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Geotechnical Characteristics of the Sediments in the near Shore Sector off Andhra Pradesh and Pondicherry, East Coast of India

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Abstract: **-** Integrated offshore investigations along selected segments off East Coast of India for port and harbors developmental activities have provided detailed information on the sea floor morphology and sediment characteristics. The data permits comparative evaluation of the region from northern parts to southern parts. The eastern continental margin of India is flanked by a narrow zone of onshore, offshore sedimentary basins with a sediment fill ranging from Early to Late Holocene. There are variations in sediment nature and geotechnical characteristics along the near shore sector of the east coast. An attempt is made to compare the geotechnical characteristics of the sediments in the near shore sector of the east coast along Andhra Pradesh and Pondicherry coasts. Detailed studies at port areas have been carried out by the East Coast Operations, Marine Wing, GSI, Visakhapatnam at selected sectors along the Andhra Pradesh and Pondicherry coasts for their development and also on case specific studies for single buoy mooring etc.

The domains are grouped under three categories 1) Open sea domain 2) Deltaic domain and 3) minor rivers / stream mouth domain. The sediments off Gangavaram and Mautyalmmapalem can be classified as open sea sediments; the sediments off Kakinada, Machilipatnam, Nizampatnam and Vadarevu as deltaic; and the sediments off those of Kottapatnam, Bavanapadu, Kalingapatanm, Bheemunipatnam, Krishnapatnam and Pondicherry can be grouped under the category of minor rivers / streams.

The difference in the geotechnical characteristics and its relation with the sediment nature, in different domains, are discussed briefly hereunder.

The wet bulk density is high in the open sea as well as in the minor river / stream domains, when compared to the deltaic domain, because of presence of low percent of finer fraction. The specific gravity is also high in the open sea and in the minor river / stream domains in view of presence of heavies with in the sand fraction. The liquid limit and the plastic limit values are high in the deltaic domain, when compared to other two domains, due to presence of higher percent of finer material. The sediments are inorganic clays of low to medium plasticity in the open sea and minor river / stream domains, as sediment types are of either sandy clay or silty clay, in general; and inorganic clays of high plasticity in the deltaic domain. The sediments are normal to active type in the open sea and minor river / stream domains, as salinity is relatively high, and inactive to normal type in the deltaic domain.

The marine sediments in the near shore zone invariably have their natural moisture content at around or even more than their liquid limit values except in a few sediment samples indicating very soft consistency of the sediments.

There is a wide variation in the geotechnical properties of the sediments off the major deltas of Godavari and Krishna than those away, which in turn, are related to texture of the sediment. The wet bulk density and specific gravity values of the marine sediments off Kakinada, Machilipatnam and Nizampatnam are relatively low (wet bulk density 1.29 to 1.96 Mg/m3; Gs-2.00 to 2.67) to those at Kottapatnam, Bavanapadu, Gangavaram and Krishnapatnam (wet bulk density 1.65 to 2.17 Mg/m3; Gs-2.53 to 2.77). The deltaic sediments off Kakinada, Machilipatnam and Nizampatnam areas show an increase in their liquid and plastic limits (LL 23 – 99 % and PL 21 – 48 %) respectively than those at non-deltaic areas off Bavanapadu, Gangavaram, Mutyalammapalem and Krishnapatnam (LL 16-45 %, PL 10 – 24 %). The relatively higher values in the deltaic sediments can be explained due to their higher percent of fine size material (Clay size fraction), which has significant influence on the Atterberg limits. The un-drained shear strength of deltaic clays at Kakinada, Machilipatnam and Nizampatnam are relatively high (2.75 to 15.30 kpa). The remolded shear strength values are naturally low due to mixing of the sediments, high water content etc. Sensitivity values vary from about 1.0 for over consolidated clays to 2.80 for the quick clays.

As per plasticity chart, the sediments of Kakinada, Machilipatnam, Nizampatnam and majority from Krishnapatnam area are in the CH region (inorganic clays of high- plasticity); the sediments from Nuvvalarevu (Bavanapadu), Kalingapatnam and Pondicherry area fall in the category of CL region (inorganic clays of low

plasticity); and from Nagavalli River Mouth, Bheemunipatnam and Mutyalammapalem are in the CI range (inorganic clays of medium- plasticity).

The plotting indicates that the clay, in order of abundance, falls in the region of Illite to Kaolinite type in Nuvvalarevu (Bavanapadu) and Bheemunipatnam; Kaolinite to Illite type in Nagavalli River Mouth and Krishnapatnam; Kaolinite type in Mutyalammapalem, Kakinada, Machilipatnam and Nizampatnam; Illite to Kaolinite and with a few amount of Montmorillonite in Kalingapatnam; and Illite and small amount of Montmorillonite in Pondicherry.

The sediments Off Machilipatnam was subjected to consolidation test, the pre- consolidation pressure (ppr) was found to be higher (0.92 Kg/ cm 2) than the present over burden pressure (0.085Kg/ cm2) which indicates that the sediment is pre-consolidated or over consolidated.

Keywords: - *Geotechnical properties, East coast of India, Wet bulk density, plasticity chart, consolidation test*

I. INTRODUCTION

In view of the importance of the coastal zone and adjoining near shore zone of a rich maritime country like India with coastline of over 5700 kilometers, the potential could be harnessed, especially, by creating infrastructure through port development, which in turn, would boost the economy of the country.

Geotechnical surveys are being used for the developmental and engineering issues of ports (major and minor), harbors, entrance channels, monitoring buoys, pipe lines, oil rigs and etc. The geotechnical studies were carried out in the off shore sectors of Nuvvalarevu, Bavanapadu, Nagavalli River mouth, Dibbapalem, Santapalle, Bhimunipatnam Visakhapatnam / Gangavaram, Mutylammapalem Kottapatnam, Kakinada, Narasapur,, Machilipatnam, Vadarevu, Nizampatnam, and Krishnapatnam, in Andhra Pradesh and Pondicherry along the east coast (Fig. 1).

