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RESEARCH PAPER

Energy-based numerical models for assessment of soil liquefaction

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Abstract This study presents promising variants of genetic programming (GP), namely linear genetic programming (LGP) and multi expression programming (MEP) to evaluate the liquefaction resistance of sandy soils. Generalized LGP and MEP-based relationships were developed between the strain energy density required to trigger liquefaction (capacity energy) and the factors affecting the liquefaction characteristics of sands. The correlations were established based on well established and widely dispersed experimental results obtained from the literature. To verify the applicability of the derived models, they were employed to estimate the capacity energy values of parts of the test results that were not included in the analysis. The external validation of the models was verified using statistical criteria recommended by researchers. Sensitivity and parametric analyses were performed for further verification of the correlations. The results indicate that the proposed correlations are effectively capable of capturing the liquefaction resistance of a number of sandy soils. The developed correlations provide a significantly better prediction performance than the models found in the literature. Furthermore, the best LGP and MEP models perform superior than the optimal traditional GP model. The verification phases confirm the efficiency of the derived correlations for their general application to the assessment of the strain energy at the onset of liquefaction.

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1. Introduction

Soil liquefaction is one of the most complex phenomena studied in geotechnical earthquake engineering. Liquefaction is commonly considered as a specific feature of loose and saturated sandy soils. Liquefaction usually occurs when the pore water pressure increases to carry the overburden stress. Therefore, soil immediately loses most of its strength leading to extreme deformations, flow of water and suspension of sediment (Darve, 1996). Numerous studies have focused on analyzing the liquefaction phenomenon since it is one of the major sources for failures of critical structures. Several procedures are developed to evaluate the liquefaction potential in the field. The available liquefaction evaluation procedures are categorized into three main groups (Green, 2001): (1) stress-based procedures, (2) strain-based procedures, and (3) energy-based procedures. The stress-based procedure (Seed and Idriss, 1971) is the most widely-used liquefaction assessment method. This approach is mainly empirical and based on laboratory and field observations. The stress method has continually been refined as a result of newer studies and increase in the number of liquefaction case histories (e.g., Youd et al., 2001). The main criteria in the stress-based procedure are the shear stress level and number of cycles. Despite the continuous revisions and extensions of the stress-based method, the uncertainty on the subject of random loading still exists (Green, 2001; Baziar and Jafarian, 2007). Dobry et al. (1982) proposed the strain-based procedure as an alternative to the empirical stress-based procedure. This method was derived from the mechanics of two interacting idealized sand grains and then generalized for natural soil deposits (Green, 2001; Baziar and Jafarian, 2007).

The energy concept has widely been used in the theories of elasticity and plasticity, potential energy surface for constitutive law and energy principles (Desai and Siriwardane, 1984). The basic elements of both the stress and strain methods are incorporated in the formulation of the energy-based method. In this method, the amount of total strain energy at the onset of liquefaction is obtained from laboratory testing or field recorded data. In a typical cyclic (triaxial or simple shear) laboratory test, the stress, strain and pore pressure time histories are recorded. Hysteresis loops can be generated from these stress and strain time histories. Fig. 1 illustrates a typical hysteresis loop from a typical stress-controlled cyclic triaxial test. The strain energy for each cycle of loading is equivalent to the area inside the hysteresis loop (Ostadan et al., 1996). In other words, this area represents the dissipated energy per unit volume of the soil mass (Green, 2001). This is based on the idea that during deformation of cohesionless soils under dynamic loads part of the energy is dissipated into the soil (Nemat-Nasser and Shokooh, 1979). The instantaneous energy and its summation over time intervals are computed until the onset of liquefaction. The summation of the energy at this time is used as the measures of the capacity of the soil sample against initial liquefaction occurrence in terms of the strain energy (capacity energy).

