Turbulence Reduction by the Canopy of Coastal Spartina Salt-Marahes

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ABSTRACT


Important features of coastal salt-marshes, that of enhancing sediment accretion and protecting the shoreline from wave energy, are related to the capacity of the vegetation to reduce wave flow and turbulence. The present study investigates the poorly understood processes of turbulence attenuation by the canopy. Wave-dominated turbulence-profiles and turbulence-profiles with unidirectional flow were collected on a Spartina anglica salt-marsh in the Wash (eastern England). The results showed a significant attenuation of orbital velocities of waves by the vegetation. Under unidirectional flow, a region of high Reynolds-stress in the upper part of the canopy separates a zone with reduced turbulence and limited vertical exchanges in the denser canopy. Both kind of turbulence reduction favour particle settling and limit vertical exchange in the denser canopy.

ADDITIONAL INDEX WORDS: Wave attenuation, vegetative flow-resistance, sediment dynamics.

INTRODUCTION

Salt-marsh vegetation has an important influence on the sedimentary processes on upper intertidal areas through flow reduction. It enhances sedimentation and it protects the bed against subsequent erosion (FRENCH and REED, 2001). Its positive impact on accretion may be crucial during a period of relative sea-level rise, especially in low-relief coastal area. Salt-marshes reduce also the wave energy reaching the shore during storms. They can be considered as an element of coastal defence, which presence allows to built a smaller seawall (KING and LESTER, 1995).

Most knowledge on the flow dynamics in and around salt-marsh canopies originated from time-average measurements of unidirectional flow, which showed reduced velocities (correlated to the vegetation density) and an absence of the logarithmic velocity-profile within the canopy (e.g., PETHICK et al., 1990; LEONARD et al., 1995; SIT et al., 1995; SIT et al., 1996; NEUMEIER and CIVOLA, 2004).

Thus, little information is available on the turbulence within the canopy, although it has a significant influence on sediment transport. The turbulence controls particle settling rate and, through the bed shear stress, bed erosion. It may also influence geochemical exchanges and biological processes such as larval recruitment and dispersion. The presence of the canopy dictates that the turbulence structure must be radically different from a standard boundary layer. LEONARD and LUTHER (1995), and LEONARD and REED (2002) measured reduced turbulence intensities under unidirectional flow in the canopy using hot-film anemometry. NEPPE (1999) and NEPPE and VIVIONI (2000) looked at turbulence in laboratory experiments with artificial vegetation under unidirectional flow.

The turbulence created by the orbital velocities of waves has a significant role for sediment transport. Especially during storms, the energy level is much higher than that of tidal currents and important amounts of sediment are mobilized (STUMPF, 1983; CARLING, 1982). For this reason, it would be valuable to know how the canopy affects the water movement due to the wave by slowing down the wave orbital-velocities and by decreasing the size of the associated turbulent eddies. However, little data exist on this subject. On the other hand, the damping of waves passing over salt-marshes is well documented for boat waves (KNUTSON et al., 1982) and for wind waves (MOELLER et al., 1996; MOELLER and SPENCER, 2002). KNUTSON et al. (1982) and MOELLER et al. (1999) have proposed models for the attenuation of wave height and wave energy across a salt-marsh.

The aim of the present paper is to illustrate with field data the vertical variations of turbulence through a salt-marsh canopy with and without waves, and to discuss how momentum is transmitted downward through the canopy. In particular, the damping of the orbital velocities of waves will be evaluated by comparing measured values and theoretical predicted values calculated from wave data.

The linear wave theory predicts the attenuated wave orbital-velocities and the attenuated pressure variation for any position in the water column for a given surface wave (TUCKER and PIT, 2001). The relevant equations for u (horizontal velocity component), w (vertical velocity component) and p (pressure variation from the mean pressure) are

\[ u = \frac{\cosh(k(z+D))}{\sinh(kD)} a \omega \cos(ka) \cos(\omega t + \phi) \]

\[ w = \frac{\sinh(k(z+D))}{\sinh(kD)} a \omega \sin(ka) \cos(\omega t + \phi) \]

\[ p = \frac{\cosh(k(z+D))}{\cosh(kD)} \rho g a \cos(ka) \cos(\omega t + \phi) \]

where, a: wave amplitude, D: water depth (positive), k: wave number (k=2\pi/L, L: wave length), x: horizontal position, z: distance below sea level (negative downward), \omega: angular frequency (2\pi/T, T: wave period), \phi: phase angle. The k is related to \omega (and to T) by the formula: \omega = g \k \tanh(kD).

