

**REPORT DOCUMENTATION PAGE**

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<b>4. TITLE AND SUBTITLE</b> Assessment of Lower Bound Bearing Strength of Foreshore Sediments using Remote Sensing: the role of sediment saturation, beach slope, and bearing failure type	<b>5a. CONTRACT NUMBER</b>
	<b>5b. GRANT NUMBER</b> N00014-17-1-2516
	<b>5c. PROGRAM ELEMENT NUMBER</b>

<b>6. AUTHOR(S)</b> Nina Stark	<b>5d. PROJECT NUMBER</b>
	<b>5e. TASK NUMBER</b>
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<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Virginia Polytechnic Institute and State University Office of Sponsored Programs North End Center, 300 Turner Street NW, Suite 4200 Blacksburg, VA 24061-0001	<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>
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<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> ONR REG Office Atlanta 100 Alabama Street, SW Suite 4R15 Atlanta, GA 30303	<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> ONR
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**12. DISTRIBUTION/AVAILABILITY STATEMENT**  
Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**  
Prepared in cooperation with Hans C. Graber, Heidi Wadman, Jesse McNinch

**14. ABSTRACT**  
Trafficability of foreshore sediments is a major concern for naval operations and for the response and management of evacuation efforts during extreme events. Two processes govern the trafficability of soils: bearing failure (or also referred to as sinkage) and traction failure. Both processes are functions of the soil's shear strength, and while traction failure may occur on a soil with adequate bearing, bearing failure does not occur without being accompanied by traction failure, leading often to even more dramatic challenges with regard to the remobilization of the vehicle. Therefore, the overarching research goal of this study is the assessment lower bound bearing strength of sandy foreshore sediments from remote sensing. In this project, remotely sensed data including aerial images, satellite images, radar and infrared images were collected in addition to obtaining foreshore slope and geomorphology, and geomechanical properties of foreshore sediments from traditional measuring techniques. Data collection included multiple sites characterized by different environmental conditions. Results documented a strong spatiotemporal variability of local moisture contents and bearing strength across sandy beaches. The project succeeded to demonstrate that this variability is reflected in optic and synthetic aperture radar satellite

**15. SUBJECT TERMS**  
beach trafficability; soil bearing strength; remote sensing

<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> UU	<b>18. NUMBER OF PAGES</b> 18	<b>19a. NAME OF RESPONSIBLE PERSON</b> Andrew Fortin
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			<b>19b. TELEPHONE NUMBER (Include area code)</b> 540-231-0373

**Contract Number:** N000141712516

**Title:** Assessment of Lower Bound Bearing Strength of Foreshore Sediments using Remote Sensing The role of

### **Major Goals:**

LONG-TERM GOALS: Trafficability of foreshore sediments is a major concern for naval operations and for the response and management of evacuation efforts during extreme events. Two processes govern the trafficability of soils: bearing failure (or also referred to as sinkage) and traction failure. Both processes are functions of the soil's shear strength, and while traction failure may occur on a soil with adequate bearing, bearing failure does not occur without being accompanied by traction failure, leading often to even more dramatic challenges with regard to the remobilization of the vehicle. Bearing strength and shear strength is commonly determined using in-situ tests (e.g., cone penetration testing) or laboratory tests of collected soil samples (e.g., direct or triaxial shear tests). However, time and access constraints prohibit the application of these methods in the case of many modern navy operations. Therefore, the overarching research goal of this study is the assessment lower bound bearing strength of sandy foreshore sediments from remote sensing. We plan to collect remotely sensed data including aerial images, satellite images, radar and infrared images in addition to obtaining foreshore slope and geomorphology, and geomechanical properties of foreshore sediments from traditional measuring techniques. With regard to the latter, we will specifically emphasize the investigation of the soil's shearing and bearing failure behavior, and the role of moisture content and foreshore slope. Analysis of the data will focus on the correlation of remotely sensed and traditionally (invasively) obtained data, as well as on the investigation of the role of foreshore slope and saturation on bearing failure behavior.

