

Separation testing for clogging risk evaluation: Influencing factors and critical analysis of the test method

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ABSTRACT: Clogging is a common phenomenon in challenging ground conditions where tunnel excavation using tunnel boring machines encounters fine-grained soil that exhibits adhesive behaviour on metal surfaces. Various laboratory tests and empirically determined methods exist to quantify the risk beforehand during the ground investigation, which aim to measure or evaluate the clogging potential of the encountered soil. The most common methods include estimating clogging risk based on the Atterberg limits, the RUB-Queens Clay Adhesion Tool (ATUR) test and its predecessors, the cone pull-out test, and the plate separation test. This paper aims to identify crucial factors that influence the results of the plate separation test. First, all the procedures mentioned above for clogging risk evaluation are explained to facilitate comparison of the methods. The results of 72 separation tests on reconstituted illite are then presented. We developed a factorial design for this study, varying the consistency of the clay (controlled by preloading stress), the loading or contact time, the loading stress-to-preloading stress ratio, and the separation speed. Excellent reproducibility is achieved using the described vacuum mixing of clay powder followed by consolidation. Moreover, it becomes evident that all stated test parameters significantly influence the measured separation resistance, often referred to as adhesion. The results derived from plate separation tests must be obtained under identical conditions to compare different soils. Only when the same testing procedure and sample preparation method are employed can the results be considered comparable. A longer contact time is recommended if the test method proves insightful. Separation resistance alone should not be used to assess the risk of clogging. It is crucial to include other properties such as mineralogy, plasticity, and soil permeability in the engineer's qualified assessment. Other, more established methods for clogging risk evaluation should be given preference.

1 INTRODUCTION

Clogging due to the stickiness of the excavated soil remains poorly understood and challenging to characterise in mechanical tunnelling. It significantly reduces the advance rate of the tunnel boring machine (TBM), leading to costly delays. To quantify the clogging risk beforehand, several methods are available. One of these is the plate separation test, which is the focus of the present work. Other established methods, namely the Hollmann-Thewes diagram based on Atterberg limits and current water content of the tested soil, the cone pullout test, and the ATUR test, are briefly described to enable the reader to gain an understanding of the physical phenomena that each of these tests examines and the measured quantities obtained. All methods are contrasted, and the plate separation test is investigated in-depth by incorporating 72 tests performed on reconstituted illite, using a factorial design that varies several test parameters to capture the method's sensitivity.

2 METHODS FOR CLOGGING RISK EVALUATION

Within the scope of planning a tunnel construction project in Germany, the expert engineer is obliged to give his or her view on the “essential changes in the properties and in the condition of soil and rock during and after excavation, particularly in combination with air, water, support fluids or other conditioning agents” by the German standard called “German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV) – Underground construction work” (Deutsches Institut für Normung, 2019). This means that some sort of classification regarding clogging risks is required, as it is a crucial phenomenon that occurs during the excavation process and is strongly linked to the stated property changes. The excavated material can be either sticky in its undisturbed state or can be transformed into a sticky material by the excavation process and contact with any type of liquid. The following section provides a brief description of the four most prevalent methods for evaluating clogging risk in Germany. The German standard does not prescribe any test method, and it remains the engineer’s qualified decision which method to use.

2.1 Atterberg limits

The most common method for evaluating clogging risk is based on the Hollmann-Thewes diagram, as depicted in Figure 1 (Hollmann & Thewes, 2013). It is an empirical heuristic based on subjective observations made during tunnel construction work by the creators, linked to the plasticity characteristics of the material, which are characterised by the Atterberg limits included in every geotechnical report. Clogging risk evaluation based on Atterberg limits and mineralogy is also recommended by the German Tunnelling Committee (DAUB, 2025).

In the diagram, the clogging risk is indicated by the colouring. For EPB shields, a consistency index of 0.4 to 0.5 is typically recommended, ensuring the pressure-tightness of the screw conveyor and workability while reducing the risk of clogging (Schröer, 2023). By knowing the natural water content and Atterberg limits, the expert engineer can determine the required gravimetric water content for the desired consistency, and critical water contents can be easily identified and avoided. The method is well established and has the advantage of using parameters derived from remoulded material.

