# FIELD OBSERVATIONS AND MODELING OF BEACH CUSP EVOLUTION IN THE PRESENCE OF AN ARTIFICIAL VEGETATION PATCH

Maqsood Mansur, Northeastern University, mansur.m@northeastern.edu; Reza Salatin, Northeastern University, salatin.r@northeastern.edu; Tyler McCormack, Northeastern University, mccormack.ty@northeastern.edu; Qin Chen, Northeastern University, q.chen@northeastern.edu; Julia Hopkins, Northeastern University, ju.hopkins@northeastern.edu; Patrick J. Dickhudt, US Army Corps of Engineers, Field Research Facility, patrick.j.dickhudt@erdc.dren.mil

## INTRODUCTION

Coastal erosion is a global problem. Sea level rise and climate change will exacerbate the retreat of coastlines (Houghton, 1996; Watson et al., 1996; Leatherman et al., 2000). Vegetation has been shown to reduce beach erosion by attenuating wave energy and trapping sediments (Feagin et al., 2015). To date, most of the studies on erosion reduction by vegetation are either theoretical, numerical, or based on laboratory experiments. Field data that quantify the effectiveness of beach vegetation as a protective measure against erosion is sparse owing to the difficulty in conducting controlled field experiments (Feagin et al., 2015). To improve our understanding of wave-beach-vegetation interaction, we conducted a field experiment from September 19 to October 10, 2021, at the US Army Corps of Engineers' Field Research Facility (FRF) in Duck, North Carolina, as part of DUNEX (DUring Nearshore Event eXperiment). For this experiment, we installed a patch of artificial vegetation in the swash zone, constructed out of materials with known mechanical properties, to test how beach vegetation attenuates wave energy and reduces erosion. It is to be noted that we used zipties to build our vegetation patch.

Figure 1 – Example of beach cusps formed at Duck, North Carolina, USA (Ciriano et al., 2005).

A notable outcome of our study was the observation of a field of beach cusps that formed on September 26, 2021, three days after installing the artificial vegetation patch on the beach. These cusps were washed out during a storm event on October 10, 2021. Beach cusps are rhythmic crescentic morphological patterns consisting of steep seaward protruding horns separated by gently curving embayments, typically observed in the swash zone of sandy and gravel beaches (Dodd et al., 2008; Vousdoukas, 2012; see also Fig. 1), with alongshore spacing ranging from 1 to 50 m (Dodd et al., 2008). Since vegetative landscapes can have non-linear interactions with sediment transport processes and the resulting self-organization of the emerging morphology (Baas, 2002), this study aims to establish a link between vegetation and the observed beach cusp formation and evolution.

Self-organization through coupled topographic-hydrodynamic feedback mechanism is one of the primary theories of beach cusp formation (Werner & Fink, 1993). On a flat beach, once surface areas develop with slightly lower relief than their surroundings, they attract and accelerate water particles, which means they have more energy, and thus, the area is eroded further. Through this positive feedback, the area becomes more and more eroded, and this creates the embayment. Areas adjacent to the embayment become areas of higher relief. These areas of higher relief slow the water down and sediment is deposited on top of them, creating the horns. In this way, interaction between the water flow and the bedform creates the beach cusps (Werner & Fink, 1993).

Formation of beach cusps by standing edge waves is another widely accepted theory of beach cusp development. Edge waves form a standing pattern with a periodic sequence of high and low amplitudes in the alongshore. These standing edge-wave patterns are hypothesized to imprint on the shoreline, giving rise to beach cusps (Guza & Inman, 1975; Inman & Guza, 1982).

Previous field studies have provided evidence supporting both theories (Coco et al., 2003; Ciriano et al., 2005; Ali et al., 2017). However, it is unclear how these mechanisms act independently or combine in certain beach scenarios to encourage beach cusp formation (Coco et al., 1999). One suggestion is that combination of both theories might be responsible for beach cusp formation since edge waves do not persist once the beach cusp is initiated (Inman & Guza, 1982). Moreover, in a field experiment on an embayed beach in Japan, facing the Pacific Ocean, beach cusp formation was thought to be triggered by a topographic depression owing to the presence of boulders at the end of the plane beach (Sunamura & Aoki, 2000). This suggests that bedform irregularities can cause swash flow perturbations resulting in beach cusp formation. Thus, there exist a possibility that the vegetation patch we installed on the FRF beach might have resulted in some topographic irregularities, which in turn caused changes in the swash dynamics and ultimately gave rise to a field of beach cusps.

In this study, field observations and field validated XBeach model are integrated to understand the beach morphological changes in the presence of an artificial vegetation patch. We investigate the relationship, between the presence of the patch and (a) observed accretion and erosion, around and through the patch as well as (b) observed beach cusp formation and evolution. We test the hypothesis that the artificial vegetation patch installed during the field experiment triggered topographic and swash flow perturbations that ultimately resulted in beach cusp development.

