Adjusting the Critical Shields Parameter Within Salt Marshes Based on Vegetation-Induced Resuspension

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Abstract. Salt marshes are vegetated coastal habitats with current- and wave-driven transport of fine sediment particles. Vegetation-induced turbulence reduces the critical velocity for sediment resuspension within salt marsh canopies, which is not captured by transport models developed for bare beds. Therefore, a comprehensive flume experiment was conducted to quantify the reduction of the critical velocity for resuspension in wave-current flows and to provide recommendations for sediment transport models. The experiments with artificial *Spartina Anglica* vegetation and two non-cohesive grain sizes under combined wave-current flows showed that vegetation reduced the critical velocity by 35–64% compared to a bare bed depending on a ratio of the current and wave velocity. These results were not sensitive to variations in stem density and grain size. We showed that the reduction in critical velocity was equivalent to a reduction of 57–88% of the critical Shields parameter depending on the same ratio of the current and wave velocity. We recommended that the so-called vegetation-adjusted critical Shields parameter could be implemented in sediment transport models to include vegetation-induced resuspension.

Keywords: Salt marshes · Sediment resuspension · Shields parameter · Vegetation · Suspended sediment transport

1 Introduction

Salt marshes are intertidal coastal habitats that consist of sediments and vegetation. They are commonly found in estuaries and along sheltered coasts, where they are exposed to currents and waves. Salt marshes are important for coastal protection thanks to their capacity to attenuate incoming waves [1]. They are also dynamic habitats that grow and erode over time [2], driven by the suspended transport of fine particles and affecting the coastal protection that salt marshes provide. Therefore, it is critical that we understand and can model sediment transport dynamics within salt marshes.

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Sediment transport models developed for bare beds (e.g. [3]) only partially apply to salt marshes. Vegetation increases the turbulent kinetic energy, which can elevate shear and lift forces on sediment particles [4]. Flume experiments with pure current [5–7] and pure wave flows [8, 9] showed that this led to a reduction in the critical velocity for resuspension. Using these results, Tinoco & Coco [6, 9] proposed a vegetation-adjusted critical Shields parameter which could model the reduction in the critical velocity for resuspension in pure currents and wave flows, but they did not study the application to simultaneous wave-current flows that typically occur on salt marshes.

Therefore, we derived a formulation for the vegetation-adjusted Shields parameter based on flume experiments with artificial *Spartina Anglica* canopies in combined wave-currents flows. We studied three vegetation densities and two non-cohesive grain sizes. Using the experimental data, a vegetation-adjusted Shields parameter is derived as function of a ratio between the current and wave velocity.

2 Methodology

2.1 Flume Experiments

Experiments were designed to mimic emergent salt marsh canopies with *Spartina Anglica* vegetation. Rigid wooden dowels with diameter $b_v = 6.4$ mm and height $h_v = 300$ mm were fitted in 1 m-long baseboards forming a staggered grid with stem densities of $n_v = 0$ (bare), 263 (sparse), 526 (medium), or 1053 (dense) stems/m^2. One baseboard was constructed with a recess of 10 mm which was filled with artificials sediments after the dowels were in place. The sediments were glass spheres with a mean diameter of $d_{50} = 70$ or 35 μm, representing two grain sizes commonly found on salt marshes [10]. Two normal baseboards and one sediment baseboard in the middle formed the vegetation canopy, which was placed in the wave-current flume of the Massachusetts Institute for Technology (Fig. 1). The flume measured 24 m in length, 0.38 m in width, and 1 m in height. The water depth was set at 0.22 m for all tests. The flume was fitted with a piston-type wave maker which generated regular waves and a variable-speed pump which controlled flow circulation in the same direction as wave propagation. Furthermore, one acoustic Doppler velocimeter (ADV) and two optical backscatter sensors (OBS) were installed to measure near-bed velocities and suspended sediment concentrations respectively. At the start of each experiment, the sediment bed was flattened and a current velocity below the critical velocity for resuspension was set by the pump. Then, the wave height was incrementally increased until resuspension was measured by at least one OBS. The critical wave velocity amplitude $U_{w,cr}$ was derived from the corresponding ADV signal. The critical current velocity $U_{c,cr}$ was defined as the depth-averaged velocity and was obtained from the pump. This procedure was repeated for wave-current conditions, pure wave conditions (no flow recirculation), and pure current conditions, for which the current velocity rather than wave height was increased. An overview of the experiments was listed in Table 1.

