Additional parameters measured in a single CPT

Click-on modules for the digital cone

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Keyword: CPT, digital cone, digital data transfer, click-on modules, seismic, conductivity, magneto, vane.

ABSTRACT: The demand to build a comprehensive and accurate picture of the subsoil by using additional parameters from in-situ soil investigation is increasing. For example it may be required to derive the in-situ properties of both soil stratigraphy and soil elasticity to design a foundation that is subject to vibration; or both the soil density and soil electrical conductivity to allocate contaminated layers and predict future distribution. In general these parameters can only be acquired by separate systems (seismic, conductivity, magneto, etc.) and in subsequent tests. Apart from being time consuming, this process may also negatively affect the accuracy of the information obtained.

A data acquisition system which eliminates these drawbacks has been developed by the engineers from A.P. van den Berg. It consists of a digital data logger "Icontrol" and a digital cone "Icone", measuring the traditional CPT parameters. The Icone is easily extendable by click-on modules to measure additional parameters and any module is automatically recognized by the Icontrol, thus creating a true plug & play system.

This paper describes how, by moving to smart digital communication, sufficient bandwidth over a thin flexible measuring cable was created to accommodate additional parameters, without the need for changing cones, cables or data loggers. The following modules are available: seismic, conductivity, magneto and vane. Feedback from fieldwork with the Icone and a selection of click-on modules highlights the user experience with this new approach.

1 INTRODUCTION

Due to its benefits, digital technology is used in many applications and is now also available to support efficient soil investigation. The possibilities of this technology have led to the development of the digital cone, the digital data logger and digital click-on modules. These new developments are described extensively after a short historical review of CPT-techniques.

2 CPT INVESTIGATION IN HISTORICAL PERSPECTIVE

Since Cone Penetration Testing (CPT) is used for soil investigation, a tremendous development has occurred in the techniques to measure soil parameters. After CPT with the mechanical cone had proven to be very useful, the development of the electrical cone brought a big step forward in ease of use and accuracy. Nowadays the advantages of digital technology are available for further improvements.

2.1 Mechanical cone

The first mechanical cone was developed in the 1930s and after two decades it was improved to a design that is still used today. The mechanical jacket cone allows to measure cone resistance and total resistance. The friction jacket cone also measures the local friction. The reading of these

parameters is carried out by means of an electric measuring body. This device provides a continuous data stream, which is then stored and processed in real time by a computer system.
Figure 1. Mechanical jacket cone and friction jacket cone

Mechanical cones are still widely used because of their low cost, simplicity and robustness. They are particularly useful in soil conditions with a high risk of cone breakage.

Because of its design and method of use the mechanical cone is limited in measuring soil parameters. For a jacket cone only cone resistance and total resistance can be measured, given a moderate accuracy due to friction between the inner rods and outer tubes. Furthermore, the mechanical cone is not suitable for investigating highly stratified soil, because a qualitative interpretation is impossible due to the coarse measuring data.

2.2 Electrical cone

The electrical cone has been developed during the 1950s and used commercially since the 1960s. Besides cone resistance and local friction, also the inclination was measured. In the 1970s the measurement of the pore water pressure was added which made soil investigation even more accurate and reliable.

The electrical cone is available with a 5, 10 and 15 cm^2 cone tip area, but the 10 cm^2 cone is most commonly used. The electrical cone is controlled by a data logger at surface level. Also the depth signal is recorded by the data logger and synchronized with the cone parameters

In comparison to the mechanical cone, the greatest advantage is that more soil parameters can be measured with a higher accuracy. A CPT performed with a pore water pressure measurement (U) enables a more reliable determination of stratification and soil type than a standard CPT. In addition, CPTU provides a better basis for interpreting the results in terms of mechanical soil properties.

The electrical cone is pushed into the soil with a constant rate and is therefore a more straightforward and faster way of soil investigation in comparison with the mechanical cone. Furthermore the real time processing and visualizing of the data obtained, facilitates a better control over the CPT-process.

The analog cone signals are subject to various disturbances especially during transfer via the cable and at connector transitions. The accuracy of an analog data acquisition system is therefore determined by the combined accuracy of individual components such as the cone, cables,

connectors and the data logger. The calibration settings are essential for a good data processing and must be read from a USB-memory stick into the data processing computer system. Accidentally changing of calibration settings and getting rid of the USB-stick may lead to errors. Finally the electrical cone is more expensive compared to the mechanical cone, so financial losses are higher in case a cone breaks off.
Figure 2. Electrical cone 10 cm^2 and 15 cm^2 area with analog data logger.

