First Observations of Saltmarsh Cliff Erosion Mechanics During Extreme Storm Conditions in a Full-Scale Wave Flume

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Abstract. Saltmarshes provide many vital ecosystem services, like wave dampening and carbon sequestration. These services are under pressure since saltmarshes are eroding worldwide. The erosion mechanics of saltmarshes are not well understood, especially during extreme storm conditions. Full-scale flume experiments were conducted on a real-life transplanted Dutch Wadden sea saltmarsh with a common brushwood dam protecting the marsh edge, to test the erosion resistance during extreme wave conditions. Little erosion occurred on the marsh platform during 40 h of exposure to various wave conditions, with most of the significant erosion occurring at the seaward edge of the marsh. Erosion was initiated by damaging and uprooting of the vegetation, exposing the substrate and leading to gradual erosion. Uprooting events frequency and erosion rates were higher during high wave conditions and water depths ($H_{m0} = 2$ m and $d_m = 4$ m). The brushwood dam did not protect the saltmarsh from eroding at the cliff. Our results demonstrate the erosion mechanics under extreme storms conditions and that uprooting may lead to instability of the saltmarsh on long-term.

Keywords: Saltmarsh · erosion · storm conditions · flume experiment

1 Introduction

Intertidal saltmarshes offer vital ecosystem functions, such as reduction of wave loads during storms, habitat for coastal species and carbon sequestration. However, many of these coastal saltmarshes are eroding globally [1]. Experimental and field-based observations on saltmarsh erosion have been made for short-term storm events time scale to decadal time scale (e.g. [2, 3]). An off-set in sediment dynamics and wave energy between the mudflat and saltmarsh can lead to cliff initiation at the marsh edge and subsequent lateral erosion of the saltmarsh. These cliffs can grow up to 0.5–1 m in

C. Coelho et al. (Eds.): CD 2025, CRL 41, pp. 403–408, 2026.
https://doi.org/10.1007/978-3-032-15473-6_62

height, reaching the high marsh in meso- to macrotidal environments depending on the local tidal levels [4, 5]. The lateral retreat of the saltmarsh cliff is shown to be most severe when water levels and cliff elevations are similar, occurring during medium to strong storm events [6]. However, storm surge levels and wave heights in meso-tidal environments (e.g. the Wadden Sea, The Netherlands) are higher than the marsh bottom level. Detailed observations on the near-bed velocities, the interaction with vegetation and their root-systems and saltmarsh erosion mechanics under extreme storm conditions typical for the design of Dutch coastal protection (e.g. 10000 years return period) are missing.

In this research, we aim to identify the erosion mechanics of a saltmarsh cliff under extreme storm conditions and quantify the effect of soil characteristics and vegetation on the erosion rate. We do this through full-scale wave flume experiments on a real-life saltmarsh, simulating extreme wave conditions with a maximum significant wave height of $H_{m0} = 2$ m and a maximum inundation depth on top of the marsh of $d_m = 4$ m.

2 Methods

A series of wave flume experiments were performed in the 300 m long, 8 m wide and 9.5 m high Delta flume at Deltares. The physical model represented a typical mudflat-saltmarsh-sea dike profile (Fig. 1). A foreshore was made of non-erodible sand cement with a gentle slope ranging from 1:9 to 1:45. A real-life saltmarsh was created by harvesting blocks (2 m long, 2 m wide and 0.7 m deep) at a field site at the Dutch Wadden sea coast during Autumn. Blocks were harvested from a high marsh at both a landward and at a seaward location, with the seaward location having a higher sand fraction. The dominant vegetation species at the site was *Elymus athericus.* The blocks were placed next to each other in the flume to form two saltmarsh transects with a total length of 70 m. The first block was placed on top of the foreshore, creating a ca. 0.6 m high saltmarsh cliff. Initially, the cliff was protected by a brushwood dam during 39 experiments. The brushwood dam was removed during the final 3 experiments to test cliff erosion. At the end of the model, a non-erodible dike was built with a slope of 1:3.6, typical for a Dutch coastal sea dike.

