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Measurement Techniques of Shingle Transport in the Nearshore Zone

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ABSTRACT

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New, innovative techniques are presented for the detection of shingle movement. A passive acoustic technique is used for the remote sensing of instantaneous gravel motion in shallow offshore areas. Noise created by the intercollision of moving particles (self-generated noise, SGN) is proportional to the transport rate. This approach is used in conjunction with measurements of waves and currents in the benthic boundary layer, to study processes associated with shingle transport. The SGN method can be used in tidally-dominated areas and those experiencing shoaling (non-breaking) waves; its use in the surf zone (beaches) is limited, due to increased ambient noise levels caused by wave breaking. A new shingle tracing technique has been developed, based upon the implantation of a miniature electronic transmitter into a shingle particle (of the same shape and specific gravity as the indigenous sediment population). This "transmitting pebble" can be detected remotely over a beach, to depths of burial of up to 70cm, offering high (80%) recovery rates. Application of the techniques developed have demonstrated the enhancing role of the waves in offshore shingle transport processes; modification of existing (steady current) shingle transport formulae are suggested, for use in the marine environment. Longshore shingle transport, in the surf zone, can be calculated using the energy flux equation, originally derived for sand. The coefficient (K) is shown to be constant for gravel particle sizes (D_{50} > 20mm) and equal to 0.017.

ADDITIONAL INDEX WORDS: *SGN method, surf zone, transmitting pebble, sediment transport.*

INTRODUCTION

Coarse clastic (gravel/shingle) deposits are common and widespread in the offshore and beach zones of certain geographic areas, especially in northern latitudes, formerly glaciated regions or tectonically-controlled coastlines. Associated shorelines have been classified according to their particular morphodynamic attributes (*e.g.*, CARTER and ORFORD, 1993), whereas offshore deposits have been related to their origin and the prevailing hydrodynamic conditions (VOULGARIS and COLLINS, 1994a). Such environments are dominated, for example, by breaking waves and tidal currents, respectively. Likewise, sediment can be exchanged between the shoreline and the offshore deposits, under the action of both storm and normal wave and current conditions.

The accurate monitoring of shingle transport, is important in relation to: gravel extraction; coastal replenishment; and sediment mobility studies (*e.g.* HR WALLINGFORD, 1993). Such uses require detailed knowledge of the relationship between hydrodynamic parameters and the resulting shingle transport in terms of magnitude and direction.

In the present contribution, the development of two new techniques for the *in-situ* measurement of shingle transport is presented: (i) a passive acoustic technique for the measurement of instantaneous shingle transport under the action of both waves and currents over the inner continental shelf; and (ii) a tracing technique, whereby shingle particles are implanted with an active emitting electronic circuit and their transport path is identified electronically in the intertidal zone. These new techniques allow for the development of more accurate formulae for modelling applications and understanding regional sediment distributions and transport pathways.

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SHINGLE TRANSPORT OVER THE INNER CONTINENTAL SHELF

Background

Wave-current interaction and the resulting flow structure have been the subject of numerous investigations (*e.g.* GRANT and MADSEN, 1979; CHRISTOFFERSEN and JONSSON, 1985; SLEATH 1991), but information concerning the associated sediment transport is limited to sandy beds. These studies rely on detailed measurements, at the water-sediment interface within the benthic boundary layer (DRAKE and CACCHIONE, 1991; VINCENT, 1991) and the use of fast-responding instrumentation for flow (*e.g.* electromagnetic (em) current meters) and sediment in suspension (acoustical and/or optical backscatter sensors) measurements.

Observations on shingle movement and associated flow characteristics are limited to gravel research undertaken in rivers a few decades ago (*i.e.*, EINSTEIN, 1950; KALLINSKE 1947; and MEYER-PETER and MULLER, 1948). The absence of data on shingle transport under the combined action of waves and currents is due mainly to the lack of systems capable of measuring transport rates at time-scales comparable to those of gravity waves, or even microscale turbulence.

The potential use of a passive acoustic technique for the detection of shingle transport was identified as early as the 1960's (JOHNSON and MUIR, 1969); subsequently, theoretical (THORNE and FODEN, 1988) and experimental (WILLIAMS *et al.*, 1989; JAGE and HARDISTY, 1991) developments were undertaken for application in a tidally-dominated environment. Such an approach, called self-generated noise (SGN), is based upon the assumption that the noise generated by the inter-collision of moving shingle particles, is proportional to the amount of material in transport and hence to shingle transport rate. This SGN technique has been utilised here for the study of gravel movement under waves and currents.

SGN Method

It has been revealed experimentally that: (i) the noise level generated by intercolliding particles is a function of their impact velocity; and (ii) the noise centroid frequency depends upon the size of the material. This frequency can vary between 2 and 15 KHz, with finer-grained material producing higher frequency noise than coarser particles. The root-mean-square (rms) level of the instantaneous acoustic waves is used to represent sediment transport; this is defined in terms of self-generated noise (SGN). Application of SGN to the measurement of shingle transport rates requires: (i) use of an underwater hydrophone, for detecting the raw noise signal of inter-particle collision; (ii) band-pass filtering of the signal, with appropriately selected cut-off frequencies, ensuring recording of noise levels associated with the collisions; (iii) real-time conversion of the filtered-raw signal into a rms level (SGN); and (4) sampling and recording of the SGN rms level, at frequencies identical to those used for the hydrodynamic measurements (Figure 1). Steps 2 and 3 take place in real-time, through the use of a specifically-designed underwater processor (VOULGARIS and COLLINS, 1994b). Finally, the recorded SGN signal is converted into actual sediment transport rates through the use of an experimentally-derived and site-specific calibration *i.e.*, from either *in-situ* (THORNE, 1986) or laboratory (VOULGARIS *et al.*, 1995) experiments.

