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Energy-based evaluation of liquefaction of fiber-reinforced sand using cyclic triaxial testing

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ABSTRACT

The present study reviews a series of cyclic triaxial tests to investigate the liquefaction characteristics of Babolsar sand reinforced with randomly distributed fibers using an energy-based approach. The effect of fiber content, fiber length, confining pressure, and relative density were studied. The test results revealed that the addition of fibers increased the number of cycles required to liquefaction, resulting in higher cumulative dissipated energy. This accounted for the higher cyclic shear resistance of reinforced sand compared to unreinforced sand. Capacity energy is defined as cumulative dissipated energy to onset of liquefaction. The test results showed that W_{liq} was significantly affected by the fiber inclusion. Comparative studies demonstrated that energy-based method is a good way to evaluate liquefaction potential of fiber-reinforced sands.

1. Introduction

Soil liquefaction has received extensive consideration in geotechnical earthquake engineering in recent decades. Liquefaction leads to the loss of shear resistance caused by generation of excess pore water pressure. It can result in loss of bearing capacity, floatation of embedded structures, ground subsidence, settlement of embankments, and lateral displacement of slopes and retaining walls [1]. The catastrophic nature of this type of failure has prompted much research to evaluate the liquefaction behavior of saturated cohesionless soils caused by cyclic loading (e.g., [2–7]).

Soil reinforcement is an effective and reliable technique for reducing the risk of liquefaction in geotechnical engineering [8–13]. The use of reinforcements to improve the strength of earthen structures dates to ancient times. For example, thatch is a mixture of cohesive soil and straw that has long been a popular building material in many parts of the world (e.g., [14]). It is only within the last few decades, however, that researchers have investigated soil reinforcement techniques using experimental, numerical and analytical approaches (e.g., [15–23]).

The use of randomly distributed fibers as reinforcement shows more satisfactory performance than conventional continuous planar reinforcements (metallic strips, geogrids, and geotextiles). However, limited studies have examined the liquefaction behavior of sandy soils reinforced with randomly distributed fibers under cyclic loading [12,13,24]. Fiber reinforcement can be a promising solution to reduce the risk of liquefaction. This procedure has been adopted in a variety of field applications such as for the construction of roads, embankments, low-rise residential buildings, and slope stabilization.

This study characterized liquefaction resistance of sand-fiber mixtures by means of the energy approach. Even though sand reinforcement with fiber does not propose a new method in geotechnical engineering, research is fast progressing in this attractive area. The test results were employed to develop a simple model that relates the capacity energy to the fiber content, fiber length and confining pressure of the sample. Starting in the late 1970's, several energy-based liquefaction evaluation approaches have been suggested; however, the authors have found no model in the literature that considers the effect of fiber inclusion.

2. Background on energy-based evaluation of liquefaction

Experimental investigation to evaluate earthquake-induced liquefaction behavior of saturated sands is common. Methods to evaluate liquefaction potential of a soil deposit can be categorized as stress-based [25], strain-based [26], and energy-based [27]. The most widely-used method is the stress-based procedure first proposed by Seed and Idriss [25].

The energy approach is an alternative method of liquefaction assessment. Several energy-based methods to evaluate the liquefaction susceptibility of soils have been proposed in the last few decades (e.g.,

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Nomenclature

B	Pore pressure parameter
C_c	Coefficient of gradation
CP	Confining pressure
CSR	Cyclic stress ratio
CTT	Cyclic triaxial test
C_u	Coefficient of uniformity
c_1, c_2. c_3, c_4	Regression coefficients of the capacity energy model
dW	Increment in dissipated energy per unit volume of material
D_r	Relative density
D_{10}	Effective diameter
D_{30}	Particle size (mm) corresponding to 30 passing percentage
D_{50}	Mean grain size
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
EBM	Energy-based liquefaction evaluation method
w_f	Fiber content
FL	Fiber length
G_1	Shear modulus in the first cycle
G_N	Shear modulus at the Nth cycle
G_s	Specific gravity of solids
K	Factor of initial shear stress
N	Number of cycles
N_L	Number of cycles to cause liquefaction
P'_0	Initial mean effective pressure
P'	Mean effective pressure
PET	Polyethylene terephthalate
PWP	Pore water pressure
r_u	Excess pore water pressure ratio
R^2	Determination coefficient
SBM	Stress-based liquefaction evaluation method
SP	Poorly graded sand
$USCS$	Unified soil classification system
ΔW, W	Instantaneous unit energy
W_f	Weight of fibers
W_{liq}	Capacity energy
W_s	Dry weight of the sand
$\gamma_{d.max}$	Maximum dry density
$\gamma_{d.min}$	Minimum dry density
σ'_0	Initial effective confining pressure
σ'_1	Maximum principal effective stress
σ'_3	Minimum principal effective stress
σ'_{h0}	Initial horizontal effective stress
σ'_{v0}	Initial vertical effective stress
τ_{static}	Initial static shear stress

[28–37]). Experimental studies have shown that the cumulative dissipated energy per unit volume of soil (or unit energy) is strongly related to the excess pore water pressure generated during undrained cyclic loading. Unit energy is a useful index for analysis of the cyclic behavior of sands. Cumulative dissipated energy is the cumulative enclosed area of hysteresis loops. The use of unit energy for evaluation of excess pore water pressure is reasonable because it depends on both cyclically-induced shear stress and strain.

