An accurate and direct approach for sample-free in-situ detection of quick clay

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Abstract. The objective of the research presented in this paper is to develop prototypes or concepts for new in-situ tests aiming to detect quick clays. Existing in-situ geophysical and geotechnical methods can indicate that a clay may be quick. But the only reliable method for detecting a quick clay is by sampling, followed by fall cone tests in a laboratory. This approach is time-consuming and costly, thus often with limited information over the depth. Attempts have been made on identifying quick clays from side friction measured by conventional CPTUu. However, the clay is not sufficiently remoulded during penetration of the CPTu rod, and the sensors of the sleeve do not have sufficient accuracy to detect the low shear strength of a remoulded quick clay. A new approach aiming to obtain both complete remoulding and accuracy for in-situ measurement of remoulded strength at round 0.3 kPa has been tested. It consists of a mixing module mounted on a total sounding rod and a T-bar on a conventional CPTu probe. Field tests prove that it is possible to fully remould quick clays and measure its remoulded shear strength with sufficient accuracy in the field applying the new concept.

1 Introduction

The Norwegian guideline on building on quick clay areas defines quick clays [1] as very sensitive clays exhibiting extremely low remoulded undrained shear strength (s_{ur}<0.33 kPa with test standard NS-EN ISO 17892-6:2017 [2]). Devastating quick clay landslides may be triggered by both human activities and natural processes and occur in Scandinavian countries [3] and Canada [4], causing significant casualties and property losses. Quick clay landslides occur in areas with large deposits of leached, marine, brittle clays. The low undrained shear strength means that the remoulded, quick clay may flow, almost like water, out of the slide pit. This opens for an accelerating retrogressive mechanism and very large slides. The Norwegian guideline on building on quick clay areas [1] defines brittle clays as clays with $s_{ur} \leq 1.27$ kPa (following standard NS-EN ISO 17892-6:2017 [2]), and special care should be taken even if the clay is just brittle, not quick.

One of the most important factors for reducing the quick clay landslide risk is accurate mapping of quick and brittle clay deposits. Existing geotechnical soundings (rotary pressure sounding [5], total sounding [5]) and in-situ tests (cone penetration test with pore pressure (CPTu [5-9]), field vane test [5] only provide indication of quick clay deposits.

In Norway, rotary pressure sounding and total soundings [5] are for a rough indication of soil stratification and depth to bedrock. If clays are involved, they will to some extent be remoulded during penetration. The axial force during penetration is measured at top of the rod and reflects the resultant axial resistance over the whole rod. This value includes resistance from all soil layers, making it unreliable for accurate detection of quick clay. However, a reduction or constant axial force with depth may indicate boring through a quick clay layer.

CPTus are extensively used in Norway for interpretation of soil layers and mechanical parameters from empirical correlations. Derived parameters such as pore pressure parameter (B_q) may indicate the occurrence of a brittle or sensitive clay. Attempts have also been made on detecting quick clays by the measured side friction on the friction sleeve. However, research has shown that (1) the conventional CPTu [5-10] device only remoulds a thin zone of clay around the rod and (2) the sensors of the friction sleeve does detect the low shear stress values of remoulded quick clays. Pan et al. (2025) [12] showed that the error in sleeve friction of an ISO Type I CPTu can be in the magnitude of 2 kPa, while the remoulded shear strength of quick

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clay, requires measuring values below 0.33 kPa. The error is mainly caused by friction from three sets of O-rings, which becomes significant when a low sleeve friction is to be measured.

Field vane tests may be used to remould the quick clays in situ. However, uncertainties due to a thin remoulded zone and partial consolidation may lead to overestimation [18-20] of the remoulded shear strength.

The only reliable current approach to verify quick and brittle clays remains to be laboratory fall cone tests on remoulded samples retrieved from the field [5]. This approach is time-consuming and costly. Thus, normally only a few samples are extracted from each borehole, providing non-continuous data over the depth.

