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Development of the Soft Ground Abrasion Tester (SGAT) to predict TBM tool wear, torque and thrust

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ABSTRACT

The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have jointly developed a new test device called the *Soft Ground Abrasion Tester* (SGAT). The ambition and purpose of the design of the test and the applied test procedure is to replicate an in situ soil – TBM excavation tool contact, in a small and simplified scale. The current development is attempting to bridge a gap when it comes to estimating soft ground and soil abrasivity, as earlier research on e.g. the NTNU/SINTEF Soil Abrasion Test™ (SAT) shows that it does not catch up all driving factors for soft ground and soil abrasivity directly. The paper summarizes the development of the SGAT apparatus, and shows its capabilities to evaluate, quantify and compare how the soil mineralogy, water content, pressure, compaction, and the use of soil conditioning additives influences the wear rate on the SGAT excavation tool. During testing the required torque and thrust are monitored and logged, making it possible to measure various soil–soil conditioning matrixes requirement for operational parameters.

1. Introduction

1.1. General

Predicting soft ground TBM tool life is a complex matter. In order to study and quantify in situ soft ground abrasivity, The Norwegian University of Science and Technology (NTNU), SINTEF Rock Engineering and BASF Construction Chemicals have developed a test device called the *Soft Ground Abrasion Tester* (SGAT). The intention for developing the apparatus is to provide a reliable test method for determination of in situ like soil's abrasivity, as well as various soils and soil conditioners' torque requirement for soft ground TBM applications. The apparatus has the capability of evaluating how soil abrasivity is influenced by water content, air-pressure, compaction or soil density as well as introduction of soil conditioning additives. The developing consortium has been successful and worked in the following manner: NTNU has managed the development based on a BASF design concept. The development has been quality assured by SINTEF. Generally, the SGAT is an open source development and other suppliers, contractors, clients and TBM manufacturers are invited to run tests on the apparatus.

1.2. State of the art on soil abrasion prediction based on hard rock test methods

So far, the research on soil abrasivity and TBM tool life on soft ground tools at NTNU/SINTEF has been limited to the Soil Abrasion Test (SAT™) (Nilsen et al., 2006c,2007; Jakobsen and Becker, 2012), and the Ball Mill Test for determining the influence of soil conditioning additives and presence of water on hard rock and soil abrasivity (Jakobsen et al., 2009; Jakobsen and Lohne, in press). The initial development of the SAT™ test procedure results from a request from a contractor, which would like to evidence that a specific soil condition was highly abrasive. All these test procedures and approaches originate from NTNU/SINTEF's research on hard rock TBM tunneling performance and tool life estimates, which have been an ongoing research activity for several decades. In 2011, there has also been initiated research on the effect of tribo-corrosiveness of rock and soil in interaction with steel (Grødal et al., 2012). The intention of this present work is to achieve a further understanding of the mechanisms which are degenerating TBM excavation tools.

Similar to the development of the NTNU/SINTEF Soil Abrasion Test (SAT™), the Technical University in Munich introduced the LCPC abrasivemeter (LCPC, 1990) for determining soil abrasivity (Thuro et al., 2007). The LCPC approach has some similarities to the SAT™ procedure available at NTNU/SINTEF, as both test methods use dried soil samples in limited fractions (LCPC 4.0–6.3 mm/

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SAT™ < 4.0 mm). The sample used for the LCPC test is however exposed to a steel impeller rotating at 4500 rpm. The high speed rotation of the steel impeller is causing crushing of soil or hard rock fragments, and this interaction causes wear on the steel.

Gwildis et al. (2010) present tool wear data from the Brightwater conveyance tunnel project, which indicate that cutterhead energy consumption together with abrasivity descriptors (e.g. SAT™, quartz content or Miller Slurry Test) are the driving factors for tool wear. The simplified test approaches such as the SAT™ test and the LCPC abrasivemeter do not have the ability to directly include the soil materials' need for cutterhead energy, as the methods are based on testing the interaction between steel and loose soil particles.

Köhler et al. (2011) present experiences from the tunneling project Lower Inn valley in Austria, and conclude that there are no recognized prediction models for estimating tool wear in shield tunneling in soil. They also consider the possibility to establish correlations between small-scale laboratory index values and real-life TBM wear rates to be unlikely, if not impossible.

1.3. New developed soft ground abrasion test methods

The first approach of developing an apparatus purely intended for soil and soft ground abrasive wear prediction was performed and published by Gharahbagh et al. (2010, 2011, 2013) and Rostami et al. (2012a,b). The Penn state soil abrasion testing system consists of a rotating blade at a fixed position which is in contact with a soil sample. The apparatus has the possibilities of evaluating the influence of various water contents, rotation speeds, higher ambient pressures and various excavation tool hardness. However, the soil sample is not consolidated prior to testing according to the test suggested by Gharahbagh et al. (2010). The soil sample density/consolidation is therefore not a controllable variable. Furthermore, the rotating tool is in a fixed position during testing (not penetrating into fresh soil sample material) and soil conditioners can only be used as an already preconditioned soil sample.

