WAVE DISSIPATION AND TRANSFORMATION OVER COASTAL VEGETATION
UNDER EXTREME HYDRODYNAMIC LOADING

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The risk of coastal flooding is increasing worldwide as a result of rising sea level, increasing
storminess, and land subsidence (Hinkel et al. 2013; Woodruff et al. 2013). Awareness of the
role that salt marshes play as natural buffer zones providing, amongst other ecosystem
services, protection from waves during storms has also increased as a result (Koch et al. 2009;
Loder et al. 2009; Gedan et al. 2011; Shepard et al. 2011; Temmerman et al. 2013). In spite of
this general recognition, crucial understanding is lacking as to just how effective marshes are
when it really matters, under extreme water levels and waves (Bouma et al. 2013; Kirwan and
Megenical 2013). Experiments undertaken in one of the world’s largest wave flumes, with a
transplanted section of natural salt marsh typical of NW European coasts, provide first
evidence of wave dissipation under storm surge conditions. The experiments showed how
energy reduction is affected by individual dissipating processes, and also identified the wave
energy threshold above which salt marsh vegetation ceases to make an effective contribution to
salt marsh defence capacity. Below this threshold, the effect of vegetation on wave attenuation
was found to be significantly larger than expected, even for high water level conditions. Above
this threshold, however, marsh vegetation was significantly damaged. The marsh substrate
itself remained remarkably stable and resistant to surface erosion under even the highest wave
energy conditions. These findings now allow, for the first time, the quantitative assessment of
flood risk reduction by salt marshes under extreme conditions and thus provide input into the
future engineering of such biophysical buffers in the face of global environmental change.

1. INTRODUCTION

Increasing pressures on coastal margins, from both physical (sea level rise, increased storminess
Jones et al. 2012) and human use (increased population densities, resource requirements (Seto 2011)
perspectives, have, over recent decades, resulted in a re-evaluation of coastal flood and erosion risk
reduction measures (Shepard et al. 2011). Natural coastal features, such as sand dunes, mudflats and
salt marshes, are now widely recognised as acting as potential barriers to wave and tidal flow or as
wave/tidal energy buffers (Barbier et al. 2011; Temmerman et al. 2013; USACE 2013). The inclusion
of such natural features into quantitative flood or erosion risk assessments, however, has been
hampered by a lack of (i) empirical evidence for their capacity to act as wave dissipaters under
extreme water level and wave conditions (when their coastal protection service is most required) and
(ii) a quantitative understanding of their ability to survive those types of conditions (Fagherazzi et al.
2006; Bouma et al. 2013; Gewin 2013; Mariotti & Fagherazzi 2013).
Previous studies have suggested that dissipation of wave energy over submerged salt marsh vegetation canopies is dependent on the water depth and incident wave energy, and that hydrodynamic thresholds may exist beyond which marshes lose their wave dissipating effect (Möller et al. 1999; Gedan et al. 2011; Yang et al. 2011). The existence of water depth or incident wave height thresholds makes intuitive sense. The orbital wave motion that can be interfered with by the submerged vegetation canopy decreases with increasing depth and with decreasing incident wave energy. Existing empirical studies have, however, been limited to observations in shallow water depths and low wave energy. Field studies have generally been limited to observations of wave spectra with significant wave heights ($H_\text{m0}$) of less than 0.3 m in water depths of less than 1 m and laboratory studies of wave heights of less than 0.3 m in depths of less than 0.6 m (Möller & Spencer 2002; Anderson & Smith 2014).

The issue of salt marsh resistance to wave impact is intricately connected to that of wave dissipation over salt marsh surfaces (Duarte et al. 2013). Under high energy conditions, it is conceivable that dissipation of wave energy is achieved by removal of material (plant and soil) from the marsh edge or surface, rather than simply dissipation by drag from the vegetation canopy. There is evidence that points to the stabilising effect of organic matter with respect to resistance of the marsh surface to erosion by waves from above. Contrasting evidence shows roots increasing erosion on exposed marsh margins (Feagin et al. 2009). Little is known, however, about the response of the marsh soil to extreme levels of wave impact upon the marsh surface, as might be experienced in storm surge conditions. The stability of the marsh surface under such conditions is clearly critical to any assessment of its usefulness as part of coastal flood risk reduction schemes.

Our large scale flume experiment had two key aims: (i) to provide empirical evidence for the existence of thresholds in incident wave height that determine the transition from regimes of wave dissipation to regimes of wave transmission across vegetated marsh canopies and (ii) to quantify the response of the marsh vegetation and soil surface to incident wave energy in such regimes. Waves were generated in a 300 m long, 5 m wide, and 7 m deep flume over a test section of almost 40 m length. The section was composed of a coherent patchwork of marsh blocks, supporting a mixed canopy of *Elymus athericus*, *Puccinellia maritima*, and *Atriplex prostrata*, all typical of mid to high marsh communities in the North Sea region.

