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Geotechnical Characterization of Very Soft Deep-Sea Sediments by In-Situ Penetrometer Testing

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ABSTRACT

Existing onshore resources of raw materials are becoming more and more depleted. If the current demands remain or increase over the coming years, alternative resource areas will become highly interesting. Given these circumstances and the recent technological advances in the field of deep-sea mining, the interest in the deep-sea is growing. Global Sea Mineral Resources NV (GSR), part of the DEME-group, has signed a contract with the International Seabed Authority (ISA) in 2013, giving GSR the exclusive rights to do exploration for polymetallic nodules in a license area in the Clarion Clipperton Fracture Zone (CCFZ), part of the Central Pacific Ocean.

The assigned area is situated around 125°W and 15°N and covers over 75000 km² divided over three areas named B2, B4 and B6. Since 2014, GSR has organised and executed two multidisciplinary research cruises in the assigned license area, mainly focussing on biological, geological and geotechnical research.

Geotechnical characterization of deep-sea bottom sediments is crucial for the development of new mining technology. In order to assess the workability of a tracked vehicle in a deep-sea environment, bearing capacity calculations are needed. This assessment requires input of soil strength parameters over several meters of depth. Such data is not publically available. As such, GSR/DEME and DotOcean NV joined forces and started the development of a penetrometer for a deep-sea environment, over 4000 m deep: the Deep-Sea GraviProbe.

This publication starts with an elaboration on the design process of the GraviProbe. Main challenges for the design are related to the testing environment, such as dealing with high pressures (over 400 bar), high accuracy measurements in soft sediments, workability and repeatability. Testing procedures of the equipment, test results and a number of highlights of the first deployment in the GSR license area at more than 4000 m depth, are also presented.

Keywords: Deep-sea mining, penetrometer, soft soil, polymetallic nodules, deep-sea sediments

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1. INTRODUCTION

In 2013, the International Seabed Authority (ISA) granted Global Sea Mineral Resources NV (GSR) a 15 year exclusive exploration right for a 75000 km² license area in the Clarion Clipperton Fracture Zone (CCFZ) in the Pacific Ocean (Figure 1). The CCFZ is a submarine fracture zone of ca. 7000 km long, well-known for the presence of polymetallic nodules at its abyssal plains at over 4000 m depth. Since the acquisition of the exploration license, two scientific research cruises have been organised and executed by GSR.

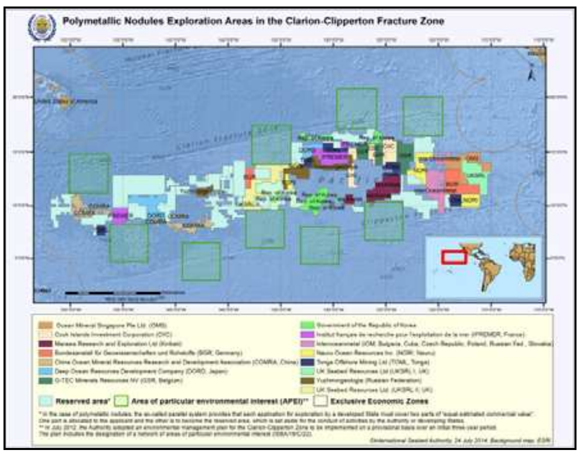

Figure 1: Exploration areas assigned by the ISA in the CCFZ (from www.isa.org.jm).

The first research cruise, named GSRNOD14A, was a 66 days cruise in July-September 2014. It was a multidisciplinary cruise, combining biological, geological, geophysical, geochemical and geotechnical research. The main objective of this cruise was to acquire a complete overview of the bathymetry in the concession area (over 80000 km² of multibeam echosounder data were gathered) and to collect the first nodule and sediment samples. Sediment samples were obtained by box core sampling. Part of the sediment samples was preserved for geotechnical testing. After the cruise, onshore laboratory testing was performed on some of the acquired samples to determine their basic geotechnical properties (classification and strength parameters).

After analysis of the bathymetry and backscatter signal data gathered during GSRNOD14A, three areas of interest inside the license area, each ca. 200 km², were selected in consultation with GSR's scientific partners and experts for more in depth investigation. High-resolution geophysical imagery and physical sampling inside these areas was executed during the 2015 expedition, named GSRNOD15A, which took place in September-October 2015. This multidisciplinary cruise had many scopes, including an important geotechnical one: detailed investigation of the strength of the upper soft seabed sediments.

