Geotechnical Engineering Challengers in the Houston Area

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ABSTRACT: Rapid growth in the urban areas such as Houston in Texas is leading to construction of civil infrastructure facilities, including bridges and highways on soft clays. Identify the pockets of soft clays and their consolidation properties are critical for designing facilities with no stability and settlement problems. In this study, soft clays are characterized based on their mineralogy, physical and mechanical properties. The X-ray diffraction (XRD) and scanning electron microscope (SEM) studies were performed to investigate the mineral composition and microstructure of the clays respectively. Both CL and CH soft clays are present in the Houston area. Based on over 100 data sets, statistical mean, standard deviation, variance and coefficient of variance and distribution of properties and property correlations for the CL and CH soft clays have been developed. The natural moisture content of 97% of the soft clay was lower than the liquid limit. Overestimation of settlement on overconsolidated soft clays may require ground improvement before construction with added delay and cost to a project. Since the soft soil shear strength is low, the structures on the soft soils are generally designed so that the increase in stress is relatively small and the total stress in the ground will be close to the pre-consolidation pressure. Hence the recompression index, determined from a consolidation test is very important parameter in estimating the settlement. Although recompression index has been quantified in the literature, its determination may not be applicable to all soft soils in its current form. The influence of stress level on the recompression index is not clearly quantified. This study also focused on developing methods for determining the recompression index of over-consolidated soft clay soils. Based on the methods used to determine the recompression index, over 750% difference in the minimum and maximum C_r values was observed for the Houston area soft clay..

INTRODUCTION

Soft clays are found in pockets in the mainly deltaic deposits of the Houston Texas. In addition to the geological factors, especially temperature, sea level changes and the type of clay have a direct effect on the lithology of the soft clays. In addition, there is very limited information on the deltaic soft clays in the literature. The prediction of consolidation settlement magnitudes and settlement rates in overconsolidated soft clay is a challenging task and it has been attracting the attention of numerous researchers in recent years. The challenges mainly come from the uncertainties about the stress effect on soil properties, subsurface conditions, soil disturbances during sampling and preparations of samples for laboratory testing, interpretations of laboratory test data, and assumptions made in the development of the one-dimensional consolidation theory (Duncan 1993, Leroueil, 1990, Holtz and Kovacs 1981). In addition to the geological factors, salinity, temperature and clay type have a direct effect on the lithology of the soft clays. The behavior of soft soils has been studied for well over four decades and there are several property relationships in the literature on soft clays (Vipulanandan et al. 2007a).

There are several parameters, which are used in the settlement analysis and are very important in the prediction of consolidation settlement magnitudes and settlement rates, obtained from the laboratory consolidation test. These parameters are compression index, C_c, recompression index (or swell index), C_r (or C_s), coefficient of consolidation, c_v, and preconsolidation pressure, σ_p. Of these consolidation parameters C_c, c_v, and σ_p have been investigated extensively. When the overconsolidated clay soil is loaded beyond σ_p, these two parameters (C_c and c_v) are critical to estimate the total and rate of settlement.

When structures are built on soft clay soils, it is important to limit the increase in stress in the soft clay layer to avoid bearing capacity failure. Hence the total vertical stress (in-situ + increase in stress) is in the range of σ_p. In this case, C_r will become more important to estimate the total settlement. Of the consolidation parameters, the least investigated parameter is C_r. The overall objective of this study was to investigate the variation in recompression index for overconsolidated soft clay soils. The soft soil is defined as having undrained shear strength of less than 25 kPa.

Geological Formation

The geology of Houston – Galveston area is complex due to cyclic deposition of sediments in the coastal plains of the Gulf of Mexico Basin. These sediments were deposited under a fluvial-deltaic to shallow-marine environments during the Miocene (25 – 5 Myrs) to the Pleistocene periods (1.8 – 0.011 Myrs). The Beaumont formation itself is generally composed of four-fifths or more of clay. Although in the Central Gulf Coast the percentage of clay might run as high as 30% to 90%. The clay is bluish gray, yellowish gray, pinkish gray, purple, and shades of red. All of these clays are characterized by the high silica, and low lime content, and highly plastic. In general, the Beaumont clay formation consists of poorly-bedded, plastic clay interbedded with silt and sand lentils, and in some locations have more or less continuous layers of sand. The Beaumont clays were oxidized and desiccated during the Wisconsin glacial stage when the sea levels were more than 120 m (400 feet) lower than at present level resulting in moderately to heavily overconsolidated clay. Finally, with the recession of the late Wisconsin glaciers, the sea level returned to its present level, leaving both formations preconsolidated through desiccation. The rates of deposits of the deltaic formations were estimated to be between 2,500-30,000 mm/1,000 years based on the information provided by Aronow (2000) and Galloway (2000 & 2005). The geological processes and the desiccation cycles are still active in the region (Vipulanandan et al. 2007b).