Nemat-Nasser and Shokooh [28] developed a mathematical model to explain densification and liquefaction of cohesionless soils using the energy concept. Further efforts to explain the relationship between pore water pressure and the cumulative energy dissipated in the soil were

Table 1

Summary of some of the previous energy-based pore water pressure models with factors of special interest (Jafarian et al. [37]).

Reference	PWP model	Parameter(s)	Soil(s)	Laboratory conditions	Laboratory data
Berrill and Davis [30]	$r_u = \alpha'\left(\frac{\Delta W}{\sigma'_{v0}}\right)^{\beta}$	Calibration parameters: α', β	New Brighton Sand	Stress-controlled, cyclic triaxial tests σ'_0 =50, 100, 150 kPa D_r = 67 to 95%	Simcock et al. [29]
Davis and Berrill [35]	$r_u = 1 - \exp\left(-\alpha\frac{\Delta W}{\sigma'_{v0}}\right)$	Calibration parameter: α	New Brighton Sand	Stress-controlled, cyclic triaxial tests σ'_0 =50, 100, 150 kPa D_r = 67 to 95%	Simcock et al. [29]
Law et al. [32]	$\frac{u_{excess}}{\sigma'_{h0}} = \alpha W_N^{\beta}$	$W_N = F_1(K_c)F_2(D_r)\frac{\Delta W}{\sigma'_{h0}}$ $F_1(K_c) = 1 - \xi\log(K_c)$ $F_2(D_r) = 10^{\varsigma(D_r - 0.7)}$ $K_c = \sigma'_{v0}/\sigma'_{h0}$ Calibration parameters: α, β, ξ, ς	Fujian standard sand	Stress-controlled, cyclic triaxial and hollow cylinder tests Isotropically consolidated: σ'_0 = 50, 100, 150 kPa, D_r = 70% Anisotropically consolidated: σ'_{h0} =100 kPa, K_c = 1.5, 1.75, and 2 D_r = 70%	
Yanagisawa and Sugano [41]	$r_u = \frac{S'_S}{a + bS'_S}$	Calibration parameters: a,b $S'_S = \frac{dW}{P'}$	Toyoura sand	Isotropically consolidated strain-controlled cyclic triaxial and cyclic torsional shear and two-directional cubic shear σ'_0 = 49,196,294,343 kPa D_r = 40,49,81,61,70%	
Wang et al. [42]	$r_u = a\frac{\Delta W}{(P'_0)^n}/\left[1 + b\frac{\Delta W}{(P'_0)^n}\right]$	Calibration parameters: a,b,n	Toyoura sand and Kawasaki clay mixtures	Stress-controlled, cyclic triaxial tests σ'_0 = 98, 196, 392 kPa Fines Content < 35%	Polito [39]
Polito et al. [43]	$r_u = \sqrt{\Delta W/PEC}$	Calibration parameter: PEC	Monterey and Yatesville sand-silt mixtures	Stress-controlled, cyclic triaxial tests $\sigma'_0 \approx$ 100 kPa, D_r = −40 to 120% 0 < Fines Content < 100%	
Jafarian et al. [37]	$r_u = \left(\frac{\alpha^{W/W_{liq}} - 1}{\alpha - 1}\right)^{\beta}$	Calibration parameters: α, β	Toyoura sand	Strain-controlled, cyclic hollow cylinder torsional shear tests P'_0= 55–166 kPa D_r = 29–77% K= 0, 0.15, 0.25, and 0.35 $K = \tau_{static}/P'_0$	

Note: r_u, excess pore pressure normalized by effective stress; ΔW, W, dissipated energy per unit volume of material; dW, increment in dissipated energy per unit volume of material; W_{liq}, Cumulative dissipated energy required for liquefaction onset; σ'_0, initial effective confining pressure; σ'_{v0}, initial vertical effective stress; σ'_{h0}, initial horizontal effective stress; τ_{static}, initial static shear stress; P'_0, initial mean effective pressure; P', mean effective pressure; D_r, relative density.