Soil Dynamics and Earthquake Engineering 66 (2014) 443–458

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Evaluation of state indices in predicting the cyclic and monotonic strength of sands with different fines contents

Abbas Qadimi [a,*], Amirabbas Mohammadi [b]

[a] Department of Civil Engineering, Bu-Ali Sina University, Hamedan, Iran
[b] Young Researchers and Elite Club, Nour branch, Islamic Azad University, Nour, Iran

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form
18 March 2014
Accepted 6 August 2014

Keywords:
Critical state
State parameter
Stress ratio
Modified state parameter
Equivalent intergranular/interfine void ratio
Sand
Fines content
Cyclic resistance
Monotonic strength

ABSTRACT

State parameter, ψ, has been widely used to combine the influence of void ratio, e, and stress level, p', on the soils behavior. Stress ratio, R_s, and modified state parameter, ψ_m, have also been proposed for the same purpose. This paper aims to evaluate and compare the different state indices in combining the effect of fines content, density and stress level for five different types of sands, by processing a large number of previously published experimental data. The use of the recently established concept of equivalent interparticle void ratio, e^*, in definition of the state indices is also evaluated. The results indicate that the influence of fines presence, in addition to the e and p', on the behavior is favorably reflected by the state indices. Unique correlations were derived between the cyclic or monotonic strength and each of the state indices, independent of the fines content. The correlations, for all the different types of soils, fell into limited types of common formulations. ψ and R_s worked generally better than ψ_m, whether defined in terms of e or e^*. The extension of straight part of critical state line was found to be an appropriate reference line for calculating R_s used in conjunction with e or e^*.

1. Introduction

The response of sandy soils to monotonic and cyclic loadings has been widely studied during the past several decades. Many researches have demonstrated that the behavior of clean sands are influenced by their void ratio and stress level. The combination of these two variables determines the state of the soil in e: ln p' space, and the location of initial state relative to the critical state line controls the behavior of the sand (e.g. Been and Jefferies [1], Qadimi and Coop [2]). Furthermore, the presence of fines in the sand would affect the behavior. In addition to the void ratio and stress level, the value of fines content as another state related variable, controls the behavior of a sand-silt mixture. Numerous laboratory studies have shown that the cyclic strength of the mixture decreases with increasing silt content, at a constant void ratio and stress level, until some threshold fines content is reached; and then increases with further increase of silt beyond the threshold value [3–8]. Some researchers have also reported a similar pattern for the dependence of monotonic strength of the sands on the silt content [9–11]. When the sand contains clay particles, some other factors like mineralogy, plasticity properties and stress history of the fines would also influence the behavior and the resistance of the soil [12–15].

Considering the simultaneous roles of void ratio, stress level and fines content in characterizing the behavior, a key question to be answered is how to combine the effect of these three variables. In other words, how to define a simple unique correlation between these three variables and the strength of the soil. Critical state soil mechanics provides an appropriate framework to predict the behavior and the resistance of sandy soils by combining the influence of density and stress level. Several researchers have successfully used this framework to describe the monotonic and cyclic behavior of clean sands or sands containing a specific amount of fines (e.g. [1,2,16–21]). The majority of these researchers have employed the state parameter, defined by Been and Jefferies [21], to combine the effect of density and stress level. Some other state indices like stress ratio, defined by Klotz and Coop [22] and modified state parameter, defined by Bobei et al. [20], have also been adopted for the same purpose. However, the capability of the state indices to reflect the simultaneous effects of initial void ratio, initial stress level and fines contents of a wide range has been rarely examined. The possibility of obtaining a unique correlation between the resistance data and the state indices, independent of fines content and stress level, is the main issue to be addressed in this area. Recently, Stamatopoulos [23]

* Corresponding author. Tel.: +98 811 8292632; fax: +98 811 8292637.
E-mail addresses: aqadimi@basu.ac.ir (A. Qadimi), aa.mohammadi87@gmail.com (A. Mohammadi).

http://dx.doi.org/10.1016/j.soildyn.2014.08.002
0267-7261/

reported a unique correlation between the cyclic strength and the state parameter for a sand with fines contents ranging from 0% to 25%. Rahman et al. [24] and Huang and Chuang [25] used equivalent intergranular state parameter, which is a revised form of the state parameter, to predict the monotonic strength and the cyclic strength of different sand-fines mixtures, respectively.

Based on this background, it appears essential to evaluate and compare the different state indices in characterizing the behavior of different types of sands over a wide range of fines contents, densities and stress levels in order to: (i) examine the effectiveness of each state index in normalizing the behavior, (ii) establish a simple yet strong type of relationship between the monotonic or cyclic strength and each of the state indices, and (iii) find the index that best predicts the behavior of the soil and is the simplest to employ. There is a lack of study involving a comprehensive evaluation of these issues.

The present work aims to conduct an extensive study covering the above-mentioned gaps in the existing literature. For this purpose, a great number of monotonic and cyclic raw data extracted from seven previously published works on five different types of soils are processed and analyzed through the critical state soil mechanics framework. In addition to the conventionally defined state indices, the other indices defined in terms of equivalent interparticle void ratio, which is a recently established alternative state variable to the void ratio, are also evaluated.

