Geotechnical characterization of upper Shanghai clays

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ABSTRACT: The Shanghai soft clays were deposited in Yangtze River Delta in the Late Pleistocene and Holocene. In this paper, the physical, mineralogical and mechanical properties of different strata were investigated by a series of laboratory tests. It was found that silt size grain particles dominated the clay materials, and illite is the major clay mineral. The liquid limit, plastic limit and activity are lower than most of the other marine clays in the world. Oedometer tests and undrained triaxial tests indicated that layer 3 and layer 4 are marine clays with a weak structure, while layer 2, 5 and 6 are overconsolidated clays. The stronger hydraulic conditions (faster stream velocity) and the origin of material in the Yangtze River account for the large amount of silt size particles and illite mineral. The less saline depositional environment is the main reason for the weaker structure in Shanghai clay.

Keywords: soft clay; depositional environment; geotechnical properties; laboratory tests; soil structure

INTRODUCTION

Shanghai located on the east tip of Yangtze River Delta. Soft marine clays was deposited on a surface on top of the Upper Pleistocene sediments. Numerous underground construction activities in the Shanghai clays over the last few decades, it is necessary to investigate the engineering properties of the Shanghai clays.

In this paper, the geotechnical properties of the Shanghai clays are investigated carefully through a series of laboratory tests. The correlation between the depositional environment and the geotechnical properties also is analyzed carefully.

GEOLOGICAL SETTING

Shanghai is located at approximately 70 km from the shoreline of East China Sea, on the large coastal plain designated as the Yangtze River Delta. The average thickness of the Quaternary strata in the delta is about 280 m to 300 m in the urban area with an annual groundwater table between 0.5 and 0.7 m from the surface. The upper Shanghai soft clay refers to the sediments deposited since the Late Pleistocene, with an average thickness of about 30 m to 40 m.

The local design codes for geotechnical engineering divide the ground into series of layers. The soil layers are defined by a number and named according to their colour and grain size distribution. The soil layer numbers and names are shown in the 2nd and 3rd columns of Table 1. These layers incorporate the Late Pleistocene series and the whole Holocene series. Layer 1 is the fill soil. Layers 2-6 are mainly clays, except the sub-layer 2-3, which is a silty sand and not wide spread in Shanghai. The layers beneath layer 7 are alternating sandy and clayey soil strata. Layer 2 is formed of overconsolidated clay which is the supporting strata for most shallow foundations. Layer 7 is a sand stratum which is mainly used for the supporting strata of pile foundations. Sub-layer 5-4 separates the Holocene series and the Late Pleistocene series (Shi et al., 2009). Layers 2~5-3 belong to the Holocene series, and those layers beneath 5-4 belong to the Later Pleistocene series. The average thickness of the upper Shanghai clays is around 30~40m.

Table 1. Quaternary stratigraphical chart, engineering geological strata and the interpretation of the depositional environments of Shanghai clay during the Late Pleistocene and Holocene (modified after SGEAEB, 2002)

Strata calendar		Engineering Geological Layer No.	Name	Avg. elev. of strata surface /m	Sedimentary facies	Formation period /ka (low limit)
		1	Fill	3.67		
Holocene	Late phase	2_1	Brown yellow clay, silty clay	2.92	Coastal-estuarine	3
		2_2	Grey-black turfy clay	2.04	Lacustrine	
		2_3	Grey silt, fine sand	0.87	Coastal-estuarine	
	Middle phase	3_1	Grey muddy silty clay (coastal plain region)	-0.29	Coastal-shallow sea	8
			Grey clay, silty clay (lacustrine plain region)	0.79		
		3_2	Grey sandy silt	-1.31		
		4_1	Grey muddy silty clay	-6.87		
		4_2	Grey sandy silt	-8.31		
	Early phase	$5_{1\text{-}1}$	Grey clay	-14.02	Coastal	10–11
		$5_{1\text{-}2}$	Grey silty clay	-17.97		
		5_2	Grey sandy clay	-26.07	Coastal-swamp	
		5_3	Grey silty clay	-28.5	Drowned valley	
Pleistocene		5_4	Grey-green silty clay	-34.42		13
		6	Dark green-brown yellow clay, silty clay	-16.49	Lake	20
		7_1	Grass yellow-grey clay, sandy silt	-18.57	Estuarine-coastal	
		7_2	Grey yellow-grey fine sand	-34.07		55

GEOTECHNICAL CHARACTERIZATION

A thin-walled tube sampler was used to recover intact soil samples for laboratory testing of engineering properties. Two boreholes were located at Lianhua Road (LHR) in Minhang District, and Shanghai Traditional Chinese Medicine (TCM) in Yangpu District, respectively.

