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Geotechnical site investigation in energetic nearshore zones: opportunities & challenges

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ABSTRACT: Coastal erosion and scour around structures in the nearshore zone represent major societal challenges with regard to coastline conservation, the protection of coastal communities and eco-systems, as well as the development of coastal structures or renewable energy projects. Despite rapidly advancing sediment erosion, scour and morphodynamics prediction tools, the models still struggle to correctly simulate the impact of severe storm events and storm event clusters, particularly regarding long-term projections considering sea level rise and climate change. Scour prediction models still struggle to accurately predict the depth and extent of the scour around a structure, and often rely on significant overpredictions which impact the cost-efficiency of the structural foundation design. A review of common erosion and scour prediction models reveals that particularly sediment characteristics appear underrepresented. This results from challenges to derive these information in the field. Areas of active sediment remobilization processes, such as the nearshore zone, are characterized by energetic hydrodynamics (waves, tides and currents), and morphodynamics (migrating bars, etc.) representing challenges and risks to people, vessels and instrumentation. Most geotechnical field instrumentation to-date are not designed or suitable for measurements in such conditions, and new devices are needed to fill this gap. This paper presents results (i) using a portable free fall penetrometer of projectile-like shape to investigate in-situ characteristics and stratification of sediment surface sediments in the nearshore zone under hydrodynamic forcing, and (ii) preliminary data using embedded pressure sensors to investigate the pore pressure response to irregular wave forcing in the nearshore zone and its potential impact on sediment erosion. The devices proved to be suitable for the deployment in energetic nearshore conditions. The data emphasize the potential regarding deriving novel information about in-situ sediment characteristics, such as changes in sediment strength under the active sediment dynamics, as well as an increase of erodibility through the development of excess pore pressures on different time scales. However, the data also reveal challenges related to calibration of the instrumentation and data processing, particularly with limited additional information about the sediment.

1 INTRODUCTION

Coastal erosion, coastal land loss and scour around structures in the nearshore zone represent major societal challenges with regard to coastline conservation, the protection of coastal communities and eco-systems, as well as the development of ocean renewable energy projects (Zhang et al. 2004; NAS 2010; Hinkel et al. 2014). Despite the rapid advancement in predicting sediment erosion, scour and morphodynamics, the models still struggle to correctly simulate the impacts of severe storm events and storm event clusters, particularly regarding long-term projections considering sea level rise and climate change (e.g., Coco et al. 2014). This issue becomes especially dramatic for locations at which coastal erosion rates have reached values in the order of meters per year, or the Arctic where the additional impact of permafrost is increasing erosion rates to more than ten meters per year (Dolan et al. 1979; Jones et al. 2008; Obu et al. 2016).

Similar problems can be identified for scour prediction models which often struggle to accurately predict the depth and extent of the scour around a structure (Falcone and Stark 2016). Currently, the most commonly applied prediction models rely on significant overpredictions of scour depth, resulting in safe, but often expensive foundation designs. Particularly in energetic areas, such as proposed bottom-mounted wave energy converter sites, this may even lead to a conflict between the costs of a safe design, and the available budget.

An analysis of common erosion and scour prediction models reveals that particularly sediment characteristics appear underrepresented. Often only the median grain size is considered, although the impacts of particle shapes, packing, bulk density, friction angles, and pore pressure behavior have been acknowledged (see section 2). A main reason for this is the lack of field investigation methods to derive these information in a safe, time- and cost-effective manner.

Areas of active sediment remobilization processes in the nearshore zone are characterized by energetic hydrodynamics (waves, tides and currents), and morphodynamics (migrating bars, etc.) representing challenges and risks to people, vessels and instrumentation. Most geotechnical in-situ instrumentation to-date are not designed or suitable for measurements in such conditions, and new devices are needed to fill this gap. The deployment under energetic conditions is thereby of highest interest to actually monitor the soil behavior with respect to active sediment dynamics.

In the following chapters, representative sediment remobilization models will be reviewed regarding the implementation of sediment characteristics. This will be followed by a discussion of potential impacts of sediment properties on sediment transport, and vice versa, variations in sediment properties with sediment dynamics. Then, two survey methods will be presented, including data examples: (i) the use of portable free fall penetrometers for the geotechnical characterization of seafloor surface sediments in areas of energetic hydrodynamics, and (ii) opportunities of long-term pore pressure monitoring using embedded pressure transducers.

2 PREDICTING THE INITIATION OF SEDIMENT TRANSPORT

2.1 *Non-cohesive sediments*

A most common method to determine the initiation of sediment remobilization is the approach by Shields (1936). Here, the critical Shields parameter, θ_{cr}, is calculated, representing a threshold value at which sediment mobilizing forces overcome sediment stabilizing forces:

$$\theta = \tau_{cr,0}/[(\rho_s - \rho_w)gd_{50}] \tag{1}$$

with $\tau_{cr,0}$ representing the critical bed shear stress for cohesionless particles, ρ_s being the sediment density, ρ_w being the water density, the gravitational acceleration g, and application of the median grain size d_{50}. θ_{cr} depends on the hydraulic conditions at the bed, particle shape, and particle packing, and thus, also on the friction angle (Kirchner et al. 1990; Van Rijn 2007). These properties are reflected in the respective $\tau_{cr,0}$. Hydraulic conditions can be estimated using the Reynolds number, and viscous effects can be assessed using a dimensionless particle size, D_*, depending on the d_{50}, relative density, and the kinematic viscosity coefficient. Van Rijn (2007) argues that the critical shear stress can be represented best in relation to D_*.

In an approach to address the sediment transport problem from general physics, Bagnold (1966) highlights the work that has to be conducted by a fluid to transport sediment as bedload. He states that the bedload work is directly dependent on the friction coefficient $\tan\phi$, representing the ratio of the shear stress over the normal stress. However, only an approximate of $\phi \approx 33°$ is provided for sands. Hsu et al. (2006) presented a model for wave-induced sediment transport and onshore sandbar migration including the friction angle, but also these authors applied the same approximated value as Bagnold (1966). This approximated value of the friction angle is challenged by the fact that friction angles depend on density, packing, particle shape and size distribution. Kirchner et al. (1990) documented the strong variations of the friction angle of water worked sediments, and measured friction angles more than twice as high for sandy sediments. These authors suggested to estimate the median friction angle from grain sizes of the abundant sediments using

$$\phi_{50} = \alpha(D/D_{50})^{-\beta} \tag{2}$$

with D being the test grain size, D_{50} being the median bed grain diameter, and α and β being empirical factors. This approach was successful when different empirical factors were applied depending on grain shape and packing. This is also supported by Stark et al. (2014) who found surprisingly high friction angles for sandy beach sediments with flat elliptic shape which proved to have a significant impact on the local beach dynamics.

It follows that sandy sediment transport prediction models would benefit significantly from a method to derive *in situ* friction angles.

