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Pre-failure instability of sand under dilatancy rate controlled conditions

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Abstract

Experimental results are presented in this paper to show that a runaway type of pre-failure instability can occur for sand under dilatancy rate controlled conditions when an appropriate strain increment ratio, $d\varepsilon_v/d\varepsilon_1$, is imposed. This type of instability is similar to the runaway type of instability observed for very loose sand under undrained conditions. Whether a soil element will undergo pre-failure instability depends on the difference between the strain increment ratio of the soil obtained from drained test, under a specified effective confining pressure, $(d\varepsilon_v/d\varepsilon_1)_s$, and the strain increment ratio imposed during the test, $(d\varepsilon_v/d\varepsilon_1)_i$, rather than the absolute magnitude of $(d\varepsilon_v/d\varepsilon_1)_i$. Based on the experimental data obtained in this study it was found that an instability line can be determined from a series of strain path tests conducted at different effective confining pressures but with the same $d\varepsilon_v/d\varepsilon_1$ by joining the peak points of the effective stress paths to the origin in the q–p' stress space. This line is similar to the instability line obtained from undrained tests on loose sand. The instability tests under dilatancy rate controlled conditions indicate that the stress ratio at the onset of instability obtained in the instability tests coincide with the peak stress ratio line. This suggests that the peak stress line can be used to predict the onset of instability under dilatancy rate controlled conditions in the same way as the use of instability line to predict the onset of instability under undrained conditions.

Keywords: Liquefaction; Sands; Laboratory testing; Shear strength

1. Introduction

Failure of geotechnical structures can be initiated by the instability of soil. The term instability used in this paper refers to a behaviour in which large plastic strains are generated rapidly due to the inability of a soil element to sustain a given load or stress. Instability normally takes place when the stress state of a soil element satisfies a failure criterion, as in the conventional stability analysis. However, instability may also occur prior to attaining the failure stress state. A typical example is static liquefaction which occurs before the effective stress path reaches the failure line (which is also the steady state line for loose sand). So far, this so called pre-failure instability has been observed mainly for saturated loose sand under undrained conditions (e.g. Lade and Pradel, 1990; Lade, 1993; Leong et al., 2000; Yang, 2002; Wanatowski and Chu, 2007, 2012; Andrade, 2009). However, the undrained condition may not be necessary. There are failure cases that occurred under drained or other than undrained conditions (e.g. Torrey and Weaver, 1984; Eckersley, 1990; Olson et al., 2000;

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Kokusho 2003; Sento et al., 2004). Failure mechanisms related to the re-distribution of void ratio within a globally undrained sand layer (Fig. 1a) or spreading of excess pore water pressure with global volume changes along a slope (Fig. 1b) have been suggested by the U.S. National Research Council (NRC) (1985). Adalier and Elgamal (2002) also observed from a series of centrifuge tests that there is a potential strength loss in dense sand as a result of pore water migration into the dense zone from the adjacent loose zone in the ground. This further indicates that flow slides can take place under other than undrained conditions. These, other than undrained or the so-called non-undrained conditions (Chu et al., 1992), have been simulated in the laboratory by the use of a strain path testing method (Chu and Lo, 1991), in which the strain increment ratio, $d\varepsilon_v/d\varepsilon_1$, imposed to a specimen, is controlled. When $d\varepsilon_v/d\varepsilon_1 > 0$, the soil specimen compresses and when $d\varepsilon_v/d\varepsilon_1 < 0$, the specimen dilates. An undrained test is only a special case when $d\varepsilon_v/d\varepsilon_1 = 0$. The strain path method also provides a better simulation of the field situations, where a soil element will normally experience both volume change and pore water pressure change simultaneously and fully drained or undrained conditions are only exceptional cases. However, the use of strain path testing method to study soil behaviour is uncommon (Topolnicki et al., 1990; Chu et al., 1992, 1993; Vaid and Eliadorani, 1998; Lancelot et al., 2004; Sivathayalan and Logeswaran, 2007; Wanatowski et al., 2008; Wanatowski and Chu, 2011).