#### **OBJECTIVES:**

1. Investigation of the role of foreshore slope on bearing failure.
2. Investigation of the role of sediment saturation on foreshore soil bearing failure and strength.
3. Identification of the most appropriate bearing failure shape type for foreshore trafficability assessment.

### **Accomplishments Under Goals:**

#### 1) Major activities

Field measurements were completed at three different beaches (Cannon Beach, Ocean Cape Beach, and Point Carrew) in Yakutat, AK, in August 2018. All three beaches are characterized by significantly different beach profiles: Cannon Beach represents a wide sand beach with the frequent formation of a ridge-runnel system. Ocean Cape Beach is narrow and features a larger grain size distribution, reaching from cobbles and gravel to medium sand. Point Carrew can be described as a hooked spit with a very wide sand deposition area and strong variations in beach slope including a runnel system. At all three beaches the following measurements were carried out: optic and radar satellite imagery, in-situ sediment strength measurements, sediment sampling for grain size analysis and later geotechnical testing, moisture content measurements, and beach profile measurements. The data set allows uniquely to correlate in-situ strength, state of saturation, and local foreshore slope. This data set complements data collected at Duck, NC, in March 2018, by offering locations of more diverse geomorphology. Additionally, ATV vehicle tracks were recorded at different speeds along the transects where in-situ bearing strength was measured.

An initial laboratory setting was tested to investigate changes in saturation with variations in foreshore beach slope. A groundwater simulation unit was set up with a scaled beach profile of Duck, NC, composed of sediment samples from Duck. Tidal cycles were simulated and moisture content variations across the beach profile were measured at different times of tidal stage.

#### 2) Specific objectives

Data sets from different locations were collected to address the objectives listed in section 1. Results were correlated, and suggest that soil moisture content is a key parameter governing bearing strength at a sandy beach. The impact of foreshore slope seems mostly affecting bearing strength through its impacts on saturation and requires further investigation of groundwater-surface water relations and associated states of saturation and moisture contents at the foreshore. Similarly, the bearing failure seems highly dependent on the apparent cohesion and the potential development of excess pore pressures governed by state of saturation, and requires more investigation regarding soil-water retention behavior and associated strength for beach sediments, and the pore pressure behavior under loading.

## Training Opportunities:

The following graduate students were involved and trained through participation in this project:

- 1) McBride, Christopher: Review of traditional methods for the assessment of beach trafficability, M.S. Civil Engineering
  - 2) Sheppard, Jaimie: Sediment characterization from SAR, M.S. Civil Engineering
  - 3) Paprocki, Julie: Assessment of moisture contents and trafficability of coastal sediments from remote sensing, Ph.D. Civil Engineering
  - 4) Florence, Matthew; Effects of groundwater dynamics on beach trafficability, Ph.D. Civil Engineering
  - 5) Brilli, Nick: Variations of sediment strength at the foreshore, M.S. Civil Engineering.
- Three of these students represent underrepresented minorities in Civil Engineering.

## Results Dissemination

Papers in referenced conference proceedings:

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*, 258-265

Papers and posters presented at professional meetings:

Manning, M., & Stark, N. (2019) Investigating Moisture Contents of Sandy Beaches in the Context of a Geotechnical Site Characterization. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.

Stark, N., Paprocki, J., Brilli, N., McBride, C., & Graber, H. C. (2019) Rapid Coastal Sediment Characterization From Satellite Imagery. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.

Paprocki, J., Stark, N., Graber, H. C., McNinch, J., & Wadman, H. (2019). Use of multispectral imagery for geotechnical characterization of sandy beach sediments. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.

Florence, M., & Stark, N. (2019) Analysis of Vertical Pore Pressure Gradients in the Lower Intertidal Zone. *Coastal Sediments 2019*, 27-31 May 2019, St. Pete, FL, USA.

