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Ground reaction curve for tunnels with jet grouting umbrellas considering jet grouting hardening

Mahdi Heidari*, Fulvio Tonon

Department of Civil Engineering, University of Texas at Austin, Austin, TX, USA

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ABSTRACT

In the calculation of the reaction curve for grounds reinforced with jet grouting umbrellas in tunnels, the jet grouting progressive hardening is ignored by assuming mean values for the jet grouting properties. In this paper, we present a new procedure that calculates the reaction curve for these grounds, considering jet grouting hardening. Tunnel excavation is represented in the ground plane-strain analysis by increasing the tunnel convergence at a rate obtained from the tunnel longitudinal deformation profile. This novelty allows us to perform the analysis at an accurate rate, which is critical for jet grouted tunnels. Using this new approach, one can estimate a lower bound for convergence of supported tunnels and hence an upper bound for pressure on the tunnel supports. Using a finite element model, we calculate the ground reaction curves for a case study tunnel with and without considering jet grouting hardening. The resulting curves illustrate that ignoring the jet grouting hardening can lead to an unsafe design of these tunnels. We use the ground reaction curve to also estimate the savings in tunnel supports due to jet grouting and the efficiency of jet grouting at different tunnel advance rates.

1. Introduction

Subhorizontal jet grouting is a pre-confinement method that reinforces the ground ahead of the tunnel face with jet grouted umbrellas [1,2] (Fig. 1a). This method is increasingly used in poor ground conditions, where the primary concern is to control the tunnel deformation at the walls (convergence) and at the face (extrusion) (Fig. 1b). Both types of deformation are supplied by the tunnel convergence ahead of the face (pre-convergence) [3]. By controlling the tunnel pre-convergence with jet grouted umbrellas, this method controls both the convergence and the extrusion in a tunnel.

Jet grouted tunnels have been analyzed in different ways in the past two decades [4–11]. The majority of these analyses use simple models that assume constant properties – stiffness and strength – for the jet grouting [4–9]. These properties, however, vary significantly as a result of the jet grouting progressive hardening over time. This variation has a considerable impact on the results of the tunnel analysis because it takes place through the loading period of the jet grouting. The deformation at a tunnel cross section takes place while the tunnel face moves for approximately three tunnel diameters [12,13]—from one tunnel diameter before the cross section to two tunnel diameters past it. Given the tunnel diameters and the advance rates in practice (0.6–1.5 m/day), the deformation at a cross section of a jet grouted tunnel occurs in a few weeks. Over this loading period, the jet grouting properties change considerably. The impact of these properties on the tunnel response is more significant in poor ground conditions [14]. Few studies that take into account the jet grouting hardening, on the other hand, use complex models that are unaffordable to the practice of tunnel design and hard to gain insight into the impacts of jet grouting on the ground response [10,11].

In this paper, we use the convergence–confinement method for the tunnel analysis. This method uses two-dimensional models that are affordable and insightful for the preliminary analysis of tunnels [15,16]. In this method, the ground (herein, the ground with jet grouting umbrellas) and the support are analyzed independently and their resulting responses are represented by the ground reaction curve (GRC) and the support reaction curve (SRC), respectively. These curves are used along with the longitudinal deformation profile (LDP) to calculate the deformation and the stresses in the tunnel. We present a method to calculate the GRC for grounds with jet grouting umbrellas that takes into account the jet grouting hardening.

The cement hardening has been considered in the convergence–confinement method to calculate the *SRC* for tunnels supported with shotcrete [17,18]. These considerations assume a longitudinal variation for the pressure at the tunnel. In this paper, we show that this variation cannot be derived for jet grouted tunnels; hence, a new method is suggested that relies on the LDP of the tunnel. We examine

* Correspondence to: Department of Civil Engineering, The University of Texas at Austin, 1 University Station C1792, Austin, TX 78712-0280, USA. Tel.: +1 512 584 0299.
E-mail address: mahdiheidari@utexas.edu (M. Heidari).

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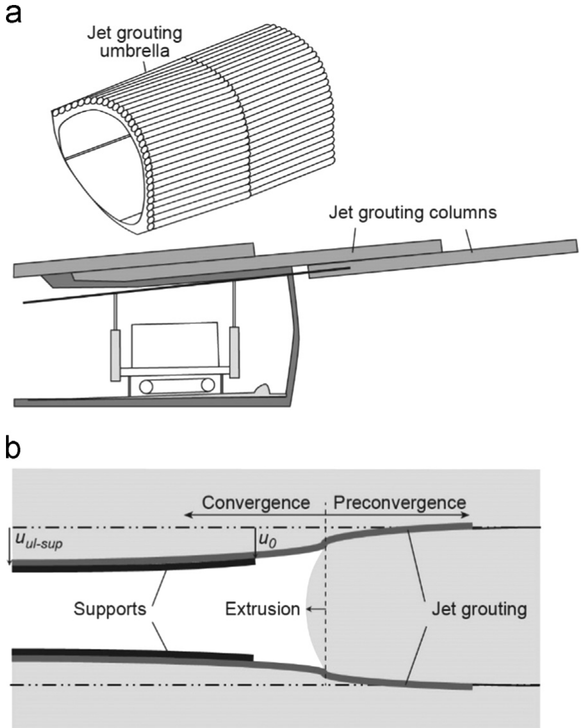

Fig. 1. Reinforcement of ground in a tunnel with subhorizontal jet grouting umbrellas. (a) Implementation of the umbrellas around the tunnel cross section ahead of the face by creating overlapped jet grouted columns (modified after [11]). (b) Location of the umbrellas vs. different types of deformation in a jet grouted tunnel. u_0 and $u_{\text{ul-sup}}$ are the initial and the ultimate convergence of the tunnel with supports.