The transport measurements are combined with simultaneous flow observations, using em current meters installed at three elevations above the sea bed. These measurements were accompanied by wave-induced pressure data, together with positioning information on the instrument platform (tripod). Technical aspects of the system and the calibration procedures are described in VOULGARIS and COLLINS (1994b) and VOULGARIS *et al.* (1995).

Experimental Area

An experiment was undertaken between 2nd April and 8th May 1993, in Christchurch Bay, off the southern coastline of England. The sea bed consisted of loose, unimodal, round shingle, with a mean grain size of 1.70cm. Mean spring and neap tidal ranges are 2.0 and 0.9m, respectively. The mean water depth was around 8m at the deployment location. Bursts of data of 10 mins were collected, at intervals of 2 hours. The sampling frequency within each burst was 5Hz.

During the deployment, horizontal currents were measured at 0.25, 0.73 and 1.23m above the sea bed, whilst vertical currents were measured at 0.73m. SGN and wave-induced pressure were measured at 0.50 and 1.50m above the seabed, respectively (VOULGARIS *et al.*, 1994, page 895, Figure 1).

The tripod was deployed at the edge of a gravel wave field, of 0.5 m wave height and 10m wavelength. As a result, flow characteristics over a rippled and flat bed were extracted, for the flood and ebb stages of the flow respectively (VOULGARIS *et al.*, 1994).

Results

Three 'typical' runs are presented here, to demonstrate the use of the SGN method to study shingle transport mechanisms and processes. The selection was based upon the different hydrodynamic conditions prevailing: (a) a time-series with practically no waves present (measured significant wave height, $H_S < 0.1$m) whilst the steady current measured at 1.23m above the sea bed was 1.08 m/s (Run C); (b) slack water with practically no mean water flow but with a fair level of wave activity ($H_S = 0.50$m; Run W); and (c) strong tidal flow (1.13m/s) with moderate wave activity ($H_S = 0.8$m, Run WC). Hydrodynamic conditions during each of the runs are listed in Table 1. In addition, 100s segments of instantaneous water depths (h), water speeds ($|U|$) and immersed weight shingle transport rate (I_b) extracted using the SGN method are shown on Figure 2.

During Run C, the sea surface was almost flat, whilst the water speed showed turbulent variation around the mean (1.08 m/s). The shingle transport rate is shown to be almost constant without any 'eruptive' transport bursts; this suggests response to the mean flow, rather than to instantaneous turbulent variations.

In Run W, steady currents were practically absent. Waves with an rms height 0.38m and a peak wave period of 7.8s were present; this led to maximum wave-induced currents 0.20m/s at 1.23m above the sea bed. Although the instantaneous current speeds are almost 5 times greater during Run C, the recorded shingle transport rates are of comparable magnitude (0.22 and 0.15 W/m^2, for Runs C and W, respectively). Mean shear stresses derived using the inertial dissipation method for the tidally-induced currents (see below) were 3.18 and 0.69 N/m^2 for Run C and W, respectively. Wave activity during Run W, however, results in a maximum (during the cycle) wave-induced shear stress of 3.29 N/m^2; this explains the magnitude of the observed transport rates at this time. The analysis suggests the use of the resultant force acting on the sea bed (*i.e.*, total shear stress) as a more accurate method to correlate shingle transport rates with the prevailing hydrodynamic conditions.

Finally, conditions during Run WC are characterised by strong tidal flows (1.13 m/s) and moderate wave activity (with

