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A unified plasticity model for large post-liquefaction shear deformation of sand

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ABSTRACT

Based on previous experimental findings and theoretical developments, this paper presents the formulation and numerical algorithms of a novel constitutive model for sand with special considerations for cyclic behaviour and accumulation of large post-liquefaction shear deformation. Appropriate formulation for three volumetric strain components enables the model to accurately predict loading and load reversal behaviour of sand, fully capturing the features of cyclic mobility. Compliance with the volumetric compatibility condition, along with reversible and irreversible dilatancy, allows for physically based simulation of the generation and accumulation of shear strain at zero effective stress after initial liquefaction. A state parameter was incorporated for compatibility with critical state soil mechanics, enabling the unified simulation of sand at various densities and confining pressures with a same set of parameters. The determination methods for the 14 model parameters are outlined in the paper. The model was implemented into the open source finite-element framework OpenSees using a cutting-plane stress integration scheme with substepping. The potentials of the model and its numerical implementation were explored via simulations of classical drained and undrained triaxial experiments, undrained cyclic torsional experiments, and a dynamic centrifuge experiment on a single pile in liquefiable soil. The results showed the model's great capabilities in simulating small to large deformation in the pre- to post-liquefaction regime of sand.

1. Introduction

Large post-liquefaction deformation is a major cause for seismic liquefaction induced hazards, and has been a subject of extensive research since its observations in several well documented earthquakes (e.g. [1–4]). In this paper, we focus on the cyclic mobility of sand and the accumulation of large but limited shear strains after sand reaches "initial liquefaction" [5] observed in numerous laboratory experiments (e.g. [6–8]), which is referred to as large post-liquefaction shear deformation (Fig. 1).

Numerous constitutive models have been developed aiming to simulate the stress–strain behaviour of saturated sands during cyclic loading, including generalized plasticity models (e.g. [9,10]), hypoplasticity models (e.g. [11,12]), multi-surface models (e.g. [13–18]) and bounding surface plasticity models (e.g. [19–23]). Pastor et al. [9] suggested predicting cyclic mobility through applying a "discrete memory factor" to the plastic modulus in their generalized plasticity model. Wu and Bauer [11] developed a simple hypoplasticity model that accounts for basic cyclic behaviour of sand, though the model's independence from stress history limits its application under complex stress paths. Wang et al. [19] proposed a bounding surface hypoplasticity model for sand which was able to simulate cyclic stress path through reducing plastic shear modulus with the accumulation of plastic shear strain. Papadimitriou et al. [20] and Dafalias and Manzari [22] developed bounding surface plasticity models that simulated sand behaviour under cyclic loading by applying evolving fabric tensors on the plastic modulus and dilatancy rate respectively, enhancing the contraction upon unloading and thus allowing the stress path to approach liquefaction during undrained loading. These models all made significant contributions to the description of cyclic mobility, but none are able to reflect the accumulation of shear strain at liquefaction during each load cycle after initial liquefaction, with stress–strain relationship following almost the same path each cycle, which contradicts experimental findings.

To reflect the shear strain generated at liquefaction, Boulanger and Ziotopoulou [23] further modified the model by Dafalias and Manzari to achieve the accumulation of shear strain after initial liquefaction by adding fabric history and cumulative fabric terms.

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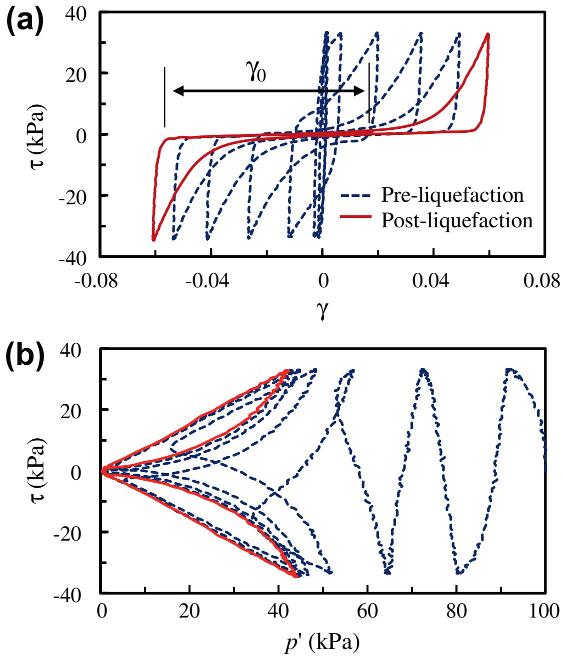

Fig. 1. Stress–strain relation and stress path of undrained cyclic torsional test for Toyoura sand at $D_r = 70\%$. (Data from Zhang et al., 1997).

In the multi-surface models by Parra-Colmenares [15], Elgamal et al. [16,17] and Yang et al. [18], in order to model the accumulation of shear strain near liquefaction state, an additional shear strain accumulation was introduced at a "neutral phase" when the effective stress path crossed the phase transformation line at relatively low effective confining pressure. These two sets of more recent models have taken a big step forward in the simulation of liquefaction behaviour of sand, however both models lack the physical basis for the formulation of post-liquefaction shear strains, causing the shear strain accumulation to occur at somewhat high shear stress instead of at liquefaction.

