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Maximum and minimum void ratios for sand-silt mixtures

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ABSTRACT

Minimum and maximum void ratios provide a general basis for comparative evaluation of material properties for soils with various densities. Either the minimum or the maximum void ratio is dependent considerably upon the fines content of soil. There are a few mathematical models in the literature for predicting the variation of minimum void ratio with respect to fines content. However, mathematical models for predicting maximum void ratio with respect to fines content are very limited in the field of geotechnical engineering. This study shows that the variation of maximum void ratio with respect to fines content of a sand-silt mixture is caused by the same mechanisms that influence the variation of minimum void ratio. Consequently, the mathematical model previously proposed by the authors for predicting minimum void ratios of sand-silt mixtures is extended to be capable of predicting the maximum void ratios of sand-silt mixtures due to the influence of fines content. The applicability of this extended mathematical model is verified by data from 24 sand-silt mixtures with various fines contents. Furthermore, based on the extended mathematical model, the relationship between the maximum and the minimum void ratios of a sand-silt mixture can be derived. The derived relationship is found to be linear and is a function of fines content. The validity of the derived linear relationship between the maximum and the minimum void ratios of a sand-silt mixture is also verified by the measured results from experiments.

1. Introduction

The values of maximum and minimum void ratios represent the loosest and densest conditions for soil, which can be used to assess the relative density of soil in situ. It has been clearly demonstrated that the relative density and the range of e_{max}–e_{min} are key parameters for estimating the behavior of soil (Selig and Ladd, 1973; Cubrinovski and Ishihara, 2002). Experimentally, the values of maximum and minimum void ratios can be determined according to the procedures specified in ASTM (ASTM D 4253–00, 2002; ASTM D 4254–00, 2002), Japanese Geotechnical Society (2000), and several other methods in the literature (Kolbuszewski, 1948; Mulilis et al., 1977; Vaid and Negussey, 1988). These methods may provide somewhat different values for the two extreme void ratios (Tavenas et al., 1973).

The values of maximum or minimum void ratios for sand are related to several factors: the particle shape, the mean particle size, the uniformity coefficient C_u, and the mechanical procedures from which the extreme void ratios are determined. There are a few experimental studies that provide empirical relations for maximum or minimum void ratio as a function of particle shape, uniformity and mean particle size for clean sand (Selig and Ladd, 1973; Youd, 1973; Santamarina and Cho, 2004; Cho et al., 2006).

For sand-silt mixtures, the main factor influencing maximum and minimum void ratios is fines content, which represents the particle size distribution of a mixture. Since the packing structure is greatly influenced by the particle size distribution, it is not surprising that the amount of fines in a sand-silt mixture has significant effects on its mechanical properties (Selig and Ladd, 1973; Aberg, 1992; Miura et al., 1997; Cubrinovski and Ishihara, 2002; Bobei et al., 2009; Peters and Berney, 2010; Fuggle et al., 2014). Experimental results have shown that the amount of fines content can influence many aspects of soil behavior such as compressional behavior, strength, steady state line, static liquefaction, undrained fragility, and instability behavior (Salgado et al., 2000; A.B. and Papageorigou, 2001; Fourie et al., 2001; Chu and Leong, 2002; Thevanayagam et al., 2002; Monkul and Ozden, 2007; Cabalar et al., 2013; Cabalar and Mustafa, 2015).

The importance of fines content has also been observed in many branches in the industry, such as ceramics processing (Reed, 1995), powder metallurgy (Smith, 2003), and concrete mixes (Powers, 1968). Early studies of packing density as a function of fines content can be found by Westman and Hugill (1930) and McGeary (1961). In the 1980s, analytical methods have been refined to account for the effect of particle size ratio by Stovall et al. (1986); Yu and Standish (1987) in the field of powder mixture, and by De Larrard (1999a, 1999b) in the field of concrete mixture. These methods have been used for concrete mixture design to optimize the packing densities of cement, mortar and concrete (e.g., Kwan and Fung, 2009; Fennis et al., 2013).

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For soils, a graphical method of estimating maximum packing density of soil with different sizes of particles was proposed by Humphres (1957) using an empirical approach. Around 1986, AASHTO T224–86 specifications postulate an empirical rule for estimating the maximum packing density of gravel-soil mixtures. Kezdi (1979) outlined an analytical method to estimate the minimum porosity of a binary mixture of granular soils. This method is only applicable to packings of very small fine particles and often overestimates the maximum packing density (Vallejo, 2001). For improving compaction control of granular fill, Fragaszy and Sneider (1991) carried out an extensive set of experiments on soils with a wide range of particle sizes, and compared the measured maximum dry densities with that predicted from the two empirically based methods: "Humphres method (Humphres, 1957)" and "AASHTO correction factor" method (AASHTO T224–86). In association with the liquefaction potential of silty-sand, Lade et al. (1998) had carried out minimum void ratio tests for different types of sand-silt mixtures. They also proposed an analytical method for predicting the minimum void ratio for spheres with different sizes. This method, similar to that of Kezdi (1979), also suffers the limitation of overestimating the packing density. Cubrinovski and Ishihara (2002) examined a large number of test data on silty-sand and presented a set of empirical equations to show the influence of fines content on the magnitude of minimum void ratio. Another line of study related to sand-silt mixtures is the concept of skeleton void ratio (Mitchell, 1993; Vaid, 1994) or termed as inter-granular void ratio (Thevanayagam, 1998), which is not the real void ratio of the sand-silt mixture, but a combined function of the real void ratio and the fines content. The inter-granular void ratio has been used to correlate the static and cyclic strength of sand-silt mixtures (Thevanayagam et al., 2002; Yang et al., 2005). Although the concept does not directly deal with the minimum or the maximum void ratio, it does provide insights on the connection between the void ratio and the packing structure of a sand-silt mixture. Apart from these studies, computer simulation analyses using the discrete element method (DEM) have also been implemented to study the characteristics of the void ratio for a mixture made of spherical particles of two different sizes (An, 2013; Fuggle et al., 2014). The trend of computer simulation results resembles that obtained from experimental tests. However, for mixtures of natural soil (such as sand-silt mixtures) with large ratio of particle sizes and complex particle shapes, it is necessary to use significantly large number of particles for the simulation. Thus, it makes the numerical simulation to be practically unfeasible.

