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Abstract

Compaction of tilled layers under the single effect of rainfall or irrigation was called slumping. Slumping affects strongly root development and plant biomass production and was observed in different soil types but sandy soils appear particularly prone to this physical degradation. Our objectives in this study were (i) to monitor in the field the changes in soil structure and water status simultaneously, (ii) to study the effects of rainfall and management practices on slumping and (iii) to propose a conceptual model for sandy soil slumping.

An experimental site was selected in Northeast Thailand and we tested the effect of tillage depth and initial water content on slumping dynamic. Plots (9 m×15 m) were tilled at (i) two depths (20 and 40 cm, called S and D respectively) in dry conditions, (ii) at 20 cm depth in dry or wet conditions (called Y and W respectively). These plots were submitted to natural rainfall for 20 or 61 days to get different total rainfall amounts (114 and 212 mm respectively). In addition, smaller plots (0.24 m^2) were used for experimental flooding irrigation (equivalent to measured rainfalls, i.e. 100 and 200 mm). Soil bulk density, soil surface elevation, soil water content and matric potential were recorded.

A decrease in soil elevation was observed in all treatments. In the absence of erosion it was interpreted as a loss of porosity which resulted from slumping. Bulk density increased in all layers of the tilled profile (from 1.38 to 1.57 g cm^{-3}). In the surface layer (0-5 cm) this increase was systematically higher compared to deeper layer. No significant difference in final bulk density was found between the S and W treatments, and between the Y and W treatments. Bulk density increased more rapidly in the Y and W treatments than in the S and D treatments, even though the cumulative rainfall was lower. After flooding experiments, bulk density was higher than after natural rainfall despite similar water amount brought to the soil.

The existence of a layer with 50 % porosity straight after tillage was explained by the capillary forces developed by water bridges between the elementary grains. Models of wet granular material indicate that a drastic loss of cohesion can occur when the liquid phase becomes continuous. Indeed slumping was observed during the downward movement of the water front inside the profile which is consistent with this hypothesis. As the existence of a continuous liquid phase along the profile is the most determinant factor of slumping, all rainfall characteristics determining the existence of such a continuous liquid phase will affect slumping, i.e. rainfall intensity, duration and frequency. For given rainfall characteristics, slumping dynamic and intensity depend on the bulk density at the onset of the rainfall or irrigation event. The high variability recorded in earlier field result from the many possible interactions between these determining factors.

Keywords: Recompaction; Bulk density; Matric potential; Northeast Thailand; Tillage; Overburden pressure

1. Introduction

Soil tillage aims at creating favorable physical conditions for crop growth by modifying the soil structure and associated properties of the tilled layer (Guérif et al., 2001). However, the desired loose structure tends to be structurally unstable and is susceptible to structural collapse thus leading to a loss of the benefits for root development provided by soil (Hartmann et al., 2008a; Hamza and Anderson, 2005). Soil recompaction (i.e. bulk density increase to initial level) is a general phenomenon which has several causes related to external and internal forces. External force is defined as loading from outside the soil profile, such as tractor loading, rainfall kinetic energy; internal force is defined as force inside the soil profile, such as overburden pressure, capillary force. Soil recompaction is commonly attributed to mechanized agriculture alone because the weight of the agricultural and forestry machinery has been increased three- to fourfold as well as the frequency of wheeling during recent decades (e.g. Soane et al., 1981a, b; Soane et al., 1982; Soane, 1990; Horn et al., 1995; Soane and Van Ouwerkerk, 1995; Soane and Ball, 1998; Hamza and Anderson, 2005). The phenomenon of bulk density increase recorded after wetting and without application of any external load was termed '*slumping'* (Kemper and Rosenau, 1984; Mullins et al.1990). While compaction, i.e. the bulk density increase resulting from mechanical loading was widely studied, much less attention has been paid to slumping.

For coarse-textured soils, Kemper and Rosenau (1984) suggested that slumping is related to soils saturation or matric potential ψ close to 0 hPa. Slumping is a ubiquitous phenomenon and was recorded under a wide range of conditions. It was recorded after a single rainfall event (20 mm in one hour) (Mead and Chan, 1988), two natural rainfall events (80 mm in 160 min) (Hartmann *et al.*, 1999), eight weeks of measuring (Osunbitan et al., 2005), and a cropping season (Hamblin and Tennant, 1979). Moreover, slumping can affect the whole tilled layer (such as down to 40 cm depth in Moffat and Boswell, 1997), and can have similar adverse effects on crop development as well as compaction resulting from mechanical loading (Kozlowski, 1999). Despite its ubiquity and importance, no study has provided yet a detailed description of the dynamics of slumping and its main field characteristics. In the context of the extension of cultivated lands to marginal areas, which often include a high proportion of sandy soils (Eswaran *et al*., 2007), it is a challenge to look for soil management that could minimize the occurrence of slumping. As a first step in this direction, the objectives of our study were: (i) to monitor the changes in soil structure and water status simultaneously at the field scale; (ii) to study the effects of rainfall and management practices on slumping and iii) to propose a conceptual model of sandy soil slumping.

2. Material and Methods

2.1. Field description

Northeast Thailand is a sandy alluvial plateau covered by an aeolian deposit (approximately 1 m thick) mainly made of quartz grains. More than 80% of the grains belong to the sand fraction (50-2000 µm) and about 10% to the silt fraction (2-50 µm) (Lesturgez et al., 2004; Bruand et al., 2004). The clay fraction (<2µm) is less than 10% and contains phylosilicates (mainly kaolinite and small amount of smectite) but also quartz grains (Bruand et al., 2004). An experimental site was selected in a village named Baan Nong Sang (WGS84: 16°10' N, 102°48' E), 30 km south of the city of Khon Kaen. The soil is representative of the region with a sandy texture (< 4 % clay), low organic matter content (< 5 g kg^{-1}) and high bulk density ($\rho_b \geq 1.6$ g cm^{-3}) (Table 1 and 2). This field was planted with cassava in 2006 and harvested in February 2007. To minimize the effect of coarse crop residues fragments (cassava branches and leaves, weeds, etc.) on the different soil physical characteristics, they were removed from the plot before tillage operations. To prevent weed growth, an herbicide was applied three times during the experiment.

