

Samantha Kularatne

Sediment Resuspension and Cycling due to Wave Groups

Abstract

Field experiments conducted to explore sediment resuspension and cross-shore cycling in nearshore environments are presented with special emphasis on the influence of wave groups. Field data presented are from City Beach, Mullaloo Beach and Leighton Beach of Western Australia and Chilaw, Sri Lanka. Measurements include simultaneous measurements of surface elevation, cross-shore current velocities and suspended sediment concentrations collected just offshore of the breaker zone. As it has been well established, wave groups appear more capable of resuspending sediments than incident waves. Results of cross-correlation and cross-spectral analysis show a considerable inconsistency especially in the direction of cross-shore sediment flux on the frequency domain at different locations and under different conditions. This lead to the hypothesis that there are additional factors such as local wave climate, grain size, beach slope and bed forms.

The author wishes to thank for Charitha Pattiaratchi of the Centre for Water Research, The University of Western Australia, for assistance in the preparation of this paper. The paper originally appeared in the *Proceedings of the COPEDEC Conference*, Colombo, Sri Lanka, in September 2003 and is reprinted here in an adapted version with permission.

Introduction

One of the most important challenges facing coastal researchers is to predict the transport of sediment in nearshore regions directly influencing coastal stability. This is a prime socio-economic concern for coastal regions globally. Although nearshore sediment transport occurs mainly in the longshore direction, the smaller cross-shore transport plays a dominant role in determining seasonal shoreline evolution, shelf morphology, and so on. Therefore, an improved understanding of the processes of sediment suspension and cycling within this highly dynamic region is essential

to make accurate predictions of cross-shore sediment transport and thus coastal stability.

Under wave-dominated conditions, which is common when the tidal range is small, sediment resuspension and transport is closely related to the local wave climate. In general, three distinct regimes of local wave climate can be identified:

- (a) periods of storm activity associated with passage of frontal systems during winter (or during monsoon season);
- (b) periods of locally generated waves caused by sea breeze systems; and,
- (c) swell wave activity during "calm" periods.

But storm or sea breeze systems occur over a short duration and swell waves dominate the nearshore wave climate for longer periods. This highlights the need to explore nearshore processes under swell wave conditions and is further emphasised by the fact that a nearshore wave climate dominated by swell provide ideal conditions for the presence of wave groups.

WAVE GROUPS

With any combination of waves a point will occur where all frequencies cancel and the resulting wave has minimal amplitude. The set of waves between two of these points is called a wave group (Figure 1).

Group bound long wave

When there is an incoming swell, Munk (1949) and Tucker (1950) first noticed the existence of longer waves, of 2-3 min period, very similar to the envelope of the visual swell, and suggested that the long waves may be caused by an excess of mass carried forward by groups of high swell. Longuet-Higgins and Stewart (1962 and 1964) further explained it as a wave group, containing larger than average waves, which depress the water surface and thereby force a long wave which is defined as group bound long wave. Therefore, wave groups are always associated with a group bound long wave (Figure 1).

The majority of previous studies on cross-shore sediment transport in nearshore regions have revealed that the suspension of sand, and hence, the cross-shore sediment flux in the nearshore region occur in an event-like manner over a range of time scales ranging from seconds (wind waves) to minutes (wave groups or infragravity waves) (Brenninkmeyer, 1976; Hanes and Huntley, 1986; Sternberg *et al.*, 1989; Osborne and Greenwood, 1993; Masselink and Pattiaratchi, 2000). However, these observations made under different conditions covering various parts of the world appear not to be very consistent especially with respect to the direction of sediment flux (onshore or offshore) under different time scales (wind waves, swell, infragravity waves, and so on). Thus, an improved understanding of the governing factors of this inconsistency in the direction of sediment flux (cycling) is important and has yet to be resolved.

Field measurements of nearshore sediment resuspension clearly show that the time series records of suspended sediment concentration indicate pronounced suspension events at low frequencies (Hanes and Huntley, 1986; Huntley and Hanes, 1987; Hanes, 1991a; Osborne and Greenwood, 1993; Masselink and Pattiaratchi, 2000; Smith and Mocke, 2002). This enhances the assumption that wave groups are more capable of stirring up sediment particles from the bed.

Figure 2 shows a comparison of time series records of cross-shore current velocity (u), envelope function of u and suspended sediment concentration from Masselink and Pattiaratchi (2000), which clearly suggest a correlation between wave groups and suspended sediment concentration.

Furthermore, past investigations have suggested that, in most of the cases, at lower frequencies (wave groups, infragravity waves) the cross-shore sediment flux is in the offshore direction and it changes into onshore direction under higher frequencies (wind waves, swell) (Huntley and Hanes, 1987; Hanes, 1988). However, contradicting results can also be found in literature where offshore fluxes are evident at incident frequencies and vice-versa (Masselink and Pattiaratchi, 2000; Smith and Mocke, 2002).

Deigaard *et al.* (1999) have investigated the influence of the group bound long wave on sediment re-suspension using a mathematical model. They developed a model in which the turbulent boundary layer flow was simulated through a mixing length model and the suspended sediment was modelled by the advection diffusion equation. It was found that the net cross-shore sediment transport depends on the grain size and the magnitude of transport. In most cases (with exception of very intensive transport conditions) the bound long waves were found to give a



Sam Kularatne (left) receiving the IADC Young Authors Award from Mr. Hans Poiesz, Chairman of the IADC Public Relations Committee, at the COPEDEC VI in Sri Lanka, September 2003.

IADC Award 2003

**Presented at the COPEDEC VI,
Colombo, Sri Lanka
September 15-19 2003**

At the sixth International Conference on Coastal and Port Engineering in Developing Countries (COPEDEC), held this past September in Colombo, Sri Lanka, Samantha Kularatne was presented with an IADC Young Dredgers Award. Mr. Kularatne graduated with a B.Sc. (Engineering) with first class (honours) specialised in Civil Engineering from the University of Peradeniya, Sri Lanka in 1998. From October 1998 to May 1999 he worked as a Research Engineer at Lanka Hydraulic Institute Ltd., Sri Lanka. He received a Master of Engineering in Coastal Engineering from the National University of Singapore in 2001 and worked as a Research Engineer at the Institute of Hydrodynamics and Water Resources, Technical University of Denmark from September 2001 to March 2002. Since April 2002 he is working on a Ph.D. in Coastal Oceanography at the University of Western Australia.

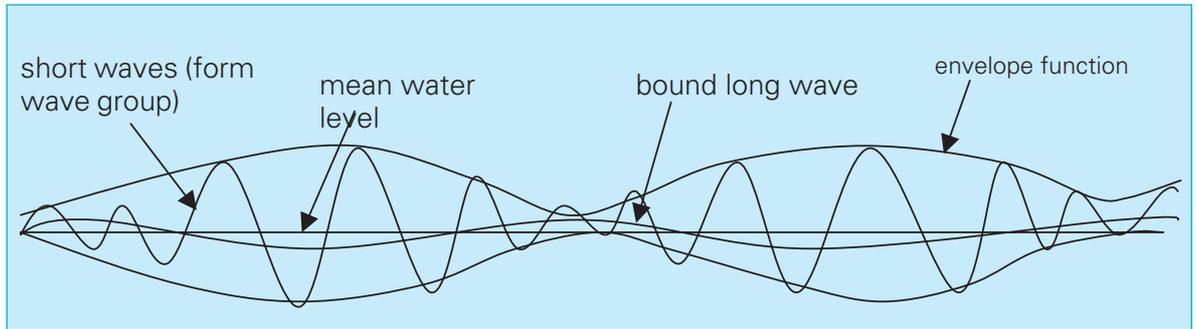


Figure 1. Wave groups and group bound long wave.

negative contribution to the sediment transport, and the bound long waves could even change the direction of the net suspended sediment transport, opposite to direction of wave propagation. Their study was restricted to plane bed (sheet flow conditions).

Therefore, the objectives of the present study are to:

- a) undertake field measurements of sediment resuspension and cycling caused by wave groups under a variety of conditions (differing wave climate, grain size, beach slope, bed forms, and so on), to define factors governing the direction of cross-shore sediment flux on frequency domain;
- b) develop a numerical model to explore the same problem in more detail, taking into account the influencing factors separately and comparing the output with field measurements. In this paper, the initial results of this study are presented.

METHODS

Field investigations

Field measurements providing the basis for the present study on influence of wave groups on nearshore sediment resuspension were carried out at number of locations:

- City Beach, Mullaloo Beach, Leighton Beach – Western Australia (Figure 3) and
- Chilaw, Sri Lanka (Figure 4) covering a range of different conditions.

All the measurements were conducted just offshore of the breaker zone.

Data on surface waves, currents and suspended sand concentrations were collected using the "S" probe, an instrument package developed at the Centre for Water Research, University of Western Australia.