Wave scenarios ranged from intermediate to extreme storm conditions. Wave-states with offshore significant wave heights ranged between $H_{m0} = 0.75$ to 2.0 m with a peak wave steepness ranging between $s_0 = 0.02$ and 0.04. The offshore water depth ranged between $d_0 = 4.4$ to 6.9 m, corresponding to a water depth on top of the marsh of $d_m = 1.5$ to 4.0 m, respectively. In total the test setup was exposed to various wave forcings for 40 h. During the experiments, the vegetation was gradually damaged. To measure the effect of a reduced standing biomass on the erosion rate of the saltmarsh, the experimental program was repeated for different vegetation states, categorized as 'healthy', 'damaged', and finally 'removed' by mowing the remaining vegetation.

Saltmarsh surface elevation measurements were taken with FARO 3D laser scanner between wave scenarios when the flume was drained. Erosion volumes were calculated by aligning and subtracting elevation scans. In this analysis, surface scans measured after removing the vegetation are used to avoid measurement errors due to standing vegetation covering the actual saltmarsh bottom (ca. last 20 h of exposure). Wave height and period were measured by wave gauges at both offshore and halfway at the marsh (x = 40 m) locations.

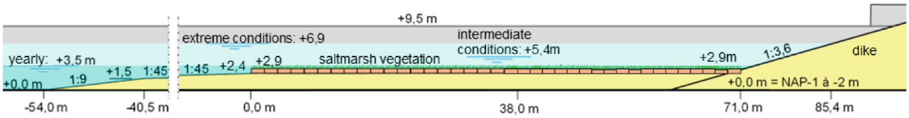

Fig. 1. Schematic cross view of the saltmarsh model in the Delta flume (courtesy of Deltares).

3 Results

During the experiments, when the standing vegetation and root systems were still intact, no significant erosion of the marsh platform was observed (Fig. 2). However, as the experiment progressed, the cumulative wave forcing lead to gradual damaging and subsequent removal of the above-ground vegetation. Slow removal of cohesive soil in between the roots led to less attachment of the vegetation to the soil. Once enough material was removed in combination with strong wave scenarios ($H_{m0} = 2$ m), large areas of vegetation were uprooted (ca. 1×1 m^2) exposing the soil beneath (Fig. 2, Fig. 3). Uprooting of the vegetation occurred sporadically along the saltmarsh both on the seaward and landward harvested transects. After removal of the roots, surface erosion rates were observed higher compared to sections with roots still intact.

Most significant erosion was measured in the first 20 m from the cliff edge (Fig. 2). Large scour holes developed at the front of both transects, contributing the most to the overall erosion volumes. The presence of the brushwood dam did not prevent the erosion of the saltmarsh cliff. The cliff continued to erode more rapidly and the saltmarsh started to erode vertically. After removal of the brushwood dam, the initial straight cliff was further scoured into a smooth sloped surface (Fig. 3).

Erosion rates after vegetation removal were further analyzed for the first 20 m from the cliff (Fig. 4). The total erosion between the experiments after mowing of the vegetation and the end of the experiment was limited, ranging between 1 to 1.5 m^3 during a total of 20 h of wave forcing. Slightly higher erosion raters were measured at the seaward harvested transect (i.e. more sandy). Higher erosion rates were measured after experiments with higher wave conditions. An increase in wave steepness did not show a significant change in erosion rates. The increase in erosion rates due to the removal of the brushwood dam is lower compared to the effect of a higher wave height (Fig. 4, hours 8 to 20).

