InProTunnel: Interfacial Processes between Mineral and Tool Surfaces - Causes, Problems and Solutions in Mechanical Tunnel Driving

Feinendegen M. (1), Spagnoli G. (2), Stanjek H. (3), Neher H.P. (4), Ernst R. (5), Weh M. (6), Fernández-Steeger T. M. (2)*, Ziegler M. (1), Azzam R. (2)

(1) Chair of Geotechnical Engineering and Institute of Foundation Engineering, Soil Mechanics, Rock Mechanics and Waterways Construction, RWTH Aachen University
(2) Chair of Engineering Geology and Hydrogeology, RWTH Aachen University
(3) Clay and Interface Mineralogy, RWTH Aachen University
(4) Ed. Züblin AG, Stuttgart
(5) Herrenknecht AG, Schwanau
(6) Marti Tunnelbau AG, Bern, CH

* Coordinator of the project

Abstract

During mechanical tunnel driving in fine grained soil or rock the excavated material often sticks to the cutting tools or conveying system, which may cause great difficulties in its excavation and transport. In the InProTunnel project this problem is faced on different scales particularly for the method of Earth Pressure Balanced (EPB) shield tunnelling. Major influences from tunnel boring machine (TBM) operation are identified by project data analyses, clogging propensity is evaluated by a new laboratory test, alternative manipulation techniques are developed based on modifications of the physico-chemical and electroosmotic behaviour of clay minerals and will be tested in an especially designed clogging test system.

1. Introduction

In the course of the joint research project »Interfacial Processes between Mineral and Tool Surfaces - Causes, Problems and Solutions in Mechanical Tunnel Driving« (InProTunnel) the problem of clogging during tunnel driving in fine grained soil or rock is investigated particularly for the method of EPB shield tunnelling. Three university institutes and four industrial partners are working on new techniques to identify the relevant effects and interactions on different scales. Furthermore, new manipulation methods for the avoidance or reduction of adhesion-caused impacts are investigated. The resulting proposals for solution will have a positive effect on the efficiency, sustainability and profitability of tunnelling projects.

In a first step, data deriving from TBM operation, geological and environmental parameters are analysed (cf. ch. 2). Detected correlations are used to identify positive or negative effects with respect to the sticking of excavated material to the cutting tools or transportation equipment.

Secondly, new laboratory tests to investigate and classify different soils and rocks are developed as until now no suitable test procedure or classification scheme for the clogging potential is available (cf. ch. 3). The adhesion of clays or clayey soft rocks in mechanical tunnel driving has already been investigated in several research projects (*Jancsecz 1991, Wilms 1995, Thewes 1999, Burbaum 2009*); nevertheless, no generally accepted (standardized) test cur-

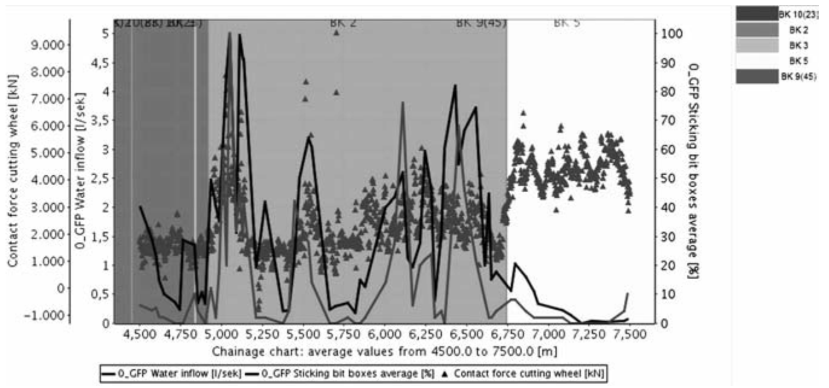


Figure 1: Graphical multi-axes evaluation of TBM and geological/geotechnical data

rently exists to determine the clogging behaviour from a practical (tunnel) construction point of view.

Clay minerals show a mechanical behaviour which cannot simply be extrapolated from classical soil mechanics. The mechanical properties of fine-grained soils like clays are intimately related to the chemical properties of the respective minerals and pore fluids. Additionally, it is well known, that electric fields strongly affect the mechanical behaviour of soft soils. Since these processes are of great importance for the occurrence of adhesion and/or clogging as well as for the development of methods for their reduction the acting mechanisms are investigated on the micro scale in a third part of the project (cf. ch. 4).

Finally, new manipulation techniques based on chemical modifications as well as electroosmotic methods will be tested in a realistic test setup. These tests are presently in the design state (cf. ch. 5).

2. Data Analysis from TBM tunnelling projects

2.2. Project Database

The data generated by tunnel driving with TBM (penetration, thrust forces, pressures of annular grouting etc.) are crucial information for the interpretation and prediction of advance rates and potential troubles. The same applies for survey data and geological or geotechnical information.

Based on a powerful SQL database an application to collect, store, process and analyse the data of tunnel projects has been developed. Project partners have direct access to the database by means of a web-based graphical user interface (GUI). The application is designed as a socalled »thin-client« based on a central server database. Thus the application is independent from operating system and can be accessed from anywhere via internet. Only an internet browser is needed to run the application.

The basic function of the database is the storage of TBM data. Moreover, survey and geological/geotechnical data or any other type of process data referenced to chainage or time can be incorporated. All kinds of data can be processed and analyzed in graphical or tabular format regarding chainage or time. Standardized charts and tables as well as individual ones can be generated. Even a multiaxes evaluation of the data is feasible. Thus, the system is capable to interconnect all data of a project to become aware of existing correlations. Detected correlations can be used to identify positive or negative effects from different parameters with respect to e.g. the degree of sticking of excavated material.

In the framework of the InProTunnel project data from one tunnel project in southern Germany, where clogging problems were encountered, are available in the database. In figure 1 values for the local water inflow at the face, the relative amount of sticking of excavated material to the cutting wheel as well as the contact force of the cutter head are given for an approximately 3 km long tunnel part. Moreover, the respective geology is plotted in the background. The chart shows, that the clogging of the cutter head is strongly related to the water inflow at the face which is directly linked to the respective geology. Another fact is, that the sticking of excavated material to the cutting tools leads to an increasing contact force of the cutter head, when regarding the respective geology. The needed energy and the corresponding construction costs increase.

