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A method to predict the soil susceptibility to compaction of surface layers as a function of water content and bulk density

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Abstract

Identifying the vulnerability of soils to compaction damage becomes an increasingly important issue in the planning and execution of farming operations. Soil compaction models are efficient tools for predicting soil compaction due to agricultural field traffic. Most of these models require the knowledge of the stress/strain relationship, as well as the mechanical parameters and their variation with different soil physical properties. Because the soil compaction depends on its water content, bulk density and texture, a good understanding of the relation between them is essential for defining suitable farming strategies according to climatic changes. In this work we propose a new pedotransfer function for 10 French representative soils collected from cultivated fields, a vineyard and forests. We investigate the relationship between soil mechanical properties and easily measurable soil properties as well as water content and bulk density. Confined compression tests were performed on remoulded soils of a large range of textures at different initial bulk densities and water contents. The use of remoulded samples allowed us examining a large range of initial conditions with low variability of measurement. A good linear regression was obtained between soil precompression stress, compression index, initial water content, initial bulk density and soil texture. The higher the clay content, the higher the soil capacity to bear higher stresses at higher initial water content without reaching severe compaction state. The initial water content played an important role in clayey and loamy soils. In contrast, for sandy soils, the mechanical parameters were less dependent of initial water content but more related to the initial bulk density. These pedotransfer functions are expected to hold for soils of surface layers with tillage but further measurements on intact samples are needed to tests their validity.

Keywords: surface soils, oedometer test, compaction, texture.

Introduction

Soil compaction is one of the major problems for soil degradation in modern agriculture and forestry. Machinery overuse has been found to be the main cause for soil compaction. Due to its persistence, compaction of the subsoil can be seen as a long-term degradation but compaction concerns also surface layers. Compaction adversely affects soil physical fertility, particularly storage and supply of water and nutrients, through decreasing porosity, increasing soil strength and hence soil resistance to root penetration and plant emergence, decreasing soil water infiltration and holding capacity. These adverse effects also reduce fertilization efficiency and crop yield, increase water logging, runoff and soil erosion with undesirable environmental problems (Soane and van Ouwerkerk, 1994). Thus, knowing the changes in soil compaction with changes in water content and bulk density is essential in planning farm operations at appropriate water contents (Arvidsson et al., 2003), or in decreasing the soil bulk density by increasing the soil organic matter through retention of crop and pasture residues or appropriate soil tillage (Hamza and Anderson, 2005).

Recently, soil protection in respect to soil compaction has become an important concern in Europe. Identifying the vulnerability of soils to compaction damage becomes an increasingly important issue both in the planning and execution of farming operations at a field scale and in planning environmental protection measures at a largest scale. Numerous studies have been undertaken to elaborate methods of soil compaction assessment. Horn and Fleige (2003) and Horn et al. (2005) chose the precompression stress (σ_p) as an indicator of soil resistance to compaction and applied, at various scales ranging from farm to country and continent level, the pedotransfer functions that relate the precompression stress and soil physical parameters. Jones et al., (2003) proposed a classification method for subsoil vulnerability to compaction based on available soil properties as texture and bulk density and on some soil moisture data at critical trafficking time. This classification method, initially developed for local field condition, was then extended to the scale of Europe.

At a large scale, modeling and spatialization are helpful means to assess soil vulnerability to compaction. The most readily available spatial information about soils in most countries is soil survey data and the corresponding climatic data. It should be however noted that most models (Bailey and Johnson, 1989; Défossez et al., 2003; Keller et al., 2006; Larson et al., 1980; O'Sullivan and Robertson, 1996; van den Akker, 2004) require the knowledge of the stress/strain relationship, and their variation with different soil physical properties. The stress/strain relationship gives two relevant mechanical parameters that are the precompression stress (σ_p) and the compression index (C_c). The precompression stress is an indicator of the soil's load support capacity; the slope of the virgin compression line, namely compression index, represents an indicator of soil susceptibility to compaction. The confined compression tests are usually used to determine these soil mechanical parameters in a laboratory. Because in agricultural fields the loading duration by vehicles is in general short (0.5s), a short loading time of between 5 and 45 min is usually adopted in laboratory oedometer tests. Different models have been developed to evaluate soil sensitivity to compaction for decision making. Based on the precompression stress notion, one approach consists in estimating the soil bearing capacity with respect to compaction; it allows constructing a map of permissible machinery ground pressure that soil can support without permanent subsoil deformation. Horn et al. (2003) and Van den Akker (2004) applied this approach for respectively, Netherland and Europe. A second approach aims at evaluating the intensity of compaction, i.e., the increase in soil dry bulk density. Obviously, this approach needs the use of both precompression stress and compression index, and is particularly applicable for the surface layers where deformation usually cannot be avoided but can be reduced as the compaction intensity depends on soil type and physical parameters (Canarache et al., 2000; Défossez et al., 2003; Gupta and Larson, 1982; Imhoff et al., 2004; Kirby, 1991;

O'Sullivan et al., 1999; Salire et al., 1994; Smith et al., 1997). This paper deals with this second approach for which both precompression stress and compression index, of surface layers are required.

