Compaction Properties of Agricultural Soils

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Summary. The compaction of field soils due to repeated rolling of agricultural vehicles is one of the main reasons for the agricultural soil degradation. A good understanding of the compaction properties of these soils is essential for an optimum organisation of agricultural activities, and therefore for environmental protection in terms of nitrate migrations. In the present work, the compaction properties of agricultural soils from four sites in France are studied after experimental data from oedometer tests. In the oedometer tests, a quick loading procedure was applied to simulate the loading of tire rolling. The soils that were initially in unsaturated state were loaded under constant water content condition. The compaction properties of these soils (i.e. the precompression vertical stress, compression index and swelling index) were then determined. The effect of initial dry density and initial water content on these properties is discussed. A possible effect of loading velocity on the apparent compressibility was observed. The results are finally discussed in the context of unsaturated soil mechanics.

Key words: compaction, agricultural soil, oedometer, quick loading, compressibility, dry density, water content

Introduction

Soil compaction induced by vehicle traffic is one of the major problems in modern agriculture. It is well-known that soil compaction increases soil strength and decreases soil hydraulic conductivity, as a result, root penetration is reduced; water extraction becomes more difficult; plants growth is therefore affected. From an economical point of view, this would result in the increase of production cost (Hamza and Anderson 2005, Raper 2005, Chan et al. 2006). Oedometer test is usually used to study the compaction properties of arable soils (Arvidsson and Keller 2004). The main parameters determined from this test are: (i) precompression stress, σ_p; (ii) the slope of the normal consolidation curve, λ; (iii) the slope of the unloading curve, κ. These parameters are useful in the modelling of agricultural soils compaction induced by vehicle traffic (Berli et al. 2003). As the conventional oedometer test is time consuming, it is common practice to use pedotransfer functions (Imhoff et al. 2004) to estimate the soil mechanical properties. Horn et al. (2005) used this method to predict the mechanical strength of arable soils in Eastern and Western Europe countries at various scales.

In the present work, oedometer tests are performed to study the compaction properties of four soils from France. The effects of dry density and water content on the compressibility of soil are discussed.

Materials and Methods

Soil samples were taken from four sites in France: (1) Mons, La Somme; (2) Epernay, Marne; (3) le Breuil, Nièvre; (4) Avignon, Vaucluse. The soils samples were taken from two different horizons: from the cultured horizon at 0–30 cm and the undisturbed horizon at 30–60 cm depth. The physical properties determined according to the French Standards (AFNOR) are presented in Table 1. The specific gravity was determined using water pycnometer on soil sieved at 2 mm; Atterberg limits were determined with soil sieved at 0.4 mm; and the methylene blue absorption was measured with soil sieved at 0.5 mm. The classification is based on the Atterberg limits.

Prior to oedometer test, the bloc of undisturbed soil from 30–60 cm depth was wetted (by spraying) or dried (in air) to have the desired water content. When the target water content value was reached, the soil bloc was put in a hermetic box during 24 h for homogenisation of water distribution. Finally, the soil sample (70 mm in diameter, 20 mm in height) was trimmed directly from the soil bloc and inserted in the oedometer cell. The soils from 0–30 cm depth were air dried and sieved at 2 mm. Prior to oedometer test, the soils were wetted (by spraying) until the desired water content was reached. They were

Table 1. Physical properties of soils studied

Soil	Mons	Breuil	Epernay	Avignon
Specific gravity, G	2.62	2.56	2.68	2.71
Liquid limit, w_L (%)	32	58	49	31
Plastic limit, w_P (%)	22	51	29	20
Plasticity index, I_P (%)	10	7	20	11
Methylene blue absorption (g/100 g)	1.4	0.4	7.4	2.3
Grain size distribution (%):				
– Clay (< 2 µm)	19	19	47	34
– Silt (2–50 µm)	75	23	33	51
– Sand (> 50 µm)	6	58	20	16
Classification	Low plasticity clay	High plasticity silt	Low plasticity silt	Low plasticity clay

then stocked in a hermetic box during 24 h for obtaining homogeneous water distribution. Afterwards, the soils was compacted directly in the oedometer cell to the desired dry density.

