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Shear strengths determined for soil stability analysis using the digital Icone Vane

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ABSTRACT: At locations where the soil is exposed to high and varying forces, for example at a dike or around a mining area, additional parameters for stability analysis should often be measured. Determination of the undrained shear strength is a commonly used method to define soil stability. The Field Vane Test (FVT) can be used for in-situ measurement and evaluation of the shear strength. It can be deployed in soft soils, but also in fine-grained soils such as silts, organic peat, tailings and other geomaterials where a prediction of the undrained and remolded shear strength is required. This paper describes a FVT system called Icone Vane, which is part of the Icone® data acquisition concept that is based on fully digital data transfer and meets the requirements of ASTM D2573/ D2573M and other FVT standards. Specific details of fieldwork with the Icone Vane performed at tailings dams are presented.

1 INTRODUCTION

Geotechnical engineers often want to estimate the shear strength and bearing capacity of soils as part of the characterization process. The shear strength of soils determines the maximum load that can be applied on it. The undrained shear strength is commonly used as soil stability parameter and there are different ways to obtain it.

This paper focuses on the comparison between the undrained shear strengths of three Brazilian tailings dams' soils measured using the piezocone penetration test (CPTU) and the field vane test (FVT).

2 PIEZOCONE PENETRATION TEST

The piezocone penetration test is an in-situ method used for determining the geotechnical soil characterization, measuring tip resistance, dynamic pore pressure and sleeve friction during penetration.

The electrical cone is pushed into the soil with a constant rate and produces a continuous profile of soil data. During a pause in penetration, any existing excess pore pressure around the cone will dissipate. The rate of dissipation depends on the compressibility and permeability of the soil. The analogic cone signals are subject to disturbances during transfer to the data logger.

The paper describes a particular digital cone (Icone®) manufactured by A.P. van den Berg, which has been available since 2006. The digital cone, differs from the analog cone by its system in which the analog signals are digitized already inside the cone.

Digitizing means that the analog signals are sampled with frequency and converted into a digital data stream. This digital data stream is more robust and less sensitive to distortion and loss of accuracy in comparison with the analog signals.

Additionally, the Icone is stronger compared to its analog predecessor.

3 ICONE AND CLICK-ON MODULES

In the past five years several click-on modules for the Icone were developed. In this chapter the following three are described: the seismic module (Fig. 1), the conductivity module (Fig. 2) and the magnetometer module (Fig. 3). A fourth application for vane testing is described in chapter 4. All modules except the Icone Vane can be used with a 10 cm^2 and a 15 cm^2 Icone®. When CPT-data is not required, the click-on modules can also be used with a dummy tip instead.

Figure 1. Seismic module with 10 cm² Icone.

Figure 2. Conductivity module with 10 cm² Icone.

Figure 3. Magneto module with 10 cm² Icone.

3.1 *Seismic module*

Seismic tests are performed to investigate the elastic properties of the soil. For this purpose a shear wave (S) or a compression wave (P) is guided into the soil. Elastic soil properties are essential input for prediction of ground-surface motions related to earthquake excitation and for assessment of: foundation design for vibrating equipment, offshore structure behavior during wave loading and deformations around exca-vations.

3.2 *Conductivity module*

The measurement of electrical conductivity in the subsoil is a function of both the conductivity of the pore water and the soil particles, the first being the dominant factor. With the Conductivity module changes in the concentration of (dissolved) electrolytes are determined without specifying the exact nature of these electrolytes. Therefore the module facilitates separation of zones with differentiated water content, including determining the water table depth and the thickness of the capillary zone or separation of fresh and salt water carrying soil layers. Another very important application of the conductivity module is detection of (the degree of) contamination in a soil body. Further soil investigation should provide details on the actual contaminants.

