An incremental pore-water pressure buildup model for horizontal site

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A revised pore-water pressure buildup model for horizontal site

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ABSTRACT: Soil liquefaction has a strong influence on ground motion so that an effective analytical method of seismic response of liquefiable sites has to be established. The key of a liquefaction model is to simulate pore-water pressure process during liquefaction. The existing pore-water pressure models are mainly total quantitative models which can seldom simulate the process of liquefaction under irregular loadings. The pore-water pressure modes predicted by the incremental quantitative model which was obtained by regressing dynamic triaxial tests data are noticeably different from those of shaking table tests and centrifuge tests. A revised incremental pore-water pressure ratio model is proposed by modifying the pore-water pressure increasing modes proposed by Sun *et al*. The proposed model was testified by shaking table testing results under sinusoidal and irregular loadings. The results indicate that the revised model can better simulate the pore-water pressure buildup process under sinusoidal and seismic loading than the original model.

INTRODUCTION

Performance-based seismic design philosophy which needs the current seismic response analysis methods can describe the seismic response and even failure process of diverse engineering structures has been widely used in engineering practice. Sand liquefaction is one interesting and controversial natural phenomena, but it can cause tremendous loss during earthquakes. Since 1964 Alaska, USA, and Niigata, Japan, earthquakes, liquefaction has become a meaningful topic in geotechnical engineering. In recent earthquakes, liquefaction still is the main concern from engineering point of view (e.g., Cubrinovski et al. 2011; Bhattacharya et al. 2011; Cox et al. 2013). In Christchurch earthquake, for example, liquefaction is to be considered as the main cause to seismic damage.

Hitherto, the influence of soil liquefaction on ground motion response has not been fully understood and no guidance is given in the seismic design codes (Youd and Carter 2005). The common knowledge on the influence of liquefaction on response spectra is that liquefaction reduces high frequency of ground motions, while the long period components of ground motions are amplified. In 1975 Haicheng earthquake and 1976 Tangshan earthquake, the damage index of the low-rise houses in liquefied villages were smaller than neighboring none-liquefied villages by 0.1 to 0.4, since the local residences were low masonry structures with natural vibration less than 0.1s (Institute of Engineering Mechanics, 1979; Liu (editor), 2002).

To evaluate ground response of sites underlain by liquefiable layers, a key is to establish a site liquefaction model which can model the pore-water pressure process. Presently, numbers of pore-water pressure buildup models have been proposed (Seed 1976; Kagawa and Kraft, 1981; Ishibashi *et al*., 1977; Feng and Shi, 1987). These models, however, are mostly total quantitative models which are applied in strength theories and can hardly accurately simulate the progress of liquefaction. The incremental quantitative models proposed by Sherif *et al*. (Sherif *et al*., 1978) and Feng *et al*. (Feng and Shi, 1987) can be used to calculate the pore-water pressure generated by irregular loading, but these models were only valid when the sand was uniformly consolidated. Sun *et al*. (2005) proposed an incremental pore-water pressure buildup model based on dynamic triaxial tests data, and the model which takes into account of non-uniform consolidation can simulate the pore-water pressure buildup process under irregular loading. In practice, the prediction of Sun *et al.* model is well consistent with the results of dynamic triaxial tests under sinusoidal and irregular loading, but differs from shaking table and centrifuge tests results (Liyanapathirana *et al*., 2002). The discrepancy remains in increasing modes. Under sinusoidal loading, the pore-water pressure by Sun *et al*. model rapidly increases in the initial a few cycles, which is different from gradual increasing in shaking table and centrifuge tests. Besides, the pore-water pressure calculation stays constant after the peak motion acceleration under seismic loading. The real seismic pore-water pressure increased gradually and continued increasing after PGA (Youd and Holzer, 1994). Therefore, the Sun *et al*. model has to be revised to appropriately simulate the pore-water pressure buildup for horizontal sites.

