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INTERNATIONAL

ORIGINAL ARTICLE Bulletin of the Maritime Institute in Gdańsk

# Practical aspects of the Cone Penetration Tests CPTU as used in the Polish Exclusive Economic Zone of the Baltic Sea

## Praktyczne aspekty sondowań statycznych CPTU w Polskiej Wyłącznej Strefie Ekonomicznej Morza Bałtyckiego

**Authors' Contribution:**
**A** – Study Design
**B** – Data Collection
**C** – Statistical Analysis
**D** – Data Interpretation
**E** – Manuscript Preparation
**F** – Literature Search
**G** – Funds Collection

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Article history: Received: 20.08.2015 Accepted: 06.11.2015 Published: 10.12.2015

**Abstract:** The cone penetration test is one of the most widely used methods in land and marine geotechnical site investigations. CPTU allows for a determination of in-situ geotechnical properties of soils, and recognizing soil stratigraphy. This article provides an overview of the CPTU testing equipment that is used for seabed investigation in the Polish Exclusive Economic Zone. It is largely based on experience gained while performing and supervising the tests. The authors describe the proper procedure of testing, and provide detailed information on preparation of the equipment (calibration, placing CPTU unit on seabed).

**Keywords:** Offshore cone penetration test, CPTU units, CPTU procedures

**Streszczenie:** Sondowanie statyczne CPTU jest jednym z najczęściej stosowanych narzędzi we współczesnych lądowych i morskich badaniach geotechnicznych. Daje możliwość rozpoznania podłoża pod kątem stratygrafii oraz parametrów gruntów warunkach in situ. Niniejszy artykuł zawiera przegląd urządzeń wykorzystywanych do sondowań CPTU dna morskiego w Polskiej Wyłącznej Strefie Ekonomicznej. W znacznej mierze oparty jest na doświadczeniach własnych, zdobytych podczas wykonywania i nadzorowania badań. Autorzy opisując procedurę sondowania, zwracają szczególną uwagę na odpowiednie przygotowanie sprzętu (kalibracja, ustawienie sondy CPTU na dnie).

**Słowa kluczowe:** Morskie sondowania CPTU, sondy CPTU, procedury CPTU

## Introduction

Cone Penetration Tests (CPTU) play an important role in modern geotechnical research. Their history dates back to the 1930s, when bolts with tapered endings were inserted into the ground using human muscle strength. Over the years, both the testing technique and the equipment have undergone intensive development and been adapted to find application in various conditions. Cone penetration tests turned out to be useful also in the field of maritime geotechnics, thus becoming a valuable source of information on parameters of soils situated below the surface of the oceans and the seas.

The specific nature of the marine environment made it necessary to introduce a series of technical solutions that would enable the sounding devices to work underwater at considerable depths. Due to the extremely adverse conditions, direct and physical human participation in the research was reduced to a minimum. The units used in the contemporary cone penetration tests of marine soils are completely automated, remote-controlled devices. Operating them is limited to no more than control over the processes of lowering and placing them on the bottom, and monitoring of the penetration process. The basic measuring tips of the CPTU systems enable measurement of: cone resistance $q_c$, sleeve friction $f_s$, and pore water pressure $u_2$. Based on these parameters, the type of soil, as well as most of the parameters of the ground substrate may be determined with help of reliable, available in the literature calculation formulas and diagrams.

The clear and simple procedures, comparatively low costs and quality of soil strength parameters provided by the soundings, allow surveys of this kind to become more and more common as a basis for designing foundations of offshore constructions. They are becoming an alternative for laboratory tests conducted onshore on marine soil samples. Expensive and hard to perform in the offshore conditions the collection of undisturbed soil samples is increasingly limited to a bare minimum. One cannot forget, however, that the programmes of marine soil investigations realized for the purposes of implementing offshore investments must not be carried out solely on the basis of cone penetration tests. There is a genuine need to verify the acquired parameters with laboratory tests.