Settlement Calculation

When the total effective vertical stress, in-situ (σ_0) + increase in stress ($\Delta\sigma$), is less than or equal to the preconsolidation pressure, σ_p, the following relationship is used to estimate the settlement, S.

$$S = \frac{C_r}{1+e_0} H \log\left(\frac{\sigma_o + \Delta\sigma}{\sigma_o}\right) \quad (1)$$

where H and e_0 are the layer thickness and the initial void ratio of the soft clay respectively. Since C_r is directly related to the settlement magnitude, accurate assessment of C_r is important in limiting the error in estimating the settlement, S. Taking the logarithm on both sides of Eqn. (1) and differentiating the equation will result in the following relationship:

$$\frac{dS}{S} = \frac{dC_r}{C_r} + \frac{dH}{H} - \frac{de}{1+e_o} + f^{'}(\sigma)\frac{d\sigma}{f(\sigma)} \quad (2)$$

where dS, dC_r, dH, de, and $df(\sigma)$ are errors in determining, C_r, H, e_o, and $f(\sigma)$ respectively (note that $f(\sigma) = \log(\sigma_o+\Delta\sigma)/\sigma_o$)..Compared to C_c, C_r is smaller and hence limiting the error in C_r (dC_r) is important in limiting the error in estimating the settlement, dS

OBJECTIVES

The overall objective of this study was to investigate the geotechnical property trends for the pockets of soft clays in Houston, Texas. The specific objectives were as follows: (a) to investigate the microstructure and general statistical property trends (signature features) for the deltaic soft clay deposits; and (b) to verify the consolidation behavior of the soft clays.

DATA COLLECTION

The soil samples were collected from various parts of the region over a period of ten years (1994 to 2003). Shelby tubes were used to collect the samples and the laboratory tests were performed according the standard methods. Data for the analyses was collected from 116 boreholes in the region. The soil sampling depths varied from 12 to 40 m (40 to 120 ft). The water table varied from near the surface to about 6 m (6 ft) in the west side of Houston.

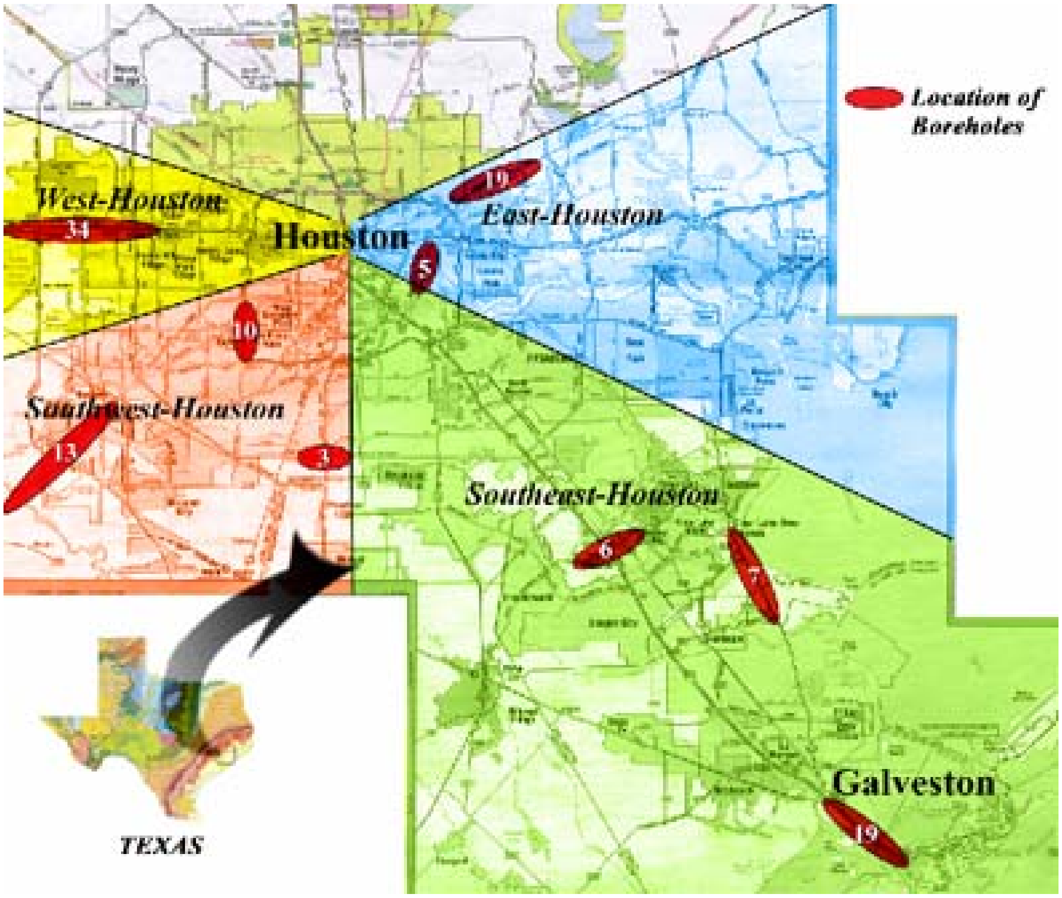

Figure 1. Data locations in the Houston-Galveston area (number of data)

ANALYSIS AND DISCUSSION

Soil samples were collected using Shelby tubes with an area ratio of less than 10%. In addition to the consolidation tests, soil was also tested to determine their physical and index properties.

