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Evaluation of static and dynamic properties of sand–fines mixtures through the state and equivalent state parameters

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ABSTRACT

The results of an experimental investigation on sands with low plastic fines content are presented. Specimens with a low plastic fines content of 0%, 15%, 30%, 40%, 50% and 60% by weight were tested in drained and undrained triaxial compression tests. The soil specimens were tested under three different categories: (1) at a constant void ratio index; (2) at the same peak deviator stress in a triaxial test; and (3) at a constant relative density. By a combination with our published experimental data in recent years, the critical state line and various state parameters have been proposed and discussed for a further understanding the behavior of sand–fines mixtures. Results indicated that a unique critical line was obtained from drained and undrained triaxial compression tests for each fines content. The effects of fines content on critical state line (CSL) were recognized and discussed. In addition, the results revealed that normalized peak undrained shear stress, cyclic resistance ratio, and compression index were found to be a good correlation with state parameter Ψ as well as equivalent state parameter Ψ^*. An increasing state parameter decreased the normalized peak undrained shear stress, and cyclic resistance ratio; however, the compression index increased with an increase in state parameter. Finally, there were no correlations such as the coefficient of consolidation–state parameter and maximum shear modulus–state parameter due to the different testing condition.

1. Introduction

Natural sand commonly consists of fines (grain size less than 0.075 mm) and sand particles with different proportions. The existence of fines significantly affects and plays a major role on liquefaction behavior as well as on the engineering properties of sands [1–6]. In addition, the plasticity of fines also leads to many complicated phenomena under undrained behavior, stress–strain relation, compressional behavior, and liquefaction resistance [7–12]. Yamamuro and Lade [13,14] concluded that increasing the non-plastic silt content in Nevada sand increased the volumetric contractive parameter of specimens in both drained and undrained triaxial tests. In addition, other studies found that the existence of non-plastic silt appeared to decrease the undrained shear strength depending on the intergranular void ratio of sand–silt mixtures [15].

Some results showed that the liquefaction resistance either increased with increasing fines content in the mixture [16–19] or decreased with increasing fines content [5,9,13,20–24]. Other studies have found that the resistance of sand to liquefaction initially decreased as the silt content increased until some minimum resistance was reached and then increased as the silt content continued to increase [8,19,25,26]. Generally speaking, the existence of fines significantly affected the engineering properties as well as the behavior of a sand. The reason can be summarized, such as grain size distribution, the arrangement of fines in a mixture, the binary packing model, the plasticity index of fines, relative density, and the shear stress condition.

In fact, the engineering properties of a sand do not only depend on the existence of fines. Besides, void ratio and stress level are also key parameters which significantly affect the engineering properties of a sand–fines mixture. It is questionable whether to answer the effects of three factors, including fines content, void ratio, and stress level on the behavior and engineering properties of a sand–fines mixture. To solve this matter, critical state soil mechanics can be considered a compatible theory to understand the behavior as well engineering properties of a sand–fines mixture. Some studies [27–31] have used the critical state, state parameter to fine this unique correlation to understand the shear strength and engineering properties of a soil.

In this study, three published experimental works, including Hsiao and Phan [32], Hsiao et al. [33] and Phan [34] were collected

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and calculated to evaluate the relationships between static, dynamic engineering properties and different state parameters. Firstly, the critical state and equivalent critical state lines were plotted with various fines content. Then, state parameter, equivalent granular state parameter ($f_c \leq fc_{th}$), and equivalent interfine state parameter ($f_c \geq fc_{th}$) were calculated. Some engineering properties, including the cyclic resistance ratio, the compression index, the coefficient of consolidation, the normalized peak undrained shear stress, and maximum shear modulus, are found the be correlated with various state parameters. The results were expected to contribute a better understanding for the using of various state parameters with respect to shear strength, behavior, and engineering properties of the sand–fines mixtures.

2. Definitions

2.1. Critical state, and steady state

Recent studies have shown that a given cohesionless soil has various fabrics at the same void ratio or relative density [13,35–37]. The behavior of the sand depends not only on density but also on the stress level applied to the specimen. This concept is an important because it answers the question of how to characterize a sand. This measure of state is called state parameter and the definition is illustrated in Fig. 1. Thus, the state parameter Ψ is determined by the void ratio (e) and effective stress level (p') of a sand relative to a critical state line. When the state of a sand is above the critical state line (CSL), corresponding to a positive Ψ, the sand has a tendency to contract upon shearing, whereas state point is located below the CSL, corresponding to a negative Ψ, the tendency of sand is to dilate during shearing.

