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# Deposited sediment settlement and consolidation mechanisms

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**Abstract**

In order to study deposited sediment settlement and consolidation mechanisms, sediment settlement experiments were conducted using a settlement column. Based on the experimental results, sediment settlement stage definition, excessive pore pressure (EPP) dissipation, and consolidation constitutive equations are discussed. Three stages, including the free settlement, hindered settlement, and self-weight consolidation settlement stages, are defined. The results of this study show that sediment settlement is mainly affected by the initial sediment concentration and initial settlement height, and the interface settlement rate is linearly attenuated with time on bilogarithmic scales during the hindered settlement and self-weight consolidation settlement stages. Moreover, the deposited sediment layer in the self-weight consolidation settlement stage experiences large strains, and the settlement amount in this stage is about 32% to 59% of the initial height of deposited sediment. EPP is nonlinearly distributed in the settlement direction, and consolidation settlement is faster than EPP dissipation in the self-weight consolidation settlement stage. Consolidation constitutive equations for the hydraulic conductivity and effective stress, applicable to large-strain consolidation calculation, were also determined and fitted in the power function form.
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*Keywords:* Sediment settlement experiment; Deposited sediment; Self-weight consolidation; Large-strain consolidation; Interface settlement rate; Consolidation constitutive equation

## 1. Introduction

Sediment deposition induced by sediment particle settlement and consolidation occurs frequently in port and waterway engineering. Deposited sediment generally has a high void ratio, high compressibility, and high moisture content, and cannot be directly used in engineering (Bryant et al., 1975; Carrier et al., 1983; Merckelbach, 2000). Long-term sediment deposition has caused serious hydraulic problems, such as port and river deposition, which has hindered the development of waterway transport and the normal operation of basic water conservancy facilities. In addition, potential land space expansion in coastal cities is urgent for future development, and the hydraulic fill method is considered the most effective way (Xu et al., 2012; Imai, 1980). Therefore, deposited sediment settlement and consolidation mechanisms require further systematic research and understanding.

Numerous basic studies have been conducted of high moisture-content sediment settlement (Imai, 1980, 1981; Zhan et al., 2008), and have mainly focused on the definition of different settlement stages according to the effective stress development and excessive pore pressure (EPP) dissipation processes. There are two sediment states during the settlement process: the suspension fluid and softly plastic solid states. In the suspension fluid state, no effective stress exists between sediment particles or flocs (Pane and Schiffman, 1985; Abu-Hejleh et al., 1996); this is defined as the initial free

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settlement stage with a constant interface settlement rate. In the softly plastic solid state, effective stresses appear and are transferred between flocs, and the interface settlement rate is attenuated with time; this is defined as the hindered settlement stage. With settlement going on, effective stresses are transferred between sediment particles, leading to the weight consolidation settlement stage (Been and Sills, 1981). The main factors in settlement stage definition are the critical values for different stages, and the critical moisture content or void ratio is usually chosen as a quantitative indicator in current research. Monte and Krizek (1976) first proposed the concept of zero effective stress status, in which the void ratio is defined as the initial void ratio. The concept of zero stress status has been generally accepted by many scholars as a criterion for definition of the initial free settlement stage (Michaels and Bolger, 1962; Carrier et al., 1983; Merckelbach, 2000; Imai, 1980). However, the initial void ratio for different sediments is still difficult to determine, and it is affected by many factors, such as the initial sediment concentration, initial settlement height, and particle grain size.

According to Michaels and Bolger (1962) and Ma and Pierre (1998), single floc structures formed by clay particle flocculation occur in the initial free settlement stage, and the suspended sediment interface appears as the sediment concentration reaches a certain limit. Subsequently, single particles and floc structures settle at different rates, and the deposited sediment layer also appears at the same time. The consolidation process of deposited sediment is induced by the self-weight load, and the nonlinear consolidation constitutive equation should be applied in consolidation calculation (Gibson et al., 1981).