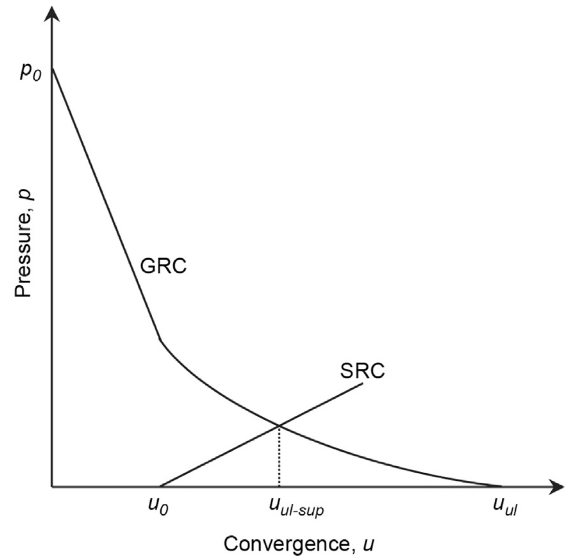

Fig. 2. A schematic convergence–confinement plot showing the ground reaction curve (GRC) and the support reaction curve (SRC). The GRC intercepts the pressure axis at the initial ground stress, p_0, and the convergence axis at the ultimate convergence u_{ul} (convergence of tunnel with no supports). The SRC intercepts the convergence axis at the initial convergence, u_0. The intersection of the GRC and SRC defines the ultimate convergence of the tunnel with supports, $u_{\text{ul-sup}}$.

a well-established relation that generates LDP's for unreinforced tunnels to assess its applicability to jet grouted tunnels. Finally, we calculate the GRC for a jet grouted tunnel using a finite element model and discuss the results with special reference to the information that the GRC of the tunnel can provide for the tunnel preliminary design.

2. Convergence–confinement method

In the convergence–confinement method, it is assumed that a tunnel cross section deforms in plane strain conditions as the tunnel face advances through the cross section. Therefore, the tunnel analysis is simplified to finding the deformations and pressures between the ground and the supports in cross section. The analysis is further simplified to finding a radial deformation and pressure by assuming axisymmetric conditions for the tunnel, i.e., assuming a circular cross section for the tunnel and assuming isotropic properties and in situ stresses for the ground [16].

The ground and the support are analyzed independently in plane strain conditions. In these analyses, the ground and the support response are characterized by calculating their radial displacement (convergence) at different radial pressures, illustrated by two reaction curves in a pressure-convergence plot (Fig. 2). Fulfilling the kinematic compatibility and the equilibrium between the ground and the support, the intersection of the curves signifies the ultimate convergence and pressure at the tunnel, attained far behind the tunnel face. The support reaction curve is horizontally offset in this plot to take into account the initial convergence—the ground convergence developed prior to support installation (Fig. 1b). The initial convergence has a marked influence on the estimated tunnel deformation and pressure, particularly in poor ground conditions [19,20].

The initial convergence is estimated by using longitudinal deformation profiles. These profiles define the variation of the tunnel convergence along the tunnel axis as a function of the distance to the tunnel face [15,21]. Among several relations proposed to define the profile for unsupported tunnels, the one suggested recently by Vlachopoulos and Diederichs [22] explicitly takes into account the radius of the ground plastic zone and defines the profile ahead and behind the tunnel face with separate relations:

$$\begin{aligned} u(x) &= \tfrac{1}{3}u_{\text{ul}}\exp\left(\tfrac{x-0.15\,R_p}{R}\right) && \text{for } x \le 0;\text{ ahead of the face} \\ u(x) &= u_{\text{ul}}\left[1-\left(1-\tfrac{1}{3}\exp\left(-0.15\tfrac{R_p}{R}\right)\right)\exp(-1.5\tfrac{x}{R_p})\right] && \text{for } x \ge 0;\text{ behind the face} \end{aligned} \tag{1}$$

where u is the tunnel convergence, and x is the distance to the tunnel face. R is the radius of the tunnel. R_p is the ultimate radius of the plastic zone developed in surrounding ground and u_{ul} is the ultimate tunnel convergence, both occurring far from the tunnel face; these two quantities are calculated by using either analytical solutions [23] or numerical modeling.

The profiles derived for unsupported tunnels, however, overestimate the profile for the tunnels with supports [20,24,25]. This error leads to an unsafe design of supports as it causes underestimation of the pressure on the supports. Among the different suggestions made to take into account the effect of supports on the LDP, the one proposed by Nguyen-Minh and Guo [26] is well established [20]. In this relation, the effect of supports is incorporated by scaling down the LDP of the unsupported tunnel with a scale factor φ. By fitting the convergences obtained from axisymmetric analysis of tunnels with different support stiffnesses, support installation distances from the face, and ground in situ stresses, this scale factor was suggested as a function of the ratio between the ultimate convergence of the tunnel with supports, $u_{\text{ul}-\text{sup}}$, and the one of the tunnel without supports, u_{ul}:

$$u(x)_{\text{sup}} = \varphi(z)\,u(x); \qquad \varphi(z) = 0.55 + 0.45\,z - 0.42\,(1-z)^3\,; \qquad z = \frac{u_{\text{ul}-\text{sup}}}{u_{\text{ul}}} \tag{2}$$

To estimate the initial convergence, u_0, for a support, Eq. (2) needs the tunnel ultimate convergence, u_{ul-sup}, which itself depends on u_0.