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Estuarine, Coastal and Shelf Science 78 (2008) 341–352
ESTUARINE COASTAL AND SHELF SCIENCE
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Nearshore sediment characteristics and formation of mudbanks along the Kerala coast, southwest India

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Received 27 June 2007; accepted 27 December 2007
Available online 11 January 2008

Abstract

In order to gain insight into the formation dynamics of mudbanks off the Kerala coast of India, extensive surveying of the nearshore bathymetry along with sediment characterization was undertaken. The textural and geotechnical properties of the surficial sediments of a mudbank were determined during pre-monsoon, monsoon, and post-monsoon periods. The mudbank sediments were clayey silts with high water and organic carbon contents, high Atterberg limits, and low bulk density, and therefore very susceptible to entrainment. During the monsoon, the mudbank regime was characterised by enhanced turbidity and a benthic fluff layer, triggered by the increasing swell of the early monsoon period. Re-suspension exposed a more consolidated, previously sub-bottom, layer which exhibited lower water content and greater shear strength than the pre-monsoon seabed. Texturally, the monsoon seabed was similar to the pre-monsoon seabed, with the same modal grain size, but the proportions of sand and coarse silt increased nearshore, while the proportions of fine and very fine silt increased offshore. There was a seaward-fining textural gradient at all times, but this became pronounced during the monsoon period. Paradoxically, the monsoonal seabed displayed greatly reduced wet bulk density. It is hypothesized that this was due to the presence of gas, probably methane, in the sediments (while the pre-monsoon sediments were fully saturated, the monsoon sediments were only 83% saturated). We speculate that the gas was forced into the surficial sediments either by wave pumping (at the onset of the monsoon) or by seaward-flowing subbottom freshwater (derived from monsoonal rains). With the waning of the monsoon, the benthic fluid mud layer rapidly disappeared and the seabed returned to its pre-monsoon state as suspended sediments were redeposited. The mudbank regime is therefore essentially an *in situ* phenomenon. It is suggested that the mudbanks are palimpsest, marshy, lagoonal deposits, rich in organic matter and derived gas, that were submerged after a marine transgression. The surficial sediment is annually entrained during the monsoon, but erosion is limited by the formation of the benthic fluid mud layer, which attenuates wave generated turbulence. Although some fine sediment disperses alongshore and offshore, most is returned to the seabed as the monsoon declines.

Keywords: mudbanks; geotechnical properties; nearshore bathymetry; sediment characteristics; Kerala coast; southwest India

1. Introduction

Mudbanks generally occur on coastlines supplied with large quantities of river-discharged muds which advect and diffuse across and along the shelf. Such coastlines (e.g. Surinam) are dominated by muds: foreshore, shoreface and shelf. However, the mudbanks of the Kerala coast of southwest India are not associated with river mouths and occur as discrete features on otherwise sandy shorelines. The Kerala mudbanks are associated with attenuated nearshore wave energy and high suspended sediment concentrations during and for some time after the period of the southwest monsoon. The combination of seabed deposit, high turbidity, and diminished wave energy constitutes the ‘mudbank regime’. Thus, while the mudbanks are permanent shoreface features, the mudbank regime itself is a seasonal phenomenon.

The Kerala mudbanks have socio-economic significance since their high biological productivity provides rich fishery

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doi:10.1016/j.ecss.2007.12.012

grounds (Damodaran, 1973; Gopinathan and Qasim, 1974) and their impact on wave energy minimises coastal erosion that prevails elsewhere on the southwest Indian coast (Kurup, 1977; Nair, 1985; Narayana et al., 2001). Despite its importance, it is not clear why the mudbank regime is so seasonally persistent. It is clear that the regime is triggered by the southwest monsoon, but the origin and fate of the fine sediments that constitute the regime remain conjectural. Therefore, we resorted to extensive surveying and mapping of the mudbank region in order to gain insights into its formation. Previous studies have suggested that there is intensive shoreward transportation of fine sediments from deeper water during the monsoon (Ramachandran and Samsuddin, 1991; Mathew and Baba, 1995). Other studies propose that it is supply of fine sediments from monsoonal river discharge that gives rise to the increased suspended sediment concentration (Mallik et al., 1988). However, in this paper we argue that the regime is essentially an *in situ* phenomenon that depends on the inherent properties of the seabed sediments and their interaction with nearshore dynamics generated by the monsoon.

2. The study area

The Ambalapuzha region of Kerala (Fig. 1) exhibits a prograding coastline with wide sandy beaches to the north and an erosional coastline with narrow sandy beaches to the south. The hinterland is marshland underlain by fine sediments. The shelf is narrow and in places palaeo-strandlines are preserved; in the Ambalapuzha region beach ridges occur at 20 m water depth. The shelf gradient is gentle and the 10 m isobath is some 4–5 km from the shore. The shoreface in several localities of the Kerala coast is characterised by mudbanks, the largest of which, in the Ambalapuzha–Purakkad region, extends 10–15 km alongshore and 5–6 km offshore.

The oceanographic regime is dominated by meteorological forcing (particularly the seasonal monsoon) rather than tidal forcing (the tidal range is only 1 m). Northerly winds dominate during the southwest monsoon (June to September) and southerly winds during the northeast monsoon (October to January). It is the southwest monsoon which is the stronger on the west coast of India and it is this monsoon which forces

