Clogging problem in Tunnel Boring Machine (TBM) drilling process

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ABSTRACT
The increasing need in underground transportation, drainage systems, and utilities renewal results in a rapid development of tunnels and trenchless construction. However, several problems can be expected in the drilling process when a Tunnel Boring Machine (TBM) meets soft soil, including face instability, surface deformation, and TBM clogging. The last-named of the three often leads to adherence of the clay on the cutting wheel, inside the excavation chamber, in the spoil-removal line or in the jamming of the cutting wheel, causing schedule delays and economic loss. Struggling with clogging problems becomes a serious issue for tunnellers and tunnelling engineers alike. Soil conditioner is often adopted to reduce the degree of clogging. This paper introduces the mechanisms of clogging, approaches used to study this problem, and the limitations of each approach, as well as methods to mitigate this problem. The mechanisms of clogging will be introduced by comparing cohesion inside the soil with adhesion between soil and metal. The methods to study clogging, which include empirical and analytical approaches, are described. Limitations and advantages of each method are summarized. Additionally, the soil conditioners normally used to reduce clogging are presented.

1 INTRODUCTION
Tunnel Boring Machines (TBMs) are used as a substitute for the conventional methods of underground construction. Today, 60– 80% of tunnels built in the world are excavated by TBMs (Jakobsen and Lohne 2013). However, when TBMs drill across the area formed by soft soil, it may encounter many problems such as face instability, surface deformation, and TBM clogging (Jack Burnam et al. 2002; Lueke and Ariaratnam 2005; Huang et al. 2011). The last-named of the three often leads to adherence of the clay on the cutting wheel, inside the excavation chamber, in the spoil-removal line or in the jamming of the cutting wheel (Kupferroth et al. 2001) (Figure 1). This creates the possibility for a reduced advance rate, increased the blocking or breakdown of excavation, high energy demand, and high cost (Ball et al. 2009).

Several factors affect the clogging potential, mainly soil properties, properties of drill bit, temperature, etc. Soil properties affecting clogging include water content, grain size distribution, and components of soil. According to the statistical data, Thewes and Hollmann (2016) found that strong clogging occurred when the consistency index of soil was between 0.5 and 0.75. When grain size increases, the ability of holding water in the soil matrix would be lower, which leads to the decrease of clogging potential. If more bentonite is involved in the drilling process, a high clogging potential is expected. Therefore, the component of soil is also very important in the assessment of clogging potential. Azadegan and Massah (2012) investigated the effect of temperature on the mass of soil remaining on the drill bit. The difference between the forces required for lifting a metal plate resting on a soil sample and for lifting a clear metal was recorded. Repeat tests demonstrated that when the temperature increases from 5°C to 30°C, the adhesion decreases following a quadratic polynomical line.

Figure 1. (a) Clogging at the front side of a hydroshield cutting wheel (top view). (b) Clogging of disc cutter housing. (c) Clogging of sieve mesh in a separation plant. (d) Clogging at the transfer point of a conveyor belt (Hollmann and Thewes 2013)

2. MECHANISMS
Fountaine (1954) investigated the adhesion between soil and a foreign surface. The adhesion can be divided into two parts. One is the result of the attraction between soil particles and a foreign object, and the other is the results of the adhesion action between water in the soil and the object. It is possible to theoretically detect the adhesion between a solid and a solid since evidence indicates that strong adhesion occurs between two metal surfaces.

The adhesion between water and metal increases with an increase in soil moisture content and reaches maximum value near the plastic limit (Lal and Shukla 2004) since a higher water cellular can provide a larger adhesion force (Nichols 1929; Baver et al. 1972). The adhesion actions between water and metal are different for coarse and fine soils. For coarse soil, solid particles contact with the metal surface by discrete rings of water. Since the spaces between particles are relatively large, the soil particles are stuck to the metal surface through individual points (Figure 2a). For fine soils, soil particles stick to the metal surface through water link (Figure 2b). This type of connection is a more important and practical type of connection (Tong et al. 1994).

Figure 2. Two distinct types of water linkage in soils a) water rings and b) a whole water film (Fountaine 1954)

Jia (2004) classified the adhesion of soil-to-solid in three parts: an intermolecular force between soil and solid material, the water ring attraction, and the attraction force of water film. This categorization is actually the same as that proposed by Fountaine (1954) except that forces for coarse and fine particles are not classified. Jia (2004) also suggested an equation to estimate the force from water ring attraction. The equation indicates that when the contact angle of water on solid material surfaces increases, the adhesion between soil and solid material decreases.

Kooistra et al. (1998) found that when clay is sheared over a metal surface, two possible shear surfaces can be expected: shear occurs at the interface between clay and a metal plate, and shear occurs within the clay. The shear at the interface consists of two components: the adhesion and a frictional component. In this case, the adhesive shear strength of clay onto the metal is less than the applied shear stress and less than the shear strength of the clay. In the second case, shear strength of soil is smaller than the applied stress and less than the shear strength between clay and a metal plate. In the second case, if the applied stress is also smaller than the shear strength at the interface, clogging occurs with a slice of clay remaining on the metal surface.

