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ORIGINAL ARTICLE

The microscopic characteristics of Shanghai soft clay and its effect on soil body deformation and land subsidence

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Abstract Compaction of the 40-m-thick, upper Shanghai soft clay contributes to land subsidence in the Shanghai region. The upper clay, a marine deposit, continuously subsides at rate of 3 mm/years despite mitigation strategies designed to control land subsidence. These strategies include the artificial injection of water into the subsurface. Data describing the particle-size distribution, pore-size distribution, microstructure, mineralogical composition, pore-solution composition, and cation-exchange capacity indicate that the clay is semidispersed, substable, and susceptible to compaction. An evaluation of soil body deformation caused by artificial injection of dilute water into a marine clay suggests that depression of the electrostatic double 1ayer in the marine clays may be responsible for the observed compaction and resulting subsidence. A decrease in the swelling pressure of the marine clays might result from a reduction in the concentration of dissolved sodium in pore fluids when calcium-bicarbonate water is injected. Thus, ironically, the strategy designed to mitigate land subsidence could be contributing to it. Increasing the concentration of dissolved salts in the injection water may prevent the collapse of the clay structure and halt or reverse the subsidence process. The analysis results indicate the deformation of soft clay by consolidation is subject to its microscopic physical and chemical features, rather than the fluctuation of groundwater level. This continuous compression contributes as a major part to the land subsidence in Shanghai.

Keywords Soft clay · Microscopic characteristics · Soil body deformation · Land subsidence · Shanghai

Introduction

Shanghai is the first city in China both to experience significant effects from land subsidence and to implement a subsidence control program. Land subsidence in Shanghai occurs in interbedded continental and marine sediments of Quaternary age that average more than 300 m thick. Most subsidence occurred prior to 1965 and was caused by aquifer compaction due to extraction of ground water. Land subsidence in Shanghai has been effectively controlled since 1965 by restricting groundwater extraction, distributing pumpage among several aquifers and many wells, injecting water through recharge wells to repressurize unconsolidated sediments, and other means. However, a shallow (1ess than 75 m below land surface), 40-m-thick, silty marine clay (ooze), the Shanghai soft clay, continues to compact at an average rate of 2–3 mm/years. Subsidence and its control has been the subject of several investigations in the Shanghai area.

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The land subsidence in Shanghai is representative in China and even in the world (Xue et al. 2005; Holzer and Johnson 1985; Gambolati et al. 2006). Research on it and the corresponding measures are of international importance (Freeze 2000). Previous studies discussed the effects of strata compression on land subsidence, mostly in a perspective of mechanics as pumping groundwater leading to a decline in the groundwater level (Liu et al. 1979; Gu et al. 1990; Monjoie et al. 1992; Dassargues et al. 1992), instead of a perspective of microscopic physical and chemical features of the fluid–solid system to discuss the inner factors controlling deformation (Liu 2001; Hu et al. 2004). At present situation of the subsiding rate being controlled within 10 mm/years, the deformation of soft layers is increasingly effecting the land subsidence, which requires a systematic analysis of the deformation features of the shallow soft layers.

This paper presents the latest data on the particle-size distribution, pore-size distribution before and after consolidation, mineralogic composition, morphology of microscopic clay structure, composition of pore solutions, and cation-exchange capacity (CEC), and the effects of these microscopic characteristics on soil body deformation and land subsidence.

History and feature of Shanghai land subsidence

Land subsidence has a long history in Shanghai, which is the first place where land subsidence was observed in China. Since the year of 1921 when is was discovered, the mean subsidence measurement and the largest measurement have, respectively, reached to 1.966 and 3.018 m by the end of 2006, with the fastest subsiding rate more than 110 mm/years from 1957 to 1961. The area with total subsidence over 1.5 m has been 1,256 km^2, forming a bowl taking downtown area as the centre. At present the mean subsiding rate remains 10 mm/years or less (shown in Fig. 1) because effective measures have been taken since 1965.