Chang et al. (2015) proposed an analytical method that can predict the minimum void ratios for sand-silt mixtures with various particle size ratios and various fines contents. The developed model was evaluated by experimental results on 33 types of sand-silt mixtures. The evaluation has shown good agreement between the predicted and the measured values.

Compared to the number of studies on minimum void ratio (or densest packing), the number of studies on mathematical models for maximum void ratio (loosest packing) is rather limited. In the present paper, we aim to extend the previously proposed minimum void ratio model to have the capability of predicting both minimum and maximum void ratios for sand-silt mixtures. We also aim to derive mathematical relationships between the maximum and the minimum void ratios for sand-silt mixtures.

2. Effect of fines content on the minimum void ratio of a binary mixture

The minimum void ratio is 0.35 for a hexagonal packing of monosize spheres. The minimum void ratio for a packing of randomly arranged monosize spheres is about 0.56–0.66 (Dullien, 1992). The particle shape has noteworthy influence on the minimum void ratio of a packing. The minimum void ratio for a packing of angular particles is generally higher than that for a packing of spherical particles. For binary mixtures of particles, the influence of fines content on packing density can be highlighted by the experimental results (McGeary, 1961) on steel shots mixtures. Fig. 1 shows the variation of void ratio with respect to fines content for six binary mixtures. The six mixtures are comprised of large particles of 3.14 mm and six other smaller sizes (i.e., 0.91, 0.66, 0.48, 0.28, 0.19, 0.16 mm).

Two characteristics of the variation of void ratio can be observed in this figure: (1) the curves showing the variation of void ratio with respect to fines content are V-shaped, and (2) the shape of these curves is significantly dependent on the size ratio of coarse particles to fine particles. Although the experiment's results were obtained from spherical shaped steel shots, it is interesting to note that these two characteristics are also displayed by the experimental result of sand-silt mixtures, even though the shape characteristics of soil particles are very different from that of steel shots.

It was recognized by McGeary (1961) that there are two distinct types of packing structures of the steel shots mixtures. The two packing structures are schematically presented in Fig. 2. For lower fines content, the packing structure is coarse-grain dominant with fine particles filled into the void space among the coarse grains. For the high fines content, the packing structure is fine-grain dominant with coarse particles inclusions embedded in the fines. McGeary considered that the change of packing structure is the main factor that influences the variation of void ratio with respect to fines content.

It is obvious that, soil with same packing void ratio may have entirely different packing structures. Thus the packing void ratio alone does not correlate well to mechanical behavior of a sand-silt mixture. Therefore, the inter-granular void ratio, defined as a function of packing void ratio and fines content, was found to better correlate the static and cyclic strength of sand-silt mixtures (Thevanayagam et al., 2002; Yang et al., 2005).

The connection between packing structure and void ratio was modeled by an analytical method proposed by Chang et al. (2015) to predict the variations of minimum void ratios with respect to fines content for sand-silt mixtures. The method will be briefly described in the next section.

3. Model for minimum void ratio of sand-silt mixtures

A sand-silt mixture is considered to be a two-phase material. The phase diagrams corresponding to the two packing structures shown in Fig.2 are constructed here in Figs. 3 and 4. For the coarse-grain dominant packing structure, the phase diagram can be plotted in Fig. 3.

Fig. 3(a) shows the phase diagram of clean sand (S1 is the solid phase, and V1 is the void phase). Its void ratio is defined as the

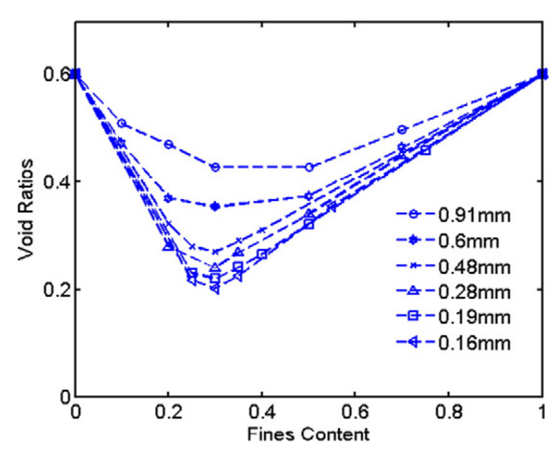

Fig. 1. Binary packing of steel shots.
(data obtained from McGeary, 1961)