Detecting quick clay with CPTu

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ABSTRACT
The cone penetration test with porepressure measurements (CPTu), is a popular in-situ test, used to investigate geotechnical properties of soils as well as layering.

In the standard test, three main variables are registered in the cone while penetrating at a fixed rate. These parameters are the cone resistance, sleeve frictional resistance and the porepressure.

There exist many classification diagrams for CPTu, and some of these include areas meant to indicate the presence of sensitive materials. These diagrams provide very useful information for a rough evaluation of soil type and layering, but when it comes to identifying sensitive materials, they have been found to be unreliable.

In this study CPTu data from 5 test sites in Norway are linked with results from laboratory tests, and divided into two categories, quick clay and non-sensitive materials, for further analysis.

The objective of the study is to show that if the standard CPTu test produces results that can be used to detect sensitive materials in the soil, then the accuracy of detection can be improved by analyzing all three variables simultaneously.

The result of the study is that this approach shows promise, and a model that improves detection rate and reduces the number false positives is presented.

A web app has been developed to aid with the 3D part of the study, as well as to provide a tool so anyone can access and use the presented models.

Keywords: Quick clay, CPTu, field investigations

1 QUICK CLAY

The term quick clay describes extremely sensitive fine-grained materials. These materials were sedimented in a marine environment following the retreat of the glaciers at the end of the last ice age.

The post-glacial rebound lifted these sediments above the sea level, exposing them to fresh water that over time washed the salt out of the porewater. Such materials can be found up to the previous sea level of the last ice age. (NGI, 1982)

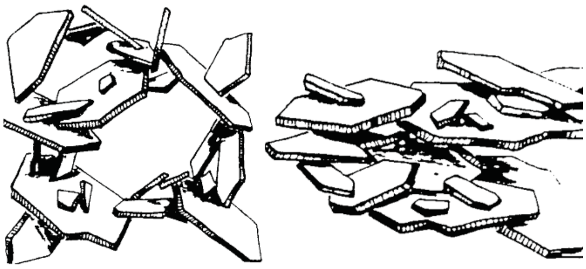
a) b)

Figure 1 A simplified drawing showing clay particles in materials sedimented in a) a marine environment and b) a fresh water environment. (Statens vegvesen 2010 - figure from Leirskred i Norge *by Jørstad F.A., 1968).*

A popular illustration of the marine clay “card-house” structure is shown in Figure 1 a) (Statens vegvesen 2010).

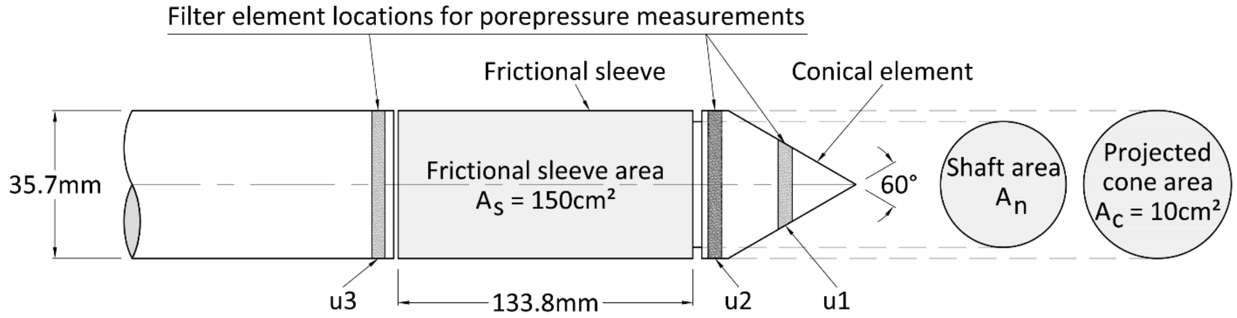

Figure 2 The standard (reference) 10cm^2 piezocone. Based on a similar figure in CEN (2012)

The edge versus face orientation of the quick clay particles allows for high water content as well as a collapsible grain structure, compared to the parallel alignment of the fresh water clay particles.

