Compaction processes in a tilled sandy soil

Lesturgez, G. [1, 2]*; C. Hartmann* [1]*; D. Tessier* [2] *and R. Poss* [1]

Keyword: sandy soil, oedometer, compaction, hydrocollapse, rearrangement

Abstract

Sandy soils are often considered as structurally inert because of their massive structure and the absence of shrink-swell properties. Frequent and severe compaction observed in agricultural fields raises the question of the processes and factors that control soil compaction and its reversibility. In the sandy upland soils of Northeast Thailand, subsoil compaction (20-40 cm) is a common feature that impairs root development and therefore is responsible for low crop production. The objective of this study was to determine the processes and factors that control soil compaction in order to improve soil management practices. Oedometer tests were conducted on aggregate beds. An initial loose layer was prepared and was subsequently submitted to a compression pressure. Two parameters were controlled: (i) the mechanical compression pressure, and (ii) the water content. A first series of experiments was carried out on aggregate beds (i) under dry conditions, (ii) under wet conditions, and (iii) by wetting dry samples under constant compression pressures. A second series of experiments dealt with the application of compression-relaxation pressures to understand their role on soil particle re-arrangement and to characterize soil elasticity.

Wet and dry compression curves appeared as envelopes delimiting the subsidence range. Results showed that soil structure collapsed almost entirely under low pressure and the phenomenon started at very low water content. The subsequent compression-relaxation curves showed the absence of soil elasticity.

We used theses results as a framework to understand sandy soil behaviour in the field. The results can explain why sandy soils are easily and inevitably compactable even under reduced traffic load. Because of low soil elasticity and the close contact between the soil particles after compaction, we suggest that a small bulk density increase can result in a high increase in penetration resistance, even in wet conditions. We conclude that alternative and adapted techniques such as slotting or biological drilling are options to manage the sandy soils in order to preserve or even improve their physical properties.

Introduction

Soil compaction in agricultural systems is a worldwide concern and has received considerable attention over the past decades (Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005). Soil compaction is defined as: “the process by which soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density” (Soil Science Society of America, 1996). The vast majority of soil compaction in modern agriculture is often attributed to heavy machinery and traffic load (Flowers and Lal, 1998). However other processes can be involved and soil compaction may occur without traffic load on soil surface. For example, the formation of a dense subsoil layer known as “fragipan” is interpreted by soil collapse under its own weight. This process occurs when a metastable arrangement of particles is wetted under a constant confining pressure (weight of the top layer in the case of natural collapse) (Assallay *et al.*, 1997; 1998).

Sandy soils are often considered as structurally inert because of their weak structure and the absence of shrink-swell properties but frequent and severe compaction observed in agricultural fields raises the question of the processes and factors that control soil compaction and its reversibility. In the sandy upland soils of Northeast Thailand, subsoil compaction (20-40 cm) is a common feature that impairs root

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[1] IRD, UR176 SOLUTIONS, Land Development Department, Office of Science for Land Development, Phaholyothin Road, Chatuchak, Bangkok 10900, Thailand, gregory.lesturgez@ird.fr

[2] INRA, Unité de Science du Sol, Centre de Recherche de Versailles-Grignon, Route de St-Cyr, 78026 Versailles, France.

development and therefore is responsible for low crop production (Bruand *et al.*, 2004). Comparisons between forest and adjacent cultivated area have proved that the compact layer commonly observed in agricultural fields was induced by intensive agriculture of the last decades (Lesturgez, 2005). Sandy soils of the region have developed mainly from light textured aeolian material (Boonsener, 1991) well known for its problematic characteristics for engineering works (Udomchoke, 1991; Kohgo *et al.*, 2000). On the other hand, deep ploughing and subsoiling have always been inefficient in overcoming this compaction in agricultural systems since soil re-compacts after the first heavy rain. This suggest that collapsibility is a key factor not only in deep profiles but also in the superficial and tilled layers (Hartmann *et al.*, 1999; Hartmann *et al.*, 2002).

Compaction of aggregates beds in a dry state, hydrocollapse (also known as hydroconsolidation) and load-upload cycles under the same pressure (traffic load conditions), can be involved in the formation or the reformation of a compact layer. The objective of the study was to investigate the processes of soil compaction in a tilled sandy soil subjected to non-flooding rains and evaluate their respective contribution to total soil compaction. Experiments focussed on uniaxial compactability, hydrocollapse and rearrangement under traffic load.