3.3 *Magneto module*

Unknown structures and obstacles, like unexploded ordnance (UXO), are a risk factor in the execution of earthworks. To avoid risks of damage and interruptions of work, these underground elements must be identified and mapped. Most underground structures contain metal such as sheet-piles, ground anchors and pipe lines or a combination of metal and concrete, such as reinforced foundation piles. Power supply cables and above structures have in common that they affect the earth's magnetic field.

Using the Magneto module, metal objects in the underground can be detected by interpreting anomalies of the earth's magnetic field.

4 ICONE VANE

The vane shear test is primarily used to determine the undrained shear strength s_u of saturated clay layers. The test can also be used in fine-grained soils such as silts, organic peat, tailings and other geomaterials where a prediction of the undrained shear strength is required. The Icone Vane meets the requirements of ASTM D2573/ D2573M.

4.1 *Principles*

The FVT consists of four rectangular blades fixed at 90° angles to each other, that are pushed into the ground to the desired depth. This is followed by the measurement of the torque required to produce rotation of the blades and hence the shearing of the soil. The chosen blade size depends on the strength of the soil and the torque capability of the tool; the stronger the soil, the smaller the blades of the vane. So, the vane is being rotated by the drive unit with a constant speed and a maximum torque of 100 Nm. The torque applied to the vane is measured continuously. Both parameters are visualized in a torque vs. rotation graph as shown in Figure 9.

The Icone® Vane has many features that facilitate an accurate vane test. The actuator is integrated in the same compact housing, enabling easier, faster and more accurate operation. The vane is pushed out of its protection tube and retracted again after the test. This advantage

Figure 4. Icone Vane (without protection tube).

allows more vane tests at different depths without the need of retrieving the tool to surface level. The vane rotation speed is adjustable from 0.1 °/s to 12 °/s for fast remoulding.

The vane tool is pushed into the soil by means of standard casing tubes and CPT-rods. Depth is measured on the pushing device and added to the field data by the Icontrol data logger. The Icone Vane can be used for onshore as well as offshore applications.

4.2 *Data processing and visualizing*

During a vane test, the vane is being rotated with a constant speed of 0.1°/s, while the required torque is measured with respect to the angle of rotation. This measured torque is analytically converted to the shearing resistance of the cylindrical failure surface of the vane used, and expressed in kPa. A typical shear curve is shown in Figure 9. The highest value of this curve is a measure for the undrained shear strength of the soil material that is being investigated. A repetition of this test, after thorough remoulding of the soil, provides a uniform curve of which the highest value is a measure of the remoulded shear strength.

5 PRACTICAL EXPERIENCES ICONE VANE

5.1 *Aim of the study*

In November 2015 the greatest environmental disaster in the Brazilian history happened, when a tailings dam in the city of Mariana /MG collapsed and generated a tidal wave of 32 to 40 million cubic meters of mining waste. This washed across villages and farmlands until reaching the shore, several kilometers away.

This happening made other mining companies study their tailings dams, using geophysics, CPTU and FVT. The aim of this study is to present the

Figure 5. Pagani TG63 & CME-550X.

peak and remolded undrained shear strength of tailings dams' soils by means of CPTU and in three different tailings dams located in the Brazilian state of Minas Gerais.

5.2 *Equipment used*

The soil investigations were performed using the Icone®) pushed into the soil by a Pagani TG63 rig and the Icone Vane penetrated by a CME-550X. These systems achieve a maximum pushing force of 100 kN, allowing depths of up to 40 m to be reached.

5.3 *Test results*

CPTU has been used in soil exploration and in estimations of the undrained shear strength of soft soils.

The cone responds to in-situ mechanical behavior of the soil and not directly to soil classification criteria based on distribution and soil plasticity. It offers the possibility to classify soil by the type of behavior.

The standard formula used for determination of the undrained shear strength (s_u) using the tip resistance (q_t) values corrected for the pore pressure effect can be written as:

$$s_u = \frac{q_t - \sigma_V}{N_{kt}} \tag{1}$$

where σ_V = total overburden stress and N_{kt} = empirical cone factor.

