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THE STABILITY OF THE TOP METRE OF THE SEA BED

ITS IMPORTANCE TO ENGINEERING AND NAVIGATIONAL PROJECTS

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ABSTRACT

Consideration is given to the importance of knowledge about the stability of the top metre of the sea bed. In this context the results of a research programme which studied the movement of the crest of a sandwave in relation to tide and surface wave conditions are presented.

INTRODUCTION

With the closure of the Suez canal in 1967, the main European oil supplies from the Persian Gulf had to be transported around the Cape. This had two major effects; firstly, it increased the travel distance and, secondly, it transferred the limiting navigational depth from the Suez Canal to the European port approaches and terminal facilities. The increase in travel distance, when equated with the economics of bulk transport, led to a rapid escalation in the size of tankers which in turn put further pressure upon the ports. For these reasons, it became necessary for each of the major oil ports to critically examine its draught limitations and in many cases carry out extensive engineering work (eg. Europort and Milford Haven).

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The limiting depth for a port is dependent upon the following factors :

(a) The draught of the vessel, including squat at different speeds in restrictive channels.

(b) The accuracy of the surveys of the critical areas. This includes the accuracy of depth measurement which may be affected by ship motion, tidal reduction and variability of depth between survey lines.

(c) Meteorological conditions and their effect on tidal heights.

(d) Temporal variability of the sea bed as a response to tides and surface waves.

It is the confidence in this knowledge which determines the necessary under-keel clearance, and hence draught, of the vessel which may use the port. (LANGHORNE, 1978). In the case of the Port of London, it is now not uncommon for deep-draught tankers to enter the port with one metre under-keel clearance. Similarly, knowledge of the temporal variability of the sea bed is vital for planning pipeline routes and for the effective burial of pipelines to the regulated depth of one metre. Pipe burial adds considerable cost to pipe laying operations and this expenditure can only be justified if there is some expectation that the objective will be achieved.

Much of the N.W. European Continental Shelf may be characterised by strong tidal flow, significant wave effect on the sea bed owing to shallow water, and large areas of potentially mobile sediments. Combinations of these conditions result in extensive areas of hydrodynamic bedforms and, in particular, sandwaves. Sandwave fields are of importance to navigation in the Dover Strait and the southern North Sea, and outer approaches to the Thames Estuary, and in the Bristol Channel. Because they are considered to occur in areas where the sea bed is particularly instable, they are also important for pipeline routing.

Since the pioneering studies of Van VEEN (1935) when the echo sounder was first introduced, much survey work has been carried out on sandwaves. In many areas their distributions have been mapped, and by inference from their asymmetry, conclusions have been drawn on the directions of net sediment transport. Recent work by CLOET (1976) has shown the variability in height which might be expected to occur along a sandwave crestline, and therefore the dangers of accepting minimum depths from a survey which uses a particular line spacing. An example of this variability in form for sandwaves in Start Bay, Devon, U.K., is shown in Figure 1. Less is known about the movement of sandwaves, or the temporal changes in their shapes and heights, despite their importance to many navigational and engineering projects.

This paper presents the results of a research programme which was conducted to study the movement of a sandwave in relation to the hydrodynamic conditions. Extensive measurements were made by divers, using sea bed reference stakes, to examine the change in shape of the bedform. The method overcame many of the problems of accuracy and repeatibility which are encountered using shipborne survey techniques (LANGERAAR, 1966).

LOCATION

The research programme was conducted in the sandwave field which occurs associated with the Skerries Bank in Start Bay (Fig. 2). Within this study, detailed measurements were made of the movement of the crest of one particular sandwave with a wave height of approximately 3.5 m and wave length of 180 m. (Position : 50° 15′ 12″ N, 03° 36′ 15″ W). Echo sounding and sidescan sonar showed that the sandwave was one of a train, with comparative straight and uniform spacing, which occurred in a water depth of approximately 10 m (Fig. 3). It was asymmetrical in cross sectional profile with its steeper slope facing south which is the direction of the tidal flow residual (ACTON and DYER, 1975). The sand in the crestal area had a median diameter of 0.32 mm (standard deviation = 0.10 mm).

The study area was approximately 4 km north east of Start Point, and in this position was partially protected from the prevailing south westerly winds. Storm waves, generated by south westerly gales, are refracted around Start Point to reach the area, but with loss of amplitude. The waves which have the greatest effect on the sea bed in the study area are those which approach from the east and south east. From these directions, where the surface wave fetch is up to 300 nautical miles, the incidence of storm waves is relatively small.

METHOD

At the beginning of the research programme, a line of mild steel reference stakes (2 m long, 0.013 m diameter) were hammered into the sea bed by divers at 50 cm intervals, crossing the crest at right angles (Fig. 3b). The top of each stake was levelled with reference to its neighbours. Because it was feared that the stakes might become dislodged by excessive erosion, the tops of the stakes were also levelled with reference to a nearby 350 kg sinker module, which effectively acted as a local bench mark. Once the stake line had been set up and levelled, the cross sectional profile of the crest of the sandwave, and changes in that profile, could be obtained by measuring the length of exposed stakes.

During the study, wave data was recorded in the area. Initially the data was obtained from a F.M. Pressure transducer system located off the shore at Hallsands (Fig. 2), and later from a Waverider buoy deployed 2.3 km to the north east of the research area. For the final part of the study, boundary layer flow measurements were made, using bottom mounted flow sensors, positioned at the crest of the sandwave.