Table 1. List of experimental conditions.

Grain size	Vegetation densities tested	Number of conditions tested per density	Total number of conditions tested
$d_{50} = 70$ μm	Bare, sparse, medium, dense	6	24
$d_{50} = 35$ μm	Bare, medium	5	10

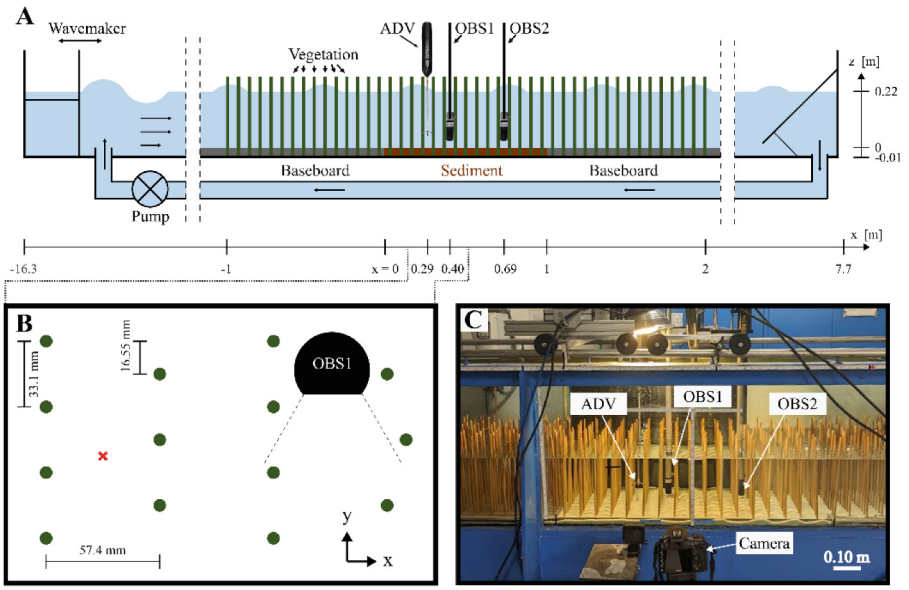


Fig. 1. (a) Side view of the experimental setup, figure not to scale. (b) Top view of the vegetation and instrument locations between $x = 0.26$ m and 0.43 m in a medium density canopy. The green circles are vegetation stems. The red cross marks the location of the ADV measurement. (c) Photo of the side view of the experimental setup. Source: van Veelen et al. [11] with minor edits.

2.2 Vegetation-Adjusted Shields Parameter

The measured critical current velocity $U_{c,cr}$ and critical wave velocity amplitude $U_{w,cr}$ were used to calculate a combined critical wave-current velocity

$$U_{wc,cr} = \sqrt{U_{c,cr}^2 + U_{w,cr}^2} \tag{1}$$

and a wave-current velocity ratio

$$\xi = \frac{U_{c,cr}^2}{U_{c,cr}^2 + U_{w,cr}^2}, \tag{2}$$

which represented the relative contributions of currents and waves to $U_{wc,cr}$. $\xi = 0$ denotes pure wave conditions, $\xi = 0.5$ marks equal current and wave velocities, and $\xi = 1$ represents pure current conditions. $U_{wc,cr}$ is fitted as function ξ to the experimental data for bare beds, resulting in $U_{wc,cr,bare}$, and for vegetated beds, resulting in $U_{wc,cr,veg}$. Following Tinoco & Coco [6, 9], the vegetation-adjusted critical Shields parameter is defined as

$$\theta_{cr,veg} = \theta_{cr,bare} \frac{U_{wc,cr,veg}^2}{U_{wc,cr,bare}^2}, \tag{3}$$

in which $\theta_{cr,bare}$ is the critical Shields parameter on a bare bed for the same sediment.

