The Sticky Property of Ypresian Clays

By

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Abstract

Construction sites may encounter many problems with the underlying soil, and excavating in soft soils is one of them. One major issue when managing soft soils is clogging, which occurs because cohesive soils tend to adhere to the cutting head of tunnel boring machines or to the cutting wheel of hydromills. This thesis focuses on Ypresian clays, which are highly adhesive. The adhesive properties of Ypresian clays can slow down excavation processes, causing economic loss to the construction companies. Studying the different mechanisms behind the clogging phenomenon and ways to qualitatively and quantitatively assess it makes it possible to evaluate the clogging potential of Ypresian clay and compare it to that of the Boom clay, a similar formation which is shown to be less sticky. The high plasticity index of Ypresian clays is proved to be an indicator of its high stickiness, and the cone pull-out test gives a value for adherence that quantifies the clogging potential. Ypresian clays also support the hypothesis that the Casagrande chart's U-line could be used as an evaluation method for clogging. In these ways, evaluating clogging potential is possible, but a standardized method has yet to be agreed on. The physics behind the evaluation methods, however, is not well understood. That is why this thesis discusses using a microscopic approach to study the origin of Ypresian clay's stickiness. Research still needs to be done to see if inter-scaling is possible between micro-, meso-, and macroscopic scales and to find out if the particles' interactions at microscopic scale can be interpreted at the macroscopic scale.

Thesis Supervisor: Herbert H. Einstein
Title: Professor in Civil and Environmental Engineering

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DEFINITIONS

Adhesion:
One of the four interacting single effect mechanisms that contribute to the clogging potential of a clay. Adhesion of clay particles on a component surface can be evaluated using the adhesion test (Thewes & Burger, 2005).

Adherence (= clogging value):

$$Adherence\ [g/m^2] = \frac{the\ weight\ of\ the\ material\ attached\ to\ the\ test\ cone}{the\ cone\ surface\ in\ the\ cone\ pull\ out\ test}$$

Cation Exchange Capacity (CEC):
The total number of cations a soil can hold, or its total negative charge. CEC is measured in millequivalents per 100 grams of soil (meq/100g).

Clay Fraction (CF):
Percentage of particles of a diameter smaller that 0.002 mm.

Consistency Index (CI):
The consistency index indicates the consistency (firmness) of a soil.
Soil at the liquid limit will have a consistency index of 0, while soil at the plastic limit will have a consistency index of 1.

$$I_c = \frac{(W_L - w)}{I_P} = \frac{(W_L - w)}{(W_L - W_P)}$$

where
W_L $(or\ LL)$: Liquid Limit
W_P $(or\ PL)$: Plastic Limit
w : Natural water content

Plasticity Index (PI):

$$I_P = W_L - W_P$$

I. Introduction

A. Background

Our world's growing population and the need to accommodate it has led to the growth of the construction industry. Structures are increasing in size, and denser cities often constrain the choice of sites that can be built on. As a consequence, many construction projects – mainly underground construction projects – involve dealing with ground conditions that are not ideal to work with. Society's increasing need for transportation, sewage and renewal of utilities has encouraged the growth of tunneling, more recently by means of tunnel boring machines (TBMs) (Spagnoli et al., 2014). The layout of a tunnel, which is defined to meet the needs of human activities, namely transportation, can hardly avoid dealing with soils that are not easily workable.

Amongst the many problems a construction site may encounter when handling the underlying soil, excavating in soft ground is one of them. Besides face stability and surface deformation, one major issue when managing soft ground is clogging. Clogging occurs because cohesive soils tend to adhere to the cutting head of the TBM or to the cutting wheel of a hydromill (Alberto-Hernandez et al., 2017). In TBMs, the clogging problem can be observed in two different areas of the machine. The suction inlet area (see Figure 1) is often affected by sticky material building up in front of the inlet grill (see Figure 2). The cutting wheel area also is affected by clogging on the cutting tool as Figure 3 shows. In hydromills – hydraulically-operated reverse circulation trench cutters – which are commonly used for excavation when building slurry walls or cut-off walls, the clogging would occur mainly to the trench cutters as can be seen on Figure 4.

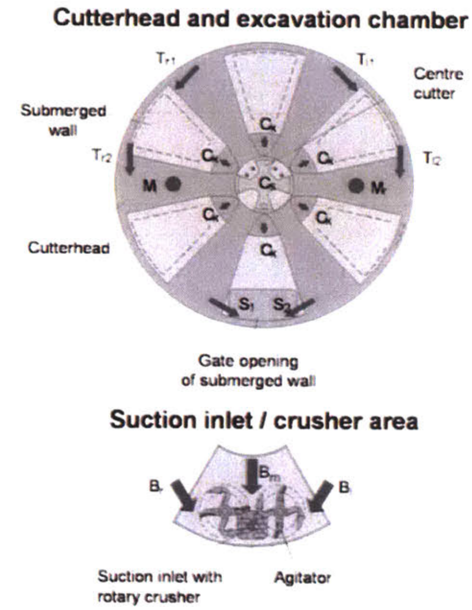


Figure 1. Scheme of the cutterhead of the Herrenknecht TBM (by Thewes & Burger, 2005)

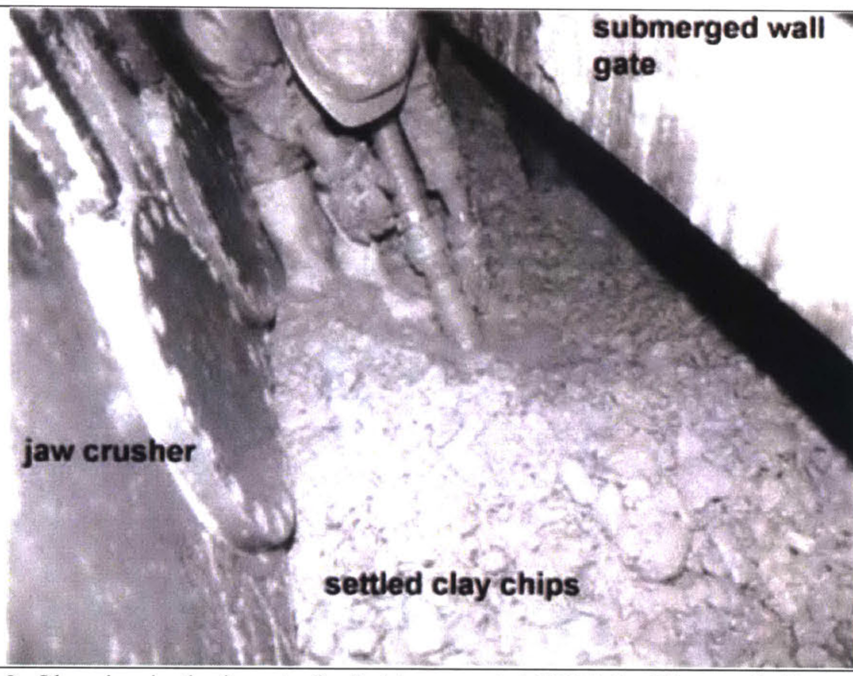


Figure 2. Clogging in the invert of a fluid-supported TBM (by Thewes & Burger, 2005)

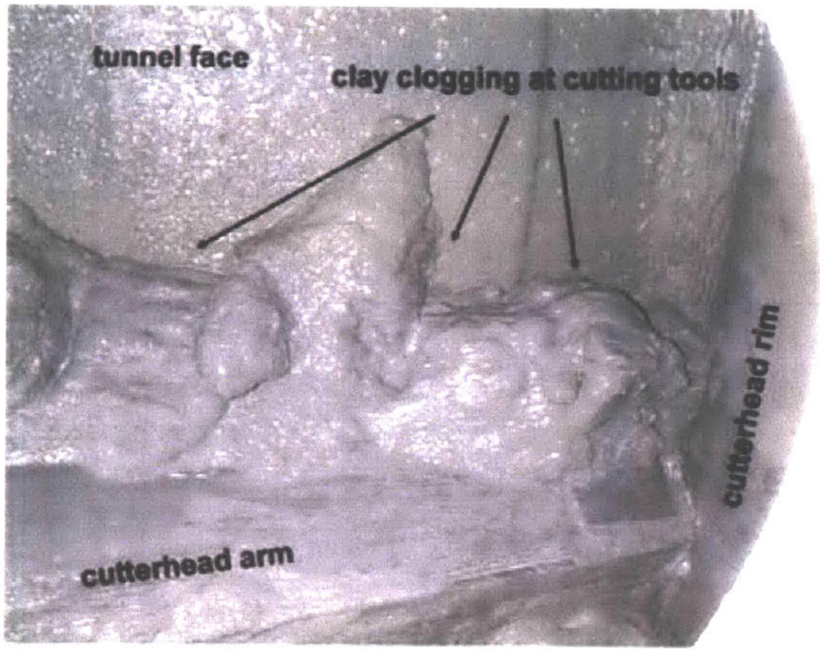


Figure 3. Clogging at the cutterhead of a fluid-supported TBM (by Thewes & Burger, 2005)

Figure 4. Clogging on the cutter trench of a hydromill in Porte Maillot, Paris

One of these cohesive soils that has been a source of problems is the Ypresian clay. Several clogging problems caused by this kind of clay are reported in the technical literature. For instance, Thewes and Burger (2005) report adhesion problems during the Westerschelde tunnel construction, a 6.6 km tunnel which was completed in 2003. Two thirds of the Westerschelde tunnel were built in the Boom Clay, which is highly sticky. During the construction of the Metro in Lille, France, Mauroy (1998) reported clogging caused by Ypresian clays in the head chamber of the TBM, the area of the shield in which the cutting wheel rotates (Spagnoli et al., 2014). Most recently, it has been observed that the high stickiness of Ypresian clays has caused delays in the construction of diaphragm walls during the enlargement of the Porte Maillot train station in Paris. In fact, the Ypresian clay was sticking to the hydromill's cutters, thus requiring workers to manually remove the clay. An evaluation of the clogging potential of several different clays was carried out by Spagnoli et al. (2012) using the cone pull-out test (see Figure 5). Spagnoli's testing has proven that of the four tested clays, a clay from Westerwald (Germany), the Ypresian clay, the Boom clay and a pure sodium smectite from India, the Ypresian clay has the highest risk of clogging (See Figure 6). The unusually high adherence of the Ypresian clay makes it a material worth studying.

The lack of efficient methods to remediate this clogging issue is causing delays in construction projects such as the Porte Maillot train station project mentioned above, thus causing economic loss for contractors who have to handle the sticky clays. According to Thewes & Burger (2005), the cost of a tunneling project can depend very much on the clogging potential of the encountered material. In clay, the advance rate, the rate at which a TBM drills through soil, can be as low as 1/10 of the regular process in granular soil. Several solutions are present in the market, especially for tunneling where clogging can bring mechanical tunneling to a complete standstill. However, these solutions are often not satisfactory. Also, the chemo-mechanical properties of clay are not always well understood, and the existing solutions to deal with the high stickiness of clays such as Ypresian clays are often empirical solutions while the mechanisms are yet to be understood. (Spagnoli et al., 2012).

The methods that are currently used to prevent clogging include conditioners that are mainly used for TBMs. For earth pressure balance shields (EPB) for instance, foam conditioning systems are used to inhibit the swelling of clay and thereby to keep it from adhering to the cutterhead. This measure does not work for fluid-supported shield machines because the circulation of the fluid in the cutterhead chamber does not allow foam to be delivered to the clay directly. In addition to foam, polymers and anti-clay agents can also be used to help reach the optimum performance of a TBM. Spagnoli is proposing the use of electro-osmosis to create a film of water on the surface of the excavation machines to prevent the clay from sticking to it. This method is not used in the industry yet, and research continues on this topic.

B. Thesis objectives

The objective of this thesis is to study the history and the properties of the Ypresian clay to understand the factors that contribute to the particularly sticky behavior of this clay. By comparing the Ypresian clay with the Boom clay from the perspective of geomechanical properties, but also by looking at their mineral composition, we hope to relate the extreme stickiness of Ypresian clays to its chemo-mechanical properties. This thesis will also discuss how the swelling mineral smectite could explain the high stickiness of Ypresian clays. A few available techniques and operational measures to prevent clogging are also given.

C. Outline

This thesis has four parts. The first part explains the burial histories of both Ypresian and Boom clays before giving details on the properties of these two clays. The second part presents the different mechanisms that are behind the sticky behavior of clays. The third part discusses the origin of Ypresian clay's stickiness. At the meso-scale, the Atterberg limits are studied in a congregated manner, then the study goes further down to a microscopic approach in which interactions between clay sheets are discussed. The last part of this thesis focuses on the existing methods to remediate the clogging caused by sticky clays. A short commentary describing the ongoing research follows.

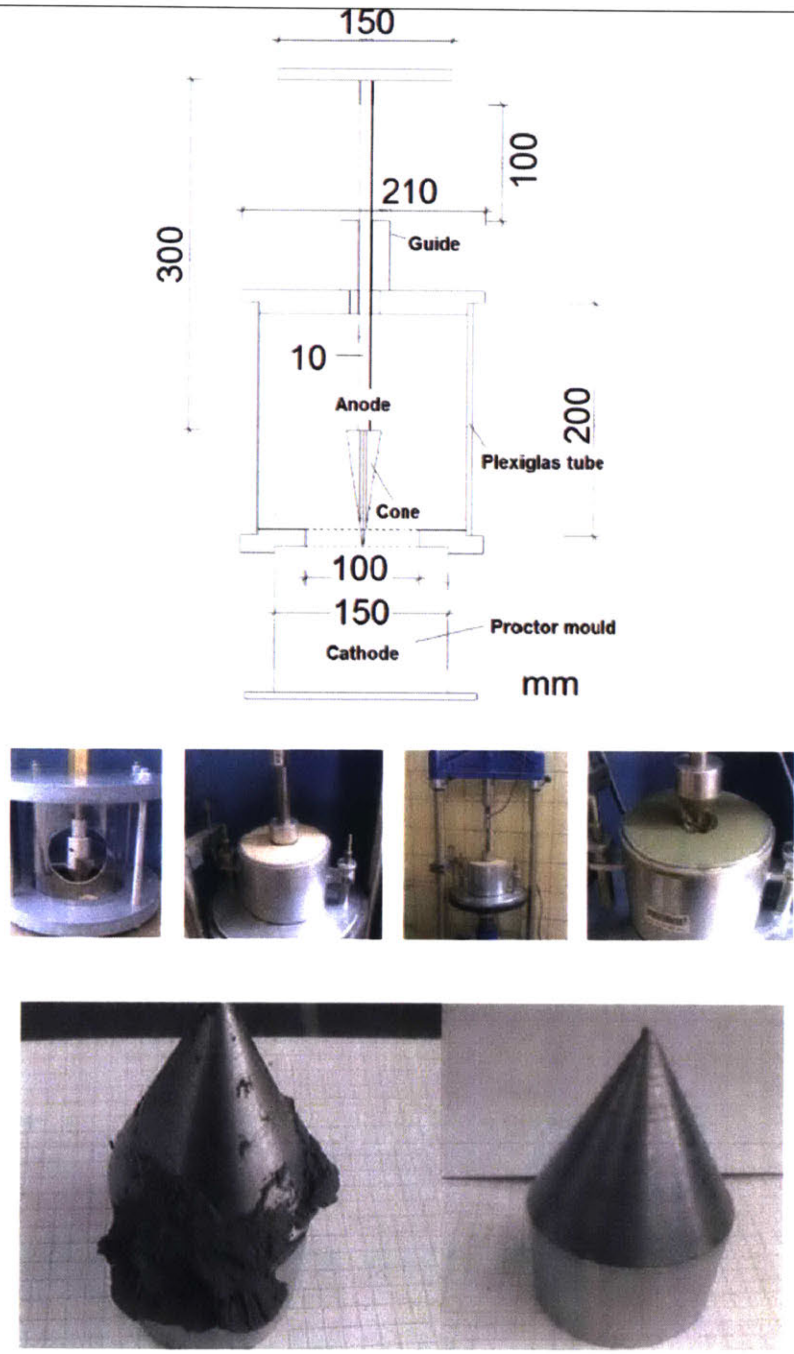
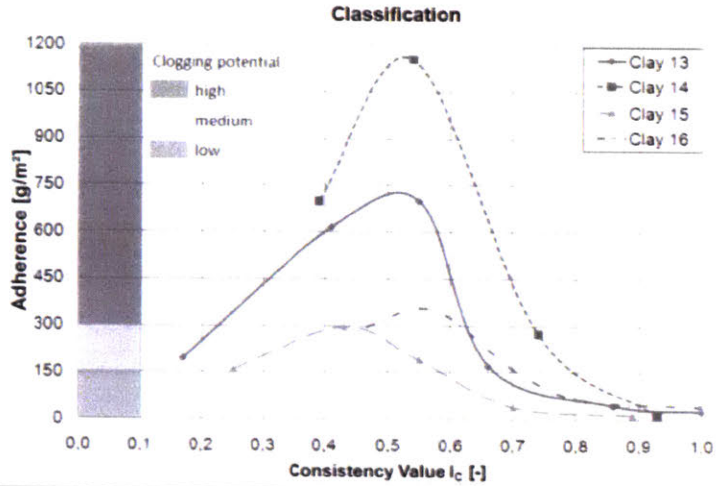