The following part of this study includes descriptions of CPTU units types employed in geotechnical surveys of the Baltic Sea's seabed performed as a part of works supervised by the Geotechnical Laboratory of the Maritime Institute in Gdańsk, as well as the procedures of preparing the equipment to work, conducting the tests, and assessing the quality of the tests performed.

## Cone penetration tests CPTU used in the polish exclusive economic zone of the baltic sea.

Recently, there may be observed a growing demand for offshore CPTU surveys in the Polish Exclusive Economic Zone of the Baltic Sea. Most of the currently planned and applied of ground investigation projects for the purposes of the implementation of offshore investments encompass the cone penetration tests, placing high demand on their quality. To ensure the best standard of the research, it is necessary for the equipment of an appropriate class, and a fully qualified staff to be provided.

The considerable cost of acquisition and operation of the devices for the submarine CPTU testing is the reason why their availability on the Polish waters is very limited. In order for the timely implementation of the projects to be guaranteed, there often arises a need to rent the equipment or fully equipped, specialized vessels from the external contractors operating on the European market. This provides an excellent opportunity to exchange the experiences, and gain knowledge of the latest technologies.

This chapter includes a short description of the units used most often off the Polish coasts.

Taking into account construction of the most basic element of a cone penetrometer, namely the rod with an instrumented measuring cone tip, there may be distinguished two types of the offshore cone penetration devices CPTU:

- cone penetrometers with rigid rods;
- cone penetrometers with coiling rods.

**Fig. 1.** CPTU ROSON penetrometer by the A.P. Van den Berg company situated on board of the R/V St. Barbara survey vessel.

An example of a penetrometer with a rigid rod is the construction by a Dutch company A. P. Van den Berg, which has already been known for many years – the ROSON 10FT placed on board of the R/V St. Barbara survey vessel – see (*Fig. 1*). Built on an extra weighted heavy steel frame of weight of 15 t measured in the air, and 10 t in the water, it works excellently with regards to the deep soundings. Driving force is transmitted onto the device's rods by means of frictional circular modules, which allows for a thrusting force of about 100 kN, and a maximum depth of penetration of 25 m (depending on the ground conditions) to be obtained with the use of a 10cm² CPTU cone.

The great weight of the device's frame results in its sinking in the seabed wherever surface sediments characterized by a low resistance and high compressibility levels occur. In certain situations, even when special mattresses are used, the settlement depth may be greater than 1 m. In such cases, the testing begins below the seabed level, and interpretation of parameters of the ground in which the device has sinked is thwarted. Another problem is to pull up the device back onto the deck.

Another type of penetrometers – the ones using coiling rods – is represented by two devices by a British company called DATEM, namely the NEPTUNE 5000 (see *Fig. 2b*), and the NEPTUNE 3000 currently on the deck of the R/V IMOR survey

