

**N000141812435: Geotechnical Soil Characterization from Remote Sensing for
the Assessment of Coastline Strength, Stability, and Trafficability**

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Period of Performance: June 1, 2018 – May 31, 2022*

Final Report

Distribution statement: Approved for public release; distribution unlimited.

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1. Major goals

The world's coastlines are characterized by a large variety of soil types ranging from rocky cliffs to sandy beaches and muddy flats. Furthermore, most coastal areas are characterized by active morphodynamics, leading to spatial and temporal changes of sediment types and sorting through erosion, transport, deposition, and mixing processes. Changes and variations in water levels may occur on temporal scales of single waves to sea level rise or extreme event-based storm surges. In areas of higher latitudes, freeze and thaw cycles, as well as changes in permafrost due to climate change, may affect the soil. All of these processes impact the soil behavior of coastal sediments, and therefore sediment strength and stability, crucial parameters for the prediction of beach trafficability as well as navigability in nearshore environments, including land-ice interaction in polar regions.

Sediment strength and stability can traditionally be determined from field testing on site, and laboratory testing of collected field samples. However, for many naval missions, access constraints and safety concerns may not allow on-site testing or the collection of physical samples. Recent advances in remote sensing represent an opportunity to determine soil properties such as sediment strength, friction angles, and moisture content without physically accessing the site. However, direct correlations between remotely sensed properties and geotechnical parameters are still rare, and thus, a directly applicable remote sensing and data analysis framework for naval operation issues such as beach trafficability is still lacking. This knowledge gap and lack of verified methodology applies particularly for remote sensing data from satellites or other platforms at large distances to the site. To address this urgent need of data and methodology, the following research questions and objectives are proposed:

- 1) Is there a correlation between geotechnical soil characteristics and multispectral signatures and SAR backscatter?
- 2) Do variations in moisture content (both liquid and frozen) significantly impact SAR backscatter and multispectral signatures?
- 3) What are the optimal ranges of SAR and multispectral imaging settings that allow accurate, remote assessment of geotechnical soil properties, accounting for variations in moisture or ice content? Can multiple types of remotely sensed data be fused (i.e. combination of SAR with Light Detection and Ranging [Lidar]) to optimize these settings?
- 4) Develop a data collection and processing framework to determine bearing capacity for assessing beach trafficability from remote sensing.

2. Accomplishments under goals

2.1 Is there a correlation between geotechnical soil characteristics and multispectral signatures and SAR backscatter?

Key geotechnical properties for the assessment of trafficability as well as for the prediction of land-sea and land-ice interaction are sediment type (regarding grain size and mineralogy), textural

properties such as bulk density, void ratio, and water content, and strength properties such as undrained shear strength. These properties govern a soil's bearing capacity or likelihood for objects to sink into the soil, as well as sediment stability and dynamics (Knight and Freitag 1962; Bagnold 1966; Van Rijn 1984; Shoop et al. 2008; Grabowski et al. 2011). Textural soil properties, i.e., the particle packing and arrangement, as well as the filling of pore space, i.e., water and gas content, highly depend on the sediment's particle sizes and mineralogy, and thus, particle shape; and strength properties depend on sediment type and texture (e.g., Briaud 2013). Therefore, knowledge of some key properties may suffice for trafficability prediction. Sediment type classification certainly represents a key property, and moisture content represents another key property that is particularly variable in coastal environments (Meyer and Knight 1961; Jones and Arp 2019; Paprocki et al. 2019).

In this work, it was explored to conduct a sediment type characterization from optic and SAR satellite images. Figure 1 shows histograms of reflectance in the red, green, and blue bands of optic satellite images of different coastal sands: black (volcanic) sand, carbonate sand, quartz sand, and a sand-gravel mixture. All distributions are derived from sand beaches and publicly available satellite images (from Google Earth). The sediment type classification was validated from literature and public soil classification records. Figure 1 demonstrates that different sand types can be distinguished from optic satellite images. Similarly, gravel beaches and mud flats were identified from distinguished reflectance distributions.

