Engineering Applications of Artificial Intelligence 45 (2015) 464–472

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

New Gene Expression Programming models for normalized shear modulus and damping ratio of sands

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
1 July 2015
Accepted 31 July 2015
Available online 28 August 2015

Keywords:
Normalized shear modulus
Damping ratio
Gene Expression Programming
Sands

ABSTRACT

As the most important dynamic properties of soils, shear modulus and damping ratio are two parameters employed to solve problems including seismic site response evaluation, dynamic analyses and equivalent-linear models. The work presented in this paper proposes two models for evaluation of the normalized shear modulus and two additional models for evaluation of the damping ratio of sands through Gene Expression Programming (GEP). The data used in the modeling entails the valid experimental results obtained from previous researchers. As compared to the secondary models, the first two models are more accurate with larger equation length. The parameters taken into account as model inputs consisted of shear strain, mean effective confining pressure, and void ratio. In order to evaluate the performance and accuracy, the proposed models were processed through several statistical measures such as Mean Square Error (*MSE*), Root Mean Square Error (*RMSE*) and coefficient of determination (R^2). Furthermore, the relative difference between predicted and measured values was calculated, which suggested that the models were desirably accurate. Finally, the model outputs were compared against other studies, the results of which demonstrated that the proposed models are capable of estimating the dynamic parameters of sands more accurately.

1. Introduction

The nature and distribution of earthquake hazards are extremely influenced by soil response under cyclic loading. To a large extent, such a response is controlled by the dynamic characteristics of the soil. Dynamic characteristics of geotechnical materials are often represented by shear modulus (G) and damping ratio (D). In order to examine the effects of the dynamic loads on civil engineering systems, it is essential to properly understand soil behavior, attain precision measurements and quantitative models describing the soil dynamic characteristics (Kramer, 1996). Moreover, the description and identification of soil are necessary prior to carrying out any geotechnical design. On the other hand, understanding the dynamic properties of soil allows a geotechnical engineer to more accurately evaluate and monitor the soil parameters. The dynamic response of soils is employed to solve several problems including slope stability, soil-structure interaction, machinery vibrations and seismic stability of structures under sea wave, wind, traffic and other dynamic loads. The relations between soil dynamic parameters are crucial for solving the abovementioned problems. Since there is a wide range of equations associated with the soil damping ratio and shear modulus, the selection of an equation greatly affects the results of engineering analyses. For that reason, the newest and most accurate methods need to be employed so as to achieve minimum error margin.

The experimental evaluation of the shear modulus and damping ratio of soils have so far been measured by numerous researchers through various devices such as Resonant Column (RC) (Hardin and Drnevich, 1972a; Khan et al., 2008, 2011; Senetakis et al., 2012; Wilson, 1988), Cyclic Triaxial (CT) (Khan et al., 2011; Yasuda and Matsumoto, 1993; Yoshimi et al., 1984), Cyclic Simple Shear (CSS) (Lanzo et al., 1997), cyclic simple Torsional Shear (TS) (Yasuda and Matsumoto, 1993) and combined device Resonant Column Torsional Shear (RCTS) (Darendeli, 2001; Lee, 2000; Menq, 2003). The significance of parameters contributing to the dynamic properties of soils has been reported by Hardin and Drnevich (1972b) and Darendeli (2001). The most important parameters contributing to shear modulus include shear strain (γ), mean effective confining pressure ($\overline{\sigma}'$) and soil conditions (i.e., D_{50}, etc.) as well as parameters contributing to damping ratio, not to mention the number of loading cycles (N) (Darendeli, 2001; Hardin and Drnevich, 1972b; Ishibashi and Zhang, 1993; Iwasaki et al., 1978; Kokusho, 1980; Stokoe et al., 1999).

Iwasaki et al. (1978) and Kokusho (1980) studied the effect of void ratio, effective confining pressure and shear strain percentage on the dynamic parameters of sands. Moreover, Seed et al. (1986) assessed through field and laboratory experiments the impact of mean

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http://dx.doi.org/10.1016/j.engappai.2015.07.022
0952-1976/

effective confining pressure, relative density and shear strain percentage on granular soils. Ishibashi and Zhang (1993) collected different laboratory data for conducting dynamic evaluation of shear modulus and damping ratio in non-plastic sands and high-plasticity clays. They offered a series of equations for soil shear modulus and damping ratio as functions of mean effective confining pressure, plasticity index and shear strain. Their equations are valid within confining pressures between 0.2 and 10 atms (Darendeli, 2001). Darendeli (2001) examined the effect of soil type conditions, loading frequency, loading cycles (f and N) and plasticity index (PI) for a broad range of soils including gravel, sand and clay at various plasticity rates. Zhang et al. (2005) introduced several equations for estimating normalized shear modulus and damping ratio of Quaternary, Tertiary and older, and residual/saprolite soils. The parameters used in equations proposed for shear modulus include shear strain range, plasticity index and confining pressure, where the proposed equation for damping ratio comprises a term as a minimum damping ratio added to a polynomial function of normalized shear modulus. In all the mentioned studies, two or three of these parameters (e, $\overline{\sigma}'$ and $\gamma\%$) have been introduced as contributing factors to dynamic properties of sands.