2.3 Digital cone

The digital cone or Icone has been available since 2006. The integration of intelligent electronics provides a range of possibilities in order to make further improvements to the electrical cone and to simplify its use. In addition, the Icone is stronger due to mechanical adjustments.

The Icone basically uses the same measuring sensors as applied in the analog cone. The difference however is that the analog signals are being digitized and multiplexed already inside the cone.

Digitizing means that the analog signals are being sampled with a certain frequency and converted into a digital data stream. This digital data stream is more robust, and therefore less sensitive to distortion and loss of accuracy in comparison with the analog signals. Another advantage of digital data transfer is the checking of signals on entry according to an established protocol. Missed or distorted data can be requested again.

By multiplexing, the various digital data streams are combined to one signal. This offers the great possibility that an almost unlimited amount of sensor signals can be combined and transmitted through a simple 4-wired cable. Also, specific sensors incorporated in customized modules can easily be added without changing cables and data loggers.

Figure 3. Icone 10 cm^2 and 15 cm^2 area with Icontrol data logger.

A built-in memory capacity gives the Icone several opportunities to increase the user friendliness. For example:

- the Icone number and calibration data are stored inside and are exchanged automatically when the Icone is connected to the Icontrol data logger.
- Extreme sensor values are stored in memory and can be read during service to explain possible calibration drift or damage to the Icone.
- The inside memory capacity allows the data storage of a full working day.

The Icontrol data logger provides power to the Icone and synchronizes the Icone signals with the depth signal, recorded from the pushing device. The Icontrol transmits the signals to a computer system, where the CPT-parameters are shown on real time graphs.

The use of smart electronics inside the Icone has provided the following benefits:

- The accuracy of the total data acquisition system is determined only by the accuracy of Icone calibration.

- Interchangeable click-on modules with specific sensors can be easily added to the Icone without the need of changing cables and data loggers.
- Specific sensors, added to the data acquisition system, are automatically recognized by the Icontrol and the corresponding display is automatically shown on the screen.
- Calibration data and Icone or module numbers are automatically transferred and are therefore no longer cause for errors.
- The Icone is able to monitor extreme measuring situations and overrule system control if needed.
- Several mechanical improvements have led to a stronger design.
- A pressure compensated Icone is available for water depths up to 4000 m.

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 extensively: the seismic module, the conductivity module and the magneto module. All modules can be used with a 10 cm^2 and a 15 cm^2 Icone. When CPT-data are not required, the click-on modules can also be used with a dummy tip instead.

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 by striking a hammer on a solid beam. 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.
- Deformations around excavations.

3.1.1 Principles

Elastic soil parameters are determined by measuring the propagation speed of an applied sound wave between two known depths. Mostly this is done by pushing the seismic module into the soil and stopping at 1 meter intervals. During the pause in penetration, a shear or compression wave is generated at surface level and the time required for the wave to reach the seismic sensors is recorded. The time difference between two consecutive seismic tests performed is a measure of the elastic properties of the soil. An even faster and more accurate way is to use two seismic modules which are mounted at a fixed distance of exactly 1 meter.

Since the time difference between two consecutive measurements is approximately 2 ms, a very consistent measurement of the trigger signal is required. This requirement is met by using the same high sensitive sensors for the trigger module and by placing this module in the immediate vicinity of the hammer.

Figure 4. Seismic module with 10 cm^2 Icone.

3.1.2 Technical specifications

The technical specifications of the seismic module are shown in table 1.

Table 1. Seismic module technical specifications

Item	Specification
Length	500 mm without Icone
Diameter	44 mm
Weight	4.8 kg without Icone
Sensors	Accelerometers X, Y and Z direction: - g-range: 2g – 50g - accuracy: 0.5% (FRO)
Data transfer	4-wire Icone cable inside CPT-rods
Connectors	Quadrax swivel connector to Icone Lemo 4-pins connector to Icontrol
Operating temperature	0° to 60°C

3.1.3 Data processing and visualizing

The output signals from the seismic sensors are being digitized inside the seismic module and from here transferred to the Icontrol data logger at surface level. From the Icontrol the signals are sent to a computer system where they are processed and recorded by the processing software GOnsite. After all tests have been performed, the data obtained are then analyzed off line by processing software, determining the propagation speed and corresponding elastic soil parameters for all investigated depth ranges. An example of how such processing can be visualized, is given in figure 5.