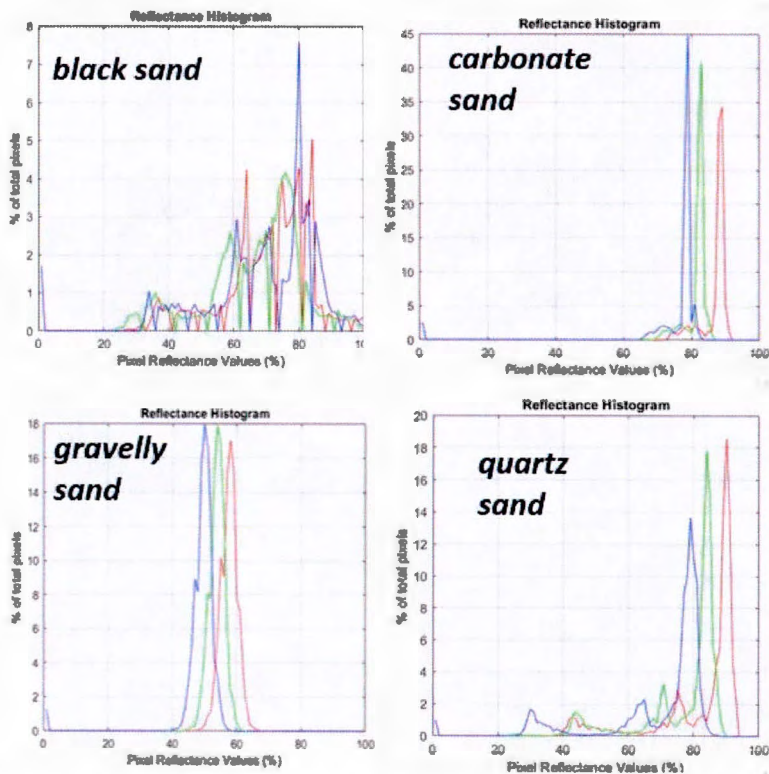


Figure 1. Reflectance in the red, green, and blue band (red, green, and blue lines) of a black sand, carbonate, gravelly, and quartz sand beach, respectively (modified after Stark et al. 2019; data processing by Parker Reed).

Four sites along tidal mud flats in the Great Bay estuary, New Hampshire, were investigated to explore the role of fines content in muddy mixtures (Table 1). Significant variations in fines content, moisture content, and undrained shear strength are visible (Table 1). Generally, moisture content increased with fines content, and undrained shear strength increased with decreasing fines content and moisture content in line with expectations (e.g., Briaud 2013). Figure 2 shows distributions of backscatter coefficient in SAR imagery obtained at the same time as sample extraction. The four sites can be clearly distinguished from the distributions. It appears that coarser sediments lead to higher backscatter coefficients and higher moisture contents, low strength, and high fines contents to wider distributions.

Table 1. Approximate fines content, gravimetric moisture content, and undrained shear strength of surficial sediment cores (< 10 cm sediment depth). Approximates are based on averages of about 10 core samples per site. Sites represent three tidal mud flats along the Great Bay estuary, New Hampshire.

Location	Fines content (%)	Moisture content (%)	Undrained shear strength (kPa)
Adams Point	90%	100%	1 kPa
Mast Cove (coarse)	18%	25%	18 kPa
Mast Cove (fine)	35%	40%	8 kPa
Woody	95%	150%	1 kPa

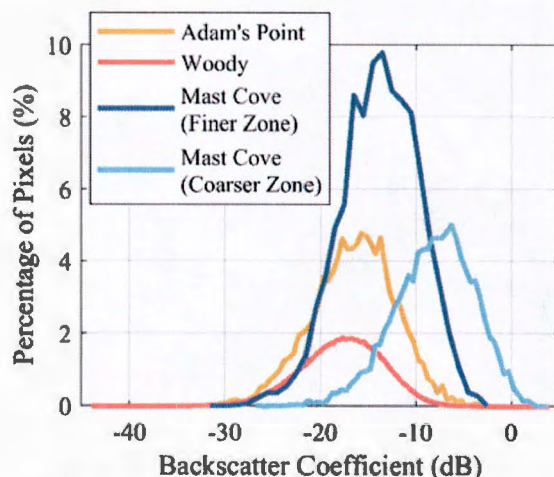


Figure 2. Distributions of SAR back scatter coefficient for four muddy tidal flats along the Great Bay estuary, New Hampshire (Paprocki et al., *in prep.*).

The results show that geotechnical properties and sediment types are reflected in optic and SAR satellite imagery. The results suggest that optic imagery is particularly suited to determine mineralogy and general sediment type (mud, sand, gravel) in an easy manner. SAR imagery showed distinct backscatter coefficient signatures for different tidal mud flats with generally

similar appearance to the eye, but significantly different strength and textural properties. However, more research is needed to understand the role of property interrelationships and sensitivity of SAR to different combinations of properties.

Moisture content has been identified as a key property, particularly in sandy environments and is addressed in section 2.2.

