

CHAPTER 317

Suspended sediment mixing in the surf zone

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Abstract

The vertical distribution of suspended sediment in the surf zone is analysed by using field measurements. The analysis focuses in the description of the shape of the profile, *i.e.* mixing coefficient, and to do this, several approaches have been followed: pure diffusion, pure convection and combined diffusion-convection. The obtained results show a strong dependence of the sediment diffusion coefficient with the sediment grain size whereas the convective length scale presented a smaller grain-size influence.

Introduction

The vertical distribution of suspended sediment inside the surf zone may be generally considered as a combination of convective and diffusive processes. The distinction between both can be done in terms of mixing lengths, which in turn depend on the hydrodynamics acting on the sediment. According to Nielsen (1991, 1992), this can be mathematically described in a time averaged form by the convection-diffusion equation

$$w_f c + \varepsilon \frac{dc}{dz} - pF(z) = 0 \quad (1)$$

where w_f is the fall velocity of the sediment, c is the time averaged suspended sediment concentration, z is the elevation above the bottom, ε is the sediment diffusivity, p is the pick-up function and $F(z)$ is the convective entrainment function.

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Equation (1) is generally truncated being the pure diffusive description the most common approach (see *e.g.* van de Graff and Roelvink, 1988 among others). In spite of this, the approach may be accurate enough to describe the suspended sediment distribution if sediment is characterised by a mean grain size (without considering the grain size distribution). However, when this distribution is taken into account, a dependence of diffusivity or mixed length with grain size can be often observed (see *e.g.* Nielsen, 1983, van de Graaf and Roelvink, 1988, van Rijn, 1993). Strictly speaking, although a slight variation of the diffusivity of a solid particle (the sediment) with respect to the one of the fluid should be expected (see *e.g.* van Rijn, 1984), large deviations between the sediment diffusivity and the fluid eddy viscosity should indicate that other mechanisms are affecting the sediment mixing.

In this work, the vertical suspended sediment distribution in the surf zone is analysed using field measurements. The analysis focuses on the shape of the distribution from the pure diffusive and/or convective approaches and, an attempt to use the combined diffusion-convection solution is also presented. This last point was introduced due to the observed dependence of the mixing coefficients with sediment characteristics.

Experimental data

The used data were acquired in a field campaign (DELTA' 93) carried out in the Trabucador Bar (Ebro delta, Spanish Mediterranean coast). The measured field data included bathymetry, waves outside and inside the surf zone, mean water levels across the surf zone, velocity field (both horizontal and vertical structure) by means of an instrumented sledge equipped with 6 electromagnetic currentmeters and a step wave gauge (see Rodriguez *et al.* 1995a for a full description of hydrodynamic measurements) and measurements of longshore suspended sediment transport across the surf zone.

Longshore suspended sediment transport were measured by means of portable sediment traps (hereinafter PST) similar to that described in Rosati and Kraus (1989). Each PST was composed by a vertical array of 5 to 6 traps, each one of the cube-type with a nozzle of 5.5x5.5 cm and with a streamer (collection bag) made with a mesh of 100 μm (Ortiz, 1995).

Measurements were taken in the inner part (inside the surf zone in all the cases) of a barred profile under wave conditions characterised by H_{rms} ranging between 0.4 and 0.6 m at 7.5 m depth and with peak periods, T_p , from 5 to 6 sec. Spilling breaking waves were representative of surf zone conditions during all the experiments, with induced longshore currents up to 0.7 m/s.

Figure 1 shows some measured vertical profiles of the longshore current, where it can be seen that for relative depths, $z/d \geq 0.1$, current velocity shows small changes in vertical, *i.e.* is nearly constant in vertical.

Longshore suspended sediment transport measurements were taken in three profiles across the surf zone, with 4 to 5 positions each. In each position, PST were operating during a time period of 2 to 5 min. After that time, PST are carried to shore and collected sand is stored in bags to be weighted and sieved at the laboratory.

