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**Slumping of cultivated sandy soils:
factors, processes and indicators**

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Résumé

Les sols sableux peuvent constituer une réserve potentielle de sols cultivables mais leur mise en valeur entraîne des dégradations de la structure et une baisse du potentiel agricole. Une dégradation très fréquente est l'affaissement des couches de sol labourées sous l'action de la pluie, ou slumping. Notre objectif était d'identifier les mécanismes et les facteurs déterminants du slumping afin de proposer des techniques de prévention. L'étude a été conduite sous pluies naturelles (au champ) et simulées (au laboratoire). Au champ, la cinétique d'évolution des caractéristiques hydriques et physiques du sol a été suivie après un labour à 20 ou à 40 cm de profondeur, dans un sol sableux tropical en Thaïlande. Au laboratoire, un sol cultivé modèle a été élaboré dans un cylindre (h et $\varnothing = 20$ cm) à partir i) du sol prélevé dans le champ expérimental, ii) de la fraction sable ($> 50 \mu\text{m}$) extraite de ce même sol. Les sols modèles ont subi des pluies d'intensité variable (de 20 à 120 mm/h) après mise en place sur une table à succion (20 à 90 hPa).

Le slumping se produit lorsque deux conditions sont réunies: (1) l'eau doit atteindre un potentiel proche de 0 hPa ce qui réduit la cohésion et aboutit à un équilibre fragile du sol comme décrit par la physique des milieux granulaires; (2) ce potentiel doit être maintenu assez longtemps pour qu'une instabilité se produise et entraîne une brusque et importante diminution de la cohésion, donc l'effondrement du matériau. Si la fraction fine ($< 50 \mu\text{m}$) est retirée du sol, aucun effondrement n'est observé, démontrant l'importance de cette fraction limono-argileuse, pourtant minoritaire ($< 10-15$ % en masse), dans l'instabilisation et le slumping.

La prévention du slumping et la gestion des sols sableux sont discutées en guise de conclusion.

Mots clés: sol sableux, granulaire, limon, densité apparente, slumping, simulation de pluie, Thaïlande

Abbreviations and glossary

w: gravimetric water content = mass of water/mass of soil ; mass wetness

ρ : soil bulk density = (total soil mass) / (total soil volume)

ρ_s : density of solids (mean particle density)

e: void ratio =(volume of water and air) / (total soil volume) =1- (ρ/ρ_s)

S: degree of saturation = $v_{\text{water}}/v_{\text{void}}=(V_{\text{water}}/V_{\text{total}}) / (V_{\text{void}}/V_{\text{total}})$

θ : volumetric water content, = $V_{\text{water}}/V_{\text{total}}=(m_{\text{water}}/\rho_{\text{water}})/(m_{\text{soil}}/\rho_{\text{soil}})=w \times \rho$

f_a : air-filled porosity (fractional air content)

v_w : water volume ratio

$\sigma' = \sigma + \chi \psi$

σ' : effective stress of unsaturated soil

σ : normal stress

χ : wet degree, 1 in a saturated soil, 0 in a dry soil

ψ : matric potential

Compaction

Reduction of the volume of a given mass of soil. *i.e.* decrease in void ratio and porosity and conversely, increase in bulk density

Change between bulk density, porosity and void ratio

Bulk density	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.55	1.60	1.65
Porosity	0.55	0.53	0.51	0.49	0.47	0.45	0.43	0.42	0.40	0.38
Void ratio	1.21	1.12	1.04	0.96	0.89	0.83	0.77	0.71	0.66	0.61

The particle density of soil particles is assumed to be 2.65 g cm⁻³.

Pressure

Force exerted over a surface divided by the area of the surface. Pressure is a scalar, *i.e.* it is independent of direction

Unit: 1 Pa = 1 N m⁻² ; 1 bar = 100 kPa

1 atm = 100 kPa

Strength

Stress at which a material fails; therefore, strength has the same unit as stress

Normal stress

Stress acting perpendicular to a plane

Shear stress

Stress acting tangential to a plane

Overburden pressure

Pressure or stress imposed on a layer of soil by the weight of overlying material.

The overburden pressure at a depth z is given by

$$p(z) = p_0 + g \int_0^z \rho(z) dz$$

where $\rho(z)$ is the density of the overlying rock at depth z and g is the acceleration due to gravity. p_0 is the pressure at the surface.

Total Potential (h)

The total potential of water in a soil is the amount of work required per unit quantity of water to move a small amount of water reversibly and isothermally from a pool of pure water at atmospheric pressure and at a reference level to the point of interest in the soil. This is the sum of the matric potential and the gravitational potential.

Matric potential (Ψ_m)

The matric potential of water in a soil is the amount of work required per unit quantity of water to move a very small amount of water reversibly and isothermally to the point of interest in the soil from a pool of pure water at atmospheric pressure at the same elevation. This is the amount of work required to move water into a soil from outside of it. Since the elevations are the same, gravity has no impact upon matric potential. Matric potential is another term for pressure potential or pressure head.

Introduction générale

Depuis plus de cinquante ans, les recherches en pédologie ont surtout concerné les sols les plus fertiles, c'est-à-dire ceux avec lesquels la productivité agricole potentielle était la plus élevée. Mais pour répondre aux besoins d'une population humaine grandissante, il est devenu nécessaire d'augmenter les surfaces cultivées. Les meilleurs sols ayant déjà été mis en valeur, pour augmenter les surfaces cultivées il a fallu mettre en valeur des terres traditionnellement considérées comme marginales ou à « problème ». C'est le cas des sols sableux. Les sols sableux sont abondants puisqu'ils couvrent environ 900 millions d'hectares à travers le monde (à noter qu'une proportion élevée est localisée dans des zones désertiques) et la FAO (Food and Agriculture Organisation) les a inscrits sur la liste des sols 'à problème' (qui comprend aussi les sols acides, salés, calcaires, les sols en pente ainsi que les vertisols et les histosols).

En effet, l'expérience acquise dans les zones en culture mécanisée montre que les sols sableux se dégradent très vite sur le plan physique. Si sous l'application d'une contrainte mécanique, leur masse volumique augmente moins que celle des autres sols, cette densification s'accompagne d'une augmentation considérable de la résistance mécanique à la pénétration et d'une importante réduction de la profondeur d'enracinement. Des observations de terrain (principalement en Australie) ont montré que **l'augmentation de masse volumique ne provient pas seulement des contraintes mécaniques exercées à la surface du sol mais qu'elle peut se produire simplement sous l'effet de la pluie**. Ce phénomène a été appelé '**slumping**' (Mullins et al., 1990), c'est-à-dire 'affaissement'. Le slumping a été observé sous divers types de sols mais il est **particulièrement important (en intensité et en profondeur) dans les sols sableux**.

Ce phénomène est préoccupant car **la résilience physique des sols sableux est quasi nulle**, c'est-à-dire qu'ils ne retrouvent pas naturellement (sous l'effet du climat ou des facteurs biologiques) leur état structural initial, même après une ou plusieurs décennies. Après affaissement, le décompactage doit donc se faire à l'aide de techniques mécaniques lourdes telle que le sous-solage ; il s'agit de faire passer une lame à travers les couches compactes

pour les fragmenter, augmenter leur porosité et réduire leur résistance à la pénétration des racines. L'amélioration obtenue grâce au sous-solage reste très aléatoire ; parfois même le sol peut se recompacter à des niveaux plus élevés qu'avant les travaux de réhabilitation. Après l'échec d'un sous-solage, il peut être nécessaire d'en envisager un second, plus profond et plus coûteux. Au delà de 40 à 50 cm de profondeur, le sous-solage n'est plus envisageable car trop coûteux pour être économiquement rentable dans des sols à faible productivité. Pour éviter de recourir à des travaux mécaniques de réhabilitation, il faudrait pouvoir mettre en œuvre des techniques de prévention du slumping.

Or, le 'slumping' n'a jamais fait l'objet d'une étude spécifique, les facteurs et les processus mis en jeu n'ont pas encore été bien identifiés ; actuellement il est donc difficile de proposer des techniques alternatives de préparation sur des bases raisonnées malgré les enjeux agronomiques et environnementaux liés à la dégradation des sols sableux. **L'objectif de notre travail de recherche est donc de fournir des éléments d'information sur les facteurs et les processus mis en jeu au service d'une réflexion sur la gestion de l'état physique des sols sableux.** Notre travail de recherche ne s'est pas appuyé sur les principes classiques de physique du sol mais plutôt sur **les théories récemment développées quant au comportement des milieux granulaires.** En effet, dès lors que la dégradation structurale ne résulte pas des contraintes mécaniques appliquées sur le sol mais plutôt d'une évolution 'spontanée' d'un matériau qui est majoritairement composé de grains rigides et sans cohésion, la physique des milieux granulaires peut apporter un éclairage nouveau sur certains aspects mal connus de la communauté des pédologues.

Le mémoire qui suit est composé de quatre parties principales :

1 – **Un état de l'art** qui concerne à la fois le 'slumping' dans les sols sableux cultivés et les développements récents de la physique des milieux granulaires, secs ou humides.

2 - **La présentation d'une expérimentation au champ** qui a permis de préciser la cinétique des changements d'état physique d'une parcelle cultivée soumise à des pluies naturelles ; les évolutions de la structure et des caractéristiques de l'eau du sol ont été suivies à l'échelle du profil du sol avec des pas de temps de la journée.

3 – **La présentation d’une expérimentation de laboratoire** qui a consisté d’abord à mettre au point un horizon labouré modèle, c’est-à-dire un système simplifié par rapport au terrain mais qui présente les comportements que nous cherchons à analyser. Pour constituer ce profil nous avons utilisé deux matériaux: un échantillon de sol provenant du terrain d’étude, et le même avec uniquement la fraction sable (50-2000 μm). Ces systèmes modèles ont été soumis à des pluies simulées. Les évolutions de la structure et des caractéristiques de l’eau du sol ont été suivies à des échelles de temps et d’espaces très fines (pas de temps de la minute et à l’échelle spatiale de l’ordre de grandeur du cm).

4 – **Une discussion générale de** l’ensemble des résultats de terrain et de laboratoire qui ont ainsi été mis en relation afin de discuter (i) la validité des modèles proposés, à partir des théories sur les granulaires pour expliquer le ‘slumping’ et (ii) une réflexion sur l’évolution structurale des sols sableux et sur les conditions d’une gestion raisonnée et durable des sols sableux et des sols à texture grossière de manière plus large.

Après la **conclusion générale**, notre mémoire se termine par des annexes qui présentent des informations (méthodologie et résultats) qui ne se trouvent pas dans le corps du mémoire mais qui sont utiles pour donner une vue plus large de notre travail expérimental.

Chapitre 1 Etat de l'art

Introduction

Cette introduction présente deux parties

- une présentation du concept de slumping durant les années 1980 et les résultats d'expérimentation les plus significatifs où l'affaissement des sols sableux est constaté et décrit, que le mot 'slumping' ait été utilisé ou non par les auteurs;
- une présentation de la physique des milieux granulaires pour représenter le sol sableux.

Le modèle le plus simple que l'on puisse imaginer et qui est régulièrement cité dans les articles de science du sol est celui d'un empilement régulier de sphères qui modélisent l'empilement d'agrégats ou de grains de sables observés sur le terrain. Depuis une vingtaine d'années, la physique des matériaux a connu d'importants développements dans l'étude des empilements de solides macroscopiques non cohésifs tels que les grains de sables, les billes, etc ; on parle de physique des milieux granulaires... Afin de pouvoir interpréter nos résultats de terrain sur cette base et concevoir un modèle sol de laboratoire qui prenne en compte les connaissances acquises par la physique des granulaires, cette revue présente aussi les développements récents dans la théorie des milieux granulaires et comporte trois parties. La première concerne l'influence sur la porosité du matériau de mélanges fraction grossière et fraction fine ; la seconde partie présente les comportements particuliers quant à la transmission des contraintes mécaniques dans les empilements de granulaires secs ; enfin la troisième partie présente l'influence de l'eau sur la cohésion des matériaux et leur capacité à développer et garder une structure.

1.1 Soil slumping

1.1.1 The birth of the concept of slumping in soil science

In general language, 'slumping' describes a drooping posture or carriage, fall or sinks heavily ("he slumped onto the couch"). In technical language, slumping is a process characterized by a reduction of stiffness and subsequent change of shape or position, under the strict effect of gravity.

An example can be found in glass technology: slumping is a technique in which heat is applied to the point where the glass becomes plastic; its increasing fluidity with temperature

allows the glass to 'slump' into a mould. Another example can be found in geology: slumping occurs when a coherent mass of loosely consolidated materials or rock layers moves a short distance down a slope (De Boer and Archibold, 2001). In soil science, the concept of slumping process was formally introduced by Mullins et al. (1990), to describe the phenomenon of bulk density increase without external loading, under the effect of water.

At the origin, slumping was described as the first stage of 'hardsetting'. Hardsetting is natural (no human intervention) degradation quite common in Australian cultivated soils. It is described as follow: hardsetting occurs "when a compact, hard, and apparently structureless condition prevails on drying" (Northcote et al., 1975). According to this definition, hardsetting could be diagnosed only when the soil was dry enough. But Mullins et al. (1987) suggested that hardsetting had two successive and distinct stages:

- the first stage is slumping and it occurs during wetting: "wetting the soil [...] allows the soil to slump so that particles or aggregates are in closer proximity";
- the second stage occurs during drying and it is harsetting *sensu stricto*: "there is a sharp drop in matric potential over a narrow range of moisture content then this may result in a correspondingly sharp increase in strength".

