Initial Results of a new Free Fall-Cone Penetrometer (FF-CPT) for geotechnical *in situ* characterisation of soft marine sediments

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Two of the most crucial sediment physical parameters controlling slope stability and trigger mechanism of mass movements are shear strength and excess pore pressure. Since both of them require in situ measurement, Cone Penetration Testing (CPT) is an ideal method to characterise *in situ.* While standard CPT tests penetrate of sediments at constant rate, a new free fall cone penetrometer (FF-CPT) for shallow-water application down to 200 m water depth has been developed. Its modular, lightweight design allows us to operate from small platforms to research vessels. The length (0.5 m – 6.5 m) and the weight (40 kg – 170 kg) of the device can be adapted according to the geological setting and main scientific interests. Here we present our initial results as a "proof-of-concept". In five locations with variable sediment composition, the lance was deployed with different penetration velocities ranging from 30 cm/s to free drop in different weight- and length-modi. Based on the primary data (acceleration, cone resistance, sleeve friction, pore pressure), we mainly focus on dissipation of insertion pore pressure and a first-order sediment classification. The results show an influence of the different penetration velocities on pore pressure regarding to its evolution over the time and on the magnitudal strength parameters. Finally, our preliminary data suggest that the time- and cost-effective use of our marine FF-CPT is an appropriate alternative to standard CPT measurements.

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Introduction

Marine sediments consist of a skeleton of mineral grains and pore space, which is usually occupied by aqueous and gaseous fluids (Maltman 1994). The stability of the sediment is controlled by the forces between the grains (cohesion) and the pressure of the fluids in the pores (Strout & Tjelta 2005). While the first depends on the mineralogy of the grains, the latter is a function of physical properties such as water content, state of consolidation, or grain size distribution. Variability in one or more sediment physical properties may result in instability and failure. Geological processes, which are capable of causing pore pressure increase and weakening of the sedimentary framework include tectonic deformation, earthquakes, rapid sediment accumulation, gas-hydrate melting or tidal/storm wave loading (e.g. Hampton et al. 1996; Locat & Lee 2002). In this context, Cone Penetration Tests (CPT) represent a widely used, time efficient method for the *in situ* characterisation of the physical properties of the sediments and their variability. (Chari et al. 1978; Konrad 1987; Bennett et al 1989; Lunne et al. 1997; Christian et al. 1993; Wright 2004). Standard probes measure the cone and sleeve resistance (as a first order estimate of sediment strength), pore pressure in defined locations (u_1, u_2, u_3), tilt, and temperature (Lunne et al. 1997). Apart from this set of primary data, a number of secondary physical-sedimentary parameters can be calculated. If the insertion pressure and velocity profile during penetration of the probe are known, undrained shear strength (Esrig et al. 1977) and consolidation ratio (Bennett et al. 1985) may be derived. As a consequence, CPT tests play a significant role in the assessment of the underground in offshore construction, and the stability of subsurface sediments deposited on continental shelves and slopes. In this paper we present the initial results of a recently developed FF-CPT device for soft sediments. In contrast to industrial CPT procedures, where the probe is pushed hydraulically at a constant rate (2 cm/s), our lightweight, cable-controlled lance may be universally deployed. Its modular design, with optionally added weights (up to 60 kg) and extension rods (0.5 m–6.5 m total length) allows us to control the maximum penetration depth and tackle various scientific questions. In this manuscript, we provide a "proof of concept" and illustrate how we vary weights, extension rods, and winch speed to accommodate for various settings (soft vs. indurated sediment) and deployment platforms (free-fall mode vs. crane or winch). In addition, long-term testing records of pore pressure dissipation after insertion may help us to assess whether intrinsic sediment strength or excess pore pressures are likely to trigger shallow submarine mass movements.

Instrument design, theoretical background, and methods

Design of the FF-CPT

A marine free-fall FF-CPT has recently been developed for 200 m water depth at the Research Centre Ocean Margin (RCOM) at the University of Bremen (Fig.1). We use the term "free-fall" to distinguish between our gravity-driven deployment style and the hydraulically pushed standard CPT tests. However, most of the deployments are carried out with controlled speed using a winch, while very rarely, we deploy in free drop (i.e. only when the underground is known to be free of rocks, etc.).

Our instrument consists of an industrial standard 15 cm^2 cone penetrometer manufactured by GEOMIL (Netherlands), which is equipped with an absolute pore pressure sensor (2 MPa), an inclinometer (25°), and a temperature sensor. Load cells measure the sediment resistance acting on the cone during penetration. The force acting on the cone, divided by the cone base area (Fig. 1a) produces the cone resistance q_c. The force acting on the sleeve friction in relation to the surface of the sleeve area (Fig. 1a) is defined as the sleeve friction f_s (Lunne et al. 1997). The sleeve friction load cell records the sum of the cone resistance and the sleeve friction. This principle defines a subtraction cone, which is used in our device. Sleeve friction is obtained from the difference in load between the friction and cone resistance load cells (Lunne et al. 1997). The tilt sensor in the lowermost part of the lance provides information on the angle of penetration. A waterproof housing at the upper end of the lance, fitted with micro controller and data-acquisition, an acceleration sensor and the power supply, provides autonomous FF-CPT measurements even on very small vessels and research platforms (Fig. 1b). Concerning weight and the length, our lance is characterised by a modular design. Depending on the sediment strength the lance can be mounted optionally with extension rods (up to 6 1-m-pieces) and weights (up to 4 x 15 kg-pieces). In the short mode, the FF-CPT weighs about 40 kg (Fig. 1c), whereas the