The laboratory investigations consisted of various basic geotechnical index properties by different test methods. In a conventional oedometer test, the specimen was 30 cm^2 in area and 2 cm in height. Each applied load increment was twice as large as the previous one, and the duration of each load was 24 hours. The specimens used for the consolidated undrained triaxial compression tests for Shanghai clays were 39.1 mm in diameter and 80 mm in height.

Index properties and natural state

Figure 1 shows the basic geotechnical properties of Shanghai clays. It can be seen that the clay content of the Shanghai clays at all depths is less than 50%, especially those at the top and bottom areas, where the clay content is as low as 20%. However, the silt content is more than 50% at all depths. The natural water content (w_n) of the Shanghai clay is 25% ~ 45%, which is larger than the liquid limit (w_L).

The clay mineral compositions for the Shanghai is modified from (Qiu and Li, 2007). The clay mineral compositions of the Shanghai clays were determined by the X-ray Diffraction (XRD) method with the clay fractions <5μm. Illite is the most common clay mineral in Shanghai clay, averaging approximately 72%. Recent researches on the large quantity of illite in Yangtze River Delta implies that it is due to the origin of the sediment carried from the Tibet Plateau by the Yangtze River.

In addition, the plasticity chart of Shanghai clays is plotted in Figure 2. All layers of Shanghai clay closed but above the A-line, it can be seen that Shanghai clay can be classified as a silty clay.

The soil properties are influenced by both the type and amount of clay materials. What the Atterberg limits (w_p and w_L) reflect are their combined effects. In order to identify the effect of each individual factor, the ratio of the plasticity index (I_p) to the clay fraction percentage, termed as the activity, is used. Figures 3 show that the activity of the Shanghai clays varies from 1.2 to 0.5, indicating that the Shanghai clay is less active than other clays in the literature.

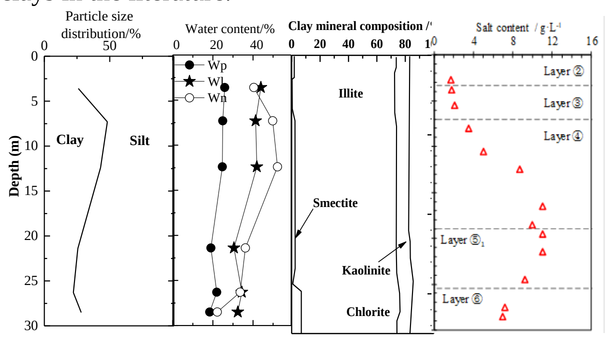

Figure 1. Geotechnical properties of the Shanghai clays (LHD site)

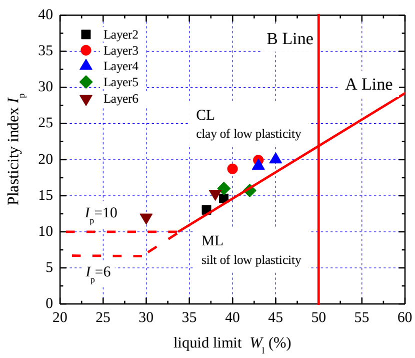

Figure 2. Plasticity chart of Shanghai clays (LHD site)

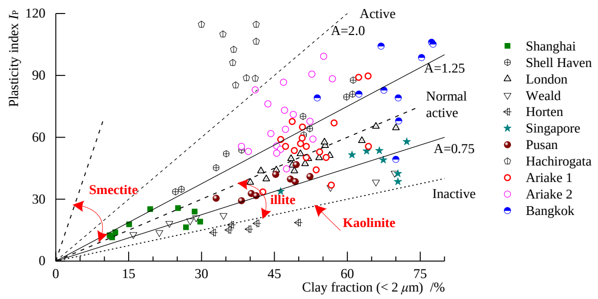

Figure 3. Activity of Shanghai clays, with comparison with other clays in the literature

Compressibility tests

Figure 4 shows the oedometer tests results of layer 2 to 6 of Shanghai clays. It can be seen that Layer 4 has a largest initial void ratio e_0=1.2, and Layer 6 has a minimum value e_0=0.6. The void ratios of other layers lie between 0.85~0.95. The *e*-lg*p* curves of Layer 4 show an obvious inflection point around 100 kPa, while those of other layers do not show obvious inflection point.

Variations of compression index Cc, swelling index Cs and the ratio of Cc/Cs with depth are plotted in Figure 5. It can be seen that: (i) the distributions of Cc and Cs follow a mode that is approximately be small at surface and bottom be big in the middle; (ii) the maximum values of Cc and Cs appear at layer 4, and the minimum values appear at layer 6; and (iii) the ratio of Cc/Cs ranges 4~10 for all soil layers.