Paprocki, J., Stark, N., Graber, H.C., McNinch, J., and Wadman, H.M., 2018. Geotechnical Characterization of Coastal Sediments from Satellite-Based Remote Sensing. Abstract #EP54B-36. AGU Fall Meeting 2018, December 10-14, 2018, Washington, DC.

Reeve, B., Stark, N. and Mewis, P., 2018. Cross-shore variations in sediment strength at a sandy beach. 36th International Conference on Coastal Engineering 2018, July 30- August 3, 2018, Baltimore, MD.

## Plans Next Reporting Period

Further dissemination plans:

1) Nina Stark, Julie Paprocki, Matthew Florence, Christopher McBride, Hans Graber (2019). Assessing beach trafficability from remote sensing. Oral presentation at the Engineering Mechanics Institute Terramechanics mini-symposium, Pasadena, CA, June 2019.

2) Julie Paprocki, Nina Stark, Hans Graber (2020). Assessment of Fine-Grained Sediment Properties From Satellite-Based Imagery. Paper requested for the 6th International Conference on Geotechnical and Geophysical Site Characterization, Budapest, Hungary, June 2020.

3) Paprocki et al. Estimating in-situ moisture contents of sandy beaches from optic satellite imagery. To be submitted to *Canadian Geotechnical Journal*.

4) Stark et al. Transitioning the assessment of beach trafficability from physical testing to remote sensing. To be submitted to *Remote Sensing*.

The results obtained will also contribute to advance progress in project N00014-18-1-2435.

