Computers & Geosciences 50 (2013) 84–94

Contents lists available at SciVerse ScienceDirect

Computers & Geosciences

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

Evolutionary-based approaches for determining the deviatoric stress of calcareous sands

Habib Shahnazari [a,*], Mohammad A. Tutunchian [a], Reza Rezvani [a], Fatemeh Valizadeh [b]

[a] School of Civil Engineering, Iran University of Science and Technology, Narmak, PO Box 16765-163, Tehran, Iran
[b] School of Engineering, Tarbiat Modares University, PO Box 14115-179, Tehran, Iran

ARTICLE INFO

Article history:
Received 3 April 2012
Received in revised form
6 July 2012
Accepted 9 July 2012
Available online 20 July 2012

Keywords:
Calcareous sands
Dataset
Modeling
Genetic programming
Triaxial experiments

ABSTRACT

Many hydrocarbon reservoirs are located near oceans which are covered by calcareous deposits. These sediments consist mainly of the remains of marine plants or animals, so calcareous soils can have a wide variety of engineering properties. Due to their local expansion and considerable differences from terrigenous soils, the evaluation of engineering behaviors of calcareous sediments has been a major concern for geotechnical engineers in recent years. Deviatoric stress is one of the most important parameters directly affecting important shearing characteristics of soils. In this study, a dataset of experimental triaxial tests was gathered from two sources. First, the data of previous experimental studies from the literature were gathered. Then, a series of triaxial tests was performed on calcareous sands of the Persian Gulf to develop the dataset. This work resulted in a large database of experimental results on the maximum deviatoric stress of different calcareous sands. To demonstrate the capabilities of evolutionary-based approaches in modeling the deviatoric stress of calcareous sands, two promising variants of genetic programming (GP), multigene genetic programming (MGP) and gene expression programming (GEP), were applied to propose new predictive models. The models' input parameters were the physical and in-situ condition properties of soil and the output was the maximum deviatoric stress (i.e., the axial-deviator stress). The results of statistical analyses indicated the robustness of these models, and a parametric study was also conducted for further verification of the models, in which the resulting trends were consistent with the results of the experimental study. Finally, the proposed models were further simplified by applying a practical geotechnical correlation.

1. Introduction

In 1968, a very large pile displacement occurred during a pile driving project on the Lavan Petroleum platform in the Persian Gulf. This was the first issue with calcareous deposits observed by engineers (McClelland (1988)). Since then, many similar construction problems in calcareous deposits, such as low resistance against pile driving, low bearing capacity, and high particle crushing potential have been reported by different researchers (Wang et al., 2011; Brandes, 2011).

Carbonate sediments have been observed in temperate and tropical areas near important hydrocarbon industries and petrochemical reserves (e.g., the Persian Gulf of Iran, Hawaiian Islands, Puerto Rico, Republic of Ireland, and Australia). Approximately 40% of ocean beds are covered by such carbonate deposits (Holmes, 1978). Carbonate sediments are mainly formed by the skeletal remains of marine organisms. Therefore, a wide variety of engineering properties can be found in these soils due to different locations and fauna that contribute to their formation. Therefore, it has been complicated to predict the geotechnical properties and mechanical behavior of calcareous soils (Kaggwa et al., 1988; Kaggwa, 1988; King and Lodge, 1988; Airey, 1993; Hassanlourad et al., 2008, 2011; Dehnavi et al., 2010; Wang et al., 2011). Research over the past 40 years has also shown fundamental differences in mechanical characteristics of calcareous soils compared to terrigenous noncarbonated soils (Datta et al., 1982; Coop, 1990; Celestino and Mitchell, 1983; Brandes, 2011; Rezvani et al., 2011).

Due to the large range of physical properties in calcareous soils, the estimation of engineering parameters such as deviatoric stress is associated with some degree of uncertainty. However, performing experimental studies is sometimes necessary. Experimental investigations also have drawbacks such as the difficulty of obtaining undisturbed samples, the use of expensive and time-consuming testing procedures, and the need for advanced laboratory testing equipments such as a triaxial apparatus. Data mining and pattern recognition techniques can help to solve this problem. These techniques can be used to develop numerical correlations based

* Corresponding author. Tel.: +98 21 73913128.
E-mail addresses: hshahnazari@iust.ac.ir (H. Shahnazari), amin@iust.ac.ir (M.A. Tutunchian), r_rezvani@iust.ac.ir (R. Rezvani), f.valizadeh@modares.ac.ir (F. Valizadeh).

0098-3004/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cageo.2012.07.006

Nomenclature

GP	genetic programming
MGP	multigene genetic programming
GEP	gene expression programming
e_{max}	maximum void ratio
e_{min}	minimum void ratio
e_{max}-e_{min} or Δe	void ratio range
C_u	uniformity coefficient
C_c	coefficient of curvature
φ_{max}	maximum friction angle
R^2	coefficient of determination
RMSE	root mean square error
MAE	mean absolute error
q	deviatoric stress
q_{max}	maximum deviatoric stress
CD	consolidated drained triaxial test
σ'_3	effective confining pressure
σ'_1	effective axial stress

on experimental results (from the literature) and propose predictive formulae for practical engineering applications.

