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SANDWAVE RESEARCH AND ITS RELEVANCE TO PRESENT DAY NAVIGATION AND ENGINEERING PROBLEMS

NATURAL ENVIRONMENT RESEARCH COUNCIL
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CONFIDENTIAL TO SHIP AND MARINE
TECHNOLOGY REQUIREMENTS BOARD

SANDWAVE RESEARCH AND ITS RELEVANCE TO PRESENT DAY NAVIGATION AND ENGINEERING PROBLEMS

INSTITUTE OF OCEANOGRAPHIC SCIENCES
INTERNAL DOCUMENT NO 19

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PREFACE

In June 1976 the Institute of Oceanographic Sciences submitted the following four research proposals to the Ship and Marine Technology Requirements Board for consideration for funding.

1. Collation of existing data relevant to the mobility of the sea bed in areas of commercial importance (50/2.1.2d)
2. Assessment of the validity of criteria used in estimating depth of movement of sea bed material (50/2.1.2e)
3. Measurement of the effect of storms in changing the sea bed topography (50/2.1.2f)
4. Stability of dredged navigational channels (50/2.1.2g)

SMTRB agreed to fund project 50/2.1.2d. For this project the collation of data has been restricted to the South Western Approaches to the British Isles and the Celtic Sea and satisfactory progress has been made to date. With regard to the remaining three proposals, it was understood that the Board recognised that sea bed movement and sandwaves constituted a problem of importance. However, the Board were not sure that the programmes were appropriate, considering the research which has been carried out over the past 20 years, and whether the results would be of general application. Consequently a review of the state of knowledge on sandwaves was requested, together with an appraisal of the limitations of this knowledge in terms of present day applied problems. A summary report was submitted in April 1977, whilst the attached full report is a comprehensive review in which the various aspects are considered in detail.

Since submitting the proposals to SMTRB, IOS has continued the research on sea bed mobility in relation to project 50/2.1.2e and 50/2.1.2f using Science Vote funds. This decision was made as it was considered that the research will produce worthwhile results with direct application to present day commercial problems in the relatively near future. Using up-to-date survey techniques, field measurements have been obtained in a selected study area with a higher accuracy than any other known survey. Unambiguous conclusions can now be gained on the magnitude of changes of the sea bed. The conclusions apply to the one selected study area, and therefore to prove the generality of the results, it is intended to set up comparative studies in different hydrodynamic/sedimentological environments.

The limited facilities within the Institute have not permitted further progress with project 50/2.1.2g.

Three direct applications for research on the mobility of the sea bed are summarised as follows:

(a) At the present time nobody can state with confidence what the minimum underkeel clearance for a deep draught vessel should be, or how frequently critical areas need to be resurveyed to ensure safe navigation. This is because it is not yet possible to correlate change of elevation of the sea bed with particular tide and wave conditions. This has important consequences on port economics, which include the size of vessel which may use the port, the dredging requirements, and the efficient use of survey vessels. This problem applies to both large vessels using major ports and also smaller vessels using smaller ports.

(b) At the present time it is the policy of oil companies to route oil and gas pipelines around sandwave fields and other areas of likely sea bed instability. This policy is adopted because the dynamics of the sea bed are poorly understood, and the necessary depth of pipe burial to ensure permanent protection is not known. Even in non-sandwave areas, the considerations used to assess the depth of burial have not been satisfactory, and frequent cases of exposure and spanning have occurred.

(c) The incidence of breaks in Post Office cables increases annually. (Over a 12 month period 40 breaks occurred in one particular cable. The cost of each repair was approximately £20,000). Though equipment is available which makes it possible to plough a cable into the sea bed to a depth of 0.6m, the use of this equipment involves considerable extra cost, (£700,000 as against £75,000 for a 100 nautical mile route). If it could be established where erosion to a depth of in excess of 0.6m was likely to occur, then selective use of the plough, in conjunction with careful route planning,would improve efficiency and reduce maintenance costs.

Future research under consideration within IOS is based upon the following research proposals:

1. Use modern high-accuracy surveying techniques to measure the changes in sandwave form and distribution at a number of different environmental sites around the British Isles. This will provide data on the magnitude of change which occurs under different conditions.
2. Relate the form changes to gross flow variables (tidal currents and surface waves) and to the characteristics of the sediments and their availability. This will lead to a better understanding of the empirical laws which describe the mobility of the sea bed and the ability to predict the changes which may occur in areas of commercial or engineering importance.

3. Make detailed measurements of the water flow, bed shear stress and sediment movement over a sandwave in order to understand the mechanisms of their formation and to develop a predictive model based upon an appreciation of the detailed physics.
4. Develop a mathematical model for sediment movement over different bed forms to complement the field measurements.

It should be stressed that the emphasis on sandwaves is because sandwaves are thought to be indicative of excessive sediment movement and sea bed mobility. In a wider context the research programme would be extended to include the study of sea bed mobility in areas free from sandwaves. In such areas the emphasis would be placed upon ascertaining the thickness of the mobile layer of the sea bed.

At the present time external funding is only requested for the first and second parts of the research proposals. If the provision of funds can be agreed in principle then the existing research proposals (submitted to the Board in June 1976) can be updated as necessary.

SUMMARY

Knowledge of the stability of the sea bed is important for navigation, submarine pipelines and cables. It is thought that sandwaves are indicative of areas of excessive sediment movement and sea bed mobility. The lack of detailed knowledge on sandwave movement, and the inability to predict the magnitude of change of the sea bed has serious consequences on many commercial and engineering projects.

During the past 25 years the main emphasis of sandwave research has been directed towards the observation and description of sandwave 'stati[illegible]ics'. Most of the data which has been obtained, was used to identify sandwave distribution, shape and composition as key factors for defining sedimentary circulation patterns. Much of the research was motivated by the geological requirement to understand the present day sedimentological environments in order to interpret ancient stratigraphic records. Less progress has been made with the quantification and description of sandwave dynamics, which include form changes and movement, as well as their mode of formation and evolution. This is mainly because of a lack of appreciation of the complexity of sandwaves, and therefore of the density of measurement required to define temporal and spatial changes in form or position. Progress has been restricted by the difficulties of making precision measurements at sea, in particular accurately fixing the position of the observing vessel.

In the past, when trying to define hydrodynamic relationships there has been a tendency for sandwaves to be approximated as simple two-dimensional features. In fact, they are complex, and a typical sandwave field has a wide variety of wave heights and lengths, with smaller less stable megaripples often superimposed on the large-scale features. The form parameters of marine sandwaves have not been interrelated satisfactorily with hydrodynamic factors. This is in contrast with flume studies in which definite relationships have been established for similar sandwave-like features.

Though no firm relationships have been demonstrated in the sea, some limits can be placed upon the ranges of depth, flow velocity and mean grain size under which sandwaves are formed. It can also be shown that surface water waves have at least a transient effect upon sandwave dynamics. In marine studies the difficulties of interpretation of data are increased by the fact that an observed feature need not necessarily be in equilibrium or quasi-equilibrium with the present day flow regime.

It is obvious that the equilibrium sandwave cannot occur unless there is a sufficiency of sediment of the right grain size available, either in situ or passing through the area, for its formation. If the flow conditions are within the ranges suitable for sandwave formation, it may then be the

abundance of sediment which also controls the ultimate height and wave length of the sandwaves formed in the area.

In some areas the sandwaves exhibit lee slopes which approximate to the angle of repose of sediment in water. In other areas lee slopes seldom exceed 10°. It is suggested that sandwaves in the former case may be active features, whilst in the second case although the surface sediments are still mobile, the main structures of the sandwaves may be relicts of a past flow regime. If this hypothesis is correct, the mechanism is probably that the once steep slopes have been downgraded by slumping as a result of wave action and the tidal flow regime has changed to one which is no longer capable of re-establishing and maintaining their original steepness.

