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Mechanical Properties of Clayey Soil Relevant for Clogging Potential

Due to its advantages, including reduced operation time and cost, tunneling with boring machines in urban areas has become a popular technique over hand-tunneling or open-trench excavations. However, tunneling in clayey soil poses a great challenge since the mechanical and physical properties of clays cause different issues, one of which is clogging. To solve this problem, engineers have treated the soils with different soil conditioners in order to change their rheological properties, improve their manageability, and eliminate undesirable characteristics. However, the root of this problem is the lack of understanding the phenomenon and characterizing it on the framework of soil mechanics. By considering the use of polymers, this paper aims to provide information regarding the theory involved in this mechanism and the factors influencing clogging potential. The authors present a systematic study of the physical and mechanical properties of plain soil and conditioned soil, which includes a direct shear test, vane shear test, and Atterberg limits test. Results show that the initial water content, roughness of shear plate, and percentage of additive have a significant effect on the clogging potential. Additionally, the results are plotted on an empirical diagram to understand the clogging potential by relating the clogging potential to soil properties.

Keywords: tunnelling; clogging; soil conditioner; geotechnical tests.

Introduction

Tunneling has emerged as an alternative trenchless technique to optimize limited urban space. The use of tunnel boring machines (TBMs) has spread even to difficult subsoil conditions, such as soft soils. Nevertheless, there are challenges that must be faced to successfully complete a tunneling project in soft soils. One of the most common issues presented during excavation is the phenomenon of clogging. However, this problem is not usually considered during the design process (Langmaack 2002; Kang et al. 2016; Alberto-Hernandez et al. 2017).

Clogging is related to the stickiness of the soil, and it occurs when soil sticks to the cutting wheel, the conveyor band, and other parts of the machine. This phenomenon causes delays and wear of the equipment, which eventually leads to economic loss. During the excavation and transportation of the material, the mechanical wear may cause a loss of strength, sometimes leading to a complete disintegration of the composite structure (Heuser et al. 2012). In order to deal with clogging, Construction Engineers tend to modify the soil by adding water or soil conditioners such as foams or polymers, which can affect the soil's mechanical properties. In that regard, the potential for clogging is a mechanism that should be understood from the physical and mechanical properties of soil.

The mechanism of clogging

Thewes and Burger (2004) conducted a study on the stickiness of clay on a steel surface, resulting in the identification of four different interactive single mechanisms involved in the clogging potential of clay formations. These mechanisms include the adhesion of clay particles on a component surface (Figure 1a), the inherent cohesion of clay particles (Figure 1a), the bridging of clay particles over an opening in the path of soil transport (Figure 1b), and the low tendency of clay toward dissolving in water (Figure 1c).

The observations indicate that the main forces involved in clogging are cohesion and adhesion. Cohesion is a well-known property and one of the main factors to be evaluated in order to comprehend the clogging phenomenon; researchers have established several methods to evaluate cohesion. On the other hand, many researchers consider adhesion to be the most important factor in evaluating the clogging potential of soils; however, no standardized method exists to measure adhesion.

Cohesion is the component of shear strength that depends on inter-particle contact, and it can be defined as the bonding of hydrogen between water molecules available in soil. Conversely, adhesion is the force that develops between clay and a foreign surface, such as metal; it can also be understood as the attraction of a water molecule in soil to a solid molecule (water-solid bond) (Ren et al. 2001). It must be pointed out that adhesion itself can be subdivided into two different components that address the relative displacement (normal or tangential) between soil particles and the steel surface (Thewes and Burger 2005). Adhesion can be expected only in cohesive soils that have at least 10-20% clay mineral contents. Basically, clogging can stem from the adhesion that occurs in the interface of clay minerals and a metal surface (Spagnoli 2011).

Fontaine (1954) was the first researcher to propose a theory on the mechanisms of adhesion. This theory introduced two different types of adhesion (Figure 2). In relatively dry and coarse soil, soil sticks to a surface by small water rings on the surface, and the water tension controls the magnitude of adhesion. In moist soil, a water film dominates the phenomenon of stickiness, and the adhesive strength per unit area will be equal to the water tension.

Later, Jia (2004) defined three different forces of adhesion of soil-to-solid materials: a) an intermolecular force between the soil and the solid materials, b) the water attraction ring, and c) the attraction force of the water film. Jia also proposed a theoretical framework to evaluate each force.