Figure 5. Cone pull-out test setup (by Spagnoli et al., 2014)



Clay 13: a clay from Westerwald, Germany
Clay 14: the extremely plastic clay known as Ypresian or London Clay from Belgium
Clay 15: Boom Clay from Belgium
Clay 16: a pure sodium smectite from India

$$Adherence\ [g/m^2] = \frac{the\ weight\ of\ the\ material\ attached\ to\ the\ test\ cone}{the\ cone\ surface\ in\ the\ cone\ pull\ out\ test}$$

$$I_c = \frac{(W_L - w)}{I_P}$$

Figure 6. Adherence of Ypresian clays compared to three other clays (by Spagnoli, 2012; clay identification added)

II. About the clays studied

While studying the stickiness of the Ypresian clay, it is interesting to compare its properties to other sticky clays' properties. Boom clay was chosen to be studied concomitantly with Ypresian clay to better understand the high stickiness that is associated with the latter. Ypresian and Boom clays are two formations that have been extensively studied because their adhesive properties have caused problems during mechanical excavation of tunnels according to Spagnoli et al. (2014). These two clays have also been investigated as potential host rocks for the disposal of high- and medium-level radioactive waste in Belgium (J. Mertens et al., 2004).

These investigations provided valuable information about the two clays that this thesis will study, for instance their burial history.

A. Burial Histories of Ypresian and Boom clays

A study completed by J. Mertens (2004) as part of the Belgian progamme concerning high-level and/or long-lived radioactive waste disposal focuses on the burial histories of the Boom Clay and the Ypresian Clay in the North Belgian region. This study provides information on past geological events since the deposition of the formations in the area of Belgium. Figure 7 displays the position of the Ypresian coastline in North-Western Europe (North Sea area).

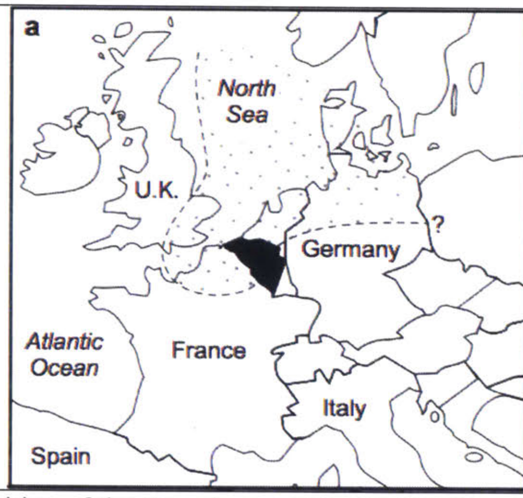


Figure 7. The position of the Ypresian coastline in NW Europe (North Sea area)

Globally, the burial history of the Ypresian and Boom clays illustrates that the North Belgian region was tectonically relatively stable since deposition. In Northern Belgium, where Boom clay overlies the Ypresian clay, tectonic movements were relatively small and no significant uplift took place (Mertens, 2004).

1. Burial History of Ypresian clay

The Ypresian clays were deposited during the Ypresian stage as its name indicates. The historical Ypresian stage concept was introduced by A. Dumont in 1849 to specify marine clays and overlying glauconitic sand occurring in the Ieper area in West Belgium (see Figure 8 –

Location of the Ieper area). The Ypresian geological stage is the lowermost Eocene Standard Stage (see Figure 9 – Geologic time scale), and ranges from 55.8 (±0.2) to 48.6 (±0.2) Ma, when the North Sea extended past Paris in the South and London in the West. During the transgression of the North Sea, more than 150m of marine sediments, most of which are rich in clay, were deposited. Figure 10 illustrates the moving of the North Sea coastline during the Ypresian stage. The Ypresian clay dips gently toward the North-North-East.

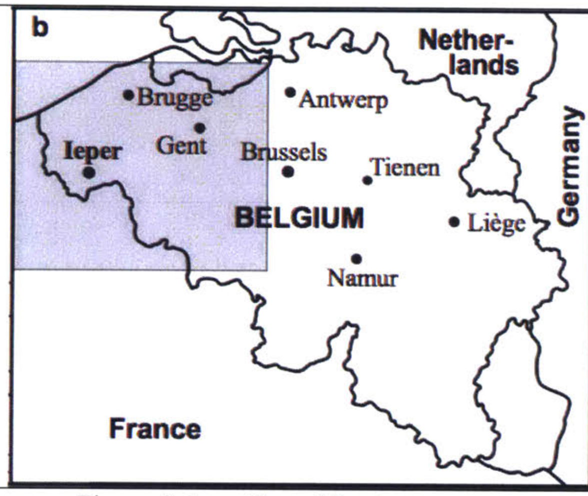


Figure 8. Location of the Ieper area

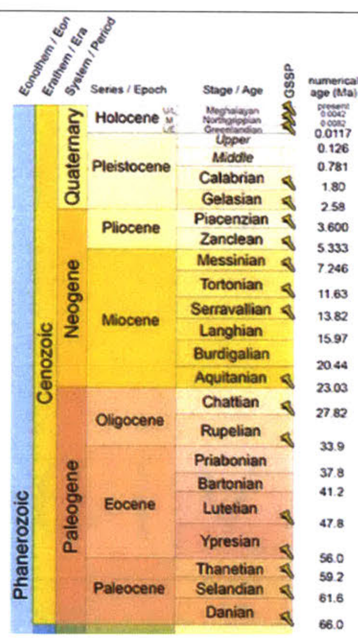


Figure 9. Geologic time scale

In some parts towards the east from Antwerp on, the middle part of the Ypresian formation can be found to be more sandy, thus making it a more heterogeneous clay formation (Mertens, 2004).

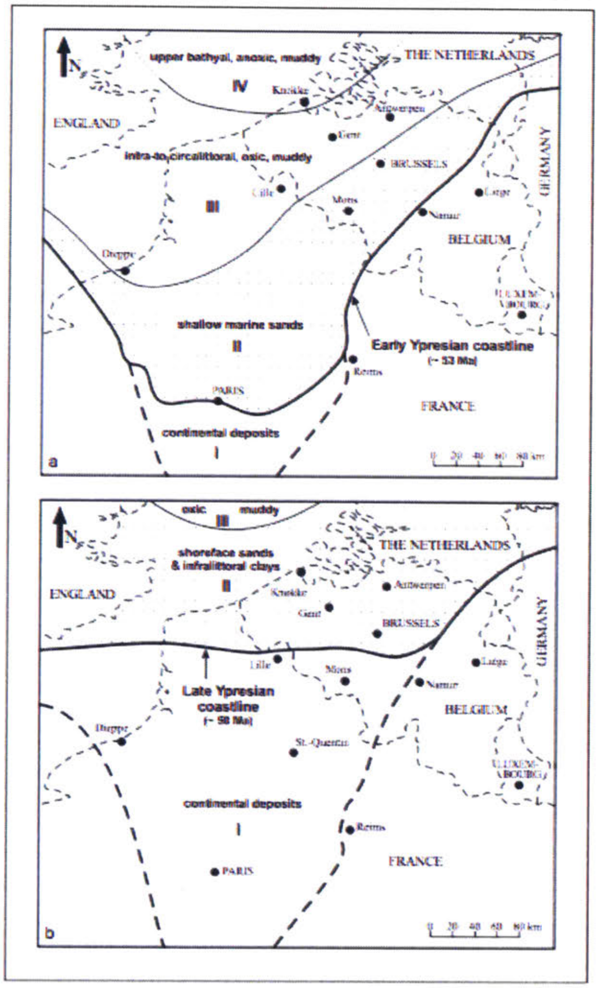
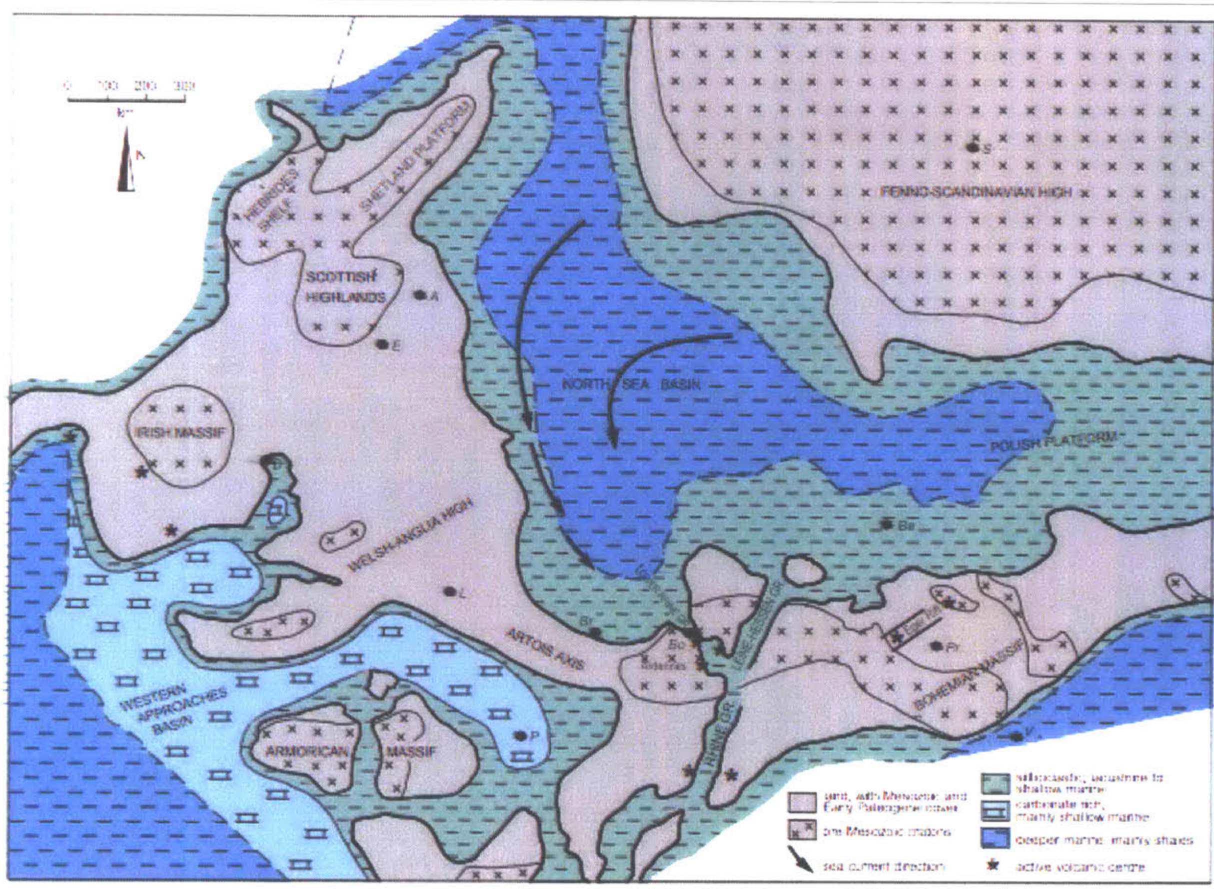


Figure 10. The positions of the Ypresian coastline in NW Europe (North Sea area) during the Ypresian stage; a: Early Ypresian, b:Late Ypresian.

The Eocene deposits which overlie the Ypresian clays, show that periods of continuous sedimentation occurred alternatively with periods where no significant sedimentation or erosion occurred. Layers of sand and clay adding up to about 100m were deposited over the Ypresian clays by the start of the Oligocene. Starting from the Oligocene, the burial history is that of the Boom clay that was deposited during the Rupelian stage.

2. Burial History of Boom clay

The Boom clay is a marine Oligocene clay several tens of meters thick. It is the unit stratotype of the Lower Oligocene Rupelian stage and a well published example of cyclostratigraphy – the subdiscipline of stratigraphy that deals with the identification, characterization, correlation, and interpretation of cyclic variations in the stratigraphic record (Vandenberghe et al. 1997). Tectonically, the Rupelian is a time interval of intense Alpine deformation. The geographical extension of the Boom Clay transgression and other Rupelian clays deposited in relatively deep water, in what can be considered as a north European branch of the Paratethys (See Figure 11), required an important subsidence of that area (Vandenberghe, 2014).



P: Paris ; L: London.

Figure 11. Palaeogeographic reconstruction of the Oligocene North Sea Basin showing the potential areas of the Boom Clay sediment (after Laenen, 1998, from Vandenberghe & Mertens, 2013).

The clay was deposited in the southern part of the North Sea basin. It can be found in Germany, The Netherlands, and Belgium as a continuous and practically horizontal layer. Early digenesis transformed some of the marly horizons into septaria beds (limestone concretions), which borrowed their name from the German clay, known as Septarienton. Like the Ypresian Clay, the Boom Clay dips towards the North-North-East and also gains thickness in this direction. The reason for this thickness gain is dual: the further north, the higher the sedimentation rate was during deposition, but also during the further burial history, the Boom Clay in the Southern part experienced significant erosion at the end of the Oligocene. The lateral continuity of this deposit illustrates the geological stability of the region since the deposition of the formation. The burial history described in the following also explains the geological stability of the region. After the Boom clay was deposited, several phases of sandy deposition followed and resulted in a thick layer of sand overlying the Boom clay, burying it at around 200 m deep. A partial erosion of a layer of sand deposited during the Chattian is a sign that a slight tectonic uplift or tilting occurred. However, no erosion was shown to have happened by analyzing the thickness of the sand layers that were deposited after the Chattian, proving that no significant uplift took place (Mertens, 2004).

B. The properties of the studied clays

The most important parameters influencing the stickiness of clays are the grain size distribution, the mineralogy, the water content and the chemistry and pH of water. Cohesive soils generally contain a large amount of highly plastic clays, which are defined by a high liquid limit and a high plasticity index (Spagnoli and Stanjek, 2012).

The availability of water during the excavation process also plays an important role in the sticky behavior of a soil. In fact, the soils that contain highly plastic clays tend to become very sticky on contact with water due to the swelling of the clay particles.

The following will help describe the clays discussed here:

1. The grain size distribution

The grain size distributions of both the Ypresian and the Boom clay are shown in Figure 12.

