SIMULATION OF POST-LIQUEFACTION BEHAVIOR OF SAND CONSIDERING EFFECT OF WATER ABSORPTION IN SHEAR

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ABSTRACT:

Existing methods of evaluation based on the undrained behavior cannot always provide a realistic prediction to post-liquefaction deformation and strength behavior of saturated sands. Redistribution of water content or void redistribution in saturated sand during a shearing application is referred to as the water absorption in shear. Previous experimental facts show that occurrence of the water absorption in shear after an earthquake is one of the main reasons why large lateral flow slides happened in liquefied looser to medium dense sands. A new constitutive model considering effect of the water absorption in shear has been developed for description of the post-liquefaction stress-strain response of saturated sand subjected to an application of monotonically shearing in any arbitrary drainage condition. Essential effectiveness of the proposed constitutive model was confirmed experimentally.

KEYWORDS: saturated sand, post-liquefaction behavior, water absorption in shear, constitutive equation

1. INTRODUCTION

Many failures and large flow slides induced by earthquakes were observed to happen after the shakes stopped (e.g., Seed et al., 1975; Shen, 1981 and Hamada, 1992). They might be triggered by earthquakes in liquefiable saturated sandy soils near river banks and quay walls, when lateral movements of these structures occurred subjected to seismic excitation. They also were initiated in slopes and embankments where there existed initial driving shear stresses (e.g., Seed et al., 1975). The delayed failures and large flow slides are actually the result of a drastic reduction or even complete loss in the shear strength of saturated sand. One of the main reasons why reduction or loss of the shear strength happened is attributed to redistribution of water content or void redistribution under a monotonically-shearing application (e.g., Seed et al., 1987). The void redistribution was first observed to occur in laboratory sand specimens by Casagrande and Rendon (1978). It is confirmed that the void redistribution may be more pronounced at the field scale than the laboratory scale using triaxial tests (Boulanger and Truman, 1996). Extensive model tests show that the void redistribution does exist in the formation of the water interlayer or water film (Liu and Qiao 1984; Arulanandan et al., 1993; Fiegel and Kutter 1994). Kokusho (1999) demonstrated that the formation of the water film plays an important role in the occurrence of large post-liquefaction lateral flow. Many laboratory tests were made to examine the post-liquefaction stress-strain response of sand for the different conditions of water inflow and initial shear stress (Zhang, 1997, Tokimatsu et al., 2001; Uchida and Vaid, 1994; Vaid and Eliadorani, 1998; and Sento et al., 2004). They indicate that existing methods of evaluation based on the undrained behavior cannot always provide a realistic prediction to post-liquefaction deformation and strength behavior of sands.

Tokimatsu et al. (1996) and Zhang (1997) developed a new test method used to reproduce the redistribution of water content in saturated sands under post-liquefaction shear applications. The redistribution of water content during shearing is referred to as "water absorption in shear" (Zhang, 1997). Their test results (Zhang, 1997 and Tokimatsu et al, 2001) showed that the water absorption in shear can appear in sands over a wide range of density, and post-liquefaction stress-strain response of sand is determined mainly by rate of the water absorption in shear. This rate is hereby defined as the rate of the water content change to the shear strain. In particular, catastrophic flow slide failures may occur in dilative sands when the rate of the water absorption in shear becomes large enough. These experimental findings imply that the water absorption in shear is likely to be responsible for large flow slides occurred in liquefied looser to medium dense sands. The object of this paper is to develop and verify a new constitutive model considering effect of the water absorption in shear for describing the post-liquefaction stress-strain response of saturated sand subjected to an application of monotonically shearing in any arbitrary drainage condition.

2. NEW CONSTITUTIVE MODEL CONSIDERING WATER ABSORPTION IN SHEAR

2.1 Relative water absorption rate

The rate of the water absorption in shear may be characterized by a ratio of the volumetric to shear strain increments, $d\varepsilon_v / d\gamma$. For the convenience of description, a new parameter named "relative water absorption rate" is denoted as α , and is defined by (Tokimatsu et al., 1996 and Zhang, 1997)

$$\frac{d\varepsilon_v}{d\gamma} = \alpha \left(\frac{d\varepsilon_v}{d\gamma}\right)_{drain} \tag{2.1}$$

in which the right term $(d\varepsilon_v / d\gamma)_{drain}$ indicates the value of $d\varepsilon_v / d\gamma$ at a completely drained condition. Obviously, $d\varepsilon_v / d\gamma$ = 0 when α = 0 and $d\varepsilon_v / d\gamma$ = $(d\varepsilon_v / d\gamma)_{drain}$ when α = 1, which correspond to completely undrained and drained condition respectively. 0< α <1 corresponds to partially drained condition, and α >1 means such a condition for which more water is injected into the element of saturated sand than for a completely drained condition.