Apart from microscopic observations, clogging potential can also be understood through the mechanical properties of soils. Based on shear stress, cohesion, and adhesion, Kooistra et al. (1998) proposed two different conditions that will lead to stickiness. If the shear stress applied is larger than the shear strength of the soil (i.e.,

cohesion plus the friction component) but smaller than the adhesive shear strength of the soil (i.e., adhesion plus the adhesive friction component), clogging will occur. This can be summarized in Equation [1]:

$$a + \sigma_n \tan \delta > c + \sigma_n \tan \phi \quad [1]$$

where σ_n is the normal stress applied, a is the adhesion, c is the cohesion, ϕ is the internal friction angle, and δ is the adhesive friction angle.

Nonetheless, clogging can still be detected when no shearing occurs, e.g., while transporting the excavated clay on the conveyor band. In such a case, the shear stress applied would be less than the shear strength of the soil ($\tau < c + \sigma_n \tan \phi$) and also less than the adhesive shear strength of the soil ($\tau < a + \sigma_n \tan \delta$).

Approaches for the assessment of clogging potential

In order to measure adhesion forces, studies have been conducted using devices varying from the very simple, which consist of shear boxes (e.g., Langmaack 2000; Yoshimi and Kishida 1981; Yusu and Dechao 1990) and pulling devices (e.g., Azadegan and Massah 2012; Sass and Burbaum 2008; Thewes and Burger 2005), to the very sophisticated, such as that proposed by Zumsteg and Puzrin (2012).

A different approach to evaluate clogging is to concentrate on the physical properties of the soil. Atterberg (1911) was one of first researchers to study soil stickiness and the concept of Klebegrenze, which is the sticky point or the minimum soil moisture content at which the cohesion of soil is less than its adhesion to a foreign object. Later, Thewes (1999) used data from actual projects to evaluate clogging potential as a function of water content and consistency index, thus developing an empirical diagram. The diagram defined a distinction of strong, medium, and little

1 clogging potential from the reports of different tunnel projects that faced delays due to
2 cleaning or change of TBM parts resulting from the wear caused by clay. However, the
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4 boundaries for the classification of clogging potential is different for different open
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6 modes, therefore Hollmann and Thewes (2013) updated it to a universal diagram. In the
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8 new diagram, as water content increases either by change of the material encountered or
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10 by addition of water or soil conditioners, a change of clogging potential occurs that can
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12 be advantageous or counterproductive depending on the initial consistency of the soil.
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17 In spite of the varied research conducted on this topic, no standard currently
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19 exists that can measure adhesion or clogging in order to define the actions that can be
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21 taken in the field to avoid the associated problems or delays. As it can be observed,
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23 there are two different approaches to the problem. The first focuses more on the
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25 adhesion forces. It aims to measure the adhesion of the soil by conducting different tests
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27 in the laboratory. The second considers only physical properties, such as water content,
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29 Atterberg limits, and consistency index. In this paper, the authors followed both
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31 approaches to assess clay samples from Edmonton, Alberta, Canada.
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38 ***Soil conditioners used to reduce the potential of clogging***

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41 The problems generated by the clogging of clay must be overcome in order to reduce
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43 equipment wear and perform an excavation on schedule. For this reason, different
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45 additives have been created in order to change the properties of soil. Reduction of
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47 strength, for instance, is one of the main objectives in using these substances because
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49 reducing the strength of soil can improve the rate of advance and the performance of the
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51 TBM. In order to reduce stickiness, different products can be selected based on their
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53 performances. However, the performance of additives is mostly evaluated subjectively.
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1 The conditioners, including polymers and foams, aim to change certain
2 undesirable properties of the excavated soils. According to Borghi (2006), soil
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4 conditioners can stabilize coarse materials, prevent groundwater from leaking into the
5 excavation, decrease permeability, prevent the segregation of soils, form a cohesive
6 matrix with reduced friction in coarse materials, change the Atterberg limits of fine
7 materials, increase or decrease shear strength, and reduce adsorption (Zumsteg and
8 Puzrin 2012).
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11 Since different products sometimes have the same effects, it therefore becomes
12 important to decide the optimum quantity and type of product to be used in a
13 determined circumstance. Given that these additives employ complex chemical
14 technology, their price tends to be high, which makes it important to select how much is
15 needed to reach the desired consistency of the soil. In the same manner, it is also very
16 important that the selected conditioner is effective for the excavated soil. Therefore, the
17 amount and the type are two vital factors to consider when selecting an additive. This
18 study will evaluate the performance of clay cutter, an additive used to reduce clogging.
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38 **Experimental program and test results of plain soil**

