Development of an Energy-based EPWP Generation Model under Different Drainage Conditions

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Abstract. Drainage conditions have significant influence on the liquefaction behaviour of soil. In this study, cyclic triaxial tests were conducted on saturated Fujian standard sand under different drainage conditions. A new infiltration device was designed to simulate the different drainage conditions by controlling the permeability coefficient of the silt inside. Permeability coefficient ratio (k_p) is introduced to measure the effect of different drainage conditions (k_p = k_i/k_0, where k_i is the permeability coefficient of the silt at different dry density; k_0 is the permeability coefficient of the saturated sand specimen). A series of cyclic triaxial tests were conducted to evaluate the response regularity of excess pore water pressure (EPWP) of saturated sand under different drainage conditions. Test results indicate that different drainage conditions have obviously effects on the EPWP generation. Based on the strain energy concept, an EPWP generation model is developed by considering the effect of drainage condition and it shows good agreement with the test observations.

1. Introduction

Soil liquefaction caused by the earthquake can result in destruction of buildings and roads[1-3]. Soil used to be considered under undrained condition during earthquake, due to the short duration of loading. A current research declared that it is unrealistic to consider soil being under undrained condition during seismic loading[4, 5]. Several studies were conducted to investigate the liquefaction behaviour of soil under different drainage conditions[6, 7]. To simulate different conditions, Yamamoto et al.[6] set a drainage control valve and introduced the coefficient of drainage effect. Wang et al.[7] considered the permeability of different liquid as an influential infector which affects drainage condition.

On the other hand, to study the EPWP response of soil under seismic loading, dissipated strain energy density (W) has been introduced as a useful indicator[8-10]. Dissipated strain energy density, which is also known as cumulative strain energy density represents the cumulative area of the hysteresis loops at a given time during cyclic loading. Green[8] presented an EPWP generation model with only one calibration parameter PEC which equals the W when r_u is 0.65, while r_u is the ratio of EPWP to effective confining pressure. Jafarian et al.[9] conducted the undrained cyclic hollow cylinder torsional tests at various conditions of relative density and initial effective confining pressure, and then an EPWP...
A generation model was proposed, which can function well in the prediction of EPWP response under the influence of two key factors mentioned above. However, majority of these EPWP generation models cannot reflect the influence of different drainage conditions. In this study, an infiltration device was produced to control drainage conditions. Based on the new device, a series of cyclic triaxial tests were carried out on saturated sand in constant relative density and stress condition. The acquired data point out that drainage conditions are influential to the liquefaction susceptibility. Based on the data, an energy-based EPWP generation model was developed to evaluate EPWP response by considering the effect of drainage conditions.

2. Experimental methods

2.1. Design and calibration of the infiltration device

A new infiltration device was designed to control the drainage conditions. The views of the infiltration device are depicted in figure 1. A space takes up the central part of the infiltration device, which is 6mm high with diameter of 27mm. Above and below the space are equally distributed holes through which water can flow in and out freely. In the space, silt soil with different dry density are enclosed. Filter paper are set above and below the silt soil, which ensuring soil particles cannot be scoured through the holes. The whole infiltration device is 12mm high with diameter of 38mm, which was designed to be the same size as triaxial sand specimen. Consequently, the latex film containing sand specimen fits tightly to the side of the infiltration device and the fluid cannot flow through this way. The infiltration device was installed above sand specimen when triaxial test was conducted, while relative position of the objects are shown in figure 1(c).

The calibration method is based on conventional triaxial seepage test. To quantify drainage control effect of the infiltration device, the permeability coefficient ratio ($k_p$) is introduced and shown in equation (1).

$$k_p = \frac{k_i}{k_0}$$

(1)

Where $k_i$ = permeability coefficient of the silt at different dry density in the infiltration device; $k_0$ = permeability coefficient of the sand specimen. According to Darcy’s law, $k_p$ can be calculated in each triaxial seepage test. Then, different dry density of silt was calibrated to the corresponding $k_p$. The results indicate that when the dry density of silt are 0.8, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.8 g/cm$^3$, the corresponding
$k_p$ are 1, 0.84, 0.68, 0.54, 0.17, 0.13, 0.12, 0.11, which is also plotted in figure 2. Especially, according to other researches focused on drainage conditions, $k_p$ is assigned zero under undrained condition.

