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LABORATORY INVESTIGATION ON THE COMPACTABILITY OF CLEAN SANDS

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Dynamic compaction induced by heavy impact or vibratory rollers is acknowledged as the most powerful process to increase the shear resistance and to reduce the deformability of granular materials. Ground improvement techniques based on this principle are currently adopted to build artificial embankments and to enhance the mechanical response of in-situ soils. In an attempt to clarify the role of grain size distribution on the compactability of granular materials, a systematic laboratory experimental investigation was undertaken on a variety of quartz-limestone sands. Samples were prepared with ten different grain size distributions, by mixing three selected uniform sands with variable percentage. Each sample was subjected to different standard and modified Proctor compaction tests where the number of blows per layer was systematically varied (i.e. impact energy). The effectiveness of each "Proctor" technique was evaluated in terms of relative density. Test results indicate that compaction effectiveness is noticeably affected by the heterogeneity of soil composition, while a limited dependency on the water content is observed. A single correlation to predict the dry unit weight of sands combining coefficient of uniformity, specific gravity and compaction energy is proposed. It was found that the proposed correlation can predict the dry unit weight under an arbitrary level of compaction energy with an error of less that 5%.

Keywords: density, compaction, grading, sands

1 Introduction

Dynamic compaction by means of heavy impact or vibratory rollers is a suitable and relatively economical ground improvement technique, particularly effective for increasing the shear resistance and reducing the deformability of loose granular soils. It is currently employed to build man-made embankments, compact backfill of retaining walls, increase the bearing capacity and reduce settlements below foundations, reduce the liquefaction potential of soil in seismic regions. Effectiveness of compaction, i.e. reduction of void ratio or increase of density for assigned input energies, is largely dependent on the grading of soil. Consequently, for each soil type, compaction procedures are optimized by means of preliminary field trials, where compaction is reproduced on smaller soil portions and measurable effects, such as density or SPT index, are related to the input energies (e.g. thickness of layers, number of passes, type and weight of rollers for manmade embankments).

Laboratory investigations provide standard methods to explore the effects of different compaction procedures, offering a good understanding of the sensitiveness of compaction on the adopted procedure (tamping, vibration, static) and on the treatment parameters (e.g. water content, input energies etc.). In view of these considerations, simple correlations to predict quickly the effects of compaction on different granular soil types are of great interest.

For fine-grained materials, several empirical equations can be found to estimate compaction characteristics (i.e. optimum water content and dry density/unit weight) obtained in standard and/or modified Proctor tests as a function of specific soil properties like liquid and plastic limits, specific gravity (G_s), grain size distribution (Basheer, 2001; Gurtug and Sridharan, 2002; Sivrikaya *et al*., 2008; Horpibulsuk *et al*., 2009; Di Matteo *et al*., 2009). On the contrary, only few correlations can be found for coarser granular materials with < 12% fines (e.g. clean sands). Korfiatis and Manikopoulos (1982) developed a formula to predict γ_{dry} obtained with modified Proctor tests based on G_S and on the slope of grain size distribution curve (s) relative to the mean diameter (D_{50}). On the other hand, correlations for predicting the relative density (D_r) of clean sands based on D_{50} and variable input energies have been proposed by Patra *et al*. (2010).

Results of a systematic campaign of laboratory tests on a sandy material assorted with different grain size compositions are herein reported to clarify the role of grain size distribution on the compactability of granular materials. Tests have been performed with different compaction procedures and different energies. Finally, a correlation is proposed to predict γ_{dry} based on the uniformity coefficient (C_u), specific gravity (G_s) and compaction energy (E).

2 Properties of Tested Material

The tested material consists of quartz-limestone sand deposited by marine agents near the coastline in southern Italy (Fossanova). The material, presently used for industrial purposes, has been sieved in order to separate three relatively uniform gradings, named in the following S1 (coarser), S2 (medium) and S3 (finer). Additionally, seven other compositions were prepared by mixing each of the above three materials with the others (with a percentage equal to 33.3 % or 66.6 %). The properties of these ten materials, as obtained from laboratory tests are listed in Table 1, while their grading curves are shown in Figure 1. It is worth noting that materials G1-3 and G3-1 are clearly gap-graded since the fraction geometrically contained between the two components is missing.

For each material, conventional maximum and minimum dry unit weights (γ_{dmax} and γ_{dmin}) were determined by adopting standard laboratory procedures (ASTM D4254 and ASTM D4253). The obtained values are reported on the two triangular plots of Figure 2. The edge of triangles is occupied by the uniform sands (S1, S2 and S3), while the borders and the center represent the admixtures with a position depending on the relative amount of each component.

