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CPTu in Consolidating Soils

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ABSTRACT: The interpretation of CPTu for normally consolidated clay soils and slightly, or, strongly overconsolidated soils have been published in many papers (Chen and Mayne, 1995, Lunne et al. 1997). For both conditions of soils (normally consolidated and overconsolidated clay), there is hydrostatic pore water pressure, however no initial excess pore water pressure exists. Hence the assumption that excess pore water pressure due to cone penetration only is valid. In soils where consolidation is still ongoing which could be due to natural deposition of the soils or soft soils under reclamation fill material, the excess pore pressure still exists, which means that prior to penetration testing, the initial excess pore pressure has not completely diminished. In this case, the measured excess pore water pressure shall be interpreted as combined existing pore water pressures and the additional excess pore water pressure due to cone penetration. In case of testings conducted at certain interval time such as during the course of consolidation in reclamation area, then the excess pore pressure response as well as the tip resistance and the friction ratio will change toward a normally consolidated condition. This paper represents research results of CPTu in reclaimed soils and naturally deposited mud resulted from eruption. The authors have developed methods for interpretation of these combined excess pore water pressures. In the end, the methods can separate between the excess pore water pressure due to penetration and the prior existing pore water pressure. The tip resistance in under-consolidating soft soils subjected to fill placement will not form a linear tip resistance (not straight line) when carefully examined and hence the interpretation were done considering the initial (remaining) excess pore pressure or the effective stress at certain time. The methods have been proved to be consistent and has the potential for prospective future interpretation.

1 INTRODUCTION

1.1 *Jakarta Bay Reclamation*

The reclamation works now being actively conducted are located in the Jakarta bay as shown on Figure 1. There will be a number of islands to be proposed and implemented for the development of the Jakarta Megapolitan City. Currently three projects are ongoing, the first one is north of Pluit area (called Pluit City) with 2 islands (E and F) of about 500 hectares of land reclamation, the Kapuk Naga reclamation works which is on the west side of the development consists of 3 islands each of about 300 hectares (C, D and E) and the New Priok Port (N). The research is mainly conducted at the first island (island D) of Kapuk Naga which has been completed. On this reclamation works, the use of CPTu for quality control has been very extensively before and during reclamation.

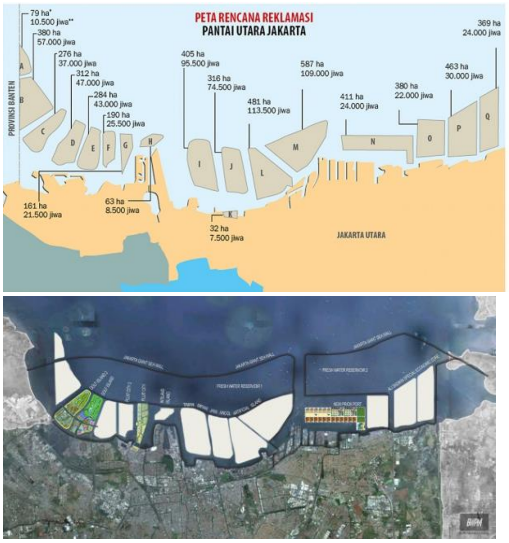


Figure 1. Reclamation Plan at Jakarta Bay (www.tempo.co, 2015)

1.2 *Mud Deposit from Eruption in East Java*

Mud eruption in East Java occurred on May 29, 2006 has been well known. The mechanism of the causes of the eruptions are still in debate, whether triggered by the drilling or pressurised fluid reactivated by the Jogyakarta quake on May 27, 2006. The debate is more from the geological point of view, and is not the main issue in this report. Instead, the main objective of this paper is to discuss mainly on the results of CPTu tests recently conducted and discuss mitigation and risk reduction.

In the early days of eruption, as much as 150,000 cubic meters discharge per day was reported, although presently only less than 5000 cubic meters of the discharge is estimated. Due to unknown characteristics of the mud, dykes were constructed to contain the mud and the areas reaching 650 hectares (Sofyan, 2015, "Recent investigation of Lumpur Sidoardjo", internal report (unpublished) delivered during the International Conference on Landslide and Slope Stability, Bali). The location of the disaster is just in the middle of the town of Porong in the district of Sidoardjo, East Java.

