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Effect of fine content on the hydraulic performance of sand-structure interface subjected to direct shearing

Effet de grain fin sur les performances hydrauliques de l'interface sable-structure soumise au cisaillement direct

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ABSTRACT: Enormous amounts of embankment dams are built on top of a profound overburden sandy layer. Due to anisotropic mechanical behavior of this soil layer, high stress level in post-construction stage can result in uneven settlement and inevitably yields large shear displacement. In this scenario, the hydraulic performance of sheared interface between dam body and overburden layer is of great importance to seepage control. Fine contents play a pivotal role in hydraulic properties, for which failing to take this factor into account may lead to a less appropriate seepage evaluation at the interface. In this study, a seepage apparatus integrated with a direct shear module is briefly presented. A series of laboratory-scale seepage tests was conducted on sheared sand-structure interface by using this apparatus. Test soils containing various proportions of fine content were investigated. It is found that fine content strengthens the soil mixture by elevating the critical hydraulic gradient, regardless of shear displacement achieved during the test. In addition, the unfavorable influence of direct shearing on the critical hydraulic state of interface is reduced with the increase of fine content. Fine content also contributes to the decrease of hydraulic conductivity at interface under direct shearing.

RÉSUMÉ : D'énormes quantités de barrages en remblai sont construites au-dessus d'une couche profonde de mort-terrain sableuse. A cause du comportement mécanique anisotrope de cette couche, un niveau de contraint élevé dans la phase de post-construction peut engendrer un tassement inégal et causer un grand déplacement de cisaillement. Dans ce cas-là, la performance hydraulique de l'interface cisaillée entre le corps du barrage et la couche de mort-terrain est importante pour le contrôle des infiltrations. Les grains fins jouent un rôle vital dans les propriétés hydrauliques, pour lesquelles une évaluation de infiltration moins appropriée peut être conduite si ce facteur n'est pas pris en compte. Un appareil d'infiltration intégré avec un module de cisaillement direct est brièvement présenté. Une série d'essais d'infiltration a été réalisée en laboratoire sur l'interface sol-structure cisaillée. Des sols d'essai contenant diverses proportions de grain fin ont été étudiés. Il est constaté que les grains fins augmentent le gradient hydraulique critique du sol, quel que soit le déplacement de cisaillement atteint pendant l'essai. L'impact défavorable dû à cisaillement direct sur l'état critique de l'interface est réduite avec l'augmentation de grain fin. Il contribue également à la diminution de la conductivité hydraulique de l'interface sous cisaillement direct..

KEYWORDS: embankment dams, direct shearing, soil-structure interface erosion, fine content.

1 INTRODUCTION

The embankment dam is an ancient hydraulic structure, and it is still widely used for water resources regulation and hydropower development (Grill et al. 2019). Because of the undesirable geological conditions, embankment dams are inevitably constructed above the profound overburden layer. Nowadays, with the dam height climbing up to 300 m level in China, the stress level at the dam site becomes increasingly high. Considering the commonly anisotropic stress-strain behavior of this overburden soil layer as a result of natural deposition(Zhu and Zhang 2013), uneven settlement of dam body could possibly occur, yielding large shear displacement between the dam and the overburden layer. To guarantee a rational design and a safe operation of the embankment dam, the hydraulic performance of this sheared interface needs to be carefully investigated.

Fine content, which represents the soil particle with grain size less than 0.075 mm, is one of the most decisive parameters which holds an influence on seepage characteristics of soil (Shafiee 2008). Previous studies show that fine content within soil matrix can reduce the hydraulic conductivity because of smaller pore radius and the electric double layer (Chapuis 2012), whilst the cohesive force between fine grains gives rise to a better hydraulic performance against seepage failure (Marot et al. 2009; Tian et al. 2020). Contact erosion (CE) along the soil-structure interface has been studied recently (Kim et al. 2019), and it is found that fine content holds the capacity to improve the critical hydraulic gradient at the interface (Xie et al. 2018, 2019). However, despite the development of certain seepage apparatuses integrated with shearing module (Lei et al. 2016), the effect of fine content on the hydraulic properties of sheared soil-structure interface has not been investigated.