2.2 *Cohesive sediments*

A number of physical, geochemical and biological properties influence the erodibility of fine, cohesive sediments, such as d_{50}, particle size distribution, bulk density, water content, temperature, mineralogy, salinity, organic content, biogenic structures and more. Grabowski et al. (2011) showed relationships to τ_{cr} of many of these properties. Amos et al. (2004) suggested the following relationship with regard to wet bulk density ρ_b:

$$\tau_{cr} = 5.44 \times 10^{-4}(\rho_b) - 0.28 \tag{3}$$

for lacustrine, estuarine, and marine muds. However, this disregards many of the other impacting factors. Many of those can be determined from sediment cores, and laboratory tests. However, the risk of sample disturbance, the difficulty of retrieving undisturbed sediment surface sediments, and the effort associated to these laboratory experiments are often hampering such detailed site investigations.

In potentially cohesive sediment mixtures of grain sizes ranging from 62-200 μm, Van Rijn (2007) suggested as a rough estimate

$$\tau_{cr} = (1 + p_{cs})^3 \tau_{cr,0} \quad (4)$$

using the proportion of the clay content in the sediment p_{cs}. While this allows a quick estimate of the critical shear stress, and thus, erodibility of mixed sediments, variations in above mentioned impacting factors may lead to significant variations of this relationship.

An assessment of critical shear stress from *in situ* measured properties, such as shear strength, would be attractive to simplify and speed up investigations of erodibility, but also to allow validation of derived sediment characteristics based on extracted sediment samples using *in situ* data.

2.3 *The impact of pore pressure with wave action*

The impact of excess pore pressures, p, on marine sediment stability has been acknowledged since the 1970s when Bjerrum (1973) associated the failure of offshore oil platforms in the North Sea to liquefaction of marine sands under storm wave action. Different processes may lead to sediment liquefaction or fluidization under ocean wave forcing:

(i) Pore pressure build-up. The hydrostatic pressure fluctuations resulting from the passing of wave crests and troughs lead to a cyclic deformation of the seabed surface, and shear forces. Resulting sediment particle rearrangement at the expense of pore space, can create excess pore pressures that exceed the effective stress (Nataraja and Gill 1983; Lin and Jeng 2000; Sassa and Sekiguchi 2001; Sumer et al. 2006). Sumer (2014) suggests to relate the excess pore pressure averaged per wave period $\bar{p}$ to the initial mean normal effective stress σ'_0 to assess the risk of liquefaction due to pore pressure build-up under ocean wave forcing, based on sand liquefaction experiments in a wave flume (Sumer et al. 2006, 2012). This means that liquefaction occurs when $\bar{p} > \sigma'_0$, and the critical excess pore pressure averaged per wave period can be estimated using

$$\bar{p}_{cr} = \sigma'_0 = \gamma' z[(1 + 2k_0)/3] \quad (5)$$

using the submerged specific weight of the soil γ', the sediment depth z, and the coefficient of lateral earth pressure k_0 which can be estimated using the friction angle and the Jaky equation (Lambe and Whitman 1969).

In most recent field experiments, Stark and Hay (2014) observed pore pressure build-up over multiple wave periods in mixed sand gravel beach sediments, and Stark and Quinn (2015) documented pore pressure build-up over short wave groups in the intertidal zone of a sandy beach. While in both cases, no full residual liquefaction like described by Sumer (2014) was observed, high excess pore pressures in the upper tens of centimeters of the beachface can likely increase sediment erodibility through lift of the particles, or even by a resulting upward flow.

(ii) Momentary sediment liquefaction may occur in response to vertical directed pressure gradients within one wave period. Turner and Nielsen (1997) expressed the impact of vertical pore pressure gradients in vertical velocities of pore water flow. The observations showed that periods of rapid water infiltration/exfiltration were commensurate with rapid pore pressure changes and upflow/downflow. Turner and Nielsen (1997) estimated that velocities ≥ 0.042 m/s are sufficient for fluidization of a bed with particles ranging from 0.1 mm to 2 mm in diameter. The subject was also investigated by Yeh and Mason (2014) for the case of a tsunami. The authors stated that the soil potentially liquefies when the vertical upward gradient of the excess pore pressure exceeds the buoyant specific weight, and proposed a modified Shields parameter to account for this effect by introducing the critical pore pressure gradient:

$$-\partial p/\partial z > \gamma' \quad (6)$$

(iii) Strong horizontal pressure gradients, p_x, induced by the passage of skewed or breaking waves can destabilize the sediment bed (Sleath 1999; Foster et al. 2006). Sleath (1999) defined the role of the horizontal pressure gradient for momentary liquefaction of some sediment layer of thickness h, expressed as the Sleath parameter, S, with a ratio between the destabilizing force p_x relative to the stabilizing force applied by gravity, similarly to the structure of the Shields parameter.

Foster et al. (2006) provided the first field evidence of the momentary liquefaction of 100s of grain thicknesses in response to large horizontal pressure gradients present in a shallow water wave environment. They defined the instantaneous Sleath parameter as:

$$S(t) = -p_x(t)/(\rho_s - \rho_w)g, \quad (7)$$

and proposed a generalized incipient motion formulation for a thickness h of sediment due to both the pressure gradient and shear stress.

The impact of pore pressure on sediment erodibility in the nearshore zone is unquestioned. However, the interaction between the above described processes, and the integration into sediment transport models is still limited. There is an urgent need for field data sets that test, validate, and advance the proposed approaches.