3. CLOGGING ASSESSMENT

Kooistra et al. (1998) proposed a method to compare the shear strength of clay and the shear strength at the interface between clay and a metal surface. Shear strengths within soil and between soil and a metal plate, adhesion of soil, empirical diagram, and simulation of drilling process are generally adopted to assess the clogging potential.

3.1. Shear strength test

In clogging assessment, shear strength of soil and shear strength between soil and a foreign object are all important in preliminarily exploring clogging potential. Therefore, both of them should be tested and compared.

3.1.1. Shear strength of soil

Normally, shear strength of soil can be measured by adopting the vane shear test. Messerklinger et al. (2011) improved the vane shear stress apparatus. In the new apparatus, confining stress is applied to the specimens. Moreover, shear velocities can be adjusted. The performance of foams and polymers are evaluated according to the magnitude of measured shear strength (Figure 3).
3.1.2. Shear strength between clay and metal surface

A direct shear test apparatus is generally used to obtain the shear stress of soil. Littleton (1976) used a shear test apparatus to measure the adhesion between soil and a steel plate by replacing the bottom half of the shear box with a solid mild steel block to obtain the shear strength under consolidated drained and quick undrained conditions (Figure 4). The clay-to-steel has a higher strength than the clay-to-clay. The failure at the interface occurs suddenly and when shear displacement increases, little change in shear stress is observed.

Figure 4. Shear box solid half (Littleton 1976)

Stafford and Tanner (1983) tested the effect of shear rate on soil-metal friction. It was noticed that frictional stress is positively related to normal stress. Soil-metal friction increases with an increase of shear rate ranging from 0.0015 to 5 m/s. Yusu and Zeng (1990) concluded that non-Newtonian fluid equation can be used to describe the relation of soil-metal friction and sliding speed. It was found that maximum friction appears when water content is close to plastic limit.

Zumsteg and Puzrin (2012) replaced the shear vane with a rotational steel plate. The rotational velocity of the plate was controlled by a step motor. The torque force was measured using a static torque sensor placed between the step-motor and the box (Figure 5).

3.2. Adhesion test

Fountaine (1954) carried out a test to determine adhesion between soil and different types of foreign material. The load required to pull the plate off the soil was recorded. Fine and coarse soils were used in the test. Different dispersion liquids used to disperse soil were also applied in the tests. Different behaviours were observed. However, although solid-solid attraction exists, it was not significant.

Sass and Burbaum (2009) suggested an adhesion test device in which adhesion force was measured through applying an adhesion test cylinder. The adhesion cylinder was pressed vertically onto the soil surface first. When the cylinder was pulled away, a force was measured which was named as adhesion force (Figure 6). Satomi et al. (2012) proposed an apparatus to measure the adhesion force, except different materials were used for the adhesion cylinder.
Feinendegen et al. (2010) developed a cone pull test apparatus. The sample was prepared in a standard proctor device, then a steel cone was inserted into a pre-drilled cone shape cavity (Figure 7). A load was applied according to the consistency of soil samples. After that, the pulling force was measured with the cone pulling out at 5 mm/min after the load was removed. The variation of tensile force was recorded in the pull-out process which can be recorded and considered as the adhesion force.

A slump cone apparatus has also been used to test the behaviour of conditional soils (Figure 8). Peila et al. (2009) tested the properties of four different conditional soils and describe the performance of the conditional soils using suitable, not suitable and borderline.

Peila et al. (2007) applied a screw conveyor to test the properties of conditional soil. The conditional soils were placed in a tank with pressure applied. Peila et al. then rotated a screw in the tank while monitoring the torque. The performance of the soil was reflected through variation of torque.

Peila et al. (2015) updated the apparatus and changed the screw from an inclined to a vertical direction (Figure 9). The torque was also measured to determine the properties of conditional soil. MacAvelia et al. (2014) created a simulation system to monitor the variation of torque during the test. In the test, feed rate and spindle speed can be varied (Figure 10).
Figure 9. Picture of the dynamic adhesion test equipment (Pellia et al. 2015)

Figure 10. Experimental set-up of drilling apparatus (MacAvelia et al. 2014)

Jakobsen and Lohne (2013) adopted the LCPC abrasivemeter, to test clogging. The LCPC abrasivemeter test was often adopted by the French. The apparatus was composed of a steel impeller, a motor, and a container. Before the test, a certain amount of soil was placed on the steel impeller. During the test, due to the rotation of the impeller, the soil remaining on the impeller reduced. The weight loss of the steel impeller was measured after each test.

