Site Characterization of a Restored Coastal Dune and Beach

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ABSTRACT

Coastal beach and dune ecosystems are critically important for shoreline protection and significant resources have been allocated to their conservation. Dune vegetation is known to modify site response to wind, waves, and storms, but little focus has been given to understanding how belowground sediment structures enhance dune stability. A first step in addressing this knowledge gap is to determine optimal methods to measure subsurface sediment properties in onshore sandy environments. Our team performed a comparison of geotechnical and geophysical methods on a restored beach and dune system on Florida's Atlantic coast. Methods included two types of dynamic cone penetrometer (DCP) systems, a multi-channel analysis of surface wave (MASW) system, a ground penetrating radar (GPR), soil vibracores, and grain size analyses. Two transects were investigated, a 50-meter cross-shore transect and an intersecting 20-meter along-shore transect. The transects were selected to study the gradient of sediment properties from the swash zone to the high dune. Key findings from this study were that the PANDA DCP provided a higher resolution of measurements compared to the standard DCP, which is extremely advantageous in the shallower, less consolidated soils. MASW shear wave velocity results showed similar trends to the DCP cone tip resistance and allowed for measurement of stiffer soils where the DCP reached refusal. In addition, the results from the DCP, GPR and vibracores compared well. Thus, the use of the DCP and GPR systems as minimally intrusive testing options in fragile dune systems was verified.

Keywords: Ground Penetrating Radar; Coastal Resiliency; Dynamic Cone Penetrometer; Shear Wave

1. Introduction

Coastal dune systems are dynamic natural infrastructure that serve as the first line of defence to protect communities, infrastructure, salt marshes, inland bays, and mainland regions from direct impacts of wave and storm surges (Rosati et al. 2006; Johnson et al. 2020). It is critical to have an accurate estimation of dune resiliency to coastal forcings like wave action, wind, etc. to determine the overwash potential. An overwash model requires three primary inputs: (1) hydrodynamic boundary conditions (wave energy and water levels); (2) land cover maps; and (3) topo-bathymetric data (Harris et al. 2020). The process to determine the hydrodynamic conditions and ground-surface elevations is well documented, however, the land cover classification determination involves significant simplifications and estimations.

In overwash models, the land cover classification controls the likelihood of sediment suspension based on flow-velocities. Land cover classification is given a specific Manning's roughness coefficient (n), which incorporates sediment and vegetation characteristics at the bed surface, and ultimately impacts flow velocities and thus sediment transport (Liu et al., 2018). For modelling purposes, there is no explicit method to determine sediment transport; potential methods include a sediment's D_{50} value, density, or critical shear stress; a basic coefficient of calibration; or incorporating vegetation stem height and root depth (Bryant et al. 2019; Harris et al. 2020). It is well documented that vegetation impacts dune resiliency to wind, waves, and storm, but little is known on how vegetation, specifically belowground biomass, enhances dune sediment stability (Harris et al. 2020). In addition, vegetation characteristics are temporally dynamic as they establish themselves with time following a disturbance or planting and vary seasonally, which adds temporal uncertainty to overwash potential.

To better understand the depth-dependent characteristics that impact beach and dune resiliency, an investigation was conducted to determine the best practices to assess dune characteristics for input in predictive modelling. The sediment characteristics of a recently restored beach and dune system on the Atlantic coast of Florida was investigated with a combination of geotechnical and geophysical methods to answer two questions: (1) what methods provide the viable results and how do they compare? and (2) how much variability in soil conditions can there be in the cross-shore and alongshore directions?

2. Methods

2.1. Field Site

The study site is a recently restored beach and dune system in northeastern Florida, USA in Flagler County, called MalaCompra Park. The wave climate is seasonal with moderate wave exposure (Walton and Adams 1976); tidal range is on the upper end of microtidal with a spring high tidal range of 1.8 m and a mean of 1.5 m (Legault et al. 2012). Wave energy is typically greatest during the winter season, with waves from the north averaging 1.2 to 1.8 m or greater in height (USACE 2010). Overall, the net sediment transport along northeastern Florida is from the north to the south, caused by winter storms, with a seasonal reversal in net sediment transport direction during the summer months (Legault et al. 2012). The coastline is characteristic of a barrier-inlet system that consists primarily of littorally-derived, reworked, riverine siliciclastic sediments with varying amounts of bioclastic locally derived material (PBS&J 2009). PBS&J (2009) determined sediments to be predominately littorally derived with varying amounts of carbonate and little to no riverine input with carbonate shell hash and quartz making up most of the sand concentration; sediments are greatly varied in distribution alongshore.