2.2. Influences on clogging from geology and TBM operation

When regarding the processes that lead to clogging problems in a TBM drive one has to distinguish between primary and secondary causes. Primary causes are mainly the following geotechnical conditions:

- The composition of the subsoil, especially the type and amount of clay minerals,
- The slaking durability,
- The water content of the soil prone to clogging and/or the availability of free water in the adjacent soil.

In this connection not only one layer or type of soil has to be regarded, but all materials that will be excavated at the same time have to be taken into consideration.

The secondary causes of clogging result from the interaction between cutting technology and subsoil. During the excavation and transport of the material the mechanical wear causes a loss of strength which may even lead to a complete disintegration of the composite structure. The varying consistency of the fine grain fraction and its percentage with respect to the total soil mass are major influences on the clogging propensity. In several TBM drives it could be observed, that a higher sand fraction in the excavated material led to considerably lower adherences.

Adherences may occur at all surfaces that are in contact with the excavated material during excavation, transport or disposal. The material first sticks to the tool surfaces due to adhesion forces. Clogging problems will follow when the amount of adhering soil leads to a narrowing in the transportation ways:

- The material is compacted and pressed to the tool surfaces or already adhering soil. By this, also material that normally shows no clogging propensity often tends to stick.
- Because of the possibly high pressure the adhesive forces may be considerably higher as well.
- If the inner strength of the soil (cohesion) is higher than the forces acting during excavation and (unpressurised) transport soil agglomerations can persist. When pressed through narrowings these aggregates may be squeezed or sheared. This leads to an exposure of their inner parts, where the water content and the clogging tendency is often much higher than in the rest of the excavated material.

If the adhering soil has no lateral support, high adhesive forces and/or cohesion is needed to prevent it from breaking of. Usually clogging is observed much less on moving parts, where not only gravitational forces like on stationary parts, but also rotational or shear forces are acting. However, the mechanical wear of the material in connection with the machinery working on the TBM leads to a massive rise of the temperature, which again results in very tough and permanent adherences. This can be very unfavourable, when these hard adherences act as a kind of support for softer material. For example, during a TBM drive the roller bit boxes are often filled with fairly wet soil. On the frontside and the backside this material is sliding (rotating) over the material in the excavation chamber or at the tunnel face, which frequently leads to the described effects. Such kind of adherences can be very long-lasting and can be carried far beyond the areas of subsoil that is originally prone to clogging.

As already seen before (cf. Fig. 1) the occurrence of clogging is very much dependent on

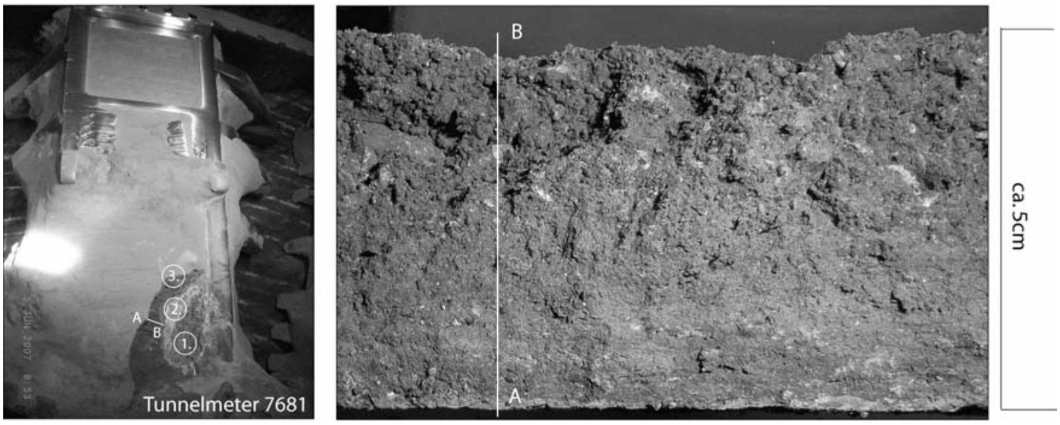


Figure 2: Adherences in the roller bit box of an EPB-TBM

the availability of water and the resulting consistency of the excavated material. When the original subsoil is relatively dry and only the tunnel driving operations cause a contact with water, then sometimes layered adherences are formed. In figure 2 heavily protracted adherences with such a layered structure are shown. The original colours are grey in the inner part (1), brown (2), grey (3) and light grey on the surface. When the picture was taken, the outer cutting wheel openings were almost free from clogging. Only the roller bit boxes showed the protracted adherences from earlier occurrences of water inflow. In the cross section A-B it can be seen how the adhering soil has been pulverized in the (rotating) contact surface to the material in the excavation chamber, has lost water due to the high temperature and changed its colour from a dark to a lighter grey. This very hard layer acts as a kind of protection for the softer soil within the roller bit box, which had to be removed by hand in the end.

3. Laboratory testing of the clogging behaviour

3.1. Cone pull-out test

For a better identification and quantification of the mechanisms affecting the clogging behaviour on a laboratory scale, the so called »cone pull-out test« has been developed (*Feinendegen et al. 2010*). The equipment and the test procedure are shown in figure 3.

The sample material is compacted in a standard proctor device, a steel cone is inserted into a pre-drilled coneshaped cavity and loaded for 10 minutes with the magnitude of the applied load between 3.8kN/m² and 189kN/m² depending on the consistency. The load is then taken off and the specimen is placed in a test stand where the cone is pulled out with a velocity of 5 mm/min. The tensile forces and the displacements are recorded.

Different clay types with varying mineralogy and plasticity have been tested up to now in a number of test series with different cones and soil consistencies. Table 1 shows the relevant properties of some selected clays.

