Interpretation of CPTu in Sensitive Fine-Grained Soils and Prediction of Residual Excess Pore Pressures in Consolidating Soils

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ABSTRACT

Robertson (1986) soil classification on Sensitive Fine Grained Soils using CPTu is of interest since the variation of these soils include those of Consolidating Soils. However, the classification does not include into detail such as the influence of the existence of excess pore pressure prior to penetration testing or what is the contribution of the excess pore pressure to the total penetration resistance. Rahardjo et al (2008) studied this phenomena by extrapolation of the dissipation test data to determine the residual excess pore pressure which play an important role in CPTu testing. Further, Rahardjo et al (2016) continued investigation of the CPTu in Consolidating Soils using Bq, Bq* and Effective Stress Concept (Rahardjo et al. 2017). These findings have been very useful when using CPTu in very soft soils and ultrasoft soils where the undrained shear strength of the soils is very low. This paper is the results of several studies of CPTu testing in marine clays, lacustrine, ultrasoft soils or even peats. The author found that there is significant value of Bq and Bq*, hence are parameters of importance when dealing with soft soils and discussed in more detail. Recent applications are in very soft soils and peats in Sumatera and East Java mud eruption which are are also included.

Keywords: CPTu; sensitive fine grain soils; Bq and Bq*; Soft Soils and Ultrasoft soils

1. Introduction

Sensitive Fine Grain Soils can be generally defined as very soft soils with high values of sensitivity and commonly found in marine clays. Salt content can also cause sensitivity. Robertson et al (1986) has defined sensitive fine grain soils using CPTu where the friction ratio is less than 2.5 and the tip resistance is less than 1 MPa of when based on pore pressure ratio Classification, the value of Bq is in the range of 0.8 – 1.4. Figure 1 shows Soil Classification proposed by Robertson (1986). However, the classification does not illustrate in detail such as considering the contribution of the excess pore pressure to the total penetration resistance or the influence of the existence of excess pore pressure prior to penetration testing such as in consolidating soils

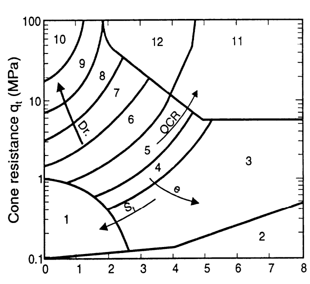

Figure 1. Soil Classification based on CPTu friction ratio (Robertson, 1986)

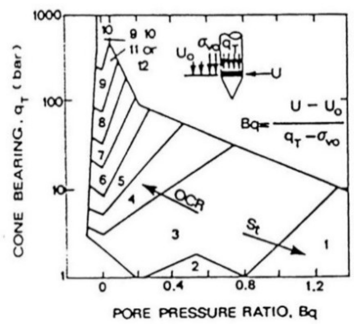

Figure 2. Soil Classification based on CPTu pore pressure ratio Bq (Robertson, 1986)

This paper describes the results of further study and investigation of soft soils, very soft soils and peats which generally fall in the category of zone 1. Of particular interest is due to the existence of initial excess pore pressure in consolidating soils which will be inclusively measured during the course of the cone penetration into the subsoils.

The background of this study was to response to many geotechnical failures during construction due to the unpredicted existence of excess pore pressures which have not been considered in the design stage and neglected during construction. An example of this phenomena was one of the reason of the failures of the Nicol Highway accident in Singapore in 2004. The area was known as reclaimed area over 30 years ago, however excess pore pressure was still measured 30 kPa which might have not been considered or neglected.

Figure 3. One of the cause of Nicol Highway Accidence in 2004 is due to the existing residual excess pore pressure

The challenge is how to detect the magnitude of excess pore pressure or to find out that the soils are still consolidating. A number of research or notifications have been done by Schmertmann (1978), Sakagami and Tanaka and Sugimoto (1989), Rahardjo et al (2008, 2013, 2016 and 2017).