But slumping was also observed in absence of hardsetting and in different situations than cultivate soils (Young et al., 1991):

'when inspection pit were dug, the moist soil replaced into the pits slumped back to the same surface level without the necessity of any treading on the disturbed surface to pack it down.

It is noteworthy that slumping and crusting being both induced by rainfall, confusion between those two processes existed. Mullins et al (1987) precised the differences:

[slumping soils are] so unstable that sudden wetting (*e.g.* from furrow irrigation) without the additional mechanical energy provided by raindrop impact is sufficient to initiate crust formation. Use of the word 'crust' may be misleading since the whole profile hardens as it dries from the surface downward.

This description provides two important precisions about slumping: firstly that kinetic energy is not part of the slumping process and secondly that slumping can affect tilled layers on all their depth, and not only the interface between soil and atmosphere.

In the definition proposed by [Mullins et al. \(1990\)](#), slumping was finally considered as a specific process (different from the other already described processes) which is related to reconsolidation of all tilled layers (not only the soil surface) and which does not necessarily imply hardsetting.

Recently, the word slumping was used for micro-morphological studies of soil surface degradation ([Bresson and Moran, 2003, 2004](#); [Augeard et al., 2008](#)). In our document, ‘slumping’ will be understood as it was defined by [Mullins et al. \(1990\)](#). **Our literature review shows that slumping was observed worldwide under different rainfall and irrigation regimes. It seems that the sandy soils and coarse textured soils are particularly affected.**

1.1.2 Characteristics of slumping in sandy soils

For light textured soils with low clay content, on one hand slumping is an ubiquitous phenomena that can be observed in many different regions of the world, under various climatic conditions and after different soil preparations; on the other hand, the kinetic, intensity and depth of slumping is highly variable.

In slumping the soil wetting is responsible of the reconsolidation; wetting can result from natural rainfall events or from artificial events (irrigation). It is in irrigated field that the importance of slumping phenomena was first reported ([Ghavami et al., 1974](#)). To develop watering procedures avoiding slumping, laboratory experiments were conducted on a loosely packed silt loam soil column subjected to various application rates of water. [Ghavami et al. \(1974\)](#) demonstrated that **maintenance of low soil densities and favorable soil profile porosities was related with a low rate of water application.**

In a field experiment on a sandy loam, [Meek et al. \(1992\)](#) confirmed this result. Soil bulk density was compared after soil loosening for plots first sprinkler irrigated and secondly flood irrigated. A bulk density of about 1.45 Mg m^{-3} was created by tillage but the soil reconsolidated with time: there was only a small amount of settling from the sprinkler irrigation (low rate wetting) and most of the bulk density increase was caused by the first flood irrigation (high rate wetting).

The kinetic of slumping is highly variable. In a loamy sand, [Cassel \(1983\)](#) noted a significant increase in bulk density of a tilled soil after the first two rainfall events, but no further change in bulk density occurred during the subsequent period. In an Australian sandy loam, [Mead and Chan \(1988\)](#) measured bulk density of freshly cultivated soil before and after simulated rainfall. After a single rainfall event (20 mm in one hour), the soil had packed down to the pre-cultivation level. In a sandy loam of North-east Thailand, [Hartmann et al. \(1999\)](#) observed reconsolidation after two natural rainfall events (total 80 mm of water).

[Osunbitan et al. \(2005\)](#) studied the changes in bulk density after ploughing in a Nigerian loamy sand soil. They observed a continuous decrease in the porosity during their eight weeks of measuring. In an Australian sandy loam, [Hamblin and Tennant \(1979\)](#) observed that it was within a cropping season that slumping, following soil preparation, produced a porosity similar to that of unploughed soil. In a sandy loam, [Busscher et al. \(2002\)](#) measured recompaction of deep tilled plots over a period of eight years and correlated recompaction with the amount of rainfall. Note that reconsolidation was not measured through increase of bulk density but through increase in resistance to penetration. Regression showed that cone index increased with the square root of cumulative rainfall amount, indicating that recompaction rate was fast at the beginning and was decreasing with increasing amounts of cumulative rainfall. [Moffat and Boswell \(1997\)](#) measured over a period of five years the effects of deep ripping (0.6 m) of a stony sandy loam which has been spread using bulldozers over an old gravel extraction mine. There was a general increase in bulk density with depth, commonly $1.2\text{--}1.4 \text{ Mg m}^{-3}$ in the upper 0.1 m and increasing to a maximum of about 1.8 Mg m^{-3} at 0.4 m depth with bulk density commonly greater than 1.5 Mg m^{-3} within 0.3 m from the surface. Recompaction was considered as relatively rapid; even in the deepest layers most took place in the first year after ripping.

In most of those studies, slumping concerned layers of different thickness depending on ploughing depth. [Osunbitan et al. \(2005\)](#) measured the top layer (0-5 cm), [Mead and Chan \(1988\)](#) on 10 cm, [Hartmann et al. \(1999\)](#) on 20 cm, [Busscher et al. \(2002\)](#) on 35 cm and [Hartmann et al. \(2002\)](#) on 40 cm. [Meek et al. \(1992\)](#) as well as [Moffat and Boswell \(1997\)](#) observed slumping down to 55 cm depth. These different results indicate that even deep tilled layers can be concerned and can partly explain the failure of deep-ploughing as a rehabilitation technique for subsoil compaction in sandy soils.

The soil preparation technique can have an effect on the kinetic or the intensity of slumping. Meek et al. (1992) observed that a treatment ‘traffic before planting’ resulted in final bulk densities at the 0.45-0.55 cm depth which were significantly lower than in the control without any traffic. The authors suggested this probably resulted from pre-plant traffic decreasing water intake rate during flood irrigation and having the soil wet with a lower soil-water potential (light trafficking before the first flooding could thus be a technique to keep loose structure in the subsoil). Hartmann et al. (2002) compared a generalized subsoiling (40 cm deep) with a slotting preparation, *i.e.* a narrow slots (10 cm wide) opened through the compact subsoil (20-40 cm) (Jayawardane et al., 1995). They noticed that kinetic of slumping was much slowly for slotting compared to subsoiling.

Kinetic and intensity of slumping can be measured from soil surface, measuring soil surface subsiding. Wilton (1964) has observed a maximum 5 cm soil surface decrease during three months. Mead and Chan (1988) calculated that after the single rainfall event the cultivated layer 10 cm had subsided by approximately 2 cm. Moffat and Boswell (1997) measured that the ridges reduced in height over the measuring period (maximum 4 cm); the main cause of height reduction was interpreted as deep reconsolidation but they did not measure the soil characteristic to check this hypothesis. Hartmann et al. (1999) in a field experiment used metallic rods deeply inserted in the subsoil to measure changes in soil surface level. For a 20 cm thick tilled layer under natural rainfall, after one month they measured a mean decrease of approx 3 cm also attributed to soil reconsolidation by slumping. Hartmann et al. (2002), for a 40 cm tilled layer under simulated rainfall of 80 mm (intensity 30 mm/h), measured a soil surface subsiding of also 2 cm approximately. This result confirmed that decrease in soil level (measured at the soil surface) is linked with increase in bulk density (along the tilled layer). It appears that until now, the decrease in soil surface level and the bulk density increase in the different layers have not been measured simultaneously.

1.2 Porosity in a mixture of coarse and fine fraction

1.2.1 Background

From a traditional perspective, soils are viewed as a packing of clay-rich aggregates assembled at different scales (Oades and Waters, 1991). A cultivated layer can be considered as a pile of aggregates, more or less stable, through which fluids circulate and plant roots can develop (Gupta et al., 1991). Aggregates can result from i) physical processes, *i.e.* cycles of wetting and drying or of freezing and thawing (Oztas and Fayetorbay, 2003), ii) from biological processes, *i.e.* animal and vegetal activity (particularly soil macro fauna and root exudates) (Horn et al., 1994; Ashman et al., 2003) and iii) from human action, *i.e.* mechanical fractioning during tillage operations (Horn et al., 1994; Hajabbasi and Hemmat, 2000; Daraghmeh et al., 2009).

The creation of clods and aggregates during tillage operations decreases the bulk density of the tilled layer by creation of large inter-aggregate pores, facilitating water drainage and storage, and facilitating also deep root development for an optimal use of stored water and mineral elements. Before the recent development and extensive use of chemical fertilizers (during the 20th century), the most efficient way to quickly improve a cultivated soil and significantly improve its productivity was repeated (manual) tillage. Anyway, annual tillage is a necessity because clods and aggregates tends to breaks and merge together; reducing the quality and functioning of the porosity and increasing the bulk density that will be reach again its original value (*i.e.* before tillage). This phenomenon is called ‘**soil recompaction**’.

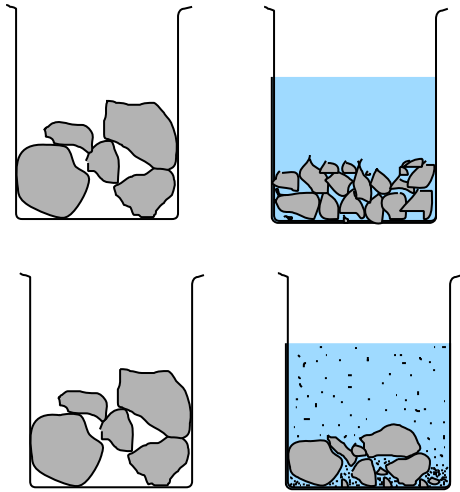


Fig. 2-1 Illustration of two important processes of aggregates destruction: slaking (on the top) which result in smaller aggregates and dispersion (on the bottom) which result in smaller aggregates and colloidal material. In both cases the smaller aggregates will be more densely packed and bulk density will be increased.

The structural stability describes i) the capability of a soil to maintain its high level of porosity after tillage or ii) the capability of aggregates to avoid destruction. Understanding and managing the conditions of structural stability is therefore a major challenge to maintain soil productivity. A large part of research in soil science was thus dedicated to this challenge (Adesodun et al., 2001; Mrabet et al., 2001; Nyamangara et al., 2001; Hernanz et al., 2002). The major factors of disaggregation and reconsolidation are the forces developed by mechanical constraints and by water during wetting. Reconsolidation during wetting results from two successive processes:

- i) slaking and dispersion, destroys large aggregates into smaller pieces,
- ii) subsequent re-organization in a more compact packing (Gupta et al., 1991; Bresson and Moran, 1995; Or and Ghezzehei, 2002; Ghezzehei and Or, 2003) (Fig. 2-1) .

In coarse textured soils, aggregation is necessarily limited due to low clay and organic matter content. Consequently, the solid fraction is made of rigid individual particles (*i.e.* sand and silt). In coarse textured soils, recompaction and slumping cannot result only from aggregates and particles being deformed, broken down or failing with subsequent rearrangement of new aggregates or particles. Slumping in sandy soils must result also from rearrangement of individual particles, *i.e.* movements relative to each other, in a closer packing. As the process described above (slaking, dispersion, and coalescence) are not mainly involved in sandy soils, the questions are: what is the process of cohesion decrease? What are the forces able to displace and reorganize individual particles?

To answer these questions we must first describe the arrangement of elementary constituents inside a tilled layer (sand, silt, and clay). If the structure consists in a pile or a stack of individual and rigid grains (and not deformable aggregates), what does a loose tilled layer look like? Moreover, what are its structural and mechanical characteristics?

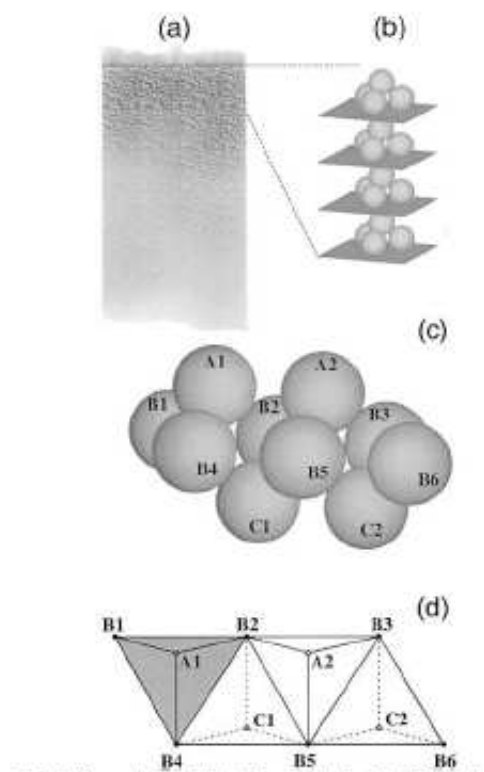


Fig. 2-2 Conceptual model of soil aggregates bed. 1) Schematic representation of soil aggregates bed, b) one-dimentional array of unit cells separated by conceptual rigid planes, c) one layer of dose-fitting unit cells, d) planar view of a layer of unit cells (Ghezzehei and Or, 2003).

