

Geotechnical Investigation of Spatiotemporal Variations at a Sand Beach characterized by Active Erosion and Sediment Remobilization Processes

Nina Stark, Nicola Brilli

Charles E. Via, Jr., Department of Civil and Environmental Engineering, Virginia Tech, 750 Drillfield Drive, Blacksburg, VA 24061, USA; e-mail: ninas@vt.edu. Corresponding author.

ABSTRACT

Intertidal beach environments are subject to a number of processes affecting spatiotemporal variations of moisture contents: tides, waves, groundwater level, rainfall, and possibly surge during and after storm events. At sandy beaches with a limited range of grain sizes, grain shapes, and mineralogies, moisture content can represent a key factor governing in-situ strength and erodibility. Here, a first insight is provided into a large field data set comprising geotechnical and environmental data collection from multiples sites. This conference contribution focuses on a subset of measurements collected at the beach of Ocean Cape, Yakutat, Alaska, characterized by a medium sand and an energetic wave climate. The beach features a complex morphology, sometimes exhibiting a ridge-runnel profile and a large cobble to boulder beach step. Co-located measurements of moisture contents, topography, and soil strength are presented, providing a new perspective on the variability of geotechnical properties at a sandy beach of complex geomorphology and active erosion and sediment remobilization processes.

INTRODUCTION

Intertidal beach environments are affected by a complex interaction of hydrodynamics, geomorphodynamics, and sediment dynamics on different temporal and spatial scales. These processes are interlinked as water levels govern the location of the swash zone and waves in the intertidal zone, etc. Local geomorphology impacts groundwater pathways, as well as wave and actual water levels through overall beach slope and presence of more complex geomorphological features such as ridge-runnel systems and even smaller features such as ripples and cusps. Vice versa, the presence of certain geomorphological features can be associated with certain combinations of hydrodynamic conditions and led to summaries of conceptual beach models (e.g., Masselink and Short 1993).

The variability of sediments in the intertidal zone of sand beaches has been observed within one beach system as well as in comparison of different beaches, and there is general consensus on the importance of those local sediment properties on sediment transport processes (Medina et al. 1994; Gallagher et al. 2011, 2016; and others). However, most studies and models relating sediment properties with geomorphodynamics consider sediment particle properties only. The most prominent property is grain size and particle density, being used, for example, for estimating

the Shields parameter (Shields 1936; VanRijn 2007). Other models and concepts utilize the particle fall velocity, if actually measured, also accounting for particle shape, and being mostly introduced with focus on sediment transport and deposition (Wright and Short 1984). However, the importance of sediment properties as a bulk material have been stressed increasingly regarding remobilization and post-deposition behavior. For example, VanRijn (2007) highlights the effects of biological and organic materials, cohesive particle-particle interaction on the critical bed shear stress for initiation of motion, and particle packing. Kirchner et al. (1990) stress effects of friction angles of coarse-grained sediments on critical bed shear stress, and Erikson et al. (2007) discuss the role of friction angles regarding beach scarp and dune recession. Moisture content of sands has been identified as a key parameter governing wind erosion of sands at beaches (e.g., Van Dijk et al. 1996; Davidson-Arnott et al. 2005; Darke and Neuman 2008).

In-situ friction angles also control the shear strength of sandy soils for dry or fully saturated sands (e.g., Briaud 2013). For partially saturated sands, an apparent cohesion adds to the shear strength through suction between the sand particles and depends on the moisture content (e.g., Briaud 2013). Friction angles can potentially vary spatially and temporally at beaches through particle size and shape re-distributions as well as packing and resulting bulk density. Moisture contents are expected to respond rapidly to hydrodynamic conditions as well as rainfall and air humidity, and are also affected by sediment conditions. Therefore, rapid and significant variations in surficial shear strength are expected at sandy beaches and are likely affecting local erosion processes (Sassa et al. 2014; Manning and Stark 2019; Sassa and Yang 2019). However, a more detailed understanding and more observations of variations in shear strength at sandy beach environments are needed to implement such geotechnical properties effectively into sediment transport and erosion models and predictions.

A large field data set including moisture content measurements, sediment sampling, in-situ testing of sediment strength, and measurements of beach topography, was collected at multiple locations throughout the last years. This conference contribution will focus on a subset of measurements collected at Ocean Cape, Yakutat, Alaska, characterized by a medium sand beach comprised of predominantly quartz sand with a significant amount of heavy minerals and an energetic wave climate. The beach also features a complex morphology, sometimes exhibiting a ridge-runnel profile and including a large cobble to boulder beach step.