Material and methods

Soil characteristics and sampling

The samples were collected in a sugarcane field located in Ban Phai District, 40-km from Khon Kaen City, Northeast Thailand (16°08′N, 102°44′E). The choice of the site was based on a previous investigation that highlighted the presence of a compact layer located at 20-40 cm depth that was representative of the general situation of subsoil compaction (Lesturgez, 2005). The soil has a sandy texture with no or very weak structure. It belongs to the Nam Phong soil series (Imsamut and Boonsompoppan, 1999) and was classified as a loamy, siliceous, isohyperthermic Arenic Haplustalf (Soil Survey Staff, 1998) or Arenic Acrisol (FAO, 1998). Three undisturbed samples were collected from the vertical face of a pit, respectively in the topsoil (0-15 cm), in the compact subsoil (15-25 cm) and underneath the compact layer (40-50cm). Selected chemical and physical characteristics of the samples are presented in Table1. Mineralogical characteristics of the studied soil were investigated using X-ray diffraction. When the sand and silt fractions were exclusively constituted of quartz, the clay fraction included kaolinite, traces of illite and a significant proportion of small quartz particles. The three samples were identical in their mineralogy and the particle size distribution of the sand fraction. They differed only in their clay content (from 70gkg^{-1} in the topsoil to 136 g kg^{-1} in the deepest layer). A last sample (pure sand material) was prepared from the topsoil horizon by sieving the >50 µm material from the whole soil after dispersion in sodium hexametaphosphate.

Sample preparation

The samples were manually crumbled in the laboratory in order to produce small aggregates similar to tillage-induced aggregates. The aggregates were poured into a ring 50mm in diameter, and 18mm in height placed on a porous plate using a small funnel fixed 5-cm above the middle of the ring. The ring was overfilled, then the surface was carefully levelled off, and the assemblage thoroughly cleaned with a small brush. The assemblage was then installed in the oedometer and the top cap gently positioned. Preliminary tests had shown that the preparation of the aggregate beds using this method allowed the formation of a metastable arrangement of aggregates with a bulk density similar to that of the topsoil after ploughing.

Design of the oedometer apparatus

The oedometer test is classically used for consolidation and compression studies of fine-grained soil samples, such as clays and silts, since it recreates the conditions of volume change with zero lateral strain (i.e. one-dimensional compression). The oedometer apparatus used (Figure 1) allows the application of an axial load that ranges from 0 to 1,500 kPa. We applied a range of 29 pressure steps (2, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,100, 1,300 and 1,500 kPa), with 5 minutes interval between each step (minimum duration to reach equilibrium). The change in volume of the samples was recorded continuously by measuring the vertical displacement of the rigid top platen used to apply the load. The design of the apparatus allows the injection of water on the top of the sample. Drainage was free through the porous plate located below the sample. The volume of water injected into and drained from the samples can also be recorded. Bulk density and average water content were derived from these measurements. The background noise of the oedometer originating from internal deformation (porous plates) and elasticity of the

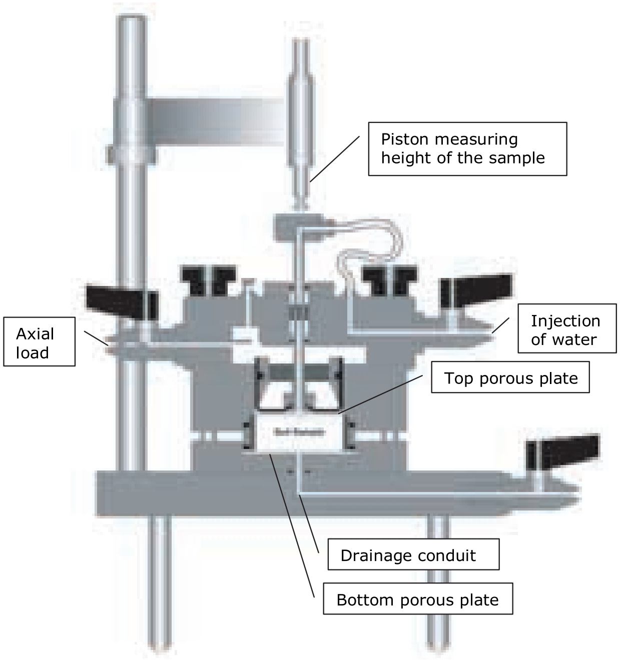

Figure 1. Oedometer apparatus

membrane was estimated during preliminary tests on uncompressible Plexiglas cylinders and results were corrected accordingly.