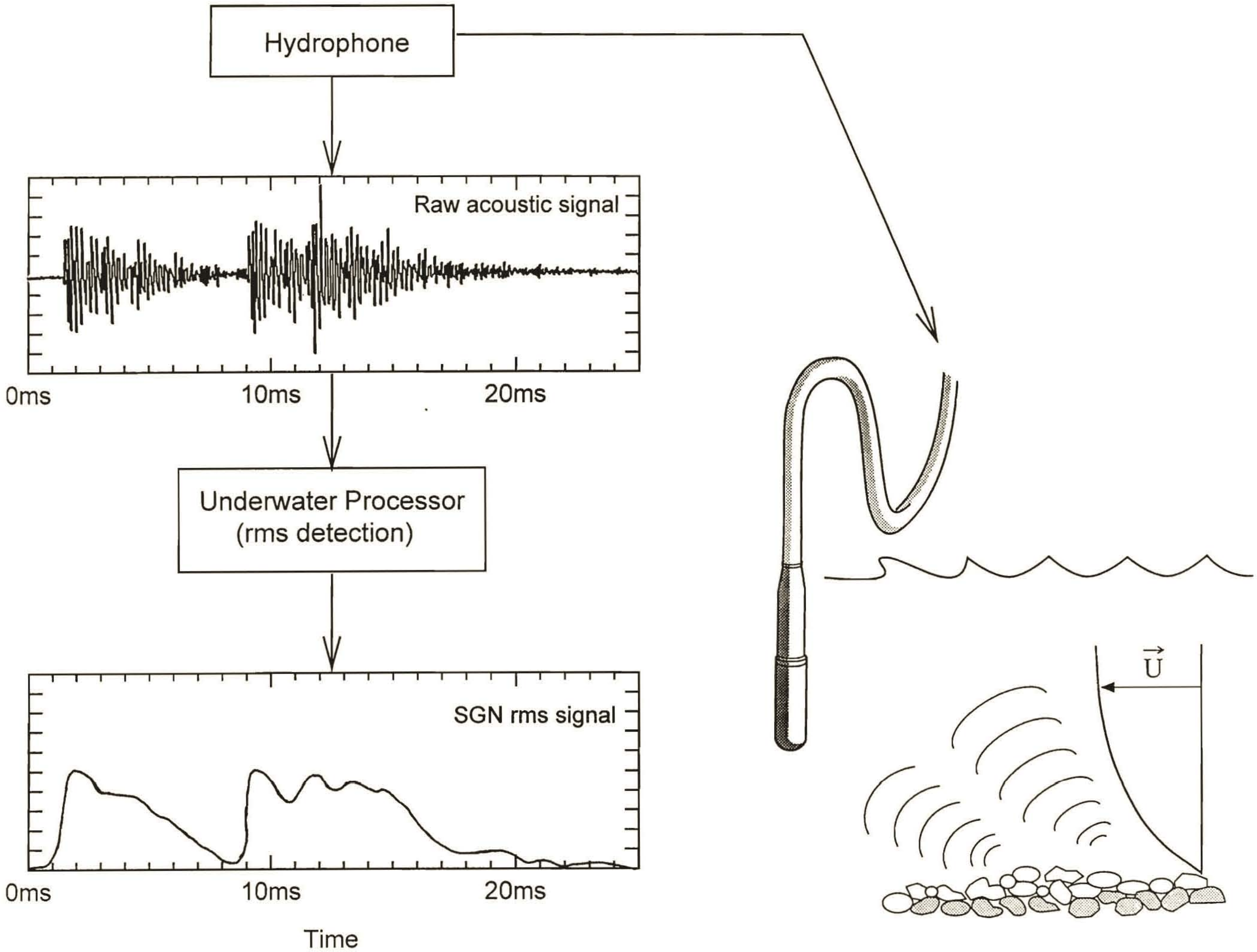

Figure 1. Schematic diagram of the SGN principle and the procedure used for the determination of shingle transport rates (see text).

an rms wave height of 0.54m and peak wave period of 5.45s). As displayed on the instantaneous water depth record (Figure 2c), wave groupiness was present during this particular run. Instantaneous current speed varied around the mean, with the observed variation associated with turbulence (high frequency) and wave-induced flows (low frequency). Correlation between the current speed and water depth time-series reveals that wave-induced velocities under the wave crest coincided with the tidal current direction, enhancing the flow; reduction in the instantaneous speed occurred during the passage of a wave trough. Such wave-induced enhancement of speed and, subsequently, instantaneous shear stress (due to both waves and currents) is reflected in the instantaneous shingle transport rates. The transport peaks under the passage of the wave crests, especially under the highest waves within a group.

Table 1. *Hydrodynamic parameters during Runs C, W and WC: root-mean-square wave height (H_{rms}); peak wave period (T_p); root-mean-square wave orbital velocity (U_{rms}), mean current speed (U_z), measured at 1.23 m above the sea bed; mean immersed weight shingle transport rate (I_b); mean shear stress (τ_c), calculated using the inertia dissipation method; and maximum wave shear stress (τ_w), calculated using Sleath's (1991) model.*

Run	H_{rms} (m)	T_p (s)	U_{rms} (m/s)	U_z (m/s)	I_b (W/m²)	τ_c (N/m²)	τ_w (N/m²)
C	0.07	7.8	0.01	1.08	0.22	3.18	0.09
W	0.38	7.8	0.08	0.04	0.15	0.69	3.29
WC	0.54	5.4	0.14	1.13	0.86	6.02	13.10

On the basis of the hydrodynamic data and shingle transport rates, the *total* shear stress (under the action of waves and currents) is the most important factor controlling shingle transport. To examine flow turbulence over the gravel bed, the turbulence spectra of the downstream horizontal velocities for each one of the time-series presented above (Figure 2) are shown on Figure 3. These data have been constructed invoking the Taylor concept of 'frozen turbulence' and have been used for the estimation of the mean shear stress (τ_c, Table 1), using the inertial dissipation method (HUNTLEY,

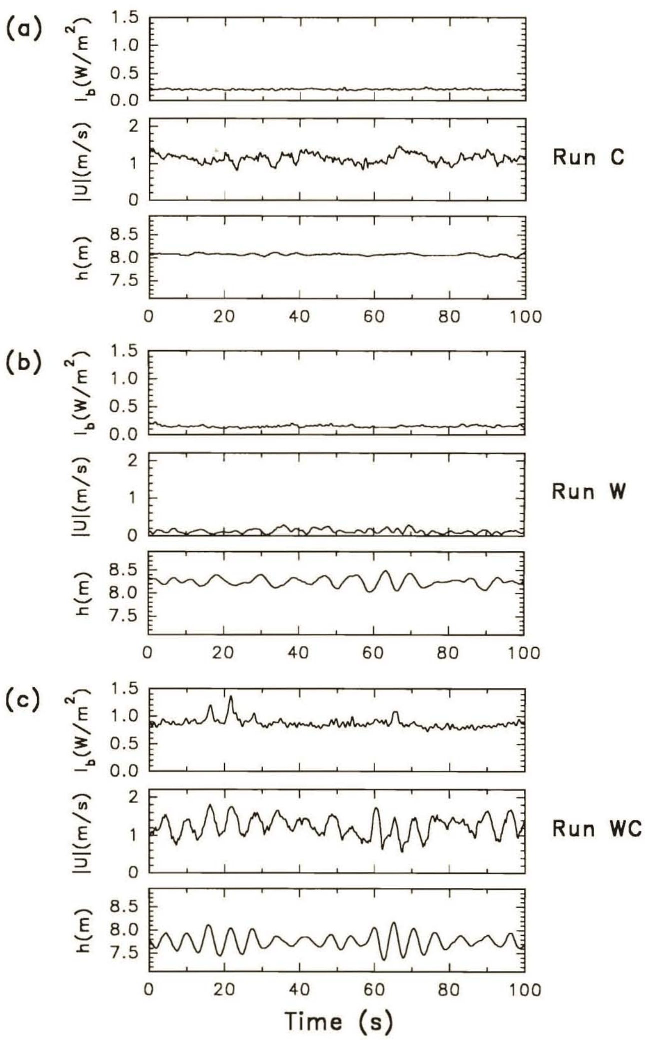

Figure 2. Time-series of instantaneous sea surface elevation (h), current speed (|U|) measured at 1.32m above the sea bed and immersed weight shingle transport rate (I_b), for Runs C, W and WC (see text).