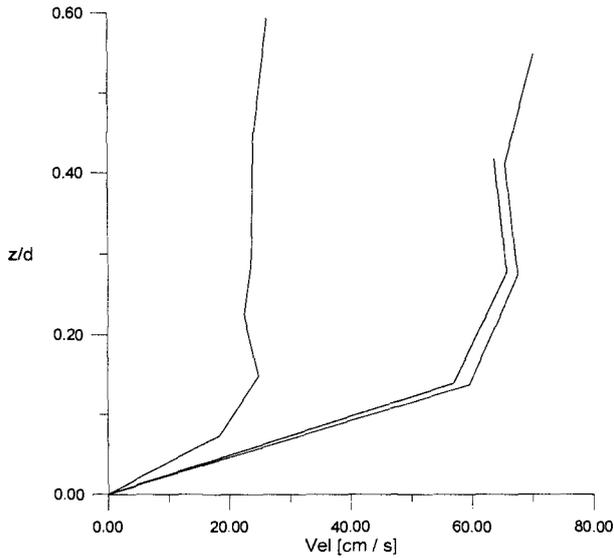


Figure 1. Typical vertical profiles of longshore currents measured during the experiments.

Vertical distribution of suspended sediment concentration

In order to obtain the vertical distribution, the first working hypothesis was that because measurements were acquired inside the surf zone, where a well mixed water column can be assumed, a *constant in vertical* mixing coefficient was considered.

Figure 2 shows the vertical distribution of the vertical eddy viscosity obtained from time series of velocity measurements inside the surf zone (see Rodríguez *et al.* 1995 for further details in the calculation of diffusivity). It can be observed that for relative depths ≤ 0.6 the calculated diffusivity can be considered as constant in vertical, whereas in the upper part of the water column values increase, due to the generation of horizontal turbulent-momentum flux during breaking (Rodríguez *et al.* 1995).

This assumption of a constant in vertical diffusivity leads to an *exponential concentration distribution* (when a pure diffusive process is considered) given by

$$C(z) = C_0 e^{-w_f z / \epsilon}$$

where C_0 is the reference concentration at the bottom, w_f is the fall velocity of the sediment, z is the elevation above the bottom and ϵ diffusion coefficient.

Or in another form (assuming a pure convective process with an exponential function to describe convection, Nielsen, 992) as

$$C(z) = C_0 e^{-z/L}$$

where L is the mixing or length scale.

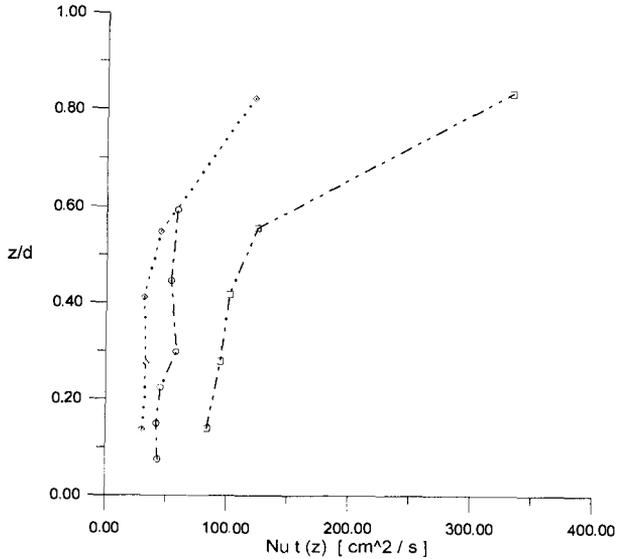


Figure 2. Vertical distribution of eddy viscosity obtained during the experiments.

When experimental profiles were fitted to a vertical distribution given by expressions (2) or (3), a good agreement was obtained. From 15 cases, covering three lines across the surf zone, the mean r^2 value of all the fits was 0.952, with a minimum r^2 value of 0.90 and a maximum of 0.995.

