CHAPTER 202

Sediment transport and wave reflection near a seawall.

Jonathon R. Miles[1], Paul E. Russell[1], David A. Huntley[1].

Abstract

This paper describes results of a field experiment to examine the effect of wave reflection on suspended sediment transport in front of a seawall. High frequency measurements of wave elevation, velocity and suspended sediment concentrations were made simultaneously on a natural beach and in front of a seawall at Teignmouth in South Devon (U.K.) in June 1995. Wave reflection at the natural beach was found to be dependent on frequency; low frequency waves being preferentially reflected while incident waves were dissipated. At the seawall the incident wave reflection coefficient was 0.9 indicating only a small amount of dissipation. The doubling of energy over the sea bed was found to greatly increase the suspended sediment concentrations in the water column, although the amount of this increase depended on the water depth. A data analysis technique was developed which allowed the incoming and outgoing wave contributions to the sediment transport to be analysed. In these accretionary conditions incoming waves transported sediment onshore in both wall and beach cases, while in the wall case sediment transported offshore by the outgoing waves balanced the onshore transport. Sediment build up which was observed at the top of the natural beach was not observed in front of the wall. Sediment maintained in suspension in front of the wall was available for longshore transport, and this was enhanced by the presence of the wall.

Introduction

Seawalls have been used for many years as a method of coastal protection on eroding shorelines. It has been suggested that the reflection of wave energy over the beach fronting the wall actually helps to erode the beach (Silvester 1977), but the processes controlling this erosion remain poorly understood. There has been considerable debate over the effect of the seawall on the beach in recent years

[1] Institute of Marine Studies, University of Plymouth, Drake Circus, Plymouth, U.K., PL4 8AA.

(Kraus, 1988; Kraus and McDougal, 1996), with experimenters carrying out laboratory experiments with moveable beds (e.g. McDougal et al., 1996) or carrying out surveys of defended and undefended coastlines (e.g. Griggs and Tait, 1988). Researchers into beach processes have identified driving forces behind beach morphology change using high frequency point measurements of suspended sediment concentrations and water velocities (e.g. Jaffe et al., 1984). This approach has been applied to the reflective seawall environment for the first time and the method and initial results are presented in this paper.

Method

To compare similar wave conditions in a surf zone with a reflective wall environment a location was required with a wall adjacent to a natural beach. The site chosen was Sprey point at Teignmouth in South Devon, UK which has a 7m high seawall fronted by a beach of slope 1/15. The sand in front of the wall is medium quartz sand with D_{50}=0.24mm. The beach is macro-tidal and morphodynamically intermediate. A rig designed to minimise interference with the hydro and sediment dynamic conditions whilst providing a stable base for instrumentation was built and bolted to the wall. An extendable rod was positioned on the front of the rig, extending close to the bed, to which the instruments were attached. Two EMCMs, (Electro Magnetic Current Meters) two OBSs (Optical Backscatter Sensors) and a PT (Pressure Transducer) were attached to this rod, 1.5m from the wall in a vertical array. A rig of instruments was also dug in to the adjacent beach on a similar depth contour so that comparisons could be made. This beach site had one EMCM, one OBS and one PT.

All of the *in-situ* monitoring devices were logged at a frequency of 8Hz and were pre-filtered between 3-4Hz. EMCM and PT offsets were determined in the field at the beginning and end of each tide. Surveys were carried out daily to establish beach morphology. Sediment samples were taken for size distribution analysis. During the period of observation and recording, in June 1995, the wind was generally light and the waves were, on average, 30cm in height at the breakpoint with an average period of 4 seconds. The robust design of the rig should enable measurements to be made in waves of up to 2m. The layout of the site is shown in figure 1:

