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State variables for silty sands: Global void ratio or skeleton void ratio?

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Abstract

While the global void ratio has long been used as a density index to characterize sand behavior, concern has been increasing about its applicability to silty sands (sand–fines mixtures), based on the proposition that the fines may fill in the void spaces formed by sand grains and make no contribution to the force transfer. The skeleton void ratio was proposed in the literature as an alternative index for mixed soils, based on the assumption that all fines act as voids. It was further modified into an equivalent skeleton void ratio by taking into consideration the fraction of fines that participates in the force transfer. This paper presents a study aimed at evaluating the three state variables as applied to sand–fines mixtures and especially to explore the rationale behind the concept of the skeleton void ratio. Based on a specifically designed experimental program, it is shown that contrasting conclusions can be drawn as to the role of fines in altering the shear behavior of clean sand when different density indices are used as the comparison basis. When comparisons are made at a constant (global) void ratio, the fines increase the degree of contractiveness, but when comparisons are made at a constant skeleton void ratio, an increase in dilativeness is seen. The equivalent skeleton void ratio does not fulfill the intent of providing a universal means for characterizing the stress–strain behavior of silty sands. This is due to the lack of mechanisms to account for the inter-granular contacts which are highly complex. The study suggests that compared with the skeleton void ratio and its modified form, the usual (global) void ratio remains a simple and useful state variable suitable for the framework of critical state soil mechanics and for geotechnical applications.

Keywords: Liquefaction; Sand; Silty sand; Stress–strain behavior; Shear strength; State variable

1. Introduction

The global void ratio, defined as the volume of voids divided by the volume of solids, has long been used in soil mechanics as a density parameter to characterize soil behavior. Fig. 1 schematically shows three distinct responses of saturated sand to undrained shearing, characterized by the post-consolidation void ratio. Under otherwise similar conditions, the dense specimen exhibits a strain-hardening response, whereas the loose specimen exhibits a highly contractive response with a marked build-up of pore pressures leading to the failure known as static or flow liquefaction. At an intermediate density, the sand contracts in the initial stage of shear and then dilates continuously to large strains, with the phase transformation state marking the transition. Various aspects of the density-dependent stress–strain–strength behavior of sands (e.g., Castro and Poulos, 1977; Alarcon-Guzman et al., 1988; Ishihara, 1993; Yang and Li, 2004; and the references therein) have been characterized within the framework of critical state soil mechanics, which defines a

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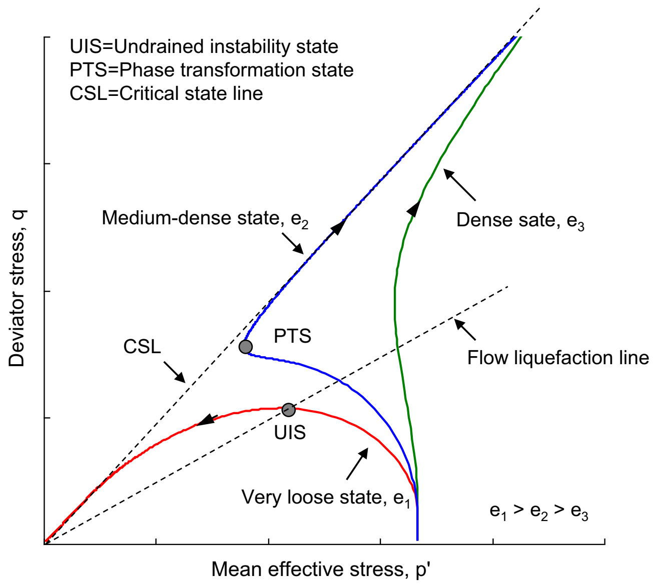

Fig. 1. Schematic illustration of typical undrained shear responses of sand at different void ratios.

unique critical state locus (CSL) in the void ratio–mean effective stress (i.e., e–p') plane such that the locus serves as a boundary separating the initial states of sand into contractive and dilative regions (Been and Jefferies, 1985; Wood, 1990; Verdugo and Ishihara, 1996).