3.2. Preliminary tests

In the following, some exemplary results of preliminary tests on the so called »clay 3«, a medium plastic clay from a quarry in the Westerwald (Germany) are illustrated. One important difference -amongst others- was, that the test cones in the later main experiments (cf. ch. 3.3) consisted of stainless steel, which has different surface characteristics than the constructional (black) steel that was used in the preliminary tests. The results thus cannot be compared directly.

It should be mentioned, that all curves shown in the following normally represent the mean values of four tests. Only when the deviation is too large, the respective data are neglected. Figure 4 shows the progress of the vertical ten-

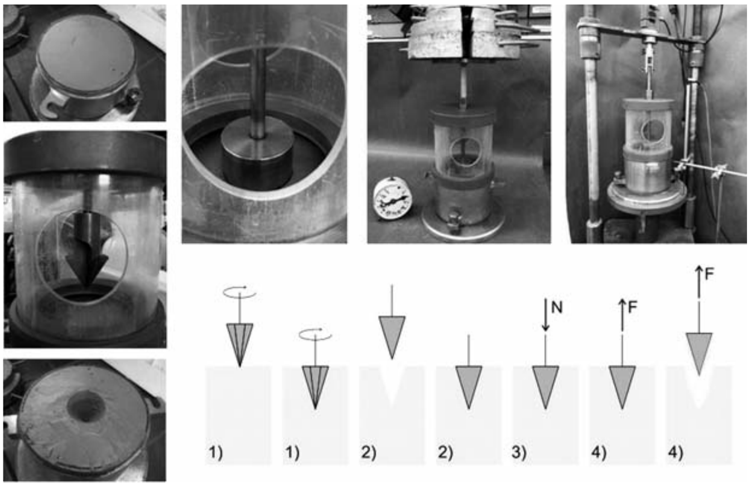
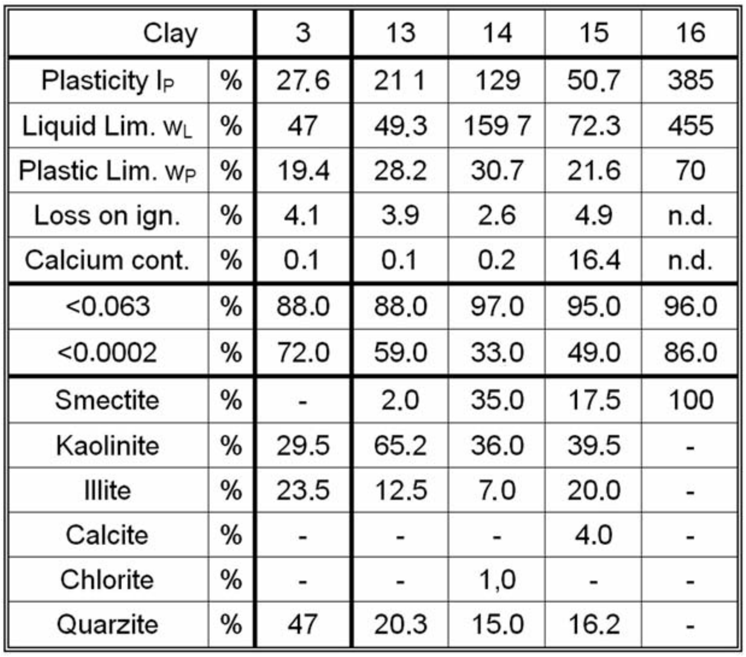


Figure 3: Cone pull-out test

Table1: Tested clays



Clay		3	13	14	15	16
Plasticity I_P	%	27.6	21 1	129	50.7	385
Liquid Lim. w_L	%	47	49.3	159 7	72.3	455
Plastic Lim. w_P	%	19.4	28.2	30.7	21.6	70
Loss on ign.	%	4.1	3.9	2.6	4.9	n.d.
Calcium cont.	%	0.1	0.1	0.2	16.4	n.d.
<0.063	%	88.0	88.0	97.0	95.0	96.0
<0.0002	%	72.0	59.0	33.0	49.0	86.0
Smectite	%	-	2.0	35.0	17.5	100
Kaolinite	%	29.5	65.2	36.0	39.5	-
Illite	%	23.5	12.5	7.0	20.0	-
Calcite	%	-	-	-	4.0	-
Chlorite	%	-	-	1,0	-	-
Quarzite	%	47	20.3	15.0	16.2	-

sile stresses for clay 3 tested with different cone inclinations at a consistency of $I_C = 0.70$. It can be seen, that with the »nearly flat« cone 0 (10°) tensile forces can only be measured for displacements less than 3mm, while with the »steep« cone 4 (72.6°) they are acting over a quite large range up to 11mm. After several comparative tests, only cone 3 (58°) was used furthermore, since it provided the most characteristic results for all analysed soils.

In figure 5 the respective results for different consistencies tested with cone 3 are shown. Here the stiff material ($I_C = 0.85$) shows quite high tensile stresses at very short displacement ways whereas for the softer material the maximum decreases with tensile forces still acting over large ways. An integration of these tensile stress-displacement curves delivers the »Pull Energy« which represents the energy that is needed to pull the cone out of the soil.

