Offshore Cone Penetration Test and Its Application in Full Water-Depth Geological Surveys

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Abstract: Characterizing seabed sediments is one of the most important processes in marine engineering surveys. Marine sediments, which are characterized by low strength, typically consist of soft fine-grained sediments (either clay, or in some regions, carbonate muds and silts) that have been deposited relatively slowly. Sampling these soft sediments is extremely difficult, and in situ testing is preferable. Cone penetration test (CPT) is widely used due to its prominent advantages in accurately determining the physical-mechanical properties and types of seabed sediments. Due to the world’s escalating demand for energy, combined with the continued depletion of oil and gas reserves in shallow waters, offshore engineering has moved beyond the immediate continental shelf into deeper waters and untested environments, thus posing a challenge to the operating water depth of CPT. The paper presents an overview of recent developments and applications in CPT technology associated with different water depths, including the cone penetration equipment suitable for the beach/shallow sea, the areas with normal water depth, and the extremely deep sea. Furthermore, the nature of CPT design has changed radically partly due to the types of engineering and partly because of the specific nature of the seabed sediments. Thus, the CPTs with multiple functions are also reviewed.

1. Introduction
With the increasing demand for oil and gas resources, the future priorities of oil and gas exploration will transfer from the land to the deep sea [1]. Compared with land exploration, marine oil and gas exploration has a higher risk due to complex ocean environments and poor engineering conditions. Marine engineering geological surveys, which are often conducted for marine oil and gas exploration as well as offshore engineering construction projects, are instrumental in ensuring project safety and in managing the risks of geological disasters. Its main purposes are to provide direct data that can guide geotechnical design and determine the geological condition of the seabed and the engineering properties of seabed sediments.

Marine sediments, especially near-surface seabed sediments in deep sea, are mainly saturated soft soils with soil particle diameters of mostly less than 0.001 mm [2, 3]. They have the specific characteristics of high plasticity, high water content, high sensitivity, low bulk density, and low shear strength. Due to these characteristics, it is difficult to obtain in situ sediments using unsatisfactory and high-cost sampling methods without disturbing the environment, and this has greatly affected the investigation of the physical and mechanical properties of marine sediments [4].
To avoid those problems, several in situ testing techniques have been developed, which later became important contents of marine engineering geological surveys in the last century. These include the cone penetration test (CPT), the dynamic cone penetration test (DCPT), the vane shear test (VST), the full-flow penetration test (FFP), and the flat dilatometer test (DMT) [5, 6]. Among these, CPT technology is widely used in engineering geological evaluations due to its advantages of fast and continuous testing and high accuracy. Multifunctional CPT probes have also been developed for various uses, such as slope failure analysis and gas hydrates exploration [7, 8].

Although CPT technology has been well applied in both shallow sea and deep sea surveys, it still has several problems in terms of testing under conditions of extreme water depths. Therefore, the current paper aims to review and summarize current knowledge of CPT used in marine engineering geological surveys, mainly concentrating on its technological development and future challenges. To provide a more focused introduction, special emphasis has been placed on multifunctional probes and test facilities designed for surveys in extreme water depths. Finally, pertinent suggestions are discussed and proposed.

2. Cone penetration test

2.1. Ordinary CPT probe
The general description of the CPT involves pushing the cone penetrometer at the end of a rod into soil at a steady rate using a counterforce device. Then, the basic testing parameters, tip resistance, and sleeve friction are measured and recorded by the transducers inside the cone penetrometer. Current recommended probe sizes have already been given by several standards, more specifically, the cone must have a diameter of 35.7 mm, a projected base area of 10 cm$^2$, and an apex angle of 60° (Figure 1). The 10 cm$^2$ cone is considered the reference standard to which the results of other penetrometers with proportionally scaled dimensions are compared. However, the 15 cm$^2$ cone is also widely used in China, causing difficulties in data interpretation. Considering this kind of dimension difference, Lunne et al. [9] argued that the shape and size of the probe are the two major factors to influence the test results. In particular, the projected base area of the probe cone, the surface area of the friction sleeve (normally 150 cm$^2$ for a 10 cm$^2$ cone) and the cross-sectional area of the probe rod may greatly affect the disturbance degree of soils and the testing parameters. In engineering geological surveys, the appropriate probe shape or size should be selected according to the testing purpose and site conditions. Nevertheless, the probe that meets international standards should be preferred.

![CPT probe diagram](image)

**Figure 1.** The dimensions and main components of the CPT probe

2.2. Multifunctional CPT probe
The cone penetration test with pore pressure measurement (known as the piezocone penetration test or CPTU), which is based on the standard cone penetrometer, has been commonly used in geotechnical and geological surveys since the 1980s [10]. Generally, the dimension of the piezocone penetrometer is about the same as that of the cone penetrometer; however, the difference between the two is that the former has an attached pore pressure sensor and a filter element. Thus, using the CPTU enables researchers to observe pore water pressure and the dissipation of pore pressure aside from obtaining basic data.