One of the possible exploitation methods for the nodules involves a seabed mining vehicle with a crawling system. As such, it is important for GSR to determine the bearing capacity of the seabed in the areas of interest. Bearing capacity analysis requires the input of soil strength parameters and the definition of strength variation with depth. Therefore, the geotechnical scope of the GSRNOD15A campaign primarily consisted of determining these strength characteristics by doing in-situ tests. These in-situ test results could then be compared with more traditional geotechnical tests on sediment samples from box cores, collected both during GSRNOD14A and GSRNOD15A.

2. THE NEED FOR IN-SITU DATA

2.1. Which data is needed?

For mining operations with a tracked vehicle on the seabed, the workability of that vehicle needs to be evaluated. The design of the tracks and the vehicle itself will be in function of the encountered soil conditions in the upper seabed sediments. As a starting point, a tracked vehicle with 2 m wide tracks, operating directly on the sea bottom is assumed. To estimate the extent of the zone underneath the tracks that will be affected by the weight of the vehicle, a reference is made to traditional soil mechanics.

In traditional soil mechanics, the vertical extent of the soil affected by a shallow foundation is defined by the well-known Terzaghi failure surface. An active zone directly below the foundation is linked at both sides to a passive zone by a transition zone. Shearing takes place along this failure surface in the subsoil. The encountered shearing resistance is determined by the strength parameters of the soil along this failure surface. It is expected that the failure surface below the tracked vehicle will be similar in shape. If it is assumed that the 2 m wide tracks are comparable to the width B of the foundation, it can be expected that the soil below the tracks will be affected by the weight of the vehicle up to 2 x B = 4 m depth. Therefore, the goal was set to achieve in-situ strength information up to 4 m below the seabed surface.

In practice, the tracked vehicle should be employable over a relatively large area. Therefore, the objective was not only to collect strength data up to 4 m deep, but also to collect these data over a large area, in an efficient, safe and fast way. Unfortunately, traditional sampling and testing techniques do not comply with this goal. As a result, collecting these data by means of penetrometer testing logically came up as the most beneficial option at that time.

2.2. Penetrometer design requirements

The application of penetrometers in shallow and deep-sea environments is not uncommon. A lot of research has been done on this subject (e.g. Stegmann (2007), Steiner (2013)) and several companies provide commercial services with penetrometers in deep-sea environments. However, for the application in this specific case, there were some additional challenges.

First of all, the depth of the three areas of interest ranges between 4500 m to 5000 m. Applications of penetrometers at such great depths are extremely scarce, if even existing at all. These depths also involve water pressures up to 500 bar, under which the apparatus needs to remain functional.

A second challenge was the expected strength of the sediments. Literature study (e.g. Tisot (1986), Rey (1988)) and results of laboratory tests on samples from GSRNOD14A, indicated only very soft sediments in the upper soil layers of the abyssal plains in the CCFZ. To acquire high accuracy measurements in these soft sediments, a penetrometer cone capable of registering very low forces during penetration of the soil is required.

Thirdly, the great depths at which the testing takes place require a penetrometer and corresponding operational procedure that allows executing several measurements during a single deployment. This eliminates the need to retrieve the penetrometer after each test, which results in a very high efficiency.

Another challenge was related to the specific dimensions and available support equipment on board of the R/V Mount - Mitchell, the research vessel for the 2015 expedition cruise. It was of critical importance that the penetrometer could be deployed with the available A-frame and winch, without major modifications.

Last but not least, when working with commercially available deep-sea penetrometers, whether or not adapted to the specific requirements of this area, the price factor and short term availability also have an important role. Considering the above, GSR and DotOcean decided to join forces and started the development of a deep-sea penetrometer from scratch, but optimised for this specific environment.

In summary, the most important design requirements for the penetrometer were: (1) strength data collection up to 4 m deep, (2) operational depths of 4000 m to 5000 m and related water pressures, (3) a high sensitivity cone for strength measurements in very soft soils, (4) a flexible system to anticipate altering ground conditions, (5) a system capable of executing high amounts of measurements during a single deployment, (6) deployment from the available research vessel and (7) a ‘one-person system’; as in system needs to be ‘simple’ in set-up, deployment and data interpretation. The result of this design process was a penetrometer called the Deep-sea GraviProbe (Figure 2). Two complete GraviProbe sets were made available for the 2015 GSR campaign; one for deployment and a spare one.

3. THE DEEP-SEA GRAVIPROBE

3.1. Components

A distinction is made between passive and active hardware components. The active components are responsible for the actual measurements. The most important passive components are shown in Figure 2.

The main body of the GraviProbe consists of a thin, hollow tube and a wider, solid base. The wider base has six threaded holes, which allow securing six threaded rods on one side and the bottom plate on the other side. Three lifting eyes are attached to the main body for hoisting operations. The hollow tube of the main body is sealed on top by a closing lid, which has a fourth lifting eye.