When silt or clay fines are present in clean sand, the sand's behavior may be significantly altered. A number of experimental studies (e.g., Pitman et al., 1994; Lade and Yamamuro, 1997; Thevanayagam et al., 2002; Georgiannou, 2006; Murthy et al., 2007) have provided data showing the effect of fines in undrained loading conditions. Nevertheless, very diverse views exist on whether the effect of fines is negative or positive for the shear strength and liquefaction potential of sand (Yang and Wei, 2012). Concerns have arisen about the effectiveness of the usual void ratio in characterizing the behavior of such mixed soils. Based on the hypothesis that fines may roll into the voids formed by sand grains, and hence, make little contribution to the force transfer mechanism (e.g., Mitchell, 1976), an index known as the skeleton void ratio was used as an alternative to characterize the mixtures of sand and fines in several studies (Kuerbis et al., 1988; Georgiannou et al., 1990; Pitman et al., 1994; Thevanayagam, 1998; Chu and Leong, 2002). The skeleton void ratio (e_s) is related to the conventional void ratio (e) as follows:

$$e_s = \frac{e+FC}{1-FC} \tag{1}$$

where FC denotes the percentage of fines content. For clean sand with a zero fines content, e_s is exactly the same as e. In deriving Eq. (1), the specific gravity of fines is assumed to be similar to that of sand grains.

Recognizing that not all fines would act as voids at a high fines content, the concept of the skeleton void ratio was further modified (Thevanayagam et al., 2002) to give an index referred to hereafter as the equivalent skeleton void ratio

$$e_{se} = \frac{e+(1-b)FC}{1-(1-b)FC} \tag{2}$$

where factor b, varying between 0 and 1, represents the fraction of fines that contributes to the force structure. Evidently, when b is zero, e_{se} reduces to e_s, meaning that the fines act as voids; when b is 1, e_{se} reduces to e, meaning that the fines act like the particles of the base sand. Note that when using Eq. (2), the fines content (FC) should be less than the threshold fines content (30–40% for most mixed soils), so that the mixed soil can be treated as being sand-dominated. Also, the fines should be non-plastic, so that the external forces can be assumed to be transmitted by direct inter-granular contacts without the chemical–physical effects of plasticity fines (Yang and Wei, 2012).

In recent years, interest has been growing in the use of the equivalent skeleton void ratio to characterize the behavior of sand–fines mixtures (e.g., Ni et al., 2004; 2006; Yang et al., 2006; Rahman et al., 2008; Rahman and Lo, 2012). The key step in doing that is the determination of factor b in Eq. (2). Most studies employed the best-fit approach to obtain the b value such that the critical state data of the base sand and its mixture with fines, when plotted in the e_{se}–p' plane, fall within a narrow band to give a single CSL. Fig. 2 illustrates the idea using the triaxial test data of Zlatovic and Ishihara (1995) on a clean sand mixed with non-plastic fines. As can be seen from Fig. 2(a), the CSL of the mixed soil in the e–p' plane tends to move downward as the quantity of fines increases. However, when these data are plotted in the e_{se}–p' plane (Fig. 2(b)), where e_{se} is calculated using $b=0.25$ as given by Ni et al. (2004), they tend to fall in a narrow band for which a best-fit CSL can be derived.

While the idea appears to be attractive, it is worth noting that the position of the best-fit CSL is different from the position of the CSL of the base sand determined by using the critical state data on its own, as readily seen in Fig. 2(b). The CSL of the base sand is therefore no longer unique as it depends on the fines added; *obviously this violates the principle of the critical state approach that specifies the existence of a unique CSL for a given sand*, rendering the concept of the equivalent skeleton void ratio logically inconsistent with its premise.

Another confusing issue in the literature is the existence of multiple b values for a given dataset. For example, for the test results on an alluvium sand mixed with 9% non-plastic fines, Ni et al. (2004) selected $b=0.7$ for characterizing the steady state or critical state strength of the mixed soil. For the same dataset, Rahman et al. (2008) predicted the value of b to be as low as 0.033 by using a semi-empirical formula that they had developed by analyzing several sets of published data. According to the definition given in Eq. (2), $b=0.7$ means that 70% of the fines participate in the force transfer, whereas $b=0.033$ means that less than 4% of the fines participate in the force transfer.

Evidently, if the concept of the equivalent skeleton void ratio is to become more widely accepted, research is needed