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Full Length Research Paper

Engineering properties of marine clays from the eastern coast of India

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The paper deals with the engineering properties of a marine clay collected from Visakhapatnam, India. First of all, the physical, chemical and mineralogical properties were determined. Thereafter, the strength and stiffness of the soil-water matrix were established. The properties under cyclic stress reversal were also studied. The detailed test results and observations are discussed sequentially in the paper.

Key words: Atterberg limit, cyclic degradation, marine clay, rate of loading, undrained cohesion.

INTRODUCTION

The soil found in the ocean bed is classified as marine soil. It can even be located onshore as well. The properties of marine soil depend significantly on its initial conditions. The properties of saturated marine soil differ significantly from moist soil and dry soil. Marine clay is microcrystalline in nature and clay minerals like chlorite, kaolinite and illite and non clay minerals like quartz and feldspar are present in the soil. The soils have higher proportion of organic matters that acts as a cementing agent.

A comprehensive review of literature indicates that considerable amount of work related to determination of engineering behaviour of marine soils has been carried out worldwide since last 50 years. Amongst various contributions, the investigations on physical, chemical and mineralogical properties of marine clay conducted by Eden et al. (1957), Noorani (1984), Shridharan et al. (1989), Mathew et al. (1997) and Chew et al. (2004) are worthy of note. Significant research on strength and stiffness characteristics was performed by Koutsoftas et al. (1987) and Zhou et al. (2005). Marine structures are usually subjected to wave induced cyclic stresses which are induced in the soil. Remarkable works of Idriss et al. (1978), Vucetic et al. (1988), Kagawa (1992) and Hyde et al. (1993) related to properties of marine soil under cyclic stress are notable.

Marine clay is uncommon type of clay and normally exists in soft consistency. Marine clay deposit of east coast of India was used for the testing with the aim to investigate its engineering properties. During construction of well foundation for a marine structure in the offshore area (about 10 m off the shoreline) of Visakhapatnam port at East coast of India, the subsoil was excavated. The soil collected from a depth of about 10 – 12 m was used for investigation.

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Notations: c_U; Undrained unit cohesion of soil, c_{Ur}; Datum undrained cohesion of soil, δ; Degradation index, E_i; Initial tangent modulus of soil, **E**; Secant modulus of soil, ϵ; Cyclic strain amplitude, λ; Actual strain rate, λ_r; Standard strain rate, **N**; No. of cycles, Φ; Angle of friction, q_U; Unconfined compression strength of soil and **t**; Degradation index.

Geotechnical properties

The marine clay collected was saturated. They were initially air dried in open atmosphere prior to testing. The various geotechnical properties are described below. It is mentioned here that three samples were taken at random and the average values of various properties are taken as the test values.

Visual characteristics

The following properties are observed from visual classification in dry condition:

Colour - Black colour.

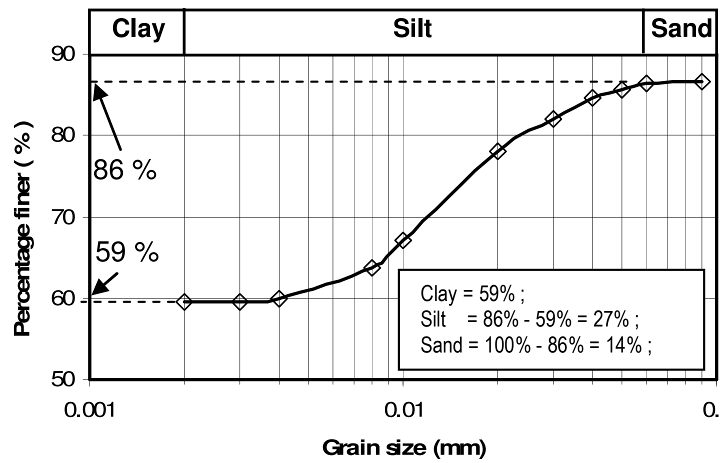

Figure 1. Grain size distribution curve.

Odour - Odour of decaying vegetation.
Texture - Fine grained.
Dry strength - Medium.
Dylatancy - Less Sluggish.
Plasticity - Highly plastic.
Classification (USCS) - Silty clay.

Grain size distribution

For determination of grain size distribution of marine clay sample, sieve analysis followed by hydrometer test was performed. From the test data, the particle size distribution curve was plotted from which it was found that the soil consists of 14% sand, 27% silt and 59% clay, by weight. The grain size distribution curve is depicted in Figure 1.

Specific gravity

Specific gravity of marine clay was determined by density bottle method. The specific gravity of the soil particles is found to be 2.62.