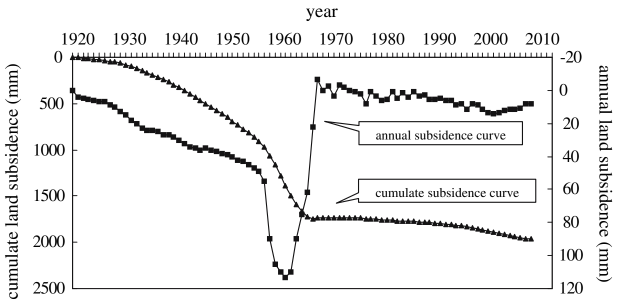

Fig. 1 The evolution of land subsidence in Shanghai

The Quaternary strata are the primary layers taking place subsidence in Shanghai. There was clear compression before 1965 when the exploitation of groundwater in sandy aquifers caused a dramatic decrease in groundwater level. Decrease in groundwater level has been obviously slower since 1965 when the groundwater exploitation was effectively restricted. Thus the lightly clayey soft layers down to 75 m deep gradually become the major part where land subsidence happens, which contributes 65% for the total subsidence.

The soft layers down to 75 m deep are of marine facies, in which the first layer (3.13–19.85 m deep) is gray muddy clay; the second one (19.85–44.30 m deep) is gray clay; and the third one (44.30–75.85 m deep) is gray silty clay inbeded with silt. As the third layer is adjacent to aquifers and contains silt lenses, its deformation relates to changes in the groundwater level. On the contrary, the upper two layers are independent to the fluctuation of the groundwater level and stay in continuous compression. Physical properties of the three layers and their recent deformation are shown in Table 1 and Fig. 2.

Physical properties of Shanghai soft clay

Historically, deformation mechanisms within the Shanghai soft clay and their effects on land subsidence were analyzed from a mechanical point of view. Traditional soil mechanics is based on the concept of effective stress, that is, volume variations and soil strength depend on effective stress transferred by the solid particles. So, emphasis during study of soil composition and mechanical properties has been nearly completely on solid phase mineralogy and structure.

Particle-size distribution

To determine if clays are naturally dispersed or flocculated each sample of Shanghai soft clay was divided in half. The particle-size distribution of one half of the sample was determined by the pipette method after the sample was totally dispersed by: ultrasonic vibration for 10 min, addition of 10 ml of 0.5 N $(NaPO_3)_6$ dispersing agent, and boiling for 30 min. The particle-size distribution of the second half of the sample was determined by the pipette method after the sample was partially dispersed by ultrasonic vibration for 10 min and introduction into the extraction liquid in 1:10 soil:water ratio. The clay content of the totally and partially dispersed split samples was compared. Based on the dispersion coefficient, μ (ratio of clay in partially dispersed split to that in the totally dispersed split), clay is in a dispersed state if $\mu \approx 1.0$ and in a

Table 1 Physical-mechanical properties of the three soft clay layers in Shanghai

Layer no.	Depth (m)	W (%)	e	ρ (g/cm^3)	w_L (%)	w_P (%)	I_P	$a_{0.1-0.2}$ (MPa^{-1})	C (kPa)	Φ (°)	C_u (kPa)	q_u (kPa)
1	3.15–19.85	40.0–59.6	1.12–1.67	1.64–1.79	34.4–50.2	19.0–26.0	17.0–25.1	0.550–1.650	11.5–15.7	8.5–16.9	18.0–44.0	42.0–77.0
2	19.85–44.30	29.8–42.5	0.85–1.22	1.75–1.90	28.3–42.9	17.3–23.8	10.2–20.0	0.280–0.710	11.5–20.0	12.7–27.4	35.0–94.0	50.0–135.0
3	44.30–75.85	29.9–40.7	0.84–1.17	1.78–1.91	29.2–43.7	17.2–23.6	10.9–21.0	0.190–0.500	14.3–28.6	16.9–28.7	84.0–143.0	–

flocculated state if $\mu < 0.4$. Results show that the clay content in some partially dispersed samples approaches that of the totally dispersed samples ($\mu = 1.0$). In these samples, the clay exists naturally in a dispersed state. In some samples, clay exists mostly in the form of floc units, so that the percentage of clay in the partially dispersed split is much less that in the total dispersed split ($\mu < 0.4$). However, in most samples clay is in a state of semidispersion and semiflocculation ($0.4 < \mu < 1.0$). Therefore, clay particles in Shanghai soft clay are mostly in state of semidispersion or semiflocculation, and clay granules are formed mainly by aggregation of clay micelles.

Pore-size distribution

The pore-size distribution of Shanghai soft clay before and after dewatering and consolidation was determined by mercury intrusion methods. The consolidated sample represents the characteristics of soft clay buried at a depth of 40 m. Results (Fig. 3) show that the pore volume of shallow (4 m deep) soft clay is more than 300 mm^3/g and that of more deeply buried clay (40 m) is significantly less about 240 mm^3/g. The decrease in pore volume with depth corresponds exactly with an increase in sample density.