3 Results

3.1 Critical Velocity

Our results showed that vegetation reduced the critical velocity for sediment resuspension in wave-current flows for both grain sizes (Fig. 2). For the coarser grain diameter of 70 μm (Fig. 2a), the presence of vegetation had a much greater effect on the critical velocity than stem density of the canopy. Therefore, a single threshold was fitted for vegetated beds using the data from all three stem densities. Vegetation reduced the critical velocity the most in pure current flows with a 64% reduction. The smallest reduction of 35% was observed in pure wave flows. The reduction for combined wave-current was within this 35–64% range.

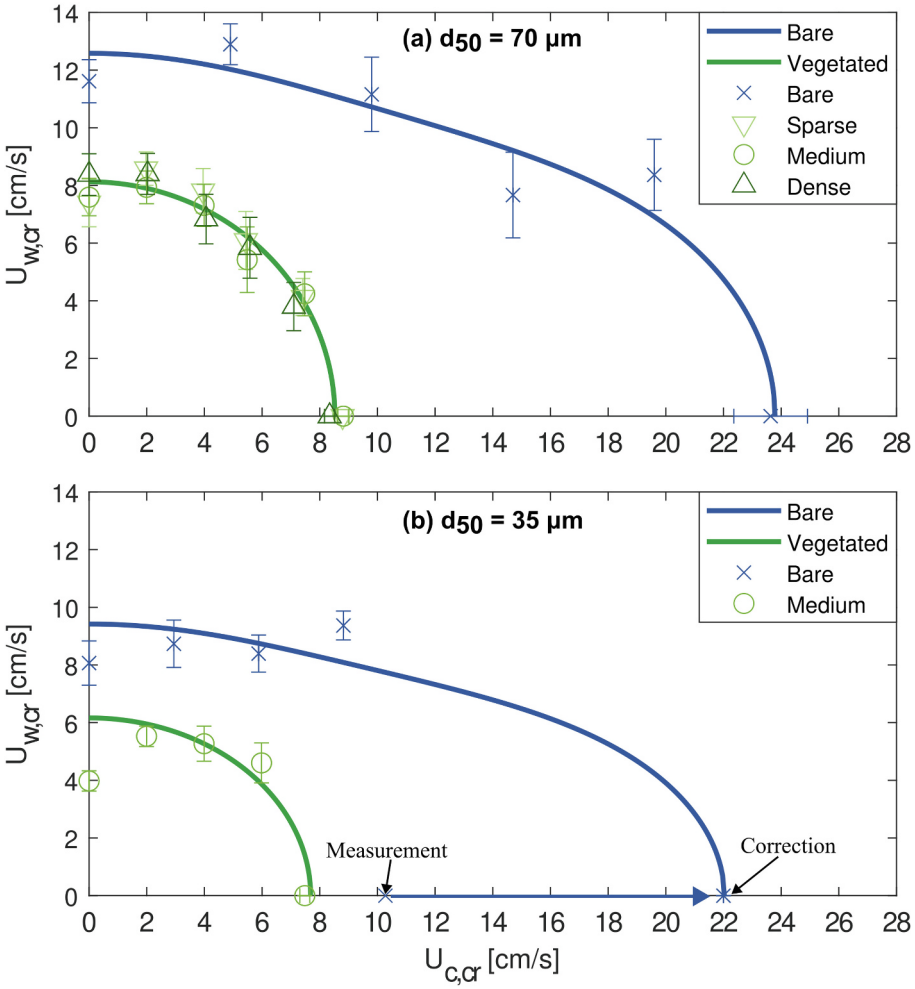


Fig. 2. The critical velocity for sediment resuspension on bare (blue) and vegetated (green) beds for grain sizes (a) $d_{50} = 70$ µm and (b) $d_{50} = 35$ µm. The markers and error bars denote the measured critical velocities and their standard deviations respectively. The solid lines are fitted thresholds. For the finest grain size (b), the bare bed pure current measurement was replaced with a value obtained from Soulsby [3], as discussed in text and marked by the arrows in (b).

