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A Simple Model for Pore Pressure Build-Up of Soil Under Dynamic Loadings

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SYNOPSIS: A simple pore pressure build-up model is introduced in this paper to simulate the effective-stress paths of saturated soils subjected to dynamic loadings. It is a five-parameter model in which two pairs of two parameters are used to define the effective-stress paths during the loading phases of first cycle and post-phase-transformations, respectively, and a dynamic pore pressure parameter is judiciously introduced to represent the increment of pore pressure due to shear loading in between the previous two phases. All parameters can be easily deduced from conventional undrained triaxial tests. Satisfactory results have been achieved for case studies including published results of laboratory uniform and non-uniform cyclic tests and seismic field measurements.

INTRODUCTION

During earthquakes, the build-up of pore water pressure in saturated soils is a very important problem in soil dynamics. It will reduce the shear resistance of soil, and, to the limit, will cause the liquefaction of ground. Since the liquefactions occurred at Niigata and Alaska in 1964, a lot of researchers have focused on this study. Up to now, many pore pressure build-up models have already been developed and used in ground response analyses. These models can be categorized as model of stress- or strain-type according to which parameter is used in the formulation. Among the stress-type models, the models proposed by Seed *et al.* (1976), Ishibashi *et al.* (1977) and Ishihara *et al.* (1980) are well known. As for the strain-type models, the models developed by Martin *et al.* (1975) and Finn *et al.* (1980) are representative ones.

These models are either too simple to directly simulate the response of pore pressure under seismic loadings, or too complicate to be readily used in engineering applications. It is the purpose of this paper to introduce a simple model which can effectively simulate the process of pore water pressure build-up in soils subjected to uniform and non-uniform loadings.

PORE PRESSURE BUILD-UP MODEL

1. Modelling for Uniform Cyclic Loads

The test data of undrained cyclic triaxial and simple shear tests show that the excess pore water pressure (Δu) increases with the number of loading cycles (N). In general, the process of pore water pressure build-up for soils subjected to uniform cyclic loading can be divided into three stages: an initial build-up stage, followed by a constantly increasing stage, and then a pre-liquefaction stage, as shown in Fig. 1. In terms of effective stress path, these three stages can be effectively modelled by the virgin effective stress path of the first cycle, the dynamic pore pressure parameter, and the effective stress path after phase-transformation line, respectively.

(1) Virgin effective stress path

During earthquakes, many records showed that the major rise of soil pore pressure is primarily induced by the peak ground acceleration (Ishihara 1981, 1987). Therefore, it is very important to accurately describe the stress path of virgin loading phase. In uniform cyclic loading test, the first cycle includes four quarter cycles of loading, unloading, reverse loading, and reverse unloading. It has been found that the loading and reverse loading can induce greater excess pore pressure than the other quarter cycles. These effective stress paths are similar in shape and can be simulated by effective stress path under monotonic undrained shear test. These stress paths are called the "virgin effective stress path" in this paper. Regarding the shape of virgin effective stress path, Ishihara *et al.* (1980) used a parabolic function, but Ghaboussi *et al.* (1978) used an elliptic function. The elliptic virgin effective stress path is adopted in the present model. As shown in Fig. 2, two parameters are needed, i.e., $\lambda = 1/A_f$ and $M_f = \tan\phi'$, in which A_f is Skempton's pore pressure parameter at the failure stage of an undrained shear test, and ϕ' is the effective friction angle in the same test.

As for the unloading and reverse unloading part of the first cycle, the effective stress paths are similar to those of constantly increasing stage and can be defined by the secant pore pressure parameter A_s defined in subsequent section.

