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.
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 occurrence 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 mud 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 mud banks 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 non-
istence of river discharge along this coast and upwelling, a very slow process (with velocity 1.6 x 10^{-3} cm/s, according to Mathew, 1982) cannot account for the high rate of sediment accumulation in the nearshore. Sediment transport by the prevailing coastal currents cannot account for the enormous quantity of fine sediment deposited in mudbank location. Apart from this, onshore transport and upwelling hypothesis cannot explain localization of mudbanks. Hence the hypotheses on the supply of mud from these sources do not appear to hold good. The subterranean passage hypothesis is discarded by various researchers (Bristow, 1938; Gopinathan and Qasim, 1974; Kurup, 1977; Ramachandran, 1989). The increase in pressure due to rise in water level in the backwaters during monsoon is insufficient to cause an underground discharge (Bristow, 1938; Ducane et al., 1938; Nair, 1976; Kurup, 1977). Corings conducted at Alleppey and Cochin rule out the possibility of any underground discharge of mud and water in these regions (Ducane et al., 1938). In certain years mudbanks have formed even before the onset of monsoon (Gopinathan and Qasim, 1974; Kurup, 1977) and sometimes during the air weather months. In December, 1965, a storm in the Arabian sea gave rise to the formation of a mudbank occupying a stretch of about 5 km between Cochin and Elamkunnapuzha (Varadachari and Murty, 1966). Previous works indicate the existence of subterranean passage only during monsoon and the formation of mudbank in the non-monsoon periods contradicts this hypothesis. Also the appearance of mud cones on the beaches during monsoon is sparsely reported.

The clay mineral distribution in the offshore regions of south-west coast of India has been studied by Rao et al. (1983). Their study shows that the offshore regions of this coast is montmorillonite rich. The field investigation of 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.
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 cohe-
sive), 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 - e.g. 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, viscoplastic 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 feedback effect of the fluid mud motions on the water waves (e.g., 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.