2. CPTu in Consolidating Soils

In consolidating soils, there exist excess pore pressure which has not dissipated or still on the stage of dissipation. The magnitude of the excess pore pressure depend on the initial pore pressure generated by the load or own weight due to sedimentation and the time elapsed. This excess pore pressure is in general neglected in most soil investigation and not detected in laboratory because the excess pore pressure diminish in the laboratory. Hence the laboratory tests have been done without "knowing" that there was excess pore pressure in its original field. Figure 4 illustrate the excess pore pressure shown in the standpipe piezometer.

All those questions are related and need to be considered in the design stage and even during construction, the values of the excess pore pressure shall be taken into account.

The interpretation of CPTu for normally consolidated clay soils and slightly, or strongly over consolidated soils can be conducted as commonly done based on published data and hydrostatic pore water pressure is assumed from information of water table, but there is no initial excess pore pressure. How ever the interpretation of CPTu in Consolidating soils should consider hydrostatic pore water pressure and also the initial excess pore pressure. Hence, care should be focused on the measured higher excess pore pressure and the need to separate between excess pore pressure due to cone penetration and residual existing pore pressure and its effect on the interpretation. Common correlations for normally consolidated soils might not be applicable

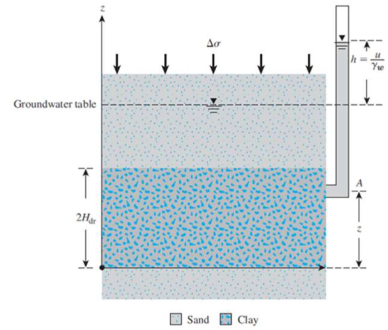

Figure 4. Illustration of excess pore pressure

In Consolidating Soils, the excess pore pressure can be due to its own weight during sedimentation, load of fill placement or can be generated by pile driving. The point of interest for practical purpose is

- What is the magnitude of the excess pore pressure?
- What is the degree of consolidation?
- What is the current shear strength?
- What is the Rate of Pore Pressure Dissipation?

Typical data of consolidating soils may be represented by Figure 4 located in North Semarang City where the city severely suffer from land subsidence and within the last 40 years the land has settled more than 50 cm causing daily flood during high tide. The data shows very soft soils with depth exceeding 20 m and are still consolidating. Referring to the distribution of the total tip resistance q_t and the excess pore pressure, u_2, the resistance is dominated pore water pressure (> 70%) as also shown by the pore pressure ratio Bq reaching as high as 1.4 and 1.5.