The variation of the precompression stress and the compression index with different physical parameters has been widely studied. In geotechnical engineering, the compressibility characteristics of a soil is usually correlated with different geotechnical properties such as the liquid limit, the plasticity index and the shrinkage limit (Giasi et al., 2003; Sridharan and Nagaraj, 2000). In agronomy and forestry, various regressions were proposed to relate the precompression stress or the compression index to numerous soil properties. More studies on the relation between the precompression stress (σ_p) and soil physical properties can be found in the literature as compared to studies on the relation between the compression index (C_c) and soil physical properties. The most studied soil physical properties are the texture, the structure and the hydric state of soil. The texture is materialized by the soil clay, silt and sand content (Gupta and Larson, 1982; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Smith et al., 1997). The structure is commonly characterized by the initial bulk density, but also by more difficult measurable variables related to the soil internal structure at the aggregate scale (Alexandrou and Earl, 1998; Canarache et al., 2000; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Rücknagel et al., 2007; Salire et al., 1994). The hydric state is characterized by the initial water content (Alexandrou and Earl, 1998; Canarache et al., 2000; Défossez et al., 2003; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Mosaddeghi et al., 2003; Mosaddeghi et al., 2006; O'Sullivan et al., 1999). In most of these studies, mechanical tests are performed on intact samples that induce a large variability of various soil properties. That can explain the contradictory effects of texture, water content and porosity on the mechanical properties observed by numerous authors (Arvidsson and Keller, 2004).

This paper considers a simplified description of soil mechanical strength: the structure via the bulk density, the hydraulic stress via the water content and the mechanical stress via the external stress. This point of view is droved by the objective of compaction assessment using accessible parameters. But it fails to describe the physical processes acting on soil mechanical strength i.e. the interaction between hydraulic, mechanics and structure in unsaturated soils. These interactions have been studied and modeled for several decades using the concept of effective stresse and the theory of critical-state for geotechnical application (Fredlung and Rahardjo, 1993). Different authors applied these concepts to analyze and model the mechanics of cultivated soils (Richards, 1992; Wulfsohn et al., 1996; Peng et al., 2004). But these concepts can not describe satisfactory important characteristics of cultivated soils mechanics such as the effect of soil structure anisotropy and the time dependent processes (Peng and Horn, 2008).

The present work is based on the hypothesis that soil water content and bulk density are the main easily accessible parameters affecting the soil mechanical strength. Oedometer tests were carried out on remolded soils of a large range of textures at different initial bulk densities and water contents. The main objective of working on remolded samples was to cover a large variation range for both initial water content and initial bulk density. Ten French representative soils taken from cultivated fields, a vineyard and forests were considered. The identified σ_p and C_c were then correlated with initial soil water content, initial bulk density and texture. A new and simple method of assessing French soil's susceptibility to compaction based on accessible parameters was finally proposed.

2. Material and methods

2.1. Soil properties

The soils studied were taken in the top soil of cultivated fields, forests and vineyard from ten sites in France. The sites vary in soil type, carbon content, cultures and management (Table.1). The soils varied significantly in texture: the clay content ranged from 31 to 683 g kg^{-1}; the sand content from 55 to 895 g kg^{-1} and the organic carbon from 8.5 to 22 g kg^{-1}. The soil's texture was classified according to FAO Classification System (FAO-UNESCO, 1974) (Figure.1). The soil's physical properties were determined following the French Standard for Geotechnical Engineering. The particle density was determined using a water pycnometer on soils passed through a 0.3 mm sieve; the Atterberg limits (liquid limit, plastic limit) were determined on soils passed through a 0.4 mm sieve.

Soil was sieved at 2-3 mm; the aggregates obtained were saturated and then adjusted to the same matric potential for 2 days. The saturated aggregates were placed in a hermetic box on a plastic grid above a desiccant (silicagel). Every 15 min, a portion of soil sample was weighed, placed in a container and then immerged in petrol for 12 hours. The soaked aggregates were spread on filter paper to let excess petrol run off. The volume of the displaced petrol corresponds to the soil volume (Archimede's principle). The dry mass of aggregates was determined after 24 hours of oven-drying at 105°C. The density of aggregates was then calculated based on the dry mass and the volume of aggregates previously determined. Five replicates was done per soil.

We measured the relationship between matric potential Ψ and gravimetric water content w in the laboratory with Richard's press method (Klute, 1986) on small aggregates. Two aggregates distributions were used: 2-3.15 mm diameter and < 2 mm diameter.

2.2. Soil compression tests

Oedometer tests were performed on soil to measure mechanical parameters as described with full details in Défossez et al. (2003). All compression tests were made on remolded samples that were air dried and sieved through a 2-mm mesh.

A large sample (1 kg) of air dried soil <2 mm was wetted by spray with distilled water to achieve the desired water content and then stocked in a hermetically-sealed box for 24 h to ensure uniform water distribution in the soil. The desired water content corresponded to the different initial gravimetric water content. The initial gravimetric water contents w_i was chosen such as they ranged between saturation and wilting point for each soils and corresponded to the matric potential Ψ=-100, -33 and -5 kPa as measured by the water retention curve of each soil.

Afterwards, each samples were prepared by compaction a fraction of large sample at initial water content w_i using a manual press at different initial bulk densities (1.1, 1.3 and 1.45 Mg m^{-3}). The compaction took place directly in the oedometer cell which is 24-mm high and 70 mm in diameter under drained conditions imposed by two porous plates. Loading was performed in steps: 15, 25, 50, 100, 200, 300 and 600 kPa. Each load was applied for 5 min with a subsequent relaxation of 2 min without loading. Vertical displacement was recorded. The gravimetric soil water content was measured before compression whereas the bulk density was later calculated based on the final sample dimension and the recorded displacement. Each compression test was performed with three replications at the same initial conditions.

The void ratio e was calculated based on soil bulk density and particle density. Based on these values, the compression curve was drawn for each sample. This curve represents the relationship between the logarithm of the applied pressure σ and void ratio e. The mechanical parameters (precompression stress and compression index) were estimated following the French Standard of the compressibility test: C_c is the slope of the virgin compression line (VCL) and σ_p is the intercept of the VCL and a regression with the first two or three points of the curve (all points before the point of the maximum curvature). This method (Figure 2) was also used by Dias Junior and Pierce (1995) and Arvidsson and Keller (2004).

The influence of initial water content and initial bulk density on C_c and. σ_p was quantified by multiple regression analysis using StatG5 software. The variability criterion is the squares regression r^2, only the values smaller than the *p* threshold by 5% were considered.