II. OBJECTIVE

The main objective of the geotechnical studies include collection of basic data on bathymetry, sediment distribution, sub-surface lithology, structure, geotechnical parameters and geochemical parameters of sediments and seawaters and evaluation of the entire data sets from an engineering approach of the sea bed.

III. HINTERLAND GEOLOGY

The onshore geological formations in Andhra Pradesh and Tamil Nadu are diverse by virtue of complexity in the lithological associations and also in the geological age. Precambrian gneissic rocks, granulites and charnockites are the most dominant litho types. Other formations are of Gondwanas, Teritaries, Quaternary and younger sequence (laterites and soils). The Precambrian rock formations (Achaean and Proterozoic) are by far the most dominant in the hinterland areas. These serve as basement rocks. Gondwanas (Upper Carboniferous to Lower Cretaceous) are noticed along the Godavari valley and coastal area sectors too. Deccan Traps with infra- and inter- trappeans range from Late Cretaceous to Eocene in age. The youngest sequences comprise Mio-Pliocene (sandstones of Rajahmundry, Cuddalore), the Pleistocene (Laterites and Gravels) and Holocene (Alluvium, River terraces, Beach sands and soils).

IV. MATERIAL AND METHODS

The main survey area comprises the seabed extending from the coastline up to 20-30 m of water depths. The sea floor is geologically examined for the nature of surface materials by grab sampling and sub-surface by coring techniques up to a maximum of four meters.

Surveys were carried out on board R.V.Samudra Kaustubh of Geological Survey of India (Fig. 1) were Bathymetry with ELAC and Bathy-1500 Survey Echo Sounders. The positioning is by Differential Global Positioning System (Leica) taking beacon receiver for differential mode and Trisponder system of Del Norte. Current observations are carried out with current meter model VALEPORT. Surface sampling in the near shore was carried with van Veen grab and core sampling with vibro-core, Water sampling by Niskin water sampler were carried out.

V. LABORATORY METHODS

The sediment sub-sample sliced at every 50 cm interval is subjected to geotechnical studies. The various geotechnical tests which include the shear strength of the un-disturbed sediment, the shear strength of re-molded sediment, the wet unit weight, the natural moisture content, the specific gravity, the Atterberg Limits (Liquid and Plastic) were conducted. From these measurements the parameters, such as, the Liquidity index, the Plasticity index, the Consistency index, the Void ratio, the Porosity, the Sensitivity and the Activity were computed by using the standard conventional formulae. Sieve analysis and pipette analysis was carried as per [1] and [2]. The Mean values are computed as per [3] and sediment type evaluated after [3]. The water analysis

carried out with the portable water analysis kit. The ranges and averages of down core variation of geotechnical parameters are given in Table I.

VI. RESULTS

A. Bathymetry and Sediment Distribution

The part of territorial waters zone extending from shoreline to inner-shelf (up to a depth of around 30 m) off the East coast of India in the Bay of Bengal has been covered. The area is sub-divided into four sectors, viz., Bavanapadu – Kakinada, Kakinada - Falls Divi point, False Divi point – Chennai and Chennai – Pondicherry sectors. The bathymetry (Fig. 2) and the profiles off south-eastern margin of India (Fig. 3) are being discussed.

B. Coast and Near Shore Zone

With presence of long stretch of sandy beaches and tidal limit within 2 m, the coast can be classified as wave dominated. The near shore sand having textural fining towards offshore is acted upon by littoral current directed towards NE during SW monsoon and SW during NE monsoon. Intensity of littoral transport is high during SW monsoon, result of which most of the spits, shoals, bars tend to grow in NE direction.

Rocky headlands extending offshore are common, particularly, from Baruva to Pudimadaka. The physiography is rather smooth with shore face having a steeper gradient merging with the inner-shelf at variable depth of 5 to 15 m. The shore face is characterized by a textural fining of sediment from the shoreline up to the inner-shelf, whereas inner-shelf has either anomalous medium to coarse sand or muddy sediment floor.

Off the deltas of Godavari and Krishna, the near shore zone is very wide with widths of 20-25 km off Machilipatnam and Nizampatnam. The pro-deltaic sediment from these rivers gives rise to the flat and wide near shore zone. Crescent bars, delta front lobes and spits are common at the river mouths. Prominent among these is 16 km long sand spit off Kakinada, and a bar with a relief of 5 m in the Nizampatnam bay between 10 and 20m isobaths. The sandy sediment continues up to a maximum of 5 m depth beyond which mud (silt + clay) commonly floors the near shore and inner shelf zone.

Beyond the deltaic influence, south of Nizampatnam Bay, and up to Chennai, the width of near shore zone varies from 10 to 15 km. Shoals occur in this zone which are either sub-parallel or at an angle with the sinuous coast line. Prominent shoals are off Pulicat and Off Ennore.

Off Chennai-Palar River, the Archaean basement is exposed adjacent to the shoreline, often cropping up in the near shore zone off Mahabalipuram. The coastal zone is narrow at Chennai and widens towards Pt. Calimere, where it attains a width of 20 km, and a submerged bar is present off Nagapattinam at < 10 m isobaths. In general, the bathymetric contours are parallel or sub-parallel to the coast. The near shore zone up to a depth of 10 m and inner-shelf zone up to 30 m are described, in brief, in view of its importance and continuity with land.

C. Sediment Distribution

The products of weathering and erosion, under variant climatic conditions from humid to arid are brought to the Bay of Bengal by major rivers and by numerous small rivers and streams. The near shore zone and the inner-shelf areas receive sediments from source rocks ranging from Precambrian sequence to Quaternary Formations comprising igneous, metamorphic and sedimentary rocks.