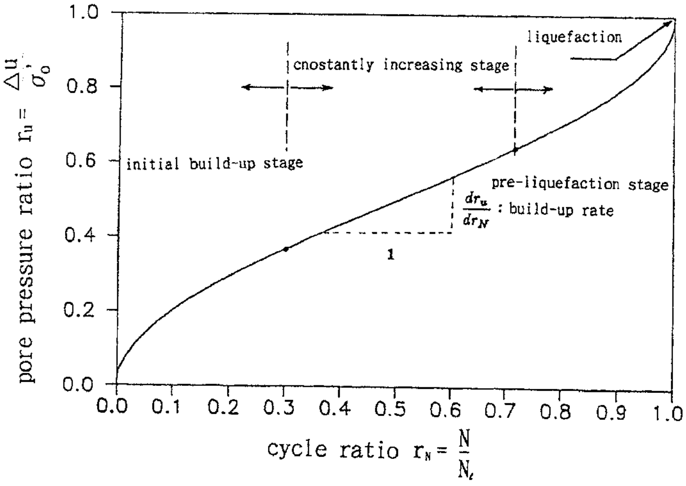


Fig.1 Typical pore pressure build-up process under uniform cyclic loads

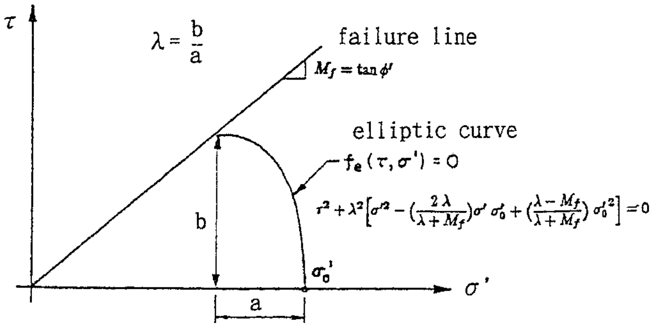


Fig.2 Effective stress path for first cycle

(2) Effective stress path for constantly increasing stage

In the constantly increasing stage, the pore pressure rise per loading cycle is nearly the same, i.e., the average rate of pore pressure build-up due to cyclic shear loading is constant. The effective stress paths during this stage look like straight lines in the test results of Yamada *et al.* (1983). They can be simulated very well by sequence of straight lines as shown in Fig. 3. The slope of secant line is the average build-up rate of pore pressure which is called the secant pore pressure parameter A_s herein.

The pore pressure parameter A_s depends primarily on soil type and magnitude of cyclic shear stress, and can be directly determined from the results of liquefaction test by

$$A_s = \frac{\Delta u}{4 n \tau} \tag{1}$$

in which Δu is the amount of pore pressure rise in n loading cycles under the application of uniform cyclic shear stress τ. A_s can also be estimated using the slope of straight portion of the normalized pore pressure rising curve (as shown in Fig. 1) by

$$\overline{\gamma_u} = \frac{\gamma_{u2} - \gamma_{u1}}{\gamma_{N2} - \gamma_{N1}} \tag{2}$$

in which, γ_{u1} and γ_{u2} are excess pore pressure ratios at two points on the straight line portion, and γ_{N1} and γ_{N2} are loading cycle ratio corresponding to γ_{u1} and γ_{u2}, respectively. From (1), (2),

$$A_s = \frac{\Delta u}{4\tau\Delta n} = \frac{\sigma_0'}{4\tau N_\ell}\overline{\gamma_u} = \frac{\overline{\gamma_u}}{4\,SR\cdot N_\ell} \tag{3}$$

in which, $SR = \tau/\sigma_0'$ is the shear stress ratio of the test, N_ℓ is number of cylces to liquefaction under applied SR in liquefaction test. The procedure of determining A_s is rather simple and straight forward from results of cyclic loading tests.

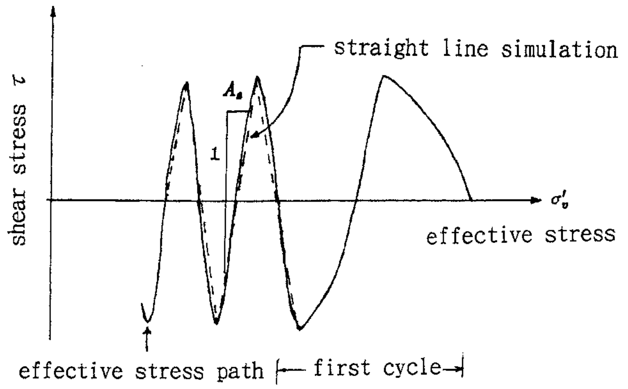


Fig.3 Effective stress path for constantly increasing stage

(3) Effective stress path after phase transformation line

The effective stress path after phase transformation line is rather difficult to be accurately recorded in a test. Ishihara *et al.* (1980) has proposed a hyperbolic model to simulate the effective stress path after the phase transformation line. It is adopted in the present model, but with minor modification, as shown in Fig. 4, to make it fit more closely with test results.

The parameters used are the slope of phase transformation line $M_s = \tan\theta_s'$ (θ_s' is angle of phase transformation line) and the effective friction angle ϕ_ℓ' under small effective confining pressure.