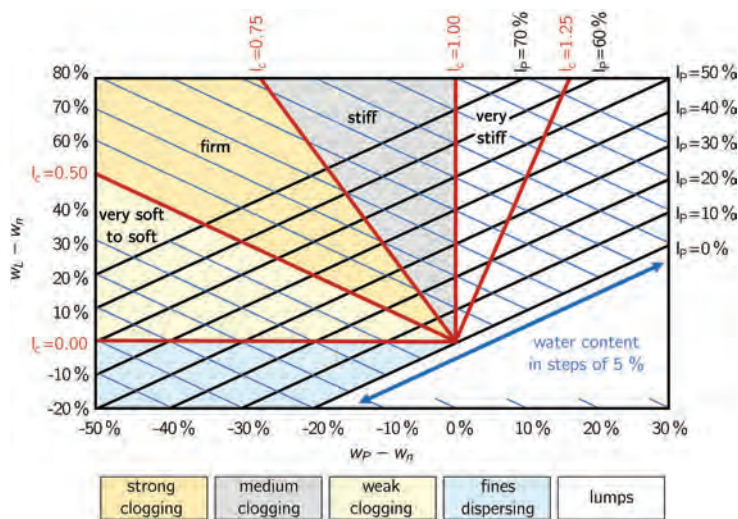


Figure 1. (Universal) classification diagram for evaluation of soil clogging, altered from Hollmann & Thewes (2013).

2.2 Cone pull-out test

The cone pull-out test has been a well-established test method in German-speaking Europe for over ten years (Feinendegen & Spagnoli, 2021). For the method, material from the project site is remoulded using an industrial meat grinder. By adding water, different consistencies (usually five with consistency indices equally spaced between 0.85 and 0.25) of the material are created and subsequently tested. Testing is performed using a metal cone with an opening angle of 58° and a diameter of 5 centimeters. The material is compacted in a metal cylinder with a diameter of 150mm and a height of 125 mm, in three layers, using 22 Proctor compac-

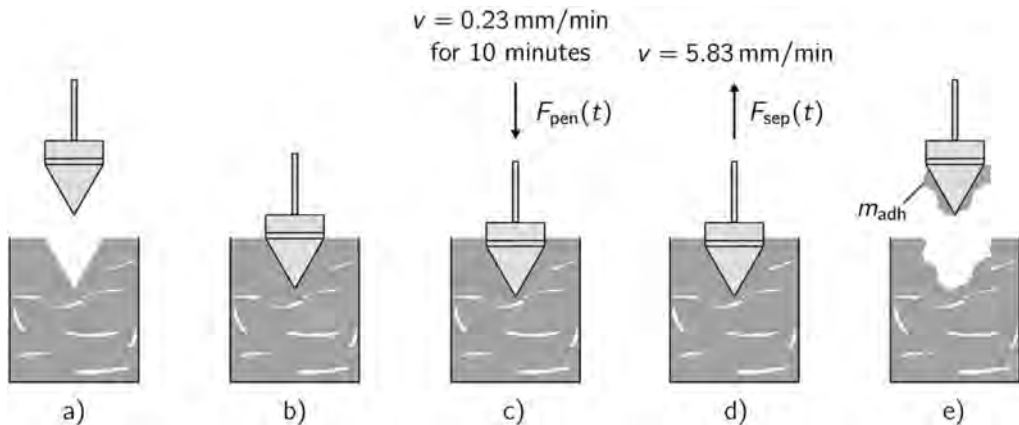


Figure 2. Simplified process description of the cone pullout test, modified from Feinendegen & Spagnoli (2021). The dimensions are not true to scale. The homogeneity of the sample can vary.

tion blows per layer, as per the German standard DIN 18127 (Deutsches Institut für Normung, 2012). Figure 2 displays the simplified testing procedure after sample preparation.