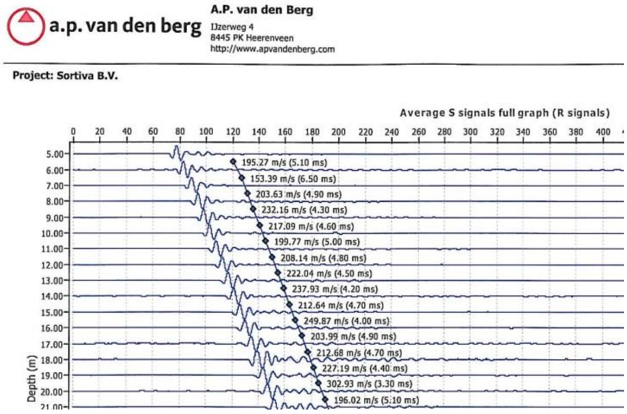

Figure 5. Results of a series of seismic tests.

3.2 Conductivity module

The measurement of conductivity in the subsoil, facilitates separation of zones with differentiated water content, including determining the water table depth and the thickness of the zone of capillary ascent. Measurement of soil electrical conductivity is a function of both the conductivity of the pore fluid and the soil particles and how they are arranged. The dominant factor by far is electrical conductivity through the pore water. However, the most important application of the conductivity module is related to evaluating the degree of contamination of a soil medium containing electrolytes.

Determination of soil conductivity is not an absolute measurement, but indicates a change in soil condition. To what extent electrolytes are dissolved, is demonstrated without distinguishing these electrolytes. So only changes of the concentration of electrolytes dissolved in pore water are determined with the conductivity module.

3.2.1 Principles

Electrical conductivity of soils is not measured directly, but is derived from the measured voltage (V) across an electrode pair at a constant supplied current (I). According to Ohm’s law, soil conductance (G) can be calculated as:

$$G = I / V \tag{3.1}$$

The electrical conductivity kappa (K) can be calculated with next formula:

$$K = C \bullet I / V \tag{3.2}$$

K is measured in milliSiemens per meter (mS/m) and *C* is a calibration factor which is found from direct calibration of the measurement module, whilst totally submerged in a solution of known conductivity.

Fig. 6. Conductivity module with 10 cm^2 Icone.

The conductivity module as shown in Figure 6 is equipped with four electrode rings which are isolated from each other by ceramic insulators. With a controlled voltage source inside the module, a known current (*I*) is induced through the soil between the outer electrodes. This current causes a voltage difference (*V*) across the inner electrodes, which voltage is held on a constant value of 50 mV by continuously controlling the current. When pushing the conductivity module into the soil with a constant rate, the conductivity is measured at depth using equation (3.2). To prevent polarization of the soil and precipitation of electrolytes on the electrodes, the voltage source operates with an alternating current at a frequency of 650 Hz.

The soil temperature is measured simultaneously with conductivity, because the solubility of an electrolyte is to a large extent dependent on temperature, and conductivity is mainly determined by the concentration of a dissolved electrolyte.

3.2.2 Technical specifications

The technical specifications of the conductivity module are shown in table 2 below.

Table 2. Conductivity module technical specifications

Item	**Specification**
Length	550 mm without Icone
Diameter	44 mm
Weight	3.7 kg without Icone
Sensors	Conductivity: - measuring range 50 - 1500 mS/m - accuracy: 0.5% (FRO) Temperature: - measuring range 0° - 50°C - accuracy: 2% (FRO)
Data transfer	4-wire Icone cable inside CPT-rods Wireless Optical data transfer
Connector	Quadrax swivel connector to Icone Lemo 4-pins connector to Icontrol
Operating temperature	0° to 60°C

3.2.3 Data processing and visualizing

In Figure 7 an example is shown of a conductivity module, measuring the salt water ingresses into the main land. The graph shows clearly that at the coordinates of measurement the transition of fresh to salt water is located at a depth of 15 meter.

