Continental Shelf Research 112 (2016) 46–67

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

On the suspension of graded sediment by waves above ripples: Inferences of convective and diffusive processes

A.G. Davies [a,*], P.D. Thorne [b]

[a] Centre for Applied Marine Sciences, School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey LL59 5AB, UK
[b] National Oceanography Centre, Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK

ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form
2 October 2015
Accepted 9 October 2015
Available online 22 October 2015

Keywords:
Sediment transport
Waves
Graded sediment
Sand ripples
Reference concentration
Suspended concentration profiles

ABSTRACT

The relationship between the grain size distribution of the sediment on the bed and that found in suspension due to wave action above ripples is assessed here using detailed, pumped sample, measurements obtained at full-scale and also at laboratory scale. The waves were regular and weakly asymmetrical in most tests, and irregular in a minority of tests. The beds comprised fine and medium sand and were rippled in all tests. The cycle-mean sediment concentrations (C) from the pumped samples were split into multiple grain size fractions and then represented by exponential C-profile shapes. The analysis of these profiles was carried out in two stages to determine: (i) the relationship between the size distribution of the sediment on the bed and that found in the reference concentration, and (ii) the behaviour of the exponential decay scale of the C-profiles. From this analysis inferences are made about the relative roles of diffusion and convection in the upward sediment flux linked to the process of vortex shedding from the ripple crests. The Transfer function (Tr) defined to relate the bed sediment size distribution to that of the reference concentration indicates that, while finer fractions are relatively easily entrained, the suspension of some coarser fractions is caused by an additional convective effect that supplements diffusion. The evidence for this becomes pronounced above steep ripples, and the Transfer function suggests further that irregular waves increase the occurrence of coarser fractions in suspension. A functional form for Tr is suggested incorporating these principles. The exponential decay scale L_S arising from the fractional C-profiles is also examined to assess the mechanisms responsible for the upward transfer of grains and a parameterisation of L_S related to ripple size is suggested. The separate findings for Tr and L_S present supporting evidence of diffusion affecting the finer fractions in suspension and combined diffusion + convection affecting the coarser fractions. The methodology developed allows the vertical profile of suspended median grain size to be predicted given knowledge of both the bed grain size distribution and also the flow conditions.

1. Introduction

Although the seabed sediment typically comprises a broad size distribution surprisingly little account is taken of this in many of the methods used in sediment transport estimation. A single representative grain size is generally used to characterise the sediment even though the seabed includes both fine grain fractions that can readily be entrained into suspension, for example by waves, and also coarse fractions that only ever form part of the bed load. The resulting grain size distribution in suspension can be significantly different from that of the seabed. Further, due to the larger settling velocities of the coarser fractions, the suspended sediment size distribution becomes progressively dominated by finer grains as height above the bed increases. This has significant implications, for example in relation to sediment sorting across beach profiles and to water quality where contaminants are attached to finer or coarser particles. If the vertical sorting of sediment grains between the bed surface material and the suspension, and hence the relative movement of finer and coarser particles, is not taken into account, this may lead to bias and inaccuracy in predicting net sediment transport rates. In a series of laboratory experiments involving different sand mixtures beneath asymmetric waves, O'Donoghue and Wright (2004) showed that the relative contributions to the net transport, in suspension and in the near-bed sheet flow layer, varied significantly depending upon the sand size and grading.

Detailed procedures for modelling grain mixtures have remained rather *ad hoc*, with observations suggesting that some grain size fractions in suspension can be far coarser than

* Corresponding author.
E-mail addresses: a.g.davies@bangor.ac.uk (A.G. Davies), pdt@noc.ac.uk (P.D. Thorne).