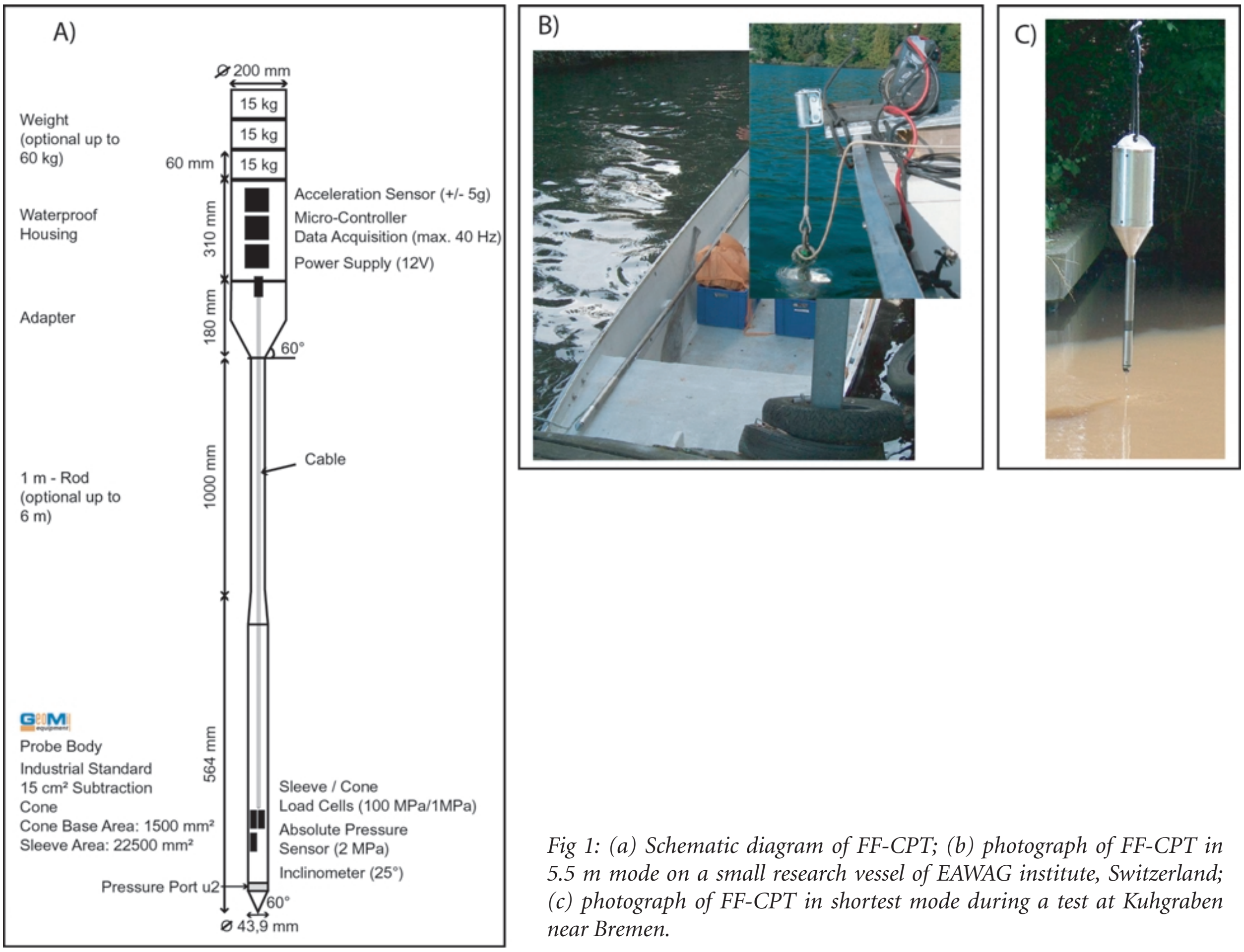

Fig 1: (a) Schematic diagram of FF-CPT; (b) photograph of FF-CPT in 5.5 m mode on a small research vessel of EAWAG institute, Switzerland; (c) photograph of FF-CPT in shortest mode during a test at Kuhgraben near Bremen.

weight totals approximately 170 kg if all extension rods and extra weights are mounted. In short to moderate mode, the FF-CPT can be deployed by two people from small platforms; recovery is aided by a standard 4x4 car winch. In this way, we ensure maximum flexibility in the use of our lance depending on different scientific questions. For further description of the design and the application of the FF-CPT see Stegmann et al. (2006).

Testing methods and data handling with the FF-CPT

Variation of the penetration velocity and the weight is useful for controlling the penetration depth. As can be seen from Figure 1, variable penetration is achieved by three factors:

(i) Length of the frontal part of the lance,
(ii) Weights added to the head of the lance, and
(iii) Penetration velocity.

While the first two parameters have to be set prior to the test (see Fig. 1b, c), the velocity is varied during the test. So far, we have tested at velocities ranging from free drop (ca. 600 cm/s) to various winch speeds upon penetration (30-200 cm/s). However, lower velocities are possible, and we have also conducted tests in clayey mud where the probe is placed at the sediment-water interface and then sinks in by its own weight (estimated rates ca. 1 cm/s in cohesive mud). In any case, velocity is decreasing with increasing penetration depth (and cohesion along the lance's surface), and has to be integrated in order to provide exact depth profiling. Almost 30 years of standard CPT testing (chiefly industrial) provide a sound base for the interpretation of data acquired during tests with non-linear penetration velocity (our FF-CPT device). The immense amount of data, predominantly collected onshore, is compiled in a fundamental and widespread overview by Lunne et al. (1997).