Figure 3 shows an example of the obtained normalised time averaged concentration profiles at different locations across the surf zone with the corresponding exponential fit for one of the monitored cross-shore profiles.

These results indicate that at least during the conditions prevailing during the field experiments, and for measurements taken inside the surf zone, the classical exponential profile describes well the time averaged concentration profiles. In this case, the averaging was done over a relatively long time period (from 20 to 50 waves) and because of this, these results cannot be considered in contradiction to those obtained by Mocke and Smith (1992) since the time scale of their analysis differs.

Cross-shore distribution of mixing coefficient

When the cross-shore distribution of the mixing coefficient was analysed, an increasing diffusivity from the shoreline towards the breaking point was observed for all the analysed cases (as expected). Fig. 4 shows the cross-shore distribution of the mixing length, L , for one of the control lines, where it can be clearly this increase in mixing towards the breakers where reaches the largest value.

Nielsen (1984) analysing the mixing length $-L-$ under non-breaking waves found that it was closely related to the bed ripple height. However, when the surf zone is considered a

different “physical entity” of L should be expected, since the mechanism inducing convection is clearly different.

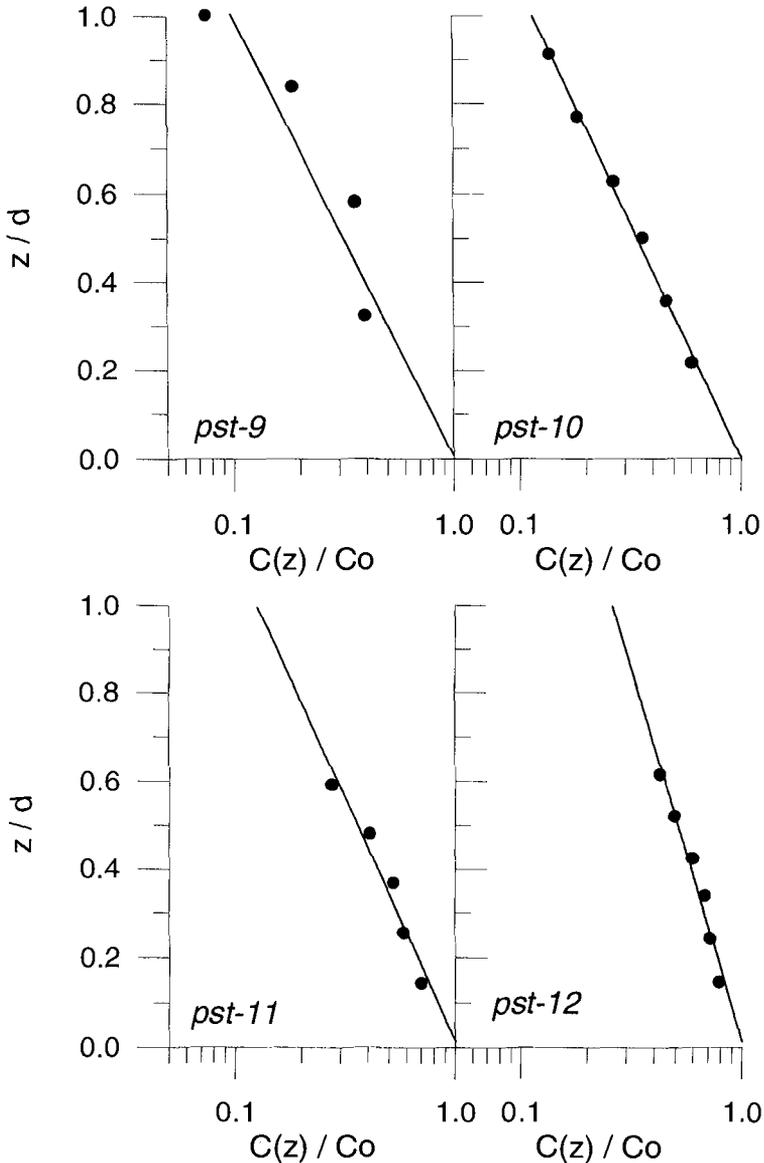


Figure 3. Normalised time averaged concentration profiles at different location across the surf zone.