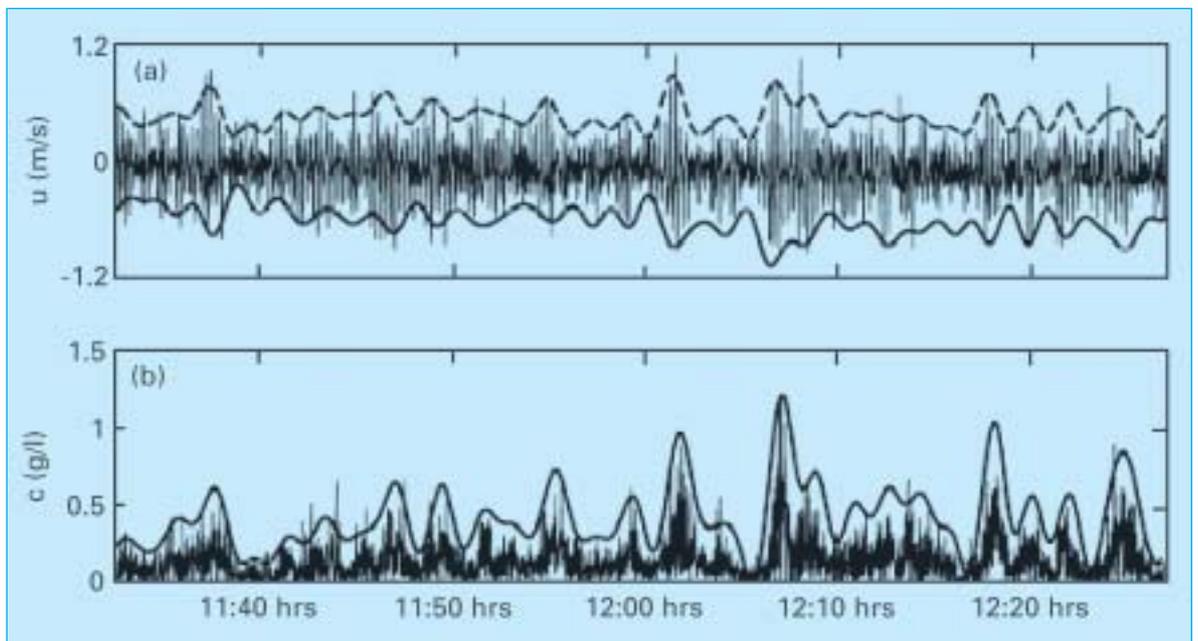


Figure 2. Time series of: (a) cross-shore current velocity u (solid line), envelope function of u (thick dashed line) and lowpass-filtered u (thick solid line); and (b) suspended sediment concentration c 0.05m from the bed (solid line) and lowpass-filtered c (thick solid line) (Masselink and Pattiaratchi, 2000).

The "S" probe consists of a Paroscientific Digiquartz pressure sensor (located 0.35 m above the bed), Neil Brown ACM2 acoustic current meter together with three optical back scatterance (OBS) turbidity sensors. The two-dimensional horizontal velocity at 0.20 m above the sea bed is recorded by the current meter while the OBS sensors record the concentration profile at three levels: 0.025 m, 0.125 m and 0.275 m, above the sea bed (Figure 5).

Bed profiles were surveyed using a total station while sediment samples collected at the field site were analysed to determine the median grain size. The mean grain sizes off Chilaw, Sri Lanka were found to be 0.2 mm and along Western Australia (Mullaloo Beach and City Beach) it was relatively coarser (0.3 mm).

Additional details of field measurements can be found in Masselink and Pattiaratchi (2000) and Pattiaratchi *et al.* (1999).

Numerical modelling

A numerical model was developed to further explore the influence of wave groups on nearshore sediment resuspension and cycling. The simulation of waves (hydrodynamics) is based on Boussinesq type equations. The classical Boussinesq theory provides a set of equations for surface water waves in the combined limit of weak nonlinearity and weak dispersion, which represents shallow water waves of moderate amplitude quite well. The standard Boussinesq equations for variable water depth were first derived by Peregrine (1967), who used depth-averaged velocity as a dependent variable. But the assumption of weak frequency dispersion effects makes the equations perform well only within shallow water and invalid in intermediate and deep water.

Novel forms of Boussinesq equations extending the validity to intermediate and deep water were achieved by improving the linear dispersion characteristics of the weakly dispersive model (Madsen *et al.*, 1991; Nwogu, 1993). Nwogu (1993) used the velocity at a certain depth as a dependent variable and the equations simulate intermediate water much better than the standard equations. Despite their improved dispersion relationship, the extended Boussinesq equations are still restricted to situations with weakly nonlinear interactions.

Adapting the approach of Nwogu (1993), but making no assumption of small nonlinear effects, Wei *et al.* (1995) derived a new set of Boussinesq equations that include additional nonlinear dispersive terms. Not only can the equations be applied to intermediate water depth, but also they can simulate wave propagation with strong non-linear interactions. These equations derived by Wei *et al.* (1995) provide the base for the wave model used in the present study (*Funwave1D*).

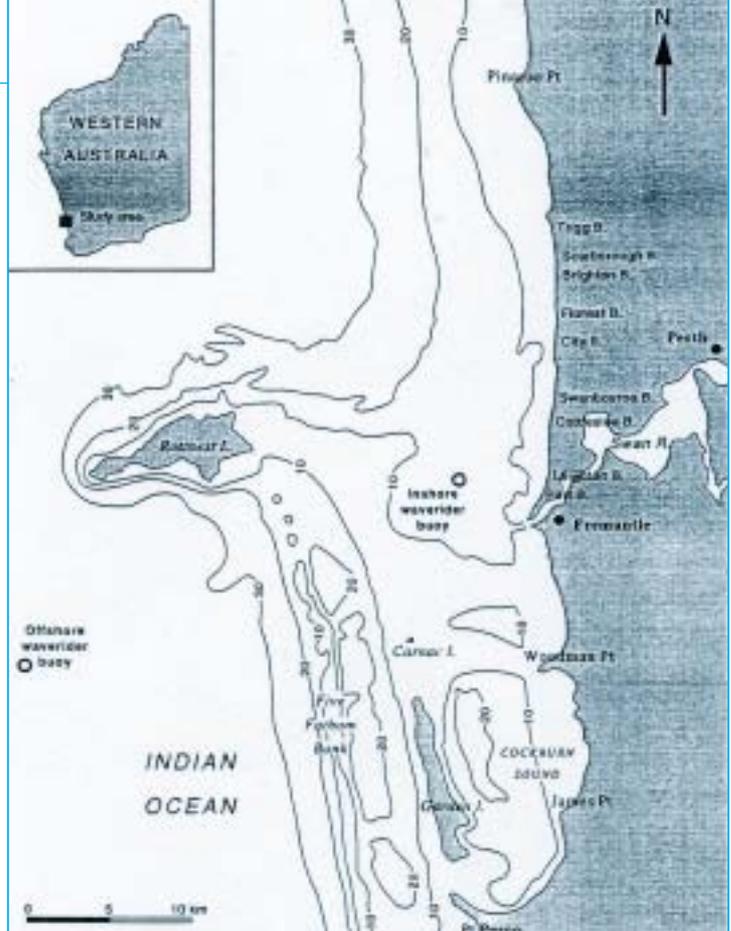


Figure 3. Study areas off Perth, Western Australia.

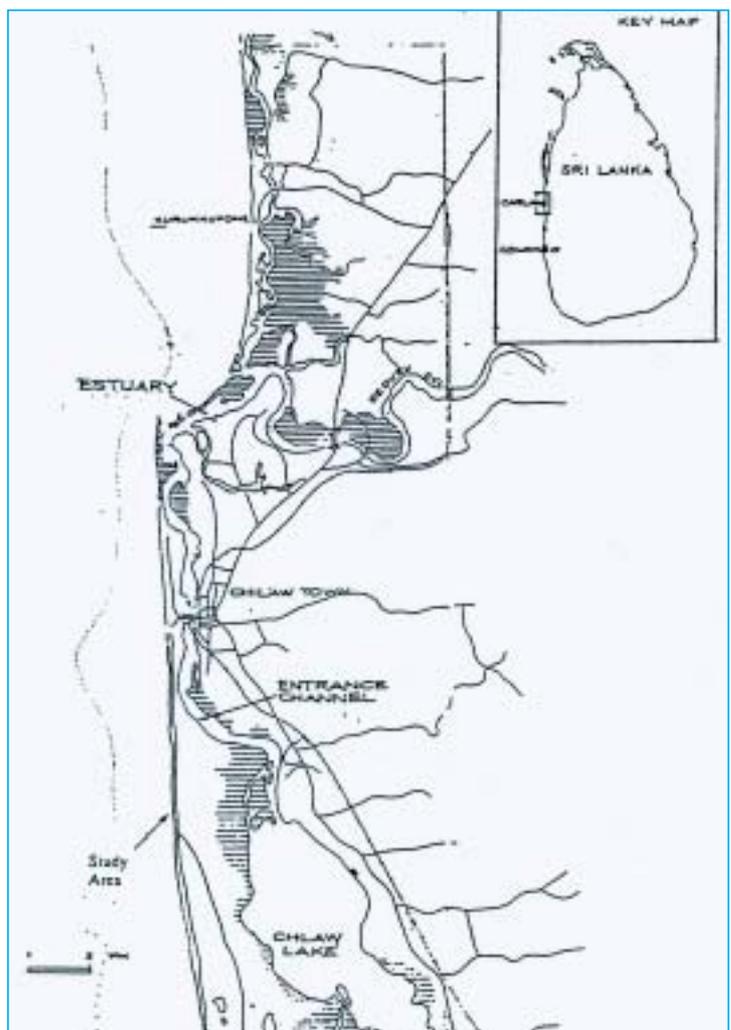


Figure 4. Study area off Chilaw, Sri Lanka.

