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Experimental Research on the Marine Hydrodynamic Action on the Consolidation Process of the Sediments in the Yellow River Estuary*

YANG Xiu-juan (杨秀娟)[a, b, 1], JIA Yong-gang (贾永刚)[b],
LI Xiang-ran (李相然)[a] and SHAN Hong-xian (单红仙)[b]

[a] *Architecture Engineering Department*, *Wenjing College of Yantai University*, *Yantai 264005*, *China*

[b] *Environmental Science and Engineering College*, *Ocean University of China*, *Qingdao 266100*, *China*

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ABSTRACT

Based on the *in-situ* measurements, the impact of the marine hydrodynamics, such as wave and tide, in the rapidly deposited sediments consolidation process was studied. In the tide flat of Diaokou delta-lobe, one $2\ \text{m}\times 1\ \text{m}\times 1\ \text{m}$ test pit was excavated. The seabed soils were dug and dehydrated, and then the powder of the soil was mixed with seawater to be fluid sediments. And an iron plate covered part of the test pit to cut off the effect of the marine hydrodynamics. By field-testing methods, like static cone penetration test (SPT) and vane shear test (VST), the variation of strength is measured as a function of time, and the marine hydrodynamics impact on the consolidation process of the sediments in the Yellow River estuary was studied. It is shown that the self-consolidated sediments' strength linearly increases with the depth. In the consolidation process, in the initial, marine hydrodynamics play a decisive role, about 1.5 times as much as self-consolidated in raising the strength of the sea-bed soils, and with the extension of the depth the role of the hydrodynamics is reduced. In the continuation of the consolidation process, the trend of the surface sediments increased-strength gradually slows down under the water dynamics, while the sediments below $50\ \text{cm}$ are in opposite ways. As a result, the rapidly deposited silt presents a nonuniform consolidation state, and the crust gradually forms. The results have been referenced in studying the role of the hydrodynamics in the soil consolidation process.

Key words: *Yellow River estuary*; *seabed soil*; *marine hydrodynamics*; *consolidation process*

1. Introduction

The Yellow River originates from Qinghai Province, and it has a length of $5464\ \text{km}$ and a catchment's area of $752000\ \text{km}^2$ (Qian *et al*., 1993). Compared with other rivers in the world, the Yellow River is well known for its high sediment concentration (Milliman and Meade, 1983). Since the 1980s, numerous studies have focused on the variation of the soil strength, which is caused by the self-weight and the hydrodynamics. For the same soil, the strength gradually increases with depth by

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1 Corresponding author. E-mail: ylinyu@163.com

self-weight (Chen, 1998), whilst it appears a non-uniform change in the depth which is caused by the hydrodynamics (Shan *et al*., 2004; Zhang *et al*., 2007). The sediments micro-structure (Wang *et al*., 2004a), mineral composition (Wang *et al*., 2004b), grain skeleton (Liu, 2004), and the granular cementation (Shan *et al*., 2006) are different from the soil in the self-weight consolidation. There are preliminary studies on the sediment deposition and consolidation process in the Yellow River mouth. However quantitative analysis about the role of the marine hydrodynamics, such as waves and tidal waves, in the sediments consolidation process, is lacking. Therefore, this paper discusses the sediment consolidation, and compares the strength variation under the self-weight with under the *in-situ* marine hydrodynamics.

2. Study Areas

Located on the west coast of the Bohai Sea with a land area of $5500\ \text{km}^2$ (Fig. 1), the modern delta of the river has shaped since 1855 when a major switch in its lower course took place. The Diaokouhe deltaic lobe examined in this paper, was formed after a displacement of the river mouth in 1965 and abandoned after 1976. At the forming time of this deltaic-lobe, the river discharge of sediment into the river mouth was about 10.6×10^8 t/a . Large amount of terrigenous substances under the coalition effect of marine agent and runoff accumulated rapidly in forming protruding spit and prograding the subaqueous deltaic accumulating body (Yu, 2002). The high silt content and rapid deposit cause the frequent diversion or shift of the river course. The abandoned lobe after diversion or shifting would happen to be eroded by wave and regressed as losing the source of sediment supply (Li *et al*., 1998). The deltaic underwater slope, including tidal flat and its lower part, the gradient of their surface is very gentle, generally $< 0.6^\circ$, the sea apart from the coast off 10 km more (Prior *et al*., 1986), its water-depth only 10 meters more, and the tidal flat about several kilometers broad is exposed during ebb tide. So it provides the convenience in a variety of field works in the tidal flats (Jia *et al*., 2007).