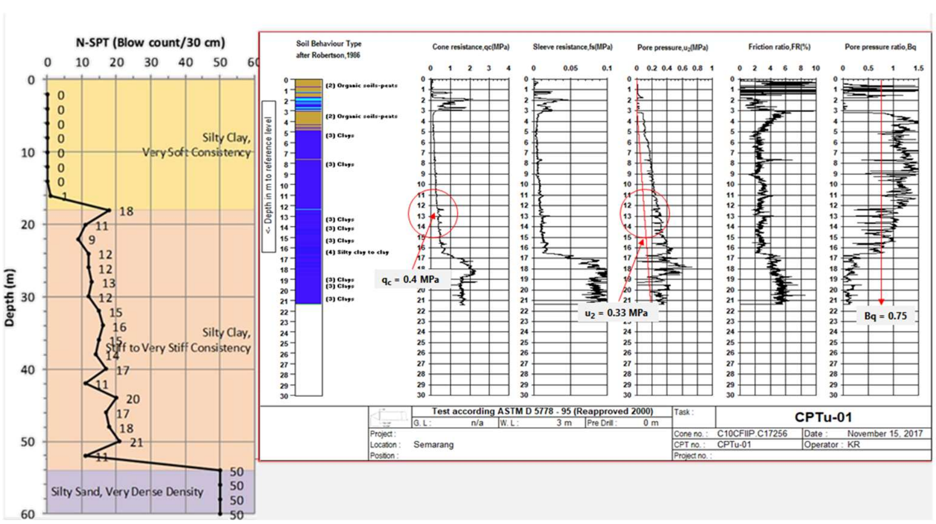

Figure 5. Typical CPTu data of Consolidating Soils in Semarang, Central Java

3. Prediction of Residual Excess Pore Pressures using CPTu

3.1. Method Proposed by Rahardjo et al (2008)

Rahardjo et al (2008) proposed to use results of dissipation test at specified depth. The dissipation curve generally decreasing by time and it is common to use the dissipation curve to predict the rate of consolidation and to derive soil permeability or the coefficient of consolidation in radial direction. Further use of the dissipation test is to extrapolate the dissipation curve until end to find the final porewater pressure at t equals to infinity for instance using plot of the pore pressure against 1/t and determine the pore pressure at infinite time 1/t = 0. This method assumes that the rest of the extrapolation curve is straight line, hence the dissipation test should be conducted sufficiently long for at least 2 hours. Other method to extrapolate the decay of excess pore pressure can be done by use of hyperbolic function to find the termination of the pore pressure u_f. This is straight forward.

In normally consolidated soils, the final pore pressure u_f should be equal to hydrostatic pressure u_o. However in consolidating soil, since excess pore pressure still exists, hence the value of u_f will be higher than the hydrostatic pressure.

After extrapolation the difference of the final pore pressure and the hydrostatic pressure is interpreted as the residual excess pore pressure. To illustrate the use of this method Figure 6 explain the interpretation method.

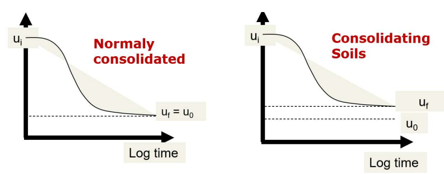

Figure 6. Extrapolation of dissipation curve to obtain residual excess pore pressures (Rahardjo et al, 2008)

3.2. Method to predict excess pore pressure from the degree of consolidation

Once the residual excess pore pressure is determined, the degree of consolidation can be established all over the depth of the soft consolidating layer. On the other hand, the residual excess pore pressure can also be determined if we can calculate the degree of consolidation.

A number of methods to determine the degree of consolidation can be found in many literatures but only a few mention the method using CPTu (Rahardjo et al, 2008, 2013, 2016 and 2017).

Rahardjo and Setionegoro (2013) collect data in Jakarta, Surabaya and Semarang where the soils conditions are either slightly overconsolidated, normally consolidated or still consolidating. In all those area, many CPTu's were conducted and data on the degree of consolidation interpreted from based on laboratory test, vane shear test as well as the dissipation test of CPTu. The data were then correlated with the Bq values and a nicely curve was derived as shown on Figure 7.

During further research on correlating the degree of consolidation and Bq values, the authors found out that when using Bq values, some uncertainties revealed due to the difference in estimating the unit weight or density for the calculation of the overburden pressure. Different values of Bq can cause deviation in interpretation of the degree of consolidation mainly if there is no support data on the soil unit weight. Although some correlation of the unit weights were proposed by Robertson and Cabal (2010) they yield a range of Bq values.

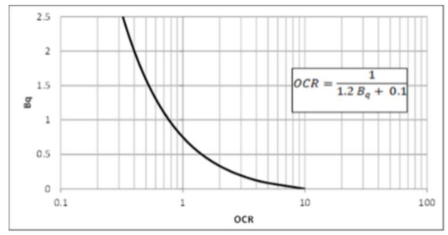

Figure 7. Correlation of The Degree of Consolidation and Overconsolidation Ratio with Bq (Rahardjo and Setionegoro, 2013)

Due to this reason, Rahardjo and Setiawan (2016 – 2017) further investigate from some project site in North Java Indonesia to use the a more independent value as Bq* which is defined as

$Bq^* = u_2/q_t$

The advantage of this value does not depend on the assumption of the unit weight of the soils and hence it become more user independent. Both are measured and really depend on one single value. Other very important advantage of Bq* is because it tells the contribution of the pore pressure response and the effective soil response. In general the maximum value of Bq* is limited to 1.0. The Bq* is then correlated with Bq values where the measured unit weights are available and yield a good curve. The by converting the Bq values into Bq*, a new curve can then generated (Figure 8 and Figure 9).