These above deficiencies of existing approaches necessitate development of an accurate, reliable, continuous and sample-free approach. Such an approach must satisfy three demands: 1) sufficient remoulding of the clays, 2) the equipment must be robust enough to avoid bending and abrasion during penetration and rotation through stiff layers, 3) the sensors must have sufficient accuracy to directly measure the weak response from remoulded quick clays. Demand 2) and 3) are seemingly contradictory, because the sensor resolution is usually proportional to measuring range, and high resolution at low stress levels is hard to obtain in a robust equipment.

In this study, we tested a two-step approach for in-situ detection of quick clays. The goal was to verify that: 1) quick clays can be fully remoulded by a proactive in-situ test equipment, a mixer; 2) one can directly measure the resistance of the fully remoulded quick clay in situ. The results from the two-step approach applied herein are to be used in future development of a more practical tool which aims for a one-step approach with remoulding and measurement of remoulded shear strength in the same operation.

2 Description of the approach

2.1 Test equipment

Given the deficiencies of existing geotechnical site-investigation methods, a two-step equipment is proposed to ensure both complete remoulding of quick clay and accurate measurement of its in-situ remoulded shear strength.

2.1.1 Mixing module

A 250 mm-diameter miniature deep-mixing device, hereafter called the mixing module, has been developed based on the rotating deep-soil mixing experience. This is done by welding several steel plates close to the lower end of a total sounding rod, Fig.1a.

The blades tilt 30 degrees from the horizontal plane, and the design aims to effectively remould of the soil during counterclockwise (seen from top) rotation with simultaneous vertical penetration. Such diameter is chosen to provide a reasonably large remoulded zone and avoid quick consolidation of remoulded quick clay, and simultaneously to avoid blade damage.

Fig. 1. Equipment for field detection of quick clay, (a) mixing module; (b) modified T-bar.

Depending on the topsoil, the penetration and rotation is either started at the terrain surface or from a predrilled depth. The mixing module penetrates vertically with a prescribed penetration velocity and a selected rotation per minute (RPM). The operator can increase remoulding amount by increasing the RPM and by reducing the vertical penetration speed.

2.1.2 T-bar

T-bars has previously been applied for determining undrained shear strength in soft clays [13] offshore. The "bearing" area of the T-bar is much larger than the "bearing" area of a conventional tip, thereby amplifying the resistance and increasing the accuracy.

In this study, the T-bar has a cross-sectional diameter of D = 40 mm and a horizontal length of L = 150 mm (standard is 250 mm). The T-bar is mounted on a normal CPTu probe (ISO Type I CPTU) Fig. 1b, by substituting the conical tip with a T-bar. The short length of 150 mm and centralizing metal "wings" on the rod, in the plane of the T-bar, ensures that the T-bar remains reasonably centralized within the 250 mm diameter column of remoulded soil. This prevents contact between the T-bar and undisturbed clay surrounding the 250mm hole, see Fig. 1.

2.2 Field test procedure

There are two steps in the field test procedure (Fig. 2):

1) Mixing
The mixing is controlled by the rotational velocity ω in rotations per minute (RPM), and by the vertical penetration velocity v_M in mm/s. Normally, $\omega \leq 90$ RPM, whereas $v_M \leq 50$ mm/s, as bounded by the common boring machine's output power. In practice, the rotational speed of ω = 60 RPM is achievable and repeatable in the field without incurring blade damage

during penetration. The penetration speed of T-bar was first set to be 20 mm/s, which is close to the penetration speed of a normal CPTU.

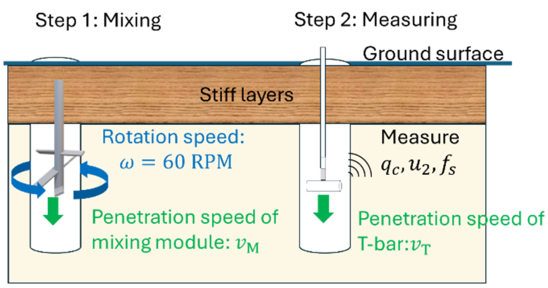


Fig. 2. Measurement procedures.

2) Measurement

The measurement is done by inserting the T-bar in the hole after removing the mixer. The T-bar is lowered with a constant penetration rate. The "tip resistance" (q_c), pore pressure (u_2) above the T-bar and the sleeve friction (f_s) are all measured. The verticality is monitored in the CPTu interface.