Distribution of Soft Soils

In the boreholes where soft soils were encountered, the largest percentage was in the top 6 m (20 ft) as shown in Fig. 2. In the western part of Houston, soft soils were also encountered at 16 m (50 ft.). In the southeast region, soft soils were located even much deeper.

Microanalysis

In order to better characterize the soft soils, Scanning Electron Microscope (SEM), Thermogravimetric Analyses (TGA) and X-ray diffraction (XRD) analyses were performed on a randomly selected sample (sample #2 in Fig. 8) from Galveston, Texas.

SEM analysis and EDS analysis

The JEOL 2000FX scanning electron microscope, which was equipped with energy dispersive X-ray spectroscopy to characterize the structure and morphology of the soil sample under high vacuum conditions, was used. Typical SEM micrograph of a sample is shown in Fig. 3. The composition of soil sample was identified using EDS analysis. Elements of Si and O were the major components in the sample. Also Fe, Al, K, and Mg were present in the samples (Fig. 3).

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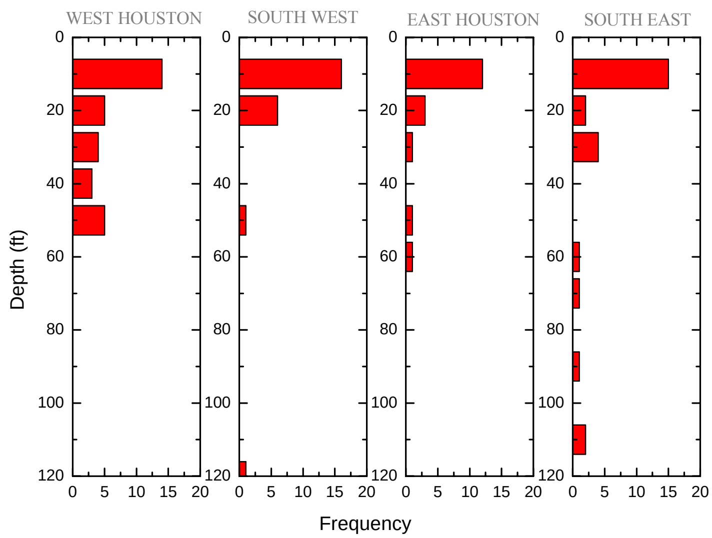
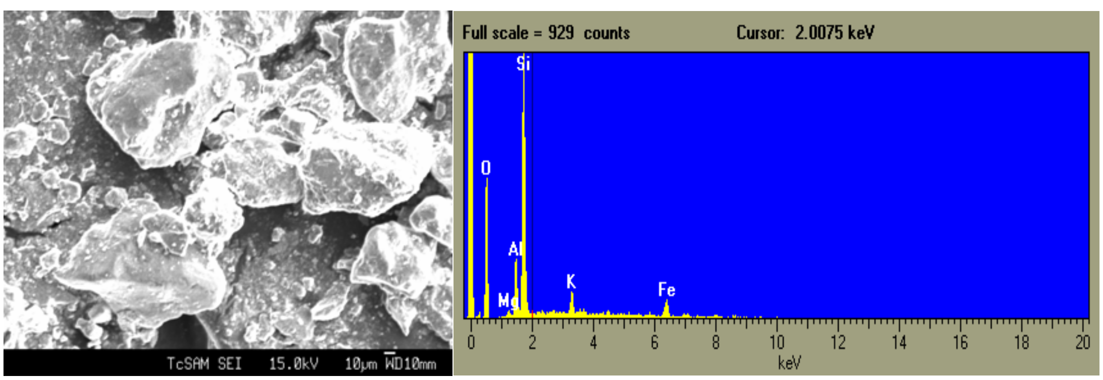


Figure 2. Distribution of soft soils with depth in the region



(a) SEM Micrograph **(b) EDS Analysis**

Figure 3. SEM Micrograph Analyses

Thermal Gravimetric Analysis (TGA)

TGA was used to determine the composition of the soil by monitoring the weight change with increasing temperature. Samples were heated at 5^0/min to 650^oC in nitrogen gas.

The weight loss up to 120^0C was 0.74% in the dry sample. The weight loss was caused by loss of moisture and organic matter. Between temperatures 120^0C and 600^0C the weight loss was 0.5 % in the sample indicating the presence of organic matter in the soil. The dehydration of clays occurs in the temperature range between of $600\text{-}850^0C$

resulting in a weight loss of 2.7%. This weight loss indicates the presence of illite and/or montmorillonite clay minerals in the soils. This was further verified using XRD.