## Honors and Awards

Nothing to Report

## Protocol Activity Status

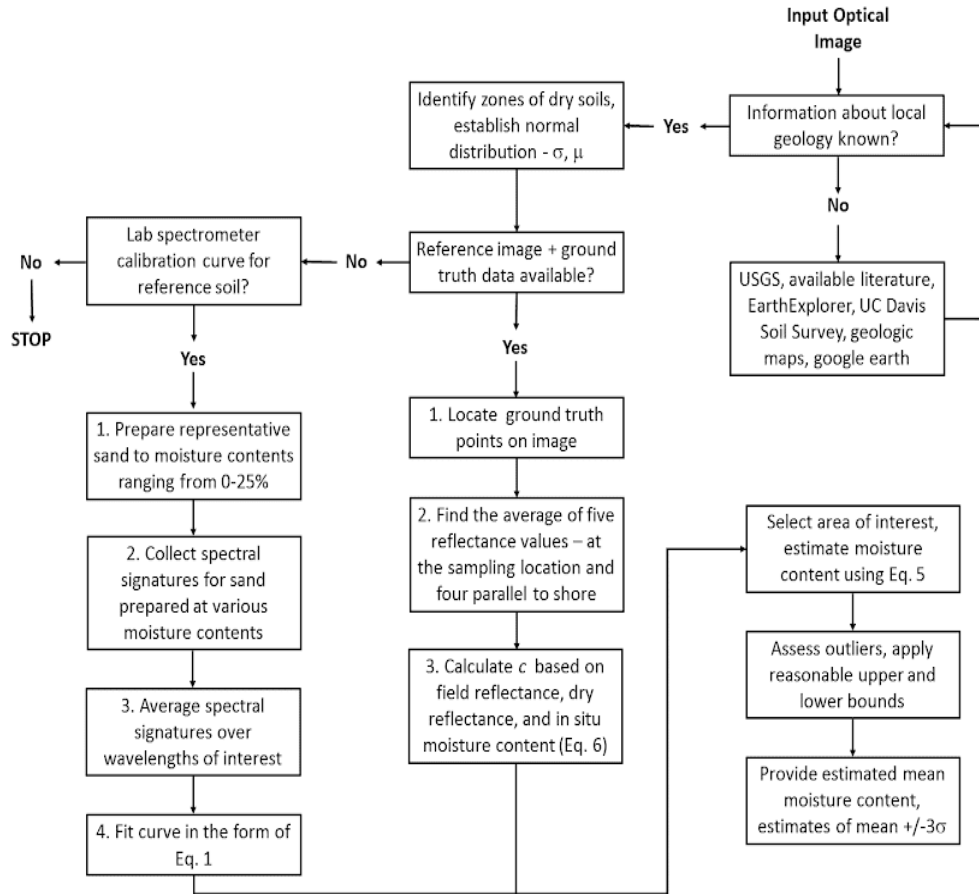




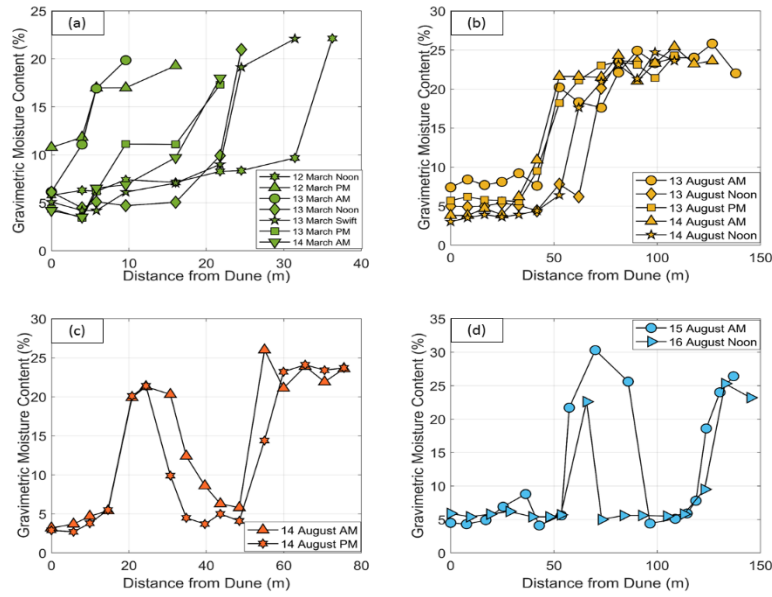


More recent results that will be integrated in upcoming publications:

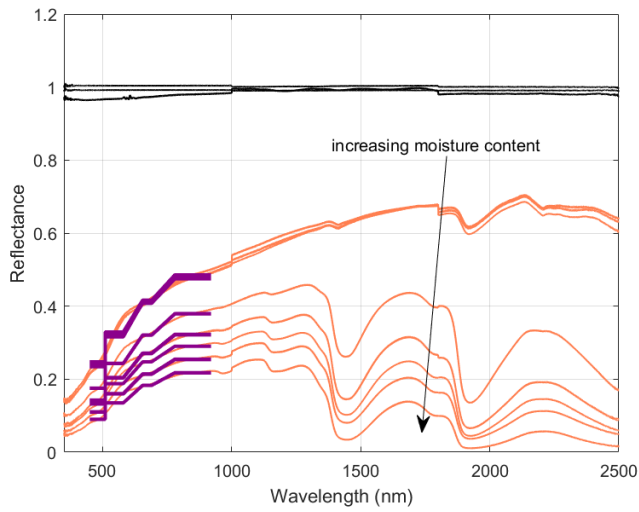
- 1) Flowchart outlining the analysis process used to calibrate model based on input data and estimate moisture content.