Semi-circular weights can be slid over the threaded rods of the main body to vary the total weight of the GraviProbe. Weights are secured onto the body with the protector plate and nuts on top.

The bottom plate is secured to the wider base of the main body by means of six hex cap screws. The shaft holder is screwed into the centre of the bottom plate and holds the shaft. The large difference in diameter between the bottom plate/body and the shaft prevents excessive penetration in softer soils.

At one side, the 4 m long shaft has a screw thread which allows connecting it to the bottom plate and main body via the shaft holder. The shaft has a diameter of 5 cm. The cone is connected to the other side of the shaft.

A custom-made camera and lighting system was also fitted onto the GraviProbe. The position of the camera and lights focused on the part of the shaft directly below the body. This camera position allows to verify whether, and in which way, 4 m penetration is achieved. The camera and lights were supplied with extra battery packs and had an operation time of ± 4 h.

Figure 2: Sketch of the Deep-sea GraviProbe.

The active hardware parts of the GraviProbe are responsible for actual measurements and data registration. The most important components are the pressure bottle, the water pressure sensor, the penetrometer cone and the accelerometers.

The pressure bottle is the heart of the GraviProbe and is located in the hollow tube of the main body. It contains the printed circuit board to which the sensors are connected, the microSD card and the battery pack. The pressure sensor is connected to the bottom of the pressure bottle. The cone is connected to the top of the pressure bottle. There are two more connections at the top: a connector to switch the GraviProbe on/off and the data-output connection.

The GraviProbe’s cone is filled, in vacuum circumstances, with a carnation mineral oil and contains the strain gage inside. The oil reservoir is sealed from the outside by a nitrile rubber membrane. The detailed inside configuration of the cone is part of DotOcean's intellectual property and will not be discussed in this publication.

3.2. Data up to 4 m deep

One of the requirements for the GraviProbe was to collect strength data up to 4 m below seabed. As a consequence, the GraviProbe should be capable of penetrating the cone and the 4 m long shaft to which it is connected, over this distance into the soil. The GraviProbe's (GP) energy to penetrate the soil over 4 m consists of a kinetic term and a potential energy term:

$$E_{pot} + E_{kin} = m \times g \times z + \frac{1}{2} \times \mathrm{m} \times v^2$$

in which:

- E_{pot} = potential energy of the GP
- E_{kin} = kinetic energy of the GP
- m = buoyant mass GP
- g = gravitational acceleration
- z = penetration depth GP
- v = velocity GP

The equation indicates that there are two parameters which can contribute positively to the available energy: (1) an increased penetration speed v and (2) an increased buoyant mass m. Due to operational and safety limitations, and in order to eliminate dynamic effects as much as possible, the penetration speed v was fixed and assumed to be equal to the speed of the winch used on board of the research vessel. Consequently, the only variable parameter is the mass m. The "naked" GraviProbe has specific dimensions and is attached to a ca. 4,5 km long cable. This configuration defines the minimum buoyant mass of the GraviProbe. However, the design with modular weights allows adding (or removing) weights to the body, in order to vary the available (potential) energy of the GraviProbe.

The energy of the GraviProbe is necessary to overcome the resistance encountered during penetration of the soil. The soil resistance is calculated using the traditional bearing capacity formulas for piles. The total soil resistance Q_t is split up into a tip resistance Q_b and resistance related to friction along the shaft Q_f:

$$Q_t = Q_b + Q_f$$

$$Q_b = A_b \times N_c \times c_u$$

$$Q_f = \sum \alpha \times A_s \times c_u$$

in which:

- Q_t = total soil resistance
- Q_b = tip resistance
- Q_f = friction resistance
- A_b = tip area
- Nc = bearing capacity factor
- A_s = shaft area
- α = friction coefficient
- c_u = undrained shear strength

The soil resistance is a function of its strength. As a starting point for a soil resistance calculation, a design soil profile, indicating variation of undrained shear strength with depth, is needed. An extensive literature study was conducted to gather the most important available geotechnical information in the CCFZ (e.g. Tisot (1986), Rey (1988)). Although the amount of data is very limited, especially in comparison to the extent of the area, there were no indications that the undrained shear strength of the soil is higher than 15 kPa at 4 m depth. With this input, a design shear strength profile was selected and applied as a starting point for soil resistance calculations.

To calculate the soil resistance, a low impact velocity is considered. In doing so, it is assumed that phenomena related to dynamic penetration (e.g. strain rate effect) are of negligible importance. As a lower bound approach, one could even neglect the dynamic effect and assume that the probe penetrates under its self-weight when placed on the sea bottom.