REGIONAL CONTEXT

Yakutat is located in Southeast Alaska (Fig. 1). Most of its offshore directed beaches are composed of quartz sands with a significant amount of heavy minerals (Wright 1972). The area is characterized by an energetic wave climate, reaching significant wave heights of up to 10 m at Cannon Beach just south of the survey site (Tschetter et al. 2016). The energetic wave climate is reflected by the thin and fairly steep beach at Ocean Cape, observations of berm erosion leading to tree removal, and breaking waves. The beach of Ocean Cape features a cobble-sand beach toe with an abundance of large boulders. Beach scarp evolution as well as a ridge-runnel system have



Figure 1. Google Earth (2020) images showing the location in Alaska (top left zoom), Ocean Cape in the context of Yakutat Bay and the city of Yakutat (left), and a close up (right) with the transect location highlighted as yellow line.

been observed by the authors occasionally from 2014-2019, but not consistently. Therefore, there is clear evidence for local erosional processes and active geomorphodynamics. Ocean Cape represents the southern point of the entrance to Yakutat Bay.

METHODS

In this conference article, a data subset of a larger, multi-location field study will be presented and discussed focusing on beach-based measurements of geomorphology and soil properties at Ocean Cape collected on August 17 and 18, 2019. Measurements from August 14 and 15, 2018 will serve a temporal comparison but will not be focus of this article. Some additional details about the results from 2018 can also be found in Stark and Manning (2019).

Measurements targeted local geomorphology, sediment properties, and geotechnical soil properties. To assess local geomorphology, an optic satellite image was taken by the WorldView 3 satellite, and profiles of beach topography were collected along a cross-shore directed profile by measuring differential height approximately every 3 m along the profile. Distances between the measurement points were extended or shortened depending on obvious changes in topography. Other measuring techniques would potentially have enabled more accurate measurements of topography, but logistical restrictions led to the decision of utilizing this simple method.

Sediment samples were carefully collected using a push tube of known volume. By means of weighing, drying and re-weighing, the bulk unit weight, dry unit weight, and gravimetric water content (ratio of mass of water and mass of soil), the volumetric water content (ratio of volume of water and total volume of sample), and void ratio were determined. The relative density was derived from the determined void ratios of the sample, and laboratory tests of minimum and maximum void ratios of the material. Samples were collected at six locations along the cross-shore

profile (referred to as OC1-6 from now on), with OC1 being located most onshore and OC6 closest to the water line (Fig. 1). Moisture contents were measured in-situ at the same locations using a *Dynamax SM150* soil moisture gauge with an absolute accuracy of $\pm 3.0\%$ volumetric water content.

Sediment strength was measured in three independent ways using (i) the vane shear option of the *GeoTAC Soil Saber*, (ii) the penetrometer option of the *GeoTAC Soil Saber*, and (iii) the portable free fall penetrometer *BlueDrop* by *BlueCDesigns*. The *Soil Saber* is a novel field survey tool that provides a digital measurement of soil resistance against rotation of a vane (with similar vane blade options as for a traditional laboratory mini-vane shear device) or against an approximately 5 mm wide squared bar that is being pushed into the soil. In both cases, penetration or rotation is manually controlled what may lead to some effects of variations in rotational or penetration velocity, but an effort was made to apply a consistent speed. The vane shear option was utilized despite the cohesionless soils, following the concept presented by Sassa et al. (2014) to investigate effects of apparent cohesion. The portable free fall penetrometer (FFP) was designed for subaqueous seafloor investigations. However, it has recently been used for beach surveys to provide a consistent measurement from the subaerial zone to the nearshore zone (i.e., in water) by e.g., Reeves et al. (2018). The device is dropped from approximate one meter above the ground and impacts the soil in free fall. While the device penetrates the soil at changing velocities (i.e., decreasing velocity when the device is being slowed down and eventually stopped by the soil), impact velocity can be considered constant with a consistent drop height following the physics of free fall. The device measures its own motion, and by doing so, the deceleration experienced during impact. Then, deceleration can be related to sediment resistance and strength, or serve as a direct proxy for changes in soil strength (e.g., Stark et al. 2012).

