A Design Procedure for the Rehabilitation of Tunnel Liners

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ABSTRACT: A design approach is discussed for the structural rehabilitation of concrete lined tunnels. Depending on the severity of damage, and on the causes that produced it, three levels of rehabilitation are illustrated. They range from light repairs of the inner surface of the tunnel to the demolition and reconstruction of large portions of its lining. In the later case, that represents the most significant problem from the engineering point of view, the use of three-dimensional stress analyses is required to evaluate the safety of the demolition/reconstruction process. The effectiveness of the proposed design approach is illustrated through a case history concerning a highway twin-tunnel located within a slope that undergoes a slow time-dependent movement.

1 Introduction

The supporting structure of concrete lined tunnels could present relevant damages due to its ageing, to weathering or to improper construction techniques. In other instances the damage depends on the overstress produced by particular geological conditions that were not adequately considered during design, e.g. occurrence of landslides, swelling or squeezing behaviour of the rock mass, etc. (Inokuma & Inano, 1996; Locatelli et al., 2001).

Previous experience related to highway tunnels in central Italy (Locatelli et al., 2004) shows that the most frequent problems often derive from the limited quality of the materials used for the supporting structures or from poor construction methods.

However, if relevant damages are observed, the geological/geotechnical conditions of the surrounding soil/rock mass should be carefully assessed and investigated to identify the actual causes of the problem. This represents a main requirement for the correct design of the rehabilitation.

Three levels of damage and rehabilitation are illustrated in the following Sections, namely: light, intermediate and heavy. Depending on the level of the damage, and on its structural or geological origin, proper provisions should be adopted for restoring or for replacing the liner. Their design, which is strictly related to the actual conditions of the concrete and of the surrounding rock mass, requires the evaluation of the rock/soil pressure acting on the original lining.

Two-dimensional (plane strain) numerical models based on the finite element technique are often sufficient to this purpose and are customarily adopted in engineering practice.

However, more sophisticated three-dimensional analyses are required when a relevant part of the liner has to be demolished and reconstructed. In this case, in fact, the stress analysis should allow for the quantitative assessment of the need for soil/rock treatments before demolition, of the maximum length of the tunnel segments to be demolished without leading to unsafe working conditions, and of the stress state generated within the new supporting structure. Due to the intrinsic three-dimensional nature of these problems standard two-dimensional calculations cannot be adopted for their solution.

A case history is illustrated in the following that concerns a highway twin-tunnel located within a slope undergoing a slow time-dependent movement. First, the stress distribution existing in the original liner is estimated through a 2D, non-linear finite element model that includes the slope and the twin-tunnels. Subsequently, a 3D model of a single tunnel is developed for analysing the details of the demolition and reconstruction process. Finally, some comments are presented on the role of three-dimensional, non-linear analyses in the framework of the adopted design procedure.

2 Levels of damage and rehabilitation

In order to provide a consistent description of the problem under examination it is convenient to subdivide the damage of the concrete liners into three levels of increasing severity, namely: *light*, *intermediate* and *heavy*. Each of them requires specific rehabilitation techniques for restoring the structural supports.

In general terms, a *light* or "spot" rehabilitation should be considered when the defects are localised within limited zones and mainly involve the inner surface of the lining. In this case the repair works need to be both quick, to minimise the time during which the tunnel will be closed to traffic, and safe. Quite obviously, they should involve a limited overall cost.

The following techniques are frequently adopted in this case:

- Installation of corrugated steel sheeting secured by nails or small rock bolts, in case of limited damaged areas or minor water infiltration.
- Installation of steel sheeting plates secured by anchors or rock bolts in case of wider zones with voids or honeycombed concrete. If the presence of large voids prevents the use of anchors, steel beams secured at their ends to stable rock zones can provide the necessary support.
- The use of exceedingly long anchors would be necessary if the radial extension of the damaged or "decompressed" rock around the tunnel is particularly large. In this case it is preferable to install steel ribs inside the lining, although this slightly reduces the inner section of the tunnel and it has to be considered as a temporary work previous to the subsequent permanent rehabilitation of the liner portion.

