DISCUSSION

The static compaction of soils

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In the static compression test described by Olivier & Mesbah (1985) the soil was compacted by quasi-static means in an oedometric mould to a compressive strength of 0.5–10 MPa. The curves obtained resemble those of the standard Proctor test (i.e. dry density plotted against moisture content). This test produces cylindrical homogeneous samples 11 cm in diameter and 13–16 cm high which can be used in simple compression and triaxial tests. It is therefore possible to study the effect of varying parameters (e.g. compaction stress, moisture content, binders and curing) on the geotechnical and mechanical properties of the compacted soils (Olivier & Mesbah, 1986). An example is given in Fig. 6.

Some conclusions arrived at in applying this test are as follows.

- (a) During compaction, the speed of the piston is an important factor if its average value is greater than 0.25 MPa/s.
- (b) The curves of dry density plotted against

moisture content are similar to the Proctor curves and present an optimum which varies with the variation in compaction stress. However, when the moisture content is close to saturation point, the curve is generally flatter than the Proctor curve. In fact, where the stress is quasi-static the sample becomes saturated at a number of points and some of the moisture is discharged.

- (c) This test is complemented by others which enable the resistance of the sample to be evaluated when it is stressed under different conditions: resistance under simple compression after compaction, resistance under simple compression after curing or after drying, resistance under tensile strength, and resistance after testing for capillary action, the latter test generally being applied to stabilized soils. It was shown that for a given compaction stress in all these instances the optimum resistance is obtained at optimum dry density (Olivier & Mesbah, 1985, 1991).
- (d) There is always a level of compaction stress which gives a compaction curve identical to

Fig. 6. Static compaction test: effect of compaction stress and treatment with 4% cement

that obtained in the standard Proctor test, but this force varies with the grain size of the soil and the behaviour of the clay. A formula has been obtained from tests carried out on different soils which can be applied to soils of varying grain size which contain plastic clays (kaolin and illite)

$$\sigma_c = -2.221[10^{-9}w_l^3(\% < 0.4 \text{ mm})^2 D'_{\max}] + 5.18 \quad (1)$$

where σ_c is static compaction stress in MPa which gives a compaction curve identical to that in a standard Proctor test, w_l is liquid limit, $(\% < 0.4 \text{ mm})$ is the percentage of grains smaller than 0.4 mm, $D'_{\max}$ is D when $D < 5 \text{ mm}$ or when $D > 5 \text{ mm}$ and the percentage of grains smaller than 5 mm is greater than 10%, and D_{10} when the percentage of grains smaller than 5 mm is less than 10%, D being the maximum grain diameter. The value of σ_c varies from 0.5 MPa to 5 MPa, higher values being obtained for very sandy or gravelly soils.

I have tried to use the results given in Fig. 3 to plot dry density against moisture content for different compaction stresses (Fig. 7), based on the assumption that the prepared samples were 76 mm cubes. The data given in the Paper are not sufficient to enable a complete compaction curve

to be drawn; however, Fig. 7 shows that the compaction curve for 4.33 MPa is reasonably close to the standard Proctor curve.

Table 3 shows the energy (obtained by integration) for different levels of compaction for four values of moisture content. The energy obtained for (γ_d, w) is slightly higher than that shown in Fig. 5, probably because of the imprecise values of Δh , which were obtained manually from Fig. 3 (see Tables 4–6).

Figure 8 shows the energy curves of Fig. 5 and the energy calculated along the compaction curve for 4.33 MPa. Along the static compaction curve, which equates to the standard Proctor curve, the energy absorbed by the soil is not constant: it decreases as the moisture content increases. This is due to the internal behaviour of the soil. On the dry side of the curve, the soil is mainly plastic and the pressure on the soil is totally absorbed by displacement of the grains. Depending on their structure and number, the grains are either displaced by force or cannot slide against each other. For this reason the dynamic or quasi-static stresses produce a greater density for the same amount of energy.

The greater the increase in moisture content, the more the free water in the soil acts as an elastic component of the behaviour of the soil. In

Fig. 7. Static compaction curves calculated from Fig. 3

Fig. 8. Static compaction curve for 4.33 MPa, and energy curves taken from Fig. 5

Table 3. Evaluation of energy needed to compact soils with different levels of stress*

Stress MPa	Energy: MJ/m ³			
	w = 13.05%	w = 14.31%	w = 15.45%	w = 19.42%
0	0	0	0	0
0.43	0.085	0.100	0.117	0.157
0.87	0.128	0.185	0.194	0.208
1.30	0.228	0.256	0.251	0.251
1.73	0.308	0.316	0.310	0.290
2.60	0.393	0.430	0.424	
3.46	0.592	0.550	0.504	
4.33	0.746	0.652	0.607	
5.19	0.943	0.891		
6.93	1.182	1.051		
8.66	1.489			

* Energy is the area under the force-compaction stroke curve.

Table 4. Data used in calculations ($\gamma_b = 20.11 \text{ kN/m}^3$)

Force: kN	ΔH : mm			
	w = 13.5%	w = 14.31%	w = 15.45%	w = 19.42%
0	0	0	0	0
2.5	30	35	41	55
5	35	45	50	61
7.5	42	50	54	64
10	46	53	57	66
15	49	57	61	
20	54	60	64	
25	57	62	65	
30	58	64		
40	61	66		
50	64			

Table 5. Calculation of the dry density for each level i of stress ($h_{\text{final}} = 76 \text{ mm}$, $\gamma_{d \text{ dry final}} = \gamma_{b \text{ bulk final}}/(1 + w)$, $\gamma_{b \text{ bulk final}} = 20.11 \text{ kN/m}^3$)*

$\gamma_{d \text{ dry final}}$: kN/m ³	17.79	17.59	17.42	16.84
Stress: Mpa	$\gamma_d(i)$: kN/m ³			
	w = 13.5%	w = 14.31%	w = 15.45%	w = 19.42%
0	9.657	9.416	9.389	9.013
0.433	12.290	12.496	13.238	14.711
0.866	12.876	13.784	14.548	15.800
1.298	13.795	14.533	15.216	16.408
1.731	14.382	15.023	15.760	16.840
2.597	14.856	15.730	16.548	
3.463	15.720	16.305	17.193	
4.328	16.288	16.713	17.419	
5.194	16.487	17.141		
6.925	17.113	17.593		
8.657	17.789			

* $\gamma_d(i) = \gamma_{d \text{ final}} \times (76 + \Delta H_{\text{final}} - \Delta H(i))/76$.