2.3 Interpretation of remoulded shear strength

The following derivation assumes that the T-bar penetrates a fully remoulded quick clay with effective stress close to zero. The T-bar reading is zeroed in free air at the terrain surface just before being lowered. As the T-bar penetrates the remoulded soil, the corrected (considering the area factor and pore pressure [22]) resultant force on the CPTu probe (Fig. 3) is:

$$Q_t = [q_c + (1-a)u_2]A_0 \tag{1}$$

where A_0 is the cross-sectional area (10 cm2) of the CPTu rod and a is the area factor specific to the applied CPTu probe.

The total force equilibrium of the T-bar gives:

$$Q_t = \gamma_{\text{clay}}\tfrac{1}{4}L\pi D^2 + u_2A_0 + N_c s_{\text{ur}}DL \tag{2}$$

where the first term accounts for the buoyancy of the horizonal T-bar beam, and γ_{clay} is the unit weight of remoulded soil. This buoyancy is considered because the T-bar ("tip") force reading was zeroed in the air. In addition, as given in the second term, the pressure in the remoulded quick clay (mud pressure) gives an upward force resultant (buoyancy) here assumed to be equal to u_2A_0. This pressure is usually not equal to the in-situ vertical total stress because the insertion of the rod increases the pressure in the remoulded clay column. Therefore, here the mud pressure is assumed to be equal to the pore pressure response u_2 as the effective stress is nearly zero in the remoulded quick clay, almost acting as a liquid. The last term, $N_c s_{\text{ur}}DL$, is the resistance against penetration.

The undrained shear strength, s_{ur}, of the remoulded quick clay can then be then calculated as:

$$s_{\text{ur}} = \frac{1}{N_c}\left(\frac{q_c - au_2}{\eta} - \frac{\pi\gamma_{\text{clay}}D}{4}\right) \tag{3}$$

where $\eta = \frac{DL}{A_0} = \frac{0.04\text{m}\times0.15\text{m}}{0.001\ \text{m}^2} = 6$ is the area amplification ratio applying the T-bar instead of the normal CPTu tip. A detailed illustration of the mechanical derivation is visualized in Fig. 3. In ordinary CPTu, the vertical stress (σ_v) is used as the reference stress. In Eq. 3, the pore pressure response u_2 accounts for the upward force u_2A_0 that presses the rod upward when we push the rod downward into a remoulded mud.

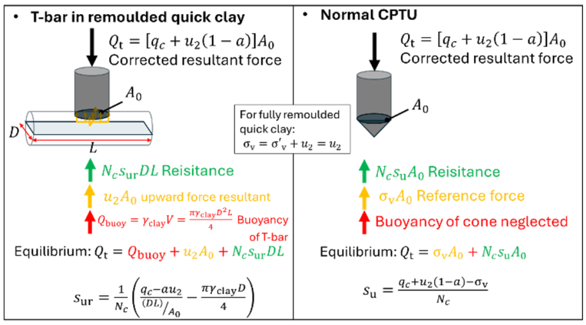


Fig. 3. Interpretation of remoulded shear strength of full remoulded quick clay, comparison between the T-bar and a Normal CPTu.

This assumption is valid only for fully remoulded quick clay, where the effective stress is zero. In cases where the clay is not fully remoulded, or if the remoulded clay re-consolidates in the pause between mixing, calibration and measuring, the force u_2A_0 underestimates the reference stress and Eq. 3 then overestimates the remoulded shear strength.

