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Analysis of laboratory tests for the determination of the clogging risk in mechanized tunnel excavation in fine-grained soils

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ABSTRACT: Clogging is one of the main problems encountered in mechanized tunnelling with EPB-TBM in fine-grained soils. This issue is usually addressed by soil conditioning, i.e. the addition of water, foam and other chemical agents during the excavation phase. Over the last two decades, encouraged by the exponential increase of tunnels excavated with EPB-TBMs, many research studies have been carried out, leading to the development of several laboratory tests and classification systems to assess the risk of clogging in fine-grained soils and the effect of conditioning. Nonetheless, due to the complexity of the phenomenon, a number of limitations remain in defining and predicting potential clogging. This also emphasizes the lack of appropriate and widely accepted test standards and the inconsistencies of the classification systems. This paper is part of a larger experimental study on clogging carried out over the last 4 years on more than 20 natural fine-grained soils sampled from real EPB-TBM tunnel projects and subjected to a series of tests aimed at determining the clogging potential. The results of the laboratory tests were systematically compared, highlighting the advantages and limitations of each test and exploring the correlations between them. The results of this investigation, also in light of the great number of tests performed on a wide range of natural soils, can be of assistance in making informed use of the existing laboratory tests and clogging risk classification systems.

Keywords: Clogging, Laboratory testing, Fine-grained soil, Conditioning, Classification

1 INTRODUCTION

Clogging is one of the most critical issues in the excavation of tunnels with Tunnel Boring Machines (TBMs) in fine-grained soils. The phenomenon of clogging is essentially due to the so-called adhering and cohering; the former refers to the forces exchanged between soil particles and metal components of the TBM cutterhead, the latter to the forces exchanged between soil particles (Thewes and Burger, 2005). The occurrence of clogging leads to the increase in torque and consumption and, in extreme cases, to the blockage of the cutterhead.

When excavating with TBMs equipped with Earth Pressure Balance technology, it should also be considered that it is necessary to modify the characteristics of the excavated soil in order to make it suitable for transmitting a stabilization pressure to the excavation face.

This is done by conditioning the soil, that is the addition of water, foam and possibly other additives such as polymers or others. Conditioning, from physical, chemical and mechanical points of view has a number of effects on the excavated soil, mainly summarized as: (1) change in water content and consequently in consistency index; (2) change in the degree of saturation by injection of foam composed mainly of air; (3) chemical modification of the soil with more or less noticeable and lasting effects depending on the chemical composition and dosage of the conditioning agents injected.

For the purposes of this publication, it is important to consider that the conditioning process, in addition to chemically modifying the soil, changes its water

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content and, consequently, its consistency in a range which is generally considered between the 0.4 and 0.6 (Feinendegen et al, 2010; Hollmann and Thewes, 2013). From this point of view, therefore, it is of particular interest to know the evolution of the clogging phenomenon as the consistency index changes.

The study of clogging should start from the analysis of the characteristics of the soil to be excavated, as the correlation of this phenomenon with certain characteristics, such as the percentage of clay and the plasticity of the soil, is rather well known. Indeed, there are different abacuses and classification schemes in the literature (Thewes and Burger, 2004; Hollmann and Thewes, 2013; Fang et al., 2023) that are quite useful in understanding the "potential clogging" of certain formations based on the analysis of their grain size distribution and Atterberg limits.

To investigate the phenomenon, several tests have been proposed over time, starting with the Hobart mixing test, in the original and later integrated and modified versions (Zumsteg and Puzrin, 2012; de Oliveira et al., 2019), and the pull-out test in flat, conical, and convex versions to assess the clogging potential (Feinendegen et al, 2010; Di Giulio et al., 2018; Spagnoli et al., 2019; Khabbazi et al., 2019). The study of clogging is constantly evolving and new tests and models are proposed annually in an attempt to refine the predictive capabilities of this phenomenon (Chen et al., 2022; Fang et al., 2023).

Each of these tests and models, however, has its advantages and limitations and it is only able to provide a partial view of the problem; therefore, conducting multiple tests and evaluations in parallel can be an effective methodology in order to achieve the broadest and most complete picture possible. Nonetheless, universally accepted procedures for the evaluation of a soil's clogging potential are still lacking.

To fill this gap, an experimental research project has been underway for several years, systematically testing a large number of natural fine-grained soils. The first results of this research project were initially published in Sebastiani et al. (2024), where the results of mixing and pull-out tests were compared, highlighting strengths and weaknesses, and also finding useful correlations between the results of the two tests and between the test results and the clay fraction.

