WAVE-MUD INTERACTION IN MUDBANKS

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CERTIFICATE

This is to certify that this Thesis is an authentic record of research work carried out by Mr. Joseph Mathew under my supervision and guidance in the Centre for Earth Science Studies for Ph.D. Degree of the Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any other degree in any University.

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CONTENTS

PREFACE

Any developmental activity along the coastal zone requires a clear understanding of the dynamic processes controlling its very existence. When most of the processes, which are common to all coastlines are fairly well known, there are some localised, but important processes requiring further research for developmental planning. The mudbanks of the southwest coast of India is one such phenomenon. Being a rich fishing ground, particularly when the rest of the sea area is hostile for fishing, it has great economic significance. Its technical importance in coastal engineering is that, it protects the coast behind it, when the major portion of the southwest coast of India faces severe erosion. When we take into consideration the transient nature of the erosion, which affects several stretches of the coast only for one or two months during the early stages of the southwest monsoon, there is a need only for a temporary protection. As the mudbanks are formed exactly during this period, they can be better utilised for erosion control, if they are known well.

The most striking feature of the mudbanks is its ability to attenuate the surface waves almost completely before they reach the shore. The mudbanks of the southwest coast of India are transient in nature. These mudbanks, which are unique to this coast, have attracted the attention of several researchers for the last few decades. Previous investigations on mudbanks covered their hydrographic features and physical processes involved in their formation.

Waves are one of the most important factors involved in the various processes controlling the mudbanks. Detailed studies on waves and their role in mudbanks are lacking. Wave energy dissipation over soft muddy bottom is dependent on the characteristics of incident waves and bottom sediment. The significance of the near-bed layer has not been considered in the previous studies. In this context, an investigation on *wave-mud interaction in mudbanks* is undertaken with the objectives to study the wave characteristics during different stages of mudbank, to study the wave-mud interaction processes and to derive a conceptual model of the mudbank.

The work is presented in six chapters. The first chapter introduces the problem with the objectives. A review of the wave energy dissipation theories, sediment characteristics, wave-mud interaction and fluid mud formation is undertaken in Chapter 2. The next Chapter describes the field methods and analytical techniques used in the study. Long-term wave data collected inside and outside the mudbank and the sediments, both suspended and bottom, are analysed and the results are presented in Chapter 4.

Wave-mud interactions in the context of mudbank generation form the theme of Chapter 5. This covers sediment suspension, fluid mud dynamics, transfer of wave energy, etc. in the context of formation, sustenance, dissipation, localisation and movement of mudbanks. The importance of this study is that an attempt has been made for the measurement of viscosity of fluid mud in space and time to evaluate the net behaviour of fluid mud. The suspended sediment concentration in the water column and influence of the hydrographical parameters on it during different stages of mudbank are also discussed. Possible mechanisms of energy transfer from surface wave to fluid mud layer are examined to account for the wave energy dissipation. Role of wave refraction in localisation of mudbank is discussed. Based on this study a conceptual model is presented to explain the formation, sustenance and dissipation of mudbank. The final chapter gives the summary and conclusions of the present investigation and gives recommendations for future studies.

Based on the present work two papers have been published :

(i) Mathew, J. and Baba, M., 1989. Modelling the wave attenuation over the mudbanks. Proc. 3rd Nat. Conf. Dock and Harbour Engng., Suratkal, 759-765.

(ii) Mathew, J. and Baba, M., 1991. On generation of mudbanks. Proc. 3rd Int. Conf. Coastal and Port Engng. in Developing Countries, Mombasa, Kenya, 918-924.

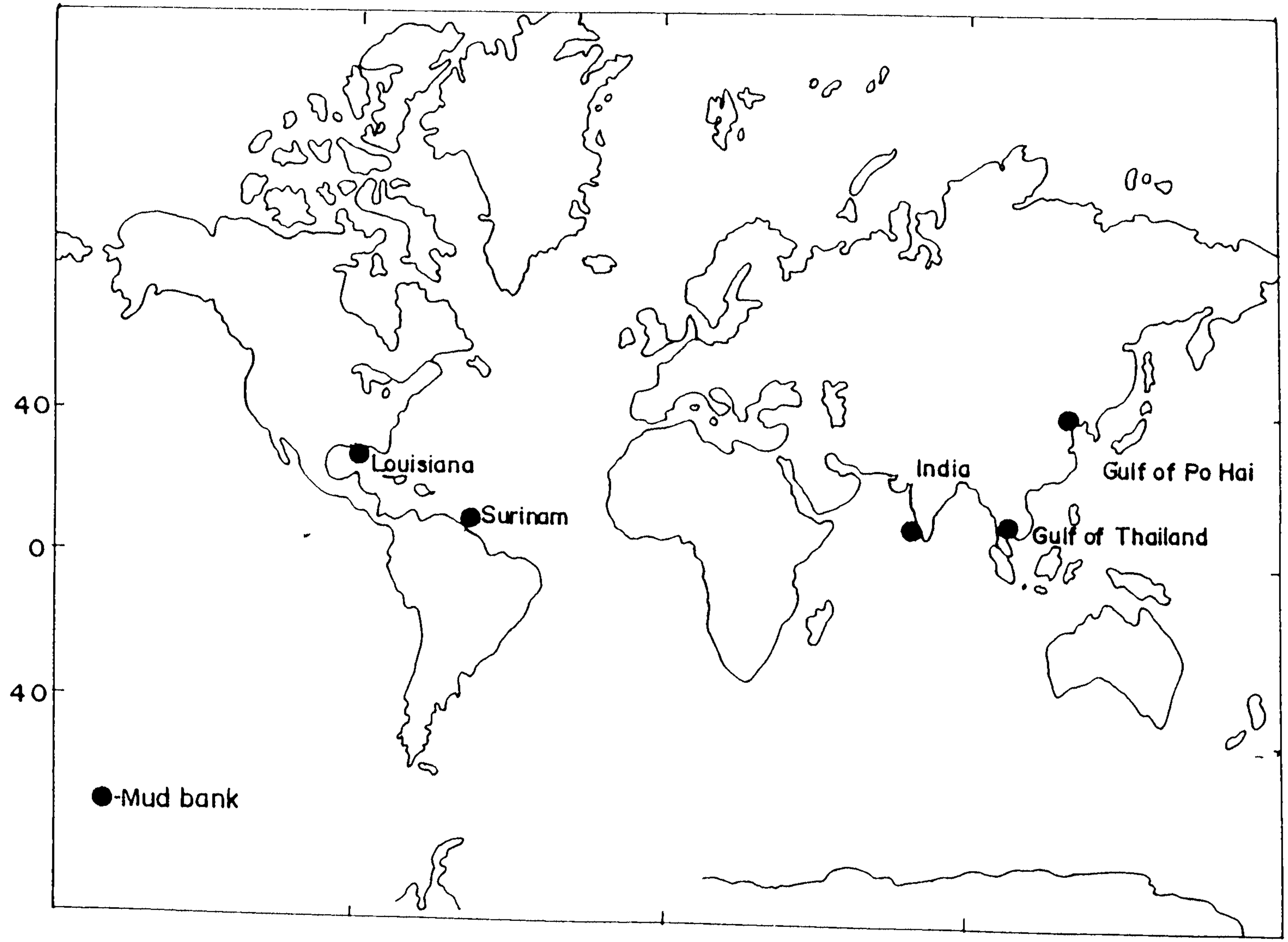
Chapter 1

1. INTRODUCTION

Several reaches of coastal waters have soft muddy bottom consisting primarily of silt and clay. Field observations and theoretical studies show that waves are attenuated rapidly when propagated over a bottom blanketed by these cohesive sediments. In certain localities the attenuation is so high that the waves get completely dampened by the time they reach the shore. Such areas, known as mudbanks, are reported along the southwest coast of India, northeastern coast of South America and a few other coasts (Fig.1.1).

Most of the mudbanks reported are adjacent to large rivers, which are the primary sources of the sediment. Examples include the northeast coast of South America (Amazon river), the Louisiana coast (Mississippi river) and the northeast coast of China (Yangtze and Hwangho rivers). The mud brought in by these large rivers flow along the adjacent coasts. These form permanent accretory features. Tidal variation along these coasts is significant and hence during low tide these sediments get exposed forming mudflats.

With a large number of rivers debouching into the sea, several mudbanks of the southwest coast of India also appear near their inlets (eg. Narakkal near Cochin, Ullal near Mangalore, etc.). However, in contrast to the mudbanks reported elsewhere there are a few of them in the southwest coast of India appearing in areas which are free from the influence of rivers. Examples of such mudbanks are Alleppey, Purakkad, Calicut. Though structurally both these mudbanks, as per the available reports (Bristow, 1938; Kurup, 1977; CMFRI, 1984), do not differ, the explanation that the source of mud is river discharge does not hold good for the latter owing primarily to its location. The river dependent mudbanks have been studied extensively when compared to the latter.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0
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Louisiana
Surinam
India
Gulf of Po Hai
Gulf of Thailand
-Mud bank

The mudbanks along southwest coast of India are, however, transient in nature. They are defined as patches of calm, turbid water with high load of suspended sediment, appearing close to the shore with a clay substratum during the rough monsoon season (Kurup, 1977, CMFRI 1984, Mallik *et al.*, 1988; Ramachandran, 1989). A typical mudbank exhibiting perfect calm condition, with the adjacent coasts experiencing intense high wave activity is shown in Fig.(1.2). About twenty such mudbanks (Fig.1.3) with dimensions of 2-5 km alongshore and 1.5-4.0 km offshore, are reported to appear along this coast during almost all the southwest monsoon seasons (Bristow, 1938; Kurup, 1977; CMFRI, 1984).

Although severe storms and hurricanes normally do not occur along this coast, the high southwest monsoonal waves attack the coast for a short period of a week or two, during June-July. Several locations of this coast are affected by severe erosion during this rough season. The mudbanks are formed during this period and wherever they are present, like the submerged breakwaters they protect the beach behind it from further erosion. The socio-economic importance of these mudbanks is well known. These mudbank zones are potential fishing grounds and the local fishermen use them as temporary harbours since the other regions are inaccessible due to rough seas.

1.1 Mudbanks - A Review

The first known record of the presence of mudbank along the southwest coast of India dates back to 1678 in an extract from Alexander Hamilton's account of the East Indies, which appeared in Pinkerton's *Collections of voyages and travels* reproduced in Travancore Administration Report, 1860 (as reported in Kurup, 1977). Cope (1755) narrates Alleppey mudbank as one with

Fig. 1.2 (a) Mudbank off Alleppey; (b) adjoining coast experiencing high wave activity

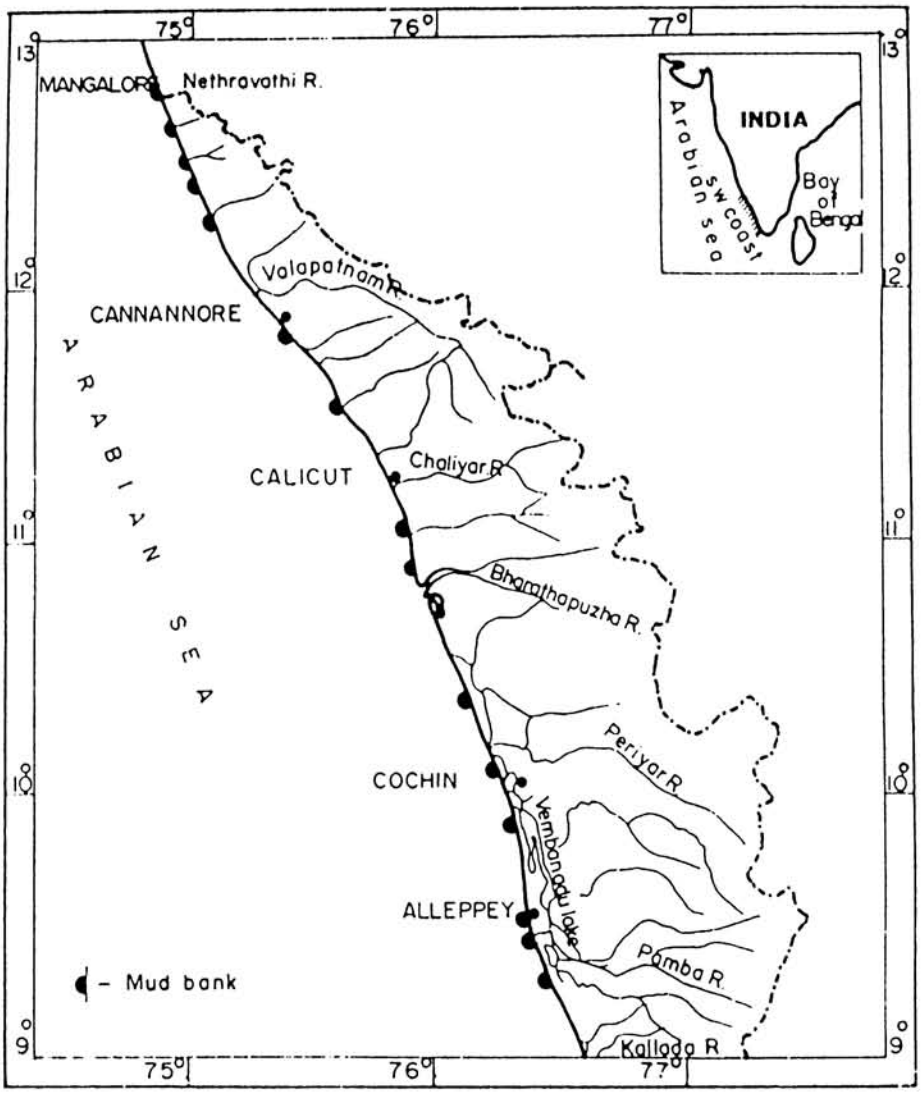

Fig. 1.3 Locations of occurence of mudbanks along south-west of India

'ew parallels. The early reports about the mudbank is contained in Bristow 1938), which includes the hypotheses on the mudbank formation, source of nud and movement of mudbank, all based on visual observations.

1.1.1 Hypotheses on the source of mud

Crawford (In: Bristow, 1938) may be credited with attempting the first possible explanation for the source of mud in mudbank. Based on his observation of mud cones on the beaches, he suggests that there exists a subterranean passage, or stream, that becomes more active during heavy rains accompanying the monsoon, carrying vast quantities of soft mud from some of the inland rivers and backwater to the sea. John Rhode (In: Bristow, 1938) suggests that a fluid mud strata exist below Alleppey, thereby postulating that the mudbank of Alleppey appears and vanishes as the level of the inland water rises and falls. Herber Drury (In: Bristow, 1938) is of the same opinion and suggests the possibility of a subterranean channel communication with the sea from the backwater, through which large quantity of mud is carried off and thrown up by the sea in the form of a bank. According to King (1881), the mudbank may be entirely due to the discharge of mud from under the land along with the percolation or underground passage of lagoon water into the sea. Philip Lake (In: Bristow, 1938) also supports the hypothesis of existence of a subterranean channel for the source of mud. Bristow (1938) disagrees with the view that the mud being pushed up in adjacent coastal area is due to the difference of pressure generated by the rise in water level in the estuary. He is of the opinion that a water bearing stratum exists at good depth, which brings down water from the hill and crops out under the sea at varying distances from the shore, thereby lifting bottom mud and anything sufficiently buoyant that lies buried in the mud. The first scientific investigation on the mudbank formation, initiated by Bristow is given in the report of

Du Cane *et al.* (1938). According to them, the mud of the mudbank might be from an older source and the laterite/alluvial sediments from the land are run down by the rivers and deposited on the sea bed close to the shore in a regular process of river discharge. The sediments thus deposited accumulate near the coast and are churned up by monsoonal waves resulting in the formation of mudbank.

More specialised investigations on various aspects of mudbanks are carried out after 1950. Ramasastry and Myrland (1959) opine that the mudbank formation is due to the upwelling and divergence near the bottom between 20 and 30 m depth contour. Nair *et al.* (1966) studied the physical and chemical properties of mud of the mudbank of Narakkal (Cochin), in order to understand the source. They concluded that the source of mud is from the near-shore areas, as it is composed of dredged material. Varma and Kurup (1969) put forward the rip current hypothesis. They suggest that the onshore and offshore transport of sediments, the former by waves and the latter by rip flow, result in the formation of the mudbank. Nair *et al.* (1966), Kurup (1969; 1977) and Gopinathan and Qasim (1974) agree with the suggestion of Du Cane *et al.* (1938) that the pre-monsoon swells churn up and bring into suspension fine mud of the bottom at shallow depths. Murty *et al.* (1984) based on their observation of mud cones on the beaches support the subterranean passage hypothesis of Crawford. Recent studies (Rao *et al.*, 1983; Ramachandran and Mallik, 1985; Ramachandran, 1989) suggest the possibility of an offshore source for the sediments of the Alleppey mudbank.

While considering the different hypotheses for the source of mud, the role of each mechanism needs to be examined. For the mudbank of Alleppey, both river and upwelling as sources of mud are ruled out owing to the nonistence of river discharge along this coast and upwelling, a very slow ·ocess (with velocity 1.6 x 10^{-3}cm/s, according to Mathew, 1982) cannot account r the high rate of sediment accumulation in the nearshore. Sediment trans- ›rt by the prevailing coastal currents cannot account for the enormous ıantity of fine sediment deposited in mudbank location. Apart from this, ongshore transport and upwelling hypothesis cannot explain localization of udbanks. Hence the hypotheses on the supply of mud from these sources do ›t appear to hold good. The subterranean passage hypothesis is discarded y various researchers (Bristow, 1938; Gopinathan and Qasim, 1974; Kurup, ǀ77; Ramachandran, 1989). The increase in pressure due to rise in water ·vel in the backwaters during monsoon is insufficient to cause an under- round discharge (Bristow, 1938; DuCane *et al.*, 1938; Nair, 1976; Kurup, 1977). orings conducted at Alleppey and Cochin rule out the possibility of any nderground discharge of mud and water in these regions (Ducane *et al.*, 938). In certain years mudbanks have formed even before the onset of ıonsoon (Gopinathan and Qasim, 1974; Kurup, 1977) and sometimes during the ıir weather months. In December, 1965, a storm in the Arabian sea gave rise › the formation of a mudbank occupying a stretch of about 5 km between ochin and Elamkunnapuzha (Varadachari and Murty, 1966). Previous works ıdicate the existence of subterranean passage only during monsoon and the ›rmation of mudbank in the non-monsoon periods contradicts this hypothesis. lso the appearance of mud cones on the beaches during monsoon is sparsely eported.

The clay mineral distribution in the offshore regions of south-west coast f India has been studied by Rao *et al.* (1983). Their study shows that the ffshore regions of this coast is montmorillonite rich. The field investigation f Gopinathan and Qasim (1974) shows thick mud deposit at a depth of 30-

40 m. They also report that liquid mud is seen in the mudbank at about 1 km offshore and its thickness increased further offshore. These studies support the possibility of an offshore source for the mudbank sediments.

1.1.2 Calmness associated with mudbank

The calm nearshore areas noticed during rough season triggered the curiosity of keen observers. Several explanations for the calmness associated with the mudbank are put forward. King (1881) suggests that the presence of oil in the mud is responsible for the calmness in the mudbank. Later analysis showed that there is no such oily matter in the mud. Another suggestion made is that the de-flocculation of sediments due to the reduction in salinity results in the increased sediment suspension and the damping of waves (Keen and Russel, In: Ducane *et al.*, 1938; Kurup, 1969; Padmanabhan and Pillai, 1971). Murty *et al.* (1984) disagreed with this view, since the salinity values observed in the mudbanks are not favourable for de-flocculation of sediments. But Ramachandran (1989) suggests that salinity reduction in the nearshore waters due to monsoonal precipitation is an ideal condition to de-flocculate and disperse the sediments into suspension in the presence of phosphate as a natural peptizer.

Keen and Russel (In: Ducane *et al.*, 1938) suggest that the calming effect is due to the viscosity and thixotropic properties of the muddy suspension. Most of the researchers (Damodaran and Hridayanathan, 1966; Dora *et al.*, 1968, Murty *et al.*, 1984; Shenoi and Murty, 1986; Mallik *et al.*, 1988) accept the view that the mud, when in suspension, increases the viscosity of the medium and causes viscous damping of waves. But Kurup (1977) opposes this with the argument that the measured concentrations of sediments in the water is too small to bring in decay in the wave energy. He suggests that the energy absorption in the near bottom visco-elastic bed effects the wave decay more than the internal viscosity of the overlying mud-laden waters. The experimental studies of MacPherson and Kurup (1981) suggest that the wave damping is due to the viscous bed.

MacPherson and Kurup (1981) apply Gade's (1958) mathematical model to the wave damping in mudbanks. Murty *et al.* (1984) question the validity of applying Gade's model to the mudbanks of southwest coast of India. They argue that the physical conditions assumed in this model are not identical with the mudbank conditions. Shenoi and Murty (1986) assume the wave profile over mudbanks as solitary-like and compute the wave amplitude dissipation owing to viscous shear beneath the solitary wave over a smooth horizontal surface. They conclude that the wave energy dissipation in mudbanks is due to the high kinematic viscosity of the water layer rather than the effect of soft muddy bottom. No measured wave profile of mudbanks of this coast is available to show its solitary nature, like the one available for the Louisiana coast. Also the effects of bottom is not accounted in their study. The arguments of Murty *et al.* (1984) that the viscosity of the medium due to sediment suspension alone result in wave damping cannot be accepted in the case of mudbanks. Kurian and Baba (1987) show that as the waves propagate in shallow water, dissipation of wave energy due to bottom friction alone can be up to 50% off Alleppey, one of the mudbank sites. Bottom friction is important wherever the water depth is substantially lower compared to the wave length so that the wave induces significant horizontal particle motions near the bottom. In mudbank the movement of bottom layer and the resulting wave energy dissipation is more important (Gopinathan and Qasim, 1974; Kurup, 1977). Hence a detailed examination of the wave-mud interaction process in mudbank is needed for further clarification of the above observations.

1.1.3 Localization of mudbank

Varma and Kurup (1969) from their wave refraction studies for a mudbank location suggest the possibility of formation of rip currents, which can carry finer sediments offshore and prevent onshore transport of sediments by waves. Thus the localization of finer sediments can take place at the rip head which, when settled, will extend the bottom contours offshore. Kurup (1977) further elaborates this hypothesis by suggesting that the location of the mudbank is decided by the location of the zone of converging littoral currents and the associated offshore flow which carries a large quantity of suspended sediments and low salinity water from nearshore regions. Mud in suspension is supplied continuously to the mudbank from both the nearshore and offshore directions, the former by rip flows and the latter by churning action of waves. A detailed study of wave refraction along the west coast of India from Cape Comorin to Goa is carried out by Reddy and Varadachari (1973). They observed that there are many places where convergence of littoral currents takes place along the south-west coast, which are zones of occurrence of mudbanks. They also agree with the rip current hypothesis of Varma and Kurup (1969) for the localization of mudbank. This hypothesis cannot account for the rapid accumulation of fine sediments in the nearshore and the formation of three to five mudbanks spaced approximately 5-10 km along the Alleppey coast.

1.1.4 Movements of mudbank

Alongshore horizontal movements of mudbanks are reported in the literature (Bristow, 1938; DuCane *et al.* 1938; Moni, 1970; Gopinathan and Qasim, 1974; Jacob and Qasim, 1974; Murty *et al.*, 1984). Year-to-year shifts and the movements within the year/season are also observed. Most of these movements are in the southerly direction, but not always consistent. Almost all the researchers attribute this to be due to the strong southerly currents prevalent during July-August. In certain years, a northerly movement of mudbank is also observed (Bristow, 1938; Gopinathan and Qasim, 1974).

According to Varma and Kurup (1969) and Kurup (1977), the shift in the location of the mudbank can be due to the shift in the location of the zone of convergence of littoral currents, which is determined by the wave refraction process. Kurup (1972) suggests that the movement of mudbank, both year-to-year and within a year, is the result of the changes in the wave refraction pattern due either to the changes in the bottom topography of the region or to the changes in the wave characteristics or both.

1.1.5 Mudbank dissipation

According to Varma and Kurup (1969) the increase in salinity of water during the post-monsoon months causes the flocculation and settling of sediments, which results in the disappearance of mudbank. Gopinathan and Qasim (1974) and Kurup (1977) conclude that the decrease in wave activity during post-monsoon months leads to the disappearance of mudbank. According to Murty *et al.* (1984) the decrease in water level in the backwater towards the end of monsoon leads to the reduction in hydraulic pressure in the subterranean strata which finally results in the cessation of supply of fresh mud. They further state that due to the decreased turbulence of water column the mud settles down causing dissipation of mudbank. Since the de-flocculation and subterranean passage hypotheses for the formation of mudbank are discarded, these hypotheses on dissipation of mudbank also does not hold good.

1.2 Objectives and Scope of the Investigation

Even after several studies, the generation, sustenance, dissipation and localisation of mudbank is yet to be explained satisfactorily. The studies conducted so far suffered from the following lacuna:

(i) Previous investigations on mudbanks covered the hydrographic features and some of the physical processes involved in the different stages of mudbank. The influence of a cohesive bed on the wave attenuation by and large remain unexplored. Only a few laboratory and field studies have been made in this vital field (Kurup, 1977; MacPherson and Kurup, 1981; CMFRI, 1984).

(ii) Further, the data gathered from different studies are incomplete to give an explanation for wave energy dissipation over a cohesive bed. The need for direct measurement of waves has been suggested by different researchers. No published evidence regarding such measurements is available till date.

(iii) Similarly, even though high suspended sediment concentration near bed layer has been noticed by different researchers, its significance on surface wave attenuation has not been studied. Most of the studies hitherto focused primarily on the upper water column. The significance of near bed layers has been neglected and no attempt has been made to study the behaviour and properties of this high concentration layer.

(iv) An offshore source of sediments for mudbank has been proposed by a few researchers recently. But the physical processes involved in its suspension and mode of transport have not been explained.

(v) Reports on the alongshore extension and movement of mudbanks are available in the literature. The role of wave forcing on these processes are, however, not included in these studies.

Because of the variety and complexity of factors involved in the mudbank formation, so far no efficient method of estimating the energy dissipation and dimensions of the mudbanks is available. To achieve this adequate field data on wave parameters from synchronized wave measurements from outside and inside mudbank is needed. Simultaneous data on nearshore currents, suspended sediment, salinity, temperature, etc. are also needed for a complete understanding of the processes controlling the mudbanks. Hence a comprehensive investigation on the wave-mud interaction processes, which appears to hold the key to the generation, sustenance and dissipation of mudbanks is undertaken. Thus the present investigation is undertaken with the following main objectives:

(i) to measure the wave characteristics during different stages of mudbank and also during the non-mudbank period;

(ii) to collect necessary supporting data on suspended sediment load, currents, physical characteristics of the sediments, salinity, temperature, etc. from the mudbank;

(iii) to study the wave-mud interaction processes involved in mudbank formation, sustenance, dissipation and localization and

(iv) to suggest a conceptual model for the mudbank.

Chapter 2

2. MUD CHARACTERISTICS AND WAVE-MUD INTERACTION - A REVIEW

Mud in aquatic environments is mainly composed of clay and silt-sized particles with small quantities of very fine sand. Mineralogical framework of the granulometric fractions include clay and non-clay components with a significant amount of organic matter. When sufficient salt is added to a suspension of dispersed mud, the suspended particles become cohesive (Migniot, 1968; Mehta *et al.*, 1989). Property characterization for cohesive sediment is more complex than that for coarse-grained material because the finer particles when they form a cohesive sediment layer lose their individual properties. Their aggregate properties depend upon the nature of sediment, type and concentration of ions in the pore-water and on the flow conditions. Furthermore, cohesion is influenced by colloidal organic matter, microbes, polysaccharides, etc. (Montague, 1986). In this chapter the characteristics of fine sediments in marine environment and the wave-mud interaction processes are discussed.

2.1 Characteristics of Fine Sediments

Sediment of size greater than 62 µm is classified as coarse-grained and lesser than that fine-grained. The coarser particles of silt, sand and gravel are generally rounded and are transported as individual particles. But the clay particles are plate-like with a diameter less than 4 µm. Their surfaces have ionic charges creating forces comparable to or exceeding the gravitational force. This causes the particle to interact electrostatically. Consequently, they do not act as separate individual particles but stick together. The degree of stickiness, ie. cohesion rises with the proportion of clay fraction in the sediment and starts becoming significant when the sediment contains more than 5-10% of clay by weight (Dyer, 1986). The degree of cohesion varies significantly among the three principal clay types, viz. kaolinite (least cohesive), montmorillonite (highly cohesive) and illite (moderately cohesive). The characteristics of cohesive sediments differ considerably from cohesionless sediments in their packing structure and physical and hydraulic properties. The transformation of dispersed particles into cohesive ones is due to ions in solution which suppress interparticular electrochemical repulsive forces. This makes the molecular attractive London-Vander Waals force to dominate (Dyer, 1986; Mehta *et al.*, 1989).

The boundary between cohesive and cohesionless sediment is not clearly defined and generally varies with the type of material. However, dominance of interparticular cohesion over gravitational force increases with decreasing particle size. Thus cohesion is much more pronounced for clays (particle size <4 μm) than silts (4 to 62 μm).

2.2 Flocculation

Flocculation is the process in which fine particles are brought together and clustered to become heavier masses so that they would be pulled down by gravity. Flocculation of suspended fine particles plays an important role in the cohesive sediment transport, changing the distribution of the particle size and density and hence the settling velocity. Flocculation is affected by various physico-chemical parameters - eg. particle size, mineralogy, dissolved ions, contained organic matter and pH, salinity as well as hydrodynamic conditions (Mimura, 1989).

For clay minerals the overall particle charge is usually negative. In a saline fluid, the free ions in the water interact with the charges on the particle, whereby the positive ions are attracted to the face and negative ones to the edges. If the charge on the face were the only factor, then the particles, which are similarly charged, would repel one another, the electrostatic force being repulsive and decreasing exponentially with distance. However, there is the London-Vander Waals attractive force which varies inversely with the square of the distance of separation and tends to largely counteract the repulsive force under certain conditions. In saline water this attractive force dominates and consequently the particles have a greater tendency to flocculate. The decrease of particle charge with increasing salinity is approximately exponential; hence flocculation tends to vary quickly and reach equilibrium situation at comparatively low salinities, provided the particle concentration in suspension is sufficiently high (Dyer, 1986). Krone (1978) reported that flocculation begins at salinities of 0.6‰ for kaolinite, 1.1‰ for illite and 2.4‰ for montmorillonite and is complete at about 1-3 ‰. Similar results are obtained by Gibbs (1983) for illite and kaolinite but flocculation of montmorillonite continued even at higher salinities. Whitehouse *et al.* (1960) also observed that flocculation of illite and kaolinite is complete above a salinity of about 4‰. Montmorillonite, however, flocculates gradually over the salinity range up to 35‰. As temperature increases, the thermal motions of the ions increase in magnitude and this leads to increased repulsion. Consequently flocculation is less effective as the temperature rises.