2.4 Uncertainties of the new approach

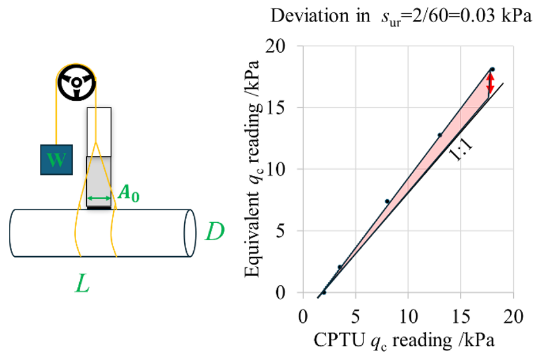
Eq. 3 reflects the mechanical relationship between the remoulded shear strength, measured values and the geometry. Geometrical parameters (D, a, η) can be very well measured and do not have significant uncertainties. Unit weight of remoulded quick clay γ_{clay} is usually between 18-20 kN/m^3, which gives a deviation at the scale of $\Delta s_{\text{ur1}} = \frac{1}{N_c}\left(\frac{\pi D * 2\ \text{kN/m}^3}{4}\right) \approx 0.006\ \text{kPa}$. The only seemingly empirical parameter is the bearing capacity factor N_c. We have a well-defined theoretical solution of N_c (bounded between 9-12) [21] for the T-bar if the clay is homogenously remoulded. Then the uncertainties of measured tip resistance q_c and pore pressure u_2 remain.

We examined the accuracy of our tip resistance sensor with a string-roller system, Fig. 4a. A weight was hung on one end of the roller, and the other end was tied to the T-bar, so an upward load with known weight was applied. The accuracy check was done before each test. The tip resistance reading was shifted from default MPa to kPa in the viewing software to facilitate accurate readings. Some reading jumps at the scale of $\pm$ 1 kPa were observed, and several readings were made to achieve a stable average value. Fig. 4a shows the scatter plot of the equivalent tip resistance calculated from the weight $\frac{W}{A_0}$. versus the tip resistance reading (q_c). The scattered plot was very linear and deviates only slightly to the 1:1 line. The intercept in the reading was recorded to serve as zero correction. After zero correction, the deviation of tip resistance read compared to the applied value (red zone) was bounded by 2 kPa. This limits the error in remoulded strength caused by the uncertainty in the tip resistance to $\Delta s_{ur2} = \frac{1}{N_c}\left(\frac{2\text{ kPa}}{\eta}\right) \approx 0.03$ kPa . This means that the tip resistance reading (q_c) has more than sufficient accuracy.

Similarly, the same calibration / verification system was used on the friction sleeve and showed that the sleeve friction has lower accuracy, characterized by a deviation of around 0.2-0.3 kPa. This is marginally acceptable. The sleeve friction is not used in Eq. 3, but it serves as an auxiliary measurement of remoulded shear strength.

It may be added that the rather recent calibration certificate from the manufacturer shows that the pore pressure sensor has an average deviation of 2-4 kPa. This contributes to a deviation of $\Delta s_{ur3} = \frac{1}{N_c}\left(\frac{a*(2\sim4\text{ kPa})}{\eta}\right) \approx 0.03\sim0.06$ kPa . This value only accounts for the resolution of the sensor itself.

The resultant uncertainties from tip resistance, pore pressure and unit weight of clay can be roughly estimated as $\sqrt{\Delta s_{ur1}{}^2 + \Delta s_{ur2}{}^2 + \Delta s_{ur3}{}^2} = 0.07$kPa.



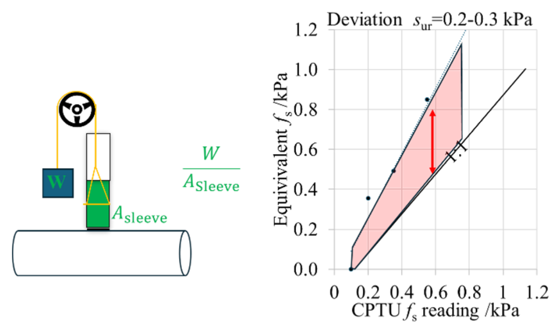


Fig. 4. Field examination of sensors before testing: (a) f Field examination of tip resistance (q_c) and (b) field examination of sleeve friction (f_s).

3 Test results

3.1 Test site NGTS Tiller-Flotten

The in-situ tests were done on the well documented National Geotechnical Test-Site (NGTS) Tiller-Flotten [10,11,14] in Trondheim, Mid-Norway. The terrain is flat and the layering is relatively homogeneous and horizontal. Historical photos show that the terrain has not undergone significant changes in the recent 70 years and no major geological processes have been active for many centuries. It is known that the upper layer (0-2.0 m) is a dry crust. The dry crust rests on a layer of low to medium sensitive clay (2.0-7.5m). Quick clay is found between 7.5 m and 20 m.