For the purpose of enhancing the understanding regarding the interfacial seepage under direct shearing, a series of tests is implemented in this paper using a new shear-module-integrated seepage apparatus. The design principal of this apparatus is briefly introduced, and the experimental setup regarding two kinds of shear-related seepage tests are presented. Based on test results, the effect of fine content on contact seepage characteristics, referred to as hydraulic conductivity and critical hydraulic gradient of soil-structure interface, are studied, with the seepage interface being subjected to direct shearing.

2 BRIEFINGS OF TEST APPARATUS

To conduct the seepage test at sheared sand-structure interface, a novel apparatus has been developed and is herein introduced briefly. This apparatus, which follows the modularization design approach, is composed of a water supply system, a shear loading system, a testing chamber, an overburden stress loading system and a soil-water collection system. A schematic diagram of this apparatus is shown in Figure 1.

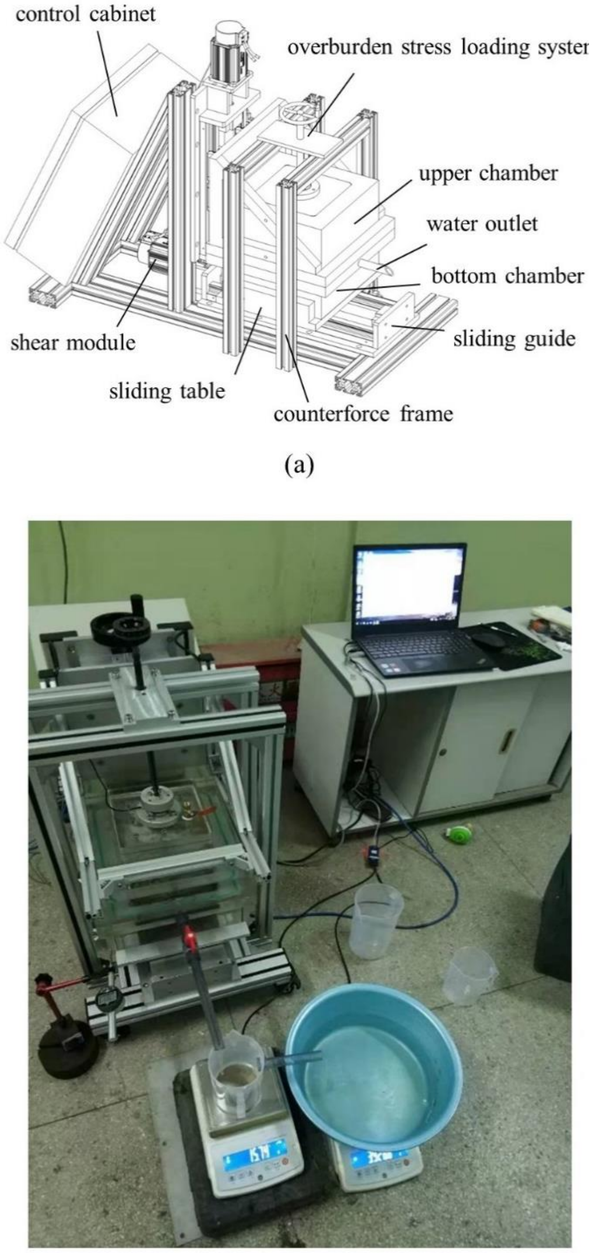

Figure 1. Shear-module-integrated seepage apparatus (a) schematic illustration and (b) photograph.

The testing chamber is made of two pieces of transparent plexiglass which are both thick enough to withstand the shear stress and the overburden stress. These two pieces, which holds the same inner dimension of 200 mm length, 200 mm width and 100 mm height, can be easily dismantled from the apparatus in the process of soil filling and be installed before specimen saturation. The upper piece is coverless and the overburden stress loading system can be assembled together. The water inlet which is connected to the height-controlled water tank and the water outlet are located at the bottom piece of plexiglass, so that water would infiltrate through the specimen horizontally. A typical soil-water collection system (Liang et al. 2017) is used to collect the eroded soil and the outflow separately. A piece of porous stone is installed at the entrance of inlet hole to provide surface inflow. The sealing issue between contact surfaces of different parts is addressed with rubber strips embedded in the groove.

A computer-controlled shear loading system along with the sliding table is independently designed from the testing chamber. When carrying out the sheared CE test, the bottom piece of plexiglass moves together with the sliding table whilst the upper piece remains fixed. It is worth noting that the permissible shear displacement is determined by the position of groove, so that the sealing rubber strip is always compressed and prevents water from flowing out of the chamber. The ensemble of multiple ribs serves as the counterforce frame against structure instability induced by direct shearing.