2.2. Control of the rainfall pattern and amount

Three experiments were conducted at different periods to get different rainfall distribution and rainfall amount:

- Experiment 1 (Exp. 1): plots were tilled on 25 May, i.e. at the beginning of the rainy season that is generally characterised by storms separated by several dry days. The experiment was stopped on 1 August;
- Experiment 2 (Exp. 2): plots were tilled on 6 July, i.e. in the middle of the rainy season to get a different rainfall pattern (more regular distribution of the rainfalls and thus less frequent dry spells). The experiment was also stopped on 1 August;
- Experiment 3 (Exp. 3): mini-plots (0.24 m^2) were artificially flooded; the amount of water added was similar to the rainfall amount recorded in Exp. 1 and Exp. 2. The experiment was done between 18 to 26 July.

Rainfall was recorded daily using the average readings from two rain gauges (±1 mm precision) that installed inside the experimental field.

2.3. Experiment 1

The objective of Exp. 1 was to study the effect of tillage depth on slumping characteristics. Soil preparation treatments consisted of two tillage depths: 20 and 40 cm, called shallow (S) and deep (D) treatments respectively. Each treatment was applied to five elementary plots (9 m×15 m each). Tillage was performed using a 120-horse-power tractor equipped with a set of disk plough. In order to increase the homogeneity of the resulting soil structure, the large clods left by mechanical tillage were broken into smaller pieces by labourers using rakes. To mimic the practice of farmers who want to avoid flooding of the seed rows, ridges were built by hand two days after tillage. The interval between ridges was 40 cm and their height ranged from 12 to 17 cm.

MonitorMeasuring days were identified by the number of days after ploughing (DAP, thus DAP 0 meaning the 25 May) and by accumulated rainfall (AR in mm) since DAP 0. Soil water potential was measured using a set of ceramic tensiometers each equipped with an electronic transducer (model 2150 and SMS-2500S, SDEC Company, France). They were installed at 5 cm intervals from 10 to 20 or 40 cm depth according to tillage depth in two different locations: underneath either the ridge or the furrow. The zero level (soil surface) was counted from the surface of the ridge or the furrow according to the location of the tensiometer. Two sets of tensiometers were installed for each treatment (S and D) as replicates. Water matric potential (ψ) was measured after each major rainfall event or after 3 to 7 days if no rainfall event occurred.

Changes in soil level were measured using a horizontal frame as a stable benchmark. It consisted of a 1×1 m^2 frame horizontally put on four metallic rods inserted 70 cm below the soil surface and fixed by cement. The distance between the frame and the soil surface was measured using a laser beam (Lasermeter Leica Disto 6A, Leica Geosystem, Switzerland) according to a 5×5 cm^2 grid (total of 361 data points). The vertical precision was 1 mm. For both treatments (D and S), replicates were installed in three of the five elementary plots. To measure changes in ρ_b and soil water content (*Wc*), after each major rainfall event, undisturbed cylinders of soil (5 cm in height and diameter) were collected every 5 cm in depth under furrows. They were weighted before and after putting in an oven for 24 h at 105°C

2.4. Experiment 2

The objective of Experiment 2 was to study the effect on slumping of the water content at tillage. Five plots (9×15 m^2) were left under rainfall, while five other plots were protected from rainfall using greenhouses. These greenhouses were built with bamboo sticks and covered by plastic sheets (0.8 m high); to avoid overheating and water condensation, they were opened at both ends so that air could circulate. To prevent preferential water infiltration along the plots, rainwater falling on the surface of greenhouses was drained out of the field. The greenhouses were removed on the 6 July and water content was measured after putting the soil sample in an oven for 24 h at 105°C.

The soil was tilled on the 6 July (DAP 0), at one depth only (20 cm) using the same tractor as in Exp. 1. Therefore the treatments consisted in two different *Wc* during tillage; the treatments were named 'dry' (Y) (plots under greenhouse before tillage) and 'wet' (W) (plots that were submitted to rainfall before tillage). Five replicates were used for each treatment. Ridges and furrows were prepared using the same procedure as in Exp. 1.

In both treatments (Y and W), a set of four tensiometers was installed below the furrow at 5 cm intervals from 10 to 25 cm depth. Changes in soil level were measured using a 1 m long horizontal board as a stable benchmark, which was supported by metallic rods as "legs" inserted into soil at 70 cm depth as in Exp. 1. One replicate of this device was installed in each of the ten subplots. The distance from the benchmark to the soil surface was measured using the laser beam every 2.5 cm (total of 38 data points). The ρ_b and *Wc* were measured using the same procedure as in Exp. 1.

2.5. Experiment 3

The objective was to mimic a continuous rainfall and to measure the consequences on slumping characteristics. Three supplementary plots were covered by greenhouses to keep the soil dry. Metallic rings (55 cm in diameter) were inserted deeply in the soil (60 cm) to be used as stable benchmark for soil level recording. The soil inside the ring was hand tilled using a small paddle and rake to mimic the soil tractor tillage and hand raking as in Exp. 1 and 2. Soil preparation treatments consisted of two tillage depths: 20 and 40 cm, called "shallow-tillage flooding" (Sf) and "deep-tillage flooding" (Df) respectively. Three rings were installed for each treatment. Unlike Exp.

1 and 2, the soil surface was flat (no ridges and furrows were built). Tensiometers were not used because the time was too short to obtain a good equilibrium between tensiometer and soil.

The amount of added water was 100 mm and 200 mm for Sf and Df treatments respectively. The soil surface was covered by a straw textile and water was added by increments of 25 mm water. To avoid kinetic energy, the water was poured on a hand as a buffer so that it gently felt on the textile over the whole surface. Infiltration time was recorded and after each addition of 25 mm water, the soil surface level was measured every 5 cm along a horizontal "board" that was put on the top of the metallic ring (10 measurement points each time) using the lasermeter. After the last addition of water and measurement of soil level, a small pit was opened inside the ring. The bulk density and water content were measured with 5 cm interval from surface to 20 and 40 cm depth in Sf and Df respectively. Three replicates samples were taken inside each ring.

2.6. Statistical analysis

The data were analyzed statistically using ANOVA by SPSS 13.0 (SPSS Inc., 2004). The least significant difference (LSD) at P = 0.05 was used to establish the significance of differences between treatment means. When applicable, paired-samples T tests were done.

3. Results

3.1. Rainfall characteristics

Fig. 1 presents the daily rainfall events and the accumulated rainfall (AR). During 61 days for Exp. 1, AR was 212 mm, approximately twice as much as in Exp. 2 (114 mm) which lasted only 20 days. Exp. 2 was done during the middle of the rainy season and had higher average daily rainfall than Exp. 1 which started earlier: 5.7 and 3.4 mm d^{-1}, respectively. More than half of AR in Exp. 2 resulted from two successive big rainfall events (22 and 36 mm) which occurred at the end of the experiment.

