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In situ TBM penetration tests and rock mass boreability analysis in hard rock tunnels

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Abstract

Boreability is popularly adopted to express the ease or difficulty with which a rock mass can be penetrated by a tunnel boring machine. Because the boreability is related to the rock mass properties, TBM specifications and TBM operation parameters, an accurately definable quantity has not been obtained so far. In order to analyze and compare rock mass boreability, a series of TBM shield friction tests were conducted in a TBM tunneling site. Two sets of TBM penetration tests were performed in different rock mass conditions during tunneling in rock. In each step of the penetration test, the rock muck was collected to perform the muck sieve analyses and the shape of large chips was surveyed in order to analyze the TBM chipping efficiency under different cutter thrusts. The results showed that a critical point exists in the penetration curves. The penetration per revolution increases rapidly with increasing thrust per cutter when it is higher than the critical value. The muck sieve analysis results verified that with increasing thrust force, the muck size increases and the rock breakage efficiency also increases. When the thrust is greater than the critical value, the muck becomes well-graded. The muck shape analysis results also showed with the increase of the thrust, the chip shape changes from flat to elongated and flat. The boreability index at the critical point of penetration of 1 mm/rev. defined as the specific rock mass boreability index is proposed to evaluate rock mass boreability.

Keywords: TBM; Rock mass boreability; Penetration test; Shield friction test; Muck sieve analysis

1. Introduction

Three terms, namely cuttability, boreability and excavatability, are usually used to describe relative performance of rock cutting tools in a rock mass. Cuttability is mainly applied in coal mining and excavatability in rock slope excavation. Boreability is extensively used in rock tunneling. US Commission on Engineering and Technical Systems (1984) defined boreability as a value expressing the boring properties of rock in terms of the penetration rate with certain numbers/types of cutters and amount of pressure applied. It expresses the ease or difficulty with which a rock type can be penetrated by a tunnel boring machine (TBM). Howarth (1987) defined boreability as the prediction of the penetration rate of a rock cutting machine in a rock mass. From the above definitions, one can see that the boreability is a comprehensive variable related to the rock mass properties, machine specifications as well as machine operation parameters. It is neither an absolute nor an accurately definable quantity. When rock mass boreability is compared or calculated, a set of conditions must be included or indicated. To be a rock mass parameter, rock mass boreability should not include machine or operational parameters.

Rock mass boreability is a comprehensive parameter reflecting the result of the interaction between rock masses and a TBM. While TBM operation parameters (Thrust, torque and rotation speed) and TBM specifications (cutter

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number, cutter diameter, cutter spacing and geometrical arrangement) are specific or normalized, rock mass boreability may be described by rock mass conditions (rock material properties, joint properties) and TBM performance (penetration rate, cutter wear) respectively. In term of rock mass properties, the third version of the NTNU model (Blindheim et al., 1983) described the rock mass boreability based on three factors: drilling rate index (DRI), bit wear index (BWI), the intensity and orientation of weakness planes in the rock mass. According to the description, the rock mass boreability takes penetration rate and cutter wear into consideration. Sundin and Wanstedt (1994) proposed a boreability index to measure the full face boreability of a rock mass based on rock mass properties. It is expressed by the result of rock indentation test multiplied by a factor for joint and weakness planes.

Based on the machine performance, Wanner and Aeberli (1979) proposed the term of specific penetration to denote the rock mass boreability. The specific penetration is the penetration per revolution, divided by thrust per cutter. Sundin and Wanstedt (1994) defined the value as the boreability index. Hamilton and Dollinger (1979) used a field penetration index to describe the rock boreability. The field penetration index, defined as the ratio of the applied thrust per cutter to the penetration per revolution, actually is the inverse of the specific penetration. In fact, the same parameters are used in these three indexes to describe the rock mass boreability calculated from the machine performance. In this paper, the latter was adopted to denote the rock mass boreability. It is noted that the boreability index is a normalized cutter force by revolution per minute (RPM) and penetration rate. Thus, it facilitates to compare the performance of different TBMs. But it is not a rock mass index.

Hamilton and Dollinger (1979) found that the boreability index is a function of the thrust. It decreases with increasing thrust per cutter. This is due to a change in the efficiency of the cutting action at the cutterhead. Borg (1988) and Bruland (1998) found that a critical thrust must be applied to overcome the rocks inherent resistance against breaking. Below this critical thrust value almost no penetration rate can be achieved and above this value the penetration rate increases rapidly with the increase of thrust force. Therefore, the previously defined boreability index calculated by the TBM performance data can not accurately represent the rock mass boreability. Only when the thrust force remains same, the calculated boreability index can demonstrate the different rock mass conditions.

In this paper, two sets of penetration tests were carried out at tunnelling sites in Singapore, in order to analyze rock mass boreability. Before these tests, in situ shield friction tests were conducted to decide the shield friction, in order to calculate the actual thrust acted on the TBM cutterhead and the thrust force per cutter. The sieve tests of muck were conducted to analyze the chipping efficiency. The muck shape was surveyed to obtain the effect of thrust force on chipping. By analyzing the penetration test results and comparing with other TBM penetration tests at other sites, a specific rock mass boreability index (SRMBI) is proposed to evaluate the rock mass boreability in different rock mass conditions. The SRMBI is defined as the boreability index at the penetration rate of 1 mm per revolution.

2. Brief description of the sites

The deep tunnel sewerage system (DTSS) is a mega infrastructure project, aiming at long term solution to meet the needs in wastewater conveyance, treatment and disposal in Singapore. The deep tunnel intercepts the flows in existing gravity sewers, upstream of the pumping stations, and routes the flows entirely by gravity to two new centralized wastewater treatment plants located at the south-eastern and south-western coasts of Singapore. The treated effluent from the new treatment plants will be discharged through deep sea outfalls into the Singapore seawater (Fig. 1).

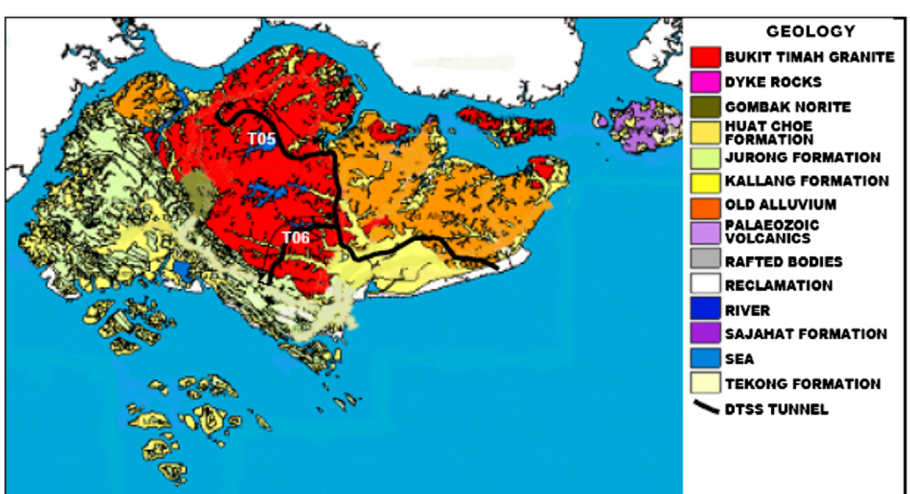

Fig. 1. Simplified geological map of Singapore and layout of the DTSS project.