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Flow deformation and cyclic resistance of saturated loose sand considering initial static shear effect

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ABSTRACT

In practical engineering, a driving stress often exists and acts on the soil elements, and this stress may have a significant effect on the deformational characteristics and liquefaction resistance of sand when the sand is subjected to seismic loadings. This paper presents a systematic experimental investigation into the undrained cyclic behavior of saturated loose sand with the static shear under both triaxial compression and extension conditions. Various combinations of the magnitude of static stresses and cyclic stresses were considered in the triaxial tests. The results indicate that different static shear stress conditions lead to two distinct failure modes, namely, flow liquefaction and residual deformation failure. The required number of loading cycles for the onset of flow deformation and failure are both related to two stress parameters, i.e., cyclic stress ratio (*CSR*) and static stress ratio (*SSR*). In viewing the failure envelope established against the two stress variables *CSR* and *SSR*, a critical *SSR* that identifies the role of the presence of initial static shear stress is obtained: when *SSR* is less than that critical value, the resistance may increase, whereas the resistance may decrease as *SSR* becomes larger. In addition, the triggering conditions of flow deformation under cyclic loading can be interpreted with the instability response of sand under monotonic loading. Combined with the observation on the cyclic deviatoric strains developed during and after the flow deformation, a unified interpretation is made to quantify the effects of both the *SSR* and *CSR* on the cyclic resistance of loose sand.

1. Introduction

Seismic loading under earthquake conditions may trigger the liquefaction of granular materials, leading to catastrophic consequences for the geo-structures in terms of damage and casualties. During earthquakes, the cyclic shear stress induced on a soil element is likely to vary in a random fashion both in magnitude and frequency. The randomness in stress series has been evaluated by converting the irregular time history of earthquake-induced cyclic stress to an equivalent series of constant amplitude stress cycles [1–3]. In the laboratory, such a treatment would greatly simplify the testing operations while reducing the financial costs significantly. Because of these merits, extensive uniform cyclic loading tests have been conducted to investigate the liquefaction resistance of saturated sands, including simple shear tests [4,5] and torsional shear tests [6–8] during the last several decades. However, as a handily-operated test with definitive stress and strain conditions applied to the testing samples, the cyclic triaxial test is still often used to characterize the cyclic response of sand (see Ishihara [9], Sawada et al. [10], Sim et al. [11], Aghakouchak et al. [12]). In the undrained triaxial tests, the liquefaction behavior of saturated sand is usually assessed by applying a symmetrical cyclic loading on the isotropically consolidated samples.

The stress states of the soil element in free-field level ground are recognized to be different from those in sloping ground, as schematically shown in Fig. 1. A soil element beneath level ground is initially subjected to the vertical effective overburden pressure on its horizontal plane. In the case of sloping ground condition, an additional static shear stress τ_s is acting on this plane [13,14]. Under cyclic loading conditions, the cyclic shear stress τ_{cyc} is superimposed with τ_s and applied on the soil element. Dating back to the pioneering work by Lee

Abbreviations: CRR_f, cyclic resistance ratio to failure; CRR_t, cyclic resistance ratio to flow deformation; *CSR*, cyclic stress ratio; D_r, relative density; e_0, initial void ratio; *N*, number of cycles; N_t, number of cycles to flow deformation; N_f, number of cycles to failure; p', mean effective stress; p_0', initial mean effective stress; *q*, deviatoric stress; q_{cyc}, cyclic deviatoric stress; q_{max}, maximum deviatoric stress; q_{min}, minimum deviatoric stress; q_{peak}, local peak deviatoric stress; q_s, initial static deviatoric stress; *RS*, residual axial strain; *SSR*, static stress ratio; ε_a, axial strain; ε_{flow}, magnitude of flow deformation; ε_{pflow}, post flow deformation; σ_v, vertical normal stress; σ_h, horizontal normal stress; τ_s, initial static shear stress

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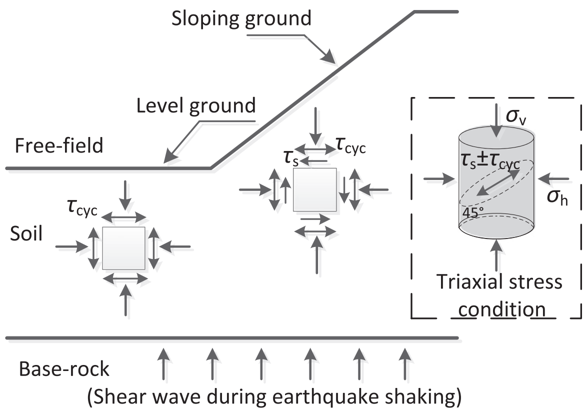

Fig. 1. Simplified stress conditions of soil elements for level ground and sloping ground during earthquake shaking.

and Seed [13], in the type of triaxial test, the application of an initial static shear τ_s was achieved by anisotropic consolidation with initial static deviatoric stress q_s (=$\sigma_v-\sigma_h$). This induces a static shear stress τ_s=1/2q_s on the 45° plane or the plane of maximum shear in the triaxial specimen [15]. Combined with the cyclic shear stress τ_{cyc}=1/2q_{cyc} acting on such plane, the triaxial stress condition shown in Fig. 1 can mimic the in-situ stress conditions approximately [13,14,16]. Based on the cyclic triaxial test results by Lee and Seed [13], the existence of initial static shear may enhance the cyclic resistance of sand. However, Vaid and Chern [17] found that the liquefaction resistance could either increase or decrease with the presence of static shear, depending on both the relative density of the sand and the static shear stress level. The possible explanation by Harder and Boulanger [18] and Vaid et al. [19] to the above contradictory observations could be due to the different roles that the initial static shear stress plays in loose and dense sands. For dense sand, the initial static shear may be argued to be beneficial to the liquefaction and cyclic resistance, but it becomes detrimental when the initial static shear stress is larger for loose sand. Recent work by Yang and Sze [16,20] further established a unified correlation between the liquefaction resistance of Toyoura sand and the state parameter ψ [21], taking account of the effects of both relative density of sand and confining pressure, with the concept of threshold static shear stress ratio. It is also found that, under simple shear conditions, the role of static shear on liquefaction resistance is dependent on the initial static stress level and the relative density of samples; see Hosono and Yoshimine [22] and Randolph [5].

