Discrete element numerical simulation on the accumulation of wave-induced excess pore pressure in silty seabed sediments

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Abstract. Marine geological disasters, such as seabed liquefactions, submarine landslides, debris flows and turbidity currents, are all closely related to the accumulation of wave-induced excess pore pressure in the seabed. Due to the limitations of physical model experiment and in-situ observations, numerical analysis has become an important method to explore the microscopic mechanism of the accumulation of excess pore pressure. Based on the discrete element porous density flow method, we simulated the changing process of excess pore pressure in seabed sediment in this study, comparing with laboratory flume experiment. The simulation results reproduce the changing process of excess pore pressure in the laboratory flume experiment. The excess pore pressure occurs in the surface of seabed and gradually transfers to the deep layer, tending to a stable value. Thus, the discrete element porous density flow method is well suitable for simulating the accumulation of wave-induced excess pore pressure. Furthermore, the method constitutes a promising tool to study the microscopic mechanism of seabed liquefaction.

1. Introduction
Wave load is one of the major ocean dynamic loads on the seabed. When water waves propagate in the ocean, they generate significant dynamic pressure field on the sea floor. This pressure field induces a stress field and an associated pore pressure fluctuation within the seabed. With the increasing of excess pore pressure and the decreasing of vertical effective stress, seabed sediment may become unstable or even liquefied [1]. With the rapid development of construction in coastal areas, more and more offshore projects are being built. Once the seabed liquefaction occurs, offshore structures and equipment will lose its stability and great damages will be caused. Due to the complexity of the seabed environment, these damages are generally irreversible. Therefore, it is vital important to study the mechanism of accumulation of excess pore pressure in the seabed.

Scholars have carried out a lot of research on the dynamic response and liquefaction of the seabed under the action of wave load. Henkel analysed effects of ocean waves on the stability of underwater slopes in soft under-consolidated deltaic sediments [2]. Zen further studied the relevant theory and experimental methods of dynamic response and liquefaction estimation of the seabed under the action of waves [3]. Later, Jeng extended the liquefaction estimation of Zen to the three-dimensional case [3].
[4]. Nataraja analysed the case of seabed foundation failure, revised the analysis method of liquefaction caused by earthquakes, and analysed the relationship between wave-induced seabed liquefaction and wave period, water depth and seabed strength [5]. The available approaches to study the mechanism of the wave-seabed interaction phenomenon were analytical approximation, and numerical simulation, as well as field and laboratory experiment, however, none of them is perfect to figure out all truth [1]. Scholtes studied the response of a sandy seabed under wave loading using a multi-scale approach. In his research, the discrete element method is coupled to a finite volume method specially enhanced to describe compressible fluid flow, and special emphasis is put on the mechanisms leading the seabed to liquefy under wave-induced pressure variation on its surface [6]. Liu investigated the occurrence and evolution of inhomogeneity silty seabed, and presented a conceptual model of soil fluidisation and the resulting arc-shaped oscillation [7]. Later, the wave-induced pore pressure attenuation and phase lag phenomena were clearly observed in the experiments, and different wave parameters and soil parameters have a significant influence on soil liquefaction [8] [9]. Song carried out an in-situ monitoring of pore pressure in the Yellow River Estuary, and he found that the overall trend of pore pressure was affected by tidal level, while amplitude of pore pressure was related to the wave height [10]. However, there is still no unified understanding of microscopic mechanisms of the excess pore pressure.

Based on the previous research methods, field and laboratory experiment can show the response of the soil under wave load intuitively, but it is difficult to operate and carry out. Finite element method is a common way to study the response of the seabed under the wave load, basing on an assumption that soil is a continuous medium, which violates the discrete nature of soil. Discrete element method is an effective way to simulate the discontinuity of rock and soil. In this paper, based on the porous network model, the discrete element porous density flow method is used to achieve the coupling simulation between fluid and solid. Based on the laboratory experiment, the discrete element numerical model is established, and the excess pore pressure accumulation under wave load is simulated and analysed, and the law and mechanism of excess pore pressure accumulation are explored.