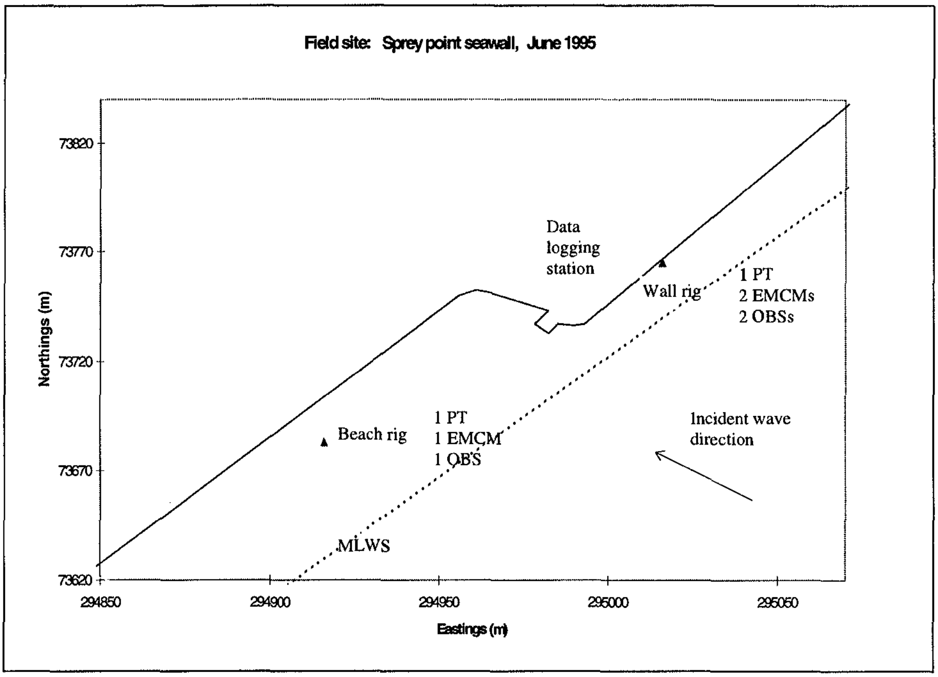

figure 1. Experiment site at Teignmouth.

Instruments were calibrated both before and after the experiment, and the calibrations were applied to the raw data. EMCMs were calibrated in a tow tank at the Royal Naval Engineering College (RNEC) at Manadon, Plymouth (U.K.). Pressure transducers were calibrated for water depth in a 3m deep tank at the RNEC. OBSs were calibrated in the laboratory using sediment samples taken from the experiment site. To calibrate the OBSs a paint stirrer was used to suspend sediment in a tank while samples of the beach sediment were filtered from next to the OBS head. This calibration of the OBSs provided an excellent linear correlation between suspended sediment concentrations and voltage output.

Time series

Time series of surface elevation and suspended sediment concentration are shown in figure 2. Time series have been selected so that water depths are similar in the wall and beach examples, in this case the water depth is approximately 0.8m. Instruments suspended from the wall are 1.2m away from it. This puts them closer to the antinode at the wall than the node 2.7m away from the wall (for a wave period of 4 seconds). The maximum surface elevation deviation from the mean is therefore clearly larger than that observed at the beach rig. Suspended sediment data which is compared in these examples is taken from OBSs at similar heights, both being approximately 18cm from the bed. The scale of the axis of the wall OBS is reduced so that the data fits the plot. In similar incident wave conditions levels of suspended sediment are clearly much larger at the wall, reaching 4 kg/m^3 at this height above the bed, while at the beach OBS sediment concentrations only reach 0.6 kg/m^3.

