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Critical state behaviour of anthropogenic clay in a direct simple shear test

Comportement à l'état critique d'argile anthropogénique dans un essai de cisaillement simple direct

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ABSTRACT: In practical engineering the direct simple shear, DSS, tests are a valuable tool for parameter assessment, despite its known shortcomings. The shear stress mobilised at the end of the test is often used as a proxy for critical state strength. Several aspects complicate conducting reliable tests at large strain, in specific for clay samples. One of these effects is slippage between the sample and the platens. When slippage occurs, the measured resistance follows from the interface properties rather than soil behaviour. To better understand the critical state behaviour of clays during a DSS tests a test series is conducted on an anthropogenic stiff silty clay. The test series not only demonstrates that critical state conditions are reached before the end of the tests, but also that slippage tends to occur after reaching critical state conditions. Complimentary series of direct shear, DS, tests were conducted to further confirm critical state conditions are obtained. This confirms the applicability of DSS tests to obtain a soil specific proxy for critical state conditions without the influence of slippage. Hence, the presented method to derive critical state strengths from DSS tests, for anthropogenic clay, and thereby discarding the influence of slippage provides useful and reliable strength parameters for design.

RÉSUMÉ: En ingénierie pratique, les essais de cisaillement simple direct (DSS) sont un outil précieux pour l'évaluation des paramètres, malgré leurs limitations connues. La contrainte de cisaillement mobilisée à la fin de l'essai est souvent utilisée comme un indicateur de la résistance à l'état critique. Plusieurs aspects compliquent la réalisation de tests fiables à grande déformation. L'un de ces effets est le glissement entre l'échantillon et les plateaux. Lorsque le glissement se produit, la résistance mesurée dépend des propriétés de l'interface plutôt que du comportement du sol. Afin de mieux comprendre le comportement à grande déformation des argiles dans des conditions de DSS, une série de tests est réalisée sur une argile limoneuse anthropogénique rigide. Cette série de tests montre non seulement que les conditions d'état critique sont atteintes avant la fin des tests, mais aussi que le glissement a tendance à se produire après avoir atteint les conditions d'état critique. Une série complémentaire de tests de cisaillement direct (DS) est réalisée pour confirmer davantage l'obtention des conditions d'état critique. Cela confirme l'applicabilité des essais OC DSS sur les argiles anthropogéniques dans la conception des digues, à condition qu'un indicateur spécifique au sol pour les conditions d'état critique ait été déterminé à partir de tests en laboratoire, plutôt que la résistance à la fin de l'essai.

Keywords: Direct simple shear testing; anthropogenic clay; shear strength; slippage; laboratory testing.

1 INTRODUCTION

Parameter assessment using DSS testing is hampered by the unclear stress state of the sample (DeGroot et al., 1992). However, it is considered the best method to represent shearing conditions along a potential failure surface (Grimstad et al., 2012) especially in soft clays with anisotropic stress-strain-strength behaviour. DSS tests involve the rotation of principal stresses during the test making it suitable to study the rotation of principal stress directions beneath an embankment which leads to varying shear strength at different locations. This study explores the derivation of critical state behaviour during DSS testing, which is crucial for obtaining a reliable parameter assesment.

Critical state conditions are typically reached at large deformations, and the mobilized strength at the end of the test is often used as a proxy for critical state strength (Leroueil et al., 1990). However, large strains in DSS tests can induce anomalies like slip planes and slip between the sample and plates, making it challenging to determine model parameters for constitutive models in practical engineering applications.

In a typical DSS test the stack of rings is sheared uniformly. Figure 1 shows an example where slip between the sample and bottom plate has occurred. Three separate zones can be distinguished: i) at the top platen, ii) in the middle, and iii) at the bottom platen. The negative influence of the boundaries on the sample in DSS testing is well acknowledged. However, it is assumed that the centre of the sample is sheared in simple shear and governs the overall behaviour (i.e. DeGroot et al., 1992, Den Haan and Grognet, 2014). The deformation pattern depicted in Figure 1 indicates that, at least at the end of the test, the mobilized resistance is influenced by friction between the sample and the bottom plate, which raises questions regarding the validity and application of the test results.

The series of DSS tests that were perfomed to study the critical state behaviour focuses in particular on determining useful critical state strength parameters before slip occurrence, which we hypothesize to be in response to a significant amount of applied strain with critical state behaviour occur before slippage occures.

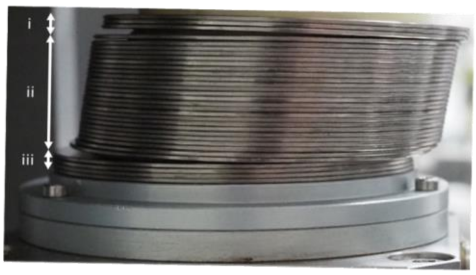

Figure 1. A result at the end of an OC DSS test with slippage.