The sensitivity of soil materials is defined as

$$S_t = \frac{c_u}{c_{ur}} \tag{1}$$

where c_u is the undrained shear strength and c_{ur} is the remoulded undrained shear strength, usually determined by the fall cone test. Quick clay is defined from the remoulded undrained shear strength alone as

$$c_{ur} < 0{,}5 kPa \tag{2}$$

Undisturbed quick clays can exhibit considerable strength, but their state can change to liquid so they flow in their own porewater when subjected to stresses above their capacity.

Because of the potential devastating consequences of even a small initial landslide in quick clay areas (NGI 1982), extensive field investigations and use of larger safety factors for geotechnical design is required in areas with sensitive soils.

2 PIEZOCONE PENETRATION TEST – CPTU

The cone penetration test is a popular soil investigation method used to evaluate the geotechnical properties of soils as well as layering.

The first variant of the cone penetration test was a mechanical cone developed in the Netherlands in the 1930s, since then the test has become increasingly popular and many cone designs have been produced. Among the biggest design advancements was the introduction of the frictional sleeve (1950s) and the porepressure element (1980s) (Lunne et al., 1997).

The design of the cone has been standardized (CEN, 2012), and the geometry of the standard (reference) 10cm^2 piezocone is shown in Figure 2.

Using a standard reference test, experience from one site can be transferred to another. This then aids in the establishment of general empirical models for evaluation of the various material properties.

2.1 Basic measurements

The test procedure consists of pushing a cone into the ground at a fixed rate of 20mm/s and taking measurements at fixed intervals. The measurements required to reach the highest Application class (CEN, 2012) are

- Cone resistance force
- Sleeve frictional resistance force
- Penetration length
- Porepressure
- Cone inclination

The cone resistance, q_c (kPa), and the sleeve friction resistance, f_s (kPa) are the basic output parameters, calculated by dividing the measurements with the projected cone and frictional sleeve area respectively.

Other parameters can also be measured with special cone types and surface equipment but this is beyond the scope of this study.

2.2 Porepressure measurements

Porepressures acting on the cone during a test will influence the load measurements. This is due to the geometry of the cone, as well as variations in the porepressure along the cone during the test.

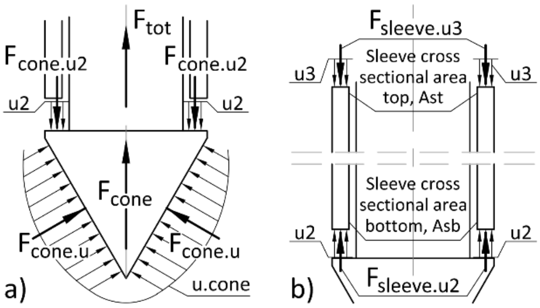

Figure 3 Porepressure influence on load measurements. Drawing created from figures and graphs in Lunne et al. (1997).

Figure 3 a) illustrates that porepressures acting on top of the conical element will result in a downward pointing force. This force reduces the measured cone resistance force, causing a lower registrations for the cone resistance.

Porepressures acting on the ends of the frictional sleeve will influence the frictional force measurements in a similar manner as illustrated in Figure 3 b.

These porepressure effects can be eliminated with the following equations

$$q_t = q_c + u_2 \cdot (1 - \alpha) \qquad (3)$$

$$f_t = f_s - \frac{u_2 \cdot A_{sb} - u_3 \cdot A_{st}}{A_s} \qquad (4)$$

where q_t (kPa) is the corrected cone resistance, u_2 and u_3 (kPa) are the porepressures measured just behind the conical part and friction sleeve respectively, α (-) is the cone net area ratio, f_t (kPa) is the corrected sleeve frictional resistance, A_{sb} and A_{st} (cm^2) are the sleeve cross sectional areas at the top and bottom of the friction sleeve and A_s (cm^2) the area of the friction sleeve.

The cone net area ratio, α (-), and the friction sleeve net area ratio, β (-), are by definition geometrical factors. They are however in practice evaluated in a pressure calibration chamber (NGF 2010).

All soundings used in this study are made using a standard 10cm^2 reference piezocone with porepressure measurements just behind the cone, at the u_2 location. In order to correct the sleeve frictional resistance, a measurement of u_3 is required.