The *intermediate* level involves the general rehabilitation of the entire internal surface of the lining. In some instances the localised restoration of some concrete sections could be also necessary.

In case of extensive damages, the cost/benefit analysis may show that the most convenient procedure consists in the restoration of the inner surface of the liner along the entire length of the tunnel.

The hydro-demolition technique is frequently used to remove a pre-defined thickness of the damaged support. Subsequently a layer of welded wire mesh is installed over its inner surface and, finally, a rapid-set dry-mix shotcrete is applied on it.

A *heavy* rehabilitation is necessary when particularly serious defects, involving large portions of the liner, are detected during inspection. As previously mentioned, they can be originated by poor construction techniques or by high stress concentrations due to geological causes. Quite often in such cases the tunnel lining needs to be completely demolished and reconstructed along large part of the tunnel or over its entire length.

3 Design approach

Having determined the extension and the characteristics of the damage, and its structural or geological causes, it is necessary to adopt a proper design approach for the restoration of the liner.

The first necessary step consists in the evaluation of the state of stress within the present support in order to assess its safety with respect to the rock pressure.

This evaluation requires a sufficient knowledge of the mechanical characteristics of the rock mass that are determined through a proper in situ and laboratory investigation. In addition it is necessary to choose a suitable numerical model for analyzing the rock-structure interaction problem.

To validate the result of analyses it is advisable to measure the stresses within the liner, e.g. by means of flat jack tests.

If the level of damage is limited, the calculations can be based on relatively simple models, like the well-known convergence-confinement method. In more complex conditions recourse can be made to elastic-plastic finite element analyses.

In this context the correct evaluation of the present stress distribution would require the simulation of the original excavation and construction processes of the tunnel. In most cases, however, the records nowadays remaining of these aspects are quite limited. Consequently the calculations are often confined to a plane-strain scheme of the opening section in which the excavation/construction steps are modeled in a simplified manner.

If the observed damages are not severe, and if the evaluated stresses show that the present liner can safely bear the rock pressure, a light or intermediate rehabilitation can be chosen.

On the contrary, if one of the above conditions is not fulfilled a heavy structural restoration is necessary. A series of relevant problems shows up in this case that concern, in particular, the quantitative evaluation of:

- The maximum length of the liner segments that can be safely demolished and re-constructed.
- The need of rock treatments before demolition.
- The structural characteristics of the new liner.

Note that the increase of length of the segment to be demolished in general reduces the costs and decreases the safety of the works. Consequently, the choice of this length is a crucial aspect of the design.

The above quantities can be determined through proper numerical analyses that simulate with sufficient details the rehabilitation works. These calculations, however, cannot be based on the relatively simple two-dimensional model used for the previous stress evaluation. In fact, the demolition and reconstruction process has an intrinsic three-dimensional nature that cannot be disregarded.

To overcome this problem, the previously developed two-dimensional mesh can be easily “extended” in the direction of the tunnel axis to obtain the necessary three-dimensional finite element grid. The initial stress state, derived from the two-dimensional calculations, is then applied to the three-dimensional mesh and the elasto-plastic analysis of the demolition of one tunnel segment is carried out.

The segment length is modified, in subsequent analyses, evaluating the consequent spreading of plastic strains in the surrounding rock and the increment of stresses in the adjacent portions of the lining. The critical evaluation of these results permits choosing the maximum length of the segment that can be demolished ensuring adequate safety condition.

On this basis the calculations proceed simulating the construction of the new segment and the subsequent demolition and construction of the segments adjacent to it. They provide the stress state in the new concrete liner and the extension of the plastic zone in the surrounding rock mass. These results permits evaluating whether the assumed characteristics of the new lining and of the rock treatments are adequate to carry the pressure exerted by the rock mass and to ensure the safety of the restored tunnel.