We used the following experiment to characterize the compaction in dry and wet conditions:

(a) To characterize the behaviour in dry conditions, an air-dried aggregate bed of the control and the three horizons was prepared with five replicates. The series of pressure steps was applied and the changes in bulk density recorded.

(b) To characterize the behaviour in a wet state, an identical set of aggregate beds was prepared. The beds were saturated by injecting water under no load until drainage began at the bottom of the samples. The series of pressure steps was then applied while the samples were kept saturated in a free draining state. The changes in bulk density were continuously recorded.

Hydroconsolidation tests

Hydroconsolidation is characterised by an abrupt change in bulk density of samples loaded at their *in situ* water content and then flooded. Hydroconsolidation under a constant load P_w was studied in a three-stage test:

(a) Air-dried samples (5 repetitions for each depth) were loaded step by step to a constant load P_w of 2, 100, 500 and 1,500kPa.

(b) While the axial load P_w was maintained on the sample, water was injected at $50mm^3min^{-1}$ through the porous plate located on the top of the sample until drainage started at the bottom of the porous plate.

(c) The load was then increased step by step on the wet samples from P_w to 1,500kPa. Water continued to be added freely at no pressure to keep the sample wet until the end of the test.

Compression-relaxation tests

The purpose of this test was to characterise subsequent compaction (i.e. rearrangement processes) under a series of identical axial loads in wet conditions. The test consisted of a series of compressions/relaxations applied on wet samples:

(a) Five samples of each horizon were saturated and then loaded step by step to create stresses P_R of 100, 500 and 1,500kPa. Water was added freely at no pressure to keep the samples wet throughout the test.

(b) A series of 70 cycles of compression (P_R) and relaxation (0 kPa) was applied on the wet samples. Bulk density was continuously recorded.

Results

Figure 2 presents the compaction curves using the classical compaction approach. Both dry and wet bulk density measurements are presented as a function of axial load. For the pure sand, compaction due to axial load was very low over the range of pressures and there was no significant difference between dry and wet curve (Figure 2-a). Compaction was low and highly heterogeneous between replicates for the three soil samples up to 25kPa. There was no significant difference between the dry and wet samples in this range of pressures (Figure 2-b, c, d). Bulk density increased sharply above 25kPa and became more homogeneous. Beyond 100 kPa, the bulk density increased with depth for any given load all soil samples (Figure 2-b, c, d). At 1,500kPa the dry bulk densities reached 1.60, 1.63 and 1.69 $Mg.m^3$ for the 0-15, 15-25 and 40-50cm depths, respectively.

Figure 3 presents the results of the hydro-consolidation test on the pure sand material. The compaction either in the dry or wet state was almost insignificant and there was no significant difference between the dry curve and the wet curve at any pressure. Therefore, the collapse was insignificant.

