Some remarks concerning EPB and slurry shields

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Some remarks concerning EPB and slurry shields

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ABSTRACT: The paper discusses the issue of shield tunneling under suboptimal geological conditions from a geotechnical and a contractual perspective. The increasing demand for urban underground spaces has promoted considerable technological progress in the field of mechanised tunneling. On the other hand, closed shields are applied more and more frequently under geological conditions that are beyond their optimum operational range. In order to reduce the risk to an acceptable level, additional measures such as ground improvement are often necessary. For ensuring tender price comparability, the cost of these measures should be estimated in the pre-tender design and be included - separately for the different shield types - in the bill of quantities.

1. INTRODUCTION

Traffic congestion and environmental constraints intensify the utilization of underground spaces in urban areas. Construction projects are being carried out more and more frequently under difficult conditions: several constraints and potential conflicts associated with nearby infrastructure or other uses of space; high potential third imparty impact; unfavourable geology involving soft ground or mixed face conditions.

The increasing demand for urban underground space has promoted technological progress in the last decade, particularly in the field of mechanised tunneling. The construction methods used in shallow soft ground tunneling beneath the water table must ensure control of the ground at the tunnel heading and, additionally, prevent seepage flow towards the working face. Slurry and EPB shields fulfill these goals for a wide range of geological and hydrogeological conditions by providing support to the tunnel face continuously during excavation. Modern closed shields limit the need for costly and time-consuming ground improvement measures such as grouting or artificial ground freezing.

Technological developments have decreased construction times and costs and this, in turn, has raised demand. It is interesting to note, furthermore, that the development of large diameter closed shields (today's largest machines exceed 15 m in diameter) does not change only the way structures are constructed but it also affects the layout of the structures itself. For example, the rail tunnel in Figure 1 incorporates the platform level functions thereby reducing construction interferences between tunnels and stations.

As shown by recent successful projects, improvements in soil conditioning methods and in the technology of additives have extended the traditional range of applicability for closed shields (typically, fine-grained soils for EPB shields, coarse-grained soils for slurry shields). This has led to the impression that the ground is in general not the key parameter for machine

![Figure 1. Platform level (Barcelona Metro)](image-url)
type selection - an attitude cultivated sometimes by the TBM industry itself. On the other hand, the set-backs experienced in some large projects underline the need for a careful evaluation of the pros and cons of the various face support types for a given geotechnical environment.

2. GEOTECHNICAL CONSIDERATIONS

The importance of the geology is clearly reflected in the recommendations from major professional organisations (e.g., AFTES 2000, BTS 2005, DAUB et al 1997 & 2000). The evaluation of the different closed shield types is particularly demanding when the geology changes frequently along the alignment (thereby necessitating frequent changes of operation mode) or when the ground conditions are beyond the optimum operational ranges both of EPB and slurry shields over long portions of the alignment. Closed-shield operation under sub-optimal ground conditions involves a higher probability of failure or of inadmissible settlement. In many cases additional measures such as ground improvement will be necessary in order to reduce the risk to an acceptable level. Urban environments are particularly adverse in this respect, as the lack of free spaces at the surface may limit the feasibility of any additional measures or increase their cost considerably. For a concise discussion of the importance of systematic risk management in the context of urban tunneling, the reader is referred to Kovári and Ramoni (2006).

A detailed discussion of the mechanics of face support with closed shields is given in Anagnostou and Kovári (1994, 1996). The stability of the tunnel face and the deformations of the ground in EPB tunneling depend for given ground conditions on the face support pressure. In a fine-grained, low-permeability ground (the typical soil for EPB application), the face support pressure is equal to the total stress prevailing in the muck within the working chamber. In the case of a coarse-grained muck (e.g. consisting of the chips generated when tunnelling through weak rock), the ground response is controlled by the joint effect of the effective stress \( \sigma' \) acting on the tunnel face and of the pore pressure \( p \) in the working chamber (Fig. 2a). A high pore pressure \( p \) reduces the magnitude of the destabilizing seepage forces acting within the ground towards the face and is favourable also regarding surface settlement because it limits pore pressure relief and consolidation of the ground. Consequently, the higher the pore pressure \( p \), the lower the necessary effective support pressure \( \sigma' \), and vice versa. However, these two parameters are difficult to control in practice as they depend on the characteristics of the excavated ground, the way the ground is mixed in the work chamber, the rotational speed of the screw conveyor and the excavation advance rate. So, the ground response to tunneling by an EPB depends to a large degree on the complex interplay of geotechnical and operational factors.