3.2. Experiments 1 and 2

3.2.1. Soil matric potential (ψ) and water content (Wc)

For Exp. 1 and Y treatment (dry protected plots) in Exp. 2, *Wc* was ranging 0.04 to 0.06 g g^{-1}; or W (unprotected wet plots) in Exp. 2, *Wc* was significantly higher ($p<0.05$), ranging 0.08 to 0.10 g g^{-1} (data not shown).

Fig. 2 presents the matric potential (ψ) measured under furrows and ridges in Exp. 1 (D treatment), under furrows in Exp. 2 (W treatment). During Exp. 1, minimum and maximum matric potential (*i.e.* driest and wettest soil respectively) were -120 and -40 hPa respectively. No significant difference was observed between tensiometers installed under a furrow or under a ridge, and no significant difference was observed between the D and S treatments (data not presented). At a given time, we recorded similar minimum and maximum ψ in Exp. 1 and Exp. 2. Moreover, no differences were observed with the W and Y treatments compared with the D treatment in the 0-20 cm layer (data not presented).

In the top layers (0-20 cm), a rapid increase in ψ was observed after rainfall events (e.g. DAP 41 and DAP 58), but a slow and regular ψ decrease was observed during the different dry spells (e.g. from DAP 47 to 51). In the 35 cm layer, changes were buffered: the ψ was significantly affected only by the two successive big rainfall events recorded at the end of the experiment (DAP 59 and 60, 22 and 36 mm respectively).

For Exp. 1 and 2, it is noteworthy that at the end of the experiments (DAP 59 and 60), the highest ψ at 10 cm depth was recorded after the first rainfall event (-40 and -50 hPa respectively in the top layer) while higher ψ was expected after the second rainfall event (approximately twice as much water input as the first event). This discrepancy is a consequence of manual monitoring: at

DAP 59, ψ was recorded shortly (< 1 h) after the rainfall event; while at DAP 60, it was recorded more than 10 h after the rainfall event. For the latter, the water front had already drained deeper in the profile as indicated by the drastic increase in ψ in the 35 cm deep layer, an increase which was not observed after the first rainfall.

At the end of the experiment, in all plots, whatever the initial *Wc* at the tillage depth, *Wc* ranged from 0.08 to 0.13 g g^{-1} (data not shown). There was no significant difference between D and S, and between Y and W.

3.2.2. Soil surface elevation and bulk density

After each major rainfall event, a decrease in soil roughness was observed: the height of ridges decreased while furrows were filled with sandy material, and consequently the field became more flat (Fig. 3). This change in the topography of the soil surface indicated movements of solid particles from the top of ridges to the bottom of furrows, but we didn't observe any erosion (particles moving outside the field). The average soil level was calculated for the different treatments (Fig. 4). A level decrease was observed in all plots (ranging from 1.2 to 1.7 cm), but no significantly difference was found between the different treatments.

Average ρ_b profiles under furrows are shown in Fig. 5. Immediately after tillage, all profiles were characterised by a regular increase with depth. For shallow tillage (S, Y, W treatments, 20 cm depth), the differences between ρ_b at top and bottom of tilled layer ranged from 0.05 to 0.10 g cm^{-3}. For deep tillage (D treatment, 40 cm depth), this increase was higher (0.15 g cm^{-3}) indicating an effect of tillage depth. When the soil was tilled in dry conditions (S, D and Y treatments), a shift towards higher ρ_b values was observed at all depths with increasing AR. Initial bulk density in the profile was already higher when ploughing was performed at wet conditions. The shift was higher in the top layer then in deeper layers. When the soil was tilled in wet conditions (W treatment), no change in ρ_b was observed in relation with increasing AR, except in the top layer (0-5 cm) at the end of the experiment.

3.3. Experiment 3

During the first addition, the infiltration rate was 450 and 600 mm h^{-1} for Sf and Df respectively (Fig. 6a). During the following additions, IR decreased until it was stabilised around 100 mm h^{-1}. The same value was observed in both treatments, suggesting that tillage depth did not influence the infiltration rate. For the first three water inputs, the sinkage rate increased at each input (-1.0, -1.2, -1.4 cm in Df treatment) (Fig. 6b). For all the following water inputs it decreased continuously (from 0.6 cm with 100 mm input to 0.1 cm with 200 mm input in Df treatment). Tillage depth affected the soil level decrease: at 100 mm water input, it was only 2.7 cm for Sf compared to 4.2 cm for Df treatment. Just after tillage, ρ_b profile increased with depth: at the bottom of the tilled layer ρ_b was about 0.3 g cm^{-3} higher than at the surface (Fig. 7). At the end of the experiment, for both Df and Sf, ρ_b shifted to higher values on all the profile, ρ_b being higher close to the surface than at the bottom (about 0.5 and 0.2 g cm^{-3} respectively).

4. Discussion and conclusion

4.1. Evidence of slumping

The soil surface reorganisation which was recorded during Exp. 1 and 2 and which consisted in a decrease in the soil roughness (Fig. 3) was commonly observed in coarse-textured soils and discussed as closely related to their low structural stability when submitted to rainfall (Mwendera and Feyen, 1994; Rudolph et al., 1997; Twomlow and Bruneau, 2000). Our results show that soil reorganisation affected not only surface but also the whole tilled horizon. In the three experiments and whatever the treatment, a soil sinkage was recorded, i.e. a decrease in soil surface elevation (Fig. 4 and Fig. 6b). As no erosion was observed during the experiment (i.e. no mass movement out of the field), such an elevation decrease in soil surface necessarily resulted from a loss of pore volume, i.e. from an increase in soil compactness. Soil sinkage did not happen regularly over time but was related to the occurrence of rainfall events, and consequently can be considered as an indicator of *soil slumping* as defined by Mullins et al. (1990). Soil sinkage cannot be observed by the naked eye even if it is probably a common phenomenon in coarse textured soils, thus explaining the rarity of its description (Wilton, 1964; Young et al., 1991; Moffat et al., 1997; Or and Ghezzehei, 2002). Even if soil sinkage is a relevant indicator of slumping occurrence, it does not provide any information about how compactness evolves with depth in the soil.