In 2019, the site was severely damaged due to Hurricane Doran, promoting the restoration. The beach and dune were restored using mined sand brought in via haul trucks. The restored beach and dune have: an average beach slope of 3:40 (7.5%), beach width of 40 m, and dune crest height of 4.3 m local mean sea level (LMSL). The restoration started in January 2023 and was completed in February 2023. The dune was then planted with Uniola paniculata (i.e., sea oats) in April 2023. The project was a cost share agreement among the Federal Emergency Management Agency (FEMA), Flagler County, and State of Florida.

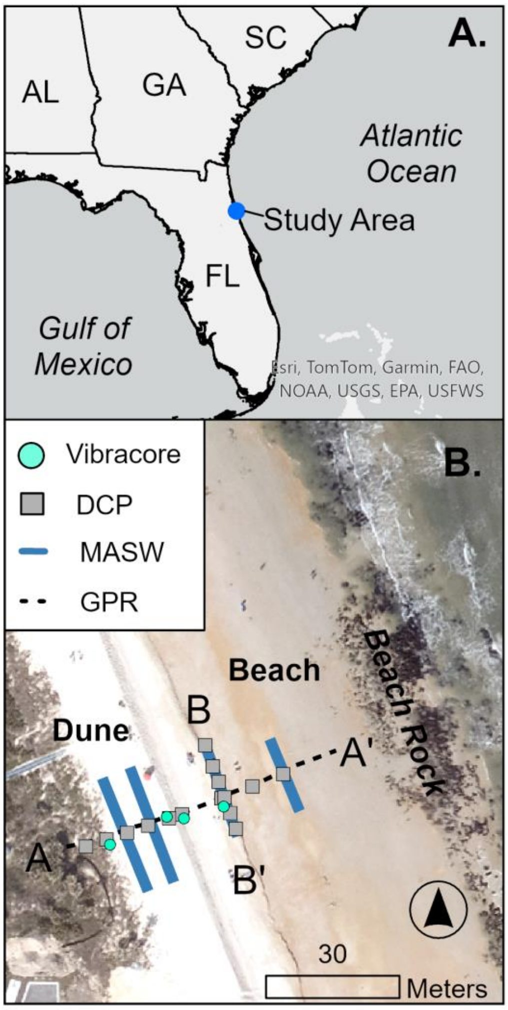

Figure 1. (a) Regional overview map of study area (northeast Florida, USA) coast; (b) Location of MalaCompra Park, Florida (USA) and sampling layout.

2.2. Dynamic Cone Penetrometers

Two different dynamic cone penetrometer (DCP) systems were used in this investigation: (1) a standard 8 kg Humbolt system configured with Vertek's SMART system and (2) SolSolution's variable-energy PANDA. The Humbolt system was performed in accordance with ASTM D6951. The PANDA DCP is a lightweight system that consists of a driving cone (2 cm^2 or 4 cm^2), a small tablet that displays real-time blow results and site profiles, a 1.7 kg hammer, an anvil for striking with the hammer, a central acquisition unit which measures rod movement, and ten 50-cm long rods (Hubler and Hanley 2021).

2.3. Ground Penetrating Radar

Ground penetrating radar profiles were collected using a RadSys Zond Aero 500 MHz GPR system. A Trimble RTK GNSS was pole mounted to the GPR cart to provide horizontal and vertical positions of the GPR data. All GPR data were post-processed Prism2 (RadarSystems, Inc.) using standard procedures, including automatic gain control, background removal, Ormsby bandpass filtering, depth-time correction from hyperbolas (where present), and stolt-FK migration (where applicable). At most sites, the local time-to-depth conversion value from hyperbola fitting was around 5 cm/ns, consistent with literature values for dry sand. For profiles without hyperbolas, the 5 cm/ns value was assumed to be accurate and applied for depth conversion. RTK GNSS data were used for topographic correction of GPR lines.

2.4. Multi-Channel Analysis of Surface Waves

A multi-channel analysis of surface waves (MASW) setup was used to evaluate shear wave velocity profiles for comparison with the other subsurface exploration methods in this study. A Geometrics ATOM wireless MASW setup from the NSF-sponsored RAPID facility at the University of Washington included a total of 10 vertical-component geophones (4.5 Hz frequency). All geophones were spiked into the ground in a linear arrangement with spacing of 0.75 m. A shorter array was used to focus on near surface shear wave velocity for comparison with the other methods used at the site. A 5-kg sledgehammer was used as the impact source. Five hammer strikes were performed during each test to increase signal to noise ratio via signal stacking. Each sledgehammer was coupled with the ground surface by a 0.3 m square aluminium plate for testing. Multiple off-end shot locations (1, 3, or 5 m) were used to ensure adequate frequency coverage in the dispersion curves.

