CHAPTER 53

THE MEASUREMENT OF OFFSHORE SHINGLE MOVEMENT

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Abstract

The objective was to obtain quantitative data on the movement of shingle under wave action in water depths of about 10 to 20 m by tracking pebbles tagged with radioactive material.

The paper describes the method of tagging, the method of position fixing, and the development of an underwater detection vehicle with a wide field of view. The field tracer tests demonstrated both increased mobility with decreasing depth and the existence of a small landward movement of shingle inshore of a depth of 12 m. Existing predictive data on the threshold of movement under waves, based on the results of previous work in the laboratory, was confirmed.

INTRODUCTION

The Hydraulics Research Station is often approached to assess the likely physical consequences on nearby coastlines, that could arise from the commercial dredging of offshore banks of gravel and shingle. In these cases attention is given to two major effects that may occasion damage to the shore-line. First, the locally increased depths of the dredged area can alter the angle of incidence of waves on to the beaches. Erosion and accretion as the coast re-adjusts to the new wave situation may have adverse consequences on amenity. Secondly, removal of offshore shingle may deprive the shore-line of its natural source of beach material. It is necessary, therefore, to assess whether the shingle that is to be dredged is moving towards the land under the present circumstances of waves and tides. Clearly, if it is not, there is no danger as far as source considerations are concerned.

The object of the study was to obtain, for the first time, quantitative data on the mobility of shingle under wave action in water depths of about 10 to 20 m.

The area offshore of Worthing was chosen as being suitable for an exploratory study of shingle movement. This part of the south coast of England is already the subject of a number of applications for commercial dredging licences. Thus research here is directly relevant to helping the licensing authorities to deal with these applications. Also, from the point of view of general study the area is attractive: the bottom topography being simple and wave conditions fairly typical of British coastal waters.

PREDICTION OF SHINGLE MOVEMENT

Existing predictive data on shingle movement under waves are based on a limited number of laboratory tests. Many of these attempted to model prototype shingle motion by means of scaled-down waves and granular bed material in laboratory wave tanks. Possible scale distortions make difficult the interpretation of the results of such tests. More reliable guidance is given by experiments in a pulsating water tunnel (Ref 1) in which full-scale oscillatory motions under waves can be represented. The conditions necessary to initiate movement of a variety of materials have been explored thoroughly with this facility and, given knowledge of the typical wave conditions, go a long way towards answering the question whether bed shingle is stationary or not.

It is found that, for the particular case of 25 mm diameter shingle, maximum oscillatory velocities of 1.4 to 1.6 m/s at the bed are required, to initiate movement for typical wave periods of 6 to 10 s. At water depths of 20 m, 10 s waves of about 6 m height are necessary to give oscillatory velocities of this magnitude. For 8 s waves, wave heights of nearly 8 m are needed. As the wave advances into shallower water, orbital velocities increase rapidly and bed shingle is progressively more vulnerable to movement. For the simple case of waves approaching a straight coast with parallel submarine contours, it is seen (Fig 1) that at 6 m water depth, threshold velocities for 25 mm diameter shingle are exceeded by waves with deep water heights of only 3 m and with periods as short as 6 s.

The quoted threshold velocities apply to shingle on a shingle bed. If shingle is present as a thin veneer on a hard rock basement, higher mobility can be expected. On the other hand, for the case of shingle coexisting with sand, the threshold velocities are probably underestimated because the sand occupies the interstices between the shingle, thus reducing the area on which drag and lift forces can be exerted.

Motion under non-breaking waves is primarily of an oscillatory nature, and as such may be expected to cause shingle to disperse normal to the wave front. This oscillation can cause a landward drift of shingle because on the forward-moving stroke the water velocity is higher and, therefore, more likely to move shingle, than the longer duration motion in the opposite direction. When pebbles have been lifted off the bed they can be entrained by tidal currents or by a second order wave-induced translatory flow known as the mass transport current. The latter arises because the orbits described by water particles under waves are not closed so that there exists a slow transference of water that is in the direction of wave propagation near the bed. Following Longuet-Higgins (Ref 2), the mass transport current at the bed increases with increasing wave height and with decreasing depth. Thus a 10 s wave, 6 m high, gives a mass transport bed current of less than 0.3 m/s in 20 m depth, but of 0.8 m/s in 10 m depth. A 10 s wave, 3 m high, gives values of less than 0.1 m/s and of 0.2 m/s for 20 and 10 m depths, respectively.

It is seen, therefore, that smaller depths are associated not only with increased bed mobility due to exposure to stronger oscillatory flows, but also, under large waves, with a net transfer of bed material in the direction of wave propagation on account of the mass transport current. In normal circumstances and neglecting tidal currents, this drift will be towards the shore. The question arises as to the likely magnitude of the bed material drift. Unfortunately, no data are available to predict the drift of solids beyond the threshold conditions. Consequently, if reliable estimates of drift quantities are to be made, recourse has to be made to field measurements of shingle movements.

EXPERIMENTAL AREA

Reserves of shingle exist offshore of Worthing in the vicinity of the 20 m mean water depth contour. Fears are expressed by the local coastal authorities that these offshore areas are sources for the shingle beaches of the nearby coastal resorts, and that the exploitation of the reserves will deprive the beaches of their natural supply.

It was decided to explore bottom shingle movement at a number of depths (9 to 18 m mean water depth), extending inshore from the shoreward boundary of the possible licence areas, by introducing marked pebbles and subsequently mapping their movement.