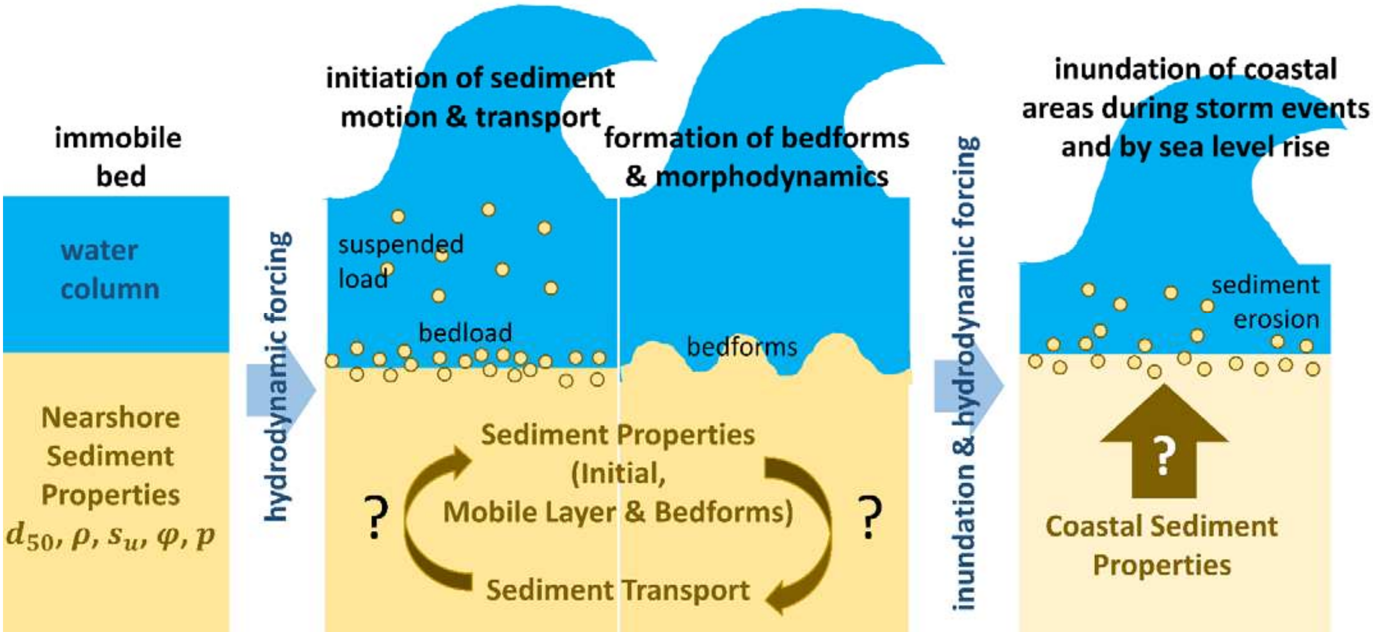

Figure 1. The impact of sediment properties such as median grain size d_{50}, bulk density ρ_b, undrained shear strength s_u, friction angle ϕ, and excess pore pressure p, on sediment transport and erosion has been acknowledged, but for most of these properties rarely been quantified. Vice versa, sediment properties change with the formation of a mobile sediment layer and bedforms, however to what extent is still rarely documented. Coastal sediments in potential inundation zones are characterized by different sediment properties than the current nearshore zone, and have experienced a different exposure history to saturation and sediment transport processes. This impacts the sediment erodibility in these areas. However, predictions still suffer from limitations in understanding between the interaction of sediment properties, hydrodynamic forcing, and geomorphodynamics.

3 THE ROLE OF SEDIMENT PROPERTIES IN AREAS OF ACTIVE SEDIMENT DYNAMICS

3.1 *Subaqueous sediment dynamics*

The initiation of sediment transport is an important problem, and has been reviewed briefly in section 2. It has been emphasized that sediment properties such particle size distribution, packing, strength, and pore pressures play an important role for the onset of sediment erosion. In areas of active sediment dynamics, this problem must even be considered in a larger spatial and temporal context. After the entrainment of particles, sediment will be transported as bedload (rolling, saltating, and sliding close to the immobile seabed), or as suspended load in the water column (Fig. 1). The transport mode has a significant impact on transport rates and volumes (Bagnold 1966). With the ongoing sediment transport, bedforms (such as ripples, bars, dunes) can be formed, destroyed, reshaped, or shifted, and a mobile sediment layer representing sediment impacted by sediment transport can be defined (Fig. 1). Sediment properties of this mobile layer as well as of the bedforms can be expected to differ from the initial sediment properties of the immobile bed. Particle size and shape distributions may change through selective sediment transport. Here, sediment size or shape fractions can vary in transport mode and rate, or some large particles, or sediment of large friction angles may not be entrained under moderate forcing conditions. Such selective sediment transport is reflected in sediment sorting along bedforms, for example (Fig. 2).

With the deposition of sediment, possible remobilization, and re-deposition on different temporal scales from single waves over tidal cycles to the reoccurrence of extreme events, also significant variations in sediment settling, consolidation, and thus, packing, density, friction angle, and shear strength must also be expected (Fig. 1).

Figure 2. Sediment sorting along large ripples in Grand Passage, Bay of Fundy, Nova Scotia. Grand Passage is characterized by maximum tidal current velocities in excess of 4 m/s, and is a proposed site for the harvesting of tidal energy. Ongoing sediment transport is clearly documented in the existence of bedforms, as well as sediment sorting.

Figure 3. Thaw mud slump at the coastline of Herschel Island, Yukon.

In some areas new and varying sediment inputs must be considered. That applies to, e.g., river outflow areas impacted by river diversion, dredging or dams, as well as large sediment input by thawing of glaciers or permafrost coastlines. For example, Herschel Island, Yukon, in the Canadian Beaufort Sea features some of the largest thaw mud slumps in the world, delivering significant amounts of fine to mixed sediments into the nearshore zone (Fig. 3).

With climate change, and the associated sea level rise, retreat of permafrost and glaciers, and increase of the storm intensities and frequencies, the erodibility of onshore areas under inundation and nearshore forcing becomes important. From above discussed processes, it follows that sediments exposed to hydrodynamic forcing in the nearshore zone will potentially exhibit different sediment properties than sediments that are usually located onshore, and do not experience hydrodynamic forcing. A more detailed understanding of the differences in *in situ* sediment characteristics, and the response to hydrodynamic forcing and morphodynamics, is crucial to predict long-term coastline evolution, erosion, and erodibility during extreme events, and thus, for coastal management and planning.

3.2 *Beach dynamics*

Beaches represent in many locations the natural border between the nearshore zone and the onshore coastal zone which are both exposed to significantly different processes and forcing conditions (see section 3.1). Resulting from water level fluctuations on temporal scales of waves, semidiurnal to lunar tidal cycles, and events, beaches are impacted by additional effects of changing water levels, ground water dynamics, water infiltration and exfiltration (Fig. 4). This leads to the fact that beaches are highly dynamic environments, while they represent at the same time recreational hot spots, and a natural barrier against ocean forcing.

Examples of significant beach dynamics can be found worldwide. Figure 5 shows traces of erosion at the high water edge at a sandy beach on the Outer Banks, USA. Figure 6 depicts the change of grain size distribution along a cross-shore profile at a steep, mixed sand-gravel megatidal beach in Advocate, Nova Scotia. Here, zones of offshore directed sediment fining, or coarsening, a fine sand zone, and a coarse mixed sediment zone can be identified, and the position of the fine sand zone is shifting in the cross-shore direction, apparently in correspondence to the lunar tidal cycle, while a storm event leads to an overall fining of the central and lower intertidal zone. Due

