PORTABLE FREE FALL PENETROMETER MEASUREMENTS: SHEAR RESISTANCE VERSUS DRAG RESISTANCE

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ABSTRACT

Portable free fall penetrometers are lightweight seafloor penetrometers deployed by hand and usually applied for the geotechnical characterization of uppermost seafloor surface sediments (≤ 1 m). Therefore, they are particularly suitable to measure changes in geotechnical properties from local and recent sediment remobilization processes. The so-called mobile or active seafloor layer (i.e., the seafloor surface layer actively affected by sediment transport processes) is usually very soft in the case of muddy sediments or very loose in the case of sandy sediments. Thus, the void ratios and the water contents are high, while the bulk density is low. Particularly in muddy sediments, this layer may even share characteristics with a high concentration suspension rather than with a soil. Accordingly, sediment resistance is expected to be comprised of contributions of shear resistance, drag resistance, and to some extent buoyancy and possible side friction. Furthermore, it may be argued that drag resistance may be the prevailing contributor to seabed resistance against a penetrator in the mobile seafloor layer. With increasing sediment depth, effects of drag are likely significantly reduced when the sediment hardly "flows" around the probe anymore, and shear resistance is expected to start dominating. However, transitions between these processes are poorly understood, and possibly particularly complex for impacts with changing penetration velocities. In this study, the issue of forces contributing to sediment resistance against a portable free fall penetrometer at high impact velocities is revisited theoretically and through literature review, and discussed in the context of applicability for the investigation and analysis of surficial seafloor sediments.

Keywords: free fall penetrometers, data analysis, seabed surface

INTRODUCTION

The need for cost-efficient tools for shallow (sediment depth ≲ 1-2 m) geotechnical seabed investigation, as well as for rapid deployment tools or the investigation of sediment erosion and deposition processes has recently gained much interest (e.g., Dayal 1980; Stark et al. 2014a,b; Randolph 2016; Peuchen et al. 2017). Different concepts of free fall penetrometers (FFPs) have been proposed to address this instrumentation need. FFPs follow the overarching concept of traditional Cone Penetration Testing (CPT), being a soil penetrator of known geometry but they may be equipped with various sensor suites. A major difference of FFP in comparison to CPT is that FFP are driven by self-weight and eventually momentum into the seabed. As a result, the penetration depth depends on the FFP shape, weight, deployment method (and particularly speed), and the sediment resistance against the FFP during penetration. Some FFP offer a similar sensor suite as CPT often complemented by accelerometers and tilt sensors to monitor the motion of the FFP closely (e.g., Stegmann et al. 2006; Peuchen et al. 2017). Other FFP, and particularly lightweight and small-scale devices, utilize only accelerometers to measure the probe's motion accurately and to derive geotechnical soil parameters from the sediment resistance force against the penetrometer (Aubeny and Shi 2006; Stoll et al. 2007; Abelev et al. 2009; Mulukutla et al. 2011; Stark et al. 2012; Morton et al. 2015; Stephan et al. 2015; Albatal et al. 2019). However, some studies raised concerns about the accuracy and quality of the estimated geotechnical parameters from FFP accelerometer data in comparison to data collected with a sensor suite similar to a CPT (Chow et al. 2017). While the collected accelerometer data has been proven to be reliable and accurate, and with considerations of a larger flexibility in penetrometer shape, size, and deployment method (Abelev et al. 2009; Mulukutla et al. 2011; Stark et al. 2012, 2014b; Morton et al. 2015; Stephan et al. 2015; Albatal et al. 2019), the following items have been identified as challenges in data processing towards estimating geotechnical parameters from accelerometer data obtained by small-scale FFP: (i) application of the most suitable strain rate correction and soil dependent strain rate factor (e.g., Steiner et al. 2013), (ii) choice of cone factor (e.g., Aubeny and Shi 2006), and (iii) identification and differentiation of the various forces contributing to the sediment resistance force during penetration (e.g., Jeanjean et al. 2012; Stark and Ziotopoulou 2017; Bilici et al. 2019). This article focuses on the latter issue (iii), providing a literature review and theoretical consideration of the matter. Due to space limitations, this article is centered around portable free fall penetrometers such as the *BlueDrop* (Fig. 1; mass ≈ 8 kg, length ≈ 63 cm) that is usually deployed manually and "free falling" through the water column. The device measures acceleration using five micro-electro-mechanical systems accelerometers of different range and accuracy, tilt, and ambient pressure.

