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Numerical analysis of tunnelling with jet-grouted canopy

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Abstract

The complex interaction between the soil and the structural elements of a tunnel built with provisional jet-grouted reinforcement is analysed with two- and three-dimensional FEM models to understand the mechanisms activated by this tunnelling methodology and to quantify the effects of possible simplifications introduced into the predictive analysis. With this goal in mind, the construction of a shallow tunnel is carefully simulated taking the geometry and the construction time sequence from a real case study. The role of soil constitutive modelling is investigated by comparing the results obtained with a linear elastic–perfectly plastic model, a hypo-plastic model, and an improved version of the latter model better reproducing the nonlinearity at the early stages of loading. Since a jet-grouted canopy, provisional sprayed concrete, and a permanent reinforced concrete lining are required to carry loads soon after their installation, the increase in stiffness and strength versus the time produced by the cement hydration has also been simulated. The outcomes of the analysis highlight the three-dimensional nature of the deformation mechanisms taking place near the advancing front, the effects produced by the different tunnelling operations, and the role of the different structural elements. Although the analysis of the settlements at the ground level reveals the importance of performing three-dimensional calculations with an accurate simulation of the nonlinearity of the soil behaviour, these aspects seem to play a minor role in the prediction of structural forces.

Keywords: Tunnelling; Jet grouting; FEM calculation; Constitutive model; Settlement; Soil–structure interaction

1. Introduction

The primary objective of tunnelling is to create a cavity in the underground and to replace the portion of excavated soil/rock with a hollow structure that is able to adsorb the stress acting on the removed material. During such an operation, the construction methodology plays a meaningful role in terms of both the ground deformations and the stress activated in the newly created lining. This concept can be easily visualised from the simple schematisation reported in Fig. 1 (Pacher, 1964). Here, the stress exchanged between the ground and a generic lining (p_r) and the radial convergence ΔR of both systems are found at the intersection between two curves, namely, a decreasing continuous line representative of the ground response and an increasing dashed line reproducing the lining stiffness. The diagram shows that, while the convergence, quantified by the abscissa of the intersection point, decreases with the stiffness of both the ground and the lining, the exchanged stress, represented by the ordinate of the same point, increases with the lining stiffness and decreases for a stiffer response of the surrounding material.

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This scheme also includes the possibility, theorized by the New Austrian Tunnelling Method (NATM-Műller-Salzburg and Fecker, 1978; Műller-Salzburg, 1978), of somehow waiting before the insertion of the lining in order to allow some relaxation at the tunnel boundaries and to permit the formation of a load-bearing ring in the ground around the excavated section (Malvern, 1969). In this case, the additional convergence, quantified in Fig. 1 by a rightward shift of the dotted curve, is accompanied by a reduction in the force that has finally built up in the lining. Such an effect, while being advantageous for tunnels excavated in firm ground or rock, is harmful and must be carefully avoided in the case of soft cohesive or deformable cohesionless soils, where leaving the excavation unprotected from the lining may induce intensive plasticisation or even softening (Attewell et al., 1986). The problem becomes particularly critical for shallow tunnels built under densely urbanised areas, as deformation may propagate up to the ground level and generate intolerable settlements.

Typical countermeasures in these cases span from the alternate excavation of smaller cross sections (partial face excavation), associated with the insertion of a sprayed concrete lining reinforced with fibres (Thomas, 2009), to the provisional improvement of the surrounding soil by ground freezing, grouting, forepoling, etc. In extreme cases, "traditional" methods may be substituted with shield heading technologies (e.g., Guglielmetti et al., 2007), the choice being dictated by a combination of factors including feasibility, construction speed, cost effectiveness, etc. (Kolymbas, 2008; Chapman et al., 2010).