The effective mean normal stress p' and the state parameter shown in Fig. 1 are determined as follows:

$$p' = \frac{(\sigma'_1 + 2\sigma'_3)}{3} \quad (1)$$

$$\Psi = e_0 - e_{cs} \quad (2)$$

where σ'_1 and σ'_3 are effective major and minor stresses, respectively; e_0 and e_{cs} are initial and critical void ratios, respectively.

The steady state of deformation for any mass of particles is that state in which the mass is continuously deforming at constant volume, constant normal effective stress, and constant velocity. The steady state is obtained only after all particles have reached a statistically steady state condition and if all particles are completely broken, so that the shear stress needed to continue deformation and the velocity of deformation remains constant. Been at al. [38] indicated that the critical and steady states are found to be equal and independent of stress path, sample

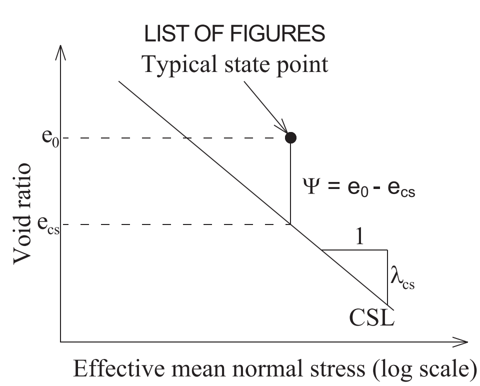

Fig. 1. Definition of state parameter (after Been and Jefferies [53]).

preparation, and initial density. Therefore, the term of critical state prefers to use in hereafter.

2.2. Equivalent state granular and interfine parameters

With regard to binary packing model proposed by Lade et al. [37], when the fines contents less than some threshold values (fc_{th}) have a small contribution to the intergranular contacts and thus play an secondary role to sustain the during loading process; however, once fines increases beyond fc_{th}, fines significantly handle the behavior as well as force chain of sand–fines mixture, and the role of large particles become to dismiss. Due to this explanation, recent studies revealed that equivalent granular and interfine void ratios are parameters to understand the behavior of a sand–fines mixture [29,30,39,40]. Thevanayagam et al. [35] defined the equivalent granular (e^*_g) in case of $f_c \leq fc_{th}$ as:

$$e^*_g = \frac{e + (1-b)f_c}{1-(1-b)f_c} \quad (3)$$

where b indicates the portions of fine particles that participate in the active intergrain contacts. The b factor is determined based on the arrangement of fines among large particles. It is significantly dependent on the shape, mineralogy, size, hardness, and plasticity index. The value of b parameter ranges from 0 to 1. A greater b value means the higher contribution of fines in the force chain of sand–fines mixture. Some studies [39–42] indicated that b value is a function of fc and $\chi = D/d$, where D is the size of sand and d is the size of the fines. Rahman et al. [43] proposed a semi-empirical equation to determine b value as follows:

$$b = \left(1 - e^{-2.5(\mathrm{fc})^2/k}\right) \cdot \left(\frac{r f_c}{\mathrm{fc_{th}}}\right) \quad (4)$$

where $k = 1 - r^{0.25}$, $\chi = D_{10}/d_{50}$, $r = \chi^{-1}$, and fc_{th} = threshold fines content.

When f_c exceeds fc_{th}, Thevanayagam et al. [35] determined the interfine void ratio (e^*_f) as follows:

$$e^*_f = \frac{e}{f_c + (1-f_c)/R^m_d} \quad (5)$$

where $R_d = D_{50}/d_{50}$ (D_{50} and d_{50} are the mean size of coarse and fine particles, respectively) and the m is reinforcement factor determined by the grain characteristics and fines packing.

Thevenayagam et al. [35] determined an unique critical state line for different fines content either in (e^*_g): ln p' or (e^*_f):ln p'. The terms of these two critical state lines are called to be "equivalent granular critical state line" and "equivalent interfine critical state line", respectively. For this study, CSL^*_g and CSL^*_f are denoted by "equivalent granular critical state line" and "equivalent interfine critical state line", respectively.

In addition, equivalent state parameter can also be determined as [29,30,39,40]:

$$\Psi^* = e^* - e^*_{cs} \quad (6)$$

where e^* = equivalent void ratio, and e^*_{cs} = critical equivalent void ratio.

3. Materials used

Soil specimens were taken from Liouguei District, located in Kaohsiung city, Taiwan. A quantity of natural sandy soil was carefully sieved to separately obtain clean sand and pure silt. The silt particles are defined as the grain size of soil that is able to pass through a No. 200 (0.075 mm) sieve. According to the AASHTO classification system, the fraction passing the No. 200 U.S. sieve is called silt and clay; however, the term silty is applied when the