Numerical Study on Vertical and Horizontal Seepage Deformation of Silty Soil

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Abstract In this paper, the PFC\textsuperscript{3D} fluid-solid coupling calculation module is used to simulate the seepage deformation process of silty sand under vertical and horizontal seepage. The seepage mechanism such as particle contact, flow field distribution, critical hydraulic slope and particle motion of silty sand under different seepage direction is analyzed. The numerical simulation results show that the critical hydraulic gradient of silty sand in vertical seepage is higher than the critical hydraulic gradient in horizontal seepage.

1. Introduction
The permeability is one of the important engineering properties of soil, which affects the construction of civil engineering. The study of the soil permeability characteristics began in 1856 when Darcy proposed the basic theory of infiltration. It has been developed for hundreds of years. Recently, researchers have used numerical methods to conduct a large number of studies on the permeability characteristics of soil \textsuperscript{[1–6]}. Zhou Jian et al \textsuperscript{[7]} applied PFC\textsuperscript{2D} to simulate the whole process of sand properties caused by seepage under different water pressures. Jiang Zhongming \textsuperscript{[8]} uses PFC\textsuperscript{3D} to carry out mesoscopic numerical simulation test on the process of seepage deformation of coarse-grained soil.

At present, there is not much research on the permeability characteristics of soils when the soil is subjected to horizontal seepage \textsuperscript{[9]}. The study of seepage deformation characteristics has not yet paid enough attention. The study of soil seepage shows that, the horizontal permeability of the soil is greater than the vertical direction, while the resistance to horizontal damage is lower than the resistance to vertical penetration damage. \textsuperscript{[10–12]}. In this paper, the PFC\textsuperscript{3D} fluid-solid coupling calculation module is applied to analyze and calculate the seepage of the silt in vertical and horizontal directions. Based on the numerical calculation, the internal contact force, seepage velocity and flow field distribution of silty soil under vertical and horizontal seepage are analyzed.

2. Particle flow simulation of silt seepage deformation in different seepage directions
Particle flow theory of discrete elements is used for simulation the motion of the solid-phase particles particle. The uniform fluid calculation technique is used to simulate the liquid medium motion in the pores.

2.1 Numerical model
Boundary conditions in the simulation of different seepage patterns of silty sand, are defined slightly
differently. For the vertical seepage, the boundary around the particle is a solid wall boundary condition, the top-bottom side is pressure boundary conditions. As for horizontal seepage, the front-rear and the top-bottom sides of the model are solid boundary conditions. The left side is set as pressure boundary condition and the right is free boundary conditions. The soil model is shown in Figure 1.

![Initial sample schematic](image1)
![Schematic diagram of meshing](image2)

Figure 1. PFC\textsuperscript{3D} particle model and mesh generation

The top side of vertical seepage model is a free boundary, so there is no pressure on it. For horizontal seepage, the sample is balanced by gravity and buoyancy. Small particles in the soil will flow out from the right side of the model, when there is seepage force in soil. Therefore, the line wall is set on the right side of the sample, as shown in the Figure 2.

![Schematic of the line wall](image3)

Figure 2. Schematic of the line wall

2.2 Numerical calculation process
Figure 3. shows the PFC3D calculation process.
2.3 Numerical simulation results

2.3.1 Infiltration and deformation of silty sand under vertical and horizontal seepage

(1) Seepage deformation under vertical seepage of silty sand

Figure 4 shows the variation of soil samples with hydraulic gradient under vertical seepage in silty soil.

![Variation of silty sand with gradient under vertical seepage](image)

Figure 4. Variation of silty sand with gradient under vertical seepage

The hydraulic gradient increases from 0.1, 0.2, 0.3... stepwise. When the hydraulic gradient is applied to 0.7, the silt soil has almost no change. When the hydraulic gradient increases to 0.8, the soil
sample rises and a small amount of fine particles are lost. When the hydraulic gradient continues to increase, the migration of particle clusters occurs on the surface of the soil. The simulation results show that the critical hydraulic gradient of the sample is around 0.8.

(2) Infiltration deformation of silty soil under horizontal seepage

The hydraulic gradient in the horizontal seepage of silty sand is also stepped up by 0.1, 0.2, 0.3...

Figure 5 shows the infiltration deformation variation with the hydraulic gradient under horizontal seepage.

![Figure 5. Variation of silt with gradient under horizontal seepage](image)

It can be seen from the figure that when the hydraulic gradient increases to $i=0.3$, the fine particles at the bottom of the sample begin to migrate. When the hydraulic gradient increase to 0.4, agglomerated particles in the sample are lost, osmotic deformation has occurred. When the hydraulic gradient is loaded to $i=0.5$, the soil has a complete seepage failure. According to the simulation results, the critical hydraulic gradient of the horizontal seepage of the silt soil is about 0.4.

2.3.2 Change of coordination number in vertical and horizontal seepage of silty sand

The coordination number of the soil is one of the parameters expressing the contact between the soil particles. Fig. 6 and Fig. 7 show the variation of the coordination number with the hydraulic gradient under the action of vertical and horizontal seepage.

![Figure 6. Coordination number variation with gradient under vertical seepage](image)

The figure shows that when the hydraulic gradient of vertical seepage is $i=0.8$ and the horizontal seepage is $i=0.4$, the coordination numbers of the soil decrease rapidly. This indicates that the infiltration deformation occurs in the soil.

In the figure, the total coordination number and the mechanical coordination number all decrease with the increase of hydraulic gradient. The total coordination number decreases more rapidly than the mechanical coordination number. This is because the particles move with the hydraulic gradient increases. Most of these movements are small particles. The migration of small particles reduces the contacts number of the soil. These small particles fill the pores of the skeleton particles. The small particles contact with the large one can maintain the mechanical coordination number.
3. Conclusion
(1) The flow velocity and particle velocity of silt increase with the hydraulic gradient, whether it is horizontal or vertical seepage.

(2) Under vertical seepage, the maximum flow velocity region of the flow field is located at the boundary of the soil. While the horizontal seepage, the maximum velocity region of the flow field is located at the upper part of the soil sample.

(3) Under vertical and horizontal seepage, the total coordination number and mechanical coordination number are decline with the rise of hydraulic gradient, and the total coordination number is smaller than the mechanical coordination number. After the deformation occurred, the coordination number decreases rapidly.

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