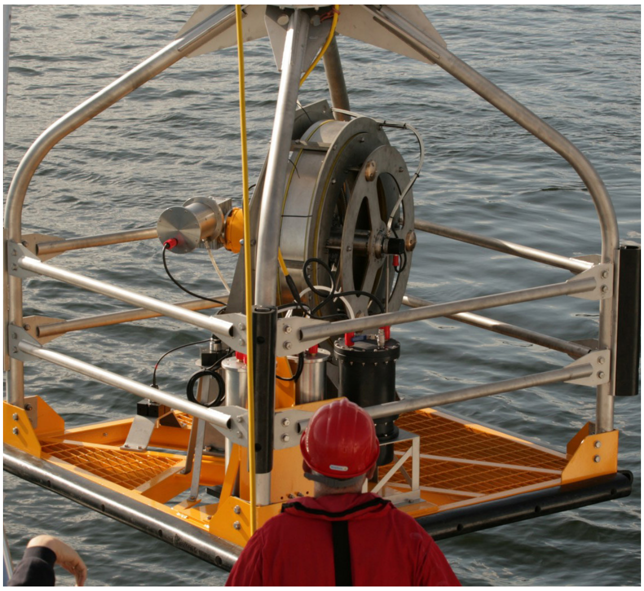

**Fig. 2a.** The NEPTUNE 3000 penetrometer by the R/V IMOR ship's side

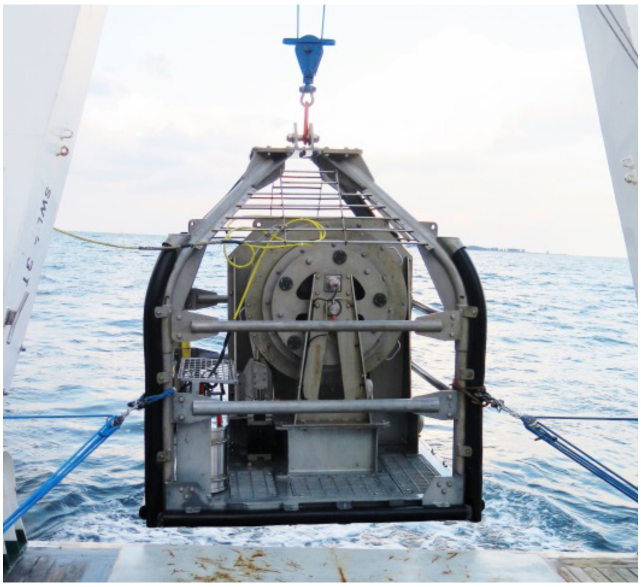

**Fig. 2b.** The NEPTUNE 5000 penetrometer by the R/V IMOR ship's side

vessel of the Maritime Institute in Gdańsk (see *Fig. 2a*). They are much smaller and lighter than the above-mentioned ROSON 10FT penetrometer. They find application mostly in surveys conducted for purposes of implementation of submarine pipelines and cables, where a necessary penetration depth does not usually exceed 5 m.

The main advantage of the constructions under discussion is their compact design, resulting from their adoption of a solution where a coiling rod (a spiral) and a drum driven by an electric motor and working together with a gear are used. The entire construction makes a compact system which may easily be used even on smaller, more economical vessels.

Neptune 3000 is a light penetrometer which enables penetration of the ground substrate up to 10 meters depth (depending on the local soil conditions) with a maximum water depth equal to 3000 m. Its weight in the air is about 1500 kg (1200 kg in the water), and it allows obtaining a maximum pushing force of ca. 10 kN. The device is compatible with 2 cm$^2$ and 5 cm$^2$ CPTU cones, for which the maximum resistance level equals respectively to 50 MPa and 20 MPa. It works also with a T-bar tip, which is dedicated to tests performed in soft soils characterized by a high compressibility..

Neptune 5000 is a heavier version of the above described Neptune 3000 penetrometer. With a weight measured in the air of 4500 kg, and 3500 kg when measured in the water, it allows obtaining a maximum thrusting force of about 35 kN. The Neptune 5000 system enables a penetration of the ground substrate up to a depth of 20 m (depending on the local soil conditions), with a maximum water depth of about 3000 m. The test may be conducted with use of 5 cm$^2$ and 10 cm$^2$ CPTU cones, or similarly as in the case of the Neptune 3000 system, with a T-bar tip. The requirements regarding the measuring tips may be found in the technical specifications, norms, and literature (e.g. Norsok Standard G-001, Lunne et al., ISO/DIS 19901-8).

All Neptune series devices feature a standard penetration speed, which equals about 2 cm/s, as was the case with the ROSON 10FT penetrometer. In comparison with the ROSON 10FT, however, the Neptune has a smaller weight, which reduces the device's sinking in the seabed, thus allowing an interpretation of the seabed surface sediments' parameters.

Table I (*Tab.* I) presents an overview of the main parameters of ROSON 10FT, NEPTUNE 3000, and NEPTUNE 5000 penetrometers.