Many seismic profiles suggest that sandwaves occur overlying a coarser layer of sediment. If it can be established that sandwaves move over a relatively stable base plain without eroding it, then this will have important implications to such engineering works as pipeline laying.

In accordance with present day engineering and commercial requirements it is important that research on sandwaves should be directed towards the quantification of sandwave dynamics and their interrelationship with tide and wave energy. It is a fundamental requirement to understand the way in which bedforms are generated by the flow, and what flow characteristics govern their form and distribution, as well as the magnitude of change brought about by changes in flow conditions (ie Spring and Neap tides as well as surface wave action).

The most important improvements in techniques which can produce an advance in knowledge are in surface and underwater position fixing. Other improvements include tidal reduction using offshore tide gauges located in the area of study, and methods of analysing side scan sonar records. It is considered that a full understanding of sandwaves can only be achieved by combining programmes of research which cover both the basic physics of the mechanisms involved and the dynamics as observed in the sea.

It is concluded that research on sandwaves should be directed towards:

1. Using modern high-accuracy surveying techniques to measure changes in sandwave form and distribution at a number of different environmental sites around the British Isles. This will provide data on the magnitude of change which occurs under different conditions.
2. Relating the form changes to gross flow variables (tidal currents and surface waves) and to the characteristics of the sediments and their availability. This will lead to a better understanding of the empirical laws which describe the mobility of the sea bed and the ability to predict

the changes which may occur in areas of commercial or engineering importance.

3. Making detailed measurements of the water flow, bed shear stress and sediment movement over a sandwave in order to understand the mechanisms of their formation and to develop a predictive model based upon an appreciation of the detailed physics.
4. Developing a mathematical model for sediment movement over different bedforms to complement the field measurements.

In a wider context the research programme should be extended to include the study of sea bed mobility in areas free from sandwaves. In such areas the emphasis would be placed upon ascertaining the thickness of the mobile layer of the sea bed.

LIST OF FIGURES

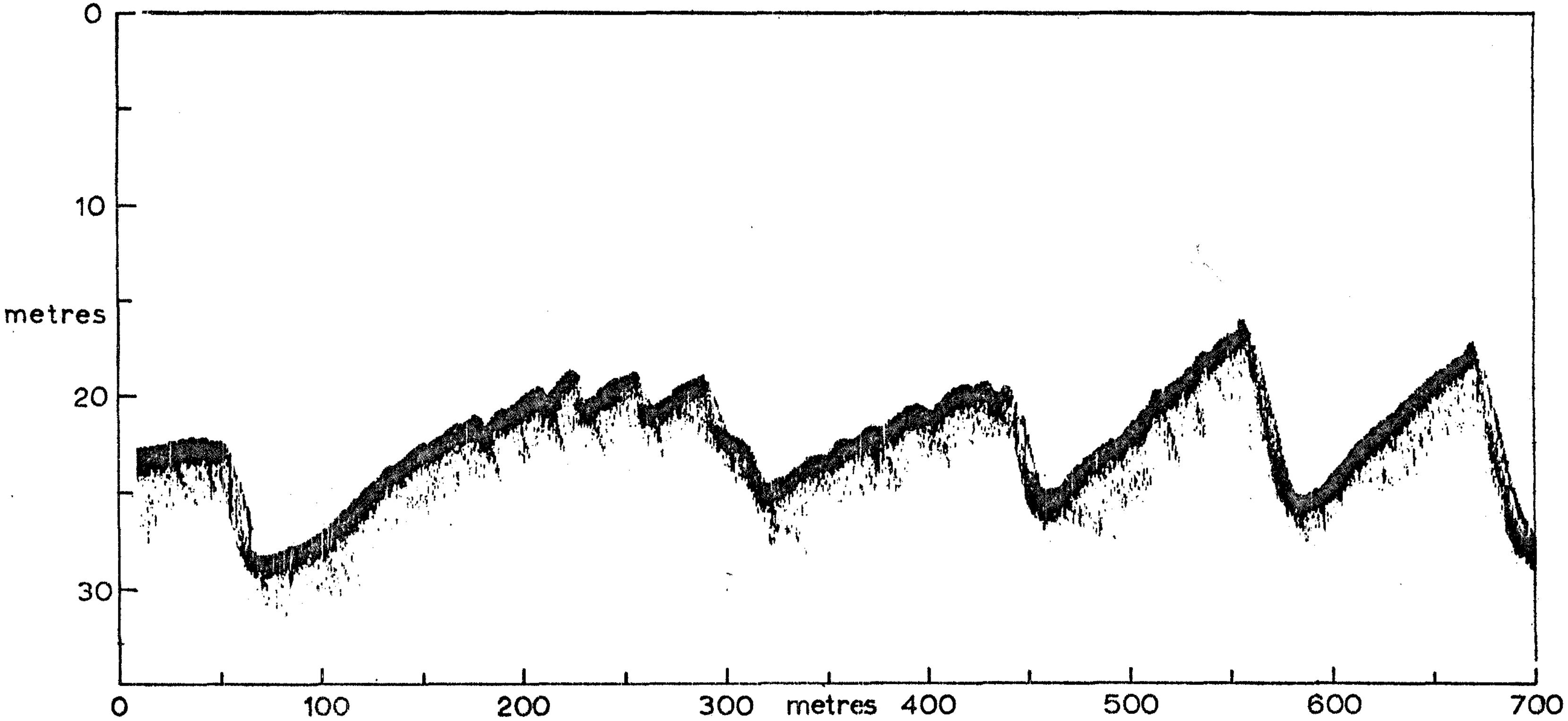
1. INTRODUCTION

When water flows over an erodible sediment, frictional forces act at the interface and the resulting shear stress moves the sediment and the boundary becomes distorted. It can be demonstrated that, under specific flow conditions, the distortion starts when grain movement is initiated and continues until a wavy sediment surface is formed. Waves of sediment commonly occur formed on the sea bed in sand-sized sediments and therefore the term 'sandwave' is frequently used.

Sandwaves are elongated depositional bedforms which are formed transverse to the dominant flow direction. In the sea they have been observed with wave heights of up to 20m and wave lengths of several hundred metres. During the past 20 years sandwaves have been studied extensively, but nevertheless it is still not possible to predict their distribution or movement, or explain their formation and evolution except in general terms. A typical echo sounding record, orientated transverse to the sandwave crestlines, is shown in Figure 1.

Observations of the presence of sandwaves in the marine environment and in rivers date back to the middle of the 19th century (Sial, 1841; Johnson, 1879). Field studies of sandwaves in the British Isles were pioneered by Cornish (1901) who made detailed descriptions and measured their movement when exposed at low tide. It was only in the 1930's with the development of echo sounding techniques that such studies could be conducted in areas which are never exposed above the water surface. Much is owed to the observation made by Van Veen (1936, 1937, 1938a & b) who attempted morphological classification of sandwaves based upon analysis of echo sounding records. He interpreted their form in relation with tidal currents and made comparisons with desert dunes. Amongst these early conclusions, Van Veen stated that horizontal movement could be a danger to navigation, and that dredging was only of limited value as it did not significantly alter the conditions which control sandwave movement.

During the 1940's and 1950's much research was carried out in order to map the distribution of sandwaves and classify their geometric properties. In accordance with flume and river studies which show that sandwaves move in the direction of the steeper lee slope, much emphasis was placed upon detecting cross sectional asymmetry and inferring directions of bed load transport. It is generally accepted that the asymmetry of a sandwave is related to an imbalance of flood and ebb tidal flow. The work of Stride and his associates is particularly noteworthy in this context (Stride and Cartwright, 1958; Stride, 1959. 1963, 1970, 1972, 1973; Caston and Stride, 1973). From their data it was possible to map the broad distribution of



Echo sounding record across a group of sandwaves.
(Skerries Bank, Start Bay.)