LITERATURE REVIEW AND THEORY

Free fall in water

The deployment of a FFP for geotechnical seafloor site investigation starts with the "free fall" through the water column. If an object falls freely through the water column, its descend will be driven by its weight ($W = mg$ with m being the mass of the object and g being the gravitational acceleration). Weight, as the driving force, is countered by buoyancy in water ($B = \rho_w g V$ with ρ_w being water density and V the volume of the object) and by drag (*D*):

$$ma = mg - B - D \tag{1}$$

with a being the acceleration of the probe. The mass and the volume of the FFP are known from specs of the probe. Water density can be estimated from the site geography, or can be determined during the field measurements.

Drag force against the motion of the penetrometer consists of form drag and skin friction drag. Form or pressure drag increases with the cross-area presented against the flow. It can be decreased through a thin and possible even sleek or streamlined body minimizing the separation of flow. Skin friction drag results from the connection between the object and the fluid. Through any connection between the fluid and the probe's hull some fluid will be mobilized by the motion of the object. Skin friction drag is increased by the formation of turbulent flow in the contact boundary layer. A possible pathway to decrease skin friction drag is to shape the object to enhance laminar flow, and/or by increasing the fineness ratio (object length/object diameter). Parasitic drag (*D*) is usually expressed as the sum of the form drag and skin friction drag using the drag equation in the following form for high velocities:

Fig. 1. *BlueDrop* portable free fall penetrometer after deployment in muddy sediments.

$$D = \frac{1}{2}\rho_w v^2 C_D A \quad (2)$$

with v being the object's velocity, A being the projected surface area, and C_D being the drag coefficient. The drag coefficient depends on the shape of the object and the Reynolds number which depends on velocity as well as kinematic viscosity. A detailed investigation of drag coefficients for torpedo-like objects (i.e., "streamlined bodies with cylindrical sections") is presented by, e.g., Brooks and Lang (1958). Jeanjean et al. (2012) utilized C_D = 0.57 for a torpedo anchor model, while Bilici et al. (2019) suggested C_D = 0.1-0.17 for the FFP investigated here (Fig. 1) based on work by True (1976), Freeman and Hollister (1989), and Mumtaz et al. (2018).

Equation 1 would suggest that a terminal velocity would be achieved within meters of free fall through the water column. However, FFP require a rope or cable for retrieval and in some cases live data transmission. The rope is subject to somewhat of buoyancy and drag (particularly skin friction drag). Furthermore, rope length will increase with the travel distance of the FFP, contributing consistently to the forces that slow down the penetrometer. Therefore, the FFP is expected to undergo an initial rapid acceleration before decreasing in acceleration and eventually transitioning to a deceleration when the fall distance has exceeded the theoretical depth to achieve terminal velocity (Stark and Ziotopoulou 2017; Bilici et al. 2019). Rope effects can be minimized by decreasing the width and roughness of the rope. Furthermore, knots, slack, and friction through contact with the deployment platform should also be avoided to decrease rope effects.

Penetration/fall through soil

The actual measurement of interest starts with the impact and penetration into the seabed surface. Intuitively, soil of any type is considered stronger than water, leading to the expectation of a deceleration of the probe. Depending on the probe's motion just prior to impact and soil conditions, this may also be expressed as a decrease in acceleration or an increase in deceleration only. This is also the key assumption when identifying the point of impact for continuously recording FFP. The change of pore pressure response may not be so intuitive and can vary significantly for different soils and speeds. However, this is not within the scope of this study.

