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Movements caused by the excavation of tunnels using face pressurized shields — Analysis of monitoring and numerical modeling results

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ABSTRACT

In this paper, monitoring results of two cross tunnel sections are presented. This underground work has been realized for a subway in an urban area (Lyon, France). By comparison with measurements of other projects, it appears that the face instability and the annular gap identified after the shield release are the main sources of short-term settlements.
These observations of vertical and horizontal movements during the tunnel excavation by a slurry pressurized tunnel boring machine are then compared with several numerical approaches. The 2D numerical approach uses the concept of volume loss and is applied to each excavation stage. It simulates approximately the observed movements but requires the use of empirical coefficients to represent in two dimensions the three-dimensional problem. The 3D approach considers more directly the physics of the problem and permits to take into account: the slurry pressure at the tunnel face, the shield conicity, the grout injection in the annular void and the grout consolidation. Three dimensional numerical calculations are the most accurate approaches to simulate all the physical processes occurring during tunneling. However this type of model assumes that all the parameters that control the movements induced by the excavation are well known. Due to the complexity of a tunneling boring machine, it is not necessarily the case.

1. Introduction

In urban areas, construction of shallow tunnels creates deformations and displacements of the surrounding soil which may affect existing structures and thus be the source of unacceptable dysfunctions. Moreover, with the development of pressurized face tunnel excavation techniques, work in poor soil conditions and difficult environments have expanded in recent years. Numerical simulation methods appear to be appropriate tools to design such structures and to forecast movements caused by the tunnel excavation, but they need to be validated.

A literature review has shown that movements generated by this excavation process are strongly influenced by the soil type but also by many parameters controlling the TBM work: slurry pressure at the tunnel face, shield overcutting, shield conicity, procedure and injection parameters of the annular void, type of grout (Rowe and Kack, 1983; Clough et al., 1985; Pantet, 1991; Moroto et al., 1995; Kastner et al., 1996). The empirical prediction methods such as numerical approaches which only simulate the final phase may be insufficient. It is therefore necessary to develop and qualify tools and methodologies allowing the correct simulation of ground movements in conjunction with the used parameters and the excavation stages.

This study is based mainly on the example of the Vaise subway (near Lyon, France) construction. This site is taken as a reference because of complete and accurate database available. The collected data contains in situ observations on various monitoring cross sections such as slurry pressure, grouting pressure, horizontal and vertical displacements in the soil mass.

In a first step, in situ observations are analyzed and permit highlighting the contribution of each parameter on field movements around the tunnel. This analysis shows the complexity of interactions.

In a second step, several numerical approaches have been tested and compared with observations.

The 2D numerical simulations, following a cross section orthogonal to the tunnel axis use concepts such as stress release (Panet, 1988) or volume loss (Benmebarek et al., 1998) at each stage of the underground work. However, these approaches require the use of empirical coefficients similar to the stress release coefficient to take into account the local three-dimensional nature of the problem.

To simulate with accuracy the impact of the tunneling key parameters, only a 3D approach taking into account each of them can directly reproduce the physics of the problem. It is thus necessary to simulate correctly the tunnel face pressure, the shield advance, the injection of the annular void controlled by pressure or volume and the grout consolidation.

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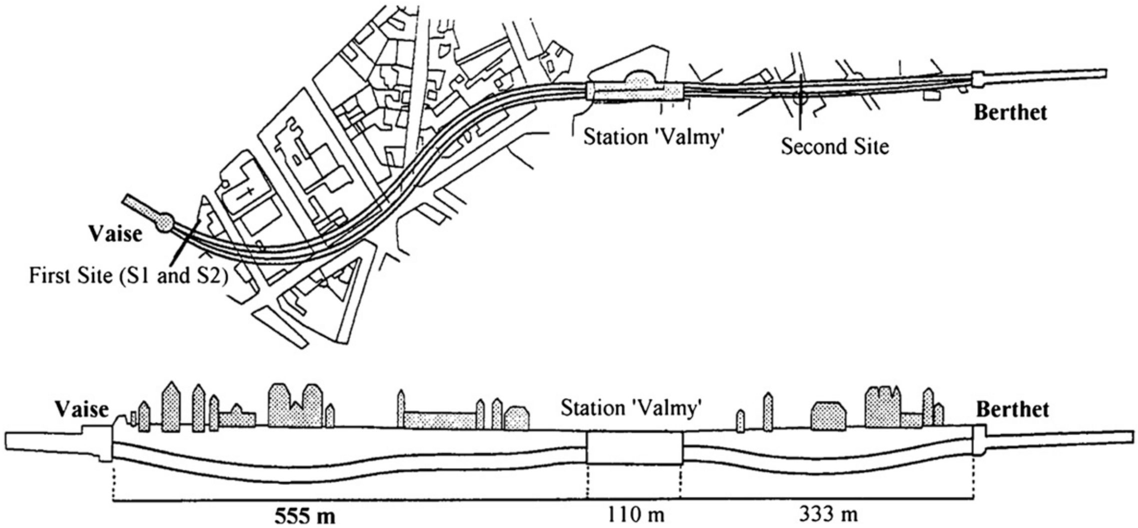

Fig. 1. Plan view of the construction site.