In this case, it was found that this length scale for convection was closely related to the local H_{rms} (see Figure 4). This fact can be used to validate the assumption of that, inside

the surf zone the sediment is picked-up from the bottom and put in suspension at an elevation above the bottom proportional to the wave height (Dean, 1973).

Thus, for the range of measured conditions and under spilling breakers, the local value of H_{rms} was found to be a good predictor of the magnitude of the convective length scale, L .

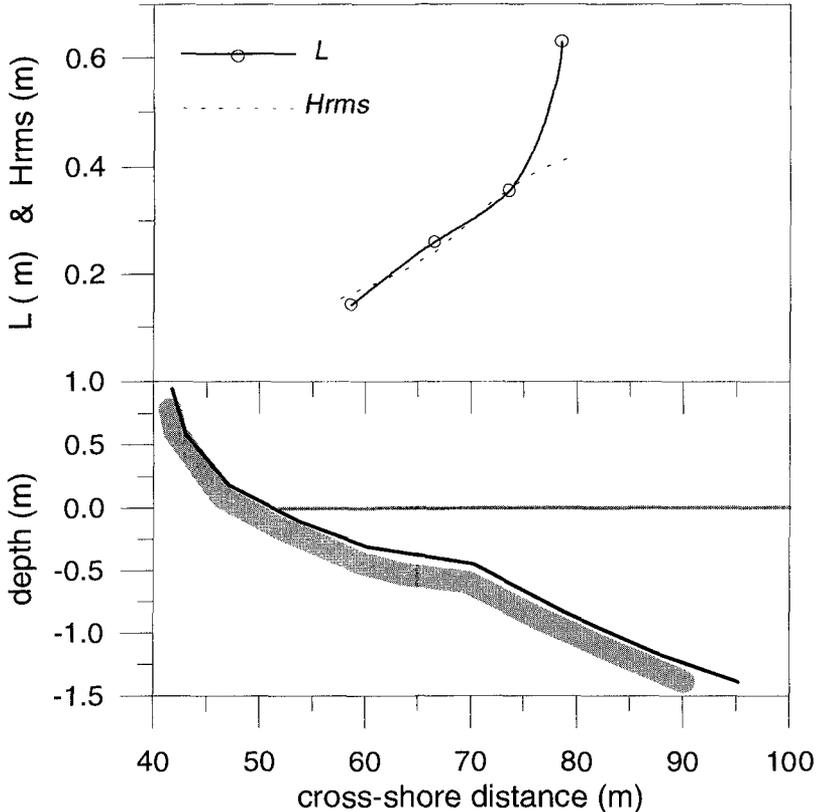


Figure 4. Cross-shore distribution of the mixing length L and H_{rms} .

When the cross-shore distribution of the mixing coefficient is put in terms of sediment diffusion coefficient, ϵ , the same pattern than before is observed (Fig. 5). This was due to that from equations (2) and (3) $L = \epsilon / w_f$, and no significant across-shore variations in sediment grain size was found.

Assuming that this sediment diffusion coefficient must be closely related to the fluid diffusion coefficient, their values should be equivalent to the vertical eddy viscosity for the fluid.

Fig. 5 shows the cross-shore distribution of the eddy viscosity for horizontal mixing using a k-model with production of turbulent energy according to Battjes (1975). It can be seen that both distributions (horizontal and vertical mixing) are qualitatively similar,

although the horizontal mixing coefficient is about two order of magnitude larger than the vertical one (see *e.g.* deVriend and Kitou, 1990). A detailed analysis of this discrepancy may be found in Svendsen and Putrevu (1994).

