Tunnelling and Underground Space Technology 57 (2016) 287–299

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Challenges and opportunities of using tunnel boring machines in mining

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A R T I C L E   I N F O

Article history:
Received 18 December 2015
Received in revised form 18 January 2016
Accepted 20 January 2016
Available online 29 January 2016

Keywords:
TBM
Mining
Difficult grounds
Challenges
Mitigation measures

A B S T R A C T

Full-face tunnel boring machine (TBM) tunnelling has unparalleled advantages over conventional drill-and-blast (D&B) techniques in terms of higher advance rates and lower risk levels in favourable ground conditions. However, there are only a few successful TBM applications in mines. The aim of this paper is to discuss the technical challenges of using TBMs in mining since the pioneering work in the 1960s. It starts with a description on the genesis of hard rock mines and coal mines and the differences of TBM tunnelling in mining and civil engineering projects. The historical applications of TBMs in mines are critically reviewed and the reasons for the unsuccessful applications are summarised and analysed from a geological point of view. Challenges, such as cutter wear, jamming and steering difficulties in difficult grounds with water inrush, fractured and faulted zones, high in-situ stresses, and gas, are explored in depth through case histories. Moreover, the corresponding mitigations measures to cope with complex grounds in mines are provided. A prospect of TBM applications in mining is presented at the end.

1. Introduction

Ever since the first modern TBM was developed and successfully used in the 1950s, over 10,000 TBMs have been applied to construct tunnels for traffic, hydropower, sewerage and water, underground storage and mining. With continuous development of technologies, a wide variety of TBMs are now available to bore tunnels of different diameters through ground conditions ranging from hard rock to soft soil and grounds in between. On the basis of ground and groundwater conditions (i.e., hard rock, soft soils, mixed and changing grounds), tunnel face and wall stability, TBMs can be broadly classified into seven types, as indicated in Fig. 1. Excellent reviews of the historical development and opportunities of using TBMs in hard rock and soft soil are provided by Stack (1982) and Maidl et al. (2012, 2013).

Although TBMs in favourable ground conditions offer unparalleled advantages over drill and blast (D&B) in terms of higher advance rates, lower risk levels and possible cost reduction, they could experience great setbacks in adverse ground conditions, which results in significant losses in safety, cost and schedule (Barla and Pelizza, 2000). Adverse ground conditions can include changing geology (Yamamoto et al., 2006; Zhao et al., 2007), mixed-face grounds (Tóth et al., 2013), squeezing grounds (Palmströ, 1995; Ramoni and Anagnostou, 2008), blocky grounds (Delisio et al., 2013), high in-situ stressed grounds (Gong et al., 2012; Yin et al., 2014), highly abrasive grounds (Gehring, 1994; Liu and Liang, 2000), large/huge groundwater inrush (Font Capó, 2012), highly fractured and faulted grounds (Barton, 2000; Paltrinieri, 2015) and gassy grounds (Copur et al., 2012). Under some circumstances, several abovementioned adverse grounds can be encountered at the same time.

Applications of TBMs in the mining industry have previously been reviewed by Handewith (1980), Stack (1982), Robbins (1984), Cigla et al. (2001), Home and Askilsrud (2011) and Brox (2013). However, only brief introductions to TBM applications in the mining industry (e.g. TBM type, diameter and tunnel length) are presented and general technical considerations of using a TBM are discussed. Conclusions are reached that TBM applications in mines are far from satisfactory when compared with that in civil engineering. Only a few out of about 100 TBM attempts in about 60 mines, e.g. the Stillwater mine (USA), the San Manual mine (USA) and some coal mines, are accepted as successful. Therefore, this paper attempts to explore a more detailed investigation into the reasons of the unsuccessful TBM applications in the mining environment and technical challenges and solutions that must be considered for the future use of TBMs in the mining industry.

Following the introduction, Section 2 describes the genesis of mines and the stemming geological difficulties for TBM tunnelling and compares the differences of TBM tunnelling in the mining and civil projects. Section 3 presents the historical use of TBMs in hard rock mines and coal mines since the pioneering work in the 1960s and discusses the general characteristics of these applications. Sections 4 and 5 critically summarises technical challenges encountered and suggested mitigation measures. A prospect of

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http://dx.doi.org/10.1016/j.tust.2016.01.023
0886-7798/