<u>XRD Analysis of soft clay sample</u>

XRD analysis was done using the Sieman D5000 X-Ray Diffractometer . The instrument was set at the scan rate of 0.02 deg/s. The XRD patterns of sample #1 and sample #2 showed two strong peaks at 20.8^o and 26.6^o typical of illite clay mineral (Fig. 5) and the formula that matched the illite peak was $(K,Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2,(H_2O)$. Illite is a non-expanding, clay-sized, micaceous mineral and was first described for occurrences in the Maquoketa shale in Calhoun County, Illinois, USA, in 1937. The name was derived from its type location in Illinois. Illite is also called hydromica or hydromuscovite.

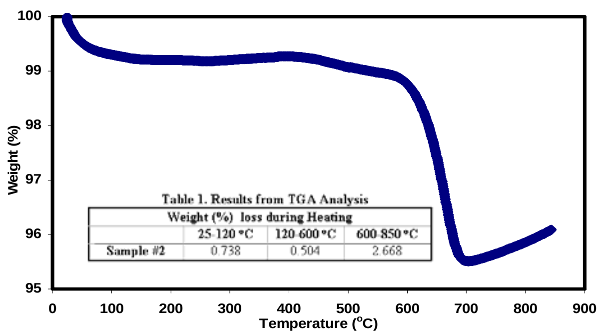


Table 1. Results from TGA Analysis

Weight (%) loss during Heating			
	25-120 °C	120-600 °C	600-850 °C
Sample #2	0.738	0.504	2.668

Figure 4. TGA analysis on clay soil (sample #2)

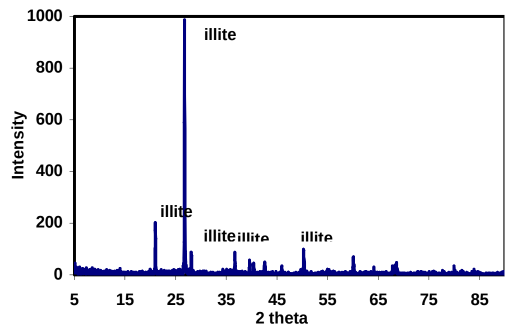


Figure 5. XRD analysis of clay soil (sample #2)

Statistical Properties

In order to establish signature trends and quantify the physical and geotechnical properties of soft clays the data was analyzed statistically. Probability distribution function was selected from beta, normal, lognormal, uniform and Wiebull based on the minimum error.

<u>Soft CL Soil</u>

(i) Natural Moisture Content. The moisture content varied from 13% to 59% with a mean of 23.9%, standard deviation of 8.7%, and coefficient of variation of 36.6%. Based on the properties studied had the highest coefficient of variation. The probability distribution function was Weibull based on 58 data.

(ii) Liquid Limit. The liquid limit varied from 22% to 49% with a mean of 33.5%, standard deviation of 6.2%, and coefficient of variation of 18.6%. Based on the properties studied had the lowest coefficient of variation. The probability distribution function was Weibull based on 38 data.

(iii) Plasticity Index. The plasticity index varied from 6% to 30% with a mean of 17.1%, standard deviation of 5.4%, and coefficient of variation of 31.8%. Based on the properties studied had the highest coefficient of variation. The probability distribution function was normal based on 34 data.

(iv) Bulk Density. The bulk density varied from 15 kN/m^3 (98 pcf) to 22 kN/m^3 (137 pcf) with a mean of 19 kN/m^3 (121.9 pcf), standard deviation of 1.3 kN/m^3 (8.3 pcf), and coefficient of variation of 6.8%. Based on the properties studied had the lowest coefficient of variation. The probability distribution function was normal based on 58 data.

(v) Undrained Shear Strength. The undrained shear strength varied from 7 to 25 kPa (1 to 3.7 psi) with a mean of 20 kPa (2.9 psi), standard deviation of 5.4 kPa (0.8 psi), and coefficient of variation of 27.3%. Based on the properties studied had the highest coefficient of variation. The probability distribution function was beta based on 58 data.

Summary: The overall average moisture content, liquid limit, plasticity index and undrained shear strength were 23.9%, 33.5%, 17.1%, and 20 kPa (2.9 psi) respectively for the CL soils. Probability distribution function for the undrained shear strength was beta.

Soft CH Soils

(i) Natural Moisture Content. The moisture content varied from 19% to 47% with a mean of 33.6%, standard deviation of 6.6%, and coefficient of variation of 19.5%. Based on the properties studied had the lowest coefficient of variation. The probability distribution function was Weibull based on 58 data.