**Tab. I.** Overview of the main parameters of the CPTU penetrometers in question.

| PARAMETERS | NEPTUNE 3000 | NEPTUNE 5000 | ROSON 10FT |
|---|---|---|---|
| Weight measured in the air | 1,5 t | 4,5 t | 15 t |
| Weight measured in the water | 1,2 t | 3,5 t | 10 t |
| Type of the rig | coiling | coiling | rigid |
| Maximum pressing force | 10 kN | 35 kN | 100 kN |
| Maximum depth of penetration | 10 m | 20 m | 25 m |

The devices discussed in this publication do not represent the full span range of technologies available in the field of the CPTU testing. They were chosen and discussed because of their long-term presence on the waters of the Baltic Sea. The latest achievements in the area of the marine deep-water cone penetration testing are not just plain penetrometers, but rather complex devices for recognition


DOI: 10.5604/12307424.1178821

of the geotechnical conditions. For example, the wireline sampling devices allow conducting the sounding and collecting samples without disturbing their structure by means of the push-in Shelby-type tube samplers. However, such appliances rarely appear on the Polish waters, and most of the research is still being performed with use of the devices presented above.

## The marine cone penetration testing procedures as illustrated by the neptune 5000 penetrometer.

In the following chapter test procedures applied in the CPTU tests conducted from the surface of the seabed are described. Observance of these procedures is crucial to ensuring correctness of the devices' work, and of the obtained results. The sub-chapters below are devoted to the consecutive stages of sounding. There are discussed the following procedures: preparation of the equipment, placing the unit on the seabed surface, as well as the procedure of conducting the cone penetration test itself. The analysis of the entire process of testing is based on the illustration of the NEPTUNE 5000 penetrometer. In case of devices provided by other manufacturers, the procedures should be analogical.

### Preparing a CPTU cone tip for the testing.

The most important element of a CPTU unit is the instrumented cone tip, which is responsible for registering and transmitting parameters of a test to a computer. Its construction should enable a measurement of such parameters as: cone resistance; sleeve friction; pore water pressure; and tip's deviation from the vertical (its inclination). Available on the market is a variety of technical solutions, which differ in terms of parameters such as: surface of the cone and the friction sleeve; the point of pore water pressure measurement; and the way the forces affecting the cone and friction sleeve are measured. Due to the issue's great extent, and the article's review character, it was passed over herein.

To ensure an appropriate quality of the penetration, a series of various tests has to be performed before beginning the tests. Some of them are conducted onshore, where the following preparations are made in the manufacturing plants:

- calibration of the force transducers;
- calibration of the pressure transducers.

The force transducers are calibrated in factory laboratories, from where they are delivered together with calibration certificates. The procedure does not differ much from the ones used in the case of the standard dynamometers. The sensors are tested at stands specifically designed for this purpose. On the basis of the successive load steps (Lunne et al. recommend from 15 to 20 steps) a chart is prepared, and relation of the sensor's readout to the actual force is determined.

The principle governing pressure transducers calibration is analogical. They are placed inside a special chamber, the construction of which is similar to a triaxial apparatus chamber. After the chamber is thoroughly sealed, the tip placed inside is exposed to the effects of the subsequent pressure steps. For every known selected value a sensor reading is taken. The points are then drawn on a chart, and the relation between the readings to the pressure is defined. Details of the procedure were described i.e. in *Cone penetration testing in geotechnical practice* by Lunne et al., and in the Norwegian standard G-001 (Marine soil investigations).

Apart from the factory calibration service, the tips in use also need to be checked directly before the testing. This is a very important step that makes it possible to detect the sensors' errors without having to repeat the research. To ensure an appropriate quality of a survey performed on board, the following steps should be taken:

- checking of the force and pressure transducers' correct functioning;
- de airing of the porous stone together with the pressure transducer.

A check of the correct functioning of the force sensors is carried out by means of loading and unloading of the penetrating cone and friction sleeve several times. Used in this process are special checking kits offered by the cone tips manufacturers. Their construction resembles the calibration stands in laboratories, but they are adequately simplified. They usually consist of a hydraulic hand pump with a manometer and a frame with an adapter set which allows assembly of the tip.

During the test, values of selected loads are compared with converted readings from the transducers. Check readings are made at least at several points of loading and unloading. After a series of surveys is completed, and when no force is applied to the transducer, its reading is compared with the initial reading from before of the survey. If the values are similar, it may be assumed that it is working correctly.