RESULTS AND DISCUSSION

Ocean Cape beach features significant longshore changes in beach width (Fig. 1 right). On the day when the multispectral satellite image was taken (July 26, 2019), the main beach width was ~ 106 m from vegetation to the sand-cobble beach toe plus another ~ 100 m intertidal beach toe in front of the beach access road. Going towards the northeast, the smallest beach width measured less than 10 m plus ~ 50 m of cobbles and boulders at the point before widening eastwards towards Point Carrew. The plane view satellite image already suggests the possibility of a ridge runnel system towards the South of Ocean Cape beach. However, the beach profile (Fig. 2) reveals the full complexity of the local geomorphology with three sets of changing from a steep beach slope of approximately $5\text{-}15^\circ$ (decreasing elevation towards the water) to $-2\text{-}3^\circ$ (increasing elevation towards water) until reaching the flatter toe at $1\text{-}3^\circ$ of beach slope. It can easily be imagined that this complex topography has major impacts on local groundwater dynamics (Horn 2002), as well as surf and wash sediment transport (Baldock et al. 2011; Masselink et al. 2011). While a direct comparison to the 2018 topography appears difficult due to a mismatch in the longshore starting point, and the significant variations in the longshore direction, none of the measured profiles from

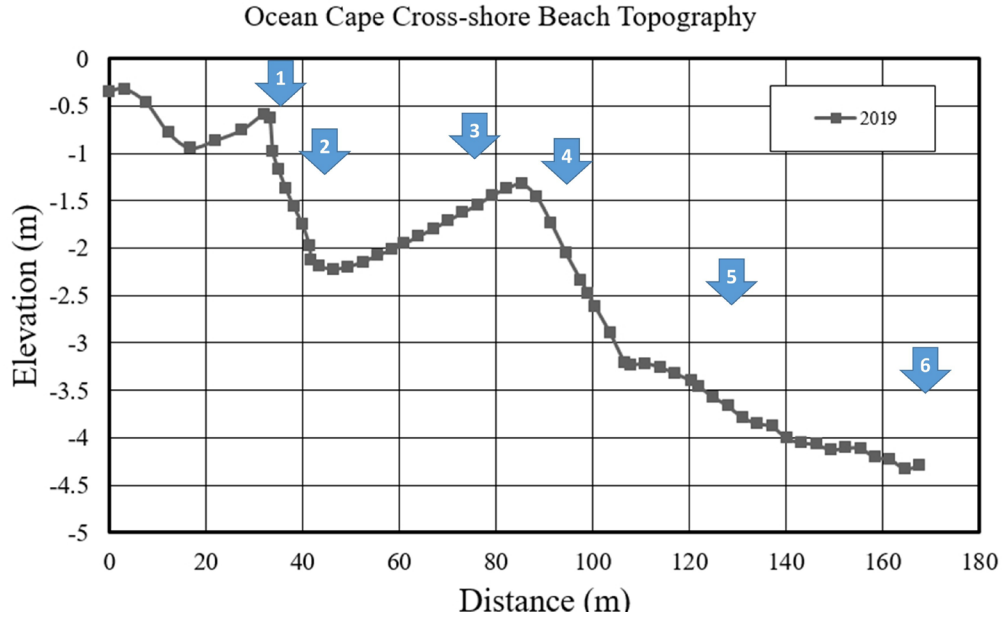


Figure 2. Cross-shore beach topography measured in August 2019 along the transect shown in Figure 1. Measurement locations OC 1-6 are highlighted as blue arrows.

2018 suggested the three ridges/terraces profile as seen in 2019 (Figure 2), but only documented the presence of one or two ridges/terraces. Similar significant variations in beach cross-shore topography have been noted at other beaches with energetic wave climates such as Carmel, California, USA (Komar 1998). Following beach classification schemes such as by Masselink et al. (2011), this points at a reflective to intermediate barred (high tide reflective to low tide dissipative) beach with a low relative tidal range (i.e., wave breaker heights are relative large compared to the mean spring tide range) and a low to medium dimensionless fall velocity (ratio of breaker height over sediment fall velocity of mid-beachface sediments times wave period).

Sediment grab samples confirmed a medium sand beach (median grain size d_{50} ranged from 0.25-0.30 mm) with limited variations in grain size other than the increasing abundance of cobbles and boulders towards the low water shoreline. In 2018, sediment samples appeared biased by either inconsistent filling of the tube or handling during transport to derive reliable values of bulk density. While trends in water content appeared valid, the magnitude of estimated water contents (up to <24% gravimetric water content; Manning and Stark 2019) appeared somewhat low. Therefore, sediment sampling was carried out with utmost care and special preparation of short push tubes which were filled entirely and closed in place in 2019. Figure 3 displays the measurements of bulk density at two consecutive days. Figure 4 shows the gravimetric moisture content for the same days determined from sampling and with the in-situ moisture gage. Differences in tidal state or weather were negligible between those dates. Thus, differences in the results were negligible. Generally, a trend of increasing bulk density towards the shoreline can be observed. Locations OC 2 and 4, the former in the deepest runnel and OC 4 at the transition between ridge and steep slope, were affected by most variability between tests repeated in the same area (radius < 10 m) (Fig. 3). The same applies to the gravimetric moisture contents, showing the expected increase in moisture

