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A worldwide SPT-based soil liquefaction triggering analysis utilizing gene expression programming and Bayesian probabilistic method

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ABSTRACT

In this context, two different approaches of soil liquefaction evaluation using a soft computing technique based on the worldwide standard penetration test (SPT) databases have been studied. Gene expression programming (GEP) as a gray-box modeling approach is used to develop different deterministic models in order to evaluate the occurrence of soil liquefaction in terms of liquefaction field performance indicator (*LI*) and factor of safety (F_s) in logistic regression and classification concepts. The comparative plots illustrate that the classification concept-based models show a better performance than those based on logistic regression. In the probabilistic approach, a calibrated mapping function is developed in the context of Bayes' theorem in order to capture the failure probabilities (P_L) in the absence of the knowledge of parameter uncertainty. Consistent results obtained from the proposed probabilistic models, compared to the most well-known models, indicate the robustness of the methodology used in this study. The probability models provide a simple, but also efficient decision-making tool in engineering design to quantitatively assess the liquefaction triggering thresholds.

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1. Introduction

There are two general attitudes towards liquefaction potential assessment, namely deterministic and probabilistic approaches. Deterministic approach is currently one of the most commonly used approaches to assess soil liquefaction based on semi-empirical correlations between the stimulating and the capacity factors. In this approach, when the seismic demand factor is equal to or greater than the liquefaction resistance capacity factor, liquefaction is expected to occur. The stress method, which was first developed nearly four decades ago, has gained great popularity among the geotechnical engineers for the soil liquefaction potential evaluation. Following the catastrophic earthquakes in Alaska and Nigata in 1964, Seed and Idriss (1971) proposed a draft guideline referred to as stress simplified method, which has been revised several times since then by retaining the original framework (Seed and De Alba, 1985; Youd et al., 2001; Cetin et al., 2004; Idriss and Boulanger, 2004, 2008, 2010; Boulanger and Idriss, 2014). Recently, Sassa and Yamazaki (2017) presented a new simplified prediction and assessment procedure taking into account the waveform and duration of earthquake. They used the concept of effective number of waves and did a quite number of liquefaction tests and statistical analyses to validate their method. Despite the popularity of the simplified evaluation method, due to the inability of these methods in considering the uncertainties through the calculations, the liquefaction probability (P_L) cannot be investigated accurately (Juang et al., 1999, 2006, 2012). Since it is difficult to choose a specific value for the factor of safety (F_s) which has a poor physical interpretation of the soil liquefaction phenomenon (Juang et al., 1999), probabilistic and more intelligent powerful techniques need to be employed to find the factor of safety and also to develop probabilistic models to determine the liquefaction probability for a specific F_s value. Thus, in recent years, using the probabilistic methods to provide boundary curves separating liquefaction and non-liquefaction local data is taken into account, and

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comprehensive researches have been performed by the geotechnical experts in order to develop a relationship between dynamic soil properties and liquefaction resistance. Currently, soft computing techniques and evolutionary algorithms have found their way into various engineering branches among which civil engineering is not an exception (Ashrafi et al., 2010; Jalal and Ramezanianpour, 2012; Jodaei et al., 2012, 2013; Jalal et al., 2013; Garmsiri and Jalal, 2014; Jalal, 2015; Fathi et al., 2015).

Hanna et al. (2007) established a neural network model for evaluating the liquefaction potential in sandy soil deposits based on Turkey and Taiwan earthquake databases, taking into account 12 dynamic and soil parameters. They proposed a general regression neural network (GRNN) model which propounded a complex relationship between soil and dynamic parameters. The accuracy of the prediction model was verified by comparing the GRNN model results against those of the simplified methods. Das and Muduli (2011) used Chi–Chi earthquake data to investigate the soil liquefaction potential based on genetic programming (GP). They compared the results of their models to the other existing static approaches. Kayadelen (2011) utilized gene expression programming (GEP) and neuro-fuzzy (ANFIS) to capture liquefaction potential of soils based on 569 published databases of past earthquakes. They obtained complex relationships between the dynamic properties of soil and liquefaction potential. Their main purpose was to present a new approach based on GEP and ANFIS for predicting the factor of safety against liquefaction occurrence. They considered the factor of safety as an output and the other parameters (e.g. standard penetration test (SPT) blow counts, fines content percentage, effective stress, cyclic stress ratio, and internal friction angle) as inputs. They explained that these modeling techniques were relatively acceptable in anticipating liquefaction hazards and can establish a complicated relationship among soil parameters and liquefaction factors. Several methods for evaluating the liquefaction potential of sandy soils have been suggested, among which the deterministic analysis has been widely used among the geotechnical experts due to its simplicity. Although the factor of safety of soils can be determined utilizing deterministic methods by applying the certain and non-dispersion parameters, facts such as anisotropic and non-uniform nature of soils, uncertainties in the seismic parameters, mismatch between the employed assumptions in modeling and the in situ conditions (model uncertainty), as well as human and instrumental errors, cause unreliable results for these methods. Therefore, the factor of safety may not be a good criterion for judging the liquefaction occurrence. In deterministic approach, establishment of exact correlation between the probability of liquefaction (P_L) and the factor of safety is not possible. In order to solve these problems, probabilistic evaluation of liquefaction is proposed, in which the degree of conservatism can be quantified in terms of P_L.

