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Measuring the undrained shear strength of very soft, clay-rich sediments

Mesure de la résistance au cisaillement non drainé des sédiments argileux très mous

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ABSTRACT: This study examines what measuring devices can best be used to measure the undrained shear strength of very soft, clay-rich sediments that are in between solid and fluid states. Although in recent years interest in these sediments for construction purposes has been growing, little information is currently available on what laboratory testing devices can be used for this purpose. In this study, kaolinite-based clay samples are prepared at different liquidity index values (in the range of 0.4 to 1.9) and tested using a Fall Cone, Lab Vane, and Direct Simple Shear device. The results show that the measured shear strength (in the transitional range of 1-10 kPa) strongly depends on the applied test conditions. The Fall Cone and Lab Vane tests provide shear strength values in the same order of magnitude. The measured strength values from Direct Simple Shear testing depend on the applied consolidation stress level but are typically lower compared to the Fall Cone and Lab Vane tests. The findings of this research indicate that the results of different devices converge when the testing conditions are moved closer together. A full overlap of the results is not likely possible as it would require the test conditions to be pushed outside the validated range of operations or simply because some test conditions are inherent to the type of test.

RÉSUMÉ: Cette étude examine les dispositifs de mesure les plus adaptés pour mesurer la résistance au cisaillement non drainé des sédiments très mous, riches en argile, se situant entre les états solide et liquide. Bien que ces sédiments aient suscité un intérêt croissant ces dernières années dans le milieu de la construction, peu d'informations sont disponibles sur les dispositifs de test en laboratoire pouvant être utilisés à cette fin. Dans cette étude, des échantillons d'argile à base de kaolinite sont préparés à différentes valeurs d'indice de liquidité (variant entre 0.4 et 1.9) et testés à l'aide d'un pénétromètre à cône, d'un scissomètre de laboratoire, et d'un appareil de cisaillement simple direct. Les résultats des tests montrent que la résistance au cisaillement non drainé (variant entre 1 et 10 kPa) dépend fortement des conditions de test appliquées. Les tests avec le pénétromètre à cône et du scissomètre de laboratoire fournissent des résistances au cisaillement non drainé de même ordre de grandeur. La résistance au cisaillement non drainé obtenue à partir du test de cisaillement simple direct dépend du niveau de contrainte de consolidation appliqué, mais est généralement inférieure aux résultats obtenus avec les autres méthodes. Les conclusions de cette recherche indiquent que, plus les conditions de test sont proches, plus les résultats des différents dispositifs convergent. Une coïncidence complète des résultats est probablement impossible, car cela nécessiterait que les tests soient effectués dans des conditions hors de leur plage opérationnelle validée, ou tout simplement parce que certaines conditions de test sont inhérentes au type de test.

Keywords: Very soft clays; undrained shear strength; direct simple shear device; fall cone; lab vane test.

1 INTRODUCTION

The strength properties of very soft, clay-rich sediments are important as interest in these sediments is growing, e.g., for wetland (re)construction, to strengthen foreshores against sea level rise or as building material for dikes. An example hereof is the "Growing Dike" initiative in the Netherlands, where locally dredged material is placed on top of a dike, with the intention to strengthen the dike as it transforms from a sediment suspension to a soil. To guarantee that these very soft materials can withstand exposure, such as wave attack, knowledge of how to measure their undrained shear strength is needed.

Measuring the undrained shear strength of very soft, clay-rich sediments is challenging as these sediments display a specific deformation behaviour that differs from that of water or most soils (Meshkati et al., 2021). As these sediments are in a transition between a fluid and solid state, they are considered (ultra-)soft from a soil mechanics perspective, but rather strong from a fluid mechanics perspective. Although the undrained shear strength (Su) is a geotechnical parameter used for soils ($Su > 10\ kPa$), similar parameters exist in the field of fluid dynamics – albeit measured with different devices and protocols and used for much softer materials ($Su < 1\ kPa$).

It remains uncertain what devices and protocols within soil and fluid mechanics are appropriate for measuring undrained shear strengths beyond the typical range of interest for both disciplines ($1 < Su < 10\ kPa$). Meshkati et al. (2021) anticipate that the suitability of devices may vary, considering that the differences in stress and strain levels studied in both disciplines span multiple orders of magnitude.

Building on Meshkati et al. (2021), a Direct Simple Shear device, Lab Vane, and Fall Cone are used to measure the undrained shear strength of artificial clay samples between fluid and solid states. The aim is to evaluate suitable measuring devices within this transitional strength range ($1 < Su < 10\ kPa$).