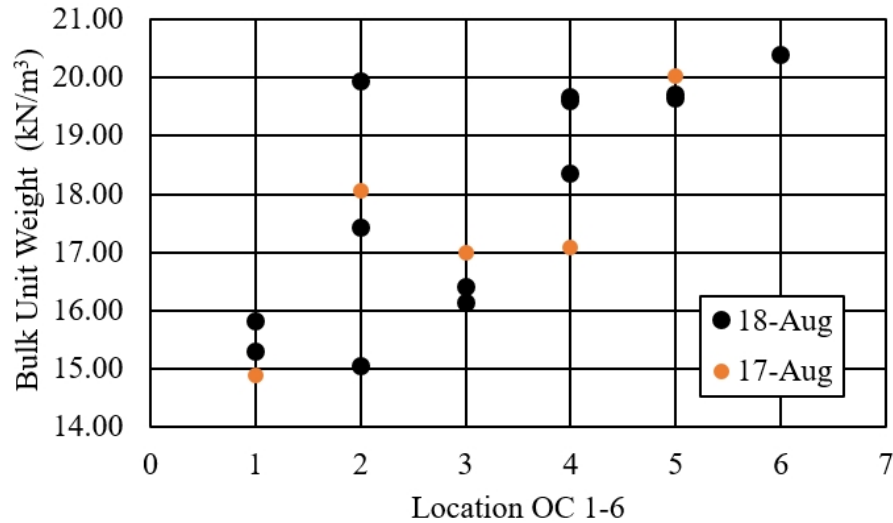


Figure 3. Bulk unit weight of sediment samples at locations OC 1-6 (towards the ocean) on August 17 and 18, 2019.

content with decreasing distance to the water and most variability at locations OC 2 and 4 (Fig. 4). Readings of the in-situ moisture gauge appeared erroneous on August 17, 2019, likely in response to handling issues. On August 18, the readings appeared valid and suggested that in-situ moisture contents of >50% were achieved at one location at OC 2, two locations at OC4, and at all locations at OC 5 and 6. This may suggest that even the careful sample extraction may limit the retaining of moisture contents, and that moisture contents beyond 35% can hardly be preserved unless additional mechanisms such as suction are being applied during sample extraction of cohesionless sediments. At the same time, the moisture gage readings may also generally be high due to calibration limitations associated with seawater salinity. Nevertheless, the sample data highlights the complexity in moisture contents and bulk density at a barred beach. Particle packing and bulk density is known to affect the critical shear stress needed to mobilize sediments (e.g., Bagnold 1966), and moisture content impacts significantly the potential for aeolian sediment transport (e.g., Bauer et al. 2009). Reeves et al. (2018) also hypothesized that the increase in sediment strength from the subaerial zone to the swash zone of a sandy beach was related to a combination of moisture content and bulk density. The data collected here support noticeable and likely related trends and variations in these properties.

Results from the three different ways of measuring in-situ sediment strength of the upper 10 cm of the beachface sediments are displayed in Figure 5. The measure of sediment strength can be expected to reflect the sand's in-situ effective friction angle, as well as potential effects of apparent cohesion from partial saturation where applicable (Briaud 2013; Sassa et al. 2014). The three methods yielded noticeably different results. The maximum deceleration was used here as a measure of variations in sediment resistance to avoid effects from empirical parameters needed for further processing of the FFP data. Impact velocities were consistently ~ 5 m/s for all deployments considered here, enabling this direct comparison of changes in maximum deceleration (Stoll et al. 2007). The vane shear yielded overall lower sediment strength values than the penetrometer. Such