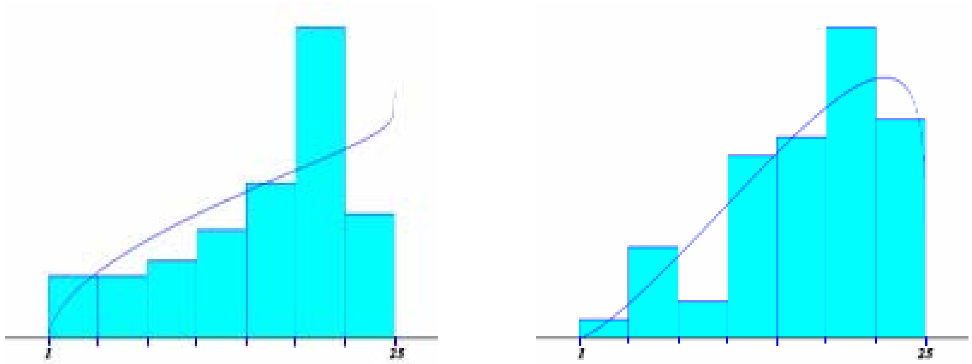
(ii) Liquid Limit. The liquid limit varied from 50% to 109% with a mean of 70.6%, standard deviation of 15.9%, and coefficient of variation of 22.6%. Based on the properties studied had the highest coefficient of variation. The probability distribution function was beta based on 40 data.

(iii) Plasticity Index. The plasticity index (PI) varied from 27% to 72% with a mean of 44.5%, standard deviation of 13%, and coefficient of variation of 29.2%. Based on the properties studied PI had the lowest coefficient of variation. The probability distribution function was beta based on 34 data.

(iv) Bulk Density. The bulk density varied from 15 kN/m^3 (97 pcf) to 21 kN/m^3 (135 pcf) with a mean of 18 kN/m^3 (114.7 pcf), standard deviation of 1.4 kN/m^3 (8.7 pcf), and coefficient of variation of 7.6%. Based on the properties studied had the highest coefficient of variation. The probability distribution function was beta based on 54 data.

(v) Undrained Shear Strength. The undrained shear strength varied from 10 to 25 kPa (1.5 to 3.7 psi) with a mean of 21 kPa (3.1 psi), standard deviation of 4.2 kPa (0.6 psi), and coefficient of variation of 19.8%. Based on the properties studied had the lowest coefficient of variation. The probability distribution function was beta based on 58 data.

Summary: The overall average moisture content, liquid limit, plasticity index and undrained shear strength were 33.6%, 70.6%, 44.5%, and 21 kPa (3.1 psi) respectively for the CH soils. Probability distribution function for the undrained shear strength was beta.



(a) Su (CL Soil) **(b) Su (CH Soil)**

Figure 6. Probability density dunctions for S_u (kPa) of CL and CH Soils

Table 1. Summary of Soft Soil Data

Type of Soil	*MC (%)*	*LL (%)*	*PL (%)*	*PI (%)*	*Bulk Density (pcf)*	*Dry Density (pcf)*	*Su (psi)*
CL Soil (Data Set=58)							
Range	13-59	22-49	8-40	6-30	98-137	62-120	1-3.7
Mean	23.9	33.5	17.5	17.1	121.9	99.1	2.8
Standard Deviation	8.7	6.2	5.4	5.4	8.3	11.3	0.8
Var	76.4	38.9	29.7	29.4	68.3	127.2	0.6
COV (%)	36.6	18.6	31.1	31.8	6.8	11.4	27.3
N	58	38	36	34	58	58	58
CH Soil (Data Set=58)							
Range	19-47	50-109	20-37	27-72	97-135	71-113	1.5-3.7
Mean	33.6	70.6	26.5	44.5	114.7	86.4	3.1
Standard Deviation	6.6	15.9	4.7	13.0	8.7	10.1	0.6
Var	42.9	253.8	22.2	168.1	76.0	101.4	0.4
COV (%)	19.5	22.6	17.8	29.2	7.6	11.7	19.8
N	58	40	33	34	54	54	58

Note: 1 pcf = 0.157 kN/m^3, 1psi = 6.895 kPa.

Property Correlations

(i) LL versus Natural Moisture Content

<u>Soft CL Soils</u>

For 97% of the deltaic clays, the natural moisture content was lower than the liquid limit (Fig. 7). The mean of the moisture content for CL soil was 23.9% compared to the mean of the liquid limit of 33.5%. The coefficient of variations for the moisture content and liquid limits was 36.6% and 18.6% respectively. Based on COV and standard deviation, the variability in the liquid limit was lower than the moisture content.

Soft CH Soils

The mean of the moisture content for CH soil was 33.6% compared to the mean of the liquid limit of 70.6%. The coefficient of variations for the moisture content and liquid limits was 19.5% and 22.6% respectively. Based on COV and standard deviation, the variability in the liquid limit was higher than the moisture content.

(ii) Plasticity Index Chart

Both CH and CL clays were present in the deltaic deposits in the Houston-Galveston area (Fig. 8). Most of the clay data were located between montmorrillonite and Illite.