The soil condition of the site is deep soft clays which causes instability of the dykes. Some dyke failures occurred which endangered the residential areas due to the flow of the mud (Rahardjo, 2015). This paper discusses the characteristics of the soil conditions from a number of drillings and CPTu tests conducted by the authors for design of the replacement of the arterial road, west of the site and for the dyke reinforcement and also in the middle of the mud. Figure 2 shows the effect of mud eruption in 2006.

Figure 2. Mud Eruption in East Java – causing thousands of houses flooded

2 PRINCIPLE OF CPTu AND THE USE OF CPTU FOR SOFT SOILS

The use of CPTu (Cone Penetration Test with pore pressure measurement) has been popular in Indonesia since 1990, specially for soft soils. The increasing use of the CPTu is due to a number of factors, such as:

- It is handy, fast and accurate for soil profiling and not depending on operators
- It can distinguish the soil resistance and the pore pressure, hence the effective reaction of the soils being measured and it can recognize drained or undrained response of the soils
- The interpretation of soil properties, although heavily relying on empirical correlations, are accurate due to many available data for comparison and justification
- Dissipation tests can be conducted to measure the permeability and consolidation characteristics of the soils, which give more reliable data

The authors have gained a lot of experience in many projects throughout the northern coast of Jakarta and also in many places where soft soil deposit create instability during construction and the problems of long term settlement.

3 DETERMINATION OF THE DEGREE OF CONSOLIDATION FROM CPTu

Degrees of consolidation are very important in reclamation projects to determine the readiness of the reclaimed land. When conducting CPTu at reclamation works, there are possibilities that the underlying soft soils are still consolidating and residual excess pore pressure still exists. Method for Interpretation of degree of consolidation may be determined by:

1. Schmertmann Method (1978)
2. B_q vs OCR Correlation (Rahardjo et al. 2015)

Schmertmann method is a method to interpret the degree of consolidation for clay layer. The method is very simple by using the cone resistance (q_c) from CPTu Data. Figure 3 illustrates the interpretation of the degree of consolidation based on Schmertmann Method (1978).

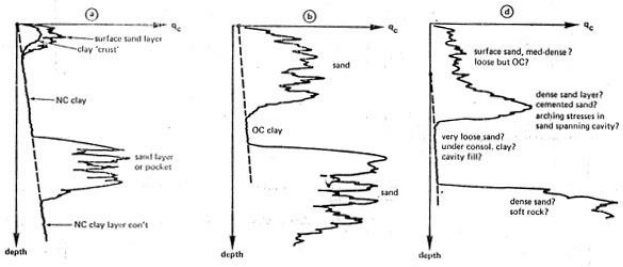


Figure 3. Interpretation of the Degree of Consolidation by Schmertmann Method (1978)

Degree of consolidation can also be interpreted by using pore pressure ratio (B_q). The correlation

between B_q vs OCR was already researched by Setionegoro (2013). The OCR value lower than 1.0 basically represent the degree of consolidation. The following equation shows the correlation between B_q vs OCR.

CPTu result can be used to obtained the B_q value. Then the OCR value can be obtained for every data B_q value by using the correlation (Rahardjo et al. 2015). To make the calculation easier the equation of the correlation is interpreted using curve expert program. The equation that represents the correlation between B_q and OCR (modified from the results of Setionegoro, 2013) is:

$$OCR = \frac{1}{(1.2B_q + 0.1)}$$

Figure 4 shows this correlation collected from several data in Indonesia.

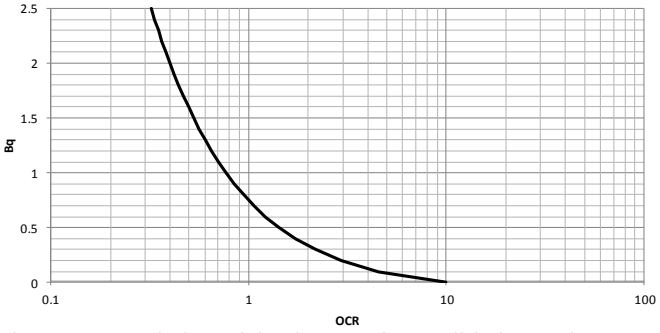


Figure 4. Correlation of the degree of consolidation and OCR from B_q values of CPTu

4 CPTu AND DISSIPATION TEST IN CONSOLIDATING SOILS

In soils where consolidation is still progressing which could be due to natural deposition of the soils or soft soils under reclamation fill material, the excess pore pressure still exists, which means that prior to penetration testing, the initial excess pore pressure has not completely diminished. In this case, the measured excess pore water pressure shall be interpreted as combined existing pore water pressure and the additional excess pore water pressure due to cone penetration.