4 A case history

The heavy rehabilitation here illustrated concerns the Valico twin tunnels of highway A15 (Autocamionale della Cisa) located in the Apennine mountain chain in central Italy (Figure 1). The highway is approximately 100 km long and about 15 km of it consist of two-lane twin tunnels.

The Valico tunnel has a length of 2040 m and crosses the Apennine chain, at an elevation of 750 a.s.l., at the Cisa pass (about 1040 m a.s.l.).

The transversal and longitudinal cracks (up to 50 mm wide) that developed during the eighties in the concrete linings in the vicinity of the north entrance of the tunnels suggested the heavy rehabilitation of relevant portion of the openings. This was based on the following steps: a) Geological study of the area, b) Geotechnical in situ investigation and laboratory tests on recovered samples, c) Evaluation of the effects of the demolition and reconstruction of the liner through two- and three-dimensional elasto-plastic finite elements analyses, d) Detailed definition of all executive phases of the rehabilitation works, e) Final numerical element analysis of the new structural support.

The geological, geomorphologic and geotechnical campaigns included borings and SPTs up to 33

m depth to characterize the formations present in the slope, namely: sandstone, shale and flisch.
The geological section shows a 15 m thick weak layer, of tectonic origin, at 11 m depth. This weak layer crossing the tunnel produced differential displacements and tensile stresses in the concrete linings that caused non-negligible damage to both openings.

Figure 1. Location of A15 (Autocamionale della Cisa).

Piezometers and inclinometers were also installed to record the slope movements and the fluctuations of the water table. Laboratory tests, that included one dimensional compression tests and direct shear tests, were performed on the recovered samples to define their geotechnical properties.
The northern tunnel (cf. Fig 2) presents a heavily damaged portion, about 35 m in length, adjacent to two moderately damaged sections, 10 m in length, on each side. The depth of cover of the damaged tunnel ranges between 15 and 23 m. The southern tunnel presents similar, but less severe, problems.
The poor state of the permanent lining, and the presence of fracture and of large gaps between it and the temporary support, suggested the demolition and reconstruction of its damaged portion.
According to the design approach previously outlined, two-dimensional plane strain analyses were first performed to evaluate the stress and strain states in the old lining and in the surrounding rock mass. To this purpose the two-dimensional mesh shown in Figure 3 was adopted that includes both tunnels and a sufficient portion of the slope around them.
The plane strain analysis was subdivided into a number of steps. First, the in situ stress state prior to the excavation of the tunnels was estimated by “activating” the elements of the mesh (subdivided into 12 layers) from bottom to top, as discussed in (Gioda & Borgonovo, 2004). The own weight of the corresponding activated elements was applied at each step.
The excavation of the tunnels was subsequently simulated subdividing it into a series of steps. To this purpose, the stress state within the element to be excavated was converted into equivalent nodal forces, these elements were eliminated from the mesh and the previously evaluated excavations forces were applied to it. The consequent stress/strain variation was evaluated through an elasto-plastic analysis. The installation of the temporary support (steel ribs and shotcrete) was taken into account by introducing equivalent beam elements.
Program FEARSM, specifically developed for the elasto-plastic Finite Element Analysis of Rock/Soil

Masses (see e.g. Gioda et al., 1994; Gioda & Locatelli, 1999), was adopted for the calculations.