Based on the assumptions above, equilibrium was searched between energy of the GraviProbe and encountered soil resistance during 4 m penetration in the design soil profile. It turned out that the weight of the GraviProbe should be 950 kg in order to penetrate 4 m of the upper soft soil.

3.3. Depth and high pressures

The areas of interest in the GSR license area are situated at more than 4000 m depth. At these depths, water pressures can be over 400 bar. During testing, these are registered using a water pressure sensor which is installed at the bottom of the GraviProbe's body. To deal with these high pressures, the GraviProbe has several modifications.

First of all, electronic components are grouped in the pressure bottle; a small pressure vessel container located in the hollow tube of the main body, and capable of withstanding pressures up to 500 bar. Another important modification is the vacuum filling of the cone with a carnation mineral oil. This makes the cone unaffected by the surrounding high water pressures and makes it possible for the strain gage inside to register relatively small forces on the cone during penetration of the soft sediments. Detailed design of the interior of the cone is part of DotOcean's intellectual property and will not be discussed in this publication.

Evidently, prior to departure and deployment, the pressure bottle, cone and water pressure sensor were subjected to different kind of pressure tests in hyperbaric chambers (see paragraph 4.1).

3.4. Cone sensitivity

The cone will penetrate very soft soil at a certain speed. It was expected that the 4 m penetration would not take more than 4 to 5 seconds. For a qualitative strength characterisation over the entire 4 m, the cone has to be able to execute lots of measurements during a relatively short period of time. A high sampling frequency is thus preferred. As such, DotOcean has selected a cone with sampling frequency of 2 kHz; 2000 measurements per second are registered and stored.

In order to register low forces on the cone tip, a strain gage was selected with an optimal measuring range between 20 N and 2000 N. With this accuracy range it was assumed that the cone is able to measure undrained shear strengths (c_u) between c_u = 0,5 kPa and c_u = 50 kPa. This range completely covers the strength values as defined in the design strength profile and has sufficient margin to anticipate for stronger soils. The configuration of the strain gage inside the cone is part of DotOcean's intellectual property and will not be discussed in this publication.

3.5. Flexible system

The total weight, and thus the (potential) energy, of the GraviProbe can be modified by adding or removing weights. These weights are semi-circular elements in lead alloy and weigh 25,4 kg per piece.

The "naked" GraviProbe, ready to use, but without any extra weights attached to it, weighs 460 kg. As a starting set-up, 18 extra modular weights were attached, bringing the total weight of the GraviProbe to 917 kg. This is in line with the mass which was determined from the energy vs. soil resistance equilibrium in paragraph 3.2.

In total, a maximum of 62 semi-circular weights, equalling 1575 kg, can be added to the "naked" GraviProbe. This brings the maximum total weight of the GraviProbe at 2035 kg. This modular weight system allows adjusting to softer of higher strength soils compared to the design strength profile. If the soils are softer, the GraviProbe will penetrate more than 4 m deep and also its base plate will start to penetrate the soil. Because of the large difference in diameter between shaft and base plate, excessive penetration will be prevented. In this case, weights can be removed to a minimum value of ca. 460 kg. If the GraviProbe does not penetrate 4 m deep because of higher encountered soil resistance, weights can be added, to a maximum of 2035 kg, to increase the energy of the GraviProbe and overcome the extra resistance. With the weight flexibility, it is definitely possible to operate within the range of the strain gage sensitivity; i.e. 20 N to 2000 N or assumed undrained shear strength (c_u) of the soil between ca. c_u = 0,5 kPa - 50 kPa.

3.6. Efficiency and simplicity of the system

With the given winch speed, it takes the GraviProbe 1,5 h to 2 h in this setting to reach the sea bottom and the same amount of time to come back up. This makes the time available for testing rather limited and it should therefore be used very efficiently. As such, the equipment and testing procedure should allow multiple penetrations and data registration without retrieval after each penetration. There are several technical characteristics of the GraviProbe which are specially designed to accomplish this.

For example, the system works on a lithium-ion based battery which is located in the pressure bottle. The power source goes down with the probe. The battery has 24h autonomy once fully charged and therefore maximizes the time available for testing once the probe is at the sea bottom. Another feature is the data storage (accelerometers, water pressure sensor and cone) on a micro-SD card in SEG-Y format. The micro-SD card is also located inside the pressure bottle. The data is stored in such way that every SEG-Y file contains 20 min. of data. This is a safety measure: if one file is corrupted, only 20 minutes of data is lost. And since the data is directly stored inside the pressure bottle, there is no need for retrieval after each test.

It was also requested that the system would be as ‘simple’ as possible, both in terms of assembly, operation, retrieval of data and interpretation. The GraviProbe has several adaptations to meet this request.