The sediments in Bavanapadu – Kakinada, Kakinada - Falls Divi point, False Divi point – Chennai, and Chennai – Pondicherry sectors, where the contribution from major rivers like Godavari and Krishna / Pennar debouche, in to Bay of Bengal, are mostly clastic fine grained sediments (silty clays or clayey silts) with more than half of the sediment comprising of particles in colloidal range.

The various sediment types observed include sand, silty sand, sandy silt, sand-silt-clay, silty clay, clayey silt, sandy clay, clayey sand, silt and clay. The sediments are, by and large terrigenous in nature.

D. Bavanapadu – Kakinada Sector

The coastal zone, in this sector, is drained by a number or rivers, which were originated in the Eastern Ghats itself, namely, Vamsadhara, Nagavalli, Kandivalasa, Champavathi, Gostani, Sarada, Varaha and Thandava from north to south, in addition to a number of minor creeks. In general, the near shore gradient is 1:200 in this sector.

The near shore zone up to 10 m isobath from the shoreline is wider off Kakinada and narrows down northwards off Bheemunipatnam and Kalingapatnam. Off Nagavalli River mouth, the offshore area has a gentler gradient in the order of 1: 205 to 1:285. The shelf break is recorded between 82 to 97 water depths and is 35 – 37 km from the coast. Two prominent ridges with a relief of 2- 6 m at 49 to 52 m and 61 to 66 m water depth at a distance of 18 to 23 km and 26 to 35 km, respectively, from the coast. Sand (up to 10m), silty sand (10 to 20 m), sandy silt (20 to 30 m) and clayey silt (beyond 30 m) are distinct sediment type. Progressive fining

of sediments towards depth is characteristic of wave dominated inner shelves environment [5](Murty and Rao, 1989).

The inner-shelf zone up to 30 m isobaths is also wider off Kakinada in the south and narrows down northwards up to off Visakhapatnam (where the shelf is minimum of 6 km off Godavari and increased towards north up to 57 km [6]. Further north, it widens up to Kalingapatnam followed by narrowing further northwards. The general gradient of inner-shelf is 1: 200 up to 20 m isobaths and 1:320 beyond the 20 m isobaths.

The inner-shelf off Bavanapadu is featureless. The shelf break occurs at a distance of 35 km and 45 kms off Kalingapatnam and Visakhapatnam, respectively, from the coast. The gradient of the inner-shelf is steeper off Visakhapatnam (1:285) and gentle (1:450) off Pentakota where the maximum width of shelf is 57 km associated with domal shaed rise of 3m to 5 m followed by a fall of 7m 11 m [6]. A 1 to 2 km wide palaeo-channel are recorded with in a water depth of 4 m and extend up to 17 m of water depth. A valley, with a depth of 6 m, as a palaeo channel, has been noticed off Sarada –Varaha Rivers.

Off Nagavalli River mouth, the offshore area has a gentler gradient in the order of 1: 205 to 1:285. The shelf break is recorded between 82 to 97 water depths having a distance of 35 – 37 km from the coast. Two prominent ridges with a relief of 2-6 m at 49 to 52 m and 61 to 66 m water depth at a distance of 18 to 23 km and 26 to 35 km, respectively, from the coast. Sand (up to 10m), silty sand (10 to 20 m), sandy silt (20 to 30 m) and clayey silt (beyond 30 m) are distinct sediment type, and this type of progressive fining of sediments towards depth is characteristic of wave dominated environment.

Off Nuvvalarevu, the shore face from the shoreline to the water depth of 11 to 14 m had a gradient of 1:31 to 1: 75. The gradient is 1:160 in the inner shelf within the water depths of 14 to 52 m, and 1:475 in the distal part (52m to 70m of water depth). The gradient of the mid shelf (70 to124 m of water depth) is 1:200. Ridges with a relief of 1 to 5m are present around 80, 92 and 114 m of water depths. The terrace at a depth of 124 m may attest to the sea level during the last glacial maxima [7] and[8]. The outer shelf that commences at 120 m depth extends beyond 200 m isobaths with a gradient of 1: 50 to 1: 75. The sediment is predominantly sandy. However, silt and clay is observed near the mouth of the tidal creek and beyond 35 m water depth.

The offshore region between Bavanapadu and Kakinada consists of a variety of sediments ranging from sands in the near shore to silty clays in the inner-shelf. The various sediment types are sand, silty sand, clayey sand, sand-silt-clay, sandy silt, clayey silt and silty clay. The sandy type sediment occupies the maximum area followed by silty sand and sand-silty-clay. The sediment off Kalingapatnam between Vamsadhara and Nagavali is a mixed type consisting of silty sand, sand-silt-clay in addition to sand, which is due to mixing of sediments contributed through these two rivers. Sand is the predominant sediment type between Visakhapatnam and Nagavalli river mouth. Predominant role was exercised by the waves coming from southerly direction and northeast flowing currents, which act as important agents responsible for the sediment dispersal in the near shore zone and mixed nature of the sediments on the inner shelf is due to the littoral current activity[5]. Sand is the major sediment type between north of Kakinada and Tandava. The sediment between Tandava and Visakhapatnam consists of sand, silty sand, sand-silt-clay and silty clay. Kakinada bay area is characterized by clayey silt, sand-silt-clay and silty-sand type sediments. The coarse grained nature of sediments in the inner shelf at 20 m isobaths and beyond is considered to be of relict nature[5], [9] shows the relict nature of the sediments.

E. **Kakinada – False Divi Point Sector:**

The Kakinada – False Divi Point sector has a crescent shoreline. In general, the bathymetric contours are parallel or sub-parallel to the coast. Major rivers Godavari and Krishna with their various distributaries join the Bay of Bengal in this sector. The sea floor in the near shore zone up to 10 m shows widening southward from Kakinada to False Divi Point. In general, the gradient is gentle (1:600). The inner-shelf off Vainateyam – Vasishta Godavari is relatively narrow (6 km), compared to the northern and southern parts of the area. In general, the inner shelf zone exhibits gentle gradient in the inter delta region (1:600), whereas it is relatively steeper (1:200) off river mouths [10]-[12].