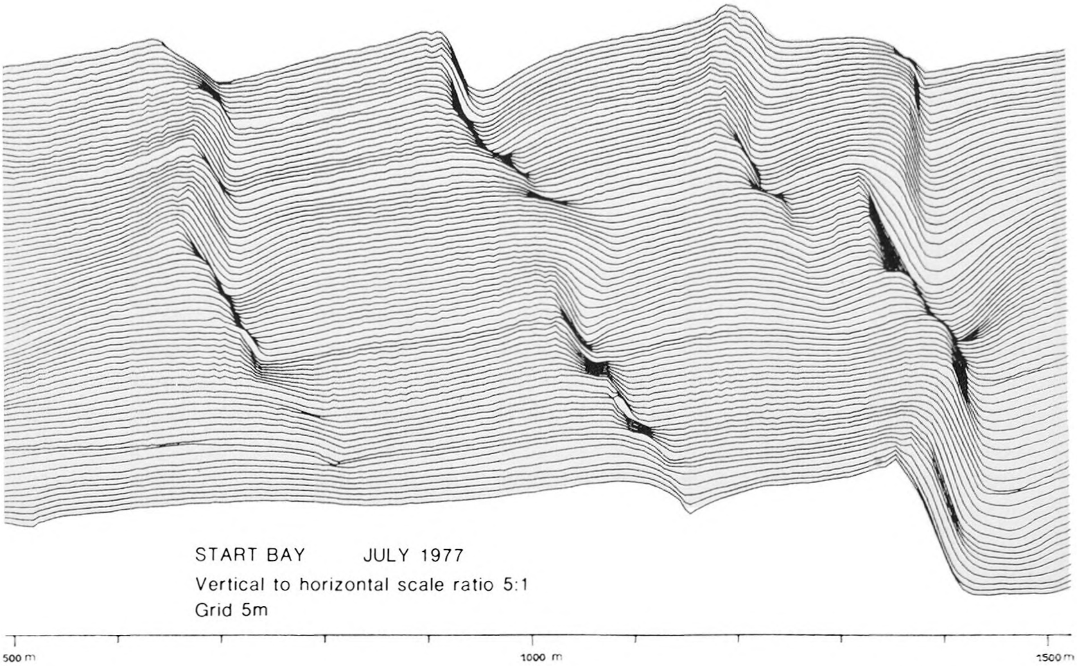

FIG. 1. – An example of the variability in sandwave morphology in Start Bay, Devon (Data analysis by R.L. CLOET, University of Bath).

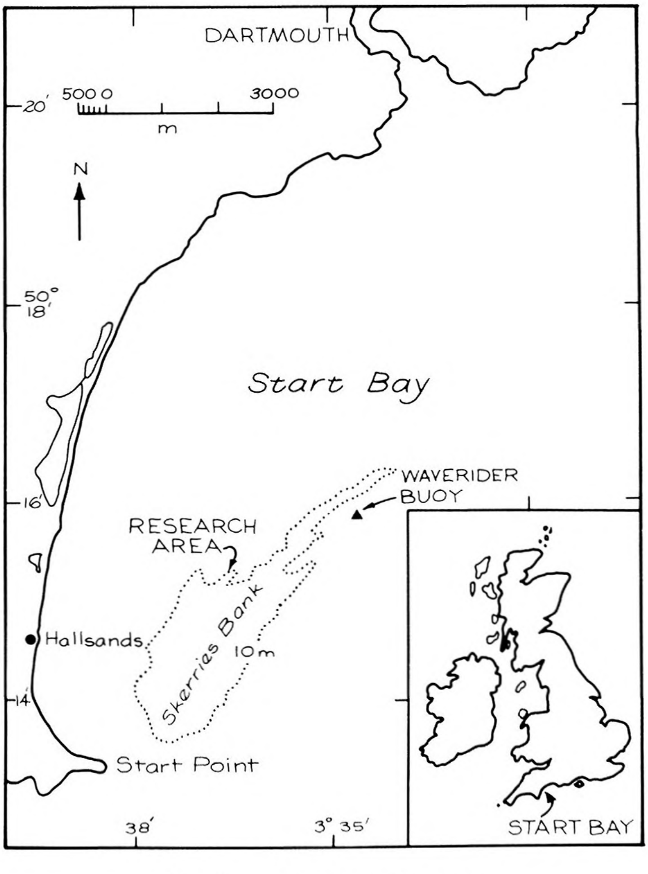

FIG. 2. – Location diagram.