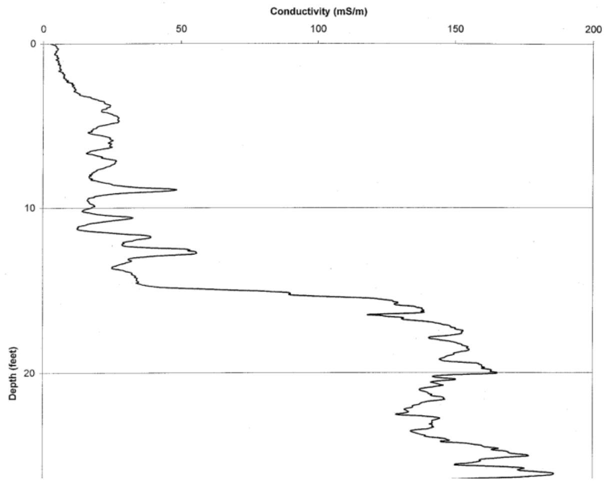

Figure 7. Results of a conductivity test.

3.3 Magneto module

Unknown structures, obstacles like unexploded ordnance (UXO), and high voltage cables 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 are built out of 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. In addition, the standard CPT-parameters can also be measured if the Icone is mounted in front of the magneto module.

3.3.1 Principles

The earth's magnetic field consists of power lines that run from North to South. Ferro metallic objects have the property to be influenced by the earth's magnetic field, causing them to act as a magnet themselves. This local magnetic field disturbs the earth's magnetic field in such a way, that the object can be detected and localized with a magnetometer.

The magnetometer sensor used is able to measure magnetic field anomalies in three orthogonal directions with an accuracy of 0.005 µT. Anomalies can be detected at a distance of 2 meter depending on the size of the object and the position relative to the natural North-South field lines. In practice it is not interesting to know the exact value of the magnetic field, but rather the difference in value at a particular location.

Figure 8. Magneto module with 10 cm^2 Icone.

When the magneto module is used without the CPT-functionality of the Icone, the pushing rate can be increased from 2 cm/s to 20 cm/s. To accurately respond to changes in the measured value, in particular when detecting UXO's, also the gradients of the orthogonal measured anomalies are determined. With the GOnsite! processing software, alarm values can be set to stop pushing when one of these gradients is exceeded.

3.3.2 Technical specifications

The technical specifications of the magneto module are shown in table 3.

Table 3. Magneto module technical specifications.

Item	**Specification**
Length	600 mm without Icone
Diameter	44 mm
Weight	4.8 kg without Icone
Sensors	Magneto: - measuring range 0 – 100 µT - accuracy: 0.005 µT Inclination: - measuring range 0° - 20° - accuracy: 0.5° (FRO)
Data transfer	- 4-wire Icone cable inside CPT-rods - Wireless Optical data transfer
Connector	Quadrax swivel connector to Icone Lemo 4-pins connector to Icontrol
Operating temperature	0° to 60°C

3.3.3 Data processing and visualizing

The parameters measured by the magneto module are the anomaly of the earth's magnetic field in three orthogonal directions and the inclination relative to the vertical Z-axis. The gradients of the anomalies are determined for analysis and assessment purposes during measurement. The position of the magneto module in the Z-plane at the actual depth is calculated in order to know more precisely the position of the measured object.

The above mentioned parameters and gradients are shown in real time graphs. An example of these graphs is shown in figure 9.

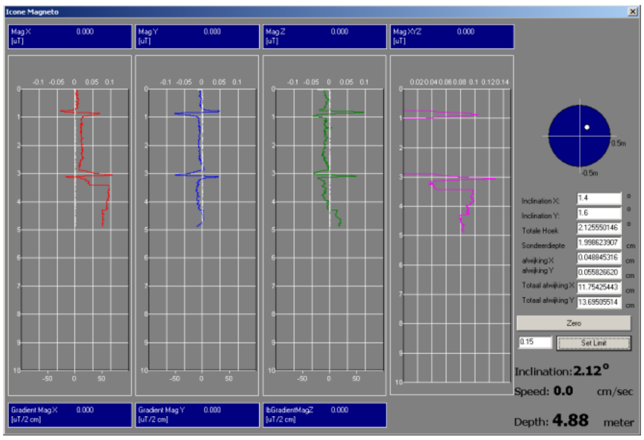

Figure 9. Results of a magneto test.

4 ICONE VANE

The vane 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.

4.1 Principles

The field vane test consists of four rectangular blades fixed at 90° angels to each other, that are pushed into the ground to the desired depth. 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 stiffness of the soil in order to perform an accurate measurement; the stiffer the soil, the smaller the blades of the vane.