2.5. Subsurface Samples

Vibracores were collected at four cross-shore stations to a maximum depth below surface of 1.5-meters. Sediment core horizontal and vertical positions were surveyed with a Trimble RTK GNSS. All sediment cores were split, photographed, described for texture (as compared to standards), mineralogy (visually) and colour (using a Munsell Soil Color Chart), and sampled. Grain size from core samples was analysed using an Instagrain camera system, an open source and open hardware camera that uses a deep learning model to estimate grain size from photos (Goldstein et al., 2022). Subsamples from cores were analysed for grain size on a sieve-shaker to spot check camera results.

3. Results and Discussions

3.1. Method Comparison

At the start of the investigation, co-located DCP tests were performed with the standard system and the PANDA. Fig. 2 shows a comparison of two readings performed on the high dune. A major difference between the systems was the applied force as the standard DCP was limited to either an 8 kg or 17 kg weight while the PANDA was driven in with a 1.7 kg hammer allowing for a variable force. This proved especially useful in the shallower substrata as the sediment was less compacted enabling the PANDA to collect higher resolution data within this region as opposed to the standard DCP which would routinely bypass the upper 20 to 30-cm of sediment. The PANDA advanced an average of 1.3 ± 0.3 cm in the upper 1-meter of substrata while the standard DCP would advance 4.7 ± 4.3 cm, Fig.2b. This shallow substratum is essential to the future overwash investigation since this is the portion that will more frequently experience erosion, so the standard DCP method was removed from following site investigations for remainder of the study.

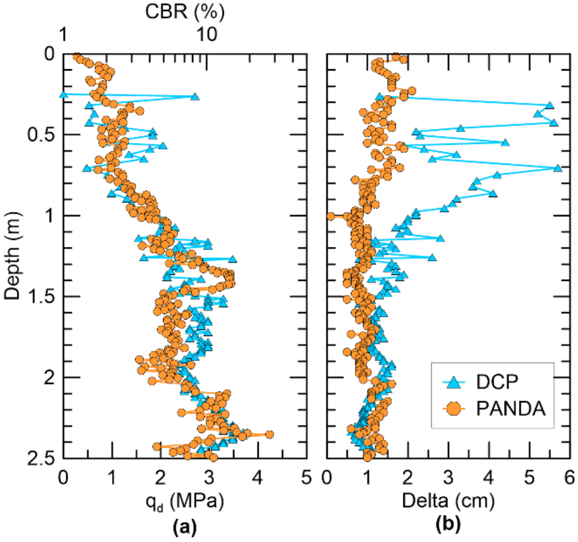

Figure 2. Comparison of (a) CBR (%) from the standard DCP system and q_d (MPa) from the Panda system and (b) delta between consecutive measurements.

Shear wave velocity (V_S) was evaluated at four locations along the cross-shore transect, as shown in Figure 1. PANDA DCP measurements were performed at the center of each MASW array for comparison between the methods. Figure 3a shows the results of DCP cone tip resistance (q_d) at Stations A, C, E, and G, while Figure 3b shows the corresponding V_S profiles. The two methods show similar results, although the DCP resistance was not able to penetrate beyond 1 m for Stations A and C, and 2 m for Station E while all V_S profiles reached approximately 4 m depth. Both DCP and V_S results show that the beach sand is stiffer within the swash zone to dry beach (Stations A and C) and decreases in stiffness on the dune (Stations E and G).

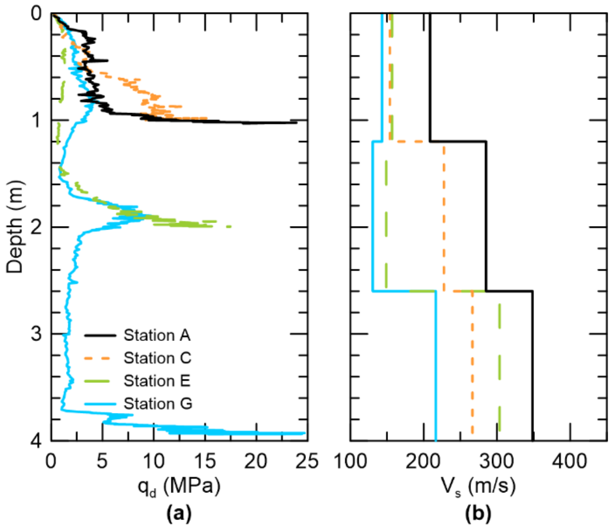

Figure 3. Comparison of (a) q_d (MPa) from the Panda system and (b) shear wave velocity profiles from the MASW system.