The residual current in the Yellow River mouth is mainly driven by wind, with a mean velocity of $0.10 \sim 0.25$ m/s . The surface residual current and local waves are subject to the monsoon, and generally direct southward in the winter and northward in the summer (SPSTC, 1991). The flood current generally flows SSE and the ebb current directs NNW (SPSTC, 1991; Chen, 1988; Wang and Su, 1989).

To acquire the physical properties of the soils in the delta, four 1-m long holes were drilled in the delta near Pile 19 (Fig. 1). Additionally, documented data of physical properties and grain size composition of deposits from the samples were measured (Table 1). Sand content in the soils is from 0 to 9.6%, and the clay content is between 0.8% and 4.8%, while the silt content is the main, from 85.6% to 99.2%. As a result, the sediment is named silt. While Quartz, Feldspar, Calcite and Dolomite make up main minerals, which is 75.8% in the silt, and it might have calcareous cementitious in the minerals. Clay minerals, part of them are illite, chlorite, Kaolinite and Montmorillonite, accounted for 24.2%.The higher clay content, the lower intensity, and the bigger deformation, even the easier to soften after soaking (Shen, 1996).

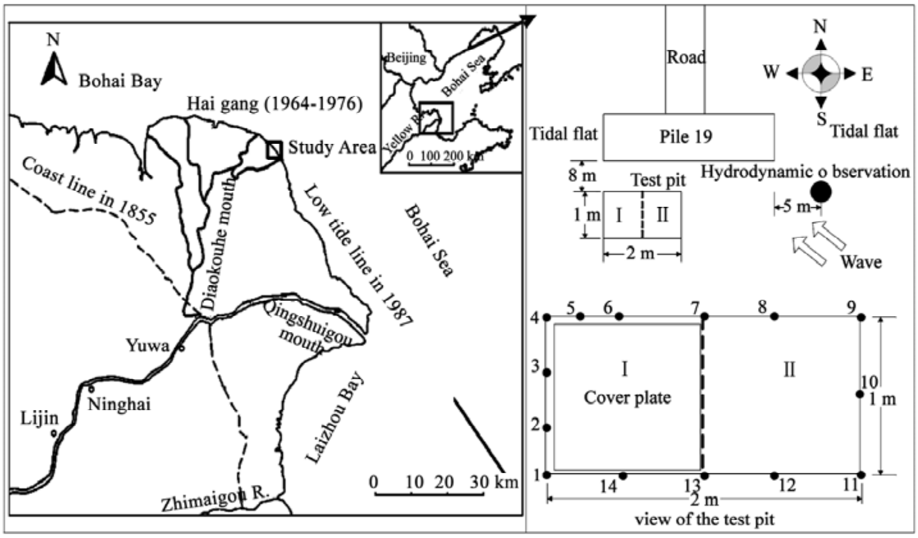


Fig. 1. Location and arrangements of the research area.

Table 1 Physical and mechanical properties of the silt

Physical properties		Water radio limit		Strength index		Formation index	
Moisture (%)	22.6~29.3	Plasticity index	7.7~8.7	Cohesive force (kPa)	10~25	Compression coefficient (MPa^{-1})	0.119 ~ 0.205
Wet density (g/cm^3)	1.88~2.00						
Void ratio	0.67~0.81	Liquidity index	0.34~0.71	Inner friction angle (°)	49.3~ 52.2		
Saturation degree (%)	95~100						