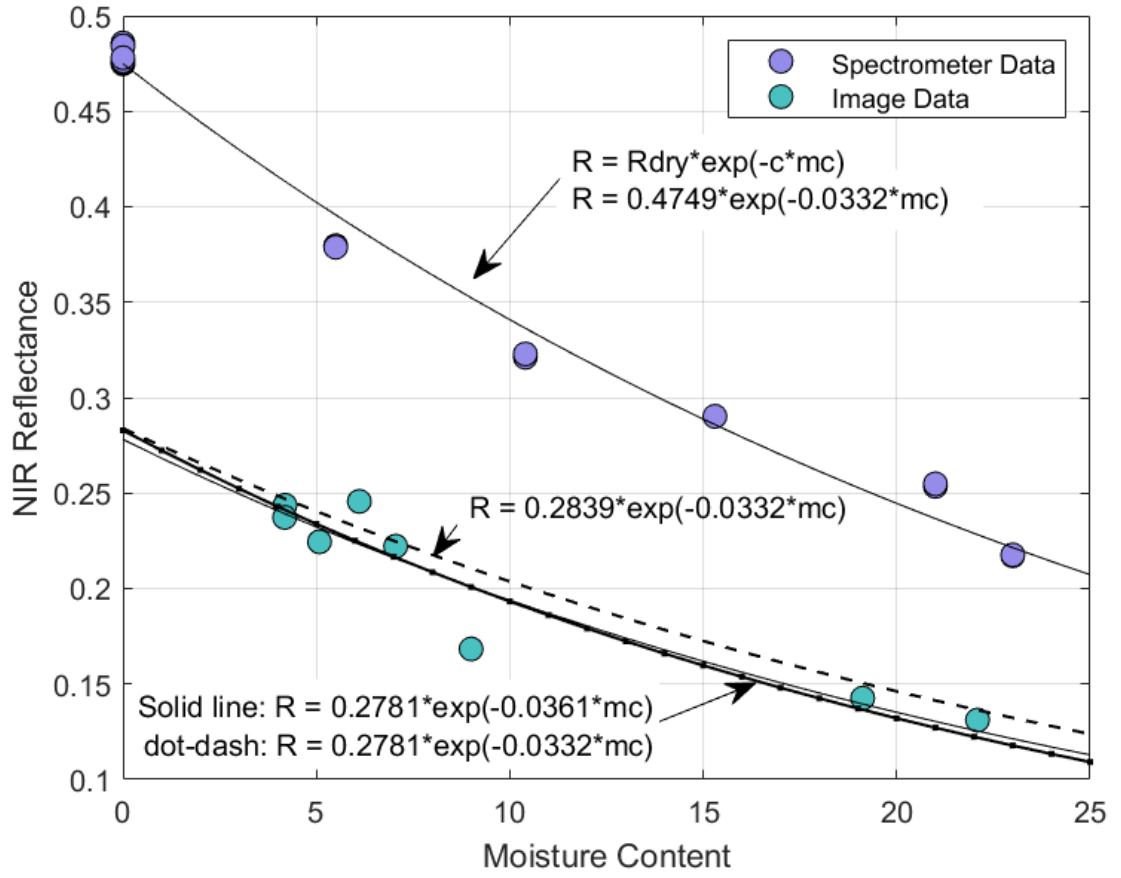
- 2) Moisture content profiles for (a) Duck, NC in March 2018, (b) Cannon Beach, Yakutat, AK, (c) Ocean Cape, Yakutat, AK, and (d) Point Carrew, Yakutat, AK. All profiles for the beaches near Yakutat, AK are from August 2018.



3) Figure 3. Signatures obtained from the spectrometer



4) Comparison of data from spectrometer and satellite image.



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**Contract Number:** N000141712516

**Title:** Assessment of Lower Bound Bearing Strength of Foreshore Sediments using Remote Sensing The role of

### **Major Goals:**

LONG-TERM GOALS: Trafficability of foreshore sediments is a major concern for naval operations and for the response and management of evacuation efforts during extreme events. Two processes govern the trafficability of soils: bearing failure (or also referred to as sinkage) and traction failure. Both processes are functions of the soil's shear strength, and while traction failure may occur on a soil with adequate bearing, bearing failure does not occur without being accompanied by traction failure, leading often to even more dramatic challenges with regard to the remobilization of the vehicle. Bearing strength and shear strength is commonly determined using in-situ tests (e.g., cone penetration testing) or laboratory tests of collected soil samples (e.g., direct or triaxial shear tests). However, time and access constraints prohibit the application of these methods in the case of many modern navy operations. Therefore, the overarching research goal of this study is the assessment lower bound bearing strength of sandy foreshore sediments from remote sensing. We plan to collect remotely sensed data including aerial images, satellite images, radar and infrared images in addition to obtaining foreshore slope and geomorphology, and geomechanical properties of foreshore sediments from traditional measuring techniques. With regard to the latter, we will specifically emphasize the investigation of the soil's shearing and bearing failure behavior, and the role of moisture content and foreshore slope. Analysis of the data will focus on the correlation of remotely sensed and traditionally (invasively) obtained data, as well as on the investigation of the role of foreshore slope and saturation on bearing failure behavior.