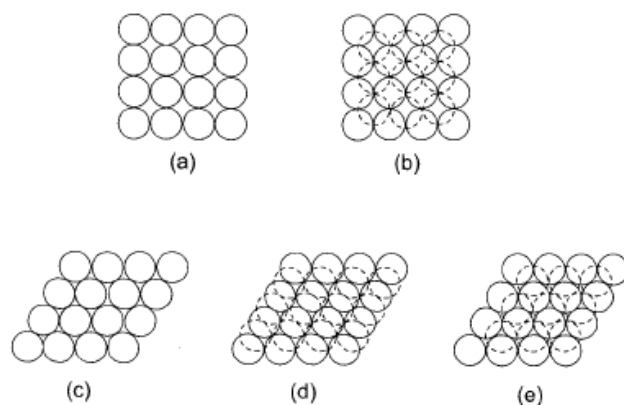


Fig 2-3 Models of packing of equal spheres, a) simple cubic, b) cubical tetrahedral, c) tetragonal sphenoidal, d) pyramidal, e) tetrahedral (Hillel, 2002).

Table 2-1 Porosity calculated for the different packing of spheres (Hillel, 2002)

Type of packing	Coordination number	Spacing of layers	Volume of unit prism	Density	Porosity (%)
Simple cubic	6	$2R$	$8R^3$	$\pi/6$ (0.5236)	47.64
Cubic tetrahedral	8	$2R$	$4\sqrt{3}R^3$	$\pi/3\sqrt{3}$ (0.6046)	39.54
Tetragonal sphenoidal	10	$R\sqrt{3}$	$6R^3$	$2\pi/9$ (0.6981)	30.19
Pyramidal	12	$R\sqrt{2}$	$4\sqrt{2}R^3$	$\pi/3\sqrt{2}$ (0.7405)	25.95
Tetrahedral	12	$2R\sqrt{2}/3$	$4\sqrt{2}R^3$	$\pi/3\sqrt{2}$	25.95

^a From Deresiewicz (1958, Table 1).

1.2.2 Porosity of monodisperse and polydisperse mixtures

Total pore volume is a global characterization of the assemblage of particles. A soil profile is often seen as a pile of soil aggregates and the aggregates are often modeled as spheres (Fig. 2-2). In many books and research papers, authors try to compare the porosity of soil layers with the porosity of a regular pack of spheres (Dexter and Hewitt, 1978; Assouline and Rouault, 1997), interpreting porosity decrease as a closer packing of the spheres (Fig. 2-3 and Table 2-1, from (Hillel, 2002)).

Such models can perhaps mimic some specific hydraulic behaviors of real soils, but not possible for natural materials, including soil profiles. Thus, it seems quite challenging to interpret recompaction of tilled layers as a closer packing of regular spheres. Several decades ago, physicists have studied the subject of close packing of spheres. An important parameter that characterizes a stacks of particle is the **volume fraction (Φ)**, defined as the ratio between the volume occupied by the grains on the total volume occupied by the stack. With regular spheres, the densest possible stack is observed for a tetrahedral packing: $\Phi = 0.74$ (26 % porosity, table 2-1). Such a dense stack, which corresponds to the minimal level of potential energy, can be observed at molecular level, but not for macroscopic spheres. If a stack of identical beads is vibrated in a container in order to increase its compactness, the stack reaches a critical volume fraction of ‘only’ **0.64** (36 % porosity) (Scott, 1960), much less than the theoretical maximum of 0.74; this packing was called ‘**random close packing**’. There is also a ‘**random loose packing**’: $\Phi = 0.55$ (45 % porosity) (Onoda and Liniger, 1990).

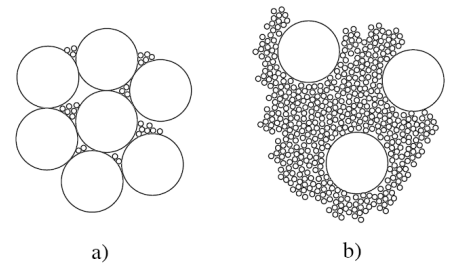
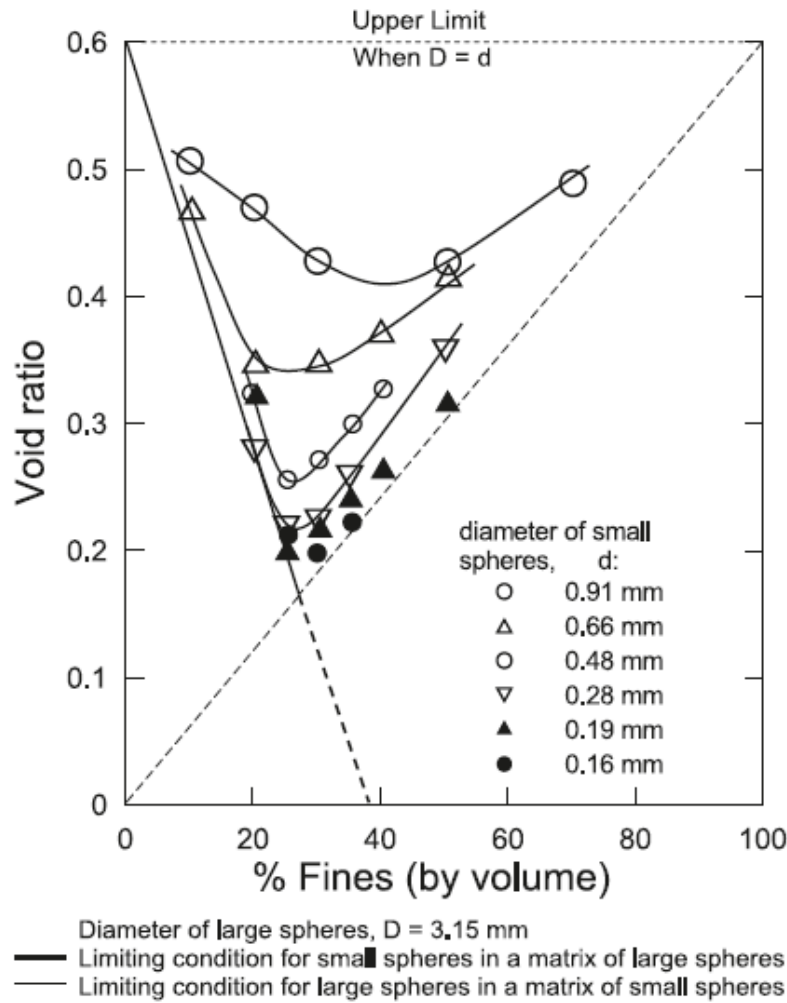


Fig. 2-4 Left: Effect of fine content on minimum void ratio of binary mix (Rahman et al., 2008). **Right:** extreme mixture cases a) a mixture where large grains are dominant (in weight and volume). Note that even on this simplified example, the number of small grains is much higher than the number of large ones); b) few large grains embedded in a majority of small grains.

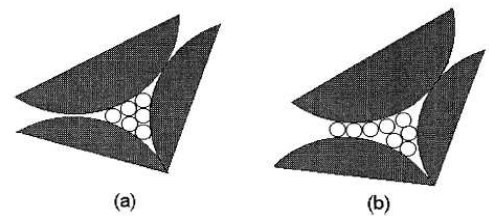
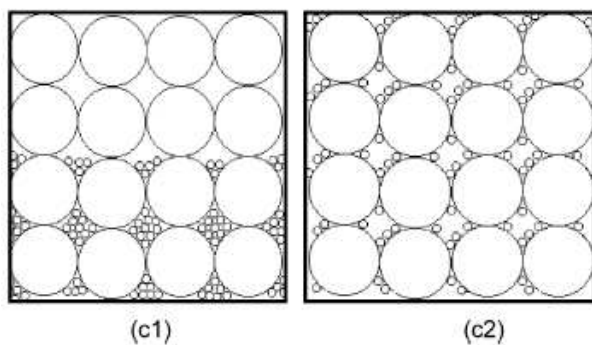


Fig. 2-5 Left: Preparation of controlled mixtures with glass beads of different sizes **Right:** Schematic representation of the arrangement of small particles between large particles: a) small particles fill the free space between skeleton particles, b) small particles wedge in the skeleton of large particles (Dias et al., 2004).

By mixing spheres of different sizes (polydispersed population), it is possible to increase the volume fraction Φ . For a bidisperse mixture, the evolution of Φ in relation with the percentage of large and small beads, and for different small beads is presented on [Fig. 2-4a](#). When the fine beads get smaller radius, Φ is increasing; a minimum value of $\Phi = 0.83$ was measured and a theoretical value of $\Phi = 0.86$ (14% porosity) was calculated. The figure shows that after reaching a maximum value around 20 to 30 % of fine grains, Φ is decreasing again.

This result indicates that, at small concentration, the fine spheres are present in the packing voids between the large spheres until those large pores are saturated; after the threshold the volume is dominated by small spheres and the volume fraction is decreasing again; [Fig. 2-4b](#) shows what the mixture looks like before and after the optimal threshold. Of course, it is just one possibility. Because with the same concentration, the small beads can be organised in different position, and would provide different behaviour to such a pile ([Fig. 2-5a](#)). If we have a closer look, even in the same global position, locally can be some differences in location that does not affect much the total porosity but have again dramatic consequences on other properties as we will see later ([Fig. 5b](#)).

For soils, similar mixtures have been studied using sand grains and clays (Vallejo and Mawby, 2000) and similar results were obtained ([Fig. 2-6](#)). Ternary mixtures (clay-silt-sand) studied by [Fiés and Bruand \(1998\)](#) have shown that clay and silt fraction form a whole where all the clay could be considered as associated with the silt fraction; consequently the threshold of 15-20% fine fraction remains unchanged and the principle of large rigid particles in contact with infilling fine fraction is still relevant.

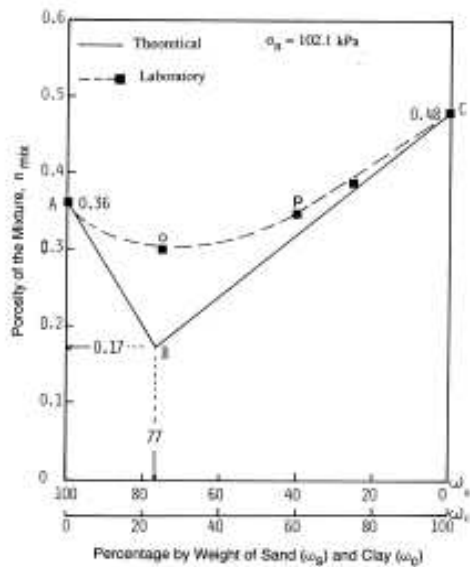


Fig. 4. Changes in porosity of the sand-clay mixtures ($\sigma_n = 102.1$ kPa).

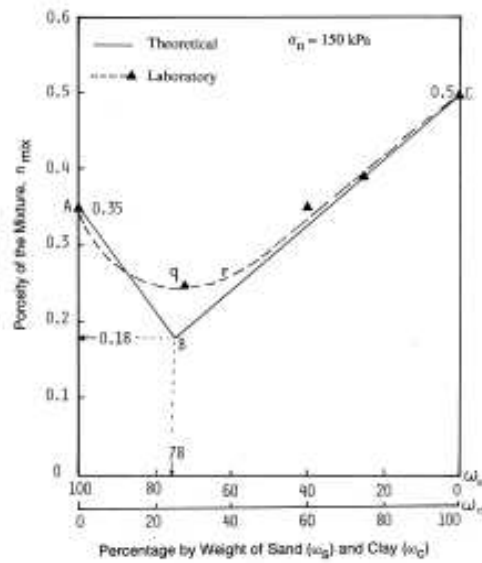


Fig. 5. Changes in porosity of the sand-clay mixtures ($\sigma_n = 150$ kPa).

Fig. 2-6 Change in porosity of the sand-clay mixture (102 kPa and 150 kPa) (Vallejo and Mawby, 2000).

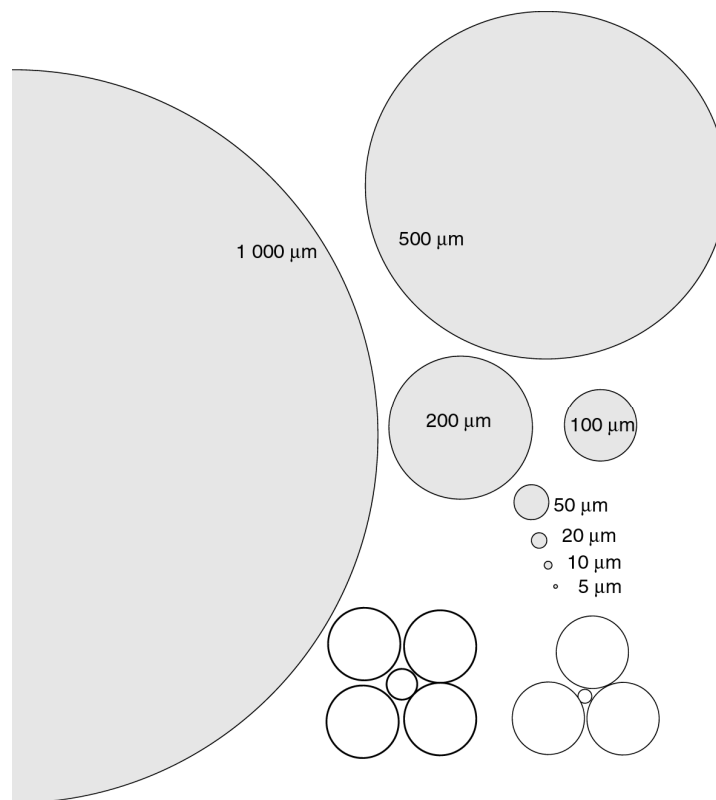


Fig. 2-7 Natural soils are highly polydisperse, this figure presents the respective size of spherical grains of the main sand and silt fractions, clay (<2 μm) is too small to be represented.