Seabed surface sediments can be very soft and even represent "fluid mud". Rheology investigates the flow of matter, including non-Newtonian fluids and plastic flow of solids. Differently than water, non-Newtonian fluids are characterized by a stress dependent viscosity. For example, Morton et al. (2016) described soft soils during penetration of a spherical FFP as a non-Newtonian fluid. Therefore, the sediment resistance force, i.e., the total force that leads to the above described expected change of motion of the FFP upon contact, and penetration through the soil, has been expressed as a sum of forces similar to the ones experienced in Eq. 1, as well as of mechanisms of soil strength (shear strength or bearing capacity). Aubeny and Shi (2006) considered soil shearing resistance and soil buoyancy for the penetration of the expendable bottom penetrometer (XBP) into clay. Stark et al. (2012) considered only shear resistance for the FFP *Nimrod* into sand. Both, the XBP and *Nimrod* fall into the group of torpedo-like shaped, lightweight FFP. Jeanjean et al. (2012) included soil buoyancy, soil end bearing resistance or shear resistance, a skin friction resistance of all surfaces parallel to the penetrator trajectory, and an inertial drag force for torpedo-anchor type of penetrators. Chow et al. (2017) followed the sum of forces proposed by Jeanjean et al. (2012) for a CPT-like shaped FFP in clay. All authors agreed on the need for a strain rate correction of the shear resistance force F_{sr}. Following the expression by Jeanjean et al. (2012), the governing equation of motion can be described as:

$$ma = mg - B_s - F_{sr} - F_f - D_s. \tag{3}$$

In this case, the soil density ρ_s needs to be considered when estimating the soil buoyancy B_s as well as when estimating the soil drag force D_s. Additionally, a soil drag coefficient needs to be chosen which depends on the Reynolds number, and thus, viscosity. However, if the soil is considered a non-Newtonian fluid, the viscosity depends on the applied shear stress (Morton et al. 2015). Jeanjean et al. (2012) suggested that the skin friction resistance F_f can be expressed through a strain rate correction factor (in fact, the same as used for the strain rate correction of the shear resistance force), an adhesion factor, the shear strength, and the applicable surface area. Morton et al. (2015) also highlight the potential role of added mass effects for a sphere penetrating into clay. This term is dependent on acceleration, soil density, and an added mass factor. It should be mentioned if this is considered during penetration, it should also be considered during free fall through the water. Finally, the length of the rope or cable being used for recovery is likely being extended by at least the penetration depth. If less rope length would be given, the deceleration of motion would be significantly affected by the rope. If significantly more rope length is given during fall and penetration, drag on a slack rope may add to the penetration resisting forces.

Bilici et al. (2019) highlight the fact that many FFPs have a length that is larger, similar, or represents a significant percentage of the maximum penetration depth. This means that not only the free fall through the water column (entire FFP body is in water) and the soil penetration (entire FFP body is embedded in the seafloor) must be considered, but in many cases, a transitional phase when an increasing length of the FFP is embedded in soil and a decreasing length of the FFP is still in water must be acknowledged, and possibly included in the analysis. This case becomes particularly important when investigating soil top layers, or when penetration depths vary significantly. In that case a sum of resisting forces have to be included for the in-water part and for the in-soil part, and has to be re-calculated for each step of penetrometer advancement.

APPLICATION

The forces presented in the previous chapter describe comprehensively the motion of the FFP during penetration. The presented expressions can be easily populated with proper knowledge of the seabed soil characteristics. However, if FFP are utilized for early site characterization or rapid surveys, such information may not be easily available. Also, in the case of investigating seafloor surface sediments that are subject to frequent remobilization processes, sediments are expected to be loose or very soft soils with strong spatiotemporal variations in water content and bulk density. Such information may even be highly challenging to obtain from common sampling, CPT, or other traditional methods.

In the following paragraphs, the properties contributing to the resisting forces are revisited from the perspective of availability in actual application. Easiest available properties are the measurement of acceleration/deceleration, being a standard measurement of today's FFPs. Three-dimensional accelerometers or inertial measurement units (IMU) measure possible deviation of the FFP from the vertical. While the theoretical correction of inclined penetrations is possible, the FFP user may also consider adopting a threshold of inclination under which the effects of inclination are negligible and over which the deployments are discarded from further analysis. This decision as well as the choice of threshold should be made based on the FFP, penetration depths, and expected effects on data quality. In the case of *BlueDrop* data analysis, a threshold of 5-10° inclination has been chosen for most studies. The device is designed by shape and weight distribution to enhance a straight free fall, and therefore, a critical mass of low inclination penetrations can be achieved in the case of most surveys. The need for correction must potentially be considered in particularly challenging environments of steep seafloor bathymetry or strong flow velocities (e.g., in energetic waves).