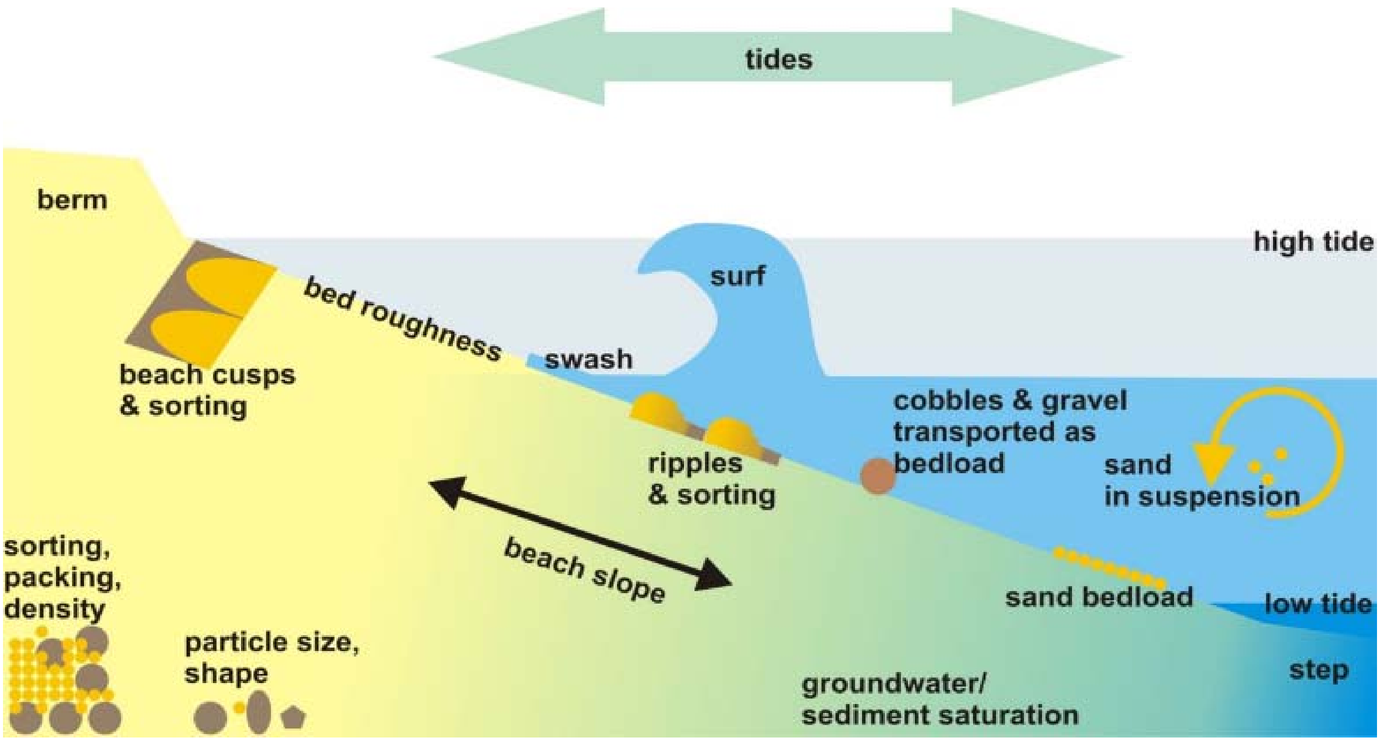

Figure 4. Concept sketch of aspects of sediment properties, sediment transport, morphology and hydrodynamics influencing beach dynamics.

Figure 5. Traces of significant erosion at a beach in Nags Head, NC, in the direct vicinity of beach properties after a moderate wind event in June 2016.

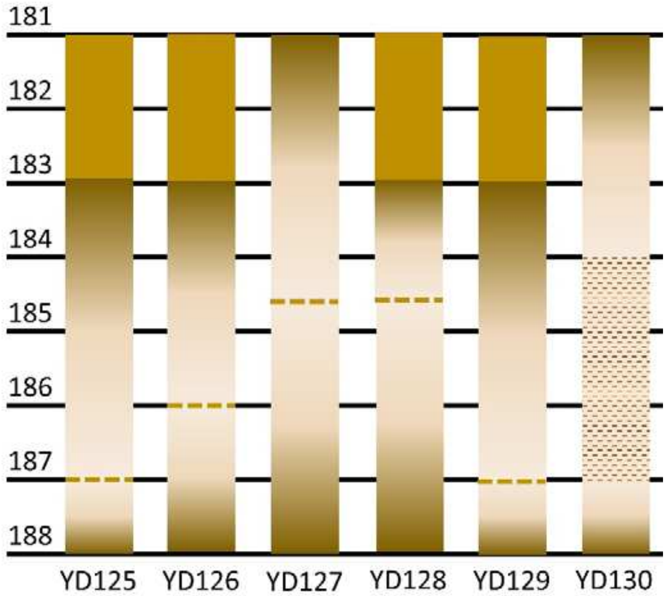

Figure 6. Conceptual representation of grain size distributions along a cross-shore transect (188 low tide water line; 181 close to the berm) at Advocate Beach, Nova Scotia, a steep, mixed sand-gravel, megatidal beach, from yeardays 125-130 in 2012. Ungraded brown indicates mixed coarse sediment, graded brown shading indicates fining towards the lighter shading. The dashed lines indicate the fine sand zone. A storm event hit the site starting in the night of yearday 129.

to the extreme tidal range at this location (~ 12 meters), the beach undergoes full saturation and drainage twice per day. The observations cannot currently be fully simulated in beach sediment transport models. Particularly, the wide distribution of fine sediment at the beachface after the storm event seems puzzling, considering an expected sediment armoring with coarse sediments prevailing under storm conditions. Hay et al. (2014) and Stark et al. (2014) found that the surprising presence of fine sediments can be associated to the creation and destruction of sorted ripples in the swash and surf zone, and large friction angles of the sandy size fraction.

Such observations and studies highlight the need for more field data sets, particularly in the framework of multidisciplinary research programs. However, *in situ* measurements during hydrodynamic forcing are difficult, and novel methods and tools are needed to obtain the desired data sets.

4 USING PORTABLE FREE FALL PENETROMETERS TO INVESTIGATE SEDIMENT TRANSPORT PROCESSES

Free fall penetrometers have been introduced to offshore geotechnical site characterization in the 1970s by researchers such as Dayal and Allen (1973) who already recognized the potential, as well as associated challenges, particularly in the data analysis. Later, Stoll and Akal (1999) presented the expendable bottom penetrometer, being a lightweight, fish-like shaped device suitable for a rapid investigation of the uppermost seafloor surface layers. Different data analysis approaches were tested for this device, including a correlation of the deceleration record directly to sediment types, or estimating undrained shear strength (Aubeny and Shi 2006; Stoll et al. 2007; Stark and Wever 2009). Motivated by these results, the ease of deployment, and the wish to design a non-expendable probe with similar capabilities, but particularly for deployments in areas of active sediment dynamics, a torpedo-shaped probe was developed, *Nimrod*, targeting specifically surficial seabed characterization with regard to geotechnical site characterization of sediment remobilization processes (Stark 2011).

Some representative results of *in situ* geotechnical investigations of sediment remobilization processes are shown in figure 7. The main findings can be summed up as follows: The sediment type was correctly identified from the deceleration values, and an equivalent of quasi-static bearing capacity can roughly be estimated (Stark et al. 2012). The evolution of a loose sediment top layer can be associated to a mobile sediment layer, and be quantified in vertical thickness with a resolution in the order of ~1 cm (Stark and Kopf 2011). Variations of this mobile top layer can be correlated to the sediment deposition and remobilization with tidal, and wave forcing (Stark et al. 2010, 2011). Areas of sediment erosion and deposition can be identified (Stark et al. 2010).