2.3 Bed Erosion

Entrainment from a consolidating or a settled bed is termed as erosion or resuspension. Erosion is dependent on the properties related to waves (bed shear stress) and erosion resistance of the mud (shear strength). Bed erosion occurs when the resultant hydrodynamic lift and drag forces on the sediment at or below the bed interface exceed the resultant frictional, gravitational and physico-chemical binding forces of the sediment grain or particle (Ross, 1988). There are two modes of erosion, surface or particle-by-particle erosion and mass or bulk erosion (Ariathurai and Krone, 1975; Wells, 1978; Mehta, 1986). In surface erosion, individual particles detach from the bed surface as the hydrodynamic erosive force (i.e. instantaneous turbulent shear stress acting on the particle surface) applied to them exceeds the resultant gravitational, frictional and cohesive bed binding force. Under mass erosion, failure occurs well below the bed surface resulting in large chunks of sediment being broken from the bed structure and subsequently resuspended. Bed fluidization is mass erosion where large structural breakdown occurs with an initially minimum change in density (Ross, 1988). Surface erosion is more typical of low concentration, low energy environments, while mass erosion occurs under higher flow and higher concentration conditions (Mehta, 1986).

Surface waves and other highly oscillatory currents have a particularly pronounced influence on erosion in comparison with unidirectional currents. Bed erosion precedes scour (resulting in decrease in bed elevation) which will continue under constant loading until the bed shear stress and the bed shear strength are equal.

The erosion of cohesive sediment is not simply a function of grain size but depends on several physico-chemical and biological parameters, as well as the deposition and consolidation history. Erosion of sand is a continuous process with each layer having the same threshold velocity as that above, whereas with cohesive bed the erosion resistance increases into the bed due to the increase of shear strength with depth. For non-uniform beds (eg. soft, semi-consolidated, etc.) the rate of erosion based on laboratory experiments was studied by Parchure and Mehta (1983) and Parchure (1984).

2.4 Deposition

Sediment particles or aggregates in suspension will redeposit on the bed if the bed shear stress drops below some threshold value (Ross, 1988). The shear stress required to maintain a sediment suspension is less than that required to suspend the sediments. Krone (1962) and Mehta (1973) conducted sedimentation experiments under steady flow condition using natural estuarine sediment and commercial kaolinite. This critical value is found to vary from 0.4 to 0.15 N/m^2 depending upon the sediment composition (Mehta, 1973).

Rates of deposition and vertical distribution of suspended material are influenced by the settling characteristics of cohesive sediments. Knowledge of the settling characteristics of suspended sediments and its depositional properties are essential for understanding the sedimentation pattern.

2.4.1 Settling Velocity

Settling velocity is usually defined as the settling rate of particles in quiescent water. Settling is affected by gravitational forces, viscous drag on the particles and interparticular interactions. It is dependent on floc and particle size, suspension concentration, local physico-chemical conditions and microbiological activities in the water or on the particle surface. Of these factors, the effect of suspended sediment concentration on the settling velocity is found to be very significant due to the changes on the frequency of inter-particular collision with changes in concentration. When the suspended sediment concentration (SSC) exceeds about 100-300 mg/l, free settling (in which individual particles settle) changes to flocculation settling (Mehta, 1989). At very low concentration, the rate of aggregation is negligible and the settling velocity does not depend on suspension concentration. In general, the settling velocity increases with concentration up to about 5,000 to 10,000 mg/l, above which it begins to decrease with increasing concentration as a consequence of hindered settling (Mehta *et al.*, 1989). Hindered settling occurs when the sediment forms a nearly continuous network through which pore water must escape slowly upwards for settling to continue. A high density suspension characterized by hindered settling is commonly referred to as fluid mud (Krone, 1962). Settling is negligible above 1,00,000 mg/l (Mehta, 1989).

According to Krone (1962) settling velocity of flocculated cohesive sediments typically increases with increasing salinity up to about a salinity of 10 ‰. At higher salinities, the effect is found to be important mainly for predominantly montmorillonitic material (Whitehouse, *et al.*, 1960). Any physical or chemical factor which influences aggregate size, density and shear strength affects the settling velocity. Marine and estuarine sediments thus exhibit a wide range of settling velocities. Reported values range from 10^{-4} to 10 mm/s for different size ranges (Burt, 1986; Chase, 1979; Krone, 1962; Mignoit, 1968; Owen, 1970; Teeter, 1986; Whitehouse and Jeffrey, 1952).

An example of the variation of the settling velocity, w_s, with concentration is shown in Fig.(2.1) which is based on measurements in a settling column using mud in salt water from the Severn estuary, U.K. (Thorn, 1981).

2.5 Fluid Mud Dynamics

Fluid mud is defined as gel-like fine-grained sediments with bulk density less than 1.25 g/cm^3 (2,50,000 mg/l) (Wells and Kemp, 1986). Einstein and Krone (1962) regarded concentration of about 10,000 mg/l as the lower concentration limit of fluid mud on grounds of viscous properties. The viscosity of fluid mud and the yield stress depend strongly on sediment concentration and factors such as salinity, temperature, pH, etc. (Mignoit, 1968; Allersma, 1980).

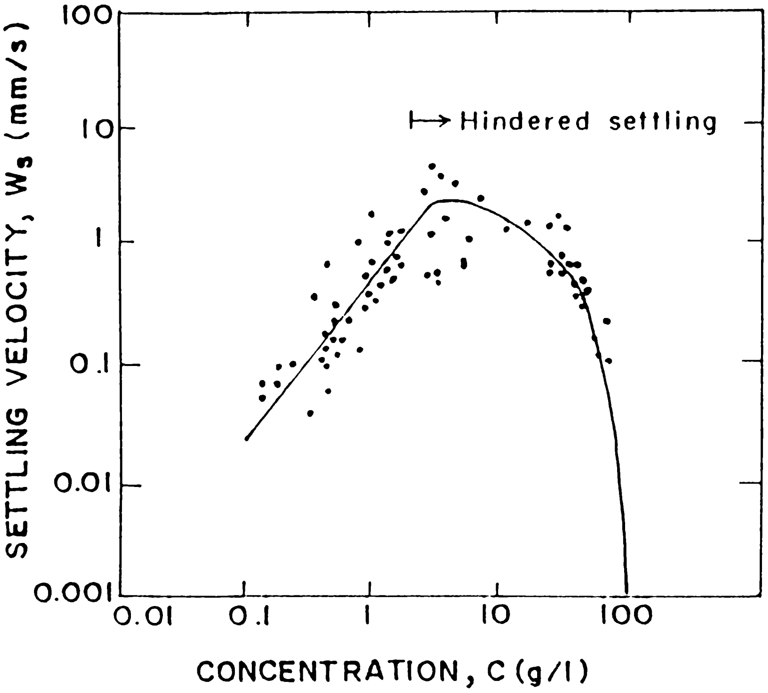

Fig. 2.1 Median settling Velocity Vs. concentration for Severn Estuary Mud (after Thorn, 1981).

When either the viscosity or the yield stress is sufficiently high, fluid mud can remain laminar under quite general conditions. Many investigations indicate that fluid mud has the mechanical properties of Bingham fluid, visco-plastic or visco-elastic due to its high concentration of fine sediment particles. This high concentration layer may be stationary or horizontally mobile. The mobile layer is differentiated from the mobile, but comparatively low concentration, mixed layer suspension by a gradient commonly termed as the lutocline (Parker and Kirby, 1982). Fluid mud occur in estuaries and along the open coasts where waves and tides play a dominant role.

2.6 Rheological Properties

Defined as 'the study of flow' the word *rheology* has its roots in Greek. Evaluation of the rheological properties are essential in studies concerning the dissipation of fluid energy within a sediment bed. The flow properties of a Newtonian fluid are characterised by a single parameter known as viscosity. This parameter is determined through Newton's law which states that a plot of shear stress versus shear rate is linear and the slope of the line is the viscosity. In other words, viscosity is the proportionality coefficient relating shear stress to shear rate. For a Newtonian fluid the shear stress-shear rate curve is a straight line passing through the origin with a slope equal to the molecular viscosity (Fig.2.2). Suspensions of clay minerals, however, show a non-Newtonian response above a concentration of about 10,000 mg/l and when the proportion of clay minerals exceeds about 20% (Dyer, 1986; Mehta *et al.*, 1989). The most common types of non-Newtonian behaviours are shown in Fig.(2.2). A material with a Newtonian response throughout, but with a finite shear strength, at zero shearing rate is a Bingham plastic. For a pseudo-plastic material at low shear rates the shear stress rises steeply, but as the shear rate increases the rate of increase in shear stress diminishes, eventual-

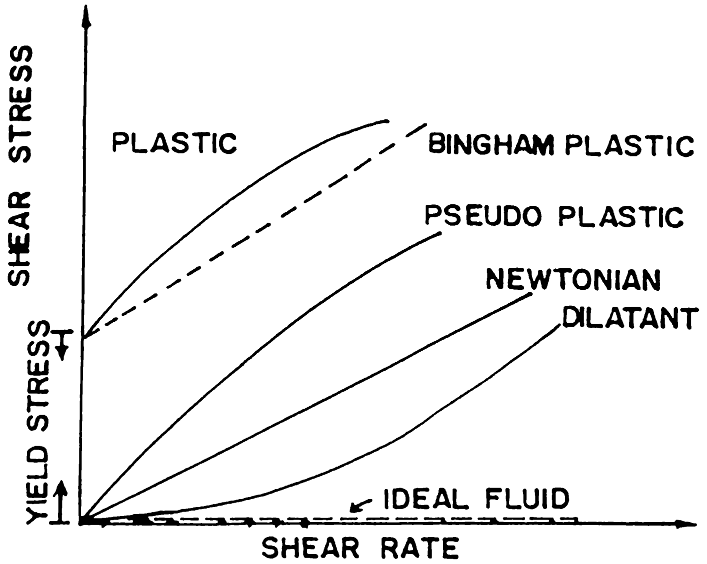

Fig. 2.2 . VARIATION OF SHEAR STRESS WITH VELOCITY GRADIENT

ly becoming linear. Liu and Mei (1987) suggests that depending on the clay concentration, chemical composition and the level of shearing rate, cohesive fluid mud can have vastly different rheological behaviours. According to them when the applied shear stress is low, fluid mud can behave like a visco-elastic solid. On the other hand, when the stress applied is sufficiently high, it can behave approximately like a Bingham plastic. Mehta and Maa (1986) suggest a visco-elastic response of muds under wave-induced loading. Based on the Bingham plastic behaviour of fluid mud, theoretical studies of wave induced mud motion has been studied by Mei and Liu (1987) with a view to calculate the damping of gravity waves over a muddy sea bed. Maa (1986) has made a similar study based on visco-plastic model. Based on viscometric tests of field samples from seven different sites along US coast, Krone (1965) found for concentration lying between 10,000 and 1,10,000 mg/l that fluid mud in laminar flows behaves almost like a Bingham plastic.

2.7 Interaction Between Waves and Cohesive Sediment Bed

Our knowledge of cohesive sediment response to hydrodynamic forcing is largely limited by evident difficulties in understanding the complex interaction between the sediment and the flow field. Studies on this subject are limited, apparently, because the change of characteristics of waves caused by the dissipation of wave energy and the resuspension of mud are inter-linked and complex. The influence of other parameters like salinity, temperature, composition of clay minerals, organisms, etc., which have measurable influence on bed characteristics, further complicates the problem.

Waves apply periodic shear stress at the water-mud interface. Whenever the shear stress exceeds the binding force (cohesive force and self weight) between particles, erosion occurs. Investigations of bed erosion have been made primarily on cohesionless materials, i.e. sand beds. Experiments dealing with cohesive sediments were initiated only recently. The studies in this field are conveniently divided into two parts: (i) the dynamic response of the water-mud system to incident waves, including the feed back effect of the fluid mud motions on the water waves (eg. wave damping) and (ii) the wave-induced erosion of sediment bed.

Continued oscillatory motion in the bed caused by wave force results in a decrease of the mechanical shear strength as well as the resistance against erosion. The wave orbital motion penetrates into the cohesive bed causing weakening of the bed and its subsequent fluidization. Low upward entrainment and long longitudinal dispersion results in the formation of a high concentration layer in the near-bed boundary. Wells and Kemp (1986) observed that waves traveling over nearshore mud shoals principally act as an agent for softening and fluidizing the muddy bed. Maa and Mehta (1987) made similar observations in laboratory flume tests.

The interaction of currents and waves with the bottom is non-linear. The precise mechanism by which waves and currents jointly interact with a muddy bed is not well understood. In laboratory studies the bottom shear stress by waves and currents are treated separately. In actual case the bottom shear stress will be greater than the sum of wave or current shear stress treated separately. Thus, even though currents serve as the main agent for transporting fluidized mud, waves also assist currents in the transportation process.

The threshold erosion velocity depends on the mineralogical composition, textural components with different biological-geotechnical characteristics, water content and consolidation properties. Velocities necessary to initiate suspension of cohesive sediment have generally been determined in the laboratory.

Zenkovitch (1967) reported that fine silts are stirred at near-bottom velocities of 7-12 cm/s, whereas NEDECO (1968) reported that fluid mud is not suspended until velocities of 70 cm/s are achieved. Other reported values are 20-100 cm/s for Chao Phya muds (Allersma, *et al.*, 1967) and 10-90 cm/s for British Guiana muds (Delft Hydraulics Laboratory, 1962). For cohesive sediments in general, Drake (1976) suggested that average velocities of 10-30 cm/s at 100 cm above the bed are necessary to initiate erosion. For erosion of unconsolidated cohesive sediments Parthenaides (1971) reported values of 18 cm/s. Wells (1978) suggests that wave-induced current velocities of 50 to 100 cm/s are sufficient to suspend fluid mud.

2.8 Sediment Transport

Waves steepen and the associated orbital velocities increase as the waves shoal and refract from deep water to the shore.In deep water the wave orbital velocity, which reaches to a depth approximately half-the wave length, is too low to move sediments. However, at some critical depth the orbital velocity at the bed becomes high enough to move sediments. This critical depth, which depends on grain size of the bed material and the wave height and period, can be as much as 100 m (SANECOR, 1979). At first sediment is only moved in a cyclic manner with the orbital movement without any displacement. However, closer inshore ripples are formed on the sea bed and still closer inshore a net sediment drift occurs.

Sediments in suspension can be transported away by on-offshore currents, longshore currents, tidal currents and other wave generated currents. At some critical point close to the shore, waves become unstable and break. The depth at which this happens varies between approximately 2.5 and 0.7 times the wave height (SANECOR, 1979) and is a function of the beach slope and incoming wave steepness. Inside the breaker zone two important phenomena take place: (i) more sediment is brought into suspension by the turbulence associated with wave breaking and (ii) longshore currents are generated which carry the sediments in both suspended and bed load modes. In this very active transport zone thus the sediments are transported alongshore by the longshore currents and in the onshore-offshore direction as a result of the internal flow field associated with the wave motion.

Fine-grained sediments are transported in suspension from fluvial systems to other depositional environments. The transport of cohesive sediment includes several basic processes such as the advection of suspended matter, flocculation of fine sediment particles, settling of flocs, deposition, consolidation and resuspension. Due to complex effects of hydrodynamic and physico-chemical properties of the water sediment system on each process, a complete understanding of overall transport behaviour of cohesive sediments are yet to be achieved (Mehta, 1986, Parthenaides, 1986).

The wave induced oscillatory shear stress at the bottom suspend the sediments and the wave induced currents transport it to the nearshore regions. According to Kemp and Wells (1987) the transport of fluid mud layer in the direction of accelerating flow is due to the wave-induced oscillatory shear stress at its lower layers. Einsten and Krone (1962) found that the differential consolidation of fluid mud, a process which reduces water content in the lower part of a layer at a more rapid rate than in the upper part, results in a characteristic increase in sediment concentration with depth. This limits the vertical flux generated at the bed and thereby restrict sediment dispersal into the interior. The result would be development of significant near-bottom sediment concentration. This causes the fluid mud layer to transport in the direction of mean flow. The studies of Kendrick and Derbyshire (1985) in the

Avon river estuary, UK, shows that a very small drag at the lutocline, i.e., regions of sharp concentration gradients, is apparently sufficient to generate measurable mud motion. This has been observed by VanLeussen and VanVelzen (1989) for Rotterdam waterway mud.

NEDECO (1965), Ippen (1966) and Dyer (1986) report that fluid mud can be transported as a mass by a creeping motion from shear exerted by overlying water, even though it has not been measured directly. Parthenaides (1971) and Krone (1962, 1972) feel that this is not possible. Field observations of Wells (1978) along Surinam coast suggest that mass movement of sediments is possible if waves are solitary-like.

2.9 Summary

The characteristics of fine-grained sediments in marine environment are discussed in this chapter. Among the three principal clay types, montmorillonite is highly cohesive, kaolinite least cohesive and illite is moderately cohesive. Flocculation of suspended fine particles are important in the cohesive sediment transport, changing the distribution of particle size and density and hence the settling velocity. Flocculation of kaolinite and illite takes place at very low salinities, but for montmorillonite, it continues at higher salinities.

Erosion and deposition of fine sediments depends on the properties related to waves and shear strength of the bed. There are two types of erosion namely, particle-by-particle erosion and mass erosion. Mass erosion is bed fluidization, resulting from the failure of binding forces of the particles at the surface. Continued oscillatory motion in the bed caused by wave force results in a decrease of mechanical strength as well as the erosion resistance of the bed. The wave orbital motions penetrate into the bed causing weakening of the bed and subsequent fluidization.

At high concentration (above 10,000 mg/l) the settling velocity decreases with increasing sediment concentration as a consequence of hindered settling. This high density suspension characterised by hindered settling is commonly referred to as fluid mud. The generally accepted lower and upper limits of fluid mud concentration is 10,000 mg/l and 2,50,000 mg/l respectively. The different non-Newtonian behaviour of fluid mud are discussed. Investigations indicate that fluid mud has different mechanical properties, viz. viscous, Bingham, visco-elastic, Bingham-plastic, etc.

Even though current serve as the main agent for transporting the fluidized mud, waves also assist currents in the transportation process. Many investigators suggest that fluid mud can be transported en masse by a creeping motion from the shear exerted by overlying water. Difference of opinion also exists whether movement without suspension is possible or not.

Chapter 3

3. DATA COLLECTION AND ANALYSES

The present investigation essentially involved the collection and analysis of nearshore wave data for a period of four years, synchronised recording of offshore and nearshore waves during mudbank and non-mudbank periods, collection and analysis of water and sediment samples, measurement of water temperature and currents and many laboratory measurements. This chapter presents the details of the instrumentation, field measurements, data analysis and the laboratory analytical techniques.

3.1 Location of Field Measurements

The location selected for the present study is off Alleppey (Fig.3.1). where mudbank is formed almost every year. The Coastal Laboratory established here monitors data on waves, breakers, currents, beach changes, sediments and meteorological parameters like wind, temperature and barometric pressure at regular intervals (Fig.3.2). The pier available here serves as a platform for the measurement of waves with direction, breaker parameters, currents, etc.

3.2 Wave Recording

The recording of waves in the nearshore is made using a pressure-type wave and tide telemetering system. The wave measurements in the offshore are made using a waverider buoy.

3.2.1 Nearshore wave recording system

The nearshore wave recording system (Fig.3.3) consists of a wave and tide telemeter (Sivadas, 1981), a wave recorder and other accessory units. The wave and tide telemeter in turn comprises of an underwater transducer, cable

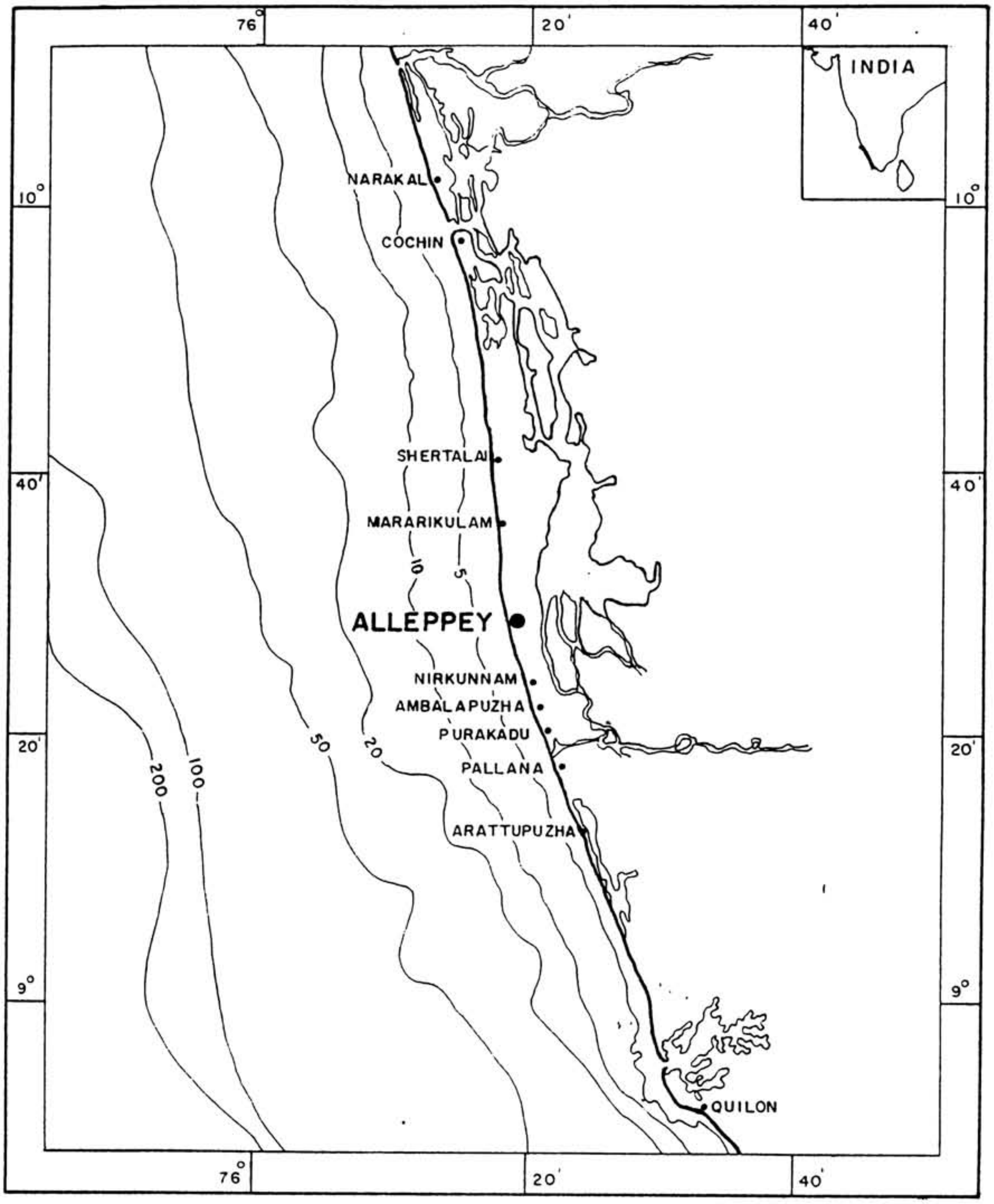

Fig 3.1 Area of Study

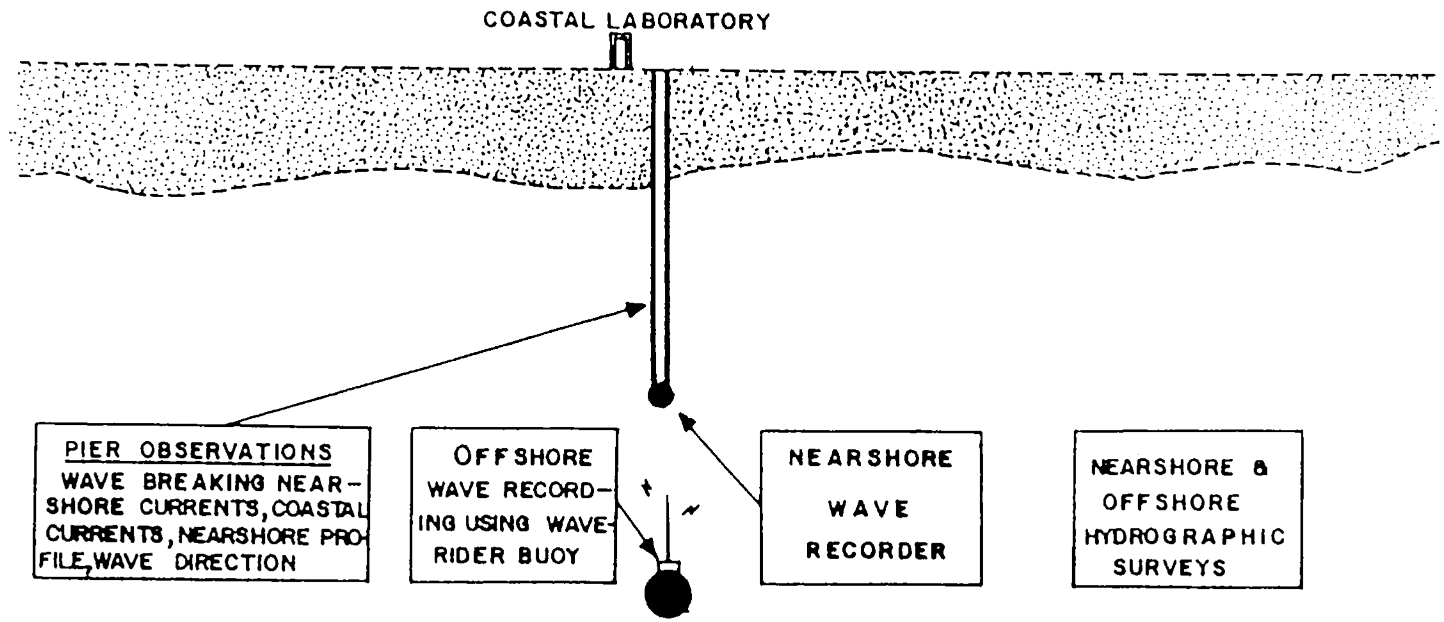

Fig 3.2 General lay-out of the Alleppey Coastal Laboratory indicating the scheme of measurements

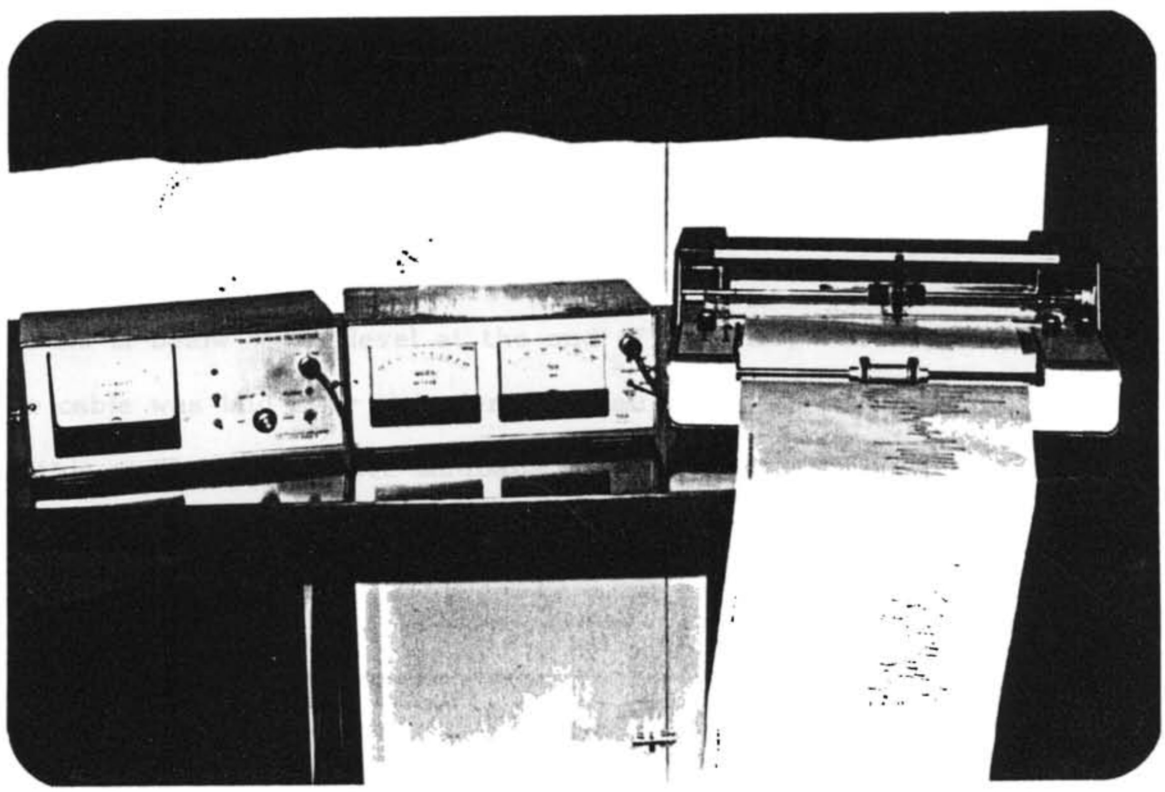

Fig 3.3 Nearshore wave recording system

and monitoring units. The transducer has a stainless steel pressure-responsive bellow with a plunger core at one end (Fig.3.4). The core moves inside an electrical coil producing changes in inductance of the coil proportional to the water level variations. The coil is connected to the monitoring unit by a 2-core cable. The bellow and coil are kept in a protective casing. The incoming signal is passed through a wave and tide separator, which separates out the low frequency tidal fluctuations using a low pass filter. The wave output is recorded on a paper chart recorder. The frequency response of the system (Fig.3.5) has been checked for a wide range of conditions and it is found that this is greater than 95% for wave periods > 3 s. The response is nearly 100% for periods above 5 s.

In the present case, the transducer of the recording system was installed 3.5 m below water level at the end of the pier, where the depth is 5.5 m. The cable was laid over the pier. Typical nearshore wave records collected using this system during pre-mudbank and mudbank periods are presented in Fig.(3.6).

3.2.2 Waverider system

The Datawell waverider system (Fig.3.7) consists of a moored buoy which transmits wave data and a WAREP receiver, which receives and records the data on paper charts. The signals sensed by an accelerometer housed in the buoy (Fig.3.8) is double integrated to obtain vertical displacement and the wave profile information is sent through a WHIP antenna in 27-28 MHz frequency band. The waverider gives 100% response for wave periods between 2 and 10 s and it is above 95% up to 18 s (Fig.3.9). Thereafter the response decreases.