Fig. 1

sandwaves and infer gross sediment circulation patterns around the British Isles. Much of the earlier research was motivated by geological interests. By understanding the structure and evolution of present day sea bed features, and their depositional environment, a better interpretation could be made of ancient stratigraphic records. This review synthesizes the present state of knowledge on bedforms derived from field and laboratory measurements, and considers what further research is necessary to help satisfy the requirements of present day applied problems. The three main applications for further research are navigation, submarine pipelines and submarine cables.

1.1 Navigation

The operating economics of modern bulk carriers require that vessels should be able to navigate at maximum capacity with a minimum of underkeel clearance, in order to reach major ports (Dickson, 1967). The potential of a port, in terms of size or draught of vessel which may be permitted, is in many cases dependent upon the water depths in the approach channels. The critical areas, which often lie at some considerable distance from the port, should be surveyed in sufficient detail to ensure that the shallowest depths are not missed (Cloet, 1976), and at a frequency which will guarantee tha changes of the sea bed do not become a danger to navigation. In such cases, it is the confidence in the accuracy of the surveys and knowledge of the magnitude of change of the sea bed which will determine the size of vessel which may use the port.

For example, the depths over the sandwave field at Longsand Head, 52 miles from the port terminals, are critical for the Port of London. As it is necessary to reach the terminals at high tide, it is necessary to cross the sandwave field at times close to low tide, or alternatively await the following tide (White, 1972). The accuracy of the surveys conducted in the sandwave area is subject to imprecise tidal reduction, which is transferred from a shore sited tide gauge, and wave effects which distort the echo sounding records. In addition, storm waves also affect the shape of the sea bed and hence the period of validity of the surveys.

Reference has been made to the Port of London where large vessels ($\leqslant$ 100,000 tons) navigate with a minimum underkeel clearance of approximately 1m, but the same criteria apply for smaller vessels using smaller ports.

1.2 Submarine pipelines

For protection from damage by trawlers and vessels anchoring, as well as from environmental conditions, it is the policy to bury oil and gas pipelines beneath the sea bed to a depth of at least 1m. In practice, the required depth of burial is not consistently achieved, and there is little knowledge of what subsequent changes in bed level may occur.

In sandwave areas, and other areas of excessive sediment movement, pipes may become exposed and suspended above the sea bed and therefore be increasingly vulnerable to damage. If such spanning occurs, it is likely to cause vibration of the pipe, which may result in damage to the concrete coating; whilst excessive spanning lengths will cause the pipe to buckle. Loss of the concrete coating can result in the pipe becoming positively buoyant (eg the Dutch Placid gas pipeline (Ocean Industry 1976) and the Shell Oil pipeline in Yell Sound (New Civil Engineer, 1976)).

The costs resulting from the break in a pipeline would be considerable in terms of loss of production, repair and pollution. Consequently pipeline routes are chosen where possible avoiding sandwave fields and other areas which are likely to be unstable (Caston, 1974). Such avoidance can be expensive (eg the approximate cost of the Ninian pipeline was £1½ million/ mile). Where sandwave fields cannot be avoided attempts are made to bury the pipe in the troughs between the sandwaves. When this is not possible, as is the case when a pipeline has to be routed transverse to the sandwave crestlines, attempts have been made to level the route.

1.3 Submarine cables

The number of submarine cable faults in the North Sea is increasing annually (Post Office, 1976). On the Covehithe to Katwijk cable some 40 faults occurred during a period of 12 months. Cable faults are usually breakages caused by fishing trawlers. Cables become increasingly vulnerable if left spanning in a sandwave field as a result of sediment movement. In international waters it has not proved possible to control or influence the individual fisherman to the extent that he will avoid charted cables, especially as sandwave fields are often prime fishing grounds. It is for these reasons that a positive relationship between cable breaks, intensity of trawling and sandwave areas has been established.

It is considered that the only ways to protect cables are either to avoid routing through high intensity trawling areas or to bury the cables beneath the sea bed. The former is not possible in the Southern North Sea. A plough has been developed which can bury a cable in sediments to a depth of 0.6m, but laying using this equipment is considerably more expensive than normal methods. The additional expenditure can only be justified if the cable will remain buried. It is concluded that, with the present state of knowledge, burial cannot be justified in such areas as sandwave fields and therefore the cables remain vulnerable.

Overburial, caused by sediment movement, is also undesirable as it is then not possible to lift the cable for repair without causing further damage.

2. DEFINITION AND CLASSIFICATION OF BEDFORMS

Sandwaves are one of a range of bedforms that have been studied in the laboratory, rivers, deserts and the sea.

No single classification covers all the environments, and no classification is considered to be fully acceptable as the mode of formation, which is the main criteria, is not understood. In the sea, most classifications have been based upon the plan and cross-sectional form of the features, as well as their size. In flumes and rivers the classification has been extended to include the relationship with certain easily measurable characteristics of the fluid flow. Conclusions gained in different studies can only be applied with caution to different environments, as in each case the basic physics of sediment movement is not the same.

2.1 Sub-aerial dunes

Bed forms with geometric properties similar to those of sub-aqueous sandwaves occur as sub-aerial dunes. The main differences are that on land:

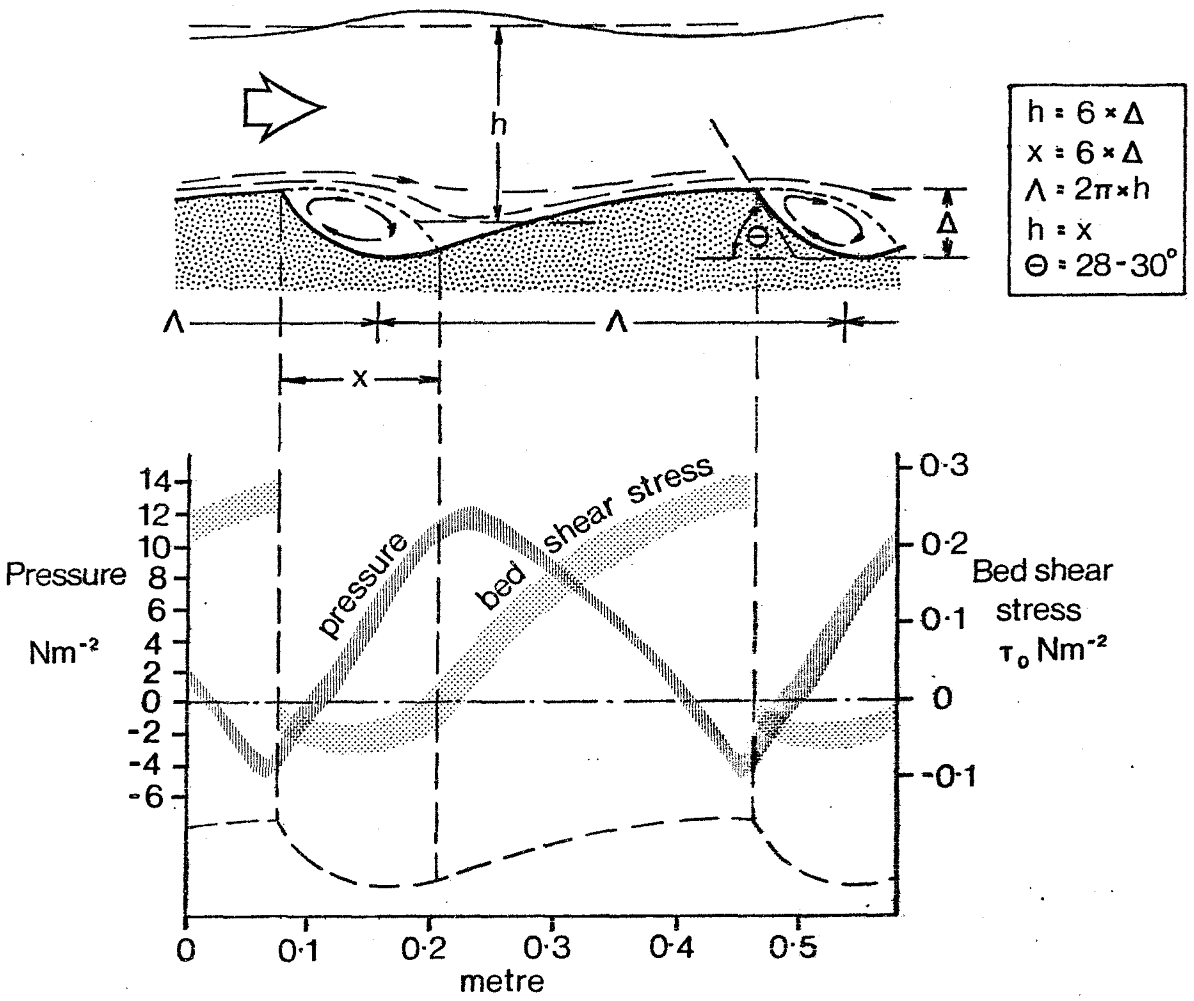
(a) The relative density of sand is greater (taking buoyancy into account, the density ratio of air to quartz sand is 1/2000, whilst that for water to quartz sand is 1/2.65).