METHODS

Study Area and Instruments

All the data were collected in a field experiment at Freiston Shore (E0°52′4″ / N52°57′22″), the Wash, eastern England. The Wash is a large embayment (600 km2) of which about 45% are intertidal. Tides are semi-diurnal with a spring tidal range of 6.8 m (PYE, 1995). The shoreline is formed by continuous seawalls, which are rimed by 500-1000 m wide, minerogenic salt-marshes (HILL, 1988).

At Freiston Shore, the present seawalls were completed in 1965/1980. Here, the 500 m wide salt-marsh is bordered by a
1.5 km wide, muddy and sandy tidal-flat (Collins et al., 1981). The lower salt-marsh is dominated by Spartina anglica, and it terminates with a 150 m wide pioneer-zone with Salicornia/Sueda maritima. Ke et al. (1994) and Ke and Collins (2000) measured tidal currents up 0.5 m/s on the lower tidal flat (with flood-dominant tidal-asymmetry), but only peak flow of about 0.1 m/s over the salt-marsh. The salt-marsh and tidal flat can be regarded as accretional (Ke and Collins, 2000).

The study area is located near the seaward vegetation-limit, at the outer edge of the Spartina marsh, which is forming dense patches 10-20 m across. There are several small, tidal gullies in the vicinity, which are 0.2-0.4 m deep and roughly shore-normal oriented. The next large creek is 70 away.

Water flow was recorded with an Acoustic Doppler Velocimeter (ADV, model Nortek/NDV/field), which measures at 25 Hz in a sampling volume of less than 0.5 cm³. The ADV was mounted on a vertical sliding mechanism, used to move the sensor rapidly between different heights above the bed (see Neumeier and Ciavola (2004) for a further description). Two kinds of vertical profiles were obtained with this system: (1) mean-current profiles of 6-10 points with 15 seconds measurements at each point (an entire profile was collected in 1½- 2½ minutes), and (2) data for turbulence analysis (6-9 points with 45-60 seconds measurements at each point). That is relatively short for the turbulence and wave analysis (effectively analysed duration 40-55 seconds). This compromise was selected to get data at several heights with one ADV within less than 10 minutes, so that the tidal flow and the water height could be assumed constant. Due to the short period of the waves (~2.5 seconds, Table 1), the analyzed intervals contained about 20 waves, which is considered representative.

Waves were measured with a pressure transducer (PT, model Druck/PDCR-1830) fixed at 0.11 m above the bed on the rig holding the ADV. The horizontal distance between PT and ADV was 0.8 m. PT data were recorded at 8 Hz continuously during the tidal inundation.

The vegetation was quantified by the standard measurements of shoot density and biomass. In addition, the vertical variation in canopy density was assessed by two methods. (1) The vertical biomass distribution was determined by cutting the harvested canopy into 0.025 m² 2.5 cm segments. (2) The lateral obstruction of the canopy to the flow was measured by taking a lateral picture of a 10 cm thick canopy in front of a red background, digitizing it and applying image analysis techniques to differentiate the vegetation from the background (see example in Figure 1). Finally the obstruction percentage was calculated for 2-cm height intervals and the results of several pictures were averaged.

![Figure 1](image-url) Vertical distribution of biomass. (A) Vertical variations of biomass measured in 2.5 cm segments. (B) Lateral obstruction by the vegetation calculated from lateral pictures of a 10 cm thick canopy as represented in (C).

The two-dimensional Reynolds stress $\tau_{xz}$ and the three-dimensional Reynolds stress $\tau_{xx}$ were computed with following formulae:

$$\tau_{xz} = -\rho \left( u \cdot \frac{\partial W_z}{\partial x} \right)$$

$$\tau_{xx} = \rho \left( u \cdot \frac{\partial W_x}{\partial x} \right)$$

where, $u$, $v$, and $w$: the turbulent velocity components in the downstream, cross-stream and vertical (positive upward) directions. $\tau_{xx}$, the most commonly used Reynolds stress, was calculated only for the profiles with unidirectional flow (experiment A). In the wave-dominated profiles (experiment B), the turbulence is much more related to the waves than to the mean flow. For this reason, $\tau_{zx}$ was used, as it is insensitive to the horizontal alignment of the $u$ and $v$ axes. All the calculations were performed in Matlab.