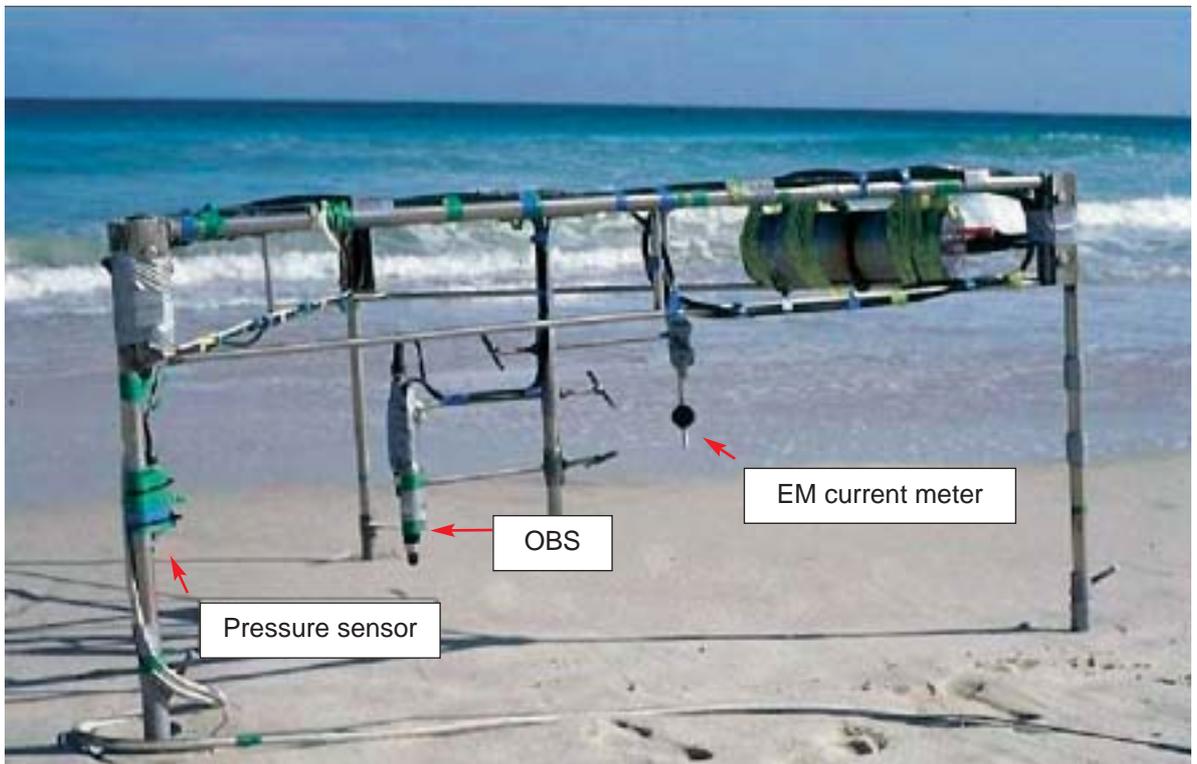


Figure 5. 'S' probe, an Instrument package consist of a Paroscientific Digiquartz pressure, Neil Brown ACM2 acoustic current meter together with three optical backscatterance (OBS) turbidity sensors. All data for this paper was obtained from this instrument package.

The numerical modelling of the process will primarily be achieved using a modified version of *Funwave1D*, an open source distribution from the Centre for Applied Coastal Research, University of Delaware, described in Kennedy *et al.* (1999). This software is developed based on the fully nonlinear Boussinesq model of Wei *et al.* (1995) and a source function method is used in generating required input wave signal (Wei *et al.*, 1999). The directional wave spectra or the time series record of the input surface elevation can be directly fed through the source function method. Both wave breaking and run-up (shoreline) are parameterised within the original code (Kennedy *et al.* 1999).

The model simulates time varying surface elevation and horizontal (cross-shore) velocity over desired bottom topographies. The surface elevation record and the bottom topography obtained through field measurements are directly input into the model allowing a highly realistic simulation of the nearshore hydrodynamics. This model has been extensively validated against laboratory data and has been used for field simulations by Chen *et al.* (2000).

The sediment transport model developed by Bagnold and Bailard (1981), which predicts instantaneous transport rates of bed load and suspended load is coupled with the hydrodynamic model in order to obtain the cross-shore sediment flux.

This enhances separate exploration of the influence of different parameters governing the direction of cross-shore sediment cycling on frequency domain using the data gathered through field experiments as well as for some hypothetical wave signals.

DATA ANALYSIS AND RESULTS

Field investigations

The role of wave groupiness on sediment resuspension was investigated by comparing time series records of cross-shore current velocity, the wave groupiness envelope and suspended sediment concentration. The groupiness envelope was computed by lowpass-filtering the modulus of the cross-shore current record at 0.01 Hz (List, 1991). Figure 6 presents time series records obtained from Chilaw, Sri Lanka during the initiation of an afternoon sea breeze and clearly indicates the correlation between wave groups and the sediment resuspension. Whereas Figure 7 the time series records of cross-shore velocities and suspended sediment concentrations, from the same location but during the monsoon season, does not show any clear evidence of pronounced groupiness as strong wind waves could presumably destroy any particular pattern. A similar set of data records from the City Beach, Western Australia

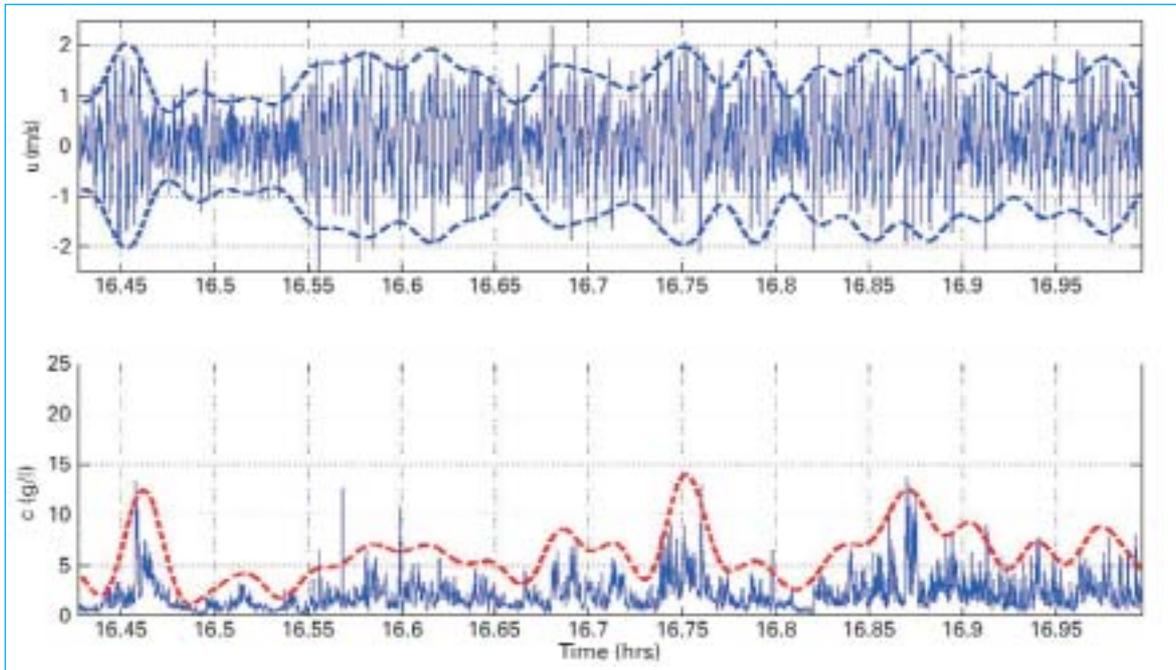


Figure 6. Time series of: (a) cross-shore current velocity u (solid line) and envelope function of u (thick dashed line); and (b) suspended sediment concentration c 0.05m from the bed (solid line) and lowpass-filtered c (thick dashed line) (Chilaw, Sri Lanka – 18-01-96).

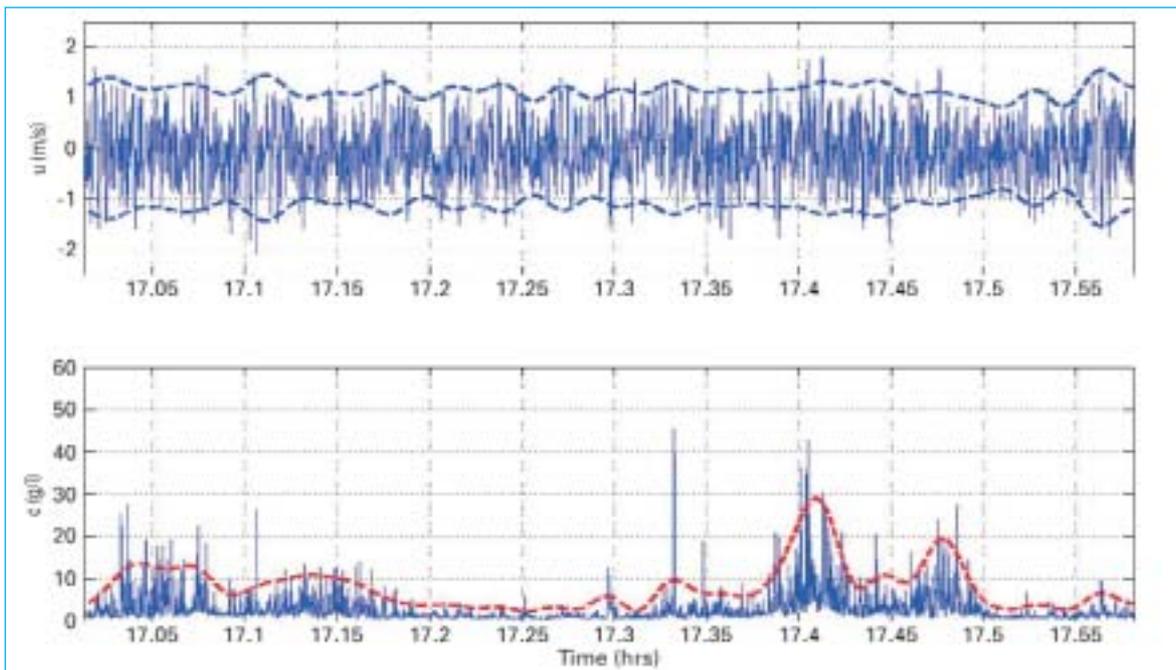


Figure 7. Time series of: (a) cross-shore current velocity u (solid line) and envelope function of u (thick dashed line); and (b) suspended sediment concentration c 0.05m from the bed (solid line) and lowpass-filtered c (thick dashed line) (Chilaw, Sri Lanka - 13-05-96 – during monsoon season).

