analyses with and without plugs slippage.

It is evident that the above-mentioned way of modelling this kind of problem well manages to reproduce the concrete wedges detachment and the structural response of the steel ribs, as well as the chemical anchors one. As anticipated, the aim of the sensitivity analysis was to deepen the knowledge about the interaction between the concrete tunnel lining and the resin of the anchors.

In each examined situations, the attention was devoted to the cohesion at the interface to be enough to avoid the slippage condition for all the chemical anchors simulated in the numerical model.

The results of the sensitivity analysis are shown in Fig. 6.

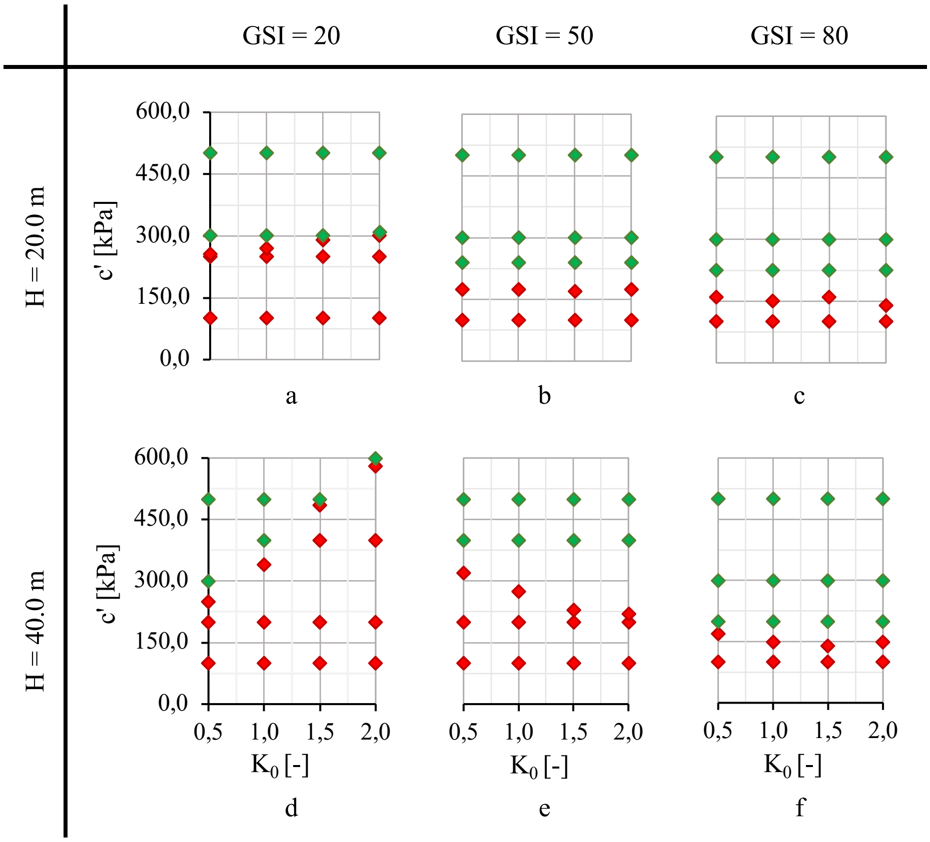

Fig. 6. Slippage (red diamonds) and safe (green diamonds) conditions of the chemical anchors in function of the cohesion (c'), the rock mass quality (GSI), the tunnel overburden (H) and the initial stress state (K_0).

Based on the results, the effectiveness of the temporary intervention is heavily influenced by the geotechnical parameters. It is evident how the cohesion needed to guarantee the stability of the repair work ($c'_{req.}$) varies substantially in the different situations. Thus, the numerical model may allow to identify the proper conditions for the application of the temporary intervention analyzed here.

For instance, analyzing Fig. 6-d, it can be realized how, whether in unfavorable conditions of tunnel overburden (H = 40.0 m) and rock mass quality (GSI = 20), the mandatory anchoring resin strength could increase of even three times depending only on the initial state of stress (K_0).

Finally, for the analyzed cases, the following conclusion can be drawn:

- the lower the quality of the rock mass (GSI), the higher the required cohesion ($c'_{req.}$),
- the higher the tunnel overburden (H), the higher the required cohesion ($c'_{req.}$),
- the influence of the initial state of stress (K_0) is revealed to be more significant with decreasing rock mass quality (GSI) and the increasing overburden (H).

4 Conclusions

This study focused on proving how numerical modelling, even at a very basic level, could assist the design of temporary tunnel interventions. The attention was devoted to a particular temporary repair work designed to cope with ≥1 m^3 volume concrete blocks detachment. Its effectiveness has been studied in function of fundamental geotechnical parameters like the quality of the rock mass in which the tunnel been excavated (GSI), the initial stress state (K_0) and the tunnel overburden (H). To this purpose, a numerical model has been built in RS^2 (Rocscience Inc.).

In the case of a 40.0 m deep tunnel excavated in a poor rock mass, characterized by a high stress state, the analysis showed that a higher strength of the resin of the chemical anchors is needed to guarantee the stability of the suspended steel ribs. Therefore, the results illustrated allowed concluding that the above-mentioned geotechnical parameters have a key influence on the temporary maintenance work design, allowing to identify proper conditions for its applications.

Acknowledgements. The work was performed in the framework of a research contract between Autostrade per l'Italia SpA and the Dept. of Structural, Geotechnical and Building Engineering, Politecnico di Torino.

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