A tertiary mixture has in reality a very large spectrum of grains of large size differences. Fig. 2-7 presents the different size because using only simplified presentation could lead to wrong impression on what the relation in space is between grains. Fig. 2-8a presents a virtual (close) packing of spheres with a large dispersion. But the characteristic of soils is not only the large polydispersivity, but also a large variety in the shape of grains (Chretien and Bisdorn, 1983). Fig. 2-8b presents a picture from a real soil for which sand grains could hardly be compared to spheres; this sample contains 20 % clay and as expected from Fig. 2-4 and Fig. 2-6, the fine clay fraction is totally filling the porosity resulting from the packing of large grains but those grains are still in contact. With only a 10 % clay content, Fig. 2-9 shows that large packing pores are still observed (Fies and Bruand, 1998); more importantly, most of the sand grains are in direct contact and the fine fraction is located in the packing porosity. Observation made on sandy soils of Northeast Thailand in soils with <6% clay also indicate the large number of direct contact between sand grains (Fig. 2-10) (Bruand et al., 2004).

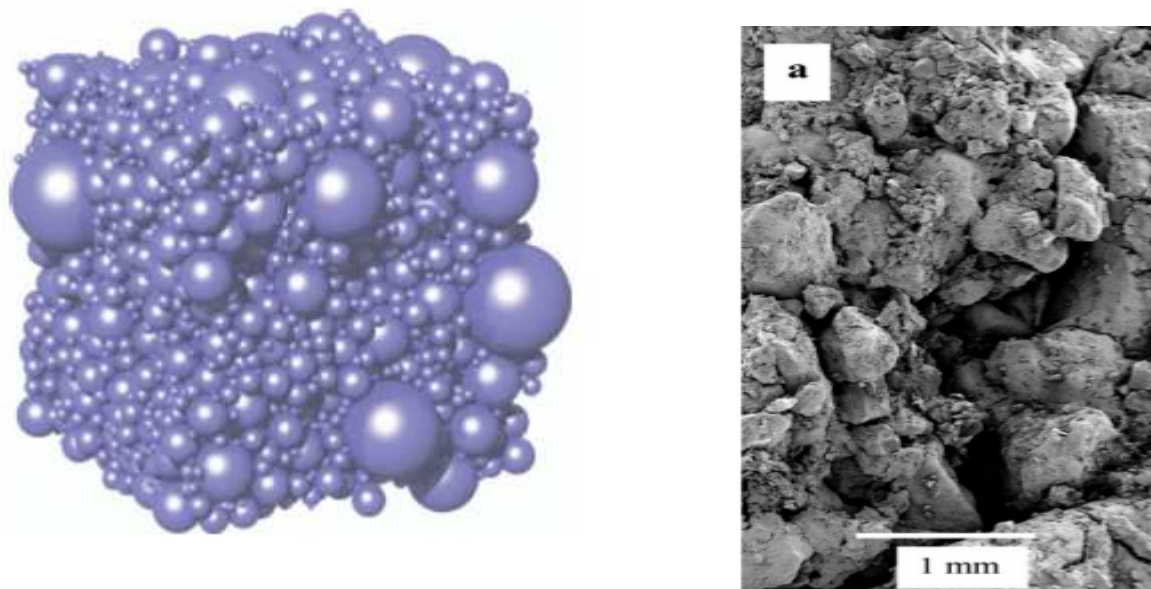


Fig. 2-8 Left: Close packed configuration of spheres from a log-normal distribution. The spread in the logarithm of radius is 0.6. Only spheres with centers lying in one periodic image of the simulation cell are shown (Chretien and Bisdorn, 1983). Right: Scanning electron microscope picture of a soil (Fabiola et al., 2003).

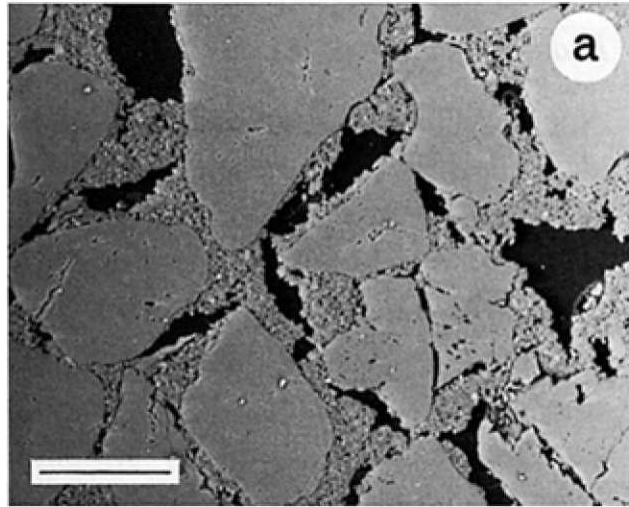


Fig. 2-9 BESI showing the lacunar pores resulting from the packing of the sand particles of the sand particles with the clay-silt phase. Clay was 10%. Black areas are pores, homogeneous grey areas are sand particles, heterogeneous dark grey areas are silt and clay particles and associated pores (bar length = 200 micron) (Fies and Bruand, 1998).

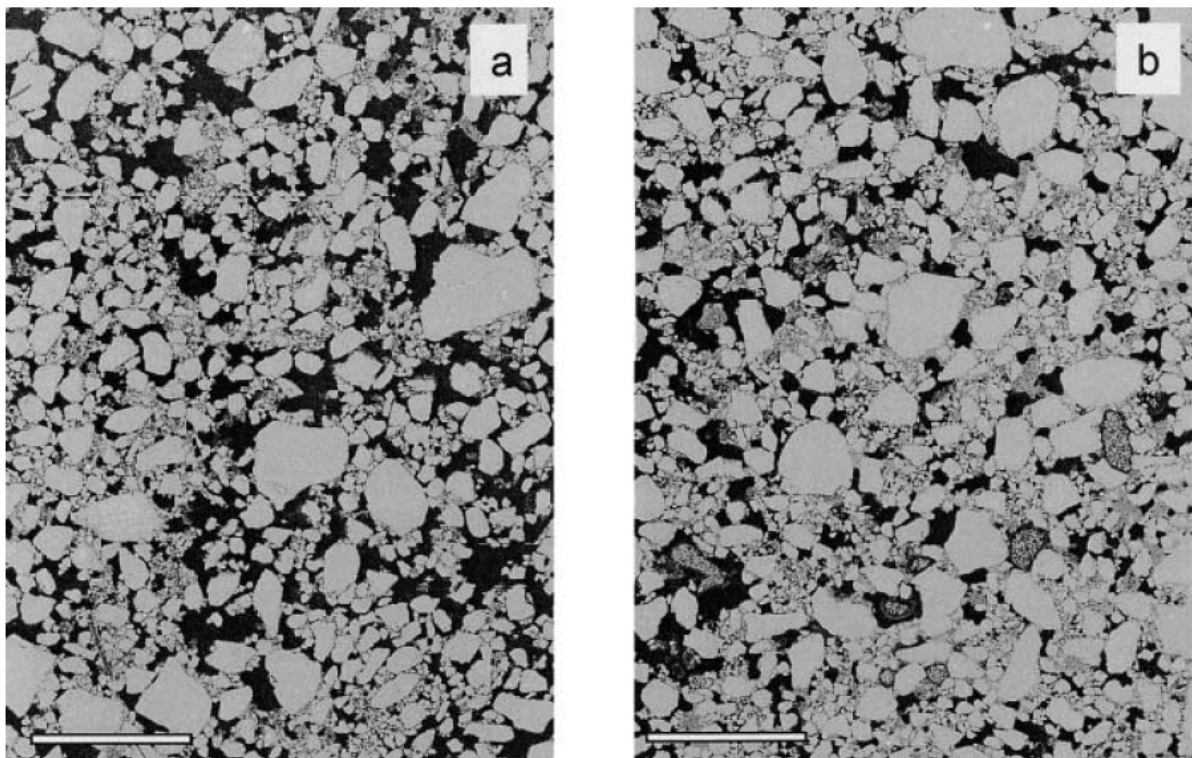


Fig. 2-10 Back-scattered electron scanning images: (a) topsoil (Ap horizon), (b) 25- to 35-cm subsoil (E horizon). Voids occupied by resin are black, homogeneous gray areas are quartz grains, very light particles in the silt range size are much heavier mineral than quartz, and heterogeneous gray areas are fine silt and clay particles and associated porosity (bar scale = 1 mm). The clay content was 3.7% for A_p and 5.3 % for E horizon (Bruand et al., 2004). See the difference in packing compared to Fig. 2-8.

1.3 Mechanical characteristics of a dry granular material

Substances known as "granular media" consist of macroscopic and rigid particles with no significant attractive force; they can have different size, shape, and surface roughness. 'Macroscopic' particles means that they are not affected by Brownian agitation, and the size is larger than approximately $1\text{ }\mu\text{m}$; 'rigid particles' means that their deformation, even under heavy load, always remain small. Many substances of everyday life composed of collections of separated solid grains behave as granular material (for example: sand, rice, ball bearings, flour, etc.) and have been used as models for research work, but grains with much larger dimension can be observed in natural environment and behave similarly to smaller ones (Duran, 1999). In this text, the word 'grain' will be used for any material presenting the properties described above.

Despite the simplicity of their constituents, granular materials display a variety of complex dynamic and static properties. For example, they defy conventional fluid-gas-solid classification (Jaeger et al., 1996; de Gennes, 1999). The granular media will conform to the shape of a container like a liquid, but it will be stable and rigid if the container is tilled (it is only if the container is tilled enough that it will flow and thus behave again as it is expected from a liquid). Another important characteristic, especially in the context of our research work, is that **disordered structures allow compaction only in relation with reorganization** of parts of the system. The complex behavior of granular materials include also size segregation, arches and chains creation, cooperative motion, etc. , some of them are possibly relevant for understanding structural stability of coarse textured soils and will be detailed in this review.

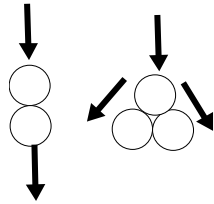


Fig. 3-1 Lateral redirection of uniaxial loading at the scale of few grains is the most common situation because the position on the left (vertical alignment of centers of gravity of two grains of spheres) is unstable.



Fig. 3-2 Collapse of a silo after the walls have cracked.

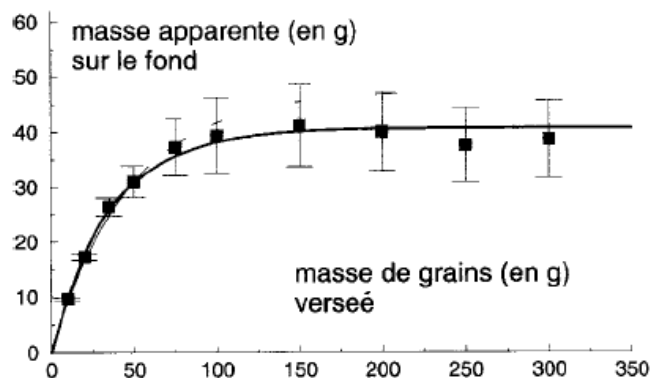
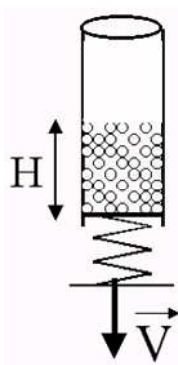


Fig. 3-3 When sand or glass beads are poured in a test tube linked to a balance, very fast the indication on the balance is stabilised, demonstrating that the pressure is no more on the bottom but on the walls of a the test tube. Despite the scale difference of several order of magnitudes, the same phenomena is occurring in a silo filled with wheat.

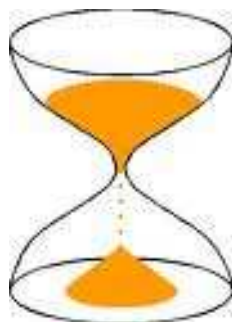


Fig. 3-4 An hourglass is another example of lateral redirection of forces; the sand flow does not depend on the weigh of the sand above the outlet.

1.3.1 Lateral redirection of forces

The contact area between two rigid particles is always extremely small (can be considered as a single point); consequently, the forces/pressures which are transferred across such small contact can be very large (Duran, 1999). For granular material, a vertical load or force is rarely transmitted below the centre of gravity of this grain; thus, most of the time there is a lateral redistribution due to the respective positions of the different grains (Fig. 3-1). At the macroscopic scale of a pile of grains, similar redirection is also observed.

Practical consequences of lateral redirection in presence of a limiting wall

Silos that contain large amount of granular material (wheat, rice, etc...) can sometimes be broken on their side but never on their lower part. This is a direct consequence of lateral redirection of force: instead of pushing on the bottom of the silo, the weight of the grains exerts a pressure on the side; if the silo was not strong enough to support such large pressure, it will break (Fig. 3-2). The lateral redirection can be easily measured by filling a test tube linked to a balance with any granular material (Fig. 3-3). After an increase of the pressure exerted at the bottom that related with weight increase, there is a steady state indicating that all the pressure is exerted on the border of the tube. Another example of the consequences of lateral redirection of forces is the hourglass: as the stress is not exerted at the bottom but laterally redirected to the glass walls, the flux of sand is constant and does not depend on the height or the pressure of the sand at the outlet (Fig. 3-4).