3 TEST METHODOLOGY

3.1 *Test material*

The granular part of soil-structure interface is a mixture of sand and clayey soil. The grain size distribution (GSD) curve of these two soils along with other physical properties are displayed in Table 1. According to ASTM D2487-17e1, test sand collected from Xinjiang Province is classified as SP, and test clayey soil excavated from Sichuan Province is classified as CL. To investigate the influence of fine content, three proportions of clayey soil, referred to as 5%, 15% and 25%, are mixed into the sand. Figure 2 describes the GSD of sand-clay mixture with different fine contents.

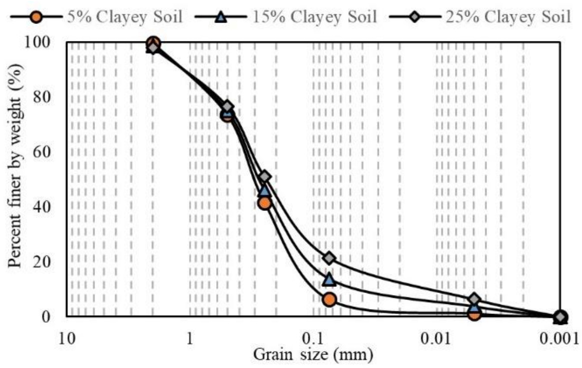

Figure 2. GSD of test soil mixture.

Table 1. Physical properties of test material

Index	SP	CL
<5mm	100%	100%
<2mm	100%	91.9%
<0.5mm	72.8%	87.9%
<0.25mm	39.4%	85.7%
<0.075mm	2.6%	77.8%
<0.005mm	0%	25.4%
Liquid limit, w_L	-	35.4%
Plasticity limit, w_P	-	15.8%
Plasticity index, I_P	-	19.6
Specific gravity, G_s	2.56	2.75
Mean particle size, d_{50} (mm)	0.319	0.019
Coefficient of uniformity, C_u	4.0	-
Coefficient of curvature, C_c	0.9	-
Maximum dry density, $\rho_{d\max}$ (g/cm^3)	1.55	1.78
Optimum moisture content[a], ω_{op}	-	17.9%

[a]Sample compacted at optimum moisture content to maximum dry density.

A concrete block is used as the structure part of test interface. It is fabricated with portland cement, water and aggregate. Special attention was paid to keep the contact surface smooth during the curing process, and we find that the surface roughness is less than 0.01 mm according to the Sand Patch Test (Santos and Júlio 2013).

3.2 *Specimen preparation*

The clayey soil was firstly crushed and sieved. Then this soil and sand was oven-dried under 105°C for 12 hours and 6 hours, respectively. A desired amount of clayey soil and dry sand was later mixed following the GSD in Figure 2. Water was added into the mixture to meet the optimum water content, after which the test soil was sealed for 24 hours. The soil was later filled into the bottom chamber and compacted by 5 layers. The dry density of each soil layer is controlled as 1.47, 1.50, 1.53 g/cm^3 for soil containing 5%, 15% and 25% clayey materials, respectively.

Before soil filling, preliminary measures concerning the tightness at the joint surface of two plexiglass chambers were conducted. The circular rubber stripe was placed and the surface was covered with silicone grease. Then plexiglass chambers were stacked together to accommodate the specimen. After soil filling, the concrete block was disposed on top. Prior to placement of the top plexiglass chamber, silicone grease was coated at all its lateral surfaces. Afterwards, the specimen as an entity was moved onto the sliding table, of which the displacement has been thoroughly reset to zero. The overburden stress loading system was then attached to the testing chamber. No overburden stress is applied throughout all tests in this paper, so that this loading system functions merely as a sealing top cover. The upper part of chamber was fixed with the motionless frame structure, and the bottom part of chamber was fixed with the movable table.

After the deployment of every apparatus setting, a low hydraulic pressure (0.5 kPa) was applied to saturate the specimen without disturbing soil particles. This process, which can be inspected through transparent side walls, would last for 6 more hours after a stable outflow with no air bubbles was observed. Then the water inlet and the water outlet were shut down and another 72 hours were given prior to sheared CE test.