Measured and derived physical properties of FF-CPT tests

Primary parameters

The crucial geotechnical parameters measured in FF-CPT tests are cone resistance (q_c), sleeve friction (f_s), acceleration, and pore pressure (u). In contrast to standard CPT tests where the lance is pushed by hydraulic force at a constant velocity of 2 cm/s, penetration velocity varies with depth both in free-fall mode and when lowered using a winch. This change in penetration velocity has profound effects on the primary parameters and is a subject of this paper. Also, the terminal depth (TD) of penetration of the FF-CPT is not a simple function of time (as in the pushed tests), but a complex deceleration path caused by the sedimentary succession encountered. The built-in acceleration sensor is used to reconstruct the penetration velocity and to assign depth to the data. As an additional control of total insertion depth, we measure the length along which material is stuck to the lance. However, this can only be done during individual tests, but not when running multiple penetration experiments (pogo-style deployment). Prior to individual measurements, calibration of the probe is performed in air as well as in the water column to monitor its potential offset. Before testing, the pore water port and filter element are filled/saturated to minimise artefacts in pressure measurement. Depending on the penetration velocity and on the duration of the test, an adequate frequency for data acquisition is chosen (up to a maximum 40 Hz). From the main parameters of FF-CPT experiments, both cone resistance and sleeve friction are strongly rate-dependent. As we are measuring in saturated sediments, the pore pressure is the sum of hydrostatic pressure and excess pore pressure (Maltman, 1994). Assuming that the pore fluid is in conjunction with the hydrostatic system at our test sites, we subtract the hydrostatic pressure of the water column plus penetration depth from the measured pressure data and obtain the excess pore pressure induced upon insertion of the lance.

Secondary paramaters

There are a number of secondary parameters which can be easily derived from the sensor data. These include both empirical, CPT-specific measures such as the friction ratio, but also well established parameters such as undrained shear strength or permeability. The main aim of estimating sediment strength by measuring cone resistance and sleeve friction is a first order sediment classification, whereby cone resistance is a measure of the stiffness of the sediment (Lunne et al. 1997). It should be noted here that this strength parameter is not a measure for static resistance, but records the dynamic resistance depending on the penetration rate. In cohesive sediments, this increase of penetration velocity results in an increase in cone and sleeve resistance (Dayal & Allen 1975a). The increase of q_c is described as a logarithmic increase with penetration velocity (for 0.13 cm/s < v > 81 cm/s). In non-cohesive, granular sediments, this relationship is less pronounced, or absent (Dayal & Allen, 1975b). To identify several soil types, the ratio between f and q (also known as friction ratio) is generally used, where greater values correspond to fine-grained sediments, and vice versa (Fellenius & Eslami 2000). The first soil classification chart for electrical penetrometer measurements was published by Douglas & Olsen (1981). Robertson (1990) used a similar method (plotting friction ratio vs. cone resistance), but recalculated the effect of pore pressure on cone resistance, as expressed in the corrected cone resistance q_t (Robertson 1990):

$$q_t = q_c + u_2 (1 - a)$$

where: q_t = cone resistance corrected for pore water pressure
q_c = measured cone resistance
u_2 = penetration pore pressure measured on cone shoulder
a = ratio between shoulder area (cone base) unaffected by the pore water pressure to the total shoulder area, here: 0.6

Robertson's classification chart includes 12 different soil types based on grain size composition, amount of organic matter, stiffness and overconsolidation ratio (Robertson, 1990). For standard CPT tests the corrected cone resistance q_t can be used to estimate the undrained shear strength of the sediment (s_u). It is represented by the ratio between the sum of q_t and the cone factor Nc, which is a function of sediment rigidity and *in situ* stress state. Lunne et al. (1997) give an overview of several theoretical solutions for the factor N_c, which ranges in natural systems from 10 – 18. Esrig et al. (1977) suggest the empirical relationship for moderately to highly sensitive marine sediments:

$$S_u = U_{imax}/6,$$

where: S_u = undrained shear strength
U_{imax} = maximum excess pore pressure.

As our tests have been carried out with different, non-linear velocities, we use this relationship to determine the undrained shear strength.

Complementary Laboratory Testing

Sediment samples have been analysed in the laboratory to get reference data for the interpretation and quality assessment of the *in situ* FF-CPT data.

Grain Size Distribution

A Beckman Coulter LS200 laser particle counter was used for grain size distribution analysis. It is capable of measuring particles between 0.37 and 2000 µm, so that the fraction coarser than 2 mm has to be separated by sieving prior to the measurement. The vessel for the sample (50-2000 mg) is moved relative to the 750 nm-laser during the measurement. Each analysis monitors 92 grain size categories controlled by a multi-element sensor. The data are presented in Table 2 and serve as a reference for the interpretation of the FF-CPT results.

Vane Shear Testing

Vane shear tests were conducted using a viscosimeter device manufactured by Haase, Germany, equipped with a miniature vane. The device is motor-driven and measures the torque and rotation angle of the vane. Shear strength values are optioned from the torque measurements and the known vane geometry following standard procedures. (e.g., DIN 18130, BS1377). Values are used for comparison with the undrained shear strength as derived from FF-CPT parameters.

Results and discussion

The test sites chosen for our initial FF-CPT testing mostly lie in the vicinity (100 km radius) of the city of Bremen for convenience's sake. The only exceptions were two short cruises with multiple deployments in "normal" as well as gas-rich muds in the Mecklenburg and Eckernförde Bights, Baltic Sea (Table 1). The two main criteria for their selection was (i) knowledge of the local deposits, and (ii) some variation in fluid char-

Table 1.

Location	Water depth (m)	Deployment	Weight (kg)	Length (m)	Penetration depth (m)	Number of individual tests	Duration of dissipitation (min)
Kuhgraben	1	controlled (50cm/s) - free drop	40 - 70	0.5	0.1 - 0.5	5	10 - 300
Hemelinger See	6	controlled (70-130 cm/s)	125 - 170	3.5	1.3 - 2.0	2	25
Wilhelmshaven	9	controlled (30cm/s)	100	5.5	2.5	1	240
Osthafen	11	controlled (30cm/s) - free drop	160	5.5	5.5 - 5.9	2	30
Baltic Sea (Mecklenburg Bight/Eckernförde Bight)	20 - 30	controlled (50 cm/s-200 cm/s)	90 - 140	2.5 - 3.5	1.9 - 2.8	3	5 - 90

Table 1: Location, water depth, and FF-CPT testing mode (velocity, added weight and length of lance, number of individual tests, duration).

ging for the pore pressure tests. With the sites selected, we cover the full range of clay-rich mud through sandy silts, some of which are normally consolidated while others are organic-rich harbour muds (e.g. Wilhelmshaven) or soupy material from pockmark fields (Eckernförde). Details about the geological setting are not so important for this paper, but the local names are given throughout for clarity (please refer to Tables 1, 2 for sites, testing procedures, etc.).

