Journal of Coastal Research	11	4	1204–1209	Fort Lauderdale, Florida	Fall 1995

Flow Structure in and above the Various Heights of a Saltmarsh Canopy: A Laboratory Flume Study

Z. Shi†, J.S. Pethick‡ and K. Pye††

† Key State Laboratory for
Estuarine & Coastal
Morphodynamics and Sediment
Dynamics
Institute of Estuarine and
Coastal Research
East China Normal University
3663 North Zhongshan Road
Shanghai 200062
P.R. China

‡ Institute of Estuarine and
Coastal Research
University of Hull
Hull HU6 7RX, U.K.

†† Postgraduate Research
Institute for Sedimentology
University of Reading
Reading RG6 2AB, U.K.

ABSTRACT

SHI, Z.; PETHICK, J.S. and PYE, K., 1995. Flow structure in and above the various heights of a saltmarsh canopy: a laboratory flume study. *Journal of Coastal Research,* 11(4), 1204–1209. Fort Lauderdale (Florida), ISSN 0749-0208.

Flow velocity profiles were measured in and above varying height (80%, 60%, 40% and 20%) of *Spartina anglica* canopies (350 stems m^{-2}) in a flume. Results demonstrate the flow complexity in and above the various heights of the canopy. The shapes of the measured velocity profiles were generally controlled by the canopy height. Furthermore, in the lower part of the canopy there is a reversal of the flow velocity gradient $\partial \bar{u}/\partial z$, resulting in a secondary flow velocity maximum in the *Spartina anglica* canopy. This suggests that turbulent stress is transported downward from the upper part of the plants within-canopy. Above the canopy, the velocity distribution is semi-logarithmic. The physical implications, especially for the entrainment of cohesive sediment, are speculated.

ADDITIONAL INDEX WORDS: *Velocity profile, secondary flow maximum, saltmarsh, flume.*

INTRODUCTION

Saltmarshes are recognized for their ability to modify currents, damp waves (KNUTSON *et al.*, 1982), promote sediment deposition and provide habitats for coastal organisms. There is little information about these processes, their magnitude or importance. These require our full understanding of fundamental hydrodynamic processes in saltmarsh canopies. Due to the shallow depth of water and slow velocity of flow in the field, it is difficult to measure the velocity using an ordinary current meter. WANG *et al.* (1993) attempted to measure the velocity of flow through saltmarsh vegetation in the field. Therefore, most existing work has been carried out in the laboratory (*e.g.*, GLEASON *et al.*, 1979; ECKMAN, 1983; PETHICK *et al.*, 1990). These studies have revealed that flow structures under saltmarsh plants are far more complicated than we previously realized. For example, when ECKMAN (1983) first carried out a laboratory study on the flow structure in an artificial saltmarsh canopy, it was found that the velocity profile within the canopy departed from the semi-logarithmic. PETHICK *et al.* (1990) found that there were two layers in their measured profiles under a saltmarsh canopy.

Other relevant and applicable studies have been made of flow through seagrass canopies (SCOFFIN, 1970; ANDERSON and CHARTERS, 1982; FONSECA *et al.*, 1982, 1983; FONSECA and FISHER, 1986; GAMBI *et al.*, 1990; ACKERMAN and OKUBO, 1993). GAMBI *et al.* (1990) also noted that there were two layers in their measured profiles. Furthermore, the velocity distribution was generally semi-logarithmic above the canopy, but it departed from semi-logarithmic in the canopy. However, they did not realize the hydrodynamic complexity and difference in and above the canopy.

Despite these extensive studies, the flow structure in and above these canopies, is far from being exhaustively described and understood. In this study, a laboratory flume experiment was under-

---

94110 received 7 June 1994; accepted in revision 29 August 1994.