Vertical normal stresses of 15, 30, 50, 100, 200, 300, 600, and 800 kPa were applied sequentially during loading stage. During unloading stage, the vertical normal stress was decreased from 800 kPa to 600, 300, 200, 100, 50, 30, 15 kPa. Each stress was applied for 5 min and the displacement (accuracy ± 0.001 mm) was read at the end of each step. At the end of test, the soil sample was taken out of the oedometer cell and its dimensions were measured using a calliper (accuracy $\pm$ 0.001 mm). Finally, its water content was determined by oven-drying at 105°C during 24 h. These measurements allowed determining the final void ratio and the degree of saturation. The initial void ratio is calculated by back analysis using final void ratio and total displacement measured.

Experimental Results

The test program and the main results are presented in Table 2. In Figure 1, the results of some test (void ratio and degree of saturation as a function of vertical stress) are shown. It can be observed that the relationship $e - \log \sigma_v$ in the unloading path is linear for all the tests. The swelling index is then calculated from the unloading path as follows: $\kappa = \Delta e/\Delta \ln \sigma_v$ (slopes in Fig. 1 divided by $\ln 10 = 2.3$). In the tests where a clear elasto-plastic behaviour is observed as test 12 (Fig. 1**a**) and test 39 (Fig. 1**d**), the compression index, $\lambda = \Delta e/\Delta \ln \sigma_v$, is calculated from the three last points in the compression curve. In test 16 (Fig. 1**b**) and test 31 (Fig. 1**c**) where a change of the slope can be observed during the compression curve, the maximum value of the slope is taken to calculate the compression index. The precompression stress (σ_p) is calculated as the interception of the compression line and the line that across the initial point and that is parallel to the unloading line. All the parameters obtained (σ_p, λ and κ) are shown in Table 2 with the void ratio (initial, e_i, and final, e_f), the water content (initial, w_i, and final, w_f) and the initial dry density (ρ_i).

In Figure 2, the precompression stress (σ_p), the compression index (λ) and the swelling index (κ) of all soils are drawn as functions of initial water content (w_i) and mean initial dry density (ρ_i). For all tests, a decrease of the precompression stress can be observed when the initial water content increases or when the initial dry density decreases. In addition, the swelling index (κ) seems to be insensible to the initial dry density and the swelling index. In the case of soils from Breuil (Fig. 2**a**) and Mons (Fig. 2**d**), it is observed that at the same water content, looser soil samples (lower dry density) have higher compression index, and that at the same dry density the compression index increases with the water content increase. For the soil from Epernay, Fig. 2**b**, the increase of water content reduces the compression index. In the case of soil from Avignon (Fig. 2**c**), wetting induced an increase following by a decrease

Table 2. Test program and results (Br.: Breuil; Ep.: Epernay; Av.: Avignon; Mo: Mons)