As u_3 is not registered in any of the cones used in this study, f_s is used for the frictional resistance in all calculations.

3 APPLICATION OF CPTU TESTS

The CPTu test is popular in Norway, and it is often used in combination with other methods to provide a more detailed description of the soil conditions at selected locations and depth intervals.

Some advantages and disadvantages of CPTu tests can be

+ A tried and tested method
+ A standardized test
+ Possible to get relevant data of good quality
+ Quick and *(often)* easy to execute
+ Can be implemented on *normal* drill-rigs
+ A strong, well-documented foundation for interpretation as well as new methods still being developed
+ Possible to get results fast (*real time*)
− Limited capacity in hard/compacted soils
− Requires skilled operators and engineers for quality results
− Difficulties maintaining saturation of porepressure system when penetrating coarse/hard materials, and therefore requires real time evaluation of test data
− Porepressure system is sensitive for low temperatures

Because of tight logging increments, the engineer *(often)* ends up with a continuous profile with relevant data. When combined with high quality laboratory tests on samples from the project site, the cone penetration test can provide a strong basis for geotechnical design.

3.1 Classification with CPTu

When it comes to evaluating soil strength, stiffness and classification, no in-situ method replaces soil sampling and laboratory testing. Collecting and testing soil samples is both time consuming and expensive, so any field methods that reduce the need for- or better focuses the sampling are valuable.

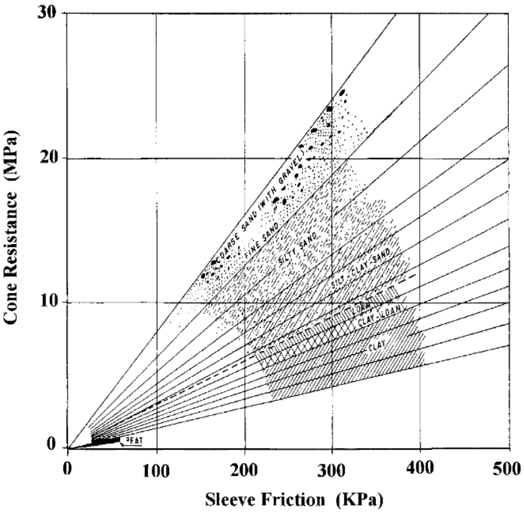

Figure 4 The first soil profiling chart for CPT, after Begemann in 1965 (from Eslami and Fellenius, 2000)

Begemann published the first soil profiling chart in 1965 which showed that the soil type should not be regarded as a function of the cone resistance or the sleeve friction alone, but rather a combination of both. (Eslami et al., 2000)

Since such charts were first introduced, using them to evaluate ground conditions has become a popular practice and this method for soil analysis is available in most software packages for CPTu interpretation.

Throughout this paper, the terms *classification* and *classification diagrams* are used to describe the analysis of CPTu data. This is not the same as *soil classification*, which refers to the determination of soil type with laboratory testing.

3.2 Derived variables for classification diagrams

There are many classification diagrams available today, and some of these are covered later in this paper. To provide a foundation for these diagrams a few relations are given

$$q_n = q_t - \sigma_{v0} \tag{5}$$

$$\Delta u = u - u_0 \tag{6}$$

$$Q_t = \frac{q_n}{\sigma'_{v0}} \tag{7}$$

$$B_q = \frac{\Delta u}{q_n} \tag{8}$$

$$F_r = \frac{f_s}{q_n} \cdot 100 \tag{9}$$

$$R_f = \frac{f_s}{q_t} \cdot 100 \tag{10}$$

$$q_e = q_t - u \tag{11}$$

$$\Delta u_n = \frac{\Delta u}{\sigma'_{v0}} \tag{12}$$

where q_n (kPa) is the net cone resistance, σ_{v0} (kPa) and σ'_{v0} (kPa) are the total- and effective vertical stresses, Δu (kPa) is the excess porepressure, u (kPa) is the measured porepressure, u_0 (kPa) is the at rest in-situ porepressure, Q_t (-) is the normalized cone resistance, B_q (-) is the porepressure ratio, F_r (%) is the normalized friction ratio, R_f (%) is the friction ratio and q_e (kPa) is the effective cone resistance and Δu_n is the normalized excess porepressure.

