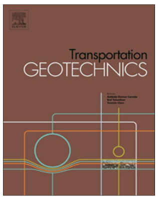
Transportation Geotechnics 4 (2015) 38–49

Contents lists available at ScienceDirect

Transportation Geotechnics

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



Predictive correlations for the compaction of clean sands

Iolli Salvatore [a], Modoni Giuseppe [a,*], Chiaro Gabriele [b], Salvatore Erminio [a]

[a] *University of Cassino and Southern Lazio, Via Di Biasio 43, Cassino 03043, Italy*
[b] *Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand*

ARTICLE INFO

Article history:
Received 15 April 2015
Revised 26 June 2015
Accepted 28 June 2015
Available online 4 July 2015

Keywords:
Compaction
Granular materials
Prediction
Artificial neural networks

ABSTRACT

This paper presents a summary of a laboratory investigation on the compaction of clean sands and a method to predict the density of material as a function of the applied energy. The experiments, carried out on marine quarzitic-calcareous sand systematically assorted to obtain sixteen different grain size distributions, include the determination of minimum and maximum index dry density together with Proctor compaction tests performed with different levels of energy. The outcomes of this experimentation have then been merged with the results of several previous works to form an extensive database used to validate the correlation among the different variables. After an overview of the literature to identify the fundamental factors of compaction and examine the existing correlations, it is suggested to synthetically express the role of all the inherent properties of the soil aggregate i.e. grading, shape and roughness of grain, with the maximum index void ratio (e_{max}). The efficacy of this choice is confirmed by the straight dependency on e_{max} of the compatibility of the material, defined as the difference between maximum and minimum index void ratios ($e_{max} - e_{min}$), and of the void ratios obtained with Proctor tests at fixed levels of energy. In particular, the combined role of e_{max} and compaction energy is quantified by an artificial neural network to formulate a predictive chart giving errors lower than 10%.

Introduction

The artificial compaction of soil is the oldest and most traditional ground improvement technique, being used from ancient ages to improve the performance of earthworks (Kerisel, 1985). From a practical viewpoint, the importance of packing and the associated dilatancy on the deformability and shear resistance of granular materials has been intuitively acknowledged well before the birth of modern geotechnical engineering (Reynolds, 1885). Thereafter, systematic studies, aimed at experimentally evaluating the effectiveness of compaction on site were carried out by Proctor in 1930, who established a procedure to quantify the role of moisture content and compaction energy and to control the density of earth-fills and embankments. Nowadays, there are plenty of constitutive models for sandy materials (e.g. Jefferies, 1993; Chiaro et al., 2013), which include the role of density, but only a few studies attempt to perform an overall prediction of the effects of compaction. Recognition of the role of the inherent characteristics of the soil and quantification of the efficacy of the compaction methods would lead, on the contrary, to a more aware choice of materials, to optimize compaction and to define appropriate in-situ control tests.

In an attempt to identify the factors governing the compactibility of granular materials, Kolbuszewski (1948), Youd (1973) observed that the conventional minimum and maximum index void ratios (e_{min} and e_{max}, respectively) decrease with the uniformity coefficient (C_u) and with the roundness of particles. Miura et al. (1997)

---

[*] Corresponding author.
E-mail address: modoni@unicas.it (M. Giuseppe).

http://dx.doi.org/10.1016/j.trgeo.2015.06.004
2214-3912/

List of symbols

e	void ratio
$e_{\max}$	maximum index void ratio (ASTM D4254, 2014)
$e_{\min}$	minimum index void ratio (ASTM D4253, 2014)
r	radius of the largest sphere fully contained in the grain
x	distance from the center of the largest sphere included in a particle to the most distant edge
C_u	uniformity coefficient
D	particle diameter
D_{50}	mean particle diameter
E_c	compaction energy (kJ/m^3) (ASTM D698-12; ASTM D1557-12)
F	compressibility index $= \frac{e_{\max}-e_{\min}}{e_{\max}}$
R	roundness coefficients
RE	relative error between predicted and experimental void ratio $= \frac{e_p-e_{\exp}}{e_{\exp}}$
γ_d	dry unit weight
$\gamma_{d\ \max}$	maximum index dry unit weight
$\chi^2 = \sum_{i=1}^{K}\frac{(O_i-A_i)^2}{A_i}$	(Pearson, 1948), where O_i is the observed frequency and A_i the expected frequency according to a prescribed distribution

performed a comprehensive laboratory investigation on approximately two hundred granular materials including clean sands, glass beads and lightweight aggregates, and found a reduction of $e_{\max}$ and $e_{\min}$ with the mean grain size (D_{50}) and with C_u. Patra et al. (2010a, 2010b) focused on the role of compaction energy, subjecting 55 different clean sands to a series of Proctor tests with variable levels of energy, and proposed an empirical relationship between density, energy per unit volume and D_{50}. Similar studies have also been performed by Korfiatis and Manicopoulos (1982), Chiaro et al. (2012, 2014).