3. Methods

In the tide flat of Diaokou delta-lobe, one $2\ \text{m}\times 1\ \text{m}\times 1\ \text{m}$ test pit was excavated (Fig. 1). The fluid sediments simulating the rapidly deposited seabed silts were made *in-situ*, and a $1\ \text{m}\times 1\ \text{m}\times 0.1\ \text{m}$ iron plate covered part of the test pit to cut off the effect of the marine hydrodynamics. Then the pit became two pits, one is named Ⅰ without hydrodynamics; the other in the east, under the hydrodynamics action, is named Ⅱ. A $1\ \text{m}\times 1\ \text{m}\times 0.1\ \text{m}$ iron plate was made to suit the west pit. In spring tide, the iron plate covered the west pit everyday to prevent the wave and tide. While in ebb tide, the plate was moved. In order to prevent the pit collapse, 14 wooden poles, 3 cm in diameter and 190 cm high, were driven into soil around the pit with 20 cm high exposed, marked the numbers 1~14. An electrical receptivity pole was put into the pit to test the soil electric property. Daily strength measurement has been carried out by the SPT and vane shear test in the two areas from July 13 to July 29, each of them having one about 1-m deep measuring point.

East of the pit, the wave-tide instrument and the current-meter were placed (Fig. 1). In the test moment, from July 13 to July 30, the wave and tide data were collected consecutively. The curves of the data as a function of time were in Fig. 2. According to the data, the speed of the wave is low; the maximum speed is 34.8 cm/s , while the mean speed is 18.7 cm/s . And the depth of water is between 0.6 m and 1.0 m . While in July, the water temperature is always higher than $24\,^{\circ}\mathrm{C}$. And from the wave index, the minimum 1/3 wave height is 2 cm , the maximum 1/3 wave height is 24 cm with the mean being 4 cm . The wave period is in 4 ~ 6 s .

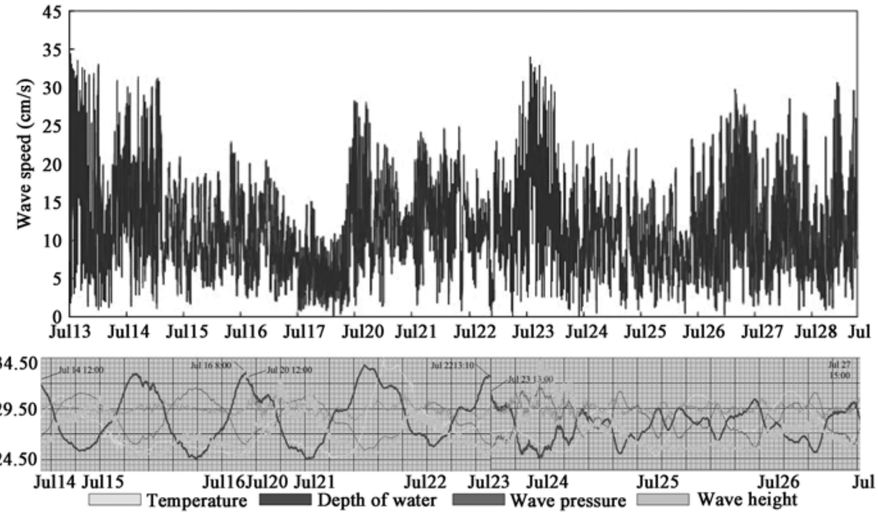


Fig. 2. Curves of the marine hydrodynamics.

4. Results

4.1 Self-weight Consolidated Process of the Rapidly Deposited Sediments

According to the documented data of the SPT and VST in Ⅰ, the variation of the penetration resistance of the soil in self-weight consolidated process is shown in Fig. 3, and the undrained shear strength and the sensitivity of the soil in different depth are given in Fig. 4.

On July 13, the homogenous soil was made and put into the pit quickly. Then penetration resistance and the undrained shear strength of the soil were measured everyday. On the second day, the soil below 50 cm depth consolidated immediately, with more than 2.93 MPa . While in the first two days, the sediment was under consolidation and affected by the consolidation pressure, thus sediments penetration resistance increased linearly in the depth direction. It then increased slowly until stabilized. It is shown that the sediments demonstrated the characteristics of self-consolidation. As a function of time, the penetration resistance of the soil in Ⅰ increased from 13 July to 17 July, and then decreased until 20 July. In the end it increased until stabilized.