Any mention of the measured porepressure, u, or the excess porepressure, Δu, without an identifying number refers to the porepressure measured just behind the conical element, at the u_2 location.

Eslami et al. (2000) pointed out that many classification diagrams rely on dependent variables. Without accepting the statements made by Eslami et al. about the possible impact of such variable dependence, one starts to wonder about the true independence of the measured values in CPTu tests.

In order to study this in more detail the following variables are introduced

$$q_{tn} = \frac{q_t}{\sigma'_{v0}} \tag{13}$$

$$q_{tnt} = \frac{q_t}{\sigma_{v0}} \tag{14}$$

where q_{tn} (-) and q_{tnt} (-) are the cone resistance normalized to the effective- and total vertical stresses.

$$f_{sn} = \frac{f_s}{\sigma'_{v0}} \tag{15}$$

$$f_{snt} = \frac{f_s}{\sigma_{v0}} \tag{16}$$

Where f_{tn} (-) and f_{tnt} (-) are the sleeve frictional resistance normalized to the effective- and total vertical stresses.

$$\Delta u_{nt} = \frac{\Delta u}{\sigma_{v0}} \tag{17}$$

$$u_n = \frac{u}{\sigma'_{v0}} \tag{18}$$

$$u_{nt} = \frac{u}{\sigma_{v0}} \tag{19}$$

Where Δu_{nt} (-) is the excess porepressure normalized to the total vertical stresses. u_n (-) and u_{nt} (-) are the porepressure normalized to the effective- and total vertical stresses.

4 IN-SITU TESTS AND SENSITIVE MATERIALS

As stated earlier, the consequences of small initial slides involving very sensitive materials can be devastating. This is why it is important to be able to accurately identify such materials quickly.

It is common practice in Norway to study the force needed to push a rotating probe though the soil at a fixed rate, and look for either very low push-resistance or alternatively depth intervals with constant or decreasing push resistance. This can be done for both the rotary pressure sounding and the totalsounding method. Such behavior is often an indication of sensitive materials as the remoulding caused by the probe acts to reduce rod-friction. Because the push-force in these tests is registered above terrain level, any friction between the rod and layers of compacted/coarse materials have the potential to *hide* sensitive layers.

In order to evaluate the soil sensitivity (*1*), in-situ tests need to be able to give an estimate of both the undisturbed and remoulded shear strength. Identifying quick clay only requires the test to be able to evaluate the remoulded shear strength.

The shear vane test is by definition suited to evaluate material sensitivity, as it can be used to evaluate both the undisturbed and the remoulded shear strength of the soil. As shown in the work of Gylland (2015), the test falls short because it apparently overestimates the remoulded shear strength and thereby underestimates the sensitivity.

CPTu classification diagrams often show zones indicating sensitive materials. Color-coded/patterned columns and diagrams are used to present results from classification which often provides useful information for the evaluation of layering and approximation of soil types. The application of such diagrams for the detection of quick clay is covered in chapter 6.

5 DATABASE OF CPTU DATA AND LABORATORY RESULTS

To provide a basis for this study, a database was created where CPTu data and laboratory results were linked together. The data was collected from actual projects.

The database currently consists of data from 37 positions from 5 test sites in Norway. The locations of the actual sites/municipalities are illustrated in Figure 5.

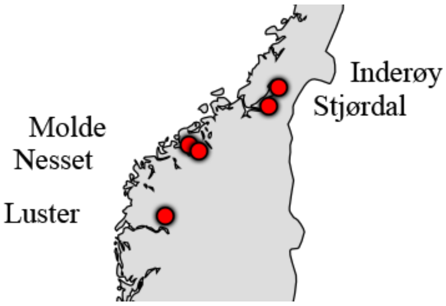

Figure 5 Test site locations currently in the database.

The CPTu tests are conducted using cones with a net area ratio $\alpha = 0{,}605 - 0{,}868$. The accuracy of the equipment used is capable of achieving Application class 1, but this class was not reached in all the soundings.