The Kakinada spit is a conspicuous geomorphic expression in this sector, where the sediment is transported to form spit [13]. The spit widens the inner shelf zone due to sediment accumulation. The continental shelf is narrow off Godavari River mouth and widens off False Divi Point. In the inter delta region the bathymetric contours of the inner shelf are parallel to the coast and depict steeping off river mouths.

The bottom sediments in this sector are sandy-silt, silty sand, clayey silt, silty clay and sand-silt-clay. The silty clay occupies maximum aerial extent followed by the clayey silt. Silty clay and clayey silt sediments characterize the inter-delta area between Vasishta - Vainateyam Godavari and Krishna River. Silt occurrence is noticed off False Divi Point. Between Krishna and False Divi Point the sediments are sandy silt, clayey silt, silty clay, silt and silty sand. Thus in the above region where the rivers like Godavari and Krishna with their various distributaries supply considerable amounts of sedimentary material are carpeted by fine-grained sediments that are mostly clayey in nature except in the near coastal area [13].

F. **False Divi Point – Chennai Sector :**

The coast in this sector is crescent to cuspate in shape. This shape of the coast possibly could have resulted due to processes of deltaic regime and tectonic activity. The rivers joining the Bay of Bengal are Gundlakamma, Paleru, Munneru, Pennar, Khandaleru (Upputeru), Swarnamukhi, Arniyar, and Korthalayar. The near shore zone is wider off Nizampatnam and narrows down southwards off Chennai. The gradient of the near shore zone is very gentle (1:2400) off Nizampatnam, and steeper off Chennai (1:190).The inner-shelf zone up to 30 m is wider (39 km) off Nizampatnam with a gentle gradient of 1:880. The width of the inner-shelf off Chennai in the southern part is relatively narrow (16 km) with a steeper gradient of 1:200. The inner shelf is narrow off Pennar, when compared with northern and southern parts. Shoals are present between 5m and 10 m isobaths off Durgrajupalem, North of Vatturupalem and off Gundalakamma River. Shoals and ridges are widely present in this area at various locations off Kottapatnam.

The region comprises of a variety of sediments ranging from sands in the near shore to silty clays or clayey silts in the inner-shelf except in the Nizampatnam Bay. The various sediment types are sand, silty-sand, sandy-silt, clayey sand, sand-silt-clay, silty clay and clayey silt. Different sediment types i.e. silty clay, clayey silt and sand-silt-clay types characterizes the Nizampatnam Bay where silty clay carpets maximum area followed by clayey silt. In the Gundlakamma - Pennar river sector, sand is the largest in aerial distribution followed by clayey silt /silty clay sediments. In the Pennar to Chennai sector, the sediment types consist of sand, sandy silt, clayey silt and silty clay where Sandy sediment dominant in this area. The sandy sediment with a patch of sandy silt occurs off Point Pundi and clayey silt is present south of Pulicat Lake, and Sandy silt towards south up to Chennai.

G. **Chennai – Pondicherry Sector:**

The coast is straight from Chennai to Palar River and is curved further southwards. The rivers joining the Bay of Bengal are Coovum, Adayar, Palar, Varaha, Malatar, Ponnayar and Gadilam. The bathymetric contours are parallel to the coastline. The near shore zone is wider in the northern part between Chennai and Palar with a maximum width of 1.5 km off Mahabalipuram and narrow between Palar and Pondicherry with a minimum width of 0.5 km off Pondicherry. The general gradient for near shore zone is 1:200. Shoals are present between 10 m and 20 m and 30 m isobaths indicating the buried river channels and strand lines.

The inner-shelf zone is relatively wide between Palar and Pondicherry than in the areas north and south in this sector. Two submarine valleys, viz., Palar and Pondicherry are reported in the southern part of this sector. Due to the presence of submarine valleys, the width of the inner shelf is narrow off Palar and Pondicherry.

The sector is composed mostly of sand followed by clayey sand and clayey silt. The clayey sand occurs south and north off Palar River; clayey sand and clayey silt are present south of Adayar River. The clay fractions brought by Adayar and Coovam Rivers admixed with clayey silt. The admixture of clay brought by Palar River resulted in clayey sand off Palar. Sand is predominant sediment type from south of Palar to Pondicherry. Clayey sand occurs in the near shore zone up to 10 m south of Pondicherry.

H. **Geochemical Studies**

1) Physico – chemical parameters of Sea water: The variations of the Physico – chemical parameters of Sea water are in Table. I. The pH decreases with increase in depth, which can be attributed to increase in CO2 content due to photosynthesis and production of organic matter followed by its oxidation. The increased concentration of H CO-3 in bottom waters may be due to total CO2 concentration thereby lowering pH value. The nutrients (NO_2; NO_3; NH_4 and PO_4) are high in surface waters because of low salinity. There is a significant co-variance among the nutrients in surface and bottom waters indicating a common source of occurrence. The observed relationship of nutrient concentration and low salinity implies a significant role played by fresh water in the nutrient budget of coastal waters. Slight decrease in the concentration of nutrients in bottom waters is attributable to the utilization by phytoplankton and biochemical processes. Relative enrichment of NO_2-N, NO_3-N and NH_4-N in surface waters could also be due to discharges of untreated sewage into the coastal waters as pollutants.

Higher ranges of oil and grease contents around Visakhapatnam could be attributed to port activities and that of the Total suspended solids are attributed to discharge of industrial pollutants and domestic sewage. The concentration of trace elements in coastal waters is due to industrial effluents and pollutants discharging into the coastal environs.