**RESULTS**

The profiling system with the ADV was deployed at two locations in close proximity (called locations/experiments A and B) during the daylight high tides of 13 and 14 June 2002, respectively. Both locations were in the central part of two Spartina patches. Location A was 20 m more seaward, in the outermost first large Spartina zone, which was surrounded by Salicornia/Sueda maritima marsh (sparse vegetation less than 10 cm high). The Spartina patch at location B was larger, denser...

**Calculation methods**

To evaluate the attenuation of the wave orbital-velocities by the canopy, the velocities measured with the ADV were compared to theoretical orbital-velocities calculated from the PT data recorded simultaneously. The actual comparison was done between the measured and the theoretical turbulent kinetic energy (TKE), which is representative of the magnitude of wave orbital-velocities. The comparisons were computed separately for the horizontal TKE and the vertical TKE, because the two attenuation factors are different and the canopy influence on turbulent flow may be anisotropic.

The following procedure was used for each point of a profile (i.e., on time-series of 40-55 seconds). (1) The spectral density of the uncorrected water-surface elevation $S(f)$ was computed from the PT data using a Fast Fourier Transform (FFT) algorithm. (2) $S(f)$ was corrected to compensate for pressure attenuation (see equation (3)) using the standard method (Tucker and Pitt, 2001) to obtain the true surface-elevation spectral-density $S(f)$. (3) The spectral density of the theoretical horizontal and vertical orbital-velocities (respectively, $S_{thx}(f)$ and $S_{thy}(f)$) were calculated from $S(f)$ by multiplying it by the square of the attenuation factors and the square of the radial frequency. (4) The spectral density of the measured vertical orbital-velocity $S_{v}(f)$ was calculated from the vertical velocity component of the ADV data. (5) The horizontal measured spectral-density $S_{h}(f)$ was obtained by adding together the spectral densities calculated from the two horizontal velocity components of the ADV data. (6) All the spectral densities were plotted and visually inspected (Figure 2). (7) The horizontal and vertical components of the measured TKE ($E_{h}$ and $E_{v}$) and theoretical TKE ($E_{thx}$ and $E_{thv}$) were calculated from $S_{thf}(f)$, $S_{h}(f)$, $S_{v}(f)$, and $S_{thf}(f)$, respectively, for the frequency range where wave energy is present using a formula of the type:

$$E_{w} = \frac{\rho}{2} \int S(f) df$$

where, $\rho$: water density, $f_{1}$ and $f_{2}$: lower and upper frequency limits (0.25-1.2 Hz, tests have shown that the exact position of these limits has little influence on the result). (8) The measured and the theoretical orbital-velocities were compared for the horizontal and the vertical attenuation by calculating the canopy-attenuation ratios $R_{h} = E_{w}/E_{w}$ and $R_{v} = E_{w}/E_{w}$. Calculation methods were carried out for each profile with unidirectional flow (experiment A). The wave-dominated profiles (experiment B), the turbulence is much more related to the waves than to the mean flow. For this reason, $\tau_{zx}$ was used, as it is insensitive to the horizontal alignment of the $u$ and $v$ axes. All the calculations were performed in Matlab.

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Turbulence in Unidirectional Flow

A representative selection of the turbulence profiles at location A are presented in Figure 4. Table 1 summarizes the sea conditions for each of them. The profiles of the time-averaged horizontal velocity $U$ (Figure 4A) are similar to previous experiments (e.g., SHI et al., 1995; NEUMIEBER and CIAVOLA, 2004): the velocity is reduced in the lower 2/3 of the canopy, with a logarithmic profile above, if the canopy is fully submerged.

The profiles of turbulent kinetic energy (TKE) show that the vertical component $E_z$ follows trends in $U$, and is strongly attenuated in the canopy (Figure 4B). The pattern is more complex for the horizontal component $E_{xz}$; high values exist in the lower part of the canopy in profile a13 (slack water just after high water).

$\tau_{av}$ is normally positive in a benthic boundary layer ( Soulsby, 1983). Here, $\tau_{av}$ is not uniform within each profile (Figure 4C). The general trend is small negative values in the lower 10-20 cm, and then larger positive values above. But several irregularities exist, e.g., profile a13 (near slack water) shows large negative values above the canopy top (30 cm). This profile is perhaps influenced near the surface by wavelets. $\tau_{av}$ is generally lower in the denser part of the canopy than above. In addition, profiles of $\tau_{av}$ are characterized by a maximum in the upper canopy (Figure 4D). This maximum is located lower in profiles a2 and a17, when the water level is lower. $\tau_{av}$ seems to be better adapted than $\tau_{av}$ to characterize the flow in the studied natural canopy.