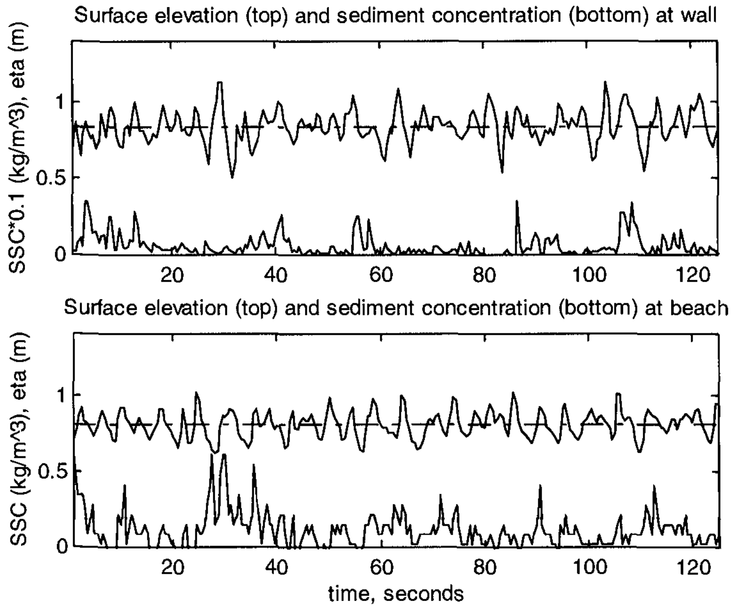

figure 2. Time series of surface elevation and suspended sediment concentrations at the wall and beach rigs. N.B. The sediment concentrations in the wall time series have been scaled down by a factor of 10.

Theory

Incoming and outgoing elevation time series were obtained from elevation and velocity time series using the method of Guza, Thornton and Holman (1984). The separation of incoming and outgoing waves forms the basis for most reflection analysis techniques which involve co-located elevation and velocity sensors. The analysis can also be extended to obtain the incoming and outgoing velocity time series. This allows the frequency dependent oscillatory sediment transport associated with the incident reflected waves to be found.

The derivation of Guza et al.'s (1984) time domain technique arises from linear shallow water theory:

The velocity potential for progressive water waves is as follows:

$$\phi = \frac{-a.g}{\sigma}.\frac{\cosh k(z+h)}{\cosh kh}\sin(kx - \sigma t)$$

The surface elevation can be obtained from this by differentiating with respect to time, and the attenuation term tends to 1 in shallow water.

$$\eta = \frac{1}{g}\left[\frac{\partial \phi}{\partial t}\right]_{z=0} \qquad \text{giving} \quad \eta = a\cos(kx - \sigma t)$$

A similar equation for velocity is obtained by differentiating with respect to x

$$u = -\frac{\partial \phi}{\partial x} \qquad \text{gives} \qquad u = \frac{gak}{\sigma}\cos(kx - \sigma t)$$

By dividing the elevation and velocity equations the following time domain transformation can be obtained relating velocity and surface elevation (provided the water is shallow).

$$\eta(t) = \frac{c}{g}u(t)$$

It is necessary to transform to the frequency domain and use full linear theory if this relationship is to be applied in intermediate or deep water.

Progressive wave surface elevation traces for waves incoming to a beach and outgoing from it can be obtained from the time series of elevation and velocity as follows:

$$\eta_{in}(t) = \left(\eta(t) + \frac{c}{g}u(t)\right)/2$$

$$\eta_{out}(t) = \left(\eta(t) - \frac{c}{g}u(t)\right)/2$$

In this case, a positive velocity implies an onshore flow, while a negative velocity an offshore flow. In order to obtain a frequency dependent reflection function (FDRF) it is necessary to carry out a spectral analysis of the incoming and outgoing elevation traces separately. After obtaining the power spectra of the incoming and outgoing elevation time series, $S_{ii}(f)$ and $S_{oo}(f)$ respectively, the frequency dependent reflection coefficient is simply:

$$R(f) = \sqrt{\frac{S_{ii}(f)}{S_{oo}(f)}}$$

This technique was examined for signal noise related bias by Huntley et al. (1995) who found that when the coherence between elevation and velocity was high, the bias in the FDRF was low. Two other techniques were discussed by Huntley et al. (1995). These were a frequency domain method by Tatavarti (1989) and a Principal Component Analysis method (Tatavarti et al., 1988). All three techniques were applied to the data in order that the frequency dependent reflection coefficient for the beach and wall cases could be identified. The three different methods were found to offer similar results. This gives confidence in the time domain method which is the most simple to program and extend for incoming and outgoing sediment analysis.