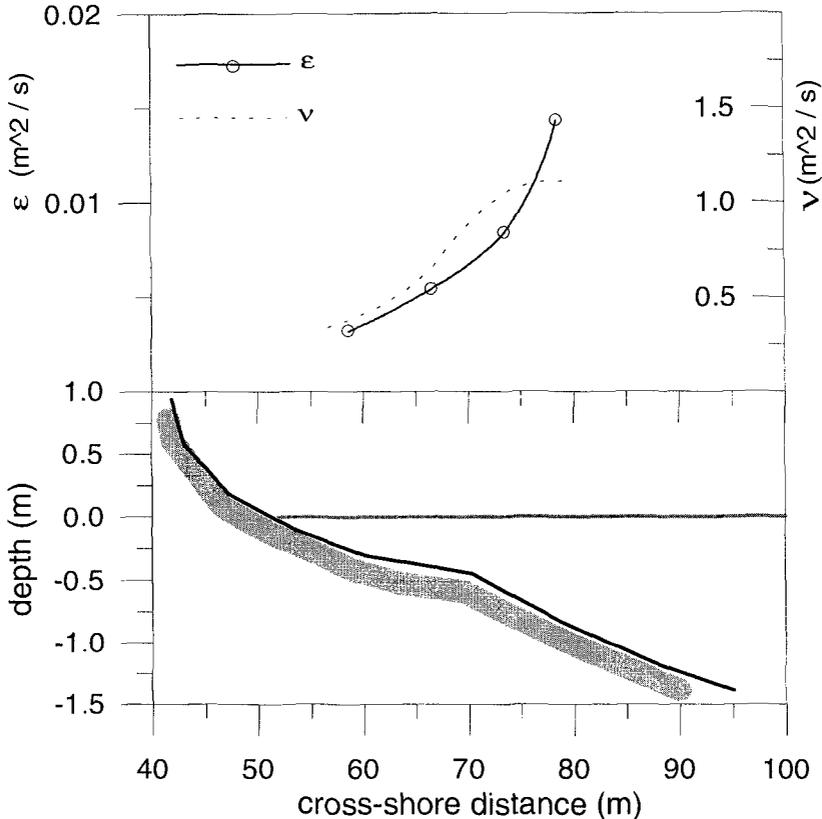


Figure 5. Cross-shore distribution of the sediment diffusion coefficient, ϵ , and calculated horizontal eddy viscosity v .

Effects of the grain size

Once the vertical suspended sediment distributions (assuming pure diffusion and convection) were analysed, the effects of the grain size on the sediment mixing was investigated. To do this, each sample was sieved into a series of fractions and, vertical distributions for each fraction were built. Once these classified vertical profiles were obtained, the same analysis than before was applied, *i.e.* fit to equations (2) and (3) to obtain the corresponding mixing coefficients for each fraction..

Figure 6 shows the obtained sediment diffusion coefficients, ϵ , for the same cases than the ones presented in Fig. 3 but considering different fractions. It can be clearly seen that diffusion coefficient is far from constant for the analysed range.

Focusing on the range of fractions characterised by a sediment fall velocity between 0.02 m/s and 0.06 m/s (out of this range some of the fractions were not statistically representative to build a “classified profile”), a linear relationship between the diffusion coefficient and the fall velocity was found: the larger the fall velocity is, the larger the coefficient will be. Similar results have been obtained for non-breaking waves by van de Graaf and Roelvink (1984) among others (see also Nielsen, 1992).

This result should indicate that for constant fluid diffusion coefficient, the sediment mixing will increase as coarser the sediment is. This discrepancy has been usually explained in terms of a greater influence of the centrifugal forces on the sediment particles with respect to the fluid in a turbulent flow. This would lead to an increase in the effective mixing length and diffusion rate for the sediment (see *e.g.* van Rijn, 1984).

However, although a small change in diffusivity between solid particles and fluid can be expected, the variations shown in figure 6 seems too high to assume that they are due to the above mentioned effect.

