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Factors influencing the adhesive strength of reconstituted illite in separation testing in the overconsolidated range

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ABSTRACT: The separation resistance, also known as adhesive strength, has been widely studied in geotechnical engineering. Typical applications range from lifting objects from the sea floor to characterising clogging potential in mechanised tunnelling. Despite the critical importance of understanding this phenomenon, specific factors influencing this adhesion remain incompletely understood. Illite, the most prominent clay mineral in ground engineering, was chosen as the test material within this study. Samples were prepared by mixing a slurry under a vacuum and subsequent consolidation, ensuring nearly identical, high-quality specimens with full saturation after additional sample saturation in a water bath. This preparation method allowed for optimal reproducibility and consistent testing conditions. The study examined the impact of various parameters on adhesive strength, including pre-consolidation stress, stress applied prior to separation, contact time, piston roughness, and separation speed. Both high and low values were tested for each factor, and each condition was repeated three times to ensure statistical reliability. The results showed that all the tested parameters significantly influence the adhesive strength of illite, except for surface roughness. Here, the response depends on the level of the other factors. The findings offer crucial insights into the factors that govern the adhesion of clay to metal. They form the foundation for developing a numerical model that incorporates adhesive strength. Future work will involve measuring suction at the clay-metal interface and utilising computed tomography to investigate the phenomena that contribute to adhesive strength in-depth.

KEYWORDS: Illite, stickiness, separation resistance, adhesion

1 INTRODUCTION

Separating an object from soil in the opposite direction as it was loaded is a problem related to different problems in geotechnical engineering. To date, two significant areas where this problem has been studied need to be separated. First, in offshore geotechnics, the lifting or extraction of objects from the sea floor has been studied extensively. In this framework, the terms often used to describe the separation are referred to as ‘footing uplift capacity’ or ‘breakout force’. Studies in this field are frequently centrifuge tests of reconstituted material under water or field tests in the ocean. It has been found that uplift resistance increases with separation speed (Mei et al., 2025) and with longer contact time at the same contact pressure (Zhang et al., 2021).

The second area is tunnelling, where the plate separation test was proposed as a laboratory test to evaluate ‘adhesion’ or ‘stickiness’, which could finally lead to the clogging potential of the soil (Thewes, 1999). Most studies in this area have been performed on remoulded and subsequently proctor-compacted samples under atmospheric conditions in soil mechanics laboratories. Here, it has also been found that faster separation and longer loading increase the resistance against separation. Increased loading in compression also increases resistance (Thewes, 1999). Fang et al. (2024) also showed the influence of faster separation. The influence of the surface roughness of the piston or object is inconclusive (Burbaum, 2009). Regarding the consistency of remoulded clay, it was found that separation resistance increases with increasing consistency index until it reduces again, reaching a maximum separation resistance at I_C values ranging from 0.4 to 0.6. Within these works, however, it is unclear whether failure has occurred within the compacted clay or at the interface. Measured values do not reflect the failure mode and might therefore contain measurements of soil tensile strength. Proctor compacted samples are more likely to fail within the soil due to the presence of macropores.

Two main physical phenomena proposed in the literature contribute to the separation resistance. The first is a thin water film at the interface, which leads to a capillary force under atmospheric conditions (Burbaum, 2009). The second is an undrained volume change-induced negative pore water pressure. The latter has been proven through interface pore water measurement, and it could be shown that nearly the entire uplift resistance can be attributed to interface suction (Mei et al., 2025).

This study aims to close the gap in prevalent research by investigating the separation resistance of a metal piston from reconstituted illite clay under atmospheric conditions. Illite clay was chosen as it is the most prominent clay mineral in the Northern Hemisphere. A factorial design is applied to study consistency, loading level, loading time, surface roughness and separation speed of undisturbed samples. The sample preparation method ensures high reproducibility, allowing in-depth statistical analysis. Other influencing factors on separation resistance, such as mineralogy of the soil, temperature and partial saturation, are known but not part of this contribution.

2 MATERIALS AND SAMPLE PREPARATION

The used soil proxy material is produced by mixing an industrial clay powder with tap water from Hamburg. The sample preparation technique is as follows.