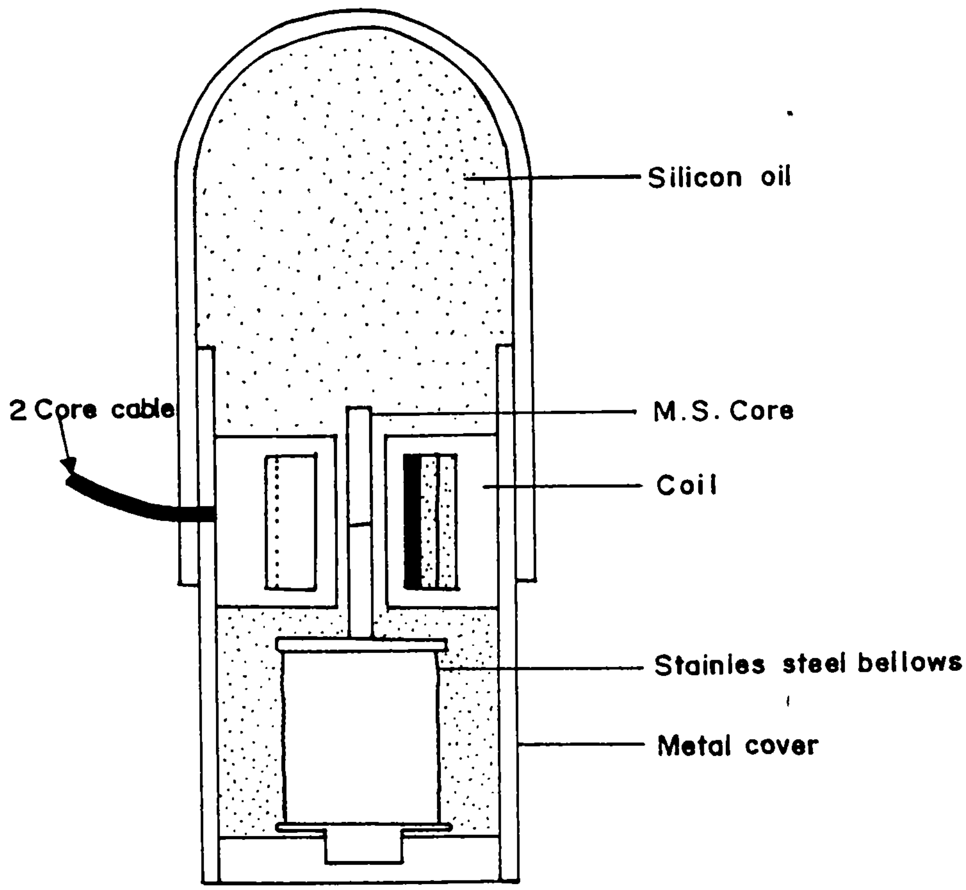

Fig. 3.4 Transducer of wave and tide recorder
(Cross section)

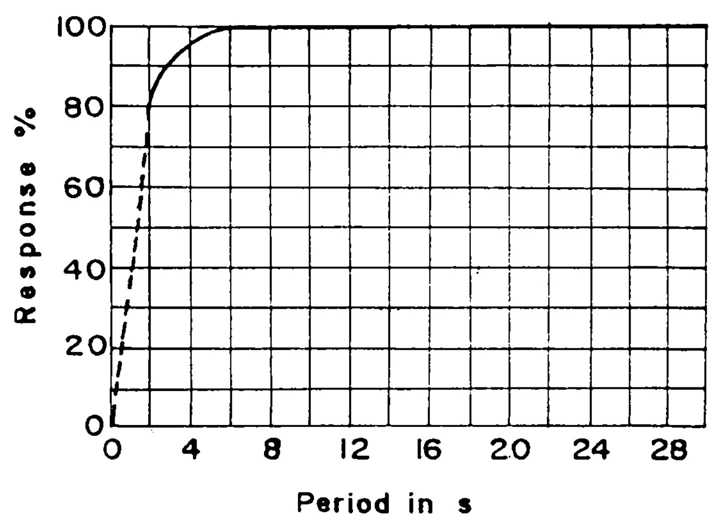

Fig.3.5 Frequency response diagram of wave recorder

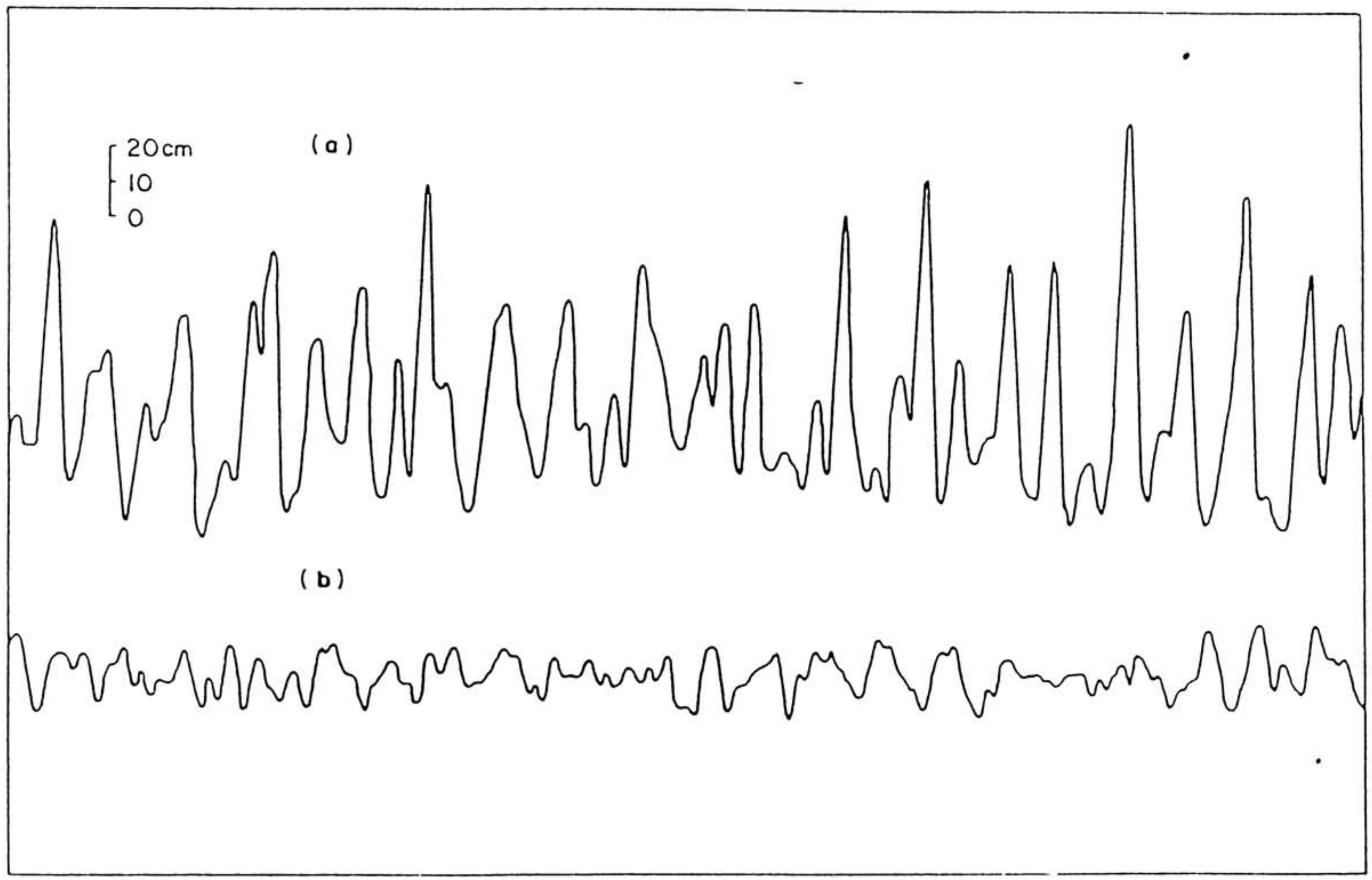

Fig. 3.6 Typical nearshore wave records: (a) before mudbank (b) during mudbank

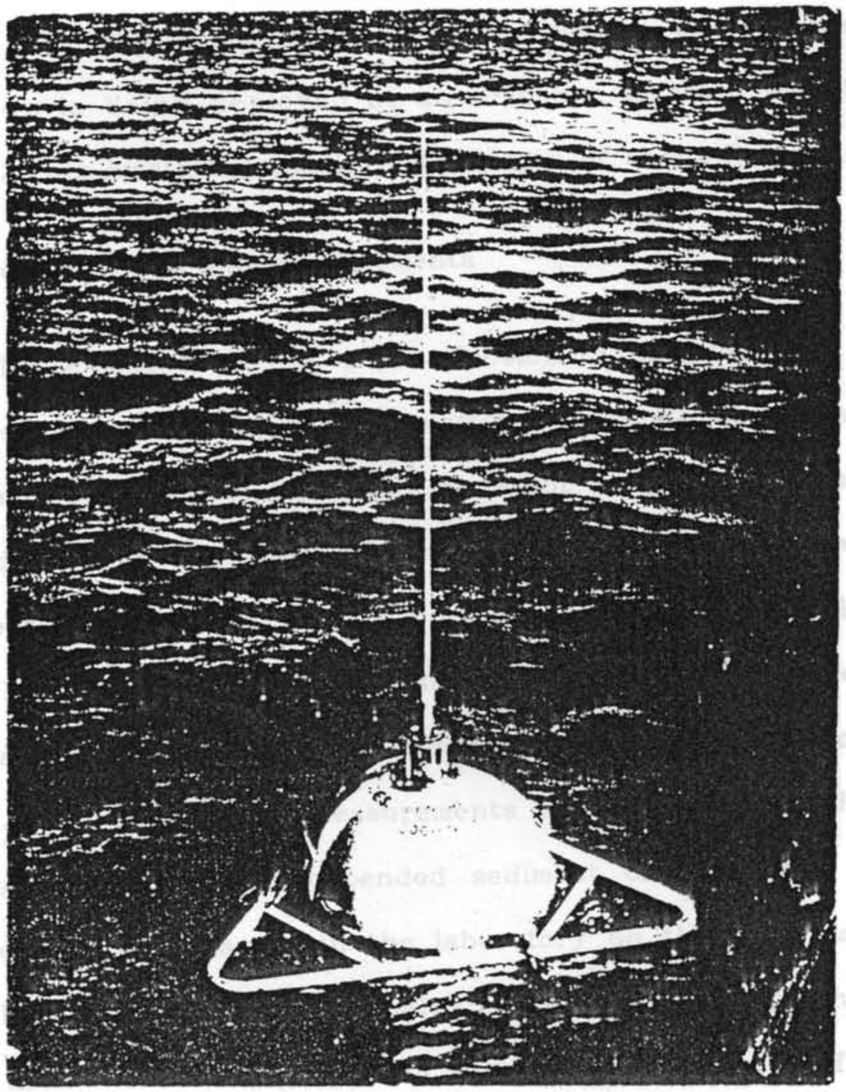

Fig. 3.7 Waverider buoy

A transmission range of 50 km is obtained over sea if the man-made noise level at the receiving site is low and the wave height is less than 10 m. These signals are received by WAREP and recorded in the manual or automatic mode. In the automatic mode there is facility to record data for durations of 5, 10, 20 and 40 min at intervals of 1, 2, 3, etc. hrs. as per requirement. The waverider buoy is being deployed at an offshore location well beyond the mudbank area. This location normally had a depth of about 7m (Fig.3.10).

3.3 Other Field Samplings and Measurements

To facilitate measurements and collection of samples from within the mudbank, a temporary self-supporting platform of length about 3m is erected at the pier end. Collection of water and sediment samples and measurement of current are done from this fixed station during different stages of mudbank. Here the average station depth is 5.5 m. Water samples are collected from surface and 1, 2, 3 and 4 m depths using a Nansen reversing bottle or Van Dorn water sampler depending on the current velocity and suspended sediment concentration. The temperature measurements of the water samples from the above depths are also made. Suspended sediment concentration and salinity are determined for each sample in the laboratory on the same day of sample collection. The water samples for analysis are stored in polythene bottles, previously rinsed with 5% HCl and then with distilled water. Surface sediment samples are collected using a Van-Veen grab. Measurements of coastal currents are done using a direct reading current meter (model SEA) from different depths. Measurements of longshore current are done using neutrally buoyant floats in the breaker zone by measuring the alongshore distance travelled by the floats in specific time intervals. The fluid mud samples are collected using Nansen reversing bottle or Van Dorn water sampler, depending on the current

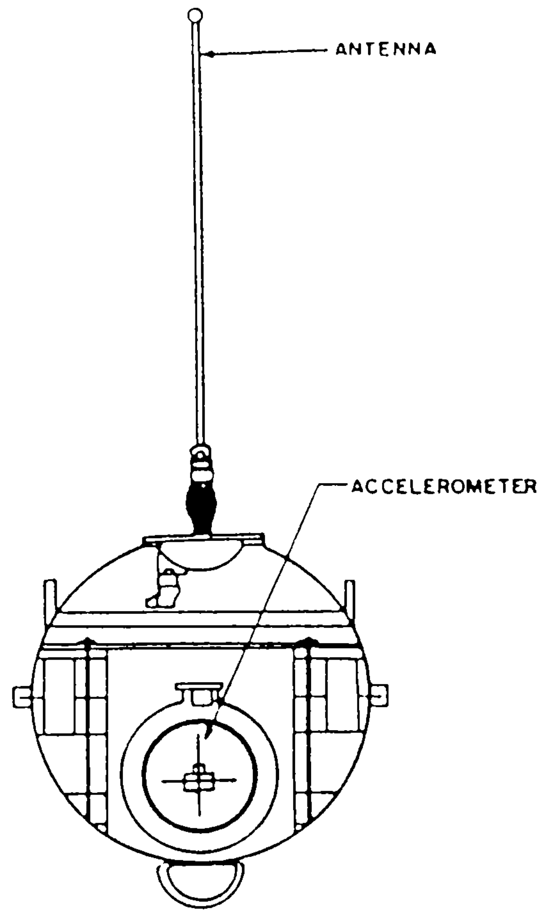

Fig. 3.8 Cross–section of the waverider buoy

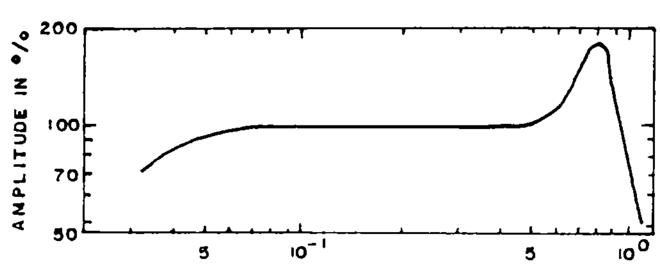

Fig. 3.9 Frequency response of waverider

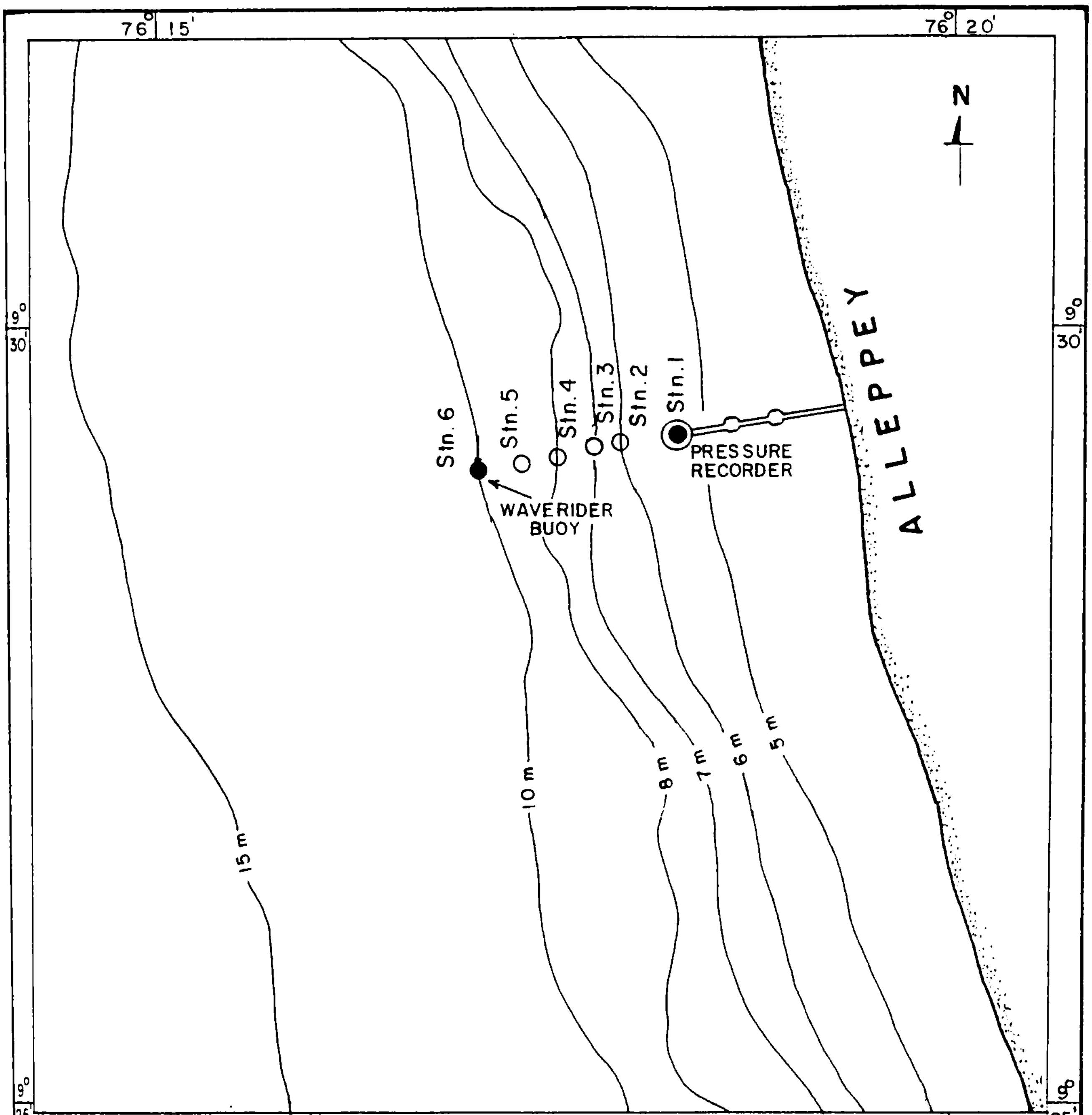

Fig. 3.10 Wave recording sites and sampling stations

conditions, during mudbank period for viscosity, bulk density, and water content determination and for textural and mineralogical studies.

In addition to the daily collection and measurements from the platform, all the samplings and measurements described above are made once at different stations inside and outside the mudbank. The sampling stations are shown in Fig.(3.10).

3.4 Analyses

3.4.1 Analysis of wave records

The wave records collected are subject to two types of analysis - Tucker and spectral methods.

3.4.1.1 Tucker analysis: The simple, fast and reliable wave record analysis procedure recommended by Tucker (1963) and modified by Silvester (1974) consists of the selection of 12 min record strips followed by measurement of the highest (A) as well as the second highest (B) crests and lowest (C) as well as second lowest (D) troughs with respect to a mean line (Fig.3.11). Then the total number of crests (N_c) and zero-up-crossing waves (N_z) in this record are counted. The zero-up-crossing period (T_z) is derived from this. The different wave height parameters like H_s, H, $H_{1/10}$, H_{rms} which depend on H_1 (= A+C), H_2 (= B+D), N_z and are derived as recommended in Silvester (1974).

3.4.1.2 Spectral analysis: Two different methods available for the spectral analysis of wave records are the auto-covariance method (Blackman and Tukey, 1958) and the Fast Fourier Transform (FFT) method. The faster FFT method is used in the present case. A Hanning window is used for smoothing.

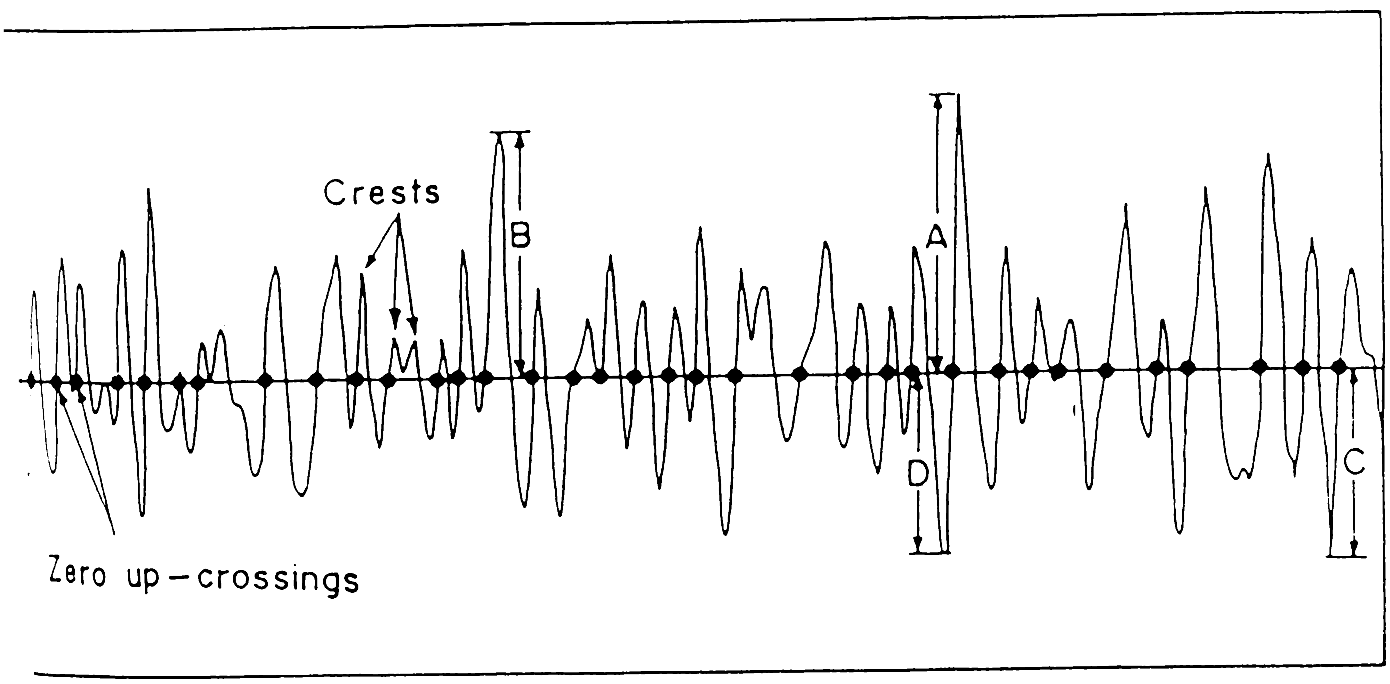

Fig. 3.11 Scheme of Tucker analysis of wave records

Since the chart paper speed could not be maintained uniform for both types of records, the digitization interval varied slightly in view of the convenience of digitization, which had to be carried out manually. While the digitization interval is 0.6 s for the pressure records, it is 0.5 s for waverider records. The waverider records collected from outside the mudbank and the corresponding nearshore pressure records are digitized for 2048 data points. The rest of the nearshore records, which are not used for any comparison with offshore records is digitized with 1024 data points.

3.4.2 Comparison of performance of waverider and pressure recorder

In the present investigation since the data derived from two different systems are to be used, their comparability had to be established. A comparison of relative performance of the two systems carried out by Kurian and Baba (1986) proves the comparability of the two systems for the major part of the gravity wave spectrum when the attenuation correction for pressure recorder data are suitably applied. The salient results of Kurian and Baba (1986) are reported below.

(i) The major uncertainty in the use of pressure recorder data is related to the pressure attenuation correction required for the wave height. The pressure attenuation correction formula used is,

$$H = H'K \cosh(2\pi d/L)/[\cosh(2\pi d/L)(1-z/d)] \quad .....(3.1)$$

where H and H' are the corrected and uncorrected wave heights respectively, z and d are the transducer and station depths respectively, L is the wave length and K is the instrument factor. The wave height parameters of pressure recorder corrected for pressure attenuation using average period and without the instrument factor gives the best comparison with waverider heights.

(ii) The spectrum from the pressure recorder is corrected for attenuation using the relationship

$$S(f) = S'(f)\ (\cosh 2\pi d/L)/[\cosh 2\pi d/(L\ (z+d))] \qquad .....(3.2)$$

where S'(f) and S(f) are the uncorrected and corrected pressure spectrum respectively. The wave spectra obtained from both the pressure (corrected for pressure attenuation) and waverider records compare well.

3.4.3 Wave refraction analysis

In connection with the present investigation, wave refraction analysis is carried out for the coastline extending from Quilon to Cochin for different deep water wave characteristics. A numerical model recommended by Kurian (1987) based on the refraction programme by Dobson (1967) is used. The refracted wave height is

$$H = H_o K_r K_s K_f \qquad .....(3.6)$$

where H is the refracted wave height, H_o is the deep water wave height and K_r, K_s and K_f are the refraction, shoaling and friction coefficients respectively. The model has the provision for the simultaneous usage of two depth grids, one coarse offshore grid and another fine inshore grid. In the present analysis only one grid is used since the fine scale bathymetric charts for the nearshore area was not available. Since the purpose of the present analysis is only the identification of the zones of convergence and divergence, the accurate computations in the nearshore zone employing the fine scale grid is not a must. Due to the same reason no friction factor is used in this analysis.

For preparation of depth grids, the Naval Hydrographic Charts nos. 220 and 221 were used. The procedure followed for computation of depths at grid points from the irregularly spaced soundings in Charts is as given in Kurian (1987). The depth grid covered an alongshore extension of about 200 km, with a grid element of 1.78 km from Quilon to Munambam. Wave orthogonals with a deep water spacing of 0.5 km were computed for predominant periods 8,9 and 10 s and directions of 240, 270, 280 and 300° N. The refraction diagram so prepared are used for the identification of zones of convergence and divergence, which are important in the case of mudbank formation.

3.4.4 Estimation of suspended sediment load

Suspended sediment load is determined following the gravimetric method. Pre-weighed membrane filter paper of pore size 0.45 μm and diameter 47 mm is used for this purpose. A filtering unit along with suction pump is employed for the filtration. Samples of volume 900-1000 ml are filtered. In order to remove the error due to salt in the residue, distilled water of volume 50 ml each is poured 3 times after the filtration of each sample. The filter paper with the residue is transferred to a petri dish and kept in room temperature for drying. The initial and final weights are taken to an accuracy of 2 decimals of a milligram. In order to apply correction for the probable loss of weight of the filter paper during filtration, the filtration procedure described above is repeated with the filtrate in 3 cases and the average loss of weight is applied as correction to the value of each sample.

3.4.5 Salinity determination

Salinity of each water sample is determined on the filtrate of each sample by Mohr's volumetric method. The silver nitrate used was standardized using standard sea water.

3.4.6 Viscosity measurement

The viscosity of the fluid mud samples are measured using Brookfield HBT viscometer (Fig.3.12), which consists of a motor, gear train, torque pointer, calibrated spiral spring, spindle, etc. The motor and the gear transmission are at the top of the instrument inside the motor housing. The main case of the viscometer contains a calibrated spring, one end of which is attached to the pointer while the other is attached directly to the dial. The dial is driven by the gear transmission and in turn, drives the pivot shelf through the calibrated spring. Below the main case is the pivot cup through which the lower end of the pivot shaft protrudes. A bearing inside the cup rotates with the dial; the pivot shaft rides on this bearing at the pivot point. The viscometer measures viscosity by measuring the force required to rotate a spindle in a fluid. The Viscometer has 8 rotating speeds from 0.5 to 100 rpm in eight unequal increments and a maximum driving torque of 57496 dyne-cm.

The spindles are made of stainless steel with different diameters. To measure the viscosity, an appropriate spindle is selected and hooked it to the viscometer, such that the torque readings are not too small to lose accuracy or too large to exceed the maximum capacity of the driving spring. The spindle is suitably centered in the sample container and immersed to the mid-point of the shaft's narrow position. A motor speed is selected and when the motor starts to turn, the torque builds up in the driving spring since the spindle motion is resisted by the fluid. The displacement of the pointer in dial scale gives the shear stress. Viscosity is calculated from this reading by multiplying with the factor for the corresponding rpm and spindle.

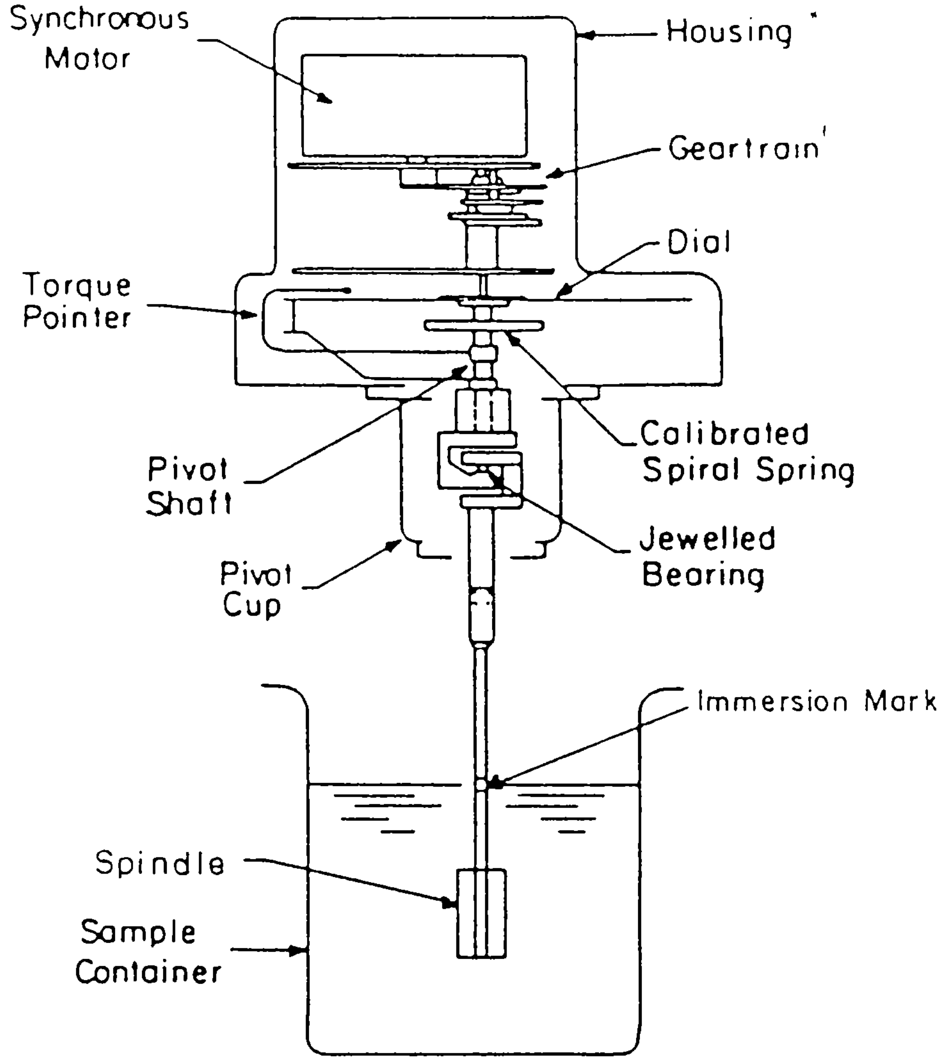

Fig. 3.12 Skeletal structure of Brookfield viscometer

3.4.7 Sediment analysis

The grain size of the fluid mud sample is determined using Sedigraph 5000D Particle Size Analyzer. In this the sedimentation velocity of the particles in a homogeneously dispersed slurry under gravitational force using a collimated beam of x-ray is measured. The particle size is determined from the sedimentation velocity.

Since the sedigraph cannot be used for grain size determination of higher grains, the particle size of surfacial samples are determined by pipette analysis method. In this method materials coarser than 63 is recovered by wet sieving. The residue is dried and weighed. The sediment washed off in the wet sieving is made up to a known volume with water and is placed in a tall cylinder. After stirring, the fluid is allowed to settle and during the settling 20 ml samples of the suspension are drawn off in a repeatable manner from a fixed distance beneath the surface. The samples are then evaporated and weighed. The residue represents the total amount of sediment finer than a particular size in suspension. This size is related to the settling velocity of the grains and the time of sampling. The velocity is calculated from Stokes' law assuming that the grain density is 2.65 g/cm^3. The results, combined with sieve analysis of the sand fraction gives a complete grain size distribution.