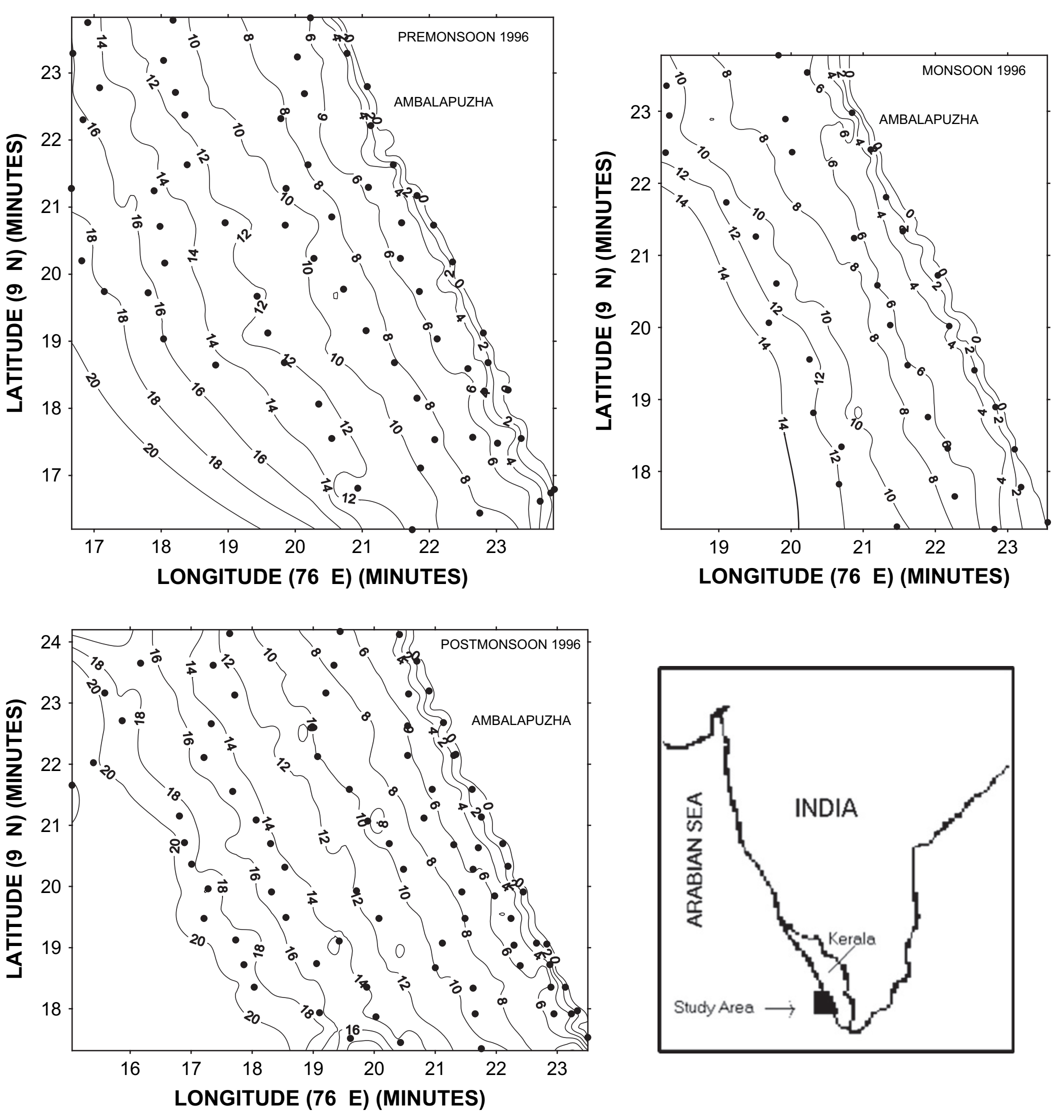

Fig. 1. Bathymetry and sample locations of the Ambalapuzha region.

the mudbank regime. The monsoonal winds establish in mid May, increase gradually until June when there is a rapid strengthening, increase to a maximum in July and August, and abate through September and October (Sharma, 1978). The monsoon is accompanied by heavy rainfall, with an average annual value of c. 300 cm. By contrast, the northeast monsoon is weak and the average annual rainfall is c. 60 cm.

The mudbank regime is a markedly seasonal phenomenon, the characteristic high turbidity developing only during the southwest monsoon. At this time, the periphery of the mudbank regime extends to about 6 km seawards from the shoreline and stretches for about 15 km along the shore. Attenuation of wave energy across the mudbanks gives rise to clearly delineated calm and rough regions. Tatavarti et al. (1999) observed significant wave heights of 2.5 m in the rough regions but negligible wave heights across the mudbank region (with a transition zone between them). The mudbank regime is clearly triggered by the onset of the monsoon and in many places it disappears with the cessation of the monsoon. However, in Ambalapuzha it is less ephemeral and persists for 2–3 months beyond the monsoon.

There have been several studies of the formation, sustenance and disappearance of the Kerala mudbank regime (Du Cane et al., 1938; Varma and Kurup, 1969; Nair, 1976; Wells and Coleman, 1981; Wells and Kemp, 1986; Mallik et al., 1988; Mehta and Jiang, 1993; Fass, 1995; Mathew et al., 1995; Mathew and Baba, 1995;) but the phenomenon remains enigmatic. These studies were concerned with physical processes and hydrographic features but they did not encompass real time nearshore measurements. In the present study real time measurements have been employed to determine nearshore wave and current dynamics. Preliminary results, including the physical properties of sediments and beach dynamics in relation to mudbank dynamics, are presented by Tatavarti et al. (1996, 1999), Manojkumar et al., 1998, and Narayana et al. (2001). This paper is concerned with the nearshore bathymetry, textural and geotechnical properties of the mudbank sediments of the Ambalapuzha–Purakkad region and tests the hypothesis that the mudbank regime is controlled by seabed sediments whose geotechnical properties make them highly susceptible to resuspension.

3. Nearshore bathymetry

A bathymetric survey was carried out to understand the detailed topographic variations in different seasons of the nearshore region of Ambalapuzha–Purakkad, and their relation to the mudbank dynamics. Surveys were conducted in the premonsoon, monsoon and post monsoon seasons and the corresponding bathymetric maps are shown in Fig. 1. The prominent feature in bathymetry is that the contours up to 4 m depth are closely spaced, indicating that the water depth increases steeply from the shore. The offshore bathymetric depth gradually increases from 4 m onwards. The waxing and waning of mudbank dimensions coincide with the changing bathymetric contours displayed for pre-monsoon, monsoon and post-monsoon seasons. The slopes of bathymetric profiles were monitored for different seasons at different spatial locations in the nearshore region of the study area.

4. Sediment sampling and analysis

Surficial sediment samples were collected from the mudbank region (Fig. 1) in the three phases of interest, i.e., in pre-monsoon, monsoon and post-monsoon seasons of 1996. Samples were collected by a Van-Veen grab and transferred into an airtight polythene covers and plastic bottles. Sample collection was done along with during the bathymetric survey. In total 65 samples in the pre-monsoon season, 37 samples in the monsoon and 84 samples in the post-monsoon were collected. However, samples could not be collected from >15 m water depth during the monsoon because of the rough sea outside the mudbank peripheries. Of these samples, 43 pre-monsoon, 21 monsoon and 40 post-monsoon were subjected to textural and geotechnical analyses. The textural characteristics were analysed following Folk, 1974 and organic carbon content estimation was performed as suggested by El Wakeel and Riley (1957). The geotechnical parameters analysed include water content, wet bulk density, shear strength and Atterberg limits comprising liquid limit, plastic limit and plasticity index. These parameters were analysed following the procedures suggested by ASTM (1994).

Water samples were taken during the monsoon period using Nansen bottles and filtered through 0.45 μm filters.

5. Results

5.1. Bathymetry

The inner shoreface gradient decreased seawards with a pronounced decrease at the 4 m isobath. The notable feature is that the nearshore bathymetric profile becomes steeper during the monsoon season ($\sim 1.5°$ slope) and slowly becomes gentler as the monsoon season recedes ($\sim 0.6°$ during post-monsoon and $\sim 0.°$ during pre-monsoon season). The nearshore profiles to the north and south of the study area are steeper relative to the central region of the study area suggesting the role of mudbank on the bathymetric variations.

5.2. Mudbank sediment distribution

5.2.1. Grain size parameters

At all seasons, the mudbank sediments were clayey silts, moderately to poorly sorted. The sediments displayed a pronounced shore normal gradient in pre-monsoon and monsoon periods (Fig. 2). This was especially marked during the monsoon when the shoreface showed a strong seaward-fining textural gradient in the silts. However, in the post-monsoon period, the sediment distribution was patchy without a regional gradient.