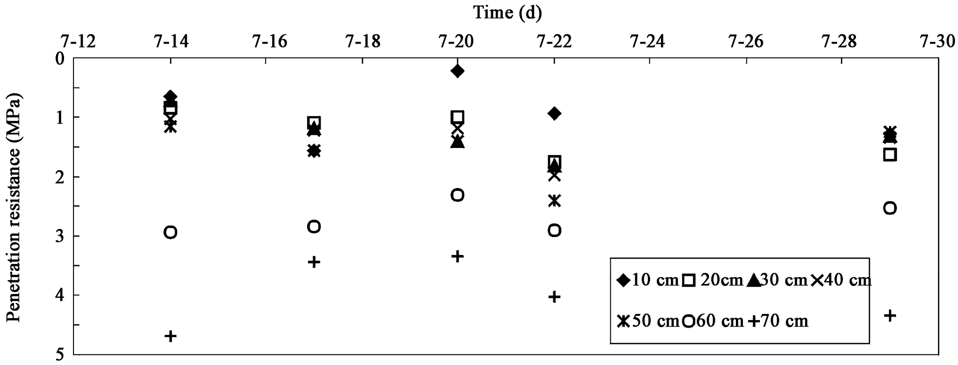
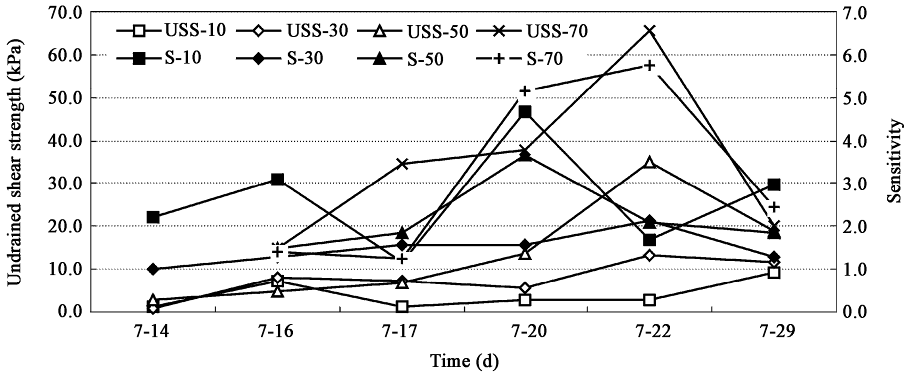


Fig. 3. Variation of the penetration resistance in different depth in Ⅰ.

The undrained shear strength displayed the same trend of the strength, and on the first day, the strength in 70 cm depth was big and it increased slowly. And above 50 cm depth, soil strength increased in the same trend. On 29 July, the strength increased as a function of depth. While in 10 cm depth, the soil sensitivity varied from 1.1 to 4.6, averaged 2.63, and namely it was high-middle sensitive soil. And in 30 cm depth, the soil sensitivity varied from 1.0 to 2.1, averaged 1.48. In this layer the soil was low sensitive. While from 50 cm to 70 cm, soils sensitivity was between 1.26 and 5.75, and the mean was 2.70. Namely it was middle sensitive soil.



USS: Undrained shear strength, S: Sensitivity

Fig. 4. Variation of the undrained shear strength and sensitivity in different depth in Ⅰ.

4.2 Consolidation Process under the Hydrodynamics

Compared with the sediments in area I, not only the self-weight operated but also the marine hydrodynamics reacted in Ⅱ. While in this environment, the consolidation process was quicker than that of the sediments in I, and its strength was closer to the seabed soils strength on July 29, namely about 17 days later, and the sediments had the same consolidation state with the undisturbed seabed soil.

In Fig. 5, the increase of the sediments strength is very fast. And on the first day, a crust appeared in 20 cm depth which is about 20 cm thick. And then this crust changed its location and thickness. In the end it stabilized in 10 cm depth about 20 cm thick. The strength was non-linearity in depth at first and increased non-uniformly with depth. At last, the sediments strength was nonuniform under the hydrodynamics action. According to the strength changes following time, two layers were divided, above 50 cm depth was the first layer, and below 50 cm depth was the other. As the first layer's strength changed day by day remarkably, yet the second layer's change was slow. Thereby, the marine hydrodynamics made great contribution to the soil strength increasing and its nonuniform state, especially above 50 cm depth, even the crust.