The laboratory data is collected from both remoulded representative samples, as well as undisturbed soil samples with a diameter of 54mm. The undisturbed and remoulded shear strengths of the test samples are determined in the laboratory using the fall cone test.

The undisturbed samples are cut into 10cm long pieces, and different tests are performed on each piece. The standard setup used has only one fall cone test for each test cylinder. This means that for most of the samples, only a 10cm depth interval has a value registered for the remoulded shear strength.

In an effort to counteract the limited amount of data from each cylinder, the values for the remoulded shear strength are inter-/extrapolated inside test cylinders.

Where the soil conditions are homogenous, the remoulded shear strength is also interpolated between test cylinders in the same position. This increases the amount of datapoints by a factor of around 13.

Such manipulation has the obvious downside of introducing *fictional* data that may skew the results.

In addition to the relevant geotechnical parameters, it is also possible to query the database in such a way that the extrapolated data and tests with an Application class lower than a specified value are excluded from the result.

Figure 6 an undisturbed 54mm soil sample after ejection and cutting. Each piece is approximately 10cm long.

The database was queried for data where the remoulded shear strength is less than 0,5kPa (*quick clay)* and again where the remoulded shear strength is larger than 2kPa (*non-sensitive)*. Samples having a with remoulded shear strength between 0,5 and 2kPa were excluded. Soundings with an Application class 3 or higher were accepted.

A presentation of the base CPTu parameters for both datasets is shown in Figure 7. This is done for all three degrees of data extrapolation.

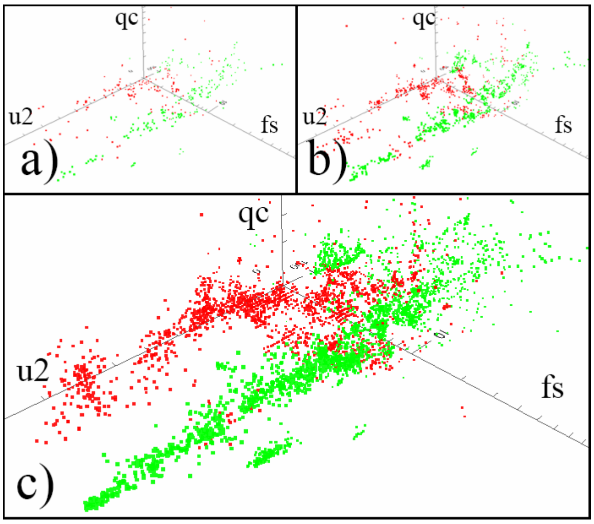

Figure 7 Quick clay (red) and non-sensitive points (green) points with and without data interpolation; a) original data, b) interpolation within the sample cylinder c) interpolation between cylinders

When the datasets in Figure 7 a) to c) are compared it can be argued that with increasing extrapolation, the general shape of the volumes defined by the point cloud becomes more distinctive, and exaggerated to a point.

6 QUICK CLAY DETECTION WITH CLASSIFICATION DIAGRAMS

The database from chapter 5 can be used to estimate how accurately classification diagrams separate the highly sensitive quick clays from non-sensitive materials.

6.1 Database results drawn on classification diagrams

In Figure 8 throughout Figure 14 points from the database are drawn on some common classification diagrams, where the data is interpolated inside each cylinder. Red points indicate *quick clay* and green points indicate *non-sensitive materials*. The sensitive area in each diagram is specified.