The values of Cu are high around Chennai - Pondicherry and low around Kakinada; the values of Pb are high around Kakinada and low around Kalingapatnam; the Zn is high around Visakhapatnam and low around Kalingapatnam ; the Cr is high around Chennai – Pondicherry and low around Kalingapatnam are the pollution and non-pollutdion signatures.

Table I: Ranges of Physico-Chemical Parameter of Sea Water

Elements	Surface	Bottom
pH	7.84 – 8.38	
Temperature ^{o}C	28.5- 30.9	28.5- 29.9
Salinity (^{o}/oo)	27.84-28.38	28.16-28.36
Specific conductivity (Milli Ohms)	55.37-62.29	58.2-68.48
DO (dissolved oxygen)	3.71-7.56	4.71-4.95
SO^{-4} (Mg/Lt)	1.7-2.13	
HCO^{-3}(Mg/Lt)	150-170	149-192
Oil grease (Mg/Lt)	7.82-53.19	
Suspended solids	14.00 -37.57	
Cu	0.89-4.14	0.26-1.545
Pb	0.84-7.45	1.51-2.93
Zn	1.28-5.53	0.225-2.89
Cr	0.04 - 2.67	0.096 - 0.01
Cd	0.001-0.06	0.053-0.06
Co	0.075-2.15	0.075-0.261
Ni	0.705-3.442	0.201-1.004
Fe	43.35-67.65	24.6-148.7
Mn	0.535-1.76	0.135-0.65

2) Geochemistry of Sediment Samples: The chemical composition of the continental shelf sediments off East Coast of India is evaluated to characterize the source and depositional processes. The elements of the crustal parts are brought to the ocean floor via riverine inputs and other sources.

The content of Si is 7.63 to 23.75 %. Si / Al ratio is generally taken as an index of the detrital clay minerals for which the ratio is 3.00. The observed Si / Al ratio is 2.93 in Visakhapatnam sector, 2.91 Chennai – Pondicherry sector and 2.40 Kakinada - Krishnapatnam sector indicating that the sediments are silica poor (or Al-rich). The content of Al is 3.95 (Kalingapatnam sector), 8.10 (Visakhapatnam sector), 7.63 (Pondicherry – Chennai sector) and 8.92 (Kakinada - Krishnapatnam sector). Higher content could be attributable to clay particle dominance. The mean Al content of 12.11 % in Godavari clays may be due to montmorillonite. The ratio of Al / Al + Fe + Mn is 0.58 (Kalingapatnam sector), 0.65 (Visakhapatnam sector), 0.57 (Chennai – Pondicherry sector) and 0.58 (Kakinada - Krishnapatnam sector) suggesting the terrigenous clay as the source of Al [14]-[16].

The sector-wise content of Fe as percentage is 2.77 (Kalingapatnam sector), 4.36 (Visakhapatnam sector), 5.67 (Chennai – Pondicherry sector) and 6.32 (Kakinada - Krishnapatnam sector). The sediments of deltaic influenced region are relatively richer in this element. The uniformly higher values of Fe may reflect the prevalence of conditions of authigenic nature also. Titanium is mostly terrigenous in origin being a chief constituent of minerals, such as, ilmenite and rutile. The content of Ti is 0.557 % (Kalingapatnam sector), 0.638 (Visakhapatnam sector), 0.265 (Chennai – Pondicherry sector) and 0.475 (Kakinada - Krishnapatnam sector). The higher values in Kalingapatnam and Visakhapatnam sectors are because of their close proximity with the source. The content of Mn is 0.068 % (Kalingapatnam sector), 0.033 % (Visakhapatnam sector), 0.062% (Chennai – Pondicherry sector) and 0.073% (Kakinada - Krishnapatnam sector).

The mean values of $CaCO_3$ is 4.97 % (Kalingapatnam sector), 10.25 (Visakhapatnam sector), 4.64 (Chennai – Pondicherry sector) and 5.85 (Kakinada - Krishnapatnam sector). Higher $CaCO_3$ content in Visakhapatnam sector is postulated that oolitic carbonate rich sediments formed at a time of low sea level on the outer shelf of the central east coast of India and remained uncovered up to the present may have a role [17],[18]. The mean values of Organic carbon are 0.957 % (Kalingapatnam sector), 1.55 (Visakhapatnam sector), 2.20 (Chennai – Pondicherry sector) and 1.58 (Kakinada - Krishnapatnam sector) respectively. The values of Organic carbon in Visakhapatnam sector is due to higher nutrient levels, which leads to higher productivity in the overlying waters due to upwelling movement [14]. The Organic Carbon in Kakinada - Krishnapatnam sector can be attributed to the extensive mangrove vegetation, deltaic cultivation and finer sediments [19] in the region which enhances the Organic carbon values.

The mean values of Cu , Zn, Co & Ni are 29, 52, 41 & 46 ppm (Kalingapatnam sector), 25.5, 45.5, 36 & 24 ppm (Visakhapatnam sector), 10.25, 77.04, 51.75 & 95.96 ppm (Chennai – Pondicherry sector) and 24.4, 58.0, 37.0 & 36 ppm (Kakinada - Krishnapatnam sector), respectively. The source of some of these elements could be from industrial effluents and discharges mobilized in to the marine environment [20].

I. **Geotechnical Studies**

The geotechnical parameters depend on the sediment type, grain size, porosity, and in which clay minerals and interstial waters play an important role. The geotechnical parameters are shear strength, water content, wet bulk density, specific gravity, the Atterberg limits, void ratio, porosity, consolidation, textural and organic characters evaluation through plasticity chart [1] and these will have engineering significance for the design and construction of under water structures. For evaluation of the geotechnical behavior of the sediments, off Gangavaram and Mutylammapalem can be grouped under open sea category. The sediments off Kakinada, Machilipatnam, Nizampatnam and Vadarevu can be grouped under off major fluvial systems (deltas) and the sediments off Bavanapadu, Nuvvalarevu, Nagavalli River Mouth, Bheemunipatnam, Kothapalem, Krishnapatnam and Pondicherry can be grouped under the minor rivers/ streams (Table II). The ranges of geotechnical parameters of the areas surveyed are in table III.