3. Results

3.1. Shapes of compression curves

The compression curves of three soils of different texture (very fine, medium fine and coarse texture) are presented in Figure 3. Almost all the compression curves have a common shape: an elastic part followed by a platic compression part (virgin compression line). The variability between the replicates was low except for samples with low bulk densities (results are not shown). For some sites, the compression curves with low bulk densities (1.1) do not show the elastic part due to the high porosity of the soils. Rao and Revanasiddappa (2003) showed that the low density soils in general present high susceptibility to collapse.

At the same initial water content, the higher the initial bulk density the lower is the soil deformation or susceptibility to compaction (Figure 3). This is consistent with the suggestions by Paz and Guérif (2000), Culley and Larson (1987), Lebert and Horn (1991), Veenhof and McBride (1996), Canarache (2000) and Imhoff el al. (2004). In contrast, at the same initial bulk density, the higher the water content the higher the soil deformation or susceptibility to compaction (Figure 3). This is in agreement with the observation of Alonso et al. (1990).

The soil mechanical parameters C_c and σ_p were determined from the compression curves. σ_p values ranged between 15 and 222 kPa. Considering that machinery in France agriculture and forestry usually exerts a ground pressure ranging from 30 kPa for sowing preparation to 250 kPa for grape transport (T. Gaudin et al;, 2006) , the identified values reflect well the stress history underwent by different soils. In the conducted tests, this history was created by initial compaction for sample preparation. The C_c values were comprised between 0.1 and 0.9. They were generally greater for soils with high clay content, illustrating the higher compressibility of such soils. Similar results were reported by Gupta (1982), Lebert and Horn (1991), McBride (1989), Smith et al. (1997), Imhoff et al. (2004) and Gregory et al. (2006).

3.2. Effects of initial water content and initial bulk density on C_c and σ_p

Figures 4 and 5 present the soil mechanical parameters C_c and σ_p versus water content and bulk density for three soil textures, a very fine, a medium fine and a coarse texture. C_c decreases when initial soil water content and initial bulk density increase. As far as. σ_p is concerned, it increases with increasing initial bulk density, but decreases with increasing initial water content.

The relative importance of initial soil water content, initial bulk density on the compression index and on the precompression stress was determined by multiple regression analysis and the results are shown in Table 2. The general expression is as follows:

$$Y = a + b*\rho_i + c*w_i \qquad \text{Eq.1}$$

where Y is either C_c or σ_p, ρ_i is the initial bulk density and w_i the initial water content. C_c and σ_p are highly correlated with water content and bulk density. The defined expression explains in average 94% and 90% of the variability of the data for C_c and σ_p, respectively. For all the soils, the p value was < 0.05, except for “Breuil”. For this soil with a coarse texture, there was no correlation between water content and C_c or σ_p. For “Les closeaux” which is a sandy loam, there was no significant correlation between σ_p and water content.

3.3 Soil texture effects

A regression analysis was performed between the mechanical parameters C_c and σ_p, and initial soil water content and initial bulk density for each soil texture class (Table 3). The results show that the correlations established were satisfactory. The model explains in average 84% and 74% of the variability of the data for C_c and σ_p, respectively. For all the texture classes, the p value was less than 0.05, except for the medium class for which the "water content" variable was removed from the relationship between σ_p, water content and bulk density. For the relation between C_c and soil bulk density and water content, a greater b factor (for bulk density) was obtained for the very fine texture class. This class includes soils with high clay content. This confirms the effect of soil texture on C_c as found above for the correlations for each soil (Table 2). The c factor (for water content) was also the largest for this class. For the relation between σ_p and initial water content and initial bulk density, it was observed that the effect of initial bulk density was more pronounced compared to that of the initial water content. We examined classification of soils according to standards used for geotechnical application; numerous correlations have been proposed for the compression index (Sridharan and Nagaraj, 2000). We performed a regression analysis for the mechanical parameters C_c and σ_p, and initial soil water content and initial bulk density based on the Cassagrande diagram that uses the Atterberg limits (Table 1). The quality of correlations was significantly lower than those obtain using the texture classes (data not shown).

4. Discussion

The set of correlations proposed in this paper for 10 French soils (Table 2 and 3) exhibited features with soil texture, initial water content and initial bulk density. A qualitative and quantitative comparison with data of literature is important to examine their validity and their innovative characteristics.

Both parameters C_c and σ_p were found to be significantly correlated with initial soil water content. The precompression stress σ_p was negatively correlated with initial soil water content. A significant negative correlation was also observed by Alexandrou and Earl (1998), Defossez et al. (2003), Imhoff et al. (2004) and Mosaddeghi et al. (2006). For some soils with a coarse texture, no clear relation has been found: correlation with initial water content was not significant. The same results were reported by Alexandrou and Earl (1998); they found a good correlation between the precompression stress and the initial water content for clayed soils but not for sandy soils. Similarly, Lebert and Horn (1991) reported that there is no correlation between the saturated hydraulic conductivity and the precompression stress for sandy soils.

The compression index C_c was negatively correlated with initial soil water content. This is in agreement with the results reported by Zhang (1997), Sanchez and Giron et al. (2001) and Défossez et al. (2003), but in disagreement with the results of Larson (1980), O’sullivan (1992), Smith (1997), Arvidsson and Keller (2004), Imhoff et al. (2004) and Mosaddeghi et al. (2006). Note that the higher the clay content the stronger is the correlation with the initial soil water content; the higher the clay content the higher the soil capacity to bear higher stresses at higher water content.