The regional mean grain size did not change much between periods except for a slight coarsening during the monsoon: pre-monsoon, monsoon and post-monsoon mean grain sizes averaged 5.46 phi (4.05–6.61 phi), 5.38 phi (4.19–5.84 phi), and 5.53 phi (4.78–6.30 phi), respectively. The monsoon coarsening was due to changes in the tails of the grain size spectra rather than in the mode which was unchanged; during the monsoon the bottom sediments showed a small increase in

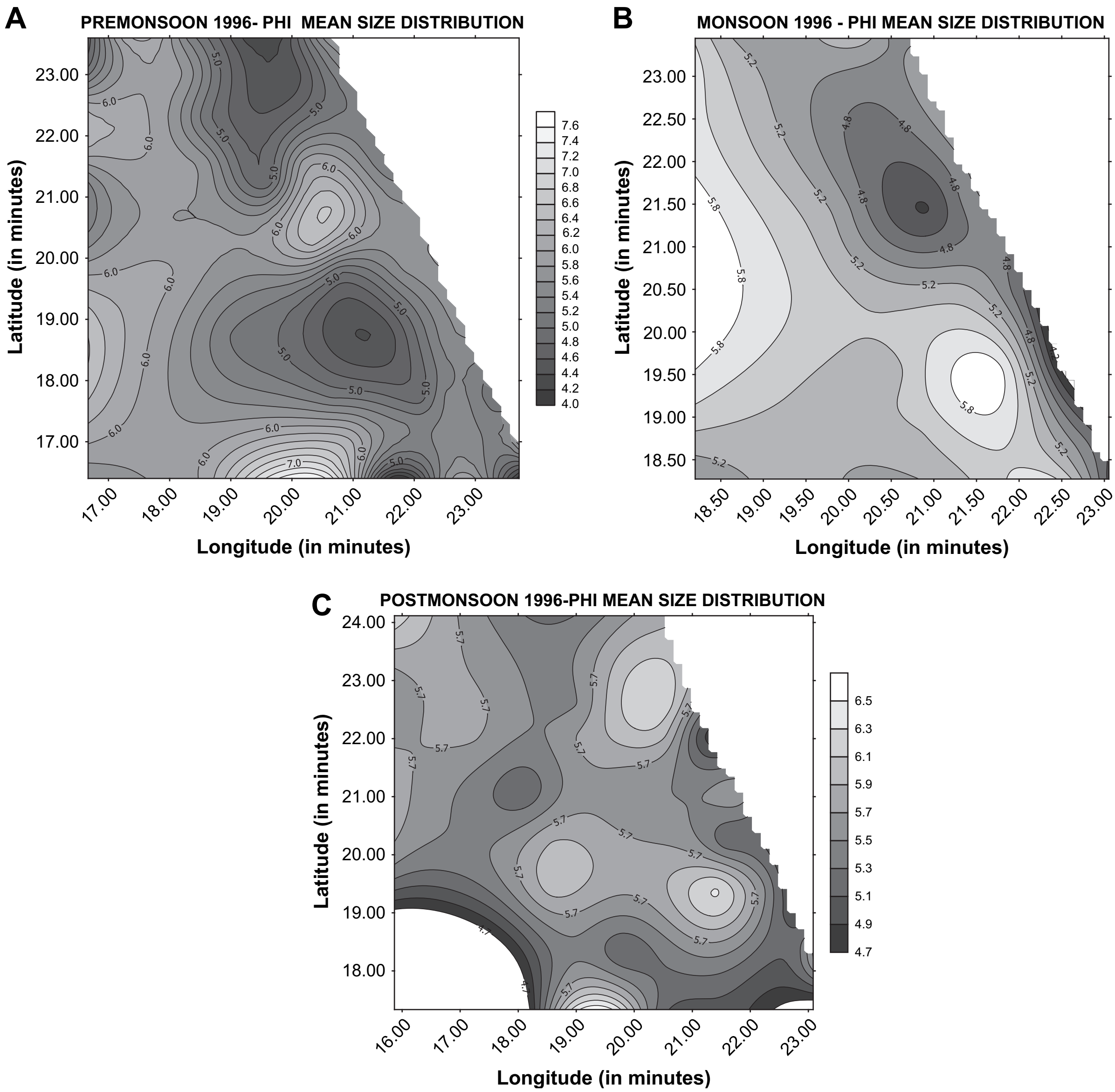

Fig. 2. Phi mean grain size distribution in (A) pre-monsoon, (B) monsoon, and (C) post-monsoon periods.

coarser fractions and a corresponding decrease in finer fractions (Fig. 3). Standard deviations were also temporally consistent but with a slight increase during the monsoon pre-monsoon, monsoon and post-monsoon averages were 1.14 phi (0.54–1.55 phi), 1.22 phi (0.87–1.41 phi), and 1.13 phi (0.81–1.51 phi), respectively.

5.2.2. Proportions of sand, silt, and clay

Water depth variation of average sand (0.6–2 mm), silt (0.002–0.06 mm) and clay (<0.002 mm) contents in different periods are shown in Fig. 4. The sand fraction constituted a small part of the mudbank sediment, increasing in the monsoon period (c. 15%) compared with pre- and post-monsoon (<5%). The silt fraction was dominant at all times (>80%). The clay fraction rarely exceeded 10% and changed little with period. The mudbank sediments can therefore be classified as marginally cohesive using the criterion of Dyer (1986).

5.2.3. Water depth variation of grain size spectra

The temporal and spatial distributions of grain size fractions are shown in Fig. 5. There were subtle, but important, changes to the distribution of sediment size fractions with water depth during the monsoon. The proportions of sand and coarse silt increased, while medium silt, fine silt, and very fine silt decreased in shallow water (c. <10 m). At the same time, medium silt, fine silt and very fine silt increased in deeper water (c. >10 m). The proportion of the subordinate clay fraction did not change much over time.

5.2.4. Silt/clay ratios

Silt/clay ratios of most samples ranged from 4 to 15 in the pre-monsoon season, from 6 to 16 in the monsoon season and from 4 to 11 in the post-monsoon season. The pre-monsoon silt/clay ratios were slightly higher, except for a few small patches. Monsoon silt/clay ratios were generally unchanged

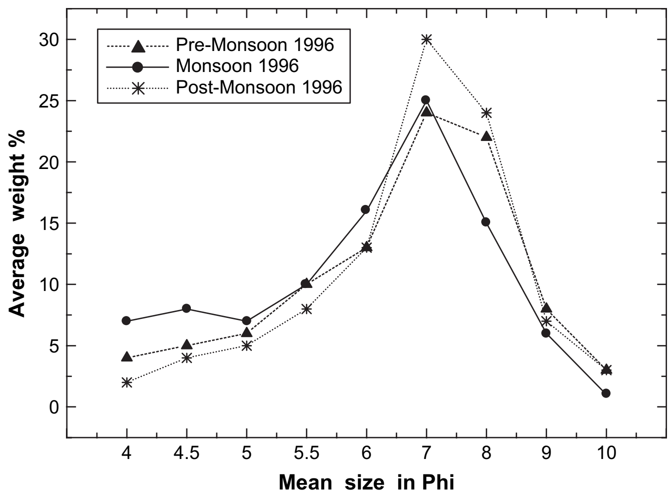

Fig. 3. Average grain size spectra during the sampling periods.

but lower values were observed in the south. Post monsoon silt/clay ratios were more than 10 in most parts, but ranged from 5 to 10 in the middle part between 10 m and 20 m water depth, and decreased to less than 5 in a few patches.