Mass, dimensions, and volume of the penetrometer are available from device specs or simple measurements. Density of water ρ_w can be determined by measurement if needed. However, density of water can change spatiotemporally with locations and depth. Therefore, it may be considered if a standard average value is acceptable. For the *BlueDrop* FFP with a mass of 7.71 kg (please note the mass may change with the respective serial number due to small internal differences and varies with tip geometry), the driving weight equals 75.9351 N. This is countered by buoyancy in fresh water (assuming ρ_w=1000 kg/m^3) of 24.2601 N and in sea water (assuming ρ_w=1025 kg/m^3) of 24.8666 N. This means the difference in buoyancy between fresh water and sea water is 0.6065 N (< 1% of the weight), and deviations in actual water density from such assumed standard values would even be smaller.

The assessment of soil buoyancy requires an estimate of soil density. If at this point buoyancy from water is already considered, only the increase of acting buoyancy from water to submerged soil becomes relevant. Richardson and Jackson (2017) report seafloor bulk densities ranging from 1185-1837 kg/m^3 for surficial unconsolidated muddy sediments with a porosity ranging from 90% to 50%, respectively, and ranging from 1837 – 2243 kg/m^3 for sandy sediments with a porosity from 50% to 25%. Fluid muds can exhibit even lower densities (Van Rijn 2016). This means that for full embedment of the FFP *BlueDrop*, the effects of buoyancy from sea water to full soil embedment would increase by 1.8195 N for a fluid mud suspension layer, by 3.8816 N for a very high water content unconsolidated mud, and by 29.5974 N for a well packed sandy seafloor. It should be noted that full embedment for the latter case is unlikely as the FFP is stopped after 10-20 cm of penetration in dense sands. Stark et al. (2016) highlighted that this effect could be increased if the FFP would be fully embedded and leave an open cylindrical cavity in its wake. However, even in this worst case, effects of soil buoyancy would be limited to up to about 7-11 % for deep penetration in soft clays and are negligible for penetrations of less than half the FFP length (~ 30 cm) (Stark et al. 2016; Stark & Ziotopoulou 2017). Thus, it can be proposed that effects of soil buoyancy are only considered for penetrations in excess of ~ 30 cm of penetration depth. Such cases can be expected to represent clayey soils. Here, variations in increase in buoyancy from sea water to full embedment could range from about 3 N to about 20 N depending on state of consolidation, and therefore, the retrieval of a physical seafloor sample to assess seafloor bulk density in the range of penetration must be recommended. A small gravity corer or push tube could provide a cost-effective method for this. Otherwise, it may be considered to develop a strategy to estimate a range of bulk density from the overall experienced sediment resistance force (or even the initial deceleration measurement) or from pore pressure response measurements (Albatal and Stark 2017; Mumtaz 2018). If none of these options is available, the use of an estimated bulk density based on expected soil type is recommended for deployments with penetration depths $\gtrsim$ 30 cm.

The effect of added mass for the deployments of FFP has been raised most recently by Morton et al. (2015). These authors described that for a FFP with spherical shape an additional force opposing the motion of the penetrometer through water and soft clays results from the acceleration of fluid/soil (here, understood as a non-Newtonian fluid) displaced by the FFP. This force depends on the acceleration, the mass of fluid displaced, and an added mass coefficient. For a spherical object, the added mass coefficient is proposed to equal 0.5 in line with theory of fluid dynamics, and thus, leads to a noticeable effect of added mass. During the transition from water to soil, this effect should increase by the increase in soil density over water density. The added mass coefficient could be determined using computational fluid dynamic modelling as demonstrated by Mumtaz et al. (2018). For example, the added mass coefficient has also been investigated in more detail for torpedo anchors (Fernandes et al. 2006). However, this effect should be restricted to a penetration depth and soil texture that allows it to behave like a fluid. A FFP of a type like the *BlueDrop* achieves its maximum velocity within few meters of free fall through the water, and rarely continues to accelerate upon contact with soil. The continuing acceleration or starting deceleration in very soft ("flowing") top layers is limited to usually < 1 *g* which allows the assumption that effects of added mass during transition from water to soil are likely negligible. However, computational fluid dynamic modelling could provide a more confident conclusion. The side-friction term as proposed by Jeanjean et al. (2012) becomes negligible for the FFP *BlueDrop* due its short cylindrical middle section in addition to the use of smooth aluminum . Therefore, it can be rejected from further analysis.