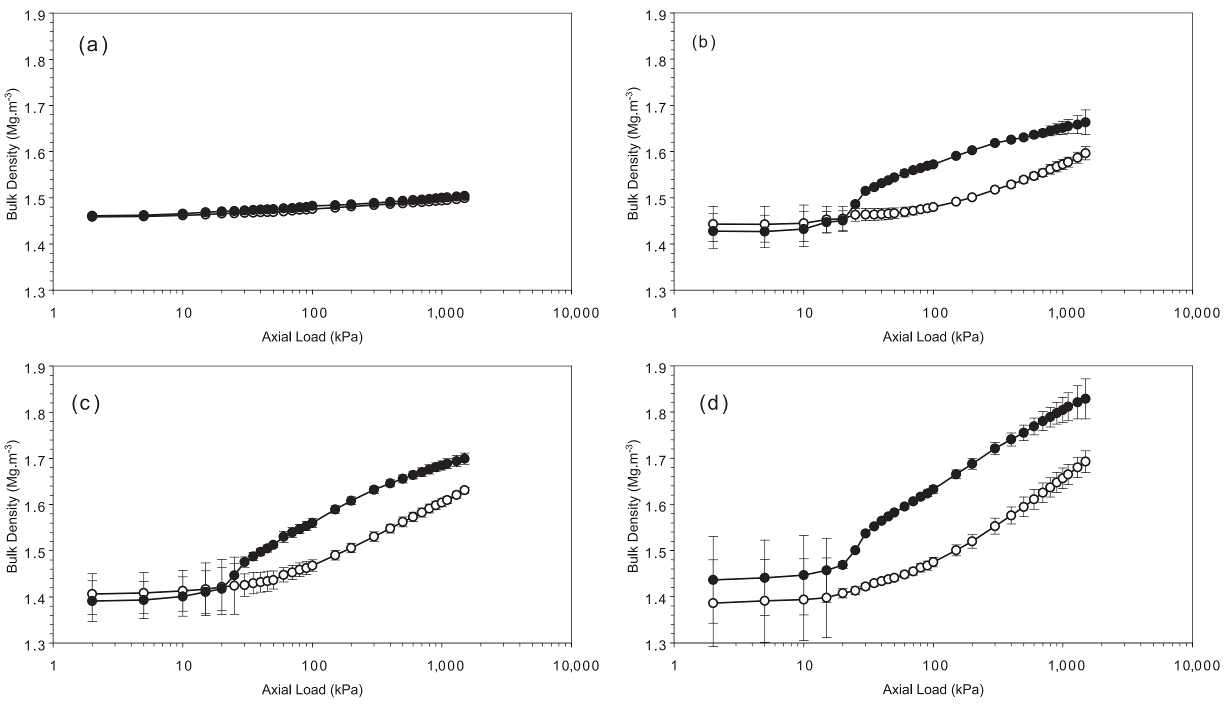

Figure 2. Air-dried (–○–) and wet (–●–) compaction curves for (a) sand fraction, (b) 0-15 cm, (c) 25-35 cm, and (d) 40-50 cm. Average and standard deviation (n = 5)

Figure 4 presents the results of the hydroconsolidation test together with the results of the compaction test for the 25-35cm depth layer. Collapse resulting from water injection (represented on the chart as white arrows), always resulted in a final bulk density between the dry and the wet compaction values. The increase in bulk density as a result of hydrocollapse was quite similar over the range 50 <Pw <1,500kPa, even though the largest bulk density change was recorded for an axial load of 100kPa. The bulk density after hydrocollapse was sometimes significantly lower than that of the wet curve ($P < 0.05$). However, the difference was no more significant when the loads were increased after hydrocollapse had occurred. As the dry and wet compaction curves tend to get closer at high pressure, we can assume that for very high loads, no more collapse will occur.

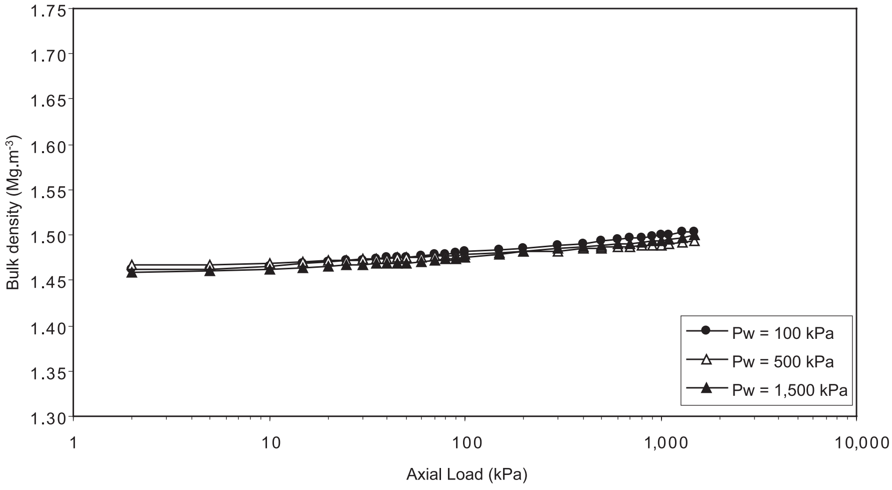

Figure 3. Hydrocollapse curves for pure sand material

Figure 5 presents the changes in bulk density with increasing water content at constant load (P_w= 1,500 kPa) for the three soil horizons.Two replicates are presented for each depth as a means to highlight heterogeneity. In agreement with the compaction in wet conditions, the lowest collapse was recorded for the 0-15cm depth sample, and the intensity of collapse increased with depth. Collapse always occurred in a range of gravimetric soil moisture between 5 and 15%.

