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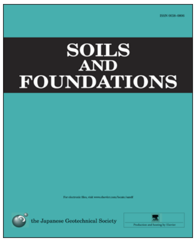

Static liquefaction-triggering analysis considering soil dilatancy

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Abstract

The failure of a sloping ground due to static liquefaction occurs when the shear stress applied by a monotonic triggering load exceeds the undrained yield (peak) shear strength of the saturated liquefiable cohesionless soil. Current practices for determining the in-situ undrained yield strength for grounds subjected to static shear stress rely on either a suite of costly laboratory tests on undisturbed field samples or empirical correlations based on in-situ penetration tests, which fail to account for the effect of soil dilatancy in decreasing the degree of strain-softening and the brittleness of cohesionless soils with an increasing penetration resistance. In this study, the effect of soil dilatancy on the static liquefaction failure of cohesionless soils is characterized by an empirical relationship between the soil brittleness index and the undrained yield strength from a database of 813 laboratory shear tests collected from the past literature. The application of this relationship for estimating the static liquefaction-triggering strength of cohesionless soils under sloping ground conditions is validated by comparing several cases of liquefaction flow failures. Finally, a procedure is briefly demonstrated for evaluating the triggering of static liquefaction in a dyke to the north of Wachusett Dam and Duncan Dam which incorporates the dilatancy behavior of cohesionless soils in a semi-empirical procedure based on in-situ penetration tests.

Keywords: In-situ testing; Laboratory tests; Liquefaction; Sands; Shear strength

1. Introduction

Failure due to liquefaction flows occurs in saturated loose cohesionless soils subjected to an initial static shear stress (e.g., in a sloping ground or beneath a foundation) when the soil resistance becomes lower than the static driving shear stress. The sudden nature and the very large shear displacements associated with liquefaction flow failures have made this phenomenon one of the most catastrophic mechanisms in the failure of slopes and embankments of saturated loose cohesionless soils. A liquefaction flow failure requires a triggering mechanism to initiate liquefaction and undrained strain-softening.

When a soil is sheared, its volume may increase (dilate) or decrease (contract) depending on its density and the magnitude of the effective stress applied on the soil. However, when this change in volume is inhibited during undrained (constant-volume) shearing, the tendency to dilate ("positive dilatancy") or contract ("negative dilatancy") is offset by an equally opposite elastic volumetric strain, which produces changes in the pore water pressure (Jefferies and Been, 2006). As illustrated in Fig. 1, static liquefaction is triggered in a saturated loose cohesionless soil by a monotonically-increasing shear load (e.g., raising the embankment height, oversteepening, the slope, toe erosion, rapid sediment accumulation, construction loading, weight of the construction/repair equipment, tidal changes, reservoir filling, slumping and progressive

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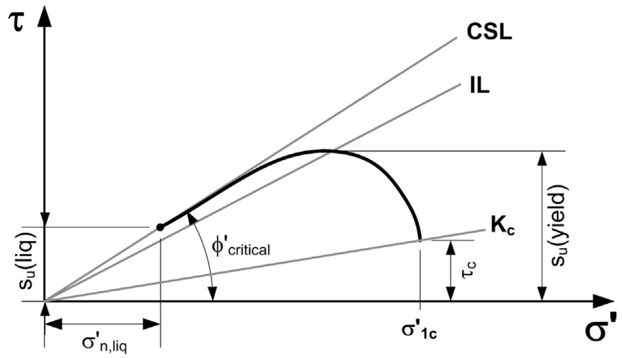

Fig. 1. Schematic liquefaction-triggering mechanism by monotonic undrained stress path.