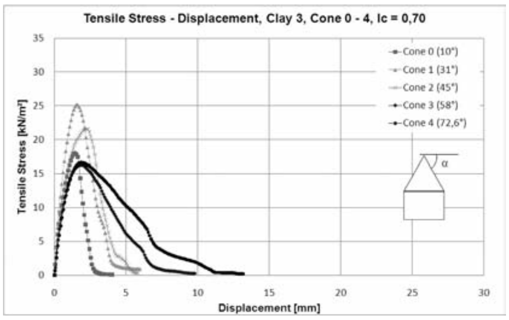


Figure 4: Tensile stress - displacement curves for different cone inclinations

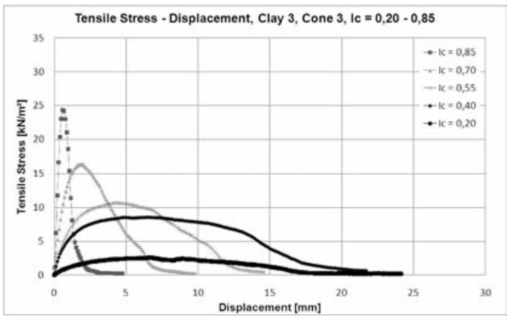


Figure 5: Tensile stress - displacement curves for different consistencies

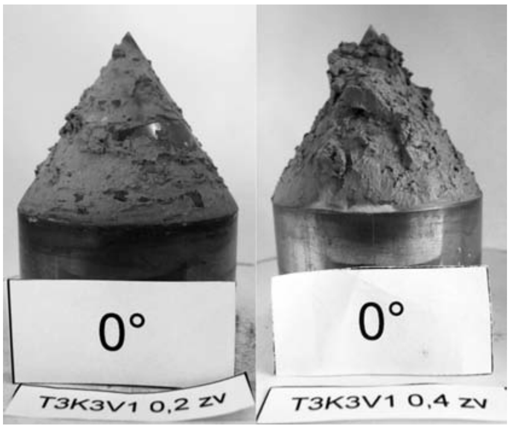


Figure 6: Adhering soil for IC = 0.20 and IC = 0.4
(0° = viewing direction)

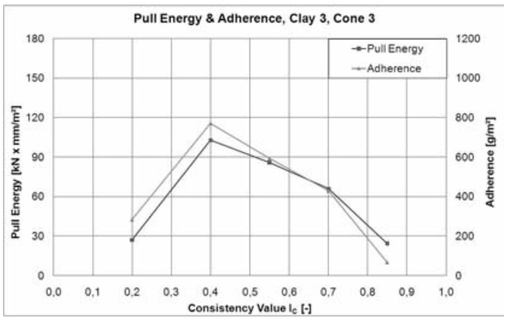


Figure 7: Pull energy and adherence over consistency

In addition to the tensile stress measurements, after each test the mass of adhering soil (cf. fig. 6) was determined by weighing. This parameter is defined as »adherence« in the following.

When plotting the pull energy, which was derived from the tensile (= bond) stresses, over the consistency and comparing it to the measured adherences, a good correlation could be observed from the first tests series (fig. 7). Both the clogging potential as well as the adherence show relatively high values in a soft to stiff consistency and a decrease towards the »wet« and the »dry« side. This corresponds quite well with the experiences from practice (*Weh et al. 2009a*, b). Clogging problems mainly occur, when the material in the excavation chamber is in or gets into a plastic state. They are usually much smaller when the soil is very dry or near liquid.

3.3. Main experiments

In the main experiments four different clays were examined: clay 13, like clay 3 from the Westerwald; clay 14, the extremly plastic so called »Ypresian Clay« (= »London Clay«); clay 15, the again well-known »Boomse Klei« and clay 16, which represents a pure smectite.
In figure 8 the curves of the pull energy over the consistency are shown for these four clays, whereas in figure 9 the corresponding adherences are plotted. It can easily be seen, that the (quantitative) correlation of these curves is not always as good as in the preliminary tests, but the (qualitative) shape is still somehow similar.
Nevertheless, from figure 9 a direct comparison of the four soils can be drawn. Clay 14, the »Ypresian Clay«, shows a characteristic steep developing with a very high maximum of adherence (1150 g/m²) at a consistency of I_C = 0.54. The curves for clay 15, the »Boomse

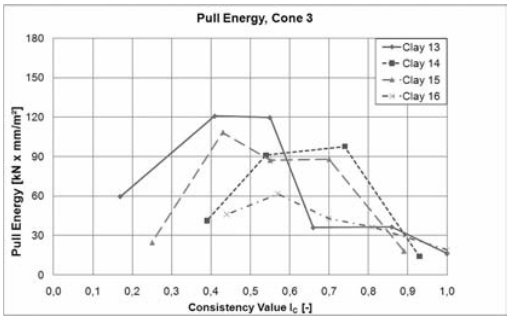


Figure 8: Pull energy over consistency

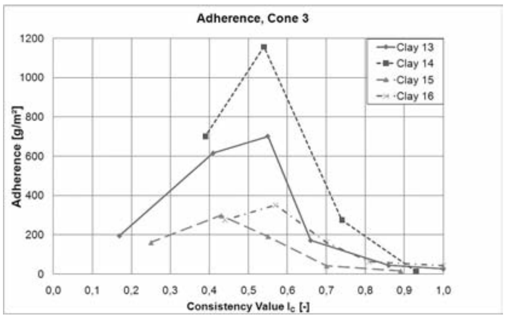


Figure 9: Adherence over consistency

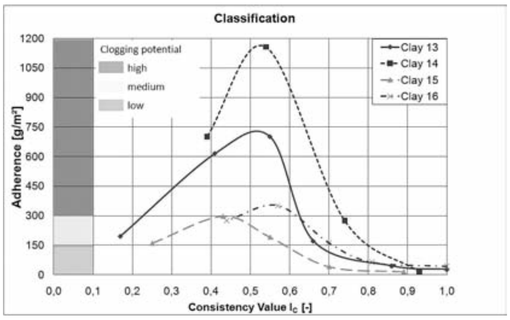


Figure 10: Draft of a classification scheme

Klei« and the pure smectite (clay 16) are more even with considerably lower adherences of 275 g/m² and 350 g/m² respectively. Finally, for Clay 13 from the Westerwald the maximum value of 700 g/m² lies in between, but the curve is a bit irregular.

3.4. Evaluation of the clogging potential

Based on the results obtained so far, a draft of a classification scheme to quantify the clogging potential of different fine-grained soils has been developed (fig. 10). Classes of high, medium and low clogging potential are assigned to the diagram with the adherences derived from the cone pull-out tests plotted over the consistency.

One can directly identify the very high risk of clogging for clay 14. In particular, the sharp increase of the curve up to the maximum of 1150 g/m² is a strong indication for problems to be expected. Also Clay 13 with a maximum adherence of 700 g/m² will lead to extensive clogging. But also for the two other clays noteworthy adherences have to be reckoned with.