Fig. 10. Icone vane (without protection tube).

The new 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 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 for performing very accurate shear tests, up 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 vane field data is digitized and multiplexed using the same protocol of all other Icone applications, so no changes of data logger and cables are needed. The Icone vane tester can be used for onshore as well as offshore applications.

4.2 Technical specification

The technical specifications of the Icone vane tester are shown in table 4.

Table 4. Icone vane technical specifications.

Item	**Specification**
Length	1500 mm (incl. protection tube)
Diameter	90 mm (incl. protection tube)
Weight	14.6 kg (complete tool)
Sensors	Torque: - measuring range 0 – 100 Nm - accuracy: 0.5% FRO Inclination: - measuring range 0° - 20° - accuracy: 0.5°
Data transfer	4-wire Icone cable inside CPT-rods
Connector	Lemo 4-pins connector to Icontrol
Operating temperature	0° to 60°C

4.3 Data processing and visualizing

During a vane test, the vane is being rotated with a very low constant speed, while the required torque is measured with respect to the angel 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 11.

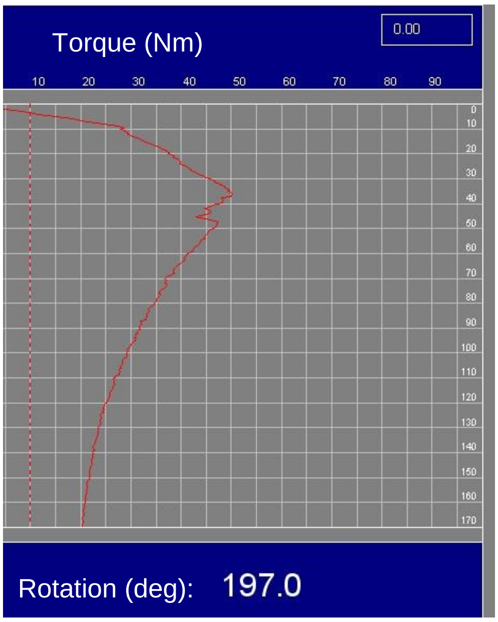

Fig. 11. Results of an Icone vane test.

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

5.1 *Seismic module*

MYV Soluciones Geotécnicas recently acquired the latest version of the seismic module. The company in Costa Rica has used this module successfully in two different projects. The first exploration was conducted for the geotechnical investigation, required for the design of a rural bridge located in Cartago, Costa Rica. The second exploration was performed for the design of a steel storage tank foundation with a diameter of 20 meters, located in Puerto Corinto, Nicaragua.

5.1.1 *Purpose investigation rural bridge*

The main purposes in using the seismic cone at this site, was to:

- Determine the soil stratification.
- Estimate the bearing capacity of shallow foundations.
- Estimate the capacity of driven piles and select a foundation alternative.
- Classify the site for seismic design using V_{S30} methodology.

V_{S30} is a methodology for mapping and classification for seismic site effect evaluation.

5.1.2 *Equipment used*

For this investigation, a 23 ton CPT truck was used. As exploration tool, a 15 cm^2 piezocone was used along with the seismic module. To generate the shear wave, a Campanella pendulum hammer, like the one shown in the picture of Figure 12, worked as the dynamic source.

Fig. 12. 23 ton CPT truck.

5.1.3 *Test results*

Refusal was found at 18 meters depth due to the presence of boulders. In this respect, a complementary SASW-profile (Spectral Analysis of Surface Waves) was carried out to acquire Vs data from 18 meters down to 30 meters.

Figure 13 shows shear wave velocity profiles obtained with different methods at the project site.