Typically N_{kt} varies from 10 to 18, with 14 as an average. This value (N_{kt} = 14) was used to estimate the peak shear strength using CPTU.

The remolded undrained shear strength ($s_{u\,(Rem)}$) can be assumed equal to the sleeve resistance (f_S).

The torque of the FVT can be converted to peak shear strength with the following equation:

$$s_u = \frac{0.86M}{\pi D^3} \tag{2}$$

where M = maximum measured torque and D = diameter of the vane.

Similarly, the remolded shear strength is derived using the torque values for the remolded condition.

Figure 6 shows on the left the cone resistance q_t in MPa and the pore water pressure u in kPa, obtained by CPTU in soils of tailings dam no. 1. The cone resistance varies from 3 to 15 MPa. The short peak values of the pore water pressure indicate small non-permeable soil layers.

Figure 6 shows on the right the soil behaviour type SBT obtained by CPTU and the undrained shear strength s_u derived and measured by using CPTU and the FVT respectively, performed in soils of tailings dam no. 1. The SBT-index indicating soil of type silty sand to sandy silt with small layers of clean sand to silty sand and clayey silt to silty clay. The FVT results indicate apparent shear strengths of 100 to 250 kPa. The CPTU and vane tests were carried out at a horizontal spacing of less than 10 m.

Figure 7 shows on the left the cone resistance q_t and pore water pressure u obtained by CPTu in soils of tailings dam no. 2. Again cone resistance varies from approximately 3 to 15 MPa. The pore water pressure is most of the time below the hydraulic pressure, indicating permeable soil layers.

Figure 7 shows on the right the soil behaviour type SBT obtained by CPTu and the undrained shear strength s_u derived and measured using CPTu and the vane tester respectively, performed in soils of tailings dam no. 2. The SBT-index indicating more layers of clean sand to silty sand in comparison with tailings dam no. 1.

Figure 8 shows the cone resistance q_t and pore water pressure u obtained by CPTu in soils of tailings dam no. 3. Also for this tailings dam cone resistance varies from approximately 3 to 15 MPa and at greater depths values go up to 20 MPa. The pore water pressure indicates non-permeable layers at a depth from 20 up to 24 m.

Figure 8 shows on the right the soil behaviour type BST obtained by CPTu and the undrained shear strength s_u derived and measured using CPTu and the vane tester respectively, performed in soils of tailings dam no. 3. The SBT-index indicating soil of type silty sand to sandy silt and at greater depths mostly clayey silt to silty clay.

The vane tests in the tailings dams were performed with a faster rotation rate than usual, in an attempt to achieve undrained conditions.

Figure 9 shows the graph torque vs. rotation in natural and remolded condition at a depth of 12 meters from the ground surface of tailings dam nº3.

The soils tested in tailings dams are composed of very heterogeneous materials and the tip resistances are measured every 1 centimeter in CPTU, which results in a graph with a large range of resistance values along the depth. Different from CPTU, in the vane test the shear strengths are measured at specific pre-determined depths by means of a vane tool of 10 centimeters of height, resulting in one average measurement of the soil layer.

Figure 10 shows the lower limit line of the peak undrained shear strengths range derived from the CPTU data, and derived s_u values for the FVT in soils of tailings dams nº 01, nº 02 and nº 03.