2.2 Do variations in moisture content significantly impact SAR backscatter and multispectral signatures?

Moisture content is a key parameter to govern soil strength and trafficability at sandy beaches (Meyer and Knight 1961; Jones and Arp 2019; Paprocki et al. 2019). Thus, it is imperative to be able to assess soil moisture content of sand beaches for the assessment of trafficability, amongst other applications. In coastal environments, this is of specific importance since soil moisture content varies with meteorological conditions as well as with tides. Figure 3 shows cross-shore beach elevation and surficial moisture content measurements at a sandy beach in Duck, North Carolina.

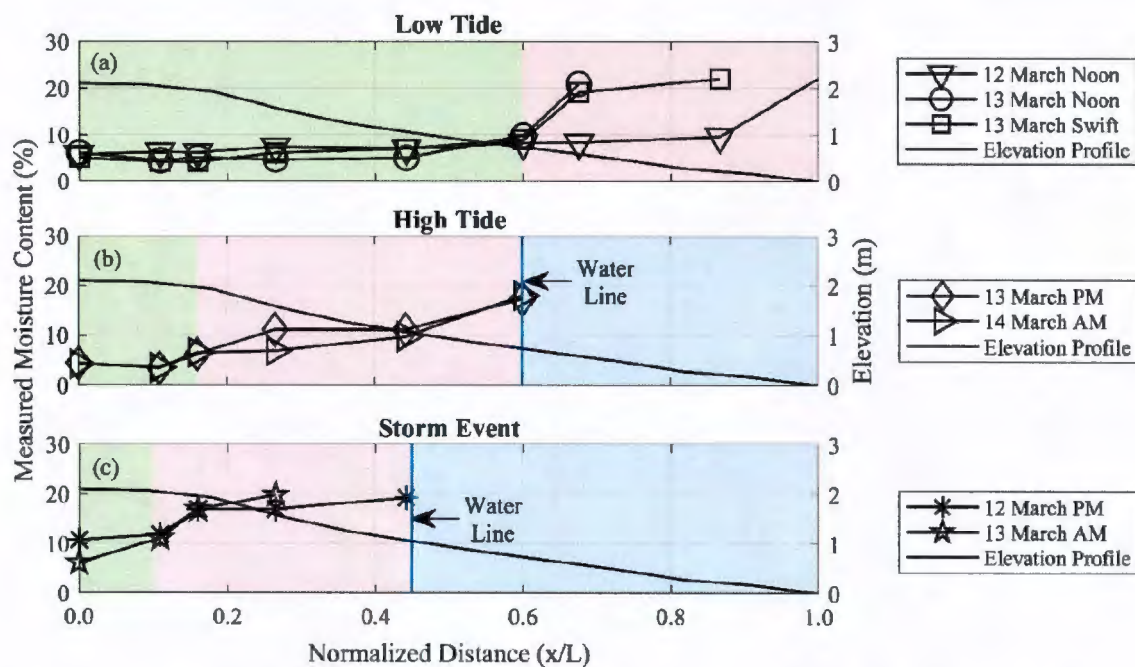


Figure 3. Cross-shore beach transects from the dune toe ($x/L = 0$) to the water line (blue line) of elevation (black solid line) and surficial moisture content (symbols) measured via core sample extraction and a conductivity based moisture probe at different times, dates, and tidal stages at a quartz sand beach in Duck, North Carolina (Paprocki et al. 2022).

Two frameworks were developed to derive instantaneous surficial (<10 cm) sand moisture content from multispectral satellite images. Framework 1 should be applied if a laboratory spectrometer is available to carry out a sediment specific calibration. Framework 2 should be applied if only the multispectral satellite image is available. Both frameworks base on an exponentially decaying function with increasing moisture content previously suggested in the literature which relates the reflectance of a sand at a certain moisture content to its reflectance in dry state, the moisture content, and a moisture content dependent calibration factor (Bowers and Hanks 1965). Both frameworks start with selecting an area of interest, selecting zones of dry sand and their reflectance in the image, and conducting a best guess estimate of the calibration factor. Framework 1 is using a laboratory spectrometer to obtain spectral signatures of the sand at different moisture contents, and by doing so, determines an updated value of the calibration factor. Framework 2 applies a zone-based averaging and groundtruthing of points per zone to estimate and update the calibration factor. With an updated calibration factor, the reflectance of dry sand in the image, and the reflectance in the area of interest, the moisture content can be determined. Please find a detailed description of the developed frameworks and results in Paprocki et al. (2022a). Best results were achieved when using the near-infrared (NIR) band of the multispectral images, leading to results as shown in Figure 4 which reveal a match between the measured and estimated moisture content. This has been tested for different sand quartz beaches throughout the project. Those beaches featured variations in mineral components, but no carbonate beaches were tested during the project due to travel restrictions.