First, a conical deepening is cut into the proctor compacted material at a given consistency using a special cutter (a). Then, contact is established (b) before the loading phase (c) starts. After 10 minutes of penetration, the cone is pulled out of the sample at a given speed (d). At the end of the test, the adhering mass of material is measured (e). During loading, the penetration force, F_{pen} , and during separation, the separation force, F_{sep} , are measured but are typically not used for evaluation. The adhering mass m_{adh} is divided by the cone's surface, yielding adherence per unit area in the unit of g/m^2 . This quantity is determined and plotted over the five consistencies. The method assumes that high adherence per unit area is associated with a higher risk of clogging. Evaluating the curve enables the identification of critical consistency or water content ranges, similar to the method described previously.

Physically, the remoulded and consequently proctor compacted material fails in tension. This means the failure surface lies mainly within the soil, and the interface strength or stickiness along the cone is high enough to force failure within the adjacent soil body. The quality of the compaction highly influences the mass of adhering material. Poor compaction and large macropores can lead to high adhering masses.

2.3 ATUR test

The RUB-Queens Clay Adhesion Tool (ATUR) is a further development of the testing method proposed by Zumsteg & Puzrin (2012). Today, it is an established test method for evaluating clogging risk and assessing the effectiveness of soil conditioning, often in combination with the slump test or flow table test, both commonly used in concrete technology. Currently, a second improved version of the test is being developed (Burgtorf et al., 2025).

Zumsteg & Puzrin (2012) proposed using a commercial Hobart® mixer to mix soil and water or soil conditioner for three minutes at 100 rotations per minute (Figure 3(a)). After mixing, the adhering soil mass m_0 is measured (b) and then related to the original total soil mass m_{tot} . This stickiness ratio, also referred to as the empirical clogging parameter λ , is then used to evaluate the clogging risk or stickiness of the material at various consistencies in the remoulded state. De Oliveira (2018) added a dropping stage where the paddle drops onto a plate (c) at least seven times, each time losing more of the material (d) that was stuck to it after the mixing stage. For this, a metal frame is used, where the mixing paddle is placed into a traverse that slides along guidance rails. The top of the paddle is placed at 40 cm. The further development was made because, on the one hand, the original procedure without drops would yield unrealistically high values. On the other hand, it was realised that little kinetic energy could already remove all the adhering material at stage (b).

After mixing and after each drop, the mass of the adhering soil body is determined, and the clogging parameter is calculated. The final value is the average value, as stated by the formula in Figure 3, which is additionally corrected by the so-called cleaning bowl factor CB used to fit the data into the Hollmann-Thewes diagram described above. This subjective factor can have a value from one to three and can be determined following de Oliveira (2018). In practice, it is often not used, and the average factor is calculated without it.

In summary, the ATUR test measures stickiness, taking into account the impact of kinetic energy. The final value indicates how much the material adheres after mixing and how much it retains stickiness when exposed to impact. Failure can occur within the soil or at the soil-paddle interface, where interface shear strength primarily governs the behaviour. When soil adheres to the blade, the resulting failure consistently occurs within the soil matrix. This internal failure mechanism can be considered a key indicator and primary criterion for assessing stickiness-induced clogging. Sample preparation before mixing can significantly influence the result, as can the arbitrary determination of the cleaning bowl factor if applied.

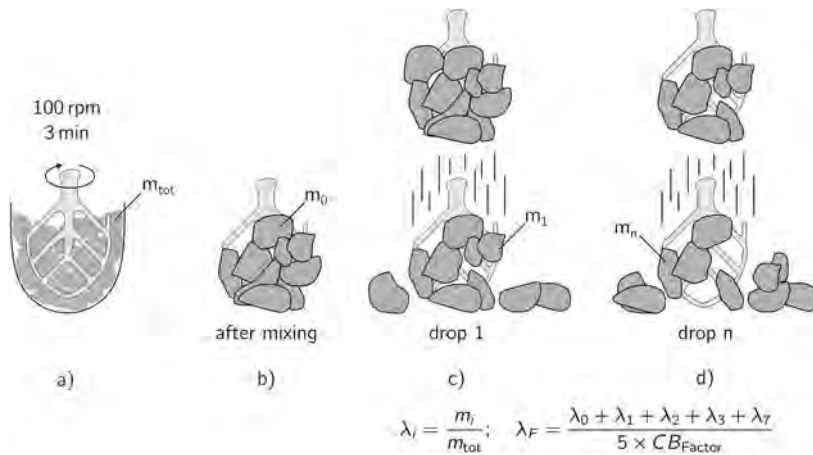


Figure 3. Simplified process description of the ATUR test, equations modified from de Oliveira (2018). The dimensions are not true to scale. In reality, there might be paste adhering to the paddle. Depicting lumps is chosen for illustrative purposes.