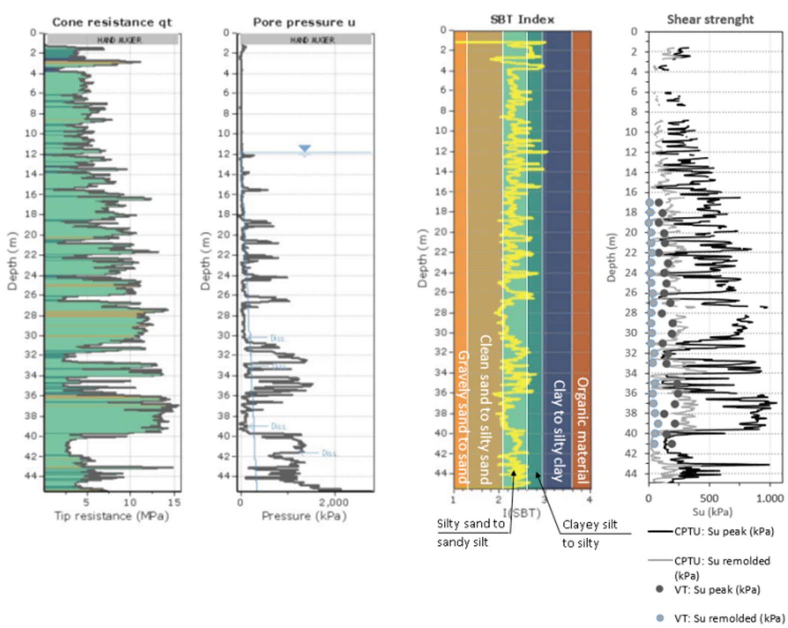

Figure 6. Parameters q_t and u measured along the depth using CPTU (figure left) + Parameters SBT and s_u measured and estimated along the depth using CPTU and vane test (figure right)– Tailings dam nº1.

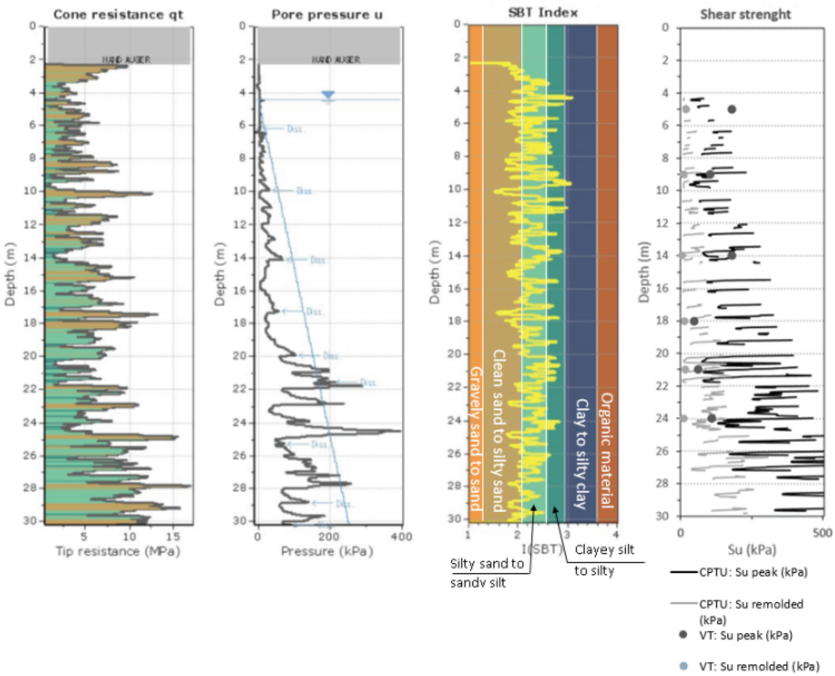

Figure 7. Parameters q_t and u measured along the depth using CPTU (figure left) + Parameters SBT and s_u measured and estimated along the depth using CPTU and vane test (figure right)– Tailings dam nº2.