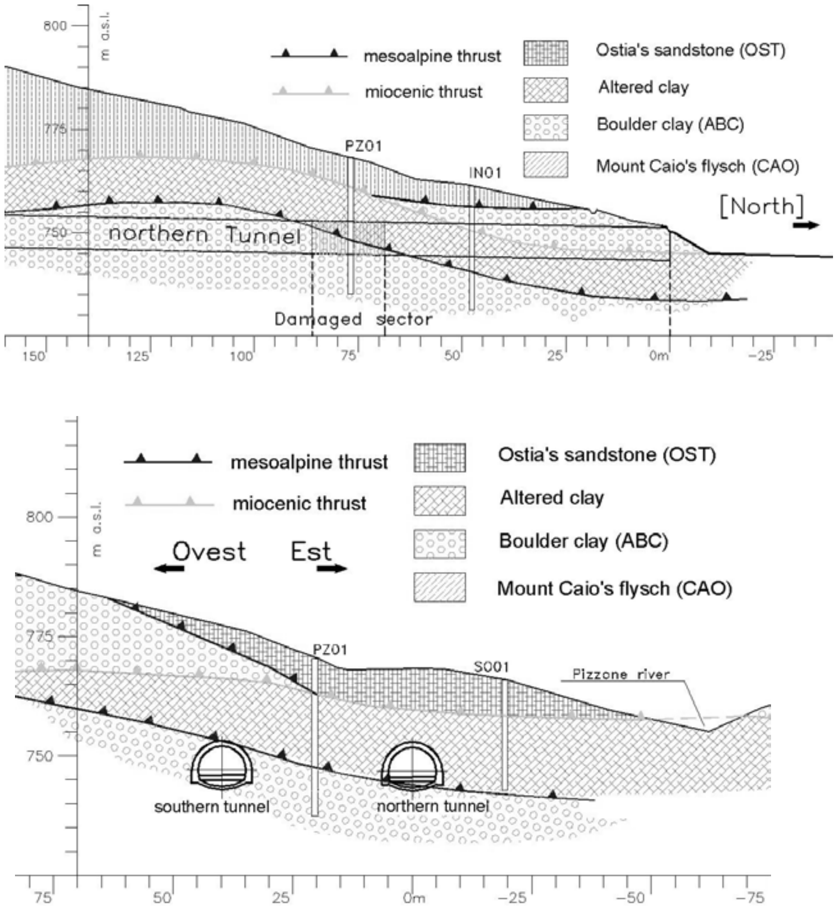

Figure 2. Geological sections of Valico tunnels with their damaged portions.

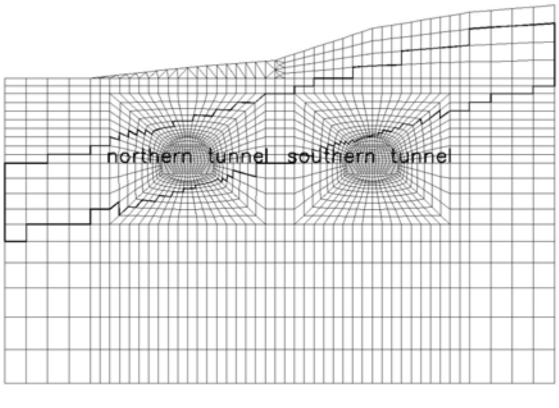

Figure 3. Finite element mesh for the plane strain analysis of Valico tunnels.

The “plastic zone” at the end of the two-dimensional analysis is shown through the contour lines of the second invariant of the deviatoric plastic strains in Figure 4.

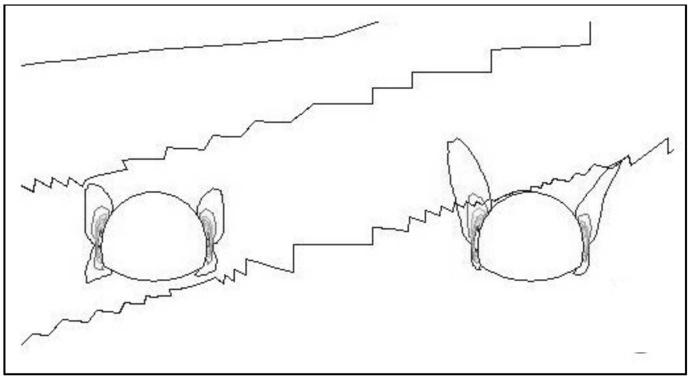

Figure 4. Contour lines of the deviatoric plastic strains at the end of the plane strain analysis.

The calculations show that the plastic strains in the rock mass in the vicinity of the northern tunnel are higher than those developing close to the southern tunnel. This is perhaps one of causes of the more severe damages present in the lining of the northern tunnel.