Table 1. Properties of tested sands.

Sand	Percentage by weight of			G_S	C_U	C_C	e_{max}	e_{min}
	S1	S2	S3					
S 1	100	0	0	2.71 [a]	1.59	0.96	0.800	0.513
S 2	0	100	0	2.69 [a]	1.60	0.96	0.821	0.505
S 3	0	0	100	2.65 [a]	1.60	0.96	0.912	0.555
M 1-2	67	33	0	2.70 [b]	2.58	0.97	0.782	0.478
M 2-1	33	67	0	2.70 [b]	1.84	0.97	0.775	0.484
M 2-3	0	67	0	2.68 [b]	2.60	0.97	0.824	0.522
M 3-2	0	33	67	2.66 [b]	1.86	0.97	0.856	0.525
G 1-3	67	0	33	2.69 [b]	6.12	0.41	0.742	0.416
G 3-1	33	0	33	2.67 [b]	1.86	0.97	0.798	0.477
T 123	33	33	33	2.68 [b]	3.51	0.72	0.764	0.454
Note: [a] from experiments (ASTM D854); [b] calculated from the combination of mixtures								

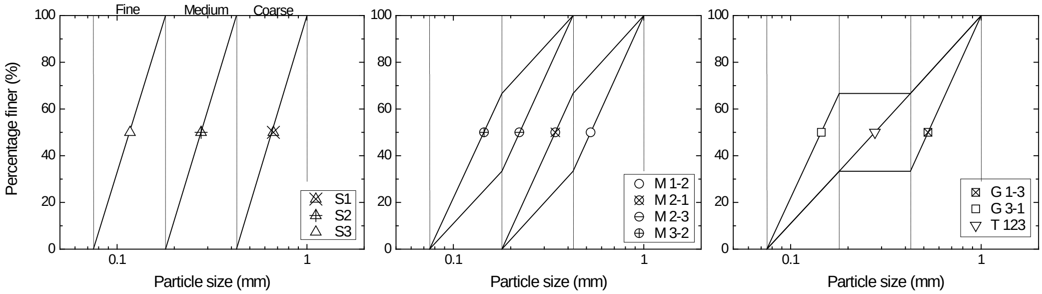

Figure 1. Grading curves of tested sands.

Iso-magnitude curves reported in the γ_{dmax} and γ_{dmin} plots show a strong similarity, both giving lower values at the edges of diagrams (minimum densities were obtained in both cases for the material S3). It is also interesting to note that the highest value of γ_{dmax} and γ_{dmin} are obtained for the gap-graded material G1-3, where the particles of smaller size (S3) are included in a matrix formed by the particles of largest size (S1), with percentages of 33% and 66%.

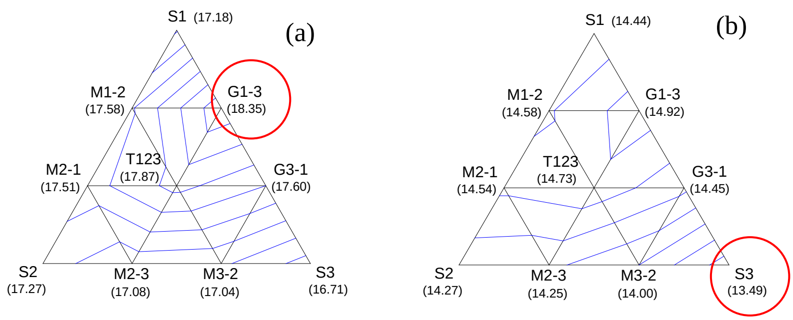

Figure 2. Gradient of (a) maximum and (b) minimum dry unit weights

3 Proctor Compaction Tests

The ten sandy materials were subjected to “Proctor” compaction tests performed with the standard (ASTM D698) and modified (ASTM D1557) procedure. Each test was performed with four different energies, by varying the number of blows per layer (see Table 2). Combining all cases (different grading and energies), 80 different testing conditions were produced.

A preliminary set of standard and modified tests conducted on the three uniform sands shows that the influence of moisture content is not particularly significant. Following this result, limited care was placed in controlling the initial moisture of samples, giving water contents generally variable between 10% and 15%.

The effectiveness of each “Proctor” technique was evaluated in terms of relative density (D_r), i.e. referring the effects of compaction to reference standard values. As a sample, the results obtained using three different compaction energies, namely 596 kJ/m^3 (case E3), 2681 kJ/m^3 (case E7) and 5362 kJ/m^3 (case E8) are summarized in Figure 3.

Case E3: For conventional standard Proctor test energy (E_{std} = 596 kJ/m^3), D_r falls in the range of 37.7-46.2% for all tested sands except for the coarser sand S1, for which D_r = 23.5%.

