RECENT DEVELOPMENTS IN MODELING LIQUEFACTION DUE TO EARTHQUAKE SHAKING

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Mechanics of Instability and Liquefaction of Silty Sand

Based on considerable amounts of prior research in the area of instability and liquefaction of granular materials, the causes and conditions for instability have been identified [1-4]. Practical experience and experimental research have shown that silty sands can be particularly prone to instability and liquefaction [5].

Saturated soils exhibit nonassociated flow and they may therefore become unstable *inside* the effective stress failure surface. Experiments have shown that soils are stable as long as they remain under drained conditions. Instability may be obtained under undrained conditions in the region where the plastic yield surface opens up in the outward direction of the hydrostatic axis. Initiation of instability also requires that the soil tends to compress during undrained shear. Thus, loading (i.e. hardening inside the failure surface resulting in large plastic strains) can occur under decreasing stresses, and this leads to unstable behavior under undrained conditions. The location of the lower boundary for instability, called the instability line, has been identified as shown schematically in Fig. 1. Together with the effective stress failure line it defines the region of potential instability. The instability of a gently inclined submarine slope and steeper slopes created by building an artificial undersea island have been analyzed [2, 3]. Conventional stability analyses indicate both slopes to be stable, but the analysis procedure clearly show the potential for instability, as actually observed in many submarine deposits of loose, fine sands and silts, and in tailings dams and spoil heaps of granular materials with properties of similar character.

Instability and failure are two different behavioral aspects of soils that exhibit nonassociated flow [1]. Although both involve reduction in shear strength and consequently may lead to catastrophic events such as gross collapse of earth structures, they are not synonymous.

It is the fact that loading of a compressible soil (resulting in large plastic strains) can occur under decreasing stresses that leads to unstable behavior under undrained conditions. Loose, fine sands and silts have sufficiently low permeabilities that small disturbances in load or even small amounts of volumetric creep may temporarily produce undrained conditions in such soils, and instability (resulting in liquefaction) of the soil mass follows. As long as the soil remains drained, it will remain stable in the region of potential instability.

When the condition of instability is reached, the soil may not be able to sustain the current stress state. This state corresponds to the top of the tear drop shaped yield surface as shown schematically on the p'-q diagram in Fig. 2. Following this top point the soil can deform plastically under decreasing stresses. The top of the undrained effective stress path, corresponding to $(\sigma_1 - \sigma_3)_{max}$, occurs slightly after but very close to the top of the current yield surface. Fig. 1 shows a schematic p'-q diagram in which the line connecting the tops of a series of effective stress paths from undrained tests provides the lower limit of the region of potential instability. Experiments show that this line is straight. Since it goes through the top points of the yield surfaces which evolve from the origin of the stress diagram, the instability line also intersects the stress origin.

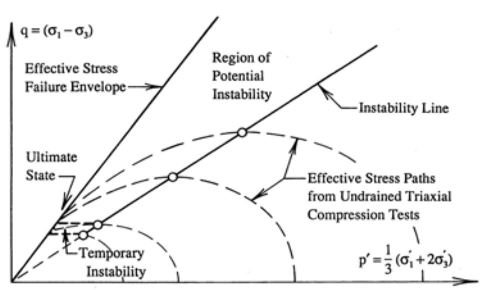

Fig. 1. Schematic diagram of location of Instability line in p'-q diagram.

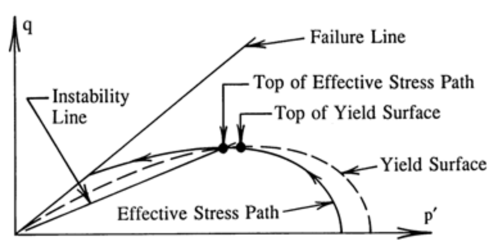

Fig. 2. Schematic diagram of location of instability line determined from Consolidated-undrained test on loose sand.

A region of temporary instability is located in the upper part of the dilatancy zone, as shown in Fig. 1. It is a region where instability may initially occur, but conditions allow the soil to dilate after the initial instability, thus causing the soil to become stable again. The approximate upper limit of the temporary instability region may be obtained from the intersection of the instability line and the total strength envelope [3]. For very loose soils the total strength envelope intersects the stress origin, and the region of potential instability reaches down to the origin of the stress diagram.

The schematic diagram in Fig. 3 shows that instability may occur in granular soil if the current stress point is located inside the region of potential instability (at point A in Fig. 3), and the soil is exposed to a rapid, short-term increase in loading, effectively causing loading under undrained conditions. If the current stress point is outside the region of potential instability (at point B), then instability may occur if sufficient load is applied rapidly under undrained conditions. Finally, instability may occur under undrained cyclic loading, even if the initial stress state is outside the region of potential instability (at point C). Instability and liquefaction occurs when the stress state reaches the plastic yield surface inside the region of potential instability.