2.4 Plate separation test

The plate separation test was first employed by Thewes (1999). In this work, a plane metal piston with a diameter of 6.18 cm is used on a sample with a diameter of 10 cm and a height of six centimetres. A ring at the top holds the sample in place. The material is proctor compacted in five layers. Different consistencies are tested; the sample is loaded with 50 kPa for

a varied time and separated at 5 mm/min. Furthermore, the loading time varies, and the sample is wetted with different liquids for varying durations.

The test can be performed on undisturbed, reconstituted, or remoulded and consequently compacted samples. The sample surface can be wetted or kept dry. The simplified test process is depicted in Figure 4 without the ring on top of the sample. After force-controlled loading of the sample at a given stress (a), the plate is separated from the sample in a displacement-controlled manner at constant speed (b). During this separation, the force is measured at its peak, which is then used in subsequent evaluation. In contrast to the two tests mentioned earlier, this test is a stress-based evaluation that does not incorporate masses of adhering soil bodies.

Two superordinate failure modes are possible: the “adhesive failure” at the interface (c1), where there is no adhering soil on the plate, and the “cohesive failure” within the soil (c2), where adhering soil is present. In the latter, the soil fails in tension. Intermediate modes are possible, where the soil adheres only to some areas of the plate. Usually, only the peak separation stress is reported and calculated from the maximum force measured. In the event of failure at the interface, this yields the true normal interface strength, uplift capacity, or separation resistance. In case of failure within the soil, a sort of tensile strength is measured, which is projected to the plate surface, yielding a slight overestimation of it, as the true failure surface will be larger than the plate’s surface. In the case of “cohesive” failure, a lower bound of interface strength is measured, as the interface strength must be higher than the tensile strength to force failure within the sample. The test does not involve a shearing load.

Historically, higher test values have been associated with increased clogging risk. Budach et al. (2019) determined quantitative thresholds to categorise clogging risk based on separation resistance from the plate separation test. For this, they combined their own testing with selected results from Thewes (1999). The samples were wetted with water before loading, and the contact time

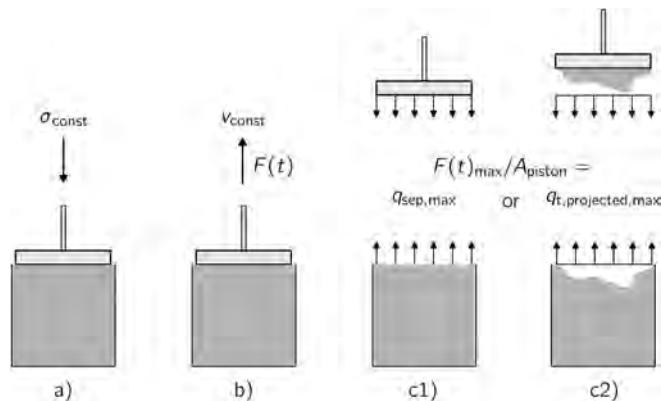


Figure 4. Simplified process description of the plate separation test. The dimensions are not true to scale. Reconstituted and therefore homogeneous material is displayed. Using proctor compaction for sample preparation will yield a homogeneity closer to that shown in Figure 2.

was 10 minutes, which was short. To determine thresholds, the data were inserted into the Thewes diagram (Thewes, 1999), which was empirically derived and is also illustrated in Hollmann & Thewes (2013) as a precursor to Figure 1. The assumption of high clogging risk was based solely on the Thewes diagram and was not verified in practice.