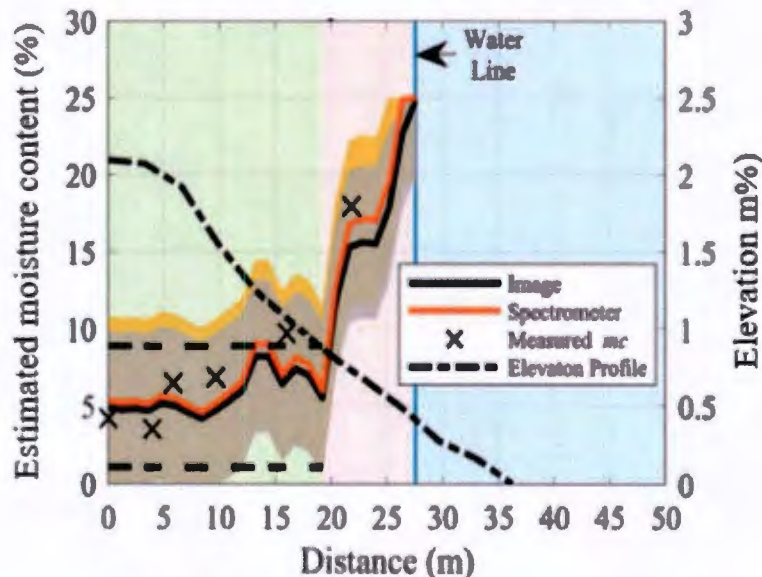


Figure 4. Cross-shore profile at a sandy quartz sand beach of estimated moisture content estimated from NIR satellite image using framework 1 (orange line), using framework 2 (black line), and measured from soil samples and moisture probe (crosses), and of elevation (dashed line) modified from Paprocki et al. (2022a).

The isolation and derivation of moisture content at sandy beaches from SAR satellite imagery is challenged by the SAR sensitivity to surface roughness. Figure 5 shows the measured moisture content and surface roughness (as RMS height) versus SAR backscatter coefficient along three cross-shore beach transects. The results suggest that the SAR data may be even more sensitive to surface roughness than to moisture content which is not surprising but an obstacle to a direct derivation of moisture content at beaches which may be subject to significant zonation with regard to roughness.

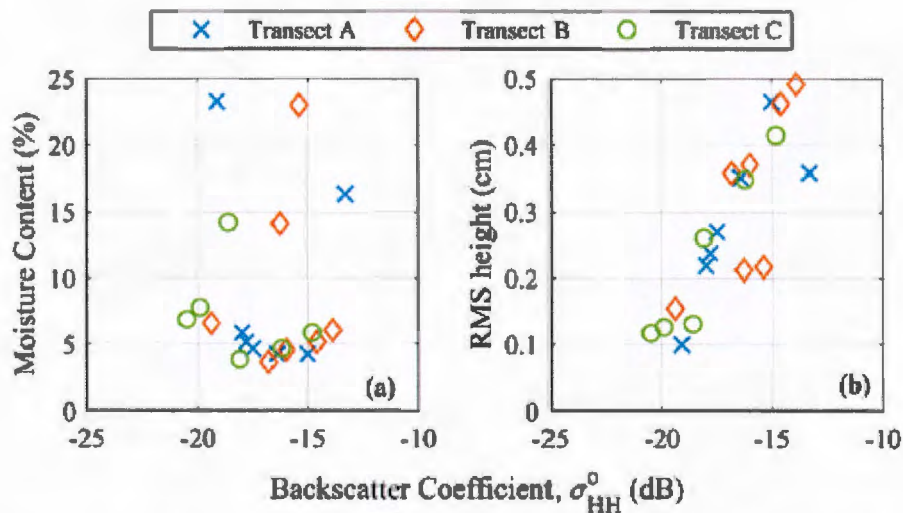


Figure 5. Measured moisture content and surface roughness (as RMS height) versus SAR backscatter coefficient along three cross-shore beach transects in Duck, North Carolina (Paprocki et al. 2022b).