Nonlinear optimization methods have been used in several problems. In the remediation of soil contamination (Chen et al., in press), an optimization system for surfactant-enhanced aquifer remediation has been developed by Qin et al. (2007). As a powerful method for nonlinear optimization, Genetic Algorithm has been successfully utilized in civil engineering analyses, particularly geotechnical engineering such as numerical modeling of stress–strain behavior under cyclic loading (Shahnazari et al., 2010), liquefaction-induced displacement (Javadi et al., 2006), dynamic soil properties (Cevik and Cabalar, 2009) and simulation of static soil shear strength (Mousavi et al., 2011). The main objective of this study is to provide new mathematical models based on GEP, which can predict normalized shear modulus (G/G_{max}) and damping ratio ($D\%$) of sands more accurately with minimum error margin, as compared to previous models. The parameters e, $\overline{\sigma}'$ and γ were considered as inputs of the proposed models. Through mathematical models from several researchers including Darendeli (2001), Rollins et al. (1998) and Ishibashi and Zhang (1993) and published experimental data, the validity and performance of these models were compared and demonstrated to be more accurate than previous models. Using the collected data, the accuracy of Darendeli (2001), Rollins et al. (1998) and Ishibashi and Zhang (1993) models was also assessed in the estimation of the normalized shear modulus and damping ratio of sands.

2. Datasets

The datasets used in this study entailed the valid experimental findings obtained by various researchers which are an outcome of several devices including Resonant Column (RC) (Moayerian, 2012; Saxena and Reddy, 1989; Senetakis et al., 2013), Cyclic Triaxial (CT) (Kokusho, 1980, 2004; Rollins et al., 1998), Cyclic Simple Shear (CSS) (Anderson, 2003; D'Elia et al., 2003; Lanzo et al., 1997), cyclic simple Torsional Shear (TS) (Iwasaki et al., 1978; Uthayakumar, 1992) and combined device Resonant Column Torsional Shear (RCTS) (Anderson, 2003; Darendeli, 2001; Lee, 2000; Menq, 2003; Stokoe et al., 2003). The number of data points for the normalized shear modulus (G/G_{max}) and damping ratio was 937 and 647, respectively. The collected dataset is more complete than the previously published works and as described in the following sections, the results indicate that this dataset is enough to produce reasonable and accurate models.

These datasets were categorized into two classes of training and testing, containing 80% and 20% of the total data, respectively. As for the training dataset, the best equation is selected based on data consistency, the validity and performance of which is then examined through subsets of testing data. Such data categorization is done in a way that both classes are as much approximate to one another as possible in terms of statistical measures (i.e. maximum, minimum, mean and standard deviation). The results of the statistical measures from the data used in this study have been illustrated in Table 1.

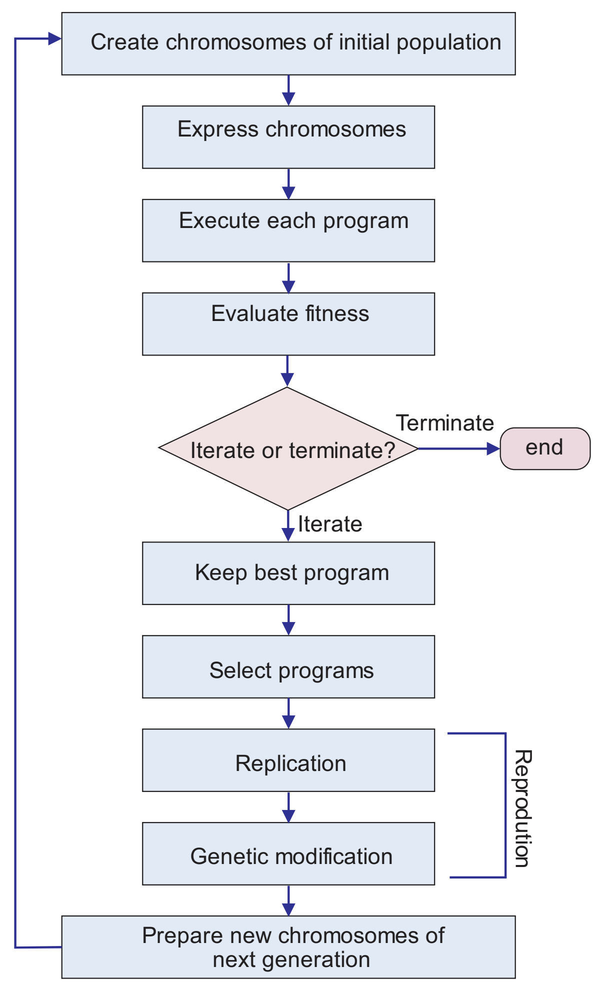

Fig. 1. The flowchart of Gene Expression Programming (Ferreira, 2004).

Table 1
The range of statistical measures for data used in the modeling.

Statistical parameters	Parameters for G/G_{max} models				Parameters for damping ratio models			
	G/G_{max}	γ %	$\overline{\sigma}'$ (kPa)	e	$D\%$	γ %	$\overline{\sigma}'$ (kPa)	e
Max	1.01	3.453	3314	0.886	25.24	0.769	3314	0.69
Min	0.030	0.00002	21	0.41	0.101	0.00002	21	0.41
Mean	0.825	0.054	381.79	0.586	3.743	0.023	479.73	0.569
Standard deviation	0.226	0.27	641.05	0.096	4.418	0.057	742.80	0.076