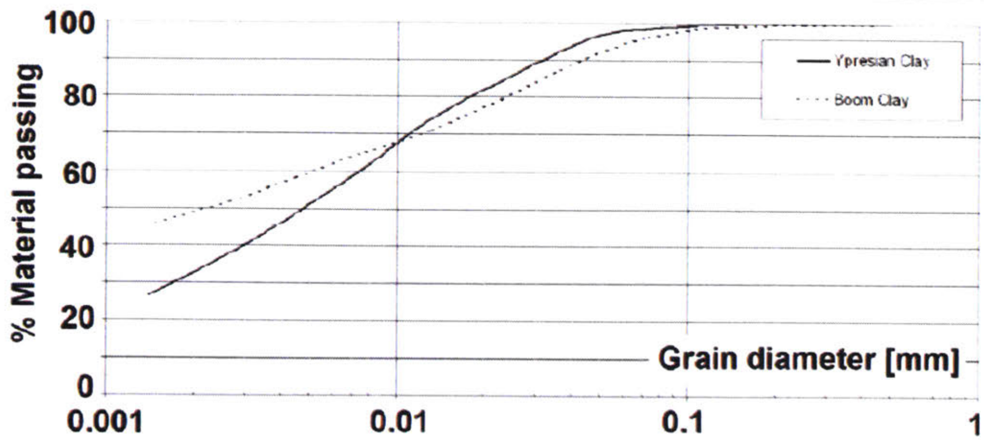


Figure 12. Grain size distributions of the Boom and Ypresian clays

It can be observed that the clay fraction percentage (CF), i.e. the percentage of particles of a diameter smaller that 0.002 mm is higher for Boom clays than for Ypresian clays:

$$CF_{Boom\ clay} = 49\%$$
$$CF_{Ypresian\ clay} = 33\%$$

$$CF_{Boom\ clay} > CF_{Ypresian\ clay}$$

2. The Atterberg Limits

The Atterberg limits (see Figure 13) – liquid limit and plasticity index – for Boom and Ypresian clays are given in Table 1.

Plasticity index is the numerical difference between the liquid limit LL and the plastic limit PL.

$$PI = LL - PL$$

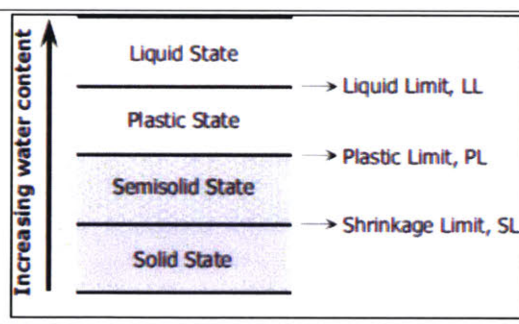


Figure 13. Atterberg limits

These results obtained by Spagnoli et al. (2014) show that Boom clay has a plasticity index of PI = 50%, and that Ypresian clay has an unusually high plasticity index of PI = 129%. This means that Ypresian clays are extremely plastic. As a consequence, there is a very large range of water content within which the clay is assumed to be in a plastic state, a state that confers the sticky behavior of the material as will be shown in section IV.B.

			Boom Clay	**Ypresian Clay**
Grain density (ρ_s)	g/cm^3	-	2.698	2.730
Dry density (ρ_d)	g/cm^3	-	1.36	1.29
Water uptake	%		96	136
Cohesion (c)	kPa		21	25
Angle of friction (φ)	°		23	23
Liquid limit (LL)	%		72	159
Plasticity index (PI)	%		50	129
Water content	%		31	35
Void ratio (e)	-		0.98	1.14
Saturation degree (Sr)	%		100	100
Loss on ignition	%		4.9	2.5
Lime content	%		5	1
SSA	m^2/g		44	59
CEC	meq/100g		21	33

Table 1. Geomechanical characteristics of the Boom clay and of the Ypresian clay (after Spagnoli et al., 2013)

Description:

liquid limit (LL)	W_L	The liquid limit is based on standard test procedures defined in ASTM Standard D4318
plastic limit (PL)	W_P	The plastic limit is based on standard test procedures defined in ASTM Standard D 4318.
plasticity index (PI)	$I_P = W_L - W_P$	The plasticity index (PI) is a measure of the plasticity of a soil. The plasticity index is range of water contents in which the soil exhibits plastic properties. • 0)- Nonplastic • (<7) - Slightly plastic • (7-17) - Medium plastic • >17 - Highly plastic
consistency index (CI)	$I_c = \frac{(W_L - w)}{(W_L - W_P)}$	The consistency index (CI) indicates the consistency (firmness) of a soil. Soil at the liquid limit will have a consistency index of 0, while soil at the plastic limit will have a consistency index of 1.
natural water content	w	$w = \frac{W_w}{W_s} = \frac{Se}{Gs}$ where $W_w: weight\ of\ water$ $W_s: weight\ of\ soil$ $S: saturation$ $e: void\ ratio$ $Gs: specific\ gravity$

The previous table also allows one to compute the clay activity:

$$\boldsymbol{A = \frac{PI}{d_{(\leq 2\mu m)}}}$$

	Boom Clay	Ypresian Clay	Usual clays
Activity	$\boldsymbol{A = 0.92}$	$\boldsymbol{A = 4.16}$	$\boldsymbol{A = 0.75 - 1.25}$

Description:

Clay activity = PI/ percent of clay sized particles
If activity $\in$ [0,75;1,25], the clay is called "normal"
If activity >1,25: the clay is a very active clay

The values for clay activity are usually between 0.75 and 1.25. Clays with an activity within this range are normal clay, clays with an activity above this range are active clays. Therefore, Ypresian clays are considered as very active (Spagnoli et al., 2014).

3. Mineral composition

X-ray diffraction (XRD) analysis done during Spagnoli's study provides the mineral composition of the clays we are interested in (see Table 2).

	Boom Clay	Ypresian Clay
Quartz	29.3	27.4
Kaolinite	10.1	1.1
Smectite	24.2	43.5
Illite	15.4	15.7
Chlorite	4.2	4.4
Pyrite	-	0.5
Calcite	6.6	-
Microcline	8.1	6.1
Albite	1.8	1.3
Hematite	0.3	-

Table 2. XRD results (after Spagnoli et al., 2014)

These results show that Ypresian clays are constituted mainly of smectites which represent 43.5% of their minerals. Quartz and illite are the other main mineral after smectite. As for Boom clays, they are composed of less smectite than the Ypresian clays (24.2%), but they have 10.1% of kaolinite compared to the 1.1% for Ypresian clays. Ypresian clays have 19.3% more smectite than Boom clays. This difference in smectite content will be studied in section III.D.2) through a microscopic approach that discusses the interactions between clay sheets.

III. Clogging Mechanisms

A. Four single effect mechanisms responsible for clogging

Thewes (1999) carried out a research programme on the adhesion of clay to steel surfaces in order to classify clay formations regarding their clogging potential. He found through practical research and laboratory tests that four different interactive mechanisms can contribute to the clogging effect of clays. Thewes explains that these mechanisms are:

- the adhesion of clay particles to a component surface (see Figure 14.a.),
- the inherent cohesion of clay particles (see Figure 14.a.),
- the bridging of clay particles over an opening in the path of spoil transport (see Figure 14.b.),
- and the low tendency of clay towards dissolving in water (see Figure 14.c.).

For the four above-mentioned mechanisms, it is said that adhesion is the most important single effect mechanism and also the one that explains best the sticky behavior of some clays. It should be noted that adhesion itself can be subdivided into two different components addressing the relative displacement (normal or tangential) between soil particles and a steel surface (Thewes and Burger 2005).

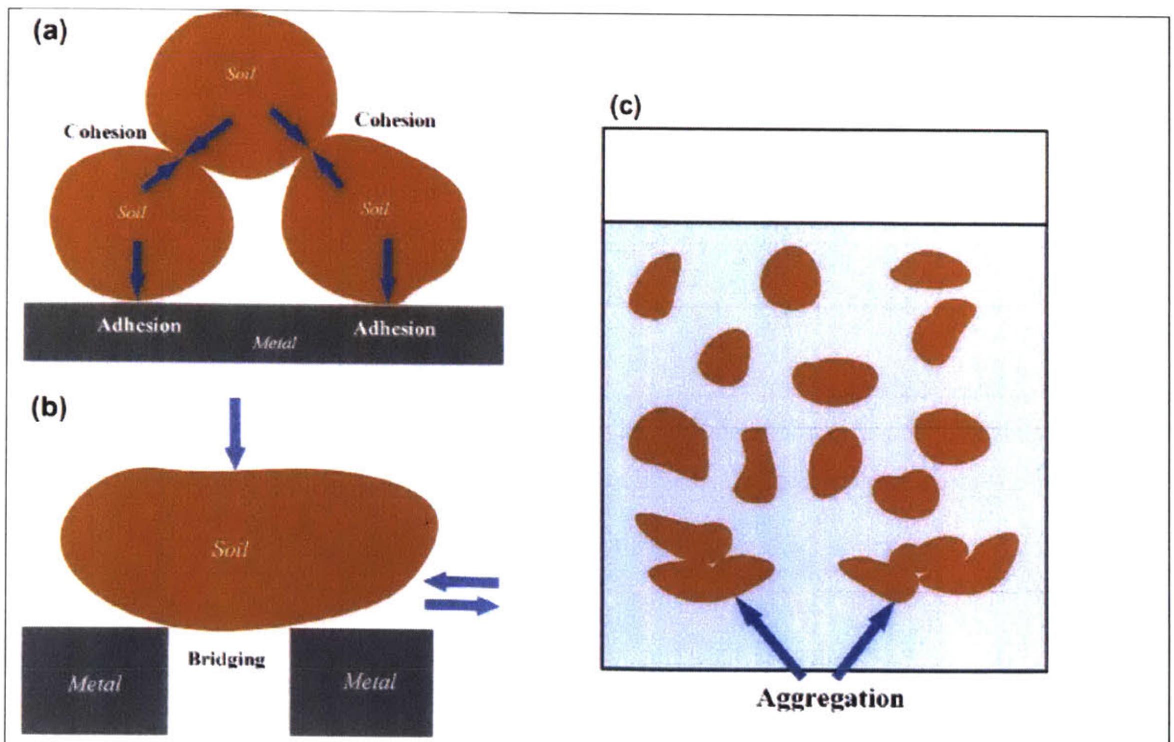


Figure 14. Clogging mechanisms – (a) cohesion and adhesion, (b) bridging, (c) aggregation (from Alberto-Hernandez, 2018)

B. Two different approaches to study clogging

There are two approaches to consider when studying clogging mechanisms.

The first one consists of identifying clogging potential by evaluating index properties of soil, including liquid limit, plastic limit, plasticity index, consistency index and natural water content. Section IV will use this approach to study the clogging potential of Ypresian clays.

The second approach is based on assessing the adhesion of soil to the metal surface. Direct shear tests, vane shear tests and other laboratory tests are utilized to measure adhesion. However, the interaction between soil and steel surfaces has not been clearly defined, and no standard testing method exists to assess the adhesive properties of soils (Sass and Burbaum 2008). The laboratory tests that have been developed to study clogging on tool surfaces are discussed in the following.

C. Tests to evaluate the clogging potential of clays

Different geotechnical laboratories have developed tests to evaluate the clogging potential of clays. However, no standardized testing exists yet, meaning that bidding contractors cannot use the results of testing procedures that may differ from laboratory to laboratory. For now, contractors can only give qualitative indication (little, medium or strong clogging) of the clogging potential of clays they encounter on site to their clients.

It is a challenging task to come up with a standardized testing method since clogging during excavation processes is complex and influenced by many variables. These variables include soils properties, water availability, but also the geometry of the excavation tool, the machine torque and the pressure applied on the soil. The following sections describe three existing testing methods, which can all in a way characterize a soil's stickiness.

1. Separation test evaluating adhesion

There is no standard way of evaluating the adhesion between soil and a steel surface, but several tests were developed attempting to do so. One of these tests is the separation test for clay adhesion presented by Thewes and Burger (2005). This test consists in pulling a piston vertically from a clay sample that is fixed to a base plate (See Figure 15). The clay sample must be wetted before the steel is put in contact with the soil. This test was developed to assess clogging of TBMs, and the fluid meant to be used to wet the clay sample should be similar to the the support fluid used when driving the TBM. If this test is used to assess the adhesion of clay particles on hydromills, the fluid to be used should be bentonite. The adhesion tests have been run on six samples of clays that are varying in their mineralogical composition. Thewes and Burger concluded from the multiple series of tests that the normal component of the adhesion of soil to a steel surface depends strongly on the content of swelling clay minerals and the consistency of the soil (See Figure 16). Other factors influencing the normal adhesion are the wetting time, the contact time, and the type of wetting fluid. Keeping in mind that this test was developed for evaluating the clogging of TBMs, it is not certain that the same conclusion may apply to adhesion of clay particles to the cutter surface of hydromills. Moreover, little practical information on the relation between the separation test and and practical tunneling experience has been published, so the conclusions drawn from this test might not be applicable in practice.

From this series of tests, the following key points were identified:

- The adhesion decreases with increasing wetting time
- The adhesion increases with increasing contact time
- The adhesion increases strongly with increasing consistency of the clay (Figure 16)
- Adhesion can be developed only with soils with a significant content of swelling minerals, such as montmorillonite or illite, the adhesion in kaolinitic clays being

comparatively low. Yet, we would like to understand why adhesion is mostly developed with clays that have a high content in montmorillonite or illite. Section IV.C. will attempt to do so.

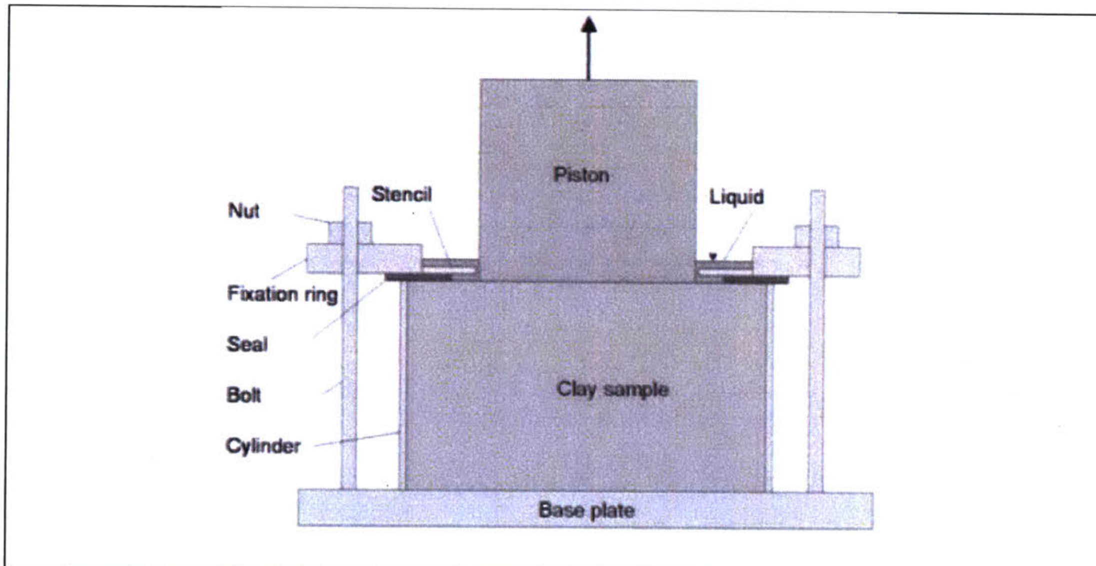
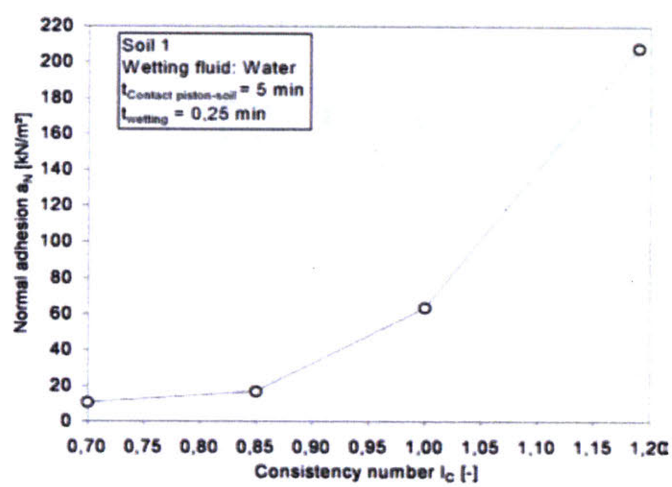


Figure 15. Schematic diagram of separation test for clay adhesion (from Thewes and Burger, 2005)



$$I_c = \frac{(LL - w)}{IP}$$

Figure 16. Results of adhesion tests with varying consistency by Thewes and Burger (2005)

The tests provided a new understanding of adhesion. The authors of this research programme state that when water is present between a steel surface and clay, the clay absorbs the water until no water can be absorbed by the clay anymore. An under-pressure then develops in the water which is at the steel-clay interface resulting in a tensile stress at the interface, which appears to be the origin of adhesion.