4.2. Soil structure after tillage

After tillage, the ρ_b profile presents two striking aspects. First, the ρ_b increased regularly with depth (from 1.26 g cm^{-3} at surface to 1.44 g cm^{-3} at 40 cm depth), thus indicating a closer packing of the soil particles when going deeper in the profile (Fig.5 and 7). Second, the ρ_b values (correspond to porosity ranging from 53 to 45%) were very low in sandy soils since it results mainly from the packing of coarse grains.

This loose packing was created by tillage: the energy developed by the disks was enough to separate most elementary particles which were lifted up, increasing their potential energy. This energy was dissipated when the particles moved downward under the effect of gravity. During the piling process, each time a contact occurred between neighbouring particles, the downward movement was hampered due to (i) mechanical friction, and (ii) capillary bridges developing between the grains. At *Wc* <0.12 g cm^{-3}, as measured before tillage (data not presented), water can be located only at the contact points between two particles, forming bridges (Willet et al., 2000;

Adams et al., 2002; Herminghaus, 2005). These bridges act as glue bonding the particles together in relation with the water interfacial tension and negative Laplace pressure (Kemper and Rosenau, 1984). The development of water bridges hampered the flow of solid particles and blocked the sand grains into a loose packing. But during the piling process, the overburden pressure was gradually increasing with depth, forcing the grains to rearrange in a continuously closer packing, resulting in a regular ρ_b increase with depth. This could be a general behaviour in tilled sandy soils (Ampoorter et al., 2007). The stability of the tilled layer results from capillary bridges and is consequently low, but in the absence of mechanical loading, it is stable until occurrence of rain and subsequent slumping.

4.3. Water characteristics inducing slumping

No relation was found between rainfall amount and slumping characteristics (occurrence, intensity, dynamic): (i) slumping was triggered by a small but variable amount of water (34 mm in Exp. 2 but only 25 mm in Exp. 3), (ii) despite similar large amounts of water brought to the soil (~200 mm), the intensity of slumping was much higher in Exp. 3 than in Exp.1 (soil sinkage of 4.6 and 1.2 cm respectively), (iii) when at the end of Exp.1 and 2, AR were very different (200 mm and 100 mm respectively), intensity of slumping was similar, i.e. same final ρ_b (>1.4 g cm^{-3} below 10 cm), and (iv) slumping was faster in Exp. 3 compared to Exp 1 (nearly finished after 75 mm water input in Exp. 3 when still observed after 132 mm water input in Exp.1) (Fig. 5).

The lack of a global relation between slumping and rainfall characteristics, suggests that not all rainfall events have the same potential to induce slumping. A soil material is stable as long as it meets the Mohr-Coulomb criterions:

$$\tau = \mu\sigma + c \qquad (1)$$

where τ is the shear stress, σ is the normal force, μ is the internal friction coefficient and c is cohesion. The cohesion is equivalent to the shear stress at zero normal force and it depends on (i) both the amount and type of clay and organic matter (i.e. permanent bonds), and (ii) the water content (Le Bissonnais et al., 1995). Sandy soils have low clay and organic carbon content, consequently water becomes a major factor of cohesion between the elementary particles and globally of structural stability (Panayiotopoulos and Mullins, 1985, Panayiotopoulos, 1989). Kemper et Rosenau (1984) suggested that slumping was related to soil saturation and resulting lack of cohesion between the elementary particles. Recent development on the physics of wet granular material, like sandy soils, suggest that slumping would occur before reaching water saturation.

Indeed, in a sandy material, the relation between soil cohesion and water content is not linear, two successive stages need to be considered (Pierrat and Caram, 1997; Iveson et al., 2002; Mitarai and Nori, 2006): at the first stage, water is located only at the contact between grains and is filling the packing pores between neighbouring grains creating separated clusters of grains (Kohonen et al., 2004; Scheel et al., 2008). The second stage starts after all the packing pores were filled with water when the liquid phase becomes continuous (Herminghaus, 2005). The second stage is characterised by a drastic decrease in development of air/water interfaces and thus a drastic drecrease in macroscopic cohesion (Soulié et al., 2006; Grof et al., 2008). Such a model suggests that slumping in sandy soils would be triggered before reaching saturation, when rainfall amount is high enough to obtain a continuous liquid phase draining down in the profile. Compared to natural tilled sandy soil, the experimental and mathematical models studied by physicists are simplified (the particles size distribution is limited and the grains are in close packing). Even so, it is still a challenge to determine Wc or ψ that corresponds to a continuous liquid phase in these models and it is not yet possible for real soils. Anyway, such liquid phase continuity in sandy material can be observed during fast downward movement of the wetting front that correspond to a locally high Wc and ψ (Kawamoto et al., 2004)

4.4. Slumping dynamics and water infiltration

In Exp.3 water supply was continuous, creating an infiltration and thus a downward movement of the wetting front. Soil and water characteristics were recorded during and immediately after (<1h) water supply. During the first water input, soil surface sinkage (indicating a rearrangement of elementary grains) was observed; sinkage intensity increased until the third addition of water, then it decreased again and even if it was small, sinkage was observed until the last water input (Fig. 6b). This result confirms that slumping occurred during the downward movement of the wetting front, i.e. before saturation, contrary to the suggestion of Kemper and Rosenau (1984). Similar fast rearrangement was already recorded in an independent field experiment during which the largest ρ_b increase occurred within the first 10 min of rainfall (Bedaiwy and Rolston, 1993).

Exp. 1 and 2 were conducted under natural rainfall events and were characterised by slower slumping dynamic. Soil and water characteristics (ρ_b, ψ, *Wc*) were monitored manually at the interval of one to seven days; consequently our device could not record any fast water front movement. Anyway, structural changes (soil surface sinkage and bulk density increased) were observed only after the limited number of major rainfall events, events that occurred similarly during Exp. 1 and 2 (Fig. 1). This observation is consistent with the hypothesis that all rainfall events do not have the same capability to induce slumping; in the context of our experiment, only events > 15 mm induced fast wetting front infiltration and significant structural changes (surface level decrease, bulk density increase).

