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Technical Paper

Elastoplastic modeling of sand–silt mixtures

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Abstract

Experimental observations have shown that the mechanical behavior of sand–silt mixtures is highly dependent on the proportions of sand and silt. Our present paper proposes a simple elastoplastic model for the stress–strain behavior of sand–silt mixtures. The inter-grain contact index is firstly reviewed. A formulation which links the inter-grain contact index with the void ratio is then proposed and validated by measuring the index void ratios of various sand–silt mixtures. The formulation is applied to determine the position of the critical state line of sand–silt mixtures from sand to silt. Based on this formulation, a simple elastoplastic model is then developed. The model parameters can be easily determined from conventional triaxial tests and measurements of the index void ratios. The predictive capability of the model was examined by comparing the simulations and the experimental results of undrained triaxial tests on Foundry and Ottawa sand–silt mixtures from sand to silt.

Keywords: Critical state; Elastoplasticity; Silty sand; Instability; Index void ratio

1. Introduction

Natural soils or man-made fills are often mixtures of fine and coarse grains. The proportions of these fine and coarse grains can change with time due to grain breakage or internal erosion. This phenomenon has a vital effect on the safety of earth structures. Therefore, the stress–strain behavior of fine and coarse grain mixtures needs to be better understood. In recent years, sand–silt mixtures have been the subject of various experimental studies (e.g., Pitman et al., 1994; Zlatovic and Ishihara, 1995; Lade and Yamamuro, 1997; Lade et al., 1998; Thevanayagam and Mohan, 2000; Salgado et al., 2000; Polito and Martin, 2001; Thevanayagam et al., 2002; Xenaki and Athanasopoulos, 2003; Naeini and Baziar, 2004; Yang et al., 2006; Murthy et al., 2007; Rahman et al., 2008; Bobei et al., 2009; Papadopoulou and Tika, 2008; Belkhatir et al., 2011; Chang et al., 2011 etc.). The effects of both the fines in silty sand and the coarse grains in sandy silt on the physical properties (e.g., index void ratio, relative density, etc.) and the mechanical behavior (e.g., instability, critical state, strength, stress-dilatancy, etc.) have been investigated.

However, few attempts have been made to model the mechanical behavior of sand–silt mixtures. Even though Yamamuro and Lade (1999) modified their Single Hardening Model yield surface formulation to enable predictions of the behavioral pattern of Nevada sand with 20% fines, their particular approach may not be easily adaptable to sand–silt mixtures with different fines contents. Rahman et al. (2008) proposed a fines-corrected state parameter for sand with a fines content of less than 30%, but several material constants are required for its use. Muir Wood et al. (2010) extended the breakage model to model the erosion in granular

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materials, with a smooth grain size distribution not including a gapped grain size distribution, but the model is not yet applicable to sand–silt mixtures from sand to silt. More recently, Chang and Yin (2011) proposed a micromechanical model for silty sand in which the fines content is relatively low (less than 20%), so that the soil behavior is primarily dominated by the coarse grain skeleton. Despite these efforts, modeling methods which focus on the soil behavior dominated by the fine grain skeleton with a secondary reinforcement of coarse grains have not found their way into the literature.

This paper is an attempt to propose a simple modeling approach for the stress–strain behavior of sand–silt mixtures from sand to silt. Firstly, the inter-grain contact index is reviewed, and a unified formulation is proposed and confirmed by the measured index void ratio of sand–silt mixtures. The formulation is applied to control the position of the critical state line of sand–silt mixtures from sand to silt. Based on this formulation, a simple elastoplastic model is then proposed. The model is validated by comparing experimental results and simulations on Foundry and Ottawa sand–silt mixtures.

2. Unification of inter-grain contact index and its application

The microstructure of a granular mixture can be constituted by various types of packing arrangements, which leads to different stress–strain responses. Note that the mode of preparation of these mixtures in the laboratory or in situ certainly plays a crucial role; however, only laboratory tests are selected and investigated as a base in this paper. Thevanayagam et al. (2002) proposed a function for different packing arrangements of the relative amount of coarse and fine grains in the mixture (Fig. 1). In the case of a coarse grain skeleton, the coarse grain contacts play a primary role in the mechanical response of the soil, and the fines offer a secondary contribution. With an increase in the fines content, the contacts between the fine grains begin to play a greater role as the coarse grains start to disperse in the mixture and provide a secondary reinforcement effect. A transition zone comes into existence before the behavior of the mixture is entirely governed by the fine grains. Prior to modeling the behavior of sand–silt mixtures with different fines contents, the influence of the fines content on the inter-grain contact index and on the position of the critical state line needs to be clarified.

2.1. Inter-grain contact index

In the case of a coarse grain skeleton, adding fines can increase the mechanical properties of the mixture more than the properties of the host coarse grain soil. According to Chang and Yin (2011), the void ratio of soil mixture e can be expressed by the void ratio of coarse grains e_{hc} and fines content f_c, as follows:

$$e = e_{hc}\left(1 - f_c\right) + a f_c \quad (1)$$

where a is a material constant depending on the fabric structure of the soil mixture (e.g., grading, particle shape, etc.). Based on Eq. (1), equivalent inter-granular contact index e_{eq} has been introduced by Chang and Yin (2011), as follows:

$$e_{eq} = \frac{e - a f_c}{1 - f_c} \quad (2)$$

which is similar to the formulation proposed by Thevanayagam and Mohan (2000), and which can be reduced to the skeleton void ratio defined by Vaid (1994) when $a = -1$.

In the case of a fine grain skeleton, the reinforcement effect by the coarse grains is introduced to obtain an equivalent inter-fine void ratio as the index of active contacts by Thevanayagam et al. (2002), as follows:

$$e_{eq} = \frac{e}{f_c + \frac{1 - f_c}{(R_d)^m}} \quad (3)$$

where R_d is the ratio of the mean size of coarse grains D_{50} to the mean size of fine grains d_{50}; m is a coefficient depending on the grain characteristics and the fine grain packing ($0 < m < 1$). Eq. (3) implies that when $f_c = 100\%$, e_{eq} converges to the void ratio of the material made of fine grains. Adopting the form of this equation, we assume that the void ratio of soil mixture e can be expressed by the void ratio of fine grains e_{hf} and fines content f_c, as follows:

$$e = e_{hf}\left(f_c + \frac{1 - f_c}{(R_d)^m}\right) \quad (4)$$

Taking into account the transition zone from a coarse grain skeleton to a fine grain skeleton, the equivalent inter-grain void ratio can be unified by the fines content by combining Eqs. (2) and (3), as follows:

$$e_{eq} = \frac{e - a f_c}{1 - f_c} \frac{1 - \tanh\left[\xi\left(f_c - f_{th}\right)\right]}{2}$$

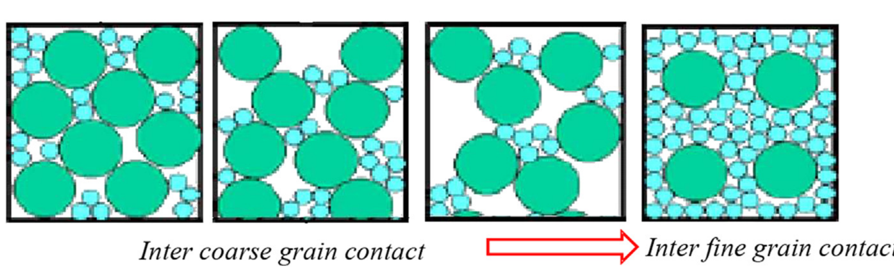

Fig. 1. Intergranular soil mix classification (after Thevanayagam et al., 2002).