Having estimated the stress state prior to the rehabilitation works, the analysis proceeded with the evaluation of the additional stresses induced by the demolition of “segments” of the old liner. This was based on the three-dimensional mesh depicted in Figure. 5, in which the rock was subdivided into eight nodes, isoparametric brick elements, whilst thick shell elements were adopted for the liner.

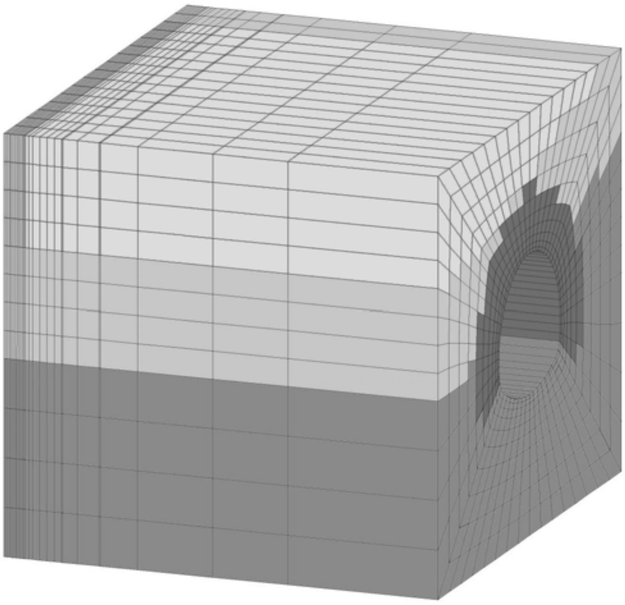

Figure 5. Finite element mesh for the three dimensional analyses of the northern tunnel.

Considering the relatively large distance existing between the two tunnels, and the limited length of the liner segments to be demolished and reconstructed, it was assumed that the interaction between the two tunnels has a negligible influence on the rehabilitation process. As a consequence, the mesh was limited to the northern tunnel only. In particular, the finite element grid was refined in a zone that includes three adjacent "segments" of the liner. Because of the problem symmetry only half of the central segment was introduced in the mesh.

In order to define the correct length of these segments, a series of elasto-plastic analyses was performed adopting different values for this key parameter. The analyses were also repeated introducing "improved" mechanical properties for the rock mass surrounding the tunnel. This takes into account the radial treatment of the rock surrounding the crown with sleeved steel micropile anchors and shotcrete, which is carried out before demolition.

The observed movements of the slope are likely to continue during time after the end of restoration. This would certainly induce fractures in the new lining if a continuous reinforced concrete support were adopted. To avoid this negative effect, suitable joints will be installed between adjacent segments of the new lining to limit the exchange of shear forces. To account for this provision the shear interaction between the segments was eliminated in the calculations.

The analysis of the entire demolition/reconstruction process was subdivided into five steps. The last one leads to the "long term" stresses in the new liner, assuming that the treatment of the rock mass looses its effects with time.

Some of the results of analyses are presented in Figures 6 and 7. In particular, the final distributions of the second invariant of the deviatoric plastic strains, for the case without rock treatments, are shown in Figure 6 and the final distributions of the bending moment in the new liner are shown in Figure 7a, b in both cases with and without treatments.

Based on the results of the finite element analyses, and of the in situ investigation, the design was developed for the replacement of the damaged liner. Its relevant technical details have been illustrated in (Locatelli et al., 2004).