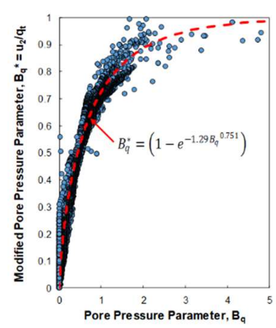

Figure 8. Correlated Bq and Bq* values from selected site (Rahardjo and Setiawan, 2016)

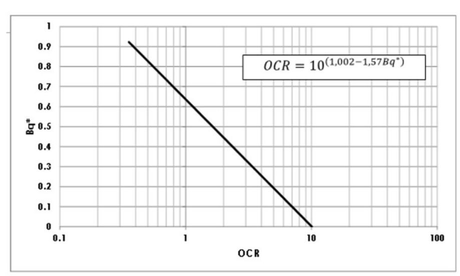

Figure 9. Correlation of The Degree of Consolidation and Overconsolidation Ratio with Bq* (Rahardjo and Setiawan, 2016)

3.3. Case 1 : CPTu in Reclaimed Land

An example of the application of these charts are illustrated in the following. Data was taken at North Semarang area where the site was reclaimed about 15 years ago without ground improvement. The original site was deep water coastal area and the backfill was 7.0 m thickness. For the purpose of new project, site investigation was conducted recently in July 2023. The data is plotted and interpreted as follows (Figure 10).

The CPTu shows that the first upper layer with thickness of 7 m is loose silty sand fill material which is interpreted from the tip resistance and friction ratio, and the underlying layer is soft clay still undergoing consolidation. The thickness of the underconsolidating layer is 18 m (depth from -7.0 m to -25 m below ground surface. Pore pressure show that they are close to the tip resistance with a range of 0.2 MPa to 0.7 MPa in comparison of a range of tip resistance of 0.3 MPa to 1.0 MPa. As shown on the following figure, the pore pressure ratio Bq could be as high as 0.7 to 2.0 which means that the soil is still in under-consolidating layer. Bq* values is higher than 60% confirm that the dominant part of the reaction against cone penetration is by water. And the "calculated effective stress" (from comparison of targeted qt and measured qt). The calculated degree of consolidation could be as low as 40% to 80% which is varying with depth and the middle layer of the soft clay the lowest degree of consolidation of about 40%. The magnitude of the tip resistance (< 1 MPa) and the friction ratio is less than or about 2% meaning that the soil classified as sensitive fine grain soils. The calculated estimate of the settlement is still as high as 78 cm which is regarded to be still unsafe for the buildings. By comparing the qt target and measured qt, it is also shown that the soil is definitely still underconsolidating. The q_t target is calculated based on the estimated shear strength of 0.22 x effective stress and N_k value of 13 (Rahardjo & Santoso, 2017). The method of this approach is regarded direct straight interpretation.