First of all, it is very simple to assemble the GraviProbe. It is a “plug and play” system with a limited amount of cables and connectors. Secondly, the overboard procedure is also relatively simple; the ship’s A-frame places the GraviProbe into a launch and recovery system (LARS) installed on the back deck. The LARS brings the GraviProbe from its horizontal position on deck to a vertical position required for deployment and testing, without damaging the cone. The LARS can be easily and quickly installed on any ship’s deck.

The operational procedure itself is also simple; there is no need for specialized equipment on board. A standard winch and A-frame are sufficient to start operations for testing. The only parameter to control during testing is winch payout: the GraviProbe can be moved up or down. During operation it is assumed that full penetration has occurred as soon as slack on the cable is visible on deck. Once this is observed, the probe is retrieved over a couple of tens of meters, moved to the next location and ready for another penetration.

Also the visualisation and related interpretation of the data is relatively easy. The data is recorded and stored as a time series. At the time the cone encounters the seabed, the GraviProbe decelerates and simultaneously, the forces on the cone increase. The moment at which the wider base plate hits the sea bottom, and the shaft and cone have thus penetrated 4 m into the soil, is associated with a very sharp deceleration and eventually a full stop of the GraviProbe (v=0). Accelerations and decelerations are continuously registered with accelerometers. The full stop is the reference point in the time series for ‘backward’ data selection; the data during the 4 m penetration. Based on a double integration procedure, this part of the time series can be converted to a depth series. This eventually results in 4 different graphs for each penetration; (1) acceleration vs depth, (2) speed vs depth, (3) dynamic cone resistance vs depth and also (4) the water pressure at the sea bottom. This procedure is executed automatically by specially developed software programs and results in a simple visualization of the data. The 4 graphs allow easy interpretation and data comparison on board and, if necessary, they allow adjustments of the GraviProbe set-up for the next operation.

4. TESTING CAMPAIGN

Despite a limited time frame, the GraviProbe was subjected to several tests before it was shipped to the departure location of the 2015 research cruise.

4.1. Pressure tests

The water pressure sensors were subjected to a pressure test in a closed hyperbaric chamber. Pressure was increased up to 600 bar in steps of 150 bar. This was also performed with the pressure bottles, containing all the electronics. Pressures were increased up to 500 bar in the hyperbaric chamber.

The two cones were also subjected to tests in hyperbaric chambers. During the test, the cones were already filled with oil and the strain gage was already mounted inside the cone. A maximum pressure of 500 bar, in steps of 50 bar with a 10 s hold at each step, was applied to the cones.

The cones were also loaded to calibrate the strain gage. For one of the cones, the load swings were performed under hyperbaric circumstances. Unfortunately, due to time constraints, the load swings for the other cone were performed under atmospheric pressure circumstances. This cone will be post-calibrated after the GSRNOD15A cruise.

The strain gage was subjected to forces varying between 0 N and 2500 N. Because very soft soils were expected, more calibration points were scheduled in the lower region, i.e. 0 N – 250 N, in order to increase the accuracy at small loadings. According to the corresponding calibration file, the strain gage, at a gain of 64 bit, is capable of registering a load increase of 377 Pa on the cone.

4.2. Full-scale tests

In July 2015 two full-scale in-situ tests with the GraviProbe were executed at the DEME-HQ harbor in Antwerp, Belgium. A bathymetric survey in the small harbor indicated at least 2 m to 3 m of very soft sediments on top of a more sandy layer, within a reachable distance from the quay wall. The same survey also indicated that within that same distance, the water depths could be sufficiently large (tide dependent) in order to fully submerge the GraviProbe. As the targeted area was close to the quay wall, the GraviProbe can be put into the water with a crane standing on the quay wall.

The first full-scale test focused on the assembly of the GraviProbe (Figure 3). It was the first time that all (passive) components were put together. For this test, the pressure bottle, the water pressure sensor and the cone were not installed on the GraviProbe. At the tip of the shaft a dummy cone was attached. Not only did this test allow us to familiarize with the different GraviProbe components and its assembly, it was also a preparation of the planned second test (with active components).

After all, for this second test, in which a test of all the electronics was foreseen, some items still needed to be checked. For example, how could the GraviProbe efficiently be brought from its horizontal assembly position into its vertical testing position without damaging the cone? It was also very important to verify the presence of the 2 m to 3 m soft sediments at the foreseen testing location, exclude the presence of obstacles or very hard substratum which could damage the cone and verify the water depth for a certain tide.

Figure 3: First full-scale test: impressions from site.

In the end, this first test was considered successful and the scope for the second test was finalized.