This issue was addressed by the development of the following data processing workflow: Backscatter coefficients are determined from the SAR image. Then, a roughness category (smooth, intermediate, or rough) is chosen based on first-best-guess and further calculated through a probabilistic procedure to achieve the highest probability for a certain category for the measured backscatter coefficient and location. From the determined roughness category, the RMS height is calculated and the moisture content is then calculated for the determined RMS height and the measured backscatter coefficient. Iteratively, the best match is determined. An initial attempt of this procedure was published in Paprocki et al. (2022b) and the full workflow and results are available in Paprocki (2022) and Paprocki et al. (*in review*). Results yielded a satisfactory match for moist sands with $R^2 = 0.74$ for all SAR incident angles considered (20-55°; Fig. 6) and better for incident angles of 20-30° ($R^2 \approx 1$; please note limited availability of data points, less than 20) and 30-46° ($R^2 = 0.84$).

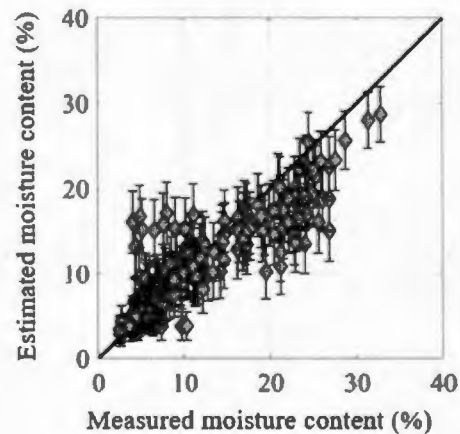


Figure 6. Estimated versus measured moisture contents for the full workflow and for SAR incident angles 20-55° and moist sands (modified after Paprocki et al., *in review*).

The results show that variations in moisture content are well reflected in multispectral and SAR satellite images. Moisture contents were successfully estimated for moist sands from multispectral and SAR imagery through new data processing workflows that are based on initial relationships developed in agricultural research. Moisture contents of muddy sediments are related to SAR backscatter coefficients (see section 2.1). However, interrelationships of moisture content to other sediment properties make it more difficult to isolate moisture content, and it appears also feasible that a direct relationship to strength properties for muddy sediments would be possible which would be preferred for the prediction of trafficability or stability.

Frozen soils were only limited investigated in this study due to a mismatch of travel restrictions in years 2020-2022 and winter weather conditions. Frozen soils are expected to feature significantly different SAR backscatter signatures than wet soils, but no detailed investigation was conducted in this study.

2.3 What are the optimal ranges of SAR and multispectral imaging settings that allow accurate, remote assessment of geotechnical soil properties, accounting for variations in moisture content? Can multiple types of remotely sensed data be fused (i.e. combination of SAR with Light Detection and Ranging [Lidar]) to optimize these settings?

Pixel resolution was found to be an intuitively important satellite image property. If available, highest pixel resolution (≤ 1 m) enables to resolve the often sharp edges and zonation of roughness and moisture content zones at beaches best. This seemed particularly important at sandy beaches, and less significant for mud flats. Larger pixel resolutions ($\leq 3-5$ m) were sufficient to determine sediment types as shown in Figure 1.

For multispectral images of sandy beaches, NIR band data correlated best to sand moisture contents (see section 2.2; Paprocki et al. 2022). For SAR imagery, low incident angles ($< 46^\circ$)

yielded the most favorable matches between measured and estimated moisture contents for moist sands of moisture contents > 5%, and incident angles between 40-50° yielded the best match for sands of any moisture content. The current data base is insufficient to make similar statements for muddy tidal flats with acceptable confidence.

Data fusion can be easily applied. Sediment types can be derived from medium resolution optic satellite images (Fig. 1) to inform next steps in assessment. For example, it can be determined that an area of interest is predominantly composed of quartz sand from a historic optic satellite image. Then, either a high resolution optic or SAR image can be used to determine the moisture content and to apply it for trafficability or stability assessments. The fusion of Light Detection and Ranging (Lidar) data and SAR data enables to omit the probabilistic analysis of surface roughness and to replace it with accurate values of surface roughness. This enhances accuracy of the derived moisture contents and trafficability assessment.

2.4 Develop a data collection and processing framework to determine bearing capacity for assessing beach trafficability from remote sensing.

Towards the assessment of beach trafficability for chosen vehicle types, the approach by Vanapalli and Mohamed (2007) was used to determine bearing capacity of partially saturated sand, in this case of moist beach sands from satellite images. Moisture content was obtained from the satellite images (multispectral and SAR; please see section 2.2) and was used to estimate soil suction based on the model by van Genuchten (1980) which was used in the bearing capacity model. Estimated bearing capacity was assessed in comparison to penetrometer-based bearing capacity measurements. A probabilistic model was then applied to plot zones of confidence (e.g., 90% probability of mobility). An initial outline of the approach is included in Paprocki (2022) and detailed results are presented in Paprocki et al. (*in review b*). The results yielded a satisfactory match between bearing capacity estimated from the moisture content derived from satellite images and penetrometer results (Fig. 7).