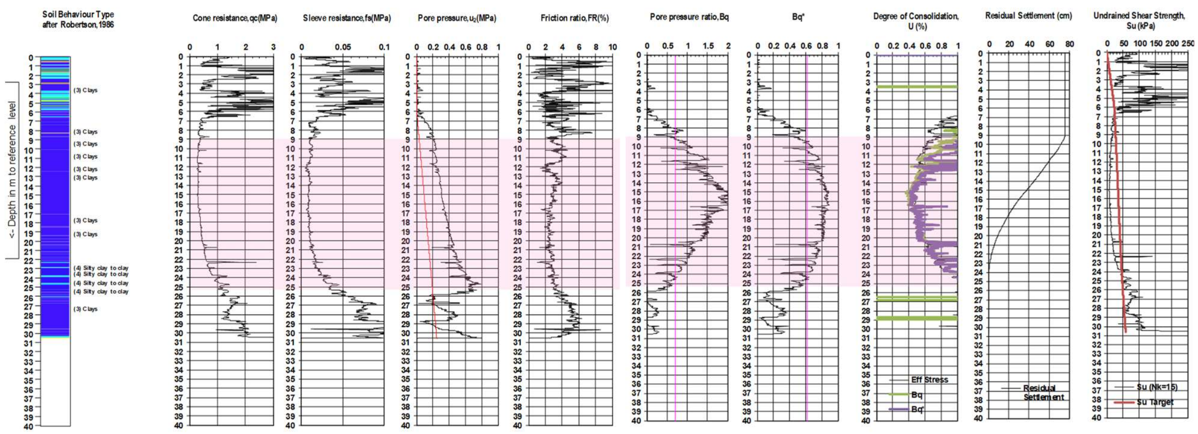

Figure 10. CPTu in Underconsolidated Soils and its interpretation on the degree of consolidation

3.4. Case 2 CPTu in peats and Very Soft Soils

The second case study is to use CPTu in peats and very soft soils located in Riau Sumatera. Riau peat is very famous due to its massive existence on the island, by about 5 million hectares area. There are several data generated from the project, however they yield more or less similar results. The following is an example of the data. The CPTu's were conducted down to 30 m and some of them are located next to the drilling holes. The data shows consistency and most of them are good data. Figure 10 shows the location of Riau peats in Sumatera island of Indonesia. Figure 12 and Figure 13 show the appearance of Riau Peat.

Peat is difficult to sample and almost impossible to obtain really good undisturbed sample except from block sample on the surface. Hence CPTu was selected to characterize the peats in Riau. Among the advantage of using CPTu for peat site characterization is because the test is conducted in situ, under own insitu stresses, easy and repeatable, obtain continuous data and fast. Among the most important aspect is because CPTu has vast data for correlation and obtain pore pressure during the course of the cone penetration into the ground.

Figure 11. Distribution of Riau Peats in Sumatera

Figure 12. Condition of Riau Peats

Figure 13. Riau peat disturbed sample at depth 4 m

Figure 14 shows typical data of CPTu on Riau peats. In this example the thickness of the peats is 7 m as detected from its high friction ratio. The rest is very soft soil still under consolidating, however the difference of this data compared to case 1 in Semarang is that the soft soil in Semarang was started as soft soil reclaimed by gravelly sand while this one of the data is naturally deposited.

The spikes of the tip resistance is mostly due to fibre in the peats. Of interest is that although the underlying peat has irregular tip resistance, however friction is relatively readable and the friction at the cone may reflect the shear strength. The pore pressure response shows that the peat is partially drain as shown from low value of the pore pressure ratio. One of the reasons is because peat has high void ratio. Based on the values of the sleeve friction it may be interpreted that the shear strength of Riau peat was estimated on the values of the between 20 – 30 kPa. Higher than the soft soils underneath.