In this study, a series of sediment settlement experiments was carried out under different initial conditions to obtain a better understanding of the settlement process of high moisture-content deposited sediment. The sediment settlement behaviors and factors were studied, the relationship between EPP dissipation and self-weight consolidation under large nonlinear strains was investigated, and, finally, the consolidation constitutive equations for the hydraulic conductivity and effective stress, applicable to large-strain consolidation calculation, were determined in the power function form as well.

## 2. Sediment settlement experiments

### 2.1. Physical properties and experimental program

Deposited sediment for laboratory settlement experiments was sampled from Shenzhen Bay, near the Pearl River Estuary and South China Sea, as part of the *Regulation Project of Shenzhen River and Bay* program.

The sediment samples were in the fluid state with the initial moisture content of 66.3%. Results of experiments on basic physical properties showed that the density was 1.61 g/cm$^3$, and the specific gravity was 2.69. Moreover, the liquid and plastic limits were $\omega_L = 48.2\%$ and $\omega_P = 28.8\%$, respectively.

In the organic content test, the burning method was applied, and the measured organic content in the sediment samples was 7.9%, which was higher than the standard value of 5%, so the deposited sediment from Shenzhen Bay had a high organic content, mainly induced by shellfish debris. According to the relative location of deposited sediment to the A-line equation of $\omega_P = 0.73(\omega_L - 20)$ on Casagrande's plasticity chart, it could be defined as high-liquid limit organic silt soil (MHO) (Qian and Yin, 1996).

During the sediment settlement experiment, a settlement column made of PMMA was used, as shown in Fig. 1. An improvement of the settlement column system was the pore pressure measurement ports on the outside wall of the column in the settlement direction. Moreover, in order to obtain the greatest pore pressure with higher accuracy, a coarse sand layer and geotextile filter were set at the bottom of the column, as shown in Fig. 1(a). Each port was fixed with an inner geotextile filter and could be connected to tubes or piezometers for pore water observation in the settlement direction (Imai, 1980). This was to avoid clogging of the pore pressure port during the consolidation process. The pore pressure observation accuracy of tubes after calibration was expected to be 0.5 mm of water head, which was equivalent to a pore pressure of about 5 Pa.

In order to determine the self-weight load of deposited sediment in the settlement direction, it was necessary to take the sediment samples out of the settlement column for the moisture test. However, it would have been difficult to extract the sediment samples from the settlement column if it was too high. Thus, in this study, the high column was segmented into several continuous parts, as shown in Fig. 1(b), and the connected parts were encircled with PMMA rings and sealing tape to prevent water leakage. During the experiment, the upper PMMA parts were removed one by one, and the undisturbed or disturbed sediment samples could be extracted layer by layer for basic physical parameter tests.

During the sediment settlement experiments, six groups of suspended sediment, S1 through S6, were prepared at different initial sediment concentrations and settlement heights, as listed in Table 1. The initial sediment concentration (defined as the dry sediment weight per liter) of the six groups varied from 75 to 400 g/L, and the initial settlement heights of S1 through S4 were close to 0.980 m, while the values of S5 and S6 were close to 0.360 m. The settlement was expected to take one year or even longer to reach the final stable status. However, the actual duration of the settlement experiments in this study was about 120 days.

### 2.2. Settlement curves and settlement rate attenuation curves

According to the sediment settlement experiment, settlement curves for the six groups of sediment on bilogarithmic scales are shown in Fig. 2(a). The interface settlement rate can be obtained according to Eq. (1):

$$v = \frac{\partial h}{\partial t} = -\frac{\Delta h}{\Delta t} = -\frac{h_i - h_{i-1}}{t_i - t_{i-1}} \quad (1)$$

where $v$ is the interface settlement rate (m/s), $\Delta t$ is the time interval (s), and $\Delta h$ is the settlement amount (m) during $\Delta t$.

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