Modeling the full stress–strain behavior of calcareous soils can be useful and aid in determining the maximum deviatoric stress. Some studies such as Javadi and Rezania (2009a, 2009b), Cabalar and Cevik (2011), and Johari et al. (2011) have used soft computing techniques to simulate triaxial tests results. This study focused on modeling the maximum deviatoric stress of calcareous sands due to unavailability of full stress-strain behaviors of some data obtained from the literature. The maximum deviatoric stress is an important engineering parameter for the evaluation of stress-strain theories of soils. For instance, it is one of the chief modeling parameters of the "Hyperbolic Model," which is a well-known constitutive model for non-linear elastic geo-materials. The maximum deviatoric stress is also necessary for calculation of the maximum friction angle.

The purpose of this study was to develop evolutionary-based models for prediction of the maximum deviatoric stress. A dataset of experimental triaxial tests on various types of carbonate sands from different locations of the world was gathered from the literature. To extend the data, an experimental investigation was performed on two different calcareous sands. By calculating the statistical properties of the extended database, the database was divided into two statistically consistent subsets, training and testing. The training subset was used to develop novel predictive models for estimation of the maximum deviatoric stress of calcareous sands in drained conditions. The testing subset was employed to measure the accuracy of the developed models.

In this study, two promising variants of genetic programming (GP) were considered to model the maximum deviatoric stress, multigene genetic programming (MGP) and gene expression programming (GEP). Statistical analyses indicated the robustness of the proposed models in terms of the coefficient of correlation (R^2), root mean square error (RMSE) and mean absolute error (MAE). A parametric study was also conducted to investigate the robustness of the new MGP- and GEP-based models. Finally, simpler formulae (with one less input parameter) were obtained by considering a geotechnical relationship between two of the input parameters. All the developed models can be used for estimating the maximum friction angle.

2. Database

The database for this study was created in two phases. The first phase focused on gathering previously published triaxial test results on calcareous sands. In order to extend the database, in the second phase, an experimental study was carried out on two calcareous sands of different origins in the Persian Gulf, Hormuz Island and Bushehr Port. The collected database consisted of 90 experimental triaxial results, 66 triaxial test results from previous studies and 24 test results from the experimental portion of the current research.

The physical properties of calcareous sands, including maximum void ratio (e_{max}), minimum void ratio (e_{min}), average particle size (D_{50}) and uniformity coefficient (C_u), and field condition properties including after consolidation relative density (Dr_{ac}) and effective confining pressure (σ'_3), were used as input parameters, and the maximum deviatoric stress (q_{max}) in drained conditions was used as the output.

It should be noted that the definition of q_{max} is important for the measurement of the maximum deviatoric stress from a deviatoric stress–strain curve. If the observed q_{max} occurs in lower than or equal to 20% strain, then q_{max} is defined as the peak point of the deviatoric stress–strain curve (see curve A in Fig. 1). If the observed maximum deviatoric stress occurs in strains higher than 20%, then q_{max} is considered to be the value of deviatoric stress at 20% strain (see curve B in Fig. 1).

In some triaxial tests, the strength of the sample was increased continuously during loading to high strain values. Many researchers have reported that a very large strain is needed to reach maximum strength in calcareous sands (Brandes, 2011; Coop et al., 2004; Sharma and Ismail, 2006). It has been stated by Sharma and Ismail (2006) that more than 20% axial strain is required in triaxial testing for carbonate soil to mobilize its maximum strength. However, at high axial strain values (more than 20%) the soil sample experiences large deformations, and the results at such a high strain are unreliable for engineering design. Therefore as mentioned above, a deviatoric stress value

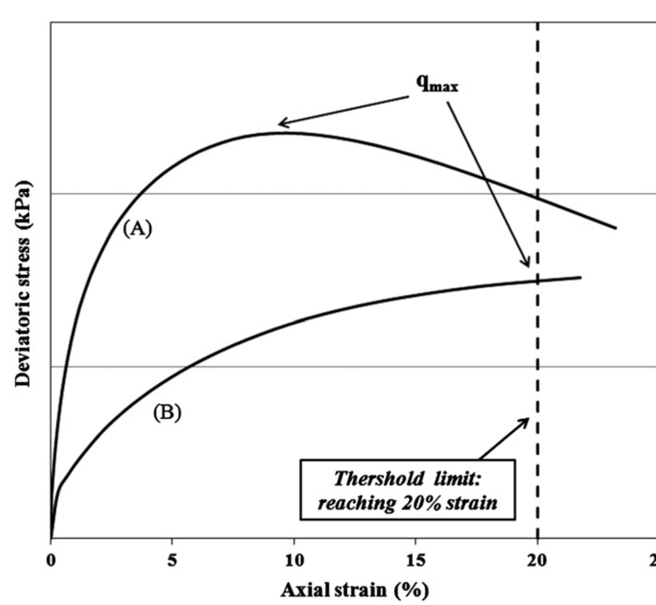

Fig. 1. Definition of maximum deviatoric stress for evolutionary-based modelings.