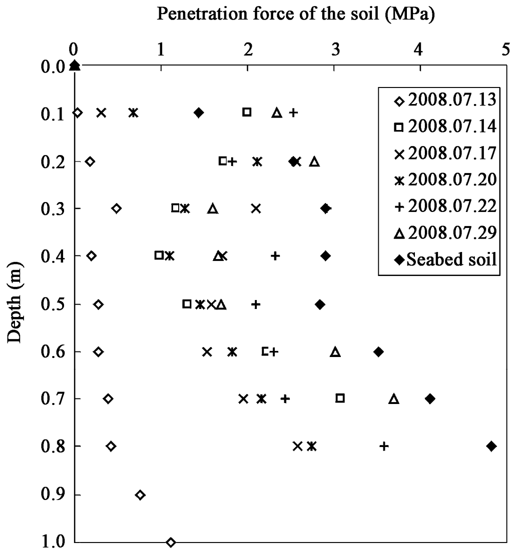
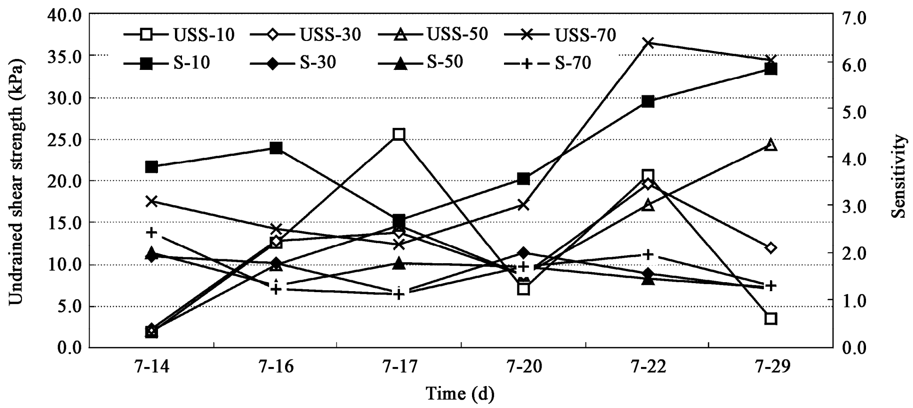


Fig. 5. Penetration resistance as a function of depth in Ⅱ.



USS: Undrained shear strength, S: Sensitivity

Fig. 6. Variation of the undrained shear strength and sensitivity in different depth in Ⅱ.

While in Fig. 6, the sediments undrained shear strength always increased day by day. From 10 cm to 50 cm, the strength of soil increased quickly, and it was not clearly different between those three layers from 14 July to 22 July, while on 29 July it was clear that the 10 cm depth soil had the smallest strength, and the next one was the 30 cm depth soil, while the 70 cm depth soil had the largest strength and it was big even on the first day. In the 10 cm depth, the soil sensitivity varied from 2.68 to 5.83, and namely it was high-middle sensitive soil. And from 30 cm to 70 cm, soil sensitivity was between 1.1 and 2.4, and namely it was middle-low sensitive soil.

5. Discussions

By comparing the two different consolidation processes, the marine hydrodynamics have a decisive impaction on the primary consolidation process. The documented data in this test show that the sediments strength in Ⅱ is under hydrodynamics and self-weight action, and the strength in I is without the marine hydrodynamics. Supposing that the strength data in Ⅱ minus the strength data in I is the hydrodynamics action on the sediments, we get the ratio of the hydrodynamics action to the self-weight action in Figs. 7 and 8.