Case E7: By increasing the compactive energy to 2681 kJ/m^3 (i.e. conventional modified Proctor), a significant improvement in compaction effectiveness is found, with D_r ranging between 46.1-68.3%. It is interesting to note that, while D_r increases much for the uniform finer sand S3, and for the materials including S3 as a fraction, On the contrary, limited improvement is observed for the coarser sands S1 and S2 (D_r = 24.7%).

Case *E8*: Using an impact energy per volume of 596 kJ/m^3, compaction efficiency of D_r > 60% could be achieved for all sand mixes containing the finer sand S3. Best results were achieved for sands G3-1 (D_r = 73.6%) and M3-2 (D_r = 68.2%), i.e. for materials containing at least 67% of the finer sand S3, and for sand S3 itself (D_r = 71.9%). Again, no significant improvement was observed for the coarser sands S1 and S2 (D_r = 27.5%).

All these results imply that compaction by means of vibration (ASTM D4254) is generally more effective than compaction produced by Proctor tests where impact efforts are given. An improvement with these latter can be obtained by increasing the input energy (the number of blow per layer), but appreciable effects are seen only for the materials containing a significant portion of finer sand S3. The role of energy on the compaction of coarser materials S1 and S2 is very limited. A possible explanation is that finer particles tend to fill voids created by coarser grains (as for materials M2-3 and G1-3) or to replace the coarser particles themselves (M3-2 and G3-1). A gap of grading may better induce soil densification (G1-3).

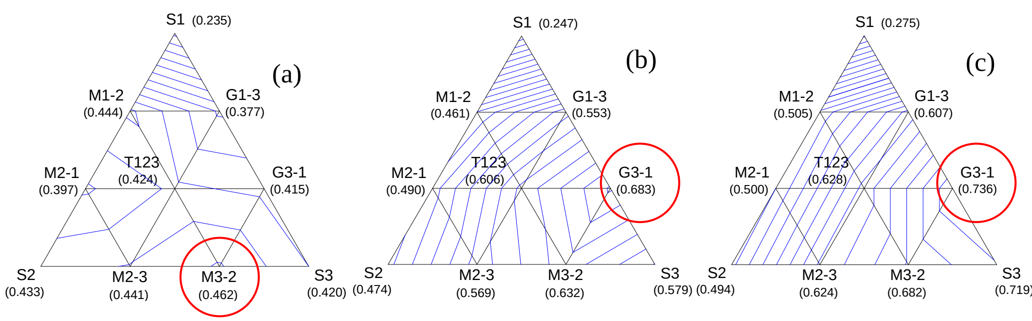

Figure 3. Relative densities obtained by (a) E3; (b) E7 and (c) E8 compaction methods.

Table 2. Dry unit weight from standard and modified Proctor tests with different compaction energies.

Method	Proctor Standard				Proctor Modified			
Case number	E1^s	E2^s	E3^s	E4^s	E5^m	E6^m	E7^m	E8^m
No. blows/layer	5	10	25	50	5	10	25	50
Energy (kJ/m^3)	119	238	596	1192	536	1072	2681	5362
E/E_{std}	0.2	0.4	1.0	2.0	0.9	1.8	4.5	9.0
Material	Dry unit weight [kN/m^3]							
S 1	14.15	14.66	15.00	15.05	14.55	14.79	15.03	15.10
S 2	14.51	15.01	15.43	15.56	15.00	15.39	15.55	15.61
S 3	13.87	14.50	14.75	15.16	14.52	15.00	15.24	15.70
M 1-2	15.15	15.47	15.78	15.93	15.35	15.71	15.83	15.96
M 2-1	15.14	15.46	15.66	15.86	15.42	15.72	15.92	15.95
M 2-3	14.50	15.01	15.37	15.58	15.13	15.36	15.73	15.89
M 3-2	14.26	14.76	15.26	15.51	15.03	15.42	15.78	15.94
G 1-3	15.26	15.80	16.05	16.30	15.96	16.39	16.64	16.83
G 3-1	14.84	15.29	15.61	15.82	15.81	16.15	16.46	16.64
T 123	14.94	15.53	15.92	16.01	15.72	16.12	16.49	16.56
Note: ^{s} standard Proctor conditions; ^{m} modified Proctor conditions E_{std}: energy applied in conventional standard Proctor tests (= 596 kJ/m^3)								