FF-CPT measurements

Initially our FF-CPT tests were aimed to study the effect of variable weight of the lance on total depth of penetration. Figure 2 provides an example of a series of tests in short mode (Fig. 1c) with variable weight and in free drop versus controlled winch speed of 50 cm/s. It can be seen that for the relatively coarse-grained sediment (Kuhgraben), each added 15 kg weight amounts to an extra 20 cm penetration.

Figure 3 exemplifies the results of a FF-CPT test in silty mud (Mecklenburg Bight, Baltic Sea, see Table 1), mainly dedicated to the penetration behaviour and the records of the different sensors. The penetrometer was launched with a speed of 200 cm/s. Acceleration (Fig. 3a), or better: decelaration, is used to obtain penetration velocity and total depth of penetration by integration. It can be seen that the initial insertion velocity of ca. 200 m/s decreases rapidly to about half that value within the uppermost 35 cm below the sea floor (cm bsf; Fig. 3a). Penetration speed then drops less rapidly for the stiffer underlying muds before the probe comes to a complete halt at 220 cm bsf. Both cone resistance qc (Fig. 3b) and sleeve friction f_s (Fig. 3c) show an increase in the upper part of the penetrated sediment, with the maximum cone resistance being >500 kPa. Figure 3d shows the "excess pore pressure" evolution upon and during penetration, with the hydrostatic pressure (P_{hyd}) having been subtracted from the total pressure readings. Again, the strongest deviation of the

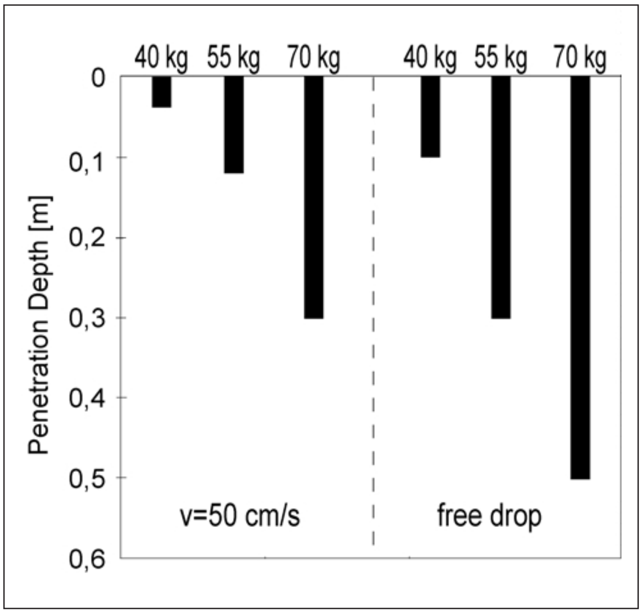

Fig 2: Example of varying penetration depth as a function of different deployment mode (winch vs. free-fall) and total weight. See also Table 1.

curve is observed at 35-40 cm bsf, suggesting that a discontinuity is met. When comparing all sensors at this depth level, it can be seen that values near 7 m/s^2 as well as profound increases in cone resistance and sleeve friction point towards a harder horizon (Figs. 3a-c). In contrast, the initial pore pressure increase induced by the impact of the FF-CPT suddenly ceases, reaching even negative pressures for a fraction of a second (Fig. 3d, 35-40 cm depth). This observation is consistent with other tests at high insertion speed in coarser-grained sediments (e.g. Kuhgraben; see below).

To gain insights into the evolution of excess pore pressure dissipation after impact of the FF-CPT, the complete data record has to be embraced. Figures 4 and 5 provide examples of pressure behaviour at various scales and modes. This is merely to shed light on the influ-

Table 2.

Location	Mean Grain Size (% clay/silt/sand)	Penetration Depth (m)	Max. excess pore pressure after insertion (kPa)	Undrained Shear strength (kPa) (in situ with CPT derived by Esrig (1977)	Undrained Shear Strength (kPa) (Vane Shear)
Kuhgraben	10/55/35	0.1 - 0.5	15	2.5	3.1
Hemelinger See	10/62/28	1.3 - 2.0	20/40	~3.5	
Wilhelmshaven	12/59/29	2.5	34.5	5.7	
Osthafen	14/73/13	5.5 - 5.9	16	2.6	2.5
Baltic Sea	14/81/5	1.9 - 2.8	43/60	7/10	

Table 2: Location, grain size distribution, excess pore pressure after insertion, and undrained shear strength from vane shear and CPT testing, based on the empirical relationship by Esrig et al. (1977).