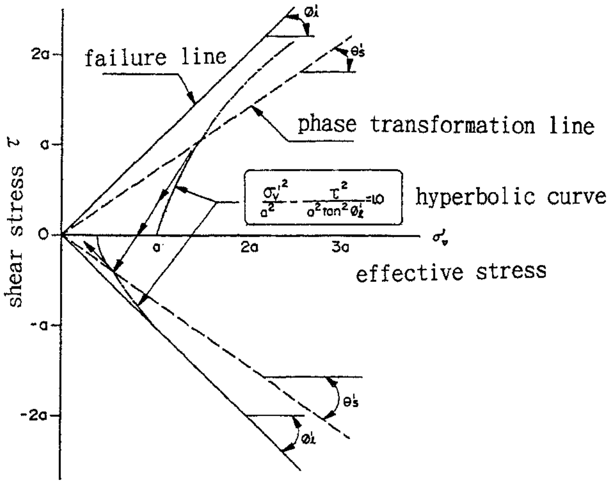


Fig.4 Effective stress path after phase transformation line

2. Modelling for irregular cyclic loads

The secant pore pressure parameter A_s defined previously can not be directly applied in cases when shear stress reverses irregularly with time. No constant increasing stage can be defined for irregular loading conditions. Therefore, a tangent pore pressure parameter A_t is introduced herein to define the increment of pore water pressure (Δu) due to an increment of shear stress ($\Delta\tau$) at specified shear stress level, i.e.

$$\Delta u = (A_t^j)\,\Delta\tau \tag{4}$$

in which the superscript j indicates the jth level of shear stress. As shown in Fig. 5, the magnitude of A_t^j can be estimated by secant pore pressure parameters obtained from uniform cyclic tests at different levels of shear stress by recurrence formula

$$A_t^j = \frac{SR^j A_s^j - SR^{j-1} A_s^{j-1}}{SR^j - SR^{j-1}} \tag{5}$$

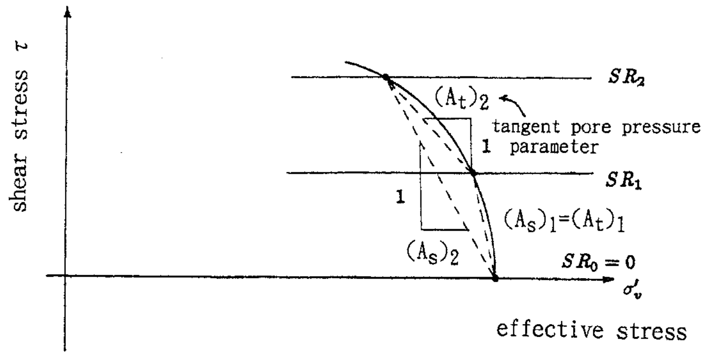


Fig.5 Graphic illustration for determining tangent pore pressure parameter A_t

in which SR^k and A_s^k $(k = j, j-1)$ are the kth level of stress ratio and the corresponding secant dynamic pore pressure parameter, respectively.

According to the procedure described above, the tangent pore pressure parameter obtained will vary with the magnitude of shear stress applied during the process of irregular loading.

By using Eq. (4), the proposed model can be directly incorporated in incremental dynamic effective stress analysis for seismic ground response.

NUMERICAL SIMULATIONS

To demonstrate the performance of the proposed model, numerical simulations for some laboratory test results and field recordings are conducted as below.

1. Laboratory Test Results

Among numerous laboratory test results published, the following three tests were chosen for numerical simulations to demonstrate the ability of the proposed model in applications.

(1) Large scale simple shear test (De Alba *et al.* 1976)

The parameters needed for the proposed model are deduced from the published results as shown in Table 1. Besides, this set of test results was also chosen for numerical simulation by using the LASS-IV model (Dikmen and Ghaboussi, 1984). The comparisons are shown in Fig. 6. The process of pore water pressure build-up during the test can be simulated very well by using the proposed model.