Noting that the reduced cyclic strength and thus increased permanent deformation of saturated loose sand upon cyclic loading would give rise to severe consequences to the structures built on the sandy grounds, the subject has attracted continuous interest in the last few decades. As shown by Vaid and Chern [14], a sudden development of axial strain and excess pore water pressure were observed at certain stages during cyclic shearing, which was referred to as the onset of flow deformation. Hyodo et al. [23] and Yang and Sze [20] revealed that the flow deformation of loose sand during cyclic loading was closely related to the strain softening behavior observed in monotonic tests, which could occur on the both sides of the triaxial compression and extension. More recently, based on the experimental tests on isotropically consolidated sand subjected to varying waveforms of cyclic loadings, Baki et al. [24] established the linkage between the cyclic and static instability under triaxial conditions. On the other hand, through a series of cyclic simple shear tests with various initial stress conditions, Sivathayalan and Ha [25] found that the flow deformation under cyclic loadings are also closely related to the instablity response of sand under monotonic loading. In addition, Georgiannou and Konstadinou [26] also observed the flow type deformation of saturated loose sand in cyclic torsional shear tests. Although the flow deformation is usually recognized to drive the loose sand to be deformed rapidly to failure, the

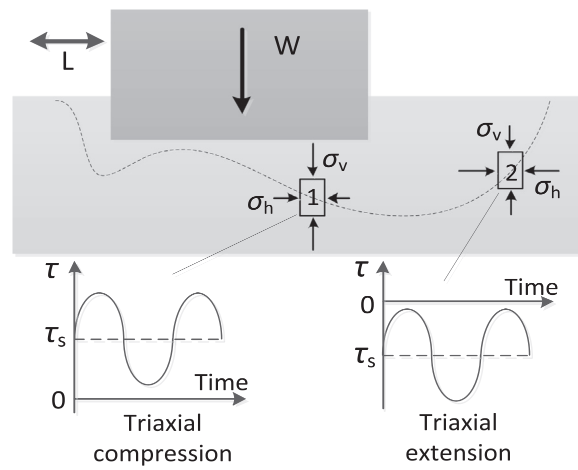

Fig. 2. Simplified stress conditions for soil elements beneath a gravity structure under cyclic loading: W, weight of structure; L, lateral cyclic loads (After Randolph [5] and Andersen [28]).

relationship between cyclic resistance and flow deformation behavior of sand has not been fully understood. In particular, the static shear stress would play different role in the flow deformation and cyclic resistance of loose sand, depending on the direction of the static shear in triaxial compression or extension stress condition.

To date, the experimental studies about initial static shear effect have focused mainly on static shear under triaxial compression condition [27]; see element 1 that is right beneath the gravity structure in Fig. 2. However, the soil element 2 which is away from the gravity structure may experience an initial static shear stress in extension mode [5,28]. The static shear stress τ_s is composed of two components. The first is the initial shear stress induced only by the effective overburden pressure. The other is the additional shear stress due to the weight of the structure, which may cause higher horizontal normal stress (σ_h) than the vertical (σ_v), thus the initial static stress would emerge in triaxial extension condition. The lateral cyclic loads, such as wind, wave, and earthquake among others will generate the cyclic shear stresses τ_{cyc} which will be also superimposed on the maximum shear plane. Thus this loading condition can be simulated by the cyclic triaxial test with a static shear in the extension mode.

Through the above literature review, the following points could be identified. First, in most of above experimental studies, the cyclic loadings were applied at relatively low rates (loading frequency f≤0.1 Hz), thus it is necessary to investigate how loose sand behaves under cyclic loading conditions with a frequency of 1 Hz, which is a standard loading frequency recommended by ASTM-D5311M-13 [29] when assessing the cyclic behavior of soil subjected to seismic loading. Second, compared with the extensive research into the cyclic behavior of sand with the existence of an initial static shear in compression mode, the effect of the initial extensional static stress is rarely investigated. Last but not least, most of the previous investigations were focused only on the cyclic resistance to liquefaction for loose sand, and the effects of flow deformation behavior on the cyclic resistance are rarely considered.

The primary aim of this study is to identify the important role of the initial static shear in the cyclic behavior of saturated loose sand, covering both compressional and extensional static stress conditions, to acquire a fundamental understanding of its flow deformation and cyclic resistance. Through a series of undrained cyclic triaxial tests, the results obtained show that different static shear stress conditions would lead to two distinct failure modes: i.e., flow liquefaction and residual deformation failure. The required number of loading cycles for the onset of the flow deformation and failure are both related to two normalized stress parameters, i.e., *CSR* (the ratio of the cyclic shear stress amplitude to that of the initial mean effective stress, $CSR=q_{cyc}/$