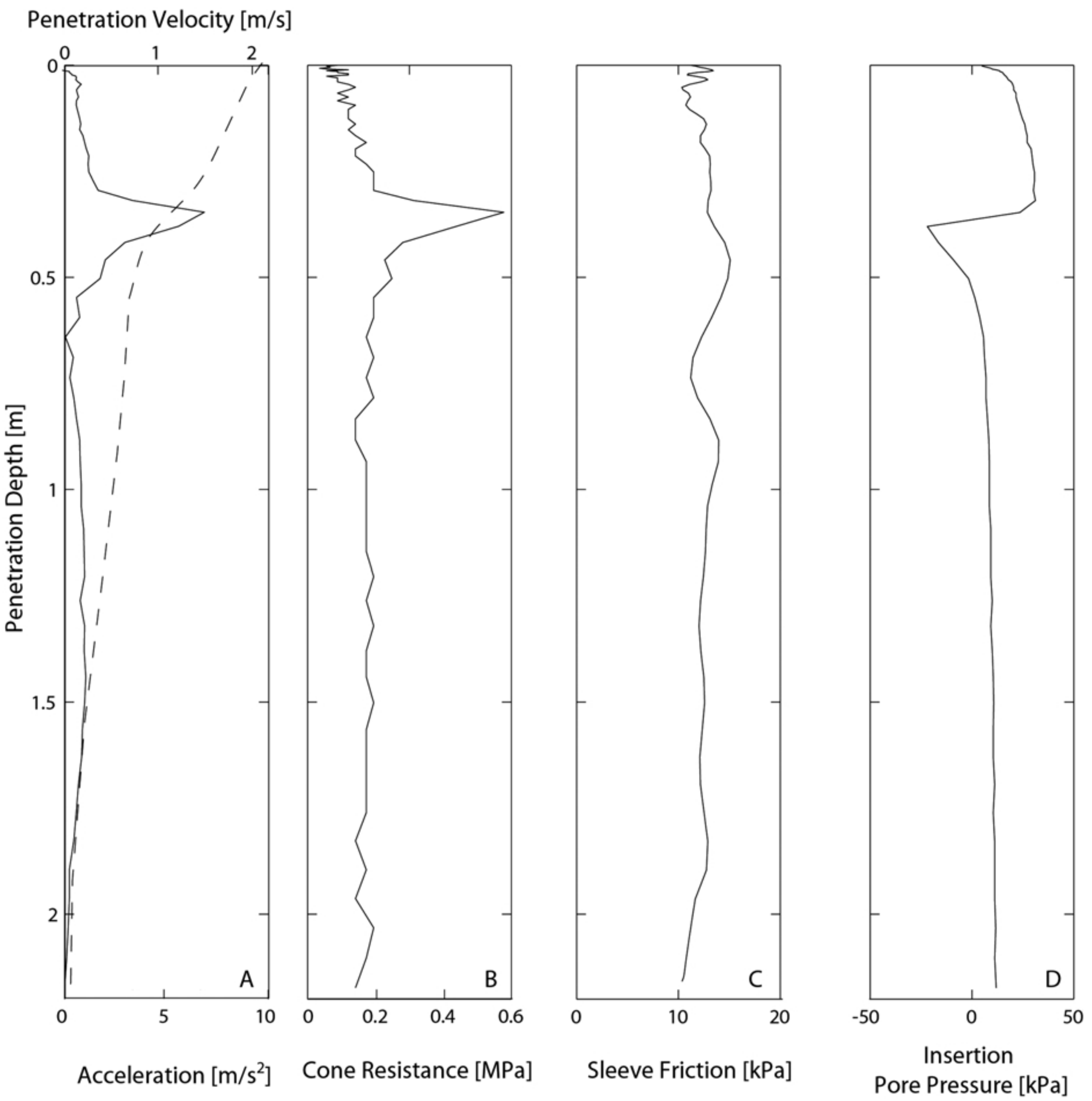

Fig 3: Diagram showing a set of parameters measured with the CPT in clayey mud in the Baltic Sea: (a) Acceleration (overlain by penetration velocity, as derived from deceleration), (b) cone resistance, (c) sleeve friction, and (d) insertion pore pressure. For details, see text and Table 1.

ence of the sediment composition, impact velocity, and different evolution of the pressure signal with time. In Figure 4, we compare the finer grained end of our suite of samples (Osthafen, Baltic Sea), while Figure 5 focuses on the coarser grained end members at Hemelinger See and Kuhgraben. Figure 4a illustrates the induced excess pore pressure evolution caused by the impact of the FF-CPT into Osthafen muds at variable rates (30 cm/s vs. free drop [according to the P_{hyd} data with time, this amounts to ca. 600 cm/s]). It can be seen that pressure increase is more inert at high insertion rate, with the excess pore pressure still increasing after 25 minutes past insertion. In contrast, moderate deployment velocity causes a distinct pore pressure maximum of about 16 kPa after less than 5 minutes, followed by an equally rapid decay to about half that value 10 minutes later (t_{50} value). We attribute this fact to a pressure pulse (or wave) of fluids being displaced and driven away from the probe in case of rapid deployment. In general, we acknowledge this effect to be more profound in coarser-grained sediments. If we disregard the artificial overpressures and compare sediments with naturally high fluid pressures of the Baltic Sea, we observe striking similarities. Figure 4b compares slow deployments (50 cm/s winch speed) into the mud from Mecklenburg Bight (regular deposition) and the Eckernförde Bight

