Relationship between pore water pressure and dissipated energy of fiber-reinforced sand

Mingming Liu¹, Gang Li¹*, Jinli Zhang², Jia Liu³ and Zhuangyi Yang²

¹Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi’an, Shaanxi 710123, China;
²State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, Liaoning 116024, China;
³School of Geological Engineering and Geomatics, Chang’an University, Xi’an, Shaanxi 710054, China

*Corresponding author’s e-mail: T_bag945@126.com

Abstract: Under the loading of earthquake, sandy soil is prone to liquefaction and resulting in the superstructure damage. Therefore, the liquefaction identification of sandy soil is the primary task of liquefaction disaster prevention. Based on the energy dissipation method, the relationship between pore water pressure ($u$) and dissipated energy density ($W$) of fiber-reinforced sand (FRS) is established, and the effects of fiber length ($FL$), fiber content ($FC$), cyclic stress ratio ($CSR$), and relative density ($Dr$) on the accumulation of $u$ are analyzed. The results showed that fiber addition can effectively slow down the liquefaction of FRS, and the curve of $u$ and $W$ can be divided into rapid growth stage, stable ascend stage and slow growth stage. When the $u$ keep constant, the $W$ increases with the increasing of $FL$ and $FC$. Whereas, the $u$ decreases with the increasing of $FL$ and $FC$ when the $W$ keep constant. The $u$ and $W$ are less affect by $CSR$, and the dense sand of FRS is less prone to liquefaction than loose sand.

1. Introduction

The liquefaction of saturated sand under earthquake loading is the main origin of earthquake disasters, thereby liquefaction identification is the primary task of liquefaction disaster prevention[1]. The energy dissipation method can be used to predict and evaluate the liquefaction of foundation. Yao et al.[2] investigated the liquefaction potential of saturated Fujian standard sand using the energy approach, and found that the dissipated energy will less affect the liquefaction if the permeability coefficient ratio larger than zero. Azeiteiro et al.[3] evaluated the liquefaction resistance of sand using stress and energy-based methods, and noted that the cycle number to induce liquefaction affect by the amplitude and location of the peak loading history. Baziar et al.[4-6] pointed out that the cell pressure and fine content have strong effects on the accumulated strain energy, and an artificial neural network model was established which account for the soil parameters and strain energy. Doygun et al.[7] studied the relationship between stored strain energy and pore water pressure ($u$), and indicated that the method provides more accurate estimates of damping ratio when the shear strain larger than 0.4%. Polito et al.[8-9] indicated that the dissipated energy to cause initial liquefaction independent of load shape and dependent on the duration of loading, and the energy-dissipation associated with stress and strain controlled cyclic triaxial tests were developed and confirmed. Yang et al.[10] used the dissipated energy to evaluate the development of $u$, and pointed out that the amount of energy dissipated was closely related to relative density ($Dr$), stress...
ratio, and cyclic stress ratio (CSR). Javdanian[11] developed a model to predict liquefaction based on strain energy theory, and verified the model by the indoor and field tests. Jafarian et al.[12] developed a model to predict the residual pore water pressure using the function of cumulative strain energy density and capacity energy, and verified the model by shaking table and centrifuge tests.

Currently, the energy dissipation method is mainly used to identify the sand liquefaction, while less focus on the fiber-reinforced sand (FRS). Based on the energy dissipation method, the relationship between $u$ and dissipative energy density ($W$) is established to analyze the influence of fiber length ($FL$), fiber content ($FC$), $D_r$, and CSR on $u$ accumulation, which can provide a reference for liquefaction identification of FRS.

2. Materials and Method

2.1. Materials

Polypropylene fiber has good anti-aging and high durability after chemical treatment. The polypropylene fiber used in the test was purchased from Jiangsu Yancheng Henggu Fiber Co., Ltd. The fiber is white, round cross-section monofilament, and with the length of 6 mm or 12 mm. The test sand is ISO standard sand from Xiamen, and it was purchased from Xiamen Aisiou Co., Ltd. The standard sand was sieved firstly by 0.5 mm to remove large particles, and the fine sand with uniform size was obtained used as test sand.

2.2. Sampling

The fibers are not easy to be evenly distributed in the dry sand, thereby the wet sand with a water content from 7% to 9% was prepared first, and then the dispersed fibers are added to the wet sand with the high-speed mixer to mixing. Subsequently, the FRS was divided into four parts and put into the mold and uniformly compact layer by layer.

2.3. Test scheme

The $D_r$ of sample is 0.3, 0.5 and 0.7, the $FL$ is 6 mm, 6+12 mm and 12 mm, and the $FC$ is 0.2%, 0.4% and 0.6%, respectively. The confining pressure is 300 kPa, the vibration frequency of axial load is 0.1 Hz, the consolidation ratio is 1.0, the waveform is sine wave, and the stress ratio is set at 3 gradients. The sample is 61.8 mm in diameter and 125 mm in height. The liquefaction standard is that when the $u$ reaches the confining pressure and the effective stress is zero, and the test is stopped when the axial strain reaches 5%.

According to the principle of energy dissipation method, the energy loss in a period of visco-elastic body can be approximately equal to the area bounded by the hysteretic curve, thereby the $W$ is obtained by the accumulation of the area of the hysteretic circle.

$$\Delta W = \int_{\dot{\varepsilon}}^{\varepsilon} c \dot{\varepsilon}^2 dt$$

$$\dot{\varepsilon} = \varepsilon_0 \omega \cos (\omega t - \delta)$$

$$\Delta W = A_0 = \pi \omega \varepsilon_0^2$$
3. Results and discussion

3.1. Effect of FL

In order to analyze the effect of FL on $u$ accumulation, the relationship between $u$ and $W$ of FRS under $D_r=0.5$, $CSR=0.195$ and 0.230 is shown in Figure 1. It can be seen that the $W$ increases with the increasing of $u$. In the early stage, the $u$ increases rapidly and the curve in a oblique line. In the middle stage, the growth rate is gradually slowed down and the curve is in an arc. At the end of liquefaction, the $W$ increases slowly and the curve in a straight line. When the $u$ keep constant, the $W$ increases with increasing of FL, indicating that more energy is consumed. When the $W$ keep constant, the $u$ of FRS with FL=6 mm increases faster and is more prone to liquefaction.