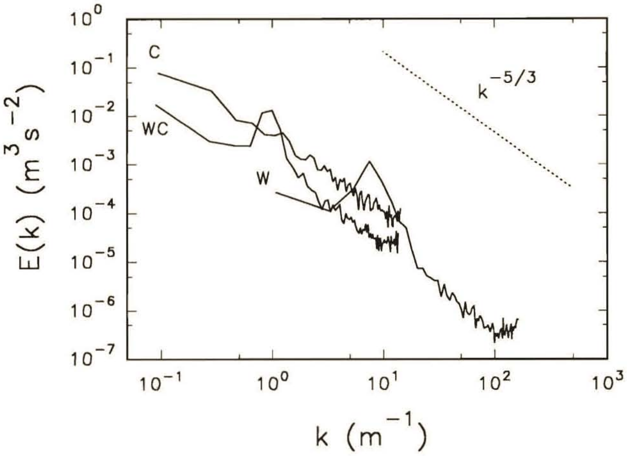

Figure 3. Downstream velocity turbulence spectra derived from the current speed time-series of Runs C, W and WC (see Figure 2).

1988). According to theory, the decay should be represented with a slope $k^{-5/3}$; this appears to be the case for the examples shown. For the run with no waves present (C) the spectra appears to follow the slope, up to very small wave numbers. When waves alone are present (Run W), a peak at wave numbers (k) corresponding to the incident wave frequency is present whilst the energy at all other frequencies, in particular that of the inertial dissipation subrange is less by 3 orders of magnitude. This pattern is expected in the absence of steady current. Finally, the spectra where waves and currents are present (Run WC) shows an energy peak at the wave frequency and high energy at the inertial subrange. Although the mean current speed is similar as that for Run C, the inertial subrange and (subsequently) mean shear stress lay higher. This relationship can be attributed to the presence of waves, which are experienced by the mean current as an additional roughness element (GRANT and MADSEN, 1979).

SHINGLE TRANSPORT IN THE SURF ZONE

Background

The energy flux approach developed for sandy beaches (KOMAR, 1971) has been used also for longshore sediment transport predictions on shingle beaches. This approach relates the longshore component of the immersed weight sediment transport rate (I_l) to the longshore component of the wave power (P_l) and the angle of wave attack (a_b) at the breaking point:

$$I_l = K \cdot P_l \cdot \cos(\alpha_b) \cdot \sin(\alpha_b) \quad (1)$$

This formula has been criticised for being completely empirical and simplifying all the processes taking place (GREER and MADSEN, 1978), but it is used widely. However, emphasis has been placed on defining the constant K, on the basis of results obtained mainly from sediment tracer experiments.

For sandy beaches, K was considered initially to be constant (≃0.29, KOMAR, 1988). However, recent data have revealed that K varies as a function of median particle size (D_{50}) (DE VALLE *et al.*, 1993). The information available for gravel beaches is based upon various experiments (Table 2), as follows: a longshore shingle transport experiment at St Gabriels, Dorset (UK), during storm (K = 0.010) and swell (K = 0.014) wave conditions (BRAY, 1990); an experiment at Chartmouth (K = 0.018, BRAY, 1990); aluminium (tracers) pebbles at Hurst Castle (K = 0.023, NICHOLLS, 1982) and off Hengistbury Head (K = 0.013, WRIGHT, 1982); and sediment traps at Shoreham (K = 0.031, CHADWICK, 1988). KOS'YAN *et al.*, (1994) used long-term bathymetric changes to extract longshore sediment transport in the Black Sea and found K = 0.012. NICHOLLS and WRIGHT (1991), in a tracer experiment examining differential longshore transport of gravel, did not identify any significant variation in K with particle size. BRAY *et al.* (1996) contacted a tracer experiment using both aluminium and electronic tracers identical to those described in this contribution. Their data revealed that K is a function of wave conditions. The averaged values of K obtained were 0.04, 0.20 and 0.36 for low, intermediate and

Table 2. *Experimentally-derived values of coefficient K, for shingle beaches.*

Author	Location	N	Mean K	D_{50} (mm)
present study	Whitstable, UK	2	0.015	22.5
BRAY (1990)	Gabriels, UK (swell)	12	0.014	32.0
BRAY (1990)	Gabriels, UK (storm)	14	0.010	32.0
BRAY (1990)	Chartmouth, UK	8	0.018	32.0
NICHOLLS (1982)	Hurst pit, UK	1	0.023	22.0
WRIGHT (1982)	Hengistbury Head, UK	6	0.013	32.0
CHADWICK (1987)	Shoreham, UK	7	0.031	—
KOS'YAN et al. (1994)	Black Sea	27	0.012	—
BRAY et al. (1996)	Shoreham, UK	4†	0.04	44.9
		2‡	0.20	
		1‡†	0.36	

Note: N is the number of estimates while K represents the mean value from each experiment
† Low wave energy conditions
‡ Intermediate wave energy conditions
‡† High wave energy conditions

high wave energy conditions, respectively. Despite the various methods of investigation, tracer experiments are the main method of calibrating equation (1), deriving values for the coefficient K to be used in sediment budget estimations (see below).