(summer 1992) gathered during an afternoon sea breeze also indicate that the complexity of wind waves could destroy any marked groupiness (Figure 8).

Cross-correlation and cross-spectral analyses were performed to quantify the different aspects involved

in sediment resuspension and cross-shore cycling. The results obtained for the data records presented in Figure 6 are shown in Figure 9 (Chilaw, Sri Lanka). Auto-spectra of the cross-shore current and sediment concentration records (Figure 9a) identify the dominant frequencies and Figure 9b presents cross-correlation

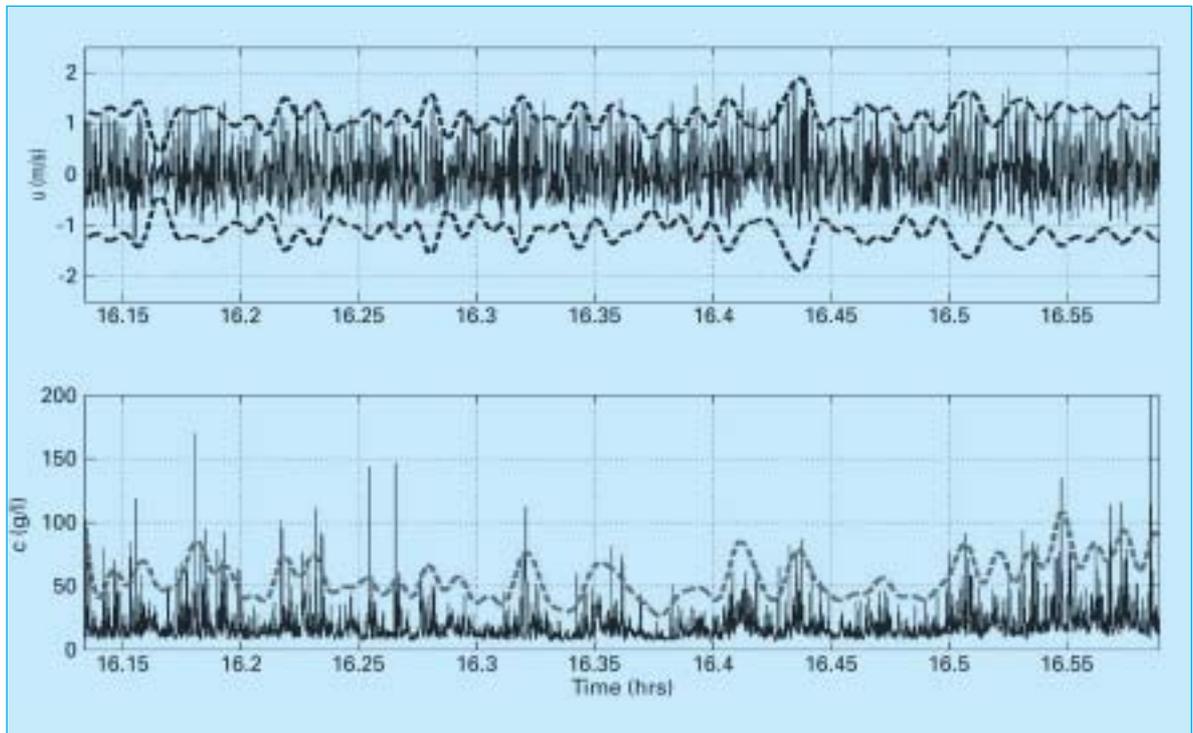


Figure 8. Time series of: (a) cross-shore current velocity u (solid line) and envelope function of u (thick dashed line); and (b) suspended sediment concentration c 0.05m from the bed (solid line) and lowpass-filtered c (thick dashed line) (City Beach, Western Australia – 23-01-92 – with an afternoon sea breeze).

between the groupiness envelope and the low-pass filtered cross-shore current. Figure 9c describes the most important result of the present project; the co-spectrum between the time series of cross-shore current and sediment concentration which portrays the directional variation in cross-shore sediment flux in the frequency domain. Finally, the cross-correlation between the groupiness envelope and low-pass filtered sediment concentration (Figure 9d) provides information on the relationship between the two time series.

Figure 9a shows that the dominant peak for cross-shore current at 0.06 Hz and for sediment concentration at 0.005 Hz. This indicates that more sediment was stirred up at low frequencies (wave groups) which is evident from Figure 6. A strong positive relationship between the groupiness envelope and the lowpass filtered cross-shore current velocity is evident from Figure 9b and this enhances the fact that there was no distinct formation of a group bound long wave. Figure 9c shows the most interesting result which is contrary to the original explanation for the direction of sediment flux (e.g. Huntley and Hanes, 1987). Here, the cross-shore sediment flux is offshore at high frequencies (swell) and onshore at low frequencies (wave groups). Figure 9d further proves that the cross-shore current velocity and the sediment concentration have a strong positive correlation with a time lag of 20s.

Results of similar analysis (cross-correlation and cross-spectral) for data collected from the same location (off Chilaw, Sri Lanka) during a period of much calmer sea conditions (in the morning with more pronounced groupiness) on the same day (Figure 10), were found to be the complete opposite to Figure 9 (especially Figure 9c) where cross-shore sediment flux is onshore at higher frequencies (swell) and offshore at lower frequencies (wave groups) (Figure 10c is in accordance with the original explanation; e.g. Huntley and Hanes, 1987). This confirms the influence local wave conditions have on sediment resuspension and the direction of cross-shore sediment flux on frequency domain. Further, a strong negative correlation between the envelope function and the low-pass filtered cross-shore current record (Figure 10b) proves the presence of a group bound long wave under a wave climate with improved wave groupiness (Longuet-Higgins and Stewart, 1964).

Comparison of the envelope function of cross-shore current record and sediment concentration obtained at Mullaloo, Western Australia is presented in Figure 11, and again it is apparent that higher sediment concentrations occur with the passage of wave groups. Results of the cross-correlation and cross-spectral analysis for this data (Figure 12) are in line with Figure 10 where cross-shore sediment flux is onshore at higher frequencies (swell) and offshore at lower frequencies (wave groups) (Figure 12c) but in complete