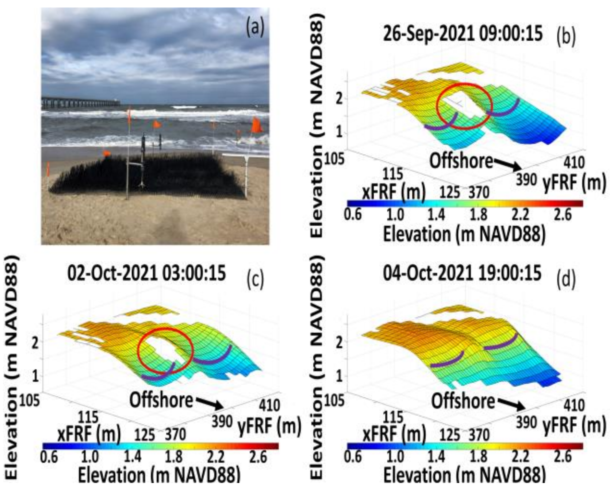

Figure 2 – (a) the instrumented (mounted by the poles) artificial vegetation patch (marked by the safety flags) on the FRF beach to the south of the research pier on the background, and surface elevation around the patch on (b) September 26, 2021, (c) October 02, 2021, and (d) October 04, 2021. x and y axes show the FRF coordinates, and z axis shows the elevation in meters with respect to NAVD88. The color bar also shows the elevation in meters with respect to NAVD88. The white areas marked by red circle are the vegetation shadow because the laser scanner could not penetrate the patch. The undulations on the plots marked by violet arcs suggest beach cusp formation and evolution.

METHODOLOGY

For the artificial vegetation patch field experiment, we installed a 5mx5m artificial vegetation patch made of cable ties, 33 cm long and 0.5 cm wide, about 20m from the shoreline to the south of the FRF pier on September 23, 2021 (Fig. 2a). We measured pressure (RBRs), velocity (ADVs), current profiles (ADCP) and surface activity (cameras) around and through the patch. We surveyed the topography daily across the patch, through the patch and seaward of the patch. We obtained beach elevation profiles from the Lidar scanning of the beach from the FRF research pier on an hourly basis and the daily topographic surveys ("FRF Data Portal," n.d.). We assessed the accretional and erosional trends around the patch and the beach cusp evolution. Further, we tracked the swash dynamics, including swash excursion, height, and slope measurement, using coastal imagery of Lidar wave runup and video cameras located at the FRF research pier (Fig. 3). We use the wave measurements from the FRF's offshore 8m Array to identify the wave conditions responsible for beach cusp formation and evolution in presence of the vegetation patch (Fig. 4).

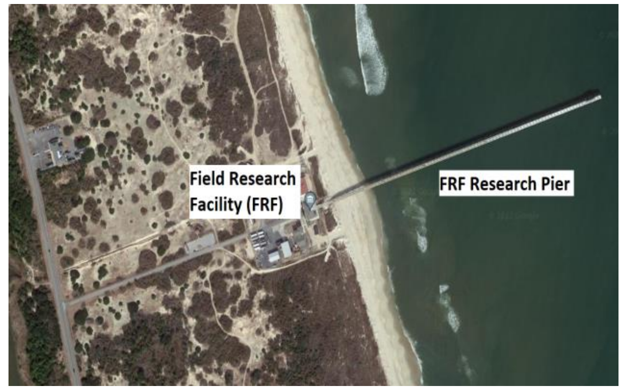

Figure 3 – Google Earth image of the FRF showing the research pier. Lidar and video cameras are mounted on the beach side of the pier. The artificial vegetation patch was installed to the south side of the pier.

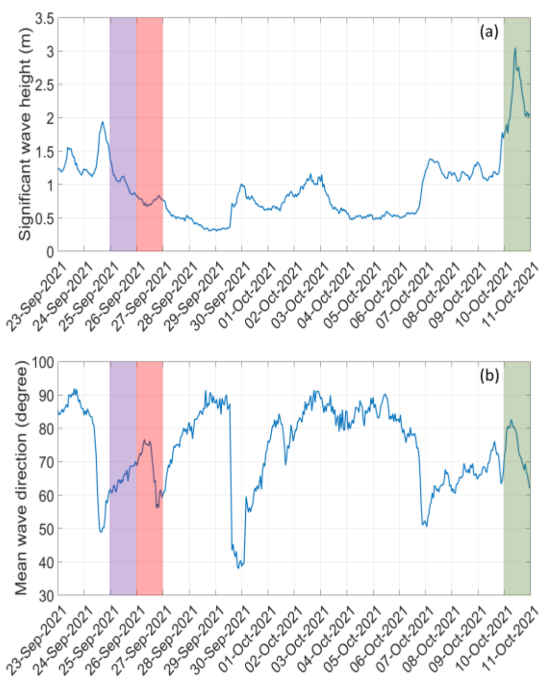

Figure 4 – (a) Significant wave height (observed) vs date and (b) Mean wave direction (observed) vs date. It is to be noted that the wave data are obtained from the FRF's offshore 8m Array. The artificial vegetation patch was installed on September 23, 2021. The beach cusps started appearing on September 25, 2021, marked by the purple shaded area; they became prominent on September 26, 2021, marked by the red shaded area; and they were destroyed during the storm on October 10, 2021, marked by the green shaded area.