The excess pore pressure is substantially higher. This could be due to three factors, the existence of the residual excess pore pressure which has not dissipated, the behavior of the soil which could be in the state of being more sensitive, and higher overburden. The value of B_q ratio could be much higher than 0.75 as indicated by Tanaka and Sakagami (1989) as boundary of normally consolidated soil. When the dissipation test is carried out ultimately, the pore pressure measured shall be the hydrostatic pressure related to the ground water table, u_0, however, this is not possible due to limited time during the test. The authors recommend to approximate the dissipation curves using hyperbolic function to obtain the final pore pressure u_f. Figure 5(a) shows the meaning of u_f. The difference between this value and the hydrostatic pressure is called the residual excess pore pressure which can be used to calculate the degree of consolidation. Figure 5(b) illustrates the method and the difference of ultimate pore pressure, u_f to the hydrostatic pressure is residual excess pore pressure due to the load. This can be used for the calculation of the degree of consolidation using the expression $u_z = 1 - \frac{\Delta u_t}{\Delta \sigma}$ where $\Delta u_t = u_f - u_0$ and $\Delta\sigma$ = overburden pressure.

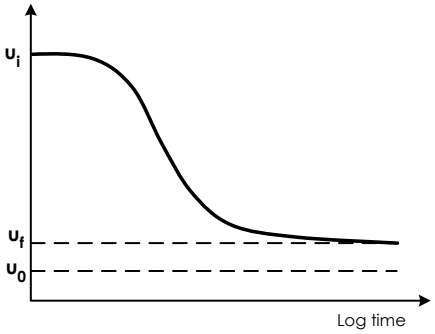


Figure 5(a) Extrapolation of dissipation test results

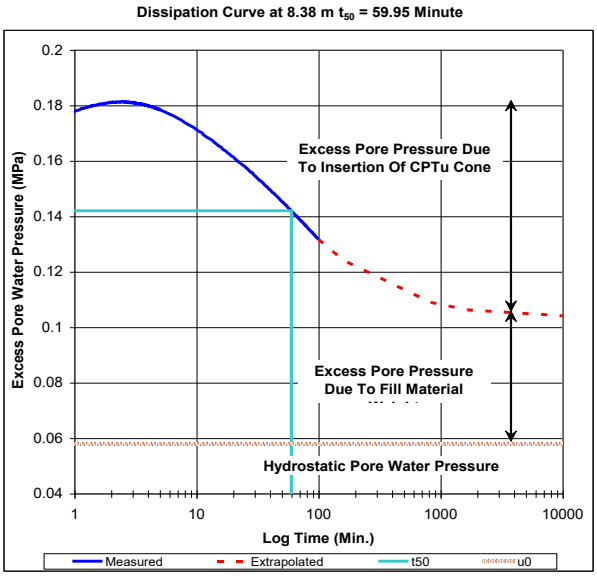
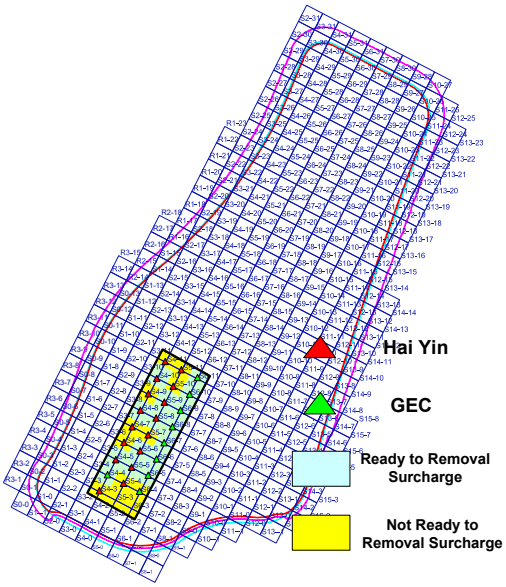