Notably, the position of the filter element must also be considered. The filter element is placed at the shoulder position of the probe cone in most tests because of the following advantages: 1) the filter element at the shoulder position cannot be easily damaged although it can be easily saturated, 2) the influence of element compression decreases, 3) the influence of penetration on the pore pressure dissipation decreases, and 4) the measured pore pressure can be directly used to correct the tip resistance.

In recent years, the CPTU has become one of the most commonly used in situ testing methods in marine engineering geological surveys [11]. With the development of CPT/CPTU, the CPT probes with various functions have also been proposed by many international research institutions (e.g., University of British Columbia, Georgia Institute of Technology, Delft University of Technology, etc.) and professional in situ test instrument development companies (Hogentogler, Vertek, ConeTec, Furgo, etc.). Since then, sensors for lateral stress, seismic, electrical resistivity, heat flow, and radioisotope measurements as well as laser-induced fluorescence and tiny cameras have been incorporated into the traditional CPT probes to achieve different engineering purposes.

Among all the probe sensors developed, the CPT with seismic measurement (SCPTU) and the CPT with electrical resistivity measurement (RCPTU) are relatively mature and widely used. In the penetration process of the SCPTU, the shear wave velocity of the soil layer can be calculated by the shear wave propagation time measured by the geophone detector or acceleration sensor inside the probe, after which the shear stiffness and modulus are determined by investigating the testing results. As we know, the earliest electrical resistivity sensor was used to estimate the porosity and density of in situ soils. In recent years, such sensors have been used to test the polluted soil or water. The RCPTU instrument is equipped with two electrodes: a current electrode and a measuring electrode. After each penetration action of the probe is completed, the soil resistivity is measured. Campanella and Weemees [12] developed an RCPTU probe with four circumferential surface electrodes, which can simultaneously measure pore pressure, water resistivity, soil resistivity and other basic parameters. This probe is commonly used to study the pollution degree and scope of groundwater.

In general, the current trend of probe research and development is geared toward multifunctionality and digitalization. In conducting research related to marine engineering geological surveys, emphasis should be given to the material selection of probes, the combined use of different kinds of probes, their functional integration, test data storage, and real-time communication.

3. Offshore CPT used in areas with normal water depths

There are basically three ways to carry out a cone penetration test under water according to the differences of penetration modes. The penetration modes include pushing from the working platform, pushing from the sea floor, and pushing at the bottom of a drilled borehole, corresponding to platform CPT, seabed CPT, and down-hole CPT, respectively.

3.1. Platform CPT

In platform CPT, the penetrometer is pushed from the offshore platform or the load-bearing vessel to the seabed soil, and the CPT equipment is fixed on the platform to provide the reaction force. During the CPT, the probe rod must pass through the sea water layer from the platform deck before it can penetrate the seabed soil. The offshore platform and the seabed are relatively static; thus the operation mode of platform CPT is basically the same as that of land CPT. However, due to the suspended section between the offshore platform surface and the seabed surface (usually several meters to more
than ten meters), the probe rod lacks radial constraints. Hence, when the water depth is relatively large, the probe rod may be deformed, bent, or even break. Although the addition of casing between the platform and the seabed decreases the bending of the probe rods to a certain extent, the adverse effect cannot be completely eliminated.

3.2. Seabed CPT

Seabed CPT is considered to be a relatively low-cost and effective testing method with a penetration testing depth that can reach 40–50 m in favorable soil conditions [11]. When conducting seabed CPT, the CPT instrument is hoisted above the seabed by cables and stably sits on the seabed by its own support system. Then, the probe is driven by hydraulic pressure as it penetrates into the tested seabed soils at a constant speed. Compared with the platform CPT or the down-hole CPT, the working process of the seabed CPT is more flexible by employing an ordinary survey ship equipped with lifting equipment.

At present, there are four well-known companies in the world engaged in the research, development, production, and sales of seabed CPT systems, namely, Fugro (NL), APvandenBerg (NL), Geomil (NL), and Datem (UK). A brief introduction of their commercial CPT equipment is provided below.

- From the 1960s to the 1970s, the Dutch company, Fugro, designed the first seabed CPT device named Seabull, and then developed a more simple and robust device, Seacalf, based on the improvement of Seabull [13, 14]. These devices were used to study the mechanical properties of marine sediments in shallow water.
- The ROSON-Series seabed CPT systems developed by APvandenBerg cover the light (thrust capacity of 25 kN or 40 kN), medium (100 kN) and heavy (200 kN) weight products. However, the penetration depth of ROSON systems is limited, because the casing is invalid on this system.
- The thrust capacity of MANTA-200 developed by Geomil also reaches 200 kN (or 250 kN). It can operate under a deeper penetration depth by using the casing.
- The British company, Datem, designed Neptune 3000 and Neptune 5000 for conducting CPT in deep sea. The maximum operation depth of the Neptune series reaches 5,000 m, but the maximum penetration depth is just 15 m.