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40 In order to present an inclusive framework that describes the latent stickiness of clayey
41 material, this study evaluated soil samples from a tunnel site located in Edmonton,
42 Alberta, and carried out an experimental program consisting of shear strength, adhesion,
43 and indices testing.
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50 The geology of Edmonton has been defined by the northern Beverly Valley, the
51 surrounding Rocky Mountains, and the Saskatchewan River. Generally, it consists of
52 bentonitic sandstone, siltstone, claystone, coal seams with bentonite beds, and glacial
53 lake sediments (Bayrock and Berg 1966). In the zones where the soil was sampled, the
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deposits can be summarized as glacial lake Edmonton sediments, glacial till, preglacial Saskatchewan sands and gravels, and a bedrock made up of sandstone, shale, and coal of the Edmonton formation (Bayrock and Berg 1966). Bayrock and Hughes (1962) sampled soil at different locations and depths in Edmonton. At each specified depth, several samples were collected and sieve analyses were carried out for each of them. Particle size distribution can be obtained after sieving using U.S. standard screens (Bayrock 1955). For material finer than 0.062 mm, it was dried and sedimentation analyses were carried out by pipette method as stated by Toogood and Peters (1953). Six samples were collected and analyzed by Bayrock and Hughes (1962) at the depth at which the authors sampled the soil in this study. Results show that average percentages of each composition are 44%, 30% and 26%, respectively. The samples, collected from the tunnel sites on the south side of Edmonton, are classified as till. In order to appropriately evaluate their consistency index in the field, fresh samples were placed immediately in the moisture room. They were selected because till has caused clogging during tunnel excavation in the city. Currently, construction staffs use water and foam to reduce the stickiness of soil.

Fundamental soil properties

The soil was sampled from a tunnel in south Edmonton which is located approximately 5 to 6 m below the ground. Since the tunnel was close an existing pipeline project, the engineers used hand-tunneling method. Therefore, it was very easy to sample undisturbed soil. In sampling process, the soil was trimmed into blocks first and then packaged into boxes with plastic bag sealing the soil. In sample preparation and test, the samples always kept upward.

The soil was dried, ground, and then mixed with the desired distilled water content; finally, the samples were placed in the moisture room for at least 16 hours. The moisture content and Atterberg limits of the soil were determined following the ASTM procedures (ASTM D4318-10e1), and the results are shown in Table 1. The consistency index (I_c) is defined as $I_c = (LL - w) / (LL - PL)$. Since the original water content of this soil is 27% ($I_c = 0.54$), two more water contents were adopted in the laboratory tests, including one water content below the initial water content at 24% ($I_c = 0.75$) and another above the initial water content at 32% ($I_c = 0.18$).

Direct shear tests

Test procedures

To characterize the samples in terms of shear strength and cohesion, a direct shear apparatus was used following the standard ASTM D6528-07. Three different water contents were evaluated and three different confining stresses were used for each sample: 75 kPa, 110 kPa, and 200 kPa, and samples were compacted with the standard proctor method (ASTM D698-12e2). After compacting the soil with desired conditions, a soil sample was placed into the chamber and consolidation was developed by applying increments of constant total normal force. The diameter of the sample was 61 mm and the height was around 33 mm. Then, the specimens were sheared at a rate of 0.002mm/s.

The direct shear apparatus was also modified to measure the adhesion forces. Instead of placing a complete soil sample into the device, a plate of the exact diameter and height filled the box to shear against soil. Considering those dimensions, two different plates were manufactured: one was produced out of an old TBM (chromium

carbide) and the other from stainless steel (Figure 3). The first plate has a roughness of 2.5 μm and the second of 1.6 μm .

The sample was placed on the bottom half of the apparatus, then the metal plate was placed on top of it. From that point, the procedure was the same as in a conventional direct shear test in which the normal confining stress was applied and shear force was used to finally shear the sample. Figure 4 depicts this arrangement.

Test results

As the confining stress increases, the shear strength also increases (Figure 5). However, it can be observed that the effect of water content is not as clear as the confining stress. The samples with $I_c = 0.18$ exhibit the lowest values of shear strength, but the sample with $I_c = 0.54$ has the greatest shear strength for 75 kPa, 110 kPa, and 200 kPa. One important factor to be taken into account is the actual overburden force expected in the excavation site, 110 kPa. In that case, the shear strength under natural water content at the time that the sample was obtained is 73 kPa.