To assess the efficacy of various methodologies, results from "Station E" at Mala Compra were plotted in Figure 4. The GPR penetrated approximately 4 meters below the ground surface and a 0.5 m section of the cross-shore profile and relative amplitude of the GPR signal (unitless) is shown in Figure 4. The PANDA was capable of penetrating to depths of 4-meters however refusal occurred just past the 2-meter depth where resistances were above 20 MPa. The DCP profile showed a slightly increasing resistance from the surface down to 0.3 m after which it remained fairly consistent at 4 MPa throughout the upper layer of pale brown sand. This layer consisted of average D_{10}, D_{50}, and D_{90} values of 0.18 mm (fine), 0.26 (medium), and 0.44 mm (medium), respectively. This layer was underlain by a 50-cm thick layer of light gray sand with heavy minerals. D_{10} values remained consistent while a slight increase in D_{50} (0.28 mm) and greater increase in D_{90} (0.6 mm) was noted. A gradual increase in DCP resistance was seen throughout this layer until it transitioned to the pale brown sand layer at 1.9 m below the ground surface, where resistances continued to increase until refusal was reached approximately 2 m below the ground surface. Utilizing this multi-method approach allowed for a more holistic understanding of substrata characteristics; additionally, the approach allows each dataset to complement one another, which aids interpretation of site stratigraphy.

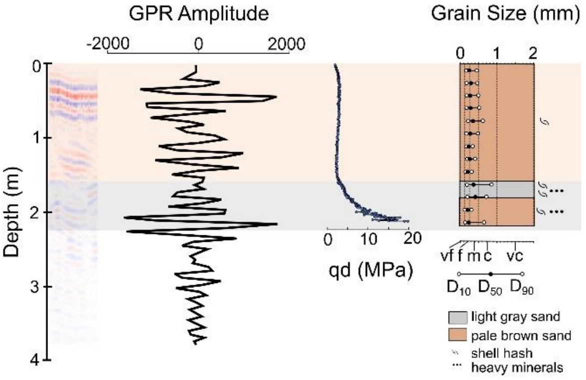

Figure 4. Comparison of GPR response/amplitude, q_d (MPa) from PANDA, and vibracore findings at Station E.

3.2. Cross- and Alongshore Variability

To understand the variability in sediment characteristics across the beach and dune system, a cross-shore and alongshore transect were performed. The cross-shore profile spanned approximately 45 m from the swash zone, starting at +0.5 m LMSL, to the restored dune, at +5.0 m LMSL, while the alongshore profile spanned 20 m along the beach face at +2.2 m LMSL. The alongshore profile intersects the cross-shore profile at Station C. An overlay of elevation profiles, GPR images, DCP soundings, and vibracores are shown in Figure 5.

The cross-shore profile was divided into two sections: the beach face and the dune, as demarcated by the dune scarp. The natural dune contained more sporadic reflections from the GPR which is indicative of aeolian deposition while the artificially created dune contained parallel horizontal layers indicative of the construction methods used to restore the dune. Dune stratigraphy was comprised of predominately pale brown sand with average D_{10}, D_{50}, and D_{90} values of 0.18mm, 0.27 mm, and 0.56 mm, respectively in the upper 2 m. DCP resistances were consistent throughout this layer at 1.7 ± 0.7 MPa. A distinct stiff layer was noted across all profiles between +2.75 to +2.1 m LMSL where resistances increased to 11.4 ± 2.9 MPa and overall grain size increased. This layer terminated at some point within the dune scarp and is interpreted as landward extension of the beach face. Based on the principle of superposition, this layer formed prior to both the natural and restored sections of the dune. Thus, the layer most likely was deposited during a period of high water such as a storm. The beach face was comprised of higher shell content (sandy shell hash to shelly sand) where average D_{10}, D_{50}, and D_{90} of 0.25 mm, 0.44 mm, and 0.9 mm, respectively, were noted within the upper 1.5 m. DCP resistances were more sporadic within this layer with Stations A and B having an average resistance of 4.3 ± 1.3 MPa down to +0.25 m LMSL, likely caused by the presence of shells.