Table 6. Calculation of the energy for each level of stress*

Stress: MPa	Energy: MJ/m ³			
	w = 13.05%	w = 14.31%	w = 15.45%	w = 19.42%
0	0	0	0	0
0.433	0.085	0.100	0.117	0.157
0.866	0.128	0.185	0.194	0.208
1.298	0.228	0.256	0.251	0.251
1.731	0.308	0.316	0.310	0.290
2.597	0.393	0.430	0.424	
3.463	0.592	0.550	0.504	
4.328	0.746	0.652	0.607	
5.194	0.943	0.891		
6.925	1.182	1.051		
8.657	1.489			

* Energy is the area under the force–compaction stroke curve.

dynamic tests when the soil contains a certain amount of clay the dissipation of energy can be felt in the vibrations of the test equipment and sometimes through the floor of the laboratory. When the stress is applied statically, the grains are displaced by force and move closer together, and simultaneously the free water is forced into the pores of the soil. In this case, if the piston stroke is slow enough, this water can be displaced and the force needed to achieve a specific compaction level is lower than under dynamic compaction.

Tests were also carried out on the soil containing plastic clay which had $D = 5$ mm, 56% of

grains smaller than 0.4 mm, 8% smaller than 2 μm , a liquid limit of 42 and a plastic limit of 22.3 (Olivier, 1994).

Equation (1) gives a stress equivalent to the standard Proctor test of 4 MPa. Fig. 9 shows the compaction curves for this material for stresses of 2–11.5 MPa, as well as for the displacement of the piston as a function of the stress. There is also fairly good agreement between the Proctor curve and the static compaction curve of 4 MPa. The force measured along the latter curve gives the results shown in Table 7. With a stress of 4 MPa, the soil was compacted to the standard Proctor level, but far less energy was required to produce

Fig. 9

Table 7. Calculation of compaction energy (MJ/m³) for two values of compaction stress*

Moisture content: %	6		8.3			8.5		10.4		
γ_d : kN/m ³ ($F_c = 4$ MPa)	20.27	20.22	21.07	20.71	20.81	20.83	20.8	20.84	20.89	20.88
Energy: MJ/m ³	0.494	0.474	0.332	0.297	0.319	0.31	0.35	0.143	0.162	0.123
γ_d : kN/m ³ ($F_c = 8$ MPa)	21.08	21.1	21.59	21.3	21.3	21.4	21.4	21	21	21
Energy: MJ/m ³	0.733	0.736	0.48	0.47	0.46	0.45	0.52	0.187	0.195	0.157

* γ_d final dry density, F_c compaction stress.

blocks of compressed soil and it was shown that

- with each type of piston stroke delivering a given value of stress, it is very important to evaluate the optimum moisture content which corresponds to the stroke and to the soil
- to obtain a certain density, static compression generally requires a level of energy lower than that for dynamic compaction.

There seems to be an error in Table 2. For soil 3, with a moisture content of 14.47%, a dry density of 17.66 kN/m³ is equivalent to a compaction energy of about 0.8 MJ/m³ (Fig. 5), not 0.384 MJ/m³. Similarly, for a moisture content of 11.6% the compaction energy shown in Fig. 5 seems to be much greater at 1.4 MJ/m³.

Authors' reply

Mrs Olivier has attempted to compare her constant stress compaction test with the static compaction test we developed. The compaction curve reported in the Paper is also a constant energy curve like the well-known Proctor curve. The Paper distinguishes between constant peak stress-variable stroke compaction and variable peak stress-constant stroke compaction. If the results of a laboratory test are to be related to what happens in a compaction operation at the site, energy used in compaction per unit volume is probably a more useful parameter. This explains our choice of the latter technique. Mrs Olivier

apparently argues that stress is a better parameter. If the same stress is operating for a longer duration the compactive effort could be more and this could lead to anomalies in the interpretation.

However, she agrees with our conclusion that static compaction generally requires less energy than dynamic compaction and also comments that the energy in Table 2 is less than the energy reported in Fig. 5. The soil used to examine size effect proved to be different although it was procured from the same site. This soil was 47% clay, 10% silt and the rest was sand. The lower energy absorption is due to the higher clay content.

REFERENCES

- Olivier, M. (1994). *Le matériau terre—compactage, comportement, application aux structures en blocs de terre*. PhD thesis, Institut National des Sciences Appliquées, Lyon.
- Olivier, M. & Mesbah, A. (1985). *Caractérisation des briques de terre crue compressées par l'essai Proctor statique*. Vaulx en Velin: Ecole Nationale des Travaux Publics de l'Etat.
- Olivier, M. & Mesbah, A. (1986). Le Matériau terre—l'essai de compactage statique pour la fabrication de briques de terre crue compressées. *Bull. Liais. Labs Ponts Chauss.*, No. 146, Nov.-Dec., 37–43.
- Olivier, M. & Mesbah, A. (1991). Comportement des matériaux fins, en géotechnique routière. *Proc. 19th Wld Rd Congr., Marrakech*, 522–523.