2 USED MATERIALS

To assess the performance of the measuring devices for the whole range of strengths that bridges the gap between fluids and solids, different clay samples were prepared with water contents between 23 and 120%.

The tested samples were predominantly kaolinite-based to minimize thixotropic behaviour. These inactive clay samples were prepared by mixing FT-S1 powder and tap water in a lab mixer. Once prepared, the samples were placed in cups, wrapped in plastic foil and given one hour to rest before testing. In addition, a stiffer prefabricated pottery clay, namely the Vingerling K147 clay by Sibelco, was used. Table 1 summarizes the tested clay sample characteristics.

Table 1. Clay characteristics.

WC (%)	LI (-)	VR (-)	Properties
Mixture FT-S1 and tap water			
118-120	1.87-1.91	3.01-3.69	KC = 64 % LL = 70-80 % PL = 15-20 % PI = 60-75 %
94	1.44	2.44-2.88	
58-59	0.78-0.80	1.54-1.77	
47-51	0.59-0.66	1.26-1.54	
43-43.3	0.51-0.52	1.14-1.30	
Vingerling K147			
22.6-24	0.41-0.50	0.60-0.64	KC = 70-90 % LL = 32.3 %* PL = 15.8 %* PI = 16.5 %*

*Note: KC is the Kaolinite Content, LL the Liquid Limit, PL the Plastic Limit, and PI the Plasticity index, PI=LL-PL. WC is the water content and LI the Liquidity Index, LI=(WC-PL)/(LL-PL). VR is the estimated void ratio. *Based on De Lange et al. (2018).*

3 TESTING APPARATUS & PROCEDURES

The strength of the clay samples is measured using the Lab Vane, Fall Cone and Direct Simple Shear device.

3.1 Lab Vane test

The Lab Vane test was performed following ASTM D4648, which entails the rotation of a vane at a constant shear strain rate within the clay specimen. The vane size is adjusted based on the material's stiffness to ensure that the device remains within its calibrated range.

The measured peak stress is known as the static peak shear stress, which is considered equivalent to Su in soil mechanics. Both parameters are shear strain rate dependent, exhibiting higher values at increased strain rates. To assess shear strain rate dependency, the blade's rotation speed is varied at 0.01, 0.1, 0.5 and 1 RPM. As the Lab Vane does not measure the corresponding shear strain rates $\dot{\gamma}$ [1/s], $\dot{\gamma}$ is estimated with the analytical approach by Maron & Krieger (1952) by performing a Controlled Shear Stress ramp-up protocol (Meshkati et al., 2021). The estimated strain rate at the clay's static yield point is in the order of $1\ \times 10^{-3}\ 1/s$ for the Vingerling clay, and between 1 and $5\ \times 10^{-3}\ 1/s$ for the FT-S1 specimens with water contents between 43 and 120%.

3.2 Fall Cone test

The Fall Cone test was performed in accordance with ISO 17892-6 and with 5 repetitions per clay specimen. Two different cones were used depending on the specimen's water content (WC). The stiffest Vingerling clay (WC=23%) was tested with a cone of 80g and 30° aperture, while the softest clays (WC > 90%) used a cone of 60g and 60° aperture. Intermediate water contents were assessed with both cones. The undrained shear strength (Su) [kPa] was derived from the cone penetration depth (d) [mm] using Hansbo's empirical equation:

$$Su = K \frac{m\,g}{d^2} \tag{1}$$

where g is gravitational acceleration [m/s^2], m is the cone mass [g], and K is a dimensionless constant (0.27 and 0.8 for the 60 and 80-gram cone, respectively).

3.3 Direct Simple Shear device

The Direct Simple Shear (DSS) tests followed ASTM D6528–17 and used specimens with a diameter of 63mm and a height of 21mm.

Prior to shearing the specimen at a constant speed of 8% of the sample height per hour (hr), a vertical consolidation stress ($\sigma_{v,i}$) was applied. $\sigma_{v,i}$ values as low as 3 kPa were used; lower consolidation stress values were unfeasible due to difficulties in maintaining grip during shearing. The sample height is kept constant during shearing to prohibit any volume changes and mimic undrained conditions. The shear strain rate dependency is tested by applying an increased, non-standard shear strain rate of 100%/hr.