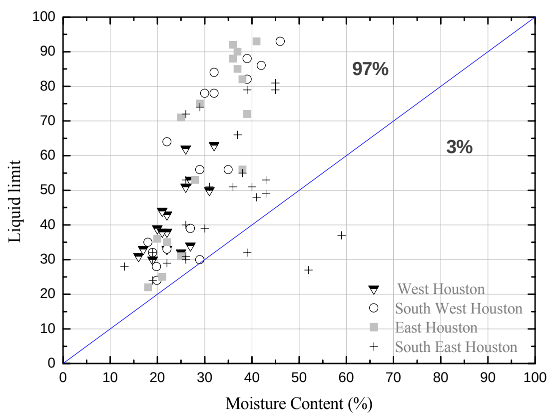


Figure 7. Comparison of liquid limit and moisture content

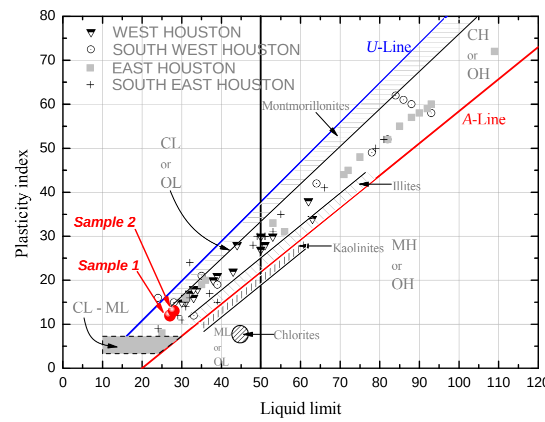


Figure 8. Plasticity chart with the soil data

(iii) Dry unit weight versus Moisture content

The variation of the dry density (γ_d) with moisture content (MC) for all soft soils is shown in Fig. 9. The dry density reduced with increasing moisture content and the least square fit of the 116 data can be represented as follows:

$$\gamma_d = -1.25 \cdot MC + 128.55 \qquad (3)$$

The moisture content was in the range of 13% to 59%. The coefficient of correlation was 0.91.

(iv) Undrained Shear Strength versus Moisture Content

The variation of the undrained shear strength with moisture content is shown in Fig. 10 for CL and CH soils. The undrained shear strength reduced with increasing moisture content and can be represented as follows:

Soft CL Soils

$$Log\ Su = -0.0077 \cdot MC + 0.62 \qquad (4)$$

The coefficient of correlation was 0.38.

Soft CH Soils

$$Log\ Su = -0.0024 \cdot MC + 0.56 \qquad (5)$$

The coefficient of correlation was 0.17.

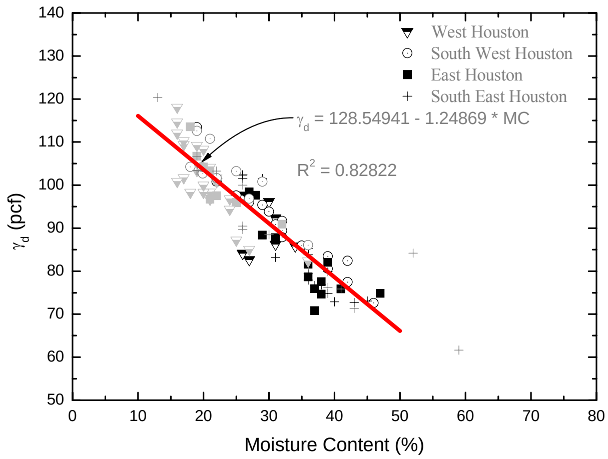
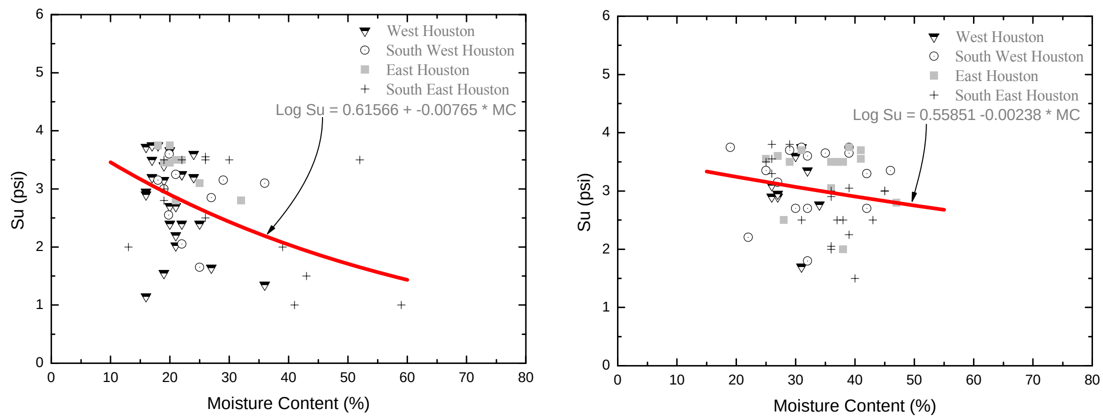


Figure 9. Variation of dry density with moisture Content



(a) CL **(b) CH**

Figure 10. Variation of undrained shear strength with moisture content

Recompression Indices (C_{rn})

