Coupling Effect of Loading Rate and Initial Shear Stress on Landslide and Soil Liquefaction

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Abstract: The coupling effect of loading rate and initial shear stress on landslide and liquefaction-induced flow slide is a major concern in engineering geology, and it has been extensively investigated from the perspective of stress or strain criteria. Initial static shear stress is generated in sloping ground conditions and increases the complexity of the stress state of soil, making the assessment of loading rate effects more challenging. This paper presents a systematic experimental study on Leighton Buzzard sand, aiming to interpret major concerns on loading rate and initial shear stress effects within an energy-based framework. The cumulative dissipated energy per unit volume is used to characterize the shear strength of sand in designed monotonic tests and the cyclic mobility of sand in liquefaction tests. Monotonic test results show that increasing loading rates significantly results in higher soil strength, while the cumulative dissipated energy at peak stress is independent of loading rates. For cyclic tests, oval-shaped shear stress paths with various frequencies are employed to simulate stress conditions commonly induced by seismic events. The cumulative dissipated energy for triggering flow failure or liquefaction can be predicted by a multi-factors model, and the model is governed by relative density and initial stress states. This energy-based method, utilizing the distinct pore pressure (pp)-cumulative energy (W) relationship, offers a unified and coherent framework for comprehending the complex interactions between loading rate and initial shear stress in soil strength determination while also providing a means to quantify these effects in practical engineering.

Keywords: ***Landslide; Soil liquefaction; Loading rate; Initial shear stress; Energy dissipation.***

Introduction

Assessing the strength of soils remains a crucial subject of engineering geology, while complicated stress conditions in practical engineering hinder the understanding of soil behavior and strength evaluation. This study focuses on two key contributors to these complex stress conditions: one is the loading rate induced by external disturbances, and the other is the initial static shear stress generated by the soil during the consolidation process in a slope (Figure 1).

The loading rate exerted on soil is time-varying during a landslide, especially at the initiation stage of a flow failure. To reveal the effects of loading rate on soil behavior, research workers make numerous attempts through element and model test techniques (Liu et al., 2023). Previous studies using triaxial tests indicated that the loading rate effect highly depends on the relative density, stress level, and draining type. Casagrande and Shannon (1948) reported findings from triaxial tests under 29 kPa vacuum pressure. Their results demonstrated roughly a 10% increase in strength as the strain rate varied within a range of [0.0035, 350] %/s, though there was significant variability in the peak principal stress ratio. Similarly, Seed and Lundgren (1954) performed a series of triaxial tests on fully saturated sandy soils under three different strain rates, revealing that the loading rate affects the time required to reach peak stress. Watanabe and Kusakabe (2013) reported that the soil strength increases with loading rates within a certain range and confirmed viscous properties resulting from loading rate differences.

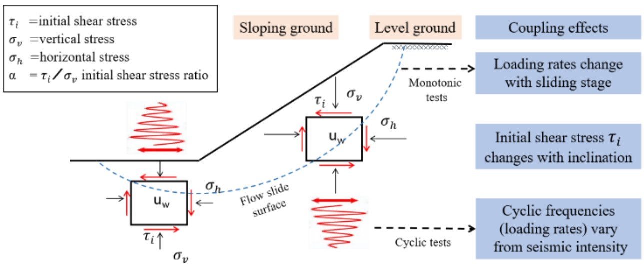

Figure 1, A typical landslide (or flow slide) process on a natural slope involving loading rate and initial shear stress variation.

Methodology

All experiments are conducted utilizing the GDS variable direction dynamic cyclic simple shear (VDDCSS) apparatus, located at the University of Nottingham, Ningbo China (Figure 2). The VDDCSS device allows for independent control of shear stress along two perpendicular axes, facilitating the multi-directional shear loading during testing. Further details regarding the VDDCSS system are available in the study by Li (2016).

The specimen tested in the VDDCSS is a short cylinder with flexible height and a diameter of 70 mm. The diameter to height should be relatively low (around 4.12) to ensure the uniformity of stress and strain distribution within the specimen. A wire-reinforced membrane is employed, consisting of low-friction Teflon-coated rings, each 1 mm in height, positioned around the specimen. These rings effectively restrict lateral normal deformation during consolidation and subsequent testing, maintaining lateral strain at zero. Consequently, K0 conditions are sustained throughout the consolidation stage.

Figure 2, Simple shear apparatus used in this study: (a) VDDCSS; (b) specimen and axes definition; (c) specimen before consolidation.

As shown in Figure 3, the vertical deformation of the specimen remains zero during the constant volume test, indicating no energy dissipation is generated by normal vertical stress in the vertical direction. Moreover, due to the lateral rigid constraint of the low-friction metal rings, horizontal normal strain also remains zero during the simple shear test, preventing energy dissipation in the lateral normal direction as well. Consequently, total energy dissipation within specimens during the constant volume simple shear process is primarily due to shear work (neglecting thermal effects), and the specific calculation method will be presented later. The energy-based approach is more suitable for analyzing NGI-type simple shear test results because, unlike triaxial compression tests, it does not involve lateral deformation of the specimen, which leads to additional energy dissipation. In conventional triaxial tests, lateral expansion or contraction of the specimen cannot be accurately monitored, making it difficult to account for energy dissipation in the lateral direction.

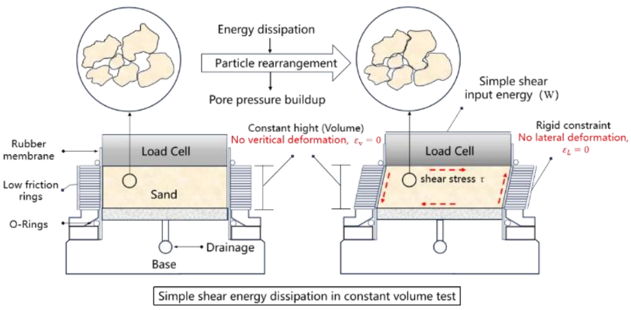

Figure 3, Specimen information and energy dissipation mechanism in an NGI-type simple shear tester.

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