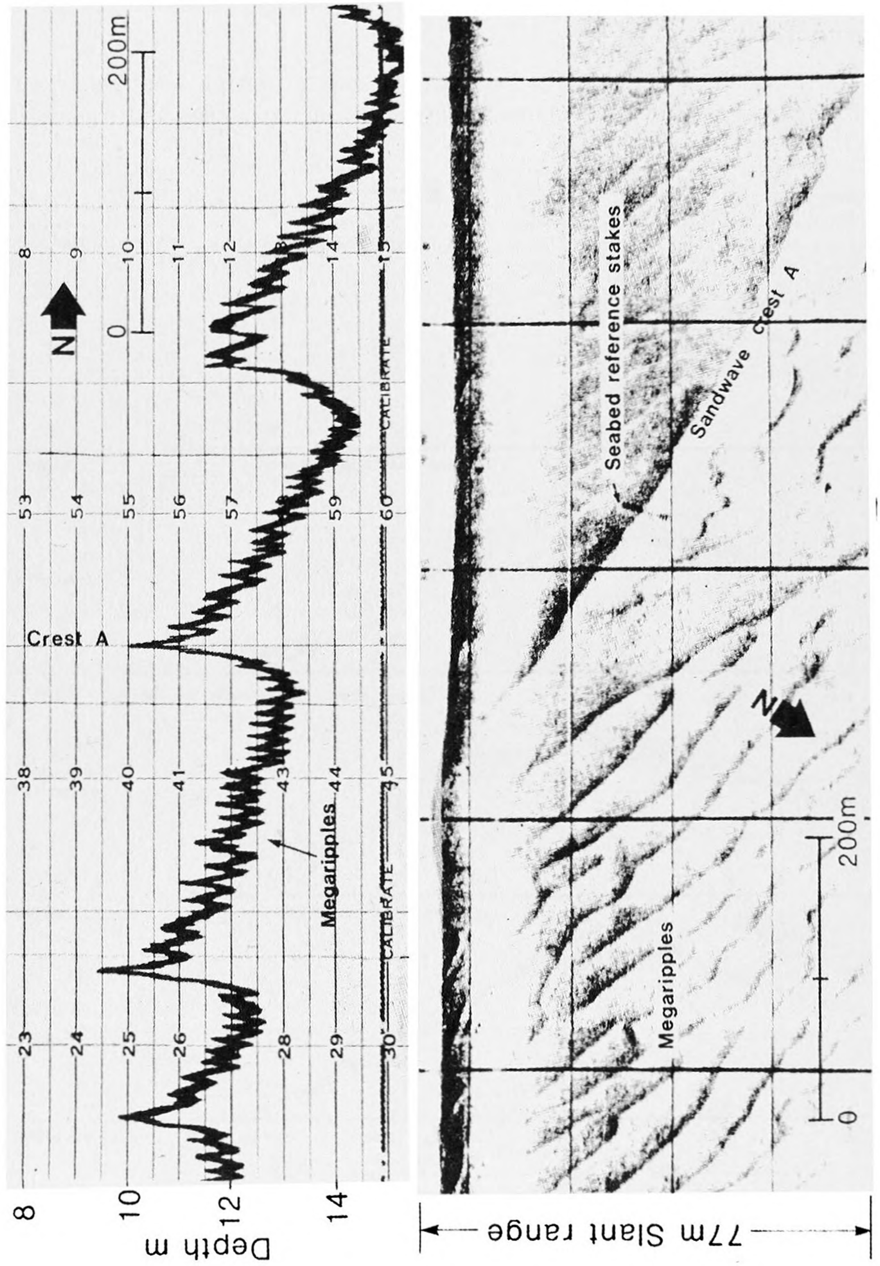

FIG. 3. – Echo sounder and sidescan sonar records obtained in the research area.

RESULTS

A) Preliminary results in relation to Spring and Neap tides

Preliminary studies of the longer term mobility of the selected sandwave were conducted over the period July 1977 to January 1978, using a line of up to 24 sea bed reference stakes.

The first results were obtained between 2-4 July at Spring tides (tidal range 4.7 to 5.0 m). Figure 4A shows the marked consistency of movement and reformation of

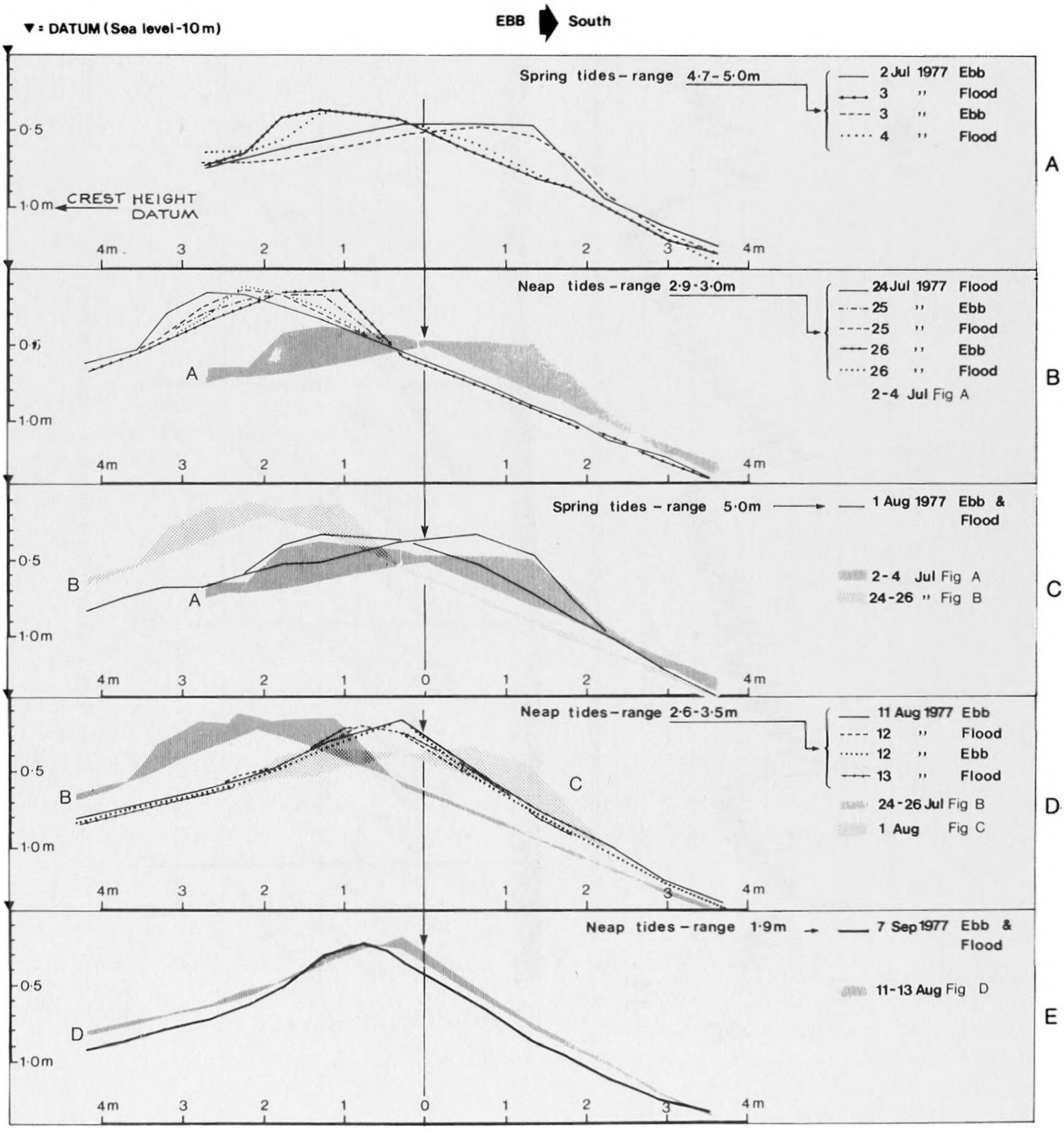

FIG. 4. – Sandwave crest profiles related to Spring and Neap tides.

the crest after flood and ebb tides. In each case, the maximum measured height was consistent to 1 cm, with the heights at the end of the ebb being 10 cm lower than those at the end of flood tides. The crest position oscillated over a distance of approximately 3.5 m and recorded sediment mobility occurred to a depth of 33 cm.

A second series of measurements were made at a time near to Neap tides three weeks later (Fig. 4B). These showed a similar consistency of movement, but with a reduced oscillation. By comparison with the results obtained at Spring tides, the crest height had increased by 25 cm and had been displaced northwards by approximately 1.9 m. For the crest to obtain this new position, the recorded depth of erosion reached 43 cm and accretion 58 cm.