As part of this research project, many conventional and experimental site investigations have been conducted, including sampling and laboratory tests including fall cone tests (NIFS report) [15-17], Rotary CPTU (DRTCPT) [10], Ball Penetrometer Test (BPT) [11], and a series of special CPTu tests with modified elongated tips [12].

The two T-bar tests with mixing module presented herein were carried out by two independent operators in March and May 2025. The results are presented in Section 3.2 and 3.3.

3.2 Field test in March 2025

Measured values from the field test in March 2025 is found in Fig. 5. First, the mixing module was mixing the soil from terrain to 8.8 m depth applying a constant rotation velocity of 60 RPM and penetration velocity v_M of 20 mm/s. From 8.8 m depth the rotation speed was kept the same, but the penetration speed was lowered to 10 mm/s, thus increasing the remoulding amount in the deepest part ending at 9.8 m depth. After checking the accuracy of the T-bars tip resistance and the sleeve friction as described in section 2, the T-bar was lowered into the same hole. The T-bar's penetration velocity v_T was the same as applied during mixing.

Fig. 5 shows that both the tip resistance and sleeve friction are abruptly reduced at around 7.5 m depth, which according to previous fall cone tests [15-17] corresponds well with the known transition depth from non-quick to quick clay.

Fig. 6a shows the calculated remoulded shear strength s_{ur} applying Eq. 3. The value is comparted to the measured sleeve friction during the same test and the remoulded shear strength from previous sampling and fall cone tests. All three remoulded shear strengths mark a clear reduction between 6-8 m depth. The T-bar calculated s_{ur} is significantly higher than the sleeve friction from terrain surface to 7 m depth, but the difference diminishes from 7 m downwards. According to previous site investigations, soil layers above 7 m depth are non-quick and significant effective stress thereby remains after remoulding. According to Section 2.3, this overestimates the remoulded shear strength in the upper soil layers.

The T-bar calculated s_{ur} becomes lower than the sleeve friction from 8 m depth and downwards, and the sleeve friction shows clear zig-zags between 0.6 to 0.8 kPa, with minimum jumps intervals at 0.1 kPa level. This indicates that sleeve friction may have reached its lower limit of accuracy and might not be able to pick up any lower values. In contrast, the T-bar calculated s_{ur} continues to go down to 0.3-0.6 kPa level, with much finer jumps in values, showing that the T-bar calculated s_{ur} has higher accuracy than the sleeve friction.

Both the calculated s_{ur} and sleeve friction show a reduction from 8-9 m segment ($v_{\mathrm{M}} = 20\mathrm{mm/s}, v_{\mathrm{T}} = 20\mathrm{mm/s}$, low remoulding) to 9-10 m segment ($v_{\mathrm{M}} = 10\mathrm{mm/s}, v_{\mathrm{T}} = 10\mathrm{mm/s}$, high remoulding). Given that the fall cone tests indicate constant remoulded shear strength from 8-10 m, natural variation of remoulded shear strength is unlikely. Possible reasons for such difference can be a) segment 8-9 m is not as remoulded as 9-10 m, b) higher penetration speed of the T-bar at 8-9 m segment gives a higher measured strength than for the 9-10m segment.

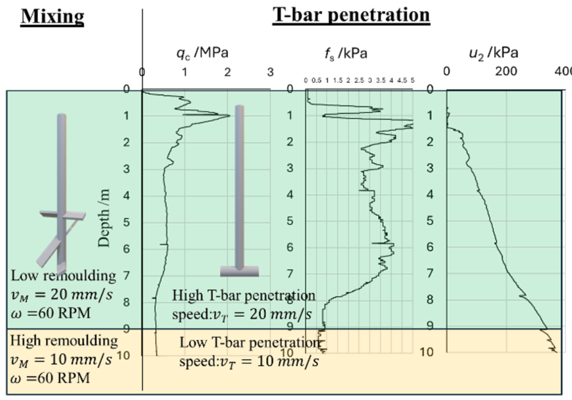


Fig. 5. March 2025 results: (a) tip resistance, (b) sleeve friction, (c) pore pressure (green zone marks standard remoulding energy during mixing, yellow zone marks higher remoulding energy.).