In Exp. 3, a steady state was reached earlier for infiltration rate than for soil elevation decrease (Fig. 6a and Fig. 6b). This suggests that infiltrability is not a good indicator of slumping (direct observations of structural changes have to be preferred). On the other hand, these data can also provide some indications on the characteristics of sand grains rearrangement at the onset of the first major rainfall. The steady state observed for infiltration when slumping was still on process indicates that the continuity of the porosity (a major factor of infiltration rate) decreased faster than total pore volume (Nimmo and Akstin, 1988; Meek et al., 1992). In a pile of grains that results from a loose packing of grains linked together only by capillary water bridges, the first grains to be unbalanced are probably the biggest ones. They are indeed the most strongly pulled by gravity and less strongly hold by capillary bridges. Once unbalanced, those grains can 'fall' in the large pores (with 50% porosity, the volume occupied by porosity is the same as occupied by particles). This reorganisation would explain the fast infiltration decrease related to (i) a decrease in the volume of large pores (i.e. that allows fast water movement), and (ii) a decrease in the continuity of the remaining smaller packing pores.

4.5. Soil factors affecting slumping

Previous experiment demonstrated that under similar rainfall events, slumping could differ in relation with soil management (Meek et al., 1988; Bedaiwy and Rolston 1993, Hartmann et al, 2008a,b). Our experiment confirmed that the relative change of ρ_b was inversely correlated with the initial ρ_b as already suggested by Bedaiwy and Rolston (1993). For exemple, compared to the shallow layers, the deep layers had the highest ρ_b after tillage, and they had also the smallest ρ_b increase during the experiment. Less slumping was also observed when the soil was initially wet compared to when it was initially dry (Fig. 6). As the wet sandy soils are more sensitive to mechanical stresses than dry soils (Panayiatopoulos et al., 1989; Meek et al., 1992), during the tillage operations the W plots were probably more affected by mechanical constraints induced by the disk than the Y plots. This suggests that the factor hampering the slumping process in W compared to Y treatment was its higher initial ρ_b and not its higher *Wc*.

While inside the profile, the relative ρ_b change was inversely correlated to the initial ρ_b, the top layer behaved differently: ρ_b increase was constant and was finally huge compared to the underlying layers. In first estimate, a different behaviour of the top layer seemed to be related to a lateral sand movement from the ridge and accumulation on the surface of the furrow (Exp.1 and 2, Fig. 3). But similar increase was recorded in Exp. 3 which had a flat surface and where no lateral movement occurred. On a flat surface, the soil structure can also be degraded by vertical segregation of clay and sand fractions due to the kinetic energy of the raindrops and result in different surface crusts (Casenave and Valentin, 1992). Such crusts are only some millimeters thick (Bielders and Bavey, 1995; Roth, 1997; Fohrer et al., 1999; Ndiaye et al., 2005) and cannot explain changes at several centimeters depth and deeper in the tilled layer. Indeed, the surface layer is characterised by (i) a very small normal force σ (Eq (1)) due to quasi absence of overburden pressure, and (ii) a frequent occurrence of high Wc, even during minor rainfall events. These two specific characteristics can explain that the particle reorganisation at the surface is different from that observed below the surface layer.

Since surface heterogeneity can induce preferential water infiltration (Twomlow and Bruneau, 2000), the presence of ridges and furrows has to be mentionned: slumping was perhaps also influenced by that specific surface topography, but we have not collected any data that allows a estimation on the effect of this factor .

4.6. A conceptual model of soil slumping

When Kemper and Rosenau (1984) and Mullins et al. (1990) suggested the existence of a specific degradation process named slumping, they did not provide any information about its kinetic, and the underlying processes and determinant factors. Here we suggest a scenario of slumping in sandy soils and a list of determinant factors based on our experiment. Slumping kinetic can be separated in three main steps (Fig. 8): (i) creation of an initial loose profile with a regular ρ_b increase with depth after tillage, the cohesion and stability of these layers resulting from the strong capillary forces between elementary grains (Fig. 8-a), (ii) during major rainfall events or under irrigation, a fast increase in ρ_b in all tilled layers, the loss of cohesion resulting from the development of a continuous (but transient) liquid phase along the profile (Fig. 8-b), and (iii) after each major rainfall, when the soil is gradually getting denser, the slumping intensity is decreasing because of steric constraints to reorganisation, except for the surface layer where bulk density seems to be continuously increasing (Fig. 8-c). As the existence of a continuous liquid phase along the profile is the most determinant factor of slumping, all rainfall characteristic determining the existence of such continuous liquid phase will affect slumping, i.e. rainfall intensity, duration and frequency. For given rainfall characteristics, slumping dynamic and intensity depends on the bulk density at the onset of the rainfall or irrigation event. The high variability recorded in earlier field works (for example: Mead and Chan, 1988; Meek et al., 1988, Hartmann et al., 1999 ; Osunbitan et al., 2005) result from the many possible interactions between these determining factors.

Further experiments should include a better control of experimental conditions associated to more accurate recording at the time scale of the rainy events to obtain new data enabling to establish a quantitative model and consequently improve our knowledge and prevision of the elementary mechanisms of slumping.

Acknowledgements

The authors thank the support from Ms Wanpen Wiriyakitnateekul and Ms Nopmanee Suvannang (LDD, Land Development Department, Thailand); and the help from Mr. Jean-Luc Maeght, Dr Claude Hammecker, Dr Christian Valentin (IRD, Institut de Recherche pour le Développement, France); Ms. Tum Nitjaporn Kunklang, Mr. Worraphan Chintachao. We thank Frédéric Darboux and David Lees for helpful comments and improving the English. We thank the anonymous reviewers and the editors for their very useful suggestions to improve the manuscript. Hongtao Hao thanks IRD for the financial support that made his study of PhD in France possible. He also thanks the constant support from Prof. SUN Bo and Prof. ZHAO Qiguo (Institute of Soil Science, Chinese Academy of Sciences, China).

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Legend of the figures

Fig. 1. Rainfall distribution and accumulated rainfall (AR) in Exp.1 and Exp.2. DAP is day after tillage for Exp.1, which started from 25 May 2007. DAP' is day after tillage for Exp.2, which started from 6 July 2007.

Fig. 2. Matric potential of a) Top: D (40 cm tillage) under furrow ( ) and under ridge ( ); b) Bottom: S (under furrow). Average values (n=3) are shown.

Fig.3. Soil surface level recorded in Exp.1, example of one subplot; left side is DAP4 and right side is DAP60. Measurements were made along a regular grid 5x5 cm (i.e. 361 measurement points).

Fig.4. Mean soil height with cumulated rainfall. D and S are Deep (40 cm) and S shallow (20 cm) tillage respectively; W and Y indicate tillage made in wet and dry soil respectively. Each line is one replicate from the subplot. The numbers indicate mean values of level decrease with standard errors in the brackets. Note: The reference level was the board arm that support lasermeter. The arm was fixed with iron sticks fixed deep in the soil. The absolute value of soil height was not important, but the relative soil height that measured at different time was our aim.