Atterberg limits

The Atterberg limits of the soil were determined by standard methods. The values evaluated were as follows:

Liquid limit - 89%
Plastic limit - 47%
Shrinkage limit - 16%

The plasticity index was as high as 42%.

Compaction test

The standard proctor compaction test was carried out

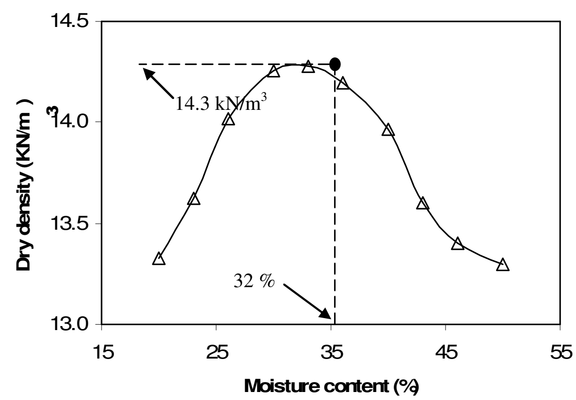

Figure 2. Plot of moisture content versus dry density.

with remoulded soil sample with varying moisture content. In each test, the standard Proctor mould (size: 100 mm diameter x 117 mm height) was filled with soil-water water mixture in three equal layers, each layer being compacted by 25 blows of a 25 N rammer with a height free fall of 300 mm. From the test results and subsequent plot of moisture content versus dry density (Figure 2), the value of maximum dry density was observed as 14.3 kN/m^3 with the optimum moisture content of 32%.

Chemical and mineralogical properties

Various chemical properties of the marine clay were determined by the methodologies suggested by Jackson (1967). The test results are listed below:

Organic matter content - 7%.
Cation exchange capacity - 30.8 m.eq/100 gm of soil.
Exchangable ferrous ion - 0.005%.
pH - 7.2.
Carbonate content - 23%.

The X-ray diffraction tests were carried out to find out the mineralogoical composition of the marine clay. Comparing the observed X-ray diffraction patterns with standard JCPDS files the mineralogical analysis was carried out. The X-ray diffraction pattern of the soil indicated the presence of clay minerals, montmorillomite, chlorite, kaolinite, vermiculite and quartz. X-ray diffraction patterns of treated clay fraction shown strong refelction of 17.65°, which was the characteristic of smectite group of clay; relatively weaker reflection of 7.25° indicated typical kaolinite clay. Additional reflections were also noted at 3.58° and 3.35°A that could be attributed to kaolinite and smectite group of clay respectively. The untreated sand and silt fractions were also subjected separately to X-ray diffraction analysis and was observed to consist of feldspar, mica, quartz, calcite and hematite. To confirm the presence of swelling of clay minerals like montmorillonite and chlorite, the soil powder was treated with hydrochloric acid. This treatment confirmed the presence of chlorite.

Strength and stiffness

The air dried marine clay was mixed with water to form a homogeneous mixture so as to prepare a remoulded test bed in the laboratory in order to conduct model experiments on piles under static and cyclic loads. The details of the findings from these experiments with piles are beyond the scope of this paper and is published elsewhere (Basack, 1999). However, the stainless steel test tank used for preparing the soil bed was of inner dimensions 600 mm diameter and 800 mm height. The soil-water mixture was placed in the tank in six equal layers initially by hand compaction and thereafter by ramming. The moisture content of soil at these test beds were kept at 54% so as to ensure adequate workability and strength. At a lesser water content, the soil-water mixture became stiffer introducing difficulty in hand compaction. Conversely, at higher water content, the strength of the test bed was observed to drop drastically to as low as 10 kN/m^3. Representative samples were collected from the test beds and routine tests [as reported below] were performed in order to ascertain the strength and stiffness of the soil.

Unconfined compression test

The stress-strain curve obtained from the unconfined compression test of the soil sample is depicted in Figure 3. The values of q_U and c_U were found to be 0.45 and 0.225 kN/m^2 respectively. The initial tangent modulus E_i and secant modulus E_s were found to be equal to 30 and 3.75 kN/m^2 respectively.

Unconsolidated undrained triaxial tests

The unconsolidated undrained triaxial tests of representa-

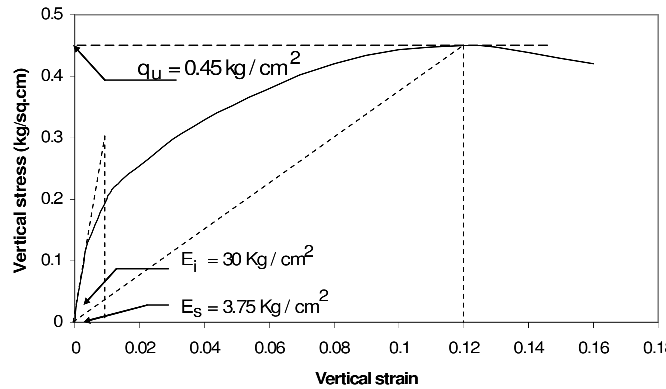

Figure 3. Unconfined compression test results.