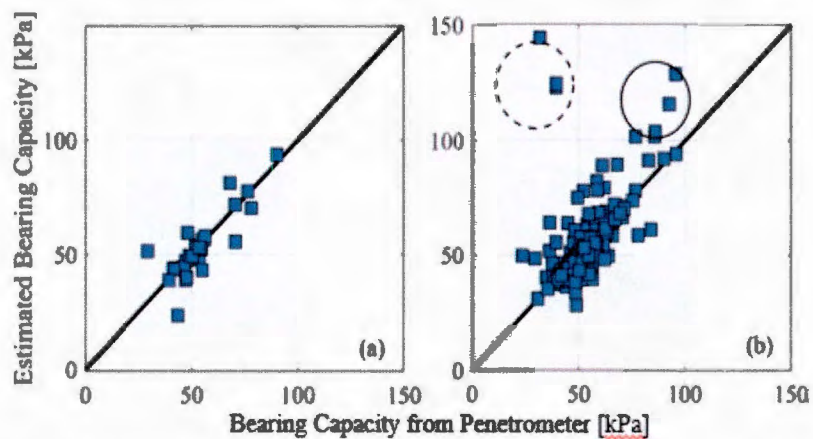


Figure 7. Estimated bearing capacity from remote sensing versus penetrometer results for locations with additional soil property data (left) and estimated values (right) applied to the van Genuchten (1980) model (modified after Paprocki et al., *in review b*).

Results showed that more detailed information on in-situ porosity clearly improve the results (Fig. 7 left). However, the use of typical soil property ranges yielded similar results unless approaching the waterline (Fig. 7 right circles) and swash. More investigations of the role of swash are needed. Relating bearing stress applied by a chosen type of vehicle to the estimated bearing capacity and its uncertainties enables a probabilistic representation of safe versus unsafe zones for a vehicle to cross, as shown in Figure 8, assuming a probability of sinkage $> 10\%$ as unsafe.

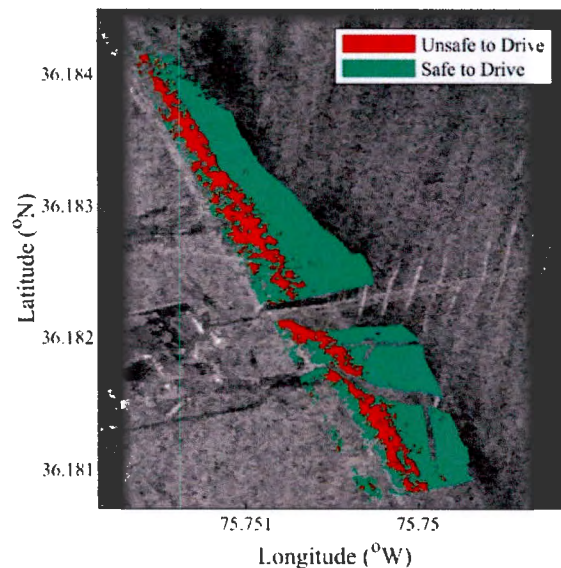


Figure 8. Regions of the beach that are safe (green coloring) versus unsafe (red, probability of failure $>10\%$) for driving based on the estimated moisture content from the SAR image collected on 08 October 2020 from the Cosmo SkyMed-2 satellite at 22:56 UTC at an incidence angle of 30.57° of Duck, NC. From Paprocki et al., *in review b*.

A data collection and post-processing procedure has been developed that enables to probabilistic prediction of trafficability of sandy beaches from multispectral or SAR images (Fig. 8). More work is needed regarding validation, investigation of the role of vertical variations of soil strength, beach slope, and the swash zone. Furthermore, more work is needed to develop a similar procedure for mixed and fine-grained sediments.

3. Results dissemination

Results were disseminated and are in progress of dissemination through publication in peer reviewed research journals, research conference contributions, a PhD thesis, and a data repository (excludes satellite images). The contributions are listed below organized by publication medium. The status is provided as published, in review, or in preparation.