Figure 5(b) Example of the determination of the residual excess pore pressure

5 CPTu IN CONSOLIDATING SOILS UNDER RECLAMATION IN JAKARTA BAY

The CPTu used for illustration in this paper is at island D. 2A island project (island D) is a reclamation project near shore at Pantai Indah Kapuk, North Jakarta. The reclamation project purpose is for land development for housing, apartments and golf. Total area of the reclamation is 312 Hectares. Depth of seabed at the project site is about 3.7 to 8.7 m bellow main sea level (MSL). The elevation of MSL is 1.2 m pp* and the final

level of the area is 0.5 m pp*. The 2A island is planned to be a polder area with dyke elevation at 6 m pp* to 9.6 m pp*. Soil condition at the project site is very soft soil with thickness of about 5 – 12 m. These conditions cause a settlement due to a fill of sand material. The reclamation was started in 2012 until 2015 and the soft soil is still consolidating. This section discusses the interpretation of degree of consolidation of 2A Island at the polder area. The location of the test sites is shown in Figure 6(a). The area has been divided into grid with 50 m intervals. There are too many data, and for this purpose only selected positions are discussed. The results of the tests are shown on Figure 6(b) and Figure 6(c).



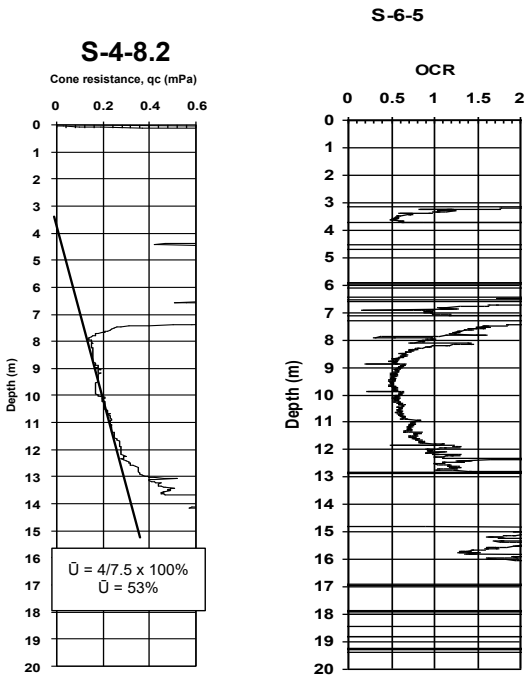


Figure 6(a) Hundreds of CPTu tests at grid of 50 m
Figure 6(b) Interpretation of the degree of consolidation based on Schmertmann Method
Figure 6(c) interpretation of the degree of consolidation based on B_q

Using the method by Schmertmann, apparently is not easy due to the fact that the shape of the q_c resistances of the soils are not the same then as assumed by Schmertmann. In fact, the straight line as expected can not be found, instead a curved such as an isochrone was seen. This is understood to be due to the fact that the middle of the soil is in a very low degree of consolidation due to its distance from the top and bottom of the soft clay. A method is being proposed based on the fact that the curved shape of the CPTu test results are more rational. It thus represents the state of the effective stress. Near the drainage boundary the degree of consolidation should be much higher due to its proximity to the drainage layer. However, this also shows the possibility the Prefabricated Vertical Drain (PVD) might not work very well.

Using the B_q method, it can be seen that the degree of consolidation of the soft clay layer varies from 50% at the middle to about 100% at the boundary of the drainage layer. This is logical as q_c represents the effective stress which in turn also related to the soil shear strength.

6 CPTu IN MUD DEPOSIT RESULTED FROM MUD ERUPTION DISASTER IN EAST JAVA

Based on laboratory tests west of this area, the soils are highly plastic materials, the natural water content ranges from 40 – 100 %. Generally, the upper part is slightly stronger showing slight overconsolidation. However, the void ratio could be as high as 1.5 – 3.0. Laboratory consolidation tests also show that the soft soils are still consolidating. Compressibility of the soils as measured from its compression index is very high with a range of 0.5 – 1.5. This explains why settlement is large (Soleman, 2012).

Figure 7. Situation at the Mud Center where CPTu were conducted

CPTu tests are also conducted in the mud area. Location of CPTu tests are just at the dykes and in the middle of the mud as shown on Figure 8. Based on insitu tests (CPTu and SPT), the soil upper layers are very soft with thickness of 15 – 25 m dominated by clays to silts and silty sands. The silty sands are mixed with clay. This soil condition

has very low bearing capacity and may cause very large settlement upon loading. The possibility of squeezing of lower soil layers are among the problems that need to be considered. Typical CPTu test results are shown in Figure 9 for the result of CPTu at the center of the mud.