1. Water and clay powder are mixed under atmospheric conditions at a gravimetric ratio of 1.05. It is assured that the powder is added gradually to the water, not the other way around.
2. The mixture is mixed under vacuum for one hour to remove air bubbles and dissolve conglomerates.
3. The smooth and air bubble-free slurry is poured into a consolidation column and consolidated to the desired consistency.
4. Sample holders are inserted, and samples trimmed.
5. Samples are put into a water bath to allow for capillary saturation from the bottom and are protected from evaporation. Saturation is finished when the samples show a shiny surface. This way, samples can also be stored for a limited period without drying out.

The consolidated proxy material is classified as a pronounced plastic clay according to DIN 18196 (Deutsches Institut für Normung, 2023) with a liquid limit of 63.6 per cent as determined by the Casagrande method and a liquid limit of 32.3 per cent. Atterberg limits determinations from the slurries follow DIN EN ISO 17892-12 (Deutsches Institut für Normung, 2022). Mineralogically, the clay powder contains 60 mass per cent illite and a total clay content of 73.8 mass per cent. This was determined by X-ray diffraction (XRD) analysis. The material has a specific surface of 95.0 m²/g and a D50 value of 0.3 µm as stated by the manufacturer, and a particle density of 2.800 g/cm³ as determined following DIN EN ISO 17892-3 (Deutsches Institut für Normung, 2016). The tap water used for mixing has a conductivity of 0.25 mS/m.

The sample preparation method yields excellent reproducibility of the samples, which allows statistical analysis of the results. Figure 1 illustrates the distribution of measured sample weights before testing, depending on the preconsolidation stress. The coefficients of variation are 0.88, 0.85, and 0.90%, which underscores the excellence of the sample preparation. The given preconsolidation pressures yield average consistency indices of 0.21, 0.44 and 0.78 before additional saturation, which correspond to very soft, soft and stiff consistency according to DIN EN ISO 14688-2 (Deutsches Institut für Normung, 2020). All tested samples show calculated degrees of saturation higher than 100 % after additional saturation.

The pistons are made from an aluminium-copper alloy. The material designation is EN AW-2007 or EN AW-Al Cu4PbMgMn (DIN material number 3.1645). The smooth surface is produced by polishing with sandpaper, while the rough one is produced through milling with a screw tap, producing frustums of pyramids.

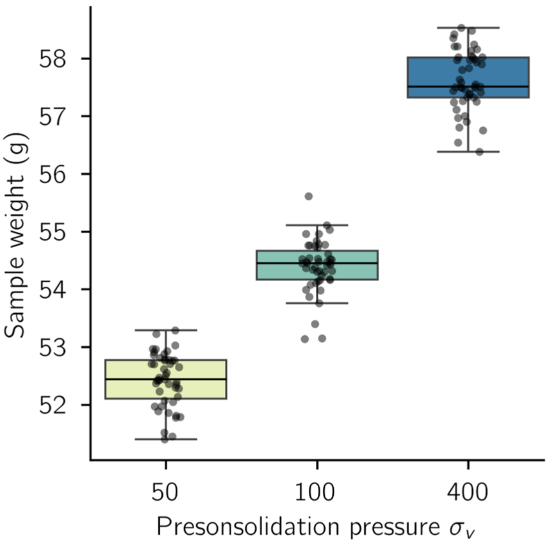

Figure 1. Boxplots of sample weights before testing in dependence on preconsolidation pressure

3 EXPERIMENTAL DESIGN AND PROCEDURE

The experimental design employs a 3 x 2^4 factorial design, resulting in a total of 48 combinations. Each test is repeated three times, yielding a total of 144 tests. The denomination of the parameters and the levels investigated are shown in Table 1.

During each test, the sample is loaded force-controlled for the given amount of time and subsequently unloaded in a displacement-controlled manner. The maximum uplift resistance, also known as adhesive strength, is defined as the maximum tensile stress measured during separation, calculated as the ratio of the maximum tensile force to the area of the piston. Samples have a diameter of 44.3 mm and a height of 20 mm, respectively. The piston has a diameter of 37.9 mm. Pullout of the sample is prevented by a 3 mm wide lip on top of the retaining piece, as depicted in Figure 2. Tests are performed in a uniaxial press that was built in-house for this purpose.