A typical *e*-logσ′ relationship for a clay soil is shown in Fig. 11. If the soil was elastic, it will load and unload along the same path (path 1234). Since the soils are considered elasto-plastic, they will unload (path 45) and reload (path 567) along a different path. Hence there is an hysteretic loop and there is no one unique slope to determine the C_r. Therefore the recompression index can be determined by different methods. In this study, the recompression index C_r will be determined by 3 different methods (Fig. 11) as follows:

1. C_{r1} is the slope of the line joining the end of the unloading part (point 5) and the intersection of the preconsolidation line and the reloading part of the recompression curve (point 6).
2. C_{r2} is the average slope of the hysteretic loop as shown on Fig. 11 (Holtz 1981).
3. C_{r3} is the slope of the unloading section of the recompression curve (Das 2004).

Even if the value of the recompression index is small in magnitude, the difference in these values can lead to significantly different settlement estimation. Series of tests were performed on samples collected from a highway bridge location in Houston near a creek and the test results are summarized in Table 2.

Compression Index – C_c: As summarized in Table 2, for the CH soils the minimum and maximum values were 0.144 and 0.446 respectively with an average value of 0.289. The coefficient of variation was 40.1%.

Recompression Index – C_{r1}: As summarized in Table 2, for the CH soils the minimum and maximum values were 0.018 and 0.041 respectively with an average value of 0.026. The coefficient of variation was 31.6%.

Recompression Index – C_{r2}: As summarized in Table 2, for the CH soils the minimum and maximum values were 0.049 and 0.162 respectively with an average value of 0.090. The coefficient of variation was 44.1%. This variation, based on COV, was the highest of all the parameters investigated.

Recompression Index – C_{r3}: As summarized in Table 2, for the CH soils the minimum and maximum values were 0.062 and 0.190 respectively with an average value of 0.107. The coefficient of variation was 41.9%.

It was observed that for the CH clay soils the ratio of C_{r3} to C_{r1} varied from 2.71 to 7.60. Hence the magnitude of the settlement estimated using C_{r1} and C_{r3} will be substantially different, approximately three times. Relationships between the compression index and recompression indices were investigated (Fig. 12) using a linear relationship as follows:

$$C_{rn} = \alpha_n C_c \quad (6)$$

For the soils tested in this one location, C_c better correlated with C_{r2} and C_{r3} compared to C_{r1} (based on the coefficient of correlation). For the CH soils at this location the α_1, α_2, and α_3 were 0.080, 0.305, and 0.356 respectively (Eqn. 6). While Cr_2 of the Houston clay was comparable to the New Orleans clay, other two indices were not. The Cr_1 of the Houston clay was lower and Cr_3 was higher than the New Orleans clay (Vipulanandan et al. 2008).

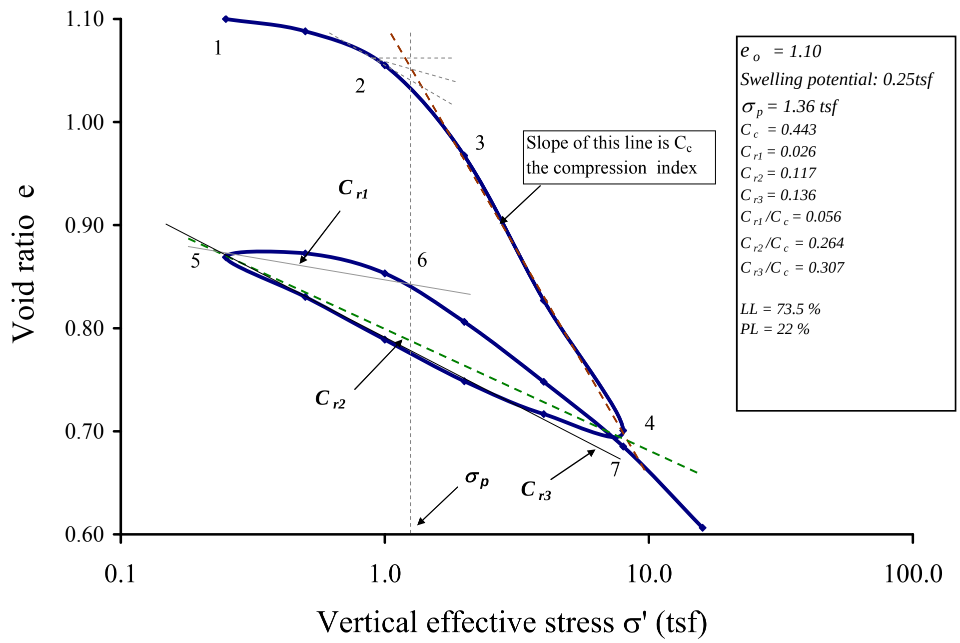
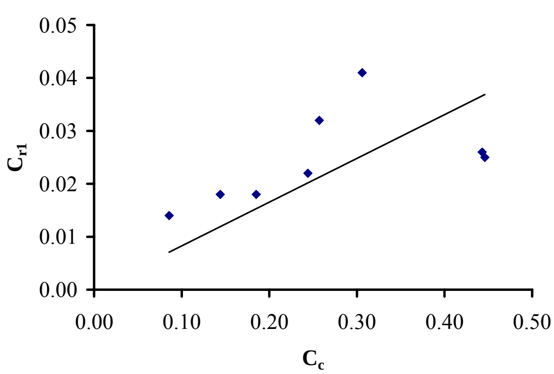