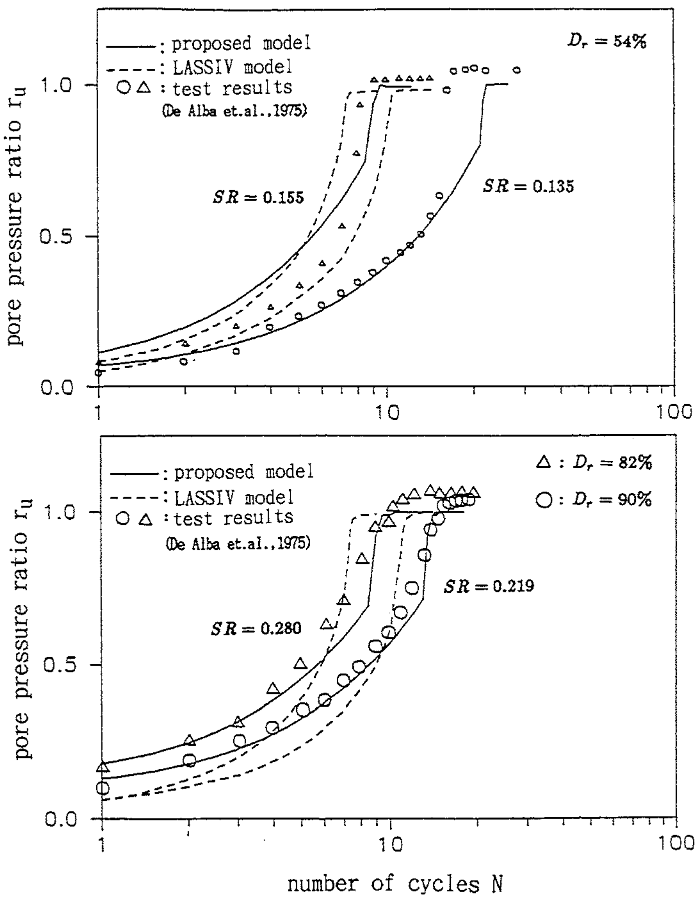
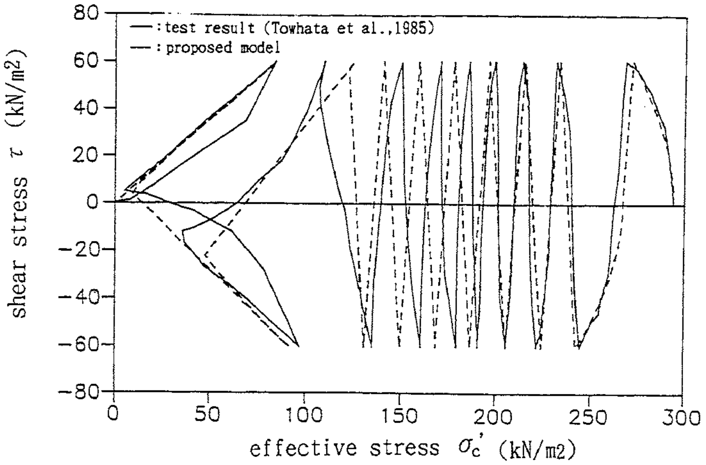


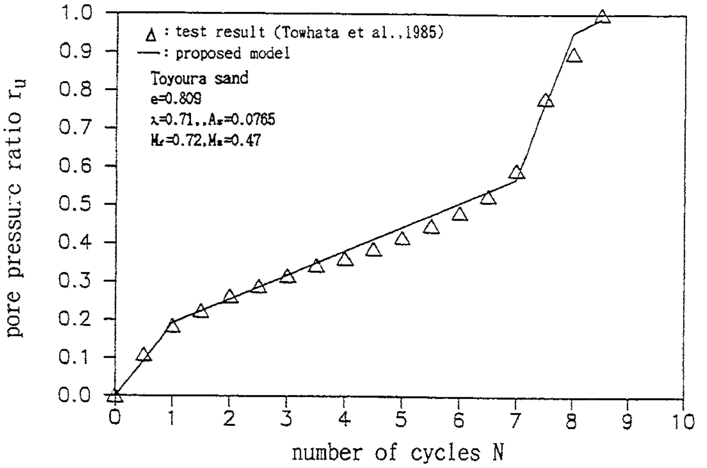
Fig.6 Simulation of large scale simple shear test results

(2) Triaxial torsional shear test (Towhata and Ishihara, 1985)

The case chosen for simulation is $e = 0.809$, $\sigma_0' = 294$ kN/m^2 and $SR = 0.206$. The parameters used for simulation are shown in Fig. 7. The comparisons of test results and the proposed model are also shown in Fig. 7. Both the effective stress path and the process of pore pressure build-up can be simulated very well by the model proposed.