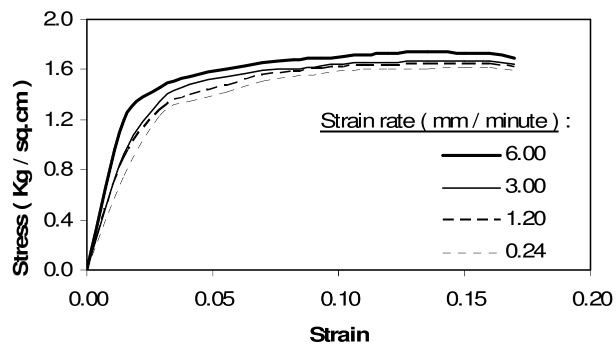

Figure 4. Stress-strain curves obtained from U.U. triaxial tests.

tive samples were tests were carried out. Loading was done at a standard rate (λ_r) of 6 mm/minute. Also, a series of U.U. triaxial tests were carried out at different strain rates (λ) as mentioned in Figure 4. The relevant stress-strain curves for a cell pressure of 1kPa are depicted in Figure 4. From the Mohr circle diagram corresponding to standard strain-rate, shown in Figure 5, the values of c_U and Φ were obtained as 0.18 KN/m^2 and 5^0 respectively. This small value of Φ is due to presence of sand and silt in the marine soil.

From the test results, the normalized values of undrained cohesion (c_U/c_{Ur}) were plotted against logarithm of normalized loading rate (λ/ λ_r), as depicted in Figure 6 which was observed to be linear. This observation confirmed that the shear strength of the marine soil increases in a logarithmic manner with the rate of loading. The slope of this straight line $F\rho$, conventionally referred as rate factor (Poulos, 1982), was estimated as 0.1. This is an important parameter for design of foundations for offshore structures (Poulos, 1982).

Vane shear tests

Vane shear tests were carried out in the remoulded test

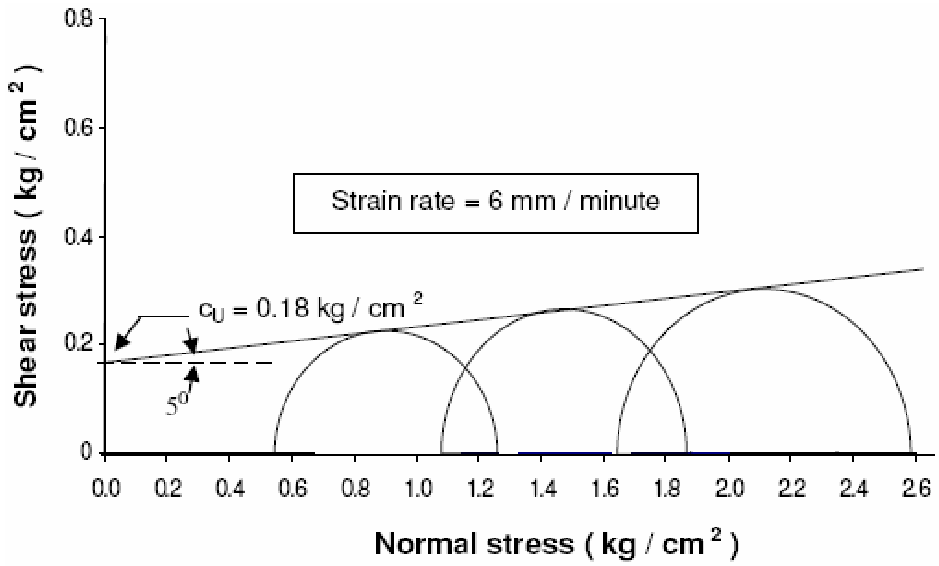

Figure 5. Mohr circle diagram for U.U. triaxial test.