3 FACTORS INFLUENCING THE PLATE SEPARATION TEST RESULTS

Analysing the influential factors on the maximum separation resistance for a given soil, researchers have found that longer loading time (Zhang et al., 2021) and faster separation (Mei et al., 2025) lead to higher resistance. A specific range of consistency will yield a maximum value of resistance,

and less resistance in lower or higher consistencies. The influence of the plate's roughness is not evident (Burbaum, 2009). Most of the testing has been conducted on remoulded and compacted samples. Sample preparation by compaction of remoulded material has proven to be difficult (compare, e.g. Burbaum (2009)), resulting in a significant amount of scatter. Therefore, in this study, the gap is closed, and influential factors are investigated for reconstituted undisturbed samples which exhibit less scatter.

3.1 Material tested and factorial design

Within this study, a total of 72 separation tests were performed. A pronounced plastic illite (liquid limit of 63.6 % and plastic limit of 32.3 %) was chosen as a proxy material because it is one of the most prominent clay minerals in engineering practice. For sample preparation, the industrial dry clay powder was mixed under vacuum with tap water and subsequently consolidated at 50, 100, and 400 kPa, yielding average consistency indices of 0.21, 0.44, and 0.78, respectively. The test procedure follows Figure 4.

The samples have a diameter of 44.3 mm and a height of 20 mm. The smooth aluminium loading piston (surface roughness parameter R_z of 1.0226 μm) has a diameter of 37.9 mm. A retaining piece holds the sample in place and prevents it from pulling out. Thus, the inner sample diameter and the loading piston diameter are not equal. The retaining piece is not depicted in Figure 4.

Table 1. Test parameter levels of the 3×2^3 factorial design.

	Parameter	Low (-)	Intermediate	High (+)
A	Preconsolidation stress (kPa)	50	100	400
B	Loading ratio $\sigma/\sigma_{\text{pre}}(-)$	0.5		1.0
C	Contact time (min)	5		120
D	Separation speed (mm/min)	0.5		5.0

Table 1 shows the parameter variations for the applied factorial design. At each consistency, the loading ratio, contact time, and separation speed are varied for both low and high values. The specimens are tested in the overconsolidated range with a loading ratio of one. Each test is repeated three times. The sample preparation provides high reproducibility of sample weight, and therefore consistency, with coefficients of variation below one per cent. Further details of the sample preparation technique and the investigation of the plate's surface roughness can be found in Schröder et al. (2026a) and Schröder et al. (2026b).

3.2 Results

The results from the factorial design are shown in Figure 5. Each cube represents a consistency level, ranging from very soft (0.21) to soft (0.44) to stiff (0.78) from left to right. Within each cube, the three parameters vary along the three axes. The loading ratio increases along the x-axis, the loading time along the y-axis, and the separation speed along the z-axis. The peak separation resistance values are given on the corners in kPa as the arithmetic means of three individual tests. The colouring is on a logarithmic scale as the distribution is skewed. In the present study, all samples failed in the “adhesive” mode, indicating that the measured values represent the true separation resistance. No failures were observed within the homogeneous, fully saturated samples.

The following trends can be obtained from the plot. In the present study, higher preconsolidation pressure, resulting in stiffer consistency and lower permeability, leads to higher separation resistance. At a given consistency, loading at preconsolidation pressure (loading ratio equal to one) gives higher resistance than loading at half of the preconsolidation pressure. Increasing contact time and separation speed also lead to higher stresses needed to separate the clay and the piston. The stiffer the clay, the greater the changes are. Especially for a low loading ratio and short contact time, the differences are minimal (at the left edges of the bottoms of the cubes).