5.2.5. Organic carbon content

Organic carbon percent for the three periods was 3.29 ± 0.30, 3.51 ± 0.31, and 3.40 ± 0.17 for pre-monsoon, monsoon and post-monsoon, respectively. Thus, there were no significant changes over time.

5.3. Suspended sediment concentration (SSC)

Near-bed SSC (average 1500 mg L^{-1}) was always greater than surface SSC (average 50 mg L^{-1}). This difference increased to up to two orders of magnitude during the peak of the monsoon when near-bed SSC reached 5236 mg L^{-1}; these high concentrations indicate the presence of a fluid mud layer close to the bed. As the intensity of the monsoon declined, near-bed SSC fell sharply within 1 week from an average 2700 mg L^{-1} to an average 270 mg L^{-1}, indicating rapid settling of suspended sediments on to the sea bed.

5.3.1. Influence of waves and currents on suspended sediment concentration

Mei et al. (1997) suggested that in addition to sediment re-suspension, waves can also move the highly concentrated fluid mud, which is known to behave as a non-Newtonian fluid. In particular, through second order Reynolds stresses, waves generate a streaming velocity that varies horizontally on the scale of the wavelength. Li and Parchure (1998) examined the physical factors influencing the suspended sediment concentration profiles and presented a semi-empirical model that accounts for the vertical fluxes of fine sediment in suspension due to waves and currents. The theoretical arguments of Mei et al. (1997) and the semi-empirical model of Li and Parchure (1998) on the importance of nearshore waves and currents in influencing the suspended sediment concentration profiles of the region may be corroborated by considering the extensive field measurements of waves and currents in the Kerala mud-bank region by Tatavarti and Narayana (2006), and the observations on suspended sediment concentrations in the preceding section.

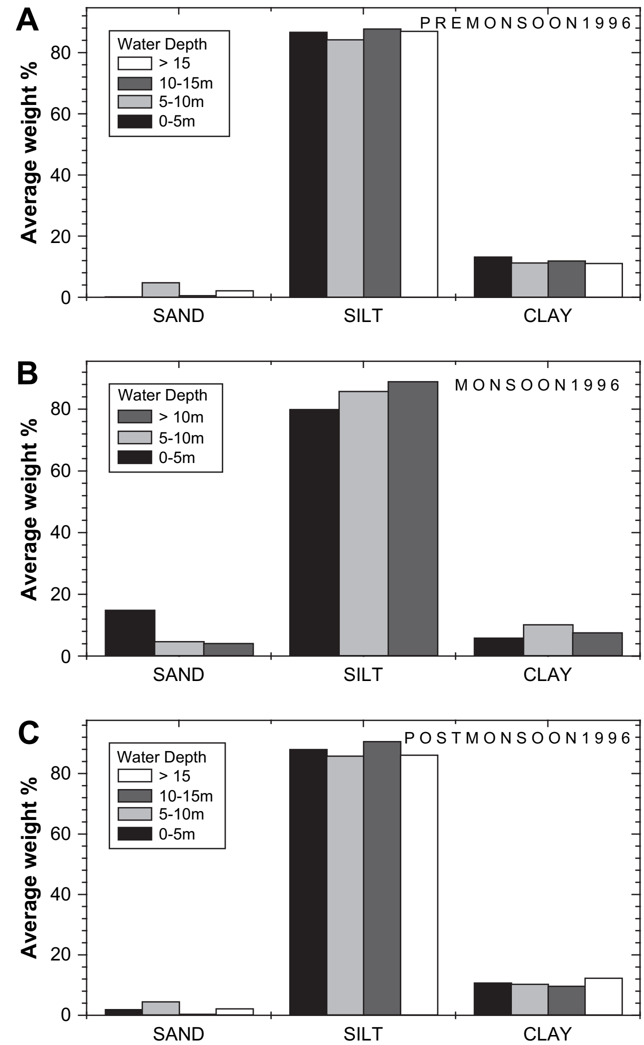

Fig. 4. Average frequency by weight of sand, silt and clay size fractions in (A) pre-monsoon, (B) monsoon, and (C) post-monsoon periods.

Tatavarti and Narayana (2006) have demonstrated that the Kerala mudbank region is predominantly influenced by small amplitude gravity waves, weak littoral currents and undertow in the non-monsoon season, because of the weak wind forcing. In the monsoon season, however, the wind energy was observed to be much greater, resulting in larger amplitude waves and stronger littoral currents. In addition, a strong infragravity band of wave frequencies with significantly high wave reflections and a stronger undertow were also observed during the monsoon season. Tatavarti and Narayana (2006) argued that the smaller breaking waves trigger far fewer sediments into suspension. The mudbank region is very limited in its spatial extent as the wave breaking occurs predominantly closer to the shore. With the onset of the monsoon, the wind forcing picks up, the wave heights start increasing and the sea

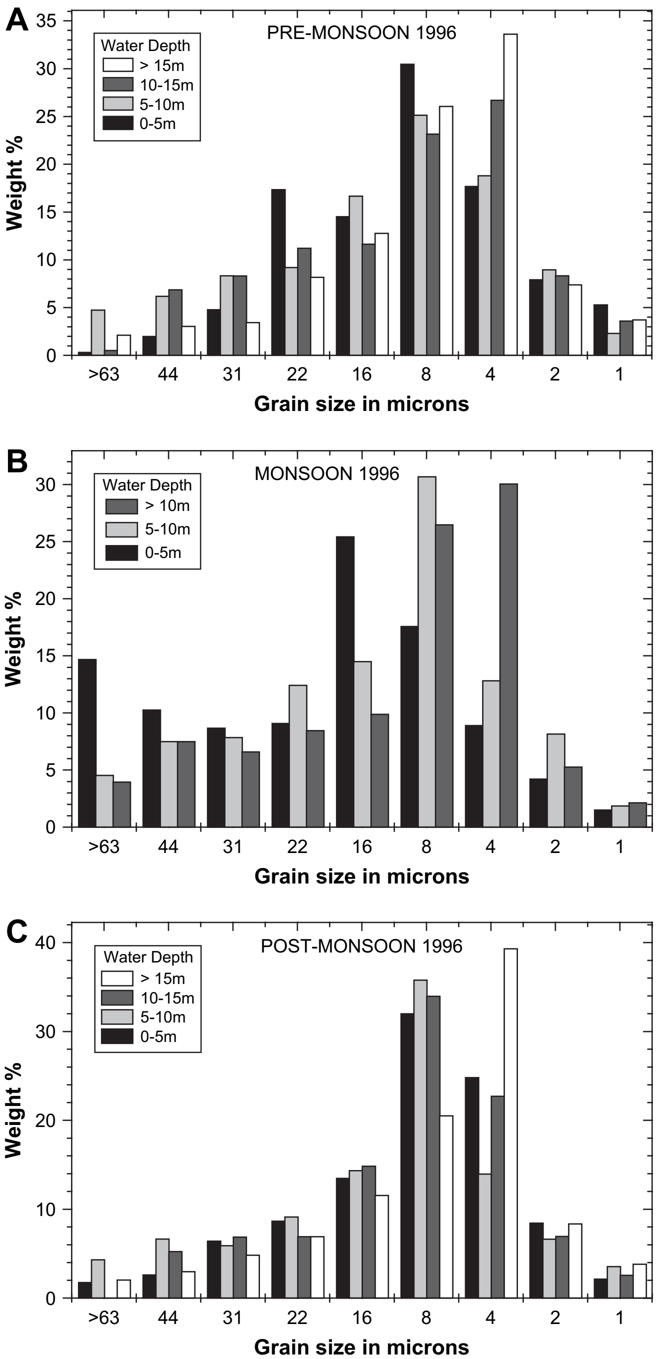

Fig. 5. Average frequency by weight of grain size fractions with respect to water depth in (A) pre-monsoon, (B) monsoon, and (C) post-monsoon periods.