An important parameter in CPTU surveys is the pore water pressure. To ensure that its readings are right, it is necessary to remove from the system of porous stone and pore pressure transducer the entire air. To de air the porous stone and the pressure transducer, the measuring tip is placed inside a chamber partially filled with glycerol, so that both of the elements are immersed in it. Next, the entire chamber is tightly closed, and connected to a vacuum pump (see Fig 3). Its job is to create negative pressure inside the chamber, which removes the air from the system.The de airing process times may vary, depending on the cone's size and the level of negative pressure inside the chamber. After the de airing, the tip is inserted on a penetrometer's rod. An installed cone is often secured with a latex membrane, which is not removed until the process of lowering the penetrometer onto the seabed starts. Thanks to this wrapping, the cone is secured against getting air in.

## Placing a penetrometer on the seabed

In accordance with the procedure described in ISO/DIS 19901-8, before the initiation of a penetrometer's lowering onto a basin's seabed process, there must occur control readings, so-called offsets (zeroing of the sensors). Offsets consist of recording the parameters' values registered by the measuring tip while it is still on a vessel's deck. The readings of the cone resistance, sleeve friction, and the pore water pressure are then zeroed in a computer program which services the survey. This makes it easier to observe the sensor values as the equipment is being lowered, and subsequently analyse the data.

The primary goal of the control readings is to check the test's quality. When performed on the ship respectively before and after the testing, as well as on the seabed- before and after the penetration, they should be of similar values. Values of the acceptable deviations in the control readings depend on the required test quality class. Their accepted limits of tolerance can be found e.g. in the Norwegian standard G-001 Marine Soil Investigations.

After all the on-board procedures are completed, prepared for the tests penetrometer, with an installed measuring cone tip is being placed in the designated survey site. To do that, the ship is positioned above the research point by means of the on-board navigation satellite systems (GPS).

The newer, specialized vessels, such as the R/V IMOR survey vessel of the Maritime Institute in Gdańsk, are equipped with dynamic positioning systems (DP). In favourable weather conditions, such systems make it possible for the ship to maintain its position with accuracy of up to 0.5 m without a need to anchor. In such situations, the computer takes control of the drive systems, and it automatically corrects the ship's position relying on navigation data. If a vessel is not equipped with an automatic DP system, it has to be anchored as the test is being carried out.

When the ship is in the right place, and the weather conditions allow for deployment, the unit is lowered onto the seabed with use of a A-frame (see *Fig*. 5) and a winch installed on the ship. During the lowering, the software controlling the device allows for a real-time observation of readings from the transducers. It is possible to compare the expected values of the hydrostatic pressure on a given depth with the readings of the pore water pressure, and the expected values of the cone resistance caused by this pressure with the actual readings of the force transducer. Most of the marine CPTU penetrometers are additionally equipped with one or two altimeters, which are devices that make it possible to determine the distance between the unit and seabed.

## Conducting the test

Before start of the test, it should be inspected how the unit was placed on the seabed . The deviation of the device's

**Fig. 3.** Measuring tips inside a vacuum chamber

frame from the vertical as measured before the test's initiation should not exceed a certain narrow range permitted by the system's producer – usually it is equal to several degrees. If the allowed limit is exceeded, the attempt at placing the device should be repeated by means of raising it at least 5 m above the seabed, changing the ship's position by 2 m at a minimum, and another lowering it onto the seabed surface. A similar procedure may be applied in cases where the penetrometer is deeply sunk in the seabed. It is important to reduce the speed of lowering the device at the final stage in order to avoid a rapid, dynamic impact on the seabed.

After the penetrometer is finally placed, once more the control readings should be taken, and the sensor readings should be zeroed. Only then will the unit be ready for the test, and penetration of the cone into the ground may start. The cone is thrusted into the ground at a constant rate of 2 cm/s. Throughout the entire operation, the software controlling the penetrometer displays the current readings, and registers the transducers readings of: cone resistance, sleeve friction, pore water pressure, the cone's deviations from the vertical, and the current depth of penetration. As the test is being conducted, their values are analysed by an experienced operator, whose responsibility is to make a decision to stop the testing when the time is right.