Fig. 5. Bulk density collected under furrow after major rainfall events during Exp.1 and Exp.2. D and S are Deep (40 cm) and S shallow (20 cm) tillage respectively (n=5); W and Y indicate tillage made in wet and dry soil respectively (n=9). DAP and DAP' are the number of days after tillage for Exp.1 and Exp.2 respectively; AR is the accumulated rainfall since tillage day. Error bar indicates standard error of mean (SEM).

Fig.6. a) Soil infiltration rate decreased with added water amount, b) Soil surface level change with added water amount. The soil was protected from rainfall under plastic before tillage. Error bars indicate standard error of means (n=9). D-f is deep flooding; S-f is shallow flooding.

Fig. 7. Bulk density after flooding. 200 mm water was added into “D-f” and 100 mm water into “S-f”. Error bar indicates standard error of mean (SEM) (n=9). D-f is deep flooding; S-f is shallow flooding.

Fig.8. Schematic diagram of possible slumping dynamic profiles in tilled sandy soil. a) just after tillage, b) beginning of slumping, c) with maximum bulk density at surface and deeper layer, d) a comparison profile after mechanical compaction, maximum bulk density occurs in the intermediate layer.

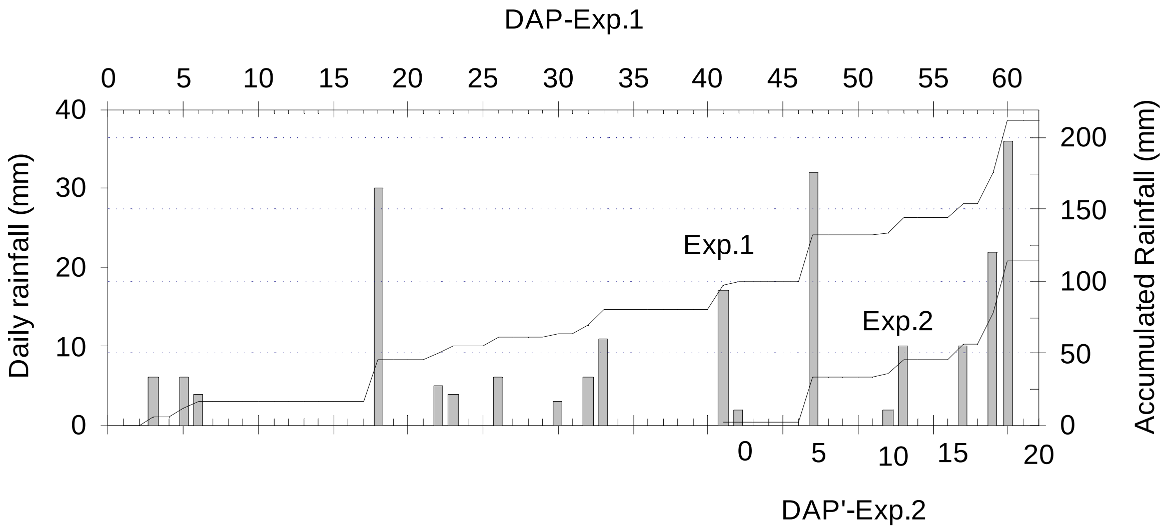
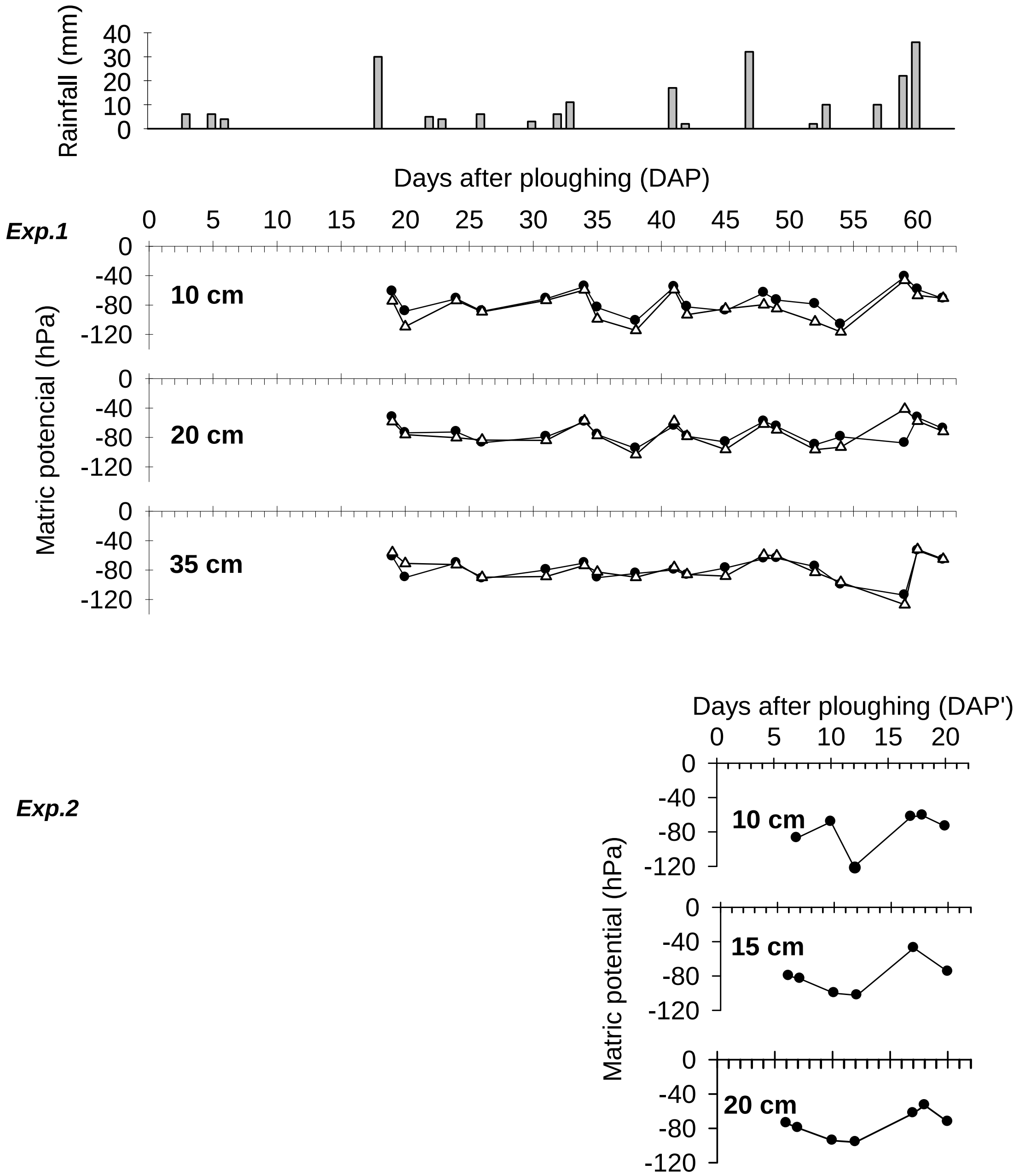