(b) Significant particle movement occurs by saltation (Bagnold, 1941).

(c) There is no equivalent action of wind-generated waves on the water surface.

2.2 Bed forms in flumes

Sandwave-like features can be produced in flumes with steady flow. In such studies, if the flow velocity is sustained above the threshold of sediment movement, transverse bed forms, or ripples, will form (Gilbert, 1914; Liu, 1957; Simons et al, 1961). These features are initiated as low amplitude ripples and propagate their form down-flow (Southard & Dingler, 1971). With increase in flow the ripples grow into larger features, called dunes, which are asymmetrical in cross sectional profile and migrate in the direction of the flow. It can be demonstrated that the migration is the result of erosion of the upstream (stoss) slope and transportation of sediment to the crest with progressive increase in bed shear stress. At the crest, where the pressure is at a minimum, the sediment may either be carried into suspension or avalanche down the lee slope. If flow separation occurs at the crest, which is determined by the form parameters and the flow velocity, then reversal of flow will occur in the lee of the steep slope, between the crest and the zone of flow re-attachment (Fig 2). Lee slopes reach the maximum angle of repose of sand in water, and analysis of internal structures reveal laminae (Foreset) orientated parallel to the lee slopes forming the major constituent of the sedimentary structure.



Theoretical flow, pressure (deviation from hydrostatic) and bed shear stress distribution over a sandwave.

[after Yalin (1972) and Raudkivi (1967)]

The geometric properties of dune bed forms in flumes have been examined by Yalin (1964). He concludes that there is a critical dune height to water depth ratio of 1/6, above which two-dimensional dunes do not occur, and that the wave length of a dune is in the order $2\pi \times$ the water depth. Dunes are distinguished from ripples, whose wavelength is a function of grain diameter, but the two types of feature can exist together.

Simons et al (1961) found that in flume experiments with water depths of up to 30 cm and flow velocities of up to 90 cm $\sec^{-1}$ (Froude Numbers between 0.38 and 0.60)(for definition see figure 5) using 0.45mm diameter sand, that the ratio of dune height to flow depth was between 1/3 and 1/5.

In flume studies, however homogeneous the granular material might be and however hard it is tried to repeat exactly the same experimental conditions, identical dunes are never produced (Yalin, 1972). The formation of dunes is therefore, to a certain extent, a random process.

Yalin (1972) outlined the following classification of bedforms from flume studies:

Antidunes:	The wave length of the bed form is coupled to the free surface water wave. The wave lengths are equal, and the waves are in phase and stationary when the Froude Number is equal to one. When Froude Numbers are greater than one the bedforms move against the flow.
Dunes:	The wavelength is a function of the thickness of the boundary layer.
Ripples:	The wavelength is a function of the sediment grain size.

2.3 Marine Sandwaves

Marine sandwaves have parameters that appear to be proportionally similar to those produced in flumes, and therefore there is a tendency to infer that the hydrodynamic laws and relationships which have been established in flumes are applicable in the sea. However, unlike in flume studies where it is possible to select and control the number of hydrodynamic variables, in the sea the variables are many. Significant differences may be the result of the oscillatory tidal currents, the added effect of water waves, a non-uniform sediment grain size and limited sediment supply. (See also Section 8 and Figure 5). In addition, observed features need not necessarily be in equilibrium with the present day flow regime. Indeed, geological evidence suggests that some bed forms, morphologically similar to sandwaves, are ancient structures formed in an environment which no longer prevails (Kirby and Kelland, 1972).

Since the early works of Cornish (1901), Kindle (1917) and Bucher

(1919) it has been appreciated that smaller sandwave-like bedforms occur formed in the surface sediments on the flanks of the larger features (Fig 1). The simultaneous occurrence of two scales of bedforms indicates two phases of instability of the sea bed. Much discussion has developed over whether two distinct sizes of features occur as opposed to a continuous transition with no particular sizes being absent. Sundborg (1956), Simons et al (1961), Allen (1963), Raudkivi (1963) and Yalin (1964) subscribe to the view that there are two separate categories, whilst Van Straaten (1953) believes that there is a continuous transition.

Diverse terminology has developed in sandwave research. This is mainly because of the lack of a satisfactory classification.

In 1935 Van Veen introduced a classification of bedforms based upon cross sectional profile and inferred movement, viz:

1. Symmetrical or trochoidal
2. First transition form or distorted trochoidal
3. Second transition form or cat's back
4. Asymmetric or moving

Both Allen (1968) and Reineck and Singh (1973) have suggested the following size classification which, in both cases, is based upon the analysis of data obtained by many research workers.

1. Current ripples (Reineck), Small Scale ripples (Allen)
   Wave length normally less than 30 cms though exceptionally with wavelengths of up to 60 cms.
2. Megaripples (Reineck), Large Scale ripples (Allen)
   Wave length greater than 60 cms (and less than 30 m according to Reineck)
3. Giant ripples or sandwaves (Reineck)
   Wave length greater than 30m and up to 1000m or more (Allen does not recognise a third group)

In order to equate these classifications with that of Yalin (1972) (Page 5), relationships with flow velocity, flow depth and grain size need to be established. In addition data on other factors, such as steepness of lee slopes and the occurrence of flow separation, would contribute to understanding the mode of formation of the different bed forms.

For the purpose of this paper Reineck's classification, based upon size, will be used, using the terms ripples, megaripples and sandwaves though the limits of size are considered to be somewhat arbitrary.

3. OCCURRENCE OF SANDWAVES

Most research on sandwaves has been conducted on the Continental Shelf where tides and waves are the major dynamic forces. Probably the largest area of sandwaves in the world is located in the Southern North Sea. McCave (1971) has estimated that sandwaves in this area cover an area of some 15,000km^2. Extensive studies have been carried out in the North Sea by Stride and Cartwright (1958), Stride (1965), Dingle (1965), Houbolt (1968), Johnson and Stride (1969), McCave (1971) and Terwindt (1971). In the USA similar qualitative studies of the large sandwave field which occurs on Georges Shoal have been reported by Jordan (1962) and Stewart and Jordan (1964). More discrete sandwave fields occur in association with offshore banks (Robinson, 1961; Jones et al, 1965; Langhorne, 1973), and where channel constraints cause flow velocities to be within the range for sandwave formation (Ludwick, 1970, 1972, 1974).

Although some limits can be placed upon the ranges of depth, flow velocity and grain size under which sandwaves are formed, it is not possible to unequivocally predict where sandwaves occur. In two apparently similar environments sandwaves may or may not be present (Terwindt 1971).