Further measurements were made on the following Spring tides (1st August) (Fig. 4C). This data showed that the crest had returned to the same position as that for the Spring tides one month earlier. The amplitude of the flood to ebb crestal oscillations was approximately the same, but the maximum measured crestal height was 5 cm higher than previously observed.

Additional results were obtained on 11-12 August (tidal range 2.6-3.5 m) and 7 September (tidal range 1.9 m) (Figs. 4D and 4E). With the greater tidal range, the crest position oscillated over a distance of 70 cm, in an intermediate position between those of previous occasions. On the latter occasion, with a tidal range of 1.9 m, the maximum measured change in sediment level, over the 5 1/2 hour tidal period, was only 2 cm. This indicated that very little sediment transport had occurred and that the flow velocities were close to the threshold for the movement of 0.32 mm grain sized sand.

Wave data showed that, during the periods of measurement discussed above, the prevailing wave conditions had little effect on the sea bed. In all cases the calculated significant wave height was less than 0.5 m. According to the threshold criteria of KOMAR and MILLER (1975) such waves, with periods of between 4 and 10 seconds, do not generate orbital velocities at a depth of 10 m which are above the threshold for the movement of the *in situ* sediments.

B) Crest movement associated with tides and surface waves

The observations were continued into the autumn and winter, using the same line of reference stakes, in order to study the dynamic trends associated with storm-generated wave conditions.

On 15-16 September four sets of measurements were made at Spring tides. These data were similar to those obtained on the previous Spring tides in terms of crestal height, flood/ebb crestal oscillation and depth of mobile sediment (figure 5 F). However, in contrast with the previous results, the axis of the oscillation of the crest had moved approximately 80 cm to the south. Prior to these observations there had been no evidence of net movement in the direction of the steeper facing slope. It was therefore considered that this movement may have been associated with the predominance of north-easterly winds which occurred during the preceding four days.

Further observations were not possible over the following three days on account of adverse sea conditions. Continuing north-easterly winds of up to 15 knots

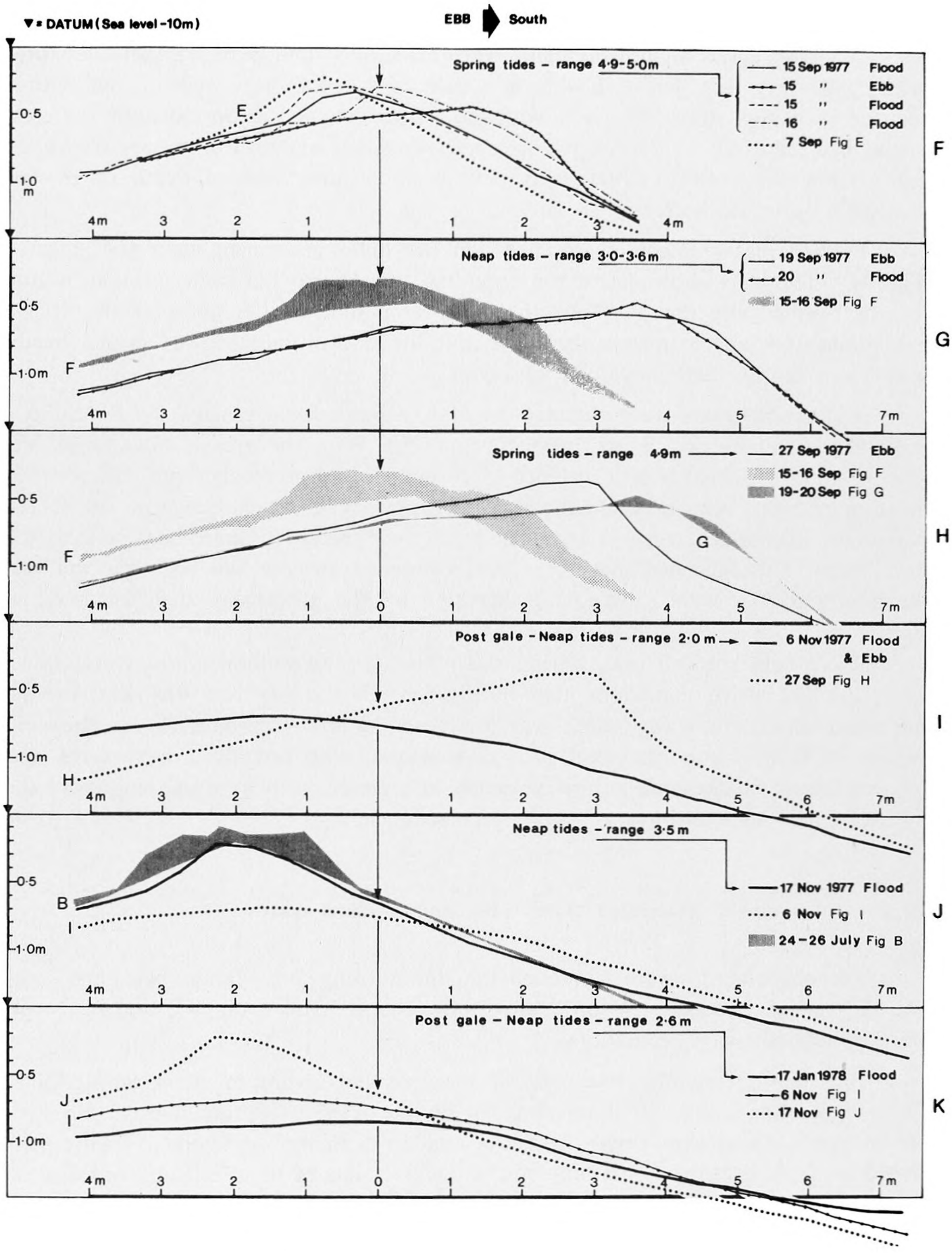

FIG. 5. – Sandwave crest profiles related to tides and surface waves.

generated waves with significant wave heights of up to 2 m and heights in excess of 1 m for 100 hours (figure 6). Such wave heights, with zero crossing wave periods of 5.5 sec, generate orbital velocities of 52 and 26 cm s^{-1} respectively at 10 m water depth.