2. METHODS

216 1.2 m x 0.8 m blocks of salt marsh were excavated in Eastern Frisia, German Wadden Sea (53°42.754 N, 07°52.963 E), in June 2012 and transported to the Large Wave Flume (Grosser Wellenkanal, GWK) in Hannover, Germany, where they were over-wintered. Marsh blocks were reassembled within the flume to create a 4.6 m wide x 40 m long, artificially illuminated test section. Waves with heights of between 0.2 and 0.5 m and between 0.1 and 0.9 m were generated in conditions of 1 m (6 test runs) and 2 m (18 test runs) water depth above the soil surface, respectively. Peak wave periods ($T_p$) for the two water depth conditions ranged from 2.1 to 3.3 and 1.5 to 6.2 s and wave tests were run under regular (N = 100 waves) and irregular (JONSWAP spectrum, N = 1000 waves) wave conditions. The vegetation canopy was typically 30 cm high, but varied between species. Wave parameters were measured using four wire gauges in front of and behind the test section to calculate wave height dissipation rates. For the regular wave tests, average wave heights of 11 waves not affected by reflection were compared in front of and behind the marsh covered test section. Spectrally derived wave heights ($H_{\text{m0}}$) were computed after reflection analysis was carried out on the time series of all waves in the irregular wave tests. The maximum extension of *Puccinellia* stems in the direction of wave travel was recorded in video footage through underwater windows and measured using the angle measuring tool in ‘Kinovea’ video analysis software. Changes to the soil surface elevation were recorded at least every third day by use of vertical pins lowered onto the surface through a rigid but movable cross-flume rig.

3. RESULTS

For the marsh section as a whole, there was no statistical difference in soil bulk density between the flume and the field (0.7 g cm$^{-3}$ in both cases), while organic matter contents were significantly lower in the flume (9.0 %) than in the field (12.4 %). Stem density (N = 15) and plant stem flexibility...
(Young’s Modulus) (N = 17) did not differ significantly between field and flume vegetation (t-test; p > 0.05).

Results show a clear change in dissipation rate which was consistent between regular and irregular waves and occurred in both the 1 m and 2 m water depth experiments. In water depths of 2 m above the soil and for regular waves, dissipation of wave energy over the test section increased linearly, from no dissipation in the case of regular waves with height $H = 0.1$ m height and period $T = 1.5$ s to a maximum of 19.5 % reduction for $H = 0.3$ m height and $T = 3.6$ s (Fig. 1a). For irregular waves, maximum dissipation of 19.9 % occurred for wave spectra with $H_m0$ of both 0.4 and 0.6 m ($H_m0$ approximates the significant wave height, $H_s$ (Fig. 1b). When incident wave heights increased beyond these levels, however, wave dissipation reduced to 13.8 % for regular waves ($H = 0.6$ m, $T = 3.6$ s, Fig. 1a) and to 18.1 % for irregular waves ($H_m0 = 0.8$ m and $T_p$ (spectral peak period of incident waves) = 4.0 s, Fig. 1b). Waves of greater height again experienced an increase in dissipation. The maximum measured dissipation was 25.6 % and 22.2 % for regular ($H = 1.1$ m / $T = 6.2$ s) and irregular ($H_m0 = 0.9$ m / $T_p$) = 6.3 s waves, respectively. These latter conditions were characterised by wave breaking. The breaking process can be assumed to have contributed significantly to the observed loss in wave height (Fig. 1a).

**Figure 1:** Wave dissipation across the fully vegetated and mowed salt marsh. **a)** Reduction in wave height (mean ± 1 SD) across 40 m of salt marsh in the flume for a range of incident regular wave heights ($H < 1$m) and periods and for water depth $h = 1$ m (circles) and $h = 2$ m (diamonds). **b)** Reduction in wave height of irregular waves at water depth of 2 m with incident wave height ($H_m0$).
In water depths of 1 m, maximum dissipation was achieved for regular waves of $H = 0.2$ m ($T = 2.9$ s), and wave height dissipation was significantly larger (45.1%) than for the dissipation threshold in 2 m depth ($H = 0.3$ m) ($p < 0.05$). As was the case for waves in 2 m depth, dissipation decreased beyond this wave height threshold (Fig. 1a). As incident wave height was increased to $H = 0.4$ m ($T = 2.9$ s), wave height dissipation decreased to 31.7% over the test section. This, too, was statistically significantly greater than the 17.8% dissipation observed for $H = 0.4$ m in 2 m depth ($p < 0.05$). In 1 m water depth, the largest generated, regular breaking waves of $H = 0.5$ m ($T = 3.3$ s), experienced less dissipation (mean = 37.9%) than the lower, non-breaking waves of $H = 0.2$ m (mean = 45.1%).