gradually becomes rough. The rough sea conditions enable larger waves to start breaking at higher water depths (i.e., the breaking zone shifts seaward). This means that there would be a stronger propensity for the sediments on the seabed to be triggered into suspension from a further seaward location. The larger waves ensure higher concentrations of sediments into suspension. During the rough monsoon season, in addition to the gravity wave band, the lower frequency (infragravity) wave band also becomes energetic. Therefore, the littoral currents and the undertow also become stronger as they are primarily driven by the nearshore wave regime. As the monsoon season progresses, the infragravity motions (3-D motions with both cross-shore and longshore dependence) become much more pronounced than the gravity waves, inside the mudbank region. This effect results from the region acting as a dissipater of gravity waves due to the high concentration of suspended sediments in the water column. Due to their longer wavelength and therefore lower steepness, the infragravity waves do not break. Hence, the degree of wave reflection also increases. The strong undertow and the reflected waves tend to push the sediment blanket on the seabed seawards. Therefore the seaward breaking waves impart their energy to trigger this sediment layer into suspension. This ensures that the offshore extent of mudbank shifts seaward. The seaward breaking waves, stronger littoral currents and undertow, coupled with the stronger infragravity wave motions with their cross-shore and longshore dependence, therefore ensures that the spatial extents of the mudbank region increase during the monsoon season. As the monsoon season ends, the strength of the wind and hence the waves subside. This ensures that the breakers approach shoreward resulting in a contraction of the mudbank.

5.4. Geotechnical properties

Geotechnical properties of the sediments are summarised in Table 1. The principal results are summarised below.

5.4.1. Water content

Water content (defined as the ratio of the weight of water to the weight of solids multiplied by 100), relative to the liquid limits of the sediments, generally varied from 124 to 254% with an average of 177% during the pre-monsoon season. In the monsoon season water content varied between 84 and 205% with an average of 143%. In the post-monsoon season water content generally varied between 131 and 345% with an average of 206%. It is observed that the water content has generally decreased from pre-monsoon to the monsoon season and increased from monsoon to the post-monsoon season. At all periods, water content was very high and close to the liquid limit values.

5.4.2. Atterberg limits

The liquid and plastic limits reflect the ability of a sediment particle to attract water to its surface and increase with the particle tendency to hold water. Liquid limits, plastic limits, and plasticity indices were high at all times and there were only minor changes over time except for plastic limit, which increased in the post-monsoon period. Generally the fabric, physico-chemistry of clay–water system and organic carbon content of sediments influence the Atterberg limits (Rosenquist, 1962; Sodorblom, 1966; Rashid and Brown, 1975; Bennett et al., 1981). The liquid limit values were plotted against plasticity index values, i.e., as plasticity chart in Fig. 6a, to understand the level of plasticity. The points are seen to fall on and around the A-line in the plasticity chart (Fig. 6a). The samples of the pre-monsoon season fall almost on the A-line, while monsoon season samples were more

Table 1
Geotechnical properties of the sediments during pre-monsoon, monsoon, and post-monsoon periods: mean values and 95% confidence limits

	Water content %	Wet bulk density (g cm^{-3})	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Vane shear (kPa)
Pre-monsoon	177 ± 8	1.33 ± 0.01	129 ± 6	49 ± 3	80 ± 4	1.04 ± 0.06
Monsoon	143 ± 12	1.23 ± 0.02	129 ± 10	49 ± 4	80 ± 8	1.38 ± 0.21
Post-monsoon	206 ± 16	1.28 ± 0.01	136 ± 5	59 ± 2	77 ± 3	0.91 ± 0.09

widely distributed on either side of the A-line. Most of the post-monsoon samples fall below the A-line. From Fig. 6a it can be inferred that the sediments are of both organic clays of medium to high plasticity and inorganic clays of high plasticity nature. In general, sediments were distributed according to their silt and clay components along the A-line of the plasticity chart. Chassefiere and Monaco (1989) have shown that the liquid limit and plasticity index reflect the type of clay minerals present in the sediments. For example, if the content of smectite mineral is higher, the liquid limit and plasticity index are also higher. If the kaolinite content is higher, the liquid limit and plasticity index are lower. We have observed high smectite content in the sediments of the mudbank, which therefore explains the high liquid and plasticity limits. The activity chart (clay percent versus plasticity index) is shown in Fig. 6b. The figure shows Skempton's (1953) classification of clays as 'active', 'normal' and 'inactive' clays. The results indicate that the sediments of mudbank are of an active nature.

5.4.3. Wet bulk density

Wet bulk density was observed to vary between 1.21 and 1.66 g/cm^3 with an average of 1.53 g/cm^3 in the pre-monsoon season, between 1.01 and 1.95 g/cm^3 with an average of 1.16 g/cm^3 in the monsoon season, and between 1.43 and 1.59 g/cm^3 with an average of 1.53 g/cm^3, during the post-monsoon season. Bulk densities therefore, were generally low and decreased further during the monsoon.

5.4.4. Shear strength

Shear strength values ranged from 0.78 to 1.49 kPa in the pre-monsoon with an average of 1.05 kPa, whereas during the monsoon season shear strength values ranged from 0.48 to 2.2 kPa with an average of 1.38 kPa. Shear strength values in the post-monsoon season ranged from 0.123 to 1.579 kPa with an average of 0.91 kPa. Thus, the vane shear strength results suggested that sediments of mudbank were of low shear strength, with shear strength increasing in the monsoon season.

6. Discussion

6.1. Sediment properties

Results show that the nearshore mudbank was blanketed with clayey silts in all seasons with minor variations, contrary to the earlier reports that the mudbank sediments were silty clays (Dora et al., 1968; Kurup, 1977; Mallik et al., 1988). Earlier studies on various mudbanks of the southwest coast of India suggested that clay was the dominant constituent (45–65%) of the mudbank sediments, followed by silt (35–45%) and sand (2–10%) (Dora et al., 1968). Mallik et al. (1988) reported 75–90% clay in the Quilandi mudbank area. Mathew and Baba (1995) reported 34% sand, 27% silt and 39% clay during the pre-monsoon period and 3% sand, 27% silt and 70% clay in the monsoon period on the Alleppey mudbank. However, Nair (1983) observed high silt (72–98%) with subordinate clay (2–28%) on the Alleppey and Narakkal mudbanks, and Rajan (1996) reported clayey silt in the upper portion of the core sample from the present study area. These last two studies support the present findings.