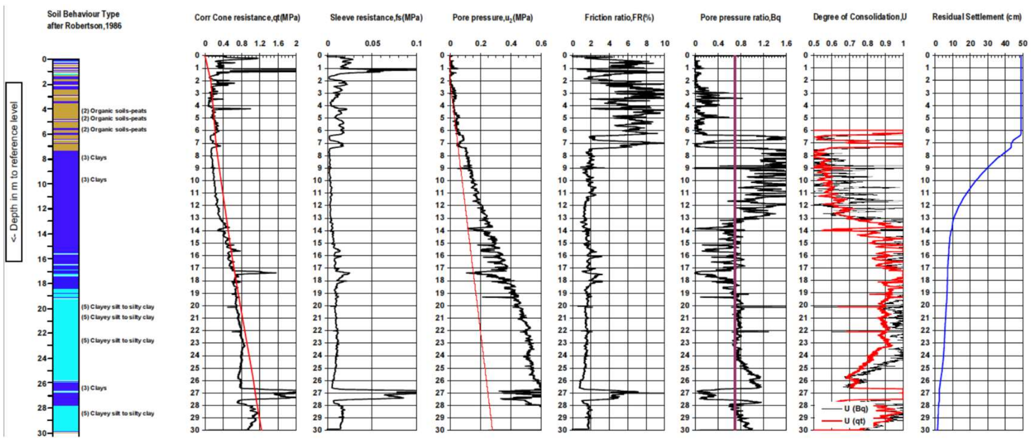

Figure 14. Typical data of CPTu on peats and very soft soils in Riau – Indonesia

The first few meters of the clay soil below the peats are often severely under-consolidating indicated as recently deposited soil. As the penetration is deeper, the soft soil degree of consolidation is higher. From 7 – 13 m the degree of consolidation is increasing with depth from 50% to about 70%. Then the lower part of the clay shows nearly consolidated soil with the interpreted degree of consolidation was about 90 – 95% or even 100%. This data match very well and consistently could be interpreted from its low shear strength in the upper layer and from the low tip resistance.

3.5. Case 3 Interpretation of CPTu test results in Mud Eruption in East Java Indonesia

Mud eruption disaster occurred in Porong - Sidoardjo, East Java on May 29, 2006 which is well known worldwide. Some publication mentioned that it was due to reactivation of fault by the subduction south of Java that has caused Jogjakarta earthquake of May 26, 2006. The location of the disaster is in the middle of the town of Porong in the district of Sidoardjo, near Surabaya International airport, and mud has blocked the major arterial roads from north to south of East Java.

Initially the mud volume ejected was 150000 m^3 daily and was contained inside in a big pool before it is pumped out into Porong River. Presently the mud has been discharged through the Porong River, and sedimentation is part of the problem.

Dykes were constructed to contain the mud, which covered areas reaching 650 ha (Sofyan 2015). The volume of the mud discharge is estimated at 5000 m^3. The soil condition of the site is deep soft clays which causes instability of the dykes. Some dyke failures occurred, endangering residential areas due to the flow of the mud (Rahardjo 2015). Figure 15 shows mud condition as seen near the centre of eruption and within years, the mud become stiffer due to drying on the surface.

All previous dykes were flooded by the mud and only dykes in the periphery still exist to defence the mud. Figure 16 describes the situation in 2008 where traffic next to the dykes still operated. This section describes the characteristics of the mud by using CPTu tests conducted by the authors for design of dyke reinforcement. The tests are also conducted in the middle of the mud area. There are several tests available however only two CPTu's to be discussed in this paper. Figure 17 shows the location of the CPTu.

Figure 15. Sidoardjo Mud characteristics upon deposition after eruption

This paper discusses the results of CPTu 9 which is located near the dyke but in the middle of the mud and CPTu 10 is located about 300 m from the centre of eruption. The area was originally flat and the average elevation of the area is + 5 m from sea level. Figure 18 shows contour of the mud during testing. Elevation of CPTu 9 was +8.0 m and elevation of CPTu 10 was +14.0 m above sea level.

Figure 16. Situation of the mud surrounded by defence dykes and the traffic nearby, this photograph was taken in 2009

Figure 17. Location of CPTu 9 and CPTu 10

Figure 19 shows the test activity of CPTu 9 which is near the dyke. Dyke crest elevation was +11.m and as CPTu 9 was conducted at elevation +8 m, it means that if there is no change of the original ground surface, the thickness of the mud measured by CPTu 9 should be about 5 m. Figure 20 shows the results and interpetation of CPTu 9.