The effect of these conditions, with associated wind stress, were observed when sea conditions moderated on 19 and 20 September (figure 5 G). The axis of the flood/ebb crestal oscillation had moved 3.5 m to the south with maximum measured erosion reaching 39 cm and deposition of 81 cm. Further measurements were made on 27 September from which it was apparent that a partial recovery of the crest position had occurred (figure 5 H). Meteorological and wave data showed that in the intervening period south-easterly winds of up to 15 knots and waves with heights of up to 3 m occurred, which probably contributed to the northerly movement of the bedform.

No further data was obtained until 6 November (figure 5I). This followed an extended period of adverse weather during which the significant wave height was in excess of 1 m for 50% of the preceding 7 days (figure 6). The results showed a considerable reduction in the sandwave profile and the loss of a defined crest position. Sediment erosion to a depth of 70 cm had occurred in comparison with the last recorded data. Adverse sea conditions, associated with winds of up to 37 knots, prevailed for the following 8 days and the next measurements were not made until 17 November at Neap tides. These observations were carried out 2 1/2 days after the sea conditions had moderated and, unexpectedly, the measurements showed a complete restoration to the Neap tidal bedform, in terms of both position and height as observed in July (cf. : figures 4 B and 5 J).

A final set of measurements were obtained on 17 January 1978. This occasion again followed an extended period of adverse weather and the data showed a reduction of crestal profile and loss of a defined crest position (figure 5 K). No wave data was recorded. Comparison of the 17 January data with that of 6 November shows that, over the 12 m of sandwave profile which was monitored, a relatively consistent post-storm profile was formed.

Shortly after these measurements, illegal trawling activities destroyed the line of reference stakes and the sequence of observations had to be terminated. During February 1978, exceptionally severe storm conditions occurred which generated significant wave heights of up to 7 m with zero crossing wave periods of 9 seconds. Though no measurements were possible, diver's inspection after the storm confirmed that the basic form of the sandwave still existed, but with a greatly reduced profile.

C) Crest movement in relation to a Neap-to-Spring-to-Neap tidal period

Over the period 31 August to 13 September 1979 a series of profiles were obtained from a new line of 31 sea bed reference stakes. The line, which again used a 0.5 m stake spacing, was set up on the same sandwave but not in the same position along the crest-line. The observations covered a Neap (tidal range 2.3 m) to Spring (tidal range 5.8 m) to Neap (tidal range 3.2 m) tidal period during which the tidal height reached the highest predicted level for the year. During the study, two self-recording current meters were positioned on the crest of the sandwave with the

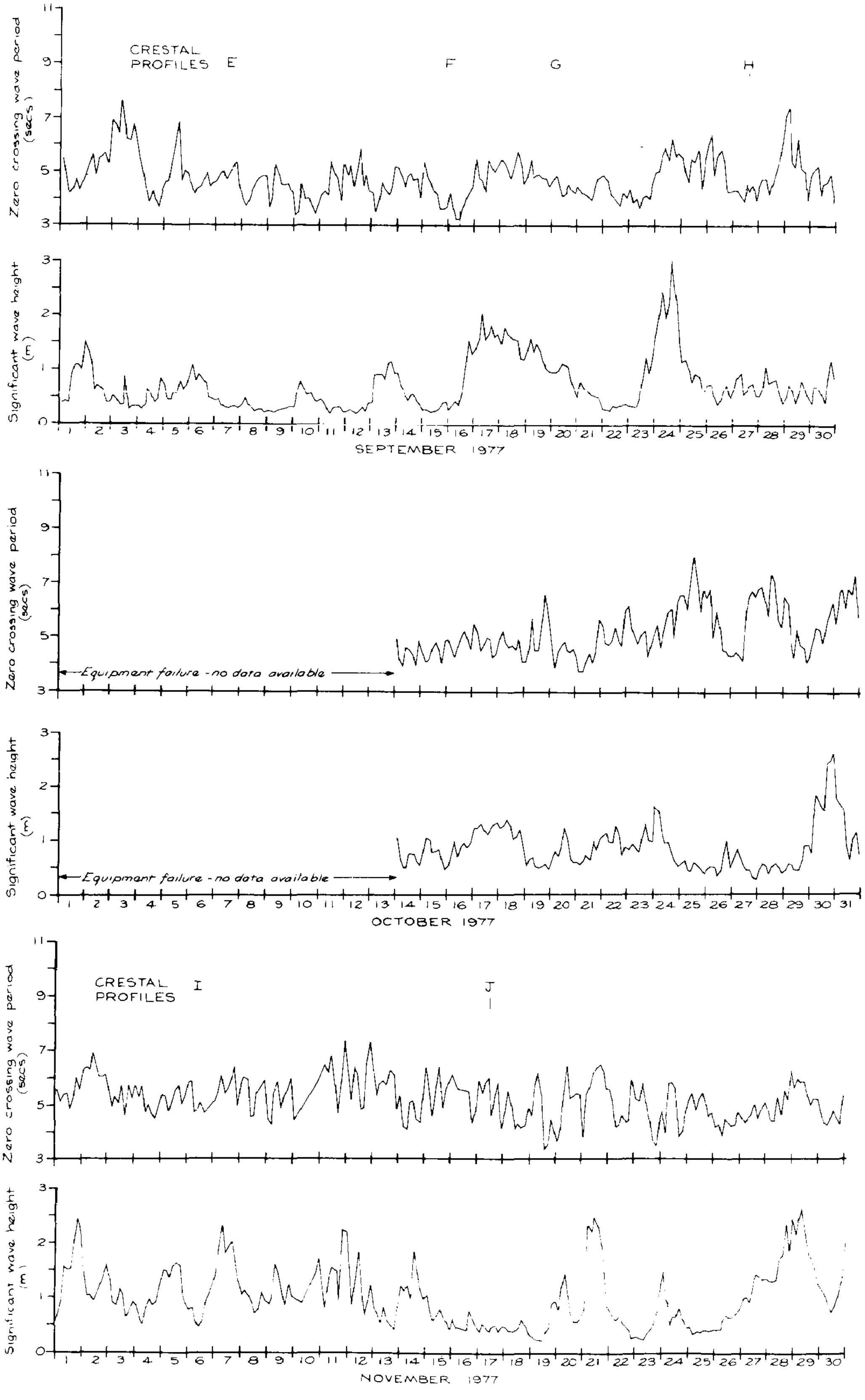

FIG. 6. – Wave data.