For the tests to be representative of areas of high dredging potential it was desired to introduce the marked pebbles on to a natural shingle floor. This condition was not easily satisfied in the case of the more inshore sites of the Worthing area. A bed reconnaissance by divers from H.M.S. Vernon, Portsmouth, extending offshore from Worthing, failed to find extensive shingle areas inshore of about 15 m water depth. The sea-floor between the reserve area and the shore at this point is very variable; sometimes bare chalk, sometimes patches of shingle, large stones and silt, and widespread weed cover. Clearly this was not a satisfactory experimental site and the search area was moved about 7 km east to offshore of Shoreham. Further diver reconnaissance eventually found locations (Fig 2) displaying suitable bottom conditions over the required depth range.

This stretch of coast is open to waves throughout the sector from ESE to WSW. The longest fetch coincides with the prevailing southwesterlies and consequently in a normal year the dominant wave attack would be expected from the southwest quarter. For the greater part of the duration of the experimental study, wave records were taken with a National Institute of Oceanography shipborne wave recorder installed on the Owers Light Vessel. These records were analysed for wave height and period after Tucker (Ref 3).

Tidal currents run generally parallel to the shore and are relatively weak: peak surface velocities being 0.8 m/s at Spring tides, and 0.5 m/s at Neap tides. These currents are insufficient to move shingle, but in conjunction with the mass transport current, they could be important in determining the direction of movement of shingle that has been already lifted from the bed by oscillatory flow under heavy wave action.

EXPERIMENTAL METHOD

In the past, qualitative studies of shingle movement have been undertaken using fluorescent or radioactive tracer pebbles (Refs 4 and 5). Although fluorescent tracers offer a convenient means of tracking movement on beaches above the low water mark where visual identification of the marked pebbles is possible;

the inability to detect them remotely from a boat is a severe handicap for deeper water operations. In this respect, the radioactive tracer method has a distinct advantage, with its capability of identifying tracer units using a radiation detector dragged over the sea-floor behind a boat.

Tracer pebbles

Previous radioactive tracer work on coastal shingle movement has been short-term using short half-life radioisotopes. In the present case, the objective was to follow movements for at least one year and the radioisotope Silver 110 m was selected as being sufficiently long-lived (half-life, 253 days) for the purpose. Again, on account of the duration of the tracking period, a tag sealed into the centre of a pebble was preferred to the alternative of a surface coating: the latter being susceptible to abrasion losses. The technique consisted of placing a short length (3 mm) of activated silver wire (20 μCi Silver 110 m) in a hole in each pebble and then filling the hole with a clear epoxy resin. Abrasion tests lasting over a week, tumbling tagged pebbles in a mixer with other beach pebbles and sand, showed no sign of damage, apart from a scratching of the epoxy resin surface which masked the presence of the underlying wire tag.

The pebbles of this part of the coast are flint and considerable difficulty was experienced in drilling holes in them. 4000 tagged pebbles were required and the failure rate of diamond drills was so high that only about 300 pebbles were prepared by drilling. It was found more economical to collect natural pebbles already having suitable holes in them (Plate 1). Only pebbles passing through a 38 mm sieve and retained on a 19 mm sieve (corresponding roughly to coarse aggregate grading) were accepted for tagging.

Pebble seeding

The four selected sites with mean water depths of 9, 12, 15 and 18 m, were each seeded with 1000 tracer pebbles in mid-September 1969. To provide a reasonably well-ordered initial distribution, the pebbles were laid by divers on the surface of the bed over a rectangular area 30 m by 60 m. The discovery of an almost completely buried mine within the seeded area at 15 m depth and subsequent failure to re-locate the mine for disposal, led to the abandonment of this site. It was considered that the risks involved in repeatedly traversing the area with a large underwater wheeled vehicle were too great to permit tracking in this area.

Pebble detection

An inherent difficulty of shingle tracer experiments is that of dctecting a sufficiently high proportion of the injected tracer units to permit quantitative interpretation of the measured spatial distributions. Tracer preparation is inevitably tedious, and the number of pebbles introduced is consequently low. There is clearly the need to optimise the areal coverage of the detector. Underwater detectors for normal applications are unable "to see" a pebble over a band much greater than one metre wide, when moving over the bed at a speed of 1 m/s. Thus, if the tracking boat runs parallel courses about 20 m apart, only 50 pebbles of a total of 1000 are likely to be detected.

In order to overcome the narrow sweep handicap, a detector with a wide field of view was developed (Plate 2). Five scintillation counters are distributed over the width of a 3-wheeled vehicle drawn behind a boat, so that they view the sea-bed over a band-width of 6 m. The vehicle weighs about 350 kg and is towed at speeds of about 1 m/s, using 90 m stainless steel tow rope (12 mm dia.) incorporating the electrical cable as its core. Detector output is provided on three twin-channel pen recorders on-board the tracking vessel. The presence of a tagged pebble is readily distinguished on the chart record as a well-defined pulse above the natural background radiation. The spare recorder channel indicates the vehicle's speed over the sea-floor, using the output from a rev. counter on the leading wheel of the vehicle.

In addition to the main tracking detector for measuring the horizontal distribution of the pebbles, a subsidiary diver-held, portable detector was employed for assessing the depth of burial of individual pebbles. Divers intensively explored the bed in the seeded area and obtained a series of maximum bed surface radiation readings, directly above tagged pebbles. With the radioactivity in each pebble being closely similar, the reading indicated the extent to which the emitted radiation was absorbed, and the depth of overburden was given from laboratory calibration of the detector.

Position-fixing

Shingle tracking imposes rather stringent requirements with respect to position-fixing. To achieve effective combing of the search area there is the need to run courses at slow speeds on parallel lines not greater than 20 m apart. At this spacing 30 per cent registration of the seeded pebbles could be obtained with the wide-view detector.