The remoulded shear strengths from fall cone tests are in this case always lower than the T-bar calculated s_{ur} and sleeve friction at the same depth. The difference between the two values in 8-9 m segment is higher than in the 9-10 m segment. Several factors may contribute: a) the remoulding applied in the field may not be enough to fully remould the quick clay; b) even for the fall cone tests uncertainties exist; c) the boundary conditions are different in the lab compared to the field; d) loading rates are different.

Nevertheless, the limited data shows that the ratio of calculated s_{ur} to fall-cone-test counterpart is around 2-3 times, but roughly at the same magnitude. Further studies are needed to provide more insights into if one can bring the T-bar calculated s_{ur} even closer to the laboratory values.

3.3 Field test in May 2025

The same equipment was used again in May 2025 by another operator to examine the repetitiveness of the proposed approach. The test site was 5 m from the previous test site in March. Three different levels of remoulding (high, medium and low, as marked by red, yellow and green zones to the left) were exerted to three segments (8-9m, 9-10m, 10-11m) by controlling the mixing modules penetration speed v_{M}. Four T-bar penetration speeds ($v_{\mathrm{T}} = 5\ \mathrm{mm/s}, 10\ \mathrm{mm/s}, 20\ \mathrm{mm/s}, 40\ \mathrm{mm/s}$, as marked by red, grey, blue and yellow) were conducted in the same hole. This was done by lifting the T-bar to 8 m after it reached 11m, rotating it 90 degrees before being repenetrated in the same hole.

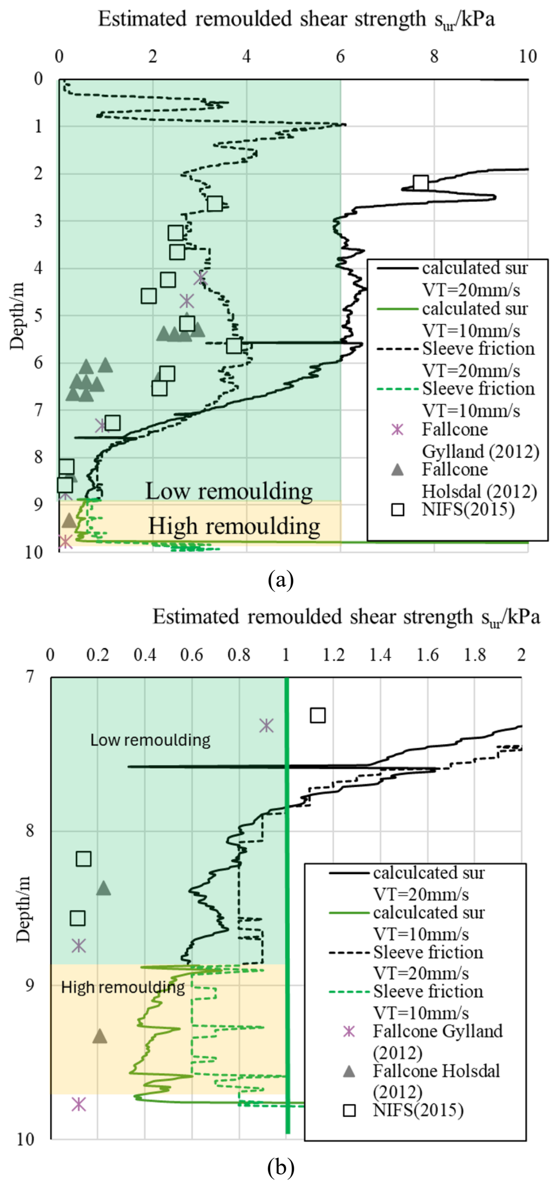


Fig. 6. Comparison among estimated remoulded shear strengths from calculated $\boldsymbol{s}_{\mathbf{ur}}$ from Eq. 3, sleeve friction and fall cone tests (Soil layers above 6 m are not quick clay, values calculated by Eq. 3 leads to significant overestimation): (a) overview and (b) detailed view.