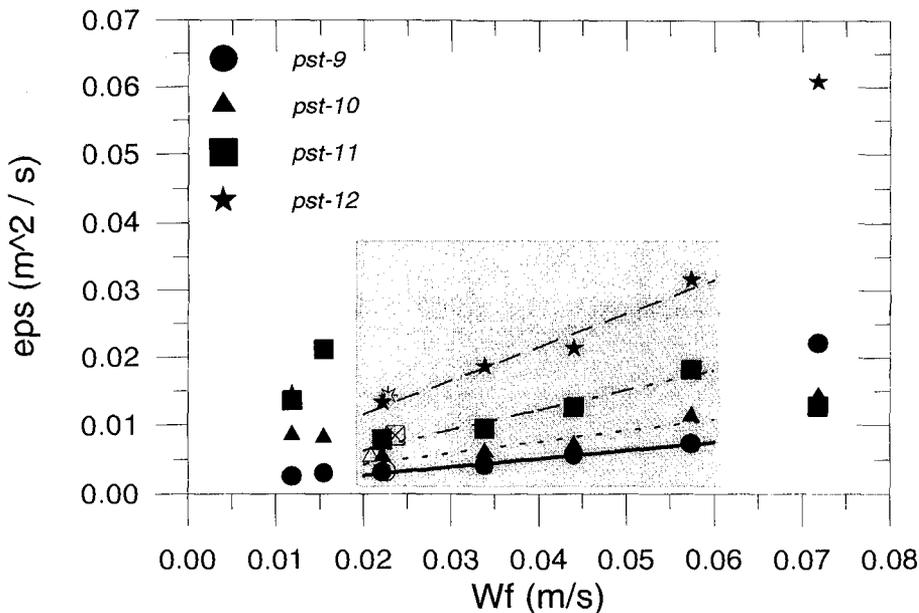


Figure 6. Variation of the diffusion coefficient ϵ_s vs fall velocity of the sediment for different locations across the surf zone. Grey rectangle indicates the range of fall velocities considered in the fit.

In fact, if the variations in diffusivity are measured as

$$\Delta\epsilon = \frac{\epsilon_{(w=0.06)} - \epsilon_{(w=0.02)}}{\epsilon_{(total\ sample)}} 100 \tag{4}$$

a mean value of 138% is obtained (considering the four locations across the surf zone).

From figure 6, it seems that the diffusivity dependence with grain size increases from shoreline (pst-9) towards the breaker point (pst-12). Although this is true in absolute

terms, when this variation is measured in relative terms (e.g. according to eq. 4), they are almost uniform, i.e. it seems to be constant across the surf zone.

Thus, the observed variations in the diffusion coefficient for the sediment mixing due to variations in grain size, introduce an uncertainty about the validity of the pure diffusion model to describe the vertical distribution of suspended sediment inside the surf zone.

Applying the same analysis to the case of pure convection model, i.e. looking to the variations in L when the different fractions are considered, the results depicted in Figure 7 are obtained.

In this case, although a variation in L is also observed, the direction of such variation is opposite to the above described one. Thus, assuming a pure convective process, as coarser the sediment is, smaller the mixing length will be. In other words, for coarser sediments, the mixing will be smaller.

This can be explained assuming that sediment response to convective process induced by wave breaking will be influenced by the sediment "weight". For heavier sediments (coarser), the theoretical distance from the bottom where they will be put in suspension (entrainment level) will be shortened as coarser the sediment is.