The distribution of pore sizes (Fig. 3) shows that in the deep sample, the volume of large (37.5–3.75 μm) and medium-size (3.75–0.375 μm) pores is dramatically less and the volume of small (0.375–0.0375 μm) and micro-size (0.0375–0.00375 μm) pores slightly more than in the shallow sample.

The undisturbed soil samples were applied with load to drain and consolidate them. Figure 3 shows curves of pore-size distribution before and after consolidation. Pore volume and pore-size distribution after consolidation are given in Table 2.

If it can be assumed that pore-size differences are strictly due to the physical effects of gravity loading on the soft clay, the pore volume of Shanghai soft clay decreases significantly after consolidation primarily because the medium-size pores are squeezed to smaller sizes or closed.

Minute structure

The data on particle size and pore-size distribution indicate that pores in Shanghai soft clay are formed mainly by bonding of clay micelles. The Shanghai soft clay has a hierarchical structure. Aside from a rigid skeleton formed by broken nonclay grains of 0.1–0.05 mm diameter, the highest level structural unit is globular or globularlike floc units (0.02–0.05 mm). Pores among floc units are about 0.01 mm (10 μm). Floc units are usually formed by

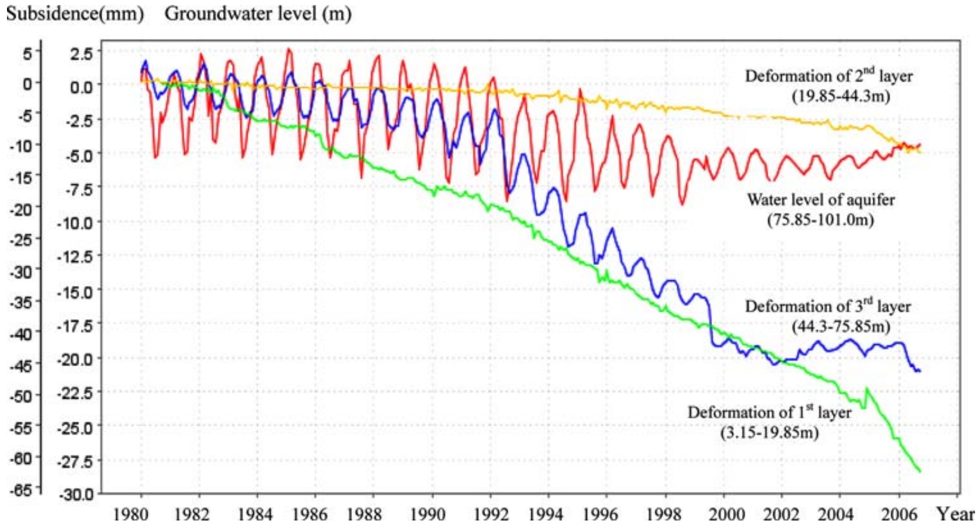

Fig. 2 Evolution of deformation of the soft layers, and groundwater-fluctuation level in Shanghai

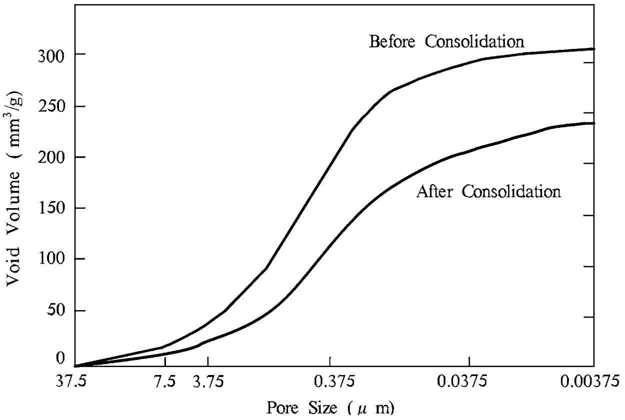

Fig. 3 Pore-size distribution of shallow Shanghai soft clay (4 m) and shallow Shanghai soft clay after consolidation at 200 kPa (equivalent to burial 40 m below land surface)

aggregated micelles and fine nonclay grams having the same size as aggregates (0.01–0.015 mm). Aggregates are formed by different clay minerals and dispersed, fine, broken nonclay grains. Aggregates bond weakly, forming pores several microns in size. The smallest structural components and fundamental structural unit of the Shanghai soft clay are hydrated lamellae or micelles. Lamellae are relatively stable particles formed of stacked crystalline sheets of a clay mineral. The morphology of lamellae depends on the clay mineral. Based on quantitative estimations of minerals in clay granules, the Shanghai soft clay contains mainly illite and montmorillonite; most other common clay minerals are present in smaller amounts (He 1989). Illite lamellae are parallel flakes and montmorillonite lamellae are wrinkled flakes. Lamellae are bound together forming inter-laminar pores (Figs. 4, 5). The large number of inter-lamellar pores explains why the Shanghai soft clay has a high percentage of medium-size pores. The distribution and interconnection of pores determines the rate of dewatering during consolidation. The size of all pores decreases under load.