Fig. 8 shows the sleeve friction for the four penetrations in the same hole from 8 to 11 meters depth. The higher values at about 11m depth may be caused by the T-bar entering non-remoulded clay below the penetration of the mixer.

It seems like the uncertainty caused by friction sleeve accuracy disturbs the picture and a clear conclusion cannot be drawn. Still, we observe that very low estimated remoulded shear strengths (assumed to be equal to sleeve friction) below 1 kPa are measured and that results from several re-penetrations are rather similar. There is a tendency of higher strength with lower remoulding.

Fig. 9 shows remoulded strength calculated based on the T-bar tests from 8 to 11 meters. The increasing strength with depth may come from less remoulding with depth and indicate that a lot of mixing is needed to fully remould the clay. The curves for the remoulded strength show limited spread which indicates good repeatability for the T-bar.

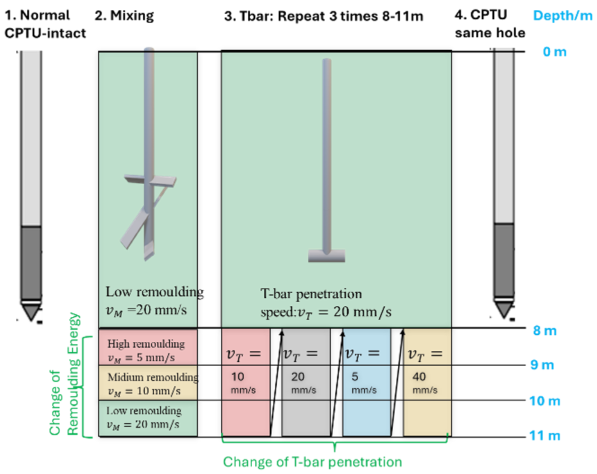


Fig. 7. Test procedures in field test in May 2025.

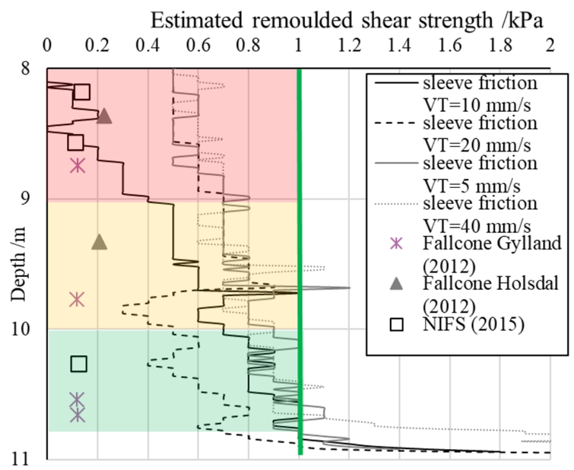


Fig. 8. Sleeve friction with different T-bar penetration rate and different amount of remoulding.

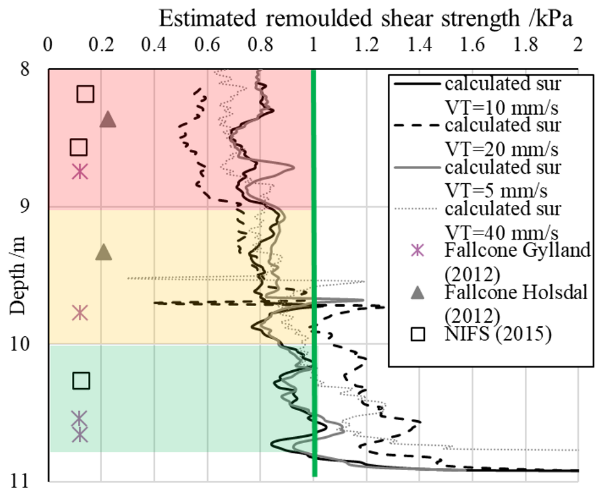


Fig. 9. Calculated s_{ur} with different T-bar penetration rate and different remoulding energy (Red zone marks high remoulding energy; yellow zone marks medium remoulding energy; green zone marks low remoulding energy).