To predict liquefaction, this strain energy is compared with the strain energy imparted by earthquake to the sand layer during the seismic design event. The experiments revealed that the build-up of the excess pore pressure is proportional to the total strain energy in all loading cycles up of the initial liquefaction. This observation has

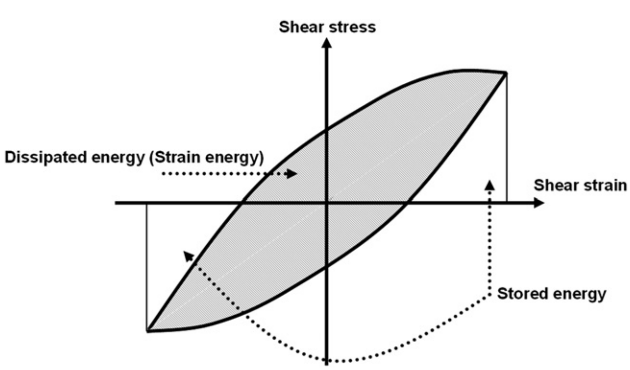

Figure 1 A typical hysteresis shear stress–strain loop (Green, 2001).

prompted the formulation of the energy-based approach. Since the late 1970s, numerous energy-based procedures have been proposed for evaluating the liquefaction potential of soil deposits (Liang, 1995; Green, 2001). The use of strain energy concept is a logical step in the evolution of liquefaction evaluation of soils for two reasons (Baziar and Jafarian, 2007). The first reason is that seismologists have long been quantifying the energy released during earthquakes and have determined simple correlations with common seismological parameters. The second reason is that some pioneer researchers developed functional relationships correlating the energy density dissipated into the cohesionless soils to the pore pressure build-up (Nemat-Nasser and Shokooh, 1979).

The energy-based approach has several advantages in comparison with the other existing methods to evaluate the liquefaction potential of soils. Some of the most important advantages of this approach are well summarized by Voznesenskya and Nordal (1999) and Dief and Figueroa (2001). However, the complexity of the liquefaction behavior suggests the necessity of developing more comprehensive models to assess it.

Genetic programming (GP) (Koza, 1992; Banzhaf et al., 1998) is a developing subarea of evolutionary algorithms inspired from the Darwin's evolution theory. GP may generally be defined as a specialization of genetic algorithms (GA) where the solutions are computer programs rather than binary strings. Linear genetic programming (LGP) (Brameier and Banzhaf, 2007) is a new branch of GP. LGP operates on programs represented as linear sequences of instructions of an imperative programming language (Brameier and Banzhaf, 2007). Multi expression programming (MEP) (Oltean and Dumitrescu, 2002) is another recent variant of GP that uses a linear representation of chromosomes. The modeling capabilities of LGP and MEP have been shown by researchers (Oltean and Grosşan, 2003; Baykasoglu et al., 2008). In contrast with traditional GP and other soft computing tools, applications of LGP and MEP in the field of civil engineering are new and restricted to a few areas (Alavi et al., 2010a; Gandomi et al., 2010a; Alavi and Gandomi, 2011).

In this research, the LGP and MEP techniques were utilized to obtain generalized relationships between the energy per unit volume dissipated during liquefaction and the soil initial parameters. A traditional GP analysis was performed to benchmark the LGP and MEP-based correlations. Further, the prediction performance of the derived correlations was compared with that of different models found in the literature.

2. Review of energy-based liquefaction evaluation models

Contrary to the stress-based and strain-based approaches, the energy-based procedures use various measures of energy as the base parameters to quantify demand (the load imparted to the soil by the earthquake) and capacity (the demand required to induce liquefaction). The energy-based liquefaction evaluation procedures are mainly grouped into approaches developed using earthquake case histories, and those developed from laboratory data (Green, 2001).

2.1. Analytical and empirical models

Numerous researches are conducted to develop energy-based models for the evaluation of the liquefaction potential (Towhata and Ishihara, 1985; Liang et al., 1995). The necessity to obtain