Measuring and Modeling the Elastic Moduli of Clay Minerals

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Summary

The P-wave velocities of naturally occurring recent sediments are measured as a function of water content. The samples are dewatered by centrifuging to stimulate compaction environment. The velocities increase with decreasing water-content and there is a sharp rise in velocity below 30% water-content.

Introduction

The present study is carried out to measure the elastic properties of shale as a function of water content that will help to understand the elastic properties of the clays as well as shales. In spite of the fact that knowledge about elastic properties of clays is essential for seismic and sonic reservoir modeling and interpretation, the elastic moduli of clays remains a debated topic. The values given by Katahara, Alexandrov and Rhyzhova, and Wang et al (50GPa for bulk modulus and 20GPa for shear modulus) are much higher than those extrapolated from studies of Tosaya, Nur and Castanga (20GPa for bulk and 7GPa for shear modulus). This study was conducted with an aim of determining the variations in acoustic velocities of natural sediments with changing porosities in a simulated compacting environment.

Objectives

This study focused first on experimental measurements of the elastic moduli of fully saturated clay – sand aggregates as a function of amount of water present. The P-wave velocities (Vp) were measured in a fully-saturated, naturally-occurring, clay-sand sediment with varying amounts of water content. The results obtained from the artificial stimulation of a compaction environment of modern sediments collected from field can be used as an analogue of naturally compacted rocks. In the second part of the study, we show comparisons between theoretical models and the results observed in our experiment.

Field and Collection of samples

Detailed lithofacies mapping and sample collection were carried out in the coastal depositional system south of Narmada estuary, in Gujrat, India (Figure 1). The region is a mud dominated, tidal estuarine environment. The sediments are dominated by mud and silt with considerable

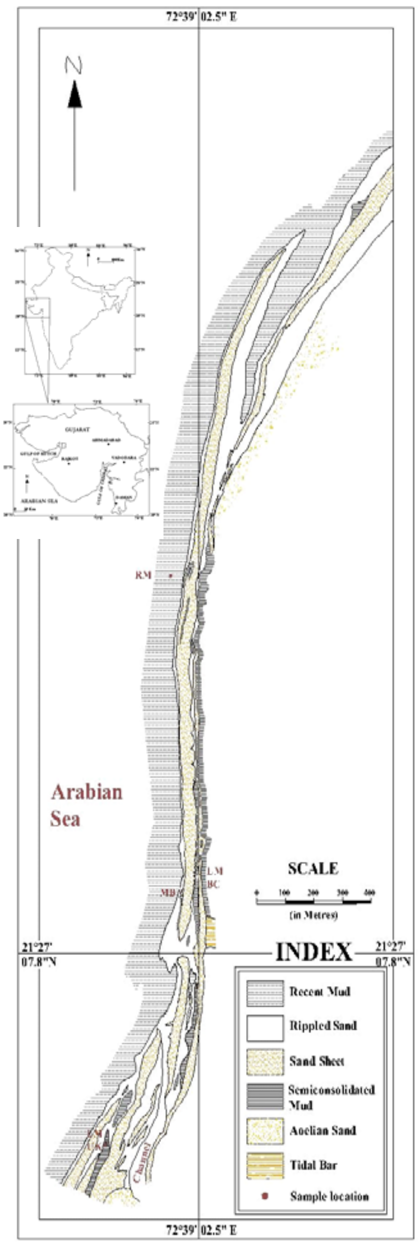

Figure 1: Lithofacies map of the area and sample locations.

amounts of sand. The intertidal region is very broad (about 6 km). Several lithofacies like mud flats, rippled sands, sand sheets, and semi-consolidated laminated muds are identified in the region. The average sand flat width is 50-100 m, usually forming where the seawater flows quickly. The width of mud flat averages over 5 km. Bars lie in a parallel orientation to the shoreline. The samples are collected from the mud-dominated facies. The sample locations are marked in the lithofacies map (Figure 1). The description of the major lithofacies is as follows:

- Recent Mud (sample RM): It occurs extensively in the gently sloping seaward part and occasionally as patches between the ripple sand units mainly in the tidal channel. The predominant sedimentary structures are horizontal, laminated bedding of alternate silt and clay layers in mm scale. They are occasionally extensively bioturbated. Muds are also present as mud-balls concentrated over the rippled sands.

- Sand: The sand facies can be subdivided on the basis of the prominent sedimentary structures:
  Rippled sand: Rippled sand is generally present near the mud and in between the sand sheets. The grain size is medium to fine sand. The sedimentary structures are mainly asymmetric, straight crested wave ripples.
  Sand sheets: These tabular deposits are present through out the length of the area and are parallel to the shoreline. They consist mainly of fine to medium grained well-sorted sand with minor amount of silt and shell material. The subsurface structures are mainly seaward dipping low-angle planer bedding (dip 2-3^{o}) to sub-horizontal plane lamination with alternate sand and heavy mineral layers, ripple lamination and seaward dipping cross lamination.