Table II: Ranges of Geotechnical Parameters in Three Domains with Sediment Types

Geotechncial parameter	Open sea domain	Off Delta domain	Off Miner River / steams
Specific gravity	2.45 – 2.89	2 -2.7	
Wet unit weighty	1.42 – 2.33 Mg/M^3	1.37 - 1.95 Mg/M^3	1.32 – 2.34 Mg/M^3
Water content	14 % - 75 %	28 % - 128 %	8 % - 141 %
Liquid limit	16 % - 63 %	32 % - 77 %	16 % - 87 %
Plastic limit	11 % - 32 %	21 % - 46 %	11 % - 36 %
Liquidity index			
Plasticity index			
Undisturbed Shear strength	2.4 – 19.4 kPa	0 – 17.7 kPa	0 – 13.05 kPa
Sediment type	Sand-silt-clay, sandy silt, silty sand, clayey sand, siltyclay and clayey silt	Silty clay,clayey silt, sand-silt-clay,Clyey sand,silty sand and sand	Sand, clayey sand, sand-silty-clay, clayey silt,silty sand andsilty clay

Table III: Ranges of Geotechnical Parameters of Minor Port Area with Sediment Types

Location	Specific gravity	Wet unit weighty (Mg/m^3)	Water content (%)	Liquid limit (%)	Plastic limit (%)	Shear strength (kPa)	Sediment type
Nuvvalarevu	2.46-2.96	1.35-2.36	6 - 58	18 - 67	13 - 29	1.6 - 7.7	Sand, clayey sand, silty sand, silty clay, sans-silt-clay, sandy clay
Bavanapadu	2.46 - 2.53	1.65 – 2.17	22 - 78	16 - 39	10 - 14	2..9 – 5..8	Sand, silty sand, clayey sand, sand-silt-clay, sandy silt & clayey silt
Dibbapalem							Sand, silty sand, sandy silt, clayey silt, sans-silt-clay, sandy clay
Nagavalli		1.37 - 2.17	15 - 77	17 - 73	9 - 36	2 - 10.2	Sand, silty sand, sandy silt, clayey silt, sans-silt-clay, sandy clay
Bheemunipatnam	2.44-2.87	1.47 – 2.34	8.5 - 57	25-57	12 - 32		Sandy sediments
Gangavaram	2.6 – 2.74			23 - 33			Sand, silty sand, sand-silt-clay and silty clay

Mutyalammapalem	2.36–2.89	1.42 – 2.24	14 - 72	60 - 63	11 - 32	2.4 – 9.4	- do -
Kothapatnam	2.29-2.85	1.33-2.22	12 - 120	17.16-78.5	10-40	2.35-9.8	Sand, siltysans,silty clay, clayey silt, sand-silt-clay
Kakinada	2.00–2.89	1.29 – 2.02	21 – 129	21 - 71	15 - 52	3.1 – 10.4	Clayey silt, sand-silt-clay and silty-sand
Machilipatnam	2.39–2.56	1.25 – 1.98	33 - 79	49 - 99	22 - 38	2..35 - 15	sandy silt, clayey silt, silty clay and silty sand
Nizampatnam	2.41–2.78	1.25 – 1.86	13 - 99	58 - 99	23 - 48	2.4 – 11.4	Silty clay, clayey silt, sand-silt-clay
Vadarevu	2.28–2.70	1.40 – 1.94	28 - 102	38 - 77	24 - 46	3.9 – 23.5	- do -
Krishnapatnam	2.15–2.73	1.16 – 2.10	23 - 41	21 - 89	12 - 46	2.4 – 13.1	Silty clays, clayey silts
Pondicherry	2.41–2.69	1.56 – 2.14	8 - 54	17 - 52	13 - 25	0 – 10.6	Sand, Clayey sand

J. **Geotechnical Properties of Sediments**

1) *Off Open Sea:* The sediments off the open sea are mainly sands followed by sand-silt-clay, sandy silt, silty sand, clayey sand, silty clay and clayey silt. The water content, in general, is minimum (14 %) in the sands and maximum (75 %) in silty clay. The water content depends on the grain diameter and sediment type. The grain diameter plays a dominant role in holding the water content in the sediment. The wet unit weight of the sediment types in the open sea, in general, varies between 1.42 Mg / m^3 (6.97 phi mean - medium silt - type of sediment sand-silt- clay) and 2.23 Mg/ m^3 (2.58 phi mean - fine sand). The wet unit weight mainly depends on the grain parameter. The specific gravity of the sediment depends on the constituent and the sediment type. The sands have higher values than the other sediment types. The values in the area, in general, vary from 2.45 (3.55 Ø mean - very fine sand – in clayey sand) to 2.89 (3.09 Ø mean - very fine sand). The un-drained shear strength varies, in general, between 2.4 kPa (5.66 Ø mean - coarse silt in sandy silt) and 19.4 kPa (3.75 Ø mean - very fine sand). The liquid limit depends on the silt and clay content and their constituents. The values in the area, in general, range from 16 % (1.89 Ø mean - medium sand) to 63 % (7.6 Ø 5 mean - very fine silt in silty clay). Silt content play a dominant role in acquiring the value compared with clay. The plastic limit of the sediments depends on silt and clay content. The values range from 11 % (3.55 Ø mean - very fine sand in clayey sand) to 32 % (7.65 Ø mean - very fine silt in silty clay).