![Figure 2. Relationship between $k_p$ and $d$ of silt in the infiltration device](image)

2.2. Materials and tests

Fujian standard sand was used to produce specified saturated specimens which is 76mm high and 38mm of diameter. The properties of the sand are as follow: $e_{max} = 0.848$, $e_{min} = 0.597$, $C_u = 5.6$, $C_c = 0.45$, and the average relative density of saturated specimens after consolidation ($D_r$) is controlled to 48.7% approximately.

In accordance with ASTM D5311/D5311M-13, Standards Test Method for Load Controlled Cyclic Triaxial Strength of Soil, a series of cyclic triaxial tests were conducted under different drainage conditions. Each test can be divided into three main procedure. First, the sand specimen with the certain infiltration device was put in the position, and the back pressure of 500kPa was applied. Second, the sand specimen was consolidated at the initial effective confining pressure ($\sigma_0'$) of 200kPa, and the time of the consolidation duration was long enough that volume of specimen was stabilized. Finally, the EPWP response was documented when dynamic load was applied. The dynamic load was in sine waves, the frequency was 1Hz and the amplitude ($\sigma_d$) was 50kPa.

3. Test results and analysis

3.1. The response of EPWP

Time histories of the EPWP were plotted in figure 3. Where $N =$ number of loading cycles. The test results can be divided into two groups by whether liquefaction occurred or not. $k_p$ in the liquefied group are from 0.17 to 0 and the typical EPWP time histories in liquefied group are shown in figure 3(a) for comparison. Then, $k_p$ in the unliquefied group are from 0.54 to 1 (fully drainage condition), and the typical results are shown in figure 3(b).

In figure 3(a), as $k_p$ increased, the EPWP of sand specimens in liquefied group responded more fiercely and liquefaction achieved more rapidly. While in figure 3(b), the EPWP accumulated just at the beginning moment of dynamic loading applied. After about two or three times of cyclic loading, the EPWP reached the peak value and began to dissipate gradually. It can be seen that the instant accumulation of EPWP response was lesser as $k_p$ increased in unliquefied group.

In figure 3(a), the sand specimens were considered under poor drainage condition when $0 \leq k_p \leq 0.17$. The sand deposits consolidated from the bottom of specimen under dynamic loading and gravity, then the pore water was driven to the upper part of specimen and EPWP accumulated till sand specimen achieved liquefaction. Furthermore, when $k_p=0$, sand specimen was considered under undrained condition. The pore water cannot flow out and EPWP was mostly redistributed within the specimen. As $k_p$ increased, the upside drainage conditions of specimens were improved and the pore water was induced...
to seepage upward. As more sand deposits were consolidated at the lower part and the more pore water was driven to the upper part. In conditions of 0<k_p≤0.17, just a small amount of pore water can flow out through the infiltration device and resulted in the pore water accumulation at the upper part of specimen. The more water accumulated at the upper part of specimens, the more liquefiable the specimens were.

In figure 3(b), the sand specimens were considered under better drainage condition when 0.54 ≤ k_p ≤ 1. It has enough drainage ability that the majority of pore water can flow out through the infiltration device under the same dynamic loading. In these tests, the pore water just accumulated in a short time and the sand specimens cannot liquefy. The peak value of EPWP was smaller as k_p increased.

