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TBM tunneling in mixed-face ground: Problems and solutions

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ABSTRACT

Mixed-face ground encountered in Tunnel Boring Machine (TBM) tunneling presents great challenges and may trigger potential hazards without warning. A detailed understanding of such unfavorable conditions is therefore critical to a successful bored tunnel. In this paper, we firstly present a brief review of the definition, classification and the factors related to mixed-face conditions. Secondly, for a better understanding of this topic, we investigate the main difficulties and problems involved in TBM tunnelling under mixed-face ground with detailed cases. Thirdly, from the viewpoint of rock-machine interaction, we give some suggestions on the corresponding mitigation measurements from three categories: (i) selection of TBM type and modification of TBM, (ii) condition of ground and (iii) optimization of TBM operation.

1. Introduction

Mixed-face ground is experienced frequently during TBM tunneling in both mountain tunnels and urban underground infrastructures, potentially bringing huge difficulties to TBM tunneling and further causing nuisance if proper countermeasures are not applied in good time.

There are numerous cases involving mixed-face excavation conditions, including: Edmonton South LRT extension in Canada, San Vicente pipeline tunnel project in America, new metro line in Singapore, Chengdu metro line 1 in China and so on. These cases provide some insight into the ground response during excavation, presenting as well as the main potential difficulties and hazards for TBM tunneling in mixed-face conditions. Normally, mixed-face conditions can lead to cutter wear, jamming of roller cutterheads, ground settlement, poor TBM performance and cost overrun [1–4]. Therefore, a detailed understanding of such unfavorable conditions is required to successfully cope with it.

This paper aims to provide a better understanding of such unfavorable conditions by: (i) a brief introduction of mixed-face ground definition, classification and influencing factors, and (ii) a detailed description of the main problems related to TBM tunneling under mixed-face conditions. Moreover, the corresponding mitigation measurements are proposed from three categories: (i) selection of TBM type and modification of TBM, (ii) ground conditions and (iii) optimization of TBM operation. Finally, further research to be conducted for better coping with these problems is emphasized.

2. Definition of mixed-face conditions for TBM tunneling

From a geological viewpoint, the mixed-face condition is defined as the simultaneous occurrence of two or more geological formations with remarkably different properties in rock/soil mechanics, engineering geology as well as hydro geology, or the same geological formation with different weathering grades [1,2]. Specifically for TBM tunnelling, Büchi [3] states that "The term mixed face conditions is used when the tunnel face consists of at least two rock types with completely different bore ability-in simple terms a mix of soft and hard rock", and suggests the Uniaxial Compress Strength (UCS) as a direct reference for the bore ability of rock. Based on this conception, a definition of mixed-face conditions as the difference in UCS between the weakest and the strongest layer of a minimum of 1:10, has apparent gained some acceptance [2].

However, it fails to incorporate TBM operation and performance parameters. To be more accurate and clear, some researchers recently proposed that mixed ground may be defined as "simultaneous occurrences at excavation face of two or more sufficient areas of grounds with significantly different properties that affect TBM operation". It consists of two or more geological formations or the same rock formation with conspicuously different fracture intensity or weathering grades.

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Table 1
Factors related to mixed face conditions for TBM tunneling.

Ground condition parameters	TBM machine parameters	Operation parameters
Mechanical properties: UCS, tensile strength, modulus, rock abrasivity, soil cohesive strength, difference in mechanical properties between weak and strong component parts of mixed face	TBM type Available operational mode Available thrust and torque	 Thrust Torque
Geological formation and geometry of such formation: percentage of the outcrop of each component type on the mixed face, size and distribution of the cobblestone, blocks or spheroidal weathering stone, occurring discontinuities	Cutterhead design (opening area on cutterhead, layout of scrapper teethes and cutting discs)	RPM (rotation per minute)
Hydrogeology properties: groundwater distribution and groundwater pressure, permeability of the weak component part and interface	Muck conveyer design	Support method

3. Classification of mixed-face conditions for TBM tunneling

Based on the geological characteristics of TBM tunneling projects worldwide, which have encountered such kinds of ground conditions [5–14], mixed-face ground can be mainly classified by three types, as shown in Fig. 1.