http://dx.doi.org/10.1016/j.csr.2015.10.006
0278-4343/

Nomenclature

a	coefficient in Eq. (A.2)
a_1,a_2	coefficients in ripple 'flow contraction' expression
A_1	semi-orbital near-bed excursion amplitude based on the wave fundamental frequency
A_*	$(=D_*^3)$ Archimedes Buoyancy Index
b	coefficient in Eq. (A.2)
b_1,b_2	coefficients in Transfer function expression (Eq. (14))
B_1,B_2	dimensional coefficients with numerical values depending upon ν, s and g
c_1-c_4	empirical constants
C	wave cycle-mean sediment concentration
C_0,C_a,C_r	sediment volumetric reference concentration at height $z=0$, $z=a$ and $z=z_r$, respectively
C_{bi}	bed sediment volumetric concentration of the ith grain fraction
C_{ri}	volumetric reference concentration of the ith grain fraction ($<\ldots>$ denotes a wave cycle-mean)
C_{cb}	cumulative %-distribution of bed sediment sizes
C_{cr}	cumulative %-distribution of reference concentration particle sizes
$C_i(z_j)$	suspended concentration of the ith grain fraction at the jth height z above the bed
$C_{cum,i}(z_j)$	cumulative concentration based on $C_i(z_j)$
$C_{sum}(z_j)$	total concentration summed over the i grain fractions at the jth height z above the bed
d	sediment grain size; this includes sizes obtained by interpolating the discrete d_m scale
d_c	maximum allowable or critical grain size in suspension
d_s	sieve size used in grain distribution analysis
d_m	grain size corresponding to central diameter for each sieve interval determined at the respective mid-points on the ϕ scale
d_{50}	median grain diameter of the sediment
d_{50b}	median grain diameter of the bed material
d_{50s}	median grain diameter of the sediment in suspension
d_i	sediment grain diameter (bed or suspended material) for which i% of the grains are finer by volume (or weight)
d_0	$(=2A_1)$ near-bed orbital diameter
D_*	dimensionless grain size (defined by Eq. (10))
f_w	wave friction factor ($f_{w,max}$ is maximum value according to Swart's (1976) formula)
g	acceleration due to gravity
H, H_s	wave height, significant wave height
k_s	equivalent bed roughness
L_S	$(=\varepsilon_s/w_s)$ decay (or distribution) length scale of the exponential C-profile
L_{ST}	total decay (or distribution) length scale for the aggregated C-profile
Re_s	Reynolds number of a settling grain $(=w_s d/\nu)$
RE	wave Reynolds number $(=U_1A_1/\nu)$
s	$(=\rho_s/\rho)$ relative sediment density
T,T_p	wave period, peak wave period
Tr	'Transfer function' relating the reference concentration to the bed sediment
u_*	friction (or shear) velocity (with prime u_*': skin friction component)
u_{*w}	peak value of friction (or shear) velocity during the wave cycle (with prime u_{*w}': as above)
U_1,U_2	first and second harmonics of the near-bed wave velocity amplitude
w	upward fluid velocity (convective velocity in Fredsøe and Deigaard's (1992) model)
w_s	sediment settling velocity
w_{sc}	settling velocity corresponding to the critical grain size in suspension d_c
X	non-dimensionalisation of grain diameter, defined by Eq. (14)
z	height above the bed
z_a	reference height above the bed at which $C=C_a$
z_r	height of reference concentration C_r
β	$(=\varepsilon_s/\varepsilon_m)$ quotient describing the local difference between the diffusion of a fluid 'particle' and a discrete sediment particle
δ_s	near-bed layer thickness in which sediment diffusivity ε_s remains constant
ε_e	estimated sediment diffusivity in Fredsøe and Deigaard's (1992) convective model
ε_m	eddy viscosity, or vertical diffusion coefficient for momentum, in a clear fluid
ε_s	sediment vertical diffusivity
ϕ	$(=-\log_2(d)$ with d in mm) Krumbein phi scale
η	ripple height
λ	ripple wavelength
ν	kinematic viscosity of water
θ	Shields parameter, peak value during wave cycle (Eq. (12)) (with prime θ': skin friction component)
ρ	density of water
ρ_s	density of sediment
σ_g	$(=(d_{84}/d_{16})^{0.5})$ geometric standard deviation of the sediment
τ_b	bed shear stress ($<\ldots>$ denotes a wave cycle-mean)
$\tau_{crit,i}$	critical shear stress for the ith grain fraction of the bed sediment in isolation
τ_e	time scale of exchange in Fredsøe and Deigaard's (1992) convective model
ω	$(=2\pi/T)$ wave angular frequency

accounted for by standard methodologies. For example, Masselink et al. (2007) estimated the sediment size in suspension above oscillatory ripples at a coarse-grained beach site to be 0.6 mm with settling velocity 80 mm/s; these values are far larger than would be predicted by the turbulent diffusion methodologies referred to later. This raises the interesting and important question: 'are all grain fractions in suspension in a given flow influenced in the near-seabed layer by the same mixing mechanisms?' The answer is implicit in some previous works (e.g. Van Rijn, 1993), but we return to the question here with the benefit of an extensive, detailed data set highlighting the suspension of graded sediments by waves above rippled beds. While arguing that the answer is 'no', we infer from the experimental data that, while the finer fractions in suspension are influenced primarily by diffusion, the coarser fractions are progressively influenced also by convection. The present study is in two parts, each involving suspended sediment data obtained beneath waves in both a full-scale wave facility and also a laboratory flume. Initially we consider the relationship between the size distribution of the sediment on the bed and that in suspension, and then the nature and causes of the concentration profiles of the individual fractions in suspension. A similar study was carried out for steady flow by Sengupta (1979) who related the size distribution of the bed material to that obtained in suspension by pumped sampling at a fixed height above the bed.