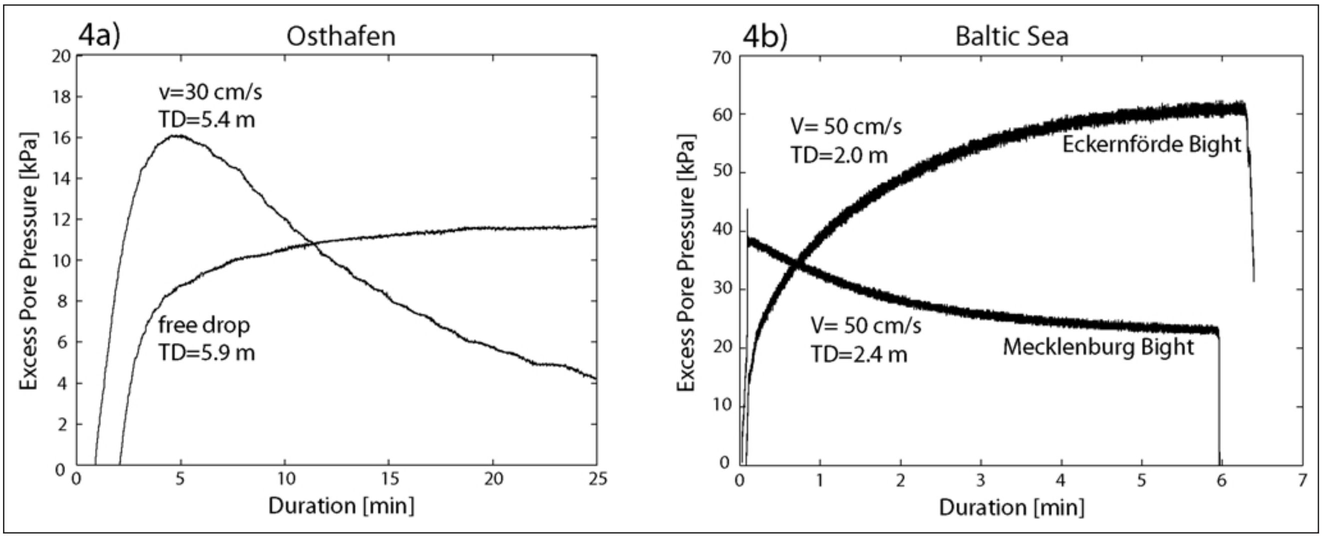

Fig 4: Pore pressure evolution during FF-CPT tests in some of our test sites. (a) Pressure response to FF-CPT insertion at 30 cm/s and free-drop (ca. 600 cm/s) into muds at Osthafen; (b) Pressure response of "normal" mud (Mecklenburg) and gassy mud of a pockmark field (Eckernförde) in the Baltic Sea, both from deployments at winch speeds of 50 cm/s. Note the different behaviour during as well as after insertion. All plots show "excess" pore pressure values along the y-axes since hydrostatic pressure was subtracted. TD means terminal depth. See text for details.

(gas-charged mud in a pockmark area). At the Mecklenburg site, a maximum pore pressure peak is reached almost immediately (ca. 44 kPa), which is followed by an exponential decay with time. In the pockmark area, however, no such peak is seen; instead, excess pore pressure is constantly increasing with time until reaching a plateau at about 60-65 kPa after 6 minutes (Fig. 4b). We interpret the latter value close to the ambient pore pressures in the gas-charged mud. However, *in situ* pore pressures at the Mecklenburg site are at best one third of those at Eckernförde, because the decay has not reached the background plateau value. Taken the observations of Figures 4a and 4b together, we can state that the FF-CPT is capable of detecting different pore pressure responses, no matter whether they are caused by deployment artefacts or natural processes.

When looking at the results of tests into the coarser grained deposits of e.g., Hemelinger See and Kuhgraben (Fig. 5), we observe a somewhat different pore pressure response than in the finer muds (Fig. 4). The first objective was to shed light on the influence of both insertion speed and total weight of the probe, as illustrated by the data from four tests in Hemelinger See (Fig. 5a). In all cases, we observe a distinct pore pressure peak upon insertion, which is rapidly followed by a drop by several kPa. Only after 1-3 minutes, pore pressure signals pick up again and rise steadily (Fig. 5a). Regardless of the total weight of the probe, it is seen that the slower deployment (dashed curves) results in a more accentuated pressure drop, but also a higher total pore pressure reading. Maximum excess pore pressures of the slow deployments exceed that with roughly twice the insertion speed by 3-8 kPa (or ca. 10-50%; see period from 5-25 mins. in Fig. 5a). The net pore pressure drop after the insertion pore pressure peak is also higher in the slow deployments (8 [125 kg] and 13 kPa [170 kg], respectively) than in their fast counterparts (6 [125 kg] and 4 kPa [170 kg], respectively). In addition to the insertion velocity, the total weight has a profound impact on both cone resistance (not shown) and excess pore pressure. In exactly the same location, doubling the speed of deployment causes almost exactly doubling of the pressure readings on the path of the curves where pore pressure build-up occurs (5-25 mins, Fig. 5a). This quasi-systematic behaviour is beneficial when relating FF-CPT data to results from standard CPT tests (see discussion below).

If the insertion velocity is increased even further, we also expect the "trough" after the initial pore pressure peak to develop more profoundly. This behaviour was already seen in the Baltic Sea mud where penetration of a silt layer caused negative excess pressures (i.e. displacement of water) after the initial increase (see Fig. 3d., 35-40 cm depth). This trend is even more profound when slightly coarser Kuhgraben sediments (Table 2) are penetrated at speeds as high as 600 cm/s (=free drop). Figure 5b shows two of the free drop tests with different total weights of the FF-CPT in comparison to a controlled deployment at 50 cm/s winch speed. A blow-up of the initial portion of each of these tests confirm the already known pore pressure response. The slow deployment causes a steady pressure increase with only ca. 5 kPa in excess of P_{hyd}. In contrast, the pore pressure evolution after free-drop deployment shows immediate negative pressures of down to –70 kPa, which become positive within less than a second and then climb to max. excess pressures of approximately 10 kPa. As a function of the difference in total weight,