2. Concepts and definitions

2.1. Equivalent interparticle void ratio (e^*)

Void ratio in its simple form is not capable of reflecting the real effect of fines presence on the behavior of the sand. This issue is attributed to differences in the contributions of the fines and the coarse grains to the force structure of the sand-fines mixture, as first reported by Mitchell [26] and Kenney [27], while the void ratio does not differentiate between their contributions. In fact, the fines below some threshold fines content (fc_{th}) have only a partial contribution to the interparticle contacts and hence a secondary role in sustaining the loads. When the fines content exceeds fc_{th}; however, the fines start taking a primary role in the force chain of the mixture. fc_{th} is the fines content at which the way the fines influence the behavior of the mixture is reversed. According to Lade et al. [28], the mixtures with more significant difference between mean sizes of coarse and fine grains would have a clearer fc_{th} and more clearly different behavior at low and high fines contents. The value of the threshold fines content has commonly, but not always, been reported within the range of 30–45% (e.g. [6,7,29]).

To consider the real role of the fines, with neither overestimating nor ignoring them in the force chain of the mixture, Thevanayagam [30] defined the concept of “equivalent intergranular void ratio” (e_g^*) for $fc \le fc_{th}$ as:

$$e_g^* = \frac{e+(1-b)fc}{1-(1-b)fc} \quad (1)$$

where b represents the portion of the fines that participates in the active interparticle contacts. The value of the b factor is controlled by the general characteristics of the particles and the grading properties of the mixture.

Since the particles of clay and silt differ in mineralogy, shape, size, hardness, plasticity and resistance, if the sand contains both of these materials, it will be necessary to take account of their part separately in the sand-silt-clay mixture. For this purpose, Ni et al. [31] extended the Eq. (1) to:

$$e_g^* = \frac{e+(1-a)cc+(1-b)sc}{1-(1-a)cc-(1-b)sc} \quad (2)$$

where cc is the clay content and sc is the silt content of the mixture. The factors a and b represent the contribution of clay and silt to the mixture's force chain, respectively. The value of the a factor is controlled by the general characteristics of the particles and the grading properties of the mixture, as the b value is. Thevanayagam et al. [9] noted that the b value should be between 0 and 1, which means the involvement of the silt particles in the mixture could be from zero to theoretically 100 percent. Ni et al. [15] demonstrated that the plastic fines, in contrast to the silts, might have negative contribution to the shear strength of the mixture, and their best possible contribution would be zero. The a value is then in the range of negative to zero.

The relationships mentioned above are only valid where $fc \le fc_{th}$. When fc exceeds fc_{th}, the role of the fines in the force structure of the mixture becomes dominant. The soil behavior changes from the case of fines-in-sand into the case of sand-in-fines and the sand grains act at most as reinforcing materials. In order to consider the actual role of both fines and coarse grains in the mixture, Thevanayagam [30] defined the concept of “equivalent interfine void ratio” (e_f^*) for $fc > fc_{th}$ as:

$$e_f^* = \frac{e}{fc+(1-fc)/R_d^m} < \frac{e}{fc} \quad (3)$$

where $R_d = D_{50}/d_{50}$ (D_{50} and d_{50} represent the mean size of coarse grains and fine particles, respectively) and the m factor depends on the grain characteristics and fines packing.

Thevanayagam et al. [9], Thevanayagam and Martin [5], Ni et al. [15,31], Yang et al. [10], Rahman et al. [32] and Maleki et al. [33] reported unique correlations between resistance data (either monotonic or cyclic) and e_g^* or e_f^* at a constant stress level or a narrow range of stresses, for different types of sands containing fines, irrespective of their fines content. Their works indicate that e_g^* and e_f^* are capable of taking into account the actual role of fines in the mixture, and are therefore appropriate alternative variables to the void ratio which cannot do so.

The nomenclature e^* (equivalent interparticle void ratio) stands for both e_g^* and e_f^* in this paper:

$$fc \le fc_{th} \rightarrow e^* = e_g^* \ \& \ fc > fc_{th} \rightarrow e^* = e_f^*$$

2.2. State

According to critical state soil mechanics, sand behavior in shearing is controlled by its corresponding position in e: ln p' or ν: ln p' space (where $\nu = 1+e$ is specific volume of the soil). In other words, it is the combination of stress level (p') and relative density (as a function of e), not density alone, that determines the sand behavior. Stress level modifies the material behavior in a way that even dense samples, when consolidated under sufficiently high confining pressures, can behave similarly to loose samples [21]. “State” is defined as the corresponding position of the soil in the e: ln p' or the ν: ln p' space. If e^* is used instead of e, this definition of state can be generalized to e^*: ln p' space, where in addition to the e and p', the value of fc controls the location of the soil state, and thus plays the role of a state variable. The soil state after the end of consolidation and creep stages, and prior to the start of monotonic or cyclic shearing is commonly termed “initial state”.

2.3. Equivalent interparticle critical state line (CSL^*)

Critical state line (CSL) is the locus of the points to which the soil state is reached in the e: ln p' space after complete shearing.