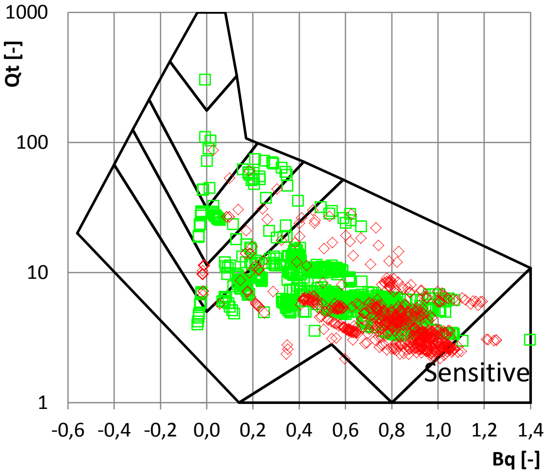

Figure 8 Datapoints on soil behaviour type chart by Robertson ’90 (Lunne et al, 1997) (Rob’90-Bq)

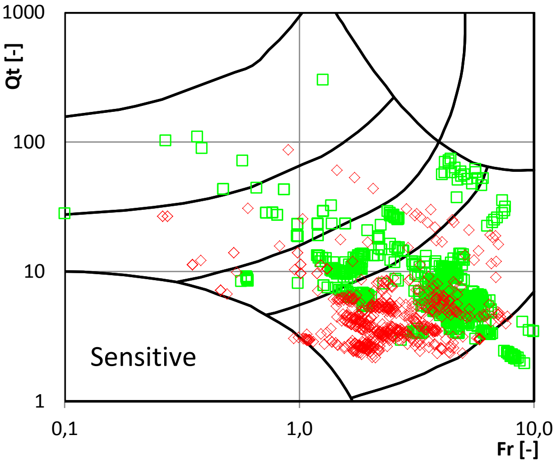

Figure 9 Datapoints on soil behaviour type chart by Robertson ’90 (Lunne et al, 1997) (Rob’90-Fr)

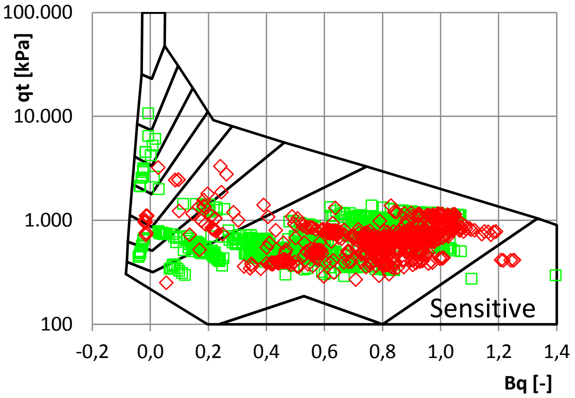

Figure 10 Datapoints on soil behaviour type chart by Robertson et al.’86 (Lunne et al, 1997) (Rob’86-Bq)

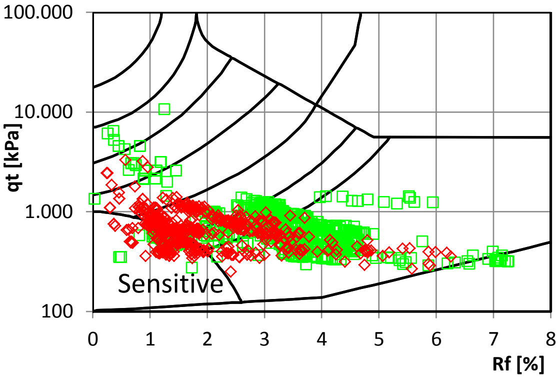

Figure 11 Datapoints on soil behaviour type chart by Robertson et al.’86 (Lunne et al, 1997) (Rob’86-Rf)

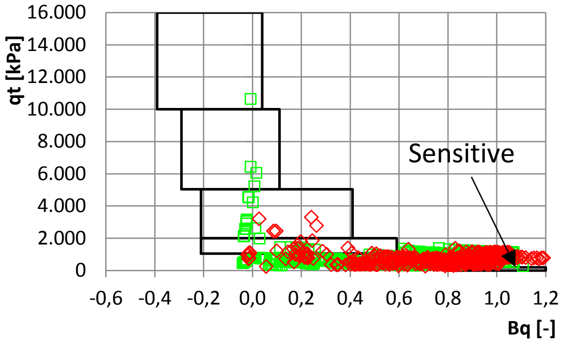

Figure 12 Datapoints on chart by Senneset et al.'89 (Eslami et al, 2000) (Sen'89)