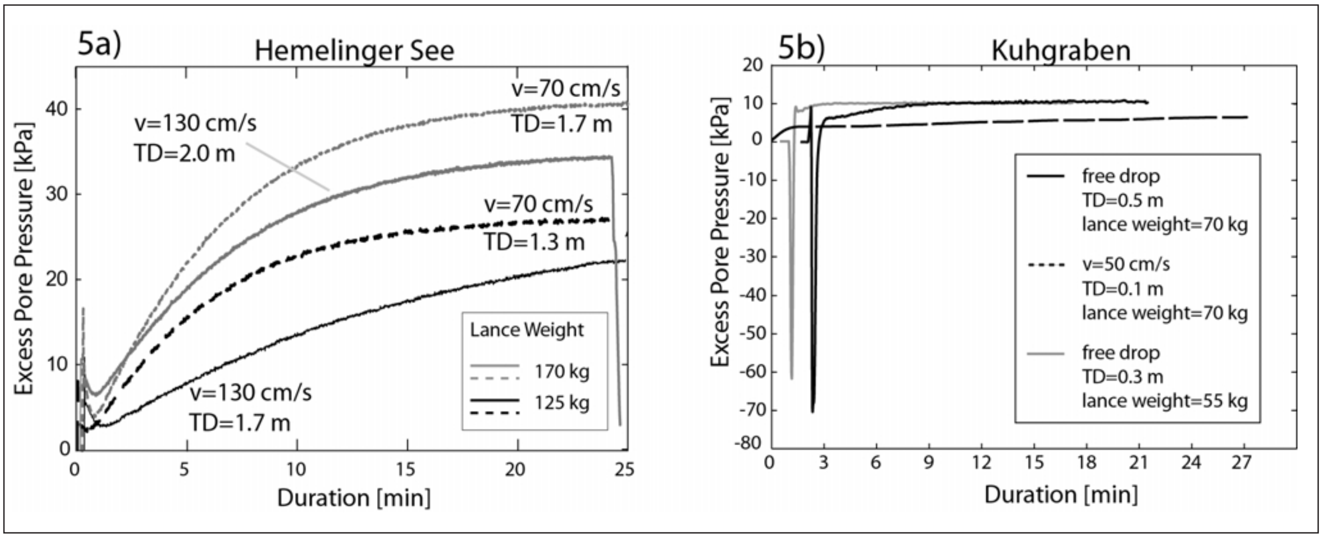

Fig 5: Pore pressure evolution at test sites Hemelinger See and Kuhgraben. (a) Comparison of four tests at Hemelinger See in sandy and clayey silt, with variable deployment rate (70 and 130 cm/s) and weight (125 and 170 kg totally) of the FF-CPT. Dashed lines represent the lower insertion speed in each mode. Note the pressure drop immediately after insertion, which is followed by an increase with time; (b) Comparison of three tests at Kuhgraben sandy and clayey silt, showing the profound difference in pore pressure response between low winch speed (50 cm/s) and free drop (upper two curves). All plots show "excess" pore pressure values along the y-axes since hydrostatic pressure was subtracted. TD means terminal depth. See text for details.

there are slight variations in the two free-drop tests. With the FF-CPT weighing 55 kg, we see a net pressure drop of 62 kPa, while the net decrease is 79 kPa in the 70 kg configuration (Fig. 5b). Similar to what was said above, this somewhat predictable behaviour is beneficial for the interpretation of FF-CPT tests when related to pushed CPT tests (see below).

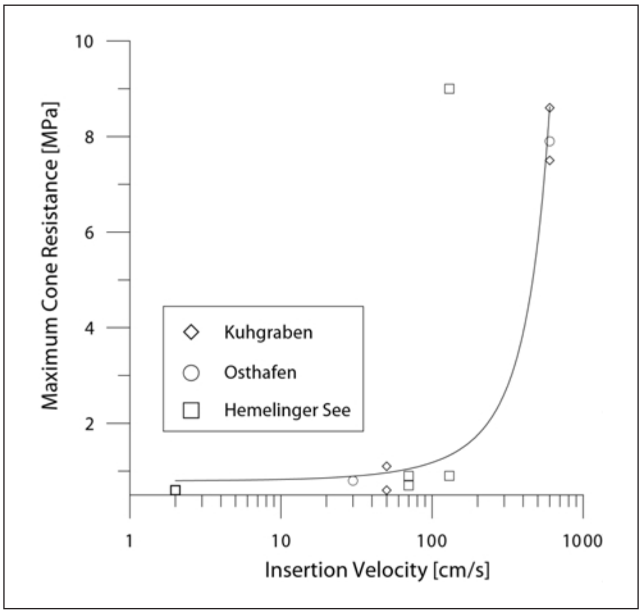

Fig 6: Cone resistance versus insertion velocity for eleven FF-CPT tests in clayey and sandy silt at our test sites. Please note the log-linear relationship in our data sets. The dashed line at 81 cm/s marks the insertion velocity highlighted by Dayal and Allen (1975b); see text for discussion.

Another way of assessing the effect of the insertion velocity on data acquired is to study variations in cone resistance. Figure 6 summarises tests at various velocities at the Hemelinger See, Kuhgraben and Osthafen sites. Without paying too much attention to the slight variations in sediment composition (see Table 2), we observe a log-linear relationship between q_t and insertion speed in these silt-dominated deposits. We will further follow that route by carrying out more tests at each site with different insertion speeds.

Geotechnical Parameters derived from FF-CPT Results

As already introduced above, CPT tests can be used for soil classification purposes when a couple of prerequisites are met. According to Robertson (1990), cone penetration testing allows to distinguish between 12 sediment classes. Plotting the friction ratio versus the corrected tip resistance q_t, and implementing these data into the above mentioned Robertson chart, we can identify the majority of our tested sediments in the fields "clay", "sensitive fine-grained soil", "silty clay to clay", and "clayey silt to silty clay" (Fig. 7). This agrees well with results from particle size analyses according to which most specimens have clay/silt contents of > 80% and ca. 95% as well as high contents of organic matter (see Table 2).

