Laboratory study on response of underwater cohesive sediment to columnar vibration source

Peng Zhao, Feier Chen and Guoliang Yu

ABSTRACT

This paper investigates the responses of cohesive sediment to mechanical vibration by experimental observation, containing: (1) the dynamic soil pressure, dynamic pore water pressure and dynamic acceleration to the vibration source; (2) the soil pressure distribution in the near field centered in an artificial columnar vibration source. Under the mechanical vibration with a frequency of 200 Hz and an amplitude of 1.15 mm, the dynamic soil pressure, dynamic pore water pressure and dynamic acceleration of underwater viscous sediment were measured in the sediment of four different depositing conditions. Results of the dynamic soil pressure, dynamic pore water pressure and dynamic acceleration of underwater viscous sediment in the near field responding to artificial vibration source are exhibited and discussed. It is found that, excited by the sinusoidal vibrator, the soil pressure presents a response of statistical sinusoidal fluctuation with the same frequency to the vibration source. In the sediment of lower initial yield stresses, the soil pressure distribution distinctly tends to firstly increase and then decrease with distance. The amplitude of the soil pressure is attenuated exponentially with distance.

Key words | artificial columnar vibrator, cohesive sediment, liquefaction, rheology, soil pressure decay

INTRODUCTION

Cohesive sediments are widely distributed at the bottom of rivers, lakes and reservoirs. They are complex mixtures of inorganic minerals and organic material, deposited by a series of physical, chemical, biological effects (Grabowski et al. 2011). Suspension of the cohesive sediment and the internal pore water may significantly result in detrimental impacts for the aquatic environments, including re-releasing the deposited pollutant and reducing the light transmission (influencing plant production and benthic community health) (Droppo et al. 2009). However, the response of the sediment to external loads is unavoidable. When there is a vibration source (such as a pier) in the underwater sediment environment, the pore water in the near field of vibration source would locally oscillate within a certain distance. This kind of vibration may result in undesired suspension of the cohesive sediment which sequentially troubles the water resources management. Understanding the responding magnitude and distance range of the underwater cohesive sediment to the vibration would help with management of sediment and make internal pollutants more controllable. Meanwhile, a controllable vibration-induced sediment suspension may supply a potential application in the management of the deposited pollutant, i.e. regular release of the sediment interior pollutant in a certain distance range by applying a controllable vibrator. In general, it is valuable to understand the response of underwater cohesive sediment to vibration for water resource management.

In recent decades, the dynamic response of underwater sediment to vibration have been investigated by many researchers. Biot (1956, 1962) outlined the general motion equations of porous saturated media. Thereafter, many
studies modified the influence of soil liquefaction by vibration damping with an equivalent linear correction (Men 1966; Stoll & Bryan 1970; Tang 1975; Castellaro 2016; Sorace & Terenzi 2017; Zhang et al. 2017a, 2017b). Qiu (2010) presented a theoretical study of Biot flow-induced damping in saturated soil during shear wave excitations and discussed the effects of soil porosity, mass coupling, and non-Poiseuille flow on Biot flow-induced damping. Phillips & Hashash (2009) presented two new soil-damping formulations implemented in a nonlinear one-dimensional site response analysis for small and large strains. These formulations were used to construct a frequency-independent viscous damping matrix that reduces the over-damping at high frequencies and modifies the extended Massing loading/unloading strain-stress relationship. Treating the solid skeleton as equivalently linear, Qiu et al. (2015) and Qiu & Huang (2017) investigated the concept of effective density for the propagation of small-strain shear waves through saturated granular materials by resonant column tests with various granular materials in dry and saturated conditions.

On the other hand, rheological characteristics of cohesive sediment have been recognized as significantly affecting the dynamic response of underwater cohesive sediment to vibration. Rheological characteristics of cohesive sediment commonly refer to its exhibited dual characters of both elasticity and viscosity when suffering external shear stress. According to Yang et al. (2014), it is possible to distinguish a cohesive sediment responding process to an external load into three phases, as shown in Figure 1: the linear change phase, the shear losing phase, and the new equilibrium phase. In the linear change phase, soil shear stress increases gradually with the external shear force exertion until the yield point, \( \tau_{\text{HB}} \), and then the shear-losing phase begins. The viscosity and the shear stress of the sediment show an exponential decrease with time and the soil deforms substantially like a liquid. Finally, under further continuous shear force, the soil comes to a new dynamic equilibrium phase when its viscosity and shear stress approach another constant.

