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Empirical modeling for predicting excavation performance of EPB TBM based on soil properties

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A R T I C L E I N F O

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A B S T R A C T

This study was conducted in order to determine the effects of soil properties on the excavation performance of an earth pressure balance tunnel boring machine (EPB TBM) used in the Istanbul Ayvali Waste Water Tunnel Project in the development of empirical performance prediction models. The tunnel alignment was divided into three general sections in terms of geological and geotechnical conditions. Soil samples were collected from 14 different locations along these sections of approximately 60 segment rings, and subjected to laboratory tests in order to determine the particle size distribution, natural water content, consistency limits (liquid limit, plastic limit, plasticity index, and consistency index), vane shear strength, fall cone penetration depth, unified soil classification, and clogging potential. The field performance data were obtained from the EPB TBM data logger, which operated in open mode without any face pressure being applied. Data analysis was carried out by statistically linking the net cutterhead torque, TBM thrust force, instantaneous cutting rate, and field-specific energy with the geotechnical properties of the excavated clayey soil by using single and linear multi-variable regression methods. The results indicate that, while the performance parameters are similar for the silty sand and lean (low plasticity) clay, the cutterhead torque and field-specific energy are higher, and the thrust and instantaneous cutting rate are lower, for high plasticity clays. The vane shear strength and consistency index may be used for predicting the cutterhead torque, fall cone penetration depth for the thrust force, plastic limit for the instantaneous cutting rate, and plastic limit and plasticity index, as well as the consistency index, for field-specific energy predictions. Additional studies are required to provide more reliable and generalized prediction models, by increasing the number of laboratory and field tests for different soil types and performance data for different EPB TBMs.

1. Introduction

The rapid increase in human population in urban areas has resulted in the need for new infrastructure systems such as metro tunnels, water tunnels, and utility lines. The demands on the limited available space, combined with increasing demands for higher-quality structures, forces decision-makers to investigate extended use of subsurface space. This need makes it necessary for engineers to determine new solutions for construction difficulties in urban areas.

The effectiveness of management is, too often, criticized for the contractual problems arising during construction. In most instances, the roots of such problems can be traced back to the initial planning. Unrealistic performance predictions result in a limited opportunity for the contractor to manage the construction effectively.

Excavation rate prediction is the most critical element in planning a TBM excavation project. The critical path of a tunnel project would normally be linked to excavation activity, and adherence to the cost and schedule would implicitly require the TBM to be excavated as planned. For the project to be successful, the planning process must provide a realistic evaluation of TBM performance expectations, reflecting both the known and unknown factors of the excavation process. For this purpose, models have been developed by researchers to estimate TBM performance by basically using geological and geotechnical data.

The parameters affecting a mechanical excavation system may be categorized into three main groups: geological and geotechnical, mechanical (machine-related), and operational and environmental factors (Herrenknecht, 1994; Copur et al., 2001; Herrenknecht and Rehm, 2005; Herrenknecht and Bappler, 2007; Lovat, 2007; Rehm, 2007; Maidl and Wingmann, 2009; Bilgin et al., 2014). Following tunnel alignment selection, an excavation machine should be selected and its operational parameters (torque, power, and thrust capacities) should be optimized for the desired performance, according to geological and geotechnical conditions. Therefore, the geological and geotechnical parameters of the tunnel alignment should be investigated during the planning stage (Herrenknecht, 1994; Herrenknecht and Rehm, 2005; Herrenknecht and Bappler, 2007; Rehm, 2007; Lovat, 2007; Marinos

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Fig. 1. Alignment of Ayvali Waste Water Tunnel.

et al., 2008; Bilgin et al., 2014). Thereafter, the performance parameters of the selected excavation machine (for example, advance rate, torque, and thrust) should be predicted for the given geological conditions. In this manner, a more accurate optimization of the job termination and cost becomes possible (Jancsecz et al., 1999; Williamson et al., 1999; Bilgin and Algan, 2012; Ilci et al., 2013; Copur et al., 2014).