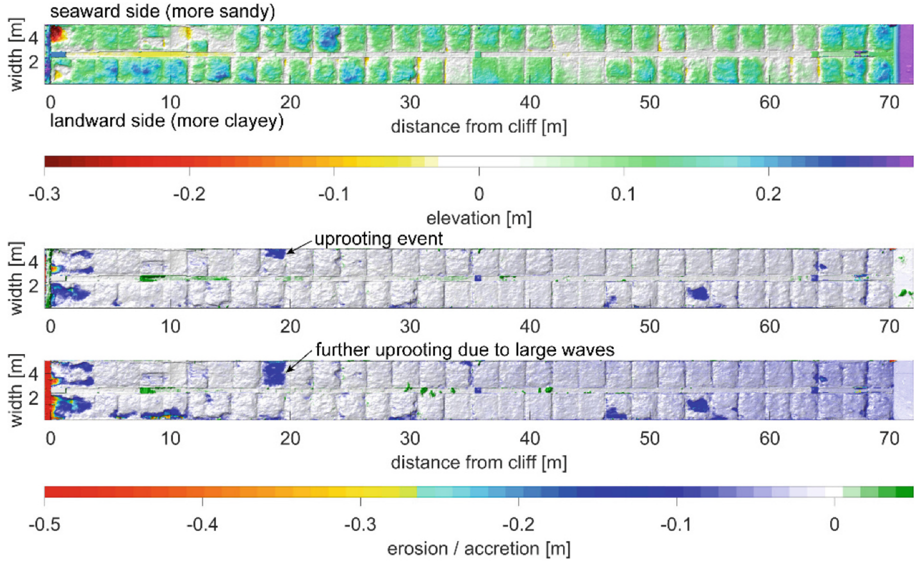

Fig. 2. Initial profile after mowing of the vegetation (top) with the upper transect (y = 4 m) harvested landward (i.e. higher clay fraction) and the lower transect (y = 2 m) harvested seaward (i.e. higher sand fraction) and the change in bathymetry after 4 h of additional testing (middle) and at the end of the experiment after 20 h of testing (bottom).

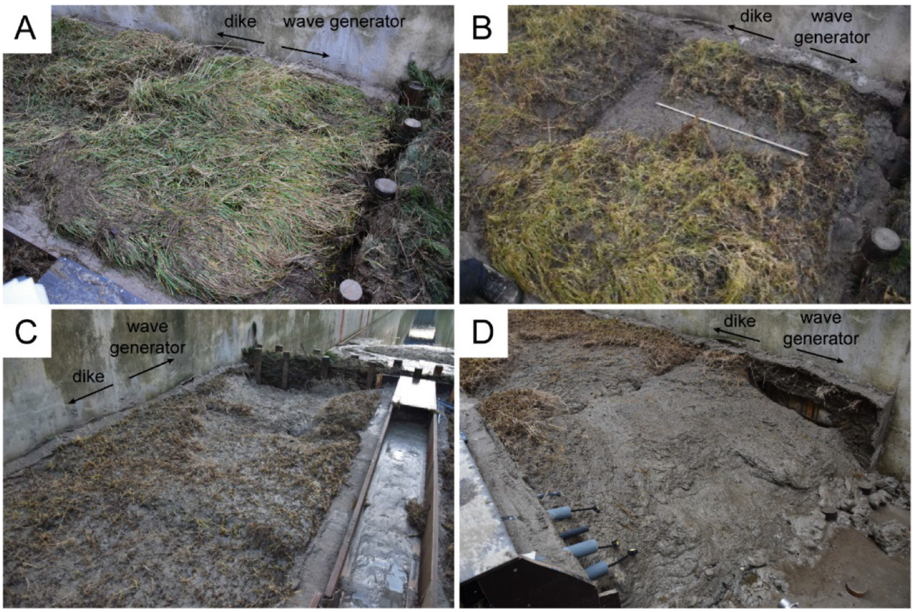

Fig. 3. Erosion at the saltmarsh cliff at the start of the experiment (A), after 17 h of testing (B), after 24 h of testing and mowing of vegetation (C) after removal brushwood dam and the end of the test program (D) (courtesy of Deltares)

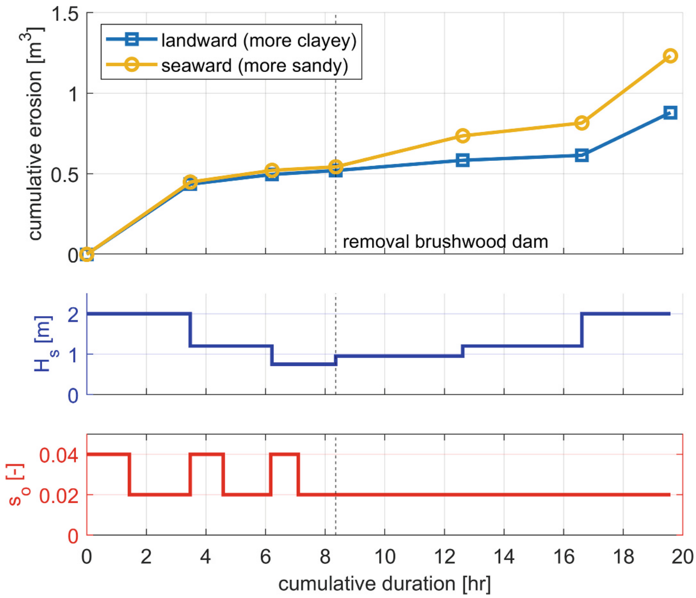

Fig. 4. Erosion volume of first 20 m saltmarsh after removal vegetation, the offshore significant wave height (H_{m0}) and wave steepness (s_0) over the cumulative duration of exposure in hours.