The mudbank sediments exhibited high water and organic carbon contents. Water content relates to sediment saturation, porosity, consolidation, and bulk density (Hjulstrom, 1935; Postma, 1967). An increase in water content should decrease the effective stress, although cohesive mud may take up sea water so that the bulk volume changes without altering interparticle bond strength (Black, 1991). This behaviour is more likely in mud containing appreciable organic matter and benthic organisms which increase the sediment's ability to hold water (Rashid and Brown, 1975; Hamblin and Davies, 1977).

The mudbank sediments showed high liquid and plastic limits values and high plasticity indices. These properties are determined by composition and texture (Chassefiere and Monaco, 1989) and, in particular, fabric (Bennett et al., 1981), physico-chemistry of the clay–water system (Rosenquist, 1962; Mitchell, 1976), and concentration of organic carbon (Rashid and Brown, 1975). It is likely that all these factors are determining the high Atterberg limits of the mudbank sediments. Enhanced levels of organic matter are associated with high water content which in turn increases the Atterberg limits (cf. Keller, 1982).

The geotechnical properties of the sediments—high water content, high organic carbon, high plasticity index, and low bulk density—are generally associated with a low critical shear stress for erosion (Smerdon and Beasley, 1961; Vanoni, 1975; Thorn and Parsons, 1980; Delo, 1988) and increased erosion rate (Mehta et al., 1982; Villaret and Paulic, 1986; Mehta, 1988). Hence the mudbank sediments are very susceptible to resuspension by the physical forcing associated with enhanced wave energy during the onset of the monsoon.

6.2. Spatial variability

The mudbank sediments displayed a pronounced seaward-fining gradient, particularly developed during the monsoon period. This is diagnostic of a wave-dominated shoreface.

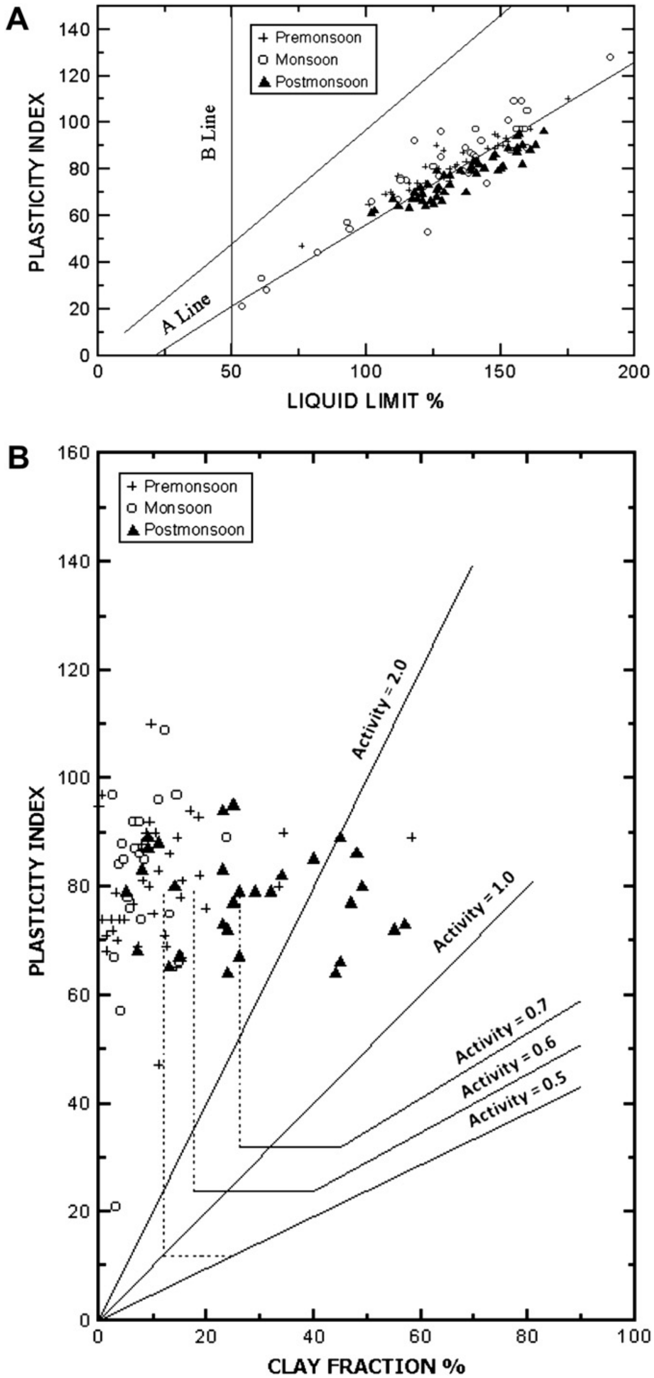

Fig. 6. Atterberg limits of mudbank sediments: (A) plasticity chart, and (B) activity chart.

Tatavarti et al. (1999) observed strong shoreline reflections and undertow over the mudbank especially during the monsoon. However, despite the shore-normal textural gradient, significant spatial gradients in geotechnical properties were not observed.

6.3. Temporal variability

The textural character of the sediments changed during the monsoon period, though this change was subtle. The modal grain size remained constant over time, but there were changes to the tails of the grain size distributions. During the monsoon period, coarse and medium silt fractions increased and fine and very fine silt fractions decreased in 0–10 m water depths; there was a corresponding increase in fine and very fine silt fractions in >10 m water depths. The clay size fraction did not vary significantly over time. At the same time, the inner shoreface steepened slightly, particularly at shallower water depths. These results show that, with the onset of the monsoon, the inner shore face experienced increasing erosion and finer fractions were preferentially resuspended and moved alongshore and seawards. These changes are consistent with resuspension by an increasing undertow that was observed by Tatavarti et al. (1999) and by Tatavarti and Narayana (2006).

There were temporal variations in some geotechnical properties that were more significant than the small changes in sediment texture. During the monsoon, seabed properties changed and a fluid mud layer developed above the bed. The low bulk density measured in the monsoon period suggests that the grab samples were derived from the fluid mud layer, but the decreased water content contradicts this. Clearly the samples were taken from the true seabed, not from the fluid mud layer. Vane shear strength increased, as water content decreased, during the monsoon. Thus, the bed sediment increased in consolidation and cohesion. We propose that erosion and resuspension of the seabed sediment had exposed an underlying, more consolidated layer of sediment (Fig. 7). The eroded material provided the source for the overlying fluid mud and the enhanced turbidity throughout the water column that is a consistent feature of the mudbank regime during the monsoon.