3.4. Semi-empirical approach

Jancsecz et al. (1999) gathered data from real tunnelling projects and stated adhesion could be correlated to simple geotechnical parameters, e.g. plasticity limit (PL), liquid limit (LL), and plasticity index (LL-LP). Thewes (1999) developed a diagram of clogging potential using plasticity and consistency index (Ic) based on site reports and laboratory measurements (Figure 11).

Figure 11. Clogging potentials for open mode shield tunnelling without water inflow (Hollmann and Thewes 2013)

Hollmann and Thewes (2013) developed a new diagram that allows for the quantification of changes in water content. Differences between plastic limit and water content, and between liquid limit and water content, should be known before using the diagram. The diagram is classified into five regions: strong clogging, medium clogging, little clogging, fines dispersing, and lumps (Thewes and Hollmann 2016) (Figure 12). This diagram can be used for different shield conditions. Consistency index is used to differentiate the clogging potential. However, the bounds between different clogging potentials are empirically determined. Tunnelling engineers prefer to use this diagram since it is user-friendly.

Figure 12. Universal classification diagram for critical consistency changes regarding clogging and dispersing (Hollmann and Thewes 2013)
Soil conditioner is normally used to reduce clogging by modifying the soil behaviour to control face pressure while excavating, to reduce abrasion, to reduce cutterhead torque, to control water, and to ensure control of the spoil passing through the screw conveyor. Once soils with the potential to cause clogging have been detected on the tunnel alignment, soil conditioner can be applied to reduce or eliminate the clogging risk (Ball et al. 2009). The benefits of using soil conditioner can be summarized as increasing the stability of the tunnel face, improving the flowability of material, reducing the driving torque, and modifying the soil properties. In that way, clogging of material, pressure inside the cutting chamber, and groundwater inflow can be effectively controlled (Milligan 2000).

Soil conditioners are often injected through the cutterhead or into the cutting chamber to make the muck flowable, lower inner friction between the soil particles, control soil stickiness, and prepare the excavated soil to be compressible during tunnelling operations (Langmaack 2000, Langmaack 2001). Selection of soil conditioner should be based on soil type, water content, geological condition, and properties of the TBM. The most important soil conditioners are foam and polymer (Gharahbagh et al. 2014).

The most popular soil conditioners are foam, polymer, and saline water. Foam is a type of mixture made from water and a surfactant (Jancsezcz et al. 1999). The function of foam is to reduce the torque of the shield and decrease the necessary energy supply. It can also reduce the soil permeability.

Foam represents the physical state of air, dispersed in liquid. The properties of foam alone have been tested by laboratory tests developed by Quebaut et al. (1998). However, when the foam is applied to the soil during the tunnelling process, foam is mixed with soil. Therefore, the properties of soil that are conditioned by foam should be tested. Gharahbagh et al. (2014) used a foam penetration test, mixing test, and slump test to evaluate the performance of foam. Supplemented tests such as permeability tests, compressibility tests, adhesion tests, and cone penetration tests were employed to determine the soil behaviour after the soil was mixed with soil conditioners. In the test, weight loss or torque force were recorded.

Polymers have a relatively long history of use and are, for the most part, spin-offs from the oil drilling industry (Kupferroth et al. 2001). Polymer types range from polyacrylamides, various gums, cellulose ethers, and carboxymethyl cellulose. The first polymers used in tunnelling were polyacrylamides (Jancsezcz et al. 1999). The function of polymers is not only to manage the face support and soil transport problem in loose, coarse soils; it can also reduce the stickiness on the conveyor belt, in the working chamber, and in the screw conveyor. Jancsezcz et al. (1999) employed the cone penetrometer test and simple shear test to test the effectiveness of soil conditioners.

Spagnoli et al. (2013) and Spagnoli et al. (2014) mixed sodium chloride with soil material and employed Atterberg limits, vane shear tests, and cone pull-out tests to test the performance of the additives. Reductions of the liquid limit and undrained shear strength were detected.

5. DISCUSSION AND CONCLUSIONS

When TBMs drill cross area formed by soft soil, clogging is one of problems that may delay the project and cause economic loss.

When shear strength of soil is smaller than the applied stress and less than the shear strength between clay and a metal plate, clogging occurs with a slice of clay remaining on the metal surface if the applied stress is also smaller than the shear strength at the interface.

To test the clogging potential, different methods are employed including testing shear strengths of soil and between soil and a metal surface, adhesion tests, simulation of drilling process, and semi-empirical methods. Cohesion and adhesion tests are difficult to be directly related to clogging assessment. Simulation of drilling process is an applicable approach to assess the clogging potential. However, size and shape of drill bit greatly affect the testing results. A semi-empirical diagram is a user-friendly approach to test the clogging.

To mitigate the clogging potential, polymer and foam are mostly used as soil additives. Foam is mostly used since its price is much cheaper than polymer.

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