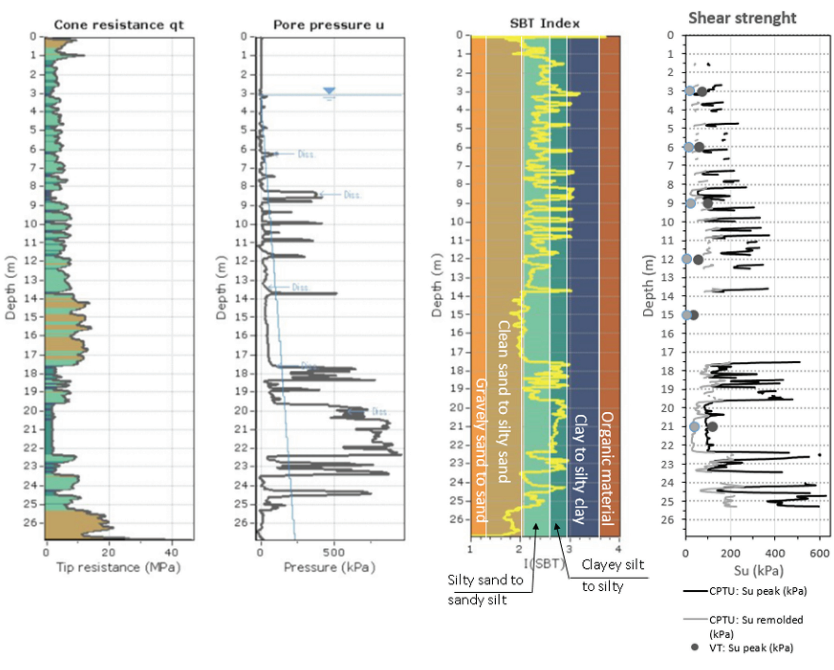

Figure 8. Parameters q_t and u measured along the depth using CPTU (figure above) + parameters SBT and s_u measured and estimated along the depth using CPTU and vane test (figure right)– Tailings dam nº3.

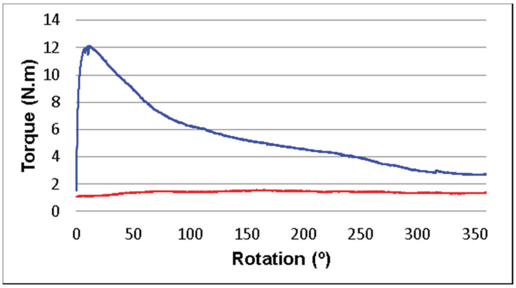

Figure 9. Graph torque vs. rotation in natural and remolded conditions—Depth 12 m—Tailings dam n°3.

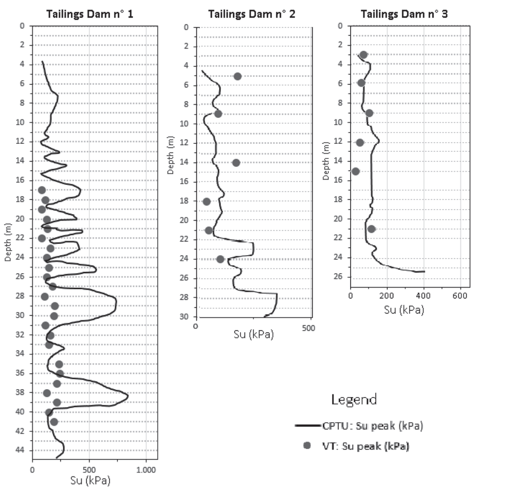

Figure 10. Lower limit line of derived s_u estimated in CPTU and s_u derived using the vane test in soils of tailings dams n° 01, n° 02 and n° 03.

The derived values of undrained shear strength for the CPTU and the FVT show local correlation for some of the zones with low CPTU q_t values.

As shown in the above graphics, the tests were made in soils of predominately silty and sandy nature, where undrained conditions may not have been achieved during the test phases of the CPTU and FVT. If undrained conditions were not achieved, then the equations for deriving undrained shear strength do not apply.

6 CONCLUSIONS

The torque obtained in the Icone® Vane is precise, as the rotation and torque measurement is right above the vane tool.

Figure 10 indicates challenges in characterising the undrained shear strength of three Brazilian tailings dams, primarily because of the silty and sandy nature of the tailings and the associated drainage conditions during CPTU and FVT.

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