Figure 6 presents the compression-relaxation curves. The bulk density increased by at least 0.1T $.m^{-3}$ at P_R=1,500kPa from the initial compaction to the end of rearrangement cycles. The soil samples presented significant elasticity. The material recovered a significant proportion of the porosity when the axial pressure was relaxed but some of the deformation is

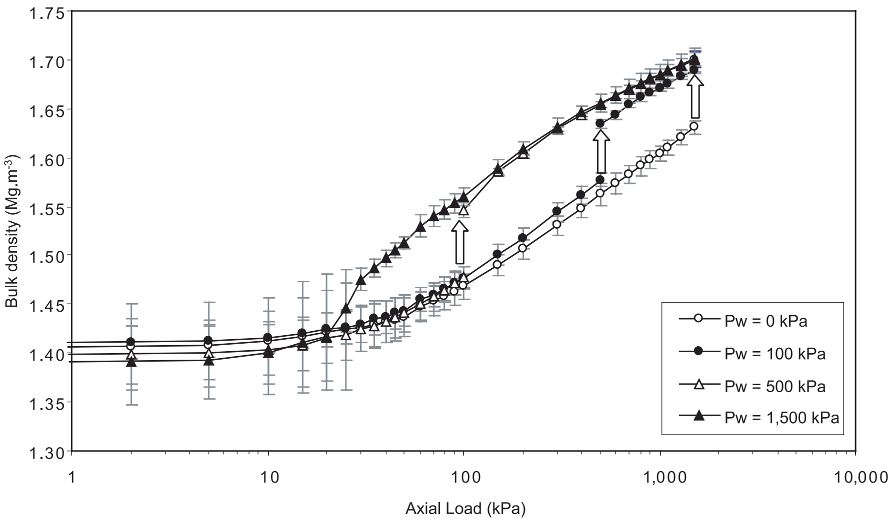

Figure 4. Hydrocollapse curves for 23-35 cm soil sample

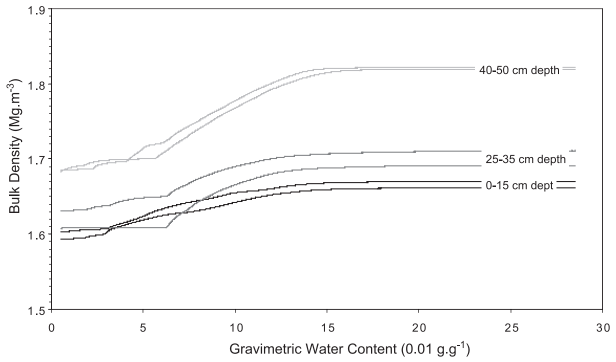

Figure 5. Bulk density versus depth during collapse at Pw = 1,500 kPa

non-reversible and the bulk density increased for each cycle. The deformation intensity decreased as the number of cycles increased. The rearrangement intensity increased with depth. Similar results were obtain at P_R=100 and 500kPa (data not shown).

Discussion

Compaction of the pure sand

For the pure sand, the sensitivity to compaction, in dry and in wet conditions as well, was very small and can be considered as being independent of the applied pressure (Figure 4). The sand grains did not reorganize under pressure, even when wet. This result suggests that the lubricant effect of the water was ineffective in the case of this material. Two factors can explain this unusual behaviour. Firstly, the bulk density was already 1.46T m $^{-3}$ at the beginning of the experiment, probably because the size of the sand grains was distributed over a large range (Table 1). Secondly, most sand grains had a jagged shape according to them aeolian origin, that probably resulted in interlocking between the grains (Lesturgez, 2005).

Compaction of soil samples

In contrast, the compaction curves recorded with the soil samples in wet condition proved that the same sandy material mixed together with clay and silt was highly compactable. In dry conditions compaction started at around 25kPa and increased with increasing pressure until 1,500kPa. In the case of aggregate beds, collapse was in part the consequence of the deformation of the aggregates (Faure, 1976). This process was not active in the pure sand material under study because aggregates were absent. Dry compaction may in part result from the deformation of clay particles. However, the contribution of this process must be limited, given the low clay content of the material (Table 1) and the high proportion of quartz grains within the clay fraction (Bruand *et al.*, 2004). The major contributing factor associated with compaction was probably due to lubrication, the planar-shaped clay minerals helping the sand grains slip against each other.

Hydrocollapse

When water is injected in the samples, hydrocollapse proved to be a phenomenon that

Table 1. Selected physical and chemical properties of the soil at the study site

	Particle size distribution (g kg^{-1}) *mesh equivalent diameter in μm*							pH	CEC (cmol$_c$ kg^{-1})	BD (Mg m^{-3})	
	<2	2-20	20-50	50-200	200-500	500-1,000	1,000-2,000			Mean	SD
10-15 cm	70	81	122	614	100	11	2	6.1	3.2	1.61	0.13
25-35 cm	86	87	122	601	94	8	2	5.6	3.0	1.75	0.04
40-50 cm	136	88	115	565	86	8	2	4.6	3.9	1.67	0.02