C_c and σ_p were found to be significantly correlated with initial soil bulk density. The precompression stress σ_p was positively correlated with initial soil bulk density and negatively correlated with initial soil water content. The values of b estimated for σ_p regressions ranged between 114 and 508. Similar results were reported by various authors (Alexandrou and Earl, 1998; Canarache et al., 2000; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Rücknagel et al., 2007): b factor varied from 374 to 460.

The compression index C_c was negatively correlated with initial soil bulk density. A imilar observation was made by McBride (1989), Salire et al. (1994) and Imhoff et al. (2004). The values of b factor for the ten soils ranged between -0.42 and -1.59. These values were similar to that estimated by Salire et al. (1994) (-0.444), but larger than that obtained by Imhoff et al. (2004) (-0.121). This can be explained briefly by the differences in compaction procedure applied by the authors.

It has been found that the higher the clay content, the greater the factor "b" for the compression index C_c. To confirm that, a correlation between "b" factors for C_c obtained for the ten soils and their clay contents (CC) was established at a constant matric potential (33kPa) . The model obtained was:

$$b = -13.41 + 47.62\ CC \qquad \text{with} \quad r^2 = 68\%$$

This result suggests that there is a significant correlation between "b" factor and the clay content. Some authors showed a good correlation between C_c and the clay content (Gregory et al., 2006; Gupta and Larson, 1982; Imhoff et al., 2004; Lebert and Horn, 1991; McBride, 1989; Smith et al., 1997). Nevertheless, the present work has not show any significant global correlation between the C_c and the clay content (CC) when all specimens were considered.

A clear effect of initial soil water content, initial dry bulk density and soil texture on C_c and σ_p was evidenced. This can be explained by remolded structure of the samples. As a large range of water content and bulk density was accounted for in the tests conducted, the elaborated correlations have a quite large validity domain. In contrast, most mechanical tests reported in literature were performed on intact samples. Working on intact sample is essential but this would limit the range of measurement variability. In addition, soil sampling in the field may also induce sample disturbance, affecting soil mechanical properties such as precompression stress. This could explain the contradictory effects of texture, water content and porosity observed by numerous authors (Canarache et al., 2000; Arvidsson and Keller, 2004; Mosaddeghi et al., 2006). The correlations proposed in this paper are expected to predict the mechanical properties of soil surface layers especially in conventional tillage system. But further measurement on intact soil structure are needed to tests their robustness. In particular, our approach on remoulded samples neglects structural effects such as age hardening (Dexter et al., 1988) and anisotropic pore structure effects (Peng and Horn, 2008), such structural processes can change significantly the mechanical properties of cultivated soils.

The present work describes the soil structure through its dry bulk density because it is easy accessible parameters. But different authors attempted to relate the macroscopic mechanical behavior of soils to their structure at the aggregate scale. Several authors proposed relations between the compression stress and respectively the precompression index and other variables related to the soil internal structure: the soil cohesion and the angle of internal friction (Lebert and Horn, 1991), the aggregate density (Rücknagel et al., 2007) and the diameter of structural aggregates (Canarache et al., 2000). As found by Rucknagel et al. (2007), a high correlation has been found in the present work between b factors the aggregate densities AD (measured in laboratory, see table 1.). The model obtained was:

$$b = -1.22 + 1.16\ AD \qquad \text{with} \quad r^2 = 79\%$$

This observation suggests that the obtained results agree with the model introducing AD as a soil structure parameter. The correlation factor (r^2) obtained here is higher compared to that obtained for the relation between the b factor and the clay content (cited above). This is an important result since it clearly identifies the factors that determine at aggregate scale the macroscopic soil strength. Nevertheless, for our purpose of compaction assessment, the soil texture is more relevant because it is easily measurable.

This paper illustrates that soil's deformability depends on the initial water content, the initial bulk density and the nature of soil internal structure. The understanding of the physical process in play would require examining more closely the interaction between soil suction, effective stresses and porosity in the framework of the mechanics of unsaturated soils (Fredlung and Rahardjo, 1993). The effect of initial soil water content on the precompression pressure could be understood in terms of air and water transfers as shown by Peng et al. (2004). For instance, our paper shows that the initial water content almost affects the precompression pressure of clay soils but not sandy soils. This illustrates the role of hydraulic properties (retention, hydraulic conductivity) on soil mechanical response as investigated by numerous authors (Fredlung and Rahardjo, 1993). The consideration of these processes is important to understand the physical process acting soil mechanical strength but they require laborious measurements of the soil air permeability, the soil saturated hydraulic conductivity and the pore structure (Peng and Horn, 2008). For a practical point of view, an indication of the compression index and the precompression stress, predicted from only easily measurable soil properties, can provide a useful measure of the mechanical state of soils for use in the management and planning of agricultural systems.

5. Conclusions

This paper proposes a correlation method to predict the soil's sensitivity to compaction for French soils based on the precompression stress (σ_p) and the compression index (C_c) by using pedotransfer functions. Correlations were established for five classes of soil textures, taking into account the physical state of the soil at wheeling, its water content and its dry bulk density. The soils investigated in this work cover a wide range of soil textures and come from different parts of France, thus representing a large proportion of French arable soils. Therefore, the correlations established accounting for a large variability in soil moisture and porosity form an important database for assessing the susceptibility of different French soil types to compaction. This would enable predictions of compression index and precompression stress to be made from readily estimated soil properties without the need to carry out compaction tests which are both laborious and time consuming. Nevertheless, in spite of their limitations these correlations established on remolded samples present a useful starting point. Further measurements are needed on intact specimens sampled at different dates depending on tillage operations and climate conditions (cycles of frozen, humectation-desiccation) that affects the soil structure of soil surface layers to confirm the correlations proposed in this paper.

These correlations combined with a model of soil compaction constitute an efficient tool for recommendation of soil conditions at wheeling and equipment in order to avoid excessive compaction in soil surface layers for sustainable landuse in France.