After replacing the top part of the sample with a steel plate, the effect of roughness, as well as the difference between cohesion and adhesion, can be clearly observed in Figure 6. For $I_c = 0.54$ and $\sigma = 110$ kPa, the shear stress developed within the clay is significantly larger than the adhesion force of the clay to smooth and rough plates. Then, the strongest stress develops when clay is sheared against the TBM plate, and the weakest force is measured between the smooth surface and the clay. These results are very similar to those observed by Littleton (1976), who conducted similar experiments using two different clays under quick drained, consolidated untrained and consolidated drained conditions. It was found that shear strength from clay to steel was 0.7-0.8 of that generated from clay to clay under different confining pressures for fast

loading cases and the ratio reduces to 0.6 for long term tests. In Figure 6, the ratios are 0.64 and 0.95 for the surfaces with different roughness. Although soil, confined stress and test method are different, the comparison can still give some idea on the relationship of the strengths between clay to clay and clay to steel.

Considering the effect of water content, it can be observed in Figure 7 that the sample with $I_c = 0.54$ exhibits the largest force of adhesion, followed by the sample with $I_c = 0.75$ and finally the sample with $I_c = 0.18$. This behaviour is quite similar to that observed in the cohesion tests.

Although the behaviour trend regarding the effect of water content is analogous, Figure 7 shows a change to the observed trend regarding adhesion and cohesion. For $I_c = 0.75$ and $I_c = 0.54$, the value of adhesion is 0.92-0.94 of the cohesion at 110 kPa of confining stress and $R = 2.4 \mu\text{m}$. However, for $I_c = 0.18$, the value of adhesive strength is 1.02 of cohesive strength, resulting in a high potential of clogging. This behaviour is similar to that described by Kooistra et al. (1998), which indicated that around the plastic limit ($I_c = 1$), the value of cohesion is 3-4 times higher than the adhesion for the soil with PL is 29% and LL is 62%. However, when water content gets closer to the liquid limit ($I_c = 0$), the adhesion force will peak and starts to be larger than cohesion force indicating a high potential of clogging as well.

Vane shear test

Since the measured torque was related closer to the tangential stresses developed during excavation with the TBM, this study used a simple vane shear apparatus (diameter = 22.2 mm and height = 37.75 mm). Sample preparation and testing followed the standard processes (ASTM 4648M-16). The samples were first mixed with different water contents similar to the direct shear tests and compacted with the standard proctor

method. The torque was measured and the corresponding shear strength was calculated.

Some researchers (e.g., Merritt 2004; Peila et al. 2009; Vinai et al. 2008) have tested the change in consistency by using concrete indexes, such as the slumping test. In this experimental procedure, the measurement is simplified by defining an index as being similar to that used by Zumsteg and Puzrin (2012), who used a concrete mixer with the conditioned soils and measured the amount of mass sticking to the paddle to define the empirical stickiness ratio:

$$\lambda = G_{MT} / G_{TOT} \quad [2]$$

where G_{MT} is the soil sticking to the tool and G_{TOT} is the total weight of the soil in the mixer.

Figures 8a and 8b show the change in consistency and the mass of soil sticking to the vane. The sample is sheared and then the mass sticking to the vane is weighed to detect the change in soil consistency; this index seems representative. As observed in Figure 8, only the water content is changed. A comparison between different water contents can be seen in Figure 9. It is noted that λ slightly increases as water content increases.

Semi-empirical diagram

Plain soil

Clogging potential can also be evaluated by employing a semi-empirical diagram proposed by Thewes (1999) and which has been updated by Hollmann and Thewes (2013). Atterberg limits and the water content of soil are used on the universal diagram, which is summarized for all types of TBMs. This evaluation is only meant as an index of the behaviour as there are no current charts to fully evaluate conditioned soils.

Figure 10 indicates the effect of water content on the clogging potential.

Increasing water content leads to a change of clogging potential from strong clogging to medium clogging. However, the result is not very consistent with that from the direct shear and vane shear tests. The difference mostly results from the principle of methods. Direct shear and vane shear apparatuses measure the strengths of soil. The measurements are simply related to the clogging potential. However, clogging potential is not only affected by soil strength: it is also impacted by the soil density, roughness of cutting surface, penetration rate, etc. The diagram is an empirical summary of clogging phenomenon. Although the results from the diagram are close to field situations, the diagram still cannot capture the main factors affecting clogging potential. Therefore, an apparatus that can take all the factors mentioned above into account is needed.