Significant progress on clarifying the role of critical state [24,25] for sand has been made over the past few decades through rigorous work by various researchers, including Been and Jefferies [26], Ishihara [27], Wood et al. [28], Li and Dafalias [29], etc. Thus making the unified constitutive description for sand of different densities and confining pressures possible, which has been an approach adopted by numerous recent constitutive models (e.g. [20,22,23,28,29]).

These previous research have provided valuable insights into the mechanical behaviour of sands. This paper looks to further the understanding of sand behaviour by presenting a constitutive model with special attention given to providing physically based modelling of large but limited shear deformation after initial liquefaction at or near zero effective stress, which has been observed in undrained cyclic triaxial and torsional shear experiments conducted by various researchers (e.g. [6–8]).

Through observations from a number of cyclic undrained torsional shear tests conducted on hollow cylinder specimens of Toyoura sand, Zhang [30] noted that after initial liquefaction, while the stress path of each cycle was very much similar (Fig. 1(b)), large but finite shear strain was generated near zero effective stress state during each cycle (Fig. 1(a)), which was referred to as large post-liquefaction deformation. The shear strain generated at liquefaction state was observed to increase with the number of loading cycles, and was defined as a "fluid-like shear strain" γ_0 [31].

To explain the physics of post-liquefaction deformation, based on observations on drained cyclic experiments, Shamoto and Zhang [32] and Zhang [33] proposed that the volumetric strain of sand consisted of two basic components: mean effective stress change induced ε_{vc}, and dilatancy induced ε_{vd}. The dilatancy induced ε_{vd} was further decomposed into a reversible and an irreversible component, namely $\varepsilon_{vd,re}$ and $\varepsilon_{vd,ir}$, as shown in Fig. 2(c) and (d). Irreversible dilatancy is the shear induced contraction of sand, which is generally caused by packing and crushing of particles. Reversible dilatancy refers to shear induced expansion and the reversal of such expansion normally caused by particle sliding and reorientation. The decomposition would then be expressed as:

$$\varepsilon_v = \varepsilon_{vc} + \varepsilon_{vd} = \varepsilon_{vc} + \varepsilon_{vd,ir} + \varepsilon_{vd,re} \tag{1}$$

Zhang and Wang [31,34] pointed out that since ε_{vc} is solely dependent on the change in effective confining pressure, there exists a threshold $\varepsilon_{vc,0}$ at which zero effective stress is reached. Once this threshold is reached, the ε_{vc} would then be determined the volumetric compatibility Eq. (1). For sand to leave liquefaction state when $\varepsilon_{vc} < \varepsilon_{vc,0}$, sufficient dilatancy would be needed, and hence sufficient shear strain would be required according to dilatancy relations. Based on the proposed mechanism, Zhang and Wang [31] formulated a constitutive model within the framework of bounding surface plasticity suited for two dimensional stress space. The model proved capable in simulating the cyclic mobility and large post-liquefaction shear deformation of sand. However, the model does underestimate contraction during initial loading and may overestimate it during load reversal. And as critical state behaviour was not considered, it does not comply with critical state soil mechanic principles and is not able to provide unified description of sand under different densities and confining pressures with a same set of parameters.

This paper builds on the work of Zhang and Wang [31] to present the formulation of a unique model that (1) achieves the simulation of post-liquefaction shear deformation based on its physics, allowing the unified description of pre- and post-liquefaction behaviour of sand; (2) directly links the cyclic mobility of sand with reversible and irreversible dilatancy, enabling the unified description of monotonic and cyclic loading; (3) introduces critical state soil mechanics concepts to achieve unified modelling of sand under different states. Modelling of large post-liquefaction shear deformation was achieved based on the physics proposed by Zhang and Wang. The proposed model is able to appropriately describe

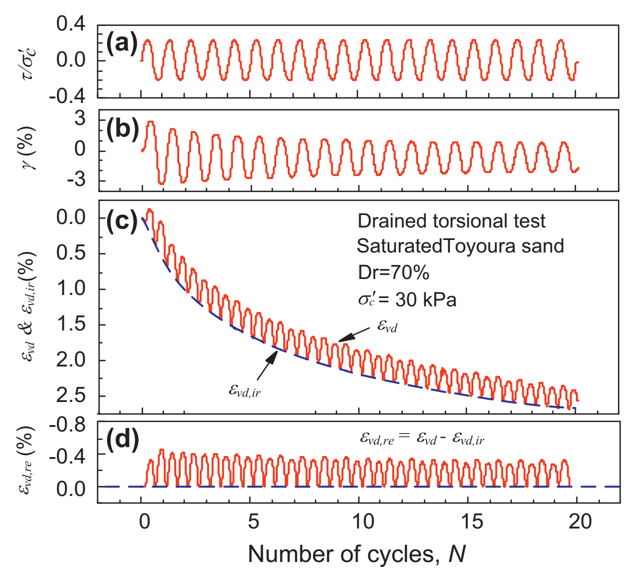

Fig. 2. The decomposition of reversible and irreversible dilatancy components in drained cyclic torsional test. (Data from Shamoto et al., 1997).