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Tables

Table 1. Soil Physical and mechanical properties of the experimental sites

Table 2. Relationship between the compression index C_c and the precompression stress σ_p, and initial water content and bulk density for the ten studied soils.

Table 3. Relationship between the compression index C_c and the precompression stress σ_p, and initial water content and bulk density for the five texture classes.

Figures

Fig.1. Soil texture at the different sites in the FAO classification scheme

Fig. 2 Determination of mechanical parameters: the compression index C_{c} is the slope of the virgin compression line (VCL) and the precompression pressure σ_{p} is the intercept of the VCL and a regression with the first two or threee points of the curve.

Fig. 3. Compression curves for three representative texture classes soils: a medium fine texture (Mons), a medium texture (Les carrés) and a coarse texture (Rivaulde). Compression tests were performed at three initial bulk density ρ_{i} =1.1, 1.3, 1.45 Mg m^{-3} and three matric potentials: -100, -33 and -5 kPa corresponding respectively to w_{i} = 18, 21, 27 % g g^{-1} for “Mons”, w_{i} = 13, 15, 17 % g g^{-1} for “Les carrés” and w_{i} = 5, 7, 12 g g^{-1} for “Rivaulde”. Each curve represents a single test.

Fig. 4. Compression index C_{c} as a function of initial water content w_{i} and initial bulk density ρ_{i} for three representative soils: Mons with a medium fine texture, Epernay with a very fine texture and Rivaulde with a coarse texture. Initial bulk density was ρ_{i} =1.1, 1.3, 1.45 Mg m^{-3} and the initial water content w_{i} was respectively 18, 21, 27 % g g^{-1} for “Mons”, 13, 15, 17 % g g^{-1} for “Les carrés” and 5, 7, 12 g g^{-1} for “Rivaulde”. Each point represents a single test.

Fig. 5. Precompression stress as a function of initial water content and initial bulk density for three representative soils (Mons, Epernay, Rivaulde). The initial bulk density was ρ_{i} =1.1, 1.3, 1.45 Mg m^{-3} and the initial water content w_{i} was respectively 18, 21, 27 % g g^{-1} for “Mons”, 13, 15, 17 % g g^{-1} for “Les carrés” and 5, 7, 12 g g^{-1} for “Rivaulde”. For some high initial water content and low initial bulk density, it was impossible to determine the precompression pressure. Each point represents a single test.

Site	Depth	Culture	Partical size distribution			Organic Carbon	Aggregate density	Particle density	LL[a]	PL[b]	Ip[c]
			Clay	Silt	Sand						
	cm		g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	Mg m^{-3}	Mg m^{-3}	%	%	
Epernay	0-30	Vineyard	683	194	123	16.8	1.88	2.52	49	29	20
Fréville	10-25	Arable	641	152	206	16.0	1.92	2.51	64	40	24
Avignon	0-30	Arable	353	476	171	10.2	1.81	2.60	31	20	11
Mons	0-30	Arable	158	787	55	8.5	1.71	2.55	29	23	6
Boigneville	0-30	Arable	208	689	104	11.3	1.52	2.53	30	21	9
Nancy	10-30	Forest	258	581	161	11.9	1.58	2.59	38	25	13
Les Closeaux	0-30	Arable	147	613	240	11.1	1.75	2.55	29	22	7
Les carrés	0-25	Arable	185	446	369	10.7	1.75	2.58	23	17	6
Breuil	10-30	Forest	141	193	666	22.0	1.61	2.44	62	44	18
Rivaulde	2-18	Arable	31	74	895	12.7	-	2.56	20	-	-

Table 1. Soil Physical and mechanical properties of the experimental sites (a Liquid limit, b Plastic limit and c Plasticity index).

Soil	Regression	r^2
Epernay	$Cc= 2.87 - 1.59*\rho_i - 0.019*w_i$	0,98
	$\sigma_p= 8.08 + 116.54*\rho_i - 2.99*w_i$	0,82
Fréville	$Cc= 2.07 - 1.01*\rho_i - 0.014*w_i$	0,97
	$\sigma_p= -16.72 + 113.75*\rho_i - 2.18*w_i$	0,96
Avignon	$Cc= 1.85 - 0.91*\rho_i - 0.012*w_i$	0,98
	$\sigma_p= 4.19 + 202.54*\rho_i - 10.92*w_i$	0,95
Mons	$Cc= 1.24 - 0.52*\rho_i - 0.009*w_i$	0,89
	$\sigma_p= -206.27 + 316.46*\rho_i - 6.70*w_i$	0,81
Boigneville	$Cc= 1.54 - 0.65*\rho_i - 0.013*w_i$	0,79
	$\sigma_p= -421.23 + 507.76*\rho_i - 9.14*w_i$	0,79
Nancy	$Cc= 1.61 - 0.82*\rho_i - 0.007*w_i$	0,97
	$\sigma_p= -262.33 + 439.40*\rho_i - 8.39*w_i$	0,97
Les Closeaux	$Cc= 1.01 - 0.43*\rho_i - 0.008*w_i$	0,98
	$\sigma_p= -158.48 + 135.00*\rho_i + 0.75*w_i$	0,97
Les carrés	$Cc= 1.11 - 0.42*\rho_i - 0.010*w_i$	0,96
	$\sigma_p= -87.35 + 139.62*\rho_i - 2.78*w_i$	0,94
Breuil	$Cc= 1.36 - 0.95*\rho_i - 0.004*w_i$	0,96
	$\sigma_p= -223.85 + 229.47*\rho_i + 1.09*w_i$	0,82
Rivaulde	$Cc= 1.27 - 0.66*\rho_i - 0.011*w_i$	0,93
	$\sigma_p= -242.08 + 242.89*\rho_i - 4.08*w_i$	0,98

Table 2. Relationship between the compression index C_c and the precompression stress σ_p, and initial water content and bulk density for the ten studied soils.