4 SPECIFIC CE TESTS AND ANALYSIS

4.1 *Fixed-shear-displacement CE test*

Similar to conventional CE tests, this kind of sheared CE test requires a progressive elevation of upstream water head. During each stage, the flow rate data would not be recorded until it became stable. We also paid attention to the phenomenon of particle dispersion in the outflow, as the continuity of soil removal, the reading of soil collection container and the trending of flow velocity contribute to the determination of CE failure. In this test, however, the soil-structure interface is misaligned along the vertical direction. In other words, a desired shear displacement resulting from direct shearing is formed between the soil and the concrete block before sheared CE test begins (see Figure 3(a)).

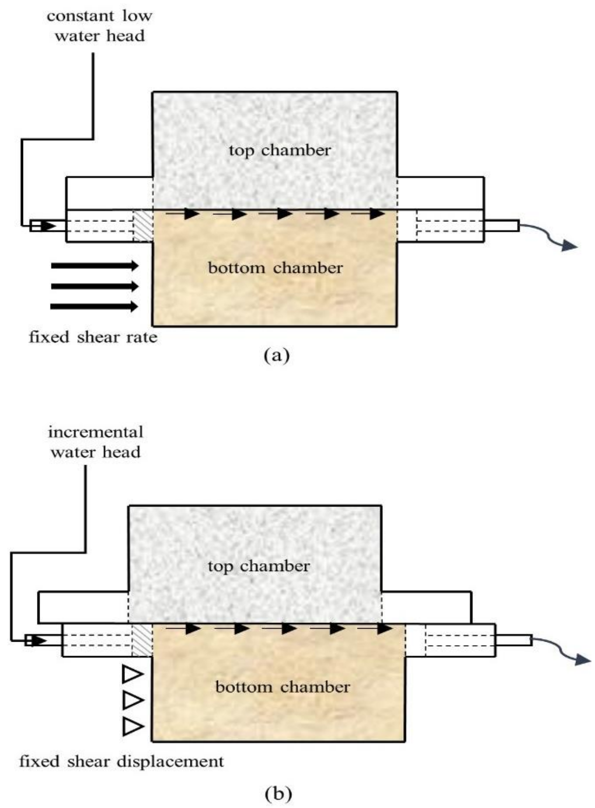

Figure 3. Illustration of shear-related seepage test (a) fixed-shear-displacement CE test and (b) constant-head permeability test under direct shearing.

Tests with various proportions of fine contents under different shear displacements were conducted. A typical scenario describing the evolution of seepage velocity and the weight of soil collection container against hydraulic gradient is shown in Figure 4. In the case of the mixture containing 25% clayey soil under 7.5% shear disturbance, both the velocity and the total mass of soil collection container undergoes an acute increase when the hydraulic gradient reaches 5.87.

By using the same criteria to determine the critical hydraulic state, test results under different shear disturbance are presented in Figure 5. It can be seen that with the shear disturbance increasing, the critical hydraulic gradient (i_{cr}) at soil-structure interface shows a downward trend with no exception. In addition, the increase of fine content strengthens the resistance against seepage failure from an overall perspective, which is in consistency with previous knowledge concluded from non-sheared CE tests.

We define a shearing impact coefficient as the ratio between i_{cr} under maximal shear disturbance (15%) and that without shearing. For specimen with 5%, 15%, 25% CL, this coefficient equals to 38.3%, 73.3%, 75.0%, respectively. It appears that the increase of fine content largely reduces the unfavorable influence of direct shearing on the critical hydraulic gradient of soil-structure interface. The reasons may be summarized as the different shearing mechanisms between cohesive and cohesionless soil (Li 2016). For cohesionless soil, a shear band with relatively low packing state, which results from particle rearrangement and particle rotation, forms at the direct shearing interface (Masson and Martinez 2001). The formation of shear band within cohesive soil is less prevailing, so that the sheared interface containing more fine contents is less vulnerable to seepage failure.