2 PORE-WATER-PRESSURE MODELLING

Sun *et al*. (2005) proposed an incremental pore-water pressure buildup model based on dynamic triaxial tests data. It can simulate the pore-water pressure building-up process of saturated sand under non-uniform consolidation. To overcome the limitations of trixial tests, a revised model considering different sand relative density is proposed as,

$$\begin{cases} u_{R,0} = 0 \\ U_N = \dfrac{C'_{1,0}}{N^{0.5}}\left(\bar{\tau}_N\right)^{A_{4,0}}\left[1 - C_{1,a}(K_c - 1)^{C_{1,b}}\right], \quad N = 1,2,3,\ldots\infty \\ u_{R,N} = u_{R,N-1} + U_N(1 - u_{R,N-1}) \end{cases} \tag{1}$$

In which, $u_{R,N}$ and U_N are the pore-water pressure incremental value and pore-water pressure ratio caused by the N^{th} stress cycle with respect to the initial average effective stress; K_c is the consolidation ratio; $\bar{\tau}_N$ is the effective shear stress ratio which can be calculated by,

$$\bar{\tau}_N = \tau_N / \bar{\sigma}_{N-1} \tag{2}$$

τ_N is the shear stress amplitude of the N^{th} cycle; $\bar{\sigma}_{N-1}$ is the average effective stress of the $(N\text{-}1)^{th}$ cycle; N is the number of equivalent cycles; $C'_{1,0}$, $A_{4,0}$, $C_{1,a}$ and $C_{1,b}$ are coefficients which are suggested in Table 1.

Table 1 Parameters for calculating pore-water pressure ratio in the revised model

Sand relative density	$C'_{1,0}$	$C_{1,a}$	$C_{1,b}$	$A_{4,0}$
Loose ($D_r \le 30\%$)	33.71	0.38	0.56	2.61
Medium dense ($30\% < D_r \le 60\%$)	7.42	0.28	0.47	2.43
Dense ($D_r > 60\%$)	2.20	0.25	0.38	2.35

To calculate the pore-water pressure under seismic loading, an equivalent cyclic loading number N_{eq} is adopted (Ishibashi *et al*., 1977) to represent the equivalent number of loading prior to the N^{th} cycle. N_{eq} is calculated by,

$$N_{eq} = \sum_{i=1}^{N} \left[\frac{\tau_i}{\tau_N} \right]^{\beta} \tag{3}$$

where τ_i is the amplitude of cyclic shear stress at the i^{th} cycle ($1 \le i \le N$); τ_N is the amplitude of cyclic shear stress at the N^{th} cycle; and β is material parameter and taken as 2.40 (Ishibashi *et al*., 1977). Substituting N in Eq.(1) with N_{eq}, the pore-water pressure ratio under irregular seismic loading can be obtained. Before calculation, the irregular loading has to be smoothed as proposed by Chen et al. (2010). FIG.1 displays the scheme to process irregular seismic signals.

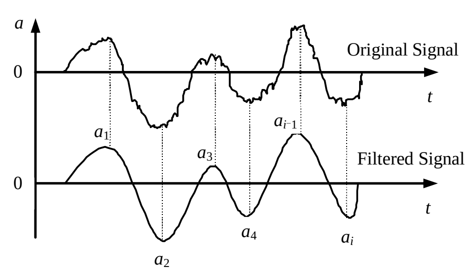

FIG.1. Signal processing of an irregular seismic loading

After smoothing irregular loading, the pore-water pressure increment in Eq.(1) is transformed into,

$$\begin{cases} U_{Np} = \dfrac{C'_{1,0}}{\left(N_{eq}\right)_p^{0.5}} \left(\bar{\tau}_{Np}\right)^{A_{4,0}} \left[1 - C_{1,a}(K_c - 1)^{C_{1,b}}\right] \\ \left(N_{eq}\right)_p = \displaystyle\sum_{i=1}^{N} \left(\frac{\tau_{ip}}{\tau_{Np}} \right)^{\beta} \end{cases} \tag{4}$$