Shear tests

Figure 6 shows the effective stress paths obained from consolidated undrained (CU) triaxial tests of Shanghai clays. CU triaxial tests were performed on each layer with three different confining stresses. For layer 3~6, the black curve represents a confining stress equal to the in-situ mean effective stress, and the red and blue curves represent confining stresses smaller (approximately half) and larger (approximately double) than the in-situ stress, respectively. While for layer 2, which is known as a overconsolidated clay, large confining stresses were used to check the effect of overconsolidation on stress path.

It can be seen from this figure that: (1) The specimens of layer 2, 5 and 6 under in-situ stress condition show a strain-harding behavior, indicating they are overconsolidated soils. While those of layer 3 and 4 under in-situ stress conditions show a strain-softening behavior, indicatting they are structured soils. (2) Layer 5-2 and 6 seem to own a strong overconsolidation, still show strain hardening even being subjected to a larger confining stress. While layer 5-1 is weakly overconsolidated. This results indicated similar as those of the oedometer tests.

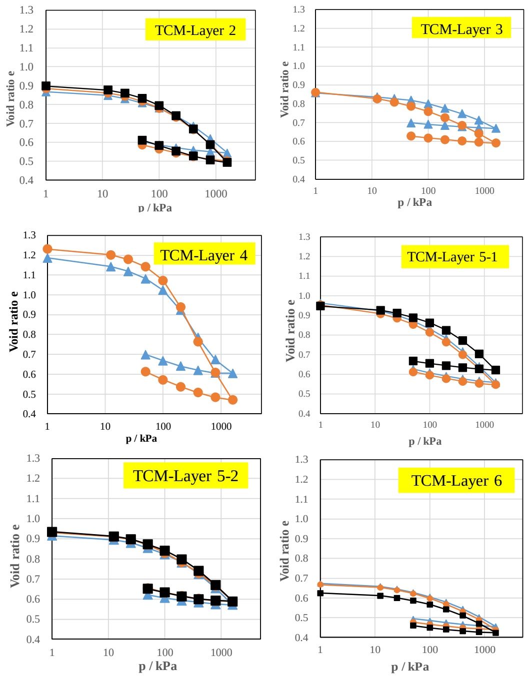

Figure 4. e-logp curves from oedometer tests (TCM site)

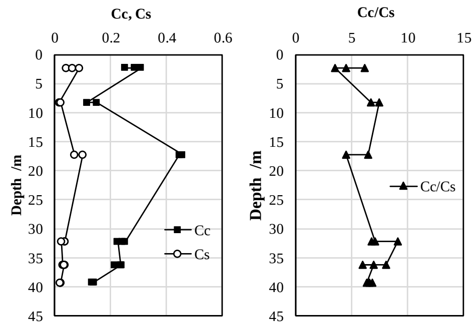

Figure 5. Variation of Cc, Cs and Cc/Cs in the ground (TCM site)

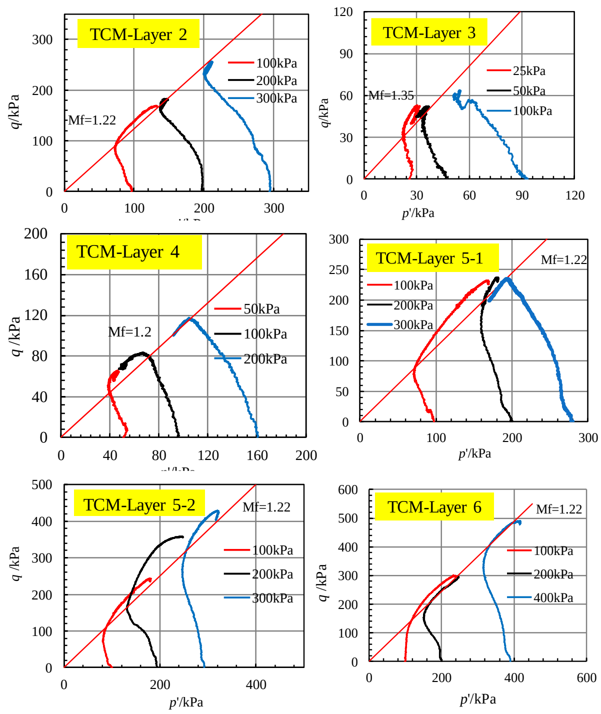

Figure 6. Effective stress pathes of conlidated undrained traixial tests of Shanghai clays (TCM site)

RELATIONSHIP BETWEENDEPOSITIONAL ENVIRONMENT AND GEOTECHNICAL PROPERTIES

Effect of dispositional environment to grain size distribution and clay mineralogy

Since the Pre-Miocene, the Yangtze River became a huge river much like its present size. This river has one of the biggest annual water discharge volumes in the world, and it carries a large amount of sediments from the middle and lower reaches. Therefore, the hydraulic condition are more suitable for deposition of silt size particles, than the clay size particles, accumulated in this area, as is shown in Figures 1.

