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Cutter force measurement on tunnel boring machines – Implementation at Koralm tunnel

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ABSTRACT

Loading of a disk cutter on tunnel boring machines (TBM) is usually estimated from global machine thrust. In order to be able to measure cutting forces of an individual disk cutter, a new measurement method was developed and published in a previous paper (Entacher et al., 2012). This study presents the implementation process of the measurement method at the first TBM of the Austrian Koralm tunnel. Results show that peak forces are a multiple of average forces and that the distribution of forces across the tunnel face can be very irregular. The occurring forces are in very good agreement with geological features of the tunnel face such as highly fractured zones and orientation of schistosity.

1. Introduction

The present paper is a continuation of the article "Cutter force measurement on tunnel boring machines – System design" published by Entacher et al. (2012) in which a newly developed measurement method was described. The presented method is suitable for measuring forces acting on disk cutters – the main excavation tool of hard rock tunnel boring machines (TBM) – in real time. Previous attempts to measure cutting forces were carried out by Gobetz (1973), Hopkins and Foden (1979), Samuel and Seow (1984) and Zhang et al. (2003). These studies give valuable insight into the behavior of a disk cutter during rock cutting. However, in all studies the measurement equipment was designed in such way that it affects TBM operation, i.e. cutter change. Hence, recordings were conducted in a very limited time period and used for scientific purposes only. Within the Mobydic project which was part of Tunconstruct (Beer, 2009), an instrumented cutter was designed that aims to monitor disk cutters by measuring cutting forces, temperature and rotation. It is reported that these cutters were used in various tunneling projects. However, as in all other previous attempts, the sensors for force measurement are located inside the cutter which results in a disturbance of the construction process when cutters are changed because data links have to be disconnected and reconnected in the dirty environment of a TBM cutterhead.

The development of the new measurement method by was governed by the constraint that cutter change must remain unaffected. This should allow for a potential long-term use on a TBM. Besides scientific insight, cutter force measurement could then prove to be a valuable tool for tunneling sites by e.g. detecting cutter overloading and correlating cutting forces with geological features in real-time. Consequently, the main difference between the newly developed method and previous ones is that all sensors are placed in the cutter saddle instead of the cutter itself. Fig. 1 schematically shows how the measurement method works. The outer larger bolts (cutter disk bolts) are used for cutter change. The smaller inner bolts (saddle bolts, marked red in Fig. 1a) hold the inserts in place. They are equipped with strain gauges whose signal is calibrated to be proportional to the bolts pre-stress. As soon as a load is applied to the cutter, pre-stress decreases due to the deformation of the structure. Hence, normal, rolling and side force can be calculated from the saddle bolts signals. It should be noted that the measurement bolts remain fixed during cutter change. They are only loosened when inserts are changed which happens rarely.

In January 2013, the first TBM of the Koralm tunnel main construction lot (KAT 2) started to operate. Three cutters of this TBM were equipped with sensors to measure cutting forces. The present study describes the implementation of the measurement equipment ranging from calibration tests, arrangement of protection devices, design of data communication and storage to TBM operation and presentation of results. The works were carried out in close cooperation with Geodata GmbH, Net-Automation

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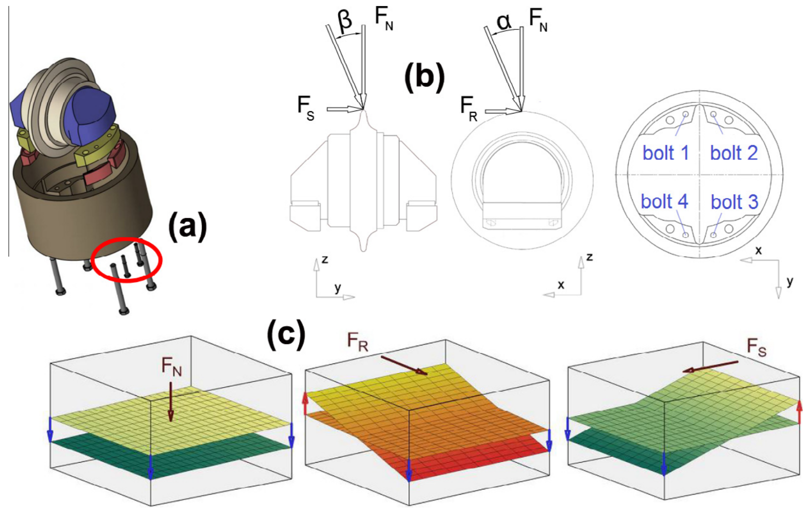

Fig. 1. Cutter force measurement method, measurement bolts (a), definition of normal (F_N), rolling (F_R), side (F_S) force, α and β (b), schematic sketch of bolt deformation during loading (c).