2) Off Deltas: The sediments of deltas are entirely different from that of open sea sediments. The sediment types encountered are mainly silty clay, clayey silt, clay, sand – silt – clay, silty sand and sand. The water content ranges from 28 % (3.35 Ø mean - fine sand in silty sand) to 128 % (9.09 Ø mean – clay in silty clay). The water content increases with clay. The type of the constituent of the grain plays a dominant role in absorbing water. The wet unit weight values range between 1.37 Mg / m3 (7.64 Ø mean - very fine silt in clayey silt) and 1.95 Mg / m3 (3.35 Ø mean - very fine in sand – silt- clay). The specific gravity of the sediments increases with the silt content. The values range from 2.00 (7.64 Ø mean - very fine silt in clayey silt) to 2.7 (7.38 Ø mean - very fine silt in clayey silt). The liquid limit depends mainly on the clay percentage and phi mean. With phi mean the liquid limit also increases, but at times, it may not be so due to clay mineral nature and silt content. The liquid limit value varies from 32 % (3.69 Ø mean - very fine sand in silty sand) to 77% (8.59 Ø mean - very fine silt in silty clay). The plastic limit has a bearing on the percent and constituent of clay and silt. However, the clay content has the maximum influence on the plastic limit. The value varied from 21 % (9.75 phi mean - sediment type silty clay) to 46 % (8.45 Ø mean - coarse clay in silty clay). The un-drained shear strength shows that the top of the core is always with lesser value than at the down the core, as the top part contains more pores and the sediment is, generally, slurry. The values vary from 0 kPa (7.15 Ø mean - very fine silt in silty clay) to 17.7kPa (8.76 Ø mean - very coarse clay in silty clay).

3) *Off Minor Rivers / Streams:* The occurrence of sediments in the river mouths and streams are different in their phi mean and nature of the sediments, when compared to delta and open sea areas. The sediments are sand, clayey sand, sand-silt-clay, clayey silt, silty sand and silty clay. The water content in the areas mainly depends on the phi mean value and the content of the constituent. The minimum value is 8 % (0.57 Ø mean - coarse sand in sand) and the maximum is 141 % (silty clay).The wet unit weight is having a bearing on the sand and silt content rather than clay. The minimum value is 1.32Mg/ m^3 (4.47 Ø mean - coarse silt in sandy silt). The specific gravity values are low, when compared to open sea and deltaic sediments. They have

wide range of 3.5 Ø to 9.5 Ø. This is due to the sediment type, the phi mean and the silt percent. The value vary from 2.17 (8.61 Ø mean - coarse clay in silty clay) to 2.87 (0.76 Ø mean - sand).The liquid limit values of these sediments fall between the values of off open sea and the deltaic sediments. The grain size and the sediment constituent play dominant role for the liquid limit values. The silt and clay content and their nature determine the liquid limit. The minimum value is 16 % (2.72 Ø - fine sand in sand) and the maximum value is 87 % (silty clay sediment).

The plastic limit of these sediments show marked difference from the other two domains. These values fall between the two domains. Silt and clay content in the sediment play a dominant role for the determination of the plastic limit. Even though the grain size is less and silt percent is more, plasticity value increases due to the presence of swelling clay mineral as a constituent in the sediment. The minimum value is 11 % (3.93 Ø mean - very fine sand - silty sand sediment) and the maximum value is 36 % (8.86 Ø mean - coarse clay).The un-drained shear strength of the sediments of this domain show the values are from 0 kpa to 13.05 kpa. Most of the samples fall in the range of 0.5 and 2 suggesting the clays are mainly of Normal-type; Active-type are also present with equal in percentage. In all the areas illite is also present. Montmorillonite is also present in Bavanapadu and Krishnapatnam (Murty, 1989, Naidu et al, 1984).

VII. DISCUSSIONS

Ocean floor sediments, are net resultant of various agents/processes at work constantly on the land and the off shore regime. These sediments are affected by various oceanic processes and the sediments exhibit different characters through size variation results in water holding capacity and constituent clay mineral which results in diversity of engineering properties of the sediments. There are also differences in the environments from the place of origin to the place of deposition. The near shore and inner-shelf sediments are distinctive from those occurring on the outer shelf, slope and other regions. The sediments of the near shore and inner shelf are mainly terrigenous with mixtures of allochemical and authigenic constituents in minor proportion. Study of these different sediment types and their geotechnical properties from a specialized field, which enables understanding the behavior of the geological materials.

The east coast of India experience large sediment influx mainly through Godavari – Krishna fluvial systems and also from rivers, such as, Pennar, Cauvery etc, to a lesser extent and also the Ganges – Brahmaputra River system also contribute [5], [21]. The fine-grained detritus is derived from the continental suite of rocks, which are not only diverse in lithlogical composition, but also are of different geological ages from Precambrian basement rocks up to Mio-Pliocene, Pleistocene. Peninsular rocks contribute to illite, smectite, Kaolinite, chlorite is considered to be very low [5], [15], [16]. Mineralogical, these clays are very distinctive. K, Al, Si are main for Kaolinite and illite; and Na, Al, Mg, Si define montmorillonite. Properties like cation exchange capacity also vary among the minerals. While Kaolinite has low plasticity, low swelling, montmorillonite has high plasticity and swelling and high colloidal activity.

The plotting indicates that the clay, in order of abundance, falls in the region of Illite to Kaolinite type in Nuvvalarevu (Bavanapadu) and Bheemunipatnam; Kaolinite to Illite type in Nagavalli River Mouth and Krishnapatnam; Kaolinite type in Mutyalammapalem, Kakinada, Machilipatnam and Nizampatnam; Illite to Kaolinite and with a few amount of Montmorillonite in Kalingapatnam; and Illite and small amount of Montmorillonite in Pondicherry.