Table 1. *Characteristics of the mean-flow under various heights of Spartina anglica canopies (100% = 300 mm).*

Flow Condition	100%H	80%H	60%H	40%H	20%H
Temperature (T; °C)	20	20	20	20	20
Water depth (D; mm)	348	346	338	342	332
Mean velocity (U; m s^{-1})	0.051	0.049	0.028	0.038	0.033
Canopy roughness (Reynolds number; Re.)		13,357	5,732	5,197	2,262

taken to study the flow dynamics in a coastal saltmarsh (*Spartina anglica*) canopy. Due to the complexity of the natural saltmarsh environment, no attempt has been made to actually mimic field conditions. The fundamental objectives of the present laboratory flume-based study were to examine the flow structure in and above a *Spartina anglica* canopy and to assess the effect of the *Spartina anglica* canopy height on flow dynamics.

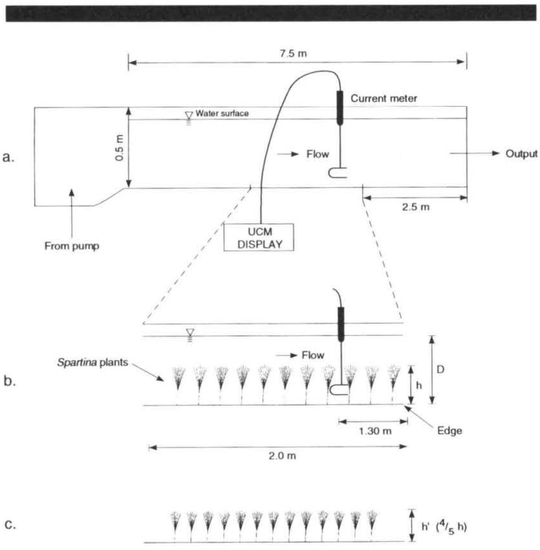

Figure 1. (a) Experimental arrangement; (b) Definition sketch; (c) Roughness (*Spartina anglica* canopy) details.

MATERIALS AND METHODS

Spartina anglica (cordgrass) is one of the pioneer communities, which grows in the coastal, estuarine intertidal zones. Live *Spartina anglica* plants were collected in January 1992 along the north side of the Humber estuary, U.K. They appeared the same in size; the average diameter was 4 mm. The height of collected plants ranged from 310 to 340 mm. They were chopped to the same height, 300 mm (h), corresponding to the mean of those measured in the field.

It was extremely difficult to measure the density of saltmarsh vegetation cover in the field. In the present study, the stem density, which is defined as the number of plant stems per m^2 was used to quantify the vegetation cover. A field survey demonstrated a various range of *Spartina anglica* plant stem density. The density (350 stems m^{-2}) used in the present flume study is within the range of the observed field density. Maximum flow velocity (0.051 m s^{-1}, Table 1) corresponds to the mean value of the measured flow velocity in the field.

The experiments were carried out in an Armfield recirculating laboratory tilting flume (Figure 1a) at the School of Earth Resources and Geography, University of Hull, U.K. The flume is 7.5 m long, 0.3 m wide and 0.5 m high, with glass side walls and a smooth concrete floor. *Spartina anglica* stems (210) were held in place by attachment to a concrete plate (0.6 m^2) with drilled holes. *Spartina anglica* stems were inserted through the holes (Figure 1b). The alignment (spacing) of the plants was controlled by evenly inserting each stem into a 30 mm^2 quadrant area. The 210 *Spartina anglica* stems (h′) were chopped to four levels (80%, 60%, 40% and 20% h) so that the various heights of *Spartina anglica* canopies were cautiously simulated in the experiment (Figure 1c). Given that stem diameter varies with height, there is a possible interaction of the change in diameter effect with height and flow effects and the change in probable stiffness with height (using more of the main stem and less of the leaf components).