A more recent approach is suggested by Barzegari et al. (2013). The test device consists of rotating steel plates in contact with soil samples or crushed rock. The soil sample can be tested under pressure, and the test device allows utilization of additives.

Due to the assessment of simplified abrasion measurements presented by Köhler et al. (2011), Gwildis et al. (2010) and Jakobsen and Becker (2012), as well as the lacking possibility to run tests on a consolidated sample in the Penn State system, a development of a more advanced prediction method is needed. The development of the new SGAT is an attempt to develop a laboratory approach that after further assessment and work, may work as a pre-investigation tool on tool life for soft ground and soil TBM tunneling.

1.4. Research questions

Jakobsen and Becker (2012) and Jakobsen et al. (2013) evaluated the SAT™ values against observed tool life for some recently completed tunneling projects with bentonite slurry face support. In this evaluation, one of the reasons for empirical outliers were identified as the influence of the soil grading. Single graded soils with high SAT™ values did not cause any reduction in excavation tool life. This effect is, as stated by Gwildis et al. (2010), explained by the relative low amount of energy the TBM needs to apply in order to excavate such soils, and thus relatively low contact pressures between the soft ground tunnel face and the TBM excavation tools.

These previously missing effects of soil and soft ground compaction, together with influence of soil conditioning additives are the main reason for developing the apparatus. If the development proves to provide valid and reliable predictions of tool life, a secondary effect of the apparatus can be to obtain laboratory data about how soil conditioning additives, compaction, water influence isolated influences tool life, and use these experiences on SAT™ values. The research questions we intend to answer in this paper are:

- To what extent does the soft ground and soil compaction influence the soft ground TBM excavation tool life?
- Is the excavation tool life influenced by the amount of energy the TBM utilizes in order to excavate the soil and soft ground?
- To what extent does the water content influence the soft ground TBM excavation tool life?
- To what extent can the use of soil conditioning additives increase the soft ground TBM excavation tool life and influences other TBM parameters like torque and thrust?

2. The New Soft Ground Abrasion Tester (SGAT)

The SGAT apparatus consists in the actual status of a drive unit (rotation and vertical movement), a shaft attached to an exchangeable cutterhead-like tool consisting of two steel bars of Vickers Hardness 227 equal to 20 HRC, a testing chamber for the soil sample with a lid which is airtight up to 6 bars pressure, and a foam pump, see Fig. 1. During testing, water, bentonite or soil conditioning additives can be added continuously and directly at the cutterhead-like tool, replicating the real TBM operation. The current steel type, which the results in this paper comprise, is a carbon steel with the chemical composition presented in Table 1.

The drilling tool consists of two steel bars attached to a holder. The tool is designed in order to achieve mixing between the soil sample and the possible used soil conditioning additives, and to achieve relatively high contact forces between the lower steel bar (Fig. 2) and the compacted soil sample during the test. The use of two separate steel bars to form the drilling tool does also provide a possibility to distinguish between primary wear, wear on the lower steel bar, and secondary wear recorded on the upper steel bar. The length of the steel bars is 13 cm, which allows large grains (⩽20 mm) to pass between the drilling tool and the periphery of the testing chamber. The inside periphery of the test vessel consist of steel. For verification issues, some tests have been run without the lid in order to see whether the soil sample rotates along with the tool, which has not been the case.

The rotation speed is variable between 0 and 100 rpm. The fixed maximum speed of 100 rpm is chosen in order to avoid erosive wear, and to reduce the possibility of high impacts between the steel and soft ground and soil fragments. Running tests on 100 rpm results in a travel speed of approximately 0.7 m/s, which is in the range of a TBM excavation tool, which typically ranges between 0.1 and 1.5 m/s dependent on the tool position.

Several techniques have been tried in order to apply soil conditioning additives, during the development of the SGAT apparatus. Fig. 4 shows the three main approaches, (a) applying the soil conditioning additive on top of the compacted soil sample prior to testing, (b) injecting foam continuously during testing and (c) pre-mix the soil and soil conditioning additive prior to testing. The by far closest to reality technique for applying soil conditioning additives is by injecting through the points shown in Fig. 2, equal to the method shown in Fig. 3b.

2.1. Preliminary test procedure

Generally, all soil samples have been dried for 48 h in a ventilated oven at 30 °C prior to testing. After the drying, grains above 10 mm are removed from the sample. The next step is to add water and properly mix water and soil. Similarly to Rostami et al.