Physio-chemical properties of Shanghai soft clay

Shanghai soft clay has a pore ratio greater than 1; the volume of water at saturation is greater than the volume of solids. Previously, little attention has been is given to the liquid phase. Physio-chemically, however, soil surfaces and water are not inert. Water and soil particles interact, influencing physical and physio-chemical properties of materials. Physio-chemical interaction between soil and water proceeds relatively slowly, but its effects can be significant. Therefore, one must analyze physio-chemical deformation mechanisms within the soft clay.

Chemical composition of pore fluids

The concentration of easily soluble salts in soils can be used to infer the degree of clay micelle flocculation. When salt content varies from high to medium to low, the stability of a colloidal suspension of dispersed clay micelles varies from unstable (flocculated) to stable (dispersed) and then to substable (semidispersed). Generally, when the salt content in Shanghai soft clay is greater than 500 mg/100 g soil, micelles flocculate rapidly; with a salt content of 300–500 mg/100 g soil, micelles are in the highest state of dispersion; and with salt of less than 300 mg/100 g soil, micelles are in state of semidispersion. During sedimentation of the Shanghai soft clay, micelles flocculated and precipitated to form a marine deposit with a flocculated structure because of the high electrolytic concentration of ocean water (primarily, the concentration of NaCl).

Table 2 Pore-size distribution after consolidation of soft clay

Sample no.	Consolidation pressure (MPa)	Consolidation degree (%)	Pore volume (mm^3/g)	Variance (%)	Pore size distribution (%)									
					>7.5 µm	Variance (%)	7.5–3.75 µm	Variance (%)	3.75–0.375 µm	Variance (%)	0.375–0.0375 µm	Variance (%)	<0.0375 µm	Variance (%)
1238	0.2	13.45	245.70	−21.68	4.07	−1.69	2.44	−68.10	40.29	−23.85	36.22	+27.63	16.98	+145.28
1239	0.3	11.18	242.87	−22.64	3.71	−41.76	1.22	−61.76	44.47	−13.82	35.00	+19.45	15.60	+63.52
1240	0.4	9.53	234.21	−21.17	2.27	−25.08	1.28	−68.32	40.81	−21.77	42.34	+29.72	13.30	+63.79

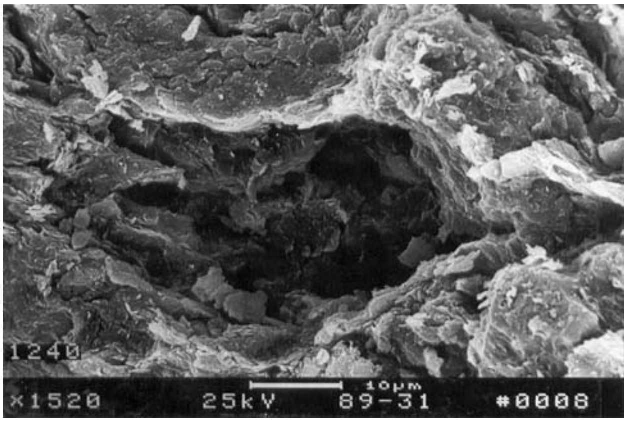

Fig. 4 Electron microscopic photo of pores in a first-level (*Gray* sludgy soil) structural unit

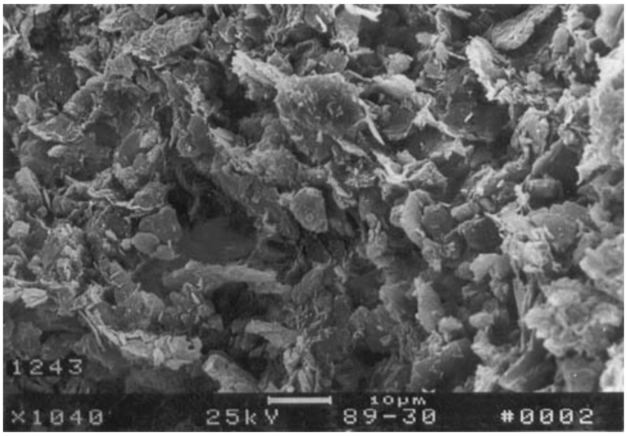

Fig. 5 Electron microscopic photo of pores in a second-level (*Gray* clay) structural unit