Theses three examples also show that behaviors or granular materials **are not scale dependent**, they are similarly observed for grains and piles of very different sizes.

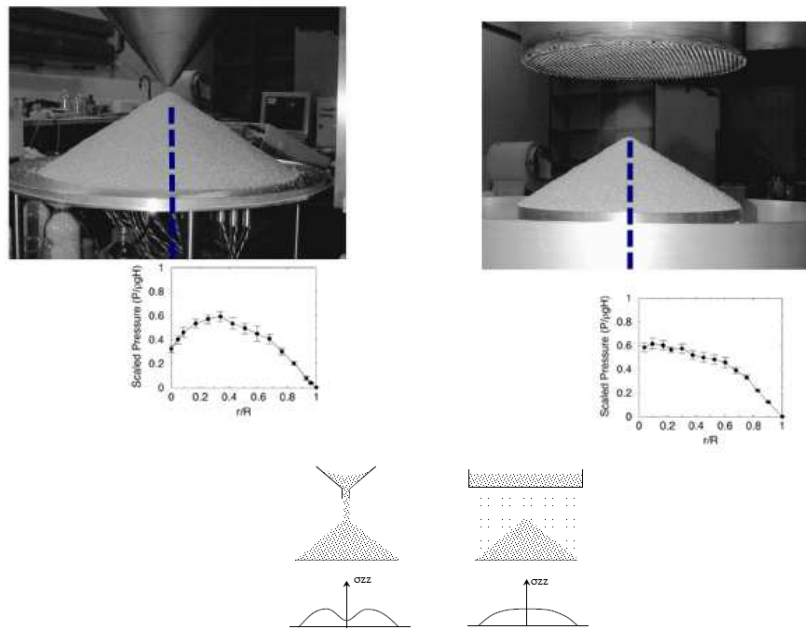


FIG. 3.6 – La contrainte sous un tas dépend du mode de construction.

Fig. 3-5 The stress distribution was affected by two different filling methods. The figures are plotted as dimensionless normal stress profiles, $P/\rho gh$, vs dimensionless radial distance r/R , beneath conical piles of granular materials of height H and radius R . The construction techniques are illustrated by the accompanying photographs (Vanel *et al.*, 1999).

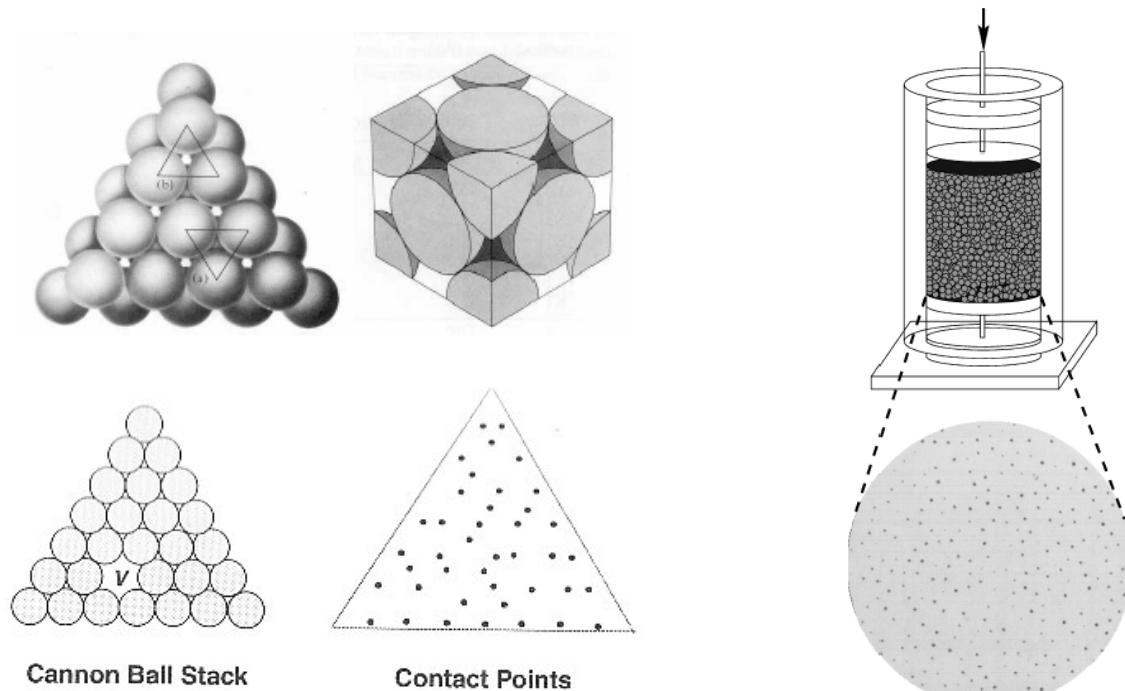


Fig. 3-6 LEFT top - Theoretical example of a pile of perfect spheres, perfectly piled with 6 contact points with the neighbours; **LEFT bottom** - Real grains marble beads, ball bearing, cannon balls, etc. are not perfect spheres, even though the structure appears to have a high degree of order, many parameters are actually undetermined, including number of contacts (Durant, 1999). **RIGHT** – The contact of the beads on the bottom of a column do not present a regular order (Mueth *et al.*, 1998).

1.3.2 Lateral redirection exist even in the absence of borders

Walls and borders are convenient indicators of the existence of lateral redirection. But even in the absence of any border (like in cultivated soils), lateral redirection exists and has measurable consequences on granular material behaviour. For example, under a hip of sand or gravel, we would expect the highest pressure on the ground being exerted below the top of the hip, but it is not the case. Under the top of the heap there is a ‘dip’ in the pressure profile, *i.e.* a lower pressure compared to the neighbouring areas (Fig. 3-5a). As redirection depends on the way the grains have been piled, *i.e.* the ‘history’ of the material, changing the way the heap was created changes the characteristic of redirection. If the pile is created from a ‘dispersed source’, the pressure profile of the dip in the profile pressure disappears (Fig. 3-5b).

1.3.3 Intergrain contacts inside a pile of grains

The previous section has indicated that the theoretical closest packing of grains ($\Phi = 0.74$) is not observed in natural material at macroscopic scale. Similarly, an ordered pile, in which all grains would have the same number of contact with their neighbours (Fig. 3-6 top left), cannot be observed with natural grains at macroscopic scale. As a pile of grain is characterised by disorder and heterogeneity in the piling pattern; similar heterogeneity is observed in the spatial distribution of contacts between grains. This can easily be experienced if trying to build a pile with marble or glass beads, or with bowling or canon balls: the number of contacts is reduced compared to the optimal number observe on geometrical models (Fig. 3-6 bottom left). No regular pattern can be observed at the contact points at the bottom of a pile of grains. It presents a random distribution that reflects the heterogeneity of the contacts existing inside the pile.

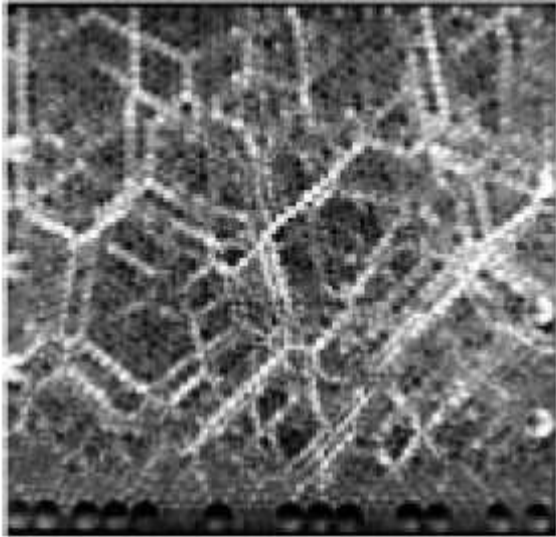


Fig. 3-7 Pile of photoelastic disks.

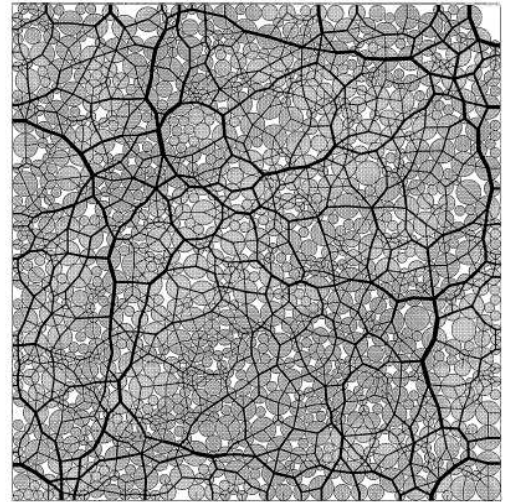
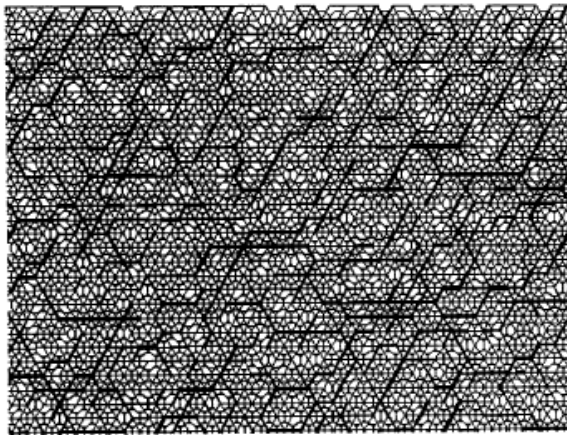
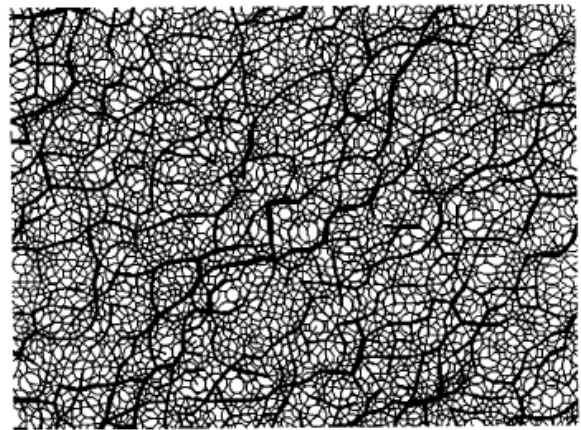


Fig. 3-8 Network of normal forces in a sample. Forces are encoded as the widths of intercenter connecting segments (Radjai et al., 1999).



$r_d = 0.01$, load = 1 unit



$r_d = 0.3$, load = 1 unit

Fig. 3-9 Effect of randomness on the force chains development. Left low randomness (high order), right high randomness (low order), same loading as 1 unit (Ngan, 2004a).

1.3.4 Existence of forces chains

As only some of the grains are concerned by forces transmission, these grains will transmit considerable forces with a specific geometrical distribution inside the pile. Using photoelastic grains it is possible to visualise the stress distribution inside a pile of grains. [Fig. 3-7](#) presents a pile of 2D photoelastic disks: the higher the constraint, the whiter the colour of the disk. In the absence of stress, grains remain black. The white lines clearly show force chains, *i.e.* a population of grains in contact that transmit the loading force. It is possible to observe two main characteristics of this network: 1) the lateral redirection (as mentioned before), and 2) the different chains can be more or less white, indicating that they do not all carry the same loading. Strong **forces chains** that are bearing most of the load (*i.e.* above average) can be observed as well as weak force chains.

The large forces have been called '**arches**', because like architectural arches: i) they redirect laterally the pressure/force, ii) the grains below those grains located below the arch are exempt from any pressure (totally black grains are visible, *i.e.* grains with no stress at all). The grains transmitting weak or no forces could be considered as 'passive spectators' but they probably have an important effect for piles in 3D ([Radjai et al., 1999](#)).

1.3.5 Factors affecting chain forces- mathematical modelling

Photoelastic grains are a special way to show the forces chains but observations are limited in 2D. The developments of computer provided the possibility of creating diverse virtual simulations. Of those simulations, the force chains are represented by a line linking the center of the grains, the width of this line depending on the intensity of the transmitted force ([Fig. 3-8](#)). Similar to those simulations, it was possible to measure that strong forces chains transmit approximately 60 % of the forces ([Radjai et al., 1999](#)).