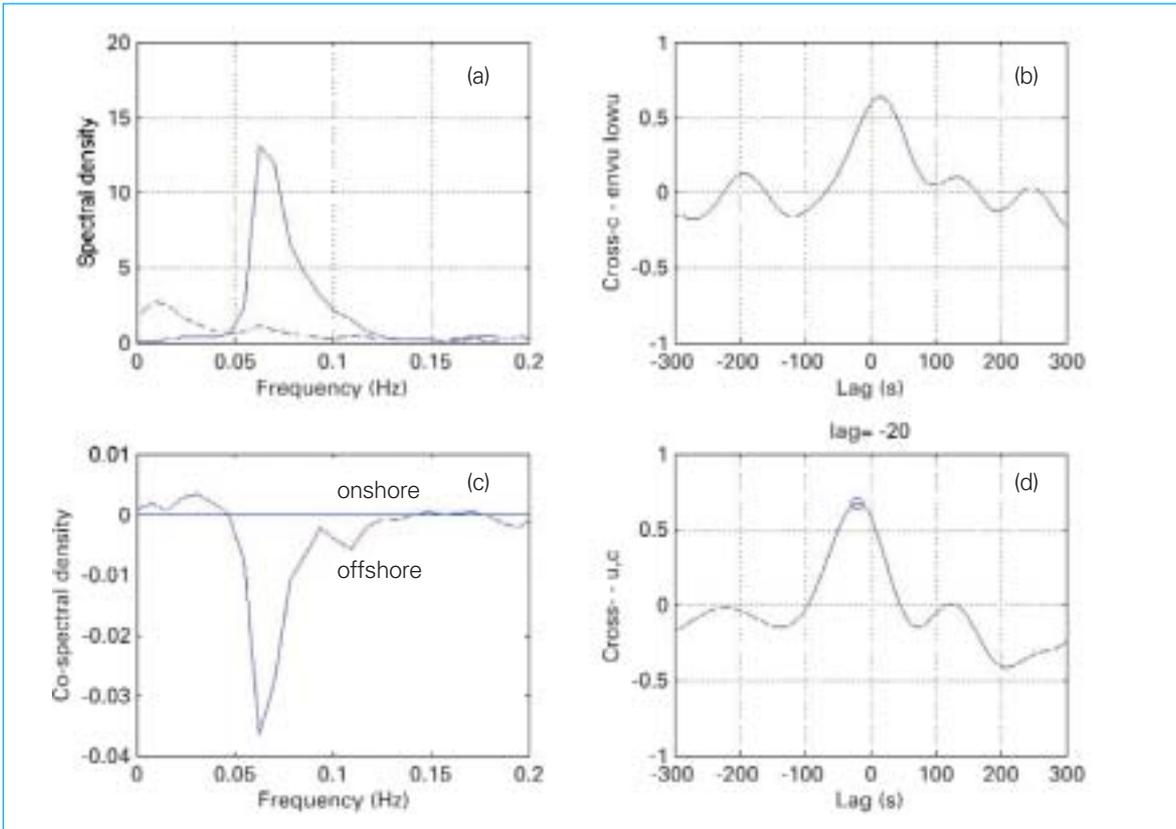


Figure 9. (a) the normalised auto-spectra of cross-shore currents (u - solid line) and nearbed suspended sediment concentration (c - dashed line); (b) cross-correlation between: an envelope function of u and lowpass-filtered u ; (c) the co-spectrum between u and c ; and, (d) envelope function of u and lowpass-filtered c (Chilaw, Sri Lanka – 18-01-96 at 16:30 hrs).

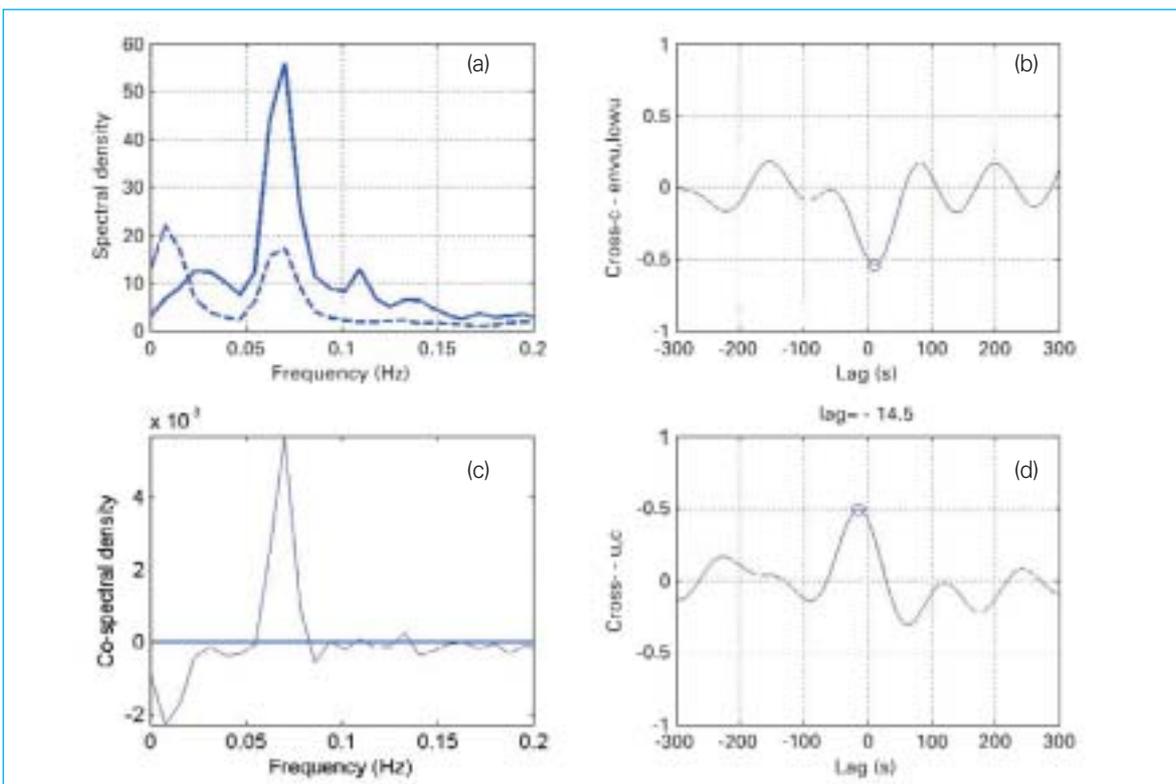


Figure 10. (a) the normalised auto-spectra of cross-shore currents (u - solid line) and nearbed suspended sediment concentration (c - dashed line); (b) cross-correlation between: an envelope function of u and lowpass-filtered u ; (c) the co-spectrum between u and c ; and, (d) envelope function of u and lowpass-filtered c (Chilaw, Sri Lanka – 18-01-96 at 11:40 hrs).

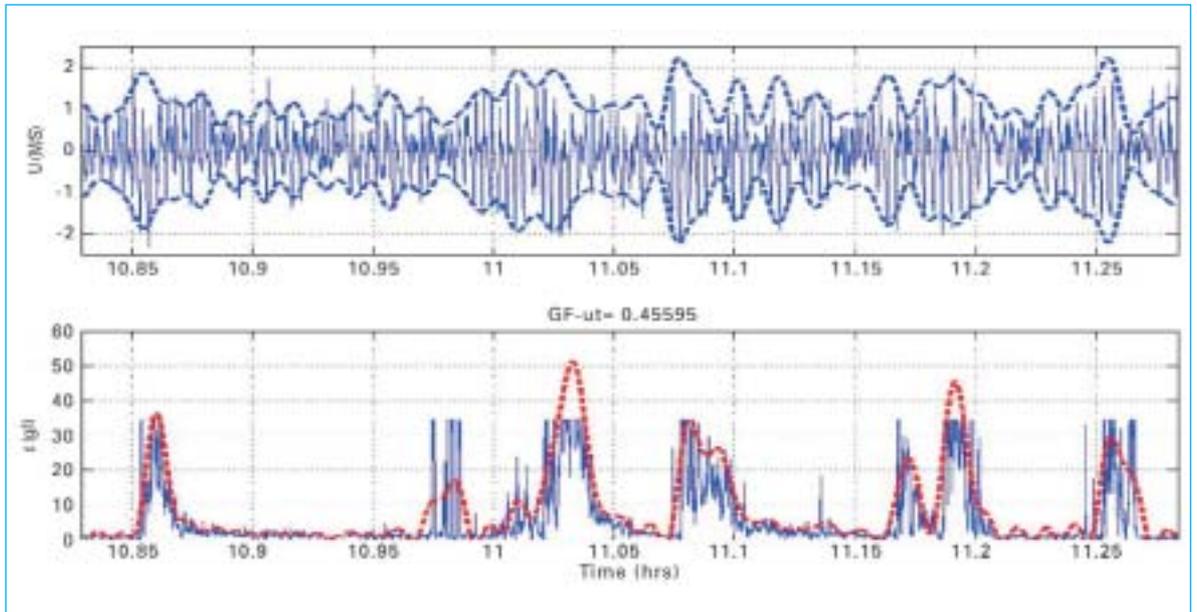


Figure 11. Time series of: (a) cross-shore current velocity u (solid line) and envelope function of u (thick dashed line); and (b) suspended sediment concentration c 0.05m from the bed (solid line) and lowpass-filtered c (thick dashed line); $GF-ut$ – groupiness factor calculated based on u (Mullaloo, Western Australia – 18-04-93).

