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Prediction of strain energy-based liquefaction resistance of sand–silt mixtures: An evolutionary approach

Mohammad H. Baziar [a,*], Yaser Jafarian [b], Habib Shahnazari [a], Vahid Movahed [a], Mohammad Amin Tutunchian [a]

[a] School of Civil Engineering, Iran University of Science and Technology, Tehran, Iran
[b] College of Civil Engineering, Semnan University, Semnan, Iran

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ABSTRACT

Liquefaction is a catastrophic type of ground failure, which usually occurs in loose saturated soil deposits under earthquake excitations. A new predictive model is presented in this study to estimate the amount of strain energy density, which is required for the liquefaction triggering of sand–silt mixtures. A wide-ranging database containing the results of cyclic tests on sand–silt mixtures was first gathered from previously published studies. Input variables of the model were chosen from the available understandings evolved from the previous studies on the strain energy-based liquefaction potential assessment. In order to avoid overtraining, two sets of validation data were employed and a particular monitoring was made on the behavior of the evolved models. Results of a comprehensive parametric study on the proposed model are in accord with the previously published experimental observations. Accordingly, the amount of strain energy required for liquefaction onset increases with increase in initial effective overburden pressure, relative density, and mean grain size. The effect of nonplastic fines on strain energy-based liquefaction resistance shows a more complicated behavior. Accordingly, liquefaction resistance increases with increase in fines up to about 10–15% and then starts to decline for a higher increase in fines content. Further verifications of the model were carried out using the valuable results of some downhole array data as well as centrifuge model tests. These verifications confirm that the proposed model, which was derived from laboratory data, can be successfully utilized under field conditions.

1. Introduction

After the disastrous damage observed during the Niigata and Alaska 1964 earthquakes, the liquefaction phenomenon has become the scope of many studies in the field of geotechnical earthquake engineering (e.g., Lee and Fitton, 1968; Seed and Idriss, 1971; Seed et al., 1975). This phenomenon is developed due to an excess pore water pressure, which is generated under undrained loading conditions in soils. In the absence of enough pore pressure dissipation, excess pore pressure can dramatically lose soil shear strength and, thus, devastating failures may occur in the structures. Liquefaction potential assessment is an important task for construction sites, which are susceptible to this phenomenon. Hence, many studies have been performed to enhance the accuracy of prediction in the methods of liquefaction potential assessment.

The most well-known approach of liquefaction potential assessment is the simplified stress-based approach, which was initially developed by Seed and Idriss (1971) and then revised and updated till today (e.g., Idriss and Boulanger, 2006; NCEER, 1997; National Research Council (NRC), 1985; Seed et al., 1975; Youd et al., 2001). In this approach, the average uniform cyclic shear stress is assumed to be representative of irregular stress history in the soil profile. Currently, the simplified stress-based approach is the most recommended approach for routine geotechnical works. Nevertheless, it has some disadvantages and uncertainties such as assumptions regarding the amount of uniform cyclic shear stress, which is imparted to the soil. Seed and Idriss (1971) proposed that 65% of the maximum shear stress was uniform cyclic shear stress, whereas Whitman (1971) proposed a factor of 67% for 20 s of excitation. Furthermore, Ishihara and Yasuda (1972) studied the Niigata earthquake records and offered a factor of 57% for equivalent average shear stress. Green and Terri (2005) also investigated the equivalent cycle concept, which is implemented to convert the random seismic load to an equivalent number of harmonic cycles.

It was experimentally observed that the required amount of cyclic shear strain for the initiation of pore pressure buildup is less affected by initial effective stress and the relative density of the soil as well as soil fabric (Dobry and Ladd, 1980; Kramer, 1996; Mulilis et al., 1975)

* Correspondence to: P.O. Box 16846-13114, Narmak, Tehran, Iran.
Tel.: +98 21 77240450; fax: +98 21 77240398.
E-mail address: baziar@iust.ac.ir (M.H. Baziar).

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Nomenclature

a_{max}	peak ground acceleration
ANN	artificial neural network
C_c	coefficient of curvature
C_u	uniformity coefficient
D_r	relative density
D_{rs}	standardized relative density
D_{50}	mean grain size
FC	percentage of fines ($<$ 0.075 mm)
FCs	standardized fines content
GP	genetic programming
LIFs	linear interpolation functions
Log W	logarithm of W
MAE	mean absolute error
MLR	multiple linear regression
R^2	coefficient of determination
RMSE	root mean squared error
ru	excess pore water pressure ratio
SH	horizontal component of plane movement due to shear waves
TIFs	trigonometric interpolation functions
v_{max}	peak ground velocity
W	capacity energy
σ'_c	initial mean effective confining pressure

and strain history (Dobry and Ladd, 1980; Kramer, 1996). Based on these observations, Dobry et al. (1982) proposed an alternative approach wherein a threshold shear strain is defined that can initialize plastic deformation and the consequent excess pore water pressure. Then, threshold shear strain is compared with the shear strain imparted by cyclic loading. Accordingly, once exciting shear strains exceed the threshold shear strain, excess pore water pressure is generated. The strong relationship between cyclic shear strain and excess pore water pressure, which allows prediction of excess pore water pressure more accurately, is the main advantage of this approach over the stress-based approach (Kramer, 1996). However, the main deficiency of this method is the fact that estimation of cyclic strains is more difficult than that of cyclic shear stress (Seed, 1980).