The sector-wise clay type is illite (low- to medium) to kaolinite (low- to medium- to high) with a little amount of montmorillonite (low) in Bavanapadu – Kakinada sector ; kaolinite (high- to very high) in Kakinada - Falls Divi point sector ; kaolinite (medium- to high- to very high) to illite (medium- to high) in False Divi point – Chennai sector ; and illite (medium) and a few amount of montimorillonite (low) in Chennai – Pondicherry sector.

A. **Sea Floor Sediments:**

The sea floor sediments in the sectors from the inner-shelf are essentially of detrital nature with minor content of biogenic materials, such as, shells and skeletons of marine organisms [17], [22]. The sea floor sediments have influence of major rivers, such as, Godavari, Krishna and Pennar.

The marine sediments of the area considered to be Late Pleistocene to Recent in age and were deposited in saline or brackish water environment. In general, the Near-shore zone comprises sands and silty sands up to 5 m isobaths, except off Godavari and Krishna rivers. The near shore sands grades into clayey silts / silty clays towards offshore. The sedimentation in Godavari and Krishna deltas is dominated by the influx of fine sediments (clayey silts, silty clays) where sediment rates reported high [15],]23]. Sandy silts / silty sands are the dominant sediment facieses, which cover parts off Kakinada, Machilipatnam and Nizampatnam. The rate of sediment dispersal is probably lesser than the rate of deposition, thus giving rise to a convex shape to the sediment pile of the deltas. The area south of Nizampatnam Bay characterized by the offshore sand bars and near shore sands grading into silty clays towards offshore.

The mean size values of the sediments off Godavari and Krishna deltas in Kakinada, Machilipatnam and Nizampatnam bays vary from 7.64 to 8.82 Ø, 7.49 to 10.24 Ø, 8.5 to 10.23 Ø, respectively, whereas the sediments off Bavanapadu and Krishnapatnam range from 2.72 to 4.67 Ø and 3.7 to 5.4 Ø, respectively; and Off Nagavalli River mouth, the mean size varies from 1.03 Ø (Medium sand) to 8.18 Ø (Very fine silt) with an average of 4.76 Ø (Very coarse silt). The sediment type off Nuvvalarevu is predominantly sand and the mean size varies from 0.25 Ø (coarse sand) to 6.20 Ø (medium silt). There is wide variation in the mean size values from 3.35 Ø (silty sand) to 9.0 Ø (silty clay) in the sediments off Vadarevu, while only a slight variation (2.5 to 3.53 Ø) in the sediments off Gangavaram. The shelf region off Krishnapatnam is influenced by discharge from Khandaleru (Upputeru) river, a tidal creek is present at this minor port and sediment load supply is minor.

B. **Geotechnical Properties**

There is a wide variation in the geotechnical properties of the sediments off the major deltas of Godavari and Krishna than those away, which in turn, are related to texture of the sediment.

The wet bulk density and specific gravity values of the marine sediments off Kakinada, Machilipatnam and Nizampatnam are relatively low (wet bulk density 1.29 to 1.96 Mg/m3; Gs-2.00 to 2.67) to those of non-deltaic areas off Bavanapadu, Gangavaram and Krishnapatnam (wet bulk density 1.65 to 2.17 Mg/m^3; Gs-2.53 to 2.77). The un-drained shear strength of deltaic sediments off Kakinada, Machilipatnam and Nizampatnam are relatively high (2.75 to 15.30 kpa). The deltaic sediments off Kakinada, Machilipatnam and Nizampatnam show an increase in their liquid and plastic limits (LL 23 – 99 % and PL 21 – 48 %), respectively than those off non-deltaic areas off Bavanapadu, Gangavaram and Krishnapatnam (LL 16-45 %, PL 10 – 24 %). The relatively higher values in the deltaic sediments can be explained due to their higher percent of fine size material (Clay size fraction), which has significant influence on the Atterberg limits.

The sediments off Bavanapadu, off Nuvvalarevu and Off Nagavalli River Mouth are characterized by mostly inorganic clays of low- to medium- plasticity ; Off Bhimunipatnam, the sediments are inorganic clays of medium- to high- plasticity ; Off Mutyalammapalem, these are of inorganic clays of low- to medium- and of high plasticity ; Off Kakinada, the sediments are of inorganic clays of high- plasticity, and inorganic silts of high- plasticity and organic clays of medium- to high- plasticity ; Off Machilipatnam and Nizampatnam, these are inorganic clays of high- plasticity and inorganic silts of high- plasticity ; Off Krishnapatnam, these are of inorganic clays of high- plasticity and inorganic silts of high plasticity, organic clays of medium- to high-plasticity, and also of inorganic clays of low- to medium- plasticity in nature; Off Pondichery, the sediments are of low- plasticity and a few inorganic clays of low- to medium- plasticity are also present.

The clay type is predominantly illite (medium) to kaolinite (high) in Nuvvalarevu (Bavanapadu) area ; illite (low- to medium) to kaolinite (low- to medium- to high) with a little amount of montmorillonite in Kalingapatnam area ; kaolinite (low- to medium- to high) to illite (low- to medium) off Nagavalli River Mouth ; illite (medium- to high) to kaolinite (medium- to high) in Bheemunipatnam area ; kaolinite (low- to medium- to high) to montimorillonite (low) in Mutyalammapalem area ; kaolinite (high- to very high) off Kakinada ; kaolinite (very high) in Machilipatnam and Nizampatnam / Vadarevu areas ; kaolinite (medium- to high- to very high) to illite (medium- to high) in Krishnapatnam area ; and illite (medium) and a few amount of montimorillonite (low) in Pondicherry area.

Consolidation characters of the sediment off Machilipatnam [24], the pre- consolidation pressure (ppr) was found to be higher (0.92 Kg/ cm 2) than the present over burden pressure (0.085Kg/ cm2) which indicates that the sediment is pre-consolidated or over consolidated. This means that the sediment was possibly under a relatively higher over burden pressure in the past.

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