In addition, the IFREMER already designed, built, and operated the Penfeld, which can operate at a water depth of 6,000 m and has a 30 m penetration depth below the seabed [15]. In reality, all the mature CPT instruments have no ability to work at a water depth of 10,000 m, which leads to huge challenges in conducting geological surveys in hadal trenches (>6,000 m).

3.3. Down-hole CPT

The main feature of the down-hole CPT is the cyclic operation method, which combines drilling and CPT. During the test process, the borehole is drilled initially and then the probe rod penetrates from the bottom of the borehole into the soil at a depth of 3 m. Before each penetration action, the soil layer where the cone penetration test has been completed is removed first by drilling in order to start the next penetration action. The drilling tool is fixed by the wave compensator and subsea pliers on the drilling ship. The penetration depth of the down-hole CPT can be the same depth as that of the drilled borehole. However, the measurement accuracy of the down-hole CPT is not as high as that of seabed CPT due to the inevitable disturbance of seabed soil by drilling. A typical down-hole CPT system, such as the WISON-APB system by APvandenBerg [16], has a maximum thrust of 150 kN, a single penetration stroke of 1–3 m, and a maximum working water depth of 3,000 m. Through the winch operation and data acquisition by remote control, the system can measure the tip resistance, sleeve friction, pore water pressure, inclined angle, and penetration depth.

4. CPT used in surveys in extreme water depths
Although the commercial or semi-commercial offshore CPT equipment can meet most of the requirements of testing in areas with normal water depths (20–6,000 m), the CPTs carried out in extreme water-depth surveys still face several challenges.

4.1. CPT used in beach/shallow sea

The beach shallow sea discussed here mainly refers to the transition zone from land to ocean, including the three parts of the intertidal zone, the amphibious zone (0–2 m water depth), and the extreme beach/shallow sea (2–5 m water depth) [17]. These areas provide very promising prospects for oil and gas reserves. However, they also present severe challenges for oil and gas field exploration and development due to the complex environments and difficult engineering conditions.

For example, in the beach/shallow sea zone of the Chinese Bohai Sea, the potential oil resources can reach (30–40) × 108 t. However, its special environment and engineering geology have threatened the oil and gas exploitation and engineering construction, and the engineering activities in this area lack mature working experiences. Moreover, offshore engineering construction projects in the Bohai Sea suffer from the environmental impacts of strong winds, storm surges, stormy waves, primary tides, and icy conditions. The engineering geology of this area has typical features, including deep silt layer with poor engineering properties, easily liquefied and scoured silty sand layers, complex and unstable seabed landform, and a seismic region influenced by fault movements. Thus, while it is necessary to carry out CPTs in the beach/shallow sea areas, such an undertaking faces several difficulties, which are summarized as follows:

- The survey operations, including in situ testing, are subject to the times of flood and ebb tides as well as the draft of the working ship.
- The special environmental conditions of the beach/shallow sea require the use of two sets of equipment for the in situ tests on land and under water.
- The use of a fixed working platform requires repeated construction, demolition and relocation, which not only increase the cost and reduce efficiency, but also affect the ecological environment of the surrounding beaches or intertidal zones.
- The soils in the beach/shallow sea areas are relatively loose with a low bearing capacity. Moreover, the soil layers are likely to liquefy under the vibration load of working vehicles, which restricts the equipment transportation and test operation.

Based on the above-mentioned considerations, CPT instruments should be lightweight and convenient to move. As there are no professional CPT instruments designed for beach/shallow sea, an instrument called CPtss was developed by Ocean University of China in 2014 [18, 19]. The weight of the main equipment is 1.8 t in the air, and it has an air pressure tank that can be used for controlling the buoyancy, thus allowing the CPtss to float on the water or sink under the water. These features allow researchers to perform continuous underway tests by using CPtss. However, the floating CPT instruments may not work at low tide, because the working ship has no way of getting into the beach/shallow sea area. Tracked vehicles are thus preferred in this condition, because they usually have pontoon bodywork. Once a certain depth is exceeded, it can rely on the buoyancy of the floating box to float the whole tracked vehicle and enable it to travel on the water, thereby ensuring amphibious capability.