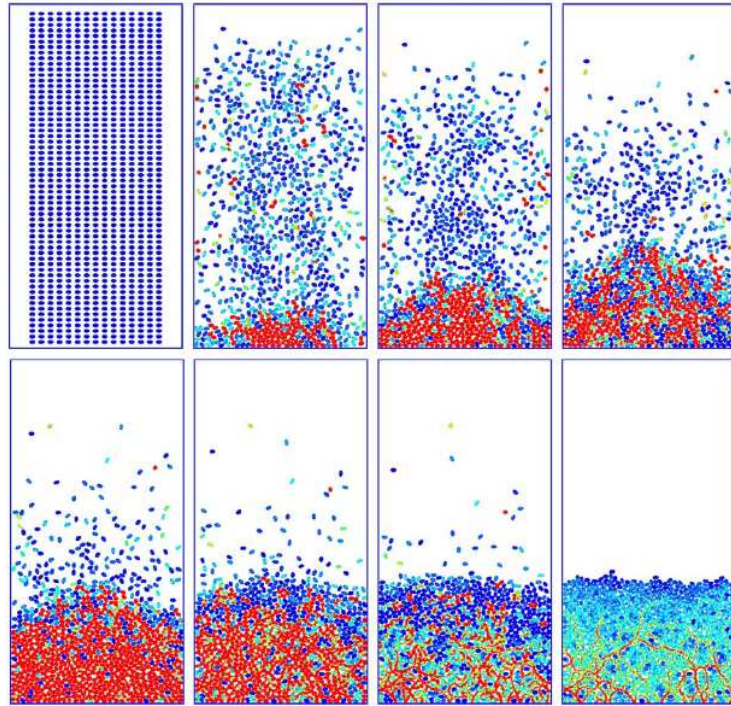


Fig. 3-10 Deposition sequence of granular particles, ellipses of aspect ratio 1.5 with friction. The colour scheme indicates the magnitude of the differential stress calculated inside each element of each particle. The stress state of the final deposit is characterized by force chain patterns that are carrying high load through several grains (Guises et al., 2009).

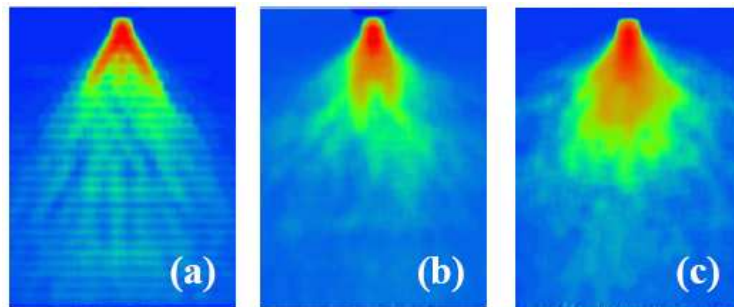


Fig. 3-11 Chains forces for spherical gains (a) and less rounded shapes (b and c) (Atman et al., 2005a; Atman et al., 2005b).



Fig. 3-12 The contact are perfectly rigid at the left side and become softer for center and right figure: with softer contacts, the distribution becomes more homogeneous (Atman et al., 2005a; Atman et al., 2005b).

Thanks to these virtual models, it was possible to estimate the factors affecting the characteristics of forces chains. Randomness of the pile affects the distribution of the chains: when the piling is ordered (low randomness) the forces are more homogeneously distributed and are thus 'weaker' (no obvious strong chain); and vice versa for increasing randomness. Moreover, for high randomness, the lateral redirection becomes more evident (Fig. 3-9) (Breton et al., 2002; Ngam, 2004). With virtual models, it is also possible to visualise the development of chains forces during the creation of a stack of grains (Fig. 3-10).

The shape of the grains as well as polydispersivity has also a large effect on the characteristics of forces chains (Fig. 3-11) as well as the rigidity at the contact (Fig. 3-12) (Atman et al., 2005a; Atman et al., 2005b).

Mechanical loading

Under uniaxial pressure, the force chains are extremely resistant: they become stronger with very few rearrangements inside the material. Nevertheless, **if the constraint is not directed exactly in the direction of the chain, small forces can destroy the chains**. The chains are **fragile**. Moreover, very small variations in the position of the grains inside the piles can induce large changes in the force transmission without necessarily changing the contact network. For example, this was observed with temperature variations (Bonamy et al., 2000).

Effect of surface rugosity

Even grains that seem perfectly smooth at macroscopic scale have a high rugosity at nanometre scale (Fig. 3-13). When a pile of grain is created, this rugosity is a major factor determining the geometrical and mechanical characteristics. Rugosity will also have two major consequences: interlocking of the grains under higher pressure and ageing of the pile (increasing stiffness of the pile with time). The other consequence is a stick and slip effect that is caused by the surfaces alternating between sticking to each other and sliding over each other, with a corresponding change in the force of friction (high at rest, low during movement).

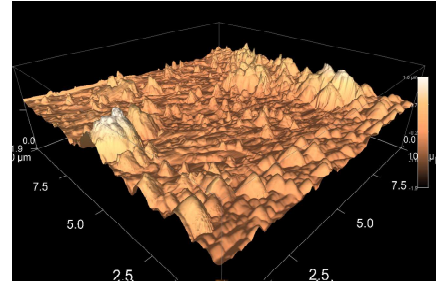
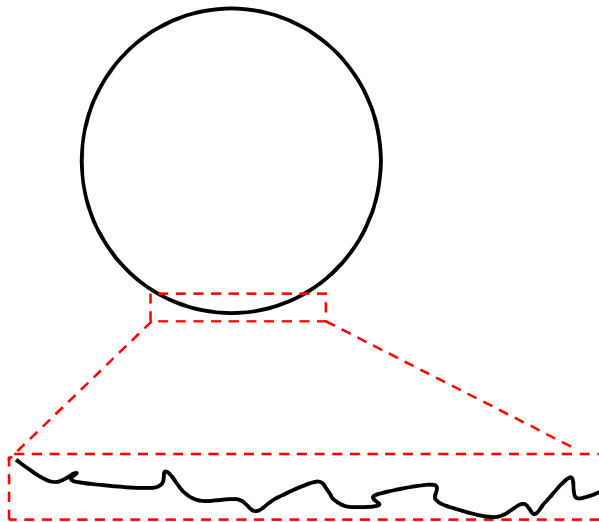


Fig. 3-13 Magnification of the surface of a smooth bead: at nanoscale the surface is no more flat, but has high rugosity.

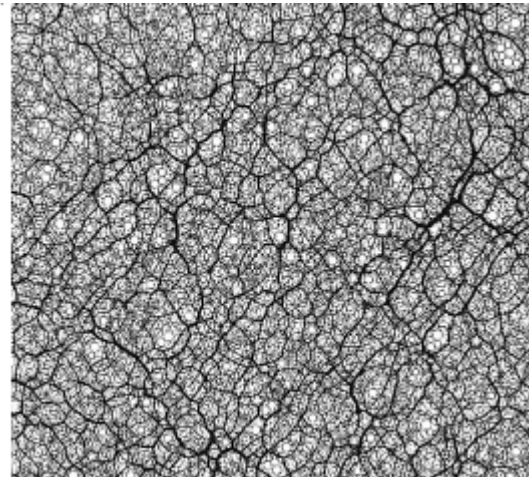
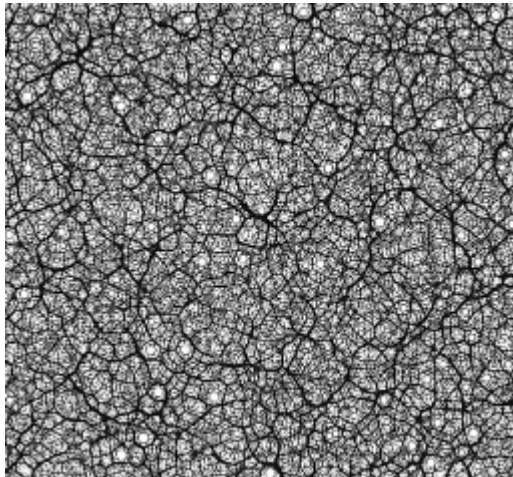


Fig. 3-14 Systems with two different friction coefficient: $\mu = 0.01$ and 0.40 (left and right respectively) (Ngan, 2004).

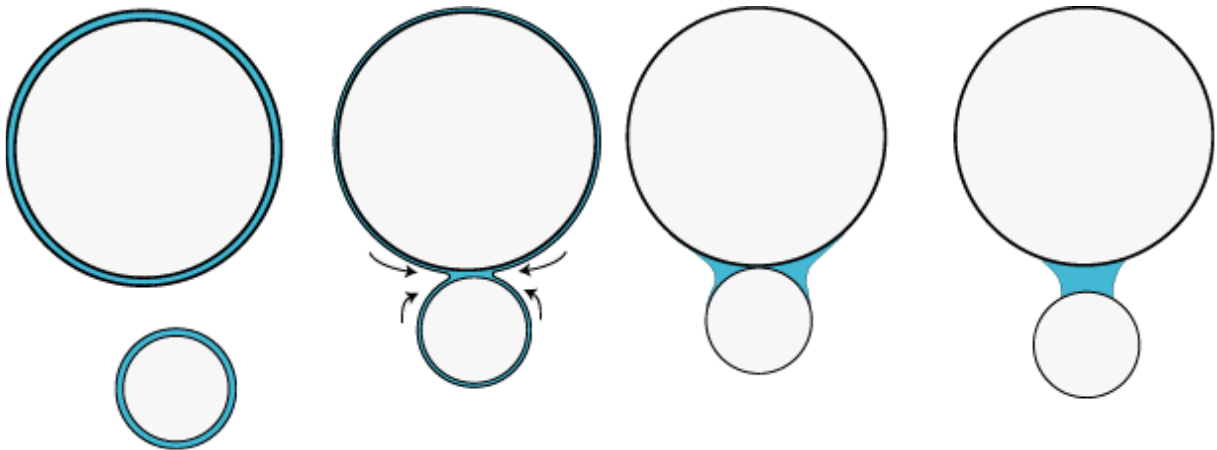


Fig. 4-1 Development of a capillary bridge when two grains come in contact: a) adsorbed layers (distance is exaggerated), b) interfacial tension attracts the two adsorbed layers c) a capillary is formed, d) this process is hysteric: it is possible to pull on the grains until a critical distance d before the bridge breaks.

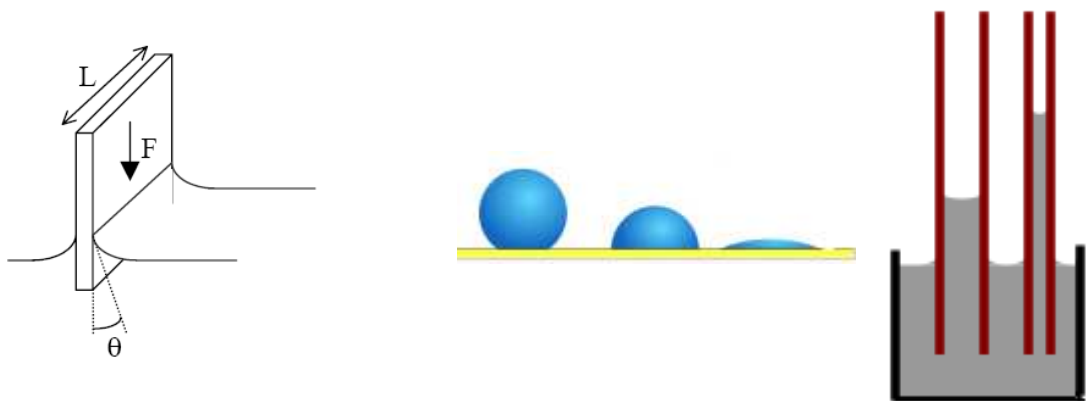


Fig. 4-2 a) Due to interfacial tension, water exerts a force $F = 1 L A \cos\theta$ with L , the length of the plate, θ is the contact angle of liquid on the plate and A the surface tension. b) Different contact angles on a glass plate (Hg on the left, H_2O on the right); c) rise of water in capillary tubes.

1.4 Cohesion of wet granular material

The two previous sections have provided some information on the piling of grains and its disordered nature, the consequences of this is a heterogeneous distribution of forces. When water is added to a sandy soil or to pure sand, even in very small amount, its stiffness and cohesion are dramatically increased. Most of us experienced it when building a sand castle. This paragraph will present 1) the characteristics of individual capillary bridges, 2) the location of water inside a granular with increasing water content, 3) the cohesion forces at different water regimes, and 4) the development of tensile strength.

1.4.1 Capillary water bridges between two solid particles

Individual grains are in contact with atmospheric moisture, thus they are covered by a thin layer of water, generally at the scale of nanometers. When two grains come in contact, water moves at the contact point and a meniscus appears and develops (Fig. 4-1a, b). The origin of this movement is **the interfacial tension**.

Surface tension is a measure of cohesive energy present at an interface; it is expressed in terms of energy per unit area ($7.3 \times 10^{-2} \text{ Jm}^{-2}$ for a water/air interface). When a thin glass plate is put in contact with water, water will exert a force on the glass plate (Fig. 4-2). In a situation where the liquid adheres to the walls of its container, we consider the part of the fluid's surface area that is in contact with the container to have *negative* surface tension. The fluid then works to maximize the contact surface area. So an increase of the area in contact with the container decreases rather than increases the potential energy. That decrease is enough to compensate for the increased potential energy that associated with lifting the fluid near the walls of the container. In capillary types, the liquid adhesion to its walls is sufficiently strong; surface tension can draw liquid up the tube in a phenomenon known as capillary action.

Liquids tend to minimise their surface area, and a spherical surface is the geometrical form with the smallest surface/volume ratio. The free energy forces the surface to deform by an

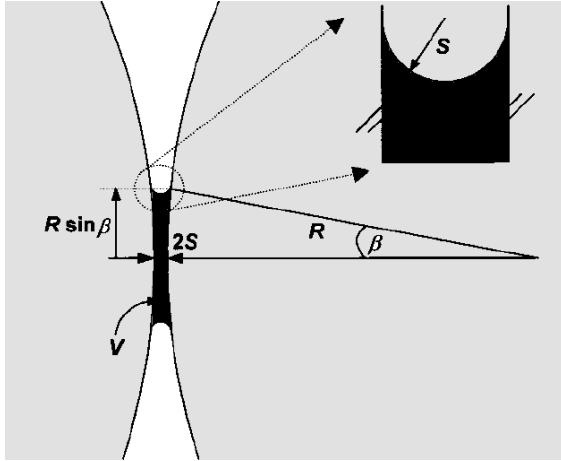


Fig. 4-3 The geometry for small liquid bridges with a contact angle of zero between two equal spheres where the radius of curvature of the bridge surface is approximately given by half-separation distance, S (Willett et al., 2000).