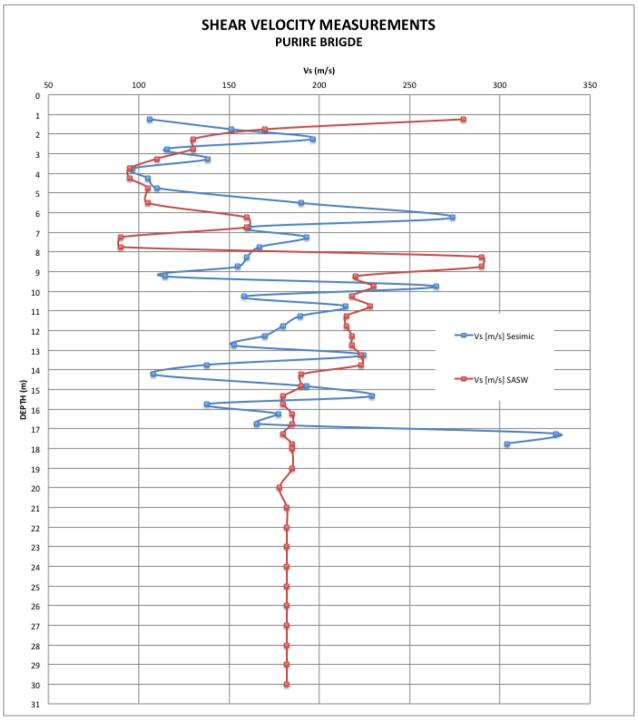

Fig. 13. Comparison between Vs from SCPTu and Vs from SASW.

The V_{S30} value obtained was 169 m/s, and based upon the Costa Rican Seismic Code, the soils classified as Site Class S4 (V_{S30} less than 180 m/s).

As observed in Figure 13, from the surface down to 8 meters depth, there is a good agreement between the Vs profiles obtained by both tests (SASW and SCPTu). From 8 meters down, Vs from SASW tends to be higher in average than the Vs from SCPTu. For the estimation of V_{S30}, the results from direct measurements (SCPTu) were considered more reliable.

As a result of the soil investigation, the foundation for the abutments of the bridge was designed using driven pile foundations.

5.1.4 Purpose investigation steel storage tank

The main purpose of the geotechnical investigation in Puerto Corinto, Nicaragua, was to obtain good quality soil data to design the foundation of the storage tank. Previous soil explorations with SPT classified the soil deposit as prone to liquefaction from the surface down to 19 meters depth. A second opinion and reassessment of the liquefaction potential was required by the owners to optimize the foundations.

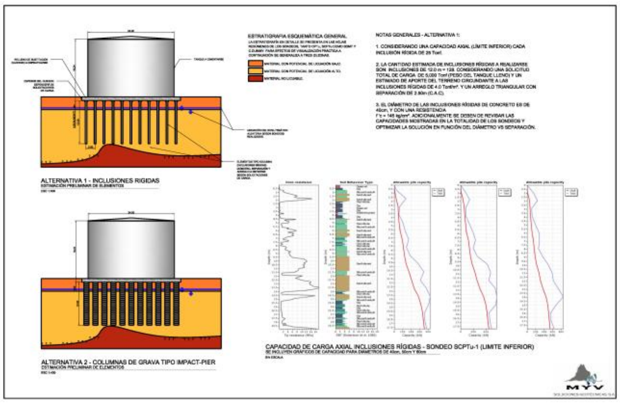

Fig. 14. Proposed foundation for the tank.

5.1.5 Equipment used

For this site, the geotechnical campaign included SDMT soundings as well as SCPTu soundings. As part of the scope, CPT disturbed samples were retrieved with MOSTAP Samplers. The heavy CPT truck was also used for this site.

5.1.6 Test results

According to the CPT tests, from the surface down to 4 meters depth, an old manually built fill layer was encountered. Based on some accounts, this fill was placed by the Nicaraguan government during the construction of Corinto Port. From 4 meters down to 19 meters depth, a medium dense sand deposit was found. Refusal was encountered at 19 meters depth which, according to previous soil reports, corresponds to the bedrock.

The next figure shows the geotechnical profile defined in each sounding.

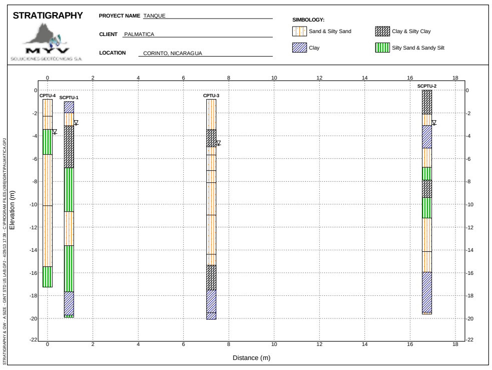

Fig. 15. Layer stratigraphy of the site.

Three different methods were used to estimate the liquefaction potential of the sand deposit: CPT-based method (Robertson 2009), DMT-based method (Monaco and Marchetti, 2007), and Vs-based method (Kayen et al, 2012). Based on the results from the above methodologies, the liquefaction prone layers were located from the surface to 13 meters depth. This finding was considered to be most beneficial in the foundation design of the tank.