3.1 Depth Limits

Dingle (1965) considers that sandwaves in the S North Sea do not occur in water depths greater than 55m as in that area, at those depths, the flow velocities are not sufficient for sandwave formation. Cartwright (1959) however has studied the occurrence of sandwaves on La Chapelle Bank, at a depth of 166m, where flow velocities reach 80cm/sec. Cartwright referred to these depositional bed forms as "lee waves" as they are associated with a discontinuity on the sea bed which sets up a perturbation in the flow under stratified conditions. Lonsdale and Malfait (1974) and Lonsdale and Speiss (1977) report on sandwaves which occur in abyssal depths (up to 4500m). These features tend to be of low amplitude ($<$ 1m) with wave lengths of up to 100m.

3.2 Sediment grain size limits

It is obvious that sandwaves are not formed unless there is sufficient sediment of the right grain size in the area, or passing through the area. Terwindt (1971) considers that sandwaves in the Southern North Sea are not found where the mean grain size exceeds 0.5mm. He further concludes that sandwaves are not formed if more than 15% of the sediment is composed of mud. These conclusions must be considered in relation to the flow velocities, which Terwindt shows to range between 60 and 90cm/sec, because Dyer (1971) reports gravel waves with mean sediment grain size of 25mm, formed on the Solent Bank where flow velocities reach nearly 2m/sec.

3.3 Flow Limits

Kenyon and Stride (1970) consider that sandwaves occur in areas where maximum surface tidal flow velocities reach between 0.6 and 1.3m/sec. At higher velocities the sand sized sediments are streamed parallel to the dominant flow directions and the bed form is characterised by sand ribbons. The range of flow velocities suggested by Kenyon and Stride (1970) are generally supported by other research studies. For example:

0.8m/sec - San Francisco Bay - Gibson (1951)
0.8m/sec - Start Bay, Devon - Robinson (1961)
1.0m/sec - Georges Bank - Jordan (1962)
0.8m/sec - Warts Bank - Jones et al (1965)
0.4m/sec - St Andrews Bay, Florida - Salsman et al (1966)
1.00m/sec - Browns Bank - Drapeau (1970)
0.60m/sec - Chesapeake Bay - Ludwick (1970)
0.60m/sec - Thames Estuary - Langhorne (1973)
0.2 to 0.3m/sec - Basin Strait - Ozasa (1974)
1.00m/sec - German Bight - Pasenau and Ulrich (1974)

Both Yalin (1972) working in flumes and Cartwright (1959) working on the edge of the Continental Shelf suggest that a discontinuity on the bed, causing a disturbance in the flow, is required for sandwaves to form. Consideration of the location of most sandwave fields around the British Isles supports this contention, as in most cases a possible discontinuity can be identified.

4. STRUCTURE OF SANDWAVES

It has long been appreciated that a clear understanding of the internal structure of a sedimentary bed form would make a very significant contribution to determining its mode of formation. Interpretation of internal structures in relation to the hydrodynamic conditions is also fundamental to assessing the depth and rate of sediment movement and the interpretation of ancient stratigraphic records. At sea many attempts have been made to study internal structures, using such techniques as high resolution, continuous seismic profiling and coring (Houbolt, 1968; Newton, 1968, Imbrie and Buchanan, 1965; Kirby and Kelland, 1972; Kirby and Oele, 1975).

The most common structures found in sandwaves are foreset and bottom set laminae (Reineck and Singh, 1973), with the bulk of the bed form being composed of the former. Studies carried out in uni-directional flow in both flumes and rivers show that foreset laminae are formed by sediment avalanching down the steep lee slopes and are indicative of horizontal movement.

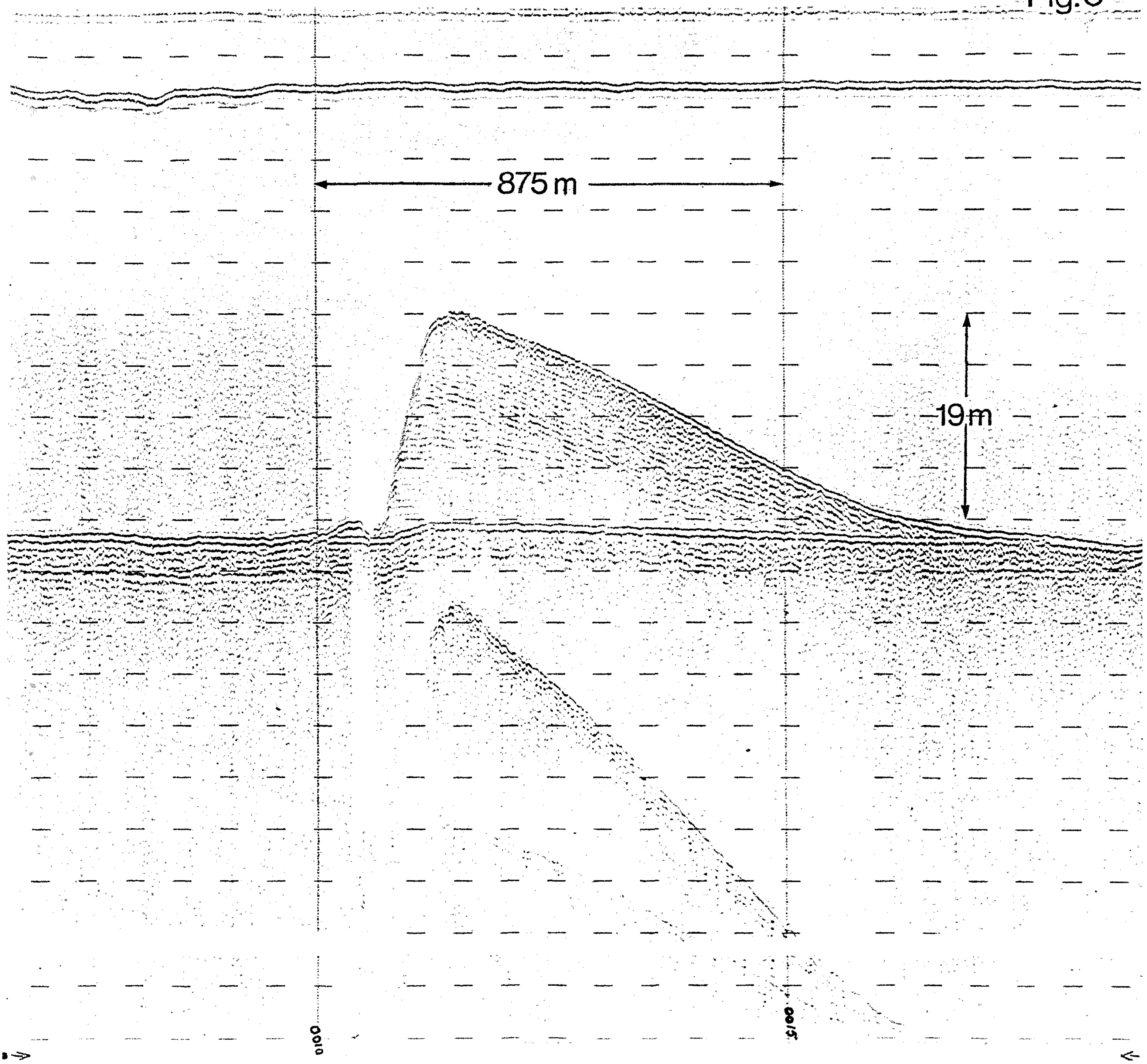
Exceptions to the general predominance of foreset laminae are common. Figure 3, for example, demonstrates that the bulk of a sandwave may be composed of laminae orientated nearly parallel to the stoss slope. This suggests that the feature has developed by progressive accumulation of sediment on its stoss slope and there is little indication of the development of foreset laminae or of horizontal movement.

Further exceptions are reported by Kirby and Kelland (1972) and Kirby and Oele (1975) for sedimentary ridges in the Southern North Sea. In an area of irregular ridges, core samples revealed well graded sediments with little evidence of internal structure. Since the thickness of the lithological unit was approximately of the same in both the troughs and on the crests of the ridges, it was considered that the succession occurred as a "drape" over pre-existing features.