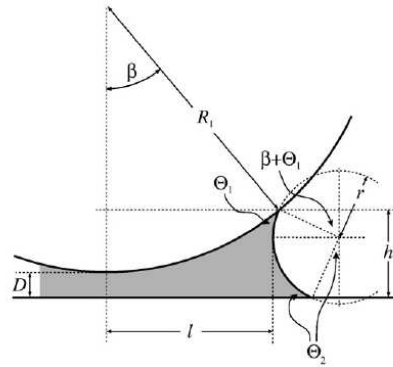
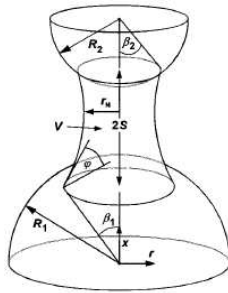


Fig. 4-4 Left : A schematic representation of a liquid bridge (Willett et al., 2000). Right – Sphere with radius R_1 interacting with a plane. The curvature of the liquid meniscus, also called **pendular ring**, is characterized by two radii: the azimuthal radius l and the meridional radius r , perpendicular to it (Butt and Kappl, 2009).

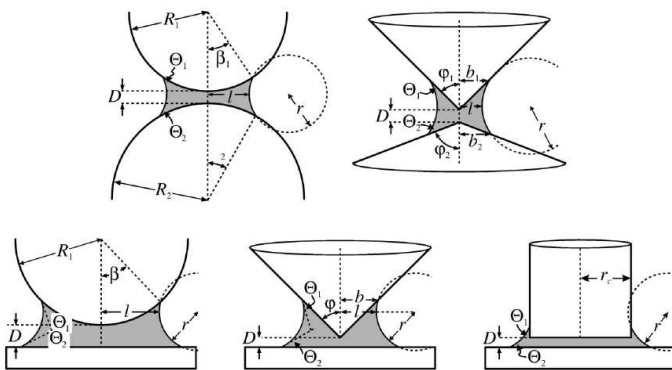


Fig. 4-5 Different geometries of solids in contact for which capillary forces can be calculated using the circular approximation (Butt and Kappl, 2009).

amount quantified by the Young-Laplace equation. This equation describes the pressure difference across a curved surface (capillary pressure) and the atmospheric pressure with:

$$P_c = (2 \gamma \cos\theta) / r$$

where P_c is the capillary pressure, γ is the interfacial (surface) tension, r is the radius of curvature of the surface and θ is the contact angle.

Inside a water bridge linking two grains, the Laplace pressure is negative. As a consequence, **the surface tensional forces pull the particles together through the liquid bridges (Pierrat and Caram, 1997)**. This capillary force depends both on physical parameters (contact angle for example) and the configuration of the solid and liquid phases (size and distance between two grains) (Willett et al., 2000; Butt and Kappl, 2009). To form fully developed capillary bridges at the contact between neighbouring grains, a certain excess of liquid volume is required. But whatever its size, inside a bridge the volume and the weight of the water are small enough so that the effect of gravity can be neglected (Adams et al., 2002); for example, for grains with a radius of 0.1 mm, the capillary force is 100 time greater than the gravity (Herminghaus, 2005). Fig. 4-3, 4-4, 4-5 present bridges between grains or planes of different shape.

Another noteworthy characteristic is the hysteresis: once that two grains have been in contact, they can be pulled away (Fig. 4-1d) and the water bridge will be stretched without breaking. It is necessary to stretch the bridge until a critical distance to break it. But increasing the distance between the grains decreases the capillary force (Adams et al., 2002).

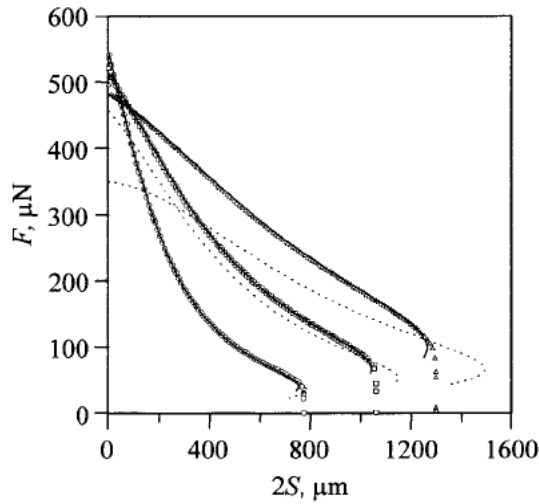


Fig. 4-6 The capillary forces as functions of the separation distance between an upper sphere of radius 2.381 mm and a lower planar surface. The experimental data for the sphere have been measured for bridge volumes of 0.620, 2.261, 5.736 uL. The corresponding calculated forces are shown which include (full lines) and neglect (dashed lines) the influence of gravity (Willett et al., 2000).

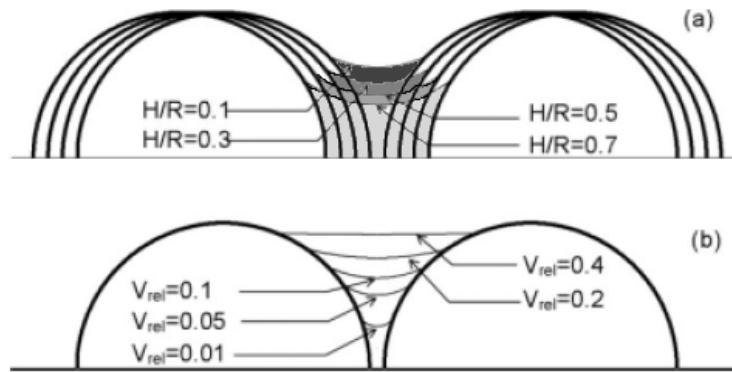


Fig. 4-7 Meniscus and spheres profiles drawn at different conditions: (top) changing the interparticle distance (R is the spheres' radius and H there distance); (bottom) increasing the volume of the bridge is increasing thicker meniscus (larger L) and decreasing the meniscus curvature (larger q). If the amount of liquid is increased sufficiently, it may cover completely the spheres, and beyond this point, the spheres will be fully immersed in the liquid and it is no more possible to speak about 'bridge' (Megias Alguacil and Gauckler, 2009).

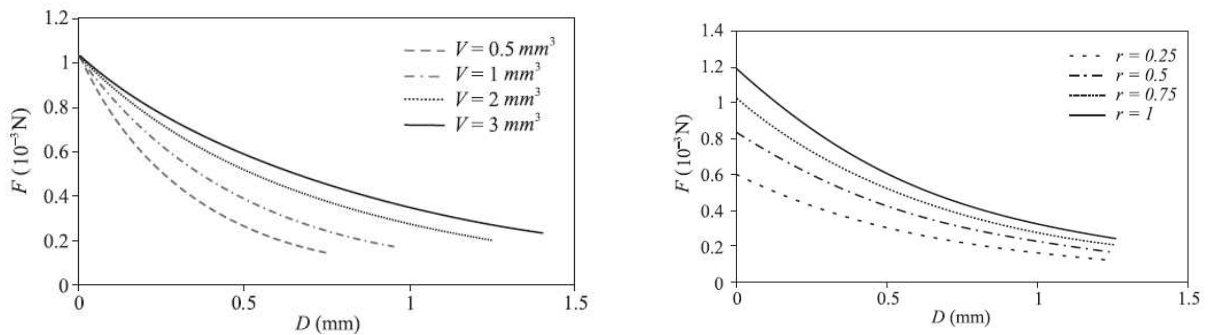


Fig. 4-8 Analytical estimate of the capillary force as a function of the inter-particle distance D , a) for different volumes V of the liquid bridge, b) for different values of the ratio $r=R_1/R_2$ (Soulie et al., 2006).

Breaking the water bridge needs to reach a critical distance (Fig. 4-6) and changes the curvate of the meniscus (Fig. 4-7 top). Other factors can affect the capillary force between two spheres and were studied with detailed analysis of forces, laboratory experiments and mathematical modelling (Pierrat and Caram, 1997; Adams et al., 2002; Soulie et al., 2006; Butt and Kappl, 2009). If we consider a capillary bridge between two spheres of radius R_1 and R_2 :

- increasing volume of a water bridge changes the curvate of the meniscus bridge (Fig. 4-7 bottom) and the increases the rupture distance (Fig. 4-8a),
- decreasing radius ratio R_1/R_2 decreases the capillary force (*i.e.* the capillary force is higher for similar spheres compared to a large and small one), but this ratio does not affect the rupture distance (Fig. 4-8b).

This first section considered the simplest situation in which only two grains are linked by a single capillary bridge. The next section will consider a pile of grains and describe the changes occurring to the location of water when the amount of water is increasing.

1.4.2 Water bridges and their evolution at different water content

In a classical soil, *i.e.* a pile of clay aggregates, an increase in water content consists in filling pores of increasing (equivalent) diameters. Due to large differences in equivalent diameter observed in a soil, a difference is made between small *intra-* aggregate micropores (also called *textural pores* as they result from the arrangement of elementary particles) and large *inter-* aggregate macropores (also called *structural pores* as they result for external structuring factors like biological activity, wetting and drying cycles, tillage, etc.).

In granular material with individual rigid grains, it is not possible to make such distinction: all pores are at textural (resulting from arrangement of individual grains) and structural the same time (packing always being disordered as reflect of the piling history and thus could be considered as structural). Consequently, in a granular material increasing water content does not mean filling larger pores but it means changing the position of water relative to the grains.

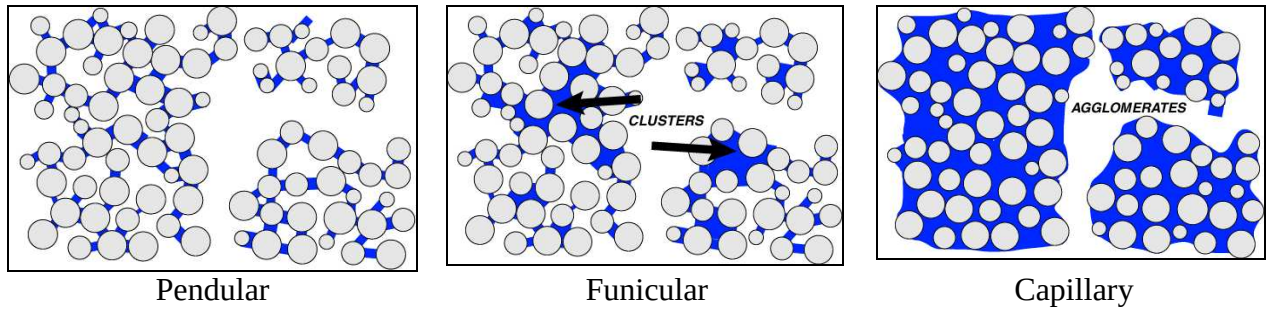


Fig. 4-9 The different water regime in a granular material: at pendular regime, water is located only in bridges strictly linking 2 grains; at funicular regime, the bridges coalesce to form clusters; at capillary regime, clusters coalesce and continuity exists in the water network, large agglomerates are created.

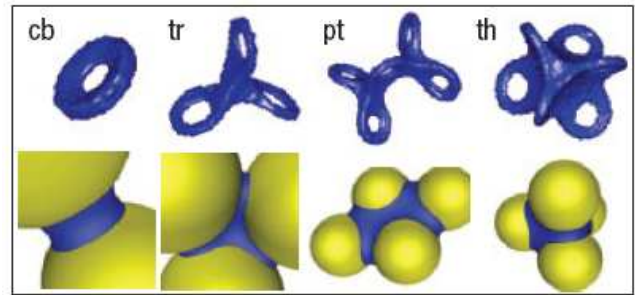
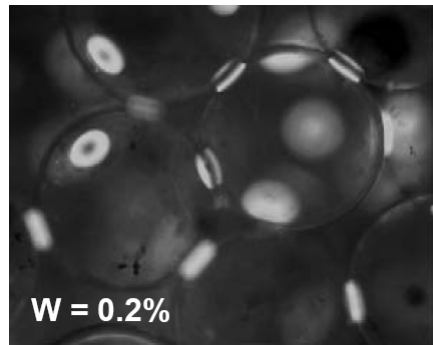


Fig. 4-10. Left: Fluorescence microscope image of the glass beads at a water content of 0.2%. Capillary bridges between the beads are clearly visible (Kohonen et al., 2004).

Right: Liquid morphologies in a wet granular pile. Top row: capillary bridge, trimer, pentamer and filled tetrahedral (th) as obtained from X-ray tomography. Bottom row: As obtained numerically (Scheel et al., 2008).

