Available online at www.sciencedirect.com
ScienceDirect
Tunnelling and Underground Space Technology 23 (2008) 38–45
Tunnelling and Underground Space Technology
incorporating Trenchless Technology Research
www.elsevier.com/locate/tust

A simplified 3D model for tunnel construction using tunnel boring machines

H. Mroueh *, I. Shahrour

Laboratoire de Mécanique de Lille (UMR 8107), Université des Sciences et Technologies de Lille, F-59655 Villeneuve d'Ascq, France

Received 5 September 2006; received in revised form 21 November 2006; accepted 28 November 2006
Available online 24 January 2007

Abstract

This paper includes a presentation of a simplified three-dimensional numerical model for the prediction of soil movement induced during tunnel construction using tunnel boring machines (TBM). The model is based upon the generalization of the convergence-confinement concept to 3D tunnel construction. It uses two parameters (L_{dec} and α_{dec}) which stand for the length of the unlined zone and the partial stress release, respectively. The value of the parameter L_{dec} can be taken equal to the tunnel diameter, while the value of α_{dec} can be determined by fitting the model to empirical formula, and then adjusted based on settlement registered during tunnel construction.

The capacity of the model is illustrated through an application to a shallow tunnel in soft soil. The comparison of the numerical results to those suggested by different authors shows good agreement.

Keywords: Tunnel boring machine; TBM design; Finite element method; Three-dimensional; Non-linear; Shield tunnelling; Convergence-confinement

1. Introduction

Construction of tunnels in soft soils induces generally soil movement, which could seriously affect the stability and integrity of existing structures (pile foundations, buildings...). In order to reduce such movement, in particular in urban areas, contractors use more and more the tunnel boring machines (TBM) for the construction of tunnels. Indeed, thanks to the application of a face pressure and to the temporary support, the TBM allows to reduce the soil disturbance due to tunneling, providing enhanced safety to existing structures (Herrenknecht, 1998; Kurihara, 1998; Kuwahara, 1999).

Analysis of the impact of the tunnel construction using TBM on the soil movement requires the solution of large 3D non-linear soil–structure interaction problem. Non-linearity results from the non-linear behavior of geomaterials, the condition at the soil–structure interface (soil – grouting-lining, soil – shield,) and the evolution of the geometry during excavation. The 3D aspect is due to the significant stress disturbance and soil movement induced ahead the excavation front. 3D elastic analyses conducted by Panet and Guenot (1982) showed ground convergence at the tunnel face which was equal to about 27% of the total settlement. Higher values, up to 50%, were observed in field measurements and computational analyses in soft ground (Moraes, 1999). Finite element modeling of the tunnel construction using TBM requires also the consideration of the complex tunnel process which includes the advance of the TBM, the application of the face pressure, the soil excavation, the installation of an immediate support behind the rotating front, the installation of the definitive support (lining ring) and the tail void grouting. A realistic consideration of these issues in the 3D calculation constitutes a high challenge (Dias et al., 2000; Cheng et al., 2002; Galli et al., 2004), because of the large effort for numerical modeling and calculation and the large uncertainties concerning the interaction between the shield and the soil, the behavior of the grouting, and the distribution of the tail void. Consequently, the use of this approach in tunnel design is still limited, because it requires impor-

* Corresponding author.
E-mail address: Hussein.Mroueh@polytech-lille.fr (H. Mroueh).

0886-7798/$ - see front matter
doi:10.1016/j.tust.2006.11.008

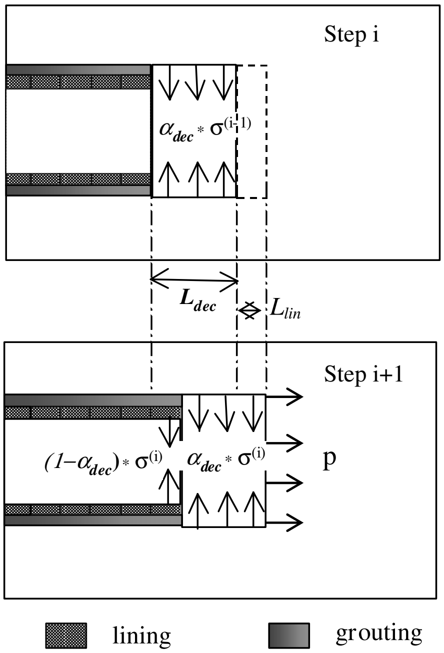

Fig. 1. Method used for the tunnel construction using TBM.