In recent years, sediment rheology has yielded valuable results. Huang & Aode (2009) studied the rheology of mud flows in Hangzhou Bay by a laboratory test, and found there was an exponential relationship between the sediment elastic modulus and the volume concentration. Cui & Bai (2014) reported the rheological properties of the cohesive sediment in Haihe Estuary, and found the cohesive sediment was elastic when it was under a small amplitude deformation. Yang et al. (2014) investigated the rheological properties of cohesive sediment under mechanical vibration loads, and argued that all the magnitudes, the shear speed and the shear duration of vibration may affect the rheological properties of cohesive sediment.

This study investigates the dynamic response of underwater cohesive sediment to the columnar vibration source based on the sediment rheology. The main objective is to study the dynamic process of soil pressure, pore water pressure and acceleration of underwater cohesive sediment responding to the columnar vibration, and the responding magnitude and distance range of underwater cohesive sediment affected by the columnar vibration. A laboratory test utilizing a cylindrical vibrating rod with a frequency of 200 Hz and amplitude of 1.15 mm in an underwater cohesive soil was conducted. Experiments encompassed epicenter distances ranging from 10 to 60 cm in five initial deposited conditions of cohesive sediment. In the experiment, several sensors were used to obtain the soil response to the vibration source, such as soil pressure, pore water pressure, and acceleration, in the near field of a vibrator. Results are shown and discussed briefly and illustrate that the underwater cohesive sediment in the new dynamic equilibrium phase exhibits a viscosity characteristic, rather than the elasticity features shown in the linear change phase. And magnitude variations of soil pressure against the distances were dimensionally analyzed by introducing the rheological

![Figure 1](https://iwaponline.com/wqrj/article-pdf/54/3/193/574573/wqrjc0540193.pdf)
model into the analysis. It was found that in the near field of a vibration source, the decay coefficient of the dynamic soil pressure is not constant but exponentially decreases with distance.

**METHODOLOGY**

**Discrimination of soil response to vibration source**

When the underwater sediment is under the vibration loads, pore water and soil particles in the sediment will move responsively to the vibration source. In a tiny space around the columnar vibration source, low pressure is formed as a result of vibrational extrusion. Then, due to the lower adhesion (Grabowski *et al.* 2011) of pore water than that of the soil particles, pore water will permeate to this space faster than the particles. The pressure will achieve a new equilibrium when the pore pressure is equal to the surface pressure of the sediment. In this scenario, the pore pressure can be regarded as an ‘excess’ component in the sediment (Cui & Bai 2014). The excess pore pressure damages the original soil structure, results in the saturated sediment tending to float or ‘boil’; the shear strength of the sediment is completely lost. The saturated sedimentary body is then considered to have been liquefied. In the present work, the instance when the pore water pressure reaches the peak and vertical acceleration of sediment changes significantly is regarded as the beginning of soil liquefaction (Figure 2).

For the soil pressure, its response to the columnar vibrator follows the principle of cylindrical wave diffusion. Figure 3 shows a mathematical view of the experimental setup for the model experiments used to study force propagation in underwater cohesive soil induced by artificial mechanical vibration. As the vibration mode of the vibrator is sinusoidal, the dynamic response of the cohesive sediments exhibited sinusoidal fluctuation of the same frequency as that of the vibration source. The amplitude of dynamic soil pressure at the surface of the vibrator is defined as $A_0$, the soil pressure amplitude at the distance of $r$ from the vibrator as $A_r$. The relationship between oscillating amplitudes and distances can be normalized as:

$$\frac{A_r}{A_0} = f\left(\frac{r}{r_0}\right) \quad (1)$$

where, $r_0$ is the radius of the vibration rod. Considering the liquefaction of soil by vibration, soil pressure in the present study was obtained when the vibration was in a steady state.

