Tunnelling and Underground Space Technology 74 (2018) 206–216

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Influence of the slurry-stabilized tunnel face on shield TBM tool wear regarding the soil mechanical changes – Experimental evidence of changes in the tribological system

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ARTICLE INFO

Keywords:
Bentonite
Tool wear
Support media
Tunnel face
Tribological system

ABSTRACT

The wear of slurry shield TBM excavation tools is a challenging topic that has been discussed over many years, Due to the complexity of the tribological system that defines the tool wear, no sufficient approach to determine the wear in a specific tunneling project has been developed up to now. The elementary step to display the application-oriented tribological system is one of the main issues regarding laboratory scale test methods. Therefore, the RUB Tunneling Device has been developed at the Ruhr-University Bochum (Germany). With this apparatus, several influencing factors regarding the tribological system of a TBM-tool can be analyzed. A unique feature of the device is the experimental simulation of a slurry shield excavation, including a realistic tunnel face support. This paper focuses on the experimental simulation of slurry shield excavation and the influence of face support on tool wear. Changes in the soil mechanical properties due to slurry penetration at the tunnel face are regarded and correlated with the tribological system of a slurry shield excavation. It is proven that the tribological system, and thus the tool wear, changes significantly due to slurry injection.

1. Introduction

1.1. General

Slurry shield TBMs with full face excavation and active face support using a fluid are usually employed for excavations in soft ground. When planning such tunneling projects, the choice of suitable penetration rates and cutting wheel revolutions per minute is necessary for smooth excavation and the reduction of wear on the cutting tools. However, cutting tool wear is inevitable during any excavation and needs to be correctly predicted. Good forecast of tool durability is demanded due to its significant impact on tunneling progress. When tools become dull or lose their functionality (due to brittle material behavior), penetration rates decrease despite an increase in the thrust force. It reduces the tunneling efficiency (Maidl et al., 2013). Thus, a tool change (replacement) becomes necessary. However, tool replacement is not possible at every location on the shield excavation path since it requires the partial or even entire lowering of the slurry level in the excavation chamber. When the slurry level is lowered, the excavation chamber is filled with compressed air, which enables an access to the tools. The process of slurry lowering is itself related to a significantly increased risk of face instability. This risk is due to support pressure deviations during lowering and the possibility of a compressed air blow-out. Moreover, every intervention is a time-consuming process. Hence, additional unplanned tool changes lead to higher excavation risk and higher overall cost. Therefore, there is a strong interest in a reliable wear prediction model for slurry TBMs. In tunneling practice, the prediction is usually based on empirical methods correlated with ground investigation, laboratory tests, and expertise gathered from previous tunneling projects in similar soil. Rostami et al. (2014) and Kuepferle et al. (2015, 2016a) analyzed the complexity of the problems of the commonly used test methods.

In general, wear is a progressive loss of material on the surface of solid or rigid bodies due to mechanical loads. When transferred to mechanized tunneling in soil, two wear systems are distinguished according to the German Society for Tribology (2002) and Düllmann (2014). In the first system, which is known as primary wear or excavation wear, cutting tools wear down due to their direct contact with

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https://doi.org/10.1016/j.tust.2018.01.011
Received 2 August 2017; Received in revised form 21 November 2017; Accepted 6 January 2018

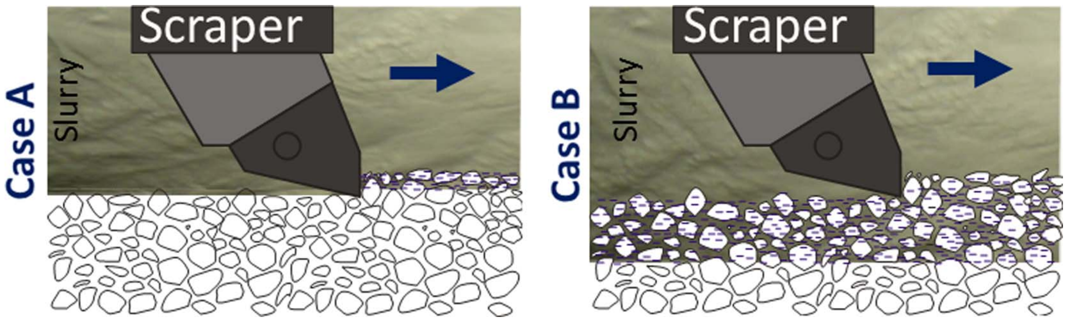

Fig. 1. Interaction cases at the slurry-supported tunnel face during excavation (Zizka et al., 2017).

the subsoil. For this type of wear, the contact force between the tools and the soil grains at the tunnel face is the governing factor in defining the amount of wear. The second system, known as secondary wear, involves passive cutting tools, the cutting wheel and other components. Secondary wear occurs due to contact between components and previously excavated soil that has been mixed with a support medium. This paper deals explicitly with primary wear, i.e. the wear due to contact between soil grains and cutting tools. Within the assessment of the primary wear mechanism in tunneling, two components must be separately evaluated:

(a) The abrasiveness of the soil particles concerning mineral composition, particle size and particle form. As shown by Düllmann (2014), Drucker (2013) and Heinrich (1995), wear increases with an increasing amount of abrasive minerals, larger particle sizes and more angular particle forms.
(b) The shear strength of the soil matrix. Soil matrix strength describes the force required to extract a single grain from the soil skeleton. The influencing factors here are the compactness of the soil and its shear parameters. The soil matrix strength determines the resistance of the soil at the tunnel face to excavation. In other words, it governs the technical-physical stresses at the contact area between cutting tool and soil grain. There is a possibility that the strength of the matrix is highly influenced by the support medium. Using this assumption, this paper aims to analyze the influence of the support medium on cutting tool wear in regards to the slurry-supported tunnel face.

1.2. Soil excavation and face support in slurry shield tunneling

Slurry shields simultaneously support and excavate soil at the tunnel face. Shields nowadays are equipped with several types of excavation tools for soil cutting. Discs, rippers, chisels/scrapers and buckets are all commonly used tools (Maidl et al., 2013). In slurry shield tunneling, the soil is cut with scrapers and buckets. Because their geometry allows the soil to be cut in only one active cutting direction, these tools are placed in pairs (tandems) on each cutting wheel arm. This way, the cutting wheel can rotate in both directions, with one tool actively cutting while the second merely moves passively along. It is the active cutting tool that is predominantly subjected to primary wear.

As mentioned previously, slurry shields simultaneously also support the tunnel face. In order to do this, the shields use of bentonite slurry (suspension). Bentonite slurry is a mixture of water and bentonite powder. Bentonite suspensions are an essential tool for stabilizing the tunnel face during both the excavation and the ring building phase. To maintain soil stability, the bentonite suspension has to withstand earth and water pressure. Therefore, the hydraulic pressure in the suspension has to counteract the groundwater pressure and has to be transferred in terms of effective stress to support the soil skeleton.

Traditionally, two support pressure transfer mechanisms and their corresponding models are distinguished (Müller-Kirchenbauer, 1977 or DIN 4126, 2013). The models have been proven on the macroscale by several experiments e.g. by Min et al. (2013), Heinz (2006) and Arwanitaki (2009). The models describe either a thin, membrane-like pressure transfer mechanism or a penetration zone mechanism. In the membrane model, bentonite particles are filtered directly at the tunnel face and do not significantly penetrate the soil, unlike in the penetration model, where the slurry intrudes much deeper into the soil's pores. The pressure transfer occurs here by shear stress between the fluid and the soil skeleton. The slurry penetration stagnates at the depth at which the suspension pressure is in balance with the transferred shear stress and groundwater pressure. Following the theory, the particular type of interaction that develops is based on the characteristic grain size of the soil, the yield point of the slurry and the slurry excess pressure (the amount of injection pressure above groundwater pressure). Müller-Kirchenbauer (1977) describes the interaction in detail and concludes that shallower slurry penetration is obtained with a smaller grain size, thicker slurry and lower slurry excess pressure. Walz (1989) stated that the membrane, also called the filter cake, develops when the pore size of the soil is smaller than the size of the suspended bentonite particles. Here, the bentonite particles are filtered at the entrance of the pore space and the remaining filtrate water drains through the soil.

The traditional models by Krause (1987), Anagnostou and Kovári (1994) and Jancsecz and Steiner (1994) were widely accepted in slurry shield tunneling for a long time, although they are based on a theory Müller-Kirchenbauer (1977) originally developed for diaphragm wall technology.

There have been recent attempts to update these models for slurry shield tunneling, with special consideration of the soil cutting process at the tunnel face. Broere and van Tol (2000), Bezuijen et al. (2001) and Bezuijen (2016) followed an approach to describe the global interaction for the whole tunnel face, while Zizka et al. (2015) focused on the local level. Thewes et al. (2016) suggested that there might be two general situations at the tunnel face regarding the interaction between cutting tools, soil and slurry (Fig. 1). The first situation occurs when a passing tool on a local point at the tunnel face cuts the entire slurry-infiltrated zone. This situation is identified as Case A. A different situation occurs for Case B, in which the passing tool damages only a certain part of the slurry-penetrated zone. In Case B, the so-called re-penetration of slurry particles in the soil skeleton is expected. Slurry re-penetration refers to the process in which slurry penetrates the soil skeleton in a location where slurry particles from the previous excavation cycle are still present. In both cases, bentonite slurry is an inevitable member of the tribological system present during the primary wear of cutting tools.

1.3. Tool wear prediction based on laboratory experiments

In recent years, a large number of experimental test methods have been developed to investigate soil abrasivity. Some of them do not distinguish between primary and secondary wear. An overview is given in Table 1. Most of the test procedures were developed to investigate one specific parameter or have been transferred to tunneling from a different application. One such test is the LCPC test, which was originally developed to investigate the crushability of stones (Fowell and