Newton (1968) working in both the tidal environment of the North Sea and the non-tidal Baltic, failed to distinguish between tide and wave formed features. In both cases the predominant structure consisted of uni-directional foreset laminae.

Continuous seismic profiling records in sandwave areas commonly reveal a strong acoustic reflection coinciding with the base of the sandwaves and often outcropping in the troughs (Fig 3). Salsman et al (1966) observing megaripples (height 30 - 60 cms, wavelength 12 - 20m) in St Andrews Bay, Florida, reported that not all the sediment deposited in the trough was eroded when next exposed by the passage of the megaripple and therefore there was a gradual increase in bed level. The process of avalanching of sediments

Fig.3



Continuous seismic profile record across a sandwave showing internal structure.

down the steep lee slopes of sandwaves results in grading of the sediments with the coarse particles accumulating at the bottom. These coarser sediments will be more resistant to further erosion, on account of their coarse grain size, and also their position in the trough between sandwaves where bed shear stress is minimal. It is inferred that in some cases the strong acoustic reflector at the base of a sandwave develops from sediment grading resulting from sandwave migration. This layer of coarser sediment, because of its resistance to erosion, therefore tends to form a base plain over which transport of finer sediments occurs. In other cases, pre-existing geological horizons may also be present.

5. MOBILITY OF SANDWAVES

Many research programmes have been carried out in order to measure sandwave movement. From flume studies Simons et al (1961) concluded that dunes progressed down flow at a rate of between 0.015 and 0.36cm s^{-1}. In rivers sandwaves have been shown to migrate at a rate of 2.5m/day, at peak discharge, in the River Loire (Ballade, 1953) and at 1.7m/day in the Mississippi (Johnson, 1879). In the tidal marine environment a wide range of movement has been reported. For example: 103m/year (Stewart and Jordan, 1964), 5 - 10cm/day (Jones et al, 1965), 1.35cm/day (Salsman et al, 1966), 35 - 150m/year (Ludwick, 1972), 25m/year (Langhorne, 1973) and 60m/year (Pasenau, 1974). As indicated, the individual research workers considered that the frequency of observations are indicative of the rates of movement averaged over the interval between measurements.

Few reports have failed to comment that the short period movement could be considerably increased when tidal flow conditions are augmented by storm generated wave action. Johnson and Stride (1969) consider that the neap tidal flow velocity can be one tenth of the spring rate in calm seas, but can be equal to the spring rate when storm waves augment the neap tides. Furthermore, when spring tides themselves are aided by storms the sediment transport rate can be an order of magnitude greater than during light winds. It is not clear which events will be preserved and recognised in the deposits formed on the sea bed. It is possible that the evidence of major storms will last longest, and only be obliterated after long periods of more normal conditions.

Despite these considerations, only a few studies have endeavoured to relate movement or morphological change to both tide and surface wave energy conditions (Davis, 1965; Newton, 1972; Langhorne, 1977). In addition, it is considered that many of the studies have been restricted by inadequate positional accuracy, an insufficient frequency and density of observation and an inadequate duration of study. Therefore the quoted rates of movement are in many cases only of limited value. The reality of these comments is emphasised by Langeraar (1966) who having completed a series of six surveys of a sandwave area over a period of 2½ years, concluded that no movement exceeded the margin of accuracy of the position fixing system which he used.

In many studies, for simplicity, sandwaves tend to be thought of as two-dimensional features, and therefore measurements of movement etc made in one position are inferred to apply to extensive crest lengths. Clearly in the natural environment such constancy seldom occurs over large distances, and in most cases sandwaves must be considered to be three-dimensional features. Although individual sandwave crests may be followed for several kilometres, their form parameters do not remain constant and it is unlikely that uniform movement will occur. Langhorne (1973) compared surveys made over a two year period in the Outer Thames Estuary, and concluded that sandwave movement did not continue at a steady rate. It appeared that part of a sandwave, which was previously showing movement, would stabilize and further movement may occur elsewhere on the same sandwave. These findings supported the suggestion of differential movement made by Stride (1970).

Little progress has been made in determining vertical changes of sandwave height despite its importance to navigation. This is mainly because of the difficulties of obtaining accurate vertical and horizontal measurements with reference to known datums. Cloet (1976) assessed the sounding error which is likely to occur in a sandwave field using standard surveying techniques. He concluded that, for a survey conducted at a scale of 1:20,000 with a line spacing of 100 metres, 3% of the least depths along crests between the survey lines would be more than 1m shallower than the recorded data. Evidence of the intervening depths was obtained from a "saturation" survey conducted with an approximate survey line spacing of 13.5m. Cloet (1976) suggested that the error may be due to undulations along the crestlines produced by megaripples. Owing to ship motion, it is not normally possible to determine the size of megaripples on the flanks of sandwaves from echo sounding records.

Extensive use of high resolution sidescan sonar and diver observation has shown that, in most cases, the surface sediments on the flanks of a sandwave are formed into smaller megaripples. These megaripples are less stable than the larger sandwaves and undergo constant modification in response to the prevailing flow conditions. In the case where a sandwave is completely carpeted in megaripples, any change in form or position of the underlying sandwave will be the result of the changes which have occurred in the megaripples (Allen and Collinson, 1974; Langhorne, 1977).

Langhorne (1977) has shown that megaripples, occurring in a sandwave field in the outer Thames Estuary, can retain their sonar identity despite sediment movement for periods of approximately six days. In the event of storm conditions, high oscillation velocities combined with tidal flow destroy the prevailing megaripples. Observations made after a storm has abated reveal short wavelength megaripples which progressively increase in wavelength until the original wavelength is attained (Fig 4). If such changes can be shown to occur on the flanks and in the troughs between sandwaves, then at least similar or greater changes are likely to occur on the crests, where the bed shear stress and surface water-wave induced motion are greater.