There are a number of refusal criteria that have to be reached. The basic constraining factor consists of the equipments' limitations. A test is stopped only when one of the conditions stated below is fulfilled:

- the maximum predefined values of cone resistance are achieved;
- the tip's deviation from the vertical is too substantial;


DOI: 10.5604/12307424.1178821

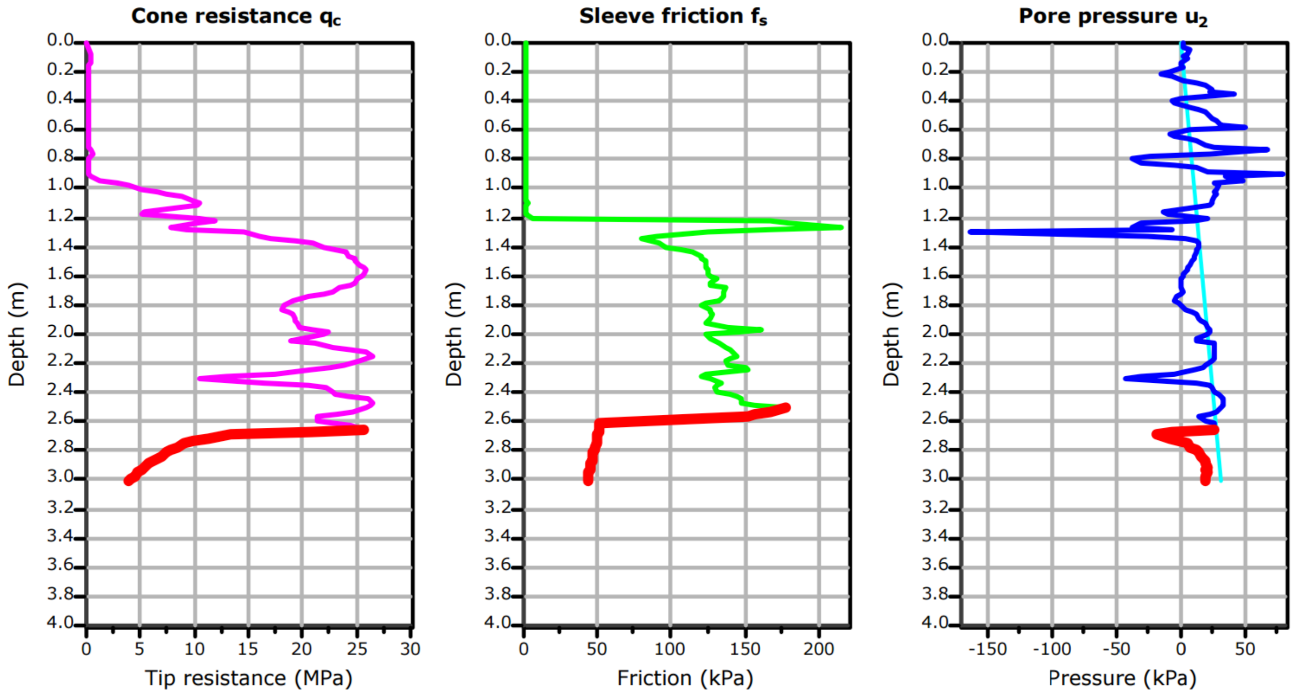


**Fig. 4.** Graph of a CPTU test ending in bending of the rod (the section shown in red)

- the maximum value of the thrusting force acceptable for the given type of penetrometer is reached;
- the required penetration depth is reached.

In case of penetrometers using the relatively susceptible coiling rods, e.g. the Neptune series devices, there is a risk of them buckling. Such situations occur usually when soils of a considerable stiffness under a layer of soils characterized by very low parameters are present. Lack of a lateral support from the weak deposits results in the spiral's buckling when it encounters a layer of a much stiffer soil. In some situations the cone starts to slide over the top of the stiffer soil stratum, and the rod bends. Situations also occur in which a thrusting force growth is not accompanied by a growth of cone resistance. This indicates that the spiral has been deformed, and it is this spiral and not the cone which is transferring the force onto the ground.

