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Field and laboratory resistivity monitoring of sediment consolidation in China's Yellow River estuary

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ABSTRACT

Traditional methods for in situ monitoring of the dynamic physical process within marine sediments are not efficient and effective enough, and determination of the consolidation state of marine sediments in the Yellow River estuary remains a challenging problem. However, the recent development of in situ testing technology for resistivity methodology creates new possibilities. Our combined analysis of laboratory and field experimental results demonstrates the consolidation process and the contemporaneous physical, mechanical and electrical properties of marine sediments in the Yellow River estuary, and we discuss the feasibility of and that influence in situ monitoring of the sediment consolidation process using a multi-electrode probe. These results demonstrate that resistivity is a good indirect predictor of porosity, which is the primary factor affecting resistivity behavior during the consolidation process. Values for empirical constants *a* and *m* for Yellow River estuary sediment can be obtained based on Archie's formula. The relationship between resistivity and the geotechnical strength of silty sediments in the Yellow River estuary shows that the penetration resistance (determined by a light penetration test) and undrained shear strength (determined by a vane shear test) are closely correlated to resistivity with a power function during the consolidation process of a uniform-originated seabed. This study confirms that resistivity monitoring using a multi-electrode probe is a relevant method to estimate the degree and state of sediment consolidation in real time and in situ. More work is needed to investigate the implications of this for the prediction and prevention of geological disasters in estuarine areas.

1. Introduction

The Huanghe River (Yellow River) is the world's largest contributor of fluvial sediment load to the ocean (Ren and Shi, 1986; Wang and Aubrey, 1987), carrying vast amounts of sediment to areas with weak tides and strong accretion in continental estuaries. Approximately 80% of these sediment loads are deposited quickly in the estuary delta (Bornhold et al., 1986; Saito et al., 2001). The dynamic behavior of marine sediments is driven by a complex interaction between oceans and lands interacting over varying spatial and temporal scales (Talke and Stacey, 2003). The engineering geological properties of the Yellow River delta are unstable and geological hazards are common, including landslides, liquefaction and subsidence, due to the long-term impact of wave and tidal current on the silty sediments deposited in the complex sedimentary environment (Feng et al., 1999). Consolidation behavior and contemporaneous changes in geotechnical properties are responsible for providing failure-resisting characteristics in the freshly deposited sediments (Meng et al., 2010). Therefore, study of the consolidation process in silty sediments of the Yellow River estuary is of great significance for the prediction and prevention of geological disasters in estuarine regions.

Field studies have been performed in the Yellow River delta by international scholars since the 1980s. Offshore, Prior et al. (1989) observed in situ seabed displacement characteristics in response to storm waves using an inclinometer, acceleration device, and pressure sensors. On shore, Shan et al. (2006), Yang et al. (2010) and Jia et al. (2011) have investigated the seabed response to wave action using field-testing methods, such as the static cone penetration test, the field vane shear test, and the pore water piezometer test, to reveal the non-uniform consolidation phenomenon of rapidly deposited silts. However, these geotechnical field testing methods are not feasible in extreme sea conditions or for long-term and real-time monitoring of the consolidation process of seabed sediments.

Electrical resistivity, one of the basic physical properties of soil, is linked to other soil physical and mechanical parameters. The physical and statistical relationships among geoelectric and physical properties are well established in the literature (e.g., Arichie, 1942; Keller and Frischknecht, 1966; Waxman and Smits, 1968; Guo et al., 2003; Liu et

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al., 2004). A practical application of electrical resistivity theory, resistivity monitoring methods have been increasingly used to solve engineering and environmental problems, including soil micromorphology (e.g., Fukue et al., 1999), monitoring of soil liquefaction (e.g., Jinguuji et al., 2007), and testing for soil pollution levels (e.g., Fukue et al., 2001). Nevertheless, attempts to relate the geotechnical properties of marine sediments to resistivity data are rare. In the Le Havre site (France), Lagabrielle et al. (2000) showed that resistivity profiling in a sea water environment can describe the offshore alluvium stratigraphy and describe its characteristics in terms of thickness and mechanical strength. Giao et al. (2003) mapped Pusan soft clay deposits in four reclamation sites and found no definitive relationships between the investigated geotechnical parameters (i.e., plasticity index, water content and unit weight) and resistivity. Cosenza et al. (2006) established qualitative and quantitative correlations between electrical and geotechnical data from Garchy (Nièvre, France) in a simple geological context and obtained a satisfactory quantitative correlation between inverted resistivity extracted from Electrical Resistivity Tomography (ERT) sections and measured water content. However, these results cannot be compared directly with each other for several reasons. The geotechnical parameters involved in these studies are not directly related with each other, and the resistivity measurement techniques used differ, resulting in a discrepancy in the precision of resistivity data.

In light of the interdependence and complexity of the factors that influence electrical resistivity in marine sediments, this study focuses on the consolidation process and the contemporaneous physical, mechanical and electrical properties of marine sediments in the Yellow River estuary observed in both the laboratory and in the field. Point-electrode and ring-electrode resistivity probes are designed to automatically detect the electrical resistivity of sediments in real time. From comparisons of simultaneous measurements of sediment physical and electrical properties, we infer how naturally occurring processes affect the electrical properties and analyze relationships between resistivity and sediment physical and mechanical properties during the consolidation process. This multi-electrode probe is a new method for in situ monitoring of sediment consolidation and can help to enhance the understanding of coastal sediment dynamics through real-time acquisition of sediment properties at specific sites.