3.2. Effect of FC

In order to analyze the effect of FC on $u$ accumulation, the curves between $u$ and $W$ of FRS under $D_r=0.5$, $CSR=0.195$ and 0.230 are given in Fig. 2. It can be seen that with the increase of $W$, the $u$ of FRS increases gradually. When the $u$ keep constant, the $W$ increases with the increasing of FC, indicating that more energy is consumed with high FC. When the $W$ keep constant, the $u$ increases faster with low FC which is easier to liquefaction.
3.3. Effect of CSR

In order to analyze the effect of CSR on \( u \) accumulation, the curve between \( u \) and \( W \) of FRS under \( D_r=0.5 \) and 0.7 are given in Fig. 3. It can be seen that \( W \) slightly decreases with increasing of CSR. According to compare the test results under different CSR, it can be concluded that the difference of \( W \) between CSRs is smaller and can be negligence. Therefore, the effect of CSR on \( u \) accumulation is insignificant.

3.4. Effect of \( D_r \)

Figure 4 shows the relationship between \( u \) and \( W \) of FRS under \( D_r=0.3, 0.5, \) and 0.7. It can be seen that the \( W \) increases with increasing of \( D_r \). Compared with the test results of dense sand (\( D_r=0.7 \)), medium dense sand (\( D_r=0.5 \)), and loose sand (\( D_r=0.3 \)), the \( W \) of dense sand is significantly higher than that of loose sand, indicating that more energy will be consumed when liquefaction occurred for dense sand. When the \( W \) keep constant, the \( u \) of dense sand is significantly lower than that of loose sand, which indicates that the dense sand of FRS is less prone to liquefaction than loose sand.

4. Conclusions

(1) The curve between pore water pressure and dissipative energy density can be divided into three stages: rapidly increases stage, steadily ascend stage, and slowly increases stage.

(2) When the pore water pressure keep constant, the dissipated energy density increases with the increasing of fiber length and fiber content. When the dissipative energy density keep constant, the pore water pressure increases faster when the fiber-reinforced sand with low fiber length and fiber content.

(3) The dissipated energy density and pore water pressure are less affect by cyclic stress ratio, and loose sand is more prone to liquefaction than dense sand.
Acknowledgments
This study was supported by the Natural Science Basic Research Program of Shaanxi Province (2021JM-535) and Special Fund for Scientific Research by Xijing University (XJ18T01).

References
[1] Zhang, X. L., Li, X. Y., Du, X. L. (2021) Hyperbolic model for estimating liquefaction potential of sand considering the influences of fine grains. Chinese Journal of Geotechnical Engineering., 43: 448-455.
[2] Yao, C. R., Wang, B., Liu, Z. Q., et al. (2019) Evaluation of liquefaction potential in saturated sand under different drainage boundary conditions—an energy approach. Journal of Marine Science and Engineering., 7: 411.
[3] Azeiteiro, R. J. N., Coelho, P. A. L. F., Taborda, D. M. G., et al. (2017) Energy-based evaluation of liquefaction potential under non-uniform cyclic loading. Soil Dynamics and Earthquake Engineering., 92: 650-665.
[4] Baziar, M. H., Sharafi, H. (2011) Assessment of silty sand liquefaction potential using hollow torsional tests—an energy approach. Soil Dynamics and Earthquake Engineering., 31: 857-865.
[5] Baziar, M. H., Jafarian, Y. (2007) Assessment of liquefaction triggering using strain energy concept and ANN model: capacity energy. Soil Dynamics and Earthquake Engineering., 27: 1056-1072.
[6] Baziar, M. H., Jafarian, Y., Shahnazari, H., et al. (2011) Prediction of strain energy-based liquefaction resistance of sand-silt mixtures: an evolutionary approach. Computers and Geosciences., 37: 1883-1893.
[7] Doygun, O., Brandes, H. G. (2020) High strain damping for sands from load-controlled cyclic tests: correlation between stored strain energy and pore water pressure. Soil Dynamics and Earthquake Engineering., 134: 106134.
[8] Polito, C., Green, R. A., Dillon, E., et al. (2013) Effect of load shape on relationship between dissipated energy and residual excess pore pressure generation in cyclic triaxial tests. Canadian Geotechnical Journal., 50: 1118-1128.
[9] Polito, C., Moldenhauer, H. H. M. (2019) Energy dissipation and pore pressure generation in stress- and strain-controlled cyclic triaxial tests. Geotechnical Testing Journal., 42: 1083-1089.
[10] Yang, Z. X., Pan, K. (2018) Energy-based approach to quantify cyclic resistance and pore pressure generation in anisotropically consolidated sand. Journal of Materials in Civil Engineering., 30: 04018203.
[11] Javdanian, H. (2019) Evaluation of soil liquefaction potential using energy approach: experimental and statistical investigation. Bulletin of Engineering Geology and the Environment., 78: 1697-1708.
[12] Jafarian, Y., Towhata, I., Baziar, M. H., et al. (2012) Strain energy based evaluation of liquefaction and residual pore water pressure in sands using cyclic torsional shear experiments. Soil Dynamics and Earthquake Engineering., 35: 13-28.