It could be therefore interpreted that manipulating the layer of water in which an under-pressure develops may help reduce the clogging effect of clay caused by the adhesion mechanism. It is indeed what Spagnoli et al. (2014) looked into when they explored the electrical manipulation of the clogging properties of Ypresian and Boom clays (detailed in section V.B.). In the context of this research, the cone pull-out test described below was used to study the adhesive properties of the clays in the laboratory.

2. Cone pull-out test

In order to study the effect of an electric field on the clogging behavior of clays, Spagnoli, Stanjek and Feinendegen used the cone pull-out test to which they added the possibility of creating an electric field in the cone of the pull-out test.

Clogging only occurs when the resisting forces within the soil matrix are smaller than the bond stress between the clay and the steel surface. To determine the clogging potential of different clays with respect to tunneling operations, the cone pull-out test was developed (Feinendegen et al., 2011). Specifically, the cone pull-out test simulates different effects besides simple shear or simple vertical separation. This test is therefore more comprehensive than the direct shear test which only reproduces shear and the separation test which only reproduces vertical separation.

In the cone pull-out test, the clay sample is prepared with the required consistency and compacted using the Proctor method. Then a steel cone is inserted into a pre-drilled cone-shaped cavity and loaded for 10 minutes (See Figure 5). The magnitude of the applied load ranges between 3.8 and 189 kN/m², depending on the consistency. The load is than taken off, and the clay specimen is placed in a test stand. While the cone is being pulled out with a velocity of 5mm/minute, the tensile forces and the displacements are recorded.

This test evaluates the clogging potential of clays by associating a clogging parameter – adherence – to a material. This parameter is determined by weighing the mass of the soil adhering on the pull-out cone and relating it to the cone surface:

$$Adherence\ (g/m^2\ ) = \frac{weight\ of\ material\ attached\ to\ the\ cone}{cone\ surface}$$

By running this test on several soil samples, it has been observed that very plastic soil has a high adherence whereas stiff material or material close to the liquid state has lower adherence. In fact, very stiff soils do not adhere on the cone and nearly liquid material slides off the cone without sticking to it.

3. The Horbart mixer

Evaluation of the stickiness of materials, in general, is often handled on a descriptive basis and depends largely on the problem encountered. With respect to tunneling problems often the so called ''mixing test'' is used to observe the soil and therefore also the sticking behavior of soil pastes during the mixing process in a mortar mixer (Egli, 2009; Ball et al., 2009). Quantification of stickiness resulting in some kind of a parameter is very rare in the literature; Feinendegen et al. (2011) recently suggested using the weight of soil sticking to the surface of a cone after a pull-out test (discussed in the previous section).

Zumteg used a "mixing test" which involves the use of a Hobart mixer with a B-flat beater (see Figure 17) to quantitatively evaluate the soil clogging potential. This method consists in pouring together the soil, water and conditioners into the mixing bowl and mixing them together for 3 min at about 100 rpm, until a homogeneous mixture can be ensured. Clearly, this preparation procedure cannot ensure a totally uniform distribution of water at the particle scale; nevertheless, it has been observed that this time period is sufficient to achieve mixture homogeneity at a larger scale and a steady state for the amount of clay sticking to the mixing paddle (Zumsteg, 2012). The empirical stickiness ratio k is given by:

$$k = \frac{G_{MT}}{G_{TOT}}$$

G_{MT} is the soil sticking to the mixing tool and G_{TOT} the total weight of soil in the mixer. The proposed evaluation of stickiness is very time efficient and simple, using a conventional procedure for soil mixture preparation. It is clear that this simple empirical stickiness ratio k cannot describe the complex phenomenon of clogging during the excavation process, but the mixing process imitates the rotational mode during excavation in a tunnel boring machine much better than, e.g. the cone pull-out test. The parameter k provides a quantitative measure of the sticking potential, for comparison and detection of effects of the used chemicals.

Figure 17. The Hobart mixer

Garroux G. de Oliveira (2017) claims that following an extended testing campaign using soils with different mineral contents, it was clear that this testing method does not provide reliable information regarding the tendency of a soil to clog in tunnel driving. It is why she proposed a new method combining the Hobart mixer with a kinetic energy impulse added via dropping the beater from a certain height. Her method aims at providing the possibility of evaluating the efficiency of soil conditioners used in tunneling.

IV. Relevant factors for the stickiness of Ypresian clays

The ability of clay to develop sticky behavior that results in clogging depends on a number of factors, which pertain to the type of soil (granular or cohesive), its grain size distribution, the type of clay minerals, the plasticity of the soil, its water content, and the presence of water. This section of the thesis will explore these factors for Ypresian clays in order to understand its unusually high stickiness.

A. Grain-size distribution and soil type

Non-cohesive soils cannot clog or turn into sticky material because there are no bonding forces holding the grains together. Cohesive clayey soils, however, are prone to clogging in most cases. The interdependency of the clogging risk and clay concentration has already been described by various authors (Hollman & Thewes, 2013). Because Ypresian and Boom clays are cohesive soils, it is not surprising that they can cause clogging during excavation processes.

Section II.B.2 indicates that the clay fraction percentage for Boom clay is higher than for Ypresian clays, but Spagnoli's cone pull-out test shows that Ypresian clays have a higher clogging potential than Boom clays (see Table 3). This table shows that for a given consistency index, Ypresian clay has a higher clogging value than Boom clay. Therefore, one understands that the value of the clay fraction percentage does not indicate by itself if a clay material will have a stickier behavior than another clay material. In fact, the type of clay affects the properties of a material, which is why Atterberg limits have strong links to the clay's underlying mechanical properties.

B. Atterberg Limits – Plasticity index and consistency index

The activity of a material given by A= Ip/CF indicates the importance of clay properties. Recall that $I_P = W_L - W_P$ and CF = % <2µm. More precisely, higher activity indicates increased importance of the clay properties. Ypresian clays are very active clays whereas Boom clays are normal clays ($A_{Boom\ clay} < A_{Ypresian\ clay}$ $as\ seen\ in\ section\ II.B.2$). It can be suggested that the higher the activity of a material, the higher the probability is for this material to cause clogging.

Clay	Clogging value (g/m²)	Ic
Ypresian	113.36	0.86
	93.12	0.69
	385.96	0.55
	205.13	0.40
Boom	4.50	0.84
	29.69	0.72
	142.15	0.55
	176.34	0.25

$Clogging\ value\ (g/m^2) = \frac{weight\ of\ material\ attached\ to\ the\ cone}{cone\ surface}$, as explained in section III.C.2.
(Note: clogging value = adherence)

$$I_c = \frac{(W_L - w)}{I_P} = \frac{(W_L - w)}{(W_L - W_P)}$$

Table 3. Clogging and consistency index (Ic) of the clays used in the experiments, by Spagnoli et al. (2014)

Instead of looking at the clay activity, the clogging tendency of cohesive soils can be directly analyzed by looking at the plasticity index, and the consistency index (Hollman and Thewes, 2013). It was previously mentioned in section III.C.2) that very plastic soils have a high adherence whereas stiff material or material close to the liquid state have lower adherence. In fact, at the liquid limit, the clays turn from a very soft to a liquid consistency without significant remaining cohesive binding (see Figure 18). The consistency index, defined as $CI = (W_L - w) / (W_L - W_P)$, is of key importance in determining whether rupture occurs within the soil, so that material remains adhering to the tool surface, or at the interface between the soil and the tool, so that nothing adheres to the tool surface (Spagnoli et al., 2014).

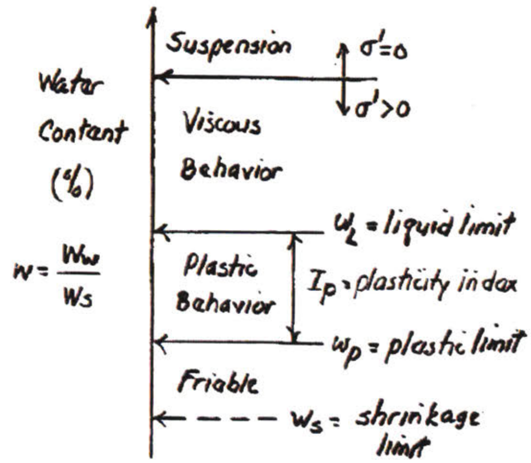


Figure 18. Atterberg limits (from notes by Prof. C.C.Ladd)

Thewes (1999) developed a diagram of clogging potential for cohesive soils based on empirical investigations in order to estimate the clogging risk for hydro-shield tunneling. This diagram, shown in Figure 19, indicates that soils with a plasticity index of more than 20% and stiff to very stiff consistency show the highest clogging potential.

The Ypresian clay has a plasticity index of 129% and a consistency index of 0.96 whereas the Boom clay has a plasticity index of 50% and a consistency index of 0.82 (See Table 4). Given the properties of both Ypresian and Boom clays, one can plot them on the clogging diagram show in Figure 19.

	Boom Clay	Ypresian Clay
Plasticity Index (%)	50	120
Consistency Index (%)	$CI = \frac{(72-31)}{(50)}$ $CI = 0.82$	$CI = \frac{(159-35)}{(129)}$ $CI = 0.96$

Table 4. Plasticity index and consistency index of Boom and Ypresian clays

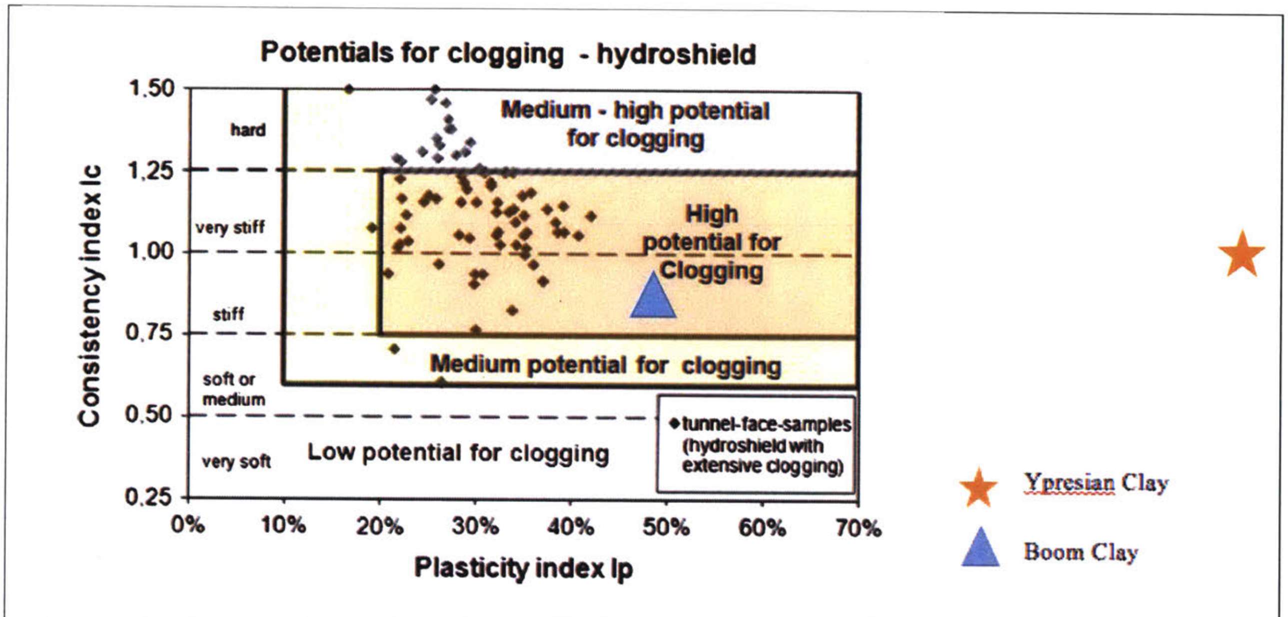


Figure 19. Clogging diagram for slurry-supported shield tunneling according to Thewes (1999)

The Ypresian clay's unusually high plasticity index places it off the chart whereas the Boom clay plots in the area of high potential for clogging. By using this diagram, one can assess the clogging potential of clays for hydroshields, but it appears that Ypresian clay has a plasticity index that is out of the typical range, which might explain it is extremely sticky behavior. Also, this diagram was designed for assessing clogging in slurry-supported shield tunneling. If the tunneling machine used is the open mode shield tunneling without ground water inflow, the clogging potential would be different. In fact, clogging would only occur if the soil's natural consistency makes it a naturally sticky material since there is no water inflow to make a hard or very stiff clay softer, hence stickier. In this case, the clogging potential diagram would be as shown by Figure 20.