In order to understand the effect of the reflected wave field on the suspended sediment transport, it is possible to carry out a cross-spectral analysis of the incoming and outgoing waves with the sediment.

It is first necessary to apply the transformation from elevation to velocity to obtain incoming and outgoing velocity time series. The appropriate transformations are:

$$u_{in} = \frac{g}{c}\eta_{in}$$

$$u_{out} = -\frac{g}{c}\eta_{out}$$

A wave crest (elevation maximum) correlated with onshore flow therefore represents a wave crest travelling onshore, while a wave peak correlated with an offshore velocity represents a wave crest travelling offshore. The equations for incoming and outgoing velocity are therefore:

$$u_{in} = \frac{1}{2}(u + \frac{g}{c}\eta)$$

$$u_{out} = \frac{1}{2}(u - \frac{g}{c}\eta)$$

It is next necessary to assume that the oscillatory sediment flux can be split into incoming and outgoing components. Jaffe et al. (1984) assumes a similar principle when considering the breakdown of the mean and oscillatory fluxes. They assume that the total velocity can be split into a mean and oscillatory component:

$$U = \bar{u} + u'$$

and that the sediment concentration is also separable into mean and oscillatory parts:

$$C_s = \bar{c}_s + c_s'$$

The time average of the flux therefore reduces to the mean flux and the flux coupling:

$$\overline{UC_s} = \overline{\bar{u}\bar{c}_s} + \overline{u'c_s'}$$

Signals are routinely de-meaned, and the remaining step is to split the oscillatory velocity into incoming and outgoing components before crossing with the suspended sediment to obtain the flux:

$$u' = u_{in}' + u_{out}'$$

The time average of the incoming and outgoing oscillatory flux is therefore:

$$\overline{u'c_s'} = \overline{u_{in}'c_s'} + \overline{u_{out}'c_s'}$$

Huntley and Hanes (1987) identified that the frequency dependent sediment transport could be found by taking the co-spectrum of the oscillatory cross shore velocity with the sediment concentration time series. The frequency dependent sediment transport associated with the incoming and outgoing waves is therefore obtained from the co-spectrum of the incoming or outgoing velocity time series with the sediment time series. The contributions of the incoming and outgoing waves to the sediment transport can therefore be identified.

Frequency dependent wave reflection

Three methods were used to determine levels of energy incoming and outgoing from the natural beach and the wall. Incoming and outgoing wave spectra were obtained from the incident and reflected time series obtained using Guza et al.'s (1984) method. The frequency dependent reflection coefficient was then determined using this method and two frequency domain methods. All three methods require that the current meter and pressure transducers are co-located and log data simultaneously. The analysis was first applied to data from the beach rig (figure 3).