![Figure 2](https://iwaponline.com/wqrj/article-pdf/54/3/193/574573/wqrjc0540193.pdf)

**Figure 2** | Pore water responding to the vibration.
EXPERIMENTS

Experiment apparatus

The experiment was completed in a test system as shown in Figure 4, in the Key Laboratory of Ocean Engineering at Shanghai Jiao Tong University. This system comprised a 1.2 m high shelf in an acrylic tank of inner diameter $\phi = 80$ cm and depth of 1 m filled with well stirred wet soft soil, an acceleration sensor, a pore pressure sensor, a soil pressure sensor, a cylindrical vibrating rod, and a monitoring rod. In addition, a computer with a data acquisition card and an electricity power box were applied. The cylindrical vibrating rod and the monitoring rod (50 mm wide and 1.1 m long) were fixed on the shelf. The acceleration sensor, pore pressure sensor, and soil pressure sensor were firmly set on the monitoring rod and connected to the computer and data acquisition card. The electricity power box provided power to the cylindrical vibrating rod. A cylindrical vibrating rod, with a frequency of 200 Hz and amplitude of 1.15 mm, diameter of 50 mm and length of 480 mm, was used as the mechanical vibration source and inserted vertically into the sediment. The vibration mode is sinusoidal.

The pore and soil pressure sensors were diffusion silicon sensors with an accuracy of $\pm 1\%$, and measured pore water and soil pressure variation in the soil, respectively. The acceleration sensor was of the three-axis type and was used to measure the deformation of the soil. All sensors had a diameter of 25 mm and a length of 10 mm. Data acquisition was performed at a frequency of 10 kHz. For a vibration frequency of 200 Hz, 50 sampling points per vibration period were collected to observe a proper reflection of soil shear force variation with time.

An Anton Paar Rheolab QC rheometer (Anton Paar GmbH, Austria) was used to measure rheological properties.
of viscous sediment samples. This rheometer is a Searle compliant rotary rheometer equipped with high precision encoders and high-performance DC motors for controlling the shear strain rate and shear stress modes. Test results were obtained using the Rheoplus software.

Materials

Soils used in the present research were collected from the Yangtze River estuary. The particle size distribution is shown in Figure 5. Different samples of clay with different water contents between 26% and 38% were obtained. And the initial yield stresses, $\tau_{B0}$, were set as four different degrees from 2,200 to 6,200 Pa. For the test sediments in the container, each sediment was uniformly mixed by a blender and then consolidated for a specific amount of time as listed in Table 1. Thereafter, soil samples were obtained from 20 cm below the surface of the sediment in the container where the sensors were installed. The mean yield stress of the sediment samples was measured by the rheometer. The dry weights of the samples were measured after drying in an oven at a temperature of 105°C for 12 h. The soil grain density, $\rho_s$, water content $\omega$, and consolidation durations are given in Table 1.

Test procedure

A total of 36 tests were completed with the four sediments. The forces were measured at horizontal distances of 10, 15, 20, 25, 30, 35, 40, 50, and 60 cm from the artificial vibration source. Before starting the vibrator, the acquisition system operated for 3 s to measure the static soil parameters. Once the vibrator was in operation, the soil pressure, pore water pressure, and acceleration were simultaneously measured for 60 s. Then, the vibrator was stopped and the acquisition system continued to run for an additional 3 s.

RESULTS AND DISCUSSION

Dynamic acceleration, soil pressure, and pore pressure responses

Figure 6 shows the time-variant amplitudes of sediment acceleration, the dynamic soil pressure, and the pore water pressure responding to the vibrator. The dynamic responses were measured at 20 cm from the columnar vibrator for 60 seconds. The tested sediment is the soil YRE1. During the whole process, it can be seen that there are three temporal components; namely, a linear deformation stage, a failing stage, and a re-equilibrium stage.