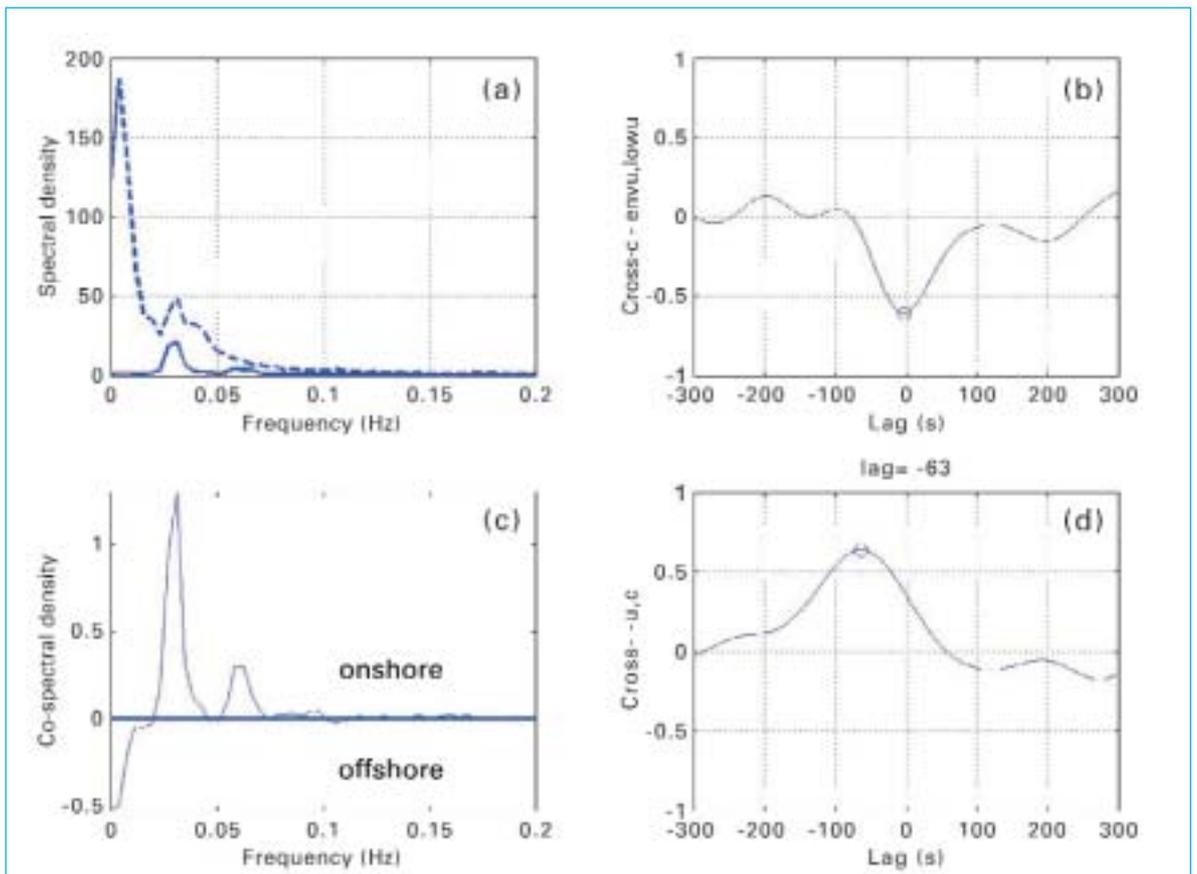


Figure 12. (a) the normalised auto-spectra of cross-shore currents (u - solid line) and nearbed suspended sediment concentration (c - dashed line); (b) cross-correlation between: an envelope function of u and lowpass-filtered u ; (c) the co-spectrum between u and c ; and, (d) envelope function of u and lowpass-filtered c (Mullaloo, Western Australia – 18-04-93).

disagreement with Figure 9 (especially Figure 9c). Data for Figures 9 and 10 were collected from Chilaw, Sri Lanka where average grain size is finer compared to Mullaloo, Western Australia.

Figure 12a indicates that the dominant peak for sediment concentration occurs at a low frequency corresponding to wave groups and Figure 12d reconfirms the correlation between wave groups and sediment concentration with a strong positive relation with a lag of 63 s. Further, Figure 12b demonstrates a strong negative relation between the groupiness envelope and the lowpass filtered cross-shore current velocity and such an out-of-phase relationship indicates the presence of the group bound long wave (Longuet-Higgins and Stewart, 1964).

Results of a similar analysis conducted for a set of data gathered at the same location (Mullaloo, Western Australia) on a different day are presented in Figure 13.

Though it depicts the same trend in cross-shore sediment flux (offshore at low frequencies and onshore at higher frequencies) (Figure 12c and 13c) it can be seen that offshore flux begins to occur at much higher frequency (Figure 13c) than in the previous case

(Figure 12c). Further, the most dominant peak of sediment concentration appears to occur at a comparatively higher frequency (0.025 Hz) (Figure 13a). All these differences and deviations of the direction of cross-shore sediment flux on frequency domain vindicate the inconsistency of the process under different conditions (wave climate, grain size, beach slope, bed forms, and so on).

Numerical analysis

Records of water surface elevation obtained at a location offshore of breaker zone (water depth of 3.4 m) off Leighton Beach, Western Australia (Figure 3) were used as input signal for the numerical model explained in the "Methods" section. Figure 14a shows a time series record of the surface elevation measured at the field and Figure 13b presents the corresponding filtered signal which is the input signal for the model.

The model layout is shown in Figure 15. The average sediment size is 0.1 mm and the beach slope is 1:30. Waves were generated at a constant depth of 3.4 m and the model output of surface elevation, cross-shore current velocity (depth averaged) and the suspended sediment concentration, 0.55 m from the bottom at a water depth of 1.2 m are presented in Figure 16.

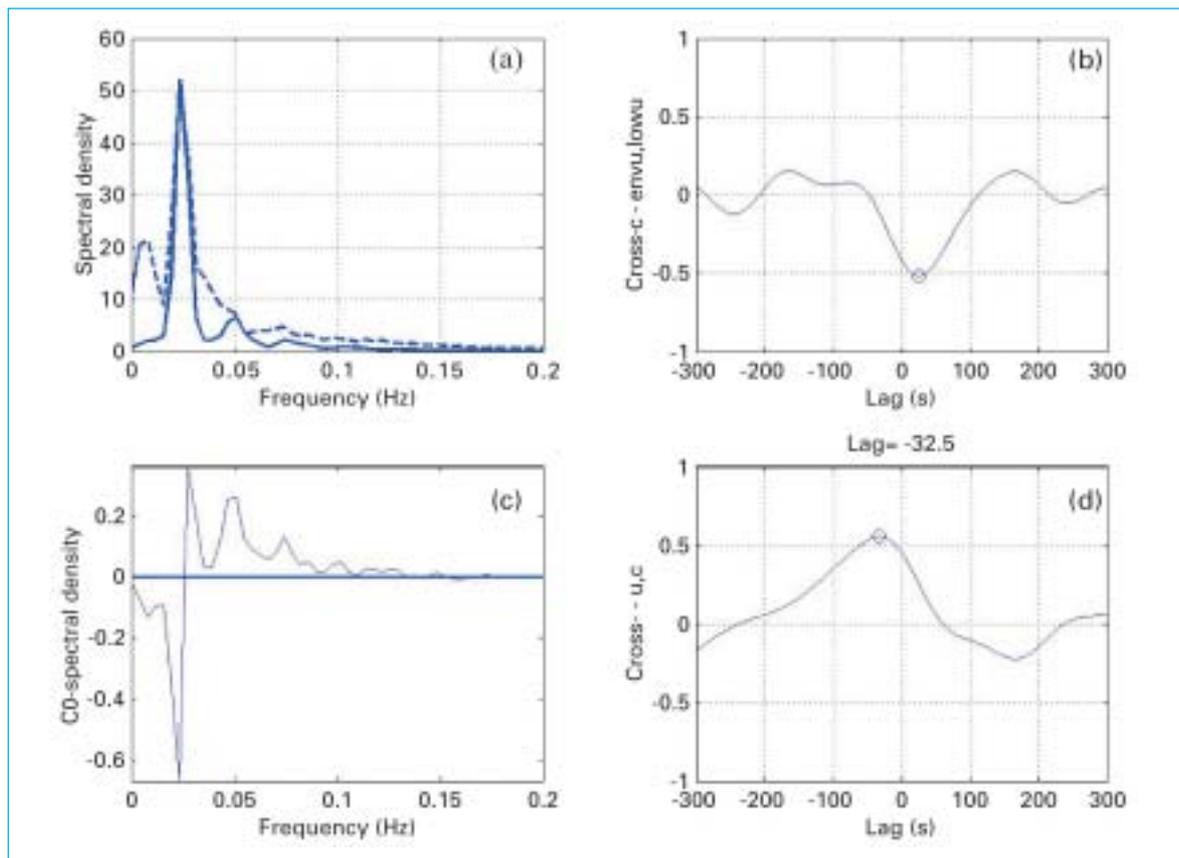


Figure 13. (a) the normalised auto-spectra of cross-shore currents (u - solid line) and nearbed suspended sediment concentration (c - dashed line); (b) cross-correlation between: an envelope function of u and lowpass-filtered u ; (c) the co-spectrum between u and c ; and, (d) envelope function of u and lowpass-filtered c (Mullaloo, Western Australia – 03-04-93).

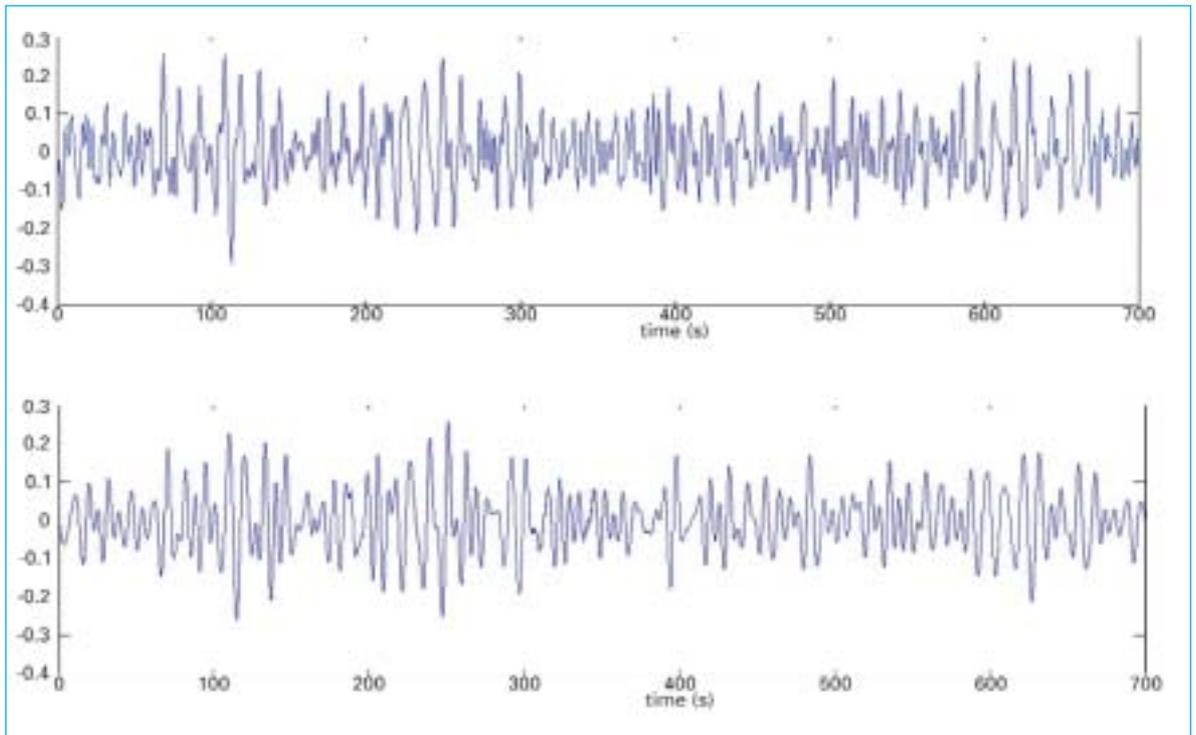


Figure 14. (a) Time series of surface elevation recorded off Leighton Beach, Western Australia. (b) Filtered signal of the surface elevation which is the input to the numerical model.