Hydrodist MRB2 was hired to provide the necessary precision. Operating at 3000 mc/s the system gives a nominal position-fixing accuracy of ± 2 m. In this specific case, the siting of slave transponder stations at Shoreham and Rottingdean yielded satisfactory intersection angles of the lattice lines throughout the working area. Apart from occasional spurious distance shifts at the most offshore site, the system proved reasonably reliable throughout the study, but it made extravagant demands on manpower.

Although the boat's position was accurately given by Hydrodist fixes, the position of the detector behind the boat was more indeterminate. Normally the detector was taken as being on the line of the boat's course, but displaced some distance behind the boat according to the length of tow. Errors would be introduced in the presence of a strong cross-wind or when tracking across the tide, and it is estimated that tolerances of 5 to 10 m on detector position are realistic.

Surveys

A preliminary bed background radiation survey was made in early September 1969 before the seeding operation. No background radiation anomalies were recorded.

Following the seeding in mid-September, subsequent surveys were made in October, November/December 1969, March and August 1970, April/May 1971. Normal practice was to run parallel courses roughly E-W along the tidal direction, maintaining a constant distance off the Shoreham slave station. Tracking was not possible with a beam sea, so when sea conditions were bad, the alternative procedure of running courses to and from the coast was adopted, holding a constant distance off the Rottingdean slave station. The running of parallel courses was greatly facilitated by the adoption of courses with a fixed Hydrodist reading on one or other of the two slaves.

Measurements of the depth of shingle burial were made on the last three surveys only.

RESULTS

The results of the various surveys are illustrated in Figs 3 to 5. The following points should be borne in mind when examining these figures:-

1. The delimitation of maximum tracer extent is subject to considerable random error, being based on the detection of a single pebble. Consequently the boundary can shift markedly in areas of low tracer density, dependent on whether or not, a particular pebble is coincident with the detector track width. The profiles of tracer pebble density with distance from the centre of the seedee zone are more valid guides to the degree of movement between surveys.

2. Profiles are not given for surveys based on tracking courses running to or from the shore, because these would not be comparable with profiles based on the more customary tracking direction.

3. The shaded rectangular area is a somewhat idealistic representation of the initial tracer distribution. The actual seeding only approximated to this form.

4. To economise on space the full extent of tracking coverage is not shown. The courses were much longer than indicated, and

normally, further parallel courses were run to the north and to the south. However, no tracer pebbles were detected at these more remote positions.

The most striking feature of the mapped distributions is the small degree of movement at all sites: even single tracer pebbles are very rarely encountered as far as 100 m from the centre of the original seeded area.

The inshore sites, at 9 and 12 m mean water depth, exhibit typical tracer distributions, with a low density scatter of tracer pebbles extending in an approximately NNE direction from a high density cluster coincident with the originally seeded area. The net drift of pebbles is small but is clearly discernible above possible experimental errors referred to earlier. Average landward pebble movement over the total observation period of 20 months is assessed at 40 and 15 m for 9 and 12 m depths, respectively.

Although Fig 5 shows a small westerly shift in the mapped tracer distribution at 18 m depth compared with the seeded position, there is no sign of the characteristic scatter of pebbles at low density. All the distributions at this site display an abrupt boundary: there are either tracer pebbles at high density, or there are none. Past experience suggests that tracer units do not shift as a group without a concomitant dispersal similar to that given at sites 1 and 2. It is concluded that the small positional shifts at site 4 are spurious and represent fixing errors between surveys. Thus no net pebble drift was recorded at 18 m depth.

After one winter, measurement of the vertical distribution of 120 tracer pebbles by divers using the portable radiation monitor at the two inshore sites showed that they were still confined to the surface 50 mm. After two winters, the vertical position of 50 tracer pebbles at each site was determined in the same manner. The mixing depth was found to be 125 mm, 50 mm and 60 mm at sites 1, 2 and 4 respectively. Further evidence of low mobility was demonstrated by the recovery of tracer pebbles by divers in May 1971. These pebbles still showed a clear resin plug through which the silver wire was visible and obviously had suffered negligible abrasion in the experimental period.

DISCUSSION

From the plots of tracer pebble distributions the most obvious movement took place early in the experiment in November 1969 when strong westerly winds gave 8 s waves with significant heights in excess of 5 m. The wave climate prevailing between each survey is shown in Fig 6 and it can be seen that the severe conditions of November 1969 were repeated in a storm during the 1970-71 winter. However, on this second occasion the horizontal displacement of the tracer pebbles was not so apparent because the pebbles were dispersed over a thicker bed layer by that time. During the summer period the tracer pebbles at all sites showed very little horizontal movement in spite of significant wave heights in excess of 3 m at Owers Light Vessel.

The extent to which the tracer results can be regarded as typical is best judged by comparison of the wave conditions prevailing during the study with the long-term average. Unfortunately wave data outside the experimental period are limited. Additional records at Owers Light Vessel are available (Ref 6) for one year (October 1968 to September 1969) only and show that wave conditions then were less severe than during the present study.

Recourse has to be made to wind frequency comparison for a longer-term standard. Analysis of 5 years of wind records for Calshot suggests that sea conditions were less disturbed during the winters 1968 to 1971 than the long-term average. It is seen (Fig 7) that strong winds from the southwest quarter i.e. those capable of generating higher and longer period waves, were less frequent during the experimental period than normal.

Wave records at Owers Light Vessel with suitable adjustments to take account of shoaling have been used to calculate bottom current conditions at each of the tracer sites. For this purpose the significant wave height i.e. the mean of the third highest waves, and the mean zero crossing period are used to compute the peak oscillatory velocity at the bed. The frequency of occurrence of bottom-water oscillations having instantaneous peak values that exceed a number of specific velocities is shown for each site, alongside the final tracer distributions, in Fig 8. The results are qualitatively consistent with data obtained from the pulsating water tunnel (Ref 1). The laboratory tests showed that maximum bed oscillatory velocities of 1.4 to 1.6 m/s were required to move 25 mm shingle. In the field the peak recorded at 18 m depth was about 1.2 m/s; so it is not surprising that the tracer distribution suggested a non-mobile bed at that depth. On the other hand, significant movement occurred at 12 m depth where peak values reached 1.7 m/s.