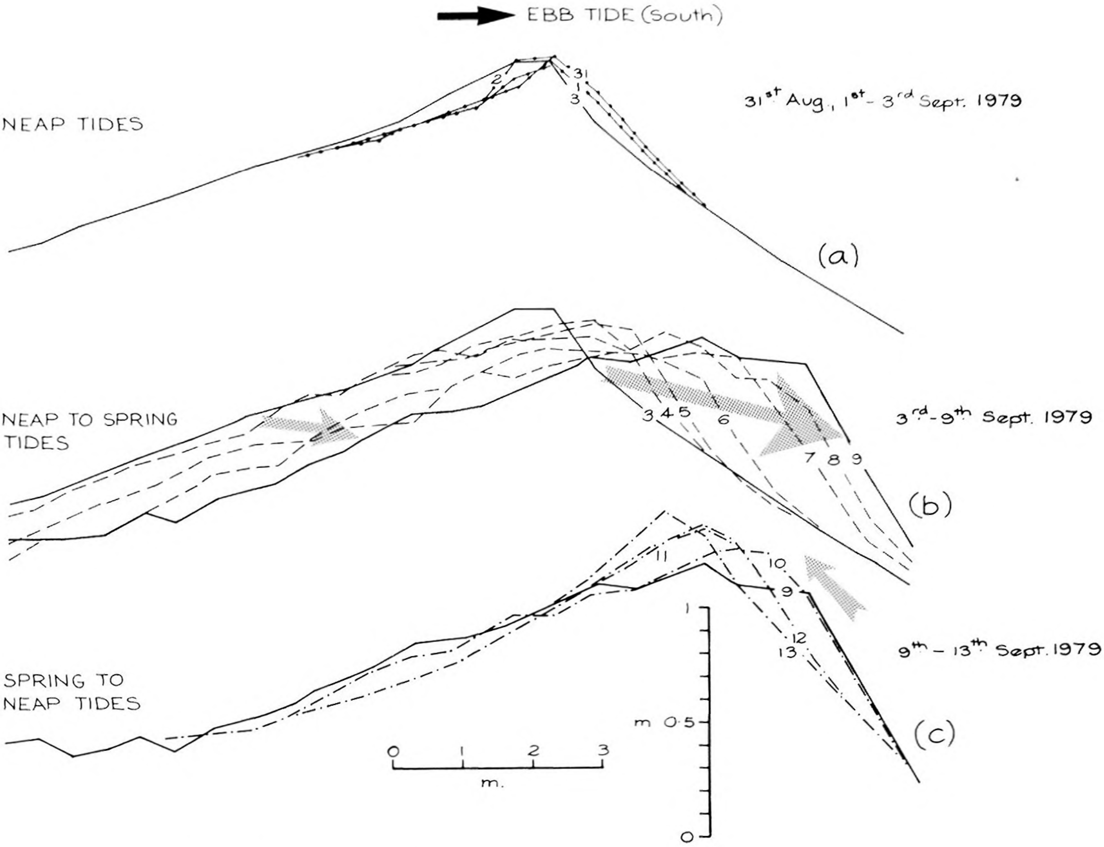

FIG. 7. – Crest profiles measured at the end of ebb tides, September 1979.

flow sensors set at one metre above the crest. At Neap tides at the beginning of the series of observations, measurements were made once a day, but when significant bedform changes were becoming apparent, two or three sets of measurements were made at successive slack water periods.

For the first three days, when the tidal range was less than 2.6 m, little appreciable bedform change occurred (figure 7 a). At higher ranges, when the threshold velocity for the movement of sand was appreciably exceeded, sediment was transported up each flank of the sandwave by successive flood and ebb tides and deposition occurred downstream from the crest (figure 7 b). The newly deposited sediment was not distributed uniformly over the downstream slope but accumulated in the lee of the crest. It could be distinguished from the in situ sediments by a break in slope at the base of the new deposit. Above the break in slope, slope angles tended towards the maximum angle of repose of sand in water, and indeed at Spring tides slope angles of up to 30° were measured between adjacent stakes.

The sediment deposited in the lee of the crest effectively displaced the position of the crest downstream, and therefore successive flood and ebb tides caused the crest position to oscillate. At Spring tides the maximum excursion reached approximately 5 m. The ensuing tide in each case eroded the newly deposited sediment, passing back over the sandwave crest, and a relatively uniform upstream flank was attained. Initially the bedform change was restricted to the crestal area and little change in the profiles of the flanks was apparent. However, as flow velocities increased towards Spring tides, marked erosion occurred on the upstream flank during the dominant ebb tides. The increase in erosion led to increased deposition; the latter extending further down the lee slope. In association, erosion also progressively reduced the crestal height. Under these flow conditions, the subordinate flood tide still maintained a relatively uniform upstream flank, but was unable to erode all the sediment deposited by the preceding ebb tide; as a result, the sandwave advanced in the direction of the dominant ebb tide. The net advance between Neap and Spring tides measured 3.6 m.

With the reduction in flow after Spring tides, the volumes of sediment transported over the crest by successive tides decreased, leading to a decline in crestal oscillation. This was accompanied by a cessation of stoss slope erosion and any further southerly advance of the lee slope (figure 7 c). During this phase, the flood tide was still able to erode the sediment deposited on the steeper south slope causing a retreat of the lee slope. As the ability of the declining flood and ebb tides to transport sediment decreased, the sediment carried over the crest accumulated close to the crest and lesser proportions were dispersed onto the flanks. This resulted in a progressive increase in crestal height. Towards Neap tides crestal stability again occurred. There was a net advance of approximately 1.5 m over the fourteen day period.

D) Planimetric Surveys

Planimetric surveys of the position of the crest of the sandwave were carried out using the diver-held acoustic ranging system described by KELLAND and BAILEY (1975). Analysis of the surveys showed that the movement of the sandwave crest was consistent for 50 m on either side of the line of reference stakes. It was therefore concluded that the profile data obtained from the line of reference stakes was representative of a relatively long length of sandwave crest.