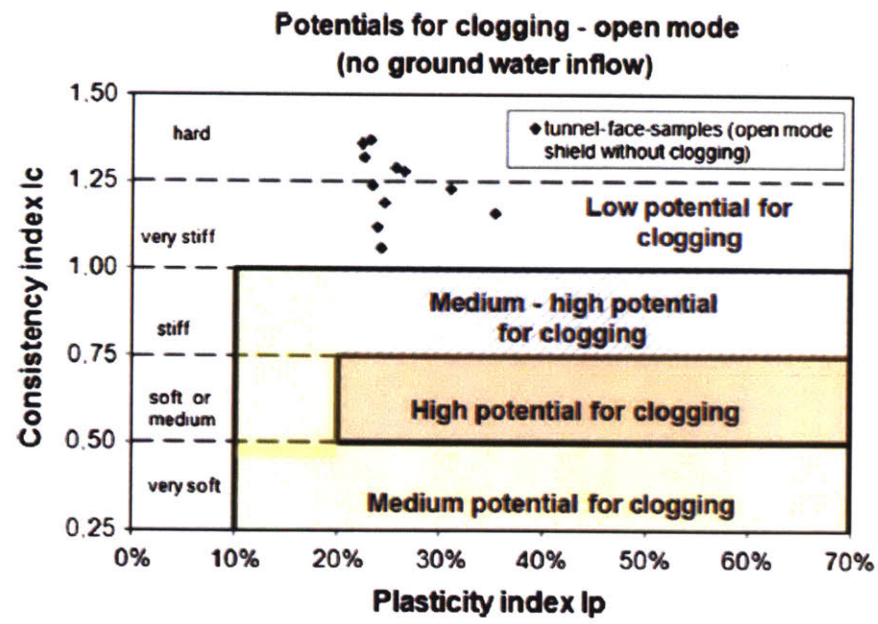
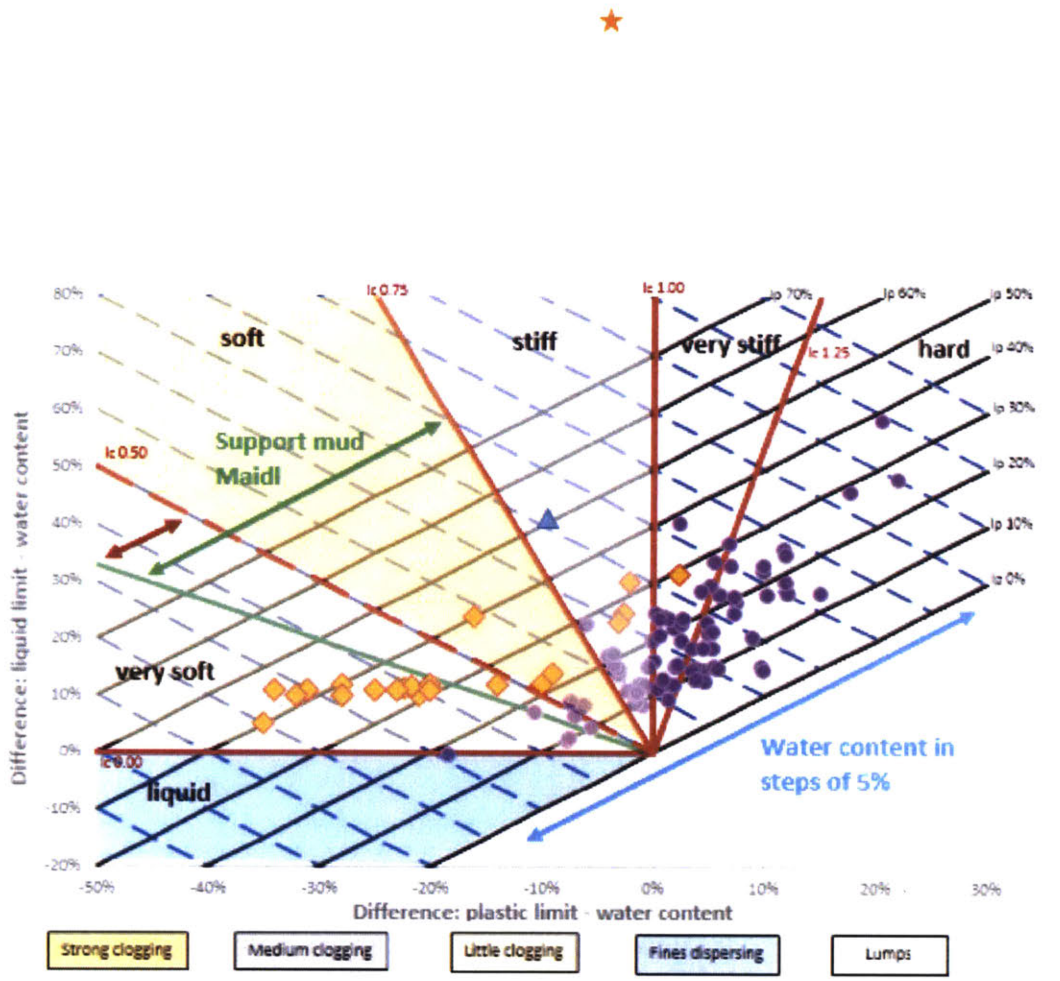


Figure 20. Clogging diagram for open mode shield tunneling according to Thewes (1999)

In this clogging diagram, the boxes corresponding to the different levels of clogging are shifted downwards since very stiff to hard materials would not naturally behave as a sticky material without water input. This diagram could also be applied for earth moving work if rainwater is not taken into account. In fact, earthwork can be comparable to open face shield excavation processes without water inflow (Hollman & Thewes, 2013).

It can be noted that no clogging potential evaluation diagram has been specifically developed for hydromills even though clogging affects slurry walls construction too.

If one wants to assess clogging potential of clays on other shield types or even on hydromills, there is a second diagram developed by Hollman and Thewes (2013), which can be used for all types of TBM shields, such as slurry supported machines, EPB machines, open TBMs without active face support and hydromills (See Figure 21).



	Boom clay ▲	Ypresian clay ★
$W_L - w$	41	124
$W_L - w$	-9	-5

Figure 21. Ypresian and Boom clays on the new evaluation diagram of clogging potential

The new generalized evaluation diagram was developed based on evaluations of the consistency of actual clogging material in the excavation chamber of various machine types whereas the first diagram (Figure 19) was developed through an analysis of a large number of hydroshield drives in clay. The reason why the first diagram developed by Thewes in 1999 cannot by applied to any excavation machine is because the consistency index depends on the water content, which changes according on the available water, and this in turn, depends on the type of excavation system used (Hollman and Thewes, 2013). The plasticity index as a parameter to evaluate clogging potential, however, can be used independently of the kind of excavation process one is looking at since it is defined by the liquid and plastic limit inherent to a material. Since problems during excavation are related to plastic or liquid consistencies, the universally applicable diagram is based on the differences between the plastic and liquid limit and the natural water content. The steps in designing this new diagram are detailed in the paper published by Hollman and Thewes, 2013. The key improvement in this diagram is that after positioning a soil on the diagram using its plastic limit, liquid limit and natural water content, this position would shift downwards to the left with increasing water content. The water content becomes a varying parameter in this improved diagram.

Plotting the Ypresian and Boom clays on this diagram (See Figure 21), it is observed that Ypresian clay is again off the chart. In order to assess the clogging potential of Ypresian clay or other soils with high plasticity index, additional contour lines can be added to the diagram and the scales of the axes can be extended (see Figure 22). However, until now, this extended part of the diagram could not yet be verified due to lack of data. Hollman and Thewes added the values of the highly plastic Aalbeke clay (see red rectangle on Figure 22) presented by Van Marcke and Laenen (2005) in this extended universal clogging diagram and showed how varying the water content may bring this clay from causing lumps, to medium clogging, to strong clogging, then little clogging and finally to fines dispersing. Ypresian and Boom clays are also represented, respectively, by a star and a triangle on this diagram, and the lines that the star and the triangle would follow when the water content of these clays vary are shown. If the star and the triangle both move down the line to where Ic = 0.55 (value highlighted in Table 3), the diagram shows that both clays would cause strong clogging. However, there is no possible comparison for knowing if one or the other will be harder to manipulate during excavation. The diagram allows one to draw some qualitative conclusions but a quantitative evaluation of clogging would require the use of a testing method such as the cone pull out test, while no standardized testing method for clogging has been established yet.

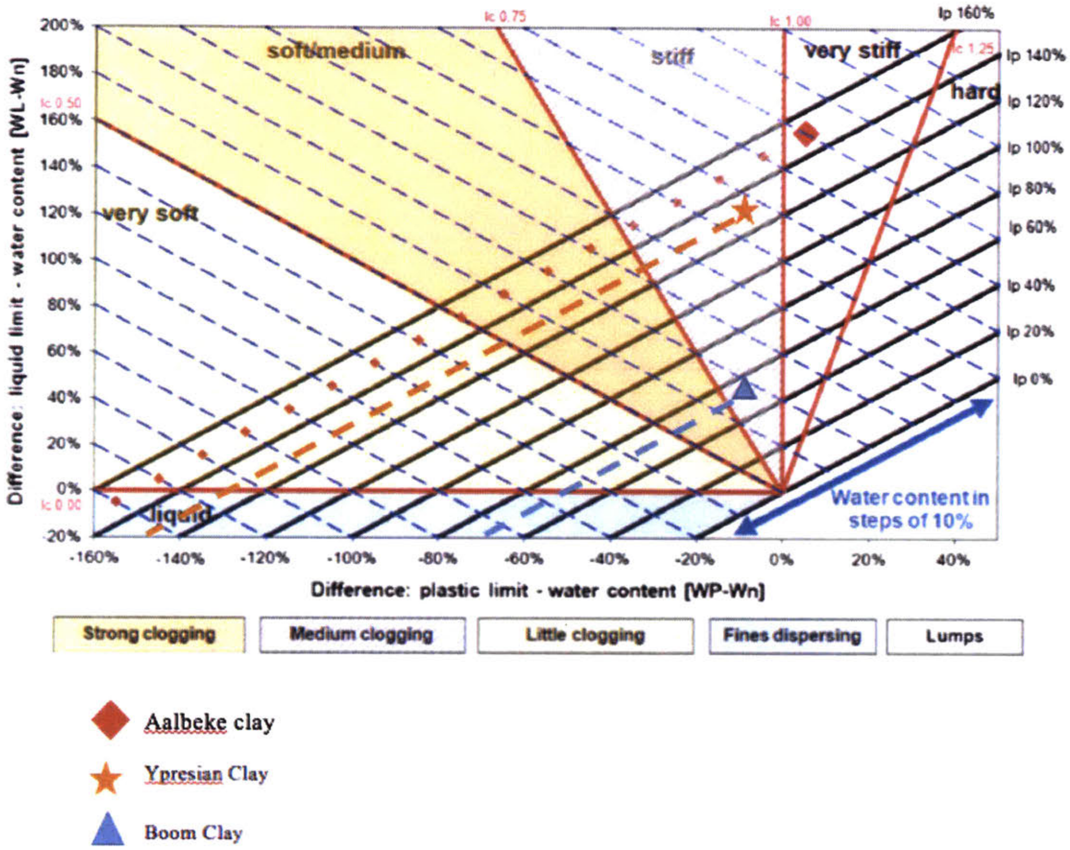


Figure 22. Extended universal classification diagram for critical consistency (by Hollman and Thewes, 2013)

General conclusions on clogging of soils can be drawn from the universal classification diagram (Figure 22). In fact, it can be deduced from it that clogging is more likely to occur the wider the range of the water content is within the critical consistencies. Therefore, the clogging risk rises with an increasing plasticity index, since the critical plastic consistencies are covered by a variety of possible water content claim the authors of the diagram. Figure 23 compares the Atterberg limits of Ypresian clays to Boom clays. The remarkable difference in the plasticity index might explain why Ypresian clays have a higher clogging risk than Boom clays (information that the evaluation diagram could not give). Soils with smaller plasticity index need very specific boundary conditions in order to become very sticky, since plasticity consistencies are only achieved within a small range of water content. With a small increase in water content, the liquid state can be quickly reached, likely resulting in fines dispersing from the cohesive fabric and a more liquid and less sticky behavior of the material.

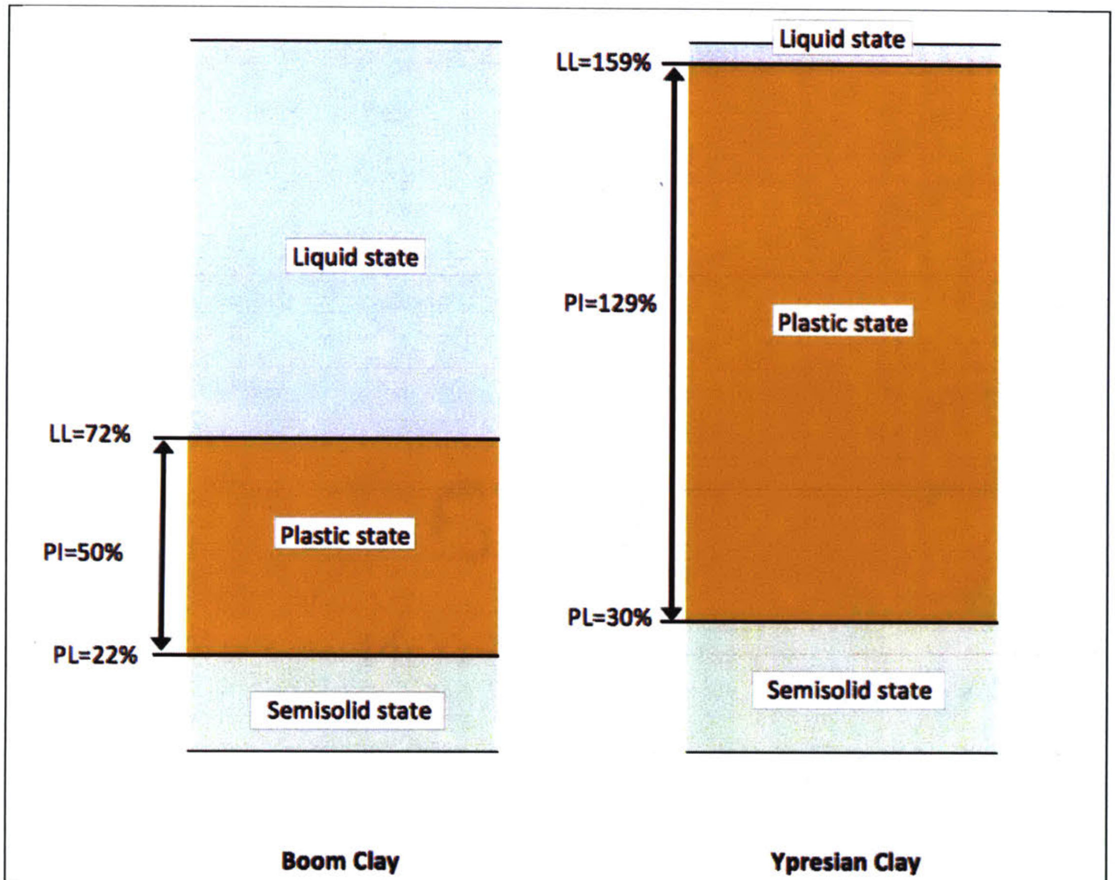


Figure 23. Atterberg limits of Boom and Ypresian clays

The universal evaluation diagram (Figure 22) is a first step in evaluating the clogging potential of a clayey material. Looking at the plasticity index will also indicate if a soil has a higher *risk of clogging* compared to another soil. Once the clogging risk for a soil has been assessed, a laboratory test (cone pull-out test for example) can be conducted on a soil sample to quantitatively evaluate the stickiness (*intensity of clogging given by the adherence value*). Once we have the adherence value, one can determine what to do. Firstly, it could be used by researchers or tunneling professionals for comparison with other data samples. It could also be used to determine the quantity of conditioners to apply to soil in tunneling. Lastly, it could eventually be used to evaluate the concentration of NaCl or other soil treatment needed.

It needs to be kept in mind that the universal diagram was designed for TBMs and might not apply for hydromills.

Another possible use of the Atterberg limits is as follows: through experience, it has been noticed that clays that are plotted close to the U-line in the Casagrande chart show a high stickiness (Prof. Germaine). This also has to do with plasticity index since the U-line is defined by:

$$I_P = 0.9\,(W_L - 8)$$

When plotting the Ypresian and Boom clays on the Casagrande chart, the previous statement seems to be true. In fact, both Ypresian and Boom clays, which exhibit sticky behavior, are plotted close to the U-line (See Figure 24). However, there is no rational explanation as to why the U-line on the Casagrande chart could be used as an indicator for clogging potential, and this evaluation method has not been proved to be reliable (oral communication, Prof. Germaine)

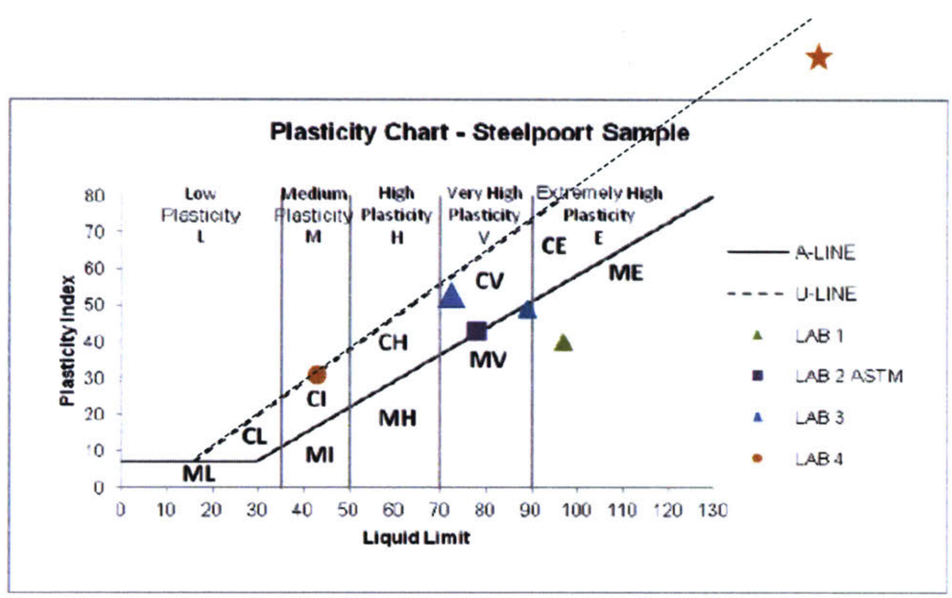


Figure 24. Ypresian and Boom clays on the Casagrande plasticity chart

If the U-line proves to be an efficient way of evaluating clogging, it could potentially be a general method that can be applied to any excavation method – for TBMs and hydromills used for slurry wall construction.