Flow mean vertical velocity profiles were taken at the site 1.3 m from the *Spartina anglica* bed edge (downstream, Figure 1b). The flow velocity was measured with a Sensordata Minilab model SD-12 ultrasonic current meter (Figure 1a). The instrument consists of a three-axis (x, y, z) probe, with three orthogonal pairs of 2 × 0.5 cm piezoelectric 4M Hz transducers mounted on a stem. The probe was adjusted so that only streamwise instantaneous velocity component u(z) was measured close to the bed. Velocity recordings began at 2.5 mm above the bed and repeated at 1 to 2 mm increments to within 5 mm of the free surface

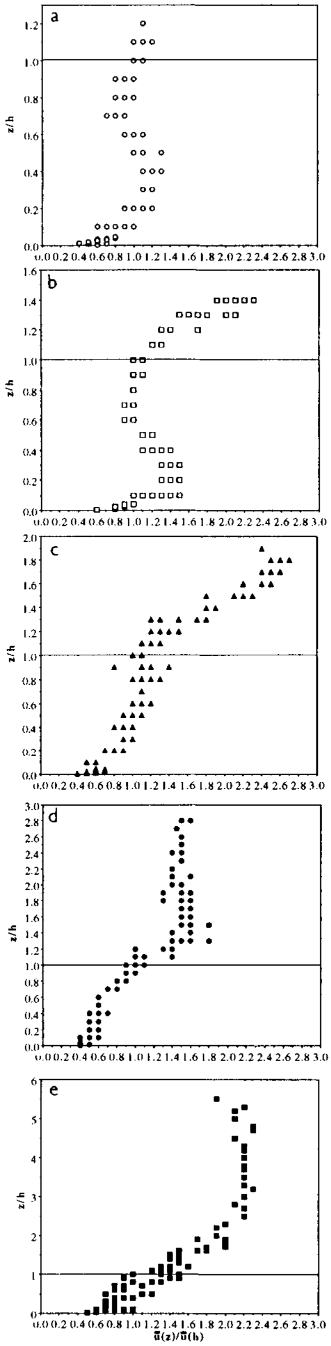

Figure 2. Profiles of mean flow velocity under various heights of *Spartina anglica* canopy (a. 100% = 300 mm; b. 80% h; c. 60% h; d. 40% h; e. 20% h).

of flow. The calibration of the sensor was checked before the experiments and a spatial resolution of ±1 mm s^{-1}. The instrument was zeroed at the beginning of measurement. A rate of 100 Hz was used for sampling. The flow velocity u(z) measured by the sensor are displayed in digital form on the instrument's control panel, with a range of ±100 cm s^{-1}. The roughness Reynolds number Re_*, was defined as Uh/ν, where U = mean flow velocity (m s^{-1}), h = height of the canopy, and ν viscosity (cm^2 s^{-1}).

RESULTS

Spartina anglica plants interacted strongly with flow, extracting momentum from the fluid via hydrodynamic drag and generating turbulence via disruption. Furthermore, current reduction and shear stress were affected by plant height. General characteristics of flow under the various heights of the *Spartina anglica* canopy are shown in Table 1. Five velocity profiles over the five different heights of the canopy were obtained (Figure 2). The profiles were presented in a dimensionless form, using h′ and the mean flow velocity u(h) at the top of the *Spartina anglica* canopy as normalizers. In general, these mean flow velocity profiles revealed different hydrodynamics in and above canopy, which were mainly affected by the height (h′) of the canopy and alignment of the plants.

Above the *Spartina anglica* canopy, the velocity profile is 'J' shaped, indicating that the velocity distribution is semi-logarithmic, fitting the von Karman-Prandtl relationship (see Eq. (1)). Similar phenomena are reported in the literature (FONSECA *et al.*, 1986; GAMBI *et al.*, 1990). That is to say, the flow above the canopy is turbulent boundary layer flow. The 'J' shape of the velocity profile becomes more distinguished with decreasing canopy height h′ (Figure 2).