Table 1. Test parameters used for the factorial design.

	Parameter	Abbr.	Low (-)	Intermediate	High (+)
A	Piston roughness (µm)	R_z	1.0		227.1
B	Separation speed (mm/min)	v	0.5		5.0
C	Contact time (min)	t	5		120
D	1/OCR (-)	-	0.5		1.0
E	Preconsolidation stress (kPa)	σ_v	50	100	400

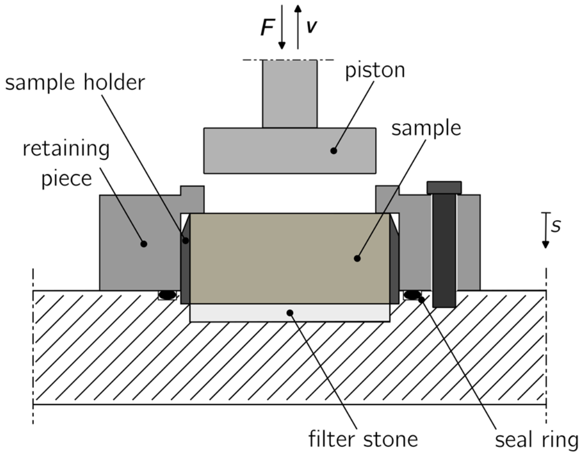

Figure 2. Details of the test set-up

4 RESULTS

The results yield a typical stress-time curve, as shown in Figure 3. After a constant load (factor D, in this case, 0.5 times the preloading stress of 400 kPa) is applied over the given time (factor C, in this case, 120 minutes), the piston is displaced at a constant speed. In the tensile regime, the maximum value is used for the subsequent analysis. Within the tested overconsolidated range, all tests exhibit adhesive failure, indicating that failure occurred at the interface without a soil body adhering to the piston, thereby increasing its surface area. Therefore, all test results yield true adhesive strength and no contribution of the soil's tensile strength.

The results of the factorial design can be graphically illustrated as three hypercubes, as shown in Figure 5. The reading of the graph is described at the marked point X, which is the lowest right corner of the lowest hypercube. The testing yielded an average separation resistance of 2.1 kPa for the samples preloaded at 50 kPa, loaded with 25 kPa for 120 minutes using a rough piston and separating the piston from the sample slowly. Following this logic, each one of the possible 48 combinations is represented by one dot. Colouring indicates the magnitude of the arithmetic mean, which is calculated from three individual tests.