![Figure 3. Time-history of excess pore water pressure](image)

**3.2. Development of an energy-based EPWP evaluation model**

The energy-based EPWP generation model by Jafarian [9] was proposed as a function of cumulative strain energy density (W) and the capacity energy (W_{liq}) of sand and is depicted herein:

\[ r_p = \left( \frac{\alpha - 1}{\alpha} \right)^{\beta} \]  

(2)

Where \( x = W/W_{liq} \), defined as strain energy ratio; \( \alpha = 0.5052-0.593(D_s/100); \beta = 0.845 \). The capacity energy (W_{liq}) is defined as the cumulative strain energy that is required for liquefaction onset. For practical purposes, W can be estimated through the numerical site response analysis by implementing a constitutive model that can simulate the nonlinear stress-strain response of the liquefiable sand layer. The instantaneous excess pore water pressure ratio which reflects liquefaction susceptibility of soil deposits can be predicted, since strain energy ratio and other conditions are determined.

In the unliquefied group of this study, different drainage conditions were taken into consideration and measured by the introduced influence factor permeability coefficient ratio (k_p). Energy-based analysis of test result with k_p of 0.17 were plotted in figure 4. Figure 4(a) showed that the time-history of cumulative energy density and the capacity energy was calculated. While figure 4(b) illustrated histories of r_p W/W_{liq} and the trend of the distributed spots was fitted to a curve based on equation (2). Other test result with different k_p were analysed Different fitting curves of corresponding k_p were drawn in figure 5 and a particular case of equation (2) with D_s of 48.7 was compared, which proved the fitting results of well function. It can be concluded from figure 5 that EPWP is more susceptible to W as k_p increases.
Figure 4. Energy-based analysis of test result with $k_p$ of 0.17: (a) Time-history of instantaneous cumulative strain energy density (b) Excess pore water pressure ratio versus strain energy ratio.

Figure 5. Fitting curves of excess pore water pressure ratio versus strain energy ratio at different permeability coefficient ratio.

The calibration parameters of the fitting curves which are shown in Table 1 are then employed to develop the established EPWP generation model (2). The linear relationship between $k_p$ and $lg \alpha, \beta$ are shown by equation (3), equation (4) and figure 6 to examine the potential effects of different drainage conditions on the EPWP response regularity. Eventually, the developed energy-based EPWP generation model is depicted as equation (5).

![Linear Regression Mean $\pm \sigma$](image)

**Figure 6.** Linear regression of $lg \alpha, \beta$ at different $k_p$.

### Table 1. Values of $lg \alpha$ and $\beta$ at different $k_p$.

| $k_p$ | $lg \alpha$  | $\beta$  |
|-------|--------------|----------|
| 0.17  | 0.0002       | 0.5      |
| 0.13  | 0.0007       | 0.55     |
| 0.12  | 0.0081       | 0.6      |
| 0.11  | 0.1163       | 0.8      |
| 0    | 0.2256       | 0.85     |

\[
lg \alpha = -0.28 - 17.23k_p \quad (Dr = 48.7) \tag{3}
\]

\[
\beta = 0.88 - 2.07k_p \quad (Dr = 48.7) \tag{4}
\]
The scatters of data, which are evident in figure 6 are associated with the uncertainties of the equation. To account for the regression errors, mean ± $\sigma$ curves are also plotted together with the mean curves. The standard errors for the slope and intercept of equation (3) are 7.04 and 0.85, and those of equation (4) are 0.76 and 0.09.

In realistic situation, when permeability coefficients of adjacent soil layers are determined, the evaluation of the liquefiable soil deposits under different drainage conditions can be more precise employing the EPWP generation model calibrated by $k_p$.

4. Conclusion
A new infiltration device installed in triaxial test apparatus was designed to simulate EPWP generation response regularity of saturated sand during seismic events under different drainage conditions.

The cyclic triaxial test results indicate that the drainage conditions significantly influence the sand liquefaction behaviour. When $k_p \geq 0.54$ in the infiltration device, sand did not liquefy under certain loading condition since pore water outflow rapidly. In contrast, when $0 \leq k_p \leq 0.17$, sand liquefied in the same loading condition. A discovery that disagrees with the common sense is that a slight increase of $k_p$ will make sand more liquefiable under dynamic loading, which was caused by flow seepage effect.

An energy-based EPWP generation model was developed with two parameters secondary calibrated by different drainage condition measured by introduced factor $k_p$.

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