The use of tracers to measure sediment transport on beaches *in-situ* has been used since the 1950's for both sand (INMAN and CHAMBERLAIN, 1959) and shingle material (KIDSON *et al.*, 1958). The method is based upon two assumptions: that the tracer behaves in the same manner as the natural sediment; and that the tracer can be adequately monitored (transport velocity, thickness), ensuring high rates of tracer recovery (VOULGARIS *et al.*, 1998). In such experiments, a recovery rate between 70 and 100% is usually considered good, whilst recovery rates between 50 and 70% are adequate (INMAN *et al.*, 1980; KRAUS *et al.*, 1982). Results from experiments with recovery rate below 50% are questionable, whilst rates below 25% suggest that most of the tracer has not been detected. These latter results are not adequate for the calculation of sediment transport rates.

Traditional tracers in shingle movement studies include: the addition of "foreign" material (CARR, 1971; VAN DER POST *et al.*, 1994); the labelling of indigenous beach material using paints, resin tagging and etching (KIDSON and CARR, 1961; 1962); the use of fluorescent dyes (REID and JOLLIFFE, 1961; VOULGARIS *et al.*, 1998); and the radioactive labelling of indigenous material (KIDSON *et al.*, 1958). The development of aluminium pebbles (WRIGHT *et al.*, 1978) reduced the limitations in the use of some of these techniques, but "litter" contamination has demonstrated the need for an alternative technique that allows rapid coverage of the study area, low labour requirements and high tracer recoveries. DYER and DOREY (1973) realising the above limitations, suggested the implementation of acoustic transponders to simulate gravel size particles which were tracked using sonar mapping techniques. They used a 47KHz transponder but the main limitation of the system was interrogation of several acoustic pebbles at the same time, limited size (transducers were 3.2cm in diameter) and density. A new electronically-active pebble has been developed which overcomes the disadvantages of previous tracing methods, permitting the accurate derivation of shingle transport rates.

Methodology

Transmitting Pebble

The electronic pebble system was designed on the basis of: (i) accurate reproduction of physical characteristics of the indigenous material; (ii) monitoring the burial depths of the tracers; and (iii) being unobstructive and not of any health risk. The system developed consists of the tracers and a detection unit (Plates 1 and 2).

The tracers utilise a radio frequency identification technique, by which low frequency radio waves are used to generate pulses of a magnetic field. Different combinations of pulses are used as individual tracer identification. Modern surface-mount technology (SMT) and integrated circuits were used for the construction of the electronic system (Plate 1). The magnetic field is generated by a current passing through a coil encapsulated within the pebble; this is sensed by a detector, which consists of a coil. The signal is amplified, then converted into an audio signal which is used for identification of the individual tracers. Initially a one coil detector was constructed (Plate 2a) but, in order to increase the area of coverage, a new 3-coil detector was developed (Plate 2b). A technical description of the transmitter and detector systems can be found in WORKMAN *et al.*, 1994. The system was developed originally to detect depths of burial down to 1m, but environmental noise appears to limit this to 70cm.

The construction of the transmitting pebbles consists of: (i) collecting a population of indigenous material for casting, by covering the natural particles with latex resin; and (ii) placing the electronic circuit, with a characteristic identification signal, in the interior of the cast. The latter is filled with a mixture of 25% epoxy resin and 75% mineral oxides, to achieve a specific gravity similar of that of the natural material. Corrasion and corrosion tests of the tracers, undertaken over 14 days, showed that weight loss was less than 2%.

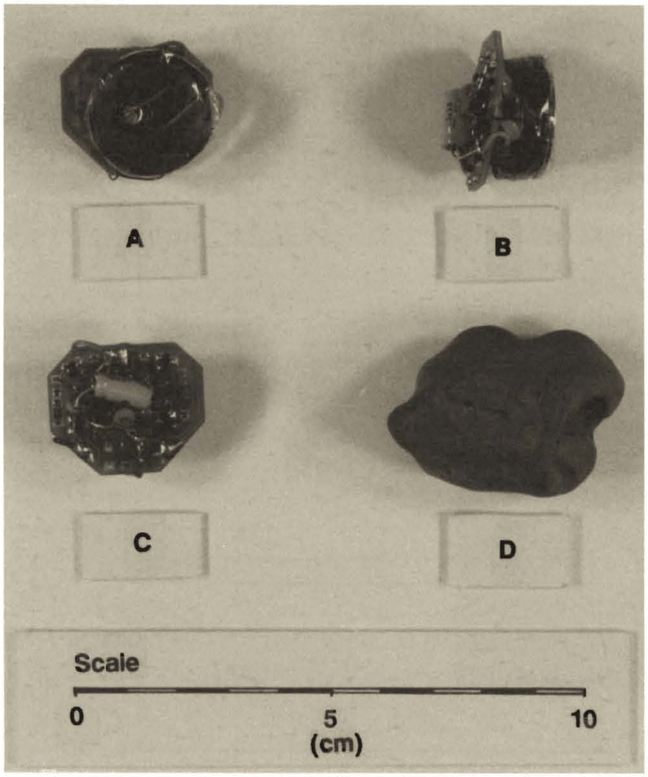

Plate 1. (a) Electronic circuit (A,B,C) used for the manufacturing of the "transmitting pebble" (D).

Experimental Procedure

A field trial was undertaken, between 23rd and 26th January 1993 at Whitstable on the north Kent coastline (outer Thames estuary, U.K). The beach is groyned and backed by a seawall; it is composed of shingle, with a mean grain size of 2.5 to 3.5cm and a slope of 1:10. Fine to coarse grained sand occurs on the foreshore, with a slope of 1:100.