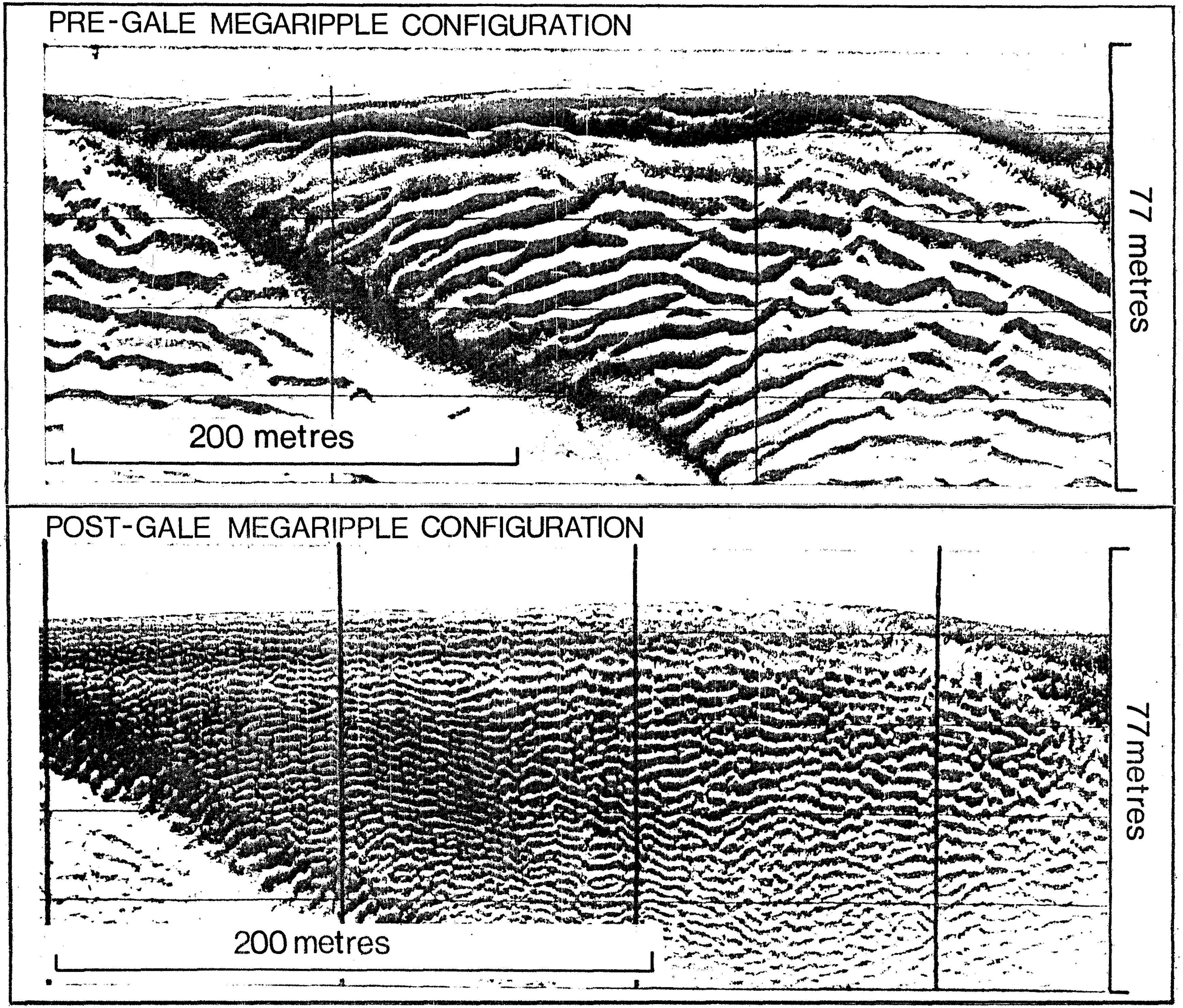


Fig.4

Sidescan sonar record showing the pre and post gale megaripple configuration on the flank of a sandwave.

A sandwave, being a ridge orientated transverse to the dominant tidal flow directions, partially protects the megaripples on either flank from the tide flowing from the opposite direction. If the protection is sufficient, then the megaripples on either flank will have asymmetrical cross sectional profiles, with lee slopes facing the crest of the sandwave and net sediment transport will be towards the crest. If the dominant tidal flow directions at the sea bed are not at 180° as is often indicated by the orientation of the megaripples, then sediment will move along the crest tending to extend its length. Similarly, sandwaves with opposing asymmetry often occur on the flanks of sand banks which are orientated transverse to the tidal flow directions (eg between the Sandettie and Falls Banks in the Dover Straits), in which case the sandwaves are an integral part of a larger sedimentological system.

6. FLOW OVER SAND WAVES

Measurements of flow over ripples and dunes in flumes have shown that the flow pattern has several characteristic features. On the upstream face of the dune the rising elevation of the bed causes an acceleration of the near bed flow and there is a decrease in surface pressure. The velocity gradient near the bed and also the bed shear stress consequently increases towards the crest, to a maximum value about equal to that for the same flow over a flat bed (Raudkivi, 1963). Upstream of that crest where the slope starts to become convex rather than concave, the velocity gradients and the bed shear stress diminish slightly. At the crest, where the steep avalanche slope commences and pressure is a minimum, flow separation often occurs. The zone of high current shear leaves the boundary and rejoins it about six ripple heights downstream of the crest (Raudkivi, 1963). In the separation zone a weakly rotating vortex occurs giving flow towards the steep lee slope.

At the re-attachment point the turbulent intensities are greatest and surface pressures maximum (Raudkivi, 1966). Rifai and Smith (1971) show turbulent intensities, normalized by the local mean velocity, reaching 45% near the re-attachment point and minimum intensities of 15% occurring near the crest. At a level about one wave height above the crest the turbulent intensities were almost uniform over crest and trough. At this level the mean flow streamlines are approximately sinusoidal, though out of phase with the actual sand boundary.

Separation does, however, not necessarily occur over all features. If the pressure increase on the lee side is not too abrupt then the flow need not separate, though there will be deceleration of the flow near the boundary.

Dyer (1970), working in the Solent, concluded that the maximum shear stress at the crest was approximately four times that in the trough, and no evidence existed for flow separation or reversal of flow. The sandwaves in the study area maintained maximum lee slope angles of approximately 10°.

7. MAXIMUM SLOPE ANGLES

Field observations have shown that in many cases maximum slope angles do not approximate to the angle of repose of sediment in water. Langhorne (1973) working in the Thames Estuary found that lee slopes seldom exceeded 15°, whilst Ludwick (1972) found lee slopes in Chesapeake Bay averaged 1.5° and only occasionally reached 6°. In such cases, flow separation is unlikely to occur, and sediment will not avalanche down the lee slope. In other areas however, lee slopes attain angles of 25° or 30° (eg: the Skerries Bank, Start Bay). The steepness of a lee slope and the degree of asymmetry of a sandwave has been long assumed to be related to the imbalance of the flood and ebb tide in that area. Mitchell (1972) has shown that with excess pore water pressure, slopes can be caused to slump as a result of loss of soil strength brought about by fluctuations in pressure. In the marine environment such pressure fluctuations can be produced by storm waves, and it is possible that, in some cases, the shallow angles of slope may be the result of slumping. In other areas, the steep avalanche slopes prevail because of both a marked imbalance of flood and ebb tide and a low incidence of storm waves reaching the area.