It appears that mass transport currents associated with heavy wave action are more important than tidal currents in determining the direction of net pebble movement at the nearshore sites. These bring about a landward drift across the tidal stream direction. The volume of shingle drift may be obtained from the product of the shift in centroid position of the horizontal tracer distributions and of the thickness of the layer in movement. The drift after two winters and one summer is estimated at 2.5 and 0.5 m^3 per metre width for the 9 and 12 m water depth, respectively.

It is evident from the absence of movement at 18 m water depth that the drift occurring at the more inshore sites is not supported by an offshore feed. Thus the nearshore shingle drift is either replenished by alongshore movements of shingle or is slowly drawing from geological reserves.

CONCLUSIONS

The field tracer test demonstrated both increase in bed mobility with decreasing depth and the existence of landward movement of shingle inshore of 12 m water depth. However, even at the two inshore sites the quantities of shingle transported towards the shore were found to be small, amounting to 1000 to 1500 m^3 and less than 500 m^3 per kilometre length of coast per annum from 9 and 12 m water depth, respectively. Dredging at these depths could interrupt the slow landward creep but the manifestation of this on the beaches would be long-delayed. For instance, the centroid shifts at the two sites indicate that the average pebble will take about 200 years to advance the 3 km from the 12 to 9 m contour. It is debatable whether changes on such a long time scale are significant when there is a strong probability that beach levels are controlled primarily by spatial and temporal variations in the littoral movement of shingle close inshore. However, at these depths, beach changes arising from alterations of wave refraction might be the primary consideration.

It is considered that shingle movements offshore of the 18 m contour along this piece of coastline will be negligible at all times. Furthermore, at these depths the mass transport current at the bed is too small to promote preferential landward drift.

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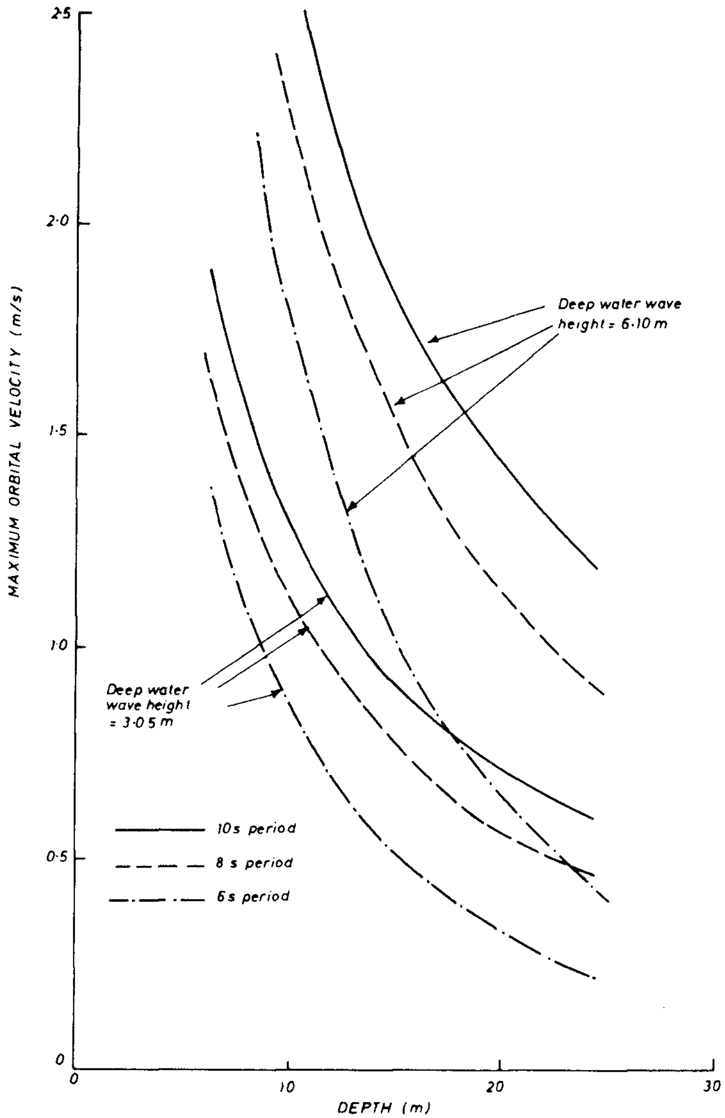
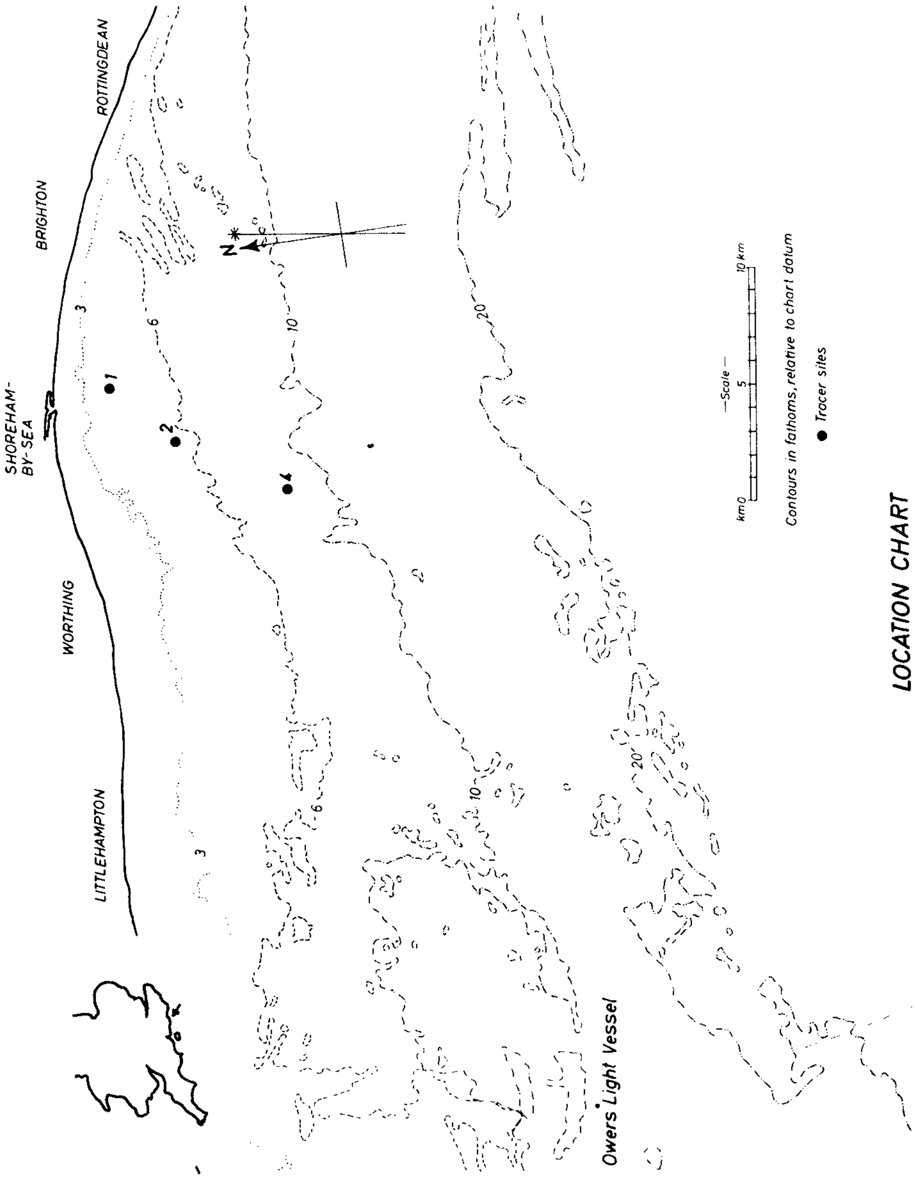