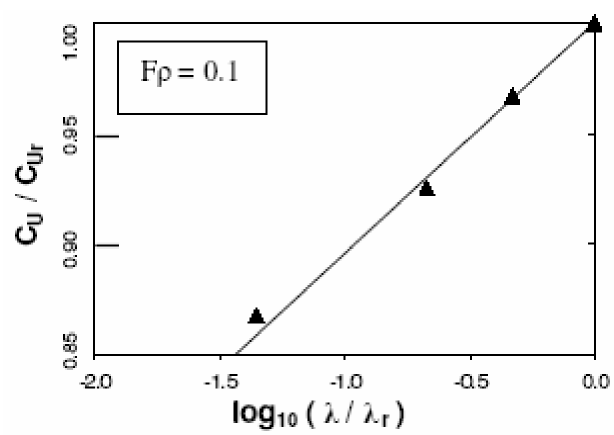

Figure 6. Unit cohesion versus loading rate.

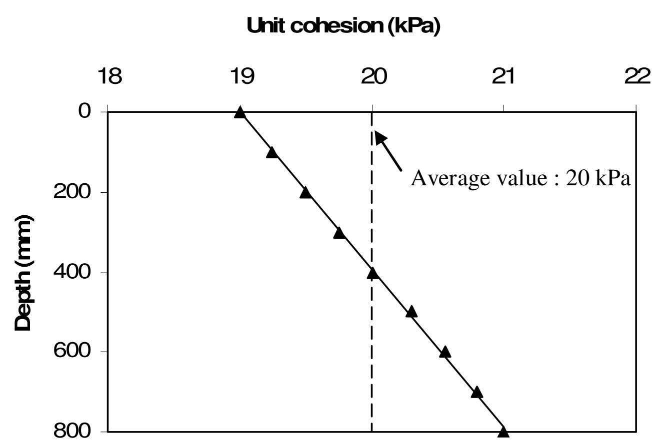

Figure 7. Variation of unit cohesion with depth.

bed at different depths. The plot of unit cohesion versus depth is depicted in Figure 7. It was observed that the unit cohesion increased fairly linearly with depth at a rate of about 2.5 kPa/m. The average value of unit cohesion was noted to be 20 kPa.

In order to investigate the variation in unit cohesion of the marine soil with water content, a series of vane shear tests were conducted in a remoulded test bed in a standard Proctor mould (size : 100 mm diameter x 117 mm height) with varying moisture content. In each test, the mould was filled with soil-water mixture in three equal layers, each layer being compacted by 25 blows of a 25 N rammer with a height free fall of 300 mm. The plot of unit cohesion versus moisture content is shown in Figure 8

It was observed that as the water content increases from 40 to 62%, the unit cohesion sharply dropped from

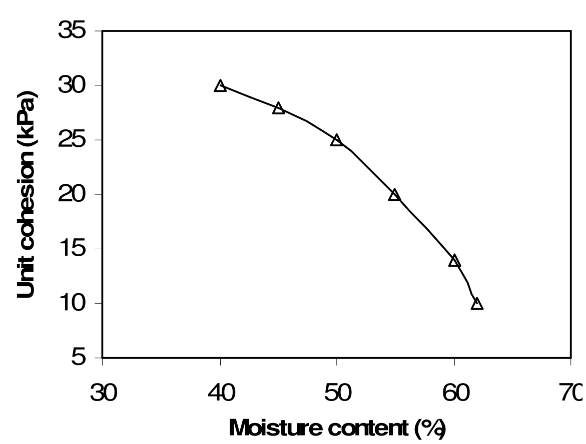

Figure 8. Variation of unit cohesion with moisture content.

Table 1. Values of degradation index.

N	δ			
	Є = 0.01%	**Є = 0.02%**	**Є = 0.03%**	**Є = 0.04%**
1	1.0	1.0	1.0	1.0
10	0.815	0.664	0.541	0.539
100	0.794	0.631	0.501	0.499
1000	0.786	0.618	0.486	0.483

30 kPa to as low as 10 kPa.

Cyclic characteristics

Offshore and near shore structures, resulting from wave action, are subjected to cyclic loading which are transmitted to the marine soil. In order to design foundations for such structures, the cyclic characteristics of the marine soil should be determined.

Idriss et al. (1978) carried out cyclic triaxial tests on soft clay and observed that the relation between degradation index δ (ratio of post-cyclic to pre-cyclic shear strength of soil) varies linearly with no. of cycles (N) in log-log scale, the negative values of the slopes of such lines are termed as degradation index (t). Mathematically, this can be expressed as: $\delta = N^{-t}$.

Vucetic et al. (1988) and Lee (1993) conducted cyclic undrained triaxial tests on soft marine clay samples and found that the degradation index t is a unique function of the cyclic strain amplitude Є and that the relation is hyperbolic. This can be mathematically expressed as: t = Є / (A + B Є), where 'A' and 'B' are constants whose values should be determined from appropriate cyclic tests.