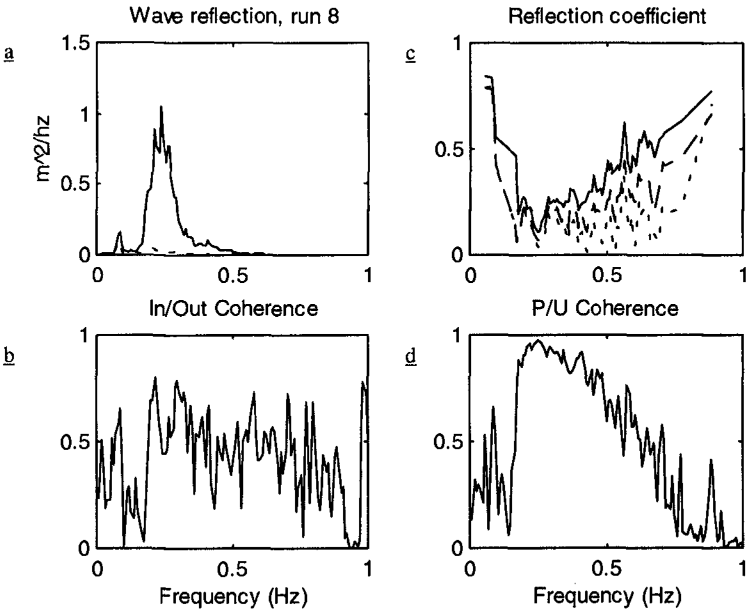

figure 3. Frequency dependent wave reflection at the beach. a: Incoming and outgoing wave spectra calculated using the time domain method. b: Coherence between calculated incoming and outgoing time series. c: Frequency dependent reflection coefficient calculated using time domain (solid), frequency domain (dashed) and principle component analysis (dotted) methods. d: Coherence between elevation and velocity. Water depth is 1.28m.

The energy spectra show clearly that the incident waves (frequency 0.25 Hz) are dissipated by the natural beach, while at a lower frequency (0.1Hz) wave reflection is taking place. By dividing the square root of the spectral estimates, the FDRF for this time domain method was obtained, and this shows a reflection coefficient of 0.1 for the incident waves on the natural beach while for the low frequency waves the reflection coefficient is 0.8. Of the three lines on the reflection coefficient figure above (top right). the lines show the methods of the time domain method (top), the frequency domain method (middle) and the Principal Component Analysis (bottom). The three methods give good agreement where there is good coherence between elevation and velocity.

A similar analysis was carried out to data from the wall rig. The results are shown in figure 4.

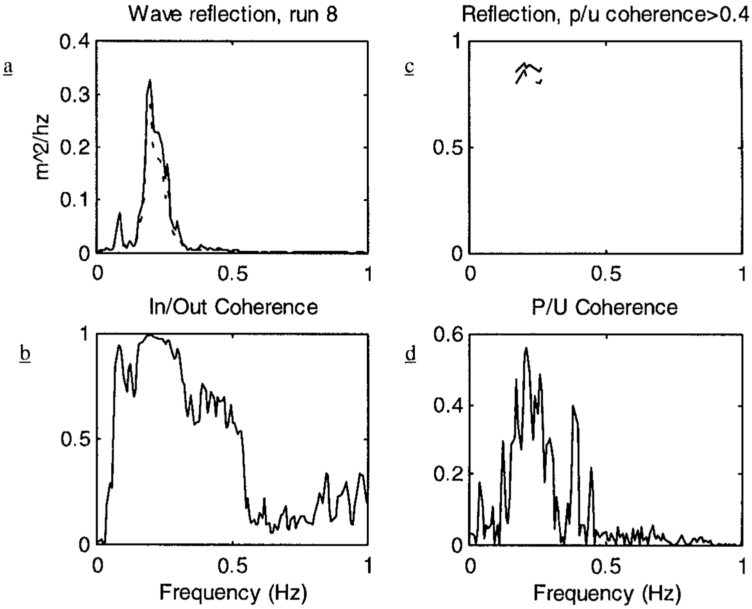

figure 4. Frequency dependent wave reflection at the wall. a: Incoming and outgoing wave spectra calculated using the time domain method. b: Coherence between calculated incoming and outgoing time series. c: Frequency dependent reflection coefficient calculated using time domain (solid), frequency domain (dashed) and principle component analysis (dotted) methods. Reflection estimates are plotted for values of P/U coherence > 0.4 so that there is 95% confidence in the coherence between P and U. This is necessary as cross spectral analysis is carried out in the determination of the FDRF using the frequency domain methods. d: Coherence between elevation and velocity. Water depth is 1.30m.

Similar amounts of energy were found in the spectra of both incoming and outgoing wave time series, indicating that reflection of the incident waves was occurring at the wall. At incident wave frequency all three methods of determining the frequency dependent reflection coefficient gave a value of 0.9 at the wall. The wall is in fact slightly sloping at the position of the rig and this may account for the reflection coefficient being less than unity.