As shown in Figure 6, the dynamic pore pressures and dynamic soil pressures are synchronous with the vibration. During the linear deformation stage, the dynamic pore pressures and dynamic soil pressures display similar increasing trends with vibration time, while the acceleration of soil fluctuates only slightly in this period. The time-variant acceleration describing the movement of the sediment illustrates that the sediment did not change in kinematics in this stage. The pore water and soil particles vibrated in a finite space, but the sediment had not been liquefied. It is also interesting that the maximum amplitude of the dynamic pore water pressure appeared first, before the dynamic soil pressure and acceleration reached the maximum value. This indicates

<table>
<thead>
<tr>
<th>$\rho_s$ (g/cm$^3$)</th>
<th>$\omega$ (%)</th>
<th>Mean initial yield stress $\tau_{B0}$ (Pa)</th>
<th>Consolidation duration (h)</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.502</td>
<td>36.33</td>
<td>2,400</td>
<td>2</td>
<td>YRE1</td>
</tr>
<tr>
<td>1.517</td>
<td>31.41</td>
<td>3,380</td>
<td>4</td>
<td>YRE2</td>
</tr>
<tr>
<td>1.632</td>
<td>29.53</td>
<td>4,670</td>
<td>6</td>
<td>YRE3</td>
</tr>
<tr>
<td>1.792</td>
<td>27.79</td>
<td>6,190</td>
<td>24</td>
<td>YRE4</td>
</tr>
</tbody>
</table>
that the pore water is more active than the soil particles in response to vibration. This stage occurred for only 1.9 s, about 380 cycles of vibration. Moreover, the amplitude of dynamic pore water decreases after reaching the maximum value. This performance relates to the pore water breaking through a certain pressure barrier. Regarding the dynamic soil pressure and acceleration, both did not begin to increase until the dynamic pore water reached a new equilibrium. Thereafter, significant changes in dynamic soil pressure and acceleration occurred, indicating the initial inner

![Figure 6](https://iwaponline.com/wqrj/article-pdf/54/3/193/574573/wqrjc0540193.pdf)  
**Figure 6** | Dynamic acceleration, soil pressure and pore pressure variations with time.

![Figure 7](https://iwaponline.com/wqrj/article-pdf/54/3/193/574573/wqrjc0540193.pdf)  
**Figure 7** | Appearance of acceleration at the beginning of vibration.
structure of the sediment had been damaged, and the sediment was liquefied. The failing stage appeared directly after the pore water pressure peak. As shown in Figure 6, with the increase of time, the excess pore water pressure gradually dissipated, the original steady horizontal acceleration also began to show irregular changes. This illustrates that after the pore water pressure became greater than the overburden pressure, the pore water and soil particles around the test point moved in the horizontal direction and the soil structure began to reshape. The amplitude of acceleration and soil pressure gradually increased to a new equilibration, which is referred to as the re-equilibrium stage. During the re-equilibrium stage, the dynamic pore water pressure, dynamic soil pressure, and vertical acceleration amplitude were in steady state. The amplitude of acceleration and soil pressure reached four times and 1.67 times, respectively, those in the linear stage, while the pore water pressure is only half what it was at peak value.

Figure 8 | Dynamic soil pressure.

Figure 9 | Data of stable soil pressure distribution for YRE1 (top left), YRE2 (top right), YRE3 (bottom left) and YRE4 (bottom right).
Figure 7 displays a close-up of the acceleration components in the horizontal direction of Accelerate-X and Accelerate-Y, and the vertical direction component of Accelerate-Z in the linear deformation stage. Due to the pore water adhesion being lower than the soil, acceleration of this stage is contributed by the pore water. As can be seen, Accelerate-Z appears as an intermittent jitter while Accelerate-X and Accelerate-Y remain steady 1 second after the vibration started. It illustrates that acceleration in the vertical direction is more sensitive than that in the horizontal direction. The pore water in this stage presents vertical permeation principally.

Figure 8 shows a statistical view of the dynamic cohesive sediments pressure range from 40 to 50 s. As can been seen during the equilibrium stage, the cohesive sediments vibrated with the same frequency. Data in this stage is intercepted and overlapped every 25 ms, so the soil pressure is shown experiencing five periods of 25 ms. The frequency of cohesive sediments was 200 Hz, which is equal to the frequency of the vibrator. Statistics show that soil pressure fluctuations present a sinusoidal trend, the same as the vibration sources applied.

Decay of soil pressure with distance

With the vibrator as the original point, the dynamic soil pressures of nine distances in the near field were measured by testing with four groups of soils. This section focuses on the distribution of the maximum soil pressures in the reshape stage. In order to obtain a stable value, data ranging from 35 to 45 s of the vibration process were filtered for analysis. Figure 9 displays the top 95% of the data of the soil pressure amplitude in this range.