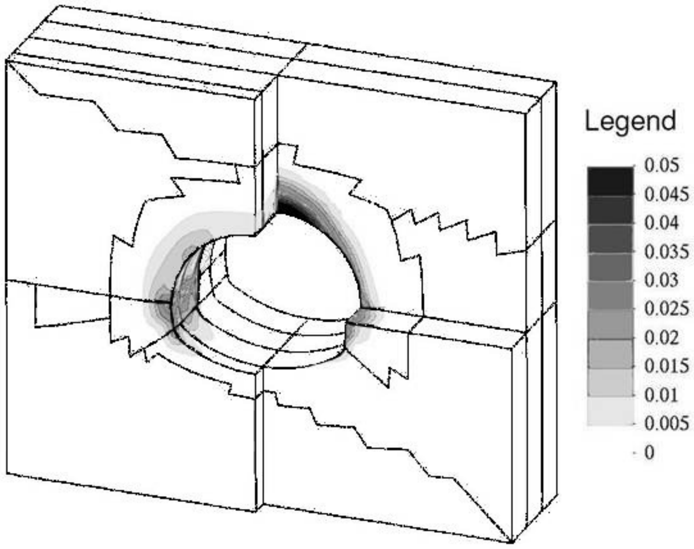

Figure 6. Distribution of the second invariant of the deviatoric plastic strains at the end of the tunnel rehabilitation (without rock treatments).

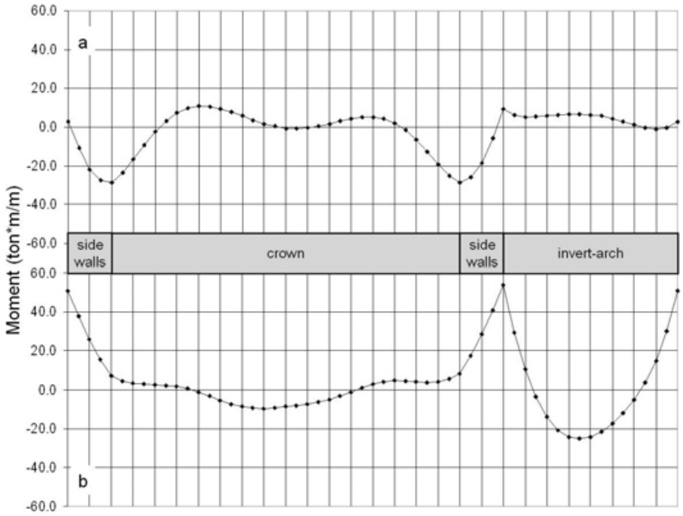

Figure 7. Bending moment distribution in the new liner: a) with and b) without rock treatments.

5 Conclusions

A design approach for the rehabilitation of damaged tunnel liners has been described that subdivides the problem into three levels of increasing complexity and cost.

The accuracy of calculations required for design is strictly related to the levels of damage and of the consequent rehabilitation. In the most severe cases recourse should be made to three-dimensional, elasto-plastic numerical calculations.

An application of this approach has been illustrated that concerns a highway twin tunnel located in the Apennine mountain chain in central Italy. This example shows that the adopted approach is able to reduce the uncertainties related to the evaluation of the stress distribution in the new supporting structures of the tunnel and in the surrounding rock. If adequate techniques are employed for the restoration, it provides also a proper level of safety during construction and involves acceptable costs of the overall rehabilitation.

6 References

Gioda G., Sterpi D., Locatelli L.. 1994. Some examples of finite element analysis of tunnels. Proc. 8th Int.Conf.of the International Association for Computer Methods and Advances in Geomechanics, Morgantown (USA), Balkema, 165–176.

Gioda G. and L. Locatelli. 1999. Back analysis of the measurements performed during the excavation of a shallow tunnel in sand. *Int.J.Numer.Anal.Methods in Geomechanics*, 23:13, 1407-1426.

Gioda G., Borgonovo G. 2004. Finite element modeling of the time-dependent deformation of a slope bounding a hydroelectric reservoir. *Int. J. of Geomechanics* (to appear).

Inokuma A., Inano S. 1996. Road Tunnels in Japan: Deterioration and Countermeasures. *Tunnelling and Underground Space Technology*, 11:3, 305-309.

Locatelli L., Di Marco G., Zanichelli C., Jarre P. 2001. Rehabilitation of highway tunnels – Techniques and procedures. Proc. AITES-ITA World Tunnel Congress, Milan.

Locatelli L., Borgonovo G., Gioda G. 2004. A Consistent Approach to the Structural Rehabilitation of Tunnel Liners. Proc. 18th Conf. on Advances in Tunnelling and Trenchless Techniques, Edmonton (Canada).