Mean suspended sediment concentrations

The next part of the investigation was to examine the effect of the increase in reflection coefficient at the shoreline on concentrations of suspended sediment. To do this, data from OBSs on the beach and wall rig were compared. During the experiment OBSs were carefully positioned on each rig so that they were at the same height above the bed and are therefore comparable. Mean concentrations were calculated for each run. Mean water depths were also calculated and sediment concentrations in each case were then plotted against depth. The results are shown in figure 5.

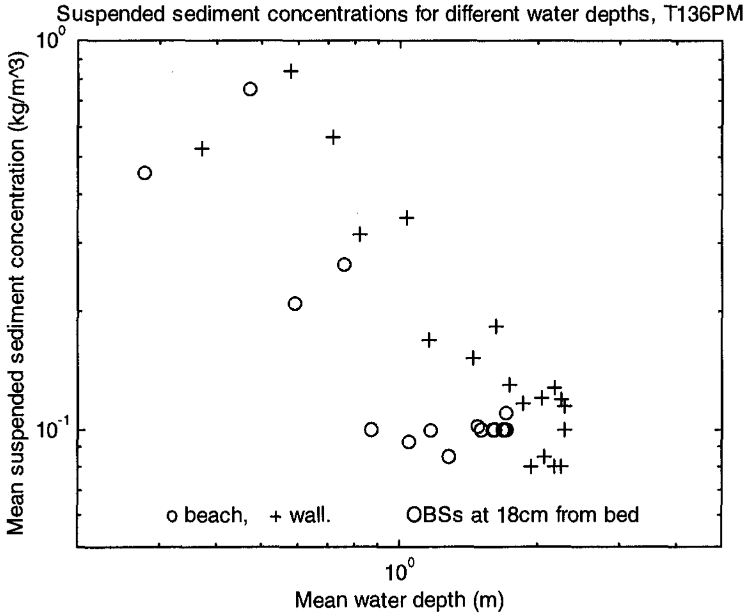

figure 5. Mean suspended sediment concentrations - comparison of data from wall and beach OBSs. Both instruments were mounted approximately 18cm from the bed. Incident waves were approximately 30cm high at the breakpoint.

The results show a greater concentration of sediment was in suspension in front of the wall than was in suspension on the natural beach when water depths were the same. Incoming wave conditions did not vary significantly during this tide, and the results therefore imply that it is the increase in wave reflection at the shoreline which must be responsible for increasing the concentrations of suspended sediment in front of the wall. The distinct linear trend in the data, especially in the wall rig data suggests that it may be possible to parameterise the mean suspended sediment concentrations in this region in terms of the reflection coefficient, water depth, height above bed and incident wave height. Further experimentation with a larger array of instruments would be necessary for this however.

Frequency dependent sediment transport

The incoming and outgoing frequency dependent sediment transport was obtained for both wall and beach rigs for each run of data logged. A clear picture emerged in all runs as to the nature of this transport and this is shown in figure 6.