The engineering properties of soil are closely related to its mineral composition. It is known that illites have a liquid limit of 60~120%, and plastic limit of 35~60%. Illites have an activity of 0.5~1 (Mitchell and Soga, 2005). Since illites account for as much as 70% of clay minerals in the Shanghai clay, above correlation can be utilized to explain the basic properties described in Figure 1. Recently, the works of He et al. (2013) revealed that the clay mineral compositions of the Yangtze River displayed a similar pattern along the main stream, illite is the major component of the sediments from the upstream to downstream. In other words, the illite in Shanghai clays is come from the Tibetan Plateau.

Effects of dispositional environment on soil structure

The sensitivity framework of Cotecchia and Chandler (2000) provides a semi-quantitative understanding of the degree of structure in a natural soil through comparison of its natural behaviour to a baseline of its remoulded clay behaviour (Bishop, 2006). In the framework, the concept of intrinsic parameters proposed by Burland (1990) provides a rigorous basis for comparison of consolidation behaviour. The ICL (Intrinsic Compression Line) curve and the SCL (Sedimentary Compression Line) curve in the figure represent the relation between void index (I_v) and vertical consolidation stress (σ'_v) of the normally consolidated remoulded clay and normally consolidated clay with only gravitational structure respectively. The SCL and the ICL are approximately parallel, such that the ratio of stresses at a given void index is around 5. In the framework of sensitivity, the I_v~lgσ'_v curves lying to the right or left of the SCL indicate a certain degree of structure or overconsolidation, respectively. And the farther away from the ICL, the stronger the structure or the larger the overconsolidation will be.

Figure 7 shows the intrinsic compression curves for layer 2~6 of Shanghai clays. Layer 3 and 4 lie between the SCL and ICL, and layer 2, 5 and 6 lie beneath the ICL. According to the sensitivity framework, layer 3 and 4 are sensitive clays with strong structure, and layer 2, 5 and 6 are overconsolidated clays. This is directly related to the depositional environment. Layer 3 and 4 were deposited in a marine environment with high sea level. Layer 2 has been exposed to evaporation effect during the post deposition period. Layer 5 was deposited at the beginning of last transgression, it should has been subjected to the loading-unloading cycles. Layer 6 was diluvium clay, also has been subjected to complicated evaporation effect and even the loading-unloading cycles.

It also can be seen from Figure 7 that compression curves of layer 4 shows a gentle change in slope, and the turning point are close to the in-situ vertical stress σ'_v. These imply that the structure of layer 4 is weak and easier to be broken down.

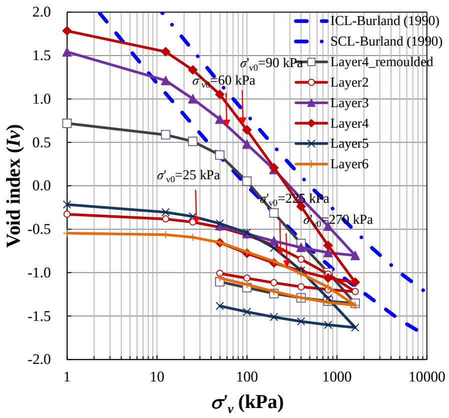

Figure 7. Application of sensitivity framework to Shanghai clays (based on data of LHR site)

CONCLUSIONS

In this paper, the geotechnical properties of upper Shanghai clays were investigated by a series of laboratory tests. The influence of depositional environment on the geotechnical properties was analyzed carefully. The following conclusions can be drawn:

(1) Shanghai clays were deposited in a deltaic environment during the last transgression-regression cycle. They are products of the sediments carried by Yangtze River and the relative sea level change during last transgression-regression cycle.

(2) Three unique physical and chemical characteristics of Shanghai clays: silt particle is the main component; illite is the main clay mineral; the vertical distribution of porewater salinity indicates the change of depositional environment.

(3) Oedometer tests and undrained triaxial tests indicated that layer 3 and layer 4 are marine clays with sensitivities less than 10, while layer 2, 5 and 6 are overconsolidated clays.

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