No	Soil	Depth (cm)	e_i	e_f	w_i (%)	w_f (%)	ρ_i (Mg/m^3)	σ_p (kPa)	λ	κ
1	Br.	0–30	1.49	0.85	24.7	24.7	1.03	34	0.225	0.012
2	Br.	0–30	1.43	0.81	18.9	18.2	1.05	45	0.235	0.010
3	Br.	0–30	1.49	0.81	25.3	22.7	1.03	24	0.224	0.012
4	Br.	0–30	1.08	0.73	23.3	22.5	1.23	65	0.153	0.009
5	Br.	0–30	1.16	0.79	24.7	24.7	1.19	67	0.163	0.012
6	Br.	0–30	1.09	0.80	17.9	18.8	1.22	106	0.133	0.009
7	Br.	0–30	0.93	0.76	20.2	19.1	1.33	165	0.111	0.008
8	Br.	0–30	0.99	0.77	24.2	24.2	1.29	129	0.135	0.011
9	Br.	0–30	1.01	0.74	25.8	25.2	1.27	114	0.148	0.010
10	Br.	30–60	1.41	0.83	18.1	17.4	1.06	50	0.259	0.007
11	Br.	30–60	1.24	0.72	24.7	23.8	1.14	35	0.181	0.010
12	Br.	30–60	1.30	0.84	16.3	13.5	1.11	95	0.222	0.006
13	Ep.	0–30	1.44	0.87	37.8	30.4	1.10	26	0.230	0.009
14	Ep.	0–30	1.64	0.84	32.5	28.6	1.02	26	0.358	0.016
15	Ep.	0–30	1.74	0.82	25.6	25.2	0.98	39	0.377	0.014
16	Ep.	0–30	1.27	0.88	37.1	29.7	1.18	29	0.146	0.015
17	Ep.	0–30	1.36	0.86	31.3	28.7	1.14	42	0.241	0.014
18	Ep.	0–30	1.41	0.78	25.6	25.0	1.11	73	0.304	0.010
19	Ep.	0–30	1.17	0.90	37.9	31.5	1.24	32	0.083	0.011
20	Ep.	0–30	1.10	0.82	30.4	28.4	1.28	56	0.133	0.012
21	Ep.	0–30	1.11	0.79	25.1	24.2	1.27	76	0.183	0.012
22	Ep.	30–60	1.16	0.90	32.5	30.6	1.24	60	0.108	0.016
23	Ep.	30–60	1.49	1.15	41.4	39.6	1.08	50	0.151	0.014
24	Ep.	30–60	1.08	0.90	30.2	29.6	1.29	83	0.093	0.013
25	Av.	0–30	1.36	0.66	16.8	16.4	1.15	37	0.247	0.011
26	Av.	0–30	1.24	0.59	22.4	19.5	1.21	19	0.258	0.014
27	Av.	0–30	1.04	0.64	28.7	20.4	1.33	15	0.103	0.015
28	Av.	0–30	1.13	0.63	16.5	16.2	1.27	77	0.228	0.010
29	Av.	0–30	1.10	0.58	22.1	19.5	1.29	26	0.229	0.014
30	Av.	0–30	0.91	0.60	28.5	20.2	1.42	20	0.096	0.014
31	Av.	0–30	1.06	0.64	16.8	16.4	1.32	98	0.212	0.009
32	Av.	0–30	0.98	0.59	21.9	19.6	1.37	28	0.154	0.013
33	Av.	0–30	0.88	0.63	28.2	19.6	1.44	23	0.068	0.013
34	Av.	30–60	0.76	0.60	19.2	18.4	1.54	99	0.089	0.012
35	Av.	30–60	0.80	0.60	23.0	19.2	1.51	77	0.086	0.012
36	Av.	30–60	0.79	0.61	21.0	19.8	1.51	45	0.083	0.014
37	Mo.	30–60	0.59	0.51	12.4	12.4	1.65	106	0.073	0.009
38	Mo.	30–60	0.79	0.63	19.5	19.5	1.46	112	0.109	0.008
39	Mo.	30–60	0.75	0.62	18.2	18.2	1.50	137	0.111	0.008
40	Mo.	30–60	0.78	0.60	29.7	20.5	1.47	68	0.105	0.012
41	Mo.	30–60	0.75	0.57	27.1	19.9	1.50	83	0.106	0.012