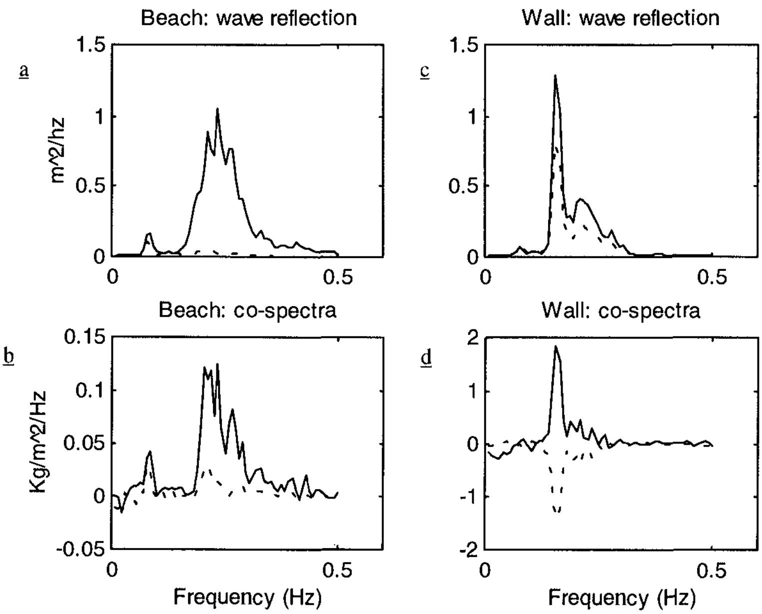

figure 6. Incoming and outgoing spectra and co-spectra in beach (a,b) and wall (c,d) cases. In the energy spectra plotted above, the solid lines represent incoming energy, the dashed lines represent outgoing energy. In the co-spectra, positive is onshore, solid lines are the cospectra between incoming waves and the sediment, dashed lines are cospectra between outgoing waves and sediment. Water depth is 1.3m

In the beach case (figure 6b), incoming waves are found to transport sediment onshore. This result is similar to that observed by Huntley and Hanes (1987). Suspension events occur at the same time as onshore directed flows, and the resultant transport is onshore. There is little energy outgoing from the beach however, and there is therefore little transport associated with the offshore directed waves.

At the wall, the situation is rather different (figure 6d). The incident waves are still responsible for onshore sediment transport, while the outgoing waves give rise to offshore transport. The onshore transport by the incoming waves is effectively halted by the outgoing waves. The net cross-shore oscillatory transport is therefore reduced. The fact that there is more sediment in suspension in front of the wall is also evident in this analysis as the magnitudes of the co-spectra are considerably larger in the wall case than in the beach case.

Longshore transport comparison

Mean longshore transport rates were calculated for both wall and beach rigs. The results are shown in figure 7.

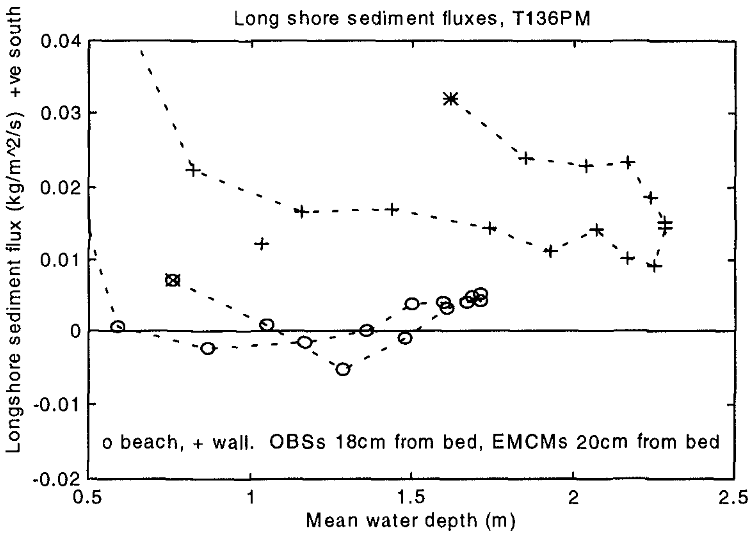

figure 7. Longshore transport rates measured at the beach and wall.

Longshore transport rates in front of the wall were found to be greater than at the beach rig at all times, and this was attributed to both the increase in suspended sediment concentrations and also an increase in the longshore current which passed in front of the wall. The south-westward direction of longshore transport in the wall case is a result of the oblique wave approach from the east (see figure 1).

During the period of observation, morphology changes were monitored using surveying techniques. Increased levels of longshore transport along the Sprey point wall resulted in the development of a small bar to the south west of the wall. (extending SW from point 294990,73740; see figure 1). Shoreward of the beach rig, a net accretion was observed. This is likely to have resulted from the onshore transport by the incident waves. At the wall rig however there was no net accretion or erosion. The balance in transport between the incoming and outgoing waves prevented accretion taking place in this region, while increased levels of sediment in suspension led to an enhanced longshore transport of sediment in front of the wall.