2. The project

The extension of the subway line D of Lyon, between the “Gorge du Loup” station and the “Vaise” station consists of two tubes of 6.27 m (outside diameter) and 950 m in length (Figure 1). They were dug between June 1993 and March 1995 under an overburden nowhere greater than 15 m. The line, entirely under the water, is located at shallow depth in a densely urbanized land across very soft soils. A typical geotechnical section is given in Fig. 2. Extensive in situ and laboratory tests performed provide a description of the different geological formations encountered. Table 1 summarizes the project data and the average geotechnical characteristics of the different layers. The tunnel alignment is situated under the water table and crosses mainly silty alluvial deposits.

The silts, located on the entire section or at the upper part of the tunnel section exhibit water contents near the liquid limit and are therefore very sensitive to disturbance.

Because of the risk of settlements or sinkholes, the excavation technique uses pressurized slurry to support the tunnel face. The tunneling boring machine consists of a shield and a follower train with four trailers. The tunnel face support is implemented by a bentonite slurry pressure whose circulation also transports soil excavated by the cutting wheel. The tunnel was excavated primarily supported by a conical shield of 6.85 m in length and with a diameter decreasing from 6.27 m to 6.24 m from the face to the shield end. The final support is made by precast concrete rings of 1 m in length and 0.35 m in thickness installed under the protection of the TBM tail.

Each ring of 6 m outside diameter, consists of five precast elements. The annular void of 13.5 cm thickness, opened by the TBM advance is filled by an inert grout injected through six pipes situated on the shield periphery (Figure 3). The injection is realized by each pipe, and its pressure is controlled by a tunnel machine robot which triggers injections according to thresholds set by the tunnel pilot. The slurry, consisting of fine sand, filler and bentonite is liquid at its initial water content of w = 14%. Its consolidation will allow this mixed material to quickly gain in strength. A decrease of 2% of its water content increases significantly its consistency.

3. Site instrumentation

The complex, difficult conditions of this work provided an opportunity to set up a research project based on accurate on-site monitoring in order to develop and assess a procedure for forecasting ground movements induced by tunneling. Instrumentation units were set up at two monitoring areas: site 1 and site 2 (Figure 1).

For the first site, two monitoring sections are realized (S1 and S2). They are located at the beginning of the track (respectively 31 m and 65 m from the “Vaise” station), before crossing under the first

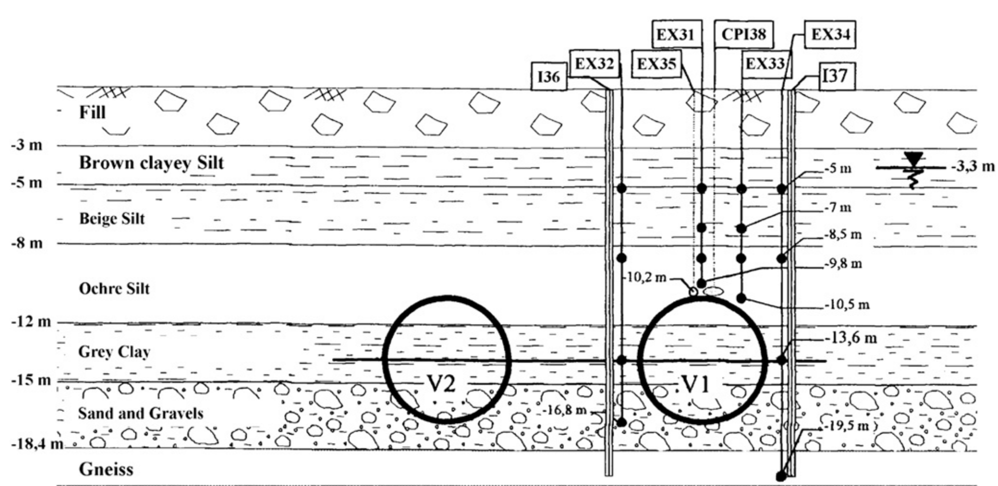

Fig. 2. Instrumentation of the Lyon–Vaise tunnel alignment — Section S2.