After the field experiment, we used the data to spin up an XBeach model to study the dynamics of the observed morphology. XBeach has been shown to be an effective tool to simulate beach cusps (Daly et al., 2021). We initialized the default surf beat mode of XBeach using bathymetry data from the FRF website ("FRF Data Portal," n.d.), water level data obtained from the NOAA station 8651370 at Duck, North Carolina, and wave data from the FRF's 8m Array. These inputs were applied to a structured grid which spans 300 m in the alongshore direction and 900 m in the cross-shore direction. A uniform grid size of 2.5 m was used in the alongshore direction. The grid spacings varied in the cross-shore direction from the offshore model boundary to the surf and swash zone. Cross-shore spacing of 1 m was used in the surf and swash zone. The offshore model boundary was at approximately 9 m depth; a maximum cross-shore spacing of 5 m was used at our model boundary, which gradually decreased towards the grid resolution of the surf and swash zone.

## RESULTS

An initial analysis of the data shows that beach cusps started appearing on September 25, 2021 and became prominent on September 26, 2021 (Fig. 3b) under accretional conditions. The cusps were observed to move in the northward alongshore direction. Finally, the cusps underwent planation (leveling of a landscape) during the storm on October 10, 2021 owing to the erosional processes of elevated water levels and high waves.

We analyze the wave height, period, and direction in the time of beach cusp formation as simulated by the XBeach model and corroborated with the field data to identify the wave conditions responsible for beach cusp initiation and evolution. We simulate the cusp features (cusp spacing and vertical height) around the vegetation patch extracted from model output bed level data and verified by the field observations.

Two relations are usually used to test the edge wave theory and the self-organization theory, respectively:
(a) for standing wave theory (Coco et al., 1999),

$$\lambda = m\frac{g}{\pi}T^2 sin\beta \quad (1)$$

where, $\lambda$ is the cusp spacing, $g$ is the acceleration due to gravity, $T$ is the incoming wave period, $\beta$ is the beach slope and m is constant whose value is equal to 1 and 0.5 for sub-harmonic and synchronous edge waves, respectively.
(b) for self-organization theory (Coco et al., 1999),

$$\lambda = fS \quad (2)$$

where, $S$ is the swash length and $f$ is a constant with a value between 1 and 3.

Using these relationships and our model, we find the relation between the cusp spacing and (a) incident wave and beach characteristic, as well as (b) swash length. Finally, we compare the morphological changes obtained from model results, with and without the vegetation patch.

## REFERENCES


Ali, Darsan & Wilson (2017): Cusp morphodynamics in a micro-tidal exposed beach, Journal of Coastal Conservation, 21(6), 777-788.
Baas (2002): Chaos, fractals and self-organization in coastal geomorphology: simulating dune landscapes in vegetated environments, Geomorphology, 48(1-3), 309-328.
Ciriano, Coco, Bryan & Elgar (2005): Field observations of swash zone infragravity motions and beach cusp evolution, Journal of Geophysical Research: Oceans, 110(C2).
Coco, Burnet, Werner & Elgar (2003): Test of self-organization in beach cusp formation, Journal of Geophysical Research: Oceans, 108(C3).
Coco, O'Hare & Huntley (1999): Beach cusps: a comparison of data and theories for their formation, Journal of Coastal Research, 741-749.
Daly, Floc'h, Almeida, Almar, & Jaud (2021): Morphodynamic modelling of beach cusp formation: The role of wave forcing and sediment composition, Geomorphology, 389, 107798.
Dodd, Stoker, Calvete, & Sriariyawat (2008): On beach cusp formation, Journal of Fluid Mechanics, 597, 145-169.
Feagin, Figlus, Zinnert, Sigren, Martínez, Silva, ... & Carter (2015): Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. Frontiers in Ecology and the Environment, 13(4), 203-210.
FRF Data Portal (n.d.): Retrieved from https://frfdataportal.erdc.dren.mil/#
Guza & Inman (1975): Edge waves and beach cusps, Journal of Geophysical Research, 80(21), 2997-3012.
Houghton (1996): Climate change 1995: The science of climate change: contribution of working group I to the second assessment report of the Intergovernmental Panel on Climate Change (Vol. 2), Cambridge University Press.
Inman & Guza (1982): The origin of swash cusps on beaches, Marine Geology, 49(1-2), 133-148.
Leatherman, Zhang, & Douglas (2000): Sea level rise shown to drive coastal erosion, Eos, Transactions American Geophysical Union, 81(6), 55-57.
Sunamura, & Aoki (2000): A field experiment of cusp formation on a coarse clastic beach using a suspended video-camera system, Earth surface processes and landforms, 25(3), 329-333.
Vousdoukas (2012): Erosion/accretion patterns and multiple beach cusp systems on a meso-tidal, steeply-sloping beach, Geomorphology, 141, 34-46.
Watson, Zinyowera, & Moss (1996): Climate change 1995. Impacts, adaptations and mitigation of climate change: scientific-technical analyses.
Werner & Fink (1993): Beach cusps as self-organized patterns, Science, 260(5110), 968-971.