To summarize, the Atterberg limits are a major component in the evaluation of the clogging potential at the meso-scale. In fact, it was seen that plasticity index and consistency index affect the value of adhesion. Plasticity index and consistency index are parameters which are controlled by inherent properties of soil, including clay mineral type, cation exchange capacity (CEC), and specific surface area (SSA). This is why the next section, mineralogy, will go further in exploring the origin of Ypresian clay's stickiness by trying to relate its inherent properties to adhesion.

C. Mineralogy

Mineralogy is the primary factor controlling the size, shape and properties of clay particles. These same factors determine the possible ranges of physical and chemical properties of any given soil; therefore, a priori knowledge of which mineral types are present in a soil provides intuitive insight as to its behavior (Mitchell and Soga, 2005). Knowing the mineralogy of Ypresian clays and comparing it with that of Boom clays may help better understand the particularly sticky behavior of Ypresian clays.

1. Kaolinite and Smectite

The mineralogical compositions of Ypresian clay and Boom clay are given in Table 2. Recall that Ypresian clays are constituted of, inter alia, 43.5% smectite and 1.1% kaolinite compared to Boom clays which are constituted of, inter alia, 24.2% smectite and 10.1% kaolinite. These are the primary minerals in the two studied clays; accordingly, the following section will explore the structure and the characteristics of these two well-known minerals.

Figures 25 and 26 explain what 1:1 and 2:1 semibasic units are, and the various ways these units can be stacked together. From Figure 25, it is understood that smectite has water and loosely held ions between the layers while kaolinite has unit layers stacked closely together without water layers intervening.

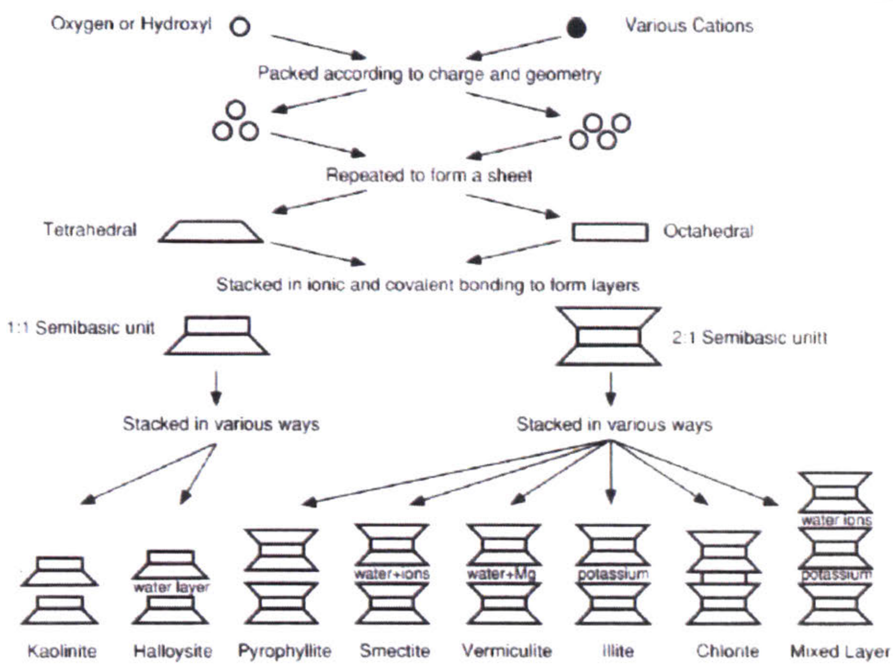


Figure 25. Synthesis pattern for the clay mineral (by Mitchell and Soga, 2005)

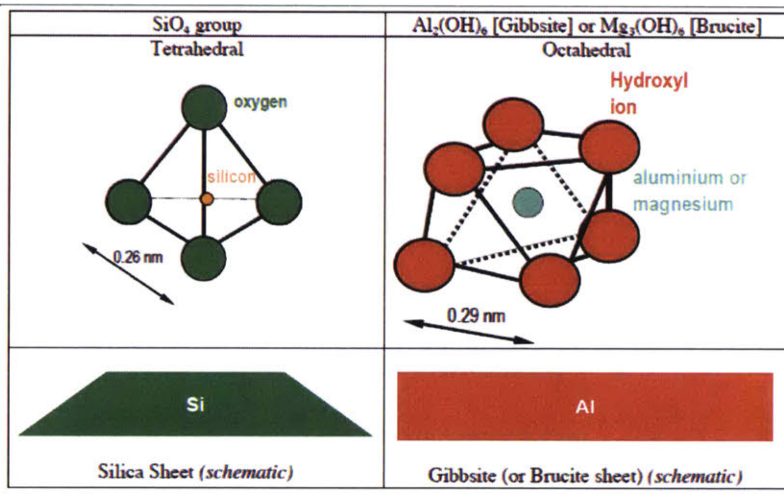


Figure 26. Clay minerals – elemental components (by A.J. Whittle)

The kaolinite minerals are non-swellable minerals composed of alternating silica and octahedral sheets (1:1 units), as shown schematically in Figure 27. The bond between successive units – also called layers or sheets – is by both van der Waals forces and hydrogen bonds. The bonding is sufficiently strong that there is no interlayer swelling caused by the presence of water. The strong bonds can also explain the tendency of clay sheets to stack one on top of the other and form chunks (Figure 28, left). As interlayer separation does not occur in kaolinite, balancing cations must adsorb on the exterior surface and edges of the particles, thus giving kaolinite a low value for its CEC (see Table 6). The specific surface area of kaolinite is about 10-20 m^2/g of dry clay.

Smectites, swellable clay minerals, consist of an octahedral sheet sandwiched between two silica sheets (2:1 units), as shown schematically in Figure 27. Bonding between successive layers is by van der Waals forces and by cations that balance charge deficiencies in the structure. These bonds are weak and easily separated by cleavage or adsorption of water or other polar liquids. The specific surface area of smectite can be very large. The primary surface area, that is, the surface area exclusive of interlayer zones, ranges from 50 to 120 m^2/g. The secondary surface area that is exposed by expanding the lattice so that polar molecules (H_2O) can penetrate between layers can be up to 840 m^2/g. Because of the large amount of unbalanced substitution in the smectite minerals, they have high cation exchange capacities, generally in the range of 80 to 150 meq/100g (See Table 6).

	Kaolinite	Smectite
CEC (meq/100 g)	3	85

Table 6. Cation Exchange Capacity of kaolinite and smectite

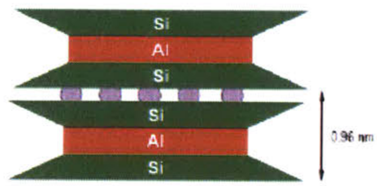
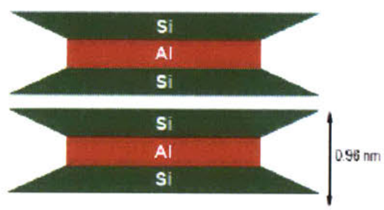
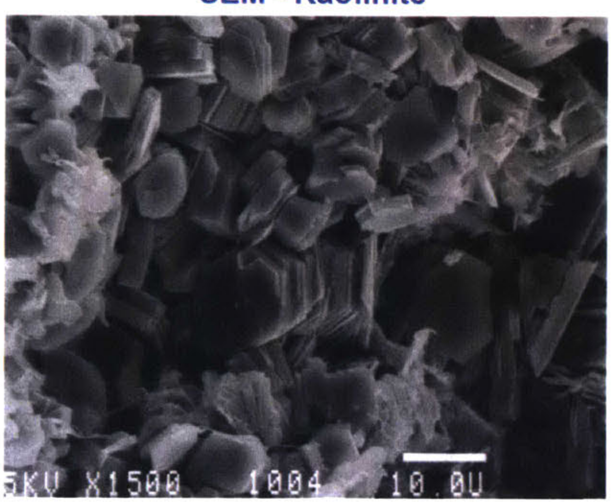
Mineral	Layer Structure	SSA* (m^2/g)	Width (μm)	Height/ Width
Kaolinite (1:1) $(OH)_8Al_4Si_4O_{10}$	 Hydrogen bonds between layers	10-20	0.3 – 3.0	0.1 – 0.33
Illite (2:1)	 Layers linked by K^+ ions	80-100	0.1 – 2.0	0.1
Montmorillonite (2:1) $(OH)_4Al_4Si_8O_{20}.nH_2O$	 van der Waal's bonds between layers Swelling related to adsorption of water between layers	800	0.1 – 1.0	0.01

Figure 27. Clay minerals, three key types (by A.J.Whittle)

SEM - Kaolinite



ESEM Micrograph - Smectite

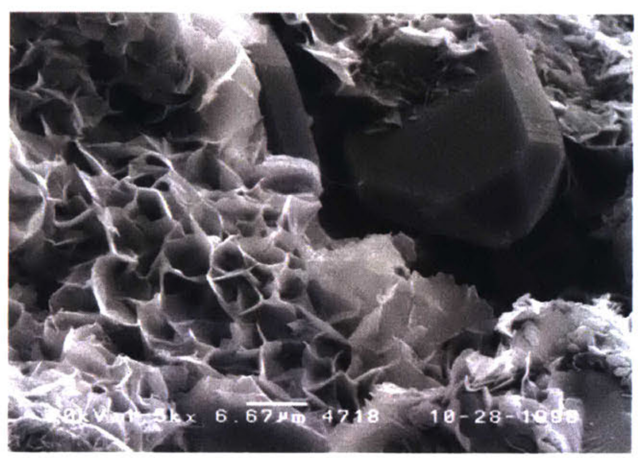


Figure 28. SEM and ESEM images of Kaolinite and Smectite (by A.J. Whittle)

The behavior of small and flaky clay mineral particles is strongly influenced by surface forces. Surfaces forces depend on Specific Surface Area (SSA), surface charge density and Cation Exchange Capacity (CEC) (values given in Figure 27 and Tables 6 and 7). The next section is an attempt to relate particles' surface forces to the behavior of clays.

Clay Mineral	Surface Potential (mV)		Surface Charge Density (mC/m^2)	
	Mean	Standard Deviation	Mean	Standard Deviation
Kaolinite	−40.94	15.52	−3.50	1.53
Montmorillonite	−62.82	10.55	−6.03	1.52

Table 7. Surface charge properties of clay minerals (from Guo and Yu, 2017)

2. Minerals' role in the sticky behavior of clays

The engineering properties of a soil depend on the composite effects of several interacting factors. The geotechnical properties of clayey soil arise from the microstructure of clay minerals. (Basmenji et al., 2016). For instance, CEC determines the potential of cohesion in clayey soils (Yukselen and Kaya, 2006). Moreover, both cohesive and adhesive forces in clay originate from the electrostatic properties of clay minerals. Depending on clay minerals, water can be strongly attracted to clay particle surfaces and results in plasticity. When the surface charge density is moderate, as in smectite, the silicate layers adsorb polar molecules, and also the adsorbed cations may hydrate, resulting in layer separation and expansion. In many ways, the force attraction between clay particles is affected by the charge distribution at their surface.

a) Intersheet and interlayer bonding in the clay mineral

Bonding between clay sheets is of the primary valence type and is very strong. However, the bonds holding these clay sheets together may be of several types, and they may be sufficiently weak that the physical and chemical behavior of the clay is influenced by the response of these bonds to changes in environmental conditions.

Isomorphous substitution in all clay minerals, with the possible exception of those in the kaolinite group, gives clay particles a net negative charge. To preserve electrical neutrality, cations are attracted and held between layers and on the surfaces and edges of the particles. Many of these cations are exchangeable cations because they may be replaced by cations of another type. The quantity of exchangeable cations is termed the cation exchange capacity (CEC) and is usually expressed as milliequivalents (meq) per 100g of dry clay. Depending on if and which cations are present between the layers, the mechanical behavior of the clay might change. For instance, interlayer separation does not occur in kaolinite while layer separation and expansion can be observed in smectites. Also, Kooistra et al. (1998) found that the higher the CEC, the more plastic the clay will behave and also higher levels of cohesiveness and adhesiveness may be expected. The CEC is much higher for smectite than kaolinite (Table 6), meaning that clays containing more smectite than kaolinite will tend to be more plastic, therefore stickier. This is why Ypresian clays, which have a higher content in smectite than Boom clays are stickier than the latter.

The type of bonding between the unit layers of the clay minerals, coupled with the adsorption properties of the particle surfaces, controls soil swelling. Adsorption and desorption processes are important in interactions between chemicals and soils. These interactions determine the flow and attenuation of various substances through soil. Changes in the surface forces owing to changes in the chemical environment may alter the structural state of a soil. This consideration is important for finding a way to remediate clogging. However, it needs to be kept in mind that the study of clay sheets' interactions at the microscopic scale cannot directly explain the macroscopic behavior of a clay. In fact, the way micro, meso, and macroscopic scales relate is complex, and research on interscalling still needs to be done. This is probably why mineralogical determinations are not made for many geotechnical investigations even though mineralogy is considered to be fundamental to the understanding of geotechnical properties.

b) Limits of focusing the study on mineralogy

Studying only the characteristics of smectite or kaolinite cannot lead to any reliable hypothesis or conclusion about Ypresian clay's mechanical behavior since other minerals constituting this clay can play a role in its behavior. Past geologic history and the sedimentation process, namely sedimentation rate, also have a significant influence on soil behavior. The presence of nannofossils in the soil can also affect its behavior as was the case in Osaka Bay where nannofossils played a role in the settlement of the Kansai International Airport islands. This is why the burial history of Ypresian clay should not be disregarded when studying its engineering properties. Figure 29 shows the nannofossils that are present in the Upper Ypresian in Belgium that could be found in Ypresian clays.

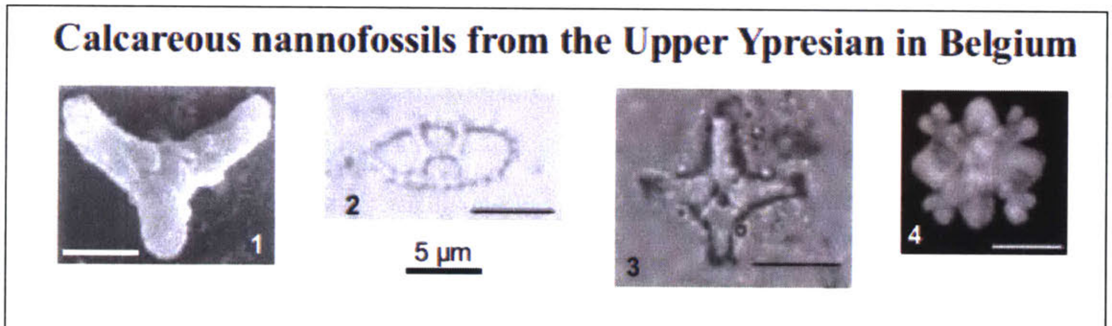


Figure 29. Nannofossils from the Upper Ypresian in Belgium (by Etienne Steurbaut, 2016)

D. Availability of free water

The amount of free water depends on the hydrological situation as well as the boundary conditions of the excavation process. Specifically, soils with stiff consistency can be transformed into sticky consistency if exposed to water for a certain time. Hydroshield tunneling is characterized by a very large amount of free water in relation to the amount of excavated soil due to the use of a support slurry, and so is slurry wall construction. Therefore, these two types of excavation processes are particularly prone to suffer from clogging effects in clayey materials. Also, the water inflow rate and inflow time, hence the standstill time (e.g.

tool change, maintenance shift etc.) affect the consistency of a soil. Therefore, the first evaluation diagram of clogging potential developed by Thewes in 1999 (Figure 19) is not very relevant because the water content cannot be established accurately, or could vary from day to day depending on the water inflow. That is why this first evaluation diagram developed was improved to the universal clogging diagram. Weh et al. (2009) provide a detailed description of the correlation between groundwater inflow and effects on a EPB-shield, which is driven in the open mode, in which he stresses the input of water availability in estimating the clogging risk of the subsoil.