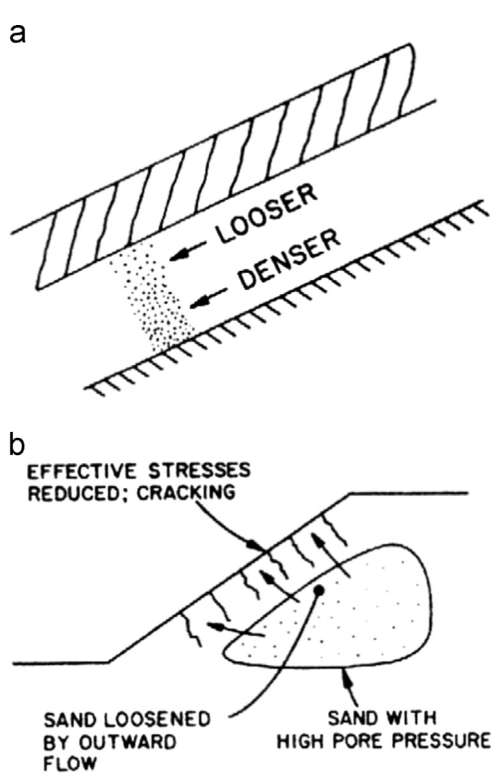

Fig. 1. Failure mechanisms identified by the U.S. National Research Council: (a) mechanism *B* for the situation where void redistributes within a globally undrained sand layer; (b) mechanism *C* for the situation where failure is induced by spreading of excess pore pressure with global volume changes.

The possibility of dilating behaviour of soil masses prior to slope collapse has also been reported in several case studies. For example, Been et al. (1987) argued that the Nerlerk berm failure case might have occurred for dilatant sand which state lies below the steady state line. Several other cases of flowslide in dilatant sand have been presented by Been et al. (1988). Fleming et al. (1989) also reported that the Salmon Creek landslide in Marin County, California, exhibited dominantly dilative transformation from solid landslide to liquid debris flow. Although some explanations to the causes of this and other failures have been proposed (Schofield, 1980; Been et al., 1988; Hadala and Torrey, 1989), the instability mechanisms of dilative sand have not been well established. Furthermore, a method to predict such failures has not been proposed yet.

The objective of this paper is to study the pre-failure instability of sand in strain path testing under dilatancy rate controlled conditions. The results of the strain path tests conducted on medium loose to medium dense sand are presented. Factors affecting the occurrence of pre-failure instability under dilatancy rate controlled conditions are analysed. The practical implications of the study are also discussed.

1.1. Material tested and testing procedures

A marine-dredged sand was used for this experimental study. The basic properties of the sand are given in Table 1. All the specimens were prepared by pluviating sand into water. For saturation, all the specimens were flushed with de-aired water from the bottom to the top for 60 min under a water head of about 0.5 m. After that a back pressure of 400 kPa was applied. The Skempton's pore water pressure parameter (*B*-value) greater than 0.96 was obtained for all the specimens. A liquid rubber technique (Lo et al., 1989) was adopted to reduce the bedding and membrane penetration errors. The specimens used were 200 mm in height and 100 mm in diameter.

All the specimens were isotropically consolidated. Shearing in all the tests was carried out using a strain path method with $d\varepsilon_v/d\varepsilon_1 = \text{const}$ (Chu and Lo, 1991). In the strain path method, when $d\varepsilon_v/d\varepsilon_1 > 0$, the soil element is in compression and water flows out of the specimen. When $d\varepsilon_v/d\varepsilon_1 < 0$, the soil element is in dilation and water flows into the specimen. An undrained test, with $d\varepsilon_v/d\varepsilon_1 = 0$, is only a special case of the $d\varepsilon_v/d\varepsilon_1 = \text{const}$ test. Since in a strain path test the volumetric change of the specimen is controlled, a change in pore water pressure occurs. This change in pore water pressure leads to a change in effective confining stress.

Table 1
Basic properties of the tested sand.

Mean grain size (mm)	Uniformity coefficient	Specific gravity	Max. void ratio	Min. void ratio	Shell content (%)
0.30	2.0	2.60	0.916	0.533	12