Soil texture classes	Regression	r^2
Very fine (2 soils)	$Cc = 2.37 - 1.18*\rho_i - 0.017*w_i$	0.95
	$\sigma_p = 7.71 + 112.21*\rho_i - 2.82*w_i$	0.88
Fine (1 soil)	$Cc = 1.85 - 0.91*\rho_i - 0.012*w_i$	0.98
	$\sigma_p = 4.19 + 202.54*\rho_i - 10.92*w_i$	0.95
Medium fine (2 soils)	$Cc = 1.36 - 0.59*\rho_i - 0.010*w_i$	0.78
	$\sigma_p = -223.71 + 347.47*\rho_i - 7.93*w_i$	0.76
Medium (3 soils)	$Cc = 1.27 - 0.62*\rho_i - 0.006*w_i$	0.74
	$\sigma_p = -136.87 + 155.19*\rho_i$	0.5
Coarse (2 soils)	$Cc = 1.36 - 0.77*\rho_i - 0.005*w_i$	0.87
	$\sigma_p = -220.68 + 191.45*\rho_i + 2.77*w_i$	0.57

Table 3. Relationship between the compression index C_c and the precompression stress σ_p, and initial water content and bulk density for the five texture classes.

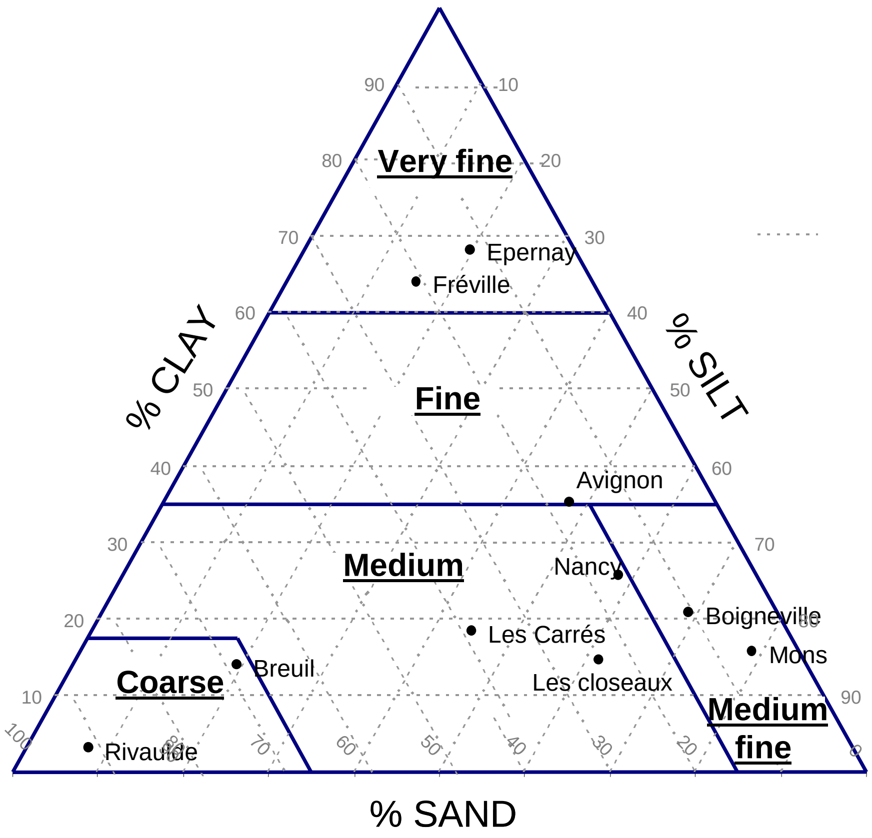


Figure 1. Soil texture at the different sites in the FAO classification scheme

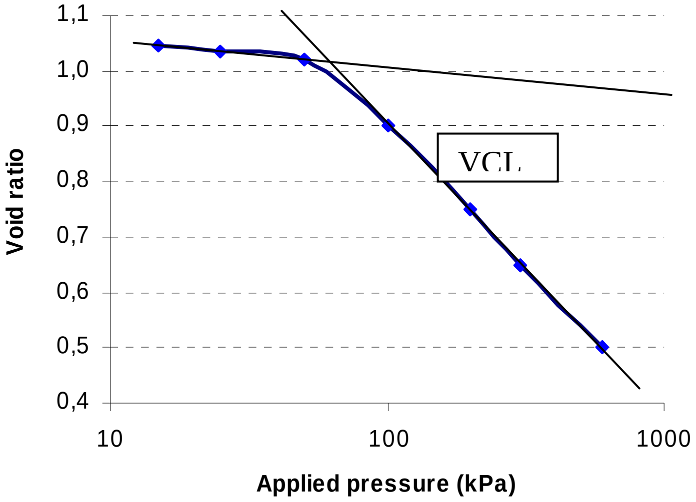


Figure 2. Determination of mechanical parameters: Cc et pc the intercept

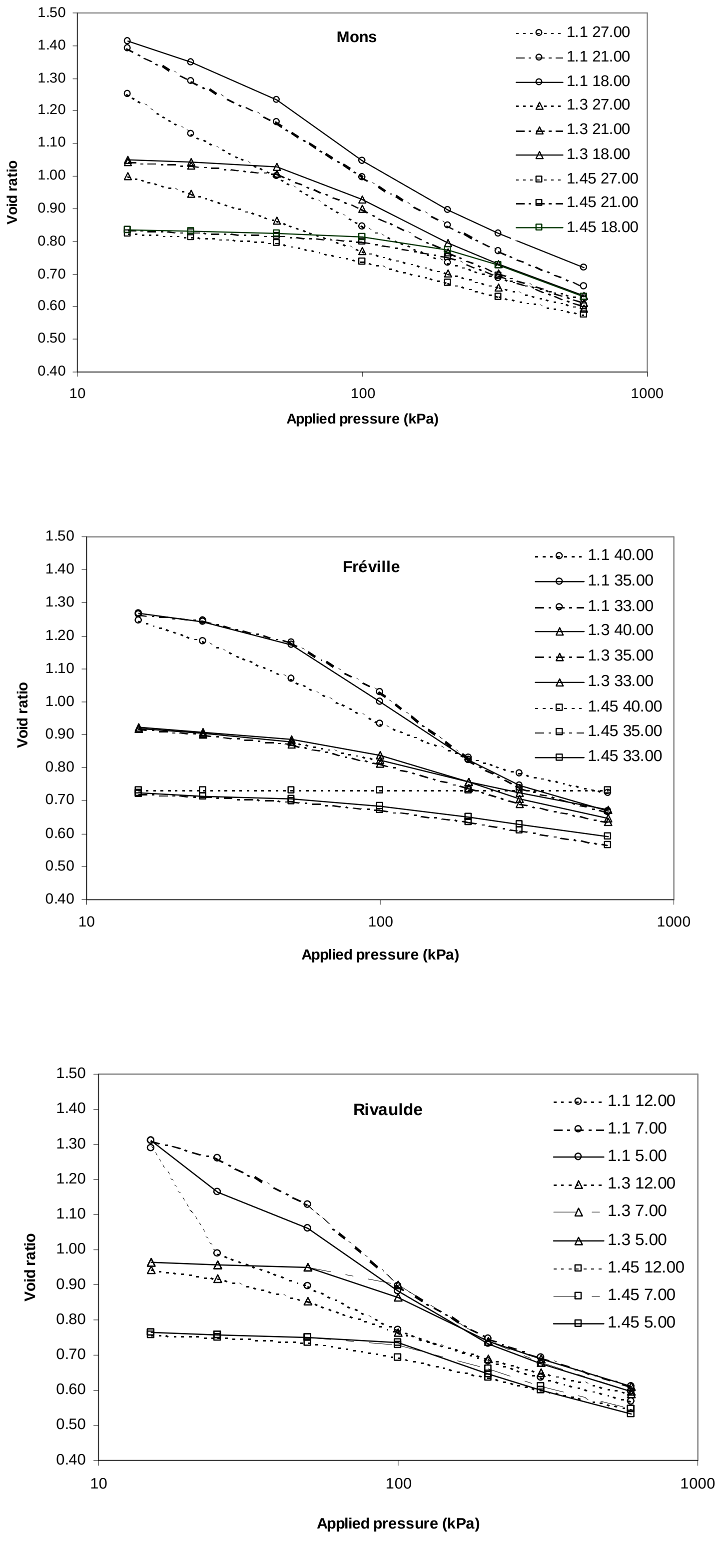


Figure 3. Compression curves for three representative texture classes soils: a medium fine texture (Mons), a medium texture (Les carrés) and a coarse texture (Rivaulde). Compression tests were performed at three different initial bulk density and three matric potentials: -100, -33 and -5 kPa corresponding at different initial water content depending on soil nature.