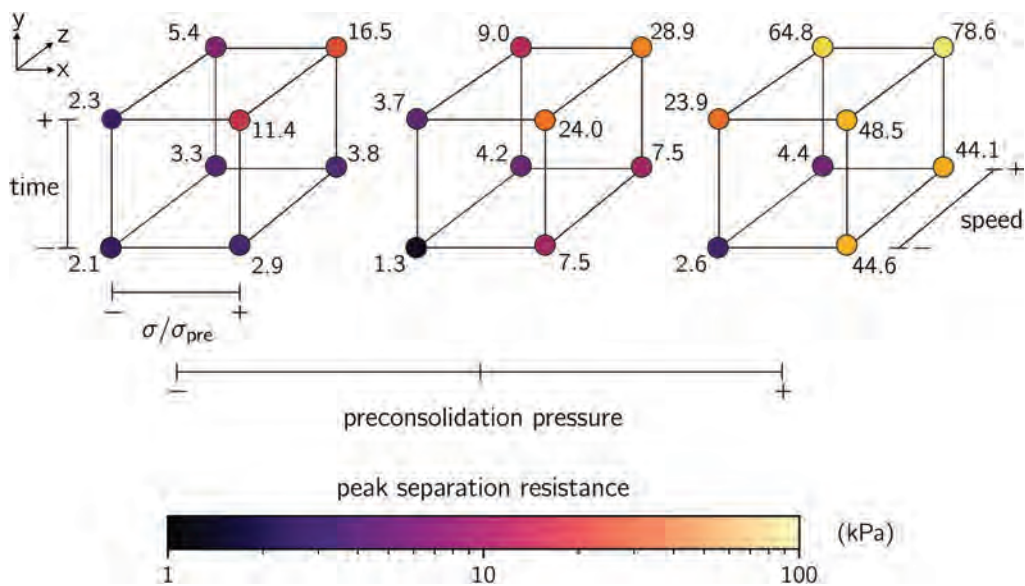


Figure 5. Graphical representation of the factorial design results. The values displayed are the arithmetic means of the peak separation resistance from three individual tests.

4 DISCUSSION

When conducting plate separation tests for clogging risk evaluation, the authors believe that reporting a single stress value and relating it to the clogging risk of the material is difficult. As described before, the plate separation test does not report adherence; it only reports maximum separation resistance, and this value does not reflect the failure mode. The importance of documenting failure modes is evident in the presented results. A stiff clay that requires very high stress for separation but fails primarily at the interface will likely yield lumps during the cutting process in practice, rather than leading to clogging. The lower the permeability, the greater the separation resistance during undrained separation, as negative pore pressures develop. It should be noted, however, that the data presented here were not obtained from remoulded material and that the samples were fully saturated. The overall governing trends, however, have been shown by other researchers and proven here.

Secondly, the testing parameters should be chosen carefully. Especially short contact times may not sufficiently reflect the influence of consistency. Therefore, longer contact times are recommended if the expert engineer considers the plate separation test insightful. Comparisons need to be performed under the same testing parameters. Special attention needs to be paid to sample preparation, as cavities inside the material can significantly influence failure modes.

The test method is not established in the industry, although, to the authors' knowledge, it has been applied in some expert reports in Germany. The correlation between all the clogging evaluation tests and procedures above remains pending. Sebastiani et al. (2025) compared the testing procedure from Zumsteg & Puzrin (2012) with plate separation tests. The plates used here were not plane but convex, and the testing procedure and sample preparation differed from those described above. However, within this study, a strong correlation was found between λ_0 and the maximum separation stress. More importantly, however, the critical consistencies of the supposed clogging risk were considerably different, and the highest separation resistance and related clogging risk were attributed to stiffer consistencies when using the plate separation instead of the mixing test.

5 CONCLUSION

In summary, the authors do not recommend the plate separation test for clogging risk assessment. If the test is deemed suitable by others, the contact time should be selected carefully,

and reporting a single value without a description of the failure mode may be misleading. If the threshold values for clogging risk in separation stress are derived from the Thewes diagram, the plate separation test provides no added value beyond the Thewes diagram. Moreover, these thresholds must be selected carefully, as they vary substantially across test parameters. Plasticity, mineralogy, and permeability are functional soil characteristics. Expert engineers are encouraged to combine these with more established clogging-risk evaluation techniques or with soil-conditioning tests of their choice. Ideally, these tests include shear loading and mixing.

ACKNOWLEDGEMENTS

This work is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 51685914. We gratefully acknowledge this support. We would also like to thank the members of Expert Group 1.11, “Wear and clogging”, of the German Geotechnical Society for the fruitful discussions on this matter, especially Tim Babendererde, Martin Feinendegen, and Lars Langmaack.

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