The results confirmed that portable free fall penetrometers deliver complementary information for the investigation of sediment remobilization processes. However, some questions remained unsolved, or were even raised by the results. A loose sediment top layer was clearly identified, and associated to sediment transport processes. However, the evolution of such a layer can express reworking of native surface

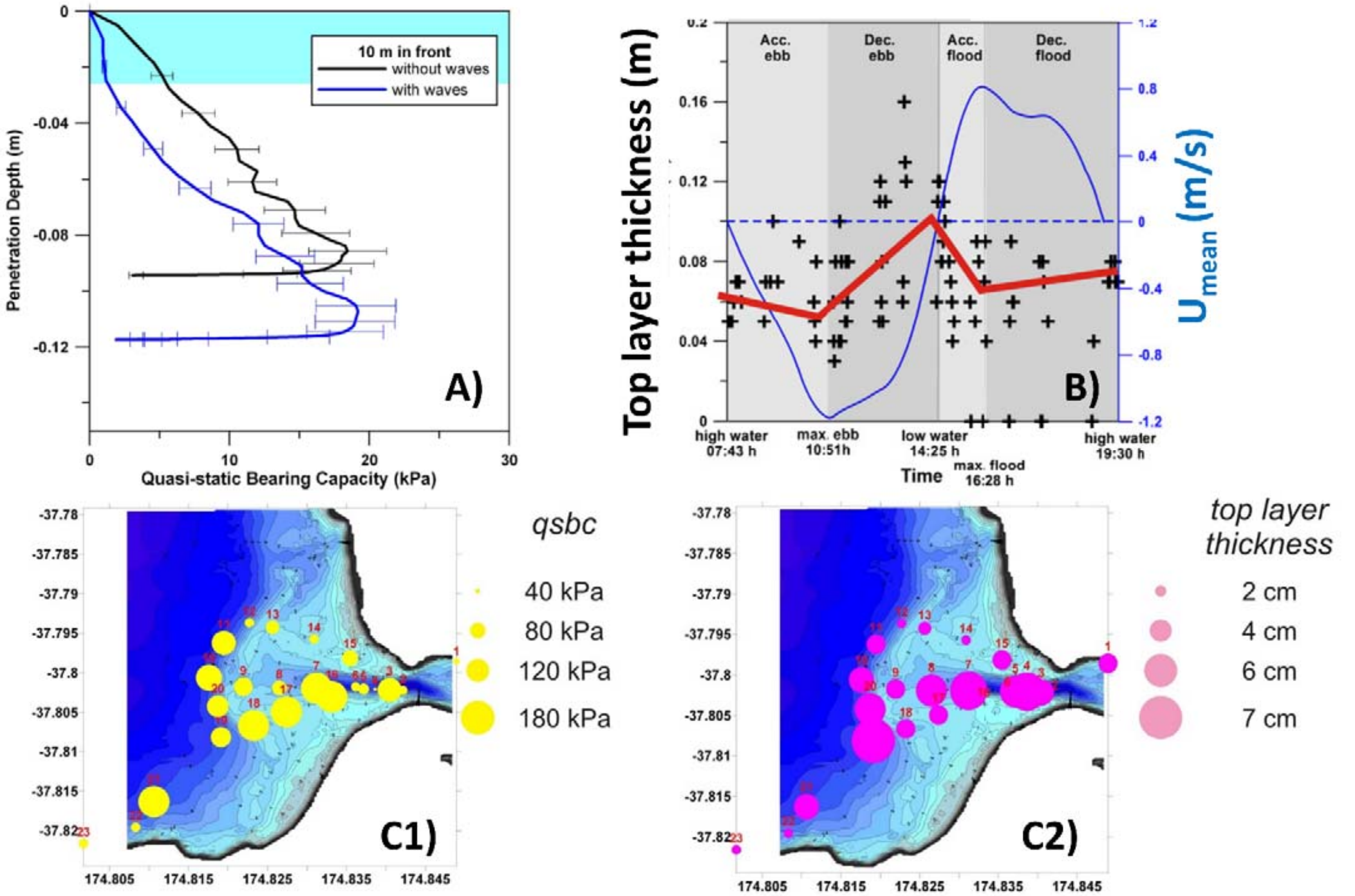

Figure 7. A) Estimates of quasi-static bearing capacity (*qsbc*) of a sandy soil under no-current-no-waves conditions (black line), and with wave action (blue line) versus penetration depth, measured in the large wave channel in Hannover, Germany. The evolution of a loose top sand layer is clearly indicated by low sediment strength in the upper 3 cm (mint shading). Figure modified from Stark and Kopf (2011). B) Thickness of a loose sediment top layer measured over one tidal cycle along subaqueous dunes in the Knudedyb tidal channel in the Danish Wadden Sea (black crosses; trend outlined in red). The mean flow velocity is indicated in blue. Scatter in top layer thickness can be associated to different locations along the dunes. The figure is modified after Stark et al. (2011). C1-2) Estimates of quasi-static bearing capacity (C1) and loose top layer thickness (C2) over an active sand bar in front of Whaingaroa Harbour, Raglan, New Zealand. Areas of low *qsbc* and high top layer thickness were associated to areas of fresh sediment deposition, while areas of high *qsbc* and low top layer thickness suggested ongoing erosion (modified after Stark et al. 2010). This allowed the prediction of the offshore migration of the southern arm of the bar which was confirmed later from aerial images. All measurements were obtained using the portable free fall penetrometer *Nimrod*.

sediments, as well as the deposition of sediment entrained at a different location and deposited here. The governing process cannot be inferred from the penetrometer data alone, but usually, information about the local hydrodynamic forcing and morphodynamics allow to derive a conclusion in this matter. Nevertheless, it would be an important step forward if more details about this mobile layer could be derived, such as bulk density or concentration, sediment grain size distribution, or if sediments behave cohesive. If such properties would be derived in a vertical profile for the mobile layer as well as its underlying substratum, this would also enable to derive conclusions regarding selective sediment transport. These information would be directly applicable to sediment transport models, and would improve the prediction of sediment erosion, transport, and deposition, and thus, potential bathymetric change. This is of high importance for addressing issues such as coastal erosion, sediment dredging and disposal projects, navigation in shallow nearshore, estuarine and riverine environments, as well as scour and seabed stability around coastal structures.

Portable free fall penetrometers have the potential to contribute further to address these issues. One consideration is to add a sampling device that would allow to retrieve a sediment sample of the penetrated layers. If such samples would be similar to mini sediment cores, stratification would be represented, and differences in sediment type, and size distribution could be assessed. Dependent on the level of disturbance, *in situ* density may be estimated. For very fine sediments, subsamples could be extracted using a syringe. For coarse sediments, high resolution images of the mini-core could be a potential method to assess particle packing and density. From this information