2.2 Establishment of post-liquefaction constitutive equation

In general, the volumetric strain ε_v of saturated sand subjected to an application of general loading can be divided into a volumetric strain component due to change in the mean effective stress ε_{vc} and a volumetric strain component due to dilatancy ε_{vd} or

$$\varepsilon_v = \varepsilon_{vc} + \varepsilon_{vd} \tag{2.2}$$

Comparing equations (2.1) and (2.2), we have $d\varepsilon_v = \alpha d\varepsilon_{v,drain}$ for the condition of a monotonically shearing application considering the occurrence of the water absorption in shear. Thus the equation (2.2) can be written as equation (2.3) in the form of

$$\alpha\varepsilon_{v,drain} = \varepsilon_{vc} + \varepsilon_{vd} \quad \text{or} \quad \alpha\dot{\varepsilon}_{v,drain} = \dot{\varepsilon}_{vc} + \dot{\varepsilon}_{vd} \tag{2.3}$$

In the case of the post-liquefaction behavior of sand, the volumetric strain due to dilatancy ε_{vd} may be determined by (Zhang et al, 1999)

$$\dot{\varepsilon}_{vd} = \frac{1}{c}(M_o - M_{cs})\dot{\gamma} \tag{2.4}$$

in which γ = shear strain; c = constant coefficient dependent on the strain path and stress parameters; M_o = shear-normal stress ratio at the phase-transformation state (Ishihara et al, 1975); and M_{cs} = shear-normal stress ratio at the critical stress state or the slope of critical stress state line. It was experimentally confirmed to be significantly influenced by the relative absorption rate α , and can be determined by (Zhang, 1997).

$$M_{cs} = \alpha M_{cs,d} + (1-\alpha) M_{cs,u} \tag{2.5}$$

where $M_{cs,d} = 3\sin\phi_d' / (\sqrt{3}\cos\theta_\sigma + \sin\phi_d' \sin\theta_\sigma)$ and $M_{cs,u} = 3\sin\phi_u' / (\sqrt{3}\cos\theta_\sigma + \sin\phi_u' \sin\theta_\sigma)$ in which the subscript index '*d*' and '*u*' correspond to completely drained and undrained condition separately, ϕ' is angle of frictional resistance obtained from cyclic tests and θ_σ is Lode angle. Figure 1 shows the variety of the angles of frictional resistance ϕ_d' and ϕ_u' with relative density.

In addition, the post-liquefaction volumetric strain due to a completely drained shearing application, $\varepsilon_{v,drain}$, may be estimated by

$$\dot{\varepsilon}_{v,drain} = \frac{1}{c}\left(M_o - M_{cs.d}\right)\dot{\gamma} \tag{2.6}$$

The volumetric strain component ε_{vc} in equation (2.3) may be given by (Shamoto et al. 1997).

$$\varepsilon_{vc} = K\left(\frac{p_i'}{p_a'}\right)^A\left(\frac{p'}{p_i'}\right)^B \tag{2.7}$$

Then substituting equations (2.4) and (2.7) into equation (2.3) gives equation (2.8) or (2.9):

$$\dot{\gamma} = \frac{cBK}{[\alpha\left(M_o - M_{cs,d}\right) - \left(M_o - M_{cs}\right)]}\left(\frac{p_i'}{p_a}\right)^A\left(\frac{p'}{p_i'}\right)^{(B-1)}\frac{\dot{q}}{M_{cs}p_i'} \tag{2.8}$$

$$\dot{q} = \frac{[\alpha\left(M_o - M_{cs,d}\right) - \left(M_o - M_{cs}\right)]M_{cs}p_i'}{cBK}\left(\frac{p_a}{p_i'}\right)^A\left(\frac{p_i'}{p'}\right)^{(B-1)}\dot{\gamma} \tag{2.9}$$

in which *A*, *B*, and *K* = constants determined by tests; p_i' = initial mean effective stress; p_a = barometric pressure; the stress parameters q and p' with respect to the three effective principal stresses σ_1', σ_2', and σ_3' are given by

$$\dot{q} = \frac{1}{\sqrt{2}}\sqrt{(\dot{\sigma}_1' - \dot{\sigma}_2')^2 + (\dot{\sigma}_2' - \dot{\sigma}_3')^2 + (\dot{\sigma}_3' - \dot{\sigma}_2')^2} \quad \text{and} \quad \dot{p} = \frac{1}{3}(\dot{\sigma}_1' + \dot{\sigma}_2' + \dot{\sigma}_3').$$