As described in the “Methods” section, the sediment concentration (transport) is modelled using Bagnold and Bailard (1981) model and the results show that higher suspended sediment concentrations occur with the passage of waves of higher amplitude (Figure 16).

Results of cross-spectral and cross-correlation analysis performed for the output from the numerical model are presented in Figure 17. It is evident that dominant peaks for both cross-shore currents and sediment concentration occur at the incident wave frequency (~ 0.1 Hz) and this further proves the lack of representation of the influence of wave groups. The need for proper simulation of low frequency

oscillations (wave groups) is confirmed again in Figure 17c as the cross-shore sediment flux is towards onshore almost throughout the whole frequency domain.

Conclusions

This paper summarises the results of measurements collected to explore sediment resuspension and cycling caused by wave groups in nearshore environments. Field data obtained at different locations (Mullaloo Beach, City Beach, Leighton Beach – Western Australia and Chilaw – Sri Lanka) under different conditions were

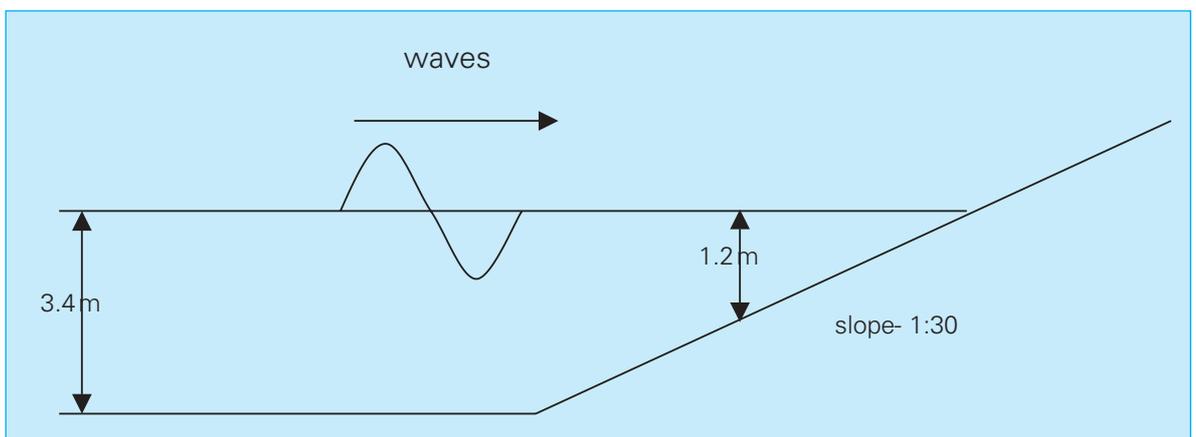


Figure 15. Model layout.

analysed in an attempt to understand the factors influencing sediment resuspension and cross-shore cycling.

The presence of pronounced wave groups depends on the local wave climate. Calm sea conditions dominated by swell have been identified as the ideal conditions for formation of well-defined wave groups and coastal waters forced by local winds (monsoons (winter) or afternoon sea breeze) do not appear to have pronounced wave groups. Far less pronounced wave groupiness could be observed under monsoon conditions or conditions surrounded by afternoon sea breeze. From the results obtained at all the locations, when wave groups were apparent, a significant relation between wave groups and suspended sediment concentrations could be observed. This further proves the well-established assumption that wave groups are more capable of stirring up sediments and keeping them up in suspension than incident waves.

The direction of cross-shore sediment flux in the frequency domain, it is generally postulated that there is onshore transport at higher incident frequencies (wind waves, swell) and offshore transport at lower frequencies (wave groups) (e.g. Huntley and Hanes,

1987). However, the results of Masselink and Pattiaratchi (2000) and Smith and Mocke (2002), as well as the results of the present study indicate that this pattern may be reversed (e.g. Chilaw, Sri Lanka – Figure 9).

This reversal can occur at the same site within a few hours with a change in local sea conditions (Figures 9 and 10). Wave climate was observed to be changed from rather calm conditions to conditions dominated by wind waves caused by an afternoon sea breeze. This explains the influence of local wave climate on the nearshore sediment resuspension and cycling.

The inconsistency in results obtained at different locations can also be influenced by the change in other parameters governing sediment resuspension. Grain size could be a decisive factor which has a direct influence on sediment resuspension and transport, and in the present study a range of mean sediment sizes were observed at different locations. Deigaard *et al.* (1999) emphasised the influence of grain size on net cross-shore sediment transport with a numerical study on net sediment transport under wave groups.

The bottom slope and the ripple geometry too could have a considerable bearing on sediment resuspension

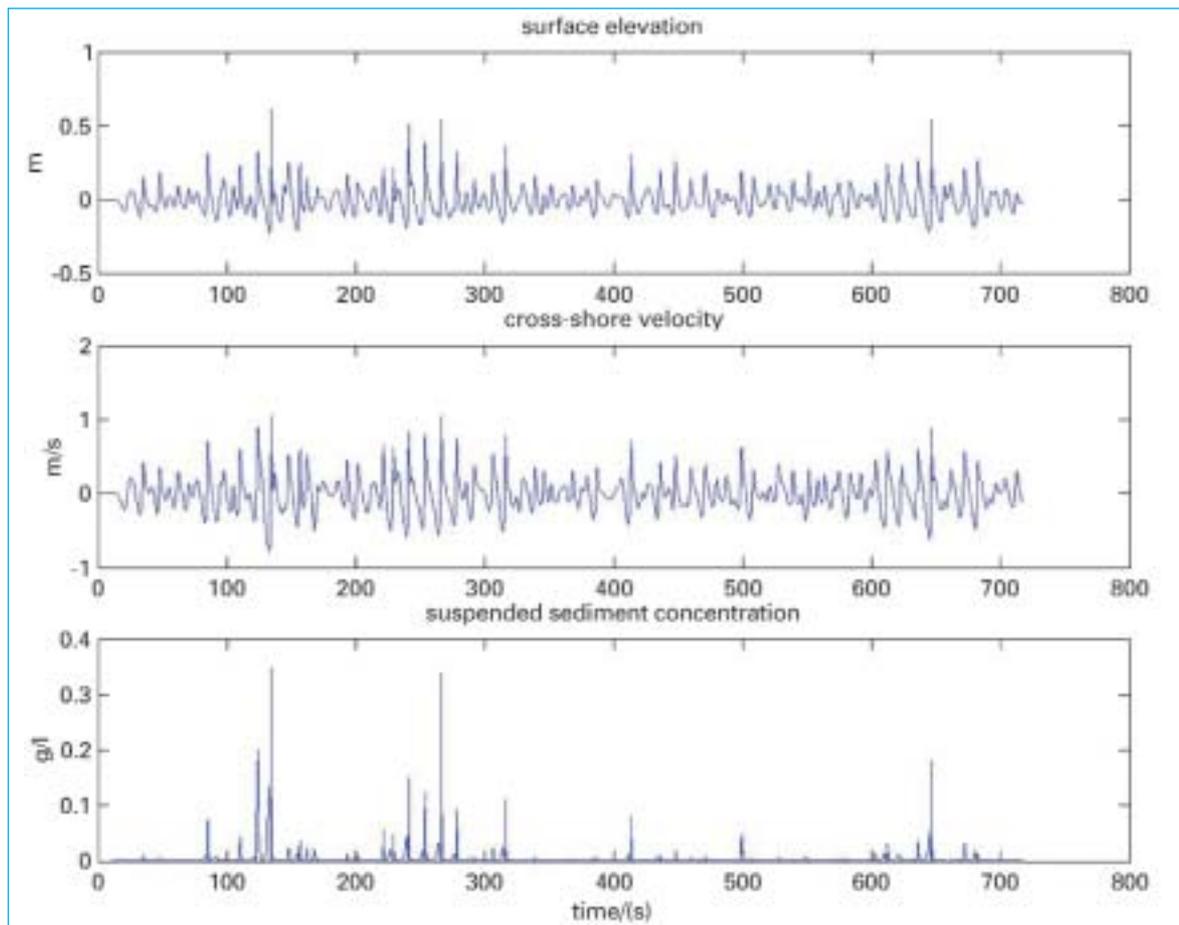


Figure 16. Model output at water depth of 1.2 m (a) surface elevation (b) depth averaged cross-shore current velocity (c) suspended sediment concentration at 0.55m from the bottom.