#### **OBJECTIVES:**

1. Investigation of the role of foreshore slope on bearing failure.
2. Investigation of the role of sediment saturation on foreshore soil bearing failure and strength.
3. Identification of the most appropriate bearing failure shape type for foreshore trafficability assessment.

### **Accomplishments Under Goals:**

The impacts of beach slope, moisture content and sediment characteristics on sediment strength: Cross-shore variations in grain size distribution, beach slope, and sediment strength were measured at three sandy beaches in Duck, NC, Yakutat, AK, and Sylt, Germany. All three beaches were characterized by different beach slopes, with Yakutat being characterized by a ridge runnel system. All three beaches exhibited minor to moderate variations in grain size along cross-shore transects, and moderate variations with sediment depth. Distinct variations in sediment strength were observed using penetrometer testing, being governed by grain size variations but mostly by differences in moisture content. Pore pressure measurements were conducted at different sediment depths and different cross-shore locations at all three beaches to monitor surface and groundwater dynamics, as well as to investigate potential impacts of excess pore pressure on soil strength and liquefaction. Negative as well as positive excess pore pressures were observed in response to wave-related hydrostatic pressure fluctuations. Furthermore, data suggested the development of partially saturated sediment layers that may contribute to sediment strength in the swash zone by negative excess pore pressures. These data sets contribute to the fundamental understanding of variations in sediment and bearing strength in response to beach slope and moisture content. In addition to the previously mentioned data sets, data was collected in May 2017 from Cannon Beach in Yakutat, AK, with a stronger emphasis on in-situ strength measurements, and friction angles. Another comprehensive data set was obtained in Duck, NC, in March 2018, with emphasis on moisture content and beach slope variations, as well as ground water dynamics. Data is still being analyzed.

Correlation to remote sensing: Optic and radar satellite imagery was collected from the location of the Unmanned Warrior 2016 experiment Scotland, United Kingdom; from Duck, NC, in 2016 and 2018; and from Yakutat, AK, in 2017. Radar satellite images from Duck, NC, in 2016, collected using TerraSAR-X, were qualitatively compared to moisture content variations across the foreshore, and yielded a favorable match. Challenges associated to a quantitative correlation are related to a non-linear relationship between moisture content and radar backscatter intensity, and the impact of variations in moisture content with sediment depth. A comprehensive data set of spatial and temporal variations of surficial moisture contents, groundwater and surface water dynamics, and sediment strength testing was collected in Duck, NC in March 2018. These measurements were complemented by simultaneous satellite-based multispectral and radar imagery with high resolution. Data processing is still ongoing. Existing in-situ data, including cone indices as traditionally used for beach trafficability assessment from the Unmanned Warrior 2016 experiment were retrieved, and were

correlated to grain size distributions and moisture content. A comparison to the remotely obtained data is ongoing.

### **Training Opportunities:**

Five graduate students and two undergraduate students received training in geotechnical engineering, coastal sciences, remotely sensed data, and reporting.

### **Results Dissemination**

#### ARTICLES

Nina Stark, J. McNinch, H. Wadman, H.C. Graber, A. Albatat, and P.A. Mallas, Friction angles at sandy beaches from remote imagery, *Geotechnique Letters*, Volume: 7, Issue: 4, First Page Number: 292, Date Published: 01/02/2018, Publication Status: Published, Publication Type: Other, Publication ID , Peer Reviewed: Y, Federal Support Acknowledgement: Y.