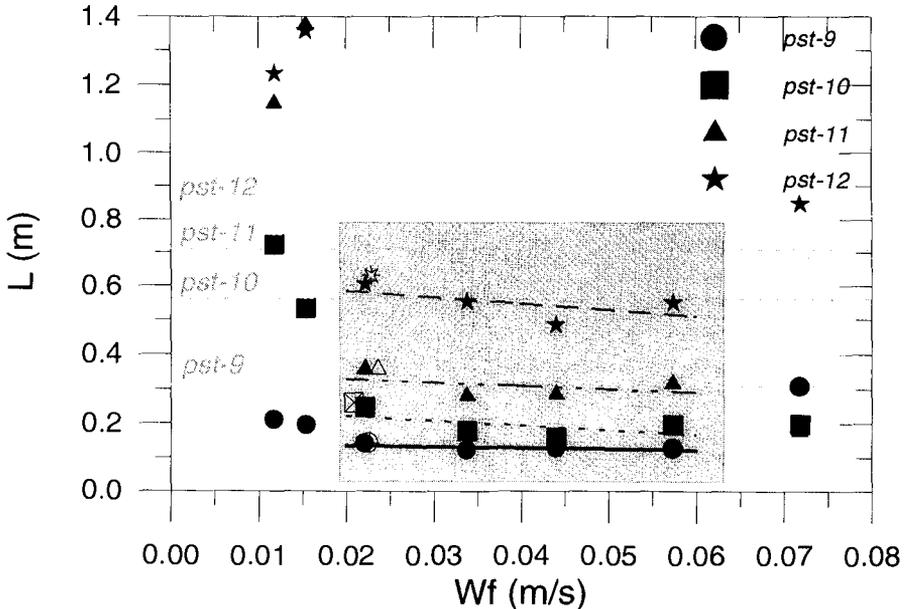


Figure 7. Variation of the length scale, L , vs fall velocity of the sediment for different locations across the surf zone. Grey rectangle indicates the range of fall velocities considered in the fit and grid lines represent largest value of L for each location (equal to the local depth).

Measuring the variations in the convective length scale, L , according to the equation 4, a mean value of 10% is obtained. The relative variations across the surf zone are also constant as it was for the previous case.

The main difference between the variations for diffusive and convective mixing lengths is that the former presented a larger variation than the convective one. In other words, the use of equation (3) to describe the vertical distribution of suspended sediment in the surf zone (assuming a pure convective process) is more "stable" in function of the sediment grain size than the use of a diffusive process. In spite of this, a small variation in the length scale was also found.

If the dominance of the process controlling the vertical distribution is measured in terms of its "stability", the convection process should be dominant under the monitored conditions.

Combined diffusion-convection process

Additionally to the above mentioned effect (variation in mixing coefficients for varying grain sizes), when the profiles for the different fractions were analysed, a change in the shape of the profile was also found. Thus, slight convex upward profiles were found to describe the fine fractions, whereas the coarser ones showed a slight concave upward shape. This change in shape was also explained by Nielsen (1992) as an indication of the presence of a combined diffusion-convection process controlling the sediment suspension.

In order to make a first attempt to describe the obtained suspended sediment profiles by using the combined diffusion-convection approach, a full solution of equation (1) was used.

In this attempt, a constant in vertical diffusion coefficient and a convective function given by an exponential law was selected (see *e.g.* Nielsen, 1992). Although this solution has not to be the best one, it was selected due to its simplicity, although presently other combined solutions are being analysed.

The integration of equation (1) with the selected description of diffusion-convection process leads to (Nielsen, 1992)

$$C = C_0 \left\{ \frac{1}{1 - \frac{\epsilon}{w_f L}} e^{-z/L} + \left(1 - \frac{1}{1 - \frac{\epsilon}{wL}}\right) e^{-wz/\epsilon} \right\} \quad (5)$$

By using the equation (5), the profiles for the different fractions presented in figure 8 were obtained. The main problem to apply this approach is that both diffusion coefficient as well as convective length scale has to be estimated. In this case, it was firstly selected the value of the diffusion coefficient by using the one corresponding to the finest fraction, and afterwards, the convective length was selected by fitting the predicted distribution to the measured profiles. In all the cases, the fitted values of convective length were in a range of 30%-40% of the obtained using a pure convective model.

