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Tunnel boring machines under squeezing conditions

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ABSTRACT

Squeezing ground represents a challenging operating environment as it may slow down or obstruct TBM operation. Due to the geometrical constraints of the equipment, relatively small convergences of one or two decimetres may lead to considerable difficulties in the machine area (sticking of the cutter head, jamming of the shield) or in the back-up area (e.g., jamming of the back-up equipment, inadmissible convergences of the bored profile, damage to the tunnel support). Depending on the number and the length of the critical stretches, squeezing conditions may even call into question the feasibility of a TBM drive. This paper sets out firstly to give an overview of the specific problems of TBM tunnelling under squeezing conditions; secondly to analyse the factors governing TBM performance by means of a structured examination of the multiple interfaces and interactions between ground, tunnelling equipment and support; and thirdly to provide a critical review of the technical options existing or proposed for coping with squeezing ground in mechanized tunnelling.

1. Introduction

In recent years, the need for new infrastructure to handle the intercity transportation of people and goods has steadily increased. The construction of such facilities often requires the excavation of long, deep tunnels such as the two base tunnels of the Alptransit Project in Switzerland (Kovári, 1995), the Brenner Base Tunnel between Austria and Italy (Bergmeister, 2007), the Lyon-Turin Tunnel between France and Italy (Nasri and Fauvel, 2005) or the Gibraltar Strait Tunnel between Spain and Morocco (Pliego, 2005). In many cases the cost of such projects can be reduced to a justifiable level only by utilizing tunnel boring machines (TBMs), because they allow significant savings in construction time and costs.

Due to alignment constraints and the uncertainties of geological exploration (which may be large, particularly for long, deep tunnels), it is not always possible to find a route that will avoid the problem of excavating in difficult geological zones with a sufficient degree of certainty (Robbins, 1992). The extent and frequency of the difficulties encountered can be decisive in terms of economical viability or even in terms of the technical feasibility of a TBM drive. In some cases of very great potential damage, a single event can cast the entire project into doubt. Minor setbacks may also become relevant if occurring frequently. The length and the number of critical stretches are very important in this respect. Short tunnel stretches with unfavourable but well-known geological conditions are not particularly risky for the economic success of a TBM drive provided that adequate countermeasures are planned in advance (Kovári, 1986a).

TBM performance can be affected by geological conditions in a great variety of ways (Barla and Pelizza, 2000). For example, boreability problems in hard rock, steering difficulties or severe vibration of the cutter head due to mixed face or blocky rock conditions, major water inflows, cave-ins ahead of the tunnel face or unstable excavation walls in highly fractured or weathered rock as well as crossing fault zones may represent difficult tunnelling conditions.

Squeezing ground conditions may also slow down or obstruct TBM operation (ITA, 2003) and sometimes even call into question the feasibility of a TBM drive. In fact, there have occasionally been some very negative experiences (including complete loss of the TBM) in the past and this has often lead to TBM drives in squeezing ground being classified as generally too risky and therefore not feasible. However, between the borderline cases of a heavily squeezing ground and a non-problematic competent rock, a wide range of conditions exist which neither exclude a priori mechanized tunnelling nor allow it without careful consideration. These cases call for a well-founded, thorough investigation of the risks, the technical feasibility and the cost of TBM application. So it is not surprising that the question of TBM applicability in squeezing conditions has kept engineers busy for more than 30 years. First remarks can be found already in Prader (1972), while more detailed conceptual considerations have been provided later by Lombardi (1981) and Robbins (1982). Other related works are, e.g., those of Kovári (1986a,b), Amberg (1992), Gehring (1996), McCusker (1996) and