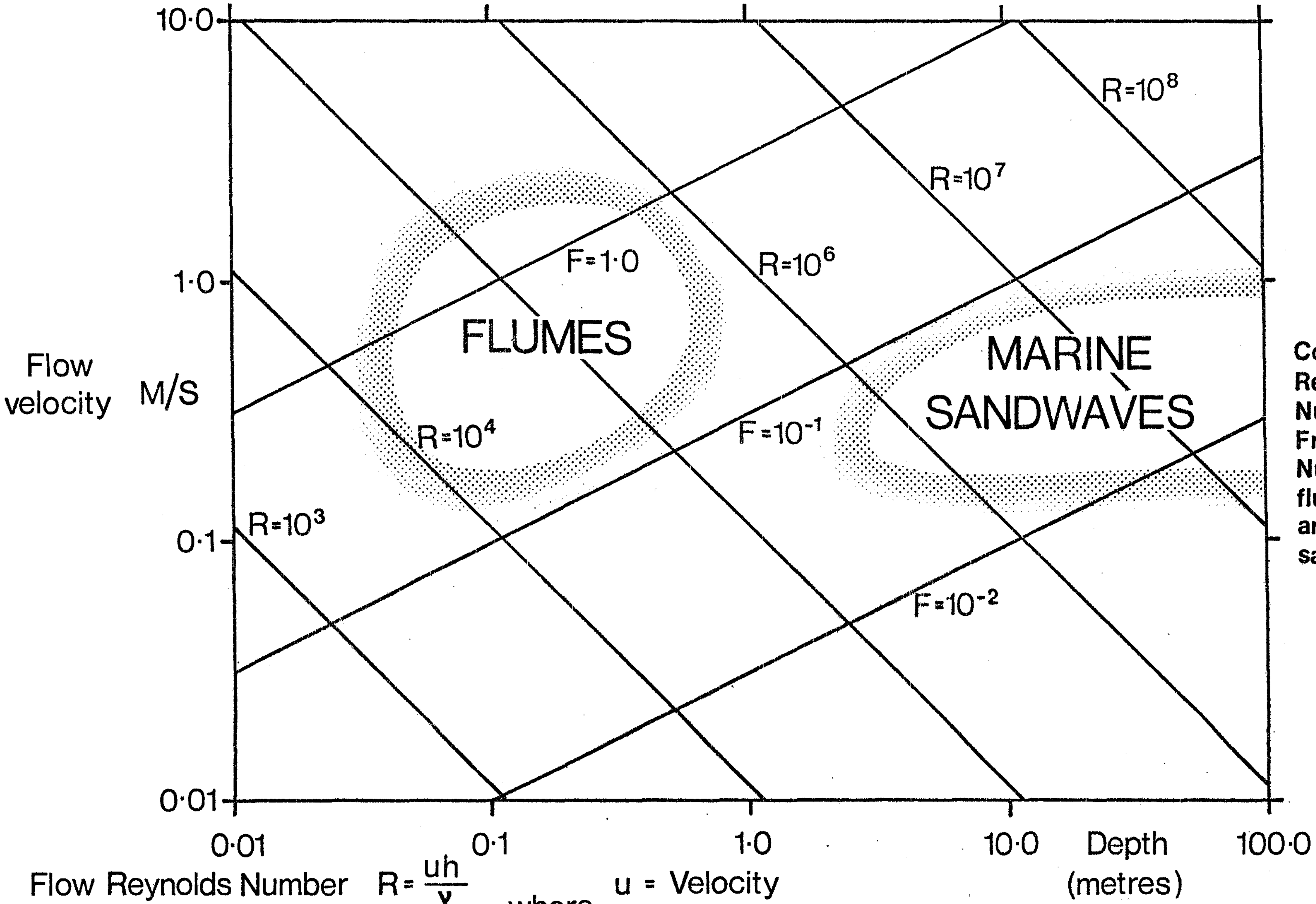
8. THEORETICAL CONSIDERATION OF BEDFORM DEVELOPMENT

Understanding the formation and the movement of bedforms may be assisted by modelling the water flow and applying existing sediment transport theory. In order to do this, to decrease the complexity of the problem and to provide comparison with existing data, it is customary to group the independent variables into non-dimensional numbers. For a steady flow the variables are: fluid viscosity (μ) and density (ρ), the diameter (D) and the density (ρ_s) of the grains, the depth (h) and the depth mean velocity of flow (u) and the bed shear stress (τ). The grain density and size can also be characterized by the grain fall velocity (ω), the shear stress by the friction velocity ($u_* = \sqrt{\frac{\tau}{\rho}}$), and the fluid properties by the kinematic viscosity ($\nu = \frac{\mu}{\rho}$).

The variables can be grouped in a variety of ways. For the fluid, the Reynolds number $\frac{uh}{\nu}$ and Froude number $\frac{u}{\sqrt{gh}}$ are important parameters in defining the similarity of flow conditions. The grain Reynolds number $\frac{u_* D}{\nu}$ defines the effect of the sediment surface on the flow near the bed. For the sediment, the Shields entrainment function $\frac{\tau}{(\rho - \rho_s)gD}$ or the mobility number $\frac{\omega}{u_*}$ are used in defining the sediment movement. Different combinations of these non-dimensional numbers are used by different workers, particularly in the civil engineering hydraulics field and there are often inconsistencies between them. It is not clear which are the appropriate factors for scaling between flume and river measurements and there are considerable differences between the sediment transport theories that have been proposed.

An example which clearly shows the difficulties of scaling from flume studies to the sea is given by consideration of the Froude number. In flumes dunes are formed and remain stable when Froude numbers are between 0.15 and 1.0, whilst in the marine environment Froude numbers are generally in the range 0.03 to 0.1. Similar order of magnitude differences occur with other non-dimensional numbers, and though it may be possible to scale one non-dimensional number it is not possible to scale them all simultaneously. Consideration of Froude Numbers in association with Reynolds Number is shown in Fig 5.

In many analytical models the flow is assumed to be inviscid, irrotational and steady. Several workers have linked this to equations for sediment transport and have studied the evolution of bed forms. Kennedy (1963) found that there were two modes of instability. One resulted from an interaction of the bed and the free surface and the other was an instability related to the sand size. His model indicates that under steady flows, at Froude numbers similar to those occurring in regions



Flow Reynolds Number $R = \frac{uh}{\nu}$

Froude Number $F = \frac{u}{\sqrt{gh}}$

where

u = Velocity

h = Depth

ν = Kinematic viscosity $1{\cdot}14 \times 10^{-6}$ sq m/sec at 15°C

Comparison of Reynolds' Numbers and Froude Numbers for flume studies and marine sandwaves.

Fig.5

where marine sand waves exist, the wavelength of the initial instability of a flat bed is highly dependent on both the Froude number and mobility number.

Other workers have included internal friction in the fluid flow equations (Smith, 1970; Fredsøe, 1974). Some of these consider the causes of the asymmetric development of dunes, but results indicating two phases of instability are fairly general. These have their parallel in ripples and dunes.

The deterministic models have been developed further using spectral models, (Jain and Kennedy 1971). These indicate that the shorter wavelength bedforms travel faster than the longer ones. Consequently with time the shorter waves merge with the longer and these grow until their heights become limited by the angle of repose and the water depth.

Though these analytical models produce some recognisable characteristics of natural bedforms, they are not at a stage where they can be used for predictive purposes. Also as they are all concerned with steady flow it is unlikely that they are generally applicable to the marine environment. A simple model for sediment movement over bedforms in an oscillatory tidal current needs to be developed, before one which accounts for the generation of bedform from an initially flat surface.

9. CONCLUSION

Present day engineering and commercial requirements necessitate that research on sandwaves should be directed towards the measurement of sandwave movements and their relationship to tides and waves. It is a fundamental requirement to understand the way in which bedforms are generated by the flow, and what flow characteristics govern their form and distribution, as well as the magnitude of changes brought about by changes in flow conditions.

During the past 25 years the main emphasis of sandwave research has been directed towards the observation and description of sandwave 'statics'. Most of the data, which was obtained by standard techniques such as echo-sounding, sidescan sonar and sediment sampling, was used to identify sandwave distribution, shape and composition as key factors for defining sedimentary circulation patterns.

Less progress has been made with the quantification and description of sandwave dynamics, which include form changes and movement, as well as their mode of formation and evolution. This is mainly because of a lack of appreciation of the complexity of sandwaves, and therefore of the density of measurement required to define temporal and spatial changes in form or position. In addition, progress has been restricted by the difficulties of making precision measurements at sea, in particular accurately fixing the position of the observing vessel.

When trying to define hydrodynamic relationships there has been a tendency for sandwaves to be approximated as simple two-dimensional features. In fact, they are complex, and a typical sandwave field has a wide variety of wave heights and lengths, with smaller less stable features often formed in the surface sediments. There is no clear analogue of sandwaves in steady flow.

The form parameters of marine sandwaves have not been interrelated satisfactorily with hydrodynamic factors. This is in contrast with flume studies in which definite relationships have been established for ripples and dunes. The reason for this is that in flume studies it is possible to select and control the number of variables whilst in the marine environment the variables are many and their interrelationship and relative significance only poorly understood.

A full understanding can only be achieved if detailed field studies are carried out and related to theoretical models. In the early studies of sandwaves the present day bed forms were used as a key to interpreting the past. In future research, for which the engineering and navigational importance is paramount, the main requirement is for prediction and therefore the present must be studied as a key for the future.

It is concluded that future research on sandwaves should be based upon the following outline programme:

1. Use modern high-accuracy surveying techniques to measure the changes in sandwave form and distribution at a number of different environmental sites around the British Isles. This will provide data on the magnitude of change which occurs under different conditions.
2. Relate the form changes to gross flow variables (tidal currents and surface waves) and to the characteristics of the sediments and their availability. This will lead to a better understanding of the empirical laws which describe the mobility of the sea bed and the ability to predict the changes which may occur in areas of commercial or engineering importance.
3. Make detailed measurements of the water flow, bed shear stress and sediment movement over a sandwave in order to understand the mechanisms of their formation and to develop a predictive model based upon an appreciation of the detailed physics.
4. Develop a mathematical model for sediment movement over different bed forms to complement the field measurements.

In a wider context the research programme should be extended to include the study of sea bed mobility in areas free from sandwaves. In such areas particular emphasis should be placed upon ascertaining the thickness of the mobile layer of the sea bed.

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