4 Discussion and Conclusion

Limited erosion was measured for both landward and seaward harvested saltmarsh transects during over 40 h of exposure to extreme wave conditions. Previous research showed similar limited erosion during wave conditions up to $H_{m0} = 1$ m [7]. Our results extend these observations to wave conditions up to $H_{m0} = 2$ m and inundation depth up to 4 m. Most of the significant erosion occurred at the first 20 m of the marsh transect. Large scour holes emerged at the first block behind the brushwood dam, contributing the most to the overall measured erosion volumes. The removal of the brushwood dam showed a small increase in erosion rates (Fig. 4, between hour 8 to 12), where higher wave heights were needed to further erode the more consolidated exposed substrate at this location (Fig. 4, hour 16 to 20).

Under high waves, strong near-bed velocities led to continuous damaging of the vegetation and eroding soil particles from the root mat. Only after sufficient detachment of the root mat and the rerunning of high wave conditions (i.e. $H_{m0} = 2$ m), large areas of vegetation roots were subsequently ripped out. These observations suggest the existence of a threshold near-bed velocity for uprooting to take place. Similar observations of uprooting have been made after hurricanes making landfall at coastal wetlands [8]. The removal of the root mat and the loss of the complete vegetation (above and below-ground biomass) means that vegetation will need several seasons to grow back to its former state. With the exposed substrate eroding at a faster rate, uprooting during extreme events can leave locations on the saltmarsh vulnerable for erosion during subsequent lower storm conditions.

Our results demonstrate the irreversible effect of extreme storm conditions on saltmarshes. Although short term erosion is limited, severe uprooting causes a weaker substrate, which takes time to be vegetated and regain its former strength. Further linking these observations to hydrodynamics and soil properties will allow for a better quantification of saltmarsh erosion under extreme wave conditions.

Acknowledgements. This work is part of the 'Living Dikes – Realising resilient and climate-proof coastal protection' project NWA.1292.19.257, funded by the Netherlands Organisation for Scientific Research (NWO). The authors want to thank M. Klein Breteler, V. van Bergeijk, G. Mourik and all lab technicians from Deltares for the management, design, construction and measurements during these experiments and support in post-processing of the data.

References

1. Deegan L et al (2012) Coastal eutrophication as a driver of salt marsh loss. Nature 490:388–392
2. Francalanci S, Bendoni M, Rinaldi M, Solari L (2013) Ecomorphodynamic evolution of salt marshes: experimental observations of bank retreat processes. Geomorphology 195:53–65
3. Feagin RA, Lozada-Bernard SM, Ravens TM, Möller I, Yeager KM, Baird AH (2009) Does vegetation prevent wave erosion of salt marsh edges? Proc Natl Acad Sci 106(25):10109–10113
4. Allen JRL (1989) Evolution of salt-marsh cliffs in muddy and sandy systems: a qualitative comparison of British West-Coast estuaries. Earth Surf Process Landforms 14:85–92
5. Van der Wal D, Wielemaker-van den Dool A, Herman PMJ (2008) Spatial patterns, rates and mechanisms of saltmarsh cycles (Westerschelde, The Netherlands). Estuar Coast Shelf Sci 76:357–368
6. Leonardi N, Ganju NK, Fagherazzi S (2016) A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes. Proc Natl Acad Sci 113(1):64–68
7. Spencer T et al (2016) Salt marsh surface survives true-to-scale simulated storm surges. Earth Surf Process Landforms 41:543–552
8. Priestas AM, Mariotti G, Leonardi N, Fagherazzi S (2015) Coupled wave energy and erosion dynamics along a salt marsh boundary, hog Island Bay, Virginia, USA. J Marine Sci Eng 3(3):1041–1065