Conditioned soil

The performance of additives in reducing clogging potential is also evaluated using the diagram. In this experimental program, one type of additive named *clay cutter* was used to reduce clogging and improve the properties of clays in order to be excavated. Clay cutter liquid is a type of polymer supplied by CETCO, an international corporation offering drilling fluid products to projects worldwide. The liquid is often used as an additive for horizontal directional drilling (HDD) bores in reactive clay soils. Its appearance is clear to amber liquid with an irritant odour. The main function of this additive is to change the consistency of the clay. Figure 11 shows when 0.2% additive is added, the change in clogging potential is not obvious. However, if the content of additive increases to 0.5% or 1%, the clogging potential decreases.

Discussion and conclusions

Vane shear and direct shear apparatuses are employed to measure soil strength. The

1 direct shear apparatus is also adjusted by replacing the top part of the box with steel
2 plates to measure the adhesive strength between soil and foreign objects. Among the
3 test results of samples with three different water contents, the soil with $I_c = 0.54$ yielded
4 at the highest strength. Although these results are only for the soil at specific location, it
5 at least provides a relationship that could be applicable to similar soils. The adhesion
6 measured for this water content is less than the cohesion. The strength between clay and
7 clay is higher than that between clay and a metal surface, and the roughness of the metal
8 has an effect on the strength.

19 The relationship between cohesion and adhesion is used to identify the clogging
20 potential according to the method proposed by other scholars. However, this method is
21 not available for some situations, such as the test results in this study detecting clogging
22 when cohesion is higher than adhesion.

29 Alternatively, a semi-empirical diagram can also be used to assess the clogging
30 potential if the Atterberg limits and water content are known. For plain soil, when $I_c =$
31 0.18, the empirical diagram indicates that the clogging potential decreases; however,
32 this is not consistent with the results from comparing adhesive and cohesive strengths.
33 When using the empirical diagram to evaluate the performance of the additive, the
34 results show that when more additive is added, lower clogging potential is expected.

43 This research has provided some ideas on the evaluation of clogging potential
44 using conventional geotechnical testes. However, limitations still exists. Although
45 cohesion and adhesion forces were compared, drilling process was not considered. In
46 addition, some factors affecting the clogging were not taken into account, including
47 penetration speed and rotational velocity. Therefore, an apparatus is expected that could
48 consider these factors and take clogging mechanism into account as well. However, this
49 research is still valuable since it tries to assess the clogging potential using mechanical

properties of soil samples and compare the results from different clogging assessment
methods.

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Table 1. Moisture content and Atterberg limits of the soil

Liquid limit, <i>LL</i> (%)	Plastic limit, <i>PL</i> (%)	Plasticity index, <i>PI</i> (%)	Water content, <i>w</i> (%)	Consistency index, <i>I_c</i>
34.5	20.5	14.0	27.0	0.54

Figure 1. Clogging potential as a) cohesion and adhesion, b) bridging and c) aggregation
(adapted from Thewes and Burger 2004)

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

Figure 3. Metal plate used to replace the soil in the shear box

Figure 4. Shearing of the soil and metal plate

Figure 5. Stress-displacement relationship for the soil under a conventional simple shear
test

Figure 6. Cohesion and adhesion at 110 kPa of confining stress

Figure 7. Changes in cohesion and adhesion for different water contents at 110 kPa of
confining stress and chromium carbide plate ($R = 2.5 \mu\text{m}$)

Figure 8. Mass sticking to the vane for a) $w = 22\%$ and b) $w = 32\%$

Figure 9. Effect of water content on the mass sticking to the vane for soils

Figure 10. Clogging potential of soil under different water contents: 24%, 27% and 32%
after Hollmann and Thewes (2013)

Figure 11. Clogging potential of soil with different concentrations of additive

Figure 3. Metal plate used to replace the soil in the shear box

[Click here to download Colour figure \(online only\) Figure 3.jpg](#)

Figure 5. Stress-displacement relationship for the soil under a conventional simple shear test

[Click here to download Non-colour figure Figure 5.bmp](#)

Figure 7. Changes in cohesion and adhesion for different water contents at 110 kPa of confining stress and chromium carbide plate ($R = 2.5 \mu\text{m}$)

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Figure 9. Effect of water content on the mass sticking to the vane for soils

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Figure 10. Clogging potential of soil under different water contents: 24%, 27% and 32% after Hollmann and Thewes (2013)

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