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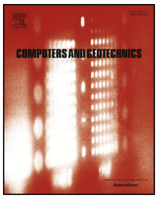

Research Paper

Unified modeling of soil behaviors before/after flow liquefaction

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ABSTRACT

Flow liquefaction of soil involves a phase transition process from solid to fluid. A constitutive model that can describe the soil behaviors of both the solid and fluid phases in a unified way was proposed. The constitutive model adopts a phase transition criterion to detect the onset of flow liquefaction and associates an elastoplastic relation and a fluid relation in a single framework. The simulated results demonstrated that the proposed model can describe the fundamental behaviors of soil in both the solid and fluid phases with a smooth transition from soil-like behavior to fluid-like behavior during the phase transition process.

1. Introduction

Soil liquefaction is one of the most dangerous threats to civil engineering structures constructed in sandy grounds when earthquakes occur, as evidenced by the 1964 Niigata earthquake in Japan [1], the 1976 Tangshan earthquake in China [2], the 1995 Hyogoken-Nambu earthquake in Japan [3], and the 2008 Wenchuan earthquake in China [4]. Liquefaction-induced ground failure can cause many kinds of geodisasters and structural damage, such as the settlement of buildings, the uplift of underground facilities, the lateral flow of ground, and even landslides. Therefore, scholars and engineers have devoted great effort to investigating the behaviors and mechanisms of soil liquefaction.

Generally, soil liquefaction behaviors can be divided into two types: cyclic mobility and flow liquefaction [5–7]. Cyclic mobility often occurs in medium-dense sand as a result of the stepwise increase in the pore water pressure and is in connection with repeated contractive and dilative responses when the effective stress approaches a zero state (Fig. 1(a)). Flow liquefaction often occurs in loose sand due to a rapid drop in shear strength and is mainly associated with a contractive response of the soil (Fig. 1(b)). Both types of liquefaction behaviors have been theoretically modeled over the past several decades. For cyclic mobility, liquefaction-induced deformation is generally finite and thus can be described by elastoplastic constitutive models established based on the principles of solid mechanics [8–13]. For flow liquefaction, however, the behavior is more complex because it involves a process in which the soil will transit from a solid phase into a fluid phase and finally result in a very large flow deformation [14]. Because liquefied soil behaves similar to a fluid after liquefaction, the post-liquefaction behavior is no longer suitable to be described by traditional elastoplastic constitutive models. In recent years, some researchers began to adopt fluid dynamics methods to study the flow process of liquefied soil. In their studies, the liquefied soil is regarded as a fluid and thus its behavior can be modeled by a fluid constitutive model. Uzuoka et al. [15] made the first attempt to use a fluid constitutive model (Bingham model) to describe the large deformation caused by flow liquefaction. Chen et al. [16] found that the post-liquefaction behavior of sand can be well simulated by non-Newtonian fluid models. Moriguchi [17] used a CIP-based fluid dynamics method to describe the large deformation of geomaterials in liquefied state. Huang et al. [18] introduced the Bingham fluid model with the Mohr-Coulomb yield criterion into the smoothed particle hydrodynamics (SPH) framework to analyze the flow process of liquefied soil. Zhou et al. [19] proposed a fluid constitutive model for liquefied sand, in which the friction resistance and viscous resistance were expressed as a thixotropic shear-thinning fluid and a non-time-variant shear-thinning fluid, respectively. Although researchers have obtained many results by using the fluid constitutive model to simulate the post-liquefaction behaviors of soil, there is a limitation in these studies that only the fluid-like behavior after liquefaction can be simulated, and the solid-like behavior before liquefaction and the transition process from the solid phase to a fluid phase are omitted. Certainly, it is practicable to use an elastoplastic model to simulate the solid-like behavior before liquefaction, and then use a fluid constitutive model to simulate the fluid-like behavior after liquefaction. However, the method used to separate the pre- and post-liquefaction behaviors is not suitable for the analysis of the entire process from solid behavior to post-liquefaction flow behavior. Particularly, the transition