2 SAMPLE CHARACTERISTICS

The research is performed on undisturbed anthropogenic samples from Ravenstein-Lith along the Meuse river in the Netherlands. The samples were retrieved above the phreatic line and tested at natural water content, γ_n, 22.2 to 42.4%. The dry density of the samples is 1.21-1.60 g/cm^3 with a void ratio of 0.65-1.15. The medium plasticity samples are characterized by a clay (< 2μm) content of 24.3%, a silt (2 < x < 63μm) content of 56.3%, a 17.5% sand (63 < x < 2000μm) content and 1.9% of organic content.

3 APPROACH AND METHODOLOGY

This study used a GDS instruments DSS apparatus with a 2 kPa loadcell with internal and external displacement sensors. Intact clay specimens were trimmed and fitted in between porous stones with distributed conical pins enclosed by a rubber membrane and a stack of low-friction rigid rings providing the lateral confinement but also allowing simple shear to occur. Bjerrum's (1973) recompression technique was used to reconsolidate the samples to the estimated in-situ vertical stress. During the stage of simple shearing a strain rate of 2%/hr was applied. Constant volume tests were conducted under undrained conditions per ASTM D6528-17 (2017) where the change in normal stress was assumed to be equivalent to the change in pore pressure (Dyvik et al., 1987). Corrections for membrane and slide table friction were applied to the horizontal load readings (Greeuw et al., 2016). In addition to DSS tests, DS tests were performed to verify at which strain level critical state conditions are reached using a Wille Geotechnik apparatus under water, following ISO 17892-10 (2018) guidelines, together with an area correction per Bareither et al. (2008).

4 RESULTS

During a DSS test, slippage was observed at the end of the test, occurring after applying some strain to the sample. This slippage along the upper and lower surfaces of the specimen leads to partial transfer of shear force from the platens to the sample, exceeding the mobilized friction at the soil-platen interface. Previous studies by e.g. Le Meil et al. (2016) have shown that using porous platens with protruding pins on cohesive soils can prevent slippage, allowing continued deformation of the specimen even after slippage has initiated. However, Le Meil et al. (2016) suggested that the embedment of protruding pins may create uneven stress concentrations in the boundary zone, as the shear strength undergoes changes when the pins cut through the soil. Consequently, the boundary zone surrounding the central region of the sample, where a simple shear stress state exists, exhibits interrelated slippage and shear. If the protruding pins cut through the soil in the boundary zone, localized softening occurs, and uniform simple shear conditions cannot be maintained due to strain localization.

The tests reveal that observed slip often corresponds to the formation of a distinct sliding plane (Figure 2). A schematic representation of this hypothesized stage is depicted in Figure 3b, where the initiation of a rupture plane occurs after a standard test onset (Figure 3a). Additionally, Figure 3c illustrates the impact of excluding rings and a membrane during testing, while Figure 3d demonstrates the strain localization that occurs along the bottom and top platens in response to ongoing slippage along the shear plane.

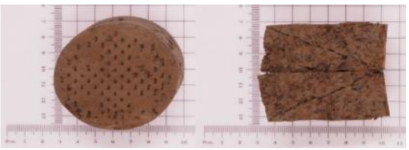

Figure 2. An OC DSS sample which experiences slip and shows a clear internal shear plane.

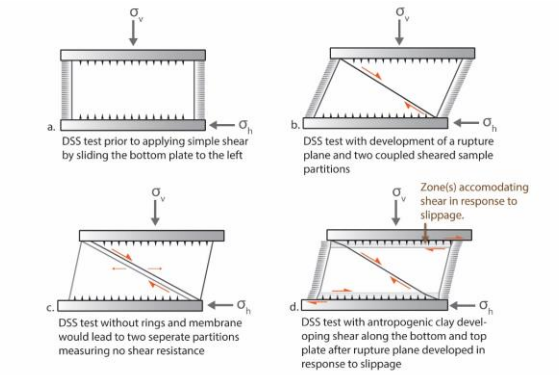

Figure 3. Schematic overview of the different stages of a DSS test result.

4.1 Tests under OC conditions

A total of seven DSS tests were conducted under overconsolidated (OC) conditions at natural water content. The corresponding stress – strain curves and normalised stress paths are shown in Figure 4 and 5 (i). The test results demonstrate unconventional behaviour with certain stress-strain curves exhibiting dips between 5 and 15% shear strain, and some normalised stress paths displaying odd behaviour in the form of a loop. Moreover, upon removing the sample from its set-up, a diagonal shear plane has formed within the sample, and it exhibits signs of slippage (see Figure 2).

In addition to tests at γ_n, five fully saturated tests were conducted (for test results see Figure 4 and 5 (ii)) and these showed, albeit less, still signs of slippage, but not a sign of the formation of shear bands or loop in the normalised stress paths.

4.2 Tests under NC conditions

Three additional normally consolidated (NC) DSS tests were conducted, and the test results align with those typically observed for NC clay (Figure 4 and 5 (iii)). In these tests, no slippage was observed, possibly due to the NC conditions where the vertical stress level surpasses the yield stress (> 100 kPa), resulting in adequate soil-platen interface grip. Moreover, no visual indications of diagonal shear zones were observed.