In this connection it should be mentioned, that all clays presented here were deliberately chosen as »sticky« clays. Other samples were examined that showed adherences of less than 100 g/m² and can thus be defined as »not prone to clogging«. Anyhow, the ranges of high, medium and low clogging potential are up to now defined arbitrarily. There is still a strong need for a verification by the EPB tunnelling praxis!

4. New manipulation techniques

4.1. Theoretical background of the chemo-mechanical coupling of clays

Clay minerals are characterized by strong electrical attractive and repulsive forces that vary significantly in magnitude depending on mineralogical composition and the charge on their surface as well as on their edges. Thus the clay mineralogy becomes important in geotechnical engineering with fine-grained soils. The region in the particles size vs. stress field where chemo-mechanical coupling may take place reflects the relevance of double layer phenomena as well as the relative balance between local contract-level electrical forces and boundary-skeletal forces resulting from Terzaghi's effective stress (*Santamarina et al. 2002*).
The chemo-mechanical coupling plays an important role for the engineering response of the material. Numerous authors have already

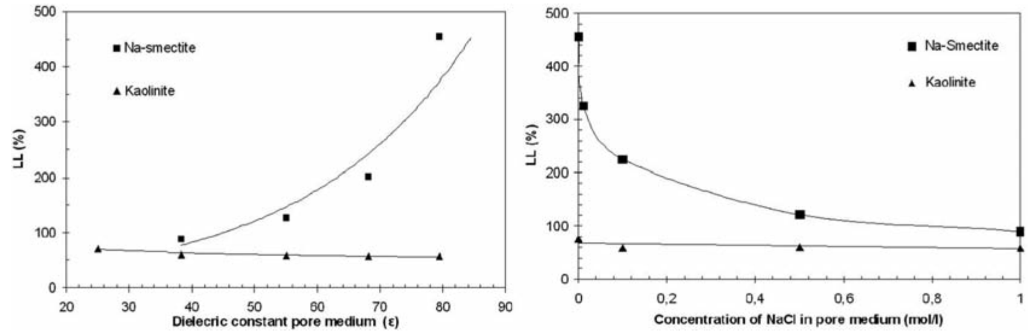


Figure 11: Variation of the liquid limit of Smectite and Kaolinite for different dielectric constant (left) or electrolyte concentration (right) of pore fluids (*after Spagnoli et al. 2010b*)

investigated the problem (*Mesri and Olson 1970; Anandarajah and Zhao 2000; Spagnoli et al. 2010a*). Dielectric constant and electrolyte concentration of the pore fluids are important controlling parameters, particularly in the case of 2:1 expanding clays such as Smectite. Kaolinite (1:1 non-expanding clay) and Illite (2:1 non-expanding clay) do not respond in the same way. In fact, they have a very thin diffuse double layer (DDL) expansion (*Gajo and Maines 2007*) due to the negligible isomorphic substitution. With increasing salt concentration the DDL thickness decreases leading to smaller specimen volume. For the following discussion, it will be assumed that the DDL theory is applicable.

Clay particle systems are frequently described as a series of parallel clay particles. The Poisson-Boltzmann equation (*Mitchell and Soga 2005*) for a single particle can be used to obtain the midplane electrolyte concentration and potential between two particles. An approximate indication of the influences of particle spacing and pore fluids chemistry can be seen in terms of thickness of the DDL. However, the variation of liquid limit for Kaolinite with fluids of different dielectric constant or electrolyte concentration is almost negligible compared to the variation which occurs for Smectite (Fig. 11). The difference in chemo-mechanical behaviour of Kaolinite and Smectite is probably due to the existence of two different mechanisms governing the liquid limit. One mechanism might be controlled by the thickness of the DDL which governs the liquid limit. *Sridharan and Venkatappa Rao (1975)* stated that the liquid limit of soils is mainly controlled by the amount of DDL held water. The most important conclusions, concerning the structure of the double layer as function of the electrolyte concentration (and / or dielectric constant) of the fluid is, that the extension of the double layer in solution decreases with increasing electrolyte concentration (or decreasing dielectric constant).

This can be seen from the fact that the liquid limit for Smectite is 455 % with water and 89% with a non polar fluid. Since liquid limit is the amount of fluid which must be added to a soil to allow the layers most distant from the soil particle to acquire the properties of free water (*Sridharan et al. 1988*), it can be stated that the fluid content at the liquid limit is contributed also by the fluid content due to the diffuse double layer. Therefore, the liquid limit is a measure for water (or fluid) held as double layer water (held with rigidity) plus water (or fluid) in the liquid state. For this reason, the decrease in liquid limit for Na-Smectite with non-polar fluids can be explained by a suppressed or thin double layer which is in accordance to equation (1).

$$\frac{1}{\kappa}=\left(\frac{\varepsilon_0 \varepsilon RT}{2n_0e^2v^2}\right)^{\frac{1}{2}} \qquad (1)$$

where $1/\kappa$ is the DDL thickness (in nm), T is the absolute temperature given in K, n_0 the ionic concentration in the bulk solution in mol/l, ε_0

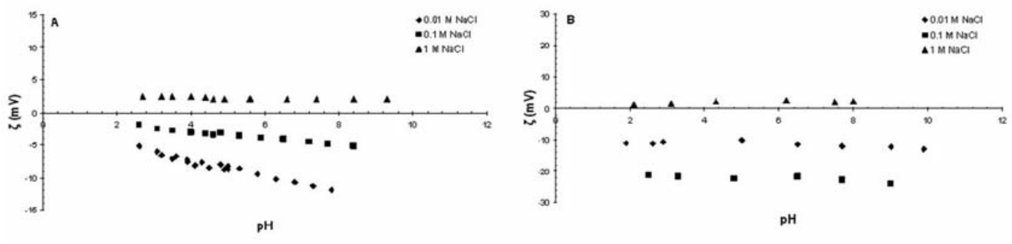


Figure 12: ζ - potential measurements for Kaolinite (left) and Na-Smectite (right)

and ε are the electric permittivity of vacuum and the relative dielectric constant of the pore fluid, respectively, whereas υ^2 is the valence of the prevailing cation. The constants are the elementary charge (e = $1.602 \cdot 10^{-19}$ C) and the gas constant (R = 8.3145 J/mol·K) (*Israelachvili 1991*).
For Kaolinite a change in the fluids dielectric constant (or electrolyte concentration) does not lead to any appreciable change in double layer thickness. In addition, it could be stated that the DDL for non-swelling clays is very small or not existing. Hence, the diffuse double layer approach does not apply for such clays.