Static instability can be predicted by a constitutive model with isotropic hardening. However, instability and liquefaction resulting from cyclic loading can be predicted with a version of the model that includes kinematic hardening, as explained below. Thus, it is possible to predict the results of seimic loading using an advanced constitutive model in a dynamic finite element program.

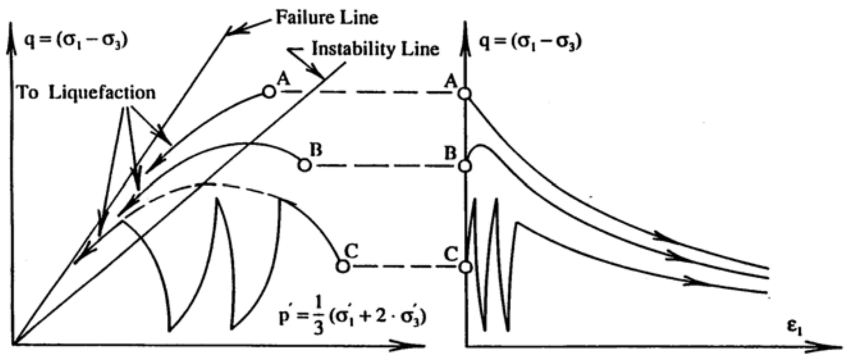

Fig. 3. Schematic diagrams showing (a) stress paths and (b) stress-strain relations for initiation of static (A, B) and cyclic (C) instability at small strains and subsequent liquefaction at large strains under undrained conditions in loose sand.

Kinematic Hardening Model for Soil Behavior During Large Stress Reversals

Modeling the behavior of soils during large stress reversals and large changes in stress involving unloading and reloading is required to capture the behavior of earth structures and soil-structure interaction problems under static as well as dynamic loading conditions. General three-dimensional stress reversals occur during earthquakes, and to capture the soil behavior during such conditions, a kinematic hardening model has been developed.

An existing Single Hardening elasto-plastic model for isotropic frictional materials [7-9]was used as the basic framework to which a rotational kinematic hardening mechanism was added [10, 11]. This model has been shown to predict soil behavior with good accuracy under drained and undrained conditions, as well as during conventional triaxial compression and true triaxial stress variations. Analyses of data from triaxial tests indicate that plastic yielding occurs during unloading and reloading, and the directions of the plastic strain increment vectors tend towards a behavior pattern, which may be described by a combination of isotropic and kinematic hardening with rotational evolution of the plastic potential and the yield surface. Thus, the model involves rotation and intersection of yield surfaces, as shown in Fig. 4, to achieve a consistent and physically rational fit with experimentally observed behavior in both triaxial and octahedral planes. The existing, isotropic work hardening law was shown to apply to isotropic as well as kinematic behavior of sand.

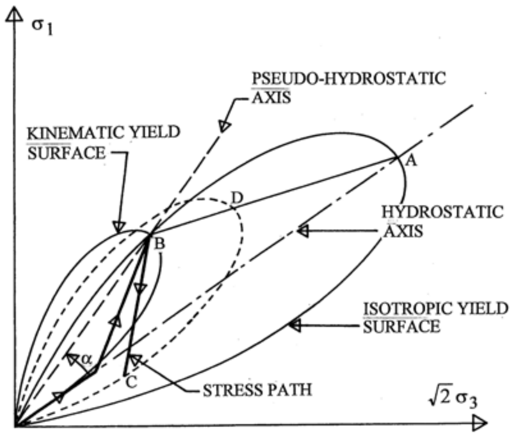

Fig. 4. Growth of rotational yield surface in triaxial plane (in magnitude and orientatin) towards isotropic yield surface upon stress reversal at point B.

The new combined model preserves the behavior of the isotropic hardening model under monotonic loading conditions, and the extension from isotropic to rotational kinematic hardening under three-dimensional conditions was accomplished without introducing new material parameters. The behavior of the proposed plastic potential was verified by studying the behavior of sand during large stress reversals produced in an experimental program incorporating conventional triaxial and true triaxial tests. Experiments were performed with various simple and complex stress paths involving large changes in stress during unloading and reloading, and the results were evaluated in terms of directions of plastic strain increment vectors superimposed on the stress space. Predicted plastic strain increment directions were compared with experimental data, and it was shown that the proposed model can capture soil behavior with reasonable accuracy within the scatter of test results. The capability of the proposed model was examined by comparing predictions with experimental data for simple and complex stress paths involving large stress reversals in the triaxial and octahedral planes.

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