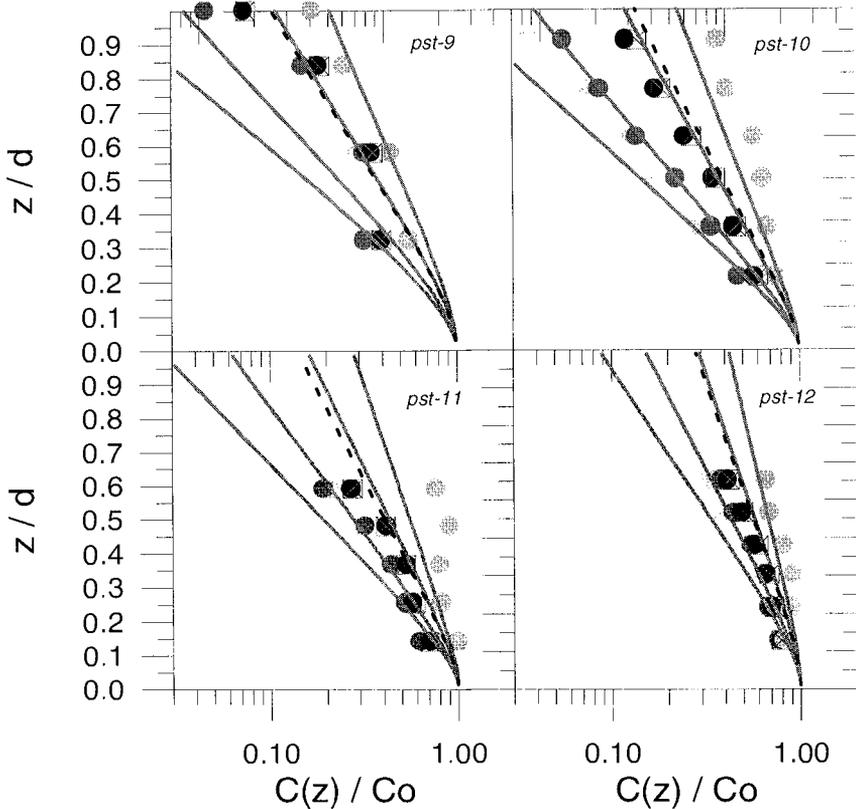


Figure 8. Use of the combined diffusion-convection approach (according to equation 5) to describe the vertical distribution of the different sediment fractions across the surf zone.

Conclusions

For the analysed conditions, several conclusions can be obtained.

- ◆ During the measured conditions, the simple *exponential profile* describes well the time-averaged vertical distribution of suspended sediment in the surf zone.
- ◆ The *length scale*, L , of the distribution can be well represented by the local value of H_{rms} inside the surf zone.
- ◆ The eddy viscosity ν_t for horizontal mixing (obtained using a K-model with production of turbulent energy according to Battjes (1975)) shows a *cross-shore distribution similar* to the vertical mixing coefficient obtained from sediment data, ϵ_s . Obtained values of ν_t are two orders of magnitude higher than ϵ_s .

- ◆ For the analysed field data, the mixing coefficient ϵ_s depends on sediment characteristics, i.e. w_f . In the range of $w_f = 0.02-0.06$ m/s, a linear relationship between ϵ_s and w_f was found. Larger the fall velocity is, larger the diffusion will be.
- ◆ Assuming that the vertical distribution can be described by the length scale, L , a linear dependency with w_f was also found.
- ◆ The magnitude of the measured variation of ϵ_s with w_f was one order of magnitude larger than the obtained for L .
- ◆ These last two conclusions lead to argue the validity of the pure diffusion model to be used in the surf zone.

A first attempt to improve the description of the vertical distribution of suspended sediment considering the different grain has been done. To do this, the approach of Nielsen (1991, 1992) was followed by using a combined solution including diffusion and convection. First results are promising although further works have to be done, specially in the description of the “convective” function.

The generalisation of the obtained conclusions should require additional field data under different energetic conditions. This additional “field effort” is being carried out in the framework of an EU funded Research Project.

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