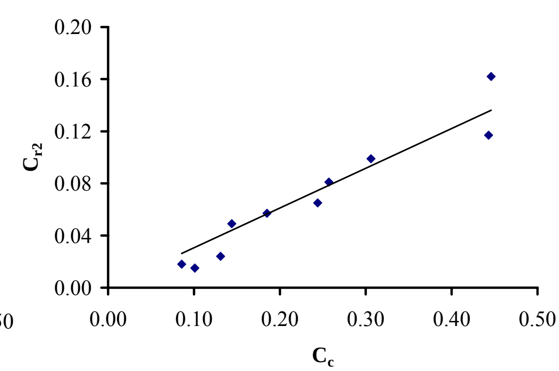
FIG. 11. Typical $e - \log \sigma'$ relationship for soft soils.

Table 2. Summary table of compressibility parameters of clay soil

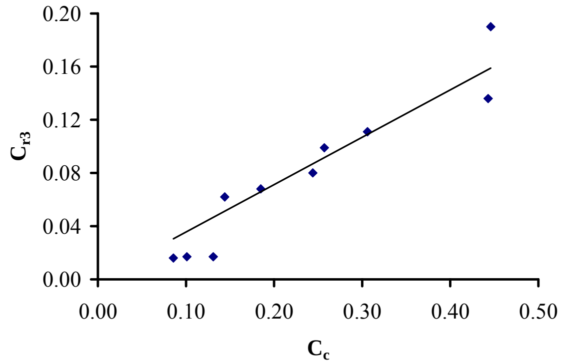
Depth (m)	Soil Type	OCR	C_c	C_{r1}	C_{r2}	C_{r3}
1	CH	9.6	0.144	0.018	0.049	0.062
3	CH	1.7	0.185	0.018	0.057	0.068
3.7	CH	2.7	0.257	0.032	0.081	0.099
4.2	CH	2.3	0.244	0.022	0.065	0.080
5	CH	2.0	0.306	0.041	0.099	0.111
5.6	CH	1.1	0.446	0.025	0.162	0.190
6.3	CH	1.2	0.443	0.026	0.117	0.136
7.7	CL	1.2	0.086	0.014	0.018	0.016
8.3	CL	1.0	0.101	0.015	0.015	0.017



(a)



(b.)



(c)

FIG. 12. Correlation of recompression indexes with the compression index: (a) C_{r1} vs C_c, (b) C_{r2} vs C_c, and (c) C_{r3} vs C_c.

CONCLUSIONS

Both CL and CH soft clays are present in the deltaic deposit of the Houston-Galveston area. Total of 116 borehole data were analyzed. Based on the analyses of the Houston and Galveston soft soils the following conclusions are advanced:

1. Several mean properties of the CL and CH soft clays have been quantified. Mean physical (moisture content) and geotechnical properties (liquid limit, plastic limit) of soft CH clays were higher than that of soft CL clays. The mean undrained shear strength of CL and CH soils was comparable. The natural moisture content of over 97% of the clays was lower than the liquid limit

2. Based on the variance, CL clay soils showed greater variation in natural moisture content, plastic limit, dry density and undrained shear strength (S_u) compared to the CH deposit. CH clay soils showed greater variation in liquid limit and plasticity index compared to the CL deposit. The variation in bulk density for the CL and CH soils was comparable. The probability distribution functions (pdf) for the various properties have been determined.

3. Based on COV, CL clay soils showed greater variation in natural moisture content, plastic limit, plasticity index, and undrained shear strength (S_u) compared to the CH deposit. CH clay soils showed greater variation in liquid limit compared to the CL deposit. The variation in bulk density and dry density for the CL and CH soils was comparable. The natural moisture content has the highest COV value and bulk density has the lowest COV value when compared with other parameters in CL soil. Also the plasticity index has the highest COV value and bulk density has the lowest COV value when compared with other parameters in CH soil.

4. XRD and TGA analyses with the plasticity index chart confirmed the presence of illite clay mineral in the soft soil.

5. Undrained shear strength of the soft clay was related to the moisture content of the soil.
6. Of the consolidation test parameters, recompression index is the least investigated in the literature.
7. Three methods of quantifying the recompression index are proposed. Based on the soil type, substantial variation in the recompression index was observed depending on the method used.
8. For the CH soils with hysteretic loop (unloading and reloading), the recompression index depends on the stress path and the stress level at which unloading is performed.

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