Irrecoverable plastic deformation of soils under drained conditions, which is accompanied by shear work and energy dissipation, was recognized to be related to excess pore water pressure generation under undrained conditions. Nemat-Nasser and Shokooh (1979) initially demonstrated that the cumulative area enclosed by the stress–strain history of soil during loading, unloading, and reloading is strongly associated with excess pore water pressure buildup. Davis and Berrill (1982) introduced an energy-based approach for liquefaction potential assessment in which the energy content of an earthquake is compared with the amount of dissipated energy required for soil liquefaction, known as "capacity energy". In the energy-based approach, the amount of the energy, which is imparted by an earthquake to the soil deposit is known as "demand energy". Subsequent studies were conducted by several researchers to enhance the capability of this concept in liquefaction potential assessment (e.g., Berrill and Davis, 1985; Davis and Berrill, 2001; Figueroa et al., 1994; Law et al., 1990; Simcock et al., 1983; Towhata and Ishihara, 1985). Furthermore, the participants of the NCEER workshop (Youd et al., 2001) suggested to continue research and development on this potentially useful topic.

Strain energy-based evaluation of liquefaction potential considers effects of strain and stress concurrently unlike the stress or strain-based approaches (Liang, 1995). Furthermore, dissipated strain energy density is capable of accounting for the effects of a complicated stress–strain history on pore water pressure buildup (Towhata, 2008). Dissipated strain energy can be linked to the fundamental earthquake parameters including earthquake magnitude (Gutenberg and Richter, 1956) and site-to-source distance while it considers the entire spectrum of ground motions as opposed to the stress-based approach, which uses only the peak value of ground acceleration (Kayen and Mitchell, 1997; Liang, 1995).

A systematic strain energy-based procedure for liquefaction potential assessment can be summarized in the following steps: (1) Estimation of strain energy demand, which is equal to the cumulative area bounded by the hysteresis stress–strain loops constructed due to earthquake loading in the field. (2) Estimation of capacity energy, which is equal to the cumulative area bounded by hysteresis stress–strain loops from the initiation of cyclic loading up to liquefaction onset. This quantity can be evaluated experimentally by conducting cyclic tests on the soil samples or empirically using the field performance of liquefiable sites. However, empirical estimation of capacity energy is difficult due to the lack of strain energy-based field information. (3) Comparison between the demand and the capacity energies for the evaluation of liquefaction potential (factor of safety).

The current study aims to propose a relationship for predicting the capacity energy of sand–silt mixtures based on a wide-ranging database of laboratory tests conducted during previous studies. This database contains 399 cyclic tests: 275 cyclic triaxial tests (Arulmoli et al., 1992; Green, 2001; Kanagalingam, 2006; Polito, 1999), 116 cyclic torsional shear tests (Liang, 1995; Rokoff, 1999; Tao, 2003; Towhata and Ishihara, 1985), and 8 cyclic simple shear tests (Arulmoli et al., 1992). A great part of this database (278 data) was previously reported and used by Baziar and Jafarian (2007) and the rest is presented in Table A1.

Genetic programming, which is a powerful tool for pattern recognition and data interpretation, was employed in this study to present an explicit predictive equation for the capacity energy of liquefiable soils. In addition, a parametric study was performed to investigate the behavior of the proposed model under various conditions. Model behavior is confirmed by comparing the results of the parametric study and those observed in experimental works. The data recorded at various instrumented sites were employed to verify the model under field conditions. This verification was carried out according to the fact that the demand energy imparted to a liquefied site through seismic motion was larger than its capacity energy. A special consideration is made for the Wildlife downhole array site during the Superstition Hills 1987 earthquake. The proposed model successfully works for this site since its performance is in agreement with those observed in reality.

2. Review of previous capacity energy models

There are various studies that have focused on the strain energy-based estimation of soil liquefaction and capacity energy. A great part of these studies involves the energy-based pore water pressure models (e.g., Hsu, 1995; Polito et al., 2008).

Results of undrained cyclic tests can be employed for direct development of relationships between capacity energy and characteristics of soil and cyclic load. Several comprehensive studies were conducted at Case Western Reserve University and the effects of various variables and properties of soil (e.g., relative