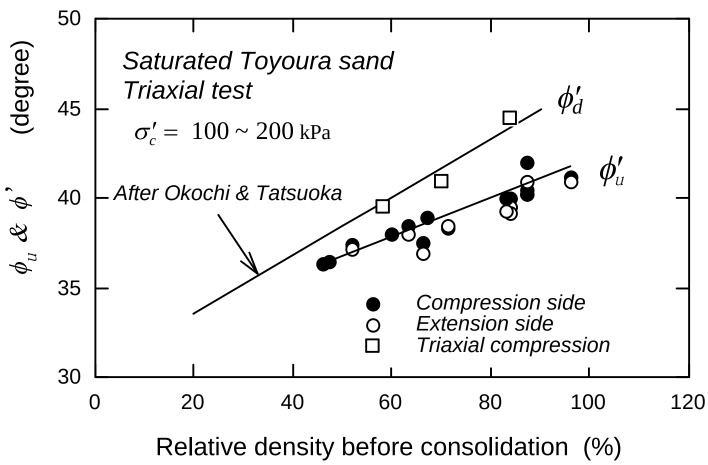

Figure 1 Variety of friction angle with relative density

3 VERIFICATION OF NEW CONSTITUTIVE MODEL

3.1 Constant water-absorption-rate shear tests

An electro pneumatic closed-loop test system has been developed by Tokimatsu and Nakamura (1986) for the purpose of minimize the detrimental influence of membrane penetration on the undrained shear strength of saturated granular soils. A constant volume shear test can readily be conducted by coupling this test system to any conventional static or cyclic shear test apparatus. Tokimatsu et al. (1996) and Zhang (1997) coupled the test system with a torsional shear test apparatus in order to investigate the effect of water absorption in shear on the post-liquefaction stress-strain response of saturated sand. By controlling the amount of the water injected into the specimen of saturated sand, shear tests can be performed under the conditions of different constant rates of the water absorption in shear. The test that satisfies the conditions keeping a constant α-value and thus a constant $d\varepsilon_v / d\gamma$-value is called "constant water-absorption-rate shear test". In such a test, the relative water absorption rate α is used as an index controlling the rate of the water absorption in shear.

The program of constant water-absorption-rate shear tests is shown in Figure 2. In Stage 1, an isotropically consolidated Toyoura sand specimen is cyclically sheared in an undrained condition while retaining a constant cell pressure, until the initial liquefaction occurs. In Stage 2 right after Stage 1, the specimen is monotonically sheared under either of the two following states: retaining $\alpha = constant$ for Case A; or retaining $\alpha = 0$ when $\tau \leq \tau_0$ and then $\alpha = constant$ when $\tau > \tau_0$ for Case B. Provided in Figures 3 and 4 are the post-liquefaction stress-strain relations of Case A tests for D_r= 45% with different α-values and the results of Case B tests. They showed strong dependency of the post-liquefaction stress-strain response on the rates of the water absorption in shear.

