Measurements and analysis of suspended sediment particle size sorting above bedforms under waves

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ABSTRACT: The relationship between the grain size distribution of the sediment on the bed and that found in suspension, due to wave action above bedforms, is assessed using pumped sample measurements for beds of fine and medium sand. The pumped samples were sieved into multiple grain size fractions and represented by an exponential concentration profile. 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 behavior of the exponential decay length scale of the concentration profiles. From this analysis inferences are made about the relative roles of diffusion and convection in the upward flux of sediment.

1. INTRODUCTION

To examine the relationship between the bed size distribution and that of the entrained suspended sediments, the present study reports on detailed pumped sample measurements over ripples, under waves. Above ripples under waves the entrainment mixing processes are often referred to as diffusive or convective depending on the steepness of the bedforms (Nielsen 1992, Davies and Thorne 2008, Davies and Thorne 2015). Normally if the ripple slopes, η/λ, (η and λ are the ripple height and wavelength respectively) are less than about 0.12 the dominant process is considered to be diffusive and it is the turbulent fluctuations in the vertical velocity component that give rise to the upward mixing process. Alternatively if the ripples have a slope greater than 0.12, the mixing close to the bed is considered to be dominated by convective coherent vortex processes involving the ejection of a sediment-laden vortex at flow reversal, carrying sediment to several ripple heights above the bed. If the sediment entrainment process is considered to be diffusive then the slope of the logarithmic concentration plotted against linear height above the bed should be inversely proportional to the settling velocity of the grains in suspension. For the case of convective processes it has been suggested that the slope will remain constant with entrainment essentially independent of settling velocity.

2. MEASUREMENTS

The observations reported here were collected in the Deltaflume of Deltares, Delft Hydraulics, the Netherlands (Thorne et al, 2002). This full scale wave flume facility 230m long, 5m wide and 7m deep allows field scale processes to be studied under controlled conditions. Measurements were carried out above two sand beds, where the median bed diameters were d_{50}=162 μm, fine, and d_{50}=329 μm, medium. A number of tests were conducted using regular and irregular waves, with periods in the range of 4-6 s and wave heights between 0.4 – 1.3 m. Pumped samples of the suspended sediments were collected at ten heights above the bed nominally between 0.05-1.55 m and particle size analysis carried out on these data sets. The pumped sampling usually lasted for about 15 min, nominally covering 180 wave periods, when 10 litres of suspended fluid was collected at each height above the bed. The samples were dried and sieved into ¼φ size fractions resulting in profiles of suspended sediment concentration above the bed for up to 15 different size fractions. An acoustic backscatter system, ABS, adjacent to the pumped samples was used to identify their local precise height above the rippled bed. To interpret the suspended sediment size profiles co-located concurrent measurements of the bedforms and the hydrodynamics were collected. The ripple dimensions were obtained using an acoustic ripple profiler, ARP, which measured a 3 m transect along the bed approximately every 60 s during the tests. Wave flow velocity was obtained using electromagnetic current meters, ECMs, at 0.30, 0.6 and 0.9 m above the bed and sampled at 5 Hz.

3. ANALYSIS

To analyse the ¼φ size fraction profiles of suspended sediment concentration, C_i, an exponential fit for the ith fraction of the form

$$C_i = C_{ir} e^{-z/L_{si}} \quad (1)$$

was applied to the measurements. This provided reference concentration, C_{ir}, at z=0 defined as the crest of the ripples and a decay length scale, L_{si} for the ith grain size fraction. There were 10 tests, 4 on the fine sand and 6 on the medium, resulting in 117 values of both parameters for the whole study.

3.1. Transfer function: T_r

To analyse the values for C_{ir} a transfer function was formed which related the cumulative %-distribution of the reference concentration particle sizes, C_{cr}, to the cumulative %-distribution of bed sediment sizes, C_{cb}. The transfer function was expressed as

$$T_r = \frac{100 - C_{cr}}{100 - C_{cb}} \quad (2)$$

T_r represents the broad trends in the relationship between the reference suspended sediment and bed size distributions. In figure 1a T_r is plotted against d/d_c, where d is the sediment grain size and d_c the critical grain size in suspension. d_c is the largest grain size expected in suspension based on solely diffusive processes entraining sediment into suspension. A commonly used criterion to determine d_c is that of Fredsøe and Deigaard (1992) who suggested that a particle should be able to remain in suspension provided that its settling velocity, w_s, is sufficiently small compared with the near-bed vertical turbulent velocity fluctuations, the magnitude of which are of the order of the (skin friction) shear velocity u'_*. Davies and Thorne (2002) used this criterion to define the maximum allowable, or critical, d_c to be that having settling velocity $w_{sc} = 0.8\, u'_{*w}$ where u'_{*w} is the peak wave-induced skin-friction shear velocity; this criterion is used here.