The spring tidal range for the area is >4m. The region is subjected to tidal surges, which are generated mainly by the north-easterly movement of deep depressions between Scotland and Iceland (SUMMERS, 1978). The winds can range from easterly to westerly without any really dominant direction. Nevertheless, combining wind climate and duration with fetch demonstrates that the dominant waves approach from the northeast, along an west-east trending coastline.

Wave Measurements

Wave conditions during the experimental period were measured using a pressure transducer. Instantaneous wave pressure was recorded for 15min, with a sampling frequency of 5Hz, at every hour and different stages of the tide. The instrument was located some 69m from the seawall, being underwater for 5 to 6 hours per tidal cycle. Spectral analysis was used for the derivation of the wave height (H_{rms}) and the peak period (T_p); these were used for the estimation of the wave power (eqn (1)). The angle of wave approach was based upon visual observations.

Sediment Transport Rate Derivation

Seventeen electronic pebbles were used in the experiment, in conjunction with 70 aluminium pebbles for comparison purposes. The tracers were located along a line perpendicular to the coast; their movement was monitored over 7 tidal cycles. Recovery rates were 82% for the electronic pebbles and 41% for the aluminium pebbles. The higher recovery rate is attributed to the system's ability to detect tracers up to a greater depth than for the aluminium tracers *i.e* 70cm compared with 45cm. Individual tracers were identified at each low water, every 6 hours, with their position being recorded using a standard theodolite (total station) system. Each tracer pebble is characterised by a vector, (x_i, y_i, z_i), where the subscript it denotes the identity of the tracer, x,y the horizontal coordinates and z the depth at which the tracer was identified. The movement of the centroid between successive surveys provides the transport velocity (U_S) which, for the longshore direction, is defined as:

$$U_{s_x}(t) = \frac{\sum_{i=1}^{N} \frac{x_i - x_o}{t}}{N} \quad (2)$$

where t is the time and N is the number of tracers moved between successive surveys.

The width of the mobile layer (X_O) at each low tide was assumed to be the maximum cross-shore distance the pebbles had been dispersed and moved, since the last tracer survey. The depth of disturbance (Z_O) was defined at each survey as:

$$Z_o = \frac{1}{2} \cdot (Z_1 + Z_2) \quad (3)$$

where Z_1 and Z_2 are the average depth of burial of the tracers being moved and those identified as not being moved since the last survey, respectively.

On the basis of the above definitions, the immersed weight sediment transport rate was calculated (KOMAR and INMAN, 1970):

$$I_l = (\rho_s - \rho) \cdot g \cdot c_b \cdot U_{s_x} \cdot X_o \cdot Z_o \quad (4)$$

where ρ_S and ρ are the solid and sea water density, respectively, and c_b is a factor accounting for porosity (taken as 0.6).

Results

During deployment only mild wave conditions prevailed, with heights of 0.15 to 0.35m, (Figure 4a). Waves were approaching almost normal to the beach during the tracer deployment (I + 0, Figure 4b); During the next tide (I + 1), the waves were approaching from the east. For the remainder of the experimental period wave approach was approximately 10 to 20 deg to the coastline *i.e* from the northwest.

The tidal ranges during the experimental period varied between 4 and 4.5m, except for the tide I + 5 (Figure 4c) with a measured tidal range in excess of 5.5m. This latter observation was in response to a storm surge.