4 Prediction of Laboratory Compaction Behavior of Clean Sands

When a soil element is compacted by the application of an external load, *e* decreases due to rearrangement of particles in a denser configuration. Certainly, variation in *e* depends on the applied energy, but it may be significantly influenced by soil gradation properties. In this study, it was found that for any assigned energy, the dependency of *e* from soil gradation properties could be satisfactorily represented by a power-form relationship (Eq. 1):

$$e = \alpha(E) C_U^{\beta(E)} \tag{1}$$

where, C_U represents the uniformity coefficient (Figure 4). The coefficients $\alpha(E)$ and $\beta(E)$ depend on E (Figure 5), with a logarithmic relation:

$$\alpha(E) = A_\alpha \ln E + B_\alpha \tag{2}$$

$$\beta(E) = A_\beta \ln E + B_\beta \tag{3}$$

Considering that γ_{dry} can be expressed as a function of the specific gravity (G_S) and void ratio (e) by the following equation:

$$\gamma_{dry} = \frac{G_S \ \gamma_{water}}{1+e} \tag{4}$$

A generalized formulation taking into account the dependence of γ_{dry} obtained from laboratory compaction tests on C_U, G_S and E is proposed:

$$\gamma_{dry} = \frac{G_S \ \gamma_{water}}{1+\alpha(E) C_U^{\beta(E)}} \tag{5}$$

For testing conditions employed in this study, coefficients A_α, B_α, A_β and B_β are -0.0368, 1.0202, -0.0085 and -0.0621, respectively. A comparison between measured (Table 2) and predicted (by Eq. 5) γ_{dry} are shown in Figure 6 for all 80 different testing conditions used in this study. It was found that, for all tested materials the proposed power correlation can predict γ_{dry} under an arbitrary level of compaction energy with an error < 5%.

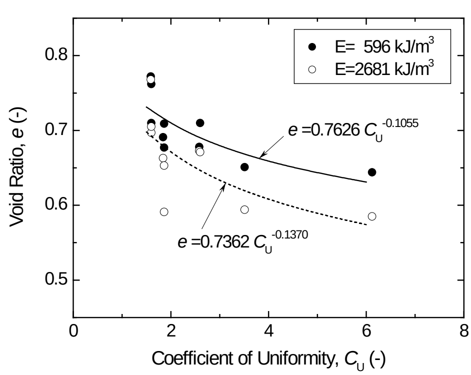

Figure 4. $e - C_U$ relationship for tested sands.

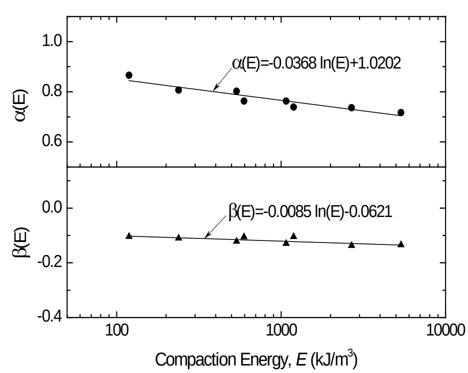

Figure 5. Variation of $\alpha(E)$ and $\beta(E)$ with E.

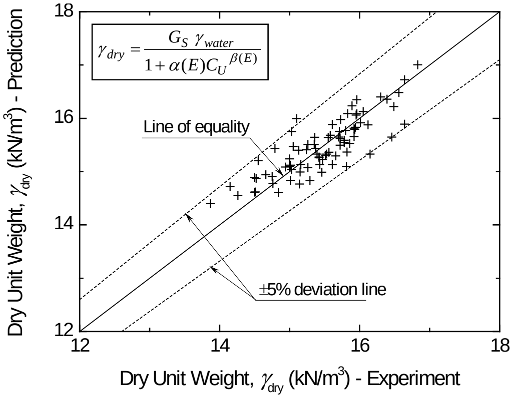

Figure 6. Agreement between experiments and predictions

5 Conclusions

In this study, results of a systematic laboratory experiments undertaken to clarify the role of grain size distribution on the compactability of granular materials are presented. Test results indicate a limited influence of the moisture content, while a large sensitiveness is seen on the procedures adopted for compaction. In particular, a greater impact effort gives higher values of relative density $D_{r,}$ particularly if the finer fraction is present. It plays a favorable role on the effectiveness of compaction, either when it fills voids between coarser particles (i.e. finer particles in a matrix of coarser particles) or when forming a matrix with floating larger particles. In addition, a gap of grading may induce better soil densification (D_r exceeding 73%). A generalized semi-empirical formulation has been finally proposed that takes into account the dependence of γ_{dry} on the uniformity coefficient C_U, and on the compaction energy E. Under the testing conditions adopted in this study, predicted γ_{dry} under various level of compaction energy differ from measured ones by an error lower than 5%.

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