In spite of their indubitable originality, these studies focus on single aspects (e.g. grading) and often characterize the soil on an empirical basis (e.g. D_{50}), neglecting factors supposed to play an important role (e.g. the heterogeneity of grain size distribution or the shape of grains). The present study, confined to clean sands, is aimed at comprehensively predicting the density of a soil assembly based on its inherent characteristics and to quantify the role of compaction energy. In order to fulfil this objective, numerous sandy materials size were assembled with variable grain size distributions. Then a series of tests was performed; including standard compaction tests for the determination of maximum and minimum index density (ASTM D4254, 2014; ASTM D4253, 2014) and compaction Proctor tests (ASTM D698, 2012; ASTM D1557, 2012) with increasing energy. The test results, combined with relevant data taken from the literature to form a wider casuistry, were used to establish general predictive relationships for the void ratio under different testing conditions.

In comparison with the previous studies, there is an effort to summarize, in a practical yet rational and effective way, the role of the most relevant soil index properties and to enlarge the experimental basis used for validation. With this aim, an artificial neural network (ANN) was implemented to capture the underlying dependency among the different variables, crossing the information from the experimental data and using this relationship to perform future predictions.

Experimental setup

The investigated sand was quarried in Fossanova, Southern Italy, from a series of dunes deposited in a coastal environment. From a mineralogical viewpoint, the grains are composed of quartzitic and calcareous materials present with similar percentage in the soil mass. Before starting the experiments, the sand was oven-dried and sieved (ASTM C136, 2014) in order to remove the material passing the #200 (i.e. 0.075 mm) sieve and to separate five relatively homogeneous classes: M0 ($4.75 > D \geqslant 2.00$), M1 ($2.00 > D \geqslant 1.00$), M2 ($1.00 > D \geqslant 0.42$), M3 ($0.42 > D \geqslant 0.18$), M4 ($0.18 > D \geqslant 0.075$), with the particle diameter (D) expressed in millimeters. Comparing the images scanned with an electron microscope (where a tension of 30 kV was applied at a working distance of 10 mm to produce 5000 times amplification), reported in Fig. 1a, and the classification proposed by Youd (1973) (Fig. 1b), the grain shape varies largely with the diameter from angular (M2) to rounded (M4), possibly due to a higher abrasion of the smaller particles in comparison with the larger ones. According to this classification, the roundness coefficients (R), defined as the ratio between the radius (r) of the largest sphere fully contained in the grain and the distance (x) from the center of this sphere to the most distant edge (Fig. 1c) should vary between 0.20 and 0.50 depending on the composition of the material.

The five homogeneous classes were then combined to produce an additional fourteen mixes with grading curves distributed over a relatively wide range, with D_{50} between 0.12 and 1.40 mm and C_u varying between 1.43 and 11.9. Fig. 2 shows the grain size distribution of all the tested materials, including two of the homogeneous classes (M3 and M4) and the fourteen above mentioned mixes.

The $e_{\min}$ and $e_{\max}$ were determined for each sample in accordance with the ASTM standards D4254-14 and D4253-14. Then, in a second phase, the role of compaction energy was evaluated by performing compaction tests with the standard and modified Proctor equipment (ASTM D698-12; ASTM D1557-12), subdividing the mold into respectively three and five layers and varying the number of blows per layer as listed in Table 1. The table shows that eight compaction tests were performed on each material. However, considering that in the standard Proctor equipment a hammer of 2.49 kg mass falls from 0.305 m, while in the modified tests a hammer of 4.54 kg mass falls from 0.457 m, the same energy $E_c = 1185$ kJ/m^3 is inferred by the standard test with 50 blows/layer and by the modified test with 11 blows/layer.

Unlike plastic soils, moisture content is recognized as not particularly relevant for the compaction of cohesionless materials (Hilf, 1991). However, a preliminary series of tests was conducted on some of the tested soils to verify