In the current study, a liquefaction triggering analysis is carried out using the deterministic and probabilistic methods. GEP as a genetic algorithm (GA)-based methodology is utilized to develop models for evaluating liquefaction potential in terms of liquefaction field performance indicator (*LI*) and factor of safety (F_s) based on deterministic method in two different concepts (e.g. logistic regression and classification). The comparative plots show that the results of GEP-based models are in good agreement with those based on the more commonly used approaches, which confirm the ability of the GEP in predicting soil liquefaction potential. The calibrated F_s-P_L probability models are derived through probabilistic evaluation of liquefaction potential according to the Bayesian updating technique to interpret the probability of liquefaction occurrence simplicity in terms of lacking knowledge of the uncertainties.

2. Methods of analysis

2.1. Deterministic method

Comparison of the earthquake induced cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR) is the basic analysis criterion in the liquefaction potential evaluation. The CSR is denoted as (Seed and Idriss, 1971):

$$CSR_{7.5} = 0.65\frac{a_{\max}}{g}\frac{\sigma_v}{\sigma'_v}r_d/(MSFK_\sigma K_\alpha) \tag{1}$$

where $CSR_{7.5}$ is the CSR adjusted to a benchmark earthquake of moment magnitude of 7.5; $a_{\max}$ is the peak horizontal ground surface acceleration; g is the ground acceleration; σ'_v and σ_v are the effective and total vertical stresses at the studied depth, respectively; r_d is the depth-dependent shear stress reduction coefficient; *MSF* is the magnitude scaling factor; K_σ is the overburden correction factor for CSR; and K_α is the static shear stress correction factor. The values of K_α for all of effective pressures less than 3 atm (1 atm = 101 kPa) are obtained according to Fig. 1, where the soil is divided into three areas based on D_r and $(N_1)_{60}$ of soil. In Fig. 1, $(N_1)_{60}$ is the corrected SPT blow count, and D_r is the relative density. In this plot, the value of α is equal to the static active shear stress applied to horizontal plane, which corresponds to the vertical effective stress in that plane.

Several amendments to r_d have been proposed by various researchers. In this study, r_d is calculated based on the relationship presented by Idriss and Boulanger (2010):

$$r_d = \exp[\alpha(z) + \beta(z)M_w] \tag{2}$$

$$\alpha(z) = -1.012 - 1.126\sin(5.133 + z/11.73) \tag{3}$$

$$\beta(z) = 0.106 + 0.118\sin(5.142 + z/11.28) \tag{4}$$

where M_w is the moment magnitude, and z is the depth (m).

MSF can be defined as

$$MSF = -0.058 + 6.9\exp(-M_w/4) \le 1.8 \tag{5}$$

The cyclic loading test results demonstrate that the soil susceptibility to the cyclic liquefaction will rise by increasing the overburden effective stress. In order to consider a nonlinear

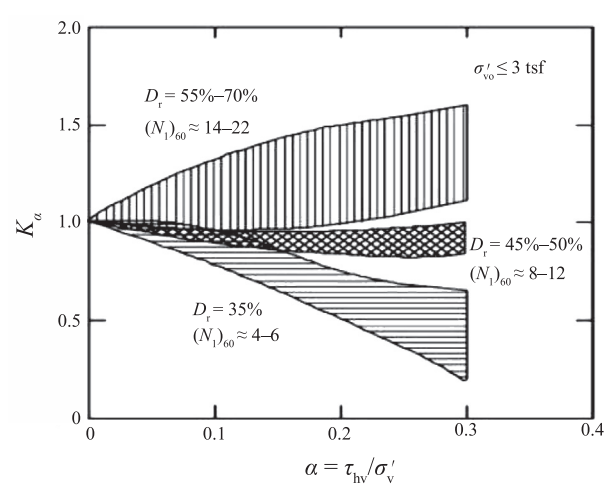

Fig. 1. Suggested K_α for effective pressures less than 3 atm (1 tsf = 96 kPa).

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