CEC is cation-exchange capacity measured in cobalt-hexamine, BD is dry bulk density measured in the field using cylinders and SD is standard deviation (n = 5).

developed fully under constant pressure and at any given pressure (Figure 3). Indeed, whatever the initial pressure, the final bulk density was almost identical to the bulk density obtained by compaction in wet conditions. This result, consistent with the observations of Assallay *et al.* (1998) on loess materials, has a direct application in predicting the collapse. Maximum collapse under any load can indeed be estimated by the difference between the dry and wet compaction curves under the considered load. Maximum hydrocollapse was recorded for P_w=200kPa, close to the value of 100kPa observed by Assouline *et al.* (1997) on aggregate beds. It has been shown in aeolian deposits that collapse needed a small amount of clay to develop (Rogers *et al.*, 1994), and that collapse intensity increased with clay content up to 25% clay (Assallay *et al*., 1998). The same increase in hydrocollapse with clay content was observed in this experiment, but the range of clay content covered by the three samples was not sufficient to determine a maximum value. The increase in water content with clay content for hydrocollapse to develop (Figure 5) suggests that the process is related to the hydration of the clay minerals. Faure (1976) mentioned the importance of the clay fraction in compaction of sandy soil and introduced the notion of water potential and clay hydration. In the three horizons hydrocollapse started between 3 and 7% of gravimetric water content. This low water content proves that the phenomenon becomes active in any horizon as soon as it gets wet. The samples presented a mechanical behaviour similar to metastable deposits (Assallay et al., 1997). These properties, usually associated with loess and loess-like deposits (Jefferson et al., 2003), are therefore not confined to silty materials and develop also in sandy soils.

Compression-relaxation cycles

The mathematical description of soil compaction is based on relationships between bulk density and applied stress (Assouline, 2002). This approach assumes that after a sample has been consolidated under a pressure P_1, the consolidation would resume only for a pressure $P_2 > P_1$ (Guérif, 1982). This theory is not applicable to the results of this study as a series of successive stresses under the same axial load resulted in a substantial increase in bulk density (Figure 6). The relaxation between successive stresses allowed the internal friction between sand grains to decrease and therefore permitted the network of forces to reorganise during the next axial load, leading to increased bulk density. The asymptotic shape of the curve showed the development of the soil structure towards the highest possible bulk density. The rearrangement test in a wet state is probably the most representative test to simulate vehicle traffic load as it models as series of confined uniaxial stresses under the same pressure.

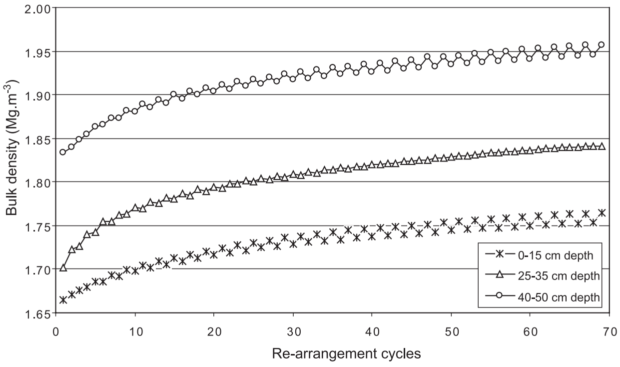

Figure 6. Bulk density during compression-relaxation cycles (0-1,500kPa)

Contribution of the different processes to total soil compaction

The contribution of dry compaction, hydrocollapse and compression-relaxation cycles to bulk density increase was estimated from our results at a load of 1,500kPa. The last series, namely “field” is the bulk density measured in the field using cylinders (Figure 7). The effect of the three processes on bulk density increased with clay content. However, the contribution of the three processes to bulk density increase remained similar in relative value whatever the clay content. Dry compaction represented around 50% of total compaction, when hydrocollapse and rearrangement ranged between 20 and 30%. In the field dry compaction and hydrocollapse under low pressure (weight of the upper soil horizons) are the first two processes to develop after tillage. The many tillage operations usual in the region induce through a succession of traffic loads, rearranges the fabric to produce the usual massive aspect of the soil with high bulk density. The close lay out of grains, with small particles filling the voids left between bigger ones, has been described by Bruand *et al.* (2004) as the main factor of high resistance to penetration of the compact layer. Finally, as soil sensitivity to compaction increases with clay content and clay content increases with depth, the most sensitive horizons are the deepest. As a consequence the deeper the soil tillage, the higher is the risk of compaction and the final density. The bulk density is highest in the 20-40cm layer probably because this layer supports the wheels of the tractors during ploughing (at least three times a year). Surface axial load due to vehicle traffic may also be transmitted to subsoil horizons through the massive and often dry