3.4.8 Mineralogical study

The mineralogical assemblages of surfacial and fluid mud samples are examined by x-ray diffraction method. Air-dried powdered samples are scanned from 2° to 30° 2θ at 2° min^{-1} with CuK radiation. The major clay minerals are identified by computing its inter-planar spacing from its principal reflections. Kaolinite is identified by its reflection at 7.15 and 3.57 A°, montmorillonite 14A°, illite 10A° and gibbsite 4.9A°. The relative proportions of the clay minerals are determined by measuring the area of their principal reflections. The percentages of major clay minerals are thus determined. Even though a true quantitative evaluation of clay minerals are not possible by this method, a reasonable good approximation of clay minerals can be obtained.

Chapter 4

4. WAVES AND SEDIMENTS IN MUDBANK

When the waves enter shallow waters, firstly the waves themselves get transformed in shallow water under the influence of sea bottom conditions including the sediment characteristics and secondly, these transformed waves cause mobility to the bottom sediments, causing extensive changes to the bottom conditions.

The wave transformation processes such as refraction, diffraction, reflection, shoaling, bottom friction, percolation, etc. on a sandy bed are fairly known. But, the effect of a cohesive bed on waves is least known, except for a few theoretical and laboratory studies. Field data on this aspect, particularly, is scanty. Moreover, in the zones of occurrence of mudbanks of the southwest coast of India, where the bed consists of silty-clay and clayey-silt (Ramachandran and Samsuddin, 1991) the processes of wave transformation are practically unknown. These are addressed in this chapter.

In addition, the characteristics of sediments of mudbank area during mudbank and non-mudbank periods are studied. The suspended sediment concentration in the water column during different stages of mudbank and its mineralogy and textural characteristics are examined. Also the rheological behaviour of fluid mud, which is observed in the mudbank is presented.

4.1 Waves and Their Transformation in Mudbank

Long-term wave climatology for a mudbank location (off Alleppey) based on field measurements is presented. Also, synchronised wave data from outside and inside the mudbank, which has been done for the first time for the mudbanks of this coast, are studied to achieve a complete understanding of the behaviour of waves during its propagation over mudbanks and the process of wave energy dissipation. For comparison, results of the studies on wave transformation based on synchronised offshore and nearshore wave data at the same location during non-mudbank period are also presented.

4.1.1 Long-term wave climatology off Alleppey

The basic parameters required to establish the wave climatology of a location are height, period and direction. An understanding of wave spectra will throw more light into the energy distribution in the wave field.

4.1.1.1 Wave height : Significant wave height is the most commonly used height parameter. The daily nearshore significant wave heights (H_s) during 1986 to 1989 are presented in Fig.(4.1). The wave intensity is less during the period October-April. The waves get intensified by the end of May and high waves persist for a week or two which is followed by the formation of mudbank in most of the years. Except for the monsoon period (May-September), the H_s values are less than 0.75 m for most of the time. There is no significant inter-annual variability in the seasonal trend. The H_s values range from 0.05 to 2 m for the study period (1986-89). It may be noted that this has been consistent during the earlier five-year period also as reported by Hameed (1988). He observed a maximum significant wave height of 3 m for this coast. It is interesting to note that the highest and the lowest values of H_s occur during the rough monsoon period. The lowest value, incidentally, is due to the presence of mudbank.

4.1.1.2 Wave period : A plot of the daily zero-crossing period (T_z) is given in Fig.(4.2) for different years. The T_z values range between 10 and 18 s for non-monsoon period (October-April) and 7 and 10 s for monsoon period (May-September). The predominant periods during monsoon season are 8 & 9 s. There

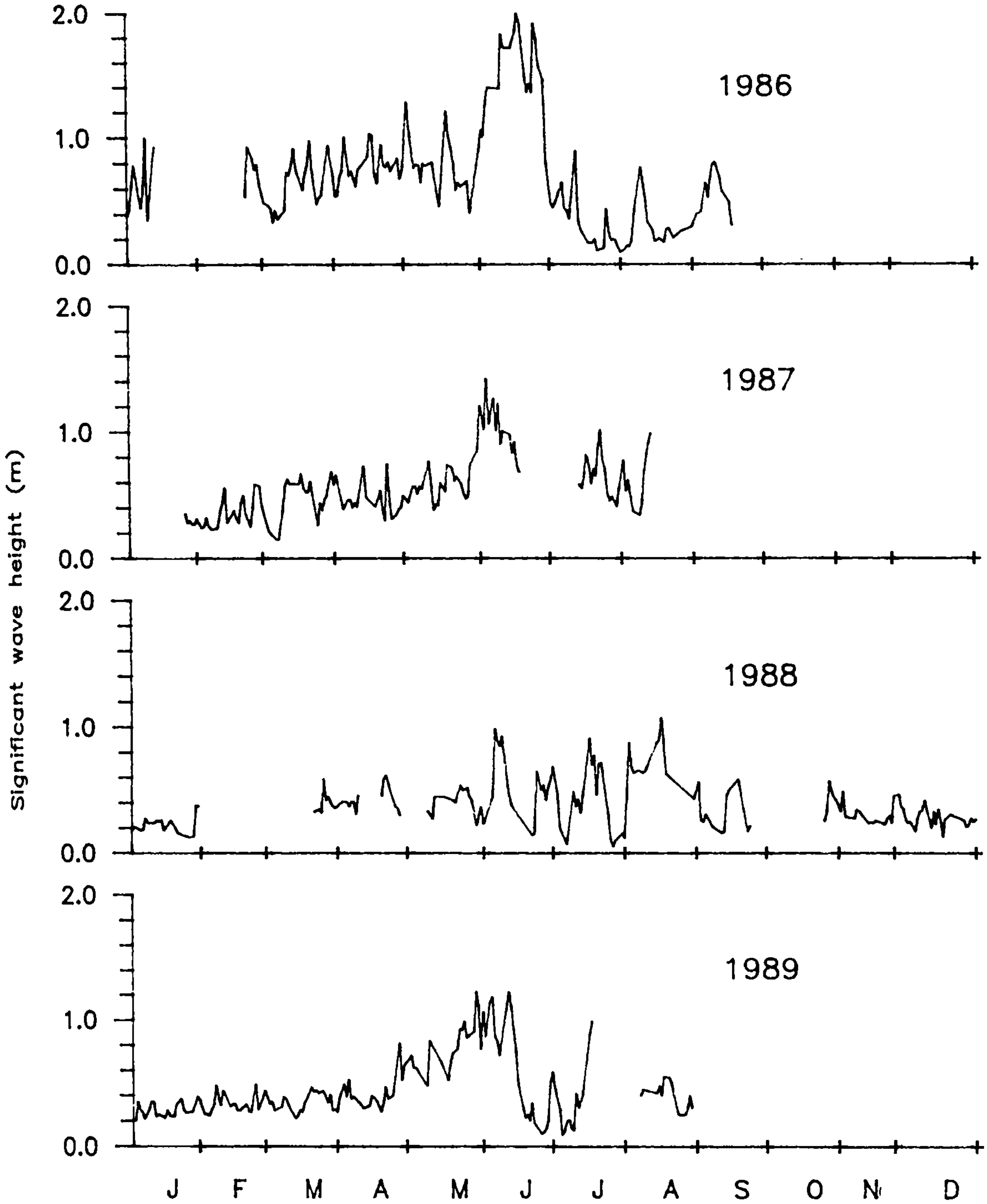

Fig. 4.1 Daily (1200 hrs) variation of nearshore significant wave height

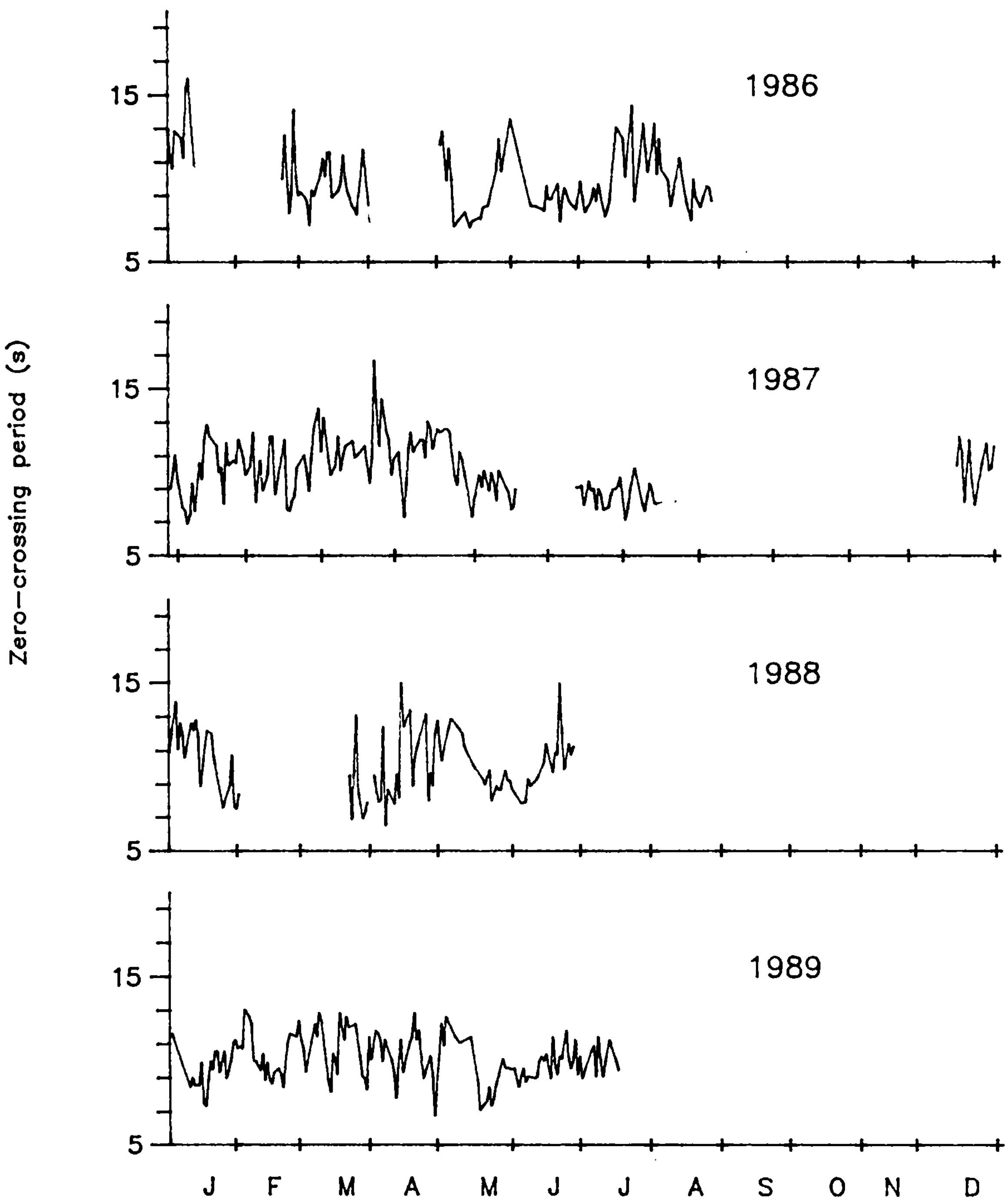

Fig. 4.2 Daily (1200 hrs) variation of nearshore zero-crossing period

is no significant year-to-year variation except for the peaks of the pre-monsoon swells.

4.1.1.3 Wave direction : The nearshore wave directions for this coast range from 235° to 280° N (Fig.4.3). The dominant wave directions during monsoon range from 240 to 265° N indicating that the waves reach more or less parallel to the coast during this season, the normal to the shoreline being 260° N. A comparison with the deep water wave directions reported in the Indian Daily Weather Reports reveals that the waves reach the nearshore after undergoing considerable refraction.

4.1.1.4 Monsoonal wave spectra : Examples of typical non-mudbank monsoonal nearshore wave spectra are shown in Fig.(4.4). Almost all the spectra are single-peaked and the energy is confined to the 0.05-0.2 Hz frequency range. There is not much variation in the shape of individual spectra both in terms of the size and number of peaks. During the non-monsoon period, the wave spectra generally have very low energy. By the initiation of monsoon the energy increases and soon attains the maximum value.

4.1.1.5 Wave transformation without mudbank : The wave transformation features are studied by comparing the synchronised offshore and nearshore wave heights and spectra. The offshore wave recording is done just outside the zone of occurrence of mudbank (see Chapter 3). The time of propagation of waves from offshore station to the nearshore is not accounted in this comparison considering the stationarity of waves and the short distance between the nearshore and offshore wave recording stations. A plot of the nearshore significant wave heights against the corresponding offshore wave heights is given in Fig.(4.5). It can be seen that there is some attenuation in wave height in most of the cases. The line of best fit is

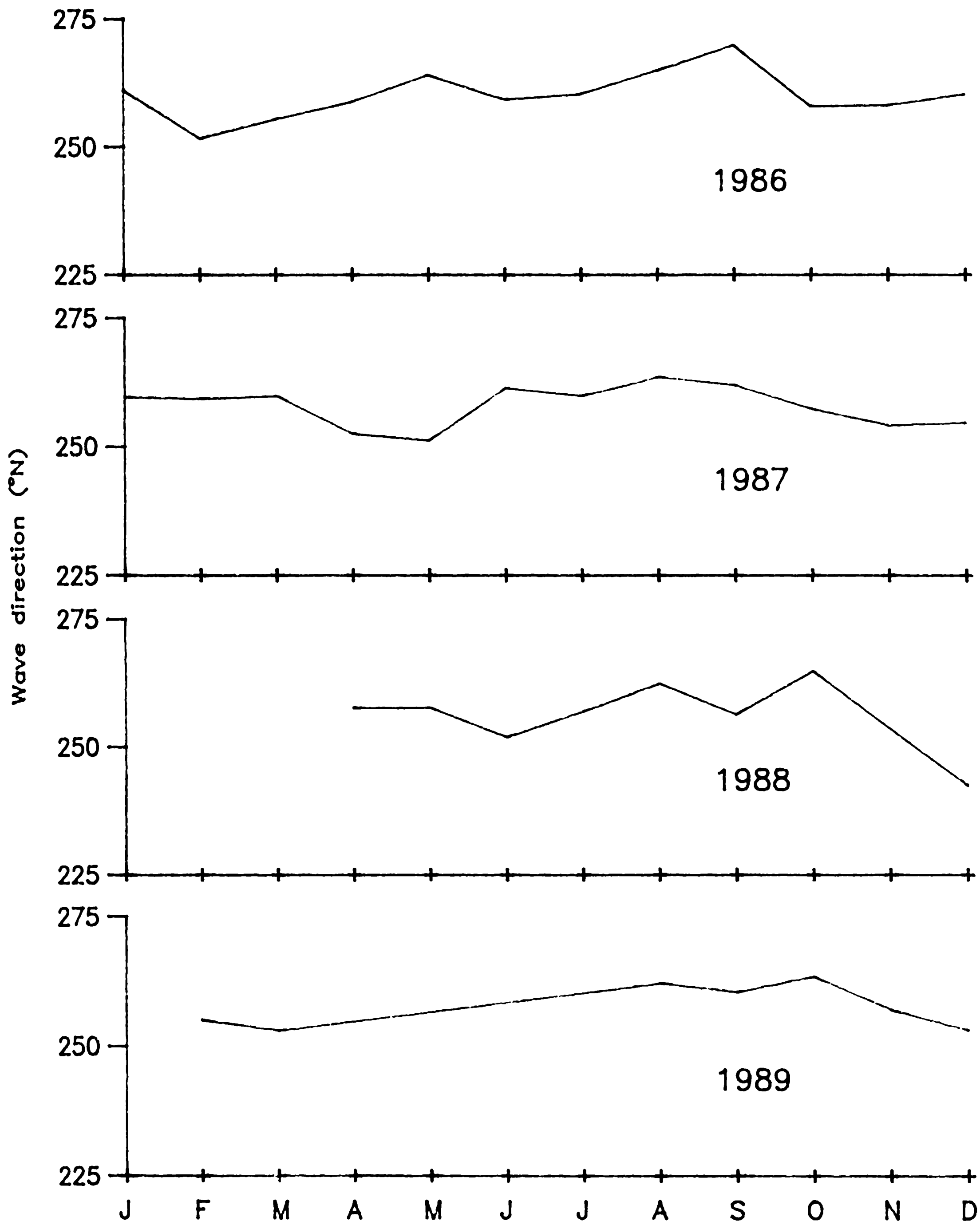

Fig.4.3 Monthly variation of wave direction

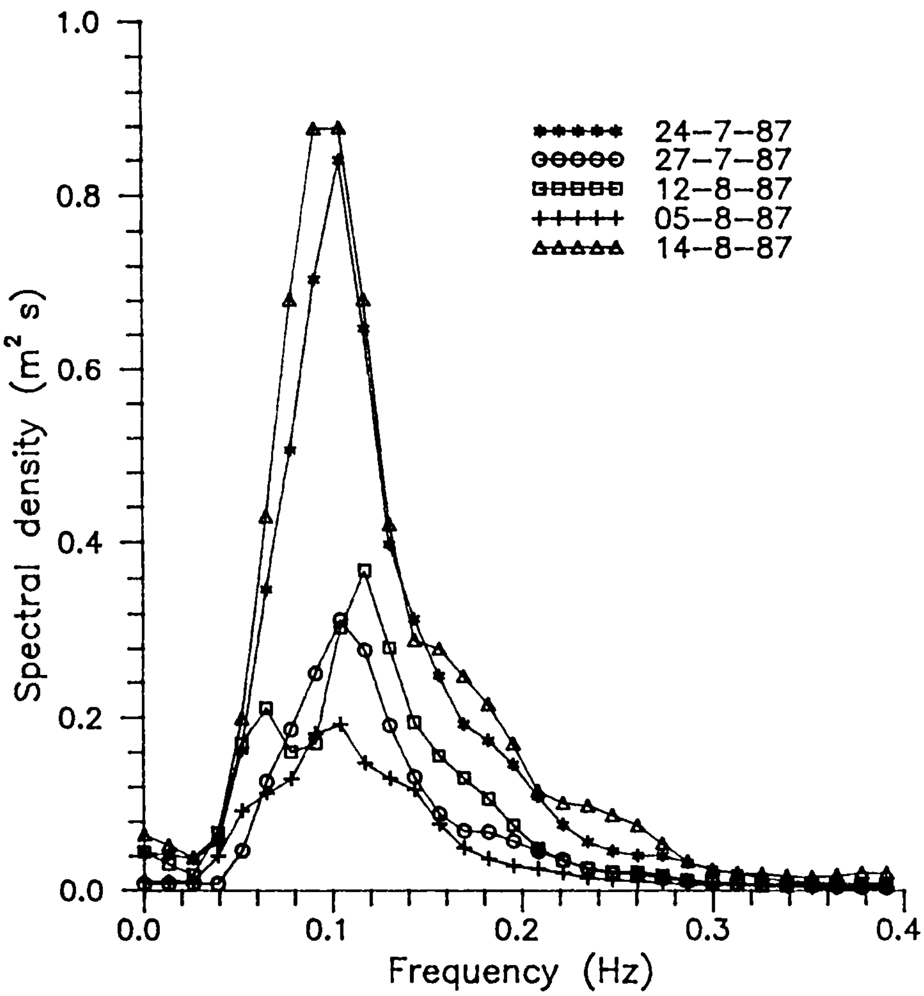

Fig. 4.4 Typical non-mudbank monsoonal wave spectra

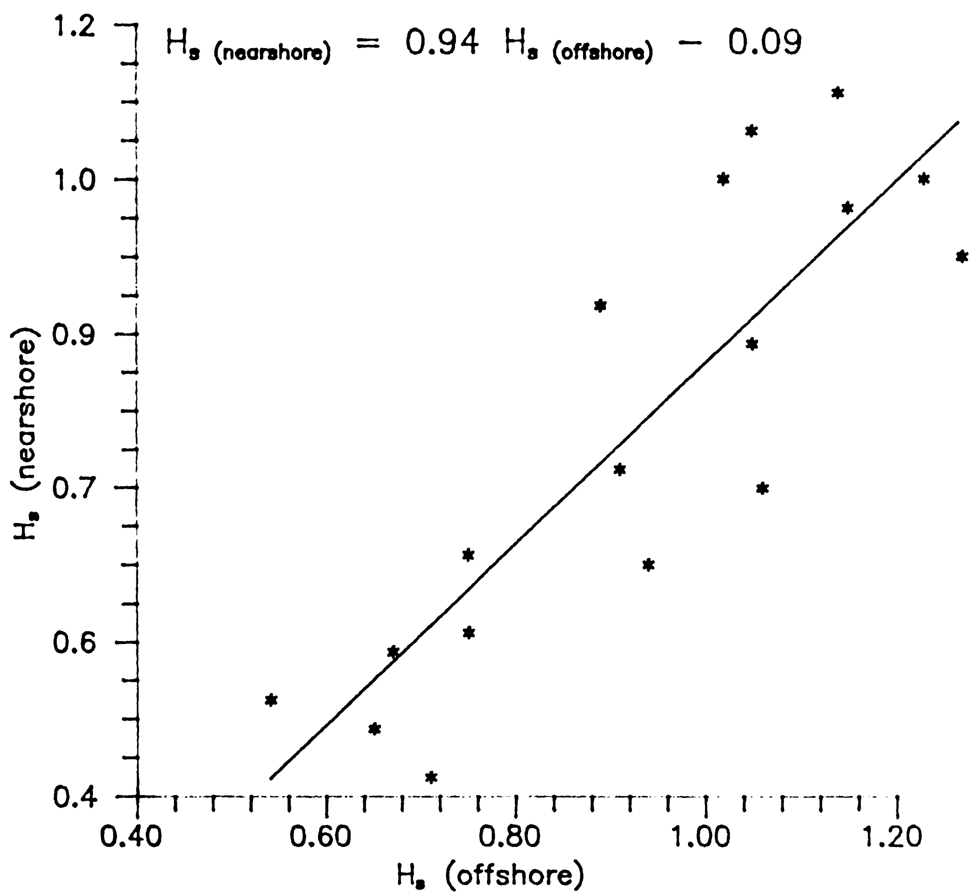

Fig. 4.5 Comparison of synchronous nearshore and offshore significant wave heights in the absence of mudbank

$$H_{s(nearshore)} = 0.94\ H_{s(offshore)} - 0.09 \qquad .....(4.1)$$

Attenuation of wave height is in the range -3 to 30 %. This is well within the range reported by Kurian (1987) who observed an attenuation up to 50% for deep water waves propagated for a distance of 18 km in the shallow waters. The nearshore wave spectra and the corresponding offshore wave spectra for the non-mudbank period are compared in Fig.(4.6). The energy losses are in the range of 0-40% except in a few cases, where a slight increase in energy is observed. In most of the cases the energy loss is less than 25%. The peak frequencies are found to coincide in a majority of the cases indicating the retention of the major portion of the energy density around the same peak frequency even after transformation. A detailed study of the wave height and spectral transformation along this coast has been conducted by Kurian (1987). He suggests that bottom friction is the deciding factor in the dissipation of wave energy for this coast in normal conditions.

4.1.2 Wave characteristics associated with mudbank

4.1.2.1 Wave height : The nearshore significant wave height (H_s) during various stages of mudbank for different years are presented in Fig.(4.7a-d). In the year 1987 mudbank has not formed in the location of study but appeared in the adjacent coast. It is found that mudbank is formed after an increase in wave height. The duration of mudbank sustenance is seen to be related to the wave height during the pre-mudbank period and its persistence. It can be seen from Fig.(4.7a) that the mudbank is more sustained during 1986 when the pre-mudbank waves are more intense (H_{smax} = 2 m) and persistent. Fig.(4.7c) shows that the mudbank sustenance is the least during 1988, when the pre-mudbank waves are least intense and persistent. Intermittent occurrence and disappearance of mudbank is observed during 1988.

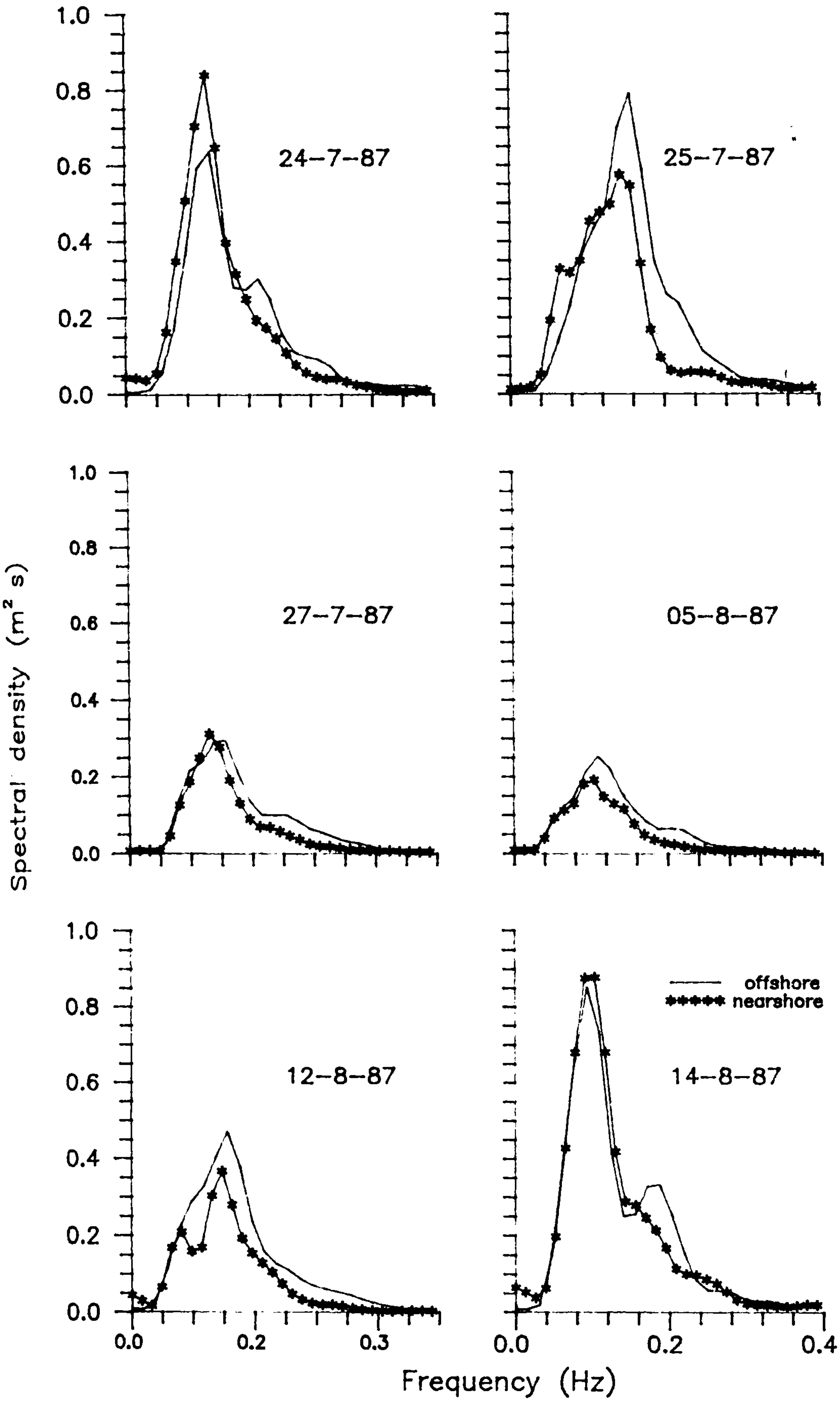

Fig. 4.6 Comparison of synchronous nearshore and offshore wave spectra in the absence of mudbank

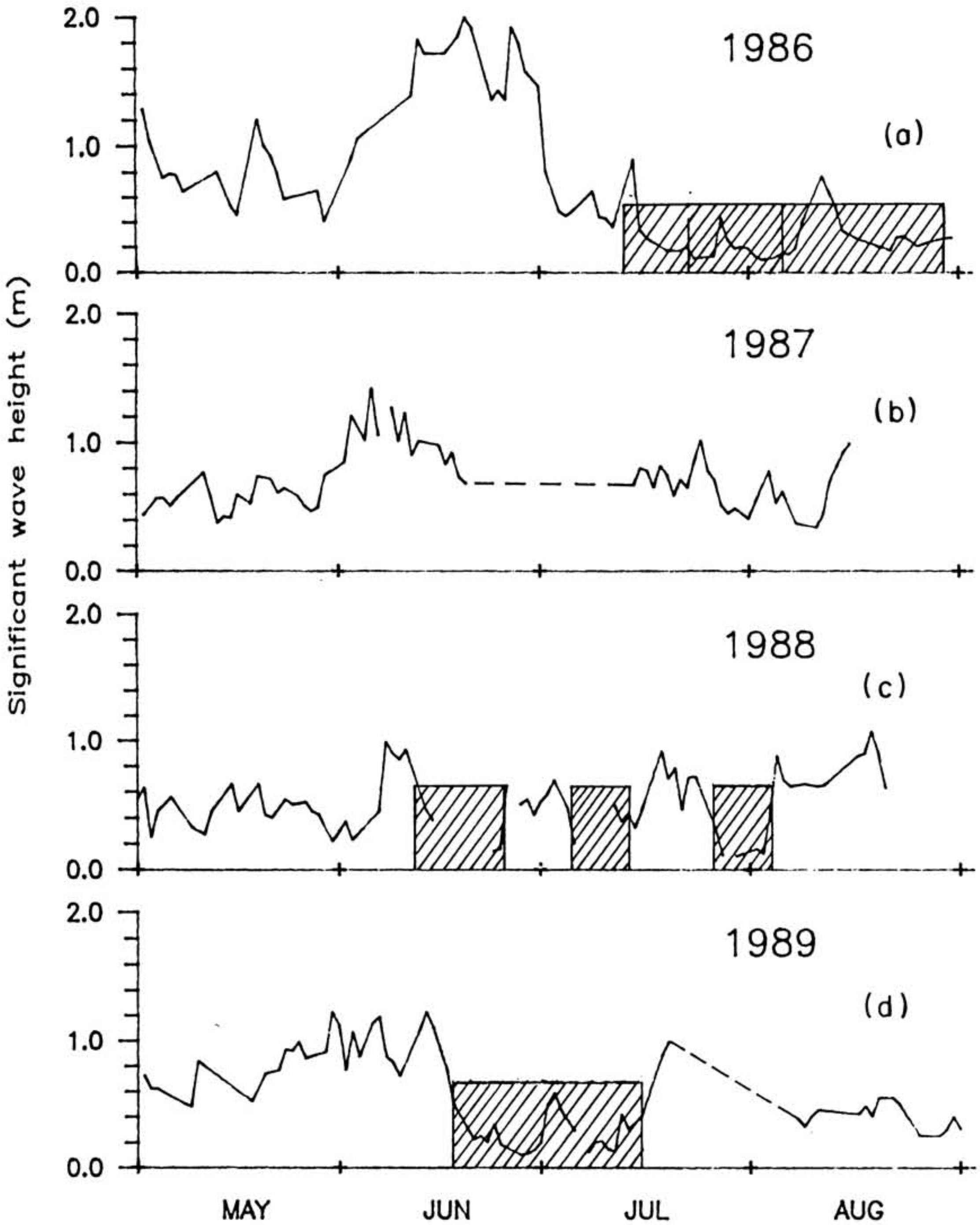

Fig. 4.7 Daily nearshore significant wave height during the monsoon period. The hatched area indicate active mudbank occurrence.

