Design of a Modular, Marine Free-Fall Cone Penetrometer

A Time and Cost-Effective Device for In-Situ *Geotechnical Characterization of Marine Sediments*

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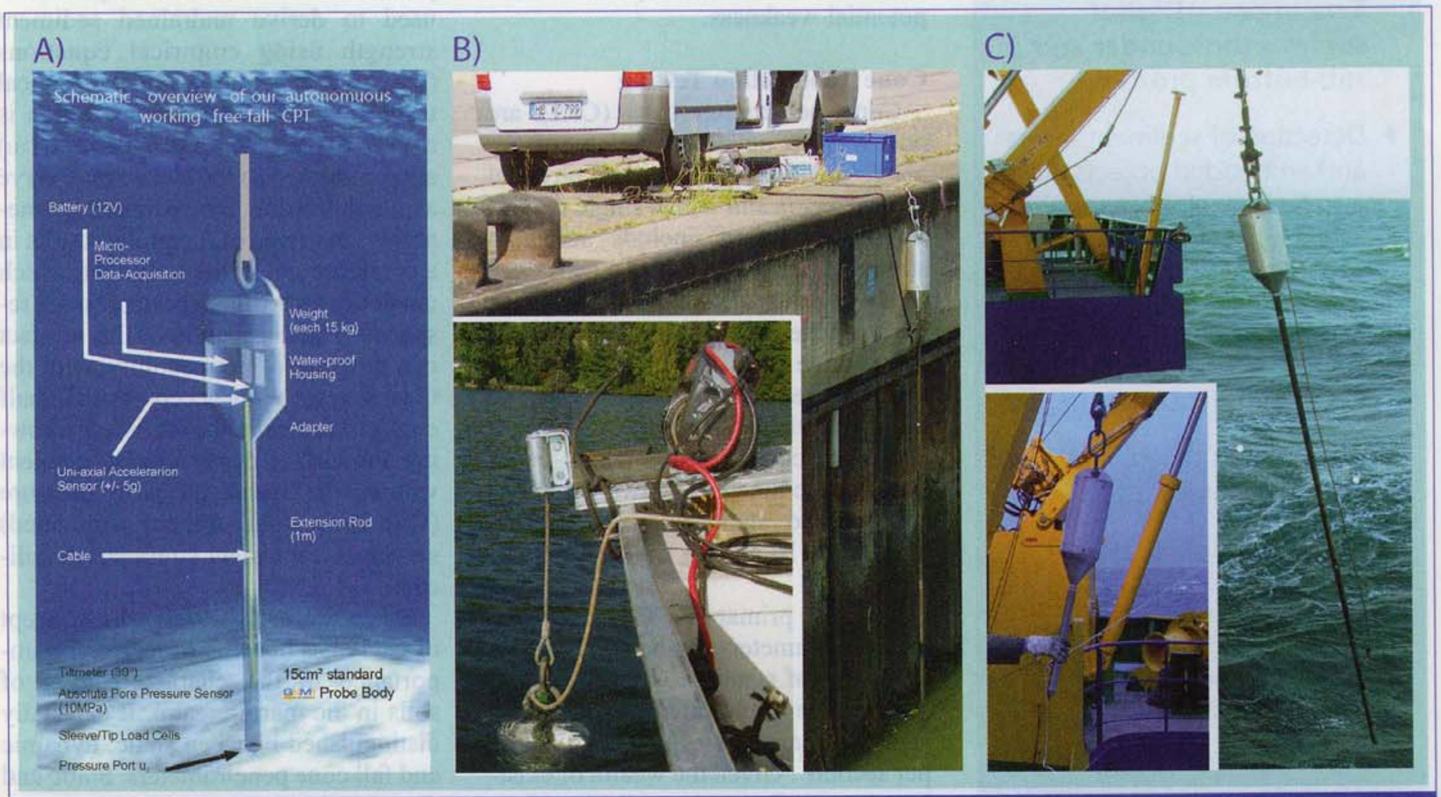
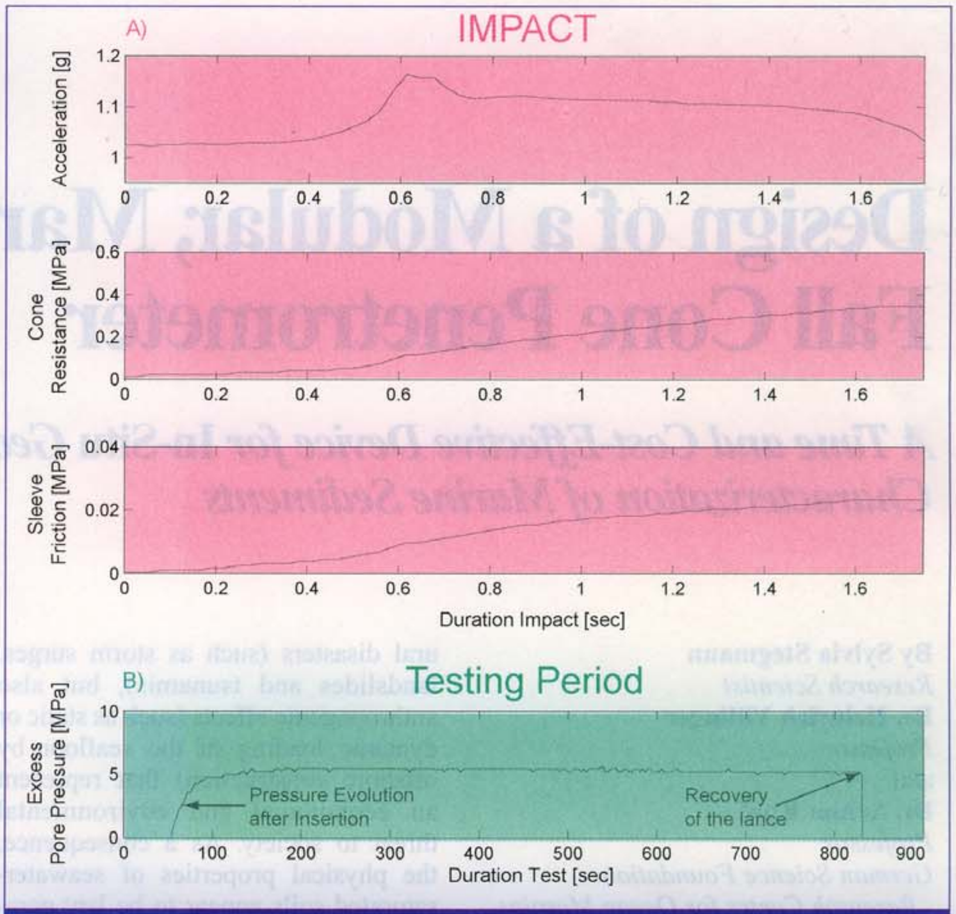
Increasing human impact on near-coast areas and toward the continental shelves and slopes requires a profound knowledge of the uppermost seafloor sediments. It is not only natural disasters (such as storm surges, landslides and tsunamis), but also anthropogenic effects (such as static or dynamic loading of the seafloor by offshore construction) that represent an economical and environmental threat to society. As a consequence, the physical properties of seawater-saturated soils appear to be key parameters in the assessment of sediment stability.