4.2. CPT used in hadal zones

In the ocean, the areas where the water depths range from 6,000 to 11,000 meters are called hadal zones; these comprise mainly of ocean trenches and are considered the deepest marine areas on earth [20]. Hadal zones, which consist of trenches, are mainly distributed at the continental margins. Although they only account for 1%–2% of the global subsea area, the vertical depth accounts for 45% of the total depth of the ocean; thus, the hadal trench is of great significance to the marine ecosystem [21].

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The water depths of the hadal trench areas often reach 10,000 meters, while pressure levels can reach up to 100 MPa. These conditions place greater requirements on the working depth of CPT instruments and the accuracy of the pore pressure sensor. The working depth of current CPT instruments is generally less than 6,000 m, and there is still a considerable gap from full water-depth tests. Using the hadal lander to take CPT instruments into the extremely deep sea may be a feasible solution. There were a few successful attempts to explore the extremely deep sea using a hadal lander, including the two hadal landers developed by the Hadal Environment and Education Programme (HADEEP, 2006–2011), which were used in several trenches in the North and South Pacific Ocean across a depth range of 5,500–10,000 m [22, 23]. Moreover, the manned submersible named Deepsea Challenger has successfully dived into the New Britain trenches and into the bottom of the Challenger Deep in the Mariana trench [24]. However, no in situ tests were considered in these attempts.

Piezoresistive and capacitive sensors are two kinds of sensors that are widely used in in situ testing measurements due to their numerous advantages. However, piezoresistive sensors using diffused silicon technology have semiconductors that can be easily affected by temperature; thus, they are not suitable for complex marine environments. The capacitive sensors have poor anti-electromagnetic interference and are unable to work safely and reliably in harsh environments for a long time. Moreover, they cannot easily transmit measurement signals over long distances. Considering these disadvantages of normal sensors, fiber Bragg grating (FBG) sensors are deemed more preferable, because of their advantages of intrinsic safety, corrosion resistance, anti-interference, and the possibility of re-using them. In addition, using the bellows and an open pressure-differential structure for the probes can promote the testing accuracy.

Table 1. Comparison of existing CPT equipment

| Operating water depth area | CPT equipment | Company | Penetration mode | Design point | Applicable conditions | Comment |
|----------------------------|---------------|---------|------------------|--------------|----------------------|---------|
| Normal water-depth area (20–6,000 m) | Platform CPT | Fugro, APvandenBerg, Geomil, etc. | From platform or vessel | Continuous testing and high precision and repeatability | Most water depths; various geotechnical conditions | Commercial and widely used |
| Extremely shallow sea (<5 m) | Down-hole CPT | Self-developed | From seabed or borehole | Light weight and flexibility | The area that is greatly influenced by tide | Easily neglected |
| Extremely deep sea (>6,000 m) | e.g., floating CPT | Self-developed | From seabed or vehicle | High safety and ease of use | The area with unknown engineering conditions, which are hardly reached | High cost and immature |
The characteristics of sediments in the hadal trenches cannot be predicted in advance, but as we know, the strength of the near-surface seabed sediments in deep sea can be as low as 1–5 kPa [25]. The use of CPT alone may not be able to meet the needs of in situ testing in very soft soils, because of the influences of overburden stress and pore pressure acting on the back face of the cone [26]. Therefore, Randolph et al. [27, 28] proposed the application of full-flow penetrometers, such as a T-bar or ball probe, to increase the measurement accuracy. In hadal trenches, it is better to use all three in situ testing methods, including CPT, FFP, and VST, in order to overcome various geotechnical conditions. The penetration sequence of these three kinds of probes depends on the mechanical properties of the testing seabed soils. There is also an option to write the intelligent measurement program into the control system of the testing instrument. Combined with the introduction and discussion of the CPT equipment used in beach/shallow sea and areas with normal water depths, the comparison of the CPT equipment suitable for areas with different water depths is summarized in Table 1. The brief framework of CPTs for full water-depth surveys is presented in Figure 2.

5. Conclusion
The CPT is an in situ testing method that can be used to evaluate the geotechnical properties and has been widely applied in marine engineering geological surveys. There are three types of offshore CPTs, namely, platform CPT, seabed CPT, and down-hole CPT, which are suitable for most water depths. The CPT probe is optional depending on the changes in marine environments and survey purposes. Future studies aimed at developing CPT probes should pay more attention to the material selection, the functional integration, the combination of different kinds of probes, the test data storage, and the capability to undertake real-time communication.

The CPT instruments used in extreme water-depth survey are discussed in this work. In beach/shallow sea, the floating CPT instruments and track vehicles are effective due to the considerations of flood tide or ebb tide. In hadal trenches, the CPT, FFP, and VST are recommended to be performed at an intelligent sequence, and all the measurement equipment can be carried by a hadal lander. In order to achieve the purpose of conducting full water-depth geological surveys, the difficulties related to such explorations should be further investigated and resolved.
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