To investigate the cyclic characteristics of the marine soil under consideration, specifically the variation of shear strength with number of cycles at different rate of loading, samples were collected from the test beds and a series of cyclic tests were performed in unconsolidated and undrained state under strain controlled mode. All such tests were conducted with conventional triaxial set-up manually. The cell pressure was kept at 1 kPa and the rate of loading was standardized as 6 mm/minute. After completion of desired number of cycles at desired strain amplitude, the degraded values of the undrained cohesion of the soil were determined by carrying out conventional triaxial static test till failure. The ratio of post-cyclic to pre-cyclic values of undrained cohesion, referred herein as degradation index δ (Idriss et al., 1978), was calculated from each test. The values are presented in Table 1.

In the present case, the degradation index was plotted against number of cycles in log-log scale, as shown in Figure 9. The relations were found to be linear, the negative values of the slopes of which are termed as degradation index (t). The values are presented in Table 2. The plot of Є versus t was observed to be hyperbolic (Figure 10) having the values of A and B as 0.02643 and 8.581.

Table 2. Values of degradation parameter, t.

Є (%)	0	0.01	0.02	0.03	0.04
t	0	0.089	0.1	0.1044	0.1044

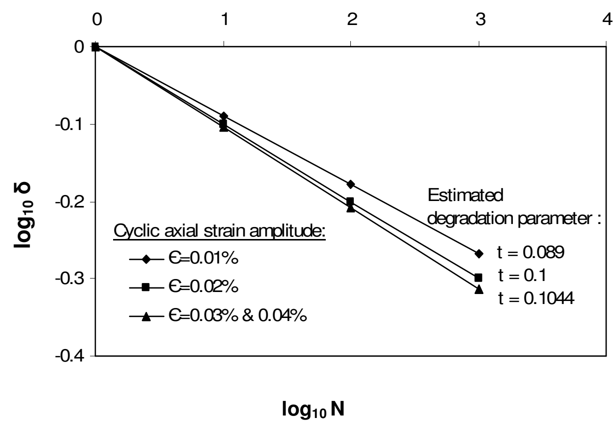

Figure 9. A plot of degradation index versus no. of cycles in log-log scale.

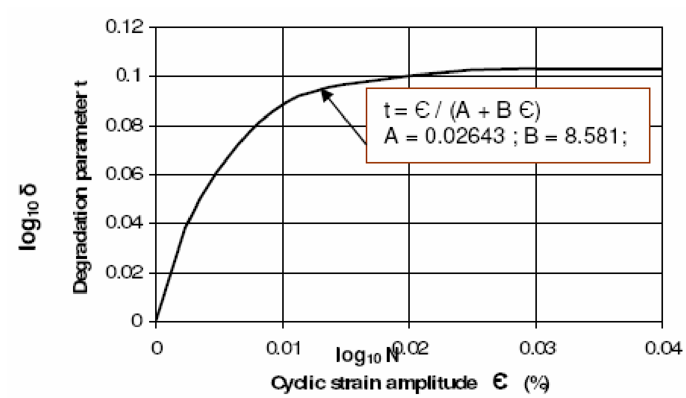

Figure 10. A plot of degradation parameter versus cyclic strain amplitude.

Conclusion

Marine clay is uncommon type of clay and normally exists in soft consistency. Marine clay deposit of east coast of India was used for the testing with the aim to investigate its engineering properties. The collected marine soil was found to be blackish, less sluggish, highly plastic, silty clay. The liquid limit, plastic limit and the plasticity index were observed to be significantly high, whereas the optimum moisture content was below the plastic limit. From chemical analysis, the marine soil was found to possess significant proportion of carbonate content, organic matter content, cation exchange capacity and marginally alkaline. The X-ray diffraction pattern of the soil indicated the presence of clay minerals like montmorillomite, chlorite, kaolinite, vermiculite and quartz and also feldspar, mica, calcite and hematite. From U.U. triaxial test of a remoulded clay sample, the values of c_U and Φ were estimated as 0.18 KN/m^2 and 5^o respectively. The values of c_U obtained from unconfined compression test slightly varied as 0.225 KN/m^2. The normalized undrained cohesion of the marine clay was found to bear linear relation with logarithm of rate of strain, as observed from a series of U.U. triaxial tests. Vane shear tests on remoulded test bed at different depths indicated that the unit cohesion increases with depth fairly linearly with an average value of 20 kPa. It was also observed that with increase in moisture content, the unit cohesion of the soil sharply dropped down to a value as low as 10 kPa. Cyclic strain controlled tests carried out with remoulded clay samples indicated linear relation of degradation index with no. of cycles in log-log scale. The variation of degradation parameter with cyclic axial strain amplitude was observed as hyperbolic.

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