Occasional spurt in wave activity during the mudbank sustenance is also observed which is related to the occurrence of high swells in deep water. This has been noticed by other researchers also (Kurian, 1988; Hameed, 1988) for this and other locations along the south-west coast of India.

4.1.2.2 Wave period and direction : No significant changes are observed in the wave period during the occurrence of mudbank compared to the pre-mudbank condition (Fig.4.2). Since the waves were extremely small the directions are not discernible.

4.1.2.3 Mudbank wave spectra : Examples of wave spectra during the pre-mudbank, mudbank and post-mudbank periods of 1986, 1988 and 1989 are given in Fig.(4.8-4.10). In the pre-mudbank stage, a rapid decay towards the low frequencies and a moderate decay towards the high frequencies are observed. The spectrum becomes narrow just before the mudbank formation and loses energy gradually during the formative stage until the mudbank is fully developed, when the energy content of the spectra is the least.

No detectable shift in the peak frequency is noted in any of the spectra during the development as well as the decay stages. The spectral peaks are mostly observed at frequencies 0.09-0.10 Hz (periods 10-11 s) before mudbank formation and shift to 0.11-0.13 Hz (periods 8-9 s) by the formation of mud-bank. Occasional lower values (< 0.06 Hz) are also observed during mudbank period. The peak spectral density reaches a maximum of 0.77 m^2 s just before mudbank formation and reaches the lowest value of 0.01 $m^2 s$ when the mud-bank is fully developed. The spectral moment m_o correspondingly takes the values of 0.095 and 0.001 m^2. Occasionally secondary peak, though not prominent, in the high frequency side is observed in the mudbank spectra (Fig.4.11) indicating the presence of sea waves in the mudbank area.

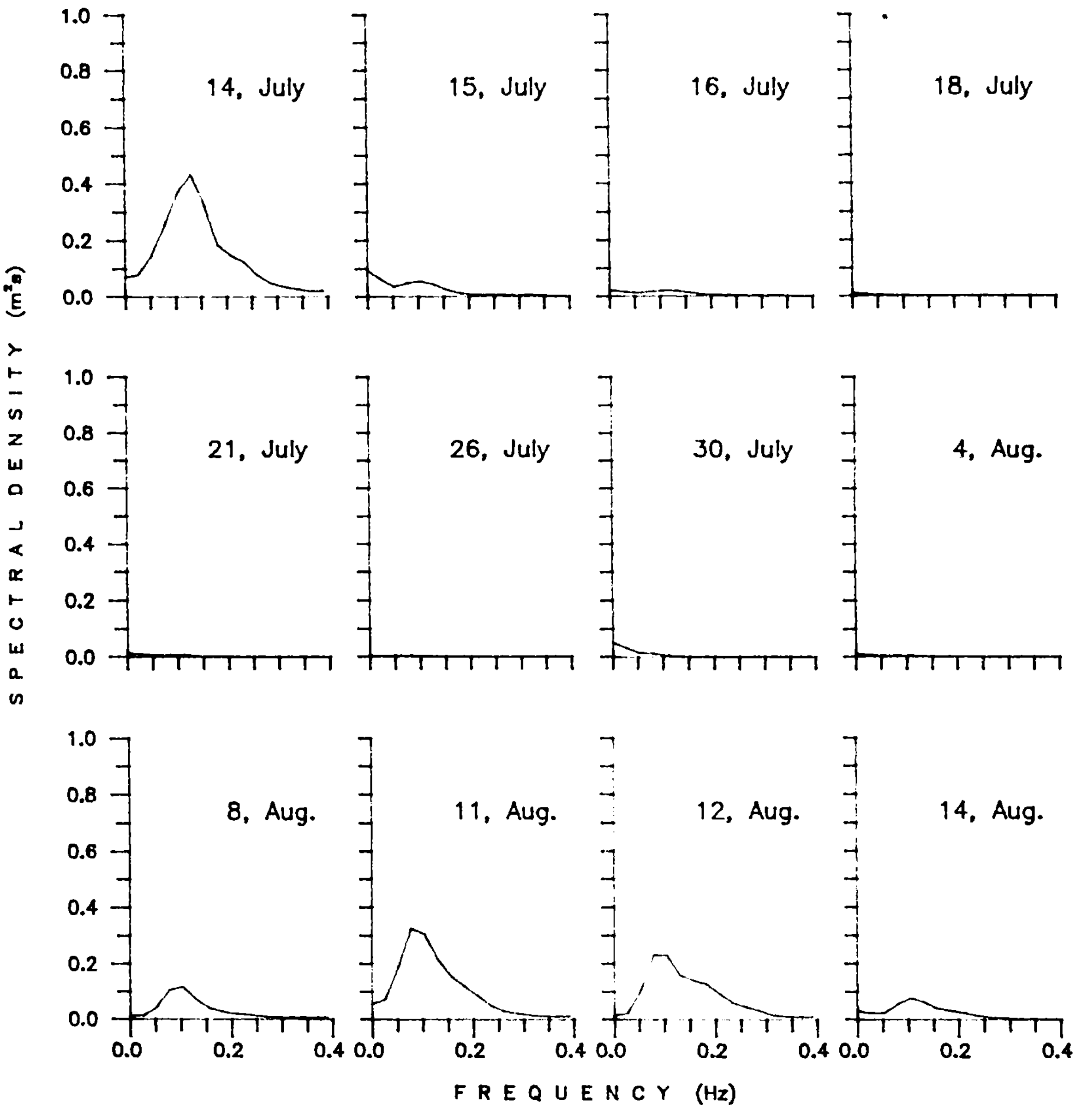

Fig. 4.8 Systematic transformation of nearshore wave spectra during pre–mudbank, mudbank and post–mudbank conditions for 1986.

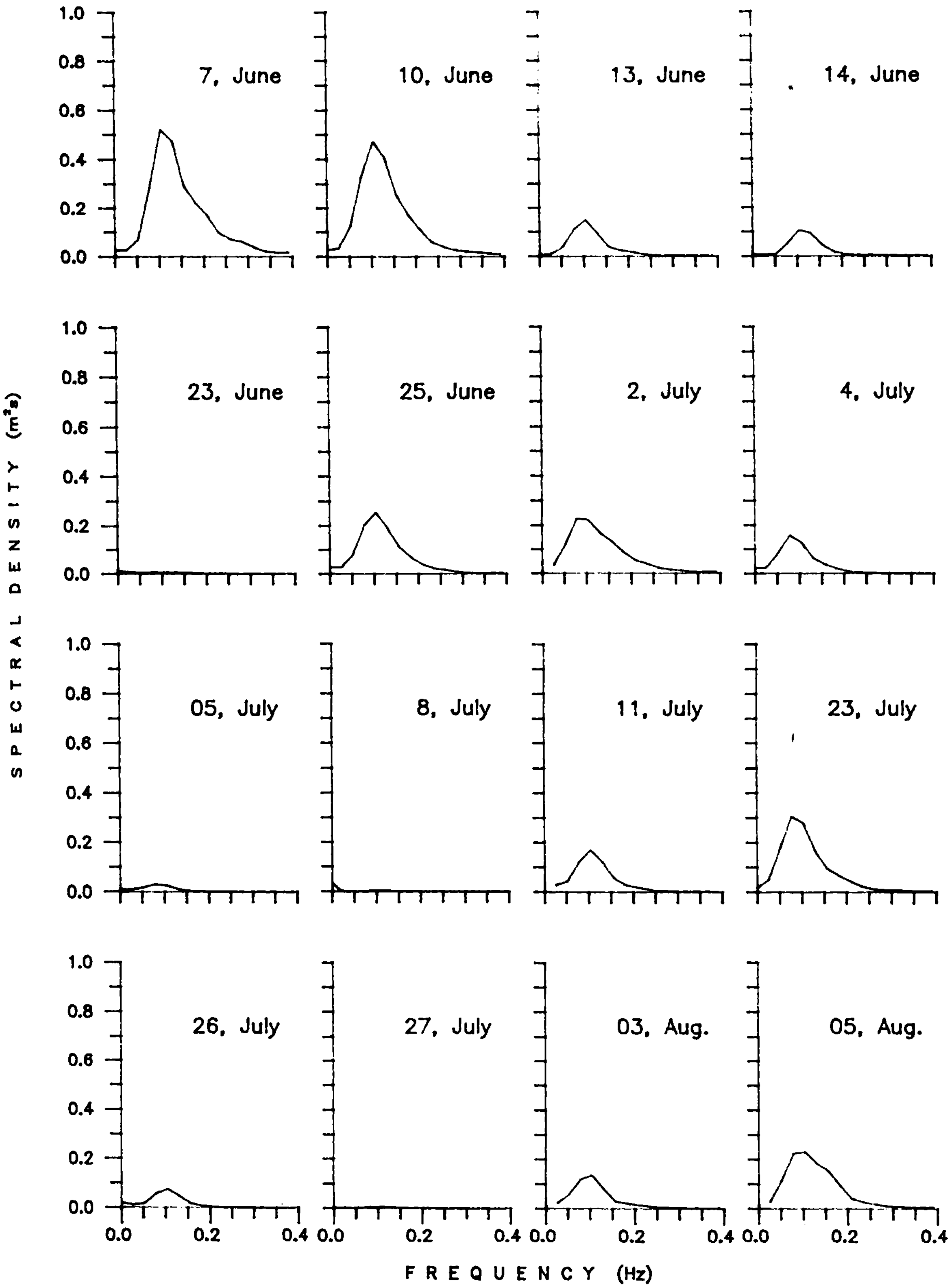

Fig. 4.9 Systematic transformation of nearshore wave spectra during pre-mudbank, mudbank and post-mudbank conditions for 1988.

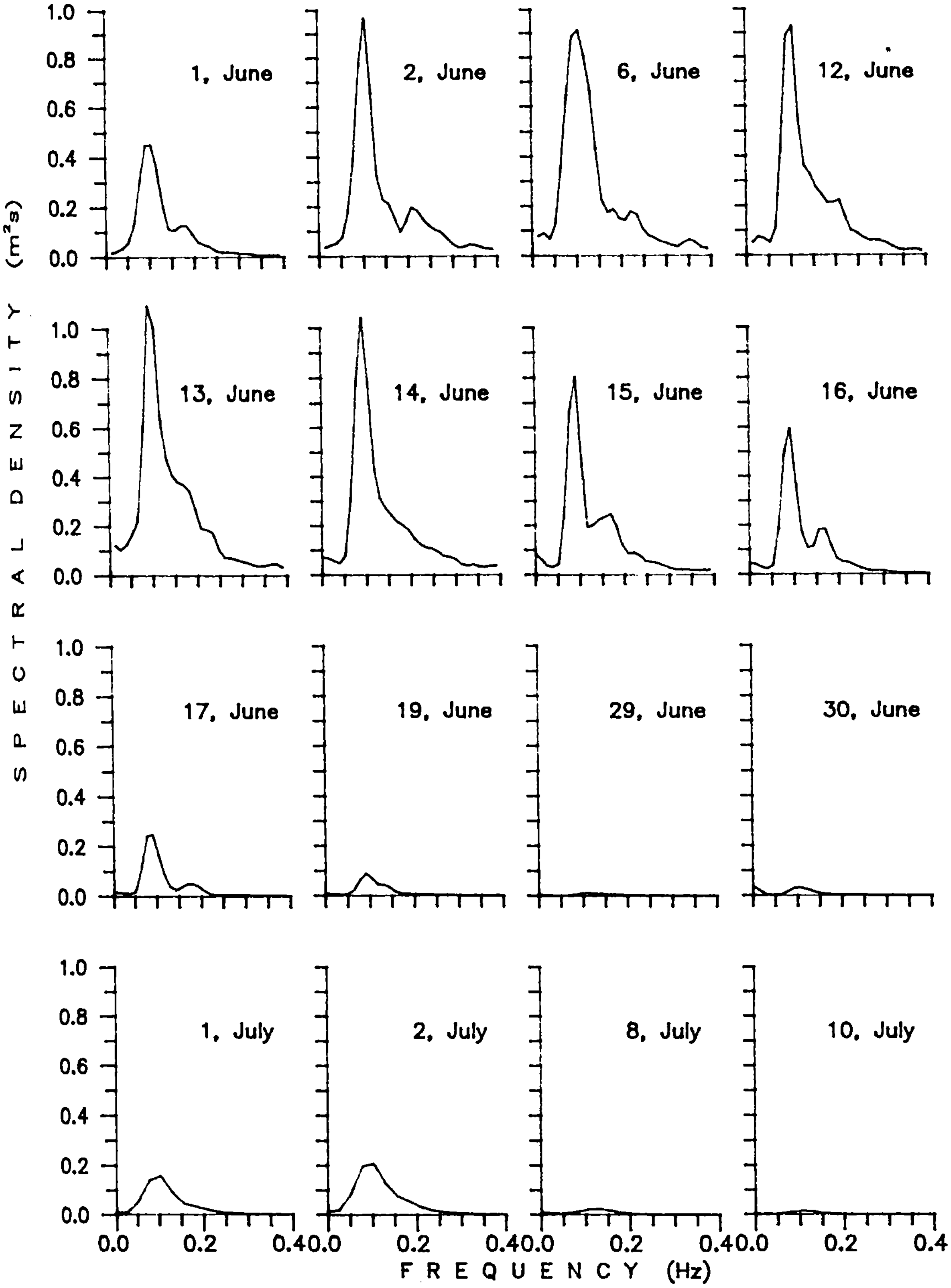

Fig. 4.10 Systematic transformation of nearshore wave spectra during pre-mudbank and mudbank conditions for 1989 (The mudbank dissipated on 20th July due to high wave activity, which damaged even the wave recorder and hence no spectrum could be presented showing the dissipation stage).

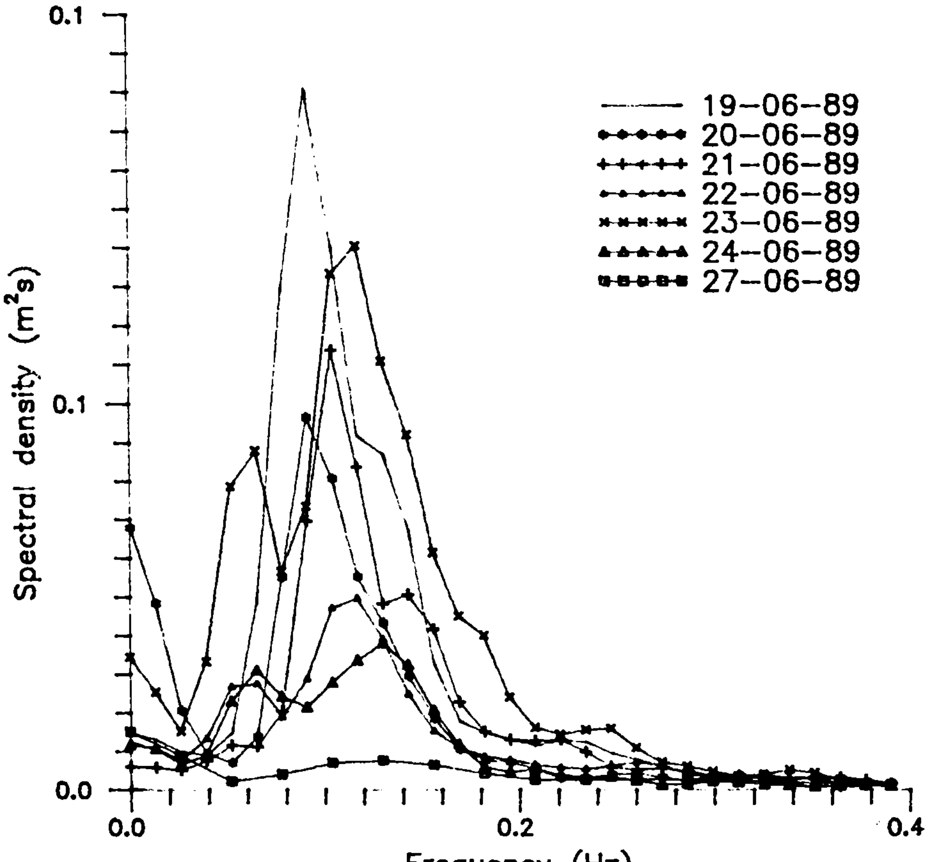

Fig. 4.11 Mudbank wave spectra with the density scale magnified

While a gradual decrease in wave energy is observed in the formative stages of mudbank, a rapid increase in energy is observed in the dissipative stage (Fig.4.8&4.9). The spectral characteristics during dissipative stage are similar to that in the formative stage.

4.1.2.4 Wave transformation in mudbank : The characteristics of wave transformation during the formative and dissipative stages of mudbank are studied by comparing the wave parameters obtained from the offshore recording point outside the mudbank and the nearshore recording station within the mudbank (see Chapter 3).

A comparison of the significant wave height inside mudbank against the corresponding wave height outside the mudbank (Fig.4.12) shows the drastic decrease occurring within a distance of just 1.1 km during the wave propagation to nearshore. It is to be remembered that the data correspond to a period of intense wave activity in the offshore. The line of best fit for the data is

$$H_{s(mudbank)} = 0.24\ H_{s(offshore)} + 0.09 \qquad .....(4.2)$$

It is observed that in the developing and dissipating stages of mudbank the wave height is attenuated by about 75-85% by the time it reaches the nearshore recording station and almost 100% before it reaches the shoreline. In a fully developed mudbank almost 100% dissipation of wave height occurs within a distance of few wavelengths over the mudbank zone (Fig.4.10).

The most conspicuous aspect of transformation of wave spectra in the presence of mudbank is its high rate of energy reduction. Fig.(4.13) shows examples of wave spectra inside and outside the mudbank. An 80-90% reduction in spectral energy is observed. The peak frequencies, however, are found to coincide in a majority of the cases, as in the case of non-mudbank condition.

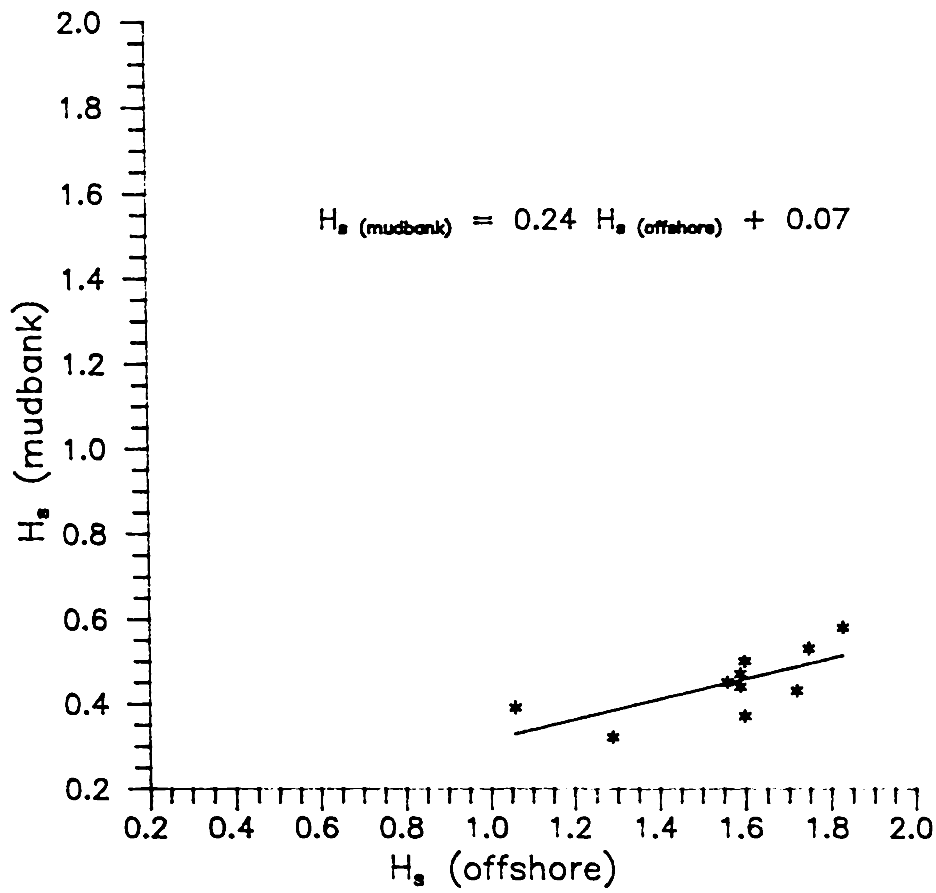

Fig. 4.12 Comparison of synchronous mudbank and offshore (inside & outside the mudbank respectively) significant wave height

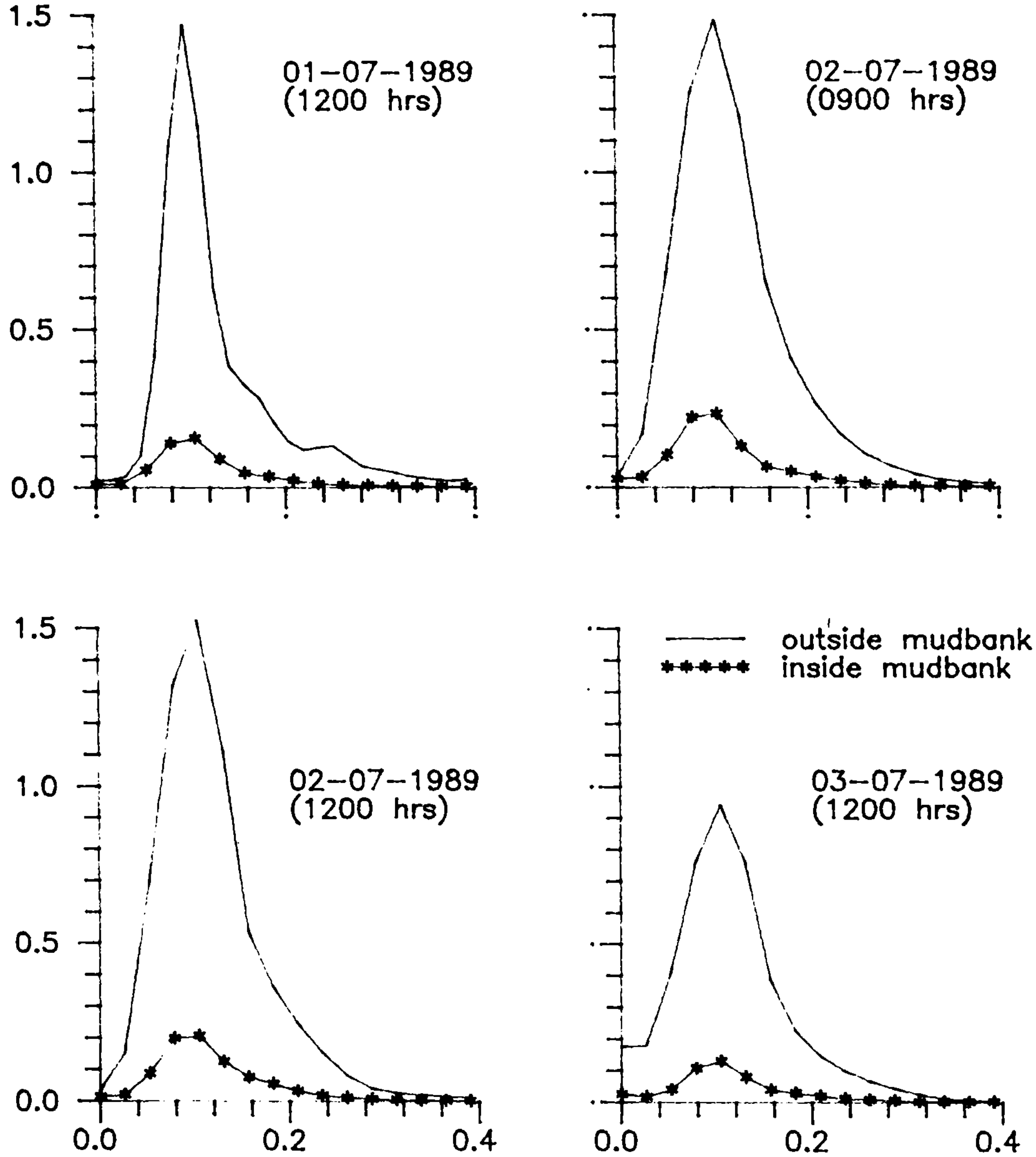

Fig 4.13 Comparison of synchronous offshore and mudbank spectra

4.2 Sediment Characteristics

4.2.1 Suspended sediment

The availability of fine-grained sediments in the locality or their transport to the location or both is an essential prerequisite for the formation of mudbank. The suspended sediment concentration of the nearshore zones of Alleppey coast is very low and it is below 5 mg/l in the upper layers during most part of the year. During rough sea conditions sediment concentration increases up to 1000 mg/l.

Fig.(4.14) shows the vertical variation of suspended sediment concentration (SSC) at the study area during a non-mudbank period (July, 1987). The surface SSC value at different locations towards offshore is less than 7mg/l. Bottom SSC value reach a maximum of 46.4 mg/l in the nearshore. In the offshore locations the bottom SSC ranges between 6.5 and 19 mg/l.

Fig.(4.15) shows the vertical distribution of suspended sediment during different stages of mudbank. In the pre-mudbank condition the surface column has SSC in the range 600-900 mg/l marking the triggering of mudbank. This coincides with the maximum nearshore significant wave height during this period (1.23 m) and frequent spilling breakers observed in the offshore indicating turbulent sea condition. Further, the moderately high currents with velocity of 66 cm/s also contribute to the turbulence of the nearshore. After a couple of days from then, the SSC values in the upper layers show a drastic decrease (to less than 100 mg/l), whereas the near-bed layer concentration increases up to 12500 mg/l (Fig.4.15b). This could be due to the settling of suspensates at the surface layers resulting from the observed decrease in the wave height and current velocity, thus making a depletion of SSC at the surface and corresponding enrichment at the near-bed layer.

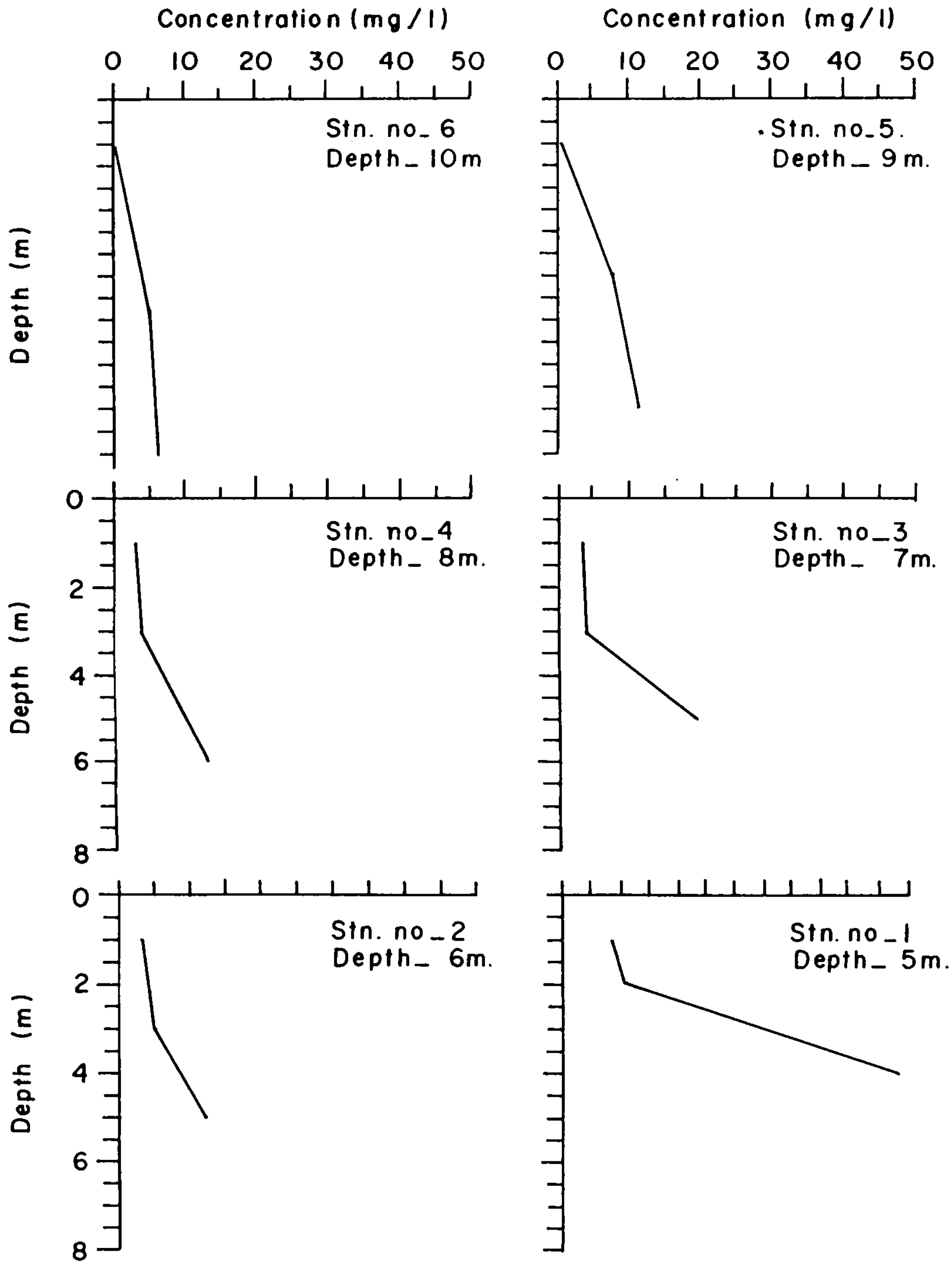

Fig.4.14. Vertical variation of suspended sediment concentration during non_mudbank period (July, 1987). See Fig. 3.10 for station locations.

