Microscopic Mechanism Analysis on Liquefaction of Dredged Silty Sand in Land Reclamation Based on Discrete Element Method

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Abstract. Cyclic consolidation-undrained triaxial tests were performed to investigate the liquefaction behavior of dredged silty sand in land reclamation. The liquefaction behavior of dredged silty sand in the triaxial tests was simulated using discrete element method. Constant volumetric method and initial liquefaction standard were introduced in the simulations. The micro-parameters of dredged silty sand were inversed. The liquefaction micro-mechanism of dredged silty sand was analyzed based on the numerical simulations. The pore water pressure of samples reached effective consolidation pressure and average coordination number decreased quickly when the initial liquefaction was reached.

Introduction

With the development of the large-scale land reclamation project construction along the coastal areas of China, the medium-coarse sands of intertidal zone, shallow sea, river estuary and channel have been exhaustedly exploited. The medium-coarse sands of planning ocean exploration area are over extracted. However, the strata under the medium-coarse sands containing a large number of the fine and silty sands cannot be used because they can't satisfy the requirements of foundation drainage and liquefaction resistance design. The underlying fine and silty sands are wasted and aggravate the shortage of backfill material of the reclamation project. To use the fine and silty sand as backfill material, the problem of liquefaction must be solved.

The macro mechanism of sand liquefaction has been studied a lot previously [1-2]. The micro-mechanism of liquefaction was investigated by lots of researcher using DEM [3-7]. However, few study concerned the liquefaction of dredged fine and silty sands. The previous experience on normal deposited fine and silty sand cannot be used directly in dredged fine and silty sands because the physic-mechanical properties between reclamation silty sand and undisturbed silty sand sedimentation under natural conditions are quite different. So it was necessary to investigate the liquefaction micro-mechanism of dredged fine and silty sands.

The liquefaction micro-mechanism of dredged silty sand was discussed based on triaxial tests and numerical simulations. Based on the Particle flow code (PFC²D) [8], the liquefaction micro-mechanism of reclamation silty was analyzed from a microscopic perspective, which can help to understand the liquefaction micro-mechanism deeply.
Cyclic Triaxial Test

Cyclic triaxial tests were performed to simulate the dynamic response of dredged silty sand. The sand samples were dredged silty sands collected from Tagang area of Eastern Economic Zone of Shantou City, Guangdong Province, China. The sample sands were pretreated by drying and sieving the size of 0.075–0.250 mm to eliminate uncertain influencing factors. Clay particles were prepared by kaolin. The density of the samples was 1520 kg/m$^3$. The maximum and minimum pore ratio was 1.077 and 0.667 respectively. Before the test, the required sands were boiled and cooled. After that, the required clay particles were added and stirred into the pulp after soaking with vacuum exhaust. The mixture was layered into split-mold tied into latex film, and then removed the split-mold under negative pressure.

GDS dynamic triaxial apparatus was used in the experiments (Fig. 1). The dimensions of the samples were 39.1 mm in diameter and 80 mm in height. The samples were saturated by first percolating carbon dioxide through the specimen for 30 mins followed by application of deaired water. Back pressure was applied to complete the saturation process for 120 mins. The minimum $B$-value obtained for the tests was 0.95. In addition to different consolidation stress ratio tests, all tests were performed using isotropic consolidation. The consolidation pressure was 100 kPa.

![Figure 1. GDS test equipment.](image)

Deformation standard was adopted in the failure criterion of anisotropic consolidation. The corresponding value of double amplitude strain was 5% ($\varepsilon_f = 5\%$). Pore pressure standard was adopted in the failure criterion of isotropic consolidation. When the dynamic pore pressure reached initial effective confining pressure, liquefaction occurred ($\Delta u/\sigma_c = 1$).