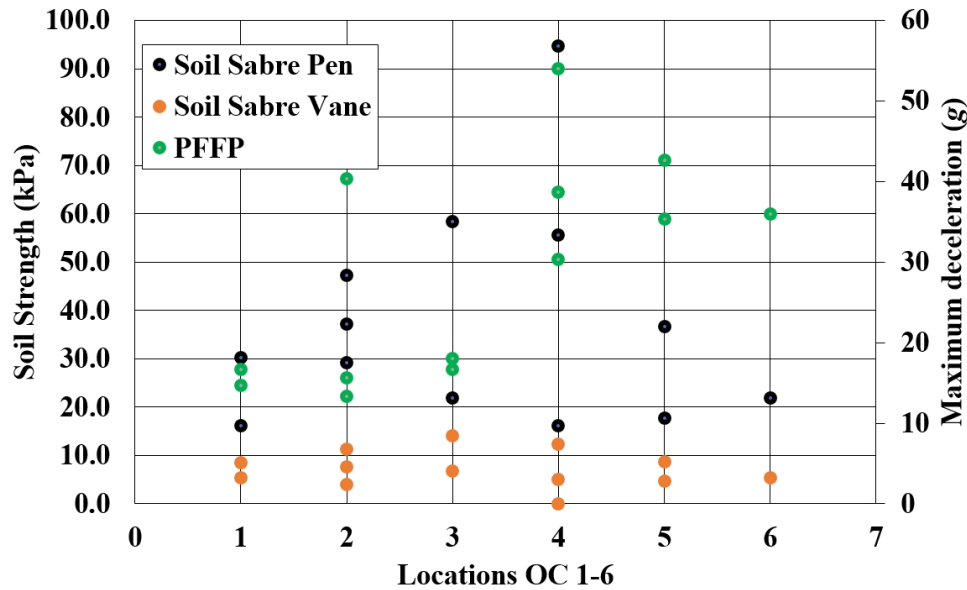


Figure 5. Sediment strength measured using the *Soil Saber* penetrometer and vane and maximum deceleration measured by the PFFP *BlueDrop* as a proxy of sediment strength locations at OC 1-6 (towards the ocean) on August 18, 2019.

significant differences between vane shear results and penetrometers are well known, and therefore, expected (e.g., Lunne et al. 1976). The vane shear results are not mimicking trends observed in bulk density or moisture content, but exhibit somewhat of an increase in strength towards OC 3 (low water content and moderate bulk density), and then a decrease in strength towards areas of higher moisture contents. This may suggest a closer relationship to moisture contents which are known to affect sediment strength through an apparent cohesion in a non-linear way (Briaud 2013; Sassa et al. 2014). The Soil Saber penetrometer readings suggested most variability in strength at positions OC2 and 4, similarly to observations in bulk density and water content. However, some inconsistency between repeated tests at locations OC 3 and 5 makes it overall difficult to identify possible trends. One may argue that the data suggests a similar trend as the vane shear with an increase in strength towards OC 3-4 coming from the onshore and offshore directions. For the FFP results, most variability between repeated tests were observed again at locations OC 2 and 4. However, the FFP seemed to suggest generally weaker soils from OC 1 to 3 and significant stronger sediments from OC 4 to 6 where also water content and bulk density were higher. This matches observations by Reeves et al. (2018) and Manning and Stark (2019) at sandy beaches. The FFP is larger in size and faster in penetration than the Soil Saber penetrometer. This means a different drainage regime may apply to the different penetrometers with likely fully drained to partially drained conditions for the Soil Saber penetrometer and fully undrained to partially drained conditions for the FFP. The latter would suggest that viscosity effects of the pore water (i.e., viscosity driven strain rate effects) may add to sediment resistance instead of seeing the non-linear water content – strength behavior (Albatal et al. 2019). It can be summarized that in-situ soil strength of a sandy beach at Ocean Cape appears to be related to variations in moisture content and somewhat bulk density, but that special attention has to be given to the method of in-

situ soil strength measurement and its process-based relationship to moisture contents. It is expected that these variations in geotechnical soil behavior across sandy beach environments affect local sediment erodibility, i.e., that local erodibility may vary noticeable spatiotemporally at sandy beaches even if variations in grain size are limited.

CONCLUSION

In current erosion prediction and assessment models often only limited geotechnical sediment properties are considered, or if so, they are considered constant. In this preliminary study, significant variations in soil strength, moisture content, and bulk density were found along a cross-shore transect of complex geomorphology and known for active erosion and sediment remobilization processes. Variations in these properties are expected to affect local erodibility and to vary on different temporal and spatial scales. Difficulties in high quality sediment sampling to preserve geotechnical soil properties of cohesionless sediments as well as differences in in-situ testing of soil strength were identified as challenges to obtain data sets that may enable an integration of geotechnical soil properties into erosion prediction and assessment. However, the latter differences may also offer insights into soil behavior to different stresses. In conclusion, geotechnical properties of surficial beach sands can vary significantly across beaches characterized by a complex geomorphology and active erosion and sediment remobilization processes. However, no detailed guidance exists yet about best practices to measure geotechnical properties at intertidal sand beaches, and significant differences in sensitivity to different environmental conditions of the respective methods were expected and confirmed. More data sets are needed to gain a more fundamental understanding of the soil behavior and governing processes, but also more research is needed regarding the optimization of data collection strategies. The potential knowledge gained from inclusion of geotechnical processes and properties will likely contribute to the improvement of beach erosion prediction and assessment.

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