The aim of the second full-scale test was to perform actual measurements. Therefore the pressure sensor and cone were connected to the pressure bottle and all components were installed into the GraviProbe. This was also the moment to test the GraviProbe software, which is needed to switch the electronics on/off and retrieve and visualize the data after testing.

The test was executed according to the same operational procedure as the first full-scale test. The crane lowered the GraviProbe through the water column at a controlled speed. As soon as the cone and the shaft started to penetrate the soft sediment, a clear decrease in weight on the load cell of the crane was observed. After 2 m to 3 m of penetration, an even sharper decrease in weight on the load cell of the crane occurred. This was identified as the moment when the very soft soil layer was fully penetrated by the cone and the harder substratum (sandy layer) below was encountered. At that moment, the crane stopped lowering the GraviProbe and started retracting it in order not to damage the cone. Next, the crane repositioned its boom and a new location was tested using the same procedure. After testing, the pressure bottle was connected to a computer and the data was retrieved. DotOcean has provided two software programs to read the produced SEG-Y data files.

The first program is the “Raw Data Viewer”. This tool can read a SEG-Y file and visualize the different sensor registrations, i.e. forces on the cone and water pressure, in time. An example of a SEG-Y file obtained during this second full-scale test is given in Figure 4. The x-axis indicates the time in seconds and the y-axis indicates the integer values of the sensor registrations. For example, the black line in Figure 4 depicts the registration of the strain gage, thus the forces on the cone. The three peaks, at regular moments in time, correspond to penetrations in the soil and thus a sharp increase of the forces acting on the cone. Based on the calibration file of the strain gage, these integer values can be translated to actual forces in Newton and to stresses in Pascal.

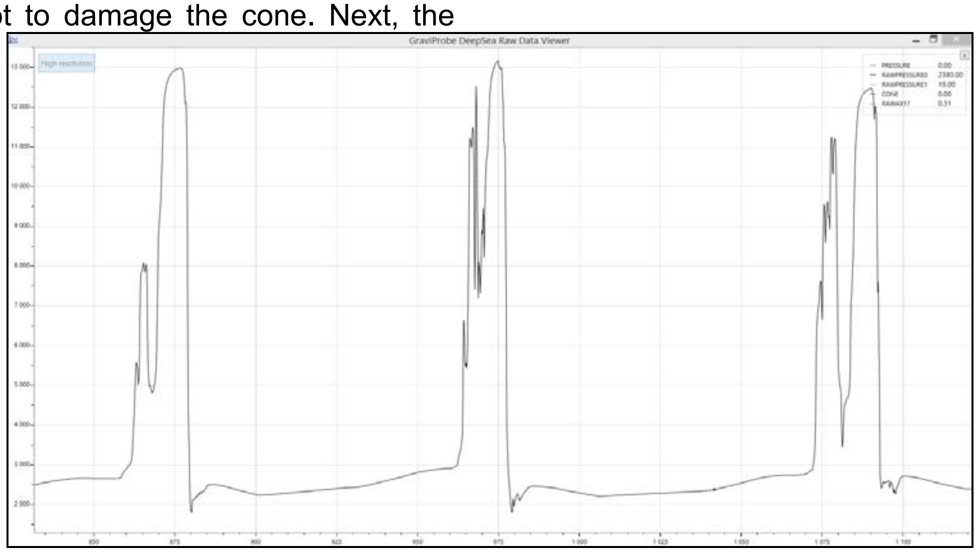

Figure 4: GraviProbe DeepSea Raw Data Viewer with cone-signal (black).

The second program is the “Deep-sea GraviProbe software”. This is a more advanced program which automatically generates different graphs for further interpretation. The program reads the SEG-Y files and automatically identifies the peaks corresponding to a penetration of the GraviProbe within the time series. The program selects all the sensor registrations within that time frame and combines them with the accelerometer data during that same time frame. As explained before, the combination of these data allows the production of 4 different graphs for each penetration; (1) acceleration vs depth, (2) speed vs depth,

(3) dynamic cone resistance vs depth and also (4) water pressure at the sea bottom. Graphs presented in Figure 5 belong to one of the penetrations executed during the second full-scale test. Because of the very shallow depth in this testing area, the fourth graph of the water pressure is omitted.

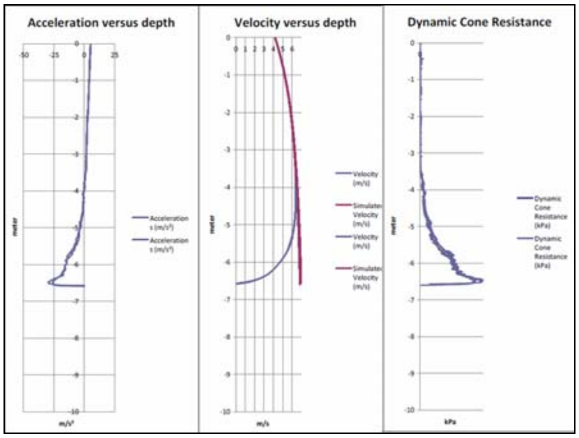

Figure 5: Automatic generation of acceleration, velocity and dynamic cone resistance vs. depth at a penetration location.