The alongshore profile consisted of four distinct stratigraphic layers. The uppermost unit (+2.2 to +1.7 m LMSL; 0.5 m thickness) was comprised of a shelly fine to medium sand (D_{50} = 0.38mm) with DCP resistances of 1.6 ± 0.8 MPa. This unit was planar and bedding

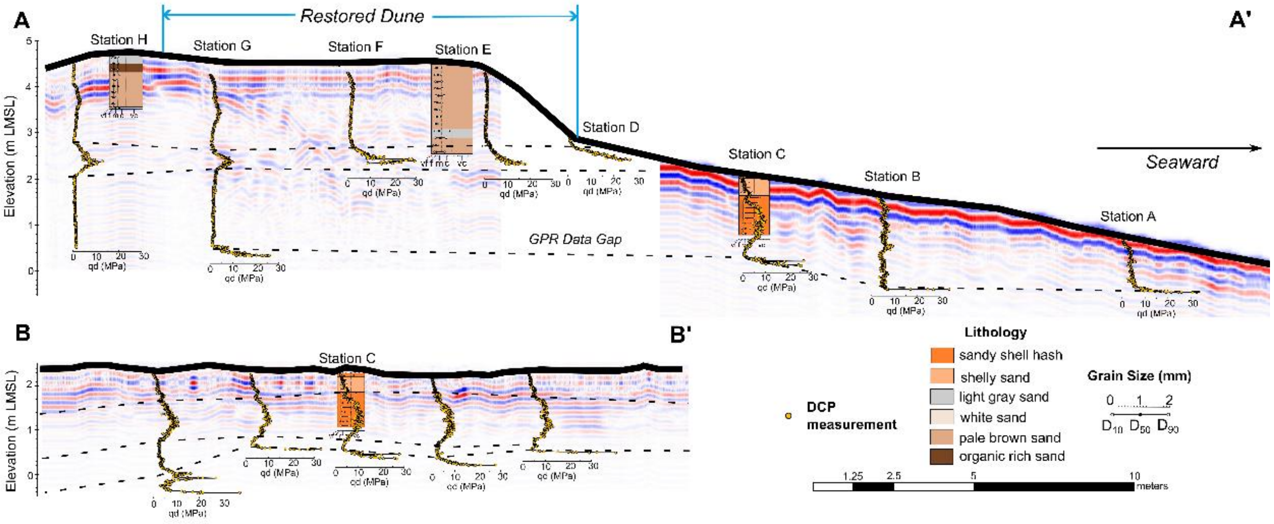

Figure 5. Comparison of cross-shore (A to A') and alongshore (B to B') profiles.

generally follows the surface topography. This unit was underlain by a medium to coarse grained shell-hash layer with some sand that increased in thickness from approximately 0.4 to 0.55 m moving northward along the transect. DCP resistances were more sporadic throughout this layer (5.1 ± 1.2 MPa) and increased gradually, followed by a subsequent decrease at the approximate midpoint of the layer; the GPR profile revealed variably planar to dipping (4 to 13°) beds in this layer. The layer was underlain by a less resistant (2.6 ± 0.7 MPa) layer that pinched out from ~0.1 m thick in the north to over 0.5 m thick in south. At the base of the measurable stratigraphy (-0.5 to 0.5 m LMSL) was a highly resistant layer where the DCP reached refusal at over 30 MPa. The basal layer is interpreted as a coquina layer and most likely is the onshore extension of the beach rock visible in aerial imagery (Fig. 1). Locally the unit is known as the Anastasia Formation which is a Pleistocene-aged deposit commonly consisting of cemented shell material found along the Florida Atlantic Coast (Missimer and Maliva, 2005).

4. Conclusions

This study applied multiple geotechnical and geophysical techniques to assess site variability across coastal beach and dune environments. Two main questions were investigated: (1) what methods provide the best results and how do they compare? and (2) how much variability in soil conditions is there in the cross-shore and alongshore directions? Findings herein showed that the ability to vary input force of the PANDA DCP provided for higher profile resolution when compared to the standard DCP systems, which is especially favourable in softer sediments. MASW V_S results showed similar trends to the DCP cone tip resistance and allowed for measurement of stiffer soils where the DCP reached refusal. The combination of DCP, GPR, and vibracore data provided a holistic understanding of site stratigraphy by attributing increases in grain size and reflectance/resistance with varying depositional environments. As for site variability, the alongshore profile indicates little variability in the shallow (<2 meter) stratigraphy but greater variability at depth (>2 meter). As compared to the cross-shore profile, alongshore variability in resistance, grain size, and bedding is relatively minimal. Thus, future work should focus on measuring cross-shore variability on widely spaced transects.

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