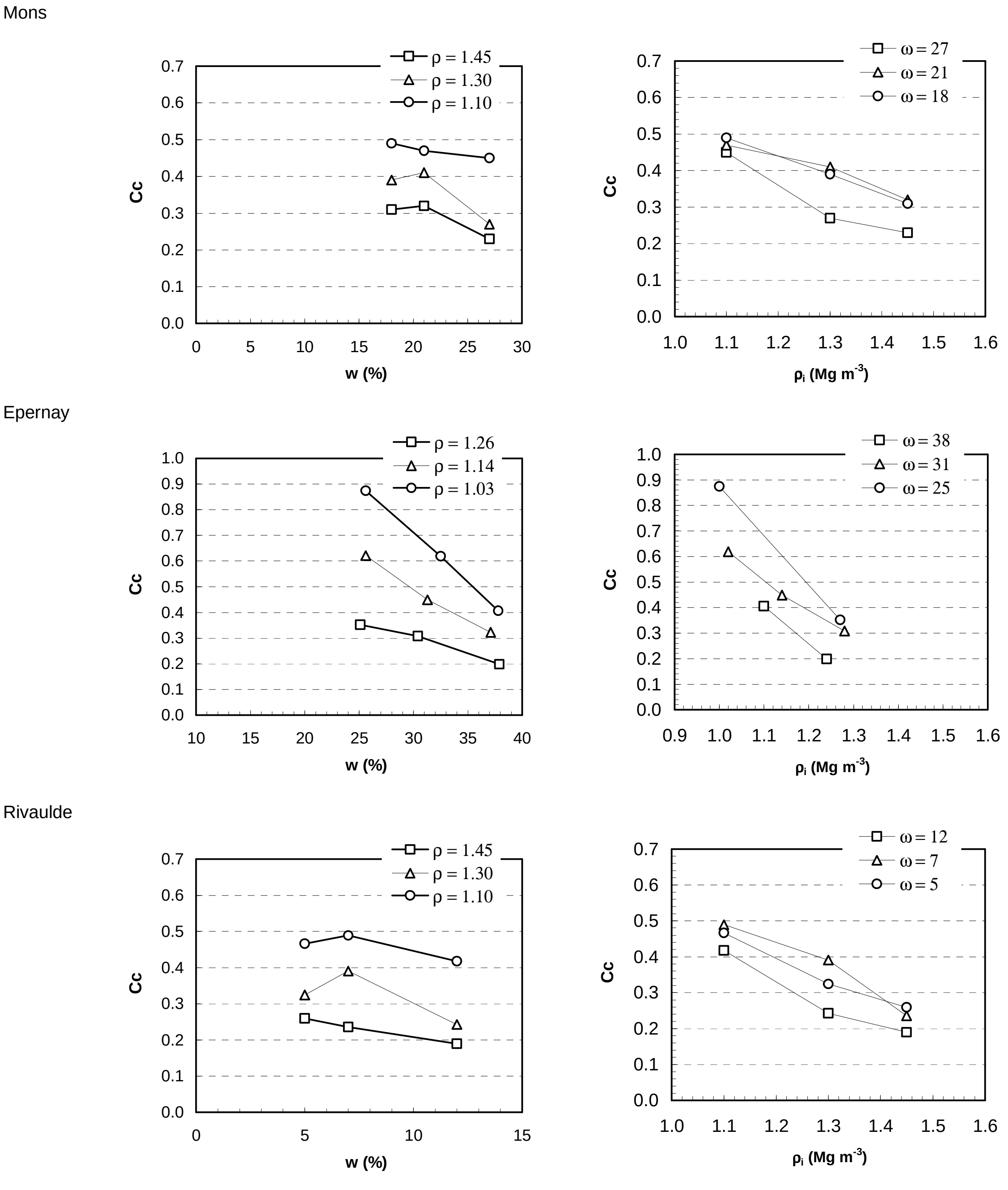
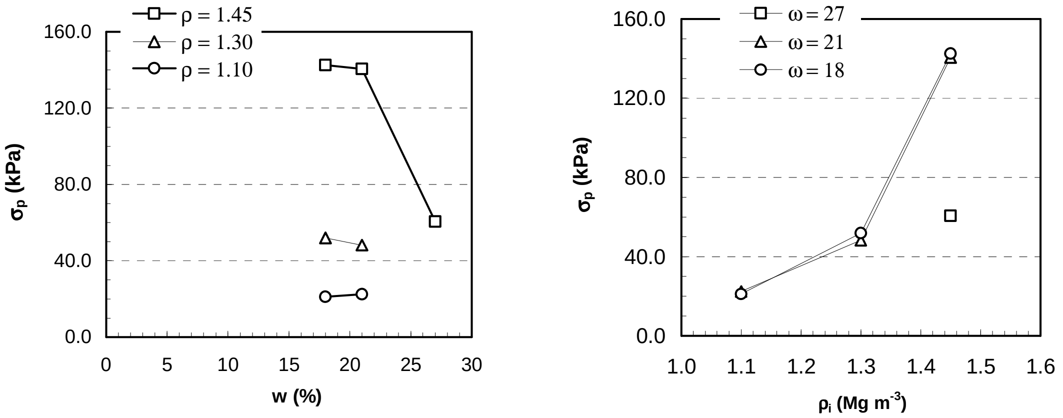
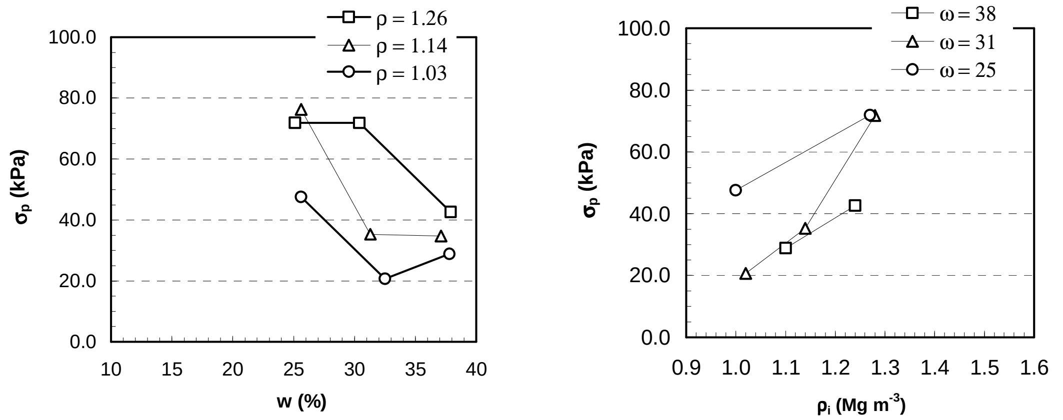


Figure 4. Compression index as a function of initial water content and initial bulk density for three representative soils: Mons with a medium fine texture, Epernay with a very fine texture and Rivaulde with a coarse texture.

Mons



Epernay



Rivaulde

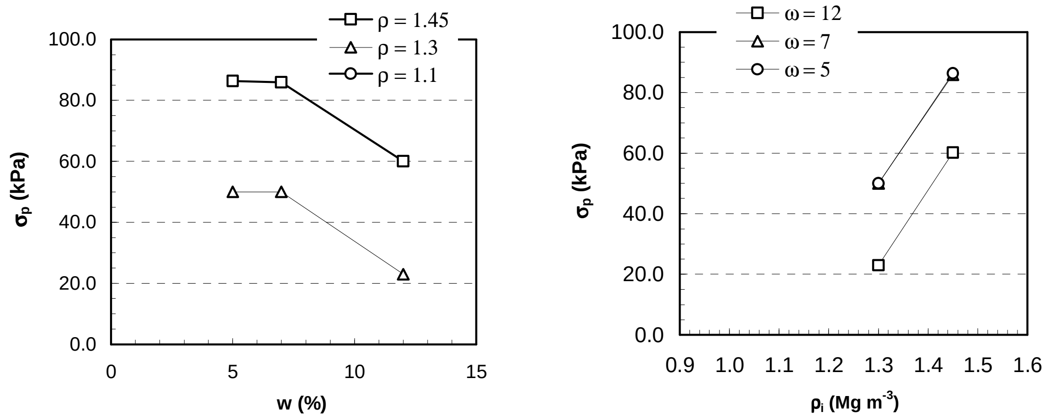


Figure 5. Precompression stress as a function of initial water content and initial bulk density for three representative soils.