Within the *Spartina anglica* canopy, the velocity profile is 'S' shaped, indicating two interesting features. First, the mean flow shear was high in the upper part and very low in the lower part of the *Spartina anglica* canopy (Figure 2). Another important feature is that there is a reversal of the flow gradient $\partial \bar{u}/\partial z$ in the lower part of the *Spartina anglica* canopy, resulting in a secondary maximum near z/h′ = 0.4 (Figure 2a), z/h′ = 0.2 (Figure 2b). This counter-gradient was not apparent at the low *Spartina anglica* canopy heights (Figure 2d, e).

DISCUSSION

Characteristics of the Turbulent Flow under *Spartina anglica* Plants

In the general context of fluid dynamics, under conditions of a smooth-wall boundary layer, there is a thin viscous or laminar sublayer next to the wall which is of the order of a few millimeters thick. The motion within this is definitely not laminar, but the profile of mean longitudinal velocity is linear. Above the viscous sublayer is a transitional, or buffer, layer and above this the fully turbulent logarithmic layer in which $\bar{u}(z)$ is proportional to ln(z). Within the logarithmic layer, the velocity profile was expressed by the von Karman-Prandtl equation

$$u/u_* = 1/k \ln(z/z_0) \qquad (1)$$

where u(z) = mean velocity at height, z, above the bed (m s^{-1}); u_* = shear velocity (m s^{-1}); k = von Karman's constant (0.4 in unstratified flow), z = height above the bed (m), z_0 = roughness length (m). It was also shown that a semi-logarithmic flow formula applies to flow close to the *Spartina anglica* canopies (Figure 2). Similar behaviors have been reported in the literature (GAMBI *et al.*, 1990; PETHICK *et al.*, 1990). The shear stress (τ) can be obtained using the following equation:

$$\tau = \rho u_*^2 \qquad (2)$$

Within canopy, the vertical flux of momentum, or shear stress, $\tau(z)$, is

$$\tau(z) = \rho K_M \delta\bar{U}/\partial z \qquad (3)$$

where $\tau(z)$ = the kinematic shear stress (N m^{-2}), K_M = diffusion coefficient for momentum exchange, and $\delta\bar{U}/\partial z$ = mean velocity gradient.

As shown in Figure 2a, b, there was a reversal of the flow velocity gradient, resulting in a secondary flow velocity maximum in the lower part of the *Spartina anglica* canopy. A similar feature was found in air flow through agricultural canopies (SHAW, 1977; WILSON and SHAW 1977), and forest canopies (RAUPACH and THOM, 1981; RAUPACH *et al.*, 1991). This feature attenuated when the *Spartina anglica* canopy height decreased (Fig. 2). Many authors have discussed their observations of this feature. These include "below-through" from the leading edge of a plant stand, slope effects, or the influence of gaps in the upper story of the canopy. However, none of these possible gradient-reversal mechanisms satisfactorily accounts for all the observations (SHAW, 1977), so counter-gradient momentum transport must be accepted as a real feature of many canopy flows (RAUPACH and THOM, 1981). Recently, RAUPACH *et al.* (1991) have doubted the reality of such a feature of flow velocity. They argued that most previous data were gathered with cup anemometers, which are prone to substantial overspeeding in the highly turbulent flow within the canopy, so that observations of bulges in u(z) within the canopy provide no proof of counter-gradient momentum transfer. The present study on the flow through saltmarsh suggests that the velocity gradient-reversal is a true feature within a saltmarsh canopy.

Entrainment and Deposition of Cohesive Sediments

The flow modifications and flow patterns under various heights of *Spartina anglica* influence both physical and biological aspects of saltmarshes, such as the concentration of cohesive suspended particulates within the saltmarsh and nutrient exchange at the sediment-water interface. These features have important physical implications for the formation of saltmarshes. Estimation of turbulence parameters is known to be important in the entrainment and deposition of cohesive sediments. Many functional relationship can be used to define critical conditions for particle entrainment but usually a non-dimensional Shields entrainment ratio (θ) is used, relating the entraining force to the resisting force:

$$\theta = \tau/(\rho_s - \rho)gd \qquad (4)$$

where τ = shear stress (N m^{-2}), ρ_s = density of sediment (g cm^{-3}), ρ = density of water (g cm^{-3}), g = acceleration due to gravity (m s^{-2}), d = diameter of particles (mm). In Eq. (4), the shear stress (τ) promoting entrainment is resisted primarily by the weight of the particle. Low shear stress results into local sediment deposition and high shear stress promotes entrainment (ECKMAN, 1983). FONSECA and FISHER (1986) and GAMBI *et al.* (1990) suggested that the seagrass canopy provides a mechanism for the deposition of suspended sediment by increasing the shear of flow.

The deposition rate of cohesive sediments can be expressed by KRONE's (1962) equation:

$$dm/dt = \omega_s C(1 - \tau_b/\tau_d) \qquad \tau_b < \tau_d \qquad (5)$$

where dm/dt is the mass of sediment exchange per unit area (kg m^{-2} s^{-1}), τ_b = applied bed shear stress (N m^{-2}), τ_d = the critical shear stress for deposition (N m^{-2}), ω_s = the settling rate of the flocs (m s^{-1}), and C = the suspended sediment concentration (kg m^{-3}). When the applied bed shear stress (τ_b) is less than the critical shear stress for deposition (τ_d), the sediments deposit. With reference to this study, the variation in shear stress and turbulence within the *Spartina anglica* canopy will affect the flocculation, settling and deposition process of the cohesive sediments. The leaves of *Spartina anglica* plants can trap cohesive sediments and affect the concentration of suspended particles (C) and their deposition rate, dm/dt. The entrainment and transport of suspended particulates are also influenced by wind-generated waves in a natural saltmarsh community in the field. However, this is beyond the scope of the present study.

Flume uses for simulation of benthic environments resulted from the recognition that a variety of physical and biological processes were strongly influenced by water motions at the boundary with solid surfaces and that these processes in the bottom boundary layer can be modeled in the flume (NOWELL and JUMARS, 1987). Whilst these laboratory experiments above are not scale models of field conditions, they are general indicators of natural sedimentary processes. Because the deposition and distribution of estuarine fauna and detritus in a *Spartina anglica* canopy are strongly influenced by the frictional characteristics of the estuarine intertidal zone floor, nursery and refuge value of *Spartina anglica* also may vary directly with their influence on canopy friction and sediment movement. Environmental factors such as temperature and salinity generally are acknowledged as contributory factors in affecting occurrence of fauna, but hydrodynamic factors have received little study in the estuarine intertidal saltmarsh habitat. Hydrodynamic gradients exist that can affect feeding and recruitment as demonstrated by the variation in the velocity gradient (Figure 2).

In the future, *in situ* measurements are necessary to verify fluid flow patterns in the flume and to determine their physical or biological significances.

CONCLUSIONS

The primary objective of this study was to measure velocity profiles over different heights of a *Spartina anglica* canopy and thereby evaluate the response of flow structure to the canopy height. The following conclusions were drawn.

(1) Velocity profiles are semi-logarithmic above the canopy and non-logarithmic in the canopy. Within the canopy, there is a reversal of the flow velocity gradient $\partial\bar{u}/\partial z$, resulting in a secondary flow velocity maximum in a *Spartina anglica* canopy.

(2) Under a given density of a *Spartina anglica* canopy, the canopy height (h′) seemed the main factor controlling flow structure.

(3) Based on results, saltmarsh canopy should exert a strong influence on suspended sediment concentration (C), settling velocity (ω_s) and deposition rate (dm/dt) of the cohesive sediment through effects on shear stress and turbulence of flow.