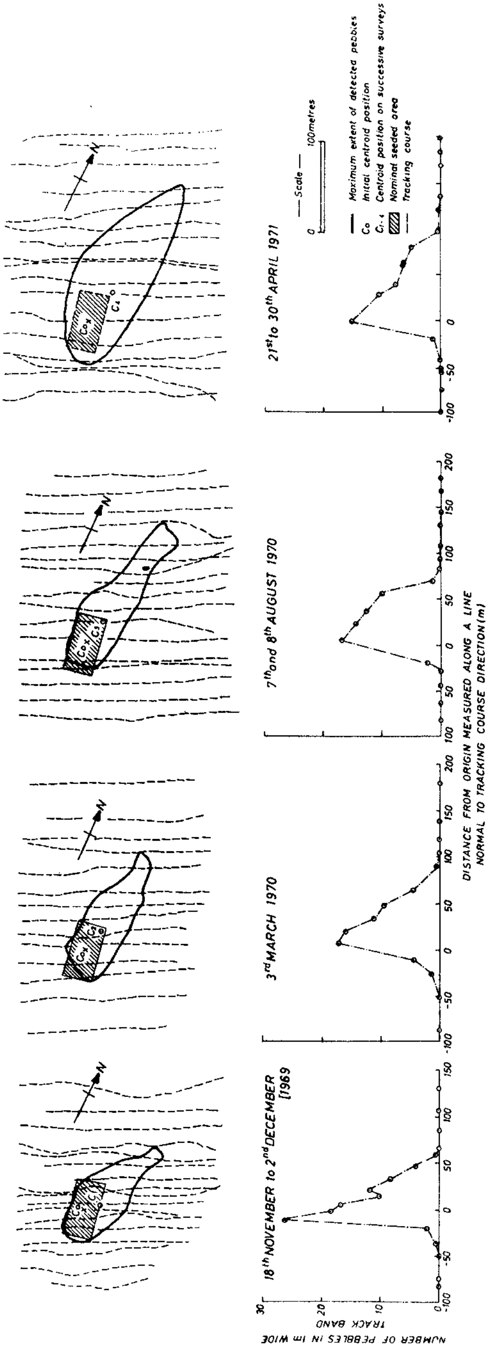
EFFECT OF DEPTH ON MAXIMUM ORBITAL VELOCITY AT BED

FIG 1



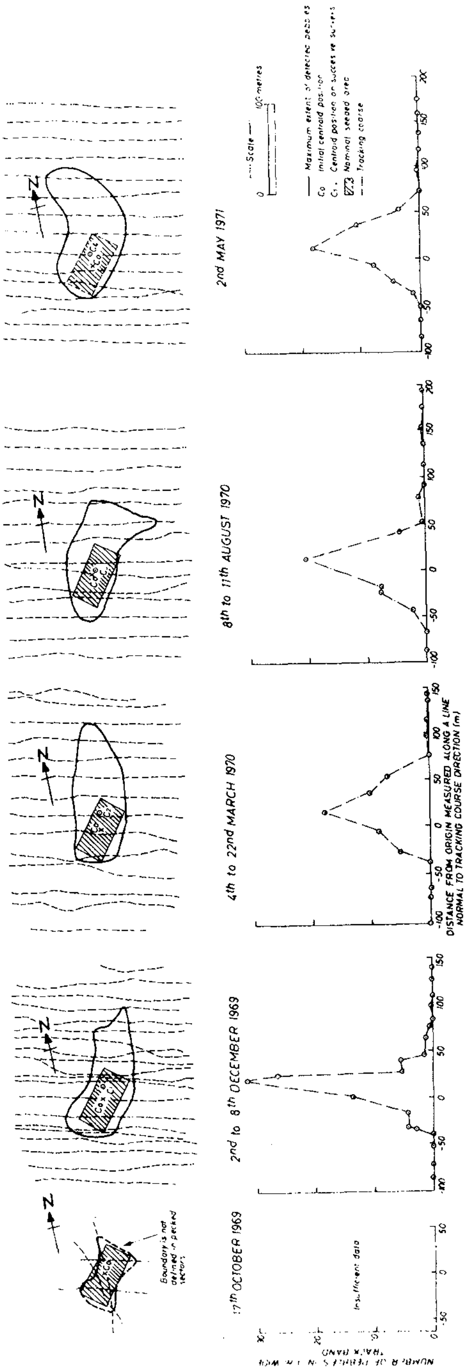
LOCATION CHART

FIG 2



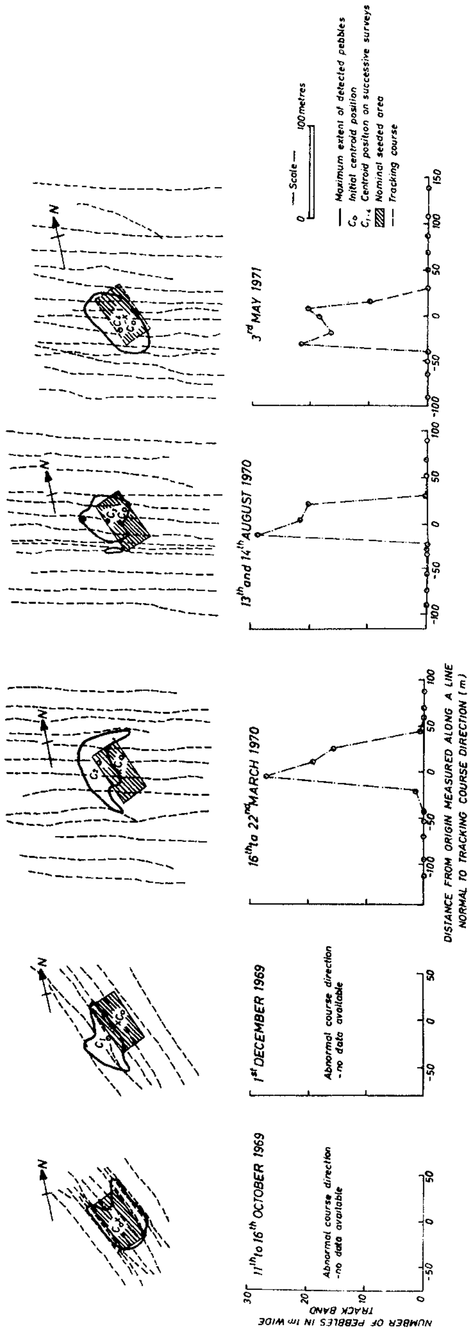