Figure 18. Contour of mud and Elevation of the test

Figure 19. The geotechnical team conducted CPTu 9 inside mud area at elevation +9 m

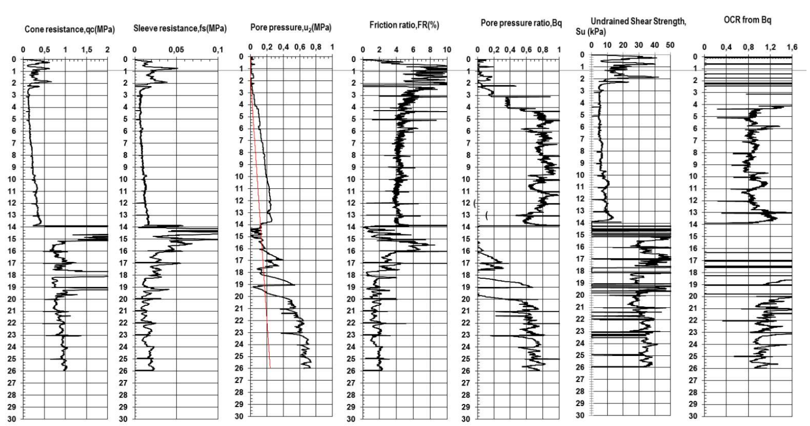

Figure 20. Results and interpretation of CPTu 9

Based on the results of CPTu 9, it can be concluded :

- The upper 2 m is crust of the mud with tip resistance of 0.3 – 0.4 MPa and increased shear strength of 20 kPa
- The mud thickness at this area was measured 14 m and this means that this point has settled 14.0 – 5.0 m = 9 m of settlement which is significant
- The original ground was found below the mud consisting of medium stiff clay with q_t = 0.7 – 1.0 MPa
- Interpreted degree of consolidation of the mud after 10 years based on Bq value was on the average 80%
- The shear strength of the mud has reach 5 – 10 kPa increasing with depth

CPTu 10 was located about 300 m away from the centre of the eruption and at elevation +14 m as shown on Figure 20. The penetration was done using manually driven CPT machine at 2 cm rate of penetration.

The results of CPTu 10 is shown on Figure 22 and its interpretation is on Figure 23. The test was able to penetrate 27 m below ground surface but the anchor refusal has started, hence the test was terminated at that depth. It is interesting that until end of penetration, the original ground has not been found and the test elevation was at +14 m, or about 9 m above original ground level. Hence the settlement of this point has been much more than 26 m. A number of interesting facts can be resulted from Figure 23.

Figure 21. GEC team conducted CPTu 10 about 300 m from centre of eruption at elevation +9 m

Based on the results of CPTu 10, it can be concluded:

- The upper 1 m is crust of the mud with tip resistance of 0.6 – 0.8 MPa which is still soft
- The sleeve resistance is still low and smallest in the middle representing its low shear strength
- The Bq and Bq* was plotted together for comparison and the interpreted degree of consolidation are similar
- The middle part of the mud has low degree of consolidation and estimated about 50%
- Shear strength is quite low, less than 2 – 3 kPa in the middle part and less than 10 kPa in the upper and lower part
- Excess pore pressure is still high along the depth of the mud