Nina Stark, J. Sheppard, H.C. Graber, J.E. McNinch, H. Wadman, Geotechnical Characterization of Beach Sediments using SAR: Ideas, Challenges and Preliminary Data, 12th European Conference on Synthetic Aperture Radar, Volume: , Issue: , First Page Number: , Date Published:, Publication Status: In press, Publication Type: Other, Publication ID , Peer Reviewed: Y, Federal Support Acknowledgement: Y.

Cagdas Bilici, N. Stark, A. Albatat, J.E. McNinch, H. Wadman, Quantifying the effect of wave action on seabed surface sediment strength using a portable free fall penetrometer, CPT'18, Volume: , Issue: , First Page Number: , Date Published:, Publication Status: In press, Publication Type: Other, Publication ID , Peer Reviewed: Y, Federal Support Acknowledgement: Y.

#### CONFERENCE PRESENTATIONS BASED ON ABSTRACTS

Nina Stark, J.E. McNinch, H. Wadman, H.C. Graber, A. Albatat, and P.A. Mallas, Friction Angles at Sandy Beaches from Remotely Sensed Imagery, *Ocean Sciences Meeting 2018*, Date Published: 12/15/2017, Publication Status: Published, Publication Type: Other, Publication ID 302062, Peer Reviewed: Y, Federal Support Acknowledgement: Y.

Nina Stark, J. Paprocki, V. Jones, Spatial and Temporal Variations in Moisture Content at a Sandy Beach and the Impact on Sediment Strength, *ASCE Geo-Congress 2019*, Date Published:, Publication Status: Accepted, Publication Type: Other, Publication ID 0137\_0212\_00201, Peer Reviewed: Y, Federal Support Acknowledgement: Y.

Bridgit Reeve, N. Stark, P. Mewis, Cross-Shore Variations In Sediment Strength At A Sandy Beach, *International Conference for Coastal Engineering 2018*, Date Published:, Publication Status: Accepted, Publication Type: Other, Publication ID 1172, Peer Reviewed: Y, Federal Support Acknowledgement: Y.

Madeline Manning, B Reeve, J. Sheppard, N. Stark, Novel Methods for In-situ Geotechnical Characterization of Sandy Beaches and its Importance for Coastal Erosion, *IEEE/MTS Oceans 2018*, Date Published:, Publication Status: In review, Publication Type: Other, Publication ID 180225-001, Peer Reviewed: Y, Federal Support Acknowledgement: Y.

### **Plans Next Reporting Period**

During the next reporting period, the following aspects will be addressed: 1) Detailed analysis of infrared imagery from Claytor Lake state park beach. 2) Statistical analysis of impacts of resolution, number of images, and environmental conditions on the determination of friction angles from local slope angles. 3) Document and relate variations of moisture content, beach slope, bearing failure type and sediment strength across the foreshore. 4) Correlate cone indices to sediment characteristics that can be inferred from remote sensing. 5) Correlate remote sensing images with geotechnical parameters. 6) Test derived relationships in

different environments.

Additional this research will be expanded in scope and detail in the framework of the Young Investigator Award 2018 project titled: "Geotechnical Soil Characterization from Remote Sensing for the Assessment of Coastline Sediment Strength, Stability and Trafficability" focusing on data fusion of satellite-based optic and radar imagery to develop a framework to determine geotechnical properties and coastal trafficability from remote sensing.

### Honors and Awards

Nothing to Report

### Protocol Activity Status

### Technology Transfer

Nothing to Report

### Distribution Statement:

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Approved for public release; distribution is unlimited.