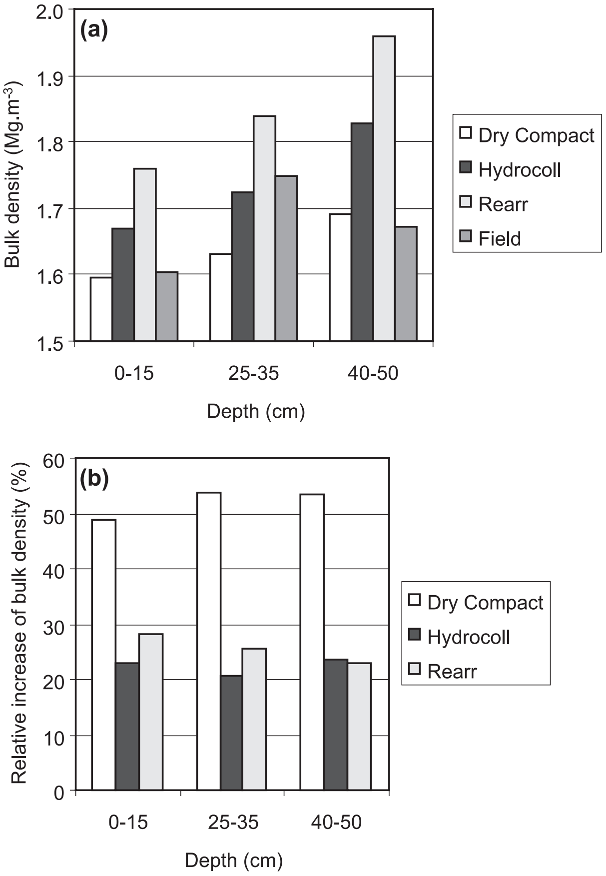

Figure 7. Dry compaction, hydroconsolidation and rearrangement (compression-relaxation cycles for each depth at Pw = 1,500 kPa

topsoil, increasing bulk density through rearrangement processes. In the field the highest bulk density values were recorded in the 20-40 cm (Figure 7) depth interval despite the higher sensitivity to compaction of the lower horizon (Figure 2). Two kinds of tillage operations are to distinguish: frequent tillage of the 0-20 cm interval depth and some punctual deep tillage operations with the objective to break the compact layer. As the soil is highly collapsible and sensitive to rearrangement, the density of the post-tilled layer reach inevitably high values as a function of time. The frequency of tillage in the topsoil (0-20cm) does not allow high density as in the 20-40cm interval depth as the structure return frequently to the tilled state. However, the 20-40cm interval depth benefits as it has the enough time to accumulate the combine effect of the traffic load. As for the lower layers (>40 cm depth), tillage operation have never change organisation of the structure and if aggregates beds from this layer are highly sensitive, the actual weakly developed structure is stable. It has been shown that tilled layers are much more sensitive to compaction than massively structured or already compacted subsoil (Schäfer-Landefeld *et al.*, 2004). Porosity of this layer is mainly constituted of biopores which are usually stable because they develop in a stable structure (Dexter, 1987; Bruand *et al.*, 1996). These results suggest that the deeper the soil is tilled, the higher is the risk in obtaining high bulk densities. Deep tillage is therefore not an option to rehabilitate compact subsoils due to the instability of the resulting structure. However, alternative techniques such as slotting (Hartmann *et al.*, 1999) or biological drilling (Lesturgez *et al.*, 2004) have proved to be efficient is such unstable soils. These techniques ensure the development of pathway for the roots through the compact layer and preserve the massive and stable structure surrounding them.

Conclusions

The compaction of the sandy material studied under uniaxial load was trivial, even in wet conditions. The same material was highly sensitive to compaction when mixed with silt and clay. The sensitivity to compaction increased with increasing clay content. Compaction in the dry state, hydrocollapse (collapse under increasing water content at constant pressure) and rearrangement under a series of successive loads were more pronounced when clay content increased. However, the contribution of each phenomenon to final bulk density was approximately constant whatever the clay content. Most part of soil compaction (around 50%) was due to dry compaction. Hydrocollapse explained about half of the remaining compaction. Hydrocollapse was responsible for sharp increases in bulk density as a result of small increases in water content (gravimetric water content between 3 and 7%), even under low pressure. The rearrangement under successive loads explained 20 to 30% of the final bulk density, even though the bulk density was already higher than 1.65Mgm $^{-3}$ after dry compaction and hydrocollapse. As clay content increased with depth, the deeper horizons were the most sensitive to compaction. The highest bulk densities were however measured in the 20-40cm layer in the field. The direct traffic load resulting from the many ploughings a year usual in the region is probably a part of the explanation but the structural effect of deep ploughing (which changed the massive structure of the layer into a metastable organisation of aggregates very sensitive to densification) is probably the main factor. Deep tillage is therefore not an option to rehabilitate compact subsoils due to the instability of the resulting structure and alternative techniques conserving part of the initial stability are recommended.