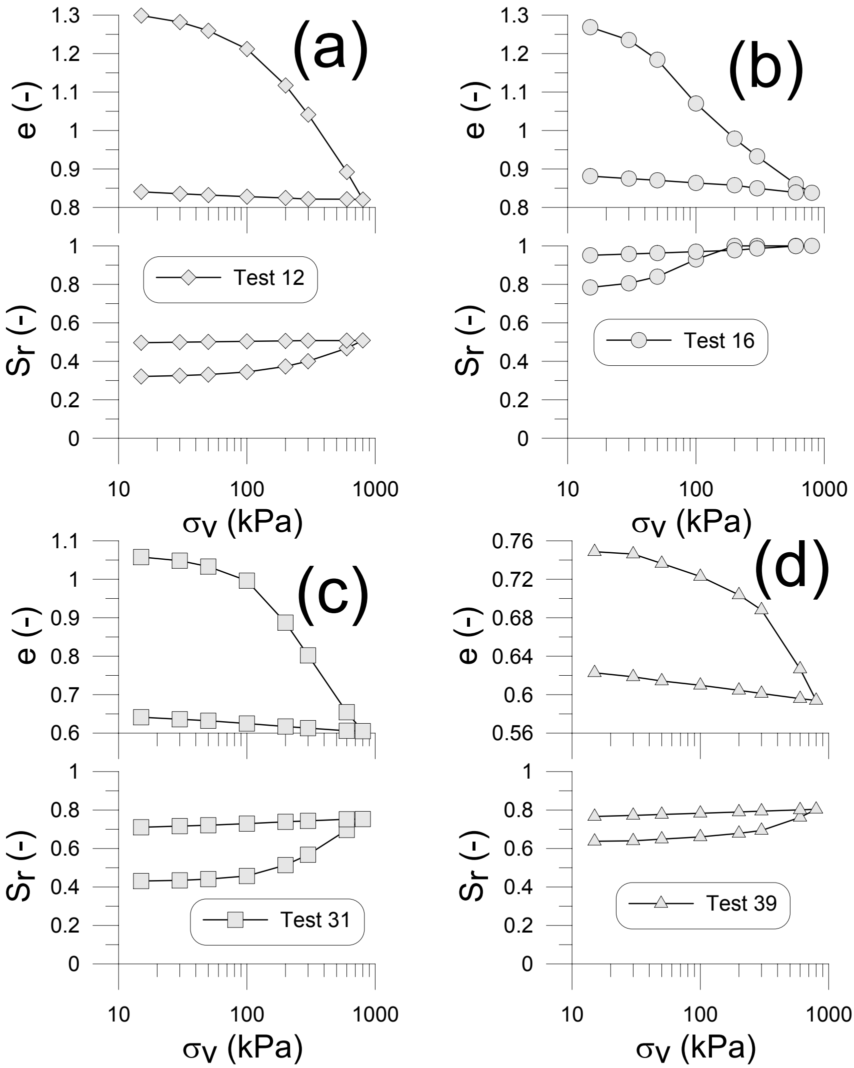

Fig. 1. Void ratio (e) and degree of saturation (S_r) as a function of vertical stress (σ_p): (a) Breuil; (b) Epernay; (c) Avignon; (d) Mons

of compression index in case of loose soils ($\rho_i = 1.25 - 1.35\,\mathrm{Mg/m^3}$). On the contrary, wetting induced only a decrease of compression index in the case of dense soils ($\rho_i = 1.40\,\mathrm{Mg/m^3}$).