TBM performance prediction for soils is gaining popularity, and limited studies exist that are focused on EPB TBM performance prediction. Bilgin and Algan (2012) proposed an instantaneous cutting rate prediction model for fractured rock formations excavated by an EBP TBM in open (semi-closed) mode. Bilgin et al. (2008, 2013) investigated the performance of EPB TBMs on fractured rock formations. Bilgin et al. (2012) developed a deterministic performance prediction model for a single-shield TBM equipped with chisel tools for cutting medium-strength clayey ground. The German Committee for Underground Construction (DAUB) developed charts for EPB TBM application ranges based on soil properties such as the fine grain fraction, consistency, permeability, and swelling behaviors (DAUB (German Committee for Underground Construction), 2010). Maidl and Wingmann (2009) defined crucial soil parameters for EBP TBMs and provided recommendations for estimating the performance of EPB TBMs based on operational conditions by evaluating the data obtained from several projects.

Kasper and Meschke (2004) used 3D numerical simulation models to estimate the thrust requirements of soft ground TBMs. Manuel and Luis (2005) developed a discrete element model for predicting the face stability, torque, and thrust requirements for excavation. Yang et al. (2006) investigated the torque, thrust, and counter-pressure within the excavation chamber for two different cutterhead opening ratios (30% and 70%) by means of model tests. Key performance indicators were analyzed by Ulrich and Marc (2011) for EPB TBM performance estimation by using data from different projects. Wu and Qu (2009) used a 3D model to simulate the cutterhead excavation process of an EPB TBM. The application of discrete element analysis for performance optimization was investigated by Glenn and Mustafa (2011). Lambrughi et al. (2012) developed a 3D finite element numerical model for simulating the EPB TBM excavation process. An inverse method with in-situ data was used by Zhang et al. (2013) for performance prediction. Ates et al. (2014) suggested certain empirical models for determining the specifications of different hard and soft ground TBM types, based on a large database. Copur et al. (2014) used a stochastic model integrated into a deterministic model for estimation of EPB TBM performance in rock excavation. Zhang et al. (2015) proposed mathematical models for predicting the torque and advance speed of EPB TBMs. Zhang et al. (2016) applied a mechanical decoupling model for predicting thrust under different geological conditions.

It remains important to describe the scientific relationships between soil parameters and EPB TBM performance, although the studies mentioned above have demonstrated the relationships among different parameters. This study aims to define the effects of soil parameters on the performance of an EPB TBM used in the excavation of the Ayvali Waste Water Tunnel in open mode, without applying any face pressure and with almost no conditioning, as well as to develop empirical performance prediction models. After summarizing the EPB TBM performance during excavation of three different lithological units, the engineering properties of the 14 soil samples obtained from the tunnel alignment were determined. The particle size distribution, natural water content, Atterberg limits, fall cone penetration, and vane shear tests were performed on the soil samples, and the clogging potential, consistency, and plasticity indices were defined according to the test results. The laboratory and field investigation results were used in order to statistically link the soil characteristics to the EPB TBM field performance (cutterhead torque, TBM thrust force, instantaneous cutting rate, and field specific energy), by using single- and multi-variable regression methods to develop empirical prediction models.

2. Ayvali Waste Water Tunnel project

The Ayvali Tunnel project (Ayvali 2) is a wastewater project excavated in the Zeytinburnu district located on the European side of Istanbul, with the specific goal of transporting wastewater from Zeytinburnu to the Yenikapi Treatment Plant through the Bayrampasa, Bagcilar, and Gungoren alignment. The tunnel alignment is illustrated in Fig. 1. The project owner is Istanbul Water and Sewage Administration (ISKI), and the contractor is Eferay-Silahtaroglu Construction JV.

The tunnel, which has a length of 1969 m, was excavated by an EPB TBM with an excavation diameter of 3.96 m, equipped with both ripper and 15.5-in. disc cutters, and manufactured by Lovsuns Tunneling Canada Limited. The tunnel excavation was carried out in open mode (half-filled with excavated soil), without any counter-pressure being applied to the tunnel face, because the face was stable. The soil conditioning was generally performed with a very low foam concentration ratio of approximately 0.5% and the foam expansion and foam injection ratios were 8 and 100%, respectively, throughout the studied tunnel sections. A photograph of the EPB TBM is presented in Fig. 2 and some of its technical features are summarized in Table 1. Precast segmental lining rings, each including six segments, were used for primary lining of the tunnel. The excavated material was transported by a rolling stock with four wagons, each with a capacity of 7.2 m^3. The segment length, and inner and outer diameters were 1.30, 3.30, and 3.70 m, respectively. The void between the tunnel perimeter and segment rings was grouted by means of a two-component grouting material. Following

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