2. Method

The soil body is a relatively continuous medium macroscopically, while microscopically, it’s a structural system composed of a series of particles, pores and fissures. Microscopic discrete and discontinuity problems are difficult to solve by traditional continuity-based methods (such as finite element method). Cundall and Strack first proposed the particle discrete element method (DEM) to study the movement and interaction of granular materials [11]. In the particle discrete element method, the soil model is composed of many discrete particles, which represent continuous and discontinuous media by stacking these particles. This method can be used to simulate large deformations, nonlinear changes, and dynamic evolution, common in geotechnical engineering. In this paper, a discrete element simulation system MatDEM was used to simulate the accumulation process of excess pore pressure in seabed under wave load.

2.1. Basic connection in DEM model

In this paper, tightly stacked rules were used in the discrete element model in Figure 1 [12]. The model consists of a series of elastic elements that obey Newton's equation of motion, and connected to each other by a breakable spring. Among the particles, the force can only appear at the contact points between adjacent elements (Figure 1).

The normal force between the elements is expressed by \( F_n \), which is given by the following formula:

\[
F_n = K_n \cdot X_n
\]

\( K_n \) and \( X_n \) are spring normal stiffness and normal relative displacement, \( X_n \) is the difference between the unit distance and particle diameter. When the units are connected to each other, a tensile force is generated. When \( X_n \) exceeds the \( X_0 \) (fracture displacement), the connection is broken. The maximum normal force \( (F_{n_{max}}) \) when the connection is unbroken between the units is:
When connection is unbroken

$$F_{n\text{max}} = K_n \cdot X_b$$

If the connection is broken, the tension between the units no longer exists. However, when the two units are compressed contact ($X_n<0$), the pressure will still exist:

$$F_n = K_n \cdot X_n \quad X_n < 0 \text{ When connection is broken}$$

In addition, the shear force (tangential force) $F_s$ is also considered in the model (Figure 1). When the particles are in contact with each other and relative sliding occurs, the direction of friction force is opposite to the direction of relative displacement. Assuming that the tangential direction between the particles is also connected by a breakable spring, then $F_s$ can be expressed as:

$$F_s = K_s \cdot X_s$$

$K_s$ and $X_s$ are tangential stiffness and tangential relative displacement respectively. For an unbroken unit connection, the maximum shear force ($F_{s\text{max}}$) is determined by the Coulomb criterion:

$$F_{s\text{max}} = F_{s\text{0}} - \mu_p \cdot F_n \quad \text{When connection is unbroken}$$

Among them, $F_{s\text{0}}$ is the shear resistance between the units, $\mu_p$ is the friction coefficient between the units, and $F_n$ is the normal force (the pressure is defined as negative and the tension is positive). When the external force exceeds the maximum shear force, the connection between the units will break and the shear resistance ($F_{s\text{0}}$) between the units will disappear. The tangential force ($F_s$) is shown as equation (6):

$$F_s = -\mu_p \cdot F_n \quad \text{When connection is broken}$$

For the above closely stacked discrete element model, when the arrangement of the spherical unit particles is fixed, the mechanical properties of the model can be determined by the properties of the spherical unit. There are five spherical element parameters in the model, including normal stiffness coefficient $K_n$, tangential stiffness coefficient $K_s$, fracture displacement $X_b$, shear force $F_{s\text{0}}$, and friction coefficient $\mu_p$. Based on small deformation assumptions, the parameters of tightly stacked model can be derived, such as Young’s modulus, shear modulus, Poisson’s ratio, tensile strength, compressive strength, shear strength and internal friction angle.

2.2. Principles of fluid-solid coupling

In this paper, the discrete element porous density flow method is used to realize the fluid-solid coupling of sediment. The basic idea of this method is establishing pore fluid domains through particle accumulations. The pore pressure is determined by the pore fluid density and temperature, and the seepage flow is calculated between the pores based on the Darcy’s law. Applying pore pressure to the solid particles is the basis to realize the fluid-solid coupling simulation.