All tests show sediment in suspension for $d/d_c>1$ suggesting that a convective mechanism, as well as turbulent diffusion, is responsible for the upward flux of sediment. The presence in suspension of grains having $d>d_c$ is far more pronounced for the medium sand than the fine sand cases, with the steeper ripples formed in the medium sand, $\eta/\lambda=0.13\pm0.01$, being more capable than the low ripples, $\eta/\lambda=0.07\pm0.02$, in the fine sand of suspending coarser fractions. This reinforces the suggestion of a convective transfer mechanism associated with vortex shedding from the steeper ripple crests supporting the entrainment of the larger size fractions.

To try and bring out the underlying behavior of the measurements presented in figure 1a a number of non-dimensional scaling parameters were investigated. One of the more successful approaches was to include both bed stress and rippled bed effects into the abscissa parameterization. This led to the following expression

$$T_r = 0.5\left[1.05 - \tanh\left(b_1(X - b_2)\right)\right] \quad (3)$$

$$X = \frac{d}{d_c}\frac{\theta'^{0.5}}{\eta/\lambda}$$

θ' is the skin friction Shields parameter. Comparison of this function in figure 1b, the dashed lines, with the measured fine and medium transfer functions averaged over all the regular and irregular wave cases separately, the solid lines, show good agreements. The values of the constants (b_1,b_2) corresponding to the dashed curves in figure 1b are (0.4,4.5) for the regular waves and (0.35,7.5) for the irregular waves.

3.2. Decay length scale: L_s

After some assessment of the normalization for the ordinate, the decay length scales L_{si} for each test were non-dimensionalised by L_{st}, the decay length scale for the aggregated concentration profile corresponding to the sum of all the grain fractions for that test. Again the abscissa uses X given in equation (3). Plots of L_{si}/L_{st} against X are given in figure 2.

Figure 2a shows that with the results plotted logarithmically the curves are reasonably well clustered together with a change of slope in L_{si} / L_{st} at about X=7. The results from each L_{si} / L_{st} test have been interpolated linearly with increment 0.1 in X, and have then been averaged together to yield the black bold line shown. The average curve for L_{si}/L_{st} is repeated in Figure 2b together with a simple representative two-part, power law, curve fit:

$$\frac{L_S}{L_{ST}} = c_3 X^{c_4} \qquad (4)$$

with the coefficients (c_3,c_4) equal to (3.63,–1.1) for X<7 and (0.82,–0.3) for X>7. The bulk of the grain fractions fall within Hallermeier's (1981) transitional settling range and using this it can be shown (Davies and Thorne, 2015) that the line slope (–1.1) for the smaller grain fractions corresponds to a diffusive behaviour. In contrast, the line slope (–0.3) for the larger fractions suggests an additional, convective, component in the upward sediment flux. Had the line slope become zero for X>7, there would have been a suggestion of 'pure convection' as in the model of Fredsøe and Deigaard (1992) and the similar model of Van Rijn (1989). As it turns out the present Deltaflume data lies between these two extremes, with the slope –0.3 suggesting a combined convective + diffusive sediment flux for X>7.

4. CONCLUSIONS

The relationship between the grain size distribution of the sediment on the bed and that found in suspension has been assessed. The transfer function, T_r, showed a consistent pattern of grains being found in suspension with sizes greater than the critical size d_c. This suggests that the suspension is caused in part by convective effects that supplement diffusion and this becomes particularly important for the coarser fractions. The variation of L_{si}/L_{st} has been compared with equation (4) from which it has been concluded that, for finer fractions in suspension having X<7, the C_i-profiles are characteristic of a purely diffusive process. In contrast, for fractions having X>7 a combined convective + diffusive upward transfer of grains is suggested. The separate findings for T_r and the L_{si}/L_{st} present supporting evidence of diffusion affecting the finer grain fractions in suspension and combined diffusion + convection affecting the coarser fractions.