5. RESEARCH CRUISE GSRNOD15A

5.1. Scope GraviProbe

The GraviProbe's scope was to collect as much strength data as possible up to 4 m deep, over a relatively large area. Ideally, the penetrations are relatively close to each other - in order to make interpolations from one point to another - and the results can be verified and confirmed by other data.

The deployment location for the GraviProbe was determined taking into account several considerations. The preferred testing location should be an area where only soft sediments occur. Hitting hard outcrops or other obstacles could damage the GraviProbe's cone. Therefore, deployment preferably takes place in the so-called "high-resolution box"; a selected small area where high-resolution side scan sonar measurements and photographs are available (=another type of data acquired during the GSRNOD15A research cruise). These data allow eliminating as much as possible the presence of hard rock outcrops or other obstacles.

The preferred testing area should also be situated relatively close to a GSRNOD15A box core sampling location. This enables the comparison between the in-situ and laboratory strength measurements of GSRNOD15A. Furthermore, the preferred testing area should be close to a location where a GSRNOD14A box core sample was taken. This enables the comparison between the in-situ strength measurements of GSRNOD15A and laboratory strength measurements of GSRNOD14A.

Also from an operational point of view some considerations were taken into account. First of all, good weather conditions are required in order to get the GraviProbe overboard safely and observe correctly slack on the cable during penetration. Secondly, the GraviProbe operations should be aligned with the deployment of other types of equipment and their testing locations. It is also important to note that the R/V Mount Mitchell is not equipped with a dynamic positioning system. Therefore, the testing locations were located along a linear trajectory and not in a grid. To follow the scheduled trajectory, one had to make the best use of the existing currents and wind at that time.

Eventually, keeping in mind the considerations as formulated above, a ± 3 km to 4 km straight line was selected in the designated high-resolution area (Figure 6). Depending on the testing area, 12 to 15 points were selected along this line at a distance of ± 250 m from each other. At each point 5 penetrations with the probe were planned.

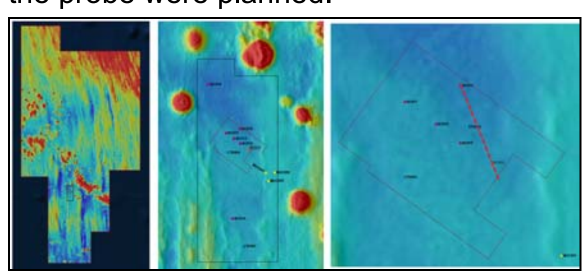

Figure 6: (left) License area B6, (middle) area of interest B6 South, (right) high-resolution box inside B6 South and proposed GraviProbe trajectory for testing.

It was assumed that these 5 penetrations, at very short distances from each other, would result in similar strength profiles and would confirm the testing results at a specific location. On the other hand, testing at points located about 250 m from each other would allow to observe possible regional variations within a testing area. Comparison of the measurements between the three different testing areas enables the potential identification of larger scale regional variations.

5.2. Operational procedure

The GraviProbe is moved using the ship's A-frame and tugger lines from its storage position on deck into the launch and recovery system (LARS). Then, the GraviProbe is "switched on" and camera and lights are installed. While sailing to the first testing location, the GraviProbe is put overboard and starts descending (Figure 7).

Figure 7: GraviProbe ready for descent.

During the descent, 10 to 20 second stops were executed at regular depth intervals. These depths were located with the cable counter on the winch. The purpose of these stops was two-fold: (1) recognition point in the data time series and (2) opportunity to match water depth with water pressure. The descent was stopped before the GraviProbe was expected to touch the seabed. As soon as the ship reached the first testing location, the descent continued until the first penetration took place; i.e. until slack on the cable was observed on deck. Then the GraviProbe was retracted over ± 30 m to 50 m above seabed and released again for the next penetration. This operation was repeated 5 times in total at each location. Considering 12 to 15 different locations per operation, in total 60 to 75 penetrations were realized during a single deployment.

During the operation itself, metadata were registered, both automatically and manually. These metadata, for example time of important events or observations, are simplifying data processing afterwards.

5.3. Results

The first deployment of the GraviProbe took place on 21/09/2015. Once the GraviProbe was back on board, the camera material was analysed and confirmed that the GraviProbe penetrated the sea bottom each time as planned (Figure 8). Preliminary analysis of the data on board also indicated consistent results, in the expected range (Figure 9).