![Figure 1](image1.png)  
![Figure 2](image2.png)  

**Figure 1.** Normal spring force and tangential spring force between particles [12].

**Figure 2.** (a) Discrete element stacking particles (b) Pore fluid domain (c) Particle and pore systems.
The first step is to build a stacked particle model, and according to the contact relationship between particles, a series of interconnected fluid domains are established by connecting the centre of adjacent particles. Thus, a pore topological network is formed, and finally a model of pore fluid network with particle skeleton is obtained (Figure 2).

To calculate the flow through the pores, at first, we need to calculate the pressure of a single pore unit. Here comes the state equation for a single pore unit:

$$P = f(\rho, T)$$

Because of a pressure difference, a pressure gradient is created:

$$J = \frac{\Delta P}{l}$$

Among them, $\Delta P = P_j - P_i$, $P_j$ is the adjacent pore pressure, $P_i$ is the central pore pressure, and $l$ is the seepage path of the two pores. According to the Darcy’s law, fluid-solid coupling is able to be realized.

3. Experimental study and numerical analysis

3.1. Experimental study on wave-induced pore pressure

We conducted a flume experiment to explore the law of pore pressure development and later to compare with the numerical simulation. The experiment was conducted in the wave flume designed by Shandong Provincial Key Laboratory of Marine Environmental Geology Engineering (Ocean University of China), which is 14 m long, 0.4 m wide and 0.7 m high, as Figure 3 shows.

The water used in experiment was standard seawater, and the experiment soil was taken from the internal mudflat of the abandoned Diaokou course coast in the Yellow River Delta. The thickness of experimental seabed was 0.6 m. Before laying the seabed, we fixed three pore-pressure transducers in the soil at the depth of 0.2, 0.3, and 0.4 m (Figure 3). The experiment is divided into three groups one by one according to the wave height, 5 cm, 10 cm and 15 cm. Among the three series of experiments, the seabed in the 5 cm wave height group did not undergo shear failure. While the soil in the 10 cm and 15 cm wave height groups underwent shear failure to varying degrees, and the seabed was deformed. Therefore, in this numerical simulation, only the 5 cm wave height group experiment was analysed.

Excess pore water pressure at wave height of 5 cm is shown at Figure 4.

The excess pore pressure at 0.3 and 0.4 m in the seabed is obviously greater than that at 0.2 m, however, the vibration amplitude of excess pore pressure at the depth of 0.3 m is the largest up to 0.5 kPa. We can
indicate that there is a maximum value area of excess pore pressure in the seabed, in which the excess pore pressure response is the most significant, and the shear failure is most likely to happen. We also found that the initial zone of shear failure was just at the depth of 0.3 m. This means the more the excess pore pressure accumulates and the larger the vibration amplitude of excess pore pressure is, the soil is easier to be destroyed. It can be seen from the experiment that the seabed failure process is closely related to and directly controlled by the accumulation of excess pore pressure.

3.2. Numerical simulation

3.2.1. Model setup
In this study, the discrete element software MatDEM developed by Nanjing University was used. Based on the innovative matrix discrete element calculation method and the three-dimensional contact algorithm, MatDEM is able to realize the numerical simulation of the wave induced excess pore pressure accumulation process of seabed sediments. According to the laboratory device shown in the Figure 3, the discrete element model was established in MatDEM. In order to simplify the calculation, the wave maker and wave absorbing device sections were ignored here, and only the water body above the sediment was kept. The first step was to build a model box with the size of 3.8 m×1.0 m, and randomly added particles with average radius of 0.005 m to the model box. The total number of particles was 24870.