Louda et al. (2004) suggested that the underlying layer of fine-grained carbonate sediments in the north central Florida Bay must have resulted from a process of hydrogelation due to an increase in organic carbon content which generates increase in water content. They hypothesized that this hydrogelation must have stabilized the bottom layer of sediments, and also may have been responsible for the many unique physical and chemical properties of the sediments in Florida Bay. Although intriguing, the presence of a consolidated layer of sediment at

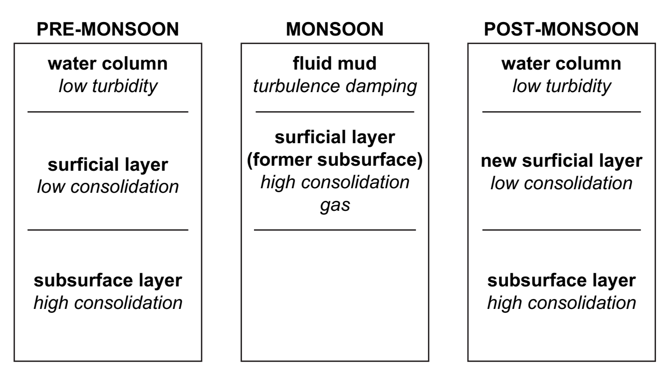

Fig. 7. Schematic of sediment dynamic processes in the mudbank during different seasons. Pre-monsoon: low SSC water column overlying seabed sediment that becomes more consolidated with depth. Monsoon: erosion of surficial layer exposes more consolidated subsurface layer and generates benthic fluid mud and high SSC in water column. Post-monsoon: fluid mud and re-suspended sediment settle back to bed as a low consolidation layer and SSC declines.

the bottom in the Kerala mudbank region may also be explained by the process of hydrogelation due to the high content of organic matter and the ensuing high water content in the sediments.

However, the decreased bulk density during the monsoon is not readily compatible with a decrease in water content. It is consistent with decreased water content only if there was a change in sediment mineralogy, organic content, or saturation. The change in bulk density was too great to be accounted for by a change in sediment density and there was no significant change in organic carbon content during the monsoon. The change in bulk density can be accounted for by a change in water saturation. For saturated sediment, the bulk density is given by Eq. (1):

$$\rho_{mc} = \rho_s \rho_w \frac{1+\omega}{\rho_w + \omega\rho_s} \tag{1}$$

where ρ_{mc} is calculated bulk density, ρ_s is sediment specific gravity, ρ_w is seawater density, and ω is measured water content. For pre-monsoon and post-monsoon sediments, the calculated and measured densities were very comparable, but for monsoon sediments, the measured densities were significantly less than the calculated densities. Hence the monsoon sediments were not fully saturated. Saturation S_r is given by Eq. (2):

$$S_r = \frac{\omega\rho_s\rho_{mm}}{(\rho_s + \omega\rho_s)\rho_w - \rho_{mm}} \tag{2}$$

where ρ_{mm} is the measured bulk density. The mean saturation of pre-monsoon, monsoon, and post-monsoon sediments using Eq. (2) was 102 ± 1, 87 ± 3, and $100 \pm 1\%$, respectively (with 95% confidence limits). We postulate that the lowered saturation during the monsoon could be produced by gas. The occurrence of gassy sediments along the inner shelf of the west coast of India has been reported (e.g. Karisiddaiah et al., 1993; Karisiddaiah and Veerayya, 1994). The authors of this paper have observed degassing of methane from the marshy hinterland of the Kerala coast; this phenomenon intensifies during the monsoon season. The influence of gas on the geotechnical properties of marine sediments is well documented (e.g., Silva and Brandes, 1998). We suggest that the postulated increase in gassiness of the sediments is a response to wave pumping at the onset of the monsoon; this would occur before full development of the fluid mud layer since once the fluid mud is formed, wave energy is attenuated. Alternatively subsurface fresh water flow from the marshy, lagoonal hinterland during heavy monsoonal rains may force subsurface gas into the surficial sediments.

6.4. Inter-relationships of geotechnical parameters

Bivariate plots of geotechnical parameters showed some expected relationships. Thus water content increased with increasing organic carbon content during all seasons (average $r = 0.56$) because of the water absorbing nature of the organic matter. Similarly, this could be taken as an indication of hydrogel formation amongst organic matter (Louda et al., 2004).The Atterberg limits also increased with increasing organic matter because of its ability to absorb water (Busch and Keller, 1981). The plasticity index increased with organic carbon content during all three seasons (average $r = 0.75$). Other relationships (e.g., those involving vane shear stress) were not significant. However, plots involving water content, bulk density and organic carbon showed interesting features, as follows.

6.4.1. Water content vs wet bulk density

The interrelationship between water content and wet bulk density (Fig. 8a) showed a strong inverse correlation in the pre-monsoon ($r = -0.75$) and post monsoon ($r = -0.84$). However, in the monsoon it showed a slight positive correlation ($r = 0.39$). An inverse correlation would be expected for a mineralogically homogeneous population of samples, as seen in the pre- and post-monsoon samples. The monsoon relationship, although not very strong, runs counter to expectation. It can be explained in terms of the gassy sediment hypothesis: the added contribution of gas was sufficient to mask or even to reverse the expected correlation.

6.4.2. Organic carbon vs wet bulk density

An inverse correlation that was observed between these two parameters was significant and weak in the post- and pre-monsoon periods, respectively (Fig. 8b). The relationship

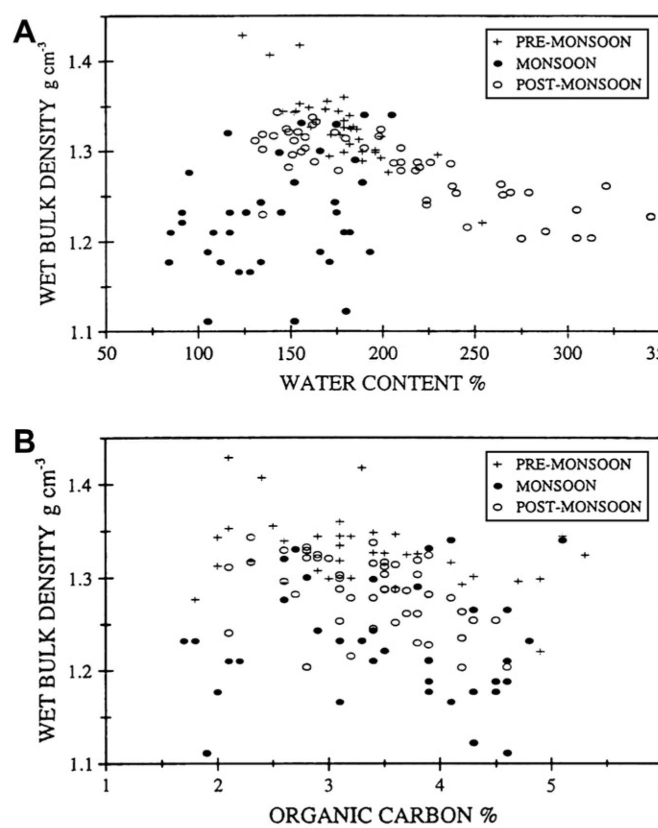

Fig. 8. Bivariate plots of (A) water content versus wet bulk density, and (B) organic carbon content versus wet bulk density.

was muted during the monsoon, presumably because of the additional change to the bulk density at that time. This affected all other bivariate plots of bulk density for the same reason.