Table 1. Sea conditions and result summary for the turbulence profiles.

<table>
<thead>
<tr>
<th>Profile ID</th>
<th>Time referred to HW</th>
<th>Water column height</th>
<th>Wave height $H_w$</th>
<th>Wave period $T$</th>
<th>$R_e$ at 8 cm above bed</th>
<th>Mean horizontal surface velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>a2</td>
<td>-62 min.</td>
<td>0.32 m</td>
<td>0.01 m</td>
<td>2.4 s</td>
<td>0.84</td>
<td>6.8 cm/s</td>
</tr>
<tr>
<td>a9</td>
<td>-17 min.</td>
<td>0.82 m</td>
<td>0.02 m</td>
<td>2.5 s</td>
<td>0.73</td>
<td>12.6 cm/s</td>
</tr>
<tr>
<td>a13</td>
<td>+32 min.</td>
<td>0.73 m</td>
<td>0.02 m</td>
<td>2.3 s</td>
<td>0.75</td>
<td>4.8 cm/s</td>
</tr>
<tr>
<td>a17</td>
<td>+67 min.</td>
<td>0.35 m</td>
<td>0.01 m</td>
<td>2.6 s</td>
<td>0.82</td>
<td>5.0 cm/s</td>
</tr>
<tr>
<td>b7</td>
<td>-21 min.</td>
<td>0.79 m</td>
<td>0.08 m</td>
<td>2.4 s</td>
<td>0.84</td>
<td>8.2 cm/s</td>
</tr>
<tr>
<td>b9</td>
<td>-2 min.</td>
<td>0.86 m</td>
<td>0.09 m</td>
<td>2.5 s</td>
<td>0.73</td>
<td>6.2 cm/s</td>
</tr>
<tr>
<td>b10</td>
<td>+6 min.</td>
<td>0.86 m</td>
<td>0.09 m</td>
<td>2.3 s</td>
<td>0.75</td>
<td>3.8 cm/s</td>
</tr>
<tr>
<td>b12</td>
<td>+21 min.</td>
<td>0.80 m</td>
<td>0.07 m</td>
<td>2.6 s</td>
<td>0.82</td>
<td>2.2 cm/s</td>
</tr>
</tbody>
</table>
DISCUSSIONS

Effects of Waves on Salt-marshes

The wave climate was not stable and it sometimes changed significantly between the different time-intervals analyzed. To avoid the problem of comparing wave turbulences that were not measured simultaneously, we calculated theoretical orbital-velocities from PT data using linear wave theory (following, e.g., Neumeier and Amos, 1991; Drennan et al., 1992). For this, we assume that, contrary to the velocities, the wave pressure-variations are not significantly attenuated by the vegetation and they reach undisturbed the pressure sensor.

In the absence of vegetation, the ratios $R_v$ and $R_w$ should be equal to 1, i.e., the measured values and the theoretically calculated values of TKE should be identical. Reasons for differences (i.e., for variations of $R_v$ and $R_w$ from 1) are (a) the flow hindrance by the canopy, (b) instrument errors, (c) wave differences between the PT and the ADV (the horizontal distance is 0.8 m). The accuracy of the ADV and the PT is largely adequate for present purposes. Flow perturbation by the structure supporting the sensors and vibrations were minimised. Due to the small distance between the ADV and the PT, differences should be small, less than 5% in $R_v$ and $R_w$, including other errors. Differences could account for some of the variability in the profiles of Figure 3A.

Figure 2. Details of the wave attenuation for profile B10: spectral densities of the wave orbital-velocity $S_u(f)$ and $S_w(f)$ (horizontal and vertical, respectively, measured from the ADV), and $S_{u,v}(f)$ and $S_{w,v}(f)$ (horizontal and vertical, calculated from the wave data). Examples for 3 heights above the bed are shown: 3 cm (close to the bed), 18 cm (lower third of the canopy), and 56 cm (just above the canopy). The vertical dotted lines mark the frequency interval that was integrated to calculated $E_u$, $E_w$, $E_{u,v}$, and $E_{w,v}$. The calculation results are shown on the right hand side (see text for explanations). The typical -5/3 slope of the inertial subrange is shown on some plots.
The periods of surfaces gravity waves and of orbital velocities are longer during storms (4-8 seconds instead of 2.5 s), when sediments are mobilised on intertidal areas (CARLING, 1982). In such conditions, the vegetation influence is likely to be between the limited attenuation of the present experiment and the strong attenuation observed under unidirectional flow. Therefore, the vegetation may protect the bed against erosion and trap coarse sediments during storms.