3.2.2. Model initialization
The second step was to assign properties to the model material. The general macro mechanical properties of marine soil are shown in Table 1. Based on the macro-micro conversion formula, the model was automatically trained to get the microscopic parameters that met the simulation requirements. Detailed microscopic mechanical parameters of discrete elements units are shown in Table 2.

| Table 1 Macro mechanical properties of materials | Table 2 Microscopic mechanical parameters of the discrete element |
|-----------------------------------------------|---------------------------------------------------------------|
| Mechanical Properties                        | Mechanical Properties | Average value          |
| Young's Modulus E (MPa) 5.00                  | Normal Stiffness $K_n$ (kN•m$^{-1}$) 123                     |
| Poisson Ratio $\lambda$ 0.14                  | Shear Stiffness $K_s$ (kN•m$^{-1}$) 48.7                     |
| Tensile Strength $T_u$ (kPa) 1.0               | Fault Displacement $X_b$ (m) $1.40\times10^{-6}$             |
| Compressive Strength $C_u$ (kPa) 10           | Shear Resistance $F_{s0}$ (N) 0.898                           |
| Internal Friction Coefficient $\mu_i$ 0.5     | Friction Coefficient $\mu_p$ 0.121                            |

In the third step, 0.6 m horizontal line was taken as a limit, and then we screened out and deleted the particles above the 0.6 m horizontal line. Thus, the fluid domain on the surface of the seabed was established (Figure 5). In the model, we set the simulated sediment permeability coefficient $K$ as...
1.32×10^{-5} \text{ cm/s}, which is within the general range of permeability coefficient value of silt soil under normal consolidation pressure.

3.2.3. Wave load simulation
Corresponding to the laboratory experiment, in the numerical simulation, the load was set as 0-2 kPa to simulate the effects of wave peaks and troughs. Here we set the simulation time step as 6.67×10^{-4} \text{s}, and 5000 times iterative calculations in each cycle were conducted to achieve a wave period of 3.33s, which is similar to the experiment wave period. In the model, the particles were set to be fixed, and the excess pore pressure at the depth of 0 m, 0.2 m, 0.3 m, 0.4 m in simulated seabed were selected. Thus, we can further obtain the distribution diagram and the cumulative process diagram of excess pore pressure.

4. Results and analysis

4.1. Characteristics of excess pore pressure under single period wave
Figure 6 shows a curve of excess pore pressure (includes the standard atmospheric pressure of 100 kPa in this paper) in simulated seabed with different depths changing with time during single period. The line at 0 m represents the load applied to the surface of the simulated seabed, simulating the wave load in the flume experiment. During the first half period, the maximum load 2 kPa was applied to the simulated seabed. At the beginning, there was only standard atmospheric pressure of 100 kPa between the particles, and then, excess pore pressure at each depth was generated gradually with the pressure applied.

![Figure 6. The excess pore pressure with different depths changing with time during single period](image)

Figure 6 shows that the excess pore pressure at the depth of 0.05 m is increased significantly at the early stage. When the load was initially applied, the pressure was transmitted from top to bottom, and the excess pore pressure firstly occurred closer to the surface of the simulated seabed. This is because when the soil is fully saturated, the water between the surface soil particles is squeezed at first after the load is applied, and the soil is not permeable enough to allow water to drain out immediately. Under the action of seepage, the excess pore pressure is gradually transferred to the deep layer. The longer the loading time, the more the excess pore pressure accumulates. The pore pressure of deeper positions at the depth of 0.08 m and 0.2 m began to occur one after another, and became large with time.

In a single period, the load of 0 was applied during the last half period. We can see from Figure 6 that the excess pore pressure at a depth of 0.05 m decreased sharply immediately, and then the excess pore pressure at the depth of 0.08 m began to decrease gradually. The obvious phenomenon was that the greater the depth was, the slower the pore pressure decrease. Within a single period of wave loading, for sediments with a depth greater than 0.2 m, the excess pore pressure has been slowly rising all the time without any reduction. This is because in the deeper position, the reaction time of excess pore pressure between particles becomes longer, and the excess pore pressure at the depth greater than 0.2 m does not respond the reduction of loading decrease immediately.

After a period of loading, it can be seen that the excess pore pressure at the depth of 0.08 m is the largest, and the surface particles in the simulated seabed are affected by loading most evidently. During the first half period, the rate of increase of pore pressure is from fast to slow, and in the last half period, the same law appears in the process of pore pressure decay. We can infer that the excess pore pressure responds
significantly under a sudden change of wave load, while the load is constant, the pore pressure changes slowly.