Marine sediments can be considered as a two-phase-system: mineral particles and fluids (water, gas). The second occupies the voids between the first. Pore volume generally decreases with increasing stress onto the sediment. The lower the pore volume of the sediment, the stronger the cohesion between particles, which translates to higher shear strength. The mechanical behaviour of any sediment is controlled by the equilibrium between the force on the solids (normal stress) and the counteracting pore pressure, which is created by the incompressible, less dense fluids. It has long been known that the mechanical stability of soil is a function of mineralogical strength and excess pore pressures; the latter of which may overbear the normal stress and cohesion, causing failure, liquefaction or hydro-fracture. Soils that are especially clay mineral-



Design of the marine free-fall cone penetration test instrument: a) the schematic, b) the instrument during deployment with a portable winch, c) the instrument during deployment from the R/V Planet *in long and short (inset) mode.*



Primary parameters versus time from a test in the North Sea. Excess pore pressure rises to values above five kilopascals shortly after insertion of the instrument, and does not show significant decay over the 15 minutes of testing.

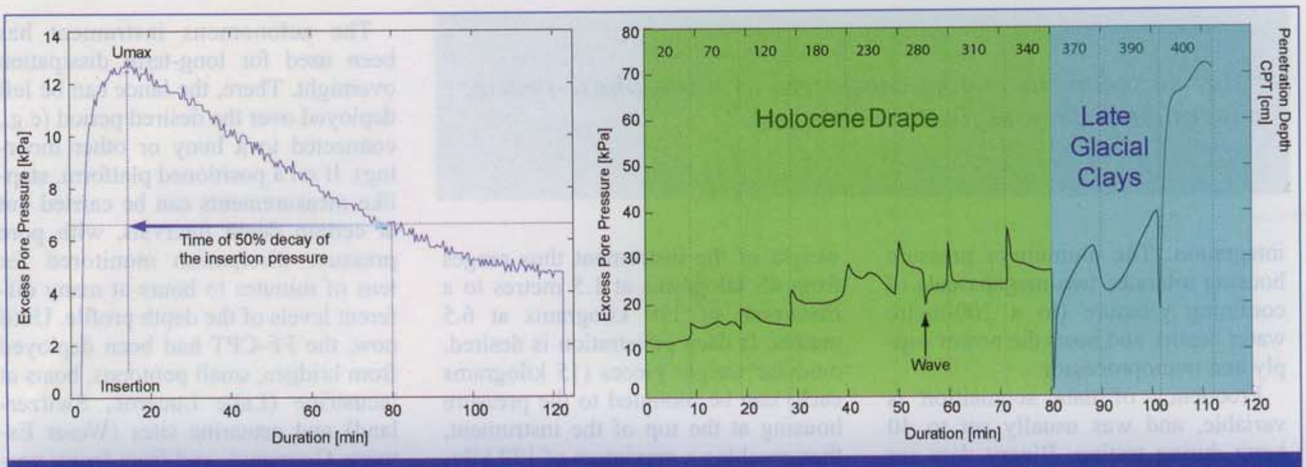
rich in their low intrinsic frictional strength and low permeability represent zones of fluid overpressures and potential weakness.

Cone Penetration Testing

Cone penetration tests (CPT) are one way to collect a variety of the above-mentioned sediments' physical parameters *in situ* with a single device. These parameters include sediment strength (derived from the resistance of the cone and the sleeve of the probe during penetration), pore pressure (in up to three positions: u_1 through u_3), temperature, tilt and deceleration. The heart of the system is a sensor-equipped, conical probe which penetrates the sediment. The two commonly accepted standard sizes for the probes are 10 and 15 square centimetres.

From the primary CPT data set, secondary parameters can be derived. The main aim of standard CPTesting is to profile the penetrated sedimentary succession at a rate of two centimetres per second^{-1}. Given the wealth of existing data, a first-order soil classification based on the friction ratio (sleeve friction/cone resistance), corrected for pore pressure effects, was established.[1] The frictional resistance of the soil to penetration of the lance may also be used to derive undrained sediment strength using empirical equations (based on laboratory soil mechanical testing).[2] The pore pressure, which is measured near the tip (u_1), beneath (u_2) and/or above (u_3) the sleeve may serve as an indication for sediment permeability. Insertion of the probe results in a displacement of the sediment, which generates an artificial pore pressure response. The dissipation of this artefact is a measure of permeability, with the t_{50} parameter being accepted as the half decay of the initial peak.[3] When allowing for further decay toward ambient values, the measured pore pressure (with hydrostatic pressure subtracted) serves as a transient stress-strain indicator.

Since the early 1970s, the concept of CPTs has become of increasing importance in the characterization of soils in the marine realm. It is usually distinguished between static, dynamic and fall cone penetrometers. Static and dynamic cone penetrometers are pushed in the sediment with constant hydraulic force provided by trucks



Results from pore pressure dissipation tests in clayey sediments. The left chart shows full penetration and two-hour decay in Wilhelmshaven, Germany. The right chart shows step-wise deployment and 10-minute intervals of pore pressure decay in lacustrine clays in Lake Lucerne, Switzerland.

(onshore) or huge seabed rigs (offshore). In contrast, the less common fall cone penetrometers are lowered on a cable and penetrate the sediment under their own momentum gained during descent. Despite the disadvantage of generally lower total penetration depths, this article revisits the concept of a free-fall instrument because it provides a more time and cost-efficient investigation of the upper marine soft sediment layers.

Concept and Performance

The newly developed lance is an easy-to-use, lightweight free-fall CPT (FF-CPT) instrument for shallow marine applications (200 metres' water depth). The probe consists of an industrial 15-square-centimetre piezocone and a waterproof housing containing a microprocessor, volatile memory, battery and accelerometer. Strain gauges inside the probe measure the cone resistance and sleeve friction by subtraction. A single pore pressure port (u_2) is equipped with an absolute 10-megapascal pressure sensor. An inclinometer is used to monitor the penetration angle at +/-30° relative to vertical, while temperature is monitored via a thermistor. An accelerometer provides information about the descent velocities and deceleration behaviour of the instrument upon penetration. Its data enable the user to calculate penetration depth during multiple deployments by

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integration. The aluminium pressure housing tolerates two megapascals of confining pressure (to a 200-metre water depth), and hosts the power supply and microprocessor.

Frequency of data acquisition is variable, and was usually set to 40 hertz during testing. Binary data are temporarily stored on a micro flash card and then downloaded to a computer. Two battery packs provide performance times of about six and 12 hours, respectively.