Acknowledgments

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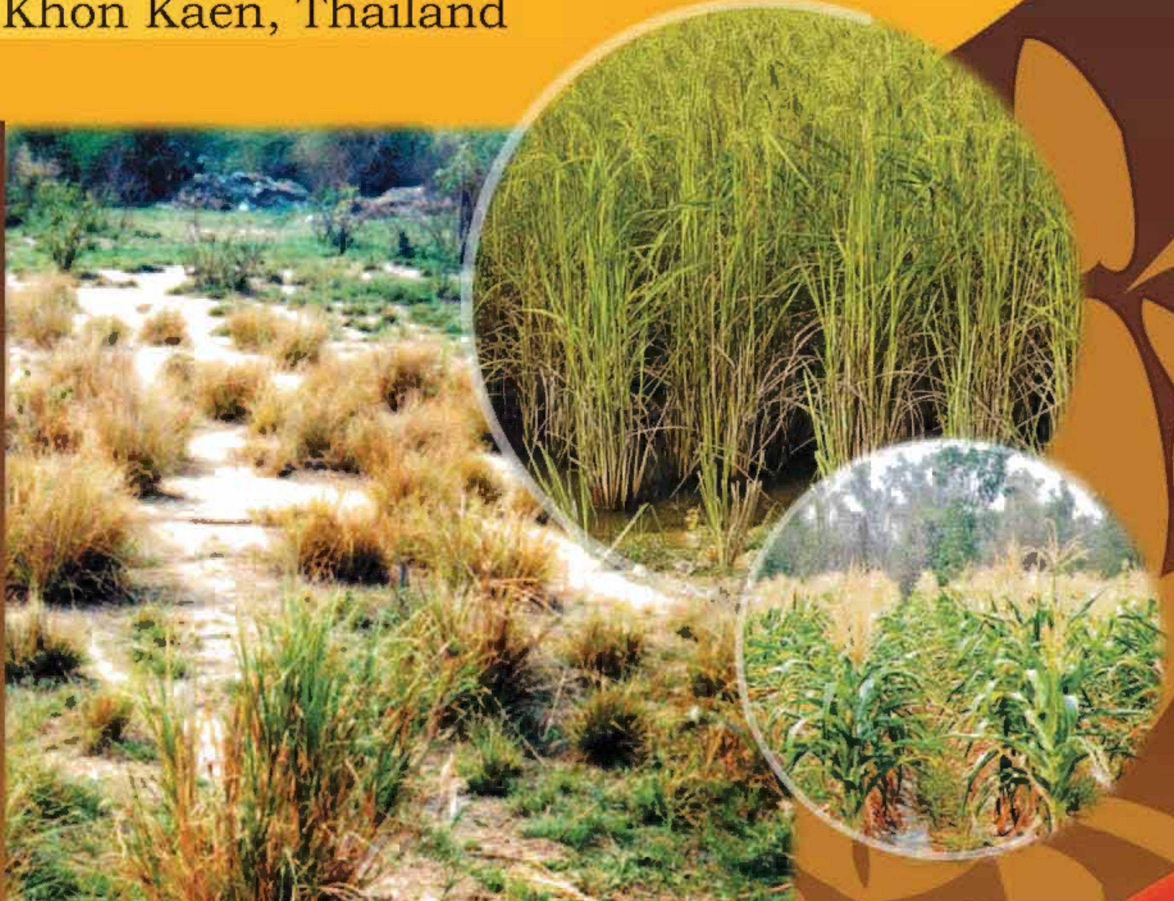

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For copies write to:
Yuji Niino
Land Management Officer
FAO Regional Office for Asia and the Pacific
Maliwan Mansion, 39 Phra Atit Road
Bangkok 10200
THAILAND
Tel: (+66) 2 697 4000
Fax: (+66) 2 697 4445
E-mail: Yuji.Niino@fao.org

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