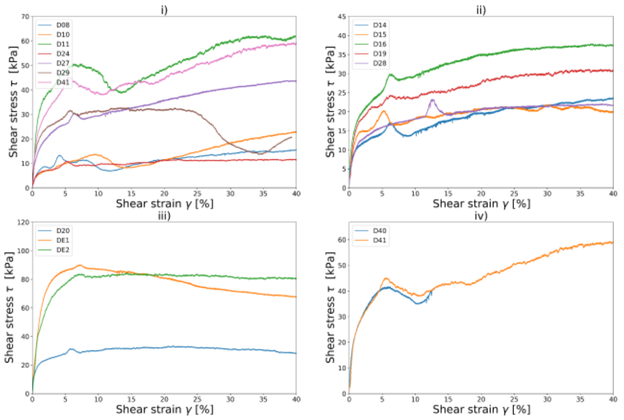

Figure 4. Shear stress - shear strain graphs of DSS tests under OC conditions at γ_n (i) OC conditions fully saturated (ii), NC conditions (iii) and fully developed and pre-maturely stopped DSS test (iv).

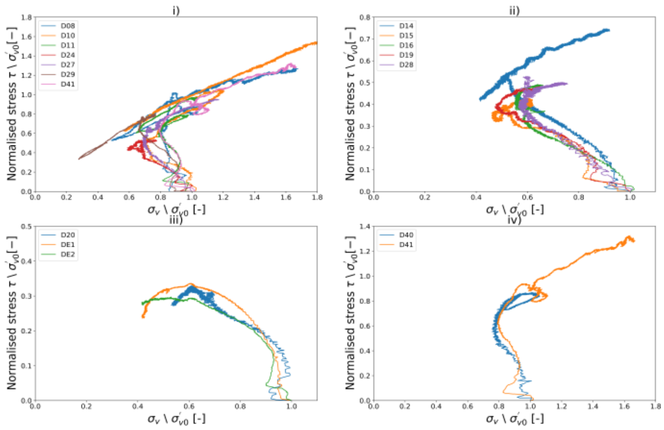

Figure 5. Stress paths of DSS tests under OC conditions at γ_n (i) OC conditions fully saturated (ii), NC conditions (iii) and fully developed and pre-maturely stopped DSS test (iv).

4.3 Direct shear tests

Although DS and DSS test are different, both in terms of failure mechanism and imposed boundary conditions, generally similar results are to be expected if these effects are accounted for (Hanzawa et al., 2007). Eight DS tests were performed which showed a constant mobilised shear stress when reaching 15% shear strain, indicating that critical state conditions have been reached and that critical state strength parameters in DSS tests can be determined earlier than the current proxy for shear strain, γ, of 40%.

4.4 Formation of the diagonal failure plane

During eight DSS tests a time-lapse video has been recorded. Test results showed both signs of slippage and development of a diagonal rupture surface. It is hypothesized that the sample has reached critical state before slip occurs. To validate this hypothesis, two DSS tests were performed on samples from the same boring with sequential depth and in-situ water content (see Figure 4 and 5 (iv)). The first test (D40) was stopped at $\gamma = 13\%$ strain and the subsequent test (D41) was performed until reaching the prescribed $\gamma = 40\%$.

In sample D40, no signs of slip were observed at $\gamma = 13\%$, but an initiation of a diagonal rupture plane was evident. Sample D41 exhibited both slippage and a fully developed rupture plane, confirming the hypothesis. This suggests that a reliable practical indication of critical state strength can be obtained using DSS tests on an OC sample, provided a soil-specific proxy for critical state conditions is determined. The findings support the hypothesis depicted in Figure 4, showing the reliability of DSS tests until the development of the sliding plane and slightly beyond, offering an indication of critical state strength just prior to slip between the sample and plates. However, test results beyond these strain levels are considered unreliable as they do not reflect the true strength characteristics of the tested soil, but rather include other factors such as membrane strength.

5 CONCLUSIONS

A series of 17 DSS tests was conducted on both NC and OC samples of an anthropogenic clay. Under NC conditions, the tests exhibited textbook behaviour without slippage, as the clay behaved plastically without the formation of discrete failure surfaces. However, under OC field stress conditions, the tests displayed a noticeable dip in the stress-strain curve, corresponding to the development of a diagonal rupture plane. Continued testing revealed slippage between the sample and platens. It was observed that the stresses measured after the formation of the rupture plane no longer represented soil behaviour but were influenced by the membrane and ring stack that forced the parts to move according to the applied displacements from the device. Consequently, in DSS tests on anthropogenic clay, the strength at large strains cannot serve as a proxy for critical state strength, as is typically assumed for NC conditions. However, this research demonstrated that if a soil-specific proxy for critical state conditions is utilized, the results of OC DSS tests can be applied to determine strength parameters for geotechnical design.

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