Based on the results of the CPTu test in the mud area, it is concluded that the mud is very deep and still consolidating as shown from the low tip resistance and high value of B_q. It is also shown from the results of the dissipation tests, the excess pore pressure is still high consisting of residual excess pore pressure due to its own weight. A separate plot of the excess pore pressure is recommended by the authors to using $B_q^{**} = u_2 / q_t$ which is more representative because it shows the proportion of the excess pore pressure response compared to its corresponding tip resistance. For this case, the ratio of $B_q^{**} = 0.9$ in the middle of the mud which shows that 90% of the measured resistance was practically by water. In soft soils, sleeve friction is practically the undrained shear strength of the soils. Figure 9 shows the friction is very low. The interpreted shear strength is in the range of 2 – 10 kPa.

Figure 8. Location of CPTu tests in the Mud Area

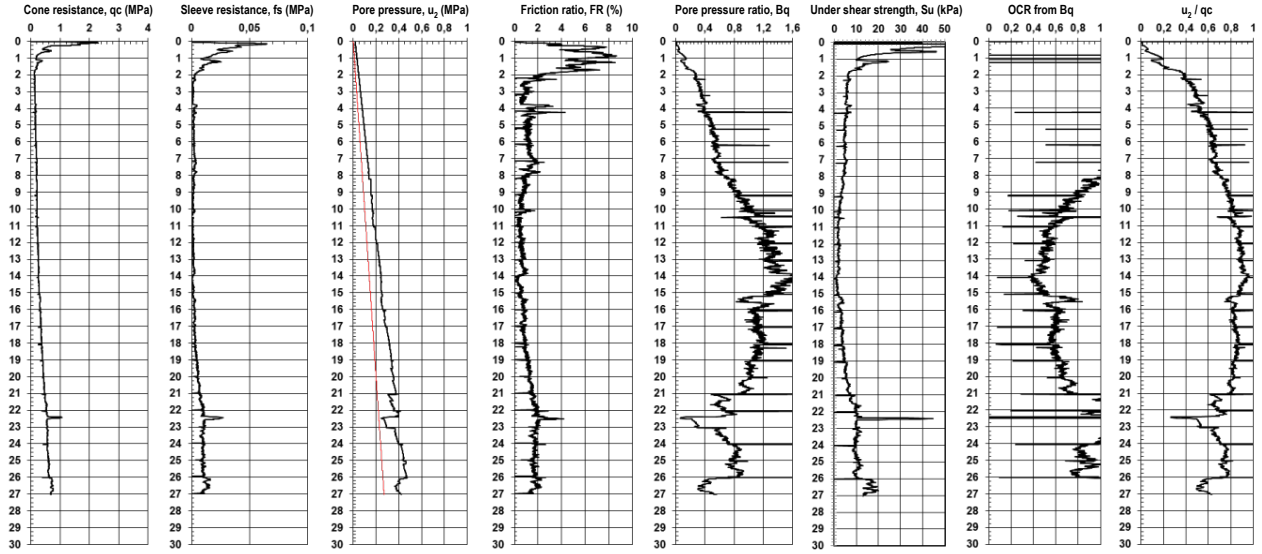


Figure 9. Results and Interpretation of CPTu-10 at the center of the Mud

Another interesting fact is that, the initial elevation of the site before mud eruption was +5.00 above sea level, and the CPTu was conducted at mud top elevation +14.00 m. Assuming that there was no settlement, the depth of the mud should be 9.00 m. However, down to 30 m, the CPTu shows that all penetration is in the mud, which means that the center of the eruption might have settle down more than 21 m.

7 CONCLUSIONS

Based on the data of CPTu, it is concluded :

- The use of CPTu for investigation of the degree of consolidation and the investigation of residual pore pressure is very effective and prospective for future use and application.
- The use of empirical correlation for degree of consolidation (OCR < 1.0) as well as the overconsolidation ratio using B_q value is very usefull.
- To obtain information on the proportion of soil resistance and pore pressure, $B_q^{**} = u_2 / q_t$, is prospective.

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