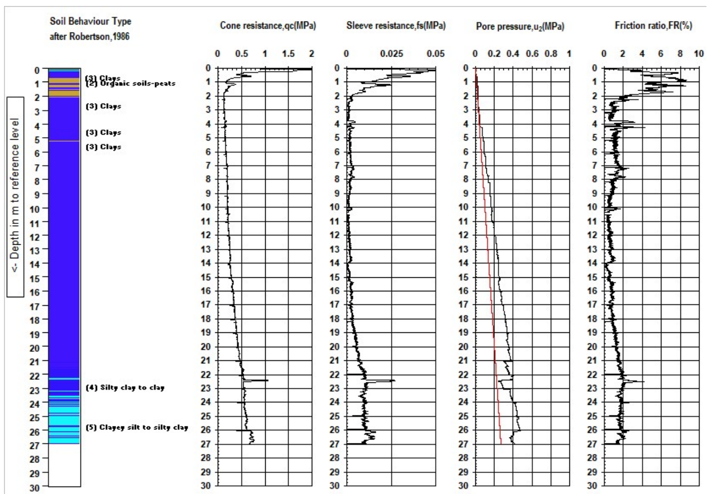

Figure 22. CPTu 10 test results for Sidoardjo mud

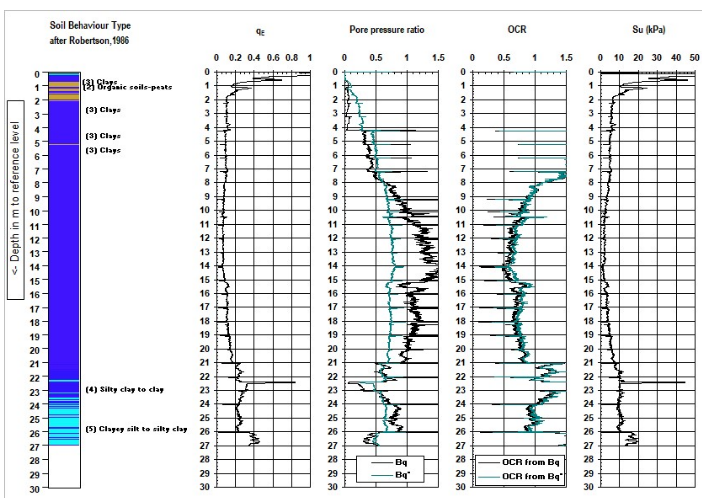

Figure 23. Interpretation of CPTu 10

Once the degree of consolidation at a depth is obtained, residual excess pore pressure can be determined using the following expression where the initial excess pore pressure could be owns weight during deposition for natural soil or the weight of the embankment for cases of reclamation work.

$$U_z = 1 - \frac{\Delta u_t}{\Delta u_i}$$

It was detected that subsidence occur progressively surrounding the mud eruption. In 2007, several survey were conducted to find overall ground subsidence due to the mud eruption and projected future ground surface assuming mud eruption continues for 30 years. The results of CPTu can be used to estimate the current subsidence in 2015. Setiawan and Rahardjo (2017) reported the interpretation of the shape of the settlement profile that might look like shown on Figure 24. And further morphology of the ground surface after 30 years might also be predicted based on the amount of material erupted. Figure 25 represents the predicted ground surface.

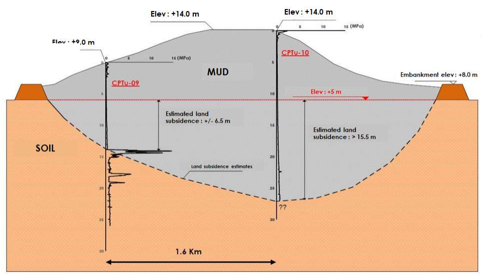

Figure 24. Interpreted ground settlement (Setiawan & Rahardjo, 2017)

Figure 25. Simulated ground subsidence due to the Sidoardjo mud eruption in 30 years

Conclusions Summary

Development of CPTu for interpretation of degree of consolidation and estimation of the existing excess pore pressure is of prime important for practical purposes and for proper interpretation of the shear strength. From the profile of the degree of consolidation, future settlement can be estimated and for design purposes, excess pore pressure shall be considered for stability analysis.

In peats, CPTu can be used to identify the thickness and drainage condition of the peat. Shear strength of the peat can also be estimated from sleeve friction.

In reclamation works and soil improvement of soft ground, the method can be used to assess achievement in the degree of consolidation and hence provide additional information compared to settlement plate data. Bq or Bq* are potential for this prediction, however Bq* is more interpreter independent, to avoid bias estimation of the total stress which depend on the unit weight of the soil. Sleeve Friction is indication of remoulded shear strength and can be prospective for future research.

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