This paper builds on the initial findings by extending the investigation to soils with higher clay content and higher plasticity. The results presented herein also allow to further test the validity of the previous findings against a larger data set.

Testing is currently continuing on an even larger scale and on a wider range of natural soils. Several conditioning agents are also being tested.

2 MATERIALS AND METHODS

As mentioned above, this study builds on the findings reported by Sebastiani et al. (2024) by extending the experimental research to soils with higher clay content and higher plasticity. Samples S9, S10 and S11 were carefully collected at the tunnel excavation depth at three different jobsites and characterized to determine their intrinsic properties.

2.1 *Soil samples*

Table 1 and Table 2 list the grain size distributions and the Atterberg limits of the soil samples determined according to ASTM D6913, ASTM D4318 and AGI Recommendations. *LL* and *PL* represent respectively the liquid and the plastic limit, *PI* the plasticity index and *A* the activity of the clay.

Along with the samples used in this study, the properties of the samples used by Sebastiani et al. (2024), samples S1 to S8, are reported for convenience.

2.2 *Laboratory tests*

The samples were tested to measure their clogging potential (Hobart mixing test and pull-out test). Prior to laboratory testing, the samples were completely dried, quartered and then brought to the desired water content. The tests methods are briefly described below.

2.2.1 *Hobart mixing test*

The Hobart mortar mixer (Figure 1) for soil conditioning testing, described by Zumsteg and Puzrin (2012), is often used to produce a homogeneous clay-chemical paste.

To quantify the clogging potential of soft clayey mixtures, the weight of soil sticking to the mixing tool after mixture preparation can be weighted; the clogging potential increases as this weight increases.

The stickiness ratio λ, which quantifies the tendency of the soil paste to remain stuck on a mixing tool, is defined as:

$$\lambda = G_{MT}/G_{TOT} \tag{1}$$

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

Table 1. Grain size distribution of the soil samples.

Sample	Clay %	Silt %	Sand %
S9	45	42	13
S10	50	38	12
S11	47	51	2
S1	40	60	0
S2	37	43	20
S3	50	42	8
S4	28	52	20
S5	12	38	50
S6	35	65	0
S7	24	51	25
S8	30	58	12

Table 2. Atterberg limits of the soil samples.

Sample	LL %	PL %	PI %	A
S9	57	17	40	0.88
S10	94	33	60	1.21
S11	62	26	37	0.78
S1	40	20	20	0.50
S2	36	21	15	0.41
S3	65	25	40	0.80
S4	48	24	24	0.86
S5	27	19	8	0.67
S6	46	22	24	0.69
S7	35	20	15	0.63
S8	48	19	29	0.97

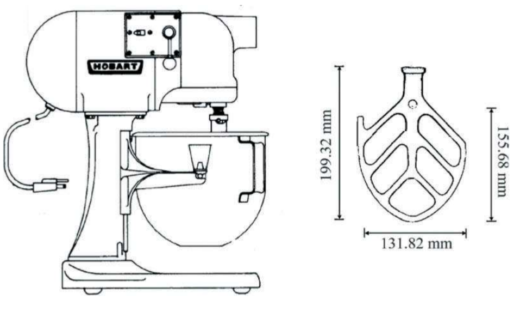

Figure 1. Hobart mixing test equipment.

2.2.2 *Pull-out test*

The pull-out test, in its many variations, is a widely used system for indirectly assessing the clogging potential by measuring the pull-out force registered by a tool first placed in contact with the sample. Different authors, following different approaches, have used this test to measure both the clogging tendency of a soil and the beneficial effects of soil conditioning (Feinendegen et al, 2010; Di Giulio et al., 2018; Khabbazi et al., 2019).

The most common versions of the test are those proposed by Feinendegen et al. (2010), using a conical tool, and by Thewes and Burger (2005), using a flat plate. In this study, the modified version described in Sebastiani et al. (2024) was adopted, essentially applying the same test methods but with a slightly convex plate (Figure 2).

3 RESULTS

In this section, the results of the laboratory tests will be presented and discussed; particular focus will be placed on correlating the results obtained with the water content and I_C value of the soil samples tested.

The following Figures 3, 4 and 5 show the results of the Hobart mixing tests performed on soil samples S9, S10 and S11 at different water contents w (and hence consistency index Ic). The results are interpolated by a Gaussian curve as a function of Ic. The results are well fitted by Gaussian curves for all

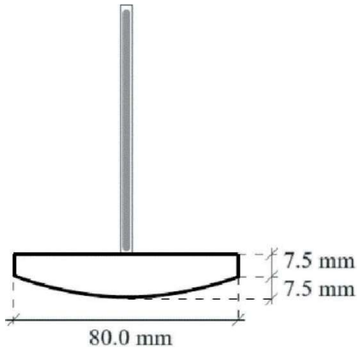

Figure 2. Detail of the pull-out test plate.