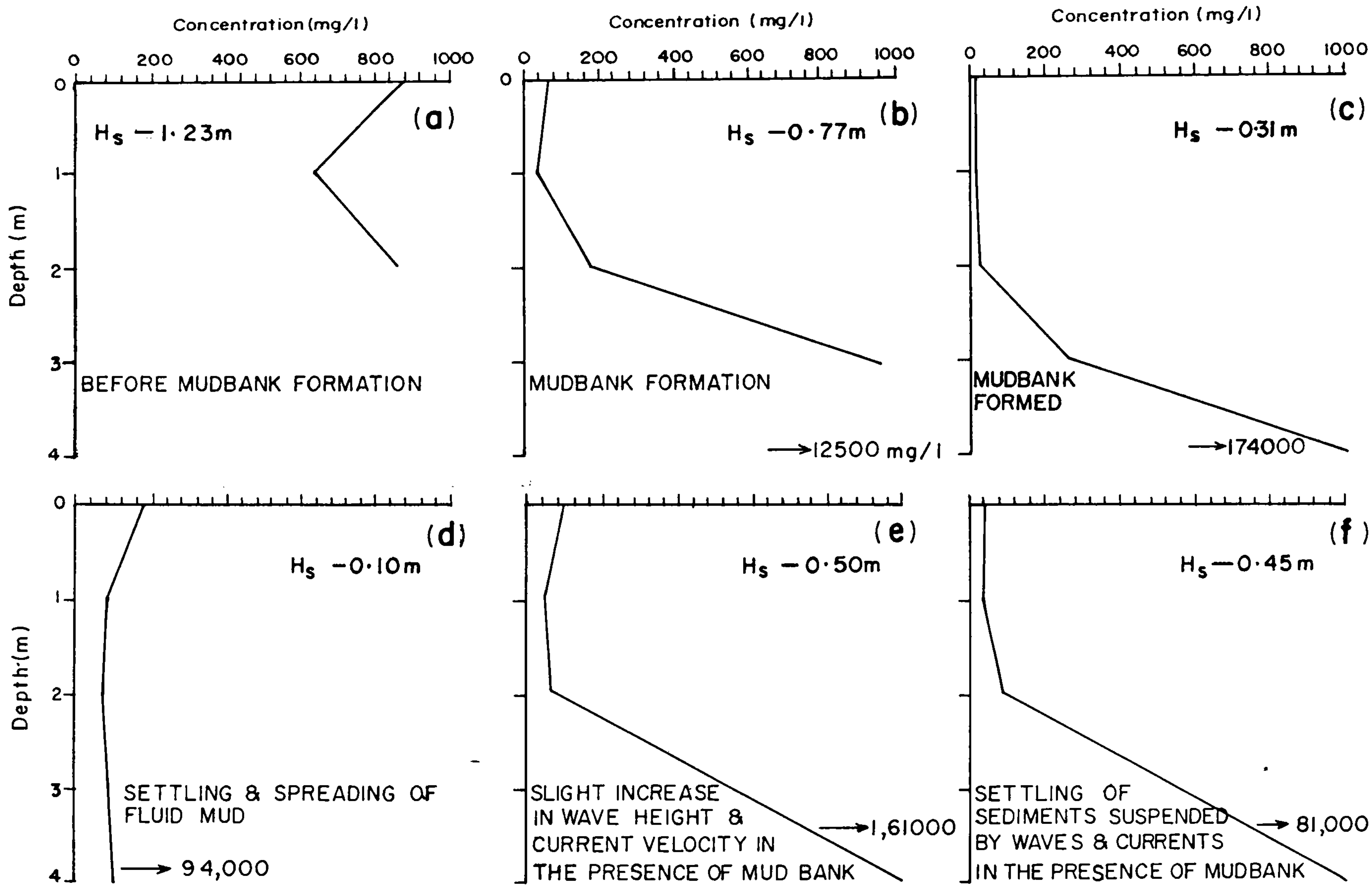

Fig.4.15. Vertical variation of suspended sediment concentration before and during mudbank

SSC further decreases after two days in the upper layers in response to the considerable decrease in dynamic forces acting on it. The concentration observed is < 30 mg/l in the upper layer with a corresponding near-bed concentration of about 1,74,000 mg/l (Fig.4.15c). This high near-bed SSC is generally defined as fluid mud (discussed in section 2.5). The observed thickness of this fluid mud layer is about 2 m.

Redispersal of sediments from upper part of fluid mud to the overlying water column is observed due to increased current velocity (55 cm/s) while calm condition prevails in mudbank (Fig.4.15d). However, the vertical profile above the fluid mud layer shows a homogeneous concentration of suspensates. The thickness of the fluid mud layer decreases to about 1 m during this time with a lateral extension of mudbank to either side. Previous observations also report similar processes (Kurup, 1977).

An increase in wave height coupled with an increase in thickness of fluid mud layer is observed after few days (Fig.4.15e). As explained in section 4.1.2.3, the wave height outside mudbank is high (≈ 2 m) while it is less than 50 cm in the nearshore during this period. Since the concentration in the upper layers is very low, a rapid settling of sediments from the upper layers is observed in the subsequent days (Fig.4.15f). The vertical distribution of SSC at four stations in the mudbank during this period is shown in Fig.(4.16). Here also the upper layers show a very low concentration. It is interesting to note that the concentration and thickness of fluid mud at the periphery is higher than that inside mudbank. The data beyond the peripheral zone could not be collected due to high offshore wave activity.

One of the hypotheses proposed earlier (Varma and Kurup, 1969) for the sustenance of mudbank is the de-flocculation of sediments in low salinity

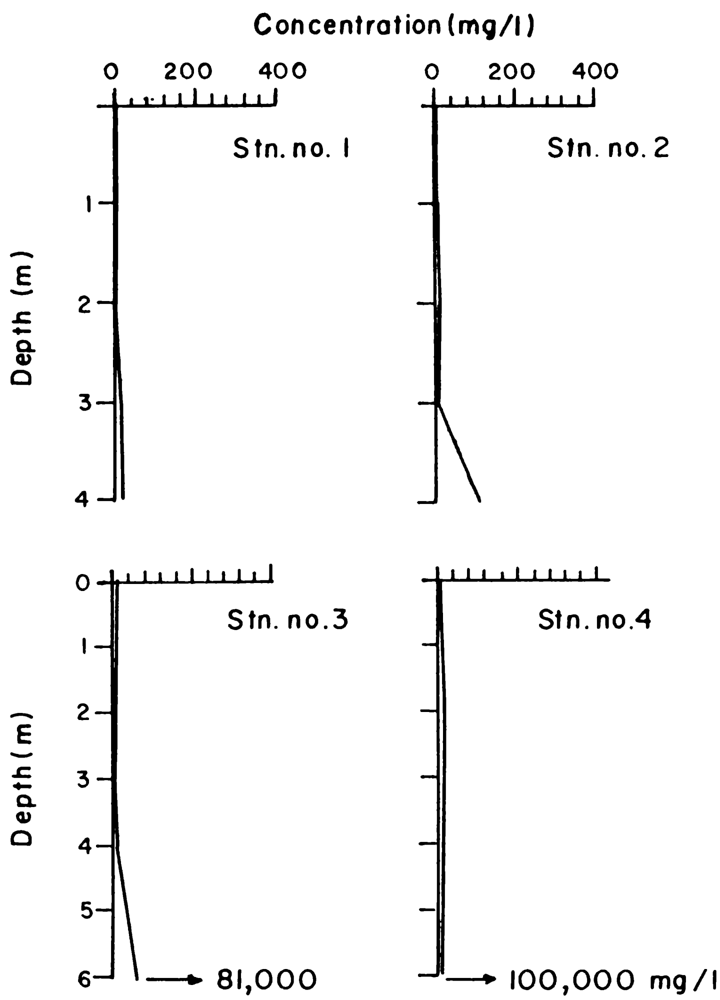

Fig.4.16. Vertical distribution of SSC at different stations in the mudbank (See Fig 3.10 for station locations)

conditions. They are of the view that the mudbank sustains due to the presence of high amount of suspended load in the water column brought by the de-flocculation process resulting in high viscosity conditions. The observed surface salinity variation during monsoonal non-mudbank period is shown in Fig.(4.17). The salinity values range between 30.46 and 33.62‰. Due to the monsoonal precipitation this variation is possible. The salinity variation during different stages of mudbank are given in Fig.(4.18). The maximum salinity value of 34.55‰ coincides with pre-mudbank period, followed by a slight decrease and a subsequent increase to the earlier value. This slight decrease observed could be due to precipitation. A few days after the formation of mudbank the lowest salinity of 29.14‰ is observed. The lower salinity values are observed only for a few days. Since salinity above 10‰ has negligible effect on sediment particle de-flocculation, the salinity value observed in the present case cannot accelerate the de-flocculation of particles. Hence the de-flocculation hypothesis for sediment suspension in mudbanks do-es not hold good to explain the turbidity, which in turn is suggested by the above researchers as the reason for the high viscosity of mudbank waters.

A comparison of SSC in the upper layers during different stages of mudbank reveals that, the maximum SSC values are encountered during pre-mudbank period. Mudbank formation creates a stress-free condition which helps in rapid settling of suspended sediments from the upper layers. This observation is contrary to the earlier reports of a highly turbid water at surface layers present throughout the period of existence of mudbank. As mentioned earlier in Chapter 1, the local fishermen use the mudbank area as a potential fishing ground and temporary harbour during rough season. The operation of hundreds of these country crafts with fishing gear create turbulence in the water column, which is otherwise a stress-free zone. The turbu-

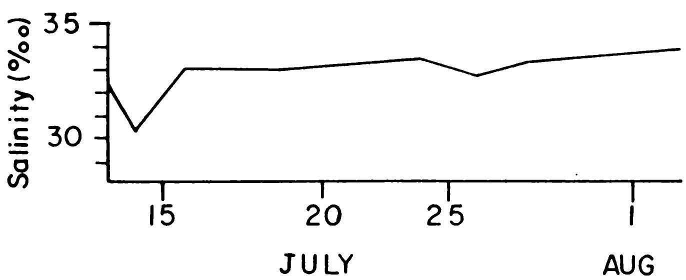

Fig. 4.17 Daily variation of surface salinity during a non_ mudbank period

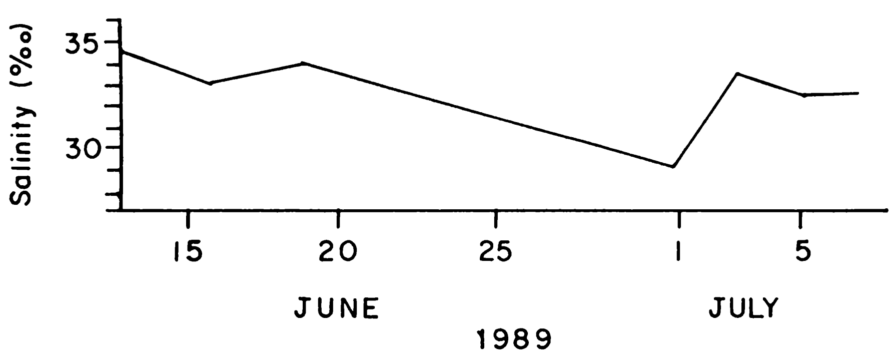

Fig. 4.18 Daily variation of surface salinity during different stages of mudbank.

lence thus created hinter the settling of fine sediments. This could be one of the reasons for the reports of high sediment concentration of the upper layers in the earlier studies.

4.2.2 Fluid mud

The different characteristics of the fluid mud, which accumulates in the mudbank zone are examined. In the initial stages, the fluid mud has a thickness of 2 m and a concentration of 1,74,000 mg/l in the superficial layers with a density of 1.27 g/cm^3. Samples from lower layers of fluid mud could not be collected since the sampler did not penetrate to the lower layers due to the high concentration of fluid mud layer. The dry density of sediment sample obtained is 2.27 g/l which is same as the value reported by James *et al.* (1987) for marine clay.

4.2.2.1 Rheological behaviour : To study the rheological behaviour of fluid mud, viscosity measurements are carried out. No previous treatment (removal of carbonates or organic matter) is done prior to analysis. The viscosity and concentration of fluid mud obtained for different stages of mudbank are given in Table (4.1). All the measurements are made at constant room temperature. Since the viscous response of fluid mud depends on mineralogy, concentration, settling time, temperature, dynamic forces and other yet unknown factors, the changes in these factors during different periods of sample collection also affect the viscosity. The viscosity of fluid mud obtained at the initial stage of mudbank is 4.76 Ns/m^2 (spindle No.1 and rpm 10 in all cases), about 4,000 times greater than the viscosity of sea water. This value represents only the upper fluid mud layer, and no data is available on the internal density distribution of fluid mud. Due to differential settling of sediments, a less concentrated layer overlies a high concentration layer. Hence the lower layers may

Table 4.1 Viscosity and concentration of fluid mud during different stages of mudbank.

Station Depth (m)	Viscosity Ns/m^2	Concentration mg/l	Remarks
5.5	4.76	1,74,000	Fully developed mudbank
5.5	3.04	1,61,000	Increased wave activity in the offshore and adjoining coasts
5.5	0.22	94,000	Reduced wave activity in the offshore. Dissipation commenced
6.5	0.16	81,000	Dissipation stage. Lower concentration in the nearshore
7.0	0.84	1,00,000	Dissipation stage. Higher concentration in the offshore

possess a higher viscosity. It is to be noted that there is an increase in viscosity for the sample associated with high current velocity and offshore waves during mudbank. The lowest viscosity obtained for the offshore fluid mud during the dissipative stage of mudbank, 0.16 Ns/m^2 is about 200 times that of sea water.

For a series of viscosity measurements made at more than one speed using a particular spindle (see Chapter 3), the rate of shear is directly proportional to the rpm at which the measurements are made. In turn, the deflection of the needle is directly proportional to the shearing force. Hence the dial reading against rpm is plotted and given in Fig.(4.19) to identify the behaviour of fluid mud. In all the cases no flow occurs until the shear stress exceeds the yield stress. Such a behaviour is called Bingham plastic flow (Fig. 2.2). Since the yield stress and viscosity increase with suspension concentration, high values are obtained for higher concentration samples (Fig.4.20). All the samples show a Bingham plastic behaviour irrespective of concentration.

4.2.2.2 Mineralogy : The relative proportions of clay mineral assemblages in the surfacial sediments and fluid mud samples are examined by X-ray diffraction method. Major clay minerals identified are montmorillonite, kaolinite, illite and gibbsite. The percentages of these four major clay mineral types determined are given in Table (4.2). Pre-mudbank surfacial sediments of nearshore show higher percentage of kaolinite (56%) followed by montmorillonite. Illite and gibbsite in all the samples are found to be very low. Fluid mud samples of mudbank show an enrichment of montmorillonite with a corresponding decrease in kaolinite. These samples are collected from the upper layers of fluid mud. Finer-sized montmorillonite naturally forms the main clay mineral in fluid mud samples compared to the coarser kaolinite particles due to differential settling.

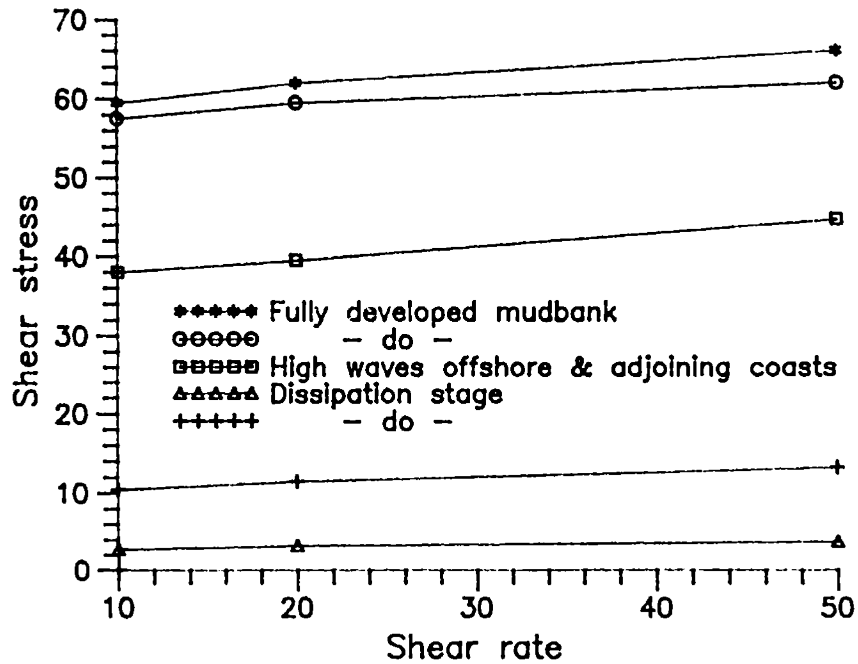

Fig. 4.19 Plot of shear stress vs shear rate during different stages of mudbank

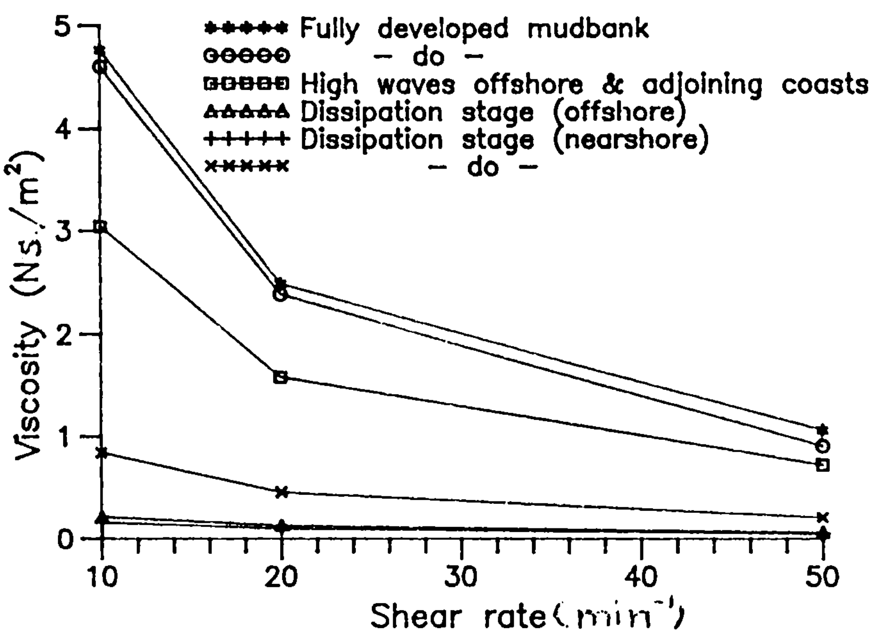

Fig. 4.20 Decrease in viscosity with increase in shear rate

Table 4.2 **Mineralogical assemblages of fluid mud and surficial sediments during different stages of mudbank** (in %)

Sample	montmorillonite	kaolinite	Illite	Gibbsite	Remarks
Surfacial sediment	34.21	56.32	6.84	2.63	Pre-mudbank.
Fluid mud	62.35	28.39	7.32	1.94	Fully developed mudbank.
Fluid mud	54.01	36.59	7.67	1.73	Dissipation stage - nearshore fuid mud.
Fluid mud	56.32	39.18	3.26	1.22	Dissipation stage - offshsore fluid mud.
Surficial sediment	34.89	56.37	5.37	3.36	Increased wave activity in the offshore and adjoining coasts.
Surficial sediment	42.24	48.28	6.90	2.58	Reduced wave activity in the offshore. Dissipation commenced.
Surficial sediment	58.59	30.84	8.81	1.76	Dissipation stage - Nearshsore sample.
Ssurficial sediment	39.83	52.28	6.64	1.25	Dissipation stage - offshsore sample.

The differential settling of sediments could be one of the reasons for higher percentage of montmorillonite in fluid mud.

4.2.2.3 Textural characteristics : The sediment size distribution of fluid mud sample determined by Sedigraph is given in Fig.(4.21). The cumulative mass percentage of sediment size shows that about 90% of the dispersed sediments are less than 2 µm in size. Analysis is repeated for confirming the result.

Grain size distribution of surfacial sediments during different stages of mudbank is given in Table (4.3). In the pre-mudbank condition the location registered a higher percentage of sand (34%) probably because the fine sediments are brought into suspension by waves and currents. Sediment samples during the phase of mudbank formation shows an enrichment of clay particles. Fine sediment settling in a comparatively calm water might have prevailed over the settling of particles. Since the sampler has to penetrate the near-bed fluid mud, the above sample represents a sediment admixture of suspension and settled bed.

4.3 Wave Energy Dissipation Over Fluid Mud

Field studies show that as wave propagates over the fluid mud, dissipation of wave energy occurs. As discussed earlier, dissipation of wave energy up to 30% due to bottom friction has been observed during non-mudbank period. But during mudbank a near-complete dissipation of wave energy is observed. The dissipation occurs within a short distance of wave propagation over mudbank. As evidenced from the present observations this dissipation is due to the presence of near-bed fluid mud layer, rather than the effect of bottom friction or any other mechanism which normally dissipates wave energy. The maximum dissipation occurs at the peripheral zone itself of mudbank. This indicates that the fluid mud has an ability to dissipate surface wave energy.

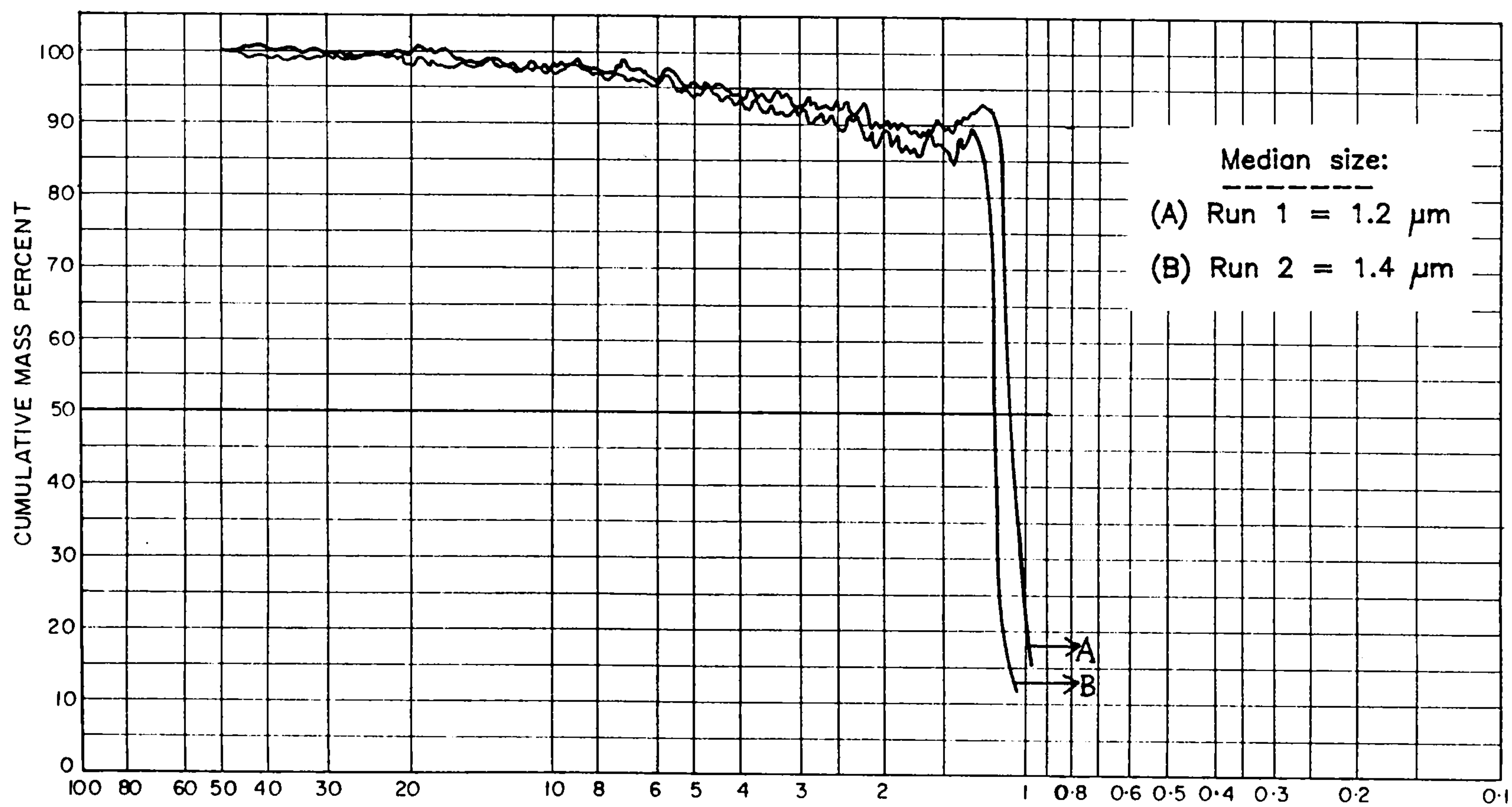

Fig. 4.21 Cumulative percentage of size fractions of fluid mud

Table 4.3 - Grain size distribution of surficial sediments during different stages of mudbank

Station depth	Sand (%)	Silt (%)	clay (%)	Remarks
5.5	34.00	27.28	38.72	Pre-mudbank.
5.5	2.74	27.39	69.87	Fully developed mudbank.
5.5	11.83	36.43	51.74	High waves in the offshore and adjoining coasts.
5.5	10.32	38.54	51.14	Reduced wave activity in the offshore. Dissipation commenced.
5.5	10.23	35.42	54.35	Dissipation stage.
5.5	7.95	43.84	48.21	Dissipation stage.

At the initial stage of mudbank formation a nearshore wave height of 31 cm is observed when 2 m thick fluid mud is present. Subsequently a complete dissipation of wave energy is observed before it reaches the nearshore recording station. Also, observed significant wave height of 50 cm at the nearshore during the high wave activity is after mudbank formation. The propagation of these waves over the fluid mud indicates that for a given concentration and thickness of fluid mud, there is a limit for dissipating wave energy.

Since the fluid mud observed in the offshore attains a higher concentration than the nearshore, the rate of energy dissipation at the peripheral zone is higher. Continued wave activity hinders the settling of fluid mud at the peripheral zone, thus helping the maintenance of the higher thickness of the fluid mud there. At the same time a stress free condition prevailing inside the mudbank due to energy dissipation and absence of currents allows particle settling in this zone and reduction in the thickness of the fluid mud layer there.

At low shear stresses, the fluid mud behaves like a visco-elastic medium. Since the dissipation of wave energy is due to the presence of fluid mud, the hydrodynamic forcing induces some movement either in the vertical or horizontal direction. Vertical oscillation of fluid mud in the Mississippi Delta has been measured by Tubman and Suhayda (1976). It is presumed that the vertical oscillation of fluid mud may be the main factor controlling the surface wave energy dissipation, even though it has not been measured in the present case. The observations indicate that the viscosity of the upper water column is negligible at all stages of mudbank. Hence the earlier hypothesis on the dissipation of wave energy due to increase in viscosity of upper water column is hard to be accepted.

4.4 Summary

Long-term nearshore wave climate based on recorded data for a location where mudbank occur almost every year has been studied in detail. For the first time synchronised wave measurements outside and inside the mudbanks have been conducted. It is observed that the pre-mudbank wave intensity and its persistence have a direct bearing on the sustenance and dimension of the mudbank. During the period of the present investigation, the mudbank is most sustained in 1986, when the pre-mudbank wave intensity and persistence is maximum.

The study of suspended sediment load shows that it is maximum in the surface during the pre-mudbank period. Since the salinity values observed are not favourable for de-flocculation, the de-flocculation hypothesis for sediment suspension in mudbanks does not hold good. Maximum bottom SSC value is 1,74,000 mg/l, which form the fluid mud. Rheological behaviour of fluid mud of mudbank has been defined. The measurements show that it behaves like a Bingham plastic. Mineralogical and textural characteristics of sediments are also studied.

The most important characteristic of mudbank is its ability to attenuate surface waves. It is observed that most of the wave energy dissipation takes place at the peripheral zone of mudbank. Based on the observations it is presumed that the oscillation of fluid mud cause wave energy dissipation. The viscosity of the upper water column is found to be negligible at all stages of mudbank. Hence the hypothesis on the dissipation of wave energy due to the increase in viscosity of upper water column is hard to be accepted.

Chapter 5

5. MUDBANK AS A WAVE-INDUCED PHENOMENA

It is found in the preceding chapter that in the context of mudbank generation, associated wave energy dissipation leading to the calmness of mudbank zone and other related processes, the wave-fluid mud interaction is of crucial importance. The generation, sustenance, movement, dissipation, localisation, etc. of the mudbank are discussed in this chapter with respect to the wave-mud interaction processes. A conceptual model for the formation, sustenance, extension and dissipation of mudbank is given at the end.

5.1 Sediment Suspension

For an examination of the extent of influence of waves on the bottom mud, simultaneous observation of wave parameters and mud transport characteristics are required. However, with the presently available methods the measurement of mud suspension rate is cumbersome, particularly in the coastal environment. The suspension of sediments under the influence of waves, however, can be subjected to theoretical analyses. The surface wave parameters required for this can be measured easily. The bottom horizontal orbital velocity can be theoretically deduced from surface measurements of wave height and period. To calculate the maximum horizontal bottom orbital velocity U_m, during a wave cycle under a monochromatic wave, the following equation, based on linear wave theory, can be used:

$$U_m = 2\pi a/T \sinh 2\pi d/L \qquad .....(5.1)$$

where *a* is the wave amplitude, *T* is the wave period, *L* is the wave length and *d* is the water depth. The use of linear wave theory to obtain maximum orbital velocity at the sea bed is justified by the experimental work of Kirkgoz (1986), who found that linear theory gives reasonable agreement with observed orbital velocities over his entire range of parameter settings, even at the transformation point of plunging breakers where higher order theories might be expected to give significantly better results. The computed values of U_m for different wave periods, heights and water depths using the above equation are given in Appendix I with a summary in Table (5.1). Velocities necessary to initiate suspension of cohesive sediment, determined experimentally by various researchers, are given in section 2.7.

A critical shear stress (yield stress), has to be reached for the initiation of the suspension of sediments from the bed. As discussed in Chapter 4, the waves in the offshore during southwest monsoon are high enough (2-3 m) to suspend the sediments from intermediate depths (30-50 m). It is presumed from these observations that the waves during monsoon are capable of suspending the fine sediments from a depth of ≈ 50 m and creating a fluid mud layer over the sea bed.

5.2 Fluid Mud Dynamics

5.2.1 Bed erosion

As discussed in section 4.2.1 the settling of sediments from the upper layers alone cannot form a fluid mud layer. The bed erodibility depends upon the previous stress history of the suspensions and not merely upon the instantaneous value of shear stress. There is a critical shear stress below which no erosion takes place. This is mainly dependent on the density of the settled mud. The erosion of mud takes place by the penetration of wave induced motion at the boundary layer. Since the wave height during the pre-monsoon period is low (≈0.5 m), these waves cannot penetrate to the bed to cause erosion. An increase in wave height is observed by the onset of monsoon

Table 5.1 Computed maximum horizontal bottom orbital velocity, U_m (cm/s) for different wave heights and periods (T) at different water depths.