According to the comparison of the tests, the proportions of action were mostly between –0.5 and 1.5, and the maximum as well the minimum occurred in the 10 cm depth. It means that marine hydrodynamics have a great effect on the surface. And it is beeline as a function of depth, gradually decreases, namely the role of the hydrodynamics is always reduced gradually with depth. From zero to 50 cm depth, most of the proportion is larger than zero, and the hydrodynamics make the soil stronger. On the contrary, below depth, the proportion is smaller than zero, that is, the hydrodynamics effect on the soil is negative. And as a function of time, this positive effect decreases day by day, while a hard layer appears between 10 cm and 50 cm depth. It can be noted that the emergence of the hard layer is directly related to the hydrodynamics.

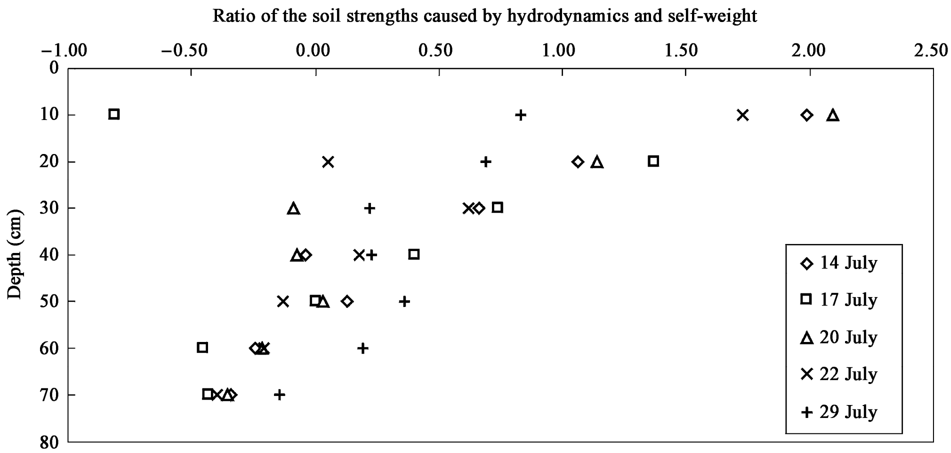


Fig. 7. Ratio of the penetration resistance in SPT.

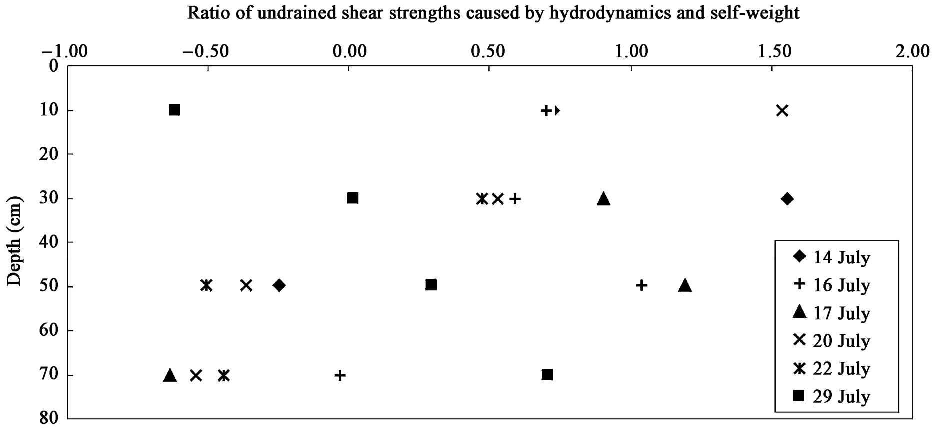


Fig. 8. Undrained shear strength in vane shear tests.

6. Conclusions

According to the field tests, the impact of the marine hydrodynamics, such as wave and tide, on the rapidly deposited sediments consolidation process was studied. It is shown that the self-consolidated sediments strength linearly increases with the depth. In the consolidation process, in the initial, wave and tide play a decisive role, about 1.5 times as much as that of the self-consolidated in raising the strength of the sea-bed soils, and with the extension of the depth the role of the hydrodynamics is reduced. In the continuation of the consolidation process, the trend of the surface sediments' increased-strength gradually slows down under the water dynamics, while the sediments below 50 cm are in the opposite ways. As a result, the rapidly deposited silts present a nonuniform consolidation state, and the crust gradually forms.

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