With the exception of extremely coarse and poorly graded gravel soils (Fig. 3), slurry shields provide a support pressure which is independent on the nature of the ground. Contrary to the situation with EPB shields, face support is determined by only one parameter (the slurry-pressure, Fig. 2b) and, moreover, this parameter can be regulated directly. As EPB shields support the face with the excavated muck itself, the geology is decisive not only for the shear strength and stiffness of the ground ahead of the face but also for the spatial distribution and the fluctuation over time of the pressure within the working chamber. EPB shields are thus more sensitive to deviations from the optimum ground conditions than slurry shields and will likely require more additional measures than slurry shields in the case of a variable geology. In addition, EPB shields are
more prone to wear, thereby necessitating more frequent maintenance in the working chamber. Safe access to the cutter head may also require additional measures depending on the lengths of the drives and the spacing of shafts.

On the other hand, a comparative assessment should take into account, that the consequences of a face failure in the case of a slurry shield will likely be more serious than with an EPB shield, because of the larger volume of the ground that can enter uncontrollably into the working chamber through displacement of the slurry. Particular attention in this respect deserves the underground of old cities as it involves a higher probability to encounter unidentified cavities such as aqueducts or ancient wells during excavation (Fig. 4). When encountering such cavities, the slurry pressure drops to that of the ground water and, if the ground is lacks sufficient cohesion, the face collapses.

It should be noted, however, that a slurry pressure in excess to the ground water pressure is required for maintaining stability only for tunneling through granular or very low cohesion ground. If the ground has some strength (e.g., weathered but not completely decomposed weak rock), hydraulic equilibrium between chamber and ground suffices for stability (Fig. 5). An excess pressure may be, nevertheless, still necessary in order to reduce settlement depending on the stiffness of the ground and on the sensitivity of the buildings. Else the slurry shield might be operated even without Bentonite, i.e. only with pressurized water.

Figure 4. Collapse of an old well filled by pottery (Athens Metro)

Figure 5. De-stabilization due to deep slurry infiltration into an extremely coarse ground (Anagnostou and Kovari 1994)

Figure 5. Necessary slurry excess pressure $\Delta p$ at limit equilibrium as a function of the cohesion $c$ ($\gamma' = 11$ kN/m$^2$, $\gamma_{slurry} = \gamma_{water}$, computational method after Anagnostou and Kovari, 1994)
3. CONTRACTUAL CONSIDERATIONS

In many geotechnical situations, both EPB and slurry-shield tunneling may be feasible but in combination with additional measures (Fig. 6). The locations and the quantities of the additional measures should be evaluated separately for each type of face support, as one and the same ground may be favourable for the one mode of operation but unfavourable for the other.

A rigorous and unbiased evaluation of the additional measures is very important, particularly when considering that, for non-geotechnical, but nevertheless important reasons, EPB shields are often, almost by default, the first choice: Slurry-shield tunneling in urban environments is generally problematic, due to the limited space available at the surface for separation plants or muck disposal. This, in combination with the lower capital costs and the simpler operation of EPB shields creates a bias in favour of the latter, although slurry shields allow for a better control of the pressure in the working chamber under mixed face conditions or when tunneling through weak rock.

The machine selection should take into account, besides the capital and operational costs, also the costs and the time needed for the additional measures. Estimates of the appropriate quantities for complex geological formations are fraught with uncertainties. Procurement methods such as design-build with a lump sum do shift a considerable portion of the geological risk to the contractors, and experience from a number of projects shows them to be unsuitable: they may lead to high contingencies in the bids or, as happens more often, to project delays or poor quality work including unacceptable settlements or even collapses. The limited time available for bid preparation, in combination with the quite understandable calculated optimism of the tender phase, do not allow for a cautious assessment of the necessary additional measures.

4. CLOSING REMARKS

Leaving the decision about the machine type to the market is undoubtedly advantageous. Nevertheless, the quantities of additional measures should be estimated by the owner or his engineers in the pre-tender design and be included - separately for the different types of face support or modes of operation - in the tender documents or in the bill of quantities. Failing this, tender price comparability will be lost.

5. REFERENCES