- Semi-consolidated Laminated Mud (sample LM-BC and LM-UK): These laminated muds occur in the elevated plains and as patchy outcrops in between the shoreline and the sand sheets. The structures and the sediment nature are more or less similar to the recent mud (showing similar type of laminated silt mud structure) but with higher degree of compaction.

Experimental Setup and Procedure

The aim of the experiment was to measure the variation of P-wave velocity with changing water content to stimulate a compaction environment. Hence this experiment has two aspects: the measurement of P-wave velocity and reducing the water content of the sample without disturbing the samples. The P-wave velocity is measured by the pulse transmission technique. The dewatering of the samples is achieved by centrifugation. In geotechnical centrifuge, the model is subjected to accelerated gravitational environment, such that the forces in the model are increased to stimulate overburden load.

Experimental set-up:
The experimental set-up, modeled after Vanario et al. (2003) consists of a container (8 cm cube) made of 5mm thick acrylic plastic sheets. The two transducers are inserted into the container from the opposite walls. Acoustic waves generated by one transducer travel through the samples contained in the sample holder and are received by the second transducer. Care is taken that the transducers are at the same height and there is no horizontal offset also. The distance between the transducer is kept shorter than the dimension of the container to avoid noise from sidewall reflection. The distance between the two transducers is measured by Vernier calipers and the transducers are screwed to keep the distance constant. This distance was used for velocity calculations. The factors that were considered in designing the dimensions of box were

1. Avoid mixing of back wall reflection signals with the main signal;
2. Have at least a three-wavelength long signal.

The calibration to correct for the system delay time is done by measuring P-wave velocities of pure distilled water at various temperatures and comparing it with the theoretical P-wave velocities of distilled water.

Dewatering the samples:
Water from the samples is extracted using a centrifuge to stimulate compaction environment that will represent compacted sediments. For expulsion of water, the base of the container is punctured. Filter paper is kept at the bottom to prevent loss of clay from the samples. The sediment is vigorously agitated and stirred to ensure no air is trapped inside. It is then poured in the container taking extreme care that no air is trapped inside during this process. The container is then kept in the centrifuge and is subjected to different g-levels (30-175). The water content of the sediment is measured by weight loss of a sub-sample taken from the top after heating it for 24 hours at 103^{o} C.

To improve the extraction of water double drainage is provided in the container. A 1-cm thick sand layer is kept at the bottom. Filter papers are placed on it to prevent mixing with the sample. Two punctured plates are placed vertically inside and space between the each plates and the container is filled with sand. The sand acts as the permeable media that allows the extracted pore fluid to flow out. The sediment slurry is poured in between the two vertical plates. At the top of the slurry, a layer of lead shots placed on a geotextile layer act as surcharge to further facilitate water expulsion from the sediment.

XRD studies for clay mineral identification:
For clay mineralogy the clay fraction is separated by pipette method. Oriented samples of clay minerals are prepared. For clay mineralogy the oriented samples are run from 2^o to 30^o at the scan speed of 1^o/min with data recorded at every 0.02^o interval. A Cu-K-alpha anode was used as detector. Identification of clay minerals can be accomplished by careful consideration of peak positions and intensities, which are compared to published values in literature. The quantitative estimation (percentage) of clay minerals was performed based on their basal peak areas (Biscaye, 1965).

Grain size determination, specific gravity and porosity:
Coarser grain size (above 0.075mm) was determined by dry sieving. To determine the fine grain size (ranging from 0.075 mm to around 0.001 mm), the hydrometer method was used that is based on the principle of sedimentation of the grains in water following Stoke's law. The hydrometer analysis data was combined with the sieve analysis to obtain a plot of percent finer versus particle size. The grain density was measured using pycnometer. Porosity was determined from the particle and bulk density.

Results:

Clay mineralogy:
The semi quantitative estimation of the clay mineral percentage is given in Table 1. The mineralogy reflects that the sediments contain mainly montmorillonite and illite with subordinate kaolinite.

Table 1: Percentage of different clay minerals in the samples. RM denotes Recent Mud and LM-BC denotes Semi-consolidated Laminated Mud.

	RM	LM-BC
Montmorillonite	54.75%	68.93%
Illite	30.35%	20.18%
Kaolinite	14.90%	10.89%

Grain size, porosity and grain density:
Table 2 shows the bulk density, grain density and the porosity of the samples. The values show specific gravity very close to quartz. Note however that since the sediment contains swelling clays, it may effect volume estimation and with it, the porosity determination.

The grain size distribution for the samples in shown in Figure 3. All the samples show a higher percentage of silt and considerable amounts of clay with amounts of minor sand.