3.4 Repeatability

Fig. 10 compares the sleeve friction and calculated s_{ur} for the same remoulding amount and penetration rate of the T-bar (namely, ω = 60 RPM, $v_M = 20\text{mm/s}, v_T = 20\text{mm/s}$). The same, limited depth interval is compared, 9-9.8 m. The two bore holes are 5 m apart. The results shows that the measured sleeve frictions from the two neighbouring tests are similar whereas the calculated s_{ur} from the T-bar measurements shows more deviation. The sleeve friction is normally expected to have more uncertainty than the T-bar calculated s_{ur}. The deviation may be because of:

1) horizontal spatial variation of remoulded shear strength.
2) partial consolidation during mixing as there was a longer pause between mixing and T-bar penetration in the in-situ test carried out in May than in March.

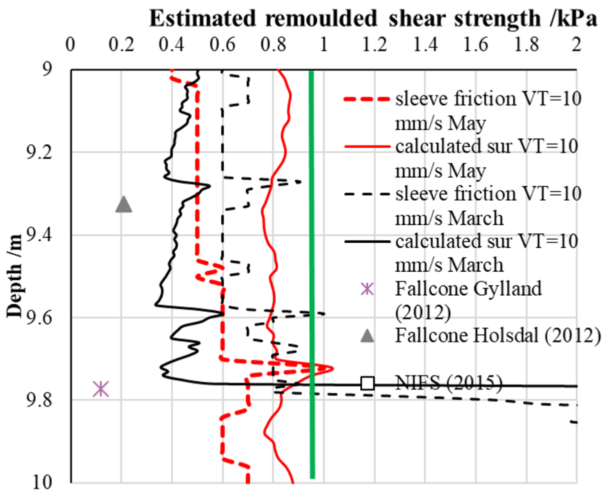


Fig. 10. Comparison between two tests in March and in May for the same depth with the same remoulding amount, the same T-bar penetration speed, but different operator.

4 Conclusions and Recommendations

4.1 Conclusions

This research shows promising results for in-situ detection of quick clay. The following conclusions can be drawn:

1) It is found that a mixing module on a rotating total sounding rod may remould the clay to a "fully remoulded" state. It is, however, found that a lot of remoulding is needed with high RPM and low penetration velocity. Even higher energy levels than used herein may be considered.
2) A CPTu with T-bar concept can be used to amplify and measure the weak response (low strength) of the remoulded quick clay. The method used herein, calculating the undrained strength from the T-bar "tip" resistance and the u_2 pore pressure, seems to work well.
3) The friction sleeve may also help detect quick clay, but the accuracy is marginally acceptable.

Application requires that the sleeve is well calibrated with proper reading of the zero point, has smooth surfaces for new O-rings and is well lubricated.

4.2 Limitations

The two-step approach proposed in this study is still a proof-of-concept study and is not intended as the final product. The results will be used in developing a more practical equipment going from the two-step to a one-step approach. The following uncertainties and drawbacks exist:

1) This approach requires two penetrations, one for remoulding and one for measuring. This means that the remoulded clay is left in the hole for a while and may get some strength increase while we prepare for the T-bar test. And the T-bar must be centralized in the hole making sure that the centralizing wings do not cut pieces of unremoulded soil from the wall into the hole. This problem may be avoided if both mixing and measuring is conducted in one operation.
2) Uncertainty in the pore pressure response (u_2) measurement. The pore pressure response measurement is exposed to lots of uncertainties apart from its own resolution. Suction during penetration through dilative layers (sand, gravel) may suck out saturation liquid and lead to significantly lower pore pressure (or even negative pore pressure).

4.3 Plans for further development

The field tests using the two-step approach show that considerable proactive soil remoulding is required for detection of quick clay in the field. It is realized that time between remoulding and measurement of strength is critical due to thixotropic effects. Further research will focus on the development of more robust and time efficient approaches. Several possibilities are under planning and may include measurement of intact strength on the way down and remoulded strength while the drill string is pulled up again.

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