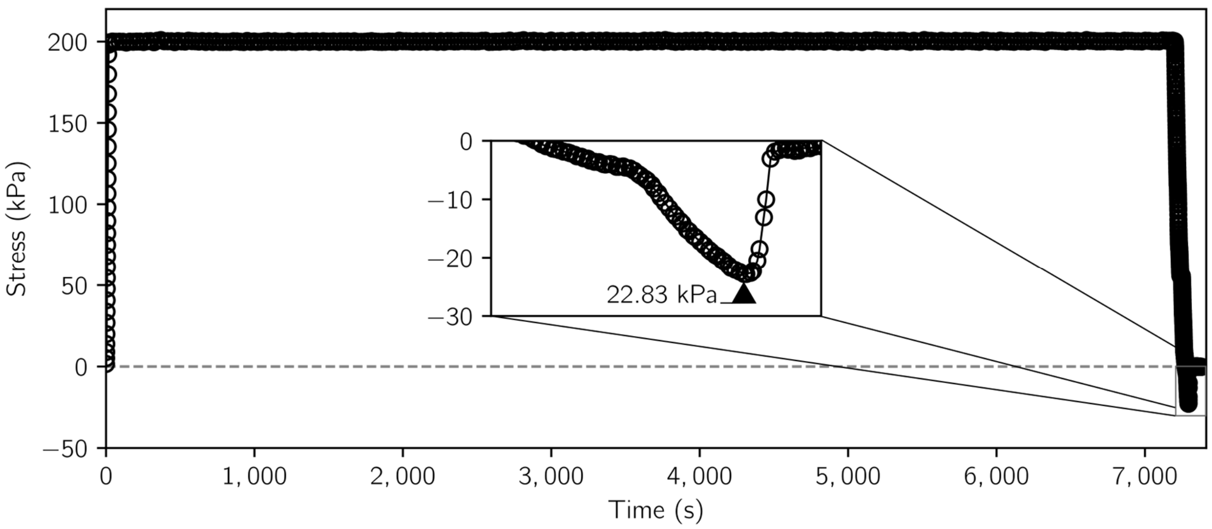

Figure 3. Example of a resulting curve of a separation test. The shown test was performed at A – ,B – , C +, D – and E +.

The results show that all the studied factors can significantly influence separation resistance. Most visible is the increase in separation resistance with consistency index or preloading stress. This becomes clear by comparing the four hypercubes from bottom (soft) to top (stiff) at each corner, which corresponds to the same configuration of the factors A to D. The densest samples, preloaded with 400 kPa, yield the highest stress required to move the piston away from the sample followed by the samples that were preconsolidated at 100 kPa. The soft samples yield the lowest values.

Longer loading times result in higher resistance in all cases. This is visible through comparison from left to right within the hypercube at a given consistency. The same is true for higher loading (comparison from bottom to top at given consistency).

The influence of separation speed is also evident. For 22 out of 24 cases, a higher separation speed leads to higher resistance. Only for tests performed at stiff consistency, with short loading times and high loading, the effect is vice versa. The square on the top left depicts this configuration.

The results for surface roughness appear inconclusive when looking at Figure 5. Therefore, the responses are shown more closely in Figure 4 to facilitate examination. Here, the responses for low and high piston roughness are pooled across the factors of speed, loading time, and loading ratio, and separated by the consistency of the tested samples. There is no clear trend evident in the comparison of the plotted arithmetic means. Future work will investigate this further, applying the ANOVA method (Montgomery, 2017). The first preliminary investigation of the data reveals that the fundamental assumptions of the ANOVA method, including the normality of residuals and errors, as well as homogeneity of variances, are not met. This is because the data distribution is positively skewed. Therefore, data transformation will be necessary (Tabachnik & Fidell, 2007). The transformation of data and in-depth statistical analysis is beyond the scope of this contribution.

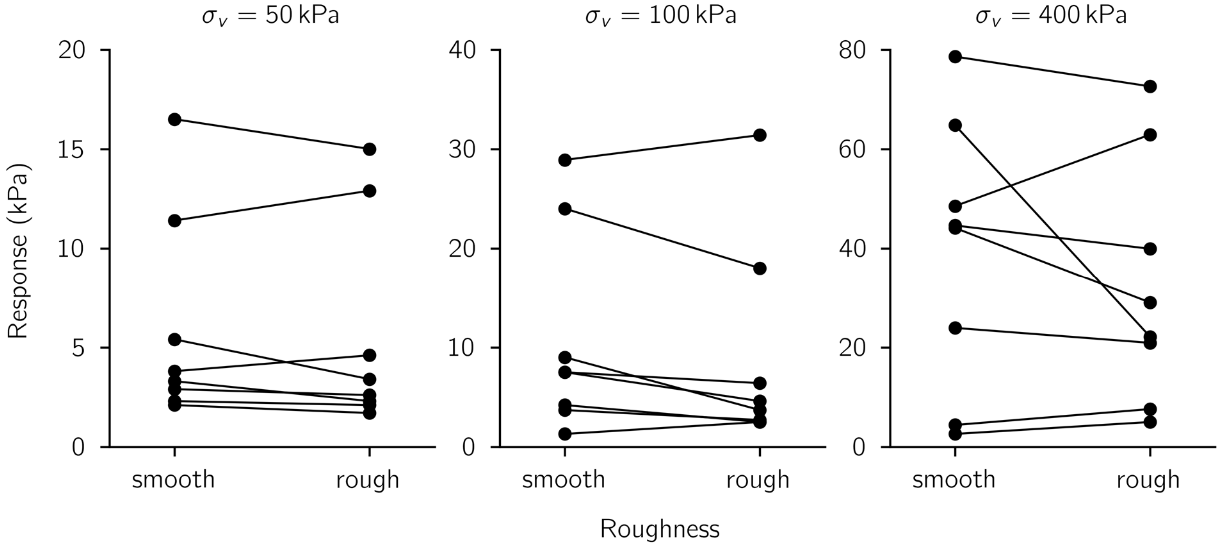

Figure 4. Influence of piston roughness at a given preconsolidation stress, or rather, consistency. Values are pooled across the factors B, C and D.