The FF-CPT is designed for both pogo-style measurements from moving platforms and mid-term deployments from a crane, winch, anchored vessel or tied to a buoy. The length of the lance varies from 1.5 metres (in short mode) up to a maximum of 6.5 metres (in long mode). The extension is accomplished by adding one-metre-long metal rods and internal extension data/power cables within them. The weight of the instrument thus ranges from 45 kilograms at 1.5 metres to a maximum of 110 kilograms at 6.5 metres. If deep penetration is desired, modular weight pieces (15 kilograms each) can be mounted to the pressure housing at the top of the instrument, then reaching a maximum of 170 kilograms.

This construction allows for variable testing methods depending on the platform, geological setting and scientific question. The lightweight version can be handled almost effortlessly by an individual. Even the 6.5-metre-long instrument can be deployed from relatively small boats by two people; recovery is facilitated by a portable four by four car winch powered by a battery. However, the easiest way to operate the device is by a regular winch and deep-sea cable on research vessels, either over the side or the A-frame.

The autonomous instrument has been used for long-term dissipation overnight. There, the lance can be left deployed over the desired period (e.g., connected to a buoy or other mooring). If on a positioned platform, step-like measurements can be carried out at certain depth intervals, with pore pressure dissipation monitored for tens of minutes to hours at many different levels of the depth profile. Until now, the FF-CPT had been deployed from bridges, small pontoons, boats at lacustrine (Lake Lucerne, Switzerland) and estuarine sites (Weser Estuary, Germany), and from larger vessels in the North and Baltic seas.

FF-CPT Results

Initial tests have been successfully carried out in muddy, gas-rich to stiff, coarse-grained sediments in lakes, estuaries and on the marine shelf in the North Sea. Depending on the sediment and deployment velocity (winch speeds of 17 centimetres per second^{-1} to free drop), the penetration depth ranges from half a metre (in fine-grained sand) to five metres (in silty clay). In the fine-grained sands, the mounting of weight pieces results in a 20-centimetre-per-15-kilogram weight

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increase of penetration depth. Pore pressure response was not significantly affected by the additional weight during impact.

In general, the results show similar cone and sleeve resistance and, hence, friction ratios as in standard CPTests when comparing the sediment grain size analyses with the CPT results. Soil classification following previous charts and studies[1] was found to be applicable at low to moderate winch speeds, while high penetration rates (greater than 80 centimetres per second^{-1}) and free-drop fail to provide meaningful results. The authors of this article suggest that additional high-velocity testing is required to empirically adjust the classification for the FF-CPT instrument.