DAP-Exp.1
0
5
10
15
20
25
30
35
40
45
50
55
60
Daily rainfall (mm)
40
30
20
10
0
Accumulated Rainfall (mm)
200
150
100
50
0
Exp.1
Exp.2
0
5
10
15
20
DAP'-Exp.2

Fig. 1

a)


Rainfall (mm)
40
30
20
10
0
Days after ploughing (DAP)
0 5 10 15 20 25 30 35 40 45 50 55 60
Exp.1
Matric potencial (hPa)
10 cm
20 cm
35 cm
0
-40
-80
-120
Exp.2
Days after ploughing (DAP')
0 5 10 15 20
Matric potential (hPa)
10 cm
15 cm
20 cm

b)

Fig. 2

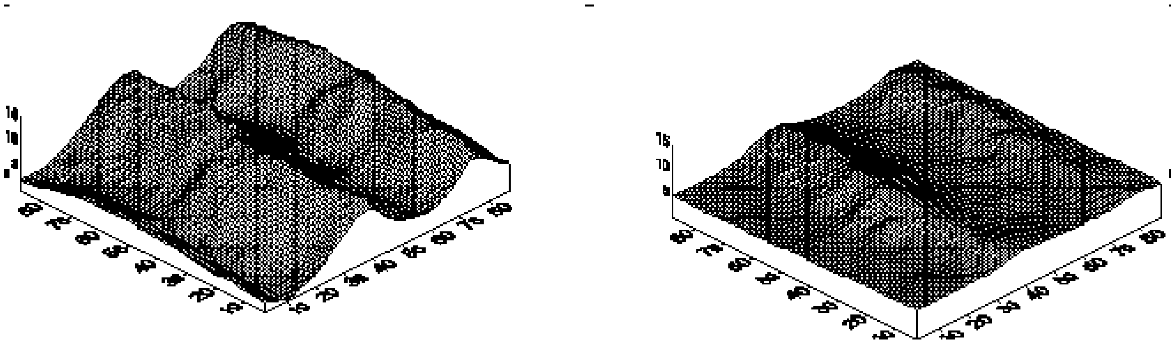


Fig.3

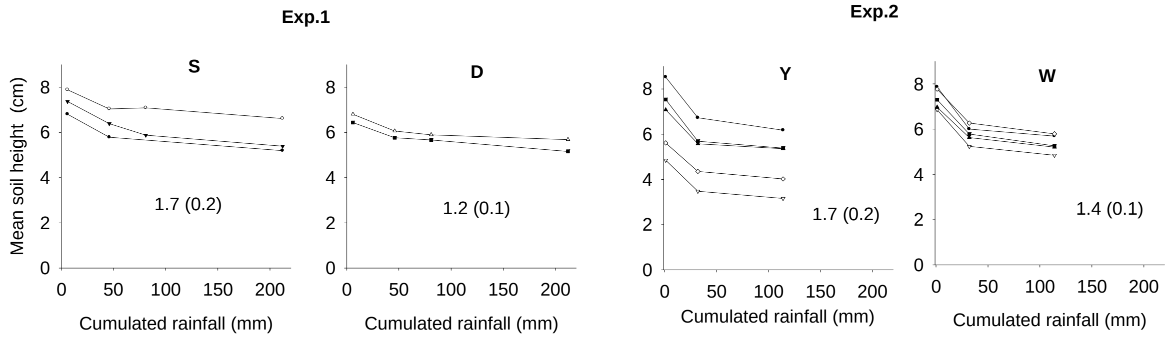

Exp.1
Exp.2
S
D
Y
W
Mean soil height (cm)
1.7 (0.2)
1.2 (0.1)
1.7 (0.2)
1.4 (0.1)
Cumulated rainfall (mm)
Cumulated rainfall (mm)
Cumulated rainfall (mm)
Cumulated rainfall (mm)

Fig.4

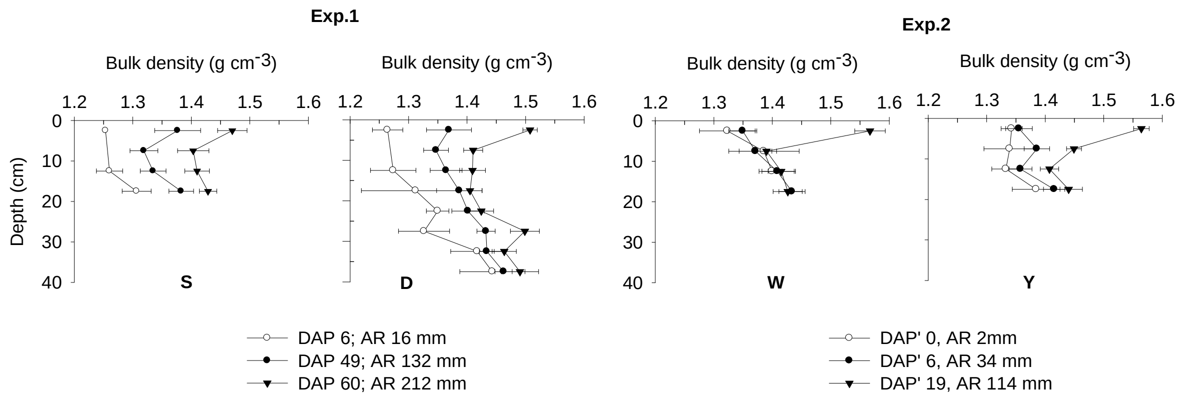
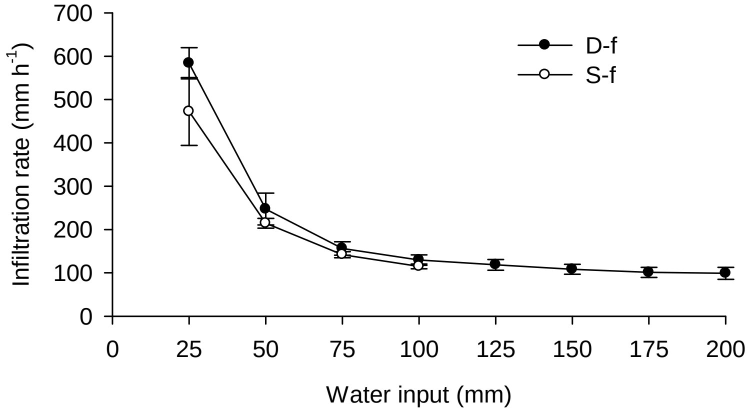
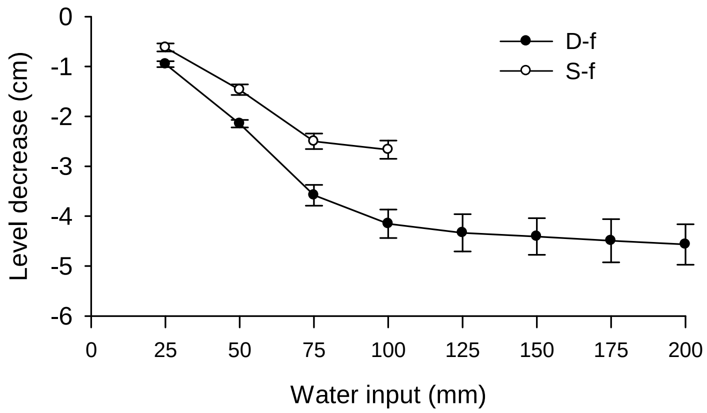