The chemical composition of pore water was determined by analyzing fluid extracted from a mixture of deionized water and Shanghai soft clay in a 10:1 ratio. With the exception of the shallowest clays, the predominant cation dissolved in pore fluids is Na^+, usually accounting for between 50 and 86% of total cations in solution. The primary anion in pore fluids is Cl^-, accounting for between 37.3 and 67.4% of total anions in solution. The percentage of dissolved Na^+ and Cl^- in the shallow clay layers and in one sandy zone is significantly lower probably because of meteoric flushing of connate water with fresher water infiltrating to and moving through the shallow groundwater-flow system.

The electrolyte concentration and predominant cation in pore fluids influence flocculation and dispersion of clay micelles. High concentrations of dissolved NaCl or plentiful dissolved Ca^{2+} will compress the electrical double layer of clay micelles, decreasing the ability of negatively charged micelles to repel one another. Micelles then approach each other more closely, allowing short range forces (Van der Waals forces) to join individual micelles, promoting flocculation of colloids. Low concentrations of dissolved NaCl in pore fluids will promote dispersion of clay colloids by increasing physio-chemical repulsion between clay micelles. As a result, the soft clay will convert from a flocculated to a dispersed structure. Because pore-solution composition varies within the soft clay, the type and stability of the clay structure will also vary. Artificial injection of fresh water can initially dilute the high concentration of NaCl electrolytes in pore fluids causing dispersion of clay micelles, but continuous injection of large quantities of $CaHCO_3$-type water will again cause flocculation of clay granules, increase aggregation, reduce swelling pressures, and promote consolidation of the soft clay.

Cation-exchange properties

Shanghai soft clay is relatively inactive as a cation-exchanger with a CEC between 11.92 and 23.53 meq/100 g. There is no significant difference between the amounts of exchangeable Ca^{2+}, Mg^{2+}, and Na^{+}. Content of exchangeable Ca^{2+} ranges from 5.09 to 12.18 meq/100 g (30.39–61.27% of the CEC), content of exchangeable Mg^{2+} ranges from 1.46 to 9.97 meq/100 g (11.54–44.85% of the CEC), and content of exchangeable Na^{+} ranges from 0.82 to 4.88 meq/100 g (4.5–27.34% of the CEC). Mg^{2+} and particu1arly Na^{+} increase repulsion of clay granules and promote their dispersion. Because exchangeable Ca^{2+} is not absolutely preponderant, it has a weak effect on flocculation of clay colloids. Therefore, although clay colloids in soft clay tend mainly to flocculate, the flocculation strength is low and the flocculation structure is in a substable state. This is one reason why Shanghai soft clay is weak, easily compressed, and unstable.

Specific surface area characteristics

The specific surface area, the sum of inner and outer surface area per unit weight of soil granules, depends on the content of clay granules and the type of clay minerals. Surface forces on clay granules increase gradually as granule size decreases. When granules are less than 1–2 μm, surface forces have a significant effect on soil properties. Specific surface area is an important index of the physio-chemical activity of clay. The specific surface area of Shanghai soft clay is between 59.14 and 129.37 m^2/g, within the normal range of clay but much less than the specific surface area of bentonite, which is typically hundreds of m^2/g. The physio-chemical activity of Shanghai soft clay is moderate, but the bonding between clay mineral granules is weak and the structure is unstable.

Conclusions

Macroscopic unfavorable engineering characteristics of the Shanghai soft clay, such as high compression and low strength, are closely related to its microscopic characteristics. Shanghai soft clay granules are not stable in water, but rather are unstable or substable aggregates. The water stability of clay aggregates is closely related to the concentration of electrolytes in pore fluids. Artificial injection reduces the concentration of dissolved NaCl in pore fluids, dispersing flocculated clay and increasing the colloidal activity of clay micelles. Long-term artificial injection of 1arge quantities of $CaHCO_3$ water will eventually flocculate soil granules and increase Subsidence; therefore, the microscopic characteristics of soft clay should be fully considered in selecting and implementing measures for controlling consolidation and deformation of the Shanghai soft clay.

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