TRACER PEBBLE DISTRIBUTIONS - SITE 1

FIG 3



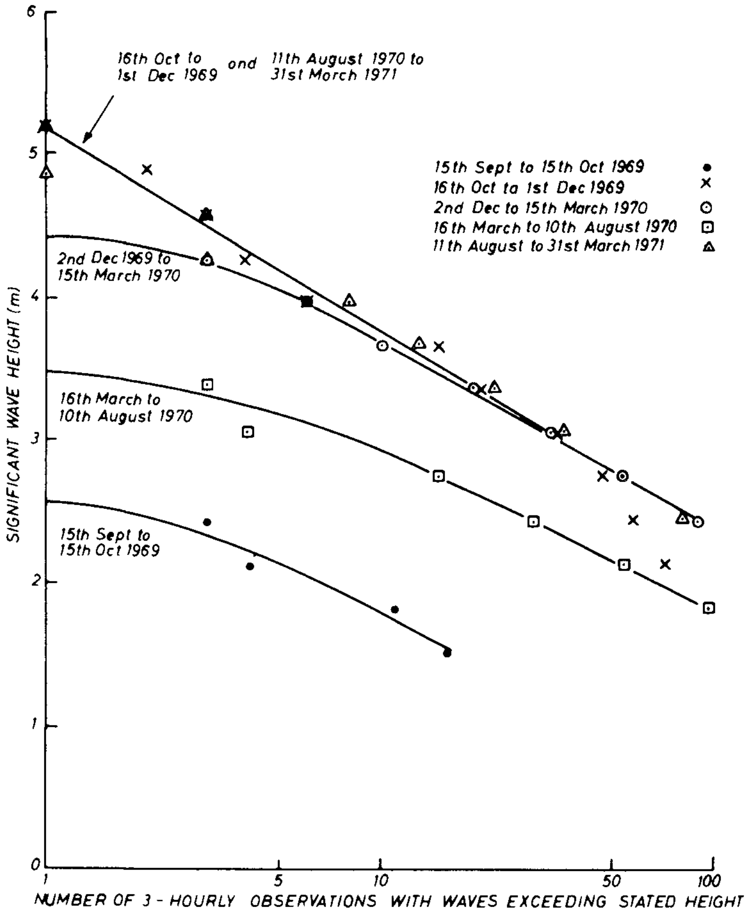
TRACER PEBBLE DISTRIBUTIONS - SITE 2

FIG 4



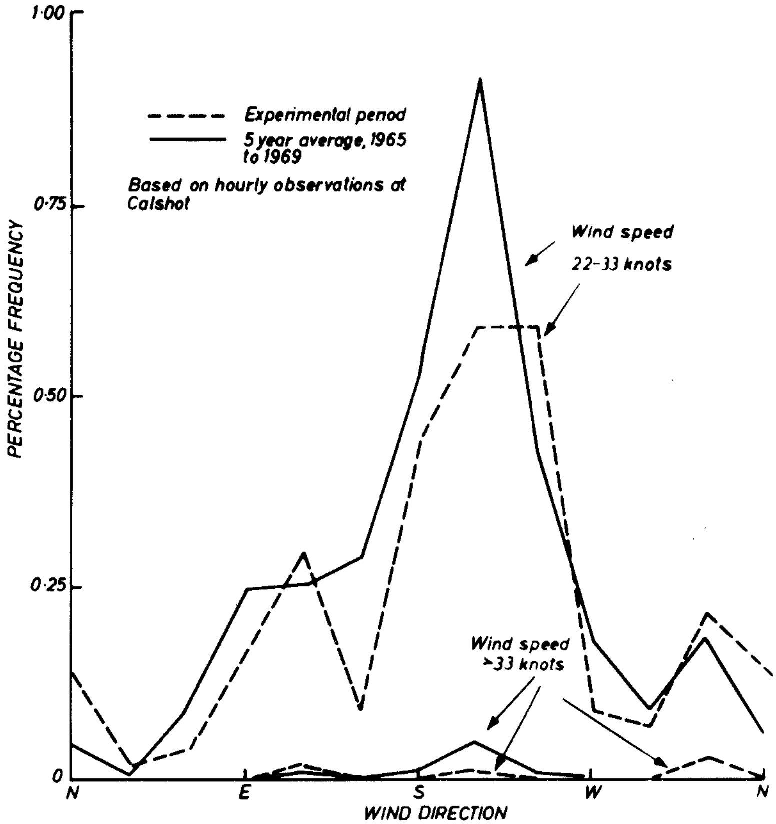
TRACER PEBBLE DISTRIBUTIONS - SITE 4

FIG 5