- Class 1: Layered or banded ground formed by rock beddings, dykes, faults or shear zones. Involved cases: Edmonton South LRT Extension with four major stratigraphic layers identified in the tunnelling zone (Canada), Lesotho Highlands Water Project with hard dykes and sills in sedimentary rocks and basalts (Lesotho), DulHasti hydro power project characterized by jointed quartzite interbedded with phyllite (India).
- Class 2: Interface ground of soil and rock, or typically weathered materials above bedrock. Involved cases: San Vicente Pipeline Tunnel Project which is located in extremely variable geologic conditions including Friars Formation Conglomerate overlying granitic rock (America), Metro L9 in Barcelona which crosses a great variety of ground types ranging from soft and hard rocks (Spain), new metro line with a complex and single rock/soil interface between the fresh granite and the overlaying clayey sand (Singapore), the Kranji tunnel with frequently changing and mixed ground from fresh rock to residual soil (Singapore), Athens Metro L3 extension within a variety of lithological formations ranging from very strong alpine limestones to recent soft littoral deposits (Greece).
- Class 3: Mixed face with locked cobblestones, rock blocks with soil materials, or isolated spheroidal weathering stone mixed with a soft formation. Involved cases: metro line 1 in Chengdu where cobblestone-soil ground was experienced (China), metro line 3 in Guangzhou with spheroidal weathering granite stone up to 1.0–5.0 m presented in strongly weathered formation (China).

4. Factors related to mixed-face conditions for TBM tunneling

As TBM performance is the result of the interaction between rock and TBM machine, both of the rock mass properties and TBM design/operation parameters should be included for this issue. The factors influencing TBM performance in mixed-face ground can be briefly summarized as shown in Table 1.

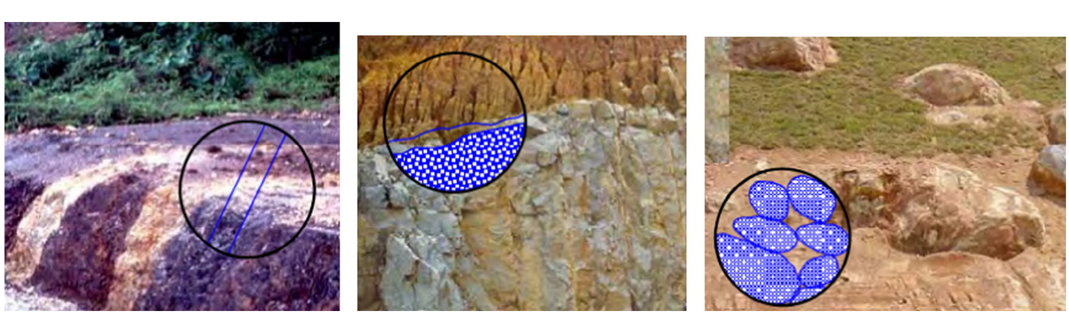
5. Main problems in mixed ground for TBM tunneling

The main troubles related to abnormal cutter wear, face instability, muck transportation problems, ground settlement, etc. are discussed in detail as follows.

5.1. Extremely high abnormal cutter consumption

Three aspects constitute high abnormal cutter consumption.

(a) Flat wear and multi-flat wear. According to Zhao et al. [8] three reasons contribute to this problem: (i) as the soft material in the mixed face cannot provide sufficient rolling force for cutters to overcome the pre-torque of cutter bearings, frequent stoppages of cutter rotation occur, which leads to flat cutter ring wear in the soft soil containing highly abrasive soil and spoil paste. (ii) The space between the cutter housing and the head plate is packed by the spoil paste, which prevents cutters from rotating and thus may causing cutter flat wear and multi-flat wear. (iii) The high transverse shock loads due to a mixed face may cause short stoppage of cutter rotation as well, leading to small flat wear of the cutter, so that cutting force and torque on the flat cutter reduces, which aggravates cutter flat development until the cutter cannot rotate at all. Moreover, it causes more load (beyond the limiting value possibly) distributed on the



(a) Class 1 (b) Class 2 (c) Class 3

Fig. 1. Three types of mixed-face ground.