6.5. Formation and maintenance of the mudbank regime

From the foregoing results, we can postulate the following scenario for the temporal development of the mudbank regime. The mudbank itself is likely to be a palimpsest deposit of Quaternary origin. The present day Kerala coast is characterised by a sandy strandline backed by a marshy hinterland of fine grained, gassy sediments. The geometry and sedimentology of the contemporary mudbank suggest that it is a palimpsest marsh deposit that has been drowned by a transgressing shoreline. It is currently being reworked by modern processes, particularly shoaling waves. However, although the mudbank regime recurs annually, there does not appear to be significant long-term erosion of the mudbank.

The onset of the monsoon is signalled by increased wave energy and resuspension; the geotechnical properties of the sediments make them particularly susceptible to entrainment and resuspension. Erosion of the surface layer exposes a more consolidated layer (with decreased water content) beneath. However, high SSC values (>5000 mg L^{-1}) give rise to a loosely consolidated fluid mud layer above the bed (cf. Wright et al., 1988). Fluid mud layers have smooth upper surfaces, and strong density gradients at their surface, which reduce shear stress and stabilises the fluid mud (Nicholas, 1986; Mehta, 1988). Thus, during the monsoon a three-layer structure is in place: a partially consolidated seabed, overlain by a stationary fluid mud, which is persistent throughout the monsoon, and a highly turbid water column (with surface SSC up to 200 mg L^{-1}).

Tatavarti et al. (1999) and Tatavarti and Narayana (2006) have shown that, as wave energy increases, low frequency motions become prominent and these shore-parallel and shore-normal motions, particularly undertow, advect suspended sediment so that the region of turbid water is extended alongshore and offshore. Hence, the mudbank regime expands laterally during the monsoon.

During the monsoon season, we have observed sporadic bursting and explosion of methane gas from the coastal sediments. Hence we speculate that the bulk density of the mudbank sediments decreases as subbottom gas is forced into the surficial sediments. This may be because subsurface gas is forced towards the surface by wave pumping during the onset of the monsoon and/or by subsurface fresh water flow from the marshy, lagoonal hinterland during heavy monsoonal rains.

As the monsoon wanes, further resuspension ceases. SSC in the fluid mud layer declines dramatically by an order of magnitude within 1 week and our observations suggest that the fluid mud layer may persist for some weeks after the cessation of the monsoon. Suspended sediment is redeposited and both the texture and properties of the seabed are much as they were before the monsoon. Although there must be some net loss of advected suspended sediment away from the mudbank, this must be small since the mudbank remains in place. The mudbank regime is therefore an annually renewable, self-sustaining phenomenon.

This conclusion contradicts previously proposed mechanisms—shoreward advection of fine sediment from offshore (Ramachandran and Samsuddin, 1991; Mathew and Baba, 1995) or seaward advection of muds from river discharge (Mallik et al., 1988)—which are not consistent with either our observations or those of Tatavarti et al. (1999) and Tatavarti and Narayana (2006) on nearshore dynamics. Du Cane et al. (1938) proposed that the mudbank phenomenon was due to pre-monsoon swells, which resuspend mud from the seabed in shallow water, but they lacked supporting observational data. Our results, as well as those of Tatavarti et al. (1999) and Tatavarti and Narayana (2006), not only provide corroborative data but also explain the mechanisms which determine the phenomenon.

However, we stress that future studies of sediment samples from onshore and offshore regions for gas analyses, using ^{13}C and $D(H_2)$ stable isotopes, are necessary to unequivocally establish our hypothesis.

7. Conclusions

The inner shoreface gradient decreased seawards with a pronounced decrease at the 4 m isobath. The nearshore bathymetric profile becomes steeper during the monsoon season and slowly becomes gentler as the monsoon season recedes. The nearshore profiles to the north and south of the study area are steeper relative to the central region, suggesting the role of mudbank on the bathymetric variations.

Contrary to previous studies on mudbanks in the region, which reported a high proportion of clay, the sediments were predominantly clayey silts with clay content usually $<10\%$. The sediments were therefore only marginally cohesive. The sediments exhibited high water content, high organic carbon content, high Atterberg limits, and low density; thus the sediments were very susceptible to resuspension.

The appropriate conditions for resuspension occurred during the increasing swells of the monsoon period. The mudbank regime at this time was characterised by greatly enhanced turbidity and a benthic fluid mud layer. The turbid water spread alongshore and offshore, so increasing the spatial dimensions of the mudbank regime. The shoreface steepened slightly, particularly nearshore, as entrained sediments were moved alongshore and offshore. It is likely that previously reported low frequency motions and strong undertow during the monsoon triggered these responses.

There were significant changes in some geotechnical properties during the monsoon: the water content decreased and the vane shear strength increased. It is hypothesized that these changes were consequent on entrainment of the pre-monsoon bed (which supplied the fluid mud layer and increased water column turbidity) and exposure of a more consolidated, previously subsurface layer. The sediments of the monsoonal seabed were similar to those of the pre-monsoonal seabed—clayey silts—but there were subtle differences. Although the modal grain size did not change, the proportions of sand and coarse silt increased nearshore, while the proportions of fine and very fine silt increased offshore. There was a seaward-fining textural gradient at all times, but this became pronounced during the monsoon period. Paradoxically, the monsoonal seabed displayed greatly reduced wet bulk density. It is hypothesized that this was due to the presence of gas (probably methane) in the sediments which was forced into the surficial sediments either by wave pumping (at the onset of the monsoon) or by seaward-flowing sub-bottom freshwater flow (derived from monsoonal rains). With the cessation of the monsoon, sediment properties returned to their pre-monsoon state. Nearbed SSC dropped by an order of magnitude in 1 week as the fluid mud returned to the seabed. The post-monsoon seabed was comparable in its properties to the pre-monsoon seabed.

The annually renewed mudbank regime appears to be an *in situ* phenomenon. It is suggested that the mudbank is essentially a lagoonal deposit that has been submerged by a marine transgression, hence its shore-parallel geometry and organic carbon- and methane-rich character. It has been preserved, rather than eroded, because the pre-monsoonal swell resuspends the easily entrained sediments to form the benthic fluid mud layer, which attenuates wave-generated turbulence and prevents further resuspension. The fluid mud layer, stationary during the monsoon, resettles on the seabed with the cessation of the monsoon. Some suspended sediment passes into the water column and this is advected away by alongshore and offshore motions. But the net loss of sediment appears to be small. Most of the sediment remains on the mudbank and the mudbank regime is an annually renewable event. With respect to both origin and maintenance, the Kerala mudbanks differ from superficially similar nearshore mudbanks of the Surinam and French Guiana coasts, which are formed and maintained by sediment flux from river discharges.

Acknowledgements

The project was funded by the Department of Science and Technology, Government of India, under the SERC Programme (ESS/CA/A1-14/94). The authors thank Dr K.R. Gupta for helpful advice during the project and Dr S.E. Jones for fruitful discussions during the manuscript preparation. The authors thank the anonymous reviewers and Prof Wolanski for their insightful comments and suggestions for improving the manuscript.

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