4.2. ζ-potential measurements

The electrokinetic behaviour of clay suspensions was investigated using an electroacoustic technique (DT1200 ζ-potential analyzer, Dispersion Technology, Inc., USA), which is based on the determination of the dynamic mobility obtained from the electrokinetic sonic amplitude signal (ESA) of the charged particles in non-dilute suspensions (*Galassi et al. 2001*). Simultaneously the electrophoretic mobility μ is calculated using the following equation (*Dukhin and Goetz 2002*):

$$\mu = \frac{2\varepsilon\varepsilon_0\zeta(\rho_p - \rho_s)\rho_m}{3\eta(\rho_p - \rho_m)\rho_s} G(s,\varphi)(1 + F(Du,\omega,\varphi)) \qquad (2)$$

where ε is the dielectric constant of pore fluids, ε_0 the dielectric constant of the vacuum, ρ_p the density of the particles, ρ_s the density of the dispersion, ρ_m the density of the medium, G is a function, Du the Dukhin number, ω the frequency and φ the volume fraction (*Dukhin and Goetz 2002*). The advantage of this technique is the ability of propagating ultrasound through samples that are not transparent for light and therefore this technique offers a unique opportunity to characterize concentrated dispersions (*Dohnalová et al. 2008*).

In figure 12 the variation of the ζ-potential for dispersions of Kaolinite and Na-Smectite with different ionic strength and pH is shown. It can be observed that for Na-Smectite, the ζ-potential is negative for the whole pH interval. It is essentially independent of pH. In contrast, the ζ-potential of Kaolinite becomes more negative with increasing pH. Increasing the ionic strength the values of ζ-potential become less negative. With a 1M electrolyte concentration for both materials, the ζ-potential is slightly positive (between 2 and 3 mV). Experimental results show that the ζ-potential is in general more negative at high pH, low ionic concentration and low ion valence (*Santamarina et al. 2002*). The increasing negative ζ-potential of Kaolinite in case of pH rise can be attributed to the deprotonation of the aluminol group on the edges of the Kaolinite, forming a complexed anion which contributes to the rise of the negative surface charge and subsequently to an increase of the repulsive forces among particles. The different electrokinetic behaviour of the tested clays results from the fact that Kaolinite has OH^- termination sites on the gibbsite face as well as on the edges, while Smectite has OH^- sites only on the edges which play a negligible role in determining the electrokinetic parameters (dominated by the constant negative charge of faces) of Smectites (*Benna et al. 1999*). Others have found that the ζ-potential of Smectite, though relatively constant at - 30 mV between 10^{-5} and 10^{-2} M, did fluctuate up to 10 mV with changes in the

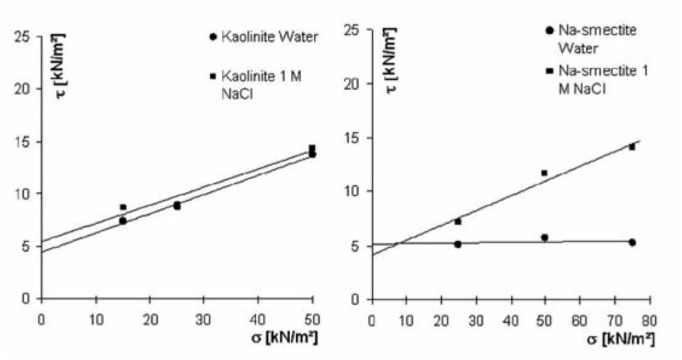


Figure 13: Modified shear test on Kaolinite (left) and Na-Smectite (right) for water and 1 M NaCl (after *Spagnoli et al.* 2010c)

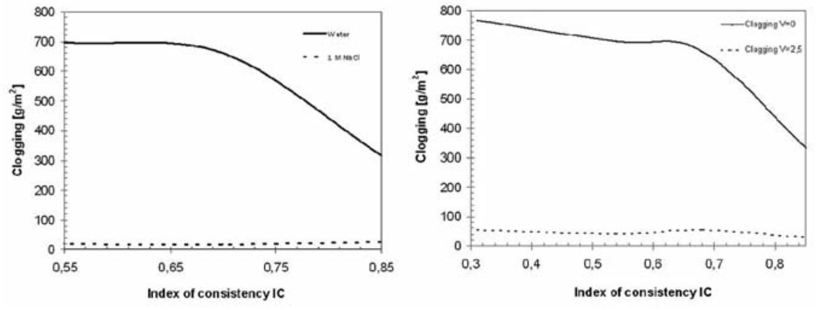


Figure 14: Variation of the clogging for Na-Smectite mixed with water or 1 mol/l NaCl (left) and with additional application of an electrical field (right)

concentration of indifferent electrolyte (*Hunter 1981*). As only 5% of the negative charge of the 2:1 clay minerals is controlled by the pH value, whereas 50% or more of the surface charge of 1:1 minerals are controlled by the pH value (*Das 2008*), it can be stated, that the ζ-potential of swellable clays is less sensitive to pH variations than that of 1:1 minerals. Regarding the positive values of the ζ- potential for 1M NaCl, we are not sure whether this is due to the rapid sedimentation in the measuring chamber or due to the higher ionic strength.