Depth (m)	Height 1 m				Height 2 m				Height 3 m			
	T=7	8	9	10	7	8	9	10	7	8	9	10
05	60.3	62.6	64.2	65.3	120.6	125.2	128.3	130.5	180.9	187.8	192.5	195.8
10	35.7	39.0	41.2	42.8	71.5	77.9	88.6	85.6	107.2	116.9	123.6	137.4
15	23.7	27.5	30.2	32.2	47.4	55.1	60.4	64.3	71.1	82.6	90.7	96.5
20	16.1	20.2	23.3	25.5	32.3	40.5	46.5	50.9	48.4	60.7	69.8	76.4
25	11.0	15.1	18.8	20.7	22.0	30.2	36.5	41.4	33.1	40.3	54.9	62.1
30	07.4	11.2	14.5	17.0	14.8	22.5	28.9	34.0	22.3	33.7	43.4	51.0
35	05.0	08.4	11.5	14.0	10.0	16.7	22.9	28.1	14.9	25.1	34.4	42.1
40	03.3	06.2	09.1	11.6	06.6	12.4	18.2	23.3	10.0	18.5	27.3	34.9
45	02.2	04.6	07.2	09.6	04.4	09.1	14.4	19.3	06.6	13.7	21.5	28.9
50	01.5	03.3	05.7	08.0	02.9	06.7	11.3	16.0	04.4	10.0	17.0	24.0
55	01.0	02.4	04.4	06.6	02.0	04.9	08.9	13.2	02.9	07.3	13.3	19.8
60	00.6	01.8	03.5	05.4	01.3	03.6	07.0	10.9	01.9	05.4	10.5	16.3
70	00.3	01.0	02.1	03.7	00.6	01.9	04.3	07.4	00.9	02.9	06.4	11.1
80	00.1	00.5	01.3	02.5	00.3	01.0	02.6	05.0	00.4	01.5	03.9	07.4
90	00.1	00.3	00.8	01.7	00.1	00.5	01.6	03.3	00.2	00.8	02.4	05.0
100	00.0	00.1	00.5	00.1	00.0	00.3	01.0	02.2	00.1	00.4	01.4	03.4

(Fig.4.1). Deep water wave statistics shows that 2-3 m high waves predominate during monsoon period. The continuous wave loading weakens the bed, resulting in mass erosion or bed fluidization. Low upward entrainment and longitudinal dispersion of this fluidized mud results in the formation of fluid mud layer in the near-bed boundary.

Examination of the possibilities for the wave-induced suspension in the nearshore regions are carried out for the predominant wave period of 9 s and a height value of 2 m in the offshore region. A critical value of 18 cm/s for initiating erosion of unconsolidated cohesive sediment, as reported by Partheniades (1971), is considered in the present study. From Table (5.1) it can be seen that this wave with the above parameters can initiate sediment suspension at a water depth of 40 m. Previous observations by Rao *et al.* (1983) and Ramachandran and Samsuddin (1991) have confirmed the availability of fine sediments in the inner continental shelf of this coast. Hence it is reasonable to presume that the inner shelf settings and wave conditions are conducive for the generation of fluid mud.

Shear strength of the sediment column increases with depth due to consolidation. The wave orbital velocity penetrates to a critical bed thickness beyond which the increase in the shear strength of the sediments prevents further erosion. A quantification of this critical bed thickness or the volume of the sediment eroded could not be carried out due to non-availability of related data.

Rao *et al.* (1983) reported that there is a substantial increase in the amount of montmorillonite towards offshore along the Kerala shelf. Ramachandran (personal communication) observed that an offshore increase in montmorillonite is complementary to an offshore decrease in kaolinite. Though there are differences of opinion on the source of montmorillonite in the inner shelf region, it is evident that offshore sediments are richer in montmorillonite. So the observation in the present study about an enriched montmorillonite composition of fluid mud leads to the conclusion that the offshore mud eroded due to wave-induced processes must be playing a significant role in fluid mud formation. Moreover, a high deposition of fine sediments within a short span of time cannot be attributed to land source especially along this coast which is devoid of any fluvitile sedimentation for a continuous stretch of 85 km.

Even during the mudbank phase, the days of higher wave/current activities coincide with the higher occurrence of coarser surfacial sediments. The sediments become silty-clay at the dissipation stage of mudbank. Also an increase in clay content towards the offshore during this period is observed. This could be due to the removal of sediments from nearshore regions due to the decrease in dynamic forcing. So the textural characteristics of the surfacial sediments represent the different stages of hydrodynamic forcing, clearly indicating a process response system between surface waves and underlying sediment.

5.2.2 Fluid mud transport

Velocity required to bring a particle in suspension is higher than the velocity required for keeping it in suspension (Dyer, 1986). The very slow settling of the finer particles helps the waves and currents in the transportation of these particles in the mean flow direction.

The currents of the west coast of India are of monsoonal origin (Rao, 1991). From April through September the predominant direction is south-south-easterly off the west coast of India. Both the current velocity and consistency in direction increases progressively. Average speeds are about 25 cm/s increasing to about 40 cm/s in July and August. On a few occasions speeds in excess of 100 cm/s are experienced. From July to September, the strength of current weakens. In October the currents are highly variable. In November reversing currents are reported with northwesterly to northerly directions predominating. From December through February westerly currents predominate. In March the currents are again variable, mainly between southeasterly and westerly to the south of Cape Comerin, but south-south-easterly along the west coast. Average speeds in the months of October through March are around 25 cm/s occasionally exceedings 100 cm/s.

The fluid mud layer formed will flow *en masse* shoreward by the combined action of waves and currents against its flow in the down slope direction due to gravitational force. In areas of low current speeds and when the flow regime is wave-dominated, a significant portion of sediment transport is confined to the near-bed region (Mehta, 1991). Hence along this coast during the monsoon season, even when the currents are weak, the high waves persisting during this period alone can transport fluid mud from offshore *en masse*. The aberrant appearance of mudbank during the December storm of 1965 (Varadachari and Murty, 1966) is an example.

The fluid mud thus transported to the nearshore zone reaches only up to a certain depth and movement further to the shallower portions is restricted due to decreased energy content in the waves and currents. Further, the transportation can bring about winnowing away of coarser fractions, ultimately resulting in a finer-grained population in the fluid mud layer in the nearshore regions.

Due to the prevailing calmness inside the mudbank, sediments from upper layers settle rapidly. Subsequently, the thickness of fluid mud layer decreases due to dewatering. Above 20,000 mg/l of particle concentrations, the settling of the particles are hindered by mutual interference and also by the upward flux of fluid escaping through the small pores in the network of aggregates. There is negligible settling above 1,00,000 mg/l SSC (Mehta, 1989).

It is observed that there is a decrease in concentration of particles in the fluid mud with time. Decrease in the thickness of fluid mud layer with time should normally result in a corresponding increase in particle concentration. Since this is not observed in the present case, it has to be presumed that the decrease in concentration and thickness of fluid mud is due to the removal of sediments from fluid mud layer. The transport could be either alongshore or offshore. The lateral extension of mudbank few days after its formation is an indication for the distribution of these sediments in the alongshore direction. Further, during the dissipation stage of mudbank an increase in the concentration of fluid mud is observed in the offshore direction indicating sediment removal from nearshore.

5.3 Transfer of Wave Energy

It is found that the vertical oscillation of the fluid mud is the mechanism by which energy from the surface wave is transferred to the bottom layers (see section 4.3). An attempt is made to find out the energy exchange process in the fluid mud medium, keeping in view the law of conservation of energy.

As part of the observations on the physical parameters, vertical temperature profiles were taken in the mudbank at its different stages (Fig.5.1). On examination of these profiles a higher temperature in the bottom fluid mud layer than the upper water column is noticed. In the normal heat exchange process in the air-sea system one expects a higher temperature in the upper layers. The other source of energy to the water column is from the waves. In the case of mudbank, part of wave energy is used for the transport of sediments from offshore at the initial stage. It is possible that during the transport, temperature of fluid mud increases due to friction. But after the mudbank formation a complete dissipation of wave energy within a short distance of its propagation over the fluid mud layer is observed. The amount of energy available in waves for different wave heights and water depths is given in Table (5.2). During the presence of mudbank this large amount of energy is dissipated within the mudbank zone. Since a stress free condition prevails within the mudbank, it may be reasonably assumed that the higher temperature obtained for the fluid mud layer could be due to the transfer of energy from the surface wave to the bottom layers. Clay is a poor conductor of heat and can maintain higher temperature for some time.

After a few days of mudbank formation no such higher temperature is observed for the nearshore fluid mud (Fig.5.2). However, a higher temperature in the fluid mud of the peripheral zone is observed even after several days of mudbank formation. This could be due to the complete dissipation of wave energy before it reaches the nearshore zone, thus curtailing the source of energy to increase the temperature of the nearshore fluid mud. Further input of wave energy in the peripheral zone balances with the heat loss to the surroundings.

5.4 Localization of Mudbank

The wave refraction pattern along this coast has been studied in detail to examine the localised formation of mudbank. Deep water wave height of 2 m is considered in all computations, since this wave height represents an aver-

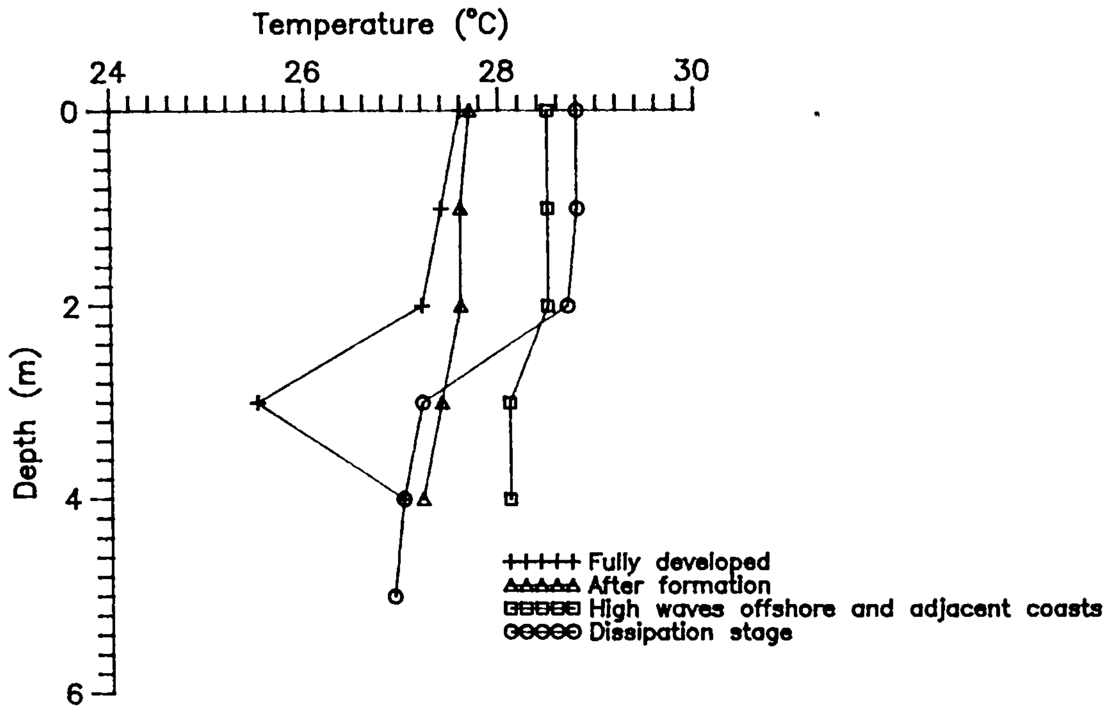

Fig. 5.1 Vertical temperature profiles at different stages of mudbanks

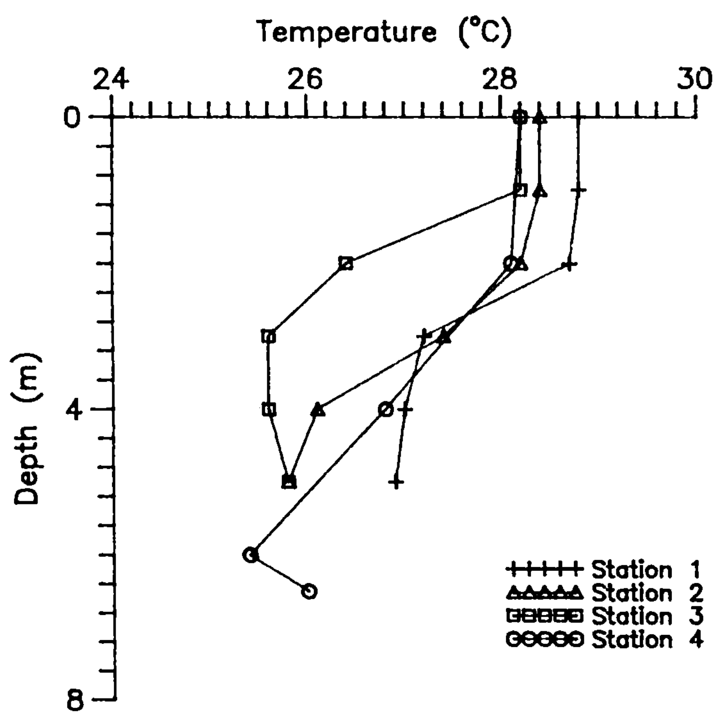

Fig. 5.2 Vertical temperature profiles at different stations during dissipation stages of mudbank

Table 5.2 Variation of wave power with water depth and wave height (for a 10 s wave).

Depth (m)	Wave height (m)	Length (m)	Power (kW/m)
10	2.0	92.32	22.68
	1.5	92.32	12.76
	1.0	92.32	5.67
8	2.0	83.77	21.16
	1.5	83.77	11.90
	1.0	83.77	5.29
7	2.0	78.92	20.27
	1.5	78.92	11.40
	1.0	78.92	5.07
6.5	2.0	76.25	19.78
	1.5	76.25	11.13
	1.0	76.25	4.95
6	2.0	73.58	19.05
	1.5	73.58	10.72
	1.0	73.58	4.76
5	1.5	67.67	10.03
	0.5	67.67	1.11
	0.25	67.67	0.26
	0.10	67.67	0.04

age deep water significant wave height of this coast during monsoon as per the Indian Daily Weather Reports. The wave refraction pattern thus obtained for few periods and directions are given in Fig.(5.3). It may be noted that in all the cases the convergence of wave energy occurs at the same locations irrespective of the directions examined. Erosion is the natural consequence of convergence of wave energy during monsoonal high wave conditions. These convergence zones coincide with the zones of occurrence of mudbanks. According to Varma and Kurup (1969), Reddy and Varadachari (1973) and Murty *et al.* (1980) the zones of occurrence of mudbanks are the zones of offshore flow resulting from the convergence of littoral currents. But the convergence of littoral currents normally occur in between the zones of convergence of wave energy. The present observations show that offshore flow resulting from such convergence of littoral currents does not generate mudbanks.

As discussed earlier, the sediments from offshore are transported to the nearshore by waves and currents. Due to the convergence of wave energy the sediments are accumulated in certain specific localities, resulting in the localized formation of mudbank. The convex shape of mudbank, as it is reported by many previous workers also, could be attributed to the wave refraction patterns. Another aspect which can be explained by the wave refraction is the year-to-year migration of mudbanks. This occurs due to the variation in bathymetric conditions created in the preceding year, which influences the wave refraction. It is also presumed that the dimensions of mudbank, alongshore as well as offshore, are determined by the intensity of energy convergence and availability of sediments. Another observation made from Fig.(5.3) is that the convergence of energy is more for higher period waves, for the same wave height and direction.

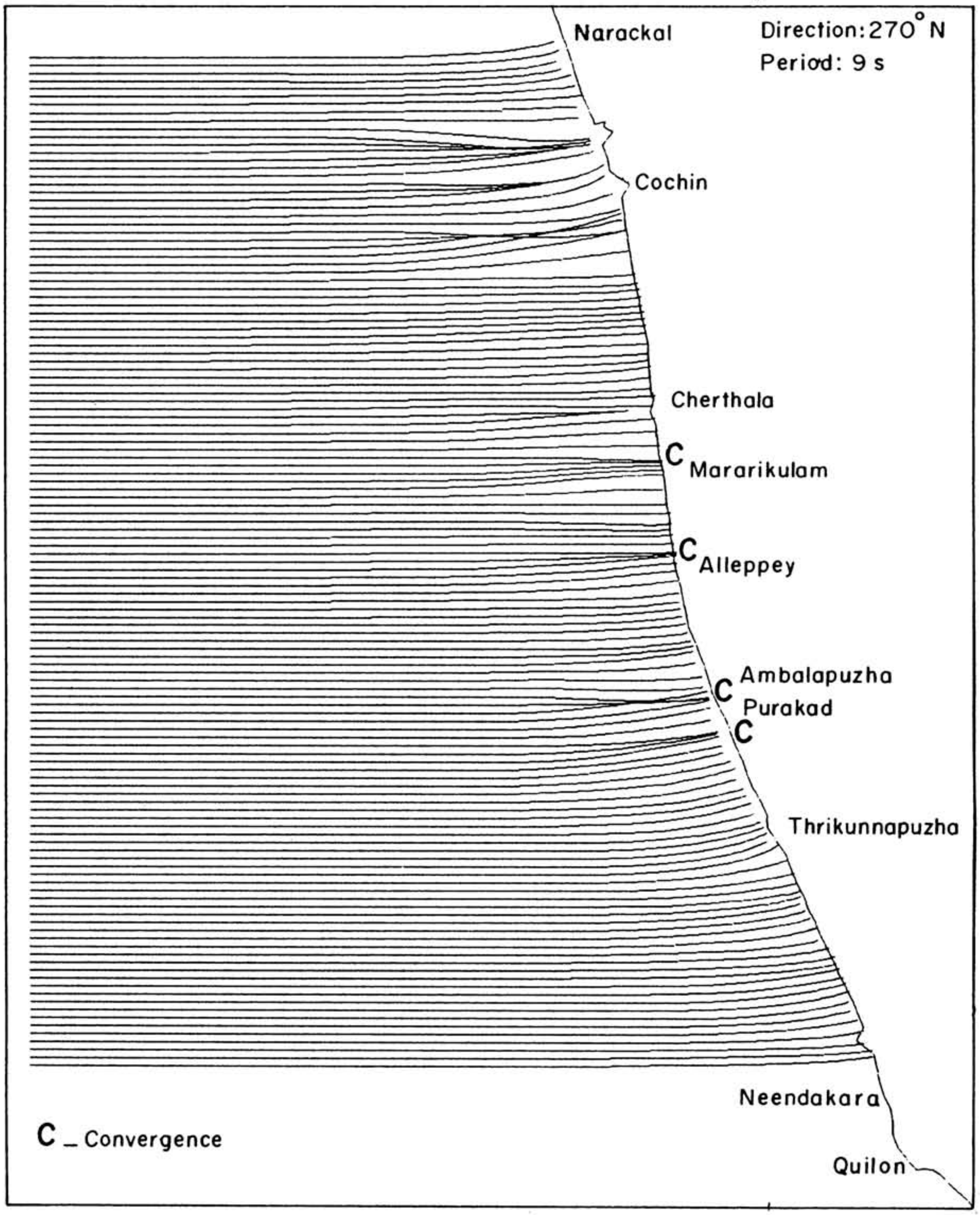

Fig. 5.3 Wave refraction pattern for westerly deep water waves

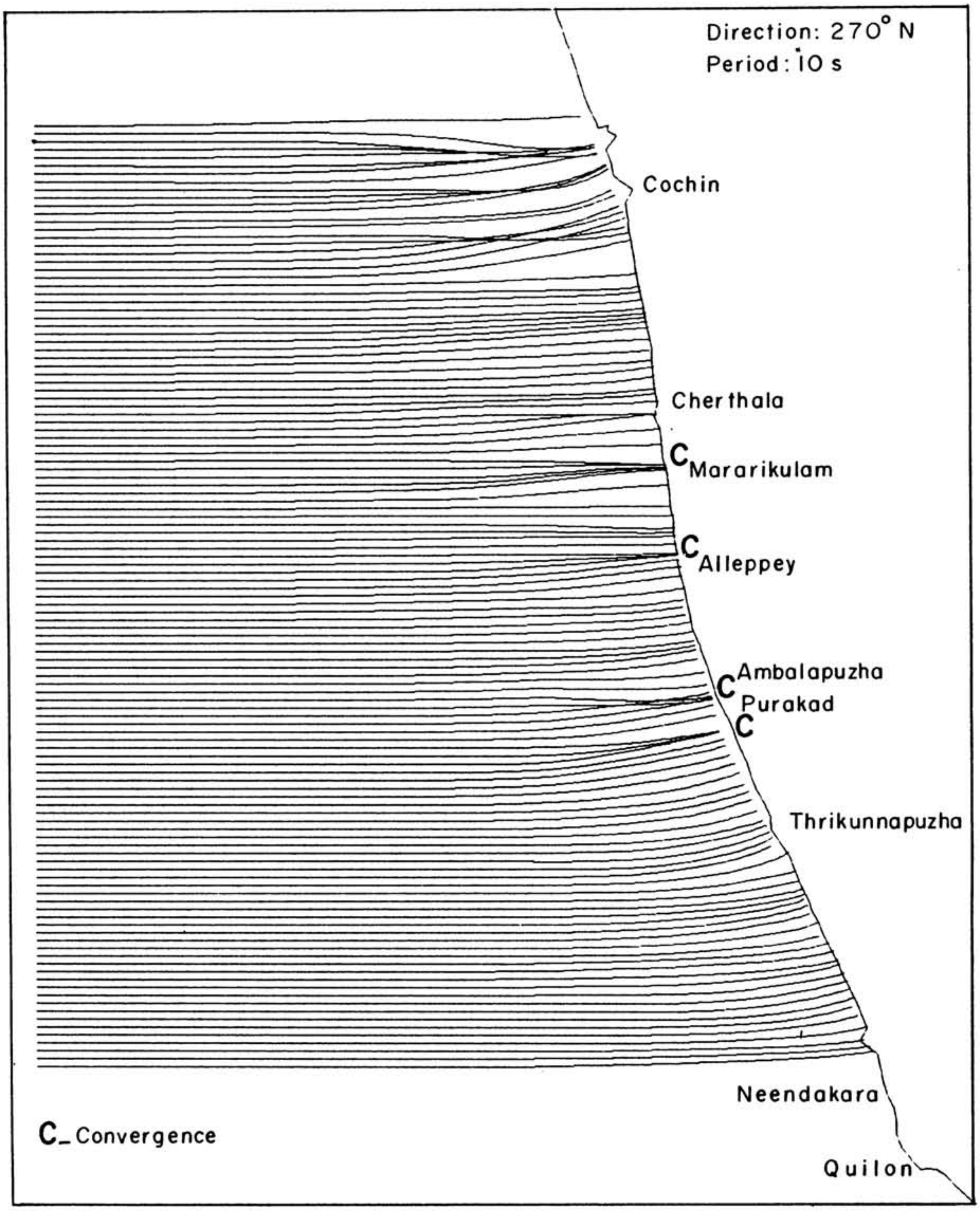
Direction: 270° N
Period: 10 s
Cochin
Cherthala
C
Mararikulam
C
Alleppey
Ambalapuzha
C
Purakad
C
Thrikunnapuzha
Neendakara
Quilon
C_ Convergence

Fig. 5.3 Contd...

The concept, that mudbanks protect the beach behind it from erosion is found to be true. However, severe erosion occurs in these zones before mudbank formation due to the convergence of wave energy. Hence mudbank protects the beach behind it only after a major episodic erosion.

5.5 Movement of Mudbank

The behaviour of a mudbank is determined by the properties and characteristics of the fluid mud layer. Several field and laboratory studies (eg. Wells, 1978; Dyer, 1986) show that the fluid mud in the bottom layer can move without altering much of its layered structure and without dispersing to the upper layers owing to its Bingham plastic nature. Movement of fluid mud can result from the forcing of longshore, coastal or tidal currents. Alleppey being a wave-dominated and inlet-free coast, the tidal effects are negligible in the transportation of sediments. The movement can probably be explained to be due to the stress applied by the prevailing currents.

For almost all the years an alongshore extension of mudbank in both directions is observed. Alongshore current fail to explain the simultaneous northerly and southerly extension of mudbank. Hence the alongshore extension of fluid mud could be due to the continued wave forcing outside the mudbank, which cannot transport the fluid mud further into the mudbank because of the wave energy dissipation and increased sediment concentration in the mudbank (see also section 5.3). Possibility of vertical entrainment of sediments from this peripheral zone fluid mud layer is limited due to the high density difference between the upper water column and the lower fluid mud layer. Hence the only possible direction of mud transport from the peripheral zone is lateral. A simultaneous extension of about 4 km towards the south and about 2 km to the north are observed during the study period. The more southerly extension could be due to the effect of prevailing wave direction and southerly current.

5.6 Mudbank Dissipation

Following the active mudbank period, it has been observed by Ramachandran and Samsuddin (1991) that the sediment from mudbank disappears, bringing the nearshore topography back to the pre-mudbank condition. Downslope movement of bed load due to gravity probably plays a role in mudbank dissipation. It seems likely that gravity-driven downslope transport may be much more significant where sediments are fine enough to remain in suspension in the bottom. Hindered settling resulting from the high concentration of fine sediments results in keeping the superficial layer in fluidized state. As the wave height decreases considerably, the increased bulk density of the fluid mud together with the downslope component of gravity produces offshore transport of the fluid mud when it overcomes the frictional resistance. The downslope movement depends on the wave and current conditions. The duration of mudbank is determined by the ability of the waves and currents in keeping the fluid mud without much settling and also in overcoming its downslope movement due to gravitational force.

5.7 A Conceptual Model of Mudbank

A conceptual model for wave-mud interaction processes in mudbank is explained based on the field observations. Water and sediment form an interacting couple in the coastal dynamic system. At low sediment concentration hydrodynamic parameters significantly control the sediments, whereas when concentration increases, lithodynamic features start controlling the hydrodynamic parameters. The presence of dense suspension in the lower layers leads to the turbulence suppression and drag reduction.

Fig.(5.4&5.5) show the probable sediment concentration and wave conditions during different stages of mudbank. Pre-monsoon conditions show a homogeneous water column with negligible suspended sediment concentration and low wave activity. By the initiation of storm wave activity with the onset of monsoon, the bottom sediments get churned up. The convergence of wave energy occurs due to wave refraction at specific location depending on the bathymetry. This concentration of energy further adds to the suspension of bottom sediments leading to an increase in the sediment concentration in the entire water column. At the same time in the offshore region, the continuous stress applied by the high waves over muddy bottom weakens the bed and fluidization of the bed occurs. The mud concentration in the boundary layer increases until they reach the required concentration (> 20000 mg/l) of fluid mud. The fluid mud thus formed is transported to the nearshore regions by waves and currents. This is followed by a reduction in wave activity, as part of the wave energy is used for the transportation of sediments from the offshore. This leads to the settling of sediments causing a drastic decrease in sediment concentration in the upper layers.

Due to the convergence of waves the fluid mud brought in by the waves from offshore is deposited at the specific locations. The dimensions of this accumulation is determined by the wave refraction patterns. As the wave propagates over the fluid mud, further dissipation of energy occurs due to the oscillation of fluid mud layer.

As the wave height decreases, the gravity-driven downslope transport of fluid mud begins leading to the dissipation of mudbank. The persistence of the mudbank conditions depend on the wave and current conditions, which can maintain the fluid mud in suspension and prevent the movement of fluid mud to the offshore.

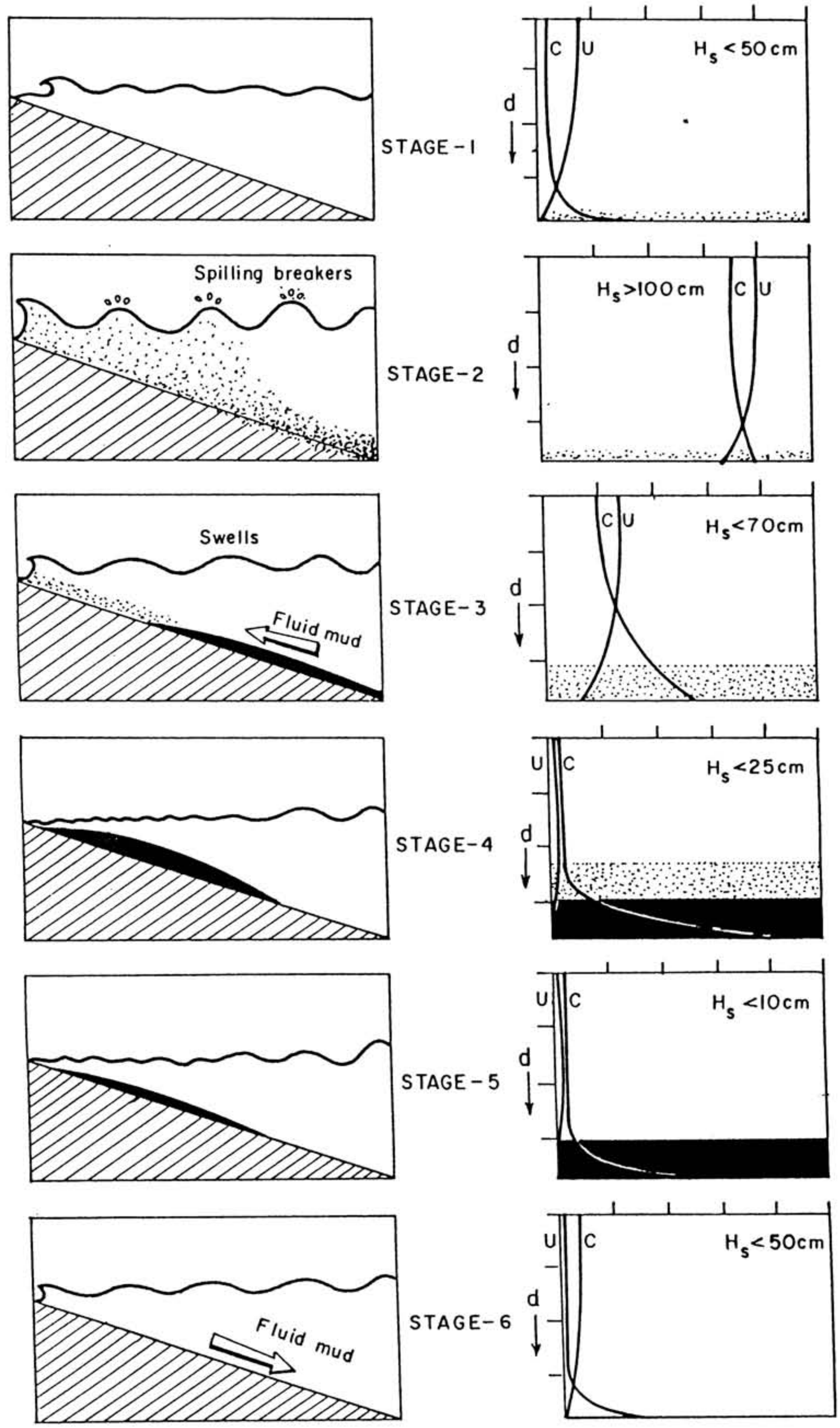

Fig. 5.4. Conceptual model of mudbank (C-Concentration, U- Orbital velocity, d - Depth)

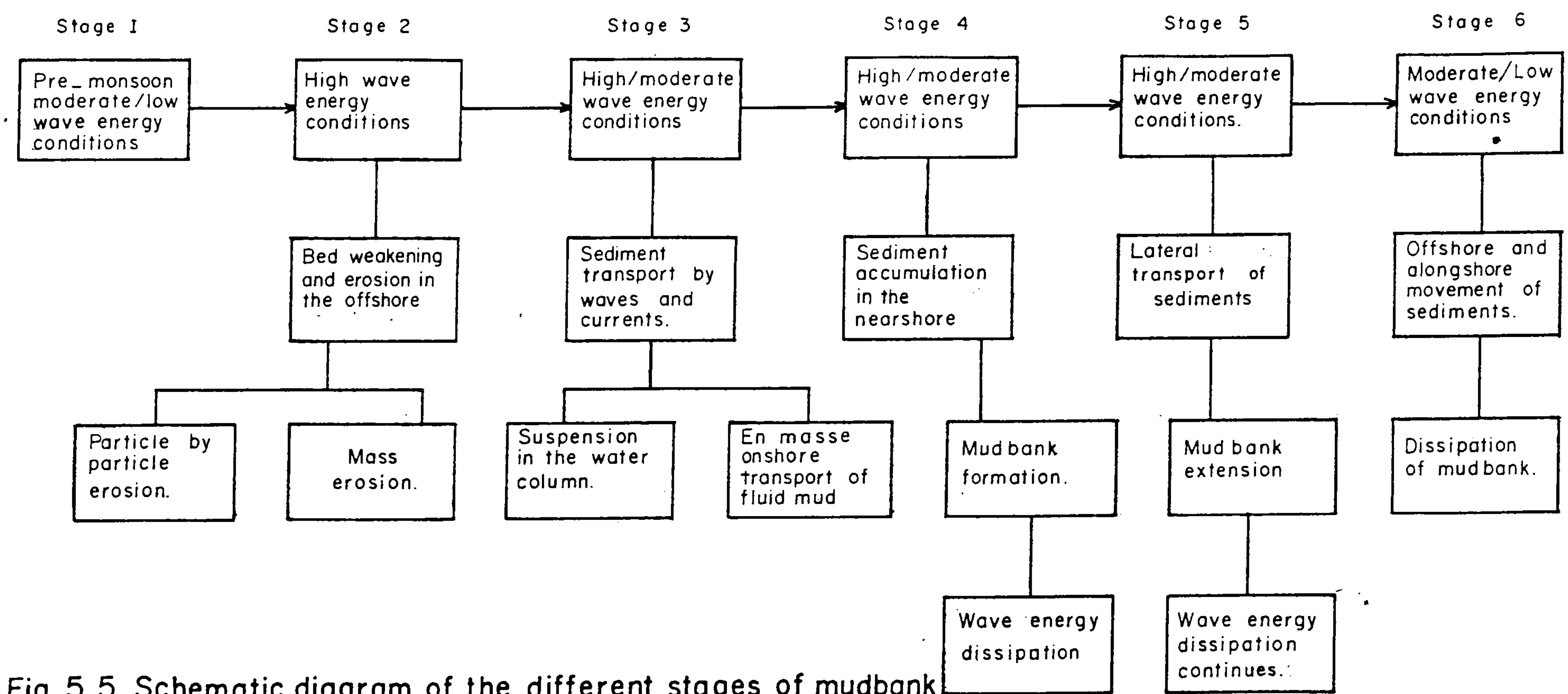

Fig.5.5 Schematic diagram of the different stages of mudbank

5.8 Mudbanks of Other Coasts

A comparison of the physical parameters of mudbank of southwest coast of India and that of other mudbanks present along the coasts of southwestern Louisiana, Surinam and Western Korea are given in Table (5.3). The fluid mud parameters are comparable in all the cases. The major difference is in the source of mud for mudbank formation. While sediment input by major rivers is available for other mudbanks, for some mudbanks of the southwest coast of India like the one in Alleppey, the major contribution of sediments is from the offshore. Also the mudbanks of southwest coast of India are transitional in nature, whereas the others are permanent.