(a) effective stress path



(b) rising curve of pore pressure ratio

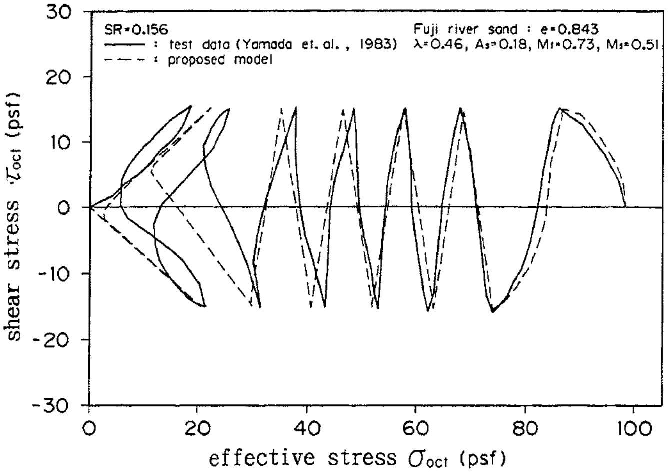
Fig.7 Simulation of triaxial torsional shear test result

(3) True triaxial test (Yamada and Ishihara, 1983)

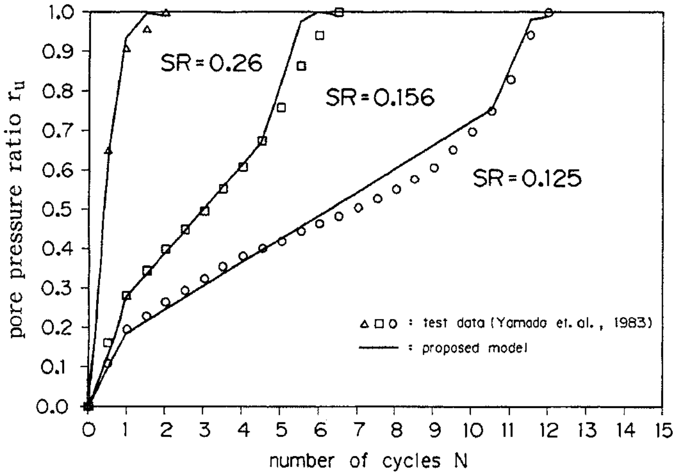
Three cases of true triaxial test, $SR = 0.26$, 0.156, and 0.125, are chosen for comparison in Fig. 8. The effective stress path for $SR = 0.156$ and the soil parameters used are shown in Fig. 8(a). Analytical results fit very well with test results.

2. Seismic Response

Based on the pore water pressure model described herein, a ground response computer program LQDYN has been developed (Hwang, 1989). It is a finite element program which has capability for non-linear effective-stress analysis. This program was used to simulate the excess (residual) pore water pressure recorded at Lotung, Taiwan, during the July 30 and November 15, 1986 earthquakes. In both earthquakes, three sets of pore pressure recordings had been chosen for simulation studies. One of them, piezometer PA3', is shown in Fig. 9. From comparisons, it can be seen that the proposed model can simulate the process of pore pressure*build-up very well. The fluctuation of pore water pressure during earthquakes can be simulated by computer program LQDYN by incorporating the responses due to vertical ground excitations. They are not shown in this paper.



(a) effective stress path



(b) rising curve of pore pressure ratio

Fig.8 Simulation of true triaxial test results

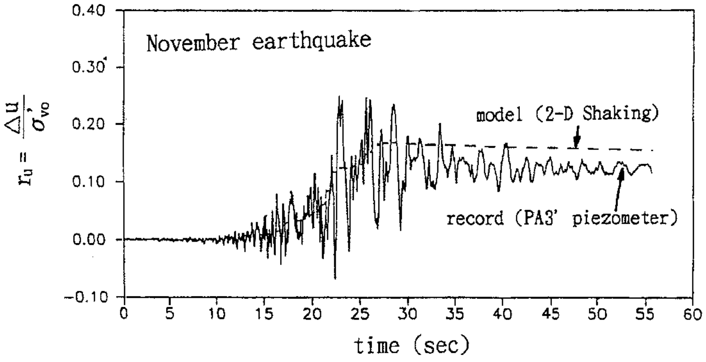


Fig.9 Residual pore pressure response of numerical analysis compared with that recorded at LSST site of Lotung, Taiwan

CONCLUSION

A simple model of pore pressure build-up is introduced herein which can be used for liquefaction analysis based on effective stress method. Its ability in application was demonstrated through simulating laboratory test results and modelling the seismic pore pressure responses during earthquakes. Since the main features of the process of pore pressure build-up of soils subjected to dynamic loadings are taken into account in the proposed model and the parameters used are simple, easily determined, and with clear physical significance , the proposed model is very suitable to be applied in seismic ground response analysis performed in time domain.

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