Upon completion of the ‘fully vegetated’ test runs with vegetation, a series of runs were repeated after carefully removing (‘mowing’) the above-ground vegetation from the test section surface. Dissipation rates over the mowed surface were significantly lower in all generated conditions for the regular test runs (t-test, $p < 0.05$) (Fig. 1a). The full spectral analysis of the irregular tests did not allow a statistical comparison of the test runs, but for all four repeated irregular test runs, $H_{m0}$ reduction was lower for the tests over the mowed surface (Fig. 1b). At (or just after) the point of maximum dissipation of non-breaking waves ($H$ and $H_{m0} = 0.4$ m; $T$ and $T_p = 2.9$ s (for regular and irregular waves respectively)), wave height reduction over the mowed section was lower than that over the section with intact vegetation cover by a factor of 0.4. This was true for both regular and irregular waves in both water depths (Fig. 1a and 1b). Thus, the vegetation cover alone accounted for 60% of wave height reduction at the point at which dissipation of non-breaking waves reached its maximum value. When $H_{m0}$ of irregular waves increased to 0.8 m in 2 m water depth, however, the vegetation cover accounted for only 30% of observed wave height dissipation (Fig. 1b). In this case, the ratio of wave height reduction between mowed section to fully vegetated section was 0.7.

Analysis of underwater video footage recorded within the first 10 m of the test section showed that the reduction in wave dissipation above the $H = 0.3$ m threshold in 2 m depth ($H_{m0} = 0.4$-0.6 m in the case of irregular waves) was due to the behaviour of the marsh vegetation under wave passage. Where incident regular waves were relatively low ($H < 0.3$ m; $T < 3.6$ s), the vegetation moved under the waves and plants interact with wave motion throughout the wave cycle. For larger waves that produce stronger currents, however, plant stems bend over during the forward motion of the wave to angles $> 50^\circ$, allowing the water flow for part of the wave cycle to skim over, rather than travel through the vegetation. Under these conditions, wave energy was retained and dissipation reduced. Plant stems remain longer in this flattened orientation relative to the duration of water motion in the direction of wave travel, thus allowing a relatively greater proportion of the wave’s orbital flow to travel unimpeded over the top of the canopy.

Wave tests in both water depths, with $H_{m0}$ (irregular waves) and $H$ (regular waves) $> 0.3$ m, also led to the fracturing of plant stems with material floating to the surface. Of the total of 98 kg of biomass present on the ca 180 m$^2$ marsh surface, 31% (30 kg) was released and floated to the surface after two days of test runs under these high energy conditions. The soil surface, however, remained stable, with an average lowering that was not significantly different from zero (i.e. 4.4 ± 10.4 mm over the entire experiment). The trend for average surface lowering from one surface exposure to the next was greatest during the test runs with the largest, breaking waves, rather than during the test runs that resulted in the largest release of plant biomass. The high resistance of the marsh surface itself to wave-driven erosion suggests that marsh surfaces can persist under storm surge conditions, even if these impacts occur repeatedly within a few days. This flume experiment supports the observation that areal marsh loss occurs primarily through the lateral retreat process of cliff undercutting and collapse, both on marsh fronts and along tidal channels (Van de Koppel et al. 2005; Friess et al. 2013).

4. **DISCUSSION AND CONCLUSIONS**

The wave dissipating potential of salt marshes has been widely cited in review studies (e.g. Gedan et al. 2011). However, few studies have reported actual measurements of wave height ($H_r$) reduction. Where attenuation rates of > 80% for distances of ca 160 m across salt marshes have been recorded they have been typically in water depths of < 1.0 m, i.e. much shallower than those typical under storm surge conditions (Möller & Spencer 2002). The evidence presented here shows that marshes can still
contribute to wave height reduction under storm conditions. This contribution is generated not only by the marsh platform but also, and significantly, by the vegetation canopy present. Specific thresholds in wave dissipation across submerged salt marsh surfaces exist and are associated with specific incident wave energy levels. These findings are a major step forward in the identification of the appropriate way in which these coastal ecosystems can realistically and sustainably be built into coastal protection schemes. While the heights of waves incident upon salt marsh margins are generally small (< 0.3 m), as their height is limited by shallow water depths (Le Hir et al. 2007), measurements have shown waves to reach heights \( H \) in excess of 0.8 m during high spring tides (Möller & Spencer 2002). Our experiments suggest that, during conditions with overmarsh water depths of 2 m, typical of storm surge impacts, dissipation of non-breaking waves can reach values of 20 % of incident wave height over a 40 m distance. This is a considerable reduction in wave energy, which can contribute in valuable ways to enhancing coastal safety whilst at the same time limiting investments in coastal flood defence infrastructure that lies behind marshes. Our results show that waves larger than \( H = 0.3 \) m (regular waves) and \( H_{\text{irr}} = 0.4-0.6 \) m (irregular waves), are not as efficiently dissipated. These larger waves cause significant damage to the vegetation canopy if occurring for time spans of several hours (as in this experiment), due to the repeated flexing of the vegetation to high bending angles of the vegetation under wave motion. The fact that marsh surfaces are able to withstand larger wave forces without substantial erosion effects, however, increases their reliability as part of coastal defence schemes. The evidence presented here supports engineering approaches that aim to incorporate salt marshes into coastal protection schemes. Any such schemes must carefully consider incident wave heights and water depths, alongside wave dissipation requirements and the ecological conditions necessary for the maintenance of a healthy vegetation canopy.

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