E) Tidal Flow

The tidal range in Start Bay reaches a maximum of 5.8 m at Spring tides. On these occasions the flow velocities measured at 1 m above the crest of the sandwave reach 87 cm s^{-1}. At high tidal ranges the velocity maxima on flood and ebb tides are approximately equal, but at lower ranges the flood maxima are generally higher than those of the ebb (fig. 8a).

The ebb (south going) tidal residual is due to the longer duration of flow on the ebb tide. However, this dominance only occurs when the tidal range is greater than 3.3 m (figure 8). At maximum tidal ranges the duration of the flood flow, above a threshold of 22 cm s^{-1}, is approximately 40% less than that of the ebb tide. Below tidal ranges of 3.3 m the flood tide maintains its dominance in terms of both minimum velocity and duration of flow.

Tidal flow measurements have shown that in the shallow water environment of Start Bay, the tidal flow is affected by the prevailing wind. For example, at Neap tides the duration of flow of the ebb tide, in excess of 22 cm s^{-1}, can be increased by up to 90 minutes with north-easterly winds and reduced to zero with southerly winds. Wind stress probably accounts for much of the scatter in the data presented in figure 8.

CONCLUSIONS

The empirical data obtained shows that the sandwave height is related to the hydrodynamic conditions. At Neap tides the crest is highest. A reduction in crestal height occurs with Spring tides, whilst a pronounced reduction occurs after storms. These conclusions are summarized in figure 9. In the research area it is not possible to extrapolate lateral movement over long periods. Tidal measurements, when correlated with wind speed and direction, show that the duration of flow of the flood and ebb tides is affected by wind stress. This can alter the magnitude and direction of the flow residual and hence the lateral movement of the sandwave crest. In addition, surface waves generate high orbital velocities at the sea bed (figure 10). A summary of the analysis of nearly a year's wave records in Start Bay is shown in

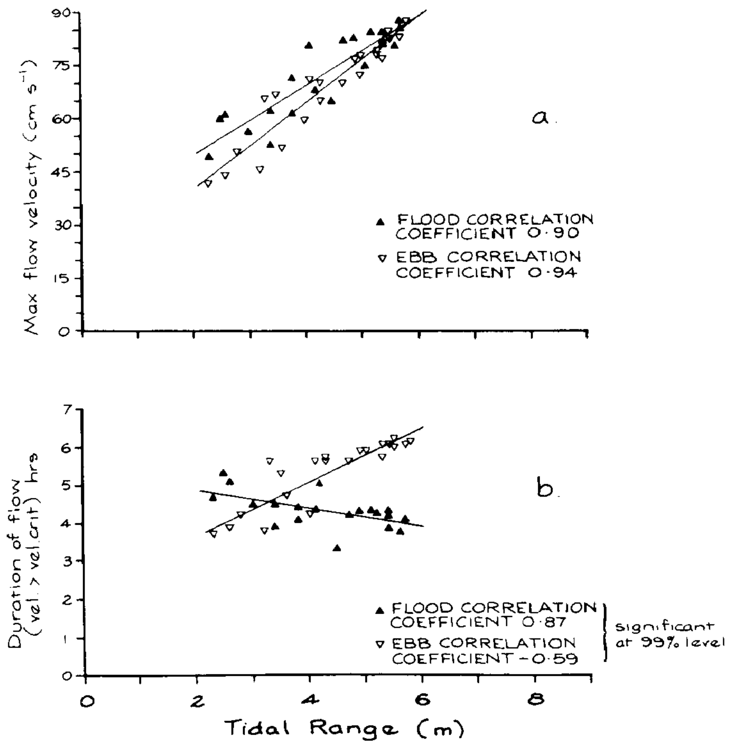

FIG. 8. – Tidal flow data. Measurements made at the crest of the sandwave.

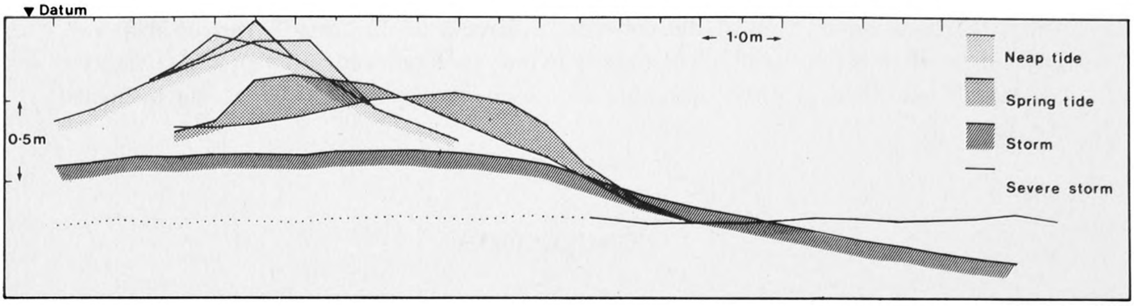

FIG. 9. – A summary of the relationship between crestal height and the hydrodynamic conditions.