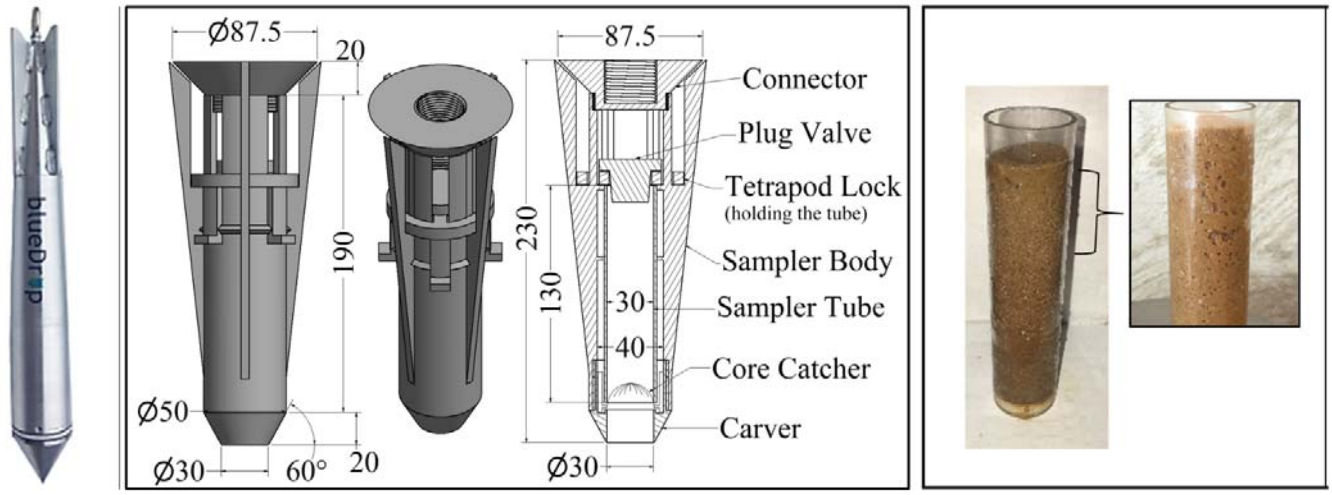

Figure 8. Left) *BlueDrop* portable free fall penetrometer (63 cm in length; approx. 8 kg). Center) Design of one of three prototype add-on samplers. Right) Representative sand sample obtained during preliminary tests. The figure is modified after Bilici and Stark (2017).

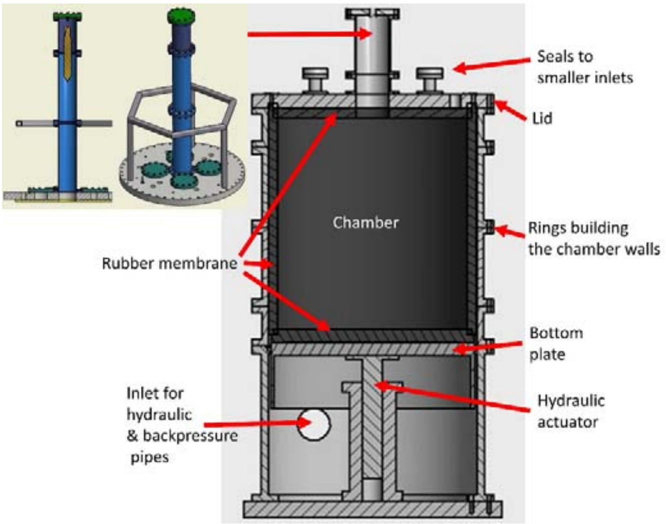

Figure 9. Concept sketch of large-scale CPT calibration chamber and modified free fall tower.

and with enough sample material, a sample could even be reconstructed for further testing in the laboratory. Bilici and Stark (2017) have developed three different prototypes of sampler add-on units for the portable free fall penetrometer *BlueDrop*, including the design of a novel core catcher mechanism, and have initiated preliminary laboratory experiments to evaluate the performance of the samplers and sample quality (Fig. 8). More tests are currently ongoing to improve sample quality, and to investigate the impact of penetration speed on the sample.

In addition to *in situ* sampling, calibration of the penetrometer acceleration/deceleration records under controlled conditions, and specifically targeting soft and loose surface sediments will advance research in this field. This is particularly important if the rapid deployment process, allowing to deploy under energetic conditions, and to cover a large number of locations in a short time, should be preserved. This has been attempted by Dayal and Allen (1973) and Stoll et al. (2007) using a large sediment sample in the laboratory, and most recently, authors such as Chow et al. (2014) and O'Loughlin et al. (2014) conducted centrifuge tests with small-sized free fall penetrometers. Another potential route to calibrate small-scale, but prototype size portable free fall penetrometers is a modified large-scale Cone Penetration Test calibration chamber (Fig. 9). A large-scale chamber with a diameter and height of ~1.5 m, and a water backpressure system would allow to simulate different seabed conditions, and to calibrate a small-scale portable free fall penetrometer with small impact of the confinement. This would enable a calibration of the penetrometer's deceleration records to different sediment types, shear strength, and bulk density, as well as to investigate the strain rate effect for high velocity impact penetrometers of different shapes in more detail.

Another potential route of seabed surface characterization using portable free fall penetrometers is the measurement of pore pressure. Stegmann et al. (2006), Seifert et al. (2008) and Chow et al. (2014) have indicated the potential of using pore pressure measurements of impact penetrometers to derive information about shear strength as well as hydraulic conductivity. The *BlueDrop* penetrometer is equipped with a 300 psi pressure gauge at the u_2 position. Stark et al. (2015) found that the pore pressure recordings during penetration reflected the sediment stratification that was identified from the deceleration and estimated strength profiles. However, the pore pressure behavior deviates significantly from documented standard Cone Penetration Test records. This can be explained with a different soil and pore pressure behavior, as well as influences of the Bernoulli effect at the often more than 200-times higher impact velocities. More research is required to investigate the specific mechanisms in more detail to potential derive information of *in situ* hydraulic conductivity and relative density directly from the penetrometer pressure recordings.

5 *PORE PRESSURE MONITORING NEARSHORE* & AT THE BEACH

Section 2.3 discusses different concepts of the impact of pore water pressure under wave forcing on sediment dynamics. Most of these concepts are based on theoretical approaches, and laboratory experiments. Few data sets from the field are available to-date. Data loggers which are smaller in size, larger in memory, and faster in sampling rate are enabling new measurement approaches. Stark and Hay (2014) embedded a wave gauge at a sediment depth of 50 cm at a mixed sand gravel megatidal beach in Advocate, Nova Scotia, and found that pore pressure build-up occurred over multiple wave cycles despite the sediment coarseness. Stark and Quinn (2015) observed excess pore pressure peaks under irregular wave forcing at a sandy beach in Yakutat, Alaska. Stark (2017) applied the approaches to assess the risk for residual liquefaction by Sumer (2014), and for momentary liquefaction by Yeh and Mason (2014) and Foster et al. (2006) on the same data set, and derived that critical values were frequently exceeded for the upper 20 cm of the beachface (Fig. 10). During the field experiment active sediment transport was observed. However, differently than these calculations may suggest, no significant erosion was observed. Thus, processes investigated in a controlled manner in the laboratory may underestimate the actual complexness of field conditions.

More field data is necessary to understand the interplay of different processes, and to potentially integrate them into a larger sediment erosion prediction scheme. Novel field instrumentation can help to make data more accessible, and field measurements more feasible. Small-scale wave gauges such as *RBR SoloD* have most recently been applied for pore pressure monitoring in different beach and nearshore environments (Fig. 11). The ease of deployment, sampling rates of 10 Hz and faster, and a continuous monitoring duration in excess of 28 days allow new data acquisition strategies in vertical, cross-shore or long-shore arrangements.