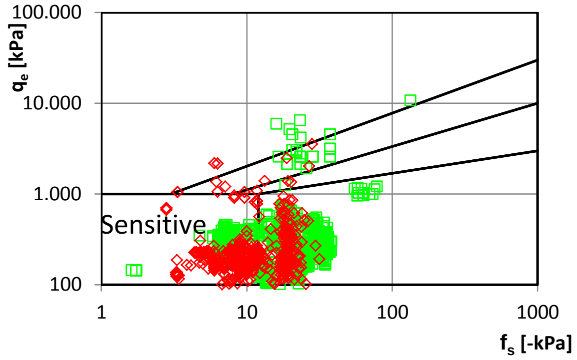

Figure 13 Datapoints on soil behaviour type chart by Eslami et al., 2000 (Esl'00)

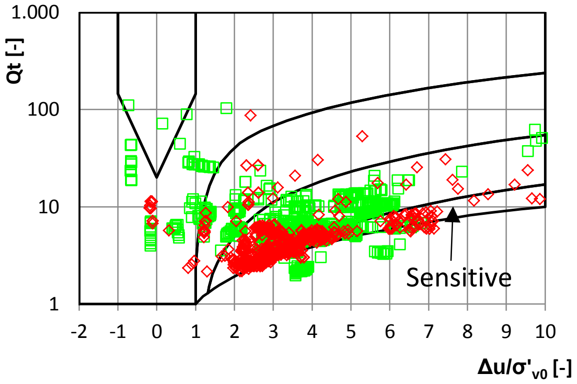

Figure 14 Datapoints on soil behaviour type chart by Schneider et al. 2008 (Sch'08)

Table 1 contains the results from the analysis with no interpolation of the data. It looks as if methods based on friction have an advantage over the others when it comes to detecting presence of sensitive materials, with the exception of Rob'90-Fr.

Table 1 Summary of classification of sensitive materials with classification diagrams for the case of no data interpolation

Diagram	**Quick clay points classified as quick clay [%]**	**Non-sensitive points classified as quick clay [%]**
Esl'00	64,9	10,3
Rob'86-Rf	38,6	8,5
Sch'08	15,2	13,0
Rob'90-Bq	0,6	0,9
Rob'86-Bq	0,6	0,9
Rob'90-Fr	0,0	0,0
Sen'89	0,0	0,0

Every method that correctly identified over 1% of the quick clay datapoints as sensitive also had a high percentage of false positives.

It should be emphasized that the points used in this study are taken from 5 test sites, as shown in Figure 5. It is likely that with a larger database these results will change.

7 VARIABLES FOR A NEW 3D MODEL

In order to analyze the data in a 3D space the program *MeanCPT* has been written (Valsson 2015). The program can present datasets in a 3D space. The axes and scales can be specified and the model rotated and moved. Choosing a set of variables for a new model was done by checking all variables shown in in chapters 2 and 3 against each axis and selecting the ones that best divided the datasets.

The result of this process was that the variables B_q (linear-), f_{sn} (logarithmic-) and q_{tn} (logarithmic scale) would give a good starting point. The datasets are shown in this 3D space in Figure 15.

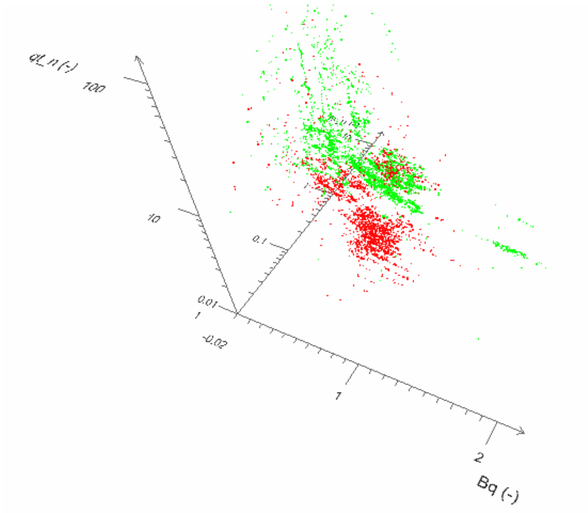

Figure 15 Quick clay and non-sensitive points viewed in the selected 3D space in MeanCPT. The view shows the separation of the datasets.