4.3. Variation of the clogging of clays

Several modified direct shear tests were performed for Kaolinite and Na-Smectite mixed with water and 1 M NaCl to reach a consistency of 0.5. The sample was gently places at a metal surface, loaded with very low pressure (15-75 kPa) for 10 minutes and then sheared with a shear rate of 0.5 mm/min. With this test the shear resistance of the interface between clay and metal may be described by the Coulomb criterion. It has two components: the adhesion (resistance at zero normal stress and a frictional component (adhesive friction; described by the angle δ). In this case, the adhesive shear strength of clay on metal is less than the applied shear stress and also less than the internal shear strength of the clay (*Kooistra et al. 1998*). *Spagnoli et al.* (2010c) described the strong variation of adhesive shear strength for Na-Smectite for different pore fluids while for Kaolinite no variation occurred. It is interesting that for Na-Smectite with water as pore fluid, the shear resistance is independent of the normal stress. The results (fig. 13) show for Na-Smectite a slight decrease of adhesion strength but a general increase in internal shear strength. From a pure mechanical point of view, clogging occurs during modified shear tests if:

$$\sigma_n < \frac{a-c}{\tan\varphi - \tan\delta} \qquad (3)$$

It is theoretically possible to predict if sticking will occur when the adhesion (a), the cohesion (c), the adhesive friction angle (δ), the internal friction angle (φ) and the normal

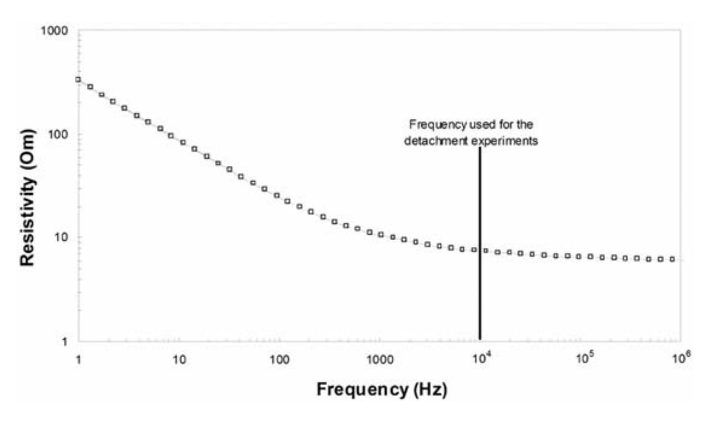


Figure 15: Resistivity of the electrode-soil system versus frequency obtained by IS measurements for Smectite

stress (σ_n) are known.

Starting from the assumption stated by the DDL theory the clogging of Na-Smectite mixed with water and 1 mol/l NaCl, adjusted to different consistencies (0.55, 0.65, 0.7, and 0.85) was investigated using the cone-pull out test. Figure 14 (left) shows that the clay mixed with the 1 mol/l NaCl fluid does not stick any more to the cone. In fact, the increased internal shear strength of the clay due to the mixing with a fluid with higher electrolyte concentration, leads to a general drop of the stickiness of the material.

Geotechnical engineers have investigated and applied electroosmosis to consolidate and strengthen clayey soils and mine tailings since the 1940s (*Casagrande 1947*). Other successful field applications of electroosmotic consolidation included *Bjerrum et al.* (1967) and *Lo et al.* (1991). *Davis and Poulos* (1980) studied the use of electroosmosis to aid pile driving in clayey soil. However, electroosmosis could also be used to reduce the clogging of the material. Therefore, experiments with the cone pull-out test were performed. The procedure is the same as explained before. In this case the cone was used as cathode while the proctor pot was the anode. A potential of 2.5 V was used in all tests by applying DC for 10 minutes. After this time the cone was pulled out. Fig. 14 (right) shows the results.

The drop in clogging for both clays is clearly visible. By applying an electric charge to the steel parts, water can be transported through the clay by electroosmosis to the interface between the clay and the steel. This creates a film of water at the clay-steel interface and therefore reduces the adherence. However, the use of DC could be a disadvantage. Extended electrical laboratory investigation was performed by using AC. Not only current intensity but also water flow depend on the electric impedance of the electrode-soil system (ERS impedance), i. e., the current intensity depends on the soil resistivity and on the electrode-soil contact (ERC) impedance. It has been shown that for DC measurements the contact impedance is often crucial for the system impedance whereas for high frequencies (e. g. 10 kHz) the influence of the contact impedance is of minor importance. Electrical impedance spectroscopy (IS) measurements were carried out (two electrodes) to study the properties of the electrode-soil system (ERS) and especially the influence of the contact impedance on the ERS impedance. IS measurements on clay samples were performed in the frequency range from 1 Hz to 1 MHz using the IAI impedance analyzer PSM1735. Fig. 15 shows that AC signals are more effective in reducing adherence than DC signals due to the lower resistivity. Therefore, with AC generally lower field strengths are needed to reduce the adherence time.

However, application of electroosmosis during operational tunnel heading could lead to problems in the tunneling practice. By applying a negative charge to the steel surface of the

TBM, this steel surface is protected from corrosion. However the anode will corrode faster compared to an uncharged surface. The anode will not only wear out faster; a rusted anode will also have a lower conductivity and as a result the amount of water transported by electroosmosis will be lower. Furthermore, the voltages used to generate an electroosmotic flow will electrolyze the water. Therefore hydrogen and oxygen gas will develop due to the following half reactions for water electrolysis:
at the anode: $2H_2O - 4e^- \rightarrow O_2\,(g) + 4H^+$
at the cathode: $2H_2O + 2e^- \rightarrow H_2\,(g) + 2OH^-$

The oxygen developed at the anode will probably not cause problems. However the hydrogen gas is flammable, and if mixed with oxygen at the right concentration it can explode. When an electric current passes through a clay specimen, the clay is heated and the temperature will rise. As the specific resistance of clay is many times larger than that of steel, the heat development in the clay is many times larger than in the steel electrodes. Also the influence of the electrical current and magnetic fields on computers and electrical machines inside the TBM is difficult to predict.