The undrained shear strength (Su) is the measured peak stress level, or in the absence of a peak stress, the strength taken at 38% shear strain (γ). Note that strength measurements are corrected for ring friction and membrane effects, which amount to roughly 1 kPa. The DSS tests are conducted for water contents below 55% due to handling limitations with softer materials. Table 2 outlines the test specifications.

Table 2. Overview Direct Simple Shear (DSS) tests.

WC (%)	Shear rate (%/hr)	$\sigma_{v,i}$ (kPa)	γ (%)
Mixture FT-S1 and tap water			
49.9	8	3	38
47.2	100	3	38
43.3	8	3	38
	100	3	38
	8	5	38
Vingerling K147			
22.9	8	3	38
22.6	100	3	28*

*Note: WC is the Water Content (WC), $\sigma_{v,i}$ the initial consolidation stress, and ϵ the shear strain level at which the undrained shear strength is determined. *Corresponds to peak stress level.*

4 TEST RESULTS

Figure 1 shows the variation in undrained shear strength (Su) with the liquidity index (LI) for all tests performed in this study. The results are expressed in terms of LI to provide an indication of the clays' plasticity and to enable a direct comparison of the two mineralogically-distinct clays, Vingerling and FT-S1. For comparison purposes, an empirical relation between LI and Su is shown, as derived by Vardanega et al. (2014) based on extensive Fall Cone testing on fine-grained materials.

For the Fall Cone and Lab Vane tests, the results show comparable undrained shear strength values, Su. Both tests closely adhere to the theoretical relation proposed by Vardanega et al. (2014).

The alignment of the DSS results with the Fall Cone, Lab Vane, and Vardanega et al. (2014), strongly depends on the applied testing conditions.

For very soft clays ($Su < 10\ kPa$), the Su values obtained through DSS testing are typically lower than those measured with the Fall Cone and Lab Vane; with variations influenced by the applied consolidation stress level ($\sigma_{v,i}$) and strain rate ($LI \geq 0.5$ in Figure 1).

Increased consolidation stress levels ($\sigma_{v,i}$) result in higher Su values. Still, even at the highest stress level of $\sigma_{v,i} = 5kPa$, the measured undrained shear strength remains at the lower bound of the Su values measured in Lab Vane and Fall Cone tests. It should be noted that the Lab Vane and Fall Cone tests are performed in the absence of a consolidation stress ($\sigma_{v,i} = 0\ kPa$).