Table 2. Porosity and particle density of the samples

Sample No	Grain density(gm/cc)	Bulk density(gm/cc)	Porosity
L.Mud BC	2.63	1.45	44.87%
L.Mud UK	2.61	1.45	44.44%
Recent Mud RM	2.64	1.30	50.76%

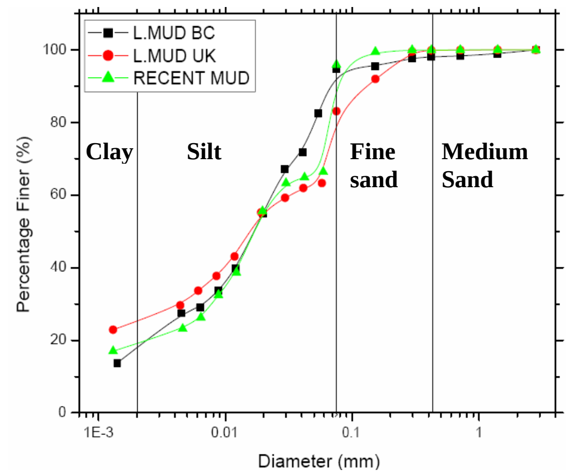

Figure 2: Grain-size distribution curves for the samples.

Acoustic measurements in RM sample:
Figure 3 shows the experimental results of the P-wave velocities (V_p) as the function of water content. The sample was centrifuged to lower the water content down to a starting point at 41.17%. This is done to ensure that during further dewatering, the upper level of the sediment should not fall below the transducers. The steps of centrifuging and their corresponding velocities are given in Table 3. In the first stage, we provided only one path for drainage. With this limited drainage, we could not achieve water contents lower than 32%. In the subsequent steps, a double drainage was built in and a surcharge load was applied as described in the experimental setup. Initial tests with this method showed a further reduction of water content to about 25%. Longer spin times using this configuration will allow us to reduce water contents below 20%.

Table 3: Steps of centrifugation

Sample RM				$ø_0$ = 50.76%	
Steps	g-level	Spin time (mins)	Surcharge Weight	Initial water content	Final water content
I	40	90	0	41.17%	32.05%
II	42.8	40	0	41.52%	27.97%
III	175	30	50 g	27.97%	25.36

The standard velocity measurements are reported at laboratory conditions of 1-atm pressure and at 23ºC (Hamilton and Bachman, 1982).

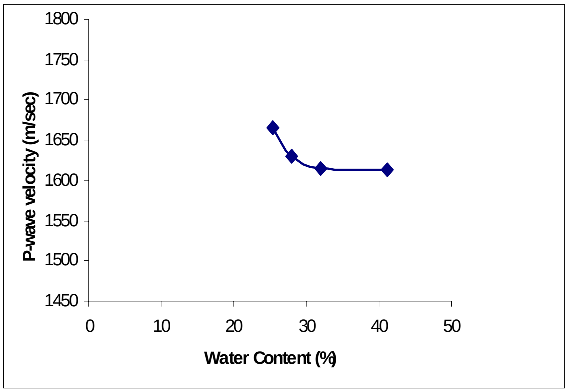

Figure 3: Velocity measured as a function of water content for sample RM

Discussion

The samples are water saturated, and so we can replace the water content by porosity. The data is modeled by taking 80% quartz and 17% montmorillonite and 3% kaolinite (in accordance to the grain size data). The V_p is plotted as function of porosity. The plot (Figure 4) shows low velocities for the sample RM. The V_p increases with reducing porosity and there sharp increase below around 30% porosity. For comparison we plot Vanorio's data on kaolinite-water suspension (Vanario et al. 2003) and Yin data on clay-sand mixture (20% and 80%, respectively) (Yin 1993). Our velocities are higher than Vanorio's data as expected since the samples contain quartz. But the V_p values are significantly lower than Yin's data. For reference, calculations with Wylle's time-average equation for a water saturated quartz-clay model (80%-20%) and 100% clay model are also plotted. The salinity of the water is taken as 35 ppm and the modulus of clay is taken from Vanorio et al (2003). The sharp increase in the V_p velocity can be due the change in load-bearing material from clay to stiffer quartz. We will further take readings with less water contents to study this trend.

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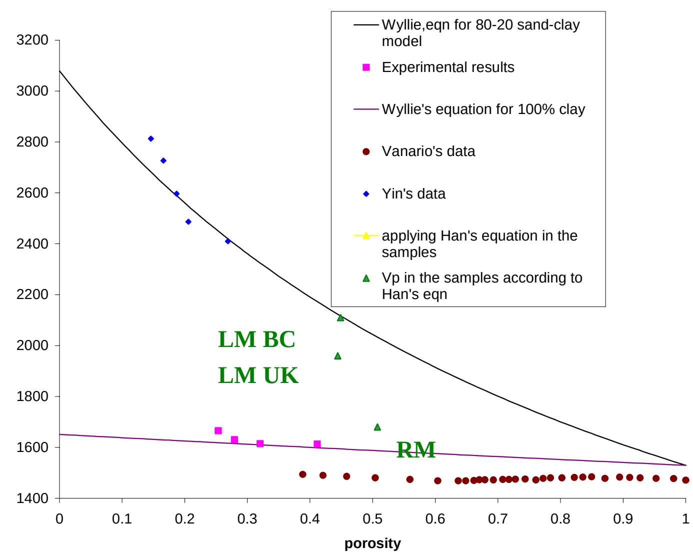

Figure 4: P-wave velocities as function of porosities are compared with the theoretical models.

EDITED REFERENCES

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