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Nomenclature

d_l	lining thickness
d_s	shield thickness
D	boring diameter
e	extrusion rate of the core
E	Young's modulus of the ground
E_k	entity of N^2 chart (the subscript k refers to the entity numbering)
E_l	Young's modulus of the lining
E_s	Young's modulus of the shield
f_c	uniaxial compressive strength of the ground or of the lining
F_b	boring thrust force
$F_{b,max}$	maximum possible boring thrust force
F_f	thrust force needed for overcoming friction
F_g	thrust force that can be reacted by the grippers
F_i	installed thrust force
G	ground
H	depth of cover
L	shield length
n	cutter head rotational speed
n_{max}	maximum possible cutter head rotational speed (TBM design)
$n_{max}{}^*$	maximum possible cutter head rotational speed (operational conditions)
N	number of physical and functional entities of a N^2 chart
p	penetration
P_A, P_B	problems in the back-up area (zone A and zone B, respectively)
S_1, S_2	tunnel support (type, quantity, parameters, distance behind face) in the machine area and in the back-up area, respectively
t_1	operational standstill time
t_2	standstill time due to jamming of the TBM
t_3	standstill time due to other problems
T	torque
T_f	required torque for overcoming friction
T_g	torque that can be reacted by the grippers
T_i	installed torque
T_r	rolling resistance of the cutter head
v_g	gross advance rate
v_n	net advance rate
$\{x–y\}$	interactions between the entities E_x and E_y of a N^2 chart
ΔD	overboring (facility, amount of the increase of the boring diameter D)
γ	unit weight of the ground
φ	internal friction angle of the ground
ν	Poisson's ratio of the ground
μ	shield skin friction coefficient
σ	ground pressure acting upon the tunnel support
σ_{max}	maximum possible ground pressure acting upon the tunnel support (bearing capacity)
σ_{TBM}	ground pressure acting upon the TBM (cutter head or shield)
τ_{TBM}	shear stress acting upon the TBM (cutter head or shield)
ψ	dilatancy angle of the ground
#	number

Schubert (2000). As can be seen from recent publications (Downing et al., 2007; John and Schneider, 2007), the topic is particularly relevant today due to the increased economic importance of mechanized tunnelling associated with the demand for long deep tunnels.

The present paper presents a qualitative discussion of the complex interactions between ground, tunnelling equipment and support based upon both tunnelling experience (Section 2) and theoretical considerations. Reference will be made to the peculiarities of the different TBM types and emphasis will be placed on the interfaces between the three essential system components: ground, tunnelling equipment and support (Section 3). Over the last decade, considerable research and development efforts have been made with the goal of widening the range of applicability for TBMs in squeezing ground either by improving established TBM types (i.e., gripper, single or double shielded TBM) or by developing new construction methods involving alternative machine designs or deformable lining systems. Reference to these works will be made in Section 4, which – starting from the basic interactions discussed in Section 3 – deals with possible measures for coping with large rock deformations or high ground pressures in mechanized tunnelling.

2. Practical experience and specific problems

A comprehensive literature search on case histories involving TBMs under squeezing conditions has been carried out in order to identify the specific problems. An extended presentation of the results of this search as well as all related references can be found in Ramoni and Anagnostou (2009).

According to tunnelling experience, squeezing behaviour may become problematic at different distances behind the tunnel face. Therefore, the specific potential hazards concern both the machine area (sticking of the cutter head, jamming of the shield) and the back-up area (e.g., jamming of the back-up equipment, inadmissible convergences of the bored profile, damage to the tunnel support). In addition to the difficulties that are directly caused by squeezing behaviour, adverse events such as clogging of the cutter head, insufficient bracing of the grippers or instabilities of the face or the tunnel wall may also occur when boring through weak ground. Often it is difficult or even impossible to distinguish the different phenomena from each other. For example, when driving through poor quality ground it may remain uncertain if the ground pressure acting upon the TBM is due to squeezing or ravelling behaviour. Furthermore, in several cases a feedback between the different problems may be observed (Kovári, 1986a).

Concerning the magnitude of the potentially problematic deformations, a marked difference exists between conventional and mechanized tunnelling. Due to the geometrical constraints imposed by the equipment, even convergences as small as one or two decimetres may lead to difficulties in the machine or in the back-up area of a TBM drive Kovári (1986b). It should be noted that relatively moderate deformations, which may be problematic for a TBM (but could be easily dealt with by conventional tunnelling), are in no way limited to the typical squeezing formations of weak rocks such as phyllites, schists, serpentinites and claystones. Experience in some stretches of the Gotthard Base Tunnel has shown that hard but highly fractured rocks may also exhibit relevant deformations and challenge TBM tunnelling, particularly if encountered at great depths.

Tunnelling experience also indicates that interruptions of the TBM drive may be unfavourable in squeezing ground, i.e., that the "time" factor may play an important role. In several cases, the TBM did not become jammed until there was a slowdown or standstill in the TBM drive, which suggests that maintaining a high gross advance rate and reducing standstill times may have a positive effect. For example, in the Tunnel 38 of the Yindaruqin