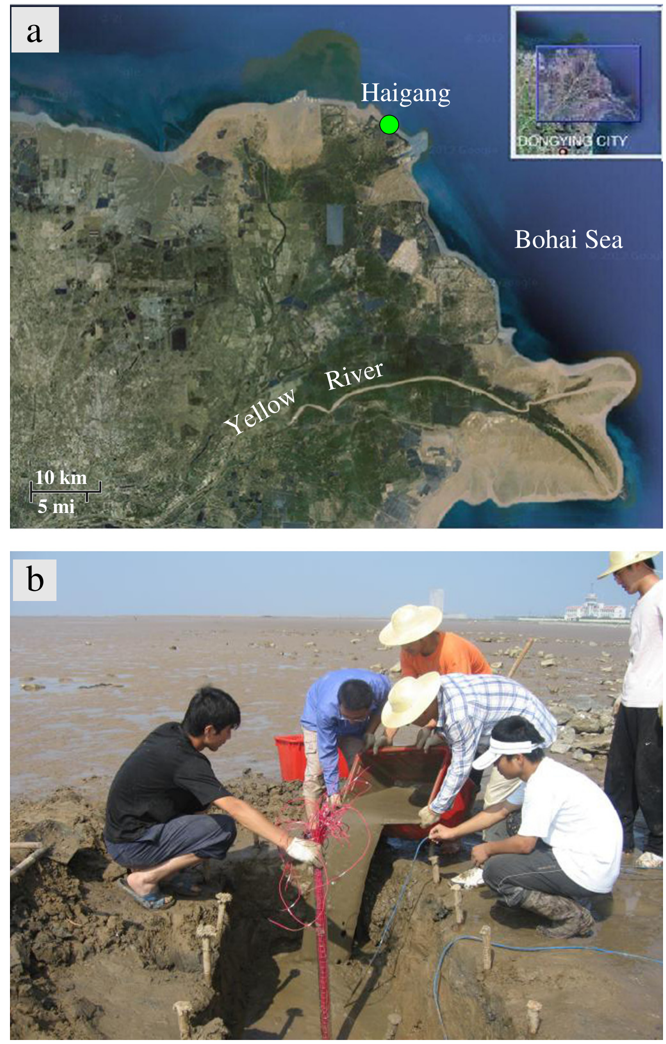

Fig. 1. a. Satellite remote sensing map of the modern Huanghe (Yellow River) delta. Haigang, where the soil samples were taken and the field test area located, is marked with green solid circle in the map. b. Photo of field test area, which is marked with the green rectangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

2. Materials and methods

2.1. Field experiments

For the field experiments, a test site was established on Haigang pile 19 of the Shengli Oil Field (38°04′05.2″N, 118°56′48.9″E), which is located in the northern mouth region of the Yellow River forming during the period from 1964 to 1976 (Fig. 1a). The gradient of the deltaic underwater slope, consisting of a tidal flat and its lower part, are so gentle (generally <0.6°) that the width of the exposed tidal flat can extend several kilometers during low tide, providing convenient conditions for field testing (Jia et al., 2011). The tidal cycle for the test site is irregularly semidiurnal, with a mean tidal range varying from 0.7 to 1.7 m, and an extreme of 2.17 m. The maximum tidal flow rate is above 120 cm/s. The average wave height is less than 0.5 m, and the largest is 3.3 m. Under extreme conditions, wave heights will reach 5.8 m (Cheng and Xue, 1997). During the field test in July of 2008, wave heights were approximately 0.02 m with light winds. The field test site consisted mainly of silt, with silt content ranging from 85.6% to 99.2%, clay content from 0.8% to 4.8%, and sand content from 0 to 9.6% (Yang et al., 2010). The physical and mechanical properties of the silt are listed in Table 1, and the mineral and clay compositions are presented in Table 2.

In order to observe the rapid deposition and consolidation of marine sediments, a test pit (2 m × 1 m × 1 m) was excavated in the tide flat, and 14 wooden poles (3 cm diameter and 190 cm height) were driven into the seabed along the boundary of the test pit to avoid pit collapse (Fig. 1b). The original soil in the test pit was dug out manually using spades and put into a container with local sea water added until the processed soil sample had a water content of approximately 30%. After the soil had been soaked for 30 min, it was stirred until a homogeneous slurry was formed. The slurry was backfilled into the test pit to simulate the fast deposition processes of sediments discharged from the Yellow River. Measurements of pore water pressure, sediment strength and the electrical properties of the deposited sediments were carried out synchronously during the experiments.

Electrical resistivity measurements were made using a Geopen E60BN-type multi-electrode resistivity survey system and a probe rod with ring electrodes, which was similar to the one developed by Campanella and Weemees (1990). As shown in Fig. 2a, 48 ring copper electrodes were located on the perspex rod at intervals of 2.5 cm. The cross-sectional area of the electrodes was 1.5 mm^2. The diameter of the probe rod was 5 cm. The resistivity-depth log was obtained with multi-Wenner arrays. The elementary Wenner array is an electrode configuration in which four electrodes are deployed in a line, with equal spacing between each measuring electrode (M or N) and its nearest current electrode (A or B). The potential of the medium between M and N electrodes can be measured (Fig. 2a). A detailed