Figure 15 shows the record of one of the seismic tests carried out with the seismic module.

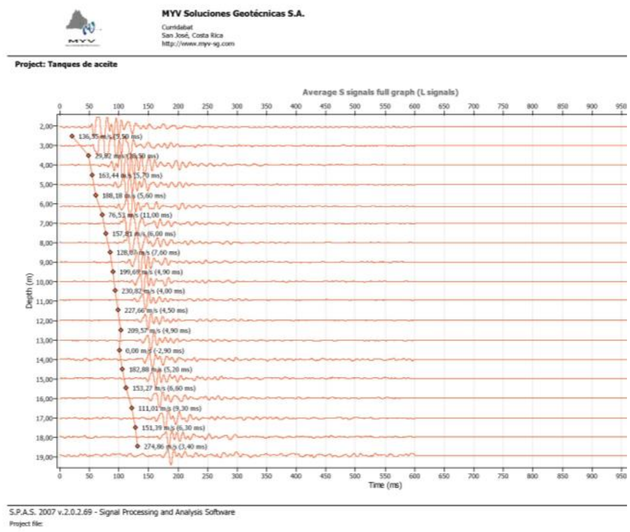

Fig. 15. Data output of the Seismic module.

Given that 2 seismic dilatometer and 2 seismic CPTs were carried out, a comparison among the different shear velocity profiles was possible.

The results of this comparison are shown in figure 16.

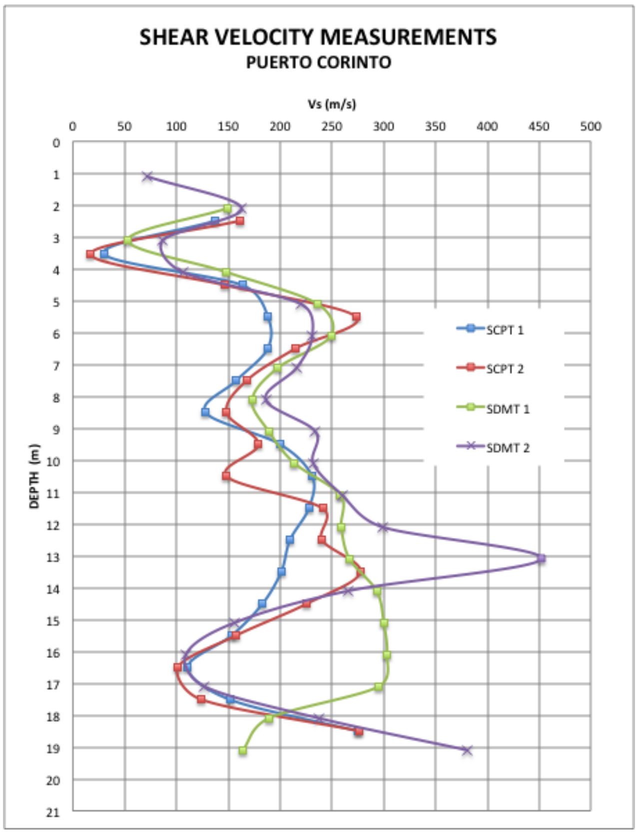

Fig. 16. Comparison of the shear velocity between two different sets of equipment.

As shown in the figure, the agreement between the different Vs profiles is rather good.

6 CONCLUSIONS

Cone Penetration Testing (CPT) as a technique for in-situ soil investigation, is a recognized and widespread method for efficiently performing of soil surveys. CPT is in the course of time continuously improved by the effective use of the latest state of the art. Recent developments, concerning the application of digital electronics inside the cone, offer a range of new features and benefits. The most prominant of these is the ability to easily extend the digital Icone by click-on modules to measure additional parameters. Any module is automatically recognized by the Icontrol data logger, creating a true plug & play system.

The Seismic module has proven to be an accurate and reliable measuring device, which can be used for different measuring techniques for soil analysis.

7 REFERENCES

Brouwer, J.J.M. (2007). In-situ soil testing. HIS BRE Press.

Lunne, T, P.K. Robertson, J.J.M. Powell (2004). Cone Penetration Testing. Sponn press.

Schnaid, F. (2009). In situ testing in Geomechanics, the main tests. Taylor & Francis.