tant modeling effort and computational time. In order to overcome this difficulty, a simplified method is proposed in this paper to model the TBM tunneling process using a three-dimensional model based on the convergence-confinement method (Panet and Guenot, 1982) with two release parameters: α_{dec} and L_{dec}, which stand for the partial stress release and the length of the unlined zone, respectively (Fig. 1). This method can be easily implemented and employed using existing programs based on either the finite element or the finite difference method.

The paper presents successively, the proposed method, its application to a model tunnel and the sensitivity of the method to the release factors α_{dec} and L_{dec}.

2. Presentation of the numerical model

Numerical modelling of the tunnel construction using TBM constitutes a hard task, because it requires consideration of complex aspects such as the soil excavation, the overcut or annular space between the jacking pipe and the excavation, the application of the face pressure, the installation of the definitive support constituted of lining rings and the grouting of the annular space. It also requires the description of the non-linear behavior of both the soil and the lining and the condition at the soil–structure interface. Modelling of the tunnel construction is also three-dimensional, because the TBM induces an important stress disturbance and soil movement ahead the excavation front. Modelling of the annular space between the ground and the lining extrados is still problematic, because of the difficulties to collect effective data on the distribution and grouting of this space.

Up to now, it seems very difficult to consider the above-mentioned issues in the practical design of tunnels. In order to overcome this difficulty, a simplified method is proposed in this paper to model the TBM process using a three-dimensional model based on the convergence-confinement method (Panet and Guenot, 1982). This method uses a step-by-step procedure. Each step corresponds to the progression of the tunnel face by a distance L_{lin} (Fig. 1). At each step of the procedure, the stress release around the tunnel head is modeled using the parameters α_{dec} and L_{dec}, which stand for the ratio of the stress release and the length of the unlined zone, respectively. The calculation procedure at the step (incr) includes:

(a) Determination of the incremental force resulting from the soil excavation (ΔF). This force is equal to the difference between the nodal force vector ($F^{(\mathrm{incr})}$) due to the external forces (self-weight, surface loads, front pressure,...) and the nodal internal forces at the previous step 'incr-1'; calculation of ΔF is carried out using the following expression:

$$\Delta F = F^{(\mathrm{incr})} - \int_{V^{(\mathrm{incr})}}^{t} B_e \sigma^{(\mathrm{incr}-1)}\, dV \tag{1}$$

$V^{(\mathrm{incr})}$ represent the volume of the soil mass at the step (incr); B_e is the strain interpolation matrix which contains the spatial derivatives of the interpolation functions ($\varepsilon = B_e \cdot u$; u nodal displacement); $\sigma^{(\mathrm{incr}-1)}$ denotes the stress tensor at the previous step (incr-1).In order to take into account the partial deconfinement resulting from the tunnel construction process (overcut, injection of the annular void, installation of the definitive tunnel support,...), a parameter α_{dec} is used for considering the partial release on the unsupported section of the tunnel; the length of this section is assumed to be equal to L_{dec}. The incremental nodal force vector in this section (ΔF) is transformed using the following expression:

$$\Delta F' = \alpha_{dec} \cdot \Delta F \tag{2}$$

(b) Activation of the lining elements located in the new section and a full release of stresses in this section.

(c) Application of the face pressure 'p' (Fig. 1); the pressure is assumed to be constant with depth; it corresponds to a 'compressed-air pressure' TBM. Note that this pressure can vary with depth to model 'slurry shield' machines or 'earth pressure balance' (EPB) machines.

The soil movement is controlled through the partial release factor α_{dec} and the parameter L_{dec} which enable users to consider the influence of the void space and grouting around the tunnel. The determination of these parameters can be carried out by an adjustment procedure using empirical models and measurements during tunnel construction.

The following section presents the application of the proposed method to a model tunnel, which will be followed by a sensitivity analysis of the model to the variation of the partial release parameters α_{dec} and L_{dec}. This analysis allows the elaboration of a methodology for the determination of these factors.