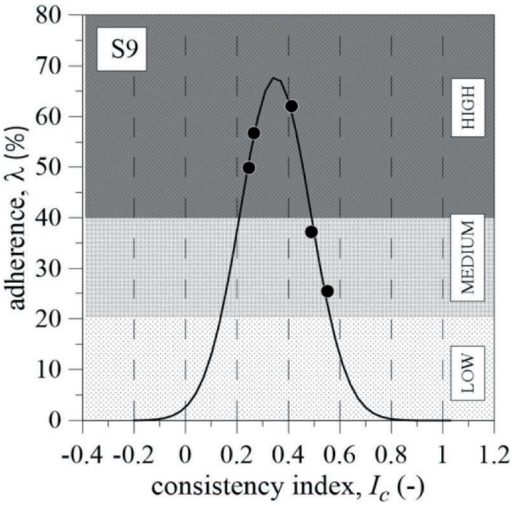

Figure 3. Hobart mixing test results for soil S9.

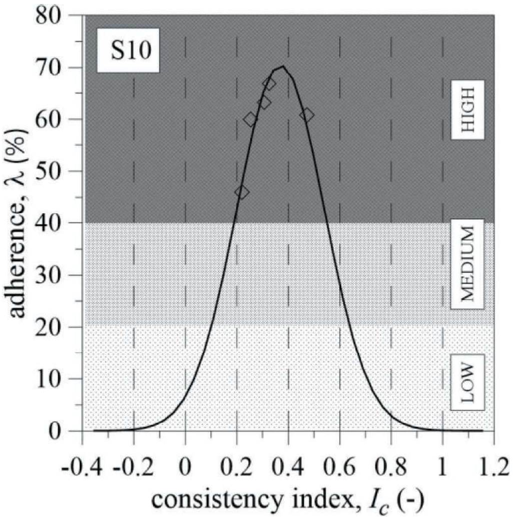

Figure 4. Hobart mixing test results for soil S10.

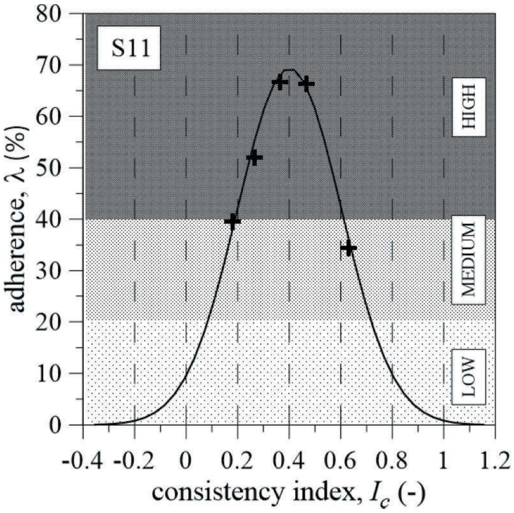

Figure 5. Hobart mixing test results for soil S11.

three soils studied. It should be noted that at high values of I_C there are some difficulties in performing the mixing test, which lead to consider the branch of the curve associated with lower values of *Ic* more reliable (de Oliveira et al. 2019).

Figures 6, 7 and 8 show the results of the pull-out tests carried out on soil samples S9, S10 and S11 at different water contents. Again, the results are well interpolated with a Gaussian curve. It can be noted that these results are substantially in agreement with those of the mixing test in terms of consistency index, with the peak values slightly shifted towards higher values of *Ic*.

Finally, Figures 9 and 10 compare the results of this study with those obtained by Sebastiani et al (2024) in terms of mixing tests and pull-out test results respectively.

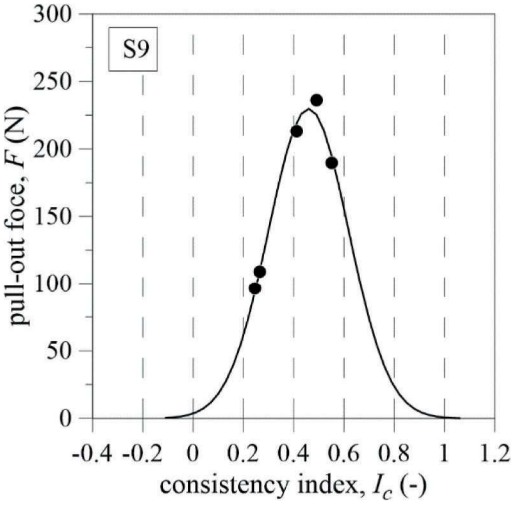

Figure 6. Pull-out test results for soil S9.