5. Clogging test system

To transfer and prove the results of the new standardized adhesion laboratory test and to verify new manipulation techniques, a Clogging Test System (CloggTS) will be developed. It is designed to support the geotechnical cohesice soft ground evaluation and conditioning related to clogging affinity in early project phases. The test also aims at coming closer to some geological-geotechnical aspects and to the reality of TBM layout with respect to material excavation and conveying processes in EPB-TBM. Some major demands on the test procedure are:

- To construct a robust, effective and economic clogging test system adapted to multiple use.
- To log those operational TBM data relevant for detecting clogging. Among those are visual notes, advance rate, face contact force of the cutting tool, torque of cutting and conveying tools, cutting tool revolution (rpm), temperature, and if so, the amount of additives given into the system. It is planned to vary operational data during testing.
- To avoid or control unwanted processes and other effects on operational data. Among these are face support managing (including material conditioning, excavation mode variation), not well documented geological changes and TBM technical adaptations. Empirically, these effects may complicate the assessment of the clogging affinity of the subsoil in TBM drives.
- To enable a systematic and complex investigation of clogging and soft ground material conditioning. This includes the detection of index properties and other characteristics of the ground and additives. Besides classical parameters also parameters relevant to clogging like ground water saturation, slake durability, adhesion stress, ζ-potential, clay mineralogy, void ratio, swelling potential or cation exchange capacity (CEC) are involved.
- To test geomaterial samples taken undisturbed if possible. High quality samples (bore cores) are preferred. By this, further geological/geotechnical ground characteristics that may be of importance for the adhesion/clogging propensity can be involved. Among those are low-scale geological interbedding and fissuring (e. g. fissured clays), ground water saturation, anisotropic ground properties and mixed tunnel face conditions.
- A complex approach with well defined testing conditions may contribute to a better understanding of the sometimes puzzling situation with respect to stickiness of soft ground materials.
- To assess the transferability of medium-scale test results to TBM projects.
- To evaluate the efficiency and applicability of chemical or physical conditioning (clay surface manipulation) of soft ground materials regarding technical, operational and environmental aspects as well as the reuse of the excavated material.

The clogging test ground samples in bore cores (diameter approx. 100mm, length approx. 0.5

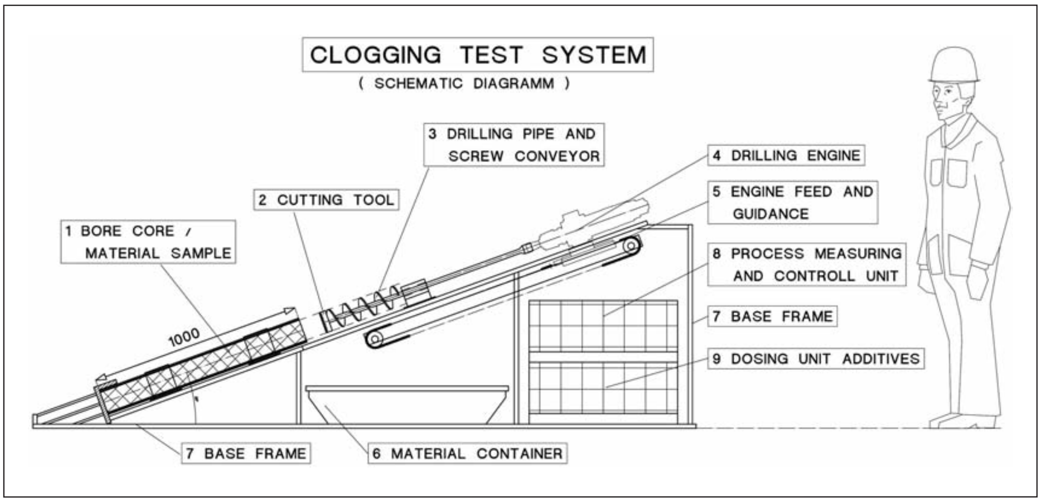


Figure 16: Clogging test system (prototype)

- 1.0 m) are cut using open steel cutting tools. The opening ratio and the design of these tools will be varied. Driving and rotation of the cutting tool assembled on a drill pipe is realized by a linear rotary drive on a guidance. The bore cores to be cut are fixed to prevent them from sliding and extruding. The material transport is realized with a screw conveying system which is affixed to a drill pipe. The test system is inclined as for the screw conveyor position in EPB drives. A simplified plan of the clogging testing system is shown in figure 16.

The process measuring and control units are used to set and vary testing parameters. Advance rate, face contact force and possibly revolution of the cutting wheel are planned to be varied during tests. These parameters shall simulate a range of operational data typical for TBM drives in clays, clay soils and clayey soft rocks.

For a conditioning the of material an adapted dosage unit is used. Water, electrolyte solutions, slurries or foam can be added to the system in front or behind the cutting tool using a channel inside the drill pipe. For possible electrokinetic tests the cutting tool could be used as cathode. For foam conditioning an adapted foam generator can be used.

6. Summary

In the joint research project InProTunnel the problem of clogging during EPB tunnel driving in fine grained soil or rock is investigated on different scales.

From the analyses of project data, amongst others based on a SQL database, some factors of prime importance for the occurrence of clogging problems were determined. In addition to the evident parameters (clay) mineralogy and particle size of the excavated material, in particular the significant influence of the water content and/or water inflow and the resulting (change of) consistency of the material could be identified.

With the cone pull-out test a practical laboratory test to investigate different soils with respect to their clogging behaviour could be designed and put into practice. Based on the newly defined parameter »adherence« a draft for a classification scheme for the clogging potential has been developed. Anyhow, the new tests still needs to be verified by the EPB tunnelling praxis.

In the context of a comprehensive examination of the chemomechanical coupling of clays the influence of different pore fluids and their impact on the mechanical behaviour has been investigated. Shear tests and cone pull-out tests show the effectiveness of modified electrolyte concentrations as well as the application of an electric charge to the steel parts with respect to a reduction of the adhesion.

Finally, the different factors affecting the clogging propensity, that have been identified so far, will be studied in a TBM-like medium-scale test. The respective test setup is currently in the concept state.

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