The moment when the rod bends can usually be observed in the plots of cone resistance  and the sleeve friction . An experienced operator is able to notice it, and subsequently stop the test. This, however, requires expertise in the subject of the device itself and the soil mechanics. An example of a plot of a CPTU test ending in bending of the rod is presented below (Fig. 1).

After the penetration is finished, the cone is retracted from the ground. It is returned to its starting position from before the survey, and the third series of control measurements follows. The device is pulled out onto the surface and placed on the ship's deck. Immediately after the unit is on, the final control measurements are executed, and so obtained is the full set of data necessary for verifying correctness of the sensors' work and assessing the test's quality in accordance with the description presented in the previous subchapter.

After the device is secured on the ship's deck, the measurement tip is cleaned of any visible dirt and inspected. The cone's condition is examined with reference to signs of mechanical damages and possibilities of its further usage. If the research cruise is to be continued, and further tests are to be performed, the cone may be placed in a vacuum chamber or secured with a membrane so that the pressure sensor and porous stone are protected before trapping air. The later solution is applied when the intervals between the subsequent tests are intended to be short.

After the test is conducted properly, the penetration's results are submitted for the analysis. This task requires in-depth knowledge in the field of geotechnics, soil mechanics, and a substantial experience. The obtained parameters of: cone resistance, sleeve friction, and pore water pressure are first calculated and corrected. Only on the basis of the these parameters may identification of the soil layers take place, and the ground's parameters may be calculated. Analysis of the cone penetration tests' results is a very broad subject. Due to the editorial limits, it could not be discussed herein. More information on interpretation of the penetration results may be found in *Cone penetration testing in Geotechnical Practice* (Lunne et al.), and in case of the shallow penetrations in *CPT interpretation in marine soils less than 5m depth – examples from North Sea* (Mitchell, R. et al. 2010).


BMI 2015; 30(1): 96-103
DOI: 10.5604/12307424.1178821
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**Fig. 5.** The RV IMOR vessel with an A - frame visible on its back

## Recapitulation and conclusions

This article does not by any means exhaust the subject of marine cone penetration tests CPTU, but rather presents a few words of introduction. Particular attention has been paid to the solutions applied within the Polish Exclusive Economic Zone of the Baltic Sea. The publication is of an illustrative character, and its primary goal is to introduce the discussed issues to persons not professionally engaged in the geotechnics. It is largely based on the employees of the Geotechnical Laboratory of the Maritime Institute in Gdańsk personal experience. The devices and procedures presented in the publication have been used many times in conducting the research and commercial projects.

Numerous crucial issues, such as construction of the cone tips, analysis of the results, and determination of the ground layers' parameters, were passed over herein because of the editorial limits. The authors hope to make up for this in future issues of the *Bulletin of Marine Institute in Gdańsk*.

## Acknowledgment

This task was supported by Applied Research Programme of the Polish National Centre for Research and Development (NCBR) under the frame of project AQUILO "Development of methods for the selection of the support structure type for offshore wind turbine in Polish sea areas", No. PBS1/A6/8/2012

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| Word count: | 4150 Page count: 8 Tables: 1 Figures: 5 References: 10 |
| Scientific Disciplines: | Life sciences section |
| DOI: | 10.5604/12307424.1178821 |
| Full-text PDF: | www.bullmaritimeinstitute.com/fulltxt.php?ICID=1178821 |
| Cite this article as: | Załęski K., Juszkiewicz P., Szypulski P.: Practical aspects of the Cone Penetration Tests CPTU as used in the Polish Exclusive Economic Zone of the Baltic Sea: BMI 2015; 30(1): 96-103 |
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| Funding: | This task was supported by Applied Research Programme of the Polish National Centre for Research and Development (NCBR) under the frame of project AQUILO "Development of methods for the selection of the support structure type for offshore wind turbine in Polish sea areas", No. PBS1/A6/8/2012 |
| Competing interests: | The authors declare that they have no competing interests. |
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