4.2. Characteristics of excess pore pressure under cyclic wave load
In order to figure out the effect of periodic cyclic wave loads to simulated seabed, 100 periods of loads were applied to the simulated seabed. Figure 7 shows the pore pressure distribution in the numerical model after the 1, 20, and 100 periods of load, which represent the simulating time of 3.33 s, 66.6 s, and 333 s, respectively. We can see from Figure 7 that as the cycles load increase, the range of excess pore pressure accumulation and the largest excess pore pressure gradually become deeper. After 20 load cycles, the location of the maximum excess pressure is changed from the depth 0.08 m to depth 0.15 m (Figure 6, Figure 8(a)). Figure 8(b) shows the cumulative curve of excess pore pressure with time at different depths after 100 cycles. After 100 load cycles, the excess pore pressure below the depth of 0.2 m is basically stable at the maximum value of 1 kPa. With the loading time becomes longer, the excess pore pressure in the simulated seabed increases at all depths, and the curve is increasing slower and slower.

![Figure 7. Excess pore pressure distribution diagram of load cycle 1/20/100 times](image)

![Figure 8. Variation of excess pore pressure after load cycle 20 times (a) and 100 times (b)](image)

4.3. Comparison between flume experiments and modelling simulations
In the flume experiment, the excess pore pressure at the depths of 0.2 m, 0.3 m and 0.4 m did not develop to a unified value at last, while in the modelling simulation, the excess pore pressure at the three depths after 250 s tended to be 1 kPa.

| Depth (m) | Experiment excess pore pressure (kPa) | Simulated excess pore pressure (kPa) |
|-----------|---------------------------------------|--------------------------------------|
| 0.2       | 1.10                                  | 0.90                                 |
| 0.3       | 0.72                                  | 0.80                                 |
| 0.4       | 0.32                                  | 0.75                                 |

Table 3 Comparison of excess pore pressure at the same depth

We selected the excess pore pressure in Figure 4 and Figure 8(b) at 125 s, about half of the total simulation time, to make a comparison between flume experiment and modelling simulation, which is
shown in table 3. The values of excess pore pressure at depths of 0.2 m and 0.3 m are similar in the flume experiment and the modelling simulation, while they differ greatly at 0.4 m. There are three possible reasons for these differences:

- The environment in the model is idealized. While in flume experiment, the measurement of pore pressure depends on tools, which is possible to create deviation.
- The discrete element model is relatively homogeneous and the modelling particles are fixed. But in the flume experiment, seabed soil mass is more complex and may be layered.
- The permeability of soil may change under a long-time action of wave load, while the permeability of simulated seabed is a constant value. Therefore, in the discrete element model, the simulation results before 125 s are well consistent with the flume experiment, but the permeability of soil in the flume experiment after 125 s, so the modelling simulation results are quite different from those in the flume experiment.

5. Conclusions
In this paper, compared with the flume experiment, the mechanism of excess pore pressure accumulation in seabed sediments under wave load was studied using discrete element numerical simulation. Several conclusions are drawn:

- Based on the discontinuous discrete element method and the porous network model, the discrete element porous density flow method is able to realize the simulation of the cumulative process of excess pore pressure in seabed sediment, and the simulation results are in good agreement with flume experiment.
- When seabed sediments were subjected to wave load, higher excess pore pressure occurs in the surface of seabed and gradually transfers to the deep layer, tending to a stable value. In addition, excess pore pressure responds significantly under the sudden change of external loading, while the loading is constant, the excess pore pressure changes slowly.
- In the discrete element numerical model, particles were set to be fixed, therefore the changes of sediment structure and permeability were not taken into account, making it difficult to simulate the liquefaction and failure of sediment. Based on the simulation of excess pore pressure, it’s necessary to make a further study on the discrete element porous density flow method to realize the coupling of fluid-solid.

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