Conclusions

This paper has described initial results of a field experiment to examine the effect of wave reflection on suspended sediment transport in front of a seawall. High frequency measurements of wave elevation, velocity and suspended sediment concentrations were made simultaneously on a natural beach and in front of a seawall. The doubling of energy over the sea bed was found to greatly increase the suspended sediment concentrations in the water column, although the amount of this increase depended on the water depth. A data analysis technique was developed which allowed the incoming and outgoing wave contributions to the sediment transport to be analysed. Incoming waves transported sediment onshore in both wall and beach cases, while in the wall case outgoing waves balanced the onshore transport. Sediment which was maintained in suspension in front of the wall was available for longshore transport, and this was enhanced by the presence of the wall.

Symbols

a	wave amplitude
c	wave celerity
c_s	sediment concentration
f	wave frequency
g	gravitational acceleration
h	water depth
k	wave number $(2\pi/\lambda)$
t	time
u	horizontal cross shore velocity
x	horizontal co-ordinate
z	vertical position. $z = 0$ at the surface, $z = -h$ at the bed
$R(f)$	frequency dependent reflection coefficient
S_{ii}	power spectrum of incoming wave time series
S_{oo}	power spectrum of outgoing wave time series
T	wave period

σ angular frequency ($2\pi/T$)
η surface elevation
λ wavelength
ϕ velocity potential
$_{in}$ denotes incoming wave
$_{out}$ denotes outgoing wave

References

Griggs, G.B. and Tait, J.F., 1988. The effects of coastal protection structures on beaches along northern Monterey Bay, California. Journal of Coastal Research, Special Issue No. 4, 93-111.

Guza, R.T., Thornton, E.B. and Holman, R.A., 1984. Swash on steep and shallow beaches, Coastal Engineering, 708-723.

Huntley, D.A. and Hanes, D.M., 1987. Direct measurement of suspended sediment transport. Proceedings, Coastal Sediments '87, ASCE, 723-737.

Huntley, D.A., Simmonds, D. and Tatavarti, R.S.V.N., 1995. On the measurement of coastal wave reflection using co-locted elevation and current sensors. Proceedings, Coastal Dynamics, 57-68.

Jaffe, B.E., Sternberg, R.W. and Sallenger, A.H., 1984. The role of suspended sediment in shore normal beach profile changes. Proceedings, Coastal Engineering, 1983-1996.

Kraus, N.C., 1988. The effects of seawalls on the beach: extended literature review. Journal of Coastal Research, Special Issue No. 4, 1-28.

Kraus, N.C. and McDougal, W.G., 1996. The effects of seawalls on the beach: part 1, an updated literature review. Journal of Coastal Research, 12 (3), 691-701.

McDougal, W.G., Kraus, N.C. and Ajiwibowo, H., 1996. The effects of seawalls on the beach part II, numerical modelling of SUPERTANK seawall test. Journal of Coastal Research, 12 (3), 702-713.

Silvester, R., 1977. The role of wave reflection in coastal processes. Proceedings of Coastal Sediments '77, American Society of Civil Engineers, 639-652.

Tatavarti, R.S.V.N., 1989. The reflection of waves on natural beaches. Unpub. PhD thesis. Dalhousie University, Halifax, Nova Scotia, Canada. 175pp.

Tatavarti, R.S.V.N. and Huntley, D.A., 1987. Wave reflections at beaches, Proceedings, Canadian Coastal Conference., Quebec City, Canada, 241-256.

Acknowledgements

The authors would like to thank Dr Mark Davidson at the University of Plymouth for helpful suggestions throughout the study, and Mr Peter Ganderton for his assistance with the field-work phase of the project.

Initial nourishment at Palm Beach, Florida. Photo courtesy of Applied Technology & Management, Inc. and Aerial Photography, Inc.

PART IV

Coastal Processes and Sediment Transport

One year after nourishment at Palm Beach, Florida. Photo courtesy of Applied Technology & Management, Inc. and Aerial Photography, Inc.