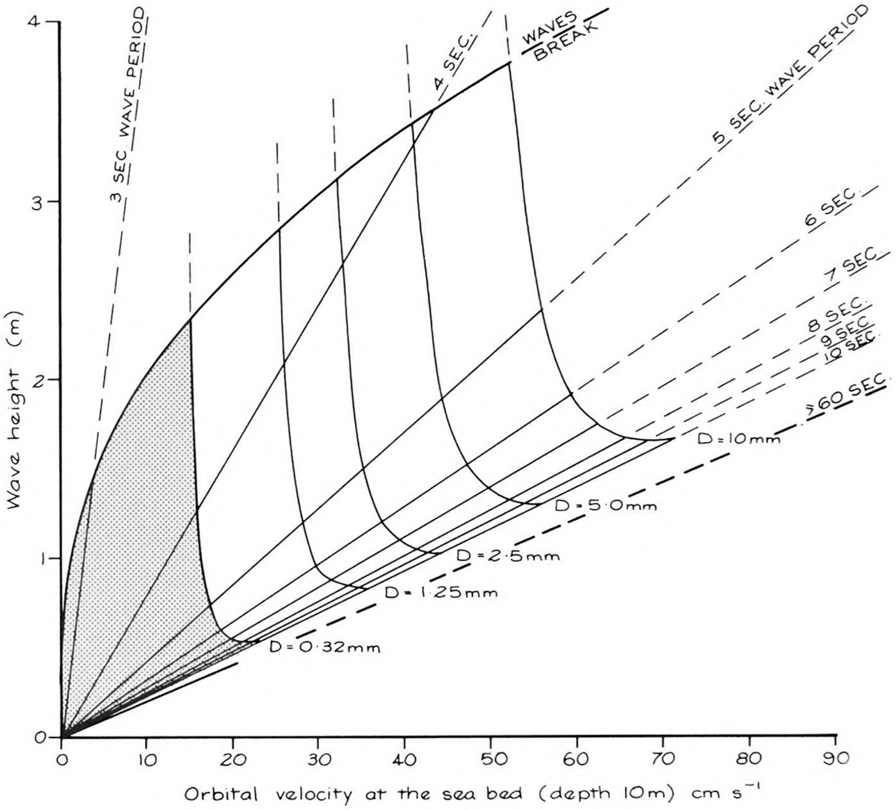

FIG. 10. – Theoretical particle orbital velocities calculated for a depth of 10 m for typical wave heights and wave periods. Threshold velocities for the movement of given sediment grain size (D) are also shown.

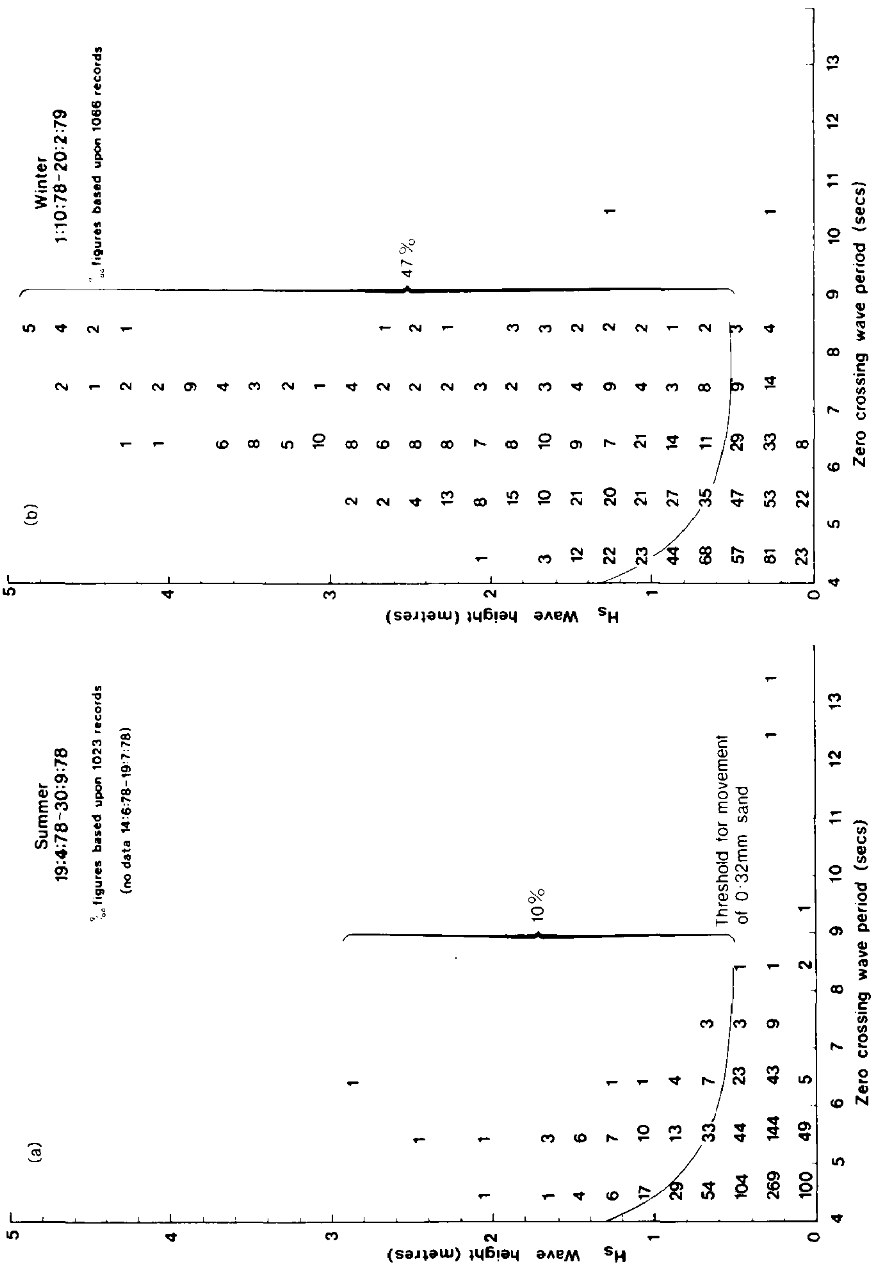

FIG. 11. – Summer and winter wave statistics – Start Bay.

figure 11. This data, when used with figure 11, shows that the threshold velocities for the movement of sand were exceeded by waves alone for only 10% of the period during summer months, but for 47% of the period during the winter. It is these excess orbital velocities, when combined with tidal flow velocities, particularly at Spring tides, that cause pronounced reductions in crestal height.

The generality of the conclusions cannot be assessed unless comparative measurements are made on different sized bedforms, in different flow velocities, flow depths, wave exposure and sediment grain sizes. However, the limited studies which have been conducted indicate that, when precision surveys are required for engineering or navigational projects, due consideration should be given to the preceding hydrodynamic conditions.

Analysis of survey data, obtained over a five year period, was carried out over a 2,000 m length of submarine pipeline passing through the sandwave field at the north of Haisborough Sand (LANGHORNE, 1980). The results showed that the length of pipe exposed ranged between 81 and 35 percent, whilst only 10% remained permanently buried during the period.

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