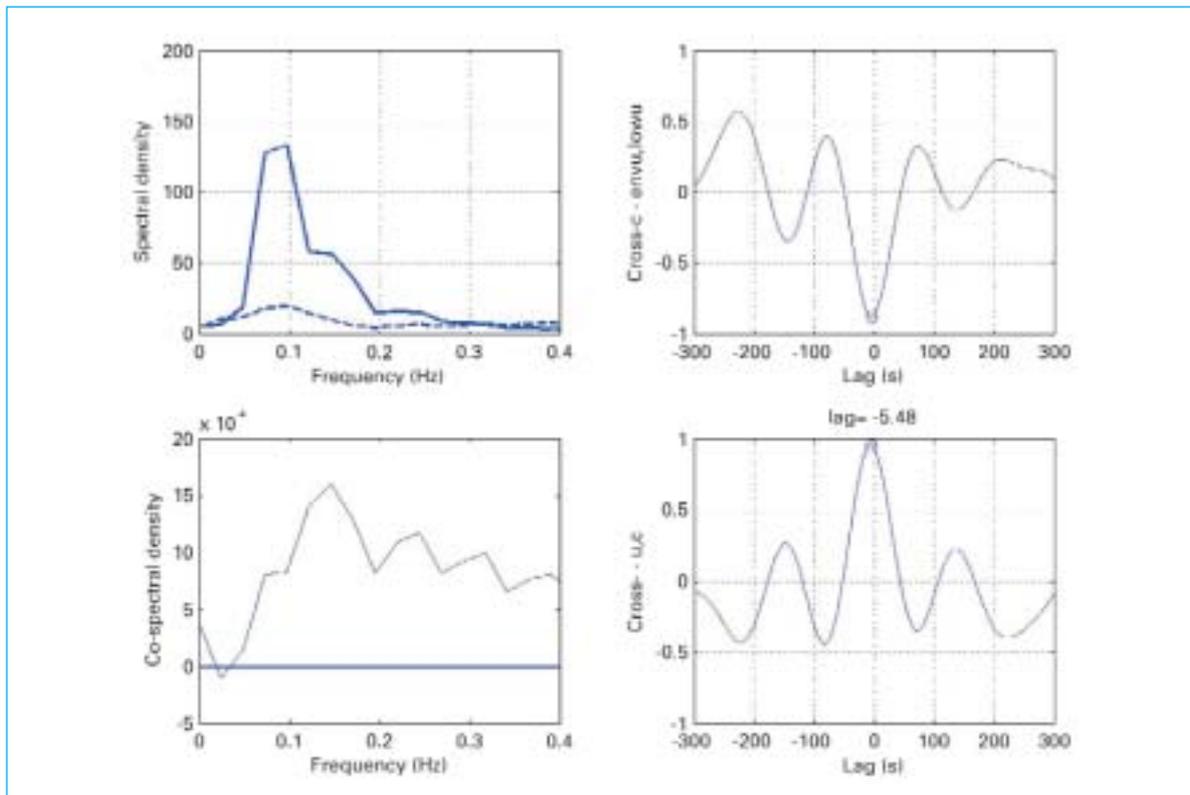


Figure 17. (a) the normalised auto-spectra of cross-shore currents (u - solid line) and nearbed suspended sediment concentration (c - dashed line); (b) cross-correlation between: an envelope function of u and lowpass-filtered u ; (c) the co-spectrum between u and c ; and, (d) envelope function of u and lowpass-filtered c (Results of the numerical model for field data collected off Leighton Beach, Western Australia).

and cycling forced by wave groups (on frequency domain) as has been documented (Vincent *et al.*, 1991; Villard *et al.*, 1999; Vincent and Hanes, 2002).

The simple numerical model described in this paper is an attempt to develop a comprehensive model to simulate sediment resuspension and cross-shore sediment cycling in a nearshore environment. The final objective of this numerical study is to develop a model that is capable of conducting separate exploration of the influence of different parameters governing sediment resuspension and the direction of cross-shore sediment cycling on the frequency domain (covering wind waves, swell, wave groups, and such).

References

Bagnold, R.A. (1966).

"An approach to the sediment transport problem from general physics". *Geological Survey Prof. Paper 422-I*, Washington DC, USA.

Bailard, J.A. (1981).

"An Energetics total load sediment transport model for plane sloping beach". *Journal of Geophysical Research*, 86(C11), 10,938-10,954.

Breninkmeyer, B.M. (1976).

"In situ measurements of rapidly fluctuating, high sediment concentrations". *Marine Geology*, 20, 117-128.

Chen, Q., Kirby, J., Dalrymple, R., Kennedy, A., Thornton, E. and Shi, F. (2000).

"Boussinesq modelling of waves and longshore currents under field conditions". *In Proceedings of 27th International Conference on Coastal Engineering*, 651-663.

Deigaard, R., Jakobsen, J.B. and Fredsoe, J. (1999).

"Net sediment transport under wave groups and bound long waves". *Journal of Geophysical Research*, 104(C6), 13,559-13,575.

Hanes, D.M. and Huntley, D.A. (1986).

"Continuous measurements of suspended sand concentration in a wave dominated nearshore environment". *Continental Shelf Research*, 6, 585-596.

Hanes, D.M. (1991a).

"Suspension of sand due to wave groups". *Journal of Geophysical Research*, 96(c5), 8911-8915.

Huntley, D.A. and Hanes, D.M. (1987).

"Direct measurement of suspended sediment transport". *Coastal Sediments '87*, ASCE, 723-737.

- Kennedy, A., Chen, Q., Kirby, J. and Dalrymple, R. (1999).**
 “Boussinesq modelling of wave transformation, breaking and runup”. I:1d. *Journal of Waterway, Port, Coastal and Ocean Eng.*, 126(1): 39-47.
- List, J.H. 1991).**
 “Wave groupiness variations in the nearshore”.
Coastal Engineering, 15, 475-496.
- Longuet-Higgins, M. and Stewart, R. (1962).**
 “Radiation stress and mass transport in gravity waves, with application to ‘surf beats’”. *Journal of Fluid Mechanics*, 13, 481-504.
- Longuet-Higgins, M. and Stewart, R. (1964).**
 “Radiation stresses in water waves: a physical discussion, with applications”. *Deep-Sea Research*, 11, 529-562.
- Madsen, P.A., Murray, R. and Sorensen, O.R. (1991).**
 “A new form of Boussinesq equations with improved dispersion characteristics”. *Coastal Engineering*, 15, 371-388.
- Masselink, G. and Pattiaratchi, C. (2000).**
 “Tidal asymmetry in sediment resuspension on a macrotidal beach in northwestern Australia”. *Marine Geology*, 163, 257-274.
- Munk, W.H. (1949).**
 “Surf beats”. *Trans. American Geophysical Union*, 30, 849-854.
- Nwogu, O. (1993).**
 “An alternative form of the Boussinesq equations for nearshore wave propagation”. *Journal of Waterway, Port, Coastal Ocean Engineering*, 119, 618-638.
- Osborne, P.D. and Greenwood, B. (1993).**
 “Sediment suspension under waves and currents: time scales and vertical structure”. *Sedimentology*, 40, 599-622.
- Pattiaratchi, C., Masselink, G. and Wikramanayake, N. (1999).**
 “Sea breeze effects on coastal processes”. *Proceedings of Fifth International Conference on Coastal and Port Engineering in Developing Countries (COPEDEC V)*, 37-48.
- Peregrine, D.H. (1967).**
 “Long waves on a beach”. *Journal of Fluid Mechanics*, 27, 815-827.
- Smith, G.G. and Mocke, G.P. (2002).**
 “Interaction between breaking/broken waves and infragravity-scale phenomena to control sediment suspension transport in the surf zone”. *Marine Geology*, 187 (3-4), 329-345.
- Tucker, M.J. (1950).**
 “Surf beats: sea waves of 1 to 5 minutes’ period”. *Proc. Royal Society*, A207, 565-573.
- Villard, P.V., Osborne, P.D. and Vincent, C.E. (1999).**
 “Influence of wave groups on sand resuspension over bedforms in a large scale wave flume”. *Proceedings of the Fourth International Symposium on Coastal Engineering and Science of Coastal Sediment Processes CS99*, New York, 367-376.
- Vincent, C.E., Hanes, D.M. and Bowen, A.J. (1991).**
 “Acoustic measurements of suspended sand on the shoreface and the control of concentration by bed roughness”. *Marine Geology*, 96, 1-18.
- Vincent, C.E. and Hanes, D.M. (2002).**
 “The accumulation and decay of near-bed suspended sand concentration due to waves and wave groups”. *Continental Shelf Research*, 22, 1987-2000.
- Wei, G., Kirby, J.T., Grilli, S.T. and Subramanya, R. (1995).**
 “A fully non-linear boussinesq model for surface waves: I. Highly non-linear, unsteady waves”. *Journal of Fluid Mechanics*, 294, 71-92.
- Wei, G., Kirby and J.T., Sinha, A. (1999).**
 “Generation of waves in Boussinesq models using a source function method”. *Coastal Engineering*, 36, 271-299.