The results of the tracer experiment are summarised on

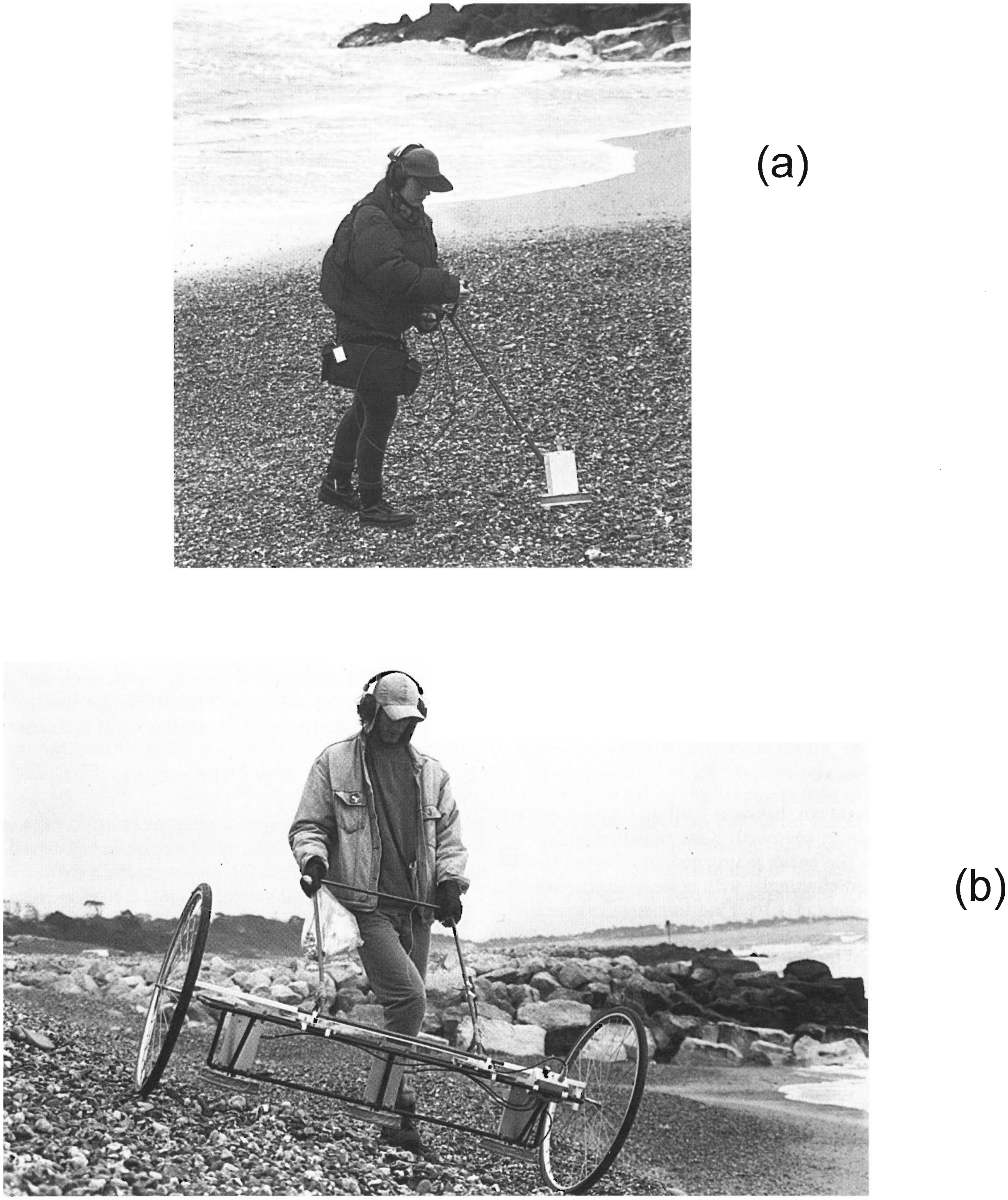

Plate 2. One coil (a) and 3-coil (b) detectors used for the recovery of the transmitting pebble tracers.

Figures 4d, e and f where it can be seen that the width of the mobile layer varied between 15 and 25m; and the depth of disturbance was 10 to 15cm. The depth of disturbance (Fig. 4e) appears to increase with increasing wave height (Fig. 4a) and angle of wave approach (Fig. 4b). Finally, immersed shingle transport rates have been estimated using equation (4) (Figure 4f).

The movement of the centroid of the tracer is shown on

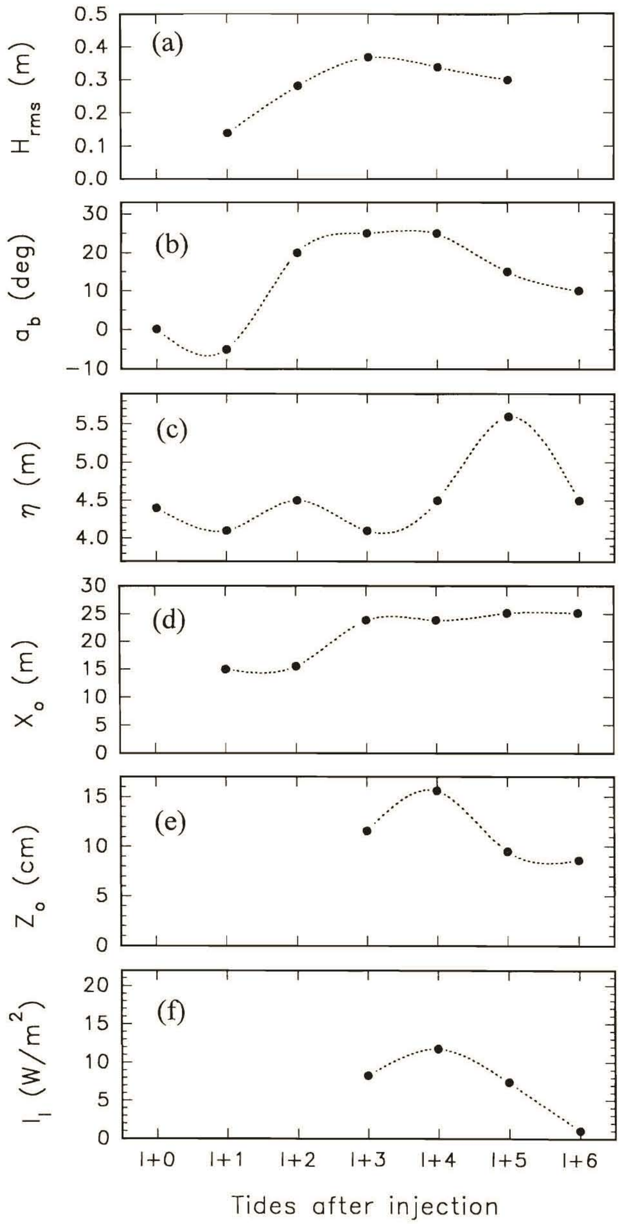

Figure 4. Tidally-averaged hydrodynamic conditions and results from the tracer experiment: (a) root-mean-square wave height, H_{rms}; (b) wave angle of approach, α_b; and (c) tidal range, η; (d) width of mobile layer, X_o; (e) thickness of mobile layer, Z_o; and (f) longshore immersed weight shingle transport rate (I_l) derived using equation (4).

Figure 5, where there is a general trend towards the east. In contrast to the wave angle of approach (15° from the northwest) during the 1 + 5 survey, the tracer moved in the opposite direction (westwards). At this time storm surge and tidal currents appear to have dominated the transport processes.