For the finest grain diameter of 35 µm (Fig. 2b), the measured pure current critical velocity was $U_{c,cr} = 10.3$ cm/s on a bare bed, which was significantly smaller than $U_{c,cr} = 19$–27 cm/s measured in previous experimental studies for a similar grain size [3, 5, 12]. Furthermore, $U_{c,cr}$ should only respond weakly to a change in grain size on a bare bed [3], whereas it is reduced by more than 50% in our experiments. Therefore, we replaced the measured bare bed pure current critical velocity with $U_{c,cr} = 22$ cm/s based on Soulsby [3]. Using the replaced value, vegetation reduced the critical velocity

for the 35 μm grains by a similar ratio as for the 70 μm grains with a 64% reduction under pure current flows and a 35% reduction under pure wave flows.

3.2 Adjusted Shields Parameter

The reduction in critical velocity by vegetation compared to a bare bed was expressed by an equivalent reduction in the critical Shields parameter defined by Eq. 3 (Fig. 3). The critical Shields parameter for a bare bed $\theta_{cr,bare}$ was reduced by 57–88% by vegetation-induced resuspension within a *Spartina Anglica* canopy. This reduction was nearly identical for both grain sizes, showing that our results can be applied across a range of grain sizes typically found on salt marshes. Like the critical velocities (Sect. 3.1), the greatest reduction in the critical Shields parameter was observed for pure current flows, the smallest reduction was found for pure wave flows. The observed reductions for pure currents and pure waves were comparable with those found by Tinoco & Coco [6, 9]. The vegetation-adjusted Shields parameter could be applied in sediment transport models for *Spartina Anglica* marshes to include vegetation-induced resuspension. The adjusted critical Shields parameter only addressed resuspension and did not include other effects such as root binding and cohesiveness.

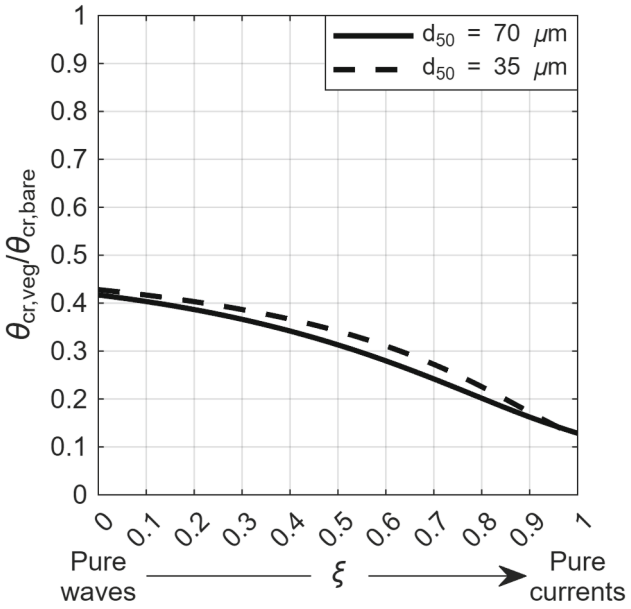


Fig. 3. Reduction in the critical Shields parameter due to vegetation-induced resuspension.

4 Conclusions

Our experimental results showed that bare bed models for sediment resuspension overestimated the critical velocity for resuspension in salt marsh canopies under combined wave-current conditions. Artificial vegetation that was inspired by *Spartina Anglica*

reduced the critical velocity by 35–64% depending on a ratio of current and wave velocities. This reduction was the same for both non-cohesive grain sizes with diameters of 70 and 35 μm. Furthermore, the critical velocity was not sensitive to stem density across the range of densities tested, suggesting that the presence of vegetation was more important than stem density for sediment transport models. We recommended that the vegetation-induced resuspension could be implemented in sediment transport models through a vegetation-adjusted critical Shields parameter. The adjusted Shields parameter was 57% to 88% lower than a bare bed critical Shield parameter depending on the ratio of currents and waves. The implementation of the vegetation-adjusted Shields parameter in sediment transport models is expected to improve predictions of suspended sediment transport within saltmarsh canopies.

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