Salt-marsh vegetation was fully submerged during all the wave-dominated profiles illustrated here. It is probable that with emergent vegetation the damping effect would be greater (MÖLLER et al., 1999). This situation may be important, because fair weather waves have their greatest influence on sediment transport over tidal flats in very shallow water (<0.5m). Its influence should be significant especially near the salt-marsh edge, where such waves are highest (GLEASON et al., 1979).

**Turbulence Structure of Unidirectional Flow**

The unidirectional-flow profiles acquired during experiment A show a reduced TKE with increasing canopy density (Figure 4). This relationship is very clear for the vertical component , but it less evident for the horizontal component , which sometimes has relatively high values in the lower part of the canopy. Other researchers observed similar results. CHRISTIANSEN et al. (2000) observed a reduction of TKE with increasing vegetation density across a salt-marsh transect. LEONARD and LUTHER (1995) observed a similar relationship between turbulence intensity (which is proportional to the root of TKE) and canopy density on vertical profiles. Furthermore, LEONARD and REED (2002) and NEPF and VIVIONI (2000) observed also much lower turbulence intensities for the vertical component than for the horizontal ones. However not all cases are so simple: LEONARD and REED (2002) described vertical profiles in an Atriplex portulacoides marsh (which has a complex canopy architecture) as “less predictable”.

The two calculated Reynolds stresses highlight the difference of vertical exchanges in the different zones of the water column. , is low, slightly negative in the denser canopy, and generally increases above this region. , is also relatively low in the denser canopy, and higher above the canopy. In addition, these two areas are separated by a maximum at 20–25 cm, in the upper part of the 30-cm high canopy. NEPF and VIVIONI (2000) showed a similar maximum in Reynolds stress near the upper canopy limit in a flume experiment with artificial vegetation.

These results suggest a division of the water column into 3 zones. (1) Above the canopy, a skimming flow exists, which tends to be similar to a “standard” benthic boundary layer, but is influenced by the water surface: TKE and stresses are relatively high. This zone corresponds to the vertical exchange zone of NEPF and VIVIONI (2000). (2) In the upper part of the canopy, a relatively thin interface layer exists, which is characterized by a maximum of Reynolds stress. This interface layer seems to move slightly downwards in shallower water, where less space is available for the skimming flow. (3) In the denser part of the canopy, mean-velocity and all turbulence parameters are low, especially and , which indicate reduced vertical exchanges of momentum. The complex flow hindrance of the canopy produces unusual negative values of . This zone corresponds to the horizontal exchange zone of NEPF and VIVIONI (2000). The description above applies to fully submerged vegetation. Only the lowest zone exists in emergent vegetation.

These results confirm the finding of previous experiments (e.g. LEONARD and LUTHER, 1995; SHI et al., 1995; LEONARD and REED 2002; NEUMIEER and CIAVOLA, 2004), that the canopy not only induces a skimming flow above it, but also creates conditions favourable for sedimentation within the denser canopy. There, the reduced mean-flow, which is visible on velocity profiles, goes together with reduced turbulence. The low values of and emphasize the reduced vertical turbulent-movements in this zone, which is of prime importance for particle settling and geochemical exchange.
The results underline the importance of the canopy structure. The turbulence reductions are related to the vertical distribution of vegetation density. That characteristic of *Spartina anglica* changes significantly with the seasons in England. Further research should look into the behaviour of salt-marsh vegetation with different canopy-architecture.

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**LITERATURE CITED**


**CONCLUSIONS**

Wave-dominated turbulence-profiles show significant attenuation of wave orbital-velocities in the denser part of a salt-marsh canopy: a further reduction of the turbulent kinetic energy (TKE) by 20-35%, which corresponds to a further reduction in orbital velocity by 10-20%, due to the vegetation presence. The studied conditions (short-period waves (2.5 s) over fully submerged vegetation) showed attenuation to be limited, and less than previous studies on unidirectional current had suggested. However, under different conditions (fair-weather waves in very shallow water with emergent vegetation, or long-period waves during storms) the attenuation of the orbital velocity by the vegetation could have a significant impact on the sediment dynamics.

Turbulence profiles collected under unidirectional-flow are characterized by a low-turbulence zone in the denser canopy, which is separated from an overlying skimming flow by an interface level with high Reynolds stress. In the denser canopy, the vertical turbulent-movements are reduced, which favour particle settling and has a significant impact on geochemical exchanges.