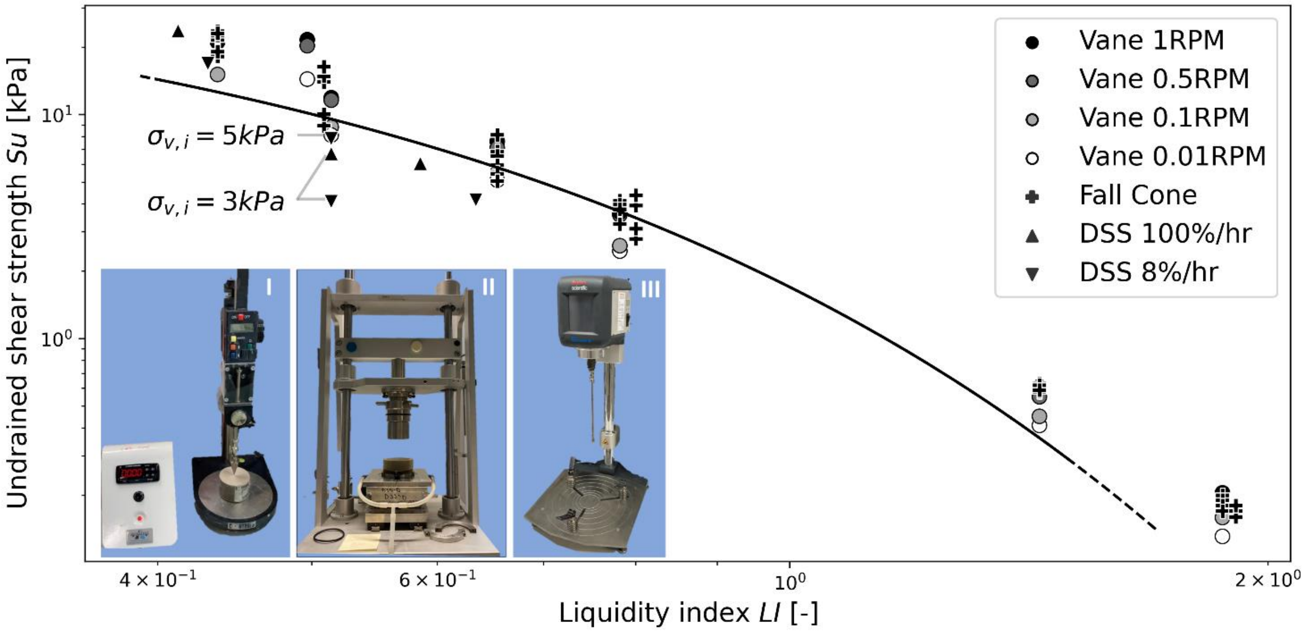

Figure 1. Undrained shear strength (Su) [kPa] at different liquidity index (LI) [-] values as calculated by the Fall Cone, Direct Simple Shear (DSS) and Lab Vane. ▼ and ▲ indicate DSS results with a shear strain rate of 8 and 100% of the sample's height per hour, respectively. The Lab Vane's rotation speed is indicated with shades of grey. The black line shows the empirical relation between Su and LI as derived by Vardanega & Haigh (2014); the dotted part is outside the validated range. The used Fall Cone (I), DSS (II) and Lab Vane (III) are shown in the lower left corner.

However, when the applied shear strain rate of the DSS approaches that of the Lab Vane, the measured undrained shear strengths are in better agreement. The Lab Vane exhibits relatively high strain rates, $\dot{\gamma}$, in the order of $10^{-3}\ 1/s$. In general, the undrained shear strength tends to increase for higher strain rates (Lefebvre and LeBoef, 1987). Accordingly, the DSS underestimates the undrained shear strength compared to the Lab Vane when operating at a lower strain rate of $\dot{\gamma} = 2.2 \times 10^{-5}\ 1/s$ (i.e. 8%/hr) (▼ in Figure 1, for $LI \geq 0.5$, $\sigma_{v,i}$=3 kPa). At the fastest applied shearing rate of $\dot{\gamma} = 2.8 \times 10^{-4}\ 1/s$ (i.e., 100%/hr), the DSS results approach the Lab Vane results (▲ in Figure 1).

For the stiffest Vingerling clay ($Su > 10\ kPa$, $LI < 0.5$ in Figure 1), the DSS results align well with the Su_p values obtained with the Fall Cone and Lab Vane for both applied shear strain rates (8 & 100%/hr). Please note that Sheahan et al. (1996) show that that the clay's sensitivity to shear strain rate decreases with an increasing over-consolidation ratio (OCR), and that the Vingerling clays are over-consolidated (OCR>1). During preparation, the Vingerling clay experienced higher consolidation stress levels than during the test. In contrast, the FT-S1 clay samples are tested under normally consolidated conditions, OCR=1.

5 DISCUSSION

Comparable undrained shear strength values, Su, are obtained between the Fall Cone and Lab Vane tests, aligning with Canelas et al. (2018) tests based on cohesive soil samples with water contents around their liquid limit. Interestingly, our results indicate that this conclusion holds even under significant variations in the Lab Vane's shear strain rate (0.01 – 1 RPM).

The results indicate that the observed discrepancy in the undrained shear strength response among the DSS and the Lab Vane device is to an extent attributed to differences in the applied shear strain rates.

Meshkati et al. (2021) argue that in geomechanics mostly small displacement are studied (small shear strains) to ensure geotechnical stability, whereas in fluid mechanics flowing materials and thus large shear strains are studied. Meshkati et al. (2021) anticipate a similar difference in the shear strain rates that are applied in both fields of discipline. This is in line with the findings in this study which shows a notable discrepancy in shear strain rates between the DSS device, commonly employed in soil mechanics, and the Lab Vane, extensively utilized in fluid mechanics.

6 CONCLUSION

This work has investigated the variation in the undrained shear strength (Su) of very soft, kaolinite-based clays for different devices and test conditions. The Fall Cone and Lab Vane tests yielded comparable Su values, whereas the Direct Simple Shear (DSS) results showed a dependency on the applied shear strain rate and consolidation stress level. The Su from DSS testing aligned well with Fall Cone and Lab Vane results for stiffer clays ($Su > 10kPa$). For very soft clays ($Su < 10kPa$), this is the case when the difference in the shear strain among the different devices is minimized. A full overlap of the undrained shear strength is not likely to be possible as this would require the shear strain rate to be pushed outside the validated range of operations or simply because some test conditions – such as a non-zero consolidation stress – are inherent to the type of test.

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