### Participants

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<b>First Name:</b>	Nina	<b>Last Name:</b>	Stark
<b>Project Role:</b>	PD/PI		
<b>National Academy Member:</b>	N	<b>Months Worked:</b>	2
<b>Countries of Collaboration</b>			

<b>First Name:</b>	Bernardo	<b>Last Name:</b>	Castellanos
<b>Project Role:</b>	Staff Scientist (doctoral level)		
<b>National Academy Member:</b>	N	<b>Months Worked:</b>	1
<b>Countries of Collaboration</b>			



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**First Name:** Madeline                      **Last Name:** Manning

**Project Role:** Undergraduate Student

**National Academy Member:** N                      **Months Worked:** 1

**Countries of Collaboration**

## **Assessment of Lower Bound Bearing Strength of Foreshore Sediments using Remote Sensing: The role of sediment saturation, beach slope and bearing failure type**

Dr. Nina Stark

Virginia Tech, Blacksburg, VA 24061  
ninas@vt.edu

Award Number: N00014-17-1-2516

### **MAJOR GOALS**

**LONG-TERM GOALS:** Trafficability of foreshore sediments is a major concern for naval operations and for the response and management of evacuation efforts during extreme events. Two processes govern the trafficability of soils: bearing failure (or also referred to as sinkage) and traction failure. Both processes are functions of the soil's shear strength, and while traction failure may occur on a soil with adequate bearing, bearing failure does not occur without being accompanied by traction failure, leading often to even more dramatic challenges with regard to the remobilization of the vehicle. Bearing strength and shear strength is commonly determined using in-situ tests (e.g., cone penetration testing) or laboratory tests of collected soil samples (e.g., direct or triaxial shear tests). However, time and access constraints prohibit the application of these methods in the case of many modern navy operations. Therefore, the overarching research goal of this study is the assessment lower bound bearing strength of sandy foreshore sediments from remote sensing. We plan to collect remotely sensed data including aerial images, satellite images, radar and infrared images in addition to obtaining foreshore slope and geomorphology, and geomechanical properties of foreshore sediments from traditional measuring techniques. With regard to the latter, we will specifically emphasize the investigation of the soil's shearing and bearing failure behavior, and the role of moisture content and foreshore slope. Analysis of the data will focus on the correlation of remotely sensed and traditionally (invasively) obtained data, as well as on the investigation of the role of foreshore slope and saturation on bearing failure behavior.

**OBJECTIVES:** 1. Investigation of the role of foreshore slope on bearing failure.  
2. Investigation of the role of sediment saturation on foreshore soil bearing failure and strength.  
3. Identification of the most appropriate bearing failure shape type for foreshore trafficability assessment.

### **ACCOMPLISHED**

*The impacts of beach slope, moisture content and sediment characteristics on sediment strength:* Cross-shore variations in grain size distribution, beach slope, and sediment strength were measured at three sandy beaches in Duck, NC, Yakutat, AK, and Sylt, Germany. All three beaches were characterized by different beach slopes, with Yakutat being characterized by a ridge runnel system. All three beaches exhibited minor to moderate variations in grain size along cross-shore transects, and moderate variations with sediment depth. Distinct variations in sediment strength were observed using penetrometer testing, being governed by grain size variations but mostly by differences in moisture content. Pore pressure measurements were conducted at different sediment depths and different cross-shore locations at all three beaches to

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## **PLANS**

During the next reporting period, the following aspects will be addressed: 1) Detailed analysis of infrared imagery from Claytor Lake state park beach. 2) Statistical analysis of impacts of resolution, number of images, and environmental conditions on the determination of friction angles from local slope angles. 3) Document and relate variations of moisture content, beach slope, bearing failure type and sediment strength across the foreshore. 4) Correlate cone indices to sediment characteristics that can be inferred from remote sensing. 5) Correlate remote sensing images with geotechnical parameters. 6) Test derived relationships in different environments.

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## **TECHNOLOGY TRANSFER**

Nothing to Report

## **ARTICLES**

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## **PARTICIPANTS**

Dr. Nina Stark, PI, Months Worked: 1.5

Dr. Bernardo Castellanos, Laboratory manager, Months worked: 0.15

Jamie Sheppard, Graduate student, Months worked: 3

Julie Paprocki, Graduate student, Months worked: 2

Brigit Reeve, Graduate student, Months worked: 2

Chris McBride, Graduate student, Months worked: 2

Madeline Manning: Undergraduate student, Months worked: 0.5

Victoria Jones. Undergraduate student, Months worked: 0.3