failure leading to steeper slopes) when the undrained effective stress path crosses the instability line (Lade, 1992) at s_u(yield). Strain-softening subsequently follows the initiation of liquefaction until a reduced post-liquefaction strength, s_u(liq), is mobilized at large shear strains (Terzaghi et al., 1996). The February 1994 flowslide failure of the Merriespruit gold mine tailings dam in Virginia, South Africa, which released 600,000 m^3 of waste tailings over a distance of more than 2000 m, killed 17 people and destroyed 280 houses (Fourie et al., 2001), and the March 1918 flowslide failure of Calaveras Dam in California, which traveled about 200 m (Hazen, 1918), are examples of liquefaction flow failures triggered by monotonic loads produced by the oversteepening of the Merriespruit tailings dam and the rapid construction of the Calaveras Dam. Liquefaction flow failures resulting from monotonically-increasing loads have also occurred extensively in natural soil deposits in offshore or coastal areas, for example, along the shores of the straits between the islands of Zeeland, Netherlands (Bjerrum, 1971; Koppejan et al., 1948) or along the banks of the Mississippi River (Castro, 1969) damaging dykes and revetments and flooding downstream lands. Olson (2001) and Muhammad (2012) described several other cases of liquefaction flow failures. Understanding and quantifying the fundamental soil behavior associated with the triggering of these tragic events is an important step in liquefaction analysis and in determining the risk of liquefaction flow failures. This is particularly necessary for the design of large and high-risk earth structures, such as mine tailing impoundments, earth dams, and heavy building foundations for which a liquefaction failure has the potential to result in a flowslides, extensive damage, and loss of lives. Proper liquefaction mitigation and soil improvement techniques could then be implemented in the design or retrofitting of these critical structures if liquefaction triggering is found. Dilatancy is a fundamental aspect of soil shearing behavior which depends on soil density and the effective stress level. Based on a large database of laboratory shear tests, this study introduces an empirical relationship between s_u(yield) and s_u(liq), which captures the effect of soil dilatancy on the undrained strength of loose cohesionless soils. This relationship is employed for the estimation of s_u(yield) from in-situ penetration tests.

2. Liquefaction-triggering analysis of sloping grounds

An analysis of liquefaction triggering can determine whether or not liquefaction and a loss in undrained strength would occur in a liquefiable cohesionless soil under given loading conditions. This involves evaluating whether the combined initial static (τ_c) and monotonic-triggering shear stresses are sufficient to overcome s_u(yield). Several methods are available for determining the s_u(yield) of cohesionless soils. These include: (A) laboratory shear tests, (B) numerical analyses of soil constitutive models (Buscarnera and Whittle, 2013; Fuentes et al., 2012; Jefferies, 1993; Mroz et al., 2003; Park and Byrne, 2004), and (C) empirical correlations with in-situ penetration tests (Mesri, 2007; Olson and Stark, 2002; Stark and Mesri, 1992). Some of the major challenges and practical limitations of these methods are described in the following paragraphs.

Laboratory shear tests (Method A) provide the only direct measurement of s_u(yield). However, as the s_u(yield) of cohesionless soils is highly sensitive to the soil composition (mineralogy and gradation), fabric, sample disturbance, and soil-mixing effects, undisturbed samples obtained by ground freezing techniques should be used. While ground freezing is the only sampling method that can preserve the in-situ microstructure of cohesionless soils and provide relatively undisturbed samples (Hofmann et al., 2000), it is an expensive and onerous procedure that is only feasible in certain large projects. Even then, the s_u(yield) measured by subjecting a limited number of undisturbed samples to a particular mode of shear (e.g., triaxial compression, triaxial extension or direct simple shear) will not represent the in-situ liquefaction-triggering behavior of the entire soil layer. This is because of the natural heterogeneity and variability of in-situ cohesionless soils and the complex loading conditions present in the field. On the other hand, although numerical analyses (e.g., finite element or finite difference analyses) with advanced soil constitutive models (Method B) can replicate a wide range of loading conditions, it is difficult to apply or validate such analyses even with the best-documented cases. This is because of the difficulties and uncertainties involved with the selection and calibration of the soil constitutive model, the complex input parameters, and the loading conditions. A number of advanced laboratory shear tests on undisturbed soil samples would be required to obtain the calibration parameters for the soil constitutive model, compromising the feasibility of this method for routine liquefaction-triggering analyses.

Accordingly, empirical correlations with the in-situ Standard Penetration Test (SPT) blow count, $(N_1)_{60}$, or Cone Penetration Test (CPT) tip resistance, q_{c1} (Method C), are often used for estimating the in-situ triggering strength because of their simplicity, convenience, lower costs, and nearly continuous measurements. These correlations, which were established based on past liquefaction flow failures (Mesri, 2007; Olson and Stark, 2003; Stark and Mesri, 1992), fall short of accounting for the fundamental effect of a soil's dilatancy potential to decrease the amount of loss in undrained strength following the triggering of static liquefaction with increasing penetration resistance.