The GraviProbe has been deployed in the three areas of interest. For each deployment, the scope as defined above was successfully achieved making use of the operational procedure as described above.

Figure 8: Impact of the wider GraviProbe body at the seabed, after 4 m penetration of the shaft & cone. Notice the perfectly straight alignment during penetration.

In the first area of interest, 12 different locations have been tested with a total of 56 penetrations observed on deck. In both the second and third area of interest, 15 different locations have been tested with for each area 75 penetrations observed on deck. At the moment, these results are still being processed, interpreted and discussed.

6. CONCLUSION

In order to determine in-situ strength parameters of very soft soils up to 4 m below the seabed in a challenging deep-sea environment, GSR and DotOcean developed the Deep-Sea GraviProbe. This penetrometer is user friendly and has several modifications to deal with pressures over 400 bar, execute high accuracy measurements in soft sediments and optimise workability, repeatability and data interpretation. Before deployment in the Pacific Ocean, the equipment has been thoroughly tested. During the 2015 GSR research cruise, the penetrometer has been successfully deployed in three different areas within the GSR license area. In total, more than 200 penetrations have been executed. Camera footage and preliminary analysis of the penetrations on board indicated 4 m penetration and consistent results. At the moment, detailed processing, analysis and interpretation of the data is executed.

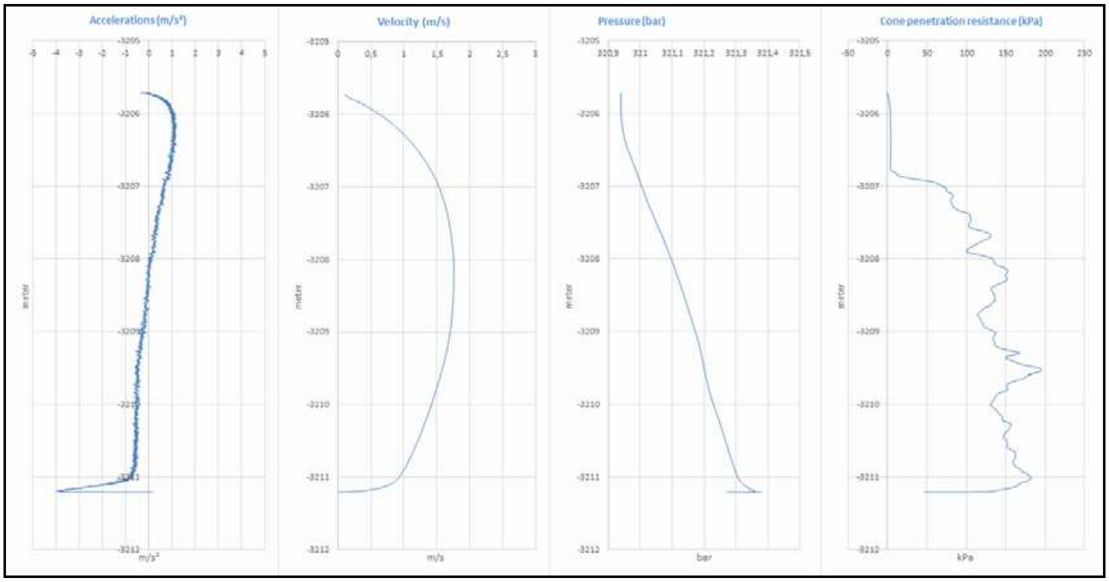

Figure 9: GraviProbe data example of penetration during first deployment.

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REFERENCES

Rey, S. (1988) “Environnements sédimentaires et propriétés géotechniques de sediments marins profound de deux zones du Pacifique Tropical nord-est”, Doctoral Thesis, Centre de recherches en mécanique et hydraulique des sols et des roches, Ecole Nationale Superieure de Géologie de Nancy, 314 p., Nancy, France.

Steiner, A. (2013) “Sub-Seafloor Characterization and Stability of Submarine Slope Sediments using Dynamic and Static Piezocone Penetrometers”, Doctoral Thesis, Faculty of Geosciences, Bremen University, 325 p., Bremen, Germany.

Stegmann, S. (2007) “Design of a free-fall penetrometer for geotechnical characterisation of saturated sediments and its geological application”, Doctoral Thesis, Faculty of Geosciences, Bremen University, 181 p., Bremen, Germany.

Tisot, J.P. (1986) “Propriétés géomécaniques des sediments des grands fronds océaniques”, Mémoires Sciences de la Terre, Foundation scientifique de la géologie et de ses applications, 351 p., Nancy, France.