The initial rapid movement of the centroid, coinciding with mild hydrodynamic conditions may reflect the fact that the tracers had not been mixed fully with the indigenous mate-

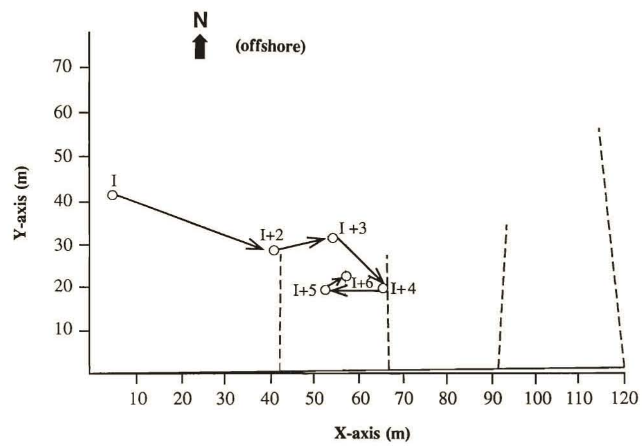

Figure 5. Tracer centroid movement during the experimental period (for details see text).

rial. However, after I + 3, the rate of movement is sufficiently consistent to indicate good mixing and adequate representation of natural shingle movement. For these reasons, only the data relating to tidal cycles I + 3 to I + 4 are used in the derivation of the coefficient K (Note: I + 6 survey has not been used due to unreliable wave data, whilst I + 5 survey has been dominated by storm surge processes). On the basis of this analysis, two values for K were obtained, 0.012 and 0.018. A mean value of 0.015 compares reasonably well with the value estimated by KOS'YAN *et al.* (1994), for an artificial gravel beach where K was found to be 0.012. The K value derived from the present study is compared with values derived from other experiments by other authors in Table 2.

CONCLUDING REMARKS

New techniques have been presented for the study of the shingle transport in the shallow offshore and nearshore zones.

The SGN acoustic technique has been developed for the study of the instantaneous monitoring of shingle transport, under the combined action of waves and currents. A combination of SGN and high frequency current time-series provide information on processes affecting shingle movement and, in particular, the enhancing role of wave action. The data presented suggest that shingle transport formulae for offshore applications should be based upon shear stress and not solely upon flow velocity. The transport formulae derived for rivers could be used in the marine environment, if they integrate the instantaneous wave-induced shear stress variations associated with wave orbital velocities. Such a formula could be of the form:

$$\vec{I}_{bwc} = \frac{1}{T}\int_{t=0}^{t=T} I_b(|\tau_{wc}(t)|, \tau_{cr}) \cdot \frac{\vec{\tau}_{wc}(t)}{|\tau_{wc}(t)|}\, dt \qquad (5)$$

where I_{bwc} is immersed weight shingle transport rate integrated over a wave cycle, $I_b(\tau,\tau_{cr})$ is the formula derived from riverine research (given as a function of bottom shear stress τ, and critical shear stress τ_{cr}, for initiation of particle move-

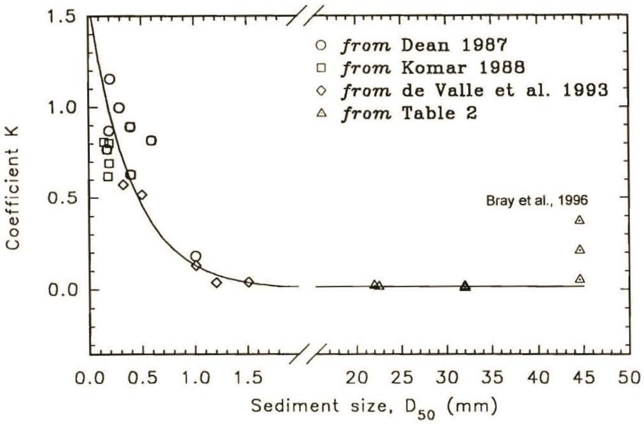

Figure 6. Variation in the coefficient K (for use in eqn (1), see text) with particle size (D_{50}) for sediment ranging from fine sands to gravels (BRAY'S *et al.* (1996) data are excluded from the analysis for the reasons explained in the text).

ment) and τ_{wc} (t) is the instantaneous total (wave and current) shear stress (estimated by applying a wave/current interaction model).

A "transmitting pebble" has been developed as a tracer for use on beaches. This novel system ensures high recovery rates, combined with easy deployment and detection procedures. Preliminary results obtained using the method agree reasonably well with these of previous experiments, comparable coefficient (K) values are statistically more significant since, they have been derived from experiments with higher recovery rates. An exception to this agreement is the results of BRAY *et al.* (1996). Their findings suggest a much higher value of K even under low wave energy conditions. The more energetic the wave conditions the higher the value of K that was obtained. This disagreement can be attributed to a number of factors. The most important appears to be the fact that the tracers used were of larger diameter than the indigenous population (BRAY *et al.*, 1996). Thus, protrusion of the tracer particles will inevitable lead to higher transport rates compared with the non protruding indigenous particles. In addition, the results for high energy conditions were obtained at the beginning of the tracer experiment where the tracer is not mixed fully with the beach material. In our experiment, the centroid movement was much faster at the initial stages and not consistent with the movement observed at subsequent tidal stages. This is an indication of inadequate mixing and thus the initial data were excluded from our analysis.

The data derived from the present study have been combined with those of other authors (Table 2), to extend the K relationship with D_{50}, presented originally for sand alone (DE VALLE *et al.*, 1993) (Figure 6). According to this analysis (excluding BRAY'S *et al.* (1996) data for the reason explained above) K for any sediment budget analysis can be selected on the basis of:

$$K = 1.6 \cdot e^{-2.5 \cdot D_{50}} \quad \text{for } D_{50} \leq 2 \text{ mm}$$
$$K = 0.017 \quad \text{for } D_{50} > 2 \text{ mm}. \qquad (6)$$

Despite the encouraging results obtained here, more research is required using a greater number of tracers to obtain statistically-significant data sets. In addition, to developing reliable tracing material and detecting methods particular emphasis should be placed on defining the width and depth of the moving layer, parameters of great importance for the determination of K. Also, transmitting pebbles should be developed for offshore areas for integration with the SGN method attempting integration of micro- and meso-scale shingle transport measurements.

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