In which the U_{Np} is the pore-water pressure ratio increment caused by the positive component of the dynamic shear stress in the N^{th} cycle; τ_{ip} and τ_{Np} are the i^{th} and the N^{th} positive shear stress amplitudes. To be noted, subscript '*p*' represents positive while '*n*' represents negative. Substituting *p* with *n* in Eq.(4), the pore-water pressure ratio increment, denoted as U_{Nn}, caused by the negative component of the dynamic shear stress in the N^{th} cycle can be obtained. As a result, the pore-water pressure increment U_N in the N^{th} shear stress cycle is evaluated by averaging the U_{Np} and U_{Nn}, which can be expressed as,

$$U_N = \frac{1}{2}\left(U_{Np} + U_{Nn}\right) \tag{5}$$

Finally, the pore-water pressure buildup for a horizontal site under seismic loading is written as,

$$\begin{cases} u_{R,0} = 0 \\ U_{Np} = \dfrac{C'_{1,0}}{\left(N_{eq}\right)_p^{0.5}}\left(\bar{\tau}_{Np}\right)^{A_{4,0}}\left[1 - C_{1,a}(K_c - 1)^{C_{1,b}}\right] \\ U_{Nn} = \dfrac{C'_{1,0}}{\left(N_{eq}\right)_n^{0.5}}\left(\bar{\tau}_{Nn}\right)^{A_{4,0}}\left[1 - C_{1,a}(K_c - 1)^{C_{1,b}}\right] \\ u_{R,N} = u_{R,N-1} + \dfrac{U_{Np} + U_{Nn}}{2}(1 - u_{R,N-1}) \end{cases}, \quad N = 1,2,3,\ldots\infty \tag{6}$$

3 VERIFIVATION OF THE REVISED PORE-WATER-PRESSURE MODEL

3.1 Sinusoidal loading

Shaking table tests on saturated sand with sinusoidal loading of different amplitudes and frequencies were conducted in the earthquake simulation laboratory at Institute of engineering mechanics. The detailed information on test apparatus and layout were presented in references (Tang *et al*., 2009; Chen *et al*., 2010). The relative density in the test was 80%, *i.e*., dense sand that normally consolidated. FIG.2 shows the inputted acceleration time histories in shaking table tests. The amplitudes of the uniform sinusoidal time histories were 0.15g as Test I and 0.25g as Test II (1.0g=9.8m/s^2), respectively. The frequencies were 2Hz and 3Hz. During the tests, the measured pore-water pressure ratios in the two tests reached to 1.0.

FIG.3 presented the tested and calculated pore-water pressure ratio by original model and revised model. In Test I, the tested pore-water pressure ratio gradually increased to 1.0, and the simulated pore-water pressure ratio by the revised model was closely consistent with the tested. In Test II, the pore-water pressure ratio rapidly increased to 0.8 at 3s due to large shaking intensity, and followed by fluctuating in the range of 0.6 to 1.0. The simulated pore-water pressure ratios by the revised model and the original model basically were well agreed with the tested. The revised model, however, better described the pore-water pressure ratio increasing process than the original model especially at the initial cycles.

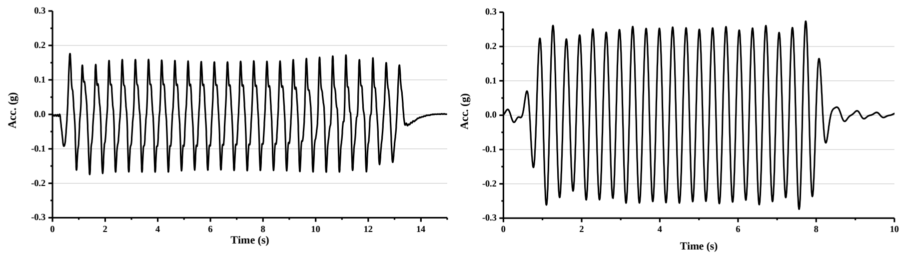

FIG.2. Time histories of the inputted uniform sinusoidal accelerations (Right: 0.15g amplitude and 2 Hz frequency; left: 0.25g amplitude and 3 Hz frequency)

