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Predicting onset of cyclic instability of loose sand with fines using instability curves

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ABSTRACT

This study utilises the equivalent granular state parameter, ψ^*, as a key parameter for studying static and cyclic instability and their linkage. ψ^* can be considered as a generalisation of the state parameter as first proposed by Been and Jefferies so that the influence of fines content in addition to stress and density state can be captured. Test results presented in this study conclusively showed that ψ^* at the start of undrained shearing and η_{IS}, the stress ratio at onset of static instability, can be described by a single relationship irrespective of fines content for both compression and extension shearing. This single relationship is referred as instability curve. However, the instability curve in extension shearing is different from that of compression. In this paper, the capacity of the instability curve in predicting triggering of cyclic instability was evaluated experimentally. An extensive series of undrained one-way (compression) and non-symmetric two-way cyclic triaxial tests, in addition to monotonic triaxial tests in both compression and extension were conducted for this evaluation. Furthermore, a published database for Hokksund sand with fines was also used. Test results show that cyclic instability was triggered shortly after the cyclic effective stress path crossed the estimated η_{IS}-zone(s) as obtained from instability curve(s) irrespective of whether instability occurs in the compression or extension side.

1. Introduction

Instability is a catastrophic failure phenomenon of loose saturated granular soils when it fails to sustain the current stress state and results in runoff deformation. Natural events such as earthquake, wave action, vibration etc. may trigger instability in field conditions [1]. Instability induced failures of submarine Nerlerk berm [2], North Dike of Wachusett Dam [3], Lower San Fernando Dam [4] etc. are the few examples of such catastrophic events.

Depending on whether the triggering action is monotonic or cyclic, the resultant instability can be referred to as static instability or cyclic instability. Fig. 1 shows typical static and cyclic instability behaviour. From a continuum mechanics point of view, instability is defined by the occurrence of $d\sigma_{ij}d\varepsilon_{ij} < 0$, where σ_{ij} and ε_{ij} are stress and strain tensors respectively and "d" represents infinitesimal increments. Static instability occurred at onset of deviator strain softening when the deviator stress attained a peak value, q_{IS} [5–9]. Sladen et al. [10] proposed the concept of the collapse line (CL) which joins the peak deviator stress points in q–p' space obtained from a number of undrained triaxial tests on specimens with same initial void ratio, e_0, but with undrained shearing commencing from different initial mean effective stresses, p'_0. According to Sladen et al. [10], CL was linear and passed through the steady state (SS) point. A similar behaviour was observed for Toyoura sand by Ishihara [11]. However, Chu and Leong [12]; Lade [7] introduced the concept of instability line (IL) which is a line joining the peak deviator stress point and origin of q–p' space (instead of SS point). Rahman and Lo [13] argued that both CL and IL are essentially the same concept but with different implied properties. To avoid confusion, a more direct and assumption independent way to characterise onset of instability by η_{IS}, the instability stress ratio as proposed by Rahman and Lo [13]. η_{IS} is defined as the stress ratio (q/p') at onset of instability and thus its use is not dependent on any implied assumptions.

Although a number of studies have been conducted in predicting cyclic instability for clean sand, such investigations for sand with fines (particle size < 0.075 mm) are rather limited. Many researchers proposed to use undrained monotonic effective stress path (ESP) obtained from a replicate specimen as a backbone curve in predicting triggering of cyclic instability. The replicate specimen was defined by the same initial void ratio, confining stress and specimen preparation method. Konrad [14] found that

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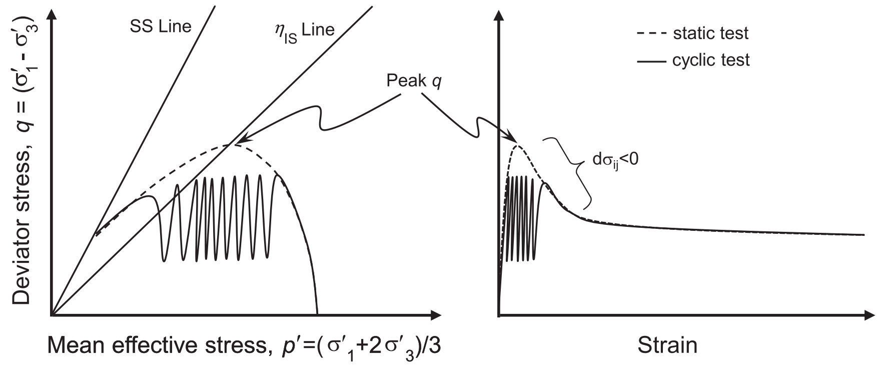

Fig. 1. Typical example of static and cyclic instability.