Peer reviewed research journals:

Paprocki, J., Stark, N., Graber, H. C., Wadman, H., & McNinch, J. E. (2022). Assessment of moisture content in sandy beach environments from multispectral satellite imagery. *Canadian Geotechnical Journal*, 59(2), 225-238. [published]

Paprocki, J., Stark, N., Graber, H. C., Wadman, H., & McNinch, J.E. (*in review*). Estimation of Moisture Content of Sandy Beaches from X-Band Synthetic Aperture Radar. Submitted to *IEEE Transactions on Geoscience and Remote Sensing*. [in review]

Paprocki, J., Stark, N., & Wadman, H. (*in review*). A Framework for Assessing the Bearing Capacity of Sandy Coastal Soils from Remotely Sensed Data. Submitted to *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. [in review]

Stark et al. Transitioning the assessment of beach trafficability from physical testing to remote sensing. To be submitted to *Remote Sensing*. [in preparation]

Stark et al. Rapid beach sediment classification from public optic satellite imagery using an Artificial Neural Network. To be submitted to *Coastal Engineering*. [in preparation]

Paprocki, J., Stark, N., Lippmann, T., & Graber, H. C. Geotechnical Investigation of Exposed Intertidal Flats at the Great Bay Estuary. To be submitted to *Remote Sensing*. [in preparation]

Paprocki, J., Stark, N. & Lippmann, T. Geotechnical Characterization of a Tidal Estuary Mudflat Using Portable Free Fall Penetrometers. To be submitted to *ASCE Journal of Geotechnical and Geoenvironmental Engineering*. [in preparation]

Conference contributions [all published]:

Stark, N., Paprocki, J., Graber, H. C., McNinch, J., & Wadman, H. M. (2018). Geotechnical Characterization of Coastal Sediments from Satellite-Based Remote Sensing. In *AGU Fall Meeting Abstracts*, EP54B-36.

Paprocki, J., Stark, N., McNinch, J. E., & Wadman, H. (2019). Spatial and temporal variations in moisture content at a sandy beach and the impact on sediment strength. In *Geo-Congress 2019: Engineering Geology, Site Characterization, and Geophysics*. American Society of Civil Engineers, 258-265.

Paprocki, J., Stark, N., Graber, H. C., McNinch, J., & Wadman, H. (2019). Use of multispectral imagery for geotechnical characterization of sandy beach sediments. In *Coastal Sediments 2019: Proceedings of the 9th International Conference*, 2553-2565.

Stark, N., Paprocki, J., Brilli, N., McBride, C., & Graber, H. C. (2019). Rapid coastal sediment characterization from satellite imagery. In *Coastal Sediments 2019: Proceedings of the 9th International Conference*, 2607-2620.

Paprocki, J., Stark, N., & Graber, H. C. (2021). Assessment of Moisture Content of Fine-Grained Soils from Multispectral Imagery. In *International Conference on Geotechnical and Geophysical Site Characterization*. <http://isc6.org/images/Cikkek/Sessions/ISC2020-221.pdf>

Stark, N., Brilli, N., Paprocki, J., & Florence, M. In Situ and Remotely Sensed Data Collection for Geotechnical Site Characterization of Intertidal Environments with Regards to Extreme Events. In *Geo-Extreme 2021*, 382-392.

Paprocki, J., Stark, N., & Graber, H. C. (2022). Geotechnical Site Characterization of Sandy Beach Sediments from Satellite-Based Synthetic Aperture Radar Imagery. In ASCE *Geo-Congress 2022*, 12-22.

Paprocki, J., Stark, N., Graber, H., & Lippmann, T., (2022). Characterization of coastal sediments using X-band synthetic aperture radar imagery. *Ocean Sciences Meeting 2022*, virtual, February 2022.

Dissertation:

Paprocki, J. A. (2022). *A Framework for Assessing Lower-Bound Bearing Capacity of Sandy Coastal Sediments from Remotely Sensed Imagery* (Doctoral dissertation, Virginia Tech). <https://vtchworks.lib.vt.edu/handle/10919/110870> [published]

Data repository (excludes satellite images): [published]

https://data.lib.vt.edu/articles/dataset/Data_Associated_with_A_Framework_for_Assessing_Lower-Bound_Bearing_Capacity_of_Sandy_Coastal_Sediments_from_Remotely_Sensed_Imagery/19438697

4. Honors and awards

Nothing to report.

5. Training opportunities

The following students were involved and trained through participation in this project. The students are listed based on their involvement.

Data collection, processing, and dissemination:

- Julie Paprocki, graduated in Spring 2022 with a PhD in Civil Engineering

Data collection and processing:

- Parker Reed (undergraduate student in Civil Engineering)

Data collection:

- Matthew Florence, graduated in Spring 2022 with PhD in Civil Engineering
- Nick Brilli, PhD student in Civil Engineering
- Saurav Shretha, PhD student in Civil Engineering
- Albin Rosado, graduated in Fall 2021 with MS in Civil Engineering
- Liz Smith, graduated in Fall 2021 with MS in Civil Engineering

6. Technology transfer

Nothing to report.