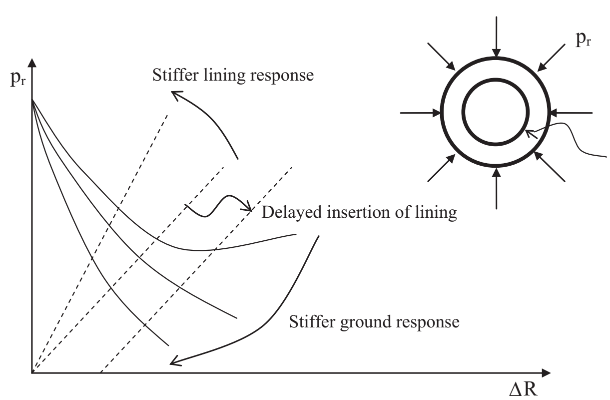

Fig. 1. Schematic interaction between ground and lining in tunnel construction (Pacher, 1964).

The jet-grouting technique consists of creating columns of cemented material by injecting grout from previously drilled boreholes. Its great success derives from the possibility of arranging the columns in many ways, to form structures of various shapes and dimensions (Croce et al., 2014). For tunnelling, a portion of cemented material is formed around the tunnel contour prior to the excavation (Croce et al., 2004) in order to stiffen the response of the material surrounding the tunnel and to reduce the stress and radial convergence in the lining (see Fig. 1). Treatments may be performed either from the ground surface (Arroyo et al., 2011) or from inside the tunnel (Russo and Modoni, 2005). In the former case, the different positions of the machinery for the ground improvement and the excavation allow the construction process to be speeded up; however, limitations arise from the relatively wide free spaces requested at the ground level. In the second solution, which is the case herein analysed, a curved roof, called a canopy, is formed by injecting a crown of partially overlapping sub-horizontal columns from the advancing front. In spite of a slower advance caused by the alternation of ground improvement and excavation, it is possible to build tunnels even in densely urbanised areas with this methodology. Starting from a generic position, tunnelling with temporary jet-grouted canopies requires the sequence of working phases illustrated in Fig. 2. It includes, following the longitudinal section from right to left, the reinforcement of the tunnel's front (Fig. 2), the creation of a conical canopy with diverging jet-grouting columns, the excavation, the addition of sprayed concrete reinforced with steel ribs, and the placement of the permanent lining.

Due to the shape of the different elements and to the sequence of the operations, a complex three-dimensional mechanism takes place during the different tunnelling phases. The deformation varies along the longitudinal profile and stress is activated in the different cross sections ruled by the

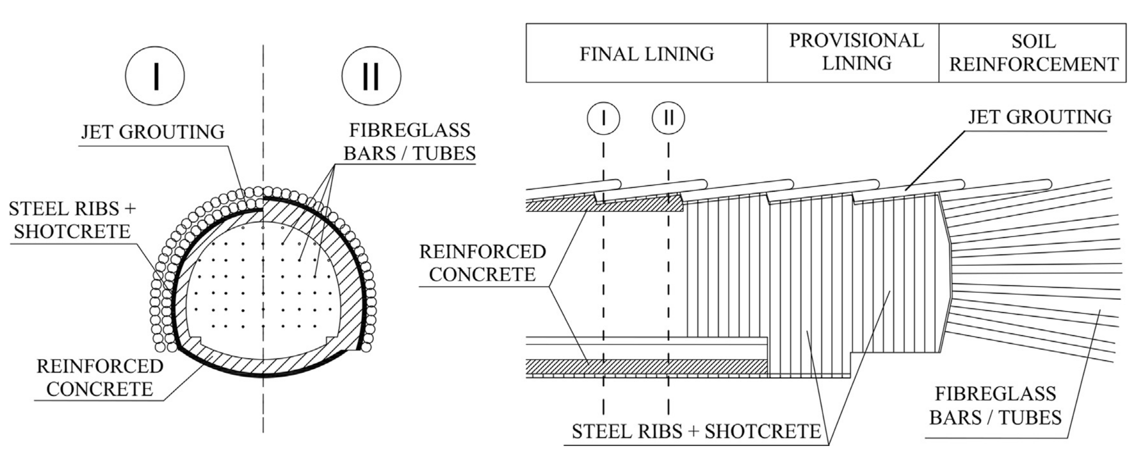

Fig. 2. Typical construction sequence of full face excavation with jet grouted canopy.