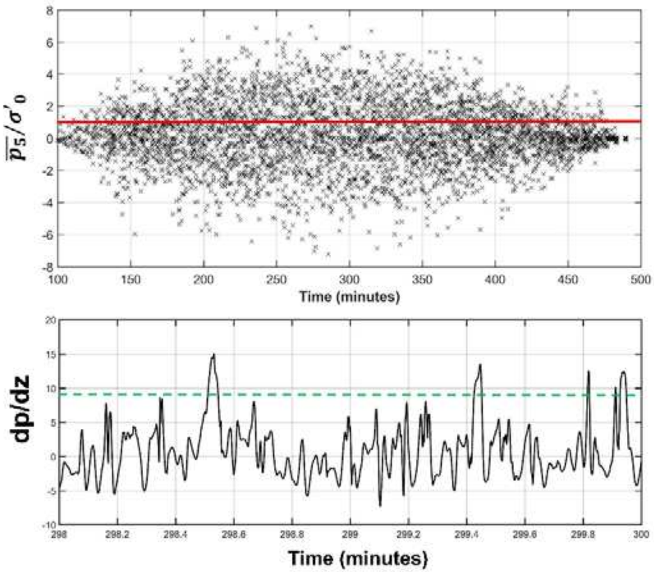

Figure 10. Upper panel) Wave-period average of excess pore pressure over initial mean normal effective stress at a sediment depth of 5 cm versus time measured at a sandy beach in Yakutat, AK. The red line indicates when theoretically residual liquefaction may be achieved under wave forcing. Lower panel) Upward directed vertical pressure gradients between a sediment depth of 25 cm and 5 cm for an excerpt of the above shown data set. The dashed green line indicates when momentary liquefaction may occur. Figure modified after Stark (2017).

Figure 11. Deployment of *RBR Solo* pressure transducers during an undergraduate research field experiment in a sandy nearshore zone in the Punta Cana, Dominican Republic.

6 CONCLUSIONS

The reliable and accurate prediction of sediment erosion, scour and deposition processes is of high importance for issues related to coastal erosion and coastline evolution, the maintenance of navigation channels, and the stability of coastal and offshore structures. The relocation and movement of significant sediment volumes occur particularly in the energetic nearshore zone where water depths are shallow, waves undergo shoaling and breaking, and tidal cycles can play an important role. The same area is the connection between offshore and onshore environments. The sediment behavior in these areas governs coastline evolution, represents important habitats, and is of increasing interest for wave energy conversion, and coastal protection structures.

Geotechnical sediment properties such as shear strength, friction angles and cohesion, as well as pore pressure behavior have been recognized as potentially important factors for improving the prediction of sediment erosion. Portable free fall penetrometers have successfully displayed variations between seabed surface top layers associated to active and most recent sediment transport processes. Preliminary pore pressure monitoring revealed that the pore pressure behavior under active wave forcing should be considered when assessing sediment erodibility, particularly under energetic wave forcing. It also indicated that some processes and their interaction may not be fully understood yet. The current gaps in understanding regarding the correlation between geotechnical soil characteristics and behavior and subaqueous sediment transport processes, and the associated limited integration into erosion or scour prediction schemes likely contributes significantly to the still existing model and prediction limitations.

To address this issue, more field investigations and data are required, highlighting the need for novel instrumentation and measurement strategies suitable for deployment in these energetic hydrodynamics or active sediment transport processes, and with limited impact on the native sediment processes.

Portable free fall penetrometer have proven to be suitable for the deployment in energetic hydrodynamics, for the classification of sediment type, estimating sediment strength, and to quantify sediment stratification. Most recently, pore pressure measurements during penetration and at rest in the sediment promise additional information about the sediment's hydraulic conductivity and density. However, more research is needed to derive geotechnical parameters directly comparable to other standard in-situ methods such as Cone Penetration Testing, and deliver more information about mobile seafloor surface layers. There is particularly a need for calibration facilities and experiments.

Pore pressure gauges embedded in beach and nearshore sediments over periods of hours to weeks indicated that the role of sediment pore pressures for sediment erosion is more important than currently considered, and that the processes are complex. The presented and similar measurement concepts may drive this field of research forward, and allow to obtain statistically valid amounts of data sets.

In summary, the coastal and nearshore zone still holds many open questions, challenges, and opportunities for researchers in the field of geotechnical engineering. At the same time, the collaboration with colleagues from different disciplines such as coastal sciences and engineering, oceanography, geology, geophysics, and sedimentology is crucial to fully understand the processes, and implement them into tools and prediction schemes important to coastal managers and communities.

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8. REFERENCES

Amos, C. L., Bergamasco, A., Umgiesser, G., Cappucci, S., Cloutier, D., DeNat, L., Flindt, M., Bonardi, M. & Cristante, S. 2004. The stability of tidal flats in Venice Lagoon—the results of in-situ measurements using two benthic, annular flumes. *Journal of Marine Systems* 51(1): 211-241.

Aubeny, C. P., & Shi, H. 2006. Interpretation of impact penetration measurements in soft clays. *Journal of Geotechnical and Geoenvironmental Engineering* 132(6): 770-777.

Bagnold, R. A. 1966. *An approach to the sediment transport problem from general physics.* Geological Survey Professional Paper 422-1.

Bilici, C., & Stark, N. 2017. Design and preliminary tests of mobile seafloor layer sampler prototypes as an add-on unit for portable free-fall penetrometers. Accepted for *Geotechnical Frontiers 2017*, Orlando, FL.

Bjerrum, L. 1973. Geotechnical problems involved in foundations of structures in the North Sea. *Geotechnique* 23(3): 319-358.

Chow, S. H., O'Loughlin, C. D., & Randolph, M. F. 2014. Soil strength estimation and pore pressure dissipation for free-fall piezocone in soft clay. *Géotechnique* 64(10): 817-827.

Coco, G., Senechal, N., Rejas, A., Bryan, K. R., Capo, S., Parisot, J. P., Brown, J.A., & MacMahan, J. H. 2014. Beach response to a sequence of extreme storms. *Geomorphology* 204: 493-501.

Dayal, U., & Allen, J. H. 1973. Instrumented impact cone penetrometer. *Canadian Geotechnical Journal* 10(3): 397-409.

Dolan, R., Hayden, B., Rea, C., & Heywood, J. 1979. Shoreline erosion rates along the middle Atlantic coast of the United States. *Geology* 7(12): 602-606.

Falcone, F.T., & Stark, N. 2016. Evaluation of the performance of scour prediction equations with regards to flow and sediment characteristics. *ASCE Geo-Chicago 2016*, Chicago, IL.

Foster, D. L., Bowen, A. J., Holman, R. A., & Natoo, P. 2006. Field evidence of pressure gradient induced incipient motion. *Journal of Geophysical Research: Oceans* 111(C5): 1-8.

Grabowski, R. C., Droppo, I. G. & Wharton, G. (2011). Erodibility of cohesive sediment: the importance of sediment properties. *Earth-Science Reviews* 105(3): 101-120.

Hay, A. E., Zedel, L., & Stark, N. 2014. Sediment dynamics on a steep, megatidal, mixed sand-gravel-cobble beach. *Earth Surface Dynamics* 2(2): 443-453.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences* 111(9): 3292-3297.