Another effect of the presence of water on adhesion is mentioned by Feng (2004) who stated that as cohesive clays with high liquid limits and plasticity index values are exposed to water, they tend to get exceedingly sticky due to the swelling potential of clay caused by its minerals. A thin layer of water called water-film at the interface of cohesive soil and a steel surface plays an important role in the adhesion of soil to steel. Actually, the first element researchers tried to define in an attempt to understand the adhesion of soils to a steel surface is the "sticky point". Fountaine (1954) mentions that the "sticky point" of a soil is the minimum soil moisture content at which the adhesion of soil to a foreign object is more than the cohesion within the soil particles. Fountaine hypothesized that there are two components acting in the adhesion between soil and a foreign object (steel surface) (See Figure 30). One is the attraction of soil particles to the other object (Figure 30 (a)), and the other is the adhesion stemming from a water film present in the interface of soil-foreign surface (Figure 30 (b)). Figure 30 (a) shows that at the contact points between the soil and the steel surface, water rings are trapped. Each of these water rings contributes to the adhesion between the soil and the steel surface, thus making the soil sticky. The water film shown in Figure 30 (b) is connected to the soil through water channels between the soil particles. This water linkage provides an adhesion related to the moisture tension.

Manipulating this water film can be an option to remediate clogging issue. It is actually what Spagnoli et al. (2014) did when studying electro-osmosis' effect on clogging (detailed in section V. B.).

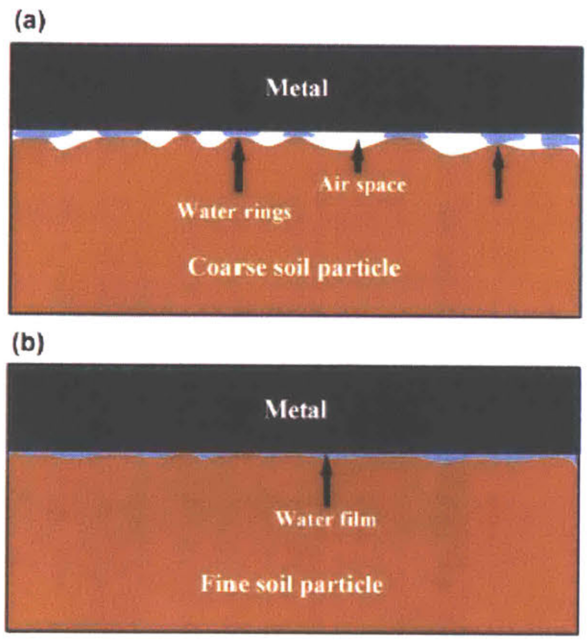


Figure 30. Two distinct types of water linkage in soils: (a) water rings and (b) a whole water film (adapted from Fountaine 1954)

V. Treatments to reduce stickiness

A. Addition of NaCl

The studies carried out by Spagnoli et al. (2011) show that adding NaCl to the pore fluid of a clay sample during the cone pull-out test decreases the adhesion of the material to the cone. In fact, a cone pull-out test was performed on an Ypresian clay sample, in which pore fluid was distilled water while another test was performed on an Ypresian clay sample, in which pore fluid was consisting of a NaCl solution with a concentration of 1mol/L. Figure 31 shows that adding NaCl to the pore fluid decreases the adherence of the material to the cone surface.

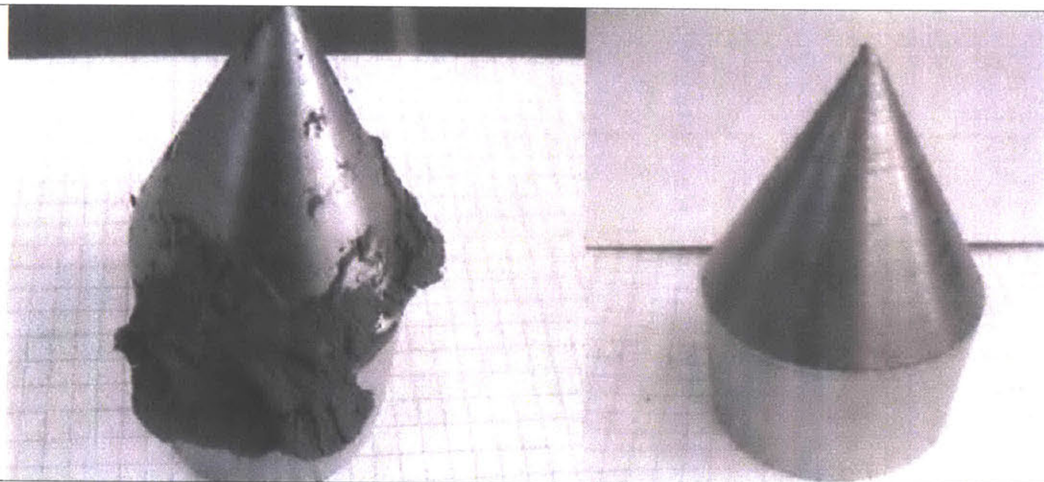


Figure 31. Modification of clogging for Ypresian Clay by increasing the NaCl concentration in the pore fluids. Left: with distilled water. Right: with NaCl 1 mol/l (after Spagnoli et al., 2011)

Di Maio (1999) investigated the exposure of bentonite to salt solution and the paper published on this study helps demonstrate why addition of NaCl to the pore fluid decreases the adhesion of a clay. Di Maio conducted experiments on remolded samples of Ponzi bentonite whose plasticity index is 320% and clay fraction 80%. The Ponza bentonite is mainly composed of Na-montmorillonite, which is the most common smectite, the main clay mineral in Ypresian clays. The specimens of Ponza bentonite were exposed to NaCl, $CaCl_2$, or KCl solutions at variable concentrations. The liquid limit was then evaluated and the numbers show that the liquid limit decreases remarkably with increasing salt concentration and that a concentration of salt of 1M is enough to take the liquid limit to a level close to the minimum (See Figure 32). The extent of changes in the liquid limit caused by varying salt concentrations suggest that noticeable changes in the mechanical behavior may be produced by diffusion of salts into the clay specimens. Based on section III.D.1., a decrease in the liquid limit also decreases the plasticity index since $I_P = W_L - W_P$. A lower value of plasticity index means that the material would be plotted lower on the plasticity chart (Figure 24) and also on the evaluation diagram of clogging potential (Figure 22), thus reducing the clogging potential.

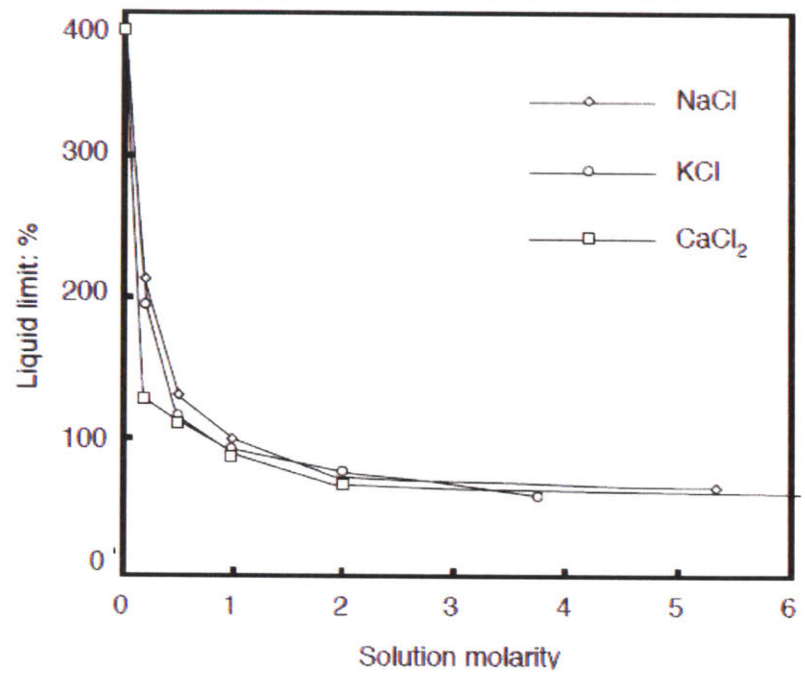


Figure 32. Influence of electrolyte concentration on liquid limit (by Di Maio 1996)

Di Maio states that at equilibrium, the mechanical behavior of clays exposed to saturated NaCl became very similar to that exhibited by the specimens that had been directly prepared with the salt solution as pore fluid. In the case where ions can actually diffuse into the pore fluid, the clay may exhibit improved mechanical properties. Therefore, exposing a sticky soil encountered during an excavation process to salt solution could be considered as a potential countermeasure to remediate clogging issues. However, the extent to which the natural pore fluid could be replaced by salt solution is hard to evaluate. The main challenge is finding a way to treat the soil in order to expose it to salt solution so that the natural pore fluid can be replaced by the desired one. One wonders if jet grouting salt solution into the soil would be an efficient method. If it is, the cost efficiency of doing so is another matter that should be studied. It should also be kept in mind that even though salt water does not make a metal rust, it accelerates the rusting process because electrons move more easily in salt water than they do in pure water. Therefore, corrosion issues should be considered when thinking of using NaCl solution on soils.

B. Electro-osmosis

According to the experiments conducted by Spagnoli et al. in 2014, electro-osmosis can reduce adhesion of soil to the steel surface. The author of the experiments found that by applying an electric charge to the steel cone of the cone pull-out test, water is transported through the clay to the interface between the clay and the steel. A water film is created at the clay/steel interface and reduces adherence by allowing the material at the surface of the cone to slide off. In this study, tests were first performed on a natural kaolinitic clay to determine the minimum voltage values needed to eliminate or decrease clogging. It was found that for V = -2.5V, clogging can be brought down to a minimum (See Figure 33). It is therefore this value of voltage that was applied when conducting the same experiment on Ypresian and Boom clays.

It can be noted that Figure 33 demonstrates that independently of the cathode being the cone or the proctor mold, the effect on clogging is the same: clogging decreases. This result is surprising given that Roy and Cooper (1996) explain that electro-osmosis drives the water toward the cone used as a cathode, suggesting that the water would be driven towards the proctor mold if the latter was used as the cathode. In fact, electro-osmosis should cause dewatering at the anode, consequently causing a decrease in the pore pressure and increase effective stress at the cone. An increase of clogging on the cone would be expected if this mechanism is the one happening in reality. However, when the proctor mold is used as the cathode, no clogging was observed. The authors therefore preferred to characterize the electro-osmosis simply as the presence of water or not (Spagnoli et al., 2014).

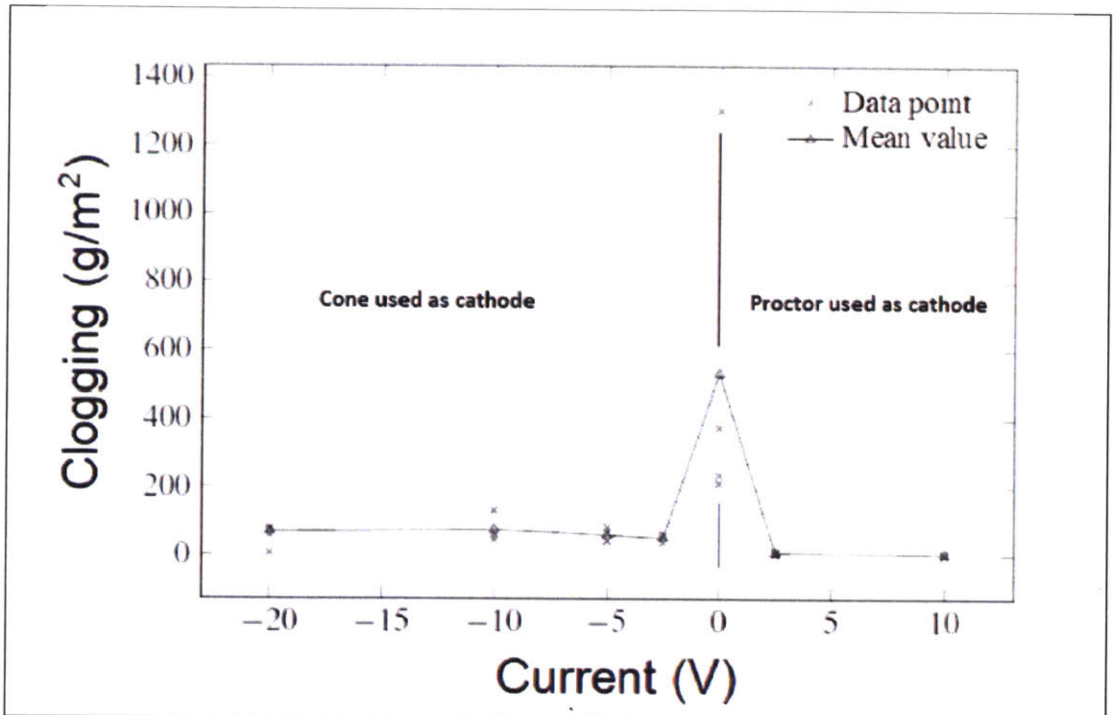


Figure 33. Preliminary results performed on a natural kaolinitic clay to determine lowest voltage to apply (by Spagnoli et al., 2014)

For the experiments conducted on Ypresian and Boom clays, the clay samples of different consistency index were prepared in the Proctor mold. Two sets of tests were run, one set for which no current is applied, and one set for which a current of V = -2.5V was applied. The results for the Ypresian clay are shown in Figure 34 and prove that applying a -2.5V current successfully reduces clogging from a very high 385.96g/m² for Ic=0.55 to a low 57.58 g/m² for the same Ic=0.55. For this value of Ic, adherence was the highest for Ypresian clay, but for other values of Ic, the applied current is still effective in reducing clogging. The pictures of the testing cones in Figure 35 clearly illustrate that electro-osmosis is an effective solution for reducing clogging. Pictures A and B in Figure 35 show the test results for a clay sample of Ic=0.86, pictures C and D show the test results for a clay sample of Ic=0.55, and pictures E and F show the test results for a clay sample of Ic=0.4. On these pictures, it can be seen that when an electric current of -2.5V is applied (pictures A, C, and E in Figure 35), less clay remains on the testing cone compared to when no current is applied (pictures B, D, F in Figure 35).