the undrained peak strength envelope in the effective stress space could be used to define the triggering of strain softening in both monotonic and cyclic undrained loading. Vaid and Sivathayalan [15] showed that strain softening under cyclic loading (one-way and two-way) occurred when the mobilised friction angle attained the value that triggered strain softening under monotonic loading of a corresponding test. Yang and Sze [16,17], demonstrated that cyclic instability under one-way cyclic loading took place when cyclic ESP reached η_{IS}-line of corresponding undrained monotonic test. Similar observation was also reported for other studies for sands [18–20] and sand with fines [21,22]. Recently, Baki et al. [23] showed that η_{IS} of an equivalent undrained monotonic specimen can be used to predict triggering of cyclic instability under one-way, two-way (symmetrical and non-symmetrical) cyclic loading. Two specimens were considered as equivalent if they had the same equivalent granular state parameter, $\psi^*(0)$; where, (0) represents at start of undrained shearing. The concept of ψ^* was proposed by Rahman and Lo [24,25] and it can be considered as a generalisation of the state parameter, ψ, as proposed by Been and Jefferies [26]. However, all research published to date are based on test pairs, one for cyclic and one for monotonic loading. No extensive investigations have been reported so far to relate triggering of cyclic instability with monotonic instability covering a wide range of testing conditions by eliminating the necessity of having a corresponding undrained monotonic ESP. After analysing a large number of experimental and published datasets for sand with fines, Rahman and Lo [13] reported that η_{IS} for a range of fines contents, f_c, can be presented as a function of $\psi^*(0)$. Thus, this leads to the hypothesis that one can predict the triggering of cyclic instability from state parameter of soil using a pre-existing relation between η_{IS} and $\psi^*(0)$ from monotonic tests. Thus, the objective of this study is to evaluate this hypothesis over a wide range of initial conditions (e, p') and fines contents. Furthermore, this evaluation will be made for both compression and extension mode of shearing.

2. Instability curve

The concept of equivalent granular state parameter, ψ^*, was developed in [25,27,28]. However, a brief summary is presented below for sake of completeness. Sand with different f_c, have different steady state lines (SSLs). In order to determine ψ as defined by Been and Jefferies [26], a family of SSLs, one for each f_c, has to be determined. To overcome this challange, a number of researchers proposed to use the equivalent granular void ratio, e^* in lieu of e [29,30], where e^* is defined as

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

where b is the fraction of fines that are active in transferring forces between soil grains. The determination of b for different f_c is much discussed elsewhere [13,23,25,27,28] and presented briefly in Appendix for completeness. Eq. 1 is valid for $f_c < f_{thre}$; where f_{thre} is defined as the limiting f_c when soil fabric changes from “fines-in-sand” to “sand-in-fines”. A number of researchers [9,27,31] showed that, for $f_c < f_{thre}$, the SSLs in e^* log(p') space essentially come to a single trend i.e. independent of f_c. The single trend is referred as equivalent granular steady state line (EG-SSL).

By considering EG-SSL as the reference, the definition of ψ can be generalised to equivalent granular state parameter, ψ^* [24] as:

$$\psi^* = e^* - e^*_{SS} \tag{2}$$

where e^*_{SS} is the corresponding e^* value at the same p'_0 on the EG-SSL. The influence of f_c is already embedded in ψ^* because e^* was used in lieu of e. Rahman and Lo [13,32,33] showed that η_{IS} and $\psi^*(0)$ exhibit a single relation irrespective of f_c based on triaxial data for Sydney sand with fines (same soil also used for this study) and published datasets for Hokksund sand by Yang [8] and Marine sand by Chu and Leong [12]. This single relationship in η_{IS}-$\psi^*(0)$ space is referred to as instability curve, IC, by Rahman and Lo [13,32,33]. However, this concept has not been investigated for undrained shearing in extension mode. Furthermore, the possibility of necking in extension shearing means the determination of η_{IS} and SSL in extension mode are major challenges.

3. Experimental investigation

3.1. Material tested

For this study, tests were performed on a soil mixture of clean Sydney sand (SP) and fines referred as MII fines. MII fines was created by adding 2/3 locally available fines collected from Majura river bank deposits and 1/3 commercially available kaolin. This sand-fines combination has f_{thre}=40% [13]. Five different fines content in the range of 0–30%, i.e. all less than f_{thre}, are presented in this paper. Thus, the tested material had a maximum MII fines content of 30% for which the maximum clay content was 6%. Both the host sand and the fines are identical to that used by Rahman and Lo [13,32,33] in establishing the concept of IC in compression shearing. Grading curves of tested soil is shown in Fig. 2. It is to be noted that in the same figure (Fig. 2), grading curves of Hukksund sand, as extracted from literature for re-analysis in this study, is also plotted.

3.2. Experimental methodology

3.2.1. Testing procedure

A triaxial testing system with PC-controlled data logging and stress/strain control capabilities was used for this study.