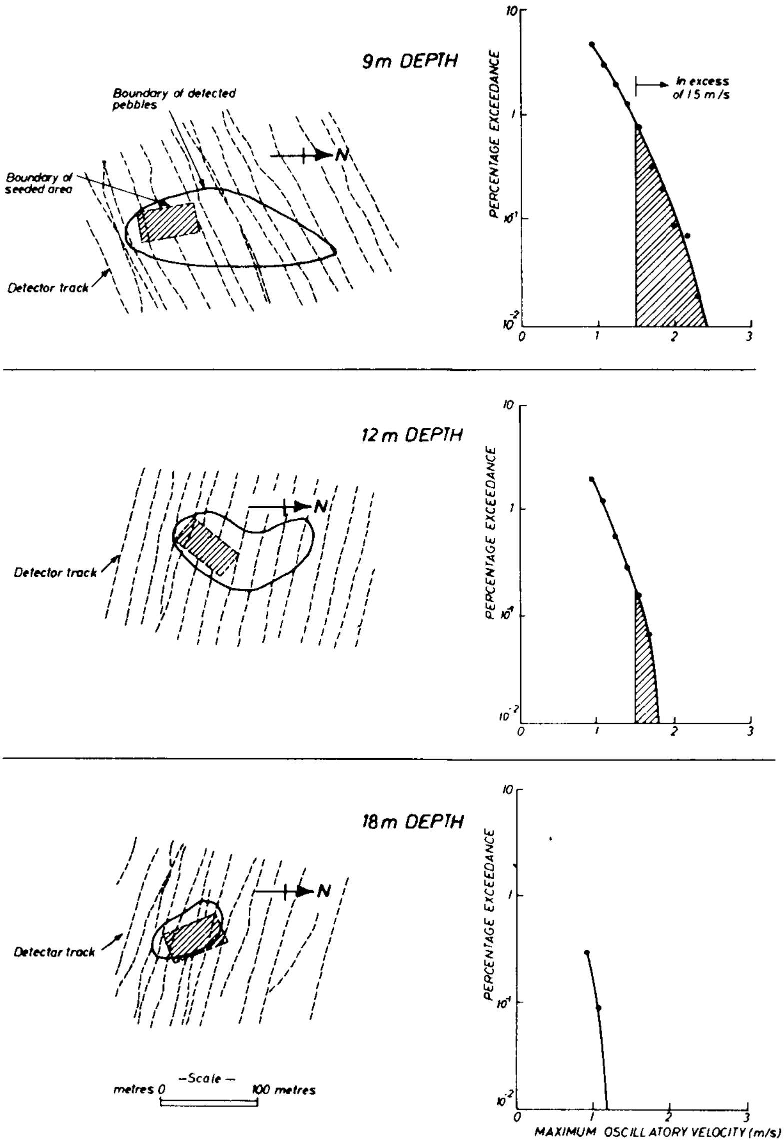
SIGNIFICANT WAVE HEIGHT EXCEEDANCES
-OWERS LIGHT VESSEL

FIG 6



WIND FREQUENCY COMPARISON

FIG 7



MAXIMUM EXTENT OF TRACER PEBBLES AND FREQUENCY DISTRIBUTION OF MAXIMUM