Rope effects associated with buoyancy as well as drag are clearly affecting the free fall through water. However, considering penetration depths of portable FFP of mostly ≲ 1.5 m as well as the fact that tension on the rope is relaxed as soon as the probe decelerates allow that rope effects are neglected for the penetration process, unless tension is forcefully sustained or increased by an addition friction mechanism on the rope.

Drag and shear resistance – Clayey soil

Drag effects versus shear resistance have become an increasing discussion point for the data analysis of FFP. As the motion of the FFP is well recorded during the free fall through the water column and the density of water can be determined or well estimated, the buoyancy can be determined as outlined above, leaving the drag coefficient as the only unknown, particularly when the fall velocity approaches an approximately constant value when the added mass force is expected negligible. The drag coefficient can also be investigated in more detail using a computational fluid dynamics model as demonstrated by Mumtaz et al. (2018). The drag coefficient in soil and in water is expected to be different, and to vary with soil conditions. It is worth mentioning at this point that no drag resistance is expected unless material is actually “flowing” against and around the FFP, while the shear resistance force is expressed as:

$$F_{sr} = N_c s_{u-op} A \quad (4)$$

where N_c is a bearing capacity factor and s_{u-op} the actual strain-rate enhanced undrained shear strength. This means that the soil is undergoing conceptually bearing capacity failures upon advancement of the FFP through the soil (Stark et al. 2012).

Most studies suggest adding drag forces and shear resistance up in the list of FFP opposing forces in soil. Conceptually, this suggests that fluid-like behavior and soil-like behavior co-exist at all times of penetration, except at the time of the penetrometer rest (i.e., when the velocity is zero) when drag forces are not existent anymore. However, it may be hypothesized that surficial high water content soil layers do not offer a traditional soil shear behavior, but predominantly are controlled by non-Newtonian fluid behavior. At deeper soil depths, fluid-like flow may be strongly restricted, potentially disallowing the direct application of the simple quadratic drag equation. Morton et al. (2015) offered the concept of a combined capacity factor that includes drag effects and shear resistance. This was achieved by defining the drag coefficient as a function of the non-Newtonian Reynolds number that depends on the velocity squared and the ratio of fluid density over shear stress. The shear stress within the flowing material was then assumed to be equal to the operative shear strength. In the bearing capacity factor those authors accounted plasticity of the soil and depth of failure. While this method represented a uniquely detailed investigation of shear resistance and drag forces on a spherical FFP, it required the assumption or determination of a number of soil parameters that may not be available in many rapid FFP surveys or areas of difficult access.

A preliminary analysis by Stark and Ziotopoulou (2017) suggested that the resistance measured in the upper ~ 6 cm of penetration into a soft clayey seabed can fully be described by expected soil buoyancy and drag, suggesting that the soil is exhibiting behavior of a suspension (i.e., fluid) rather than of the soil. Bilici et al. (2019) supported this finding for two additional clayey sites. They found that at different soil depths in the range of 5-10 cm the measured sediment resistance departed (by increase) in magnitude and functional shape from the expected quadratic velocity dependent drag behavior. They accounted the added resistance to shear resistance. Kiptoo et al. (in prep.) later obtained sediment cores using divers, box coring, and gravity coring from the same area. During immediate testing of the surface of diver cores and box cores, vane shear tests did often provide no results as the soft soil did not provide sufficient shear resistance. Stark and Ziotopoulou (2017) also suggested that the drag force decreased to less than soil buoyancy beyond about ~ 40 cm of penetration, representing at this point less than 10% of the total resistance measured. It is questionable if sediment at this depth is in fact still "flowing".

For the investigation of very soft surficial top layers observed in marine and estuarine fine-grained seafloor sediments, these considerations may suggest that sediment resistance against an FFP can be expressed in rheological rather than in soil behavior terms. This would also suggest that the layer could possibly be considered a fluid mud like seabed layer with its resulting relevance for erosion processes, naval and other applications.