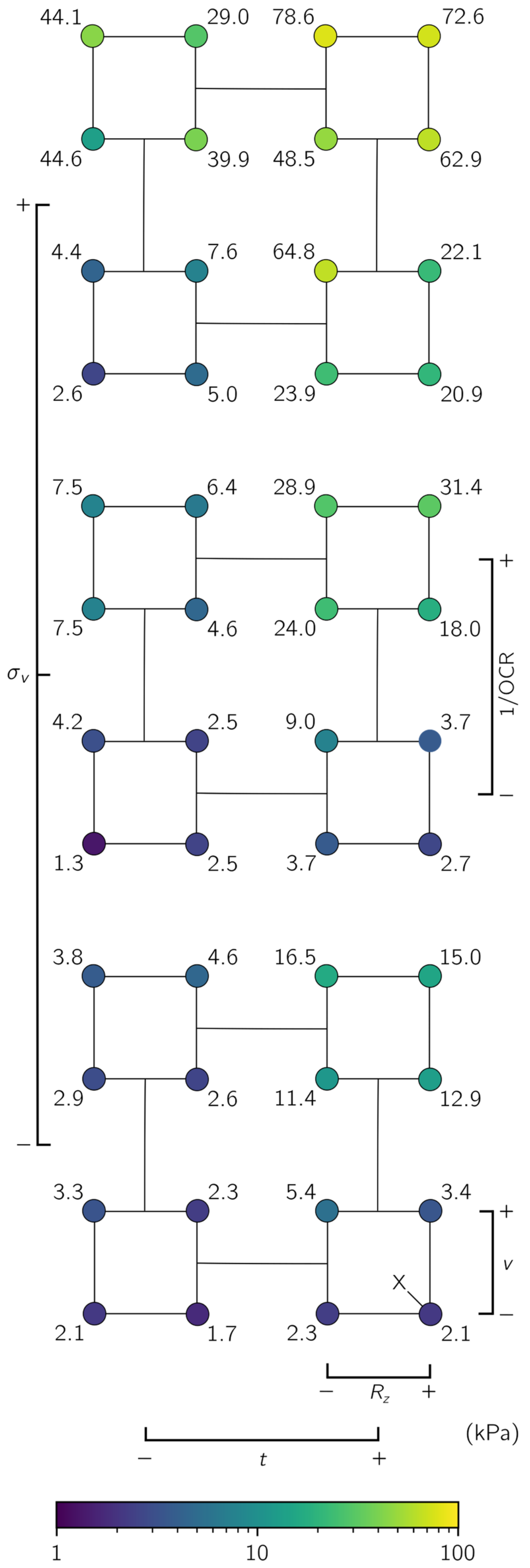

Figure 5. Results of the 3 x 2^4 factorial design

5 DISCUSSION AND CONCLUSION

144 separation tests have been performed on reconstituted illite, thereby closing a research gap in the adhesive strength of metal pistons on undisturbed reconstituted clay. Cumbersome sample preparation allows high reproducibility. This work demonstrates that increasing stress levels, contact time, separation speed, and consistency yields higher adhesive strength, as evaluated through a 3 x 2^4 factorial design. This follows the literature findings described in Section 1. Regarding surface roughness, a global trend is not visible, as significant interactions of this factor with the previously listed factors occur. Future work will investigate the dataset using statistical methods in more depth. Future research will quantify suction at the clay–metal interface and employ computed tomography to elucidate the mechanisms governing adhesive strength. This will enable the investigation of suction development during the separation phase and make the water film at the interface visible, allowing for verification of the physical concepts that govern the clay's adhesive behaviour.

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