7. Participants

<i>Virginia Tech:</i>	PI Nina Stark and students listed as under section 5.
<i>USACE:</i>	Heidi Wadman and Jesse McNinch.
<i>University of Miami:</i>	Hans C. Graber
<i>University of New Hampshire:</i>	Tom Lippmann

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- Paprocki, J. A. (2022). *A Framework for Assessing Lower-Bound Bearing Capacity of Sandy Coastal Sediments from Remotely Sensed Imagery* (Doctoral dissertation, Virginia Tech). <https://vtechworks.lib.vt.edu/handle/10919/110870>
- Paprocki, J., Stark, N., Graber, H. C., Wadman, H., & McNinch, J. E. (2022) Assessment of moisture content in sandy beach environments from multispectral satellite imagery. *Canadian Geotechnical Journal*, *59*(2), 225-238.
- Paprocki, J., Stark, N., & Graber, H. C. (2022). Geotechnical Site Characterization of Sandy Beach Sediments from Satellite-Based Synthetic Aperture Radar Imagery. In *ASCE Geo-Congress 2022*, 12-22.
- Paprocki, J., Stark, N., Graber, H. C., Wadman, H., & McNinch, J.E. (*in review*). Estimation of Moisture Content of Sandy Beaches from X-Band Synthetic Aperture Radar. Submitted to *IEEE Transactions on Geoscience and Remote Sensing*.
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REPORT DOCUMENTATION PAGE

1. REPORT DATE 28 September 2022	2. REPORT TYPE Final	3. DATES COVERED	
		START DATE June 01 2018	END DATE May 31 2022
4. TITLE AND SUBTITLE Geotechnical Soil Characterization from Remote Sensing for the Assessment of Coastline Strength, Stability, and Trafficability			
5a. CONTRACT NUMBER N00014-18-1-2435	5b. GRANT NUMBER GRANT12482729	5c. PROGRAM ELEMENT NUMBER	
5d. PROJECT NUMBER 4720004776	5e. TASK NUMBER	5f. WORK UNIT NUMBER	
6. AUTHOR(S) Nina Stark			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Virginia Tech, 300 Turner ST NW, suite 4200 Blacksburg, VA 24061-0001 USA			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) ONR		10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT approved for public release; distribution unlimited			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT The geotechnical characterization of coastal sediments is a key component for the assessment of trafficability of beaches and other coastal areas (e.g., mud flats). However, restrictions of physical access or time can disallow the deployment of common geotechnical methods. This leads to an urgent need for geotechnical soil characterization from remotely sensed data, including data collected using satellites. Correlations between geotechnical soil characteristics need to be identified, and an investigation framework for geotechnical soil characterization from remote sensing methods is needed. In this study, the derivation of moisture content, bearing capacity, and a probabilistic assessment of trafficability was targeted. The following research objectives were addressed: 1) Correlation of geotechnical soil characteristics to remotely sensed data with emphasis on multispectral reflectance and synthetic aperture radar (SAR) backscatter; 2) Analysis of moisture content with regard to changes in the SAR backscatter and multispectral reflectance; 3) Determination of optimum SAR and multispectral imaging settings to assess geotechnical soil properties, including moisture and bearing capacity. Assessment of benefits of data fusion, i.e., combination of SAR and multispectral imaging with other remote sensing techniques such as Light Detection and Ranging (Lidar); 4) Development of a data collection and processing framework to determine bearing capacity for assessing beach trafficability from multispectral images and SAR. The research objectives were achieved through controlled experiments using prepared soil patches at Kentland Farm, Blacksburg, Virginia, and field experiments on the Outer Banks and in New Hampshire. The experiments featured simultaneous data collection using remote sensing techniques, in-situ geotechnical testing, and sediment sample collection for detailed laboratory analysis. Results show that moisture content and bearing capacity variations are reflected in multispectral and SAR satellite imagery, and a trafficability assessment from satellite imagery is possible. Open questions remain related to the characterization of the beach slope, swash zone, sediment property interrelations in muddy sediments, and validation of the framework for a wide range of vehicles of interest.			

15. SUBJECT TERMS

beach trafficability, satellite-based remote sensing, geotechnical characterization

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	UU	16
19a. NAME OF RESPONSIBLE PERSON Nina Stark			19b. PHONE NUMBER (Include area code) 540-231-7152	

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE.

Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE.

State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED.

Indicate the time during which the work was performed and the report was written.

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