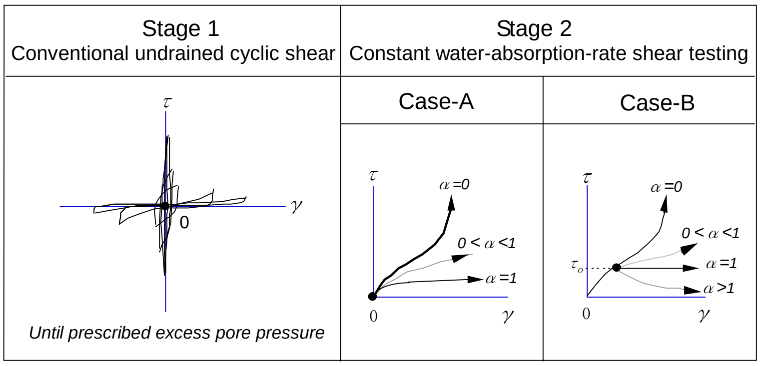

Figure 2 Test program of constant water-absorption-rate shear testing

3.2 Determination of Model Parameters

Provided in Figure 3 and 4 are typical results of Case A and B tests where the post-liquefaction stress-strain responses are shown to have their strong dependency on the relative water absorption rate α , In all the tests, it is clear that the density of the sand specimens always decreases as the water inflow, and its decrease obviously affects the post-liquefaction stress-strain response. Based on the experimental data as shown in the figures, seven model parameters c, K, A, B, M_0, $M_{cs,d}$, $M_{cs,u}$ may be determined and then listed in Table 1. The relative water absorption rate α is specified in the different tests, whereas the relative density varies with the development of the shear strain.

Table 1 Parameters of the model

$M_{cs,u}$	$M_{cs,d}$	M_o	c	K	A	B
1.16	1.22	0.93	2.6	0.9	1.0	0.6

3.3 Effectiveness of proposed constitutive equation

The results simulated by the new constitutive model are also shown in Figures 3 and 4. There exists fair agreement between the tested and computed results, showing essential effectiveness of the proposed constitutive model.