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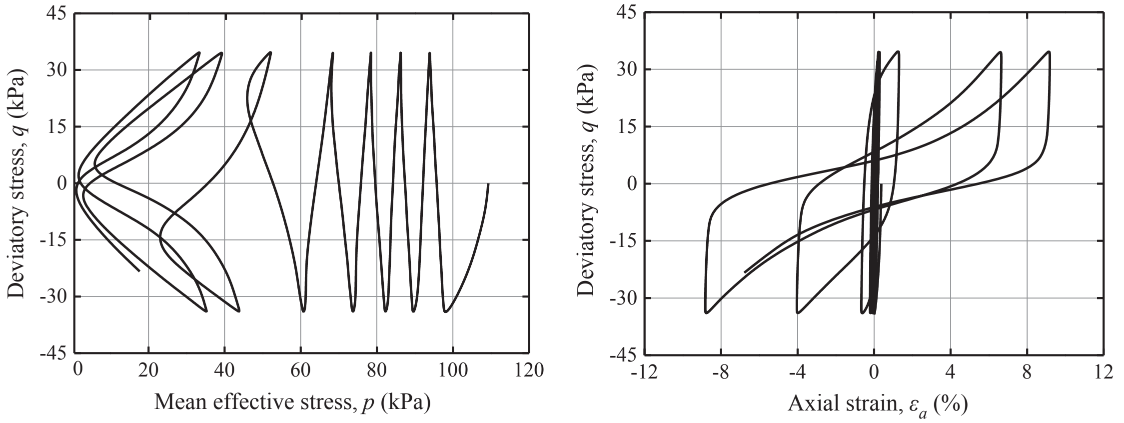
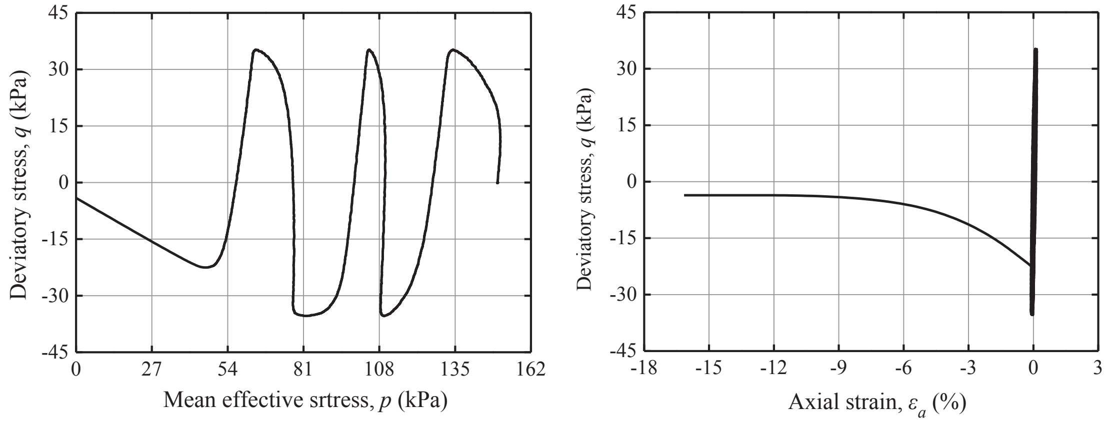


(a) Cyclic mobility (medium-dense sand, D_r=44%)



(b) Flow liquefaction (loose sand, D_r=10%)

Fig. 1. Cyclic triaxial tests on medium-dense and loose Fujian sand under an undrained condition.

process from a solid phase to a fluid phase cannot be properly described. In many cases, researchers and engineers expect to understand and predict the entire process of flow liquefaction from the initial solid state to the final fluid state in a unified manner. Hence, it is necessary to establish a constitutive model that can simulate the entire process of flow liquefaction in which the soil starts from a solid phase and then transits into a fluid phase.

Unified modeling of the entire process of flow liquefaction has attracted the interest of researchers, and some pioneering work has been carried out in recent years. Sato et al. [20] proposed a fluidal-elasto-plastic model in which the whole stress of the soil is divided into three parts: the effective stress σ_{ij}^{ep}, the viscous stress σ_{ij}^{f} and the pore water pressure p. The excess pore water pressure (EPWP) ratio is used to control the phase transition process. Andrade et al. [21] proposed a combined framework that allowed the co-existence of the classical rate-independent plasticity model and Bingham model for granular media. In this framework, the solid phase begins to transit to the fluid phase when soil stress reaches the critical state line. Later, Andrade et al. [22] proposed a critical hardening modulus to detect the onset of flow liquefaction in both cyclic and monotonic loading conditions. Through similar methods, Najma and Latifi [23] proposed a flow liquefaction criterion for contractive loose sands, and proved the criterion can be applied to predict the onset of flow liquefaction in conjunction with several existing elasto-plastic models [10–12]. Prime et al. [24,25] developed a phase transition model for geomaterials and adopted the second-order work $d^2W = d\sigma_{ij}d\varepsilon_{ij}$ as the solid–fluid transition criterion. The equation $d^2W = 0$ was the demarcation point between the solid state ($d^2W > 0$) and the fluid state ($d^2W < 0$). However, in the work by Prime et al. [24], the phase transition occurs abruptly without a smooth transition process. In summary, the previous studies mainly involve two key issues: (1) when the phase transition occurs, i.e., the criterion for the phase transition; and (2) how the solid-like behavior transitions to the fluid-like behavior. Although researchers have made great progress in these two aspects, there are still some problems and challenges. First, the criteria for phase transition defined in previous studies are sometimes inconsistent with the experimental results, in which the onset of flow liquefaction occurred usually before the effective stress reaches a critical state, and the EPWP ratio is only approximately 0.5–0.7 [26,27]. Second, the mechanical characteristics of the solid-like and fluid-like behaviors are completely different, and the smooth transition from the solid-like behavior to the fluid-like behavior is not realized and remains a challenge theoretically and mathematically.

In this paper, a simple constitutive model that can associate elastoplastic and fluid constitutive relations with phase transition criteria is proposed. The elastoplastic relation is adopted to simulate the solid-like behaviors, and a fluid relation is used to simulate the fluid-like behaviors. These two kinds of models are combined by a weighting factor that is related to the EPWP ratio. Furthermore, according to the value of the phase transition criterion, two types of liquefaction behaviors, i.e., the cyclic mobility and flow liquefaction, can be distinguished automatically. If cyclic mobility occurs, only the elastoplastic relation works during the entire process of liquefaction, while if flow liquefaction occurs, the elastoplastic relation will be smoothly transited to the fluid relation.