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# Centrifuge modelling of mangrove root-inspired systems for coastal protection

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**ABSTRACT:** Coastal zones are increasingly threatened by climate change-driven hazards such as sea level rise, intensified storm surges, and progressive shoreline erosion. Traditional engineering solutions (such as seawalls, revetments, etc.), while effective in specific locations, often lead to unintended ecological damage. As a sustainable alternative, this study investigates the use of mangrove root-inspired systems for enhancing coastal resilience through a combination of bio-inspired design, physical modelling, and centrifuge testing. The research aims to replicate and assess the stabilizing effect of mangrove root in the United Arab Emirates (UAE) coastal environment. Natural tree roots were scanned using 3D imaging, and digitally processed to extract morphological and architectural traits. A modular test package was designed and assembled for use in a geotechnical centrifuge facility, incorporating a custom wave generator and sloped test bed to simulate realistic coastal boundary conditions under elevated gravitational acceleration. One pilot centrifuge test is conducted at 30g. Results indicate that wave-induced erosion is dominated by an initial adjustment phase, followed by a transition to a quasi-stable bed state. This work contributes to the growing field of nature-based solutions by offering an innovative approach that combines ecological mimicry with physical modelling.

## 1 INTRODUCTION

Coastal regions represent some of the most dynamic and socio-economically important environments worldwide, yet they are increasingly exposed to climate change-induced shoreline erosion. Nature-based solutions have emerged as a promising alternative by leveraging biological systems (Martinez et al., 2022; Ng et al., 2026) that inherently adapt to dynamic coastal conditions. Despite growing interest in bioinspired coastal protection, experimental validation of mangrove root-soil-hydrodynamic interactions under realistic stress conditions remains limited. The study focuses on the grey mangrove (Avicennia marina), the dominant mangrove species along the UAE coastline and aims to quantify the interaction and mechanisms of root-like structures for resilient, eco-inspired coastal infrastructure.

## 2 CENTRIFUGE MODELLING FOR COASTAL RESILIENCE

Centrifuge modelling has proven effective for studying varying geotechnical infrastructures to make informed design decisions. The geotechnical centrifuge at NYU Abu Dhabi, used in the present study has a maximum capacity of 260 g-ton with an effective radius of 5 m.

The geotechnical centrifuge modelling technique coupled with additive manufacturing, 3D printing technology, and hydraulic simulation enables realistic replication of coastal loading conditions. Further, it is necessary to define representative prototype root, wave and tidal parameters from the UAE coastline.

Natural mangrove specimens are scanned using a high-resolution structured-light 3D scanner to get point-cloud data to extract key morphological and architectural features. The processed geometries were scaled according to centrifuge similitude laws (Sousa et al., 2024) and fabricated using a PolyJet digital rigid flex composite (tensile strength ≈ 6 MPa, Young's modulus ≈ 50 MPa) to produce flexible yet self-supporting root analogues, as shown in Figure 1.

The soil material was obtained from the Saadiyat Island coastal deposits of Abu Dhabi to represent typical nearshore sediments. Based on laboratory investigation, the soil is classified as non-plastic silty sand (SM) under the Unified Soil Classification System (USCS), with $D_{50}$ of 0.11 mm, specific gravity of 2.50, and in-situ density of 1.28 gm/cc. The tree was selected such that no other trees were present nearby. A circular area of 2.5 m diameter around the tree was cordoned off and excavated to a 0.6 m to extract the tree. The soil adhering to the roots was washed, and no root damage was observed.

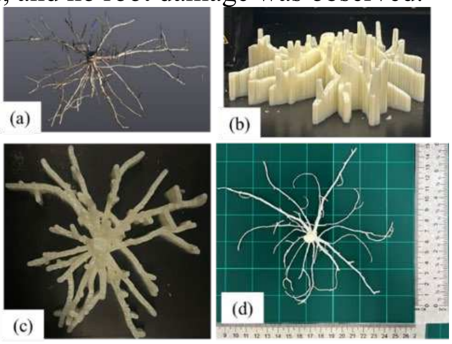


*Figure 1. Illustration of root system (a) Texture and mesh model after 3D scan, (b) & (c) during 3D printing, (d) final model roots.*

The experimental setup consists of a rigid aluminium strongbox (1240 mm × 365 mm × 480 mm) that enables investigation of wave-soil-root interaction under scaled coastal boundary conditions and a wave loading simulator (electro-hydraulic piston actuator) which drives a vertical paddle system. The paddle is capable of producing controlled, repeatable waves with frequencies ranging from 0.5 to 10 Hz. Further, the model gets instrumented with pore pressure transducers, displacement sensors, and video cameras.

One centrifuge model test was conducted at 30g on a pilot basis to understand the efficacy of the developed model test package. The model bed was prepared using the Saadiyat Island silty sand (SM) by underwater pluviation to achieve a medium to loose state (target $Dr \approx 40$ to 50%). The printed roots were embedded within the soil bed, after which additional soil layers were placed using the same technique. Baseline photographs and 3D surface scans (Pre-profile 1) were obtained at 1g, as shown in Figure 2. This ensures quantitative assessment of soil response using pre-test and post-test profiles. The model was then spun up to 30g, allowed to stabilize, and subjected to controlled wave loading while synchronized data acquisition and imaging captured model response. Surface change between test stages was quantified using an elevation difference approach, with a conservative ±1 mm threshold applied to suppress scan-scale noise.

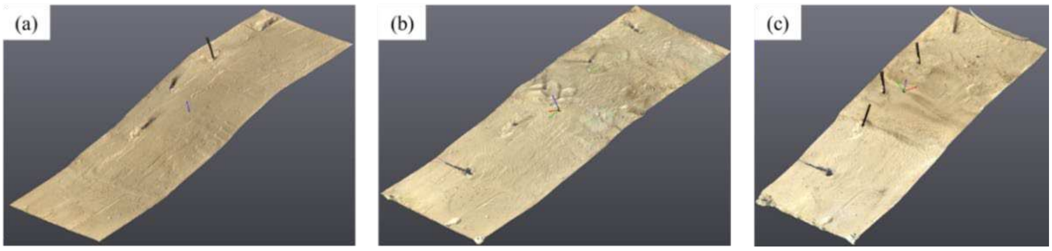


*Figure 2. 3D scan of the model soil surface (a) Baseline, (b) Post-wave profile 1, and (c) Post-wave profile 2.*

## 3 CONCLUSIONS

The pilot centrifuge test establishes that wave-induced erosion in loose coastal soils is dominated by an initial adjustment phase, during which the soil rapidly transitions to a mechanically stable configuration. Once this state is achieved, further wave loading produces only limited, spatially constrained sediment redistribution, indicating a sharp reduction in erosion susceptibility. While the results are based on a single configuration, the study demonstrates the capability of centrifuge-based wave modeling and surface differencing techniques to resolve erosion mechanisms at prototype stress levels and provides a robust baseline for future parametric investigations of bio-inspired coastal stabilization systems. These outcomes are essential for translating nature-inspired concepts into performance-based coastal protection designs.

## ACKNOWLEDGEMENTS

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