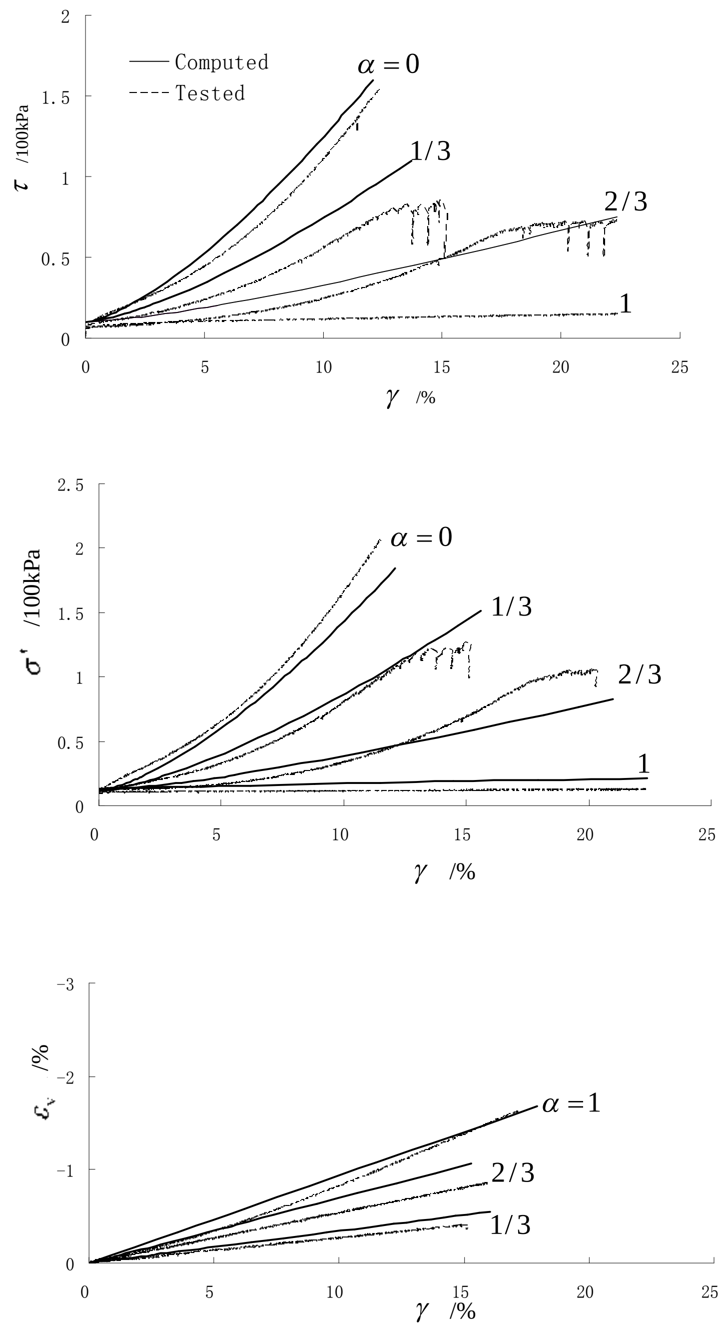

Figure 3 Results of test and simulation for Case A

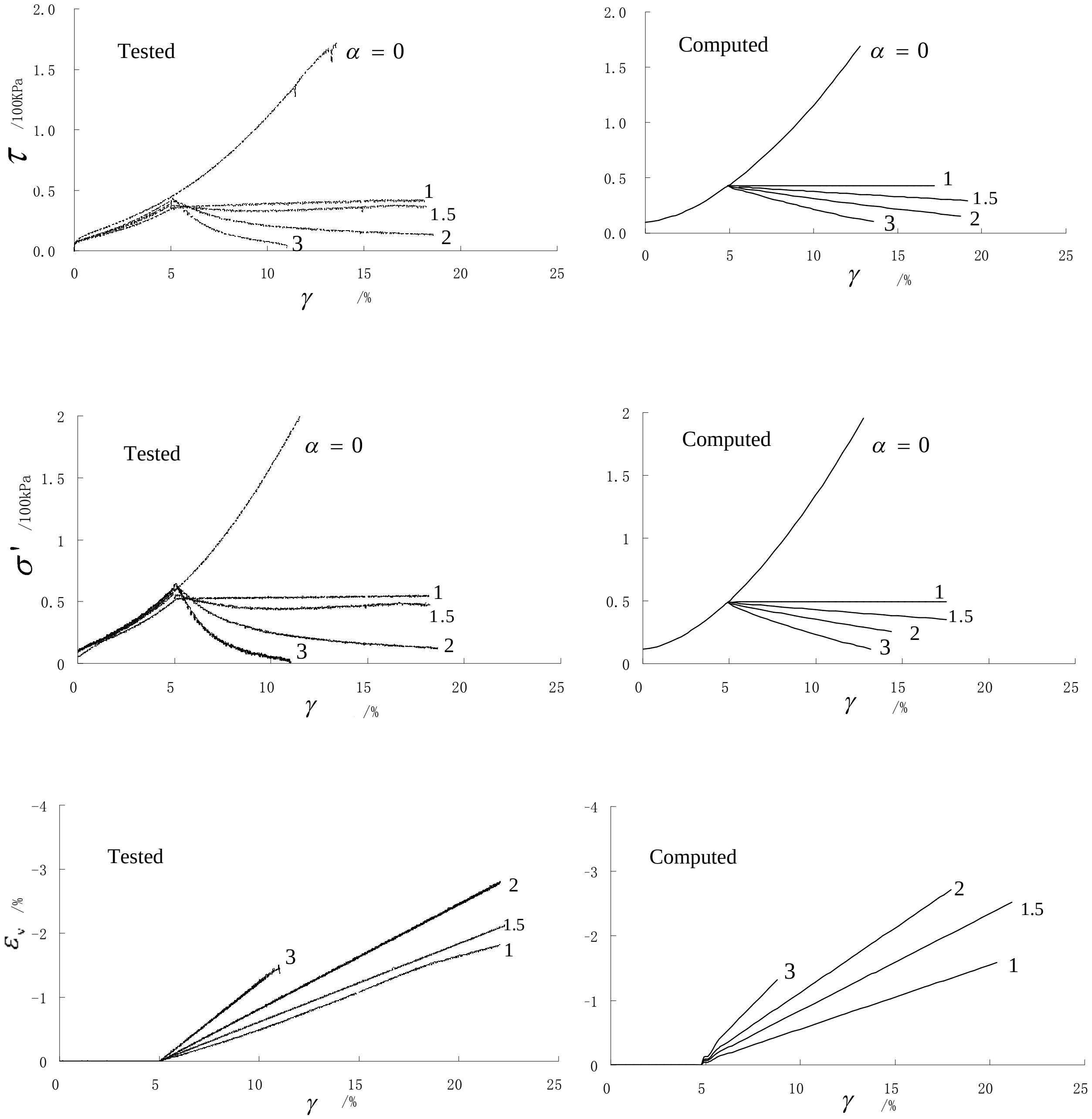

Figure 4 Results of test and simulation for Case B

4. CONCLUSIONS

Existing methods of evaluation based on the undrained behavior cannot always provide a realistic prediction to post-liquefaction deformation and strength behavior of saturated sands. Occurrence of the water absorption in shear after an earthquake is regarded as one of the main reasons why large lateral flow slides happened in saturated sand. Presented in this paper is a new constitutive model considering effect of the water absorption in shear developed for description of the post-liquefaction stress-strain response of saturated sand subjected to an application of monotonically shearing in any arbitrary drainage condition. Its essential effectiveness was confirmed experimentally.

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