Hsu, T. J., Elgar, S. & Guza, R. T. 2006. Wave-induced sediment transport and onshore sandbar migration. *Coastal Engineering* 53(10): 817-824.

Jones, B. M., Hinkel, K. M., Arp, C. D., & Eisner, W. R. 2008. Modern erosion rates and loss of coastal features and sites, Beaufort Sea coastline, Alaska. *Arctic*: 361-372.

Kirchner, J. W., Dietrich, W. E., Iseya, F. & Ikeda, H. 1990. The variability of critical shear stress, friction angle, and grain protrusion in water-worked sediments. *Sedimentology* 37(4): 647-672.

Lambe, T. W., & Whitman, R. V. 1969. *Soil mechanics*. John Willey & Sons. Inc., NY.

Lin, Y. S. & Jeng, D. S. 2000. Short-crested wave-induced liquefaction in porous seabed. *Journal of geotechnical and geoenvironmental engineering* 126(5): 481-494.

Nataraja, M. S. & Gill, H. S. 1983. Ocean wave-induced liquefaction analysis. *Journal of Geotechnical Engineering* 109(4): 573-590.

National Academy of Sciences (2010). *Advancing the Science of Climate Change*. The National Academies Press, DOI 10.17226/12782.

Obu, J., Lantuit, H., Grosse, G., Günther, F., Sachs, T., Helm, V., & Fritz, M. 2016. Coastal erosion and mass wasting along the Canadian Beaufort Sea based on annual airborne LiDAR elevation data. *Geomorphology*. DOI:10.1016/j.geomorph.2016.02.014

O'Loughlin, C. D., Gaudin, C., Morton, J. P., & White, D. J. 2014. MEMS accelerometers for measuring dynamic penetration events in geotechnical centrifuge tests. *International Journal* 14(2): 31-39.

Sassa, S. & Sekiguchi, H. 2001. Analysis of wave-induced liquefaction of sand beds. *Geotechnique* 51(2): 115-126.

Seifert, A., Stegmann, S., Mörz, T., Lange, M., Wever, T., & Kopf, A. 2008. In situ pore-pressure evolution during dynamic CPT measurements in soft sediments of the western Baltic Sea. *Geo-Marine Letters* 28(4): 213-227.

Shields, A. 1936. *Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung.* Dissertation submitted to Preussischen Versuchsanstalt für Wasserbau.

Sleath, J. F. A. 1999. Conditions for plug formation in oscillatory flow. *Continental Shelf Research* 19(13): 1643-1664.

Stark, N., & Wever, T. F. 2009. Unraveling subtle details of expendable bottom penetrometer (XBP) deceleration profiles. *Geo-Marine Letters* 29(1): 39-45.

Stark, N. 2011. *Geotechnical investigation of sediment remobilization processes using a dynamic penetrometer.* PhD thesis submitted to the University of Bremen, Germany.

Stark, N., Hanff, H., Svenson, C., Ernstsen, V. B., Lefebvre, A., Winter, C., & Kopf, A. 2011. Coupled penetrometer, MBES and ADCP assessments of tidal variations in surface sediment layer characteristics along active subaqueous dunes, Danish Wadden Sea. *Geo-Marine Letters* 31(4): 249-258.

Stark, N., & Kopf, A. 2011. Detection and quantification of sediment remobilization processes using a dynamic penetrometer. *MTS/IEEE OCEANS'11*, Kona, HI: 1-9.

Stark, N., Greer, D., Phillips, D., Borrero, J., Harrison, S., Kopf, A. 2010. In-situ geotechnical investigation of sediment dynamics over 'The Bar', Raglan, New Zealand. *AGU 2010*, San Francisco.

Stark, N., Wilkens, R., Ernstsen, V. B., Lambers-Huesmann, M., Stegmann, S., & Kopf, A. 2012. Geotechnical properties of sandy seafloors and the consequences for dynamic penetrometer interpretations: quartz sand versus carbonate sand. *Geotechnical and Geological Engineering* 30(1): 1-14.

Stark, N., & Hay, A. E. 2014. Pore water infiltration and drainage on a megatidal beach in relation to tide-and wave-forcing. *Coastal Engineering Proceedings* 1(34): 25.

Stark, N., Hay, A. E., Cheel, R. & Lake, C. B. 2014. The impact of particle shape on the angle of internal friction and the implications for sediment dynamics at a steep, mixed sand-gravel beach. *Earth Surface Dynamics* 2(2): 469-480.

Stark, N., & Quinn, B. 2015. Pore pressure monitoring of surficial coastal sediments on wave-resolving scale with outlook on liquefaction risk prediction at offshore wind and marine hydrokinetic energy converters. *MTS/IEEE OCEANS 2015*, Washington, DC: 1-7.

Stark, N., Quinn, B., Ziotopoulou, K., & Lantuit, H. 2015. Geotechnical Investigation of Pore Pressure Behavior of Muddy Seafloor Sediments in an Arctic Permafrost Environment. *ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering*: V001T10A017.

Stark, N. 2017. Pore pressure response to irregular waves at a sandy beach. Submitted to *Geotechnical Frontiers 2017*, Orlando, FL.

Stegmann, S., Morz, T., & Kopf, A. 2006. Initial Results of a new Free Fall-Cone Penetrometer (FF-CPT) for geotechnical in situ characterisation of soft marine sediments. *Norsk Geologisk Tidsskrift* 86(3): 199-208.

Stoll, R. D., & Akal, T. 1999. XBP- Tool for Rapid Assessment of Seabed Sediment Properties. *Sea technology* 40(2): 47-52.

Stoll, R. D., Sun, Y. F., & Bitte, I. 2007. Seafloor properties from penetrometer tests. *IEEE Journal of Oceanic Engineering* 32(1): 57-63.

Sumer, B. M., Hatipoglu, F., Fredsøe, J. & Kaan Sumer, S. 2006. The sequence of sediment behaviour during wave-induced liquefaction. *Sedimentology* 53(3): 611-629.

Sumer, B. M., Kirca, O. V. S. & Fredsøe, J. 2012. Experimental validation of a mathematical model for seabed liquefaction under waves. *International Journal of Offshore and Polar Engineering* 22(02): 1-9.

Sumer, B. M. 2014. *Liquefaction Around Marine Structures*. World Scientific.

Turner, I. L., & Nielsen, P. 1997. Rapid water table fluctuations within the beach face: Implications for swash zone sediment mobility? *Coastal Engineering* 32(1): 45-59.

Van Rijn, L. C. 2007. Unified view of sediment transport by currents and waves. I: Initiation of motion, bed roughness, and bed-load transport. *Journal of Hydraulic Engineering* 133(6): 649-667.

Yeh, H., & Mason, H. B. 2014. Sediment response to tsunami loading: mechanisms and estimates. *Geotechnique* 64(2): 131-143.

Zhang, K., Douglas, B. C., & Leatherman, S. P. (2004). Global warming and coastal erosion. *Climatic Change*, 64(1-2), 41-58.