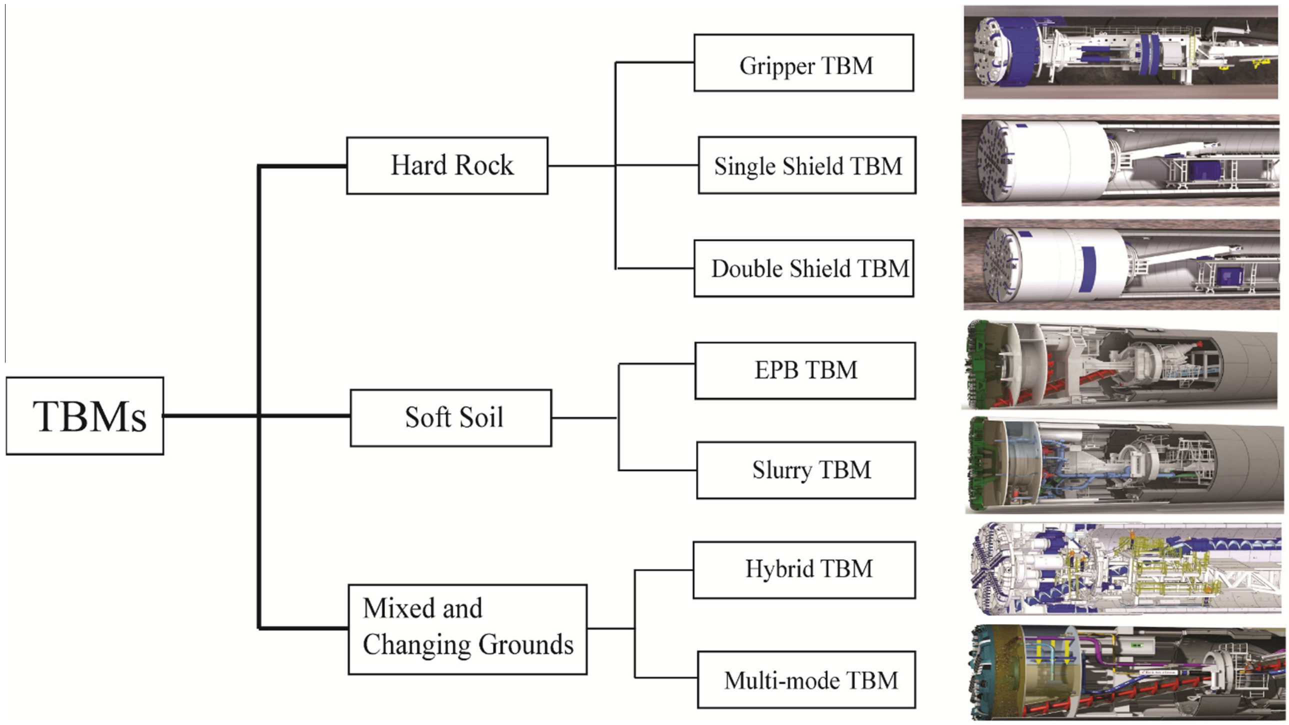

Fig. 1. A classification of TBMs.

using TBMs in mines is provided in Section 6, and finally a brief summary is presented.

2. Comparison of TBM tunnelling in mining and civil engineering

Before analysing TBM applications in mines, one needs to understand the differences between TBM tunnelling in mines and in civil projects, which are addressed from the geological point of view in the following parts.

2.1. Geology of hard rock and coal deposits

Generally speaking, the conventional mining industry includes metallic ore mining, coal mining and quarry mining. TBMs can be used to access the underground orebodies or to explore the orebodies. Non-conventional mining such as shale gas, natural gas and oil involves significantly different mining techniques and normally needs no TBMs for tunnel excavation.

A metallic ore is a geochemical anomaly which enriches one or more particular elements/minerals to a concentration that can be economically mined. For example, the concentrations of copper and gold in a rock have to be upgraded by about 80 times and 1000 times from their average concentration in the Earth's Crust before we can call the rock an ore. Generally they are formed by the remove/transport-concentrate-preserve sequence. Based on the contained elements, form of deposits, associated host rocks, and interpreted genesis of the deposit ores, ore deposits are broadly classified into syngenetic and epigenetic deposits, which can be further divided into magmatic, metasomatic, hydrothermal epigenetic, exhalative, marine-sedimentary and placer deposits (McQueen, 2005). Epigenetic deposits show forms related to the geometry of the fluid channelways such as veins or stockworks along fractures while syngenetic deposits are commonly strata-bound or stratiform (McQueen, 2005).

The deposits of coal are exclusively of sedimentary geology. Coal seams and the underlying and overlying strata are commonly layered and of relatively lower strength compared to ores and host rocks of metal mines. That is why people differ coal mines from metal mines even the uniaxial compressive strength (UCS) of coal can exceed 100 MPa. The geology of coal mines is relatively simple and easy to understand, thus will not be discussed in details in this paper. As most quarries are mined from the surface, TBMs are seldom applied in quarries.

2.2. TBM tunnelling difficulties in mining

Due to the ore genesis and tectonic activities, the geochemical, geological and geomechanical properties in the orebodies present high alteration from the surrounding host rocks (Brox, 2013). Even the orebody itself can present high alteration. Fig. 2 shows the generalised alteration-mineralisation zoning pattern for telescoped porphyry Cu deposits, illustrating the mineral difference between the orebody and the host rocks. To mine the ores in dash-lined porphyry, different strata will have to be bored through.

Given the complex geological conditions of ore deposits, tunnelling in mines at depth, especially TBM tunnelling, is anticipated to be more difficult than tunnelling in civil projects at shallower depths with relatively homogenous ground conditions. Difficult grounds mentioned in the Introduction Section are more likely to be encountered in hard rock mines. For coal mines, the geological hazards are mainly from weak grounds, water inrush and methane explosion. As most of the TBMs used in hard rock and coal mines in the early days are open-mode gripper TBMs, which are suitable for competent moderately hard rock with no major water inflow, the heterogeneity of the rock mass posed great challenges on the TBMs (Home and Askilsrud, 2011). Zheng et al. (2014) found that those geology-related problems accounted for over 70 per cent of TBM failures/terminations in mines.

2.3. Comparison of TBM tunnelling in mines and civil projects

Table 1 provides a comparison of TBM tunnelling in mining and civil projects. Apart from the difference in geology, TBM tunnelling