It should be stated that many other variable combinations were noted as viable candidates that could also give excellent results.

Using a logarithmic scale on the two axis helps exaggerate the area/volume in the model occupied by points of sensitive clay.

8 PROPOSED MODEL

*The datasets with the most data (*interpolation between test cylinders*) were chosen as a base for the new model. These sets are shown in* Figure 15.

In order to define the model, points from areas dominated by non-sensitive materials as well as from areas where quick and non-sensitive materials lie close together were removed. This task was done by hand in AutoCAD.
This process continued until the model was little more than a loosely defined volume defined by an almost entirely red point cloud.

Boundary points were then removed until the expected false positives of the model, defined by the imagined bounding volume, were estimated to be at a minimum.

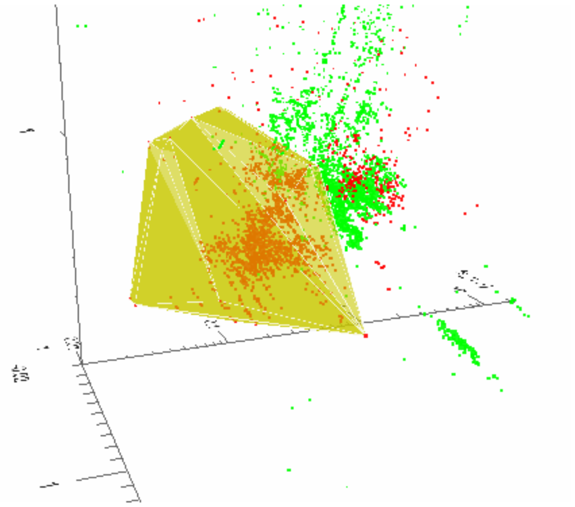

Figure 16 The resulting quick clay model shown along with the datasets in MeanCPT. The volume was defined as a convex hull, and was created using an automated tool in the program MeshLab

The model is created directly from datapoints and is meant to be an example of what is possible to achieve with this kind of study. No attempt was made to make any predictions about areas not defined with data.

The results from the detection process for the database points are shown in Table 2.

Table 2 Summary of classification with 3D model for the varying degree of interpolation

3D model	**Correct [%]**	**False pos. [%]**
Original data	75,4	6,0
Cylinder interpolation	72,2	7,7
Int. between cylinders	81,3	4,6

It is not surprising that the best results come from the dataset from which the model was defined (full interpolation between cylinders).

When compared to the results in Table 1 it is apparent that one can expect to get an increased accuracy for detection of quick clay of about 10-15%, when compared to the diagram with the greatest accuracy. If a penalty is given for false positives this means an increased accuracy of 15-20%.

The database used to create this model is however not large enough to create a general model for quick clay detection.

9 CONCLUSION

The goal of this study is to show that it is possible to define a 3D model that can detect quick clay with greater precision than many 2D diagrams in use today.

The classification diagram proposed by Eslami et al., in 2000 was by far the best 2D diagram for detecting quick clay. However, it still had over 10% of points from non-sensitive materials classified as sensitive (false positives).

The other 2D diagrams give somewhat unreliable results when it comes to detecting sensitive materials and with higher percentage of correct classification, and some had more false positives than correct values.

These results can, and likely will, change with an increased database size.

Out of all tested parameters, the ones chosen for the resulting model seemed to best separate quick clay points from points from non-sensitive materials.

Other parameter sets were observed that could potentially give good results in a study like this.

The approach shows potential and merits further exploration. Increasing the database size (*greatly)* should be prioritized in future work so that a more general model can be created.

To get more data for such studies the laboratory setup for samples from CPTu positions could be modified so that more tests of the remoulded shear strength are conducted. These tests should be close to both ends, as this would aid in the evaluation of remoulded shear strength variations within the sample.

If a number of points from a CPTu test are shown to lie inside the presented model, there is good reason to be on the lookout for quick clay in the area.

Files containing 3D model definitions can be found online, as well as a web-app to check if any depth intervals within soundings are classified as quick with this model (Valsson, 2015).

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