As shown in Figure 9, it is obvious that the main distribution of soil pressure decreases with distance. This is consistent with the propagation of vibration in elastic materials. However, data in Group YRE1 and YRE2 shows the soil pressure in the distance of $r = 10$ cm is less than that in the position of $r = 15$ cm. According to the discussion on dynamic soil pressure responding to the vibrator, vibration-induced soil pressure fluctuation and pore water fluctuation in the near field damage the original soil structure, liquefy the soil, and decrease soil pressure significantly. With lower initial sediment yield stresses (e.g. for groups YRE1 and YRE2), soil pressure distinctly tends to initially increase and then decrease with the distance. However, this tendency was not observed in groups YRE3 and YRE4.

During the experiment with groups YRE1 and YRE2, sandblasting water was observed in the near field of the vibrator. As shown in Figure 10, water fluctuated more frequently in the near field than in the far field. After a short period, water blasting was observed from where the vibrator surface was located.

By normalizing the soil pressure with the peak soil value shown in Figure 9, the relationship between oscillating amplitudes of soil pressure $A_{r}/A_{0}$ and distances $r/r_0$ are presented in Figure 11.

As shown in Figure 11(a), the pore water pressure and soil pressure appear to exponentially decay with distance from the vibrator center in the near field, and can be written as:

$$\frac{A_r}{A_{r_0}} = \alpha \left(\frac{r}{r_0}\right)^\beta$$

(2)
In this experiment, the regression parameters for the underwater sediment are $\alpha = 1.178$, $\beta = -0.262$, with standard error of 0.053 and square correlation coefficient of $R^2 = 0.90$. The calculated results, $\xi = ((A_n/A_0)/1.178)^{-1/0.262}$, are compared with the measured data in Figure 11(b). This equation shows acceptable accuracy for calculating the decay of soil pressure amplitude, as 95% of the experimental data fall into a confidence interval having a relative error of ±15%.

It is worth noting that the shear stress decay coefficient is affected not only by the distance but also by the vibration frequency of the rod. In this study, a fixed frequency of $f = 200$ Hz was used to determine the shear stress decay coefficient. Follow-up work can supplement the distribution of the shear stress decay coefficient for different frequencies.

**CONCLUSION**

This paper provides test results at a vibration of 200 Hz and 1.15 mm amplitude in two sediment samples with soils from Yangtze River Estuary and the Huangpu River. The time-variant soil pressure, pore water pressure, and acceleration under vibration were briefly discussed. A simple expression for the decay of soil pressure in underwater sediment responding to the columnar vibration source was proposed. The following conclusions were obtained.

In the vibration state, the large deformation state of the sediment does not occur immediately when the vibration starts, but after a certain period of disturbance. Then, the soil dynamically responds to the vibration, including the deformation, soil pressure, and pore water pressure. The amplitude of mechanical responses remains stable at a new equilibrium value. With the elimination of vibration, the dynamic response of the soil disappears instantly.

Excited by the sinusoidal vibrator, the soil exhibits a statistical sinusoidal fluctuation response of the same frequency as that of the vibration source.

With a lower initial sediment yield stresses, soil pressure distinctly presents a tendency to initially increase and then decrease with the increment of distance.

In the near field of vibration source, the amplitude of the soil pressure decays exponentially with distance, and the relationship can be preliminary described as $(A_n/A_0) = 1.178(r/r_0)^{-0.262}$.

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**REFERENCES**


Cui, H. & Bai, Y. 2014 Rheological properties of cohesive sediment in estuary. In: 5th Int. Conf. on Bioinformatics and Biomedical Engineering, Granada, Spain. Institute of Electrical and Electronics Engineers (IEEE), NJ, USA.


Grabowski, R. C., Droppo, I. G. & Wharton, G. 2011 Erodibility of cohesive sediment: the importance of sediment properties. Earth-Science Reviews 105, 101–120.


Zhang, Z., Wei, H. & Qin, X. 2017b Experimental study on damping characteristics of soil-structure interaction system based on shaking table test. Soil Dynamics and Earthquake Engineering 98, 183–190.

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