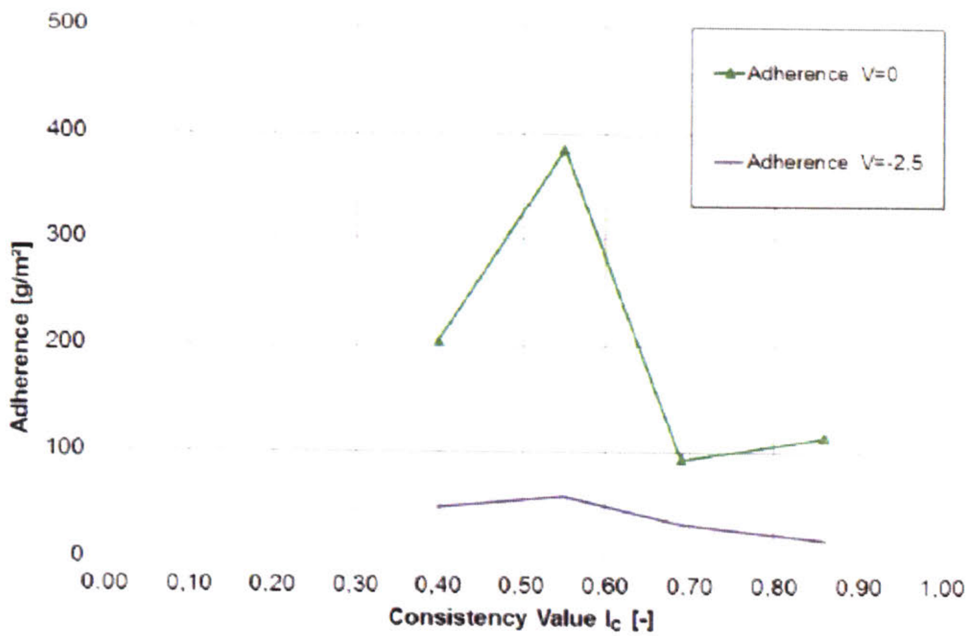


Figure 34. Adherence tests for Ypresian clay (by Spagnoli et al., 2014)

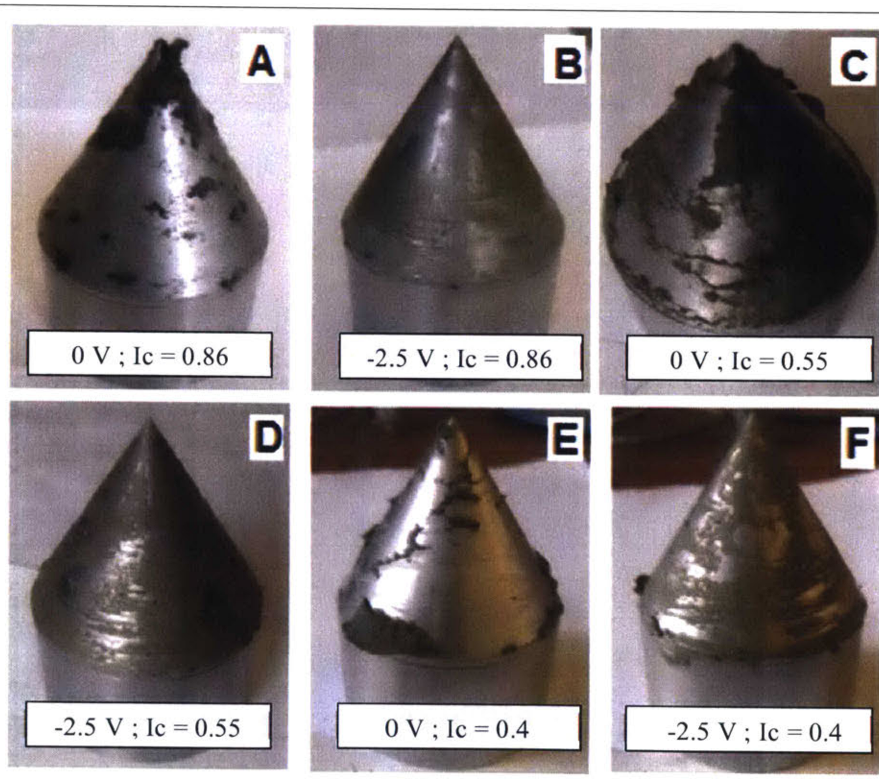


Figure 35. Photographs of the tests with the Ypresian Clay with and without application of an electric current to the pull-out cone (by Spagnoli et al., 2014)

The results for the Boom clay are shown in Figure 36 and prove that applying a -2.5V current successfully reduces clogging from a very high 142.15 g/m² for Ic=0.55 to a low 70.18 g/m² for the same Ic=0.55. The Boom clay's peak adherence is reached for a consistency index of Ic=0.25, at which the adherence has a value of 180 g/m² – a low clogging value in contrast to the Ypresian clay. It is expected given their very different plasticity index as explained in section IV.B.

The study carried out by Spagnoli shows that applying an electrical field at the cone of the cone pull-out test decreases clogging. It also demonstrates that electro-osmosis could be used to avoid clogging of clay material on excavation tool surfaces. The cutting wheels could be used as a cathode to create a water film on the tool surface, and the anode would be placed somewhere nearby in the soil. This method has never been applied in the field and more research is needed with in-situ testing to apply these laboratory results at a larger scale.

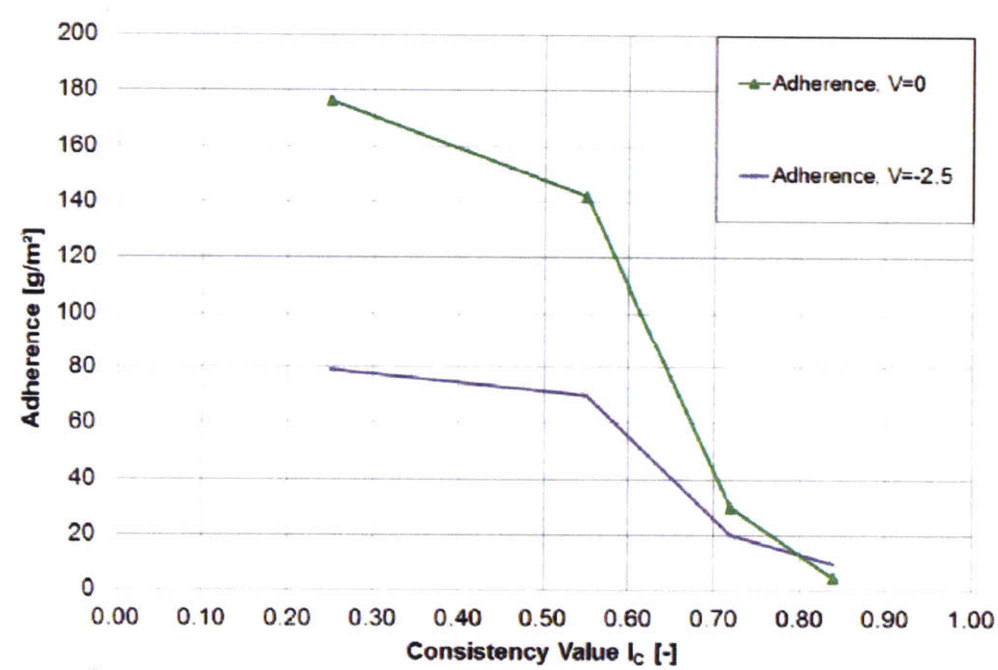


Figure 36. Adherence tests for Boom clay (by Spagnoli et al., 2014)

VI. Conclusions

In order to understand the origin of the Ypresian clay's sticky property, this thesis studied the burial history of this clay, its inherent properties and the different mechanisms behind clogging. Several laboratory tests developed to measure clogging were described, however it is understood that a standardized method has yet to be agreed on.

It was seen that the clogging potential of a soil can be assessed by looking at its Atterberg limits, which characterize soil behavior at the meso-scale. For the Ypresian clay, its unusually high plasticity index indicates that this clay formation has a high risk of causing clogging during excavation processes. Also, by using the diagrams developed based on the Atterberg limits, one can qualitatively evaluate the clogging potential of a clay. Specifically, the universal classification diagram developed by Hollman and Thewes in 2013 shows that the Ypresian clay has a large range of water content within which it causes clogging. Note that this diagram is very comprehensive as the water content is a varying parameter in it. In fact, the water content in a soil varies depending on which excavation method is used, and this evaluation diagram allows one to evaluate a soil's clogging potential for any water content that this soil may have while being manipulated. However, all the existing clogging evaluation diagrams were developed for TBMs, it is therefore suggested that more data be collected on clogging in hydromills so that an evaluation diagram specific to hydromills can be developed in the future. Collecting more data in general could also help verify the hypothesis that the U-line in the Casagrande chart could be a reliable evaluation method for clogging.

While evaluating stickiness with Atterberg limits, i.e. at a meso-scale, provides a coherent conclusion, relating it to the clay mineralogy is more complicated. In fact, if the physics behind the interactions between clay sheets is understood, it is not sure how the macroscopic behavior of a clay relates to the microscopic behavior of its clay sheets.

Several approaches exist for remediating the clogging problems. It was seen that NaCl solution has proven to be efficient in reducing, or even eliminate clogging. Possible future research could involve field testing the methods that can be used to replace a soil's natural pore fluid with NaCl solution. Successful results could make NaCl solution injection a countermeasure to the clogging problem.

Electro-osmosis is also being studied as a solution against clogging. Testing has shown that applying an electric current and using the tool surface as the cathode can significantly reduce clogging. This method has not been used in practice yet. Also for this method to be used, excavation machines, in which an electric current can be applied would need to be built.

References:

Ball R.P.A., Young D.J., Isaacson J., Champak J., Gause C., 2009. Research in soil conditioning for EPB tunneling through difficult soils. In: Proceedings of RETC, pp. 320–333.

Di Maio, Catarina. (1996). Exposure of bentonite to salt solution: Osmotic and mechanical effects. Geotechnique. 46. 695-707. 10.1680/geot.1996.46.4.695.

Egli, H., 2009. Personal Communication to R. Zumsteg, cf. R. Zumsteg and A.M. Puzrin, 2012

Etienne STEURBAUT, «YPRESIAN», Geologica Belgica [Online], number 1-2 - Chronostratigraphic units named from Belgium, volume 9 (2006), 73-93 URL : https://popups.uliege.be:443/1374-8505/index.php?id=1101.

Feinendegen, M., Ziegler, M., Weh, M., Spagnoli, G., 2011. Clogging during EPB-tunnelling: Occurrence, classification and new manipulation methods. In: Proceedings ITA-AITES World Tunnel Congress, Helsinki, pp. 767–776.

Feng, Q. 2004. Soil conditioning for modern EPBM drives, Tunnels &Tunnelling International, 36,18–20.

Fountaine, E.R., 1954. Investigations into the mechanism of soil adhesion. Journal of Soil Sciences 5 (2), 251–263.

Garroux G. de Oliveira, Daniela & Diederichs, Mark & Thewes, Markus & Langmaack, Lars. (2017). EPB Conditioning of Mixed Transitional Ground: Investigating Preliminary Aspects. M. Segad, B. Jönsson, T. Åkesson, and B. Cabane, "Ca/Na Montmorillonite: Structure, Forces and Swelling Properties," Langmuir, vol. 26, no. 8, pp. 5782–5790, Apr. 2010.

Hollman, F., & Thewes, M. (2013). Assessment method for clay clogging and disintegration of fines in mechanised tunnelling. Tunnelling and Underground Space Technology, 37, 96-106.

Khabbazi Basmenj, Amir & Mirjavan, Ali & Ghafoori, Mohammad & Cheshomi, Akbar. (2016). Assessment of the adhesion potential of kaolinite and montmorillonite using a pull-out test device. Bulletin of Engineering Geology and the Environment. 10.1007/s10064-016-0921-3.

Kooistra A, Verhoef PNW, Broere W, Ngan-Tillard DJM, Vantol AF (1998) Appraisal of stickiness of natural clays from laboratory tests. In: Proceedings of the 25th National Symposium of Engineering Geology in the Netherlands

Mauroy, F., 1998, New Development in earth pressure equipment for boring underground 355 guided transit line in France. In Negro A. and Ferreira A.A. (Editors) Proc. Tunnels and 356 Metropolises, Balkema, Rotterdam, pp. 697-702.

Mertens, J., Wouters, L., & Van Marcke, Ph. (2004). Burial history of two potential clay host formations in Belgium. Nuclear Energy Agency of the OECD (NEA): Organisation for Economic Co-Operation and Development - Nuclear Energy Agency. https://inis.iaea.org/search/search.aspx?orig_q=RN:36071496

Mitchell James K., Soga Kenichi, Fundamentals of Soil Behavior, 3rd Edition, May 2005 ISBN: 978-0-471-46302-3

Roy, S., and Cooper, G.A., 1993, Prevention of bit balling in shales - preliminary results: SPE 363 Drilling & Completion, Vol. 8, No. 3, pp. 195-200.

Sass, Ingo & Burbaum, U. (2009). A method for assessing adhesion of clays to tunneling machines. Bulletin of Engineering Geology and the Environment. 68. 27-34. 10.1007/s10064-008-0178-6.

Spagnoli, Giovanni & Stanjek, Helge & Feinendegen, Martin. (2014). Electrical Manipulation of the Clogging Properties of Ypresian and Boom Clays. Environmental and Engineering Geoscience. 20. 99-108. 10.2113/gseegeosci.20.1.99.

Spagnoli, Giovanni & Stanjek, Helge. (2012). New manipulation methods to decrease the clogging of clays during mechanical tunnel driving.

Spagnoli, Giovanni & Feinendegen, Martin & Ernst, Rüdiger & Weh, Markus. (2012). Manipulations of the sticky clays regarding EPB tunnel driving. 10.1201/b12748-17.

Spagnoli, G., Feinendegen, M., Stanjek, H., and Azzam, R., 2011c, Soil conditioning for clays 383 in EPBMs – part 2: Tunnels Tunnelling International, Vol. 43, No. 11, pp. 59-61.

Thewes, M., Burger, W., 2005. Clogging of TBM drives in clay – identification and mitigation of risks. In: Proceedings ITA-AITES World Tunnel Congress, Istanbul, Turkey, pp. 737–742.

Thewes, M., 1999. Adhesion of clay soil in tunnel drives with slurry shields (In German: Adhäsion von Tonböden beim Tunnelvortrieb mit Flüssigkeitsschilden). Berichte aus Bodenmechanik und Grundbau der Bergischen Universität Wuppertal, Fachbereich Bauingenieurwesen, Bd. 21. Shaker Verlag, Aachen.

Vandenberghe Noël, Laenen Ben, Van Echelpoel Erna, Lagrou David, Cyclostratigraphy and climatic eustasy. Example of the rupelian stratotype, Comptes Rendus de l'Académie des Sciences - Series IIA - Earth and Planetary Science, Volume 325, Issue 5, 1997, Pages 305-315, ISSN 1251-8050, https://doi.org/10.1016/S1251-8050(97)81377-8.

Vandenberghe, N. & Mertens, J., 2013. Differentiating between tectonic and eustasy signals in the Rupelian Boom Clay cycles (Southern North Sea Basin). Newsletters on Stratigraphy, 46/3, 319-337.

Vandenberghe Noël, De craen Mieke, Wouters Laurent, MEMOIRS OF THE GEOLOGICAL SURVEY OF BELGIUM N. 60 – 2014 The Boom Clay Geology From sedimentation to present-day occurrence A review

Van Marcke, P., Laenen, B., 2005. The Ypresian clays as possible host rock for radioactive waste disposal: an evaluation. ONDRAF/NIRAS, Belgian agency for radioactive waste and enriched fissile materials, <http://www.nirasafvalplan. be/nieuw/downloads/NIROND-TR-2005-01.pdf>.

Weh, M., Zwick, O., Ziegler, M., 2009a. Mechanised driving in subsoil prone to clogging, Part 1. Tunnel, No. 1/2009, pp. 25–36.

Weh, M., Zwick, O., Ziegler, M., 2009b. Mechanised driving in subsoil prone to clogging, Part 2. Tunnel, No. 2/2009, pp. 18–28.

Yukselen Y, Kaya A (2006) Prediction of cation exchange capacity from soil index properties. Clay Miner 41:827–837

Zumsteg, R., Puzrin, A.M., Stickiness and adhesion of conditioned clay pastes Tunn. Undergr. Space Technol., 31 (2012), pp. 86-96