Exp.1
Exp.2
Bulk density (g cm-3)
Bulk density (g cm-3)
Bulk density (g cm-3)
Bulk density (g cm-3)
1.2 1.3 1.4 1.5 1.6
Depth (cm)
0 10 20 30 40
S
D
W
Y
DAP 6; AR 16 mm
DAP 49; AR 132 mm
DAP 60; AR 212 mm
DAP' 0, AR 2mm
DAP' 6, AR 34 mm
DAP' 19, AR 114 mm

Fig. 5


Infiltration rate (mm h-1)
Water input (mm)
D-f
S-f

a)


Level decrease (cm)
Water input (mm)
D-f
S-f

b)

Fig.6

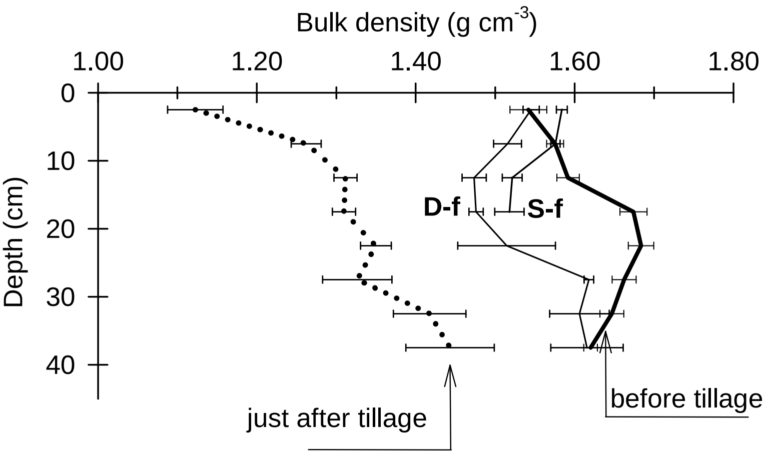

Bulk density (g cm-3)
1.00
1.20
1.40
1.60
1.80
0
10
20
30
40
Depth (cm)
D-f
S-f
just after tillage
before tillage

Fig. 7

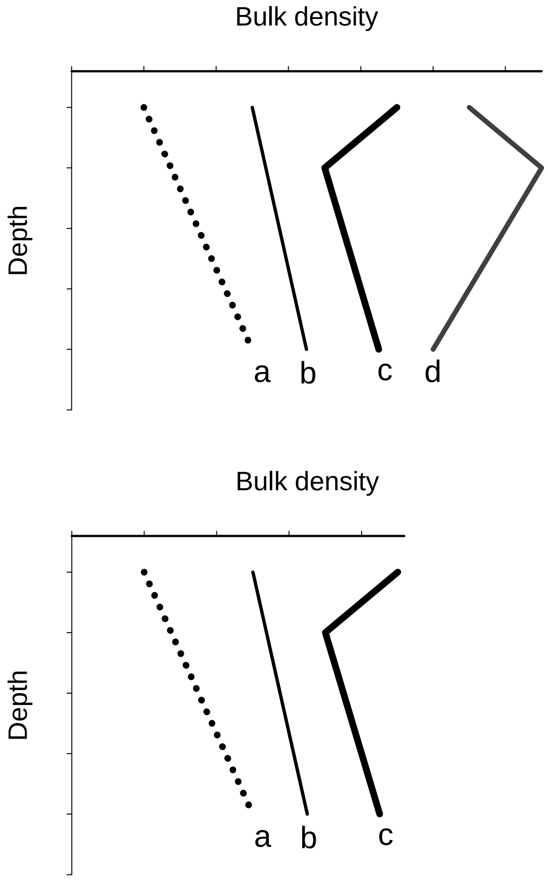


Fig.8

Tables

Table 1. Selected physical and chemical properties of soil measured one day before tillage.

Depth	Sand (%)	Silt (%)	Clay (%)	Organic mater	Bulk density	RP	SS
(cm)	50-2000 µm	2-50 µm	<2 µm	(g kg^{-1})	(g cm^{-3})	(kPa)	(kPa)
0-20	90	9	1	4.5	1.60	13	4.6
20-40	86	11	3	4.6	1.65	33	5.6
40-60	86	11	3	1.9	1.62	32	5.1

RP: Resistance to penetration, measured by datalogger penetrometer.

SS: Shear strength, measured by Hand Held Field Vane Shear Test (Helwany, 2007).

Table 2. Particle size distribution of soil (g kg^{-1}) at 0-20 cm layer. It was measured by laser diffraction granulometer (Malvern Instruments).

	Clay	Silt	Sand					
Size (µm)	0-2	2-50	50-100	100-150	150-200	200-250	250-500	500-2000
Content	26	101	205	176	209	171	112	3