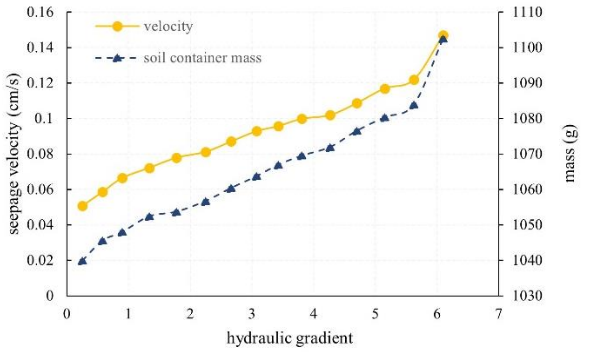

Figure 4. Typical test procedure (mixture with 25% CL under 7.5% shear disturbance).

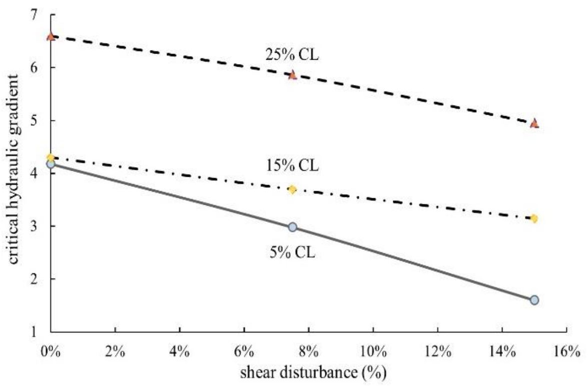

Figure 5. Critical hydraulic gradient under different conditions.

4.2 *Constant-head permeability test under direct shearing*

In this scenario, changes of hydraulic property at the soil-structure interface subjected to direct shearing is spotlighted (see Figure 3(b)). The shear rate is set to be 2 mm/min in every test. We consider this kind of shearing as drained direct shearing because of the occurrence of water circulation throughout the test. It is worth noting that the constant water head that we use throughout is 0.35, which is too low to trigger the initiation of CE however the shearing displacement progresses. In other words, changes of flow velocity at the sheared interface are mainly ascribed to direct shearing.

Permeability tests subjected to direct shearing were conducted, the detailed information of which is shown in Figure 6. As the proportion of CL increases from 5% to 25%, the level of seepage flow infiltrating through the specimen decreases progressively, indicating that fine content also dominates the permeability of soil-structure interface under direct shearing condition.

We define the hydraulic fluctuation factor as the ratio between the maximal and the minimal seepage velocity along with the development of shear displacement. In the case of 5% CL, the velocity fluctuates between 0.0396 cm/s and 0.0556 cm/s, and the fluctuation factor equals 0.712. This factor equals 0.650 and 0.654 when the test specimen contains 15% and 25% CL, respectively. The influence of fine content on the fluctuation of velocity is peripheral in comparison with that on the interface permeability. Further seepage tests of this kind are required to describe the relationship between fine content and the fluctuation of seepage velocity under direct shearing.

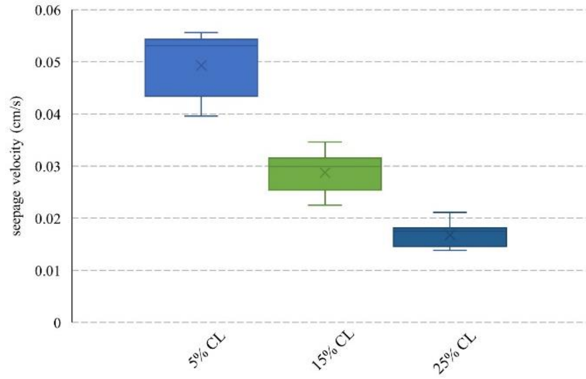

Figure 6. Shifts of seepage velocity under direct shearing.

5 CONCLUSION

The hydraulic performance of sand-structure interface was studied in this paper under direct shearing conditions, and the influence of fine contents within soil matrix was highlighted from an experimental perspective. Brief introductions regarding the shear-module-integrated seepage apparatus was given. Two specific kinds of permeability tests which is related to direct shearing were displayed.

Test results show that the soil-structure interface is increasingly prone to erosion with the development of direct shearing. Fine content strengthens the resistance of such interface against seepage failure on a global scale, and it can alleviate the negative impact of direct shearing by augmenting the shearing impact coefficient.

The evolutionary changes of seepage velocity at soil-structure interface subjected to direct shearing is also studied. It is found that the increasing fine content within soil mixture leads to a lower permeability of sheared interface, and its impact on the fluctuation of velocity during direct shearing is less decisive.

6 ACKNOWLEDGEMENTS

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