If we look at FF-CPT tests run at higher insertion velocities (100 cm/s and above), however, we observe significant disagreement between the anticipated value obtained at lower velocity (see large symbols in Fig. 7). For instance, both Osthafen clayey silt and Kuhgraben

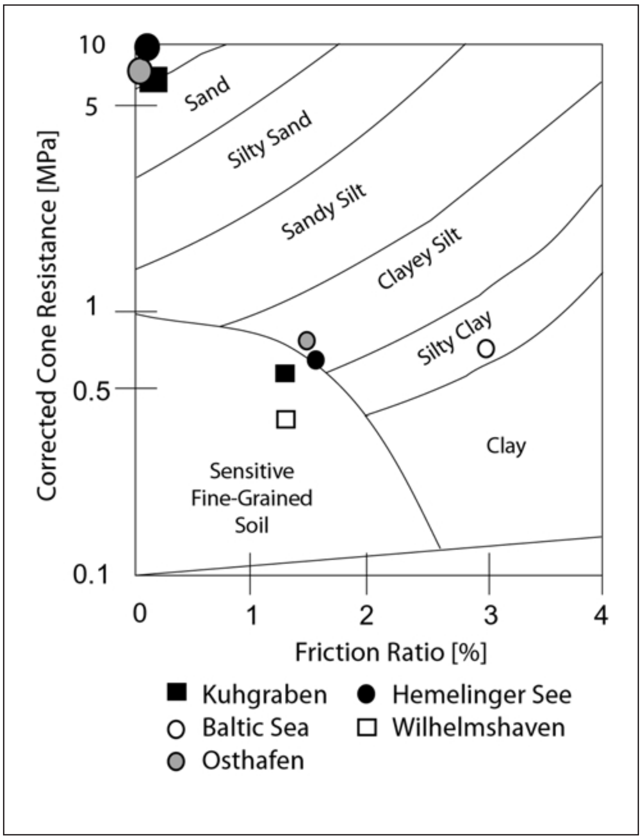

Fig 7: First-order sediment classification (based on Robertson's chart [1990], modified) of deployments at Wilhelmshaven, Osthafen, Hemelinger See, Mecklenburg Bight (Baltic Sea) and Kuhgraben. For those sites where fast (v = >81 cm/s) were carried out, results are shown as large symbols (see inset: Legend). For details, see discussion in text and Figure 6.

and Hemelinger See clayey and sandy silts show very high cone resistance values, and hence plot in the field of pure sand. This implies that for the more rapid of our deployments, a reliable soil classification is severely hindered. It can be seen that the higher the velocity, the more data shift towards the upper left portion of the diagram (Fig. 7). We conclude that friction ratios may get less reliable when penetration velocity is high, because qc is up to 4-fold higher than in the deeper section when momentum has been lost (see Fig. 3b,c). As outlined above, the force measured during penetration of the FF-CPT probe can be translated into undrained shear strength under certain assumptions (see discussion in Esrig et al., 1977). In our experiments, the insertion pressure ranged from 15 kPa to 60 kPa for the total of 13 tests conducted so far (see Table 1 for details). Based on the FF-CPT experiments, undrained shear strength was calculated for all five locations (Table 2). The finer-grained sediments in Osthafen, Wilhelmshaven, and the Baltic Sea are characterised by a relatively wide range of shear strengths from 2.6 kPa to 10 kPa. This may be explained by the different degree of consolidation, which is also mirrored by the difference in total penetration depth (1.9 m - 5.5 m). However, vane shear tests of the Osthafen mud, which were carried out on the surface of a split gravity core, gained 2.5 kPa. The coarser materials show undrained shear strengths of 3.5 kPa (Hemelinger See) and 2.5 kPa (Kuhgraben; see Table 2). Vane shear tests on the latter material were carried out as a reference measurement, and lie higher (3.1 kPa). We conclude that the elevated permeability of the Kuhgraben sandy silt allows water to dissipate very rapidly during FF-CPT impact, so that the insertion pressure monitored at u_2 is biased by negative pore pressures, and thus underestimates the total pressure upon impact.

Conclusions

- We can show that our new FF-CPT device may be used for time-effective *in situ* measurements from nearly any platform in the estuarine or marine realm (Fig. 1).
- Given the modular design of our FF-CPT, we are able to specifically address certain depth levels and hence may perform step-like dissipation tests with the probe to examine different sedimentary layers (see Stegmann et al. 2006, p.29). This includes long-term dissipation tests as well as deployments at variable penetration velocities or weights (Figs. 4-5).
- From the FF-CPT tests carried out so far in clayey and sandy silt, we obtain a log-linear relationship between cone resistance at the probe and insertion velocity. This may allow us to compare FF-CPT data with results from pushed standard CPT tests within certain limitations.
- Comparing the published soil classification charts (e.g., Robertson 1990) with our FF-CPT data and grain-size analysis, *in situ* classification of the tested sediments agrees well with the laboratory measurements (Fig. 6 and Table 2).
- Pore pressure and sediment strength should show a positive correlation in FF-CPT tests, because a certain degree of consolidation/stiffness is required to allow the build-up of a significant pore pressure artefact. Our results of combined FF-CPT, grain size and vane shear analyses indicate that clay content alone does not necessarily result in lower permeability and more rapid pore pressure build-up. In fact, the opposite is suggested when data from Osthafen and Kuhgraben mud are compared. While the first does not exceed excess pressures of 4 kPa (min. dissipation value) to 16 kPa (max.), the latter covers a range from –50 kPa (initial fluid displacement) to 10 kPa in excess of hydrostatic pressure.
- More generally, we can state that the FF-CPT is capable of detecting different pore pressure responses in marine (or estuarine) sediments, no matter whether they are caused by deployment artefacts or

natural processes. This way the device is powerful in distinguishing between the influence of pore water overpressures on the one hand, and weak strength (from q and f) on the other hand as potential triggers of slope instability.

- The correlation of the pore pressure signal and shear strength (for CPT and laboratory tests) is ambiguous, most likely because of the large number of variables such as insertion velocity, total weight etc. during FF-CPT deployment. More testing will be carried out to analyse the influence of the variable parameter of our dynamic measurements.

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