OSCILLATORY VELOCITIES AFTER 20 MONTHS

FIG 8

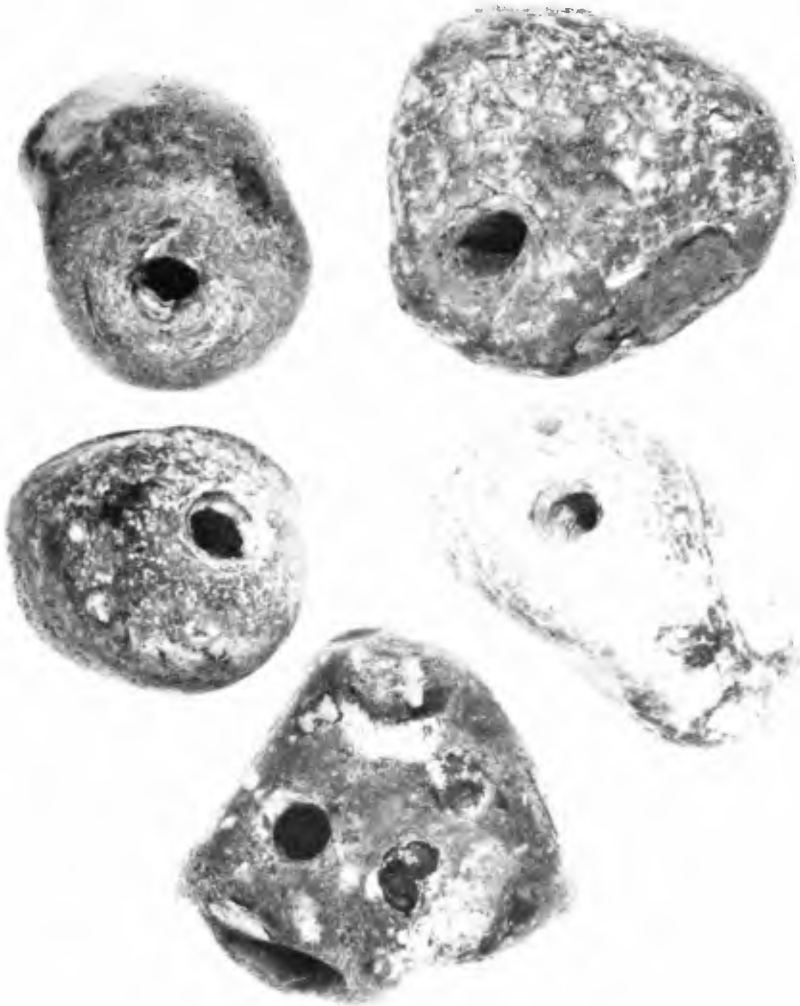


Plate 1 Natural holes in flint beach pebbles

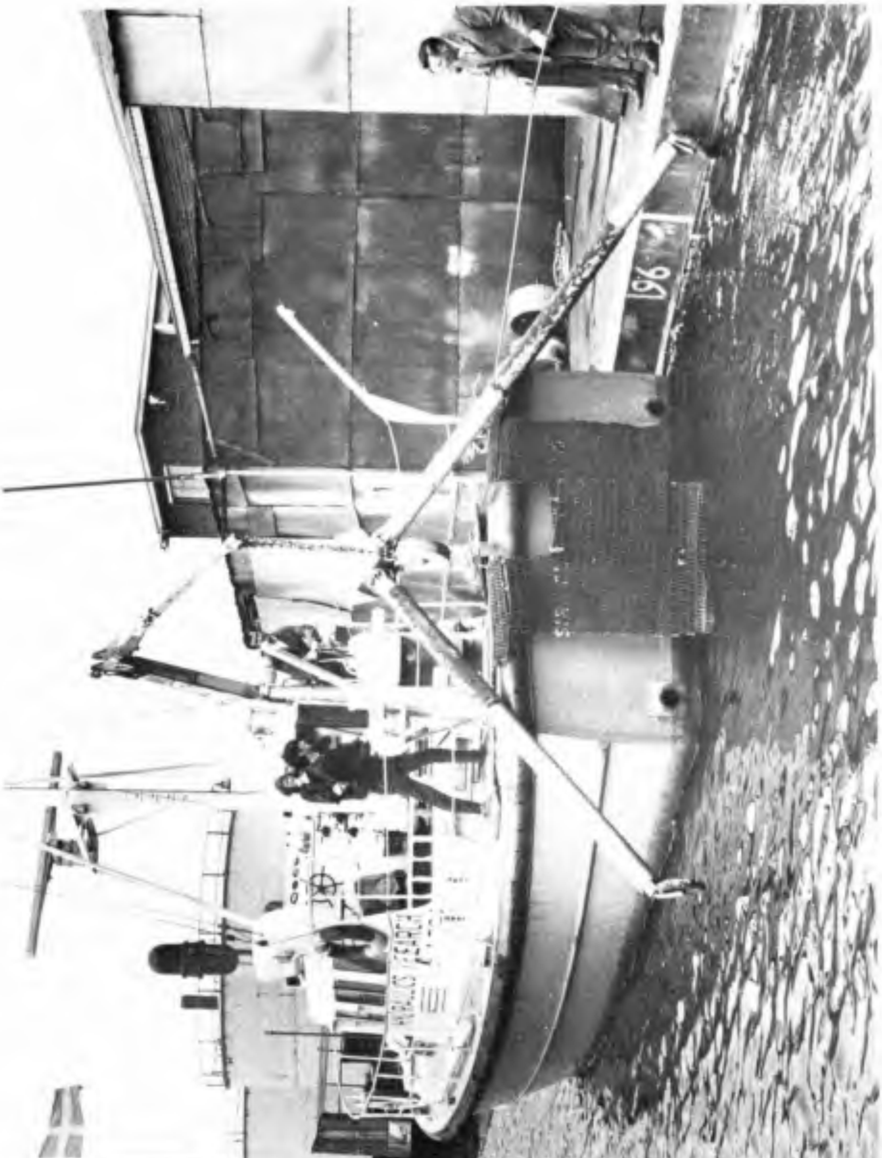


Plate 2 Wide-sweep radiation detector