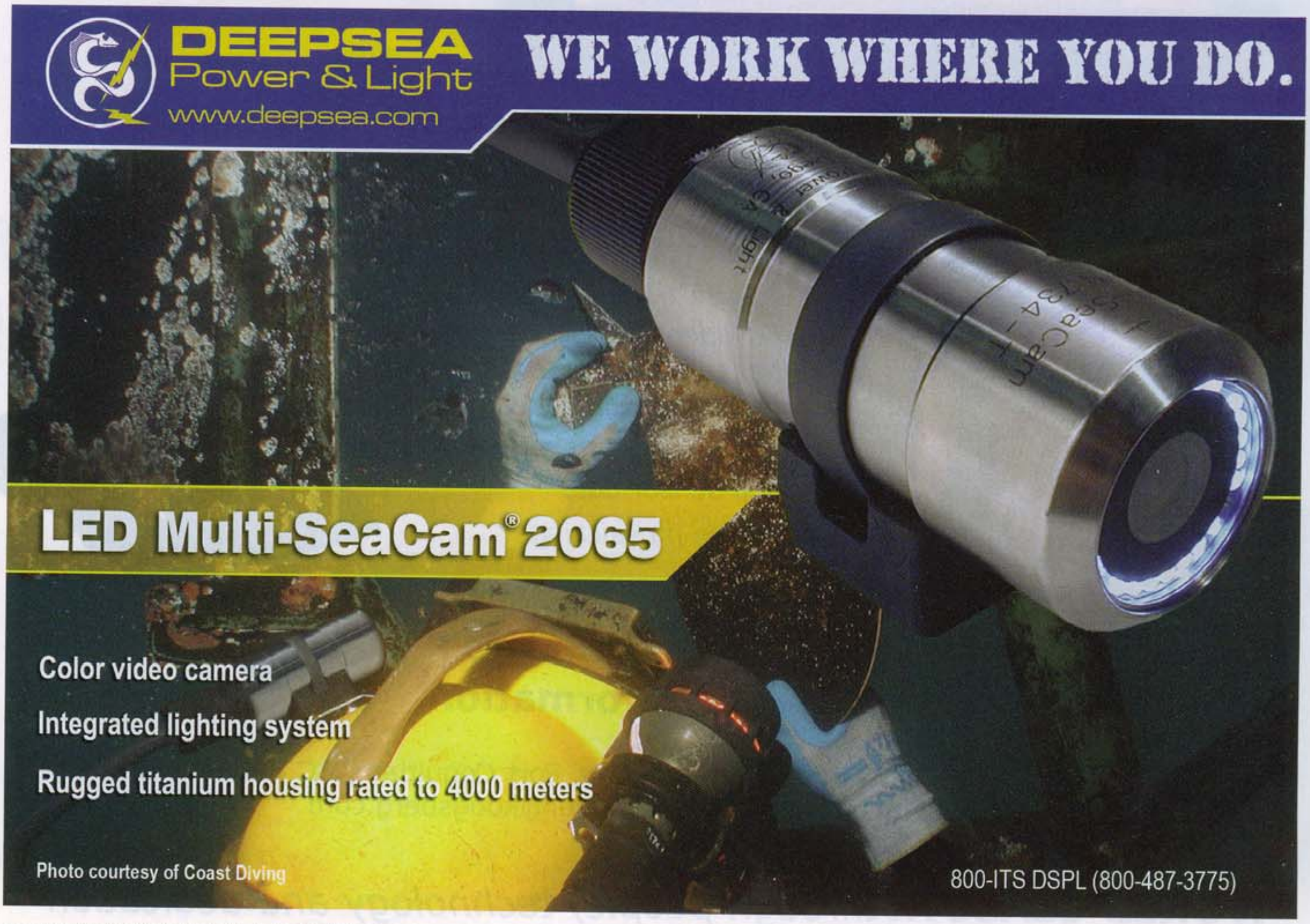
Pore pressures generally rise during impact, but often show rapid decays toward ambient values during dissipation tests. Two different strategies were followed during the longer tests, aimed at pore pressure evolution: full penetration of the probe and dissipation times of several hours, and stepwise depth profiling and arresting the instrument at each level for about 10 minutes. As an example for the first strategy, a two-hour-long dissipation test using mud in Bremerhaven, Germany, is presented. The pore pressure evolution in Bremerhaven is characterized by a build-up soon after insertion (greater than 12 kilopascals), followed by a decay to half that value (t_{50}) after approximately one hour. The second strategy was followed during measurements in glacial and post-glacial clayey sediments of Lake Lucerne.

Interestingly, a different behaviour was observed in the Holocene clays down to 340 centimetres' penetration depth, and in the late glacial clays underneath. In the hangingwall, pore pressure evolution during each measuring increment is characterized by an initial increase when lowering the instrument followed by a decay in the subsequent 10 minutes. In contrast, the late glacial clays show a significant pore pressure drop when inserting the probe further, which in turn is followed by a continuous rise in pore pressure over the 10-minute period. This change in pore pressure signal is attributed to overpressure in the footwall section, most likely due to the presence of gas.

In summary, initial tests have demonstrated that the new FF-CPT instrument represents a flexible, cost-efficient way to carry out *in-situ* geotechnical sediment characterization. Data are in general agreement with standard industry CPTesting, however, the device offers new opportunities for longer term deployments or use from small platforms and boats.

Applications

The FF-CPT is envisaged to be a valuable addition to industry CPT experiments. The lightweight, modular design of the probe makes it a good



> *"The FF-CPT is envisaged to be a valuable addition to industry CPT experiments."*

companion when approaching different scientific problems, such as the stability of sediments, the temporal evolution of fluid mud in estuaries and harbors, the collection of *in-situ* geotechnical data for construction and cable laying, the assessment of tidal forcing/resuspension, the liquefaction potential of marine soils and the groundtruthing of geophysical data.

Data indicate that this new FF-CPT represents a time and cost-efficient way for sediment characterization. Modifications to the instrument are straightforward when larger penetration depth, longer deployments or different ranges of sensors are required.

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References

For a complete list of references, contact author Sylvia Stegmann at stegmann@uni-bremen.de. /st/

For more information, please visit our website at www.sea-technology.com.

Sylvia Stegmann has developed two cone penetration test free-fall instruments during the course of her Ph.D. thesis. These instruments comprise the shallow-water probe presented in this article and a deep-water instrument (4,000 metres) to extend measurements to the continental slope. Stegmann's research is dedicated to pore pressure measurements in situ *and in the laboratory.*

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