ACKNOWLEDGEMENTS

The authors are grateful to Ms. F. Burd and Mr. B. Murphy (University of Hull) for their assistance in the field and laboratory. Dr. J. Hardisty (University of Hull) is thanked for his helpful discussion. The original draft of this paper was prepared while Z. Shi was in Reading, U.K. Professors C. Peter McRoy, R.D. DeLaune and P.L. Knutson are thanked for their thoughtful reviews of the manuscript. Ms. J. Fox (Department of Geography, University of Reading) assisted with the final drafting of Figure 1. In addition, Z. Shi acknowledges the support of the China Postdoctoral Science Foundation and the State Education Commission of P.R. China.

LITERATURE CITED

ACKERMAN, J.D. and OKUBO, A., 1993. Reduced mixing in a marine macrophyte canopy. *Functional Ecology*, 7, 305–309.

ANDERSON, S.M. and CHARTERS, A.C., 1982. A fluid dynamics study of seawater flow through *Gelidium nudifrons*. *Limnology and Oceanography*, 27, 399–412.

ECKMAN, J.E., 1983. Hydrodynamic processes affecting benthic recruitment. *Limnology and Oceanography*, 28, 241–257.

FONSECA, M.S. and FISHER, J.S., 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Marine Ecology Progress Series*, 29, 15–22.

FONSECA, M.S.; FISHER, J.S.; ZIEMAN, J.C., and THAYER, G.W., 1982. Influence of the seagrass, *Zostera marina* L., on current flow. *Estuarine, Coastal and Shelf Science*, 15, 351–364.

FONSECA, M.S.; ZIEMAN, J.C.; THAYER, G.W., and FISHER, J.S., 1983. The role of current velocity in structuring seagrass meadows. *Estuarine, Coastal and Shelf Science*, 17, 367–380.

GAMBI, M.C.; NOWELL, A.R.M., and JUMARS, P.A., 1990. Flume observations on flow dynamics in *Zostera ma-*

rina (eelgrass) beds. *Marine Ecology Progress Series,* 61, 159–169.

Gleason, M.L.; Elmer, D.A.; Pien, N.C., and Fisher, J.S., 1979. Effects of stem density upon sediment retention by saltmarsh cord grass, *Spartina alterniflora* Loisel. *Estuaries,* 2, 271–273.

Knuston, P.L.; Seeling, W.N., and Inskeep, M.R., 1982. Wave damping in *Spartina alterniflora* marshes. *Wetlands,* 2, 87–104.

Krone, R.B., 1962. *Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes.* University of California, Hydraulics Engineering Laboratory and Saint Engineering Laboratory, Berkeley, 110 p.

Nowell, A.R.M. and Jumars, P.A., 1987. Flumes: Theoretical and experimental considerations for simulation of benthic environments. *Oceanography and Marine Biology,* Annual Review, 25, 91–112.

Pethick, J.S.; Leggett, D., and Husain, L., 1990. Boundary layers under salt marsh vegetation developed in tidal currents. *In:* Thornes, J.B. (ed.), *Vegetation and Erosion.* London: Wiley, pp. 113–123.

Raupach, M.R. and Thom, A.S., 1981. Turbulence in and above plant canopies. *Annual Review of Fluid Mechanics* 13, 97–129.

Raupach, M.R.; Antonia, R.A., and Rajagopalan, S., 1991. Rough-wall turbulent boundary layers. *Applied Mechanics Review,* 44, 1–25.

Scoffin, T.P., 1970. The trapping and binding of subtidal carbonate sediments by marine vegetation in Bimini Lagoon, Bahamas. *Journal of Sedimentary Petrology,* 40, 249–273.

Shaw, R.H., 1977. Secondary wind speed maxima inside plant canopies. *Journal of Applied Meteorology,* 16, 514–521.

Wang, F.C.; Lu, T.S., and Sikora, W.B., 1993. Intertidal marsh suspended sediment transport processes, Terrebonne Bay, Louisiana, U.S.A. *Journal of Coastal Research,* 9(1), 209–220.

Wilson, N.R. and Shaw, R.H., 1977. A higher-order closure model for canopy flow. *Journal of Applied Meteorology,* 16, 1198–1205.