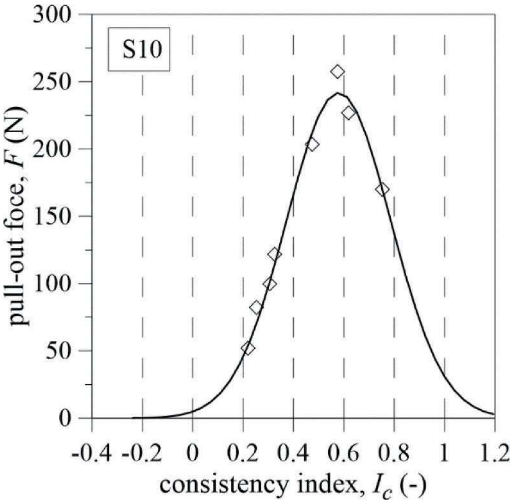

Figure 7. Pull-out test results for soil S10.

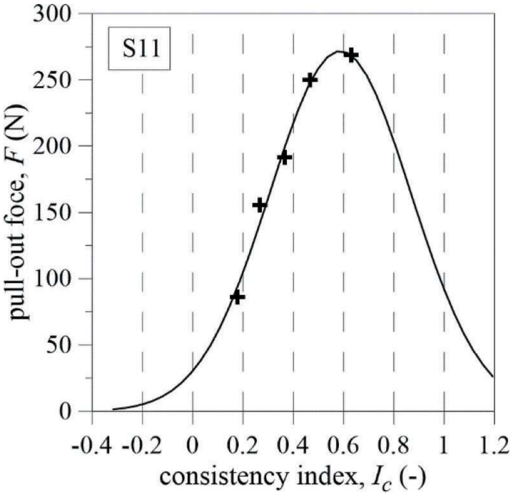

Figure 8. Pull-out test results for soil S11.

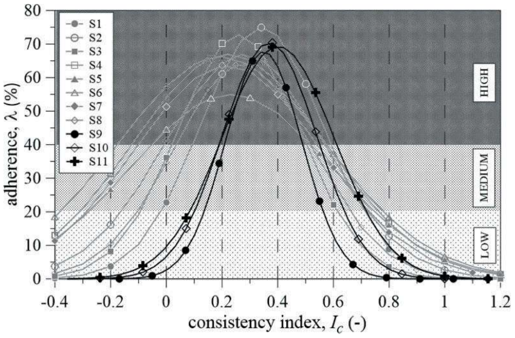

Figure 9. Comparison of the mixing tests results.

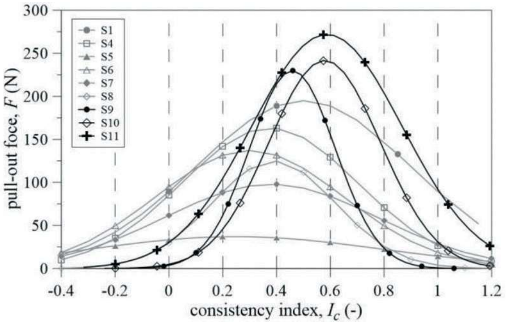

Figure 10. Comparison of the pull-out tests results.

By comparing the results obtained through the mixing tests performed on all the investigated clays, it can be noted that, although the more clayey and plastic soils (i.e. higher *CF* and *PI*) have a slightly shifted peak toward higher consistency indices, there are no remarkable differences in terms of maximum stickiness ratio. Instead, the Gaussian curves obtained through the pull-out tests highlight that as the clay fraction and plasticity increase, the peaks of the curves increase and are slightly shifted toward higher Ic values (lower water content). This results further confirm the effectiveness of the pull-out test in measuring the clogging potential, as it is well known that the clogging risk increases with the clay fraction and the soil plasticity.

4 CORRELATIONS WITH CLAY FRACTION AND BETWEEN TESTS

As said, this study aims to extend the results reported by Sebastiani et al. (2024) to soils with higher clay fraction and plasticity, and also to test the validity of the correlations found in the above study by adding new results to the data set.

The following Figures 11, 12 and 13 show the correlation between the values of peak adherence λ_{pk} and pull-out force F_{pk} estimated through the Gaussian parameters and clay fraction *CF*, overlaid on the interpolation proposed by Sebastiani et al. (2024).

The results show that the correlations remain valid also in light of the new data, accounting for some dispersion of the experimental data. The behaviour shown by the new soils strengthens the experimental bases on which the correlations are based and extend it to fields (i.e. F_{pk} > 200 N) that previously could not be reached.