5. REFERENCES

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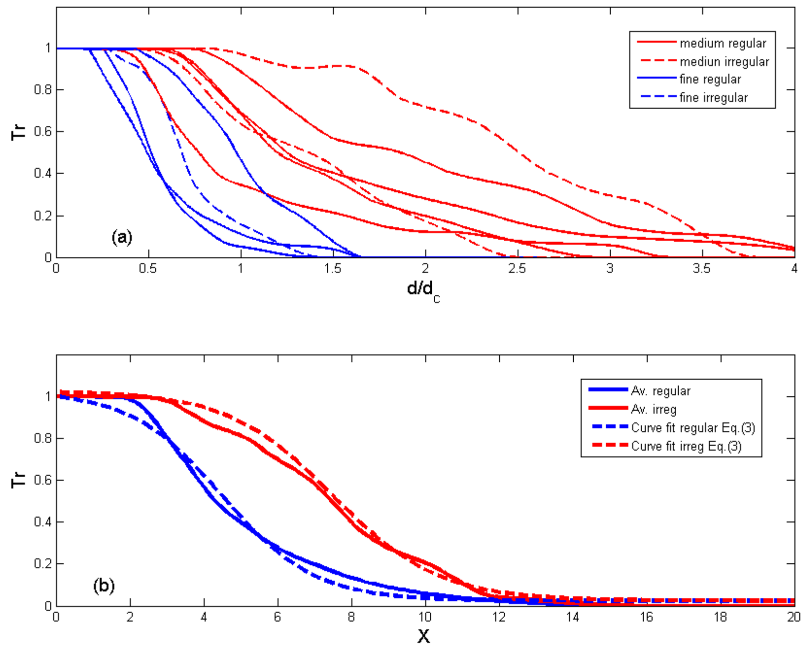

Figure 1. a) Transfer function, T_r, plotted against the normalised grain diameter, d/d_c, for all tests. b) Measured and modelled T_r plotted against X, (see equation (3)) for all tests, with averaged regular wave cases shown in blue and irregular in red.

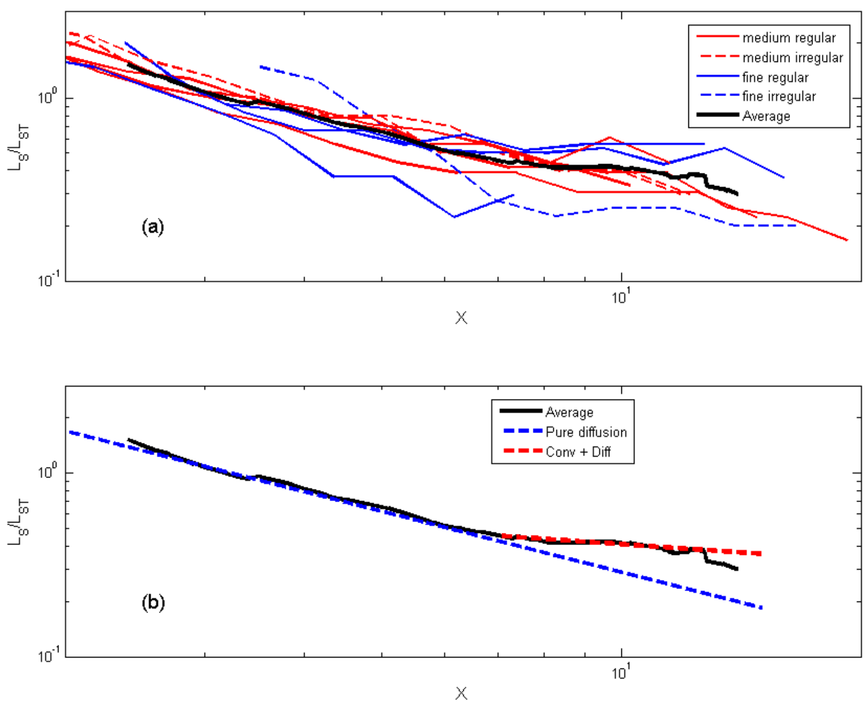

Figure 2. Normalised decay length scale L_s/L_{st} plotted against X. a) Results for all tests with the averaged behaviour indicated by the full black line. b) The averaged curve compared with equation (4) showing a diffusive behaviour for X<7 and diffusive+convective for X>7.