So far the mudbanks of southwest coast of India are defined based on suspended sediment load and the prevailing calmness. In the light of the present investigation, which recommends wave-mud interaction as the major factor, the definition of mudbank may be modified as ***a calm nearshore zone created by the near-complete wave attenuation caused by a fluid mud bottom, when the adjoining coast and offshore experience high wave activity.***

5.9 Summary

Application of periodic stress due to water waves over a muddy bottom has a number of consequences, of which the important ones are bed erosion, generation of fluid mud and wave attenuation. In the absence of a satisfactory understanding of the above processes involved in mudbank formation, the attempts made by various researchers remain incomplete. In this context a detailed examination of the wave-mud interaction process in the generation, sustenance and dissipation of mudbank has been carried out.

Table 5.3 Mudbanks - Physical parameters for Lousiana, Surinam, Korea and SW India

Location	Tidal range (m)	Wave energy	Mudbank dimension alongshore (km)	Mudbank dimension offshore (km)	Fluid mud Thickness (m)	Fluid mud Bulk density (g/cm^3)	Fluid mud Particle size (μm)	Source of mud	Occurrence
Louisiana	0.5	L-M	1-5	0.5-3	0.2-1.5	1.15-1.30	3-5	River (Missisippi)	Permanent
Surinam	2	M	10-20	10-20	0.5-2.0	1.03-1.30	0.5-1	River (Amazon)	Permanent
Korea	5-9	H	1-30	5-50	0.1-3.0	1.20-1.30	6-11	River (Yalu, Han, Kum and Yeong san)	Permanent
SW coast of India	0.5-0.7	L-M	2-8	1-3	0.5-2.0	1.08-1.30	0.5-3.0	River/ offshore	Transitional during SW monsoon

L - Low; M - Moderate; H - High

The availability of fine sediments is an essential prerequisite for the formation of mudbank. Study of the nearshore suspended sediment concentration reveals that sediments are transported from offshore regions.

Studies on wave induced erosion process reveals that waves during monsoon are capable of causing erosion from intermediate water depths. The fluid mud generated by waves are transported to the nearshore *en masse* by the combined action of waves and currents. Detailed investigation of the wave refraction pattern indicates that localization of mudbank is due to the wave energy convergence. Year-to-year migration of mudbank is due to the variations in bathymetric conditions, which is one of the deciding factor for the zones of energy convergence.

An alongshore extension of mud bank few days after its formation, as observed sometimes, is due to the wave forcing outside mudbank and the prevailing coastal currents, since fluid mud can move *en masse*. Downslope movement of bed load due to gravity is assumed to play a major role in mudbank dissipation. The duration of mudbank is determined by the ability of the waves and currents in keeping the fluid mud without much settling and also in overcoming its downslope movement due to gravitational force.

Finally based on the present investigation a conceptual model and a new definition for mudbank are proposed.

Chapter 6

6.SUMMARY AND CONCLUSIONS

A thorough study of the wave-mud interaction processes in mudbanks is essential in understanding their formation, sustenance, dissipation, etc. Previous investigations on mudbanks covered the hydrographic features and some of the physical processes involved in the different stages of mudbank. Most of the studies focused mainly on the upper water column and the significance of the near-bed layers has been neglected. Literature shows that the studies on mudbank so far conducted are without any field measurements of waves, though the interaction between the surface waves and bottom sediments is the most important aspect. The studies so far conducted are incapable of explaining several of the hydrodynamical processes involved in mudbanks.

In order to have a better understanding of the wave-mud interaction processes, a detailed examination of the characteristics and behaviour of fine sediments under different hydrodynamic conditions is carried out. The erosion and deposition of fine sediments depend on the properties related to waves and shear strength of the bed. Mass erosion is bed fluidization, resulting from the failure of binding forces of the particles at the bed surface. Settling of sediments is affected by gravitational forces, viscous drag on the particles and inter-particular interaction. It is dependent on the floc and particle size, suspension concentration, local physico-chemical conditions, etc. Of these factors, the effect of suspended sediment concentration on the settling velocity is found to be very significant. Reported settling velocity values range from 10^{-4} to 10 mm/s for different size ranges. At high concentrations (above 10,000 mg/l) the settling velocity decreases with increasing sediment concentration as a consequence of hindered settling. This high density suspension characterised by hindered settling is commonly referred to as fluid mud. The generally accepted lower and upper limits of fluid mud concentration are 10,000 mg/l and 250,000 mg/l respectively.

Review of literature on wave-mud interaction processes and modes of sediment transport shows that continued oscillatory motion in the bed caused by wave forces results in a decrease of mechanical strength as well as the erosion resistance of the bed. The wave orbital motions penetrate into the bed causing weakening of the bed and subsequent fluidization. The fluidized mud is transported by the combined action of waves and currents or individually to the depositional areas.

Long-term nearshore wave climate based on recorded data for a location, where mudbank occur almost every year, has been studied in detail. For the first time synchronised wave measurements outside and inside the mudbanks of southwest coast of India have been conducted. The synchronised data are used to study the characteristics of wave transformation in the mudbank. Also synchronised wave collected from offshore and nearshore are used to study the wave transformation processes in the absence of mudbank. Hydrographical parameters during the time of these measurements are also collected. Wave refraction studies are conducted using a numerical model.

The synchronous wave measurements from offshore and nearshore during the non-mudbank period shows wave height attenuation up to 30%. In most of the cases the energy loss is less than 25%. Also the peak frequencies are found to coincide in a majority of the cases indicating the retention of major portion of the energy density around the same peak frequency even after transformation. It is observed that the pre-mudbank wave intensity and its persistence have a direct bearing on the sustenance and dimension of the mudbank. During the period of the present investigation, the mudbank is most sustained in 1986, when the pre-mudbank wave intensity and persistence is maximum. The formation of the mudbank is always proceeded by the peak wave activity. In a fully developed mudbank, the wave attenuation is complete within a course of few wave lengths.

Application of periodic stress due to water waves over a muddy bottom has a number of consequences, of which the important ones are bed erosion, generation of fluid mud and wave attenuation. In the absence of a satisfactory understanding of the above processes involved in mudbank formation, the attempts made by various researchers remain incomplete. In this context a detailed examination of the wave-mud interaction process in the generation, sustenance and dissipation of mudbank has been carried out.

The availability of fine sediments is an essential prerequisite for the formation of mudbank. Examination of the nearshore suspended sediment concentration reveals that settling of sediments initially suspended from the nearshore bed alone cannot form a fluid mud layer as observed in the mudbank. The observation of the 2 m thick fluid mud layer with a concentration of 174 g/l at the superficial layers indicate that this could be transported from other regions. The formation of mudbank in the nearby coasts a few days before the formation of mudbank at the present study site rules out the possibility of transport of sediments by longshore currents. Mineralogical assemblages of the fluid mud show the possibility of an offshore source of sediments.

Studies on wave-induced erosion process reveal that waves during monsoon are capable of causing erosion from intermediate water depths. The availability of fine-grained sediments at these depths has been reported by previous researchers. The fluid mud generated by waves are transported to the nearshore *en masse* by the combined action of waves and currents. Being a wave dominated coast, the waves alone can transport the fluid mud from offshore.

Rheological behavior of fluid mud of the mudbank is defined for the first time. Measurements show that the fluid mud behaves like a Bingham plastic. However, depending upon the mud concentration, composition and dynamic forces acting on it, the property also can change. The maximum viscosity of the fluid mud measured, 4.76Ns/m^2 is about 4000 times greater than that of the sea water.

The sediment size distribution of fluid mud sample shows that about 90% of the dispersed sediments are less than 2 µm in size. The variation of salinity observed is 29-34.5‰. These salinity values are not favourable for a de-flocculation process. Hence the de-flocculation hypothesis for sediment suspension in mudbanks does not hold good to explain the process of turbidity.

The most important aspect of mudbank is its ability to attenuate surface waves. It is observed that most of the wave energy dissipation takes place at the peripheral zone of mudbank. Hence a stress free condition is created inside the mudbank. This indicates that fluid mud has an ability to attenuate surface wave energy within a short distance of wave propagation over it. Based on the observations it is presumed that the oscillation of fluid mud cause wave energy dissipation. However, for a given set of wave parameters, there is a critical fluid mud concentration and thickness for energy dissipation. The viscosity of the upper water column is found to be negligible at all stages of mudbank. Hence the hypothesis on the dissipation of wave energy due to the increase in viscosity of upper water column cannot hold good for mudbanks.

Pertaining to wave energy dissipation, it is found in the present study that there is a transfer of energy from the surface wave to the bottom layers. This is evidenced from the observations of higher temperature for the bottom fluid mud than the upper layers. Wave energy computations show that a large amount of energy is dissipated within the mudbank zone. Since there is no other source for heating the bottom fluid mud, it is presumed that the only possible source is the energy of waves transferred to the bottom layers.

Detailed study of the wave refraction pattern indicates that localization of mudbank is due to the wave refraction resulting in the convergence of wave energy. The dimensions of mud bank is determined by the intensity of convergence of wave energy and the availability of fine sediments.

Since a decrease in the thickness of fluid mud with time is not accompanied by an increase in concentration, it is presumed that removal of sediments from fluid mud occurs depending on the prevailing wave and current conditions. An alongshore extension of mud bank few days after its formation is observed in the present investigation. This must be due to the wave forcing outside mudbank and the prevailing coastal currents, since fluid mud can move *en masse*. Down slope movement of bed load due to gravity probably plays a major role in mudbank dissipation. The down slope movement depends on the current and wave conditions. The duration of mudbank is determined by the ability of waves and currents in keeping the fluid mud without much settling and also in overcoming its down slope movement due to gravitational force.

Comparison of the different mudbanks around the world show that while there are major rivers for sediment input for most of them, offshore sediments are the main source for the mudbanks of the southwest coast of India. Also the latter ones are transient in nature.

Finally based on the present investigation a conceptual model and a new definition of mudbank are proposed.

RECOMMENDATIONS FOR FUTURE STUDY

Systematic formation, sustenance and dissipation of mudbank could be explained in terms of wave conditions and nearshore sediment properties. Even though the offshore source of mud for mudbank could be deduced from the mineralogical and textural characteristics of sediments, a quantification of sediment eroded and critical shear stress required for the erosion to occur needs to be done.

Due to the limitation of the field measurements, the internal density structure of fluid mud layer could not be studied. Also field measurements on the oscillation of fluid mud layer is needed for a complete understanding of wave energy dissipation.

To generalise the findings the study has to be carried out in the other typical mudbanks also. Lastly, with a clear understanding of the wave-mud interaction processes and the parameters involved, attempts should be made towards numerical modelling of the mudbank processes.

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APPENDIX I

Computed maximum horizontal orbital velocity, U_m (cm/s) for different wave heights and periods at different water depths.

Depth	Height 1 m										
	T=6	7	8	9	10	11	12	13	14	15	16
05	56.8	60.3	62.6	64.2	65.3	66.1	66.7	67.2	67.6	67.9	68.1
06	49.4	53.3	55.8	57.5	58.7	59.6	60.3	60.8	61.2	61.6	61.9
07	43.5	47.7	50.4	52.2	53.6	54.6	55.3	55.9	56.3	56.7	57.0
08	38.6	43.0	45.9	47.9	49.3	50.4	51.2	51.8	52.3	52.7	53.0
09	34.5	39.1	42.2	44.3	45.8	46.9	47.8	48.4	48.9	49.4	49.7
10	30.9	35.7	39.0	41.2	42.8	43.9	44.8	45.6	46.1	46.5	46.9
11	27.7	32.8	36.2	38.5	40.1	41.4	42.3	43.1	43.6	44.1	44.5
12	24.9	30.1	33.6	36.1	37.8	39.1	40.1	40.8	41.5	41.9	42.3
13	22.5	27.8	31.4	33.9	35.7	37.1	38.1	38.9	39.5	40.0	40.4
14	20.2	25.6	29.4	32.0	33.9	35.3	36.3	37.1	37.8	38.3	38.7
15	18.2	23.7	27.5	30.2	32.2	33.6	34.7	25.6	36.2	36.8	37.2
16	16.4	21.9	25.8	28.6	30.6	32.1	33.2	34.1	34.8	35.4	35.8
17	14.8	20.3	24.3	27.1	29.2	30.7	31.9	32.8	33.5	34.1	34.6
18	13.3	18.8	22.8	25.7	27.9	29.4	30.6	31.6	32.3	32.9	33.4
19	12.0	17.4	21.5	24.5	26.6	28.2	29.5	30.4	31.2	31.8	32.3
20	10.8	16.1	20.2	23.3	25.5	27.1	28.4	29.4	30.1	30.8	31.3
22	08.7	13.8	18.0	21.1	23.4	25.1	26.4	27.5	28.3	28.9	29.5
24	07.0	11.9	16.0	19.2	21.5	23.3	24.7	25.8	26.6	27.3	27.9
26	05.6	10.2	14.2	17.4	19.9	21.7	23.2	24.3	25.2	25.9	26.5
28	04.5	08.7	12.6	15.9	18.4	20.3	21.8	22.9	23.8	24.6	25.2
30	03.6	07.4	11.2	14.5	17.0	19.0	20.5	21.7	22.6	23.4	24.0
35	02.1	05.0	08.4	11.5	14.0	16.1	17.7	19.0	20.0	20.9	21.5
40	01.2	03.3	06.2	09.1	11.6	13.8	15.4	16.8	17.9	18.8	19.5
45	0.70	02.2	04.6	07.2	09.6	11.8	13.5	14.9	16.1	17.0	17.7
50	0.40	01.5	03.3	05.7	08.0	10.1	11.8	13.3	14.5	15.4	16.2
55	0.20	01.0	02.4	04.4	06.6	08.6	10.4	11.9	13.1	14.1	14.9
60	0.10	0.60	01.8	03.5	05.4	07.4	09.1	10.6	11.9	12.9	13.8
70	0.00	0.30	01.0	02.1	03.7	05.4	07.0	08.5	09.8	10.9	11.8
80	0.00	0.10	0.50	01.3	02.5	03.9	05.4	06.8	08.1	09.2	10.1
90	0.00	0.10	0.30	0.80	01.7	02.8	04.1	05.4	06.7	07.8	08.7
100	0.00	0.00	0.10	0.50	01.1	02.0	03.1	04.3	05.5	06.6	07.5

APPENDIX I continued.

Depth	Height 2 m										
	T=6	7	8	9	10	11	12	13	14	15	16
05	113.6	120.6	125.2	128.3	130.5	132.3	133.4	134.4	135.2	135.8	136.3
06	98.8	106.5	111.6	115.0	117.4	119.2	120.6	121.7	122.5	123.3	123.8
07	87.0	95.3	100.7	104.5	107.1	109.1	110.5	111.7	112.7	113.3	114.0
08	77.2	86.1	91.9	95.8	98.7	100.8	102.4	103.6	104.6	105.3	106.0
09	68.9	78.3	84.4	88.6	91.6	93.8	95.6	96.8	97.9	98.7	99.4
10	61.7	71.5	77.9	82.4	85.6	87.9	89.7	91.1	92.1	93.1	93.8
11	55.4	65.6	72.3	77.0	80.3	82.7	84.6	86.1	87.3	88.1	88.9
12	49.9	60.3	67.3	72.2	75.6	78.2	80.1	81.7	82.9	83.8	84.6
13	44.9	55.6	62.8	67.9	71.5	74.2	76.2	77.8	97.1	80.0	80.9
14	40.5	51.3	58.8	64.0	67.7	70.5	72.6	74.3	75.6	76.6	77.5
15	36.5	47.4	55.1	60.4	64.3	67.2	69.4	71.1	72.5	73.5	74.4
16	32.8	43.9	51.7	57.2	61.2	64.2	66.4	68.2	69.6	70.7	71.6
17	29.6	40.6	48.6	54.2	58.4	61.4	63.8	65.6	67.0	68.2	69.1
18	26.6	37.6	45.7	51.5	55.7	58.8	61.2	63.1	64.6	65.8	66.7
19	24.0	34.8	43.0	48.9	53.2	56.5	58.9	60.8	62.4	63.6	64.6
20	21.5	32.3	40.5	46.5	50.9	54.2	56.8	58.8	60.3	61.6	62.6
22	17.4	27.7	36.0	42.2	46.8	50.2	52.9	54.9	56.6	57.9	59.0
24	14.0	23.7	32.0	38.3	43.1	46.7	49.4	51.6	53.3	54.6	55.8
26	11.3	20.3	28.4	34.8	39.7	43.4	46.3	48.5	50.3	51.8	52.9
28	09.0	17.4	25.3	31.7	36.7	40.5	43.5	45.8	47.7	49.1	50.4
30	07.2	14.8	22.5	28.9	34.0	37.9	40.9	43.3	45.3	46.8	48.1
35	04.2	10.0	16.7	22.9	28.1	32.2	35.4	38.0	40.1	41.7	43.1
40	02.4	06.6	12.4	18.2	23.3	27.5	30.9	33.6	35.7	37.5	39.0
45	01.4	04.4	09.1	14.4	19.3	23.5	27.0	29.8	32.1	34.0	35.5
50	0.80	02.9	06.7	11.3	16.0	20.1	23.7	26.6	28.9	30.9	32.5
55	0.40	02.0	04.9	08.9	13.2	17.3	20.8	23.7	26.2	28.2	29.9
60	0.30	01.3	03.6	07.0	10.9	14.7	18.2	21.2	23.7	25.8	27.5
70	0.10	0.60	01.9	04.3	07.4	10.8	14.0	17.0	19.5	21.7	23.5
80	0.00	0.30	01.0	02.6	05.0	07.8	10.8	13.6	16.1	18.3	20.2
90	0.00	0.10	0.50	01.6	03.3	05.6	08.2	10.9	13.3	15.5	17.5
100	0.00	0.00	0.30	01.0	02.2	04.1	06.3	08.7	11.0	13.1	15.1

APPENDIX I continued.

Depth	Height 3 m										
	T=6	7	8	9	10	11	12	13	14	15	16
05	170.3	180.9	187.8	192.5	195.8	198.4	200.1	201.7	202.7	203.7	204.4
06	148.2	159.8	167.3	172.5	176.1	178.8	180.8	182.5	183.7	184.9	185.7
07	130.5	143.0	151.1	156.7	160.7	163.7	165.8	167.6	169.0	170.0	171.0
08	115.8	129.1	137.8	143.8	148.0	151.2	153.6	155.3	156.9	158.0	159.0
09	103.4	117.4	126.6	132.9	137.4	140.7	143.4	145.2	146.8	148.1	149.1
10	92.6	107.2	116.9	133.6	128.3	131.8	134.5	136.7	138.2	139.6	140.6
11	83.2	98.4	108.5	115.4	120.4	124.1	127.0	129.2	130.9	132.2	133.4
12	74.8	90.4	100.9	108.2	113.5	117.3	120.2	122.5	124.4	125.8	126.9
13	67.4	83.4	94.2	101.8	107.2	111.3	114.3	116.6	118.6	120.0	121.3
14	60.7	76.9	88.1	96.0	101.6	105.8	108.9	111.4	113.4	114.9	116.2
15	54.7	71.1	82.6	90.7	96.5	100.8	104.1	106.7	108.7	110.3	111.6
16	49.3	65.8	77.5	85.8	91.8	96.3	99.7	102.3	104.4	106.1	107.5
17	44.4	60.9	72.8	81.4	87.5	92.1	95.7	98.3	100.5	102.3	103.7
18	39.9	56.4	68.5	77.2	83.6	88.2	91.8	94.7	96.9	98.7	100.1
19	35.9	52.2	64.5	73.4	79.9	84.7	88.4	91.2	93.6	95.4	96.9
20	32.3	48.4	60.7	69.8	76.4	81.3	85.2	88.1	90.4	92.3	93.9
22	26.1	41.5	53.9	63.2	70.1	75.3	79.3	82.4	84.8	86.8	88.4
24	21.0	35.6	48.0	57.5	64.6	70.0	74.1	77.3	79.9	82.0	83.7
26	16.9	30.5	42.6	52.3	59.6	65.2	69.5	72.8	75.5	77.6	79.4
28	13.6	26.1	37.9	47.6	55.1	60.8	65.3	68.7	71.5	73.7	75.6
30	10.9	22.3	33.7	43.4	51.0	56.9	61.4	65.0	67.9	70.2	72.1
35	06.2	14.9	25.1	34.4	42.1	48.3	53.2	57.0	60.1	62.6	64.6
40	03.6	10.0	18.5	27.3	34.9	41.3	46.3	50.4	53.6	56.3	58.5
45	02.0	06.6	13.7	21.5	28.9	35.3	40.5	44.7	48.2	50.9	53.2
50	01.2	04.4	10.0	17.0	24.0	30.2	35.5	39.8	43.4	46.3	48.7
55	00.7	02.9	07.3	13.3	19.8	25.9	31.2	35.6	39.2	42.3	44.8
60	00.4	01.9	05.4	10.5	16.3	22.1	27.3	31.8	35.6	38.7	41.3
70	00.1	00.9	02.9	06.4	11.1	16.1	21.0	25.5	29.3	32.6	35.3
80	00.0	00.4	01.5	03.9	07.4	11.7	16.2	20.4	24.2	27.5	30.4
90	00.0	00.2	00.8	02.4	05.0	08.5	12.4	16.3	20.0	23.3	26.2
100	00.0	00.1	00.4	01.4	03.4	06.1	09.4	13.0	16.5	19.7	22.6

Depth	Height 4 m										
	T=6	7	8	9	10	11	12	13	14	15	16
5	227.1	241.2	250.4	256.6	261.1	264.5	266.8	268.9	270.3	271.5	272.6
6	197.6	213.0	223.1	230.0	234.9	238.4	241.1	243.4	245.0	246.5	247.6
7	174.0	190.6	201.5	208.9	214.2	218.2	221.0	223.5	225.3	226.6	228.0
8	154.4	172.2	183.7	191.7	197.4	201.7	204.8	207.1	209.2	210.7	212.0
9	137.8	156.5	168.8	177.2	183.2	187.6	191.1	193.7	195.7	197.5	198.8
10	123.5	143.0	155.9	164.8	171.1	175.8	179.3	182.2	184.3	186.2	187.5
11	110.9	131.1	144.6	153.9	160.6	165.5	169.3	172.2	174.5	176.3	177.8
12	99.7	120.6	134.6	144.3	151.3	156.4	160.3	163.3	165.8	167.7	169.3
13	89.8	111.1	125.6	135.7	143.0	148.4	152.4	155.5	158.1	160.1	161.7
14	80.9	102.6	117.5	128.0	135.5	141.1	145.2	148.6	151.2	153.2	155.0
15	72.9	94.8	110.1	120.9	128.7	134.4	138.8	142.2	144.9	147.1	148.8
16	65.7	87.7	103.4	114.4	122.4	128.4	132.9	136.4	139.2	141.4	143.3
17	59.2	81.2	97.1	108.5	116.7	122.8	127.5	131.1	134.0	136.4	138.2
18	53.3	75.2	91.4	103.0	111.4	117.7	122.5	126.3	129.2	131.6	133.5
19	47.9	69.7	86.0	97.8	106.5	112.9	117.9	121.7	124.8	127.2	129.2
20	43.1	64.5	81.0	93.0	101.9	108.5	113.6	117.5	120.6	123.1	125.2
22	34.8	55.3	71.9	84.3	93.5	100.4	105.8	109.8	113.1	115.8	117.9
24	28.0	47.4	63.9	76.6	86.1	93.3	98.8	103.1	106.5	109.3	111.6
26	22.5	40.6	56.9	69.7	79.5	86.9	92.6	97.1	100.6	103.5	105.9
28	11.8	34.7	50.6	63.5	73.4	81.1	87.0	91.6	95.3	98.3	100.8
30	14.5	29.7	45.0	57.8	68.0	75.8	81.9	86.7	90.5	93.6	96.1
35	8.3	19.9	33.4	45.9	56.2	64.4	70.9	76.0	80.1	83.4	86.2
40	4.8	13.3	24.7	36.3	46.6	55.0	61.7	67.1	71.5	75.0	77.9
45	2.7	8.8	18.2	28.7	38.6	47.0	54.0	59.6	64.2	67.9	71.0
50	1.6	5.9	13.4	22.6	32.0	40.3	47.3	53.1	57.9	61.8	65.0
55	0.9	3.9	9.8	17.8	26.4	34.5	41.5	47.4	52.3	56.4	59.7
60	0.5	2.6	7.2	14.0	21.8	29.5	36.5	42.4	47.4	51.6	55.1
70	0.2	1.1	3.0	8.5	14.7	21.5	28.1	34.0	39.1	43.4	47.1
80	0.1	0.5	2.0	5.2	9.9	15.6	21.5	27.2	32.3	36.7	40.5
90	0.0	0.2	1.1	3.2	6.7	11.3	16.5	21.7	26.6	31.1	34.9
100	0.0	0.1	0.6	1.9	4.5	8.1	12.6	17.3	22.0	26.3	30.2

APPENDIX I continued.

Depth	Height 5 m										
	T=6	7	8	9	10	11	12	13	14	15	16
5	283.9	301.5	312.9	320.8	326.3	330.7	333.4	336.1	337.9	339.4	340.7
6	247.0	266.3	278.9	287.5	293.6	298.0	301.4	304.2	306.2	308.1	309.5
7	217.5	238.3	251.9	261.1	267.8	272.8	276.3	279.3	281.6	283.3	284.9
8	193.0	215.2	229.7	239.6	246.7	252.1	256.0	258.9	261.6	263.3	265.1
9	172.3	195.6	211.0	221.5	229.0	234.5	238.9	242.1	244.7	246.8	248.5
10	154.3	178.7	194.8	206.0	213.9	219.7	224.1	227.8	230.4	232.7	234.4
11	138.6	163.9	180.8	192.4	200.7	206.9	211.6	215.3	218.1	220.4	222.3
12	124.7	150.7	168.2	180.4	189.1	195.5	200.4	204.2	207.3	209.6	211.6
13	112.3	138.9	157.1	169.6	178.7	185.5	190.5	194.4	197.6	200.1	202.1
14	101.2	128.2	146.9	159.9	169.3	176.3	181.5	185.7	188.9	191.5	193.7
15	91.2	118.6	137.7	151.1	160.8	168.0	173.5	177.8	181.1	183.8	186.0
16	82.1	109.7	129.2	143.0	153.0	160.5	166.1	170.5	174.1	176.8	179.1
17	74.0	101.5	121.4	135.6	145.9	153.5	159.4	163.9	167.5	170.4	172.8
18	66.6	94.0	114.2	128.7	139.3	147.1	153.1	157.8	161.5	164.5	166.9
19	59.9	87.1	107.5	122.3	133.1	141.2	147.4	152.1	156.0	159.0	161.5
20	53.9	80.7	101.2	116.3	127.4	135.6	142.0	146.9	150.7	153.9	156.5
22	43.5	69.2	89.9	105.4	116.9	125.5	132.2	137.3	141.4	144.7	147.4
24	35.0	59.3	79.9	95.0	107.6	116.6	123.5	128.9	133.2	136.6	139.5
26	28.2	50.8	71.1	87.1	99.3	108.6	115.8	121.4	125.8	129.4	132.3
28	22.6	43.4	63.2	79.3	91.8	101.4	108.8	114.5	119.2	122.9	125.9
30	18.1	37.1	56.2	72.3	85.0	94.8	102.4	108.3	113.1	117.0	120.2
35	10.4	24.9	41.8	57.3	70.2	80.5	88.6	95.0	100.1	104.3	107.7
40	6.0	16.6	30.9	45.4	58.2	68.8	77.2	83.9	89.4	93.8	97.4
45	3.4	11.1	22.8	35.9	48.2	58.8	67.5	74.5	80.3	84.9	88.7
50	1.9	7.3	16.7	28.3	39.9	50.4	59.2	66.4	72.3	77.2	81.2
55	1.1	4.9	12.2	22.2	33.0	43.1	51.9	59.3	65.4	70.5	74.7
60	0.6	3.2	9.0	17.4	27.2	36.9	45.6	53.0	59.3	64.5	68.8
70	0.2	1.4	4.8	10.7	18.4	26.9	35.1	42.5	48.8	54.3	58.9
80	0.1	0.6	2.6	6.5	12.4	19.5	26.9	34.0	40.3	45.9	50.6
90	0.0	0.3	1.4	4.0	8.4	14.1	20.6	27.1	33.3	38.8	43.7
100	0.0	0.1	0.7	2.4	5.6	10.2	15.7	21.6	27.5	32.9	37.7