Drag and shear resistance – Sandy soil

Lightweight FFP penetration in sand is limited in depth to often only 10-20 cm. As confining stresses are negligible at the seabed surface, dilation occurs when penetrating relatively dense sediments increasing the friction angle to high values (Albatal et al. 2019). In very loosely packed sand top layers, more of a punching failure can be observed with little or no visible dilation and resistance resulting from intergranular friction during particle re-arrangement. Negative pore pressures, commonly observed particularly during FFP penetrations into sand (Lucking et al. 2017; Albatal and Stark 2017) match well the observation of dilatory behavior, but have also been observed in loose sands without obvious dilation, despite the fact that undrained to possibly partial drained behavior can be assumed (Chow et al. 2018; Albatal et al. 2019). Lucking et al. (2017) suggested that materials were violently expelled at FFP impact, creating the significant negative pore pressures. It may be hypothesized that sands at the penetrometer interface may be mobilized into suspension through a liquefaction/fluidization process upon impact. Sand suspensions are known to exhibit an increased viscosity over water (Woo et al. 1988). This could suggest that while the majority of the resistance against an FFP in sand is governed by high friction angles associated to dilation (Albatal et al. 2019), low resistance surface layers as already observed by Stark et al. (2012) are likely indeed associated with layers of low relative density. However, whether the low resistance is only related to limited intergranular friction during a type of punching failure or may be enhanced by the mobilization of a sand layer at the penetrometer interface into suspension requires more research. Indeed, Bilici et al. (2019) found that the sediment resistance force during penetration into a sandy seabed could be simulated in overall trend by drag forces in the upper 4 cm of penetration. However, the measured signal exhibited significant fluctuations in the same zone of penetration depth, possibly hinting at a combined effect of particle re-arrangement and drag.

CONCLUDING REMARKS AND FUTURE IDEAS

Free fall penetrometer (FFP) have come to the fore as a rapid and cost-efficient methodology for geotechnical investigation of the seabed surface (i.e., in the upper meters of the seabed surface). Lightweight, portable FFP enable access in many areas of difficult access and have been used for the geotechnical investigation of sediment remobilization processes. However, the sensor suite of portable FFP is often limited to accelerometers and pressure transducers, allowing application of a deployment optimized penetrometer shape, as well as providing an outstanding robustness. To derive more meaningful geotechnical parameters from the penetrometer change of motion during penetration, the forces acting on the penetrometer have to be fully understood. While this may appear easy conceptually, it becomes complex when considering the wide variety of seabed sediment types and textures and the associated response against the penetrator. Furthermore, it becomes truly challenging if limited information about the soil are available to determine confidently soil density, drag coefficients, or bearing capacity factors. Unfortunately, this is the case for many portable FFP surveys, as these devices are often applied where more traditional methods struggle to be safely deployed (e.g., energetic environments) or deliver reliable information (e.g., uppermost centimeters of the seabed surface). Nevertheless, it appears that some decisions for the improvement of the data processing can be made based on limited information available. Geological information of the region as well as a generalized (soil independent) data analysis procedures (following, e.g., Stoll et al. 2007; Stark and Wever 2009; Mulukutla et al. 2011; or Albatal and Stark 2017) enable a classification of sediment type, as well as an identification of soil stratification (in terms of sediment strength). Based on this knowledge and the known penetration depth, decisions can be made about the potential relevance and contribution of different forces to the equation of motion. Parameters associated with fluid dynamics may also be derived from the free fall through the water column that precedes the seabed penetration. Such parameters as well as empirical soil behavior parameters may also be defined by most recent efforts in numerical simulations. Additionally, a less user dependent analysis may be achieved in the future through the use of artificial intelligence. It can be envisioned that a neural network or Bayesian network could be trained to make these informed decisions. The latter would also assign probabilities associated with the different possible solutions. To make a step into this direction, more data sets of portable FFP data and matching detailed soil information are needed. Finally, special attention was paid to the role of drag forces and shear resistance. From the literature review and theoretical considerations presented here, it should be considered that the penetration process may include a phase of dominant drag resistance with little to no actual shearing of soil, a transitional phase, and a phase when shear resistance dominates and little to no soil flows around the penetrometer. Drag resistance may play a particularly important role if soft or very loose seabed top layers are investigated. It may be hypothesized that soft clayey layers could be better described by their rheological behavior than a traditional soil behavior. However, more research is needed to draw final conclusions on this issue.

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