The new pull-out results are in better agreement with the correlations than the mixing tests ones. Pending further investigation, this suggests that the pull-out test is more versatile and more effective in providing a measure of the clogging potential of soils with higher clay content and higher plasticity index.

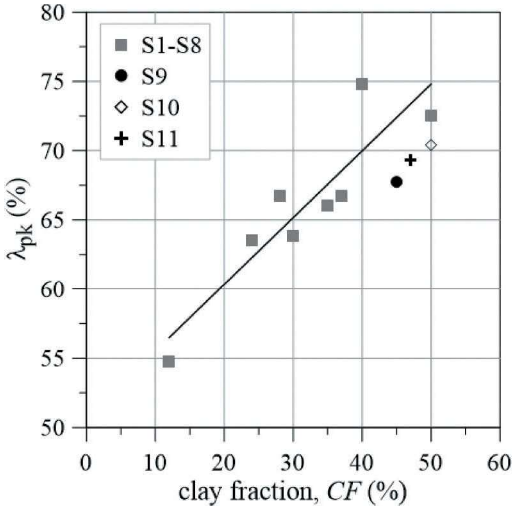

Figure 11. Correlation between estimated mixing peak values and clay fraction.

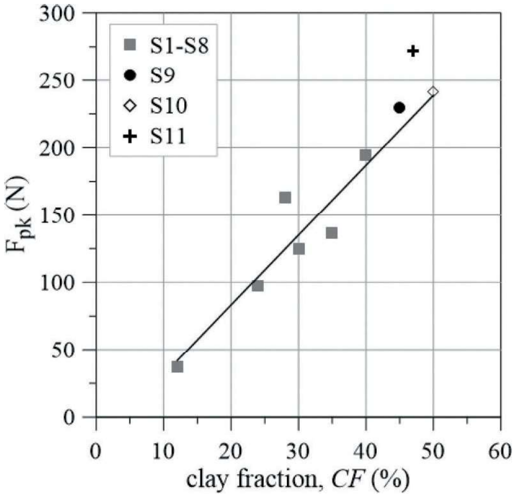

Figure 12. Correlation between estimated pull-out peak values and clay fraction.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper is part of a larger study focused on the determination of the clogging potential of natural soils through laboratory tests. The research activity carried out, now for several years, has been based on a few basic fundamentals: 1) performing laboratory tests on natural soils from real tunnels and underground works projects; 2) correlating the results of laboratory tests performed to measure the clogging risk to a strong and comprehensive geotechnical characterization and 3) developing laboratory tests in parallel to investigate their limitations and reliability, to compare results and provide useful correlations.

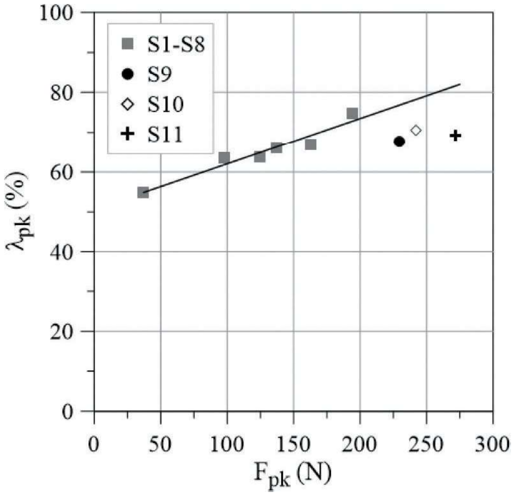

Figure 13. Correlation between estimated mixing and pull-out peak values.

The experimental activity described in this paper aimed to extend the findings of Sebastiani et al. (2024) to soils with higher clay content and plasticity and to test the validity of the proposed correlations in light of the new data.

The new data confirm that:

- gaussian curves well describe the mixing and pull-out results with respect to water content and consistency index;
- the peak of the gaussian curves resulting from the pull-out tests is slightly shifted towards higher values of consistency index than that provided by the mixing tests;
- the pull-out tests shows a greater sensitivity in measuring the clogging potential as its results amplify the differences between various soils.

The results also allowed to:

- the correlation between mixing test results and clay fraction seems to be weaker than that with the pull-out test results;
- extend the validity range of these correlations for F_{pk} values above 200 N;
- find that as the clay fraction of the soil and plasticity increase, the peaks of the curves increase and are slightly shifted toward higher values of consistency index (lower water content)
- observe that the pull-out test is more effective in detecting the increase in clogging potential associated with higher clay content and plasticity index.

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