GmbH, Aker Wirth GmbH and the construction consortium KAT 2 (Strabag AG and Jäger Bau GmbH).

2. Implementation at Koralm tunnel

2.1. Project description

The 32.9 km long Koralm tunnel is the most important part of a new high-speed railway connection between Austrian cities Graz and Klagenfurt. This link is also a key element of the Baltic–Adriatic Axis which runs from Helsinki and Gdansk to Warsaw and Northern Italy. It was suggested by the European Commission in 2011 as a top-priority axis for the re-evaluation of the TEN (trans-European) networks.

The tunnel which is designed for a travel speed of up to 250 km/h consists of two single-track tubes with cross-cuts every 500 m and one emergency stop. The tunnel is divided into three main contracts. The first one, KAT 1, was built conventionally with the New Austrian Tunneling Method (NATM), KAT 2 and KAT 3 will be built with TBM. The maximum overburden is 1200 m and altogether 80% of the tunnel will be supported with segmental lining.

The central part of the tunnel goes through the Koralpe mountain massif which consists mainly of gneisses and mica schists with subsidiary marbles, amphibolites and eclogites. A more detailed description of the project can be found in Harer and Koinig (2010).

Aker Wirth GmbH provided two telescopic shield TBMs for the construction of main contract KAT 2. They have a diameter of 9.93 m, about 80 17″ single disk cutters with an average cutter spacing of 65 mm. Including the back-up each TBM has a length of approximately 160 m and a total weight of about 1800 t.

2.2. Installation of measurement equipment

Three cutters were equipped with force measurement sensors. They are aligned along one line (see Fig. 2) with one close to the center (at a radius of $r = 0.7$ m), one in the face area ($r = 2.65$ m) and one close to the gauge area ($r = 4.2$ m). By covering these positions it is possible to obtain an adequate representation of the tunnel face which enables the recognition of geological features by observing cutting forces in different areas of the tunnel face. In order to be able to do so, the rotational angle of the cutterhead has to be known at all times. In addition, cutterhead stiffness decreases with increasing radius and cutting speed increases. Hence, valuable information regarding cutterhead structure and rock breakage, i.e. rock cutting efficiency was expected.

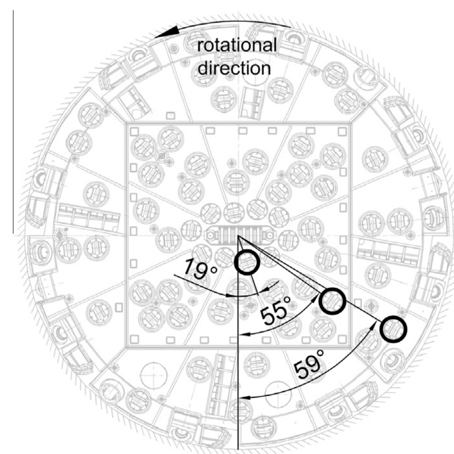

Fig. 2. Cutterhead with three sensor-equipped disk cutters (cutterhead picture (c) Aker Wirth).

Fig. 3 shows a sensor-equipped cutter. During installation, the measurement bolts are first tightened with a moment of 200 Nm in order to hold the inserts (Fig. 3a) in place. Second, cables Fig. 3b) are plugged onto the bolts which are then routed into the cutterhead structure for protection. After that, a steel cap (Fig. 3c) is installed to protect bolt and cable. It is important to seal the bottom side of the cap with silicone in order to avoid water ingression which could possibly reduce durability. The 12 cables (four for each cutter) are gathered to one bundle and covered by a protective hose. They are routed to a programmable controller where all data is recorded with a sampling rate of 100 Hz, processed and sent to a second programmable controller at the non-rotating part of the TBM using wireless radio communication. All data is then stored in a database from where it can be processed or exported. It can be accessed from the control cabin of the TBM operator and from the building-site office on the surface.

Because of the chosen cutter positions, cable lengths between sensor and programmable controller vary between 1.5 and 5 m. In order to find out whether this affects measurement results, cable lengths between 1 and 10 m were tested and compared in the laboratory. It was found that the influence is negligible.