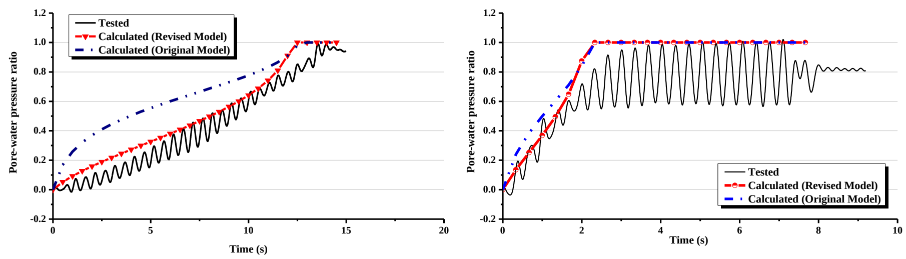

FIG. 3. Comparison of the calculated and tested pore-water pressure ratios

De Alba *et al.* used large shaking table tests to study the pore-water pressure buildup process of saturated sand (De Alba *et al*., 1976). The relative densities of the sand specimens were 82% and 90%, *i.e.*, dense sand. The dynamic stress ratios were 0.188, 0.219 and 0.28. FIG.4 illustrates the comparison of the tested results and predictions by the revised model. From FIG.9, the predicted pore-water pressure ratios were overall smaller than the tested when the dynamic stress ratios were 0.188 and 0.219; while the predictions were quite consistent with the tested for dynamic stress ratio of 0.28.

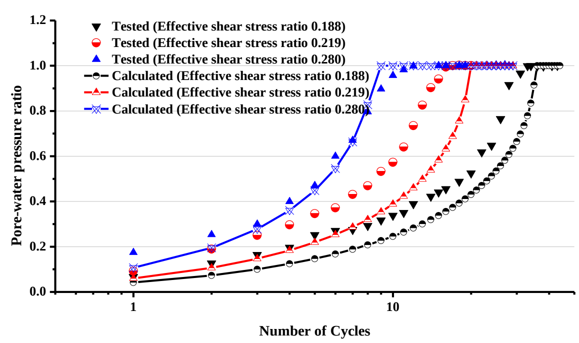

FIG.4. Comparison of the calculated and tested pore-water pressure ratios using De Alba shaking table test data

3.2 Seismic loading

The El Centro record with adjusting peak acceleration value of 0.12g was inputted during shake table test. However, the tested sand did not liquefy. The pore-water pressure ratio eventually increased to 0.3. FIG.5 presents the comparison of the tested and predicted pore-water pressure ratios. As is shown, the revised model can better simulate the process of pore-water pressure ratio buildup than the original model.

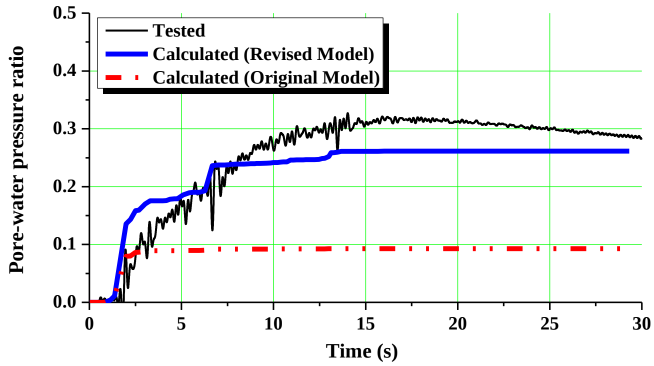

FIG. 5. Comparison of the calculated and the tested pore-water pressure ratios under seismic loading

4 CONCLUSIONS

The present pore-water pressure buildup model based triaxial tests cannot predict the modes of pore water pressure buildup due to the limitations of triaxial tests simulating horizontally deposited site. Therefore, a revised pore-water pressure model, which takes an incremental quantitative form, is proposed to simulate pore-water pressure increasing process of horizontal site under uniform sinusoidal and irregular seismic loading. The shaking table test results demonstrate that the revised model more satisfactorily predicted the pore-water pressure buildup under sinusoidal loading. Under seismic loading, the revised model can better predict the process of pore-water pressure increasing than the original model.

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