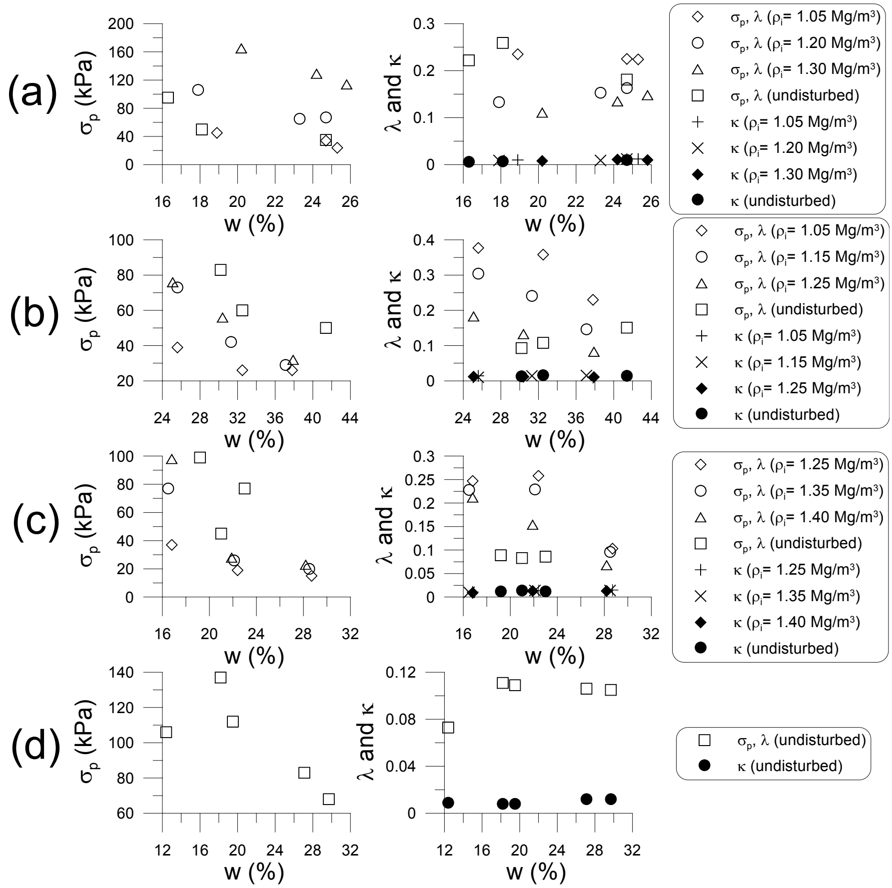

Fig. 2. Precompression stress (σ_p), compression index (λ) and swelling index (κ) as a function of mean initial water content (w_i) and initial dry density (ρ_i): (a) Breuil; (b) Epernay; (c) Avignon; (d) Mons

Discussions

In the domain of unsaturated soil mechanics, it is well-known that the precompression stress of looser soil is lower that that of denser soil. In addition, an increase of water content (that corresponds to a decrease of suction) reduces the soil strength or precompression stress (Alonso et al. 1990).

On the other hand, as the swelling index of soil depends on the stiffness of soil grains, it is independent on the soil density and on the water content in case of low plasticity soils. All these phenomena have been observed on the agricultural soils.

On the contrary, the effect of water content on the compression index observed in the present work is different from that found in the literature. After

Alonso et al. (1990), wetting softens the soil and increases then the compression index. Cui and Delage (1996) observed the same phenomenon on the compacted Jossigny silt. Nevertheless, this phenomenon can be observed only on the soils from Breuil and Mons. This contradiction can be explained by the consolidation mechanism in these tests. Indeed, in geotechnical engineering, a loading duration longer than 24 h is applied to simulate the stress generated by buildings construction. But in the present work, 5 min was applied for each loading stage in order to simulate the stress generated by rolling of agricultural vehicles. In case of plastic soils, as its permeability is low, this duration of 5 min may be not sufficient for water movement within the soil at high saturation degree. In Figure 1**b**, for example, loading increased the degree of saturation and the soil reached saturation state under 200 kPa vertical stress. The change of the compression curve slope observed in this test can be then explained by a partial consolidation of the soil.

In conclusion, wetting softens the soil and increases then the compression index. But this compression index can be reduced also by wetting due to the partial consolidation during short loading duration. This phenomenon depends on the permeability (that is influenced by soil dry density and soil plasticity) and the degree of saturation. The combination of these two trends governs the effect of water content on the compression index.

Conclusions

Oedometer tests were performed on agricultural soils taken from four sites in France. Rapid loading stage (5 min for each stage) was applied to study the soil compaction due to agricultural vehicles traffic. The effect of dry density and water content on the compaction properties of soils was observed. Generally, the soil is more compressible at lower dry density or higher water content. Nevertheless, in case of plastic soils or dense soils, wetting reduces the compression index. The consolidation mechanism was discussed to reveal the effect of loading duration on the compression index.

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