Numerical Modeling

PFC2D Model

The numerical simulation was performed by a two-dimensional discrete element method code (Itasca PFC$^{2D}$). The maximum diameter was 0.47 mm, the minimum diameter was 0.18 mm, the initial porosity was 0.41, and uniform distribution was selected. The numerical sample was 3.91 cm in width and 8 cm in height, which was equal to the cyclic triaxial tests. The linear contact model was used to guide the particle interactions in the normal and tangential directions. The total number of particles used in the simulation was 5542 (Fig. 2). According to the published reference$^7$, enlarged the average particle size appropriately had no obvious effect to the macroscopic mechanical properties when the particle number exceeded 2000. The grain size distribution of cyclic triaxial tests and numerical simulation is shown in Fig. 3.
Micro-parameters Inversion

In order to simulate the cyclic triaxial tests precisely, the improved deviatoric stress of cyclic triaxial tests was taken as the load in numerical calculations. The deviatoric stress curves of cyclic triaxial tests and numerical simulation are shown in Fig. 4. The sample volume was kept as constant by adjusting the moving velocity of the lateral wall to simulate the constant volume condition of GDS dynamic triaxial test. Under the constant volume condition, the changing process of pore pressure in the samples was monitored by the lateral effective confining pressure. The deviatoric stress \( q \), effective mean principal stress \( p' \), deviator strain \( \varepsilon \), and excess pore water pressure \( u \) is

\[
\begin{align*}
q &= \frac{\sigma_1' - \sigma_3'}{2} ; p' = \frac{\sigma_1' + \sigma_3'}{2} ; \\
\varepsilon &= \varepsilon_1 - \varepsilon_3 ; u = \sigma_{00} - \sigma_3
\end{align*}
\]

(1)

where \( \sigma_1' \) and \( \sigma_3' \) are effective axial and lateral stress respectively (kPa); \( \varepsilon_1' \) and \( \varepsilon_3' \) are effective axial and lateral strain respectively; \( \sigma_{00} \) is initial effective lateral confining pressure (kPa).

The pore water pressure of numerical simulations has good consistency to that of triaxial tests. The numerical simulation based on DEM can effectively reflect the response of pore pressure as shown in Fig. 5. The pore water pressure increased sharply in previous cycles, and then slowly increased until initial liquefaction. The numerical simulation results were in good agreement with cyclic triaxial tests. The inversed micro-parameters is shown in Table 1.
Table 1. Model parameters used in PFC simulations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$k_a$ (N/m)</th>
<th>$k_s$ (N/m)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$1.3 \times 10^7$</td>
<td>$1.3 \times 10^7$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Microscopic Mechanism of Liquefaction**

Based on the numerical simulation, the coordination number and average contact force between particles can be analyzed. The relation between macroscopic and microscopic response can be obtained to investigate the liquefaction mechanism of reclamation silty sand. The coordination number varying curve with increasing number of cycles is shown in Fig. 6.

![Figure 6. Coordination number varying curve.](image)

The coordination number decreased gradually with increasing number of cycles, and the coordination number decreased sharply when the initial liquefaction was reached (Fig. 6). The contact number among particles was reduced, and the particles were even in suspending state when the sample reached the initial liquefaction. The contact force between particles actually reflected the changes of macroscopic effective stress. When the contact force of model reached the value of 0 kPa, the particles were in suspending state actually meaning that liquefaction occurred. The contact force and pore water pressure curve are shown in Fig. 7.

![Figure 7. Contact force and pore water pressure curve.](image)
The pore water pressure increased continually with increasing cycles (Fig. 7). The contact force continued to decrease in the X direction until reached the value of 0 kPa, which means that the sample achieved the initial liquefaction state when the pore water pressure increased to effective consolidation pressure.

Conclusions

Cyclic consolidation-undrained triaxial tests were performed to investigate the liquefaction behavior of dredged silty sand. Cyclic undrained triaxial tests were simulated by DEM using constant volume method. The liquefaction phenomenon of triaxial tests was reproduced in numerical simulations. The mechanical properties of dredged silty sand reflected by simulation were basically consistent with the laboratory tests. The microscopic mechanism of the liquefaction of dredged silty sand was analyzed and inversed in the simulations. The average coordination number of model gradually decreased with increasing cyclic numbers. When the numerical model reached initial liquefaction, the average coordination number decreased quickly. At the same time, the contact force in X direction between particles linearly decreased to zero and pore water pressure reached effective consolidation pressure.

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