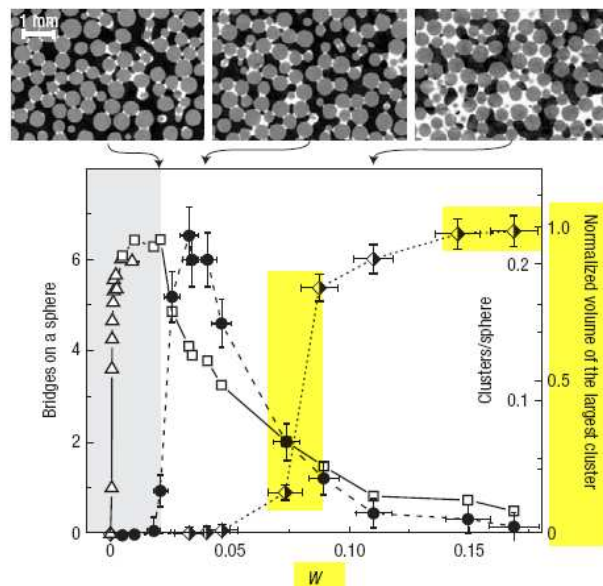


Fig. 4-11 Development of clusters when water content is increasing. Top: sections through 3D tomograms of the analyzed samples at Water =0.02, 0.04 and 0.11, from left to right grains are grey, air is black and water is white). Bottom: Frequencies of liquid objects as extracted from X-ray tomography images. Left axis (open symbols): Average number of capillary bridges on a sphere (triangles: fluorescence microscopy; squares: X-ray tomography). Right axis: Average number of clusters per sphere (filled symbols), and normalized volume of the largest cluster (half-filled symbols (Scheel et al., 2008).

Three water regimes are generally identified (Pierrat and Caram, 1997; Iveson et al., 2002b; Mitarai and Nori, 2006):

- 1) The **pendular** regime: water is located in capillary bridges at contact points between grains (Fig. 4-9a);
- 2) the **funicular** regime: with increasing water content, the capillary bridges coalesce and the excess water fills the packing voids between neighbouring grains, creating ‘water clusters’ (Fig. 4-9b). Recently, it is possible to count the number of cluster for different water content. For example, at water content of $0.11 \text{ cm}^3 \text{ cm}^{-3}$, clusters represent about 90% of the entire liquid volume, note that a percolation transition can be seen $W \approx 0.08$ (Fig. 4-10) (Kohonen et al., 2004; Scheel et al., 2008);
- 3) the **capillary** regime: finally all clusters will be connected (percolation transition), and some grains will be totally surrounded by water (Fig. 4-9c). The water network has such a connectivity that “a paramecium cell would be able to swim from one end of the sample to the other without leaving the water” (Herminghaus, 2005). Pierrat and Caram (1997) suggested that capillary regime could occur for saturation levels $>90\%$, but this in models at close packing.

The pendular regime has the clearest definition from a physical point of view; thus it was largely studied (Nase et al., 2001; Adams et al., 2002; Iveson et al., 2002a; Ngan, 2004b; Soulie et al., 2006; El Shamy and Gröger, 2008; Mitarai and Nakanishi, 2009). However, the funicular and capillary regimes are more complex and difficult to experiment therefore difficult to model. The funicular and capillary regimes were studied only recently by direct observation of water bridges (Kohonen et al., 2004; Scheel et al., 2008) and on virtual models (Kohonen et al., 2004; Mitarai and Nori, 2006).

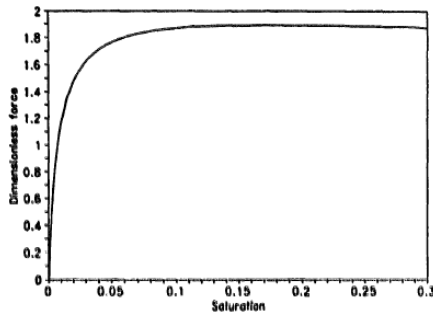


Fig. 4-12 Dimensions force as a function of saturation (Pierrat and Caram, 1997).

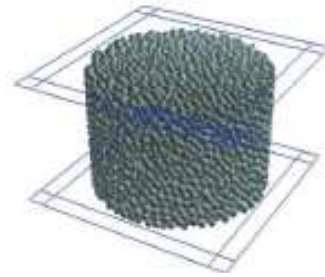
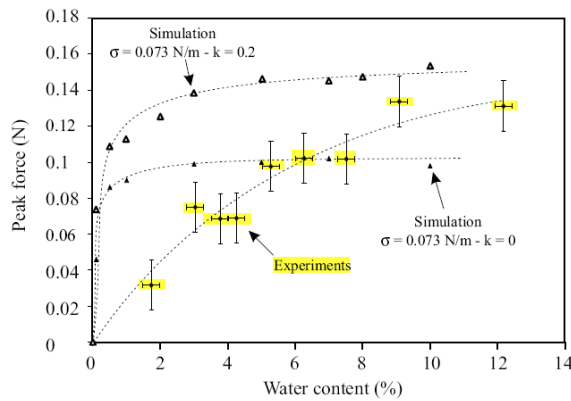


Fig. 4-13 Left: Evolution of the peak force with water content in experiments (see Fig. 4-12) and simulations (figure on the right). The dashed lines are drawn as a guide to the eyes (Soulie et al., 2006).



Fig. 4-14 LEFT Experimental device (see description in Soulié et al. 2006), First picture the cylinder of wet glass bead before mechanical testing; two last pictures: glass bead cylinders at 1 and 10% water content respectively, at the end of the test: brittle and ductile failure respectively. For brittle material, failure is caused by the break down of the bonds and propagates subsequently into the material (the tensile strength is not controlled by the average stress but by the largest local stress). For ductile material, the shear strengths controlled by the mean tensile force (Soulie et al., 2006).

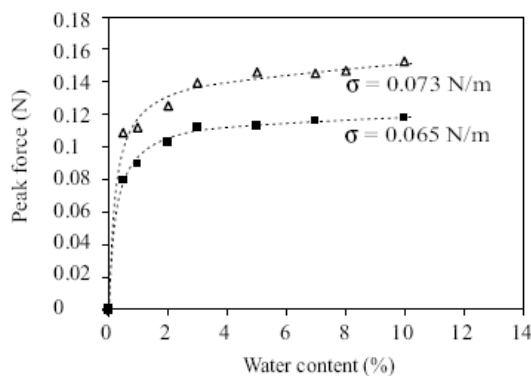


Fig. 4-15 Evolution of the peak force with water content for two different values of the surface tension. The dashed lines are drawn as a guide to the eyes (Soulie et al., 2006).

With increasing water content, location of water inside the grains assemblage is changing and the amount of cluster is abruptly increasing (Fig. 4-11); the associated decrease of solid/liquid and air/liquid interfaces should therefore also affect the cohesion.

1.4.3 The cohesion at different water regimes

At this **pendular** regime, the extension of both interfaces (liquid/solid and liquid/air) is the highest and thus the cohesion is also the highest compared to the other two regimes. Specific behaviors exist at very low water content ($<2-3\%$, Fig. 4-9). It will not be mentioned here because cultivated sandy soils generally have higher water content. At pendular regime, the cohesion is not only the highest compared to other regimes but it is very stable for a wide range of water content (Fig. 4-12). The exact range depends on the type of techniques used to assess cohesion, the packing density and the shape of the grains.

Soulié et al. (2006b) tested the cohesion by pressing a pile of wet grains and measuring the peak force, on virtual models and on real grains (Fig. 4-13, 14a). If the plateau is clearly visible on the virtual models, on the real experiment, cohesion is continuously increasing with increasing water content. Some uncertainty in the experiment data can come from changes in mechanical behavior of the sand pile (Fig. 4-14 right); But more importantly, the rules governing the distribution of water inside the granular material have a strong impact on the results on virtual models. The really distribution of water inside granular materials is poorly known: even if the liquid is homogeneously distributed at a macroscopic scale, the number of liquid bridges by particle remains unclear and cannot be taken into account in the models. Note also on Fig. 4-13 that at all water contents, the peak forces are higher when some distance is kept between grains ($k=0.2$) compared to grains in contact ($k=0$). The history of piling and its consequences on distance between grains has thus to be taken into account.

Finally, the quality of interfacial water can affect the cohesion (Fig. 4-15). This was observed by changing the interfacial tension, but similar changes could be observed for cultivated soils in case of clay dispersed in the soil water or in case of saline solutions. But the quality of the soil solution has perhaps less impact than the other characteristics influencing the cohesion.

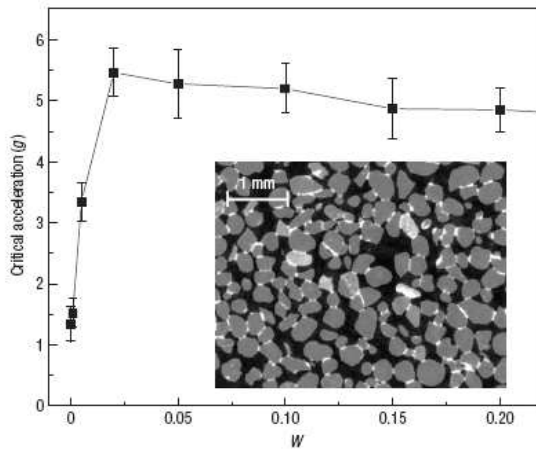


Fig. 4-16 Stiffness of a wet granulate consisting of non-spherical grains. Critical acceleration for fluidization by vertical agitation, determined for sand wetted by water. The error bars are standard deviations. Inset: Section through a 3D tomogram of the sample at $W = 0.03$ (Scheel et al., 2008).

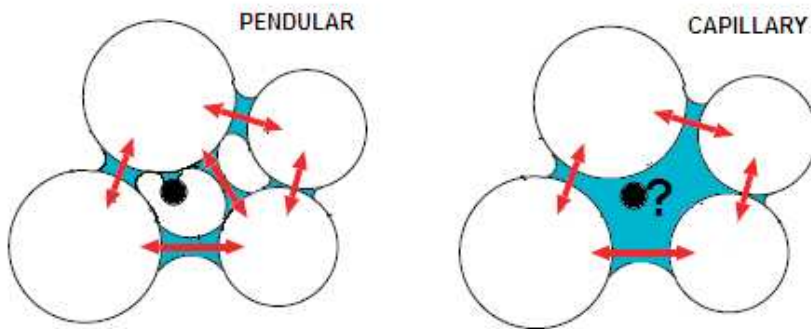


Fig. 4-17 Schematic description of interaction of the model for the pendular state, and capillary state (Mitarai and Nakanishi, 2009).

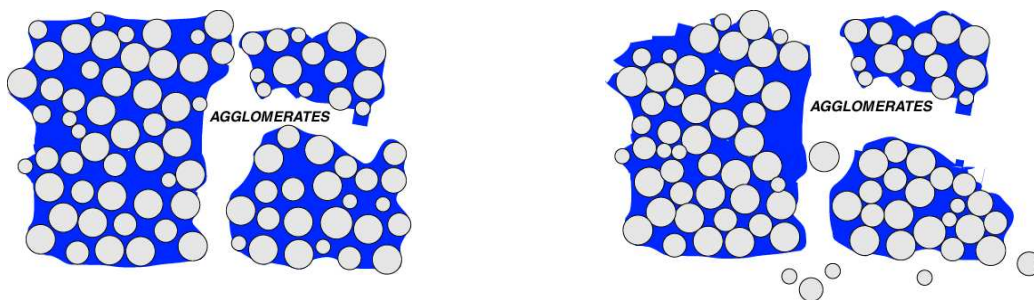


Fig. 4-18 Bottom: when reaching the capillary stage (left) reorganisation of grains inside the agglomerates is possible but capillary cohesion still exists agglomerates (right) even if it is under different configuration.

At funicular regime, the water bridges connect more than two grains simultaneously and the decrease in air/quid interfaces should result in a decrease of cohesion. The data from [Scheel et al. \(2008\)](#) ([Fig. 4-16](#)) show a continuous decrease since the pendular regime and no specific transition is observed fitting with the large development of clusters at water content of $0.08 \text{ m}^3 \text{ m}^{-3}$.

Capillary regime occurs when all clusters are connected (percolation transition). After such a connection, some grains are totally surrounded by water and some grains still have a simultaneous contact with air and water, and therefore concave menisci should still exist at the surface of the agglomerates ([Fig. 4-9 right](#)) ([Pierrat, 1997](#), [Iveson et al., 2002](#), [Mitarai and Nori, 2005](#), [Grof et al., 2008](#)). For grains that are totally surrounded by water, no capillary force exists anymore to link them with their neighbours and therefore they can potentially move simply under the effect of gravity ([Fig. 4-17](#)). This is unlike the grains at the periphery of the agglomerates: they are attracted by interfacial tension of the water which tends at the same time to minimise its extension; thus at the periphery of agglomerates, negative pressure (concave menisci) provides cohesion to the agglomerate but a weak cohesion ([Fig. 4-18](#)).

[Fig. 4-19](#) shows the evolution of cohesion of two grain piles with different grain shape and packing. In the case of regular packing of spheres, *i.e.* quite well ordered material, the transition from one regime to the next one are very clear and have clear effect on the cohesion with sharp change at transitions ([Fig. 4-19 left](#)). When the shape of grains is not regular and the pile has a larger disorder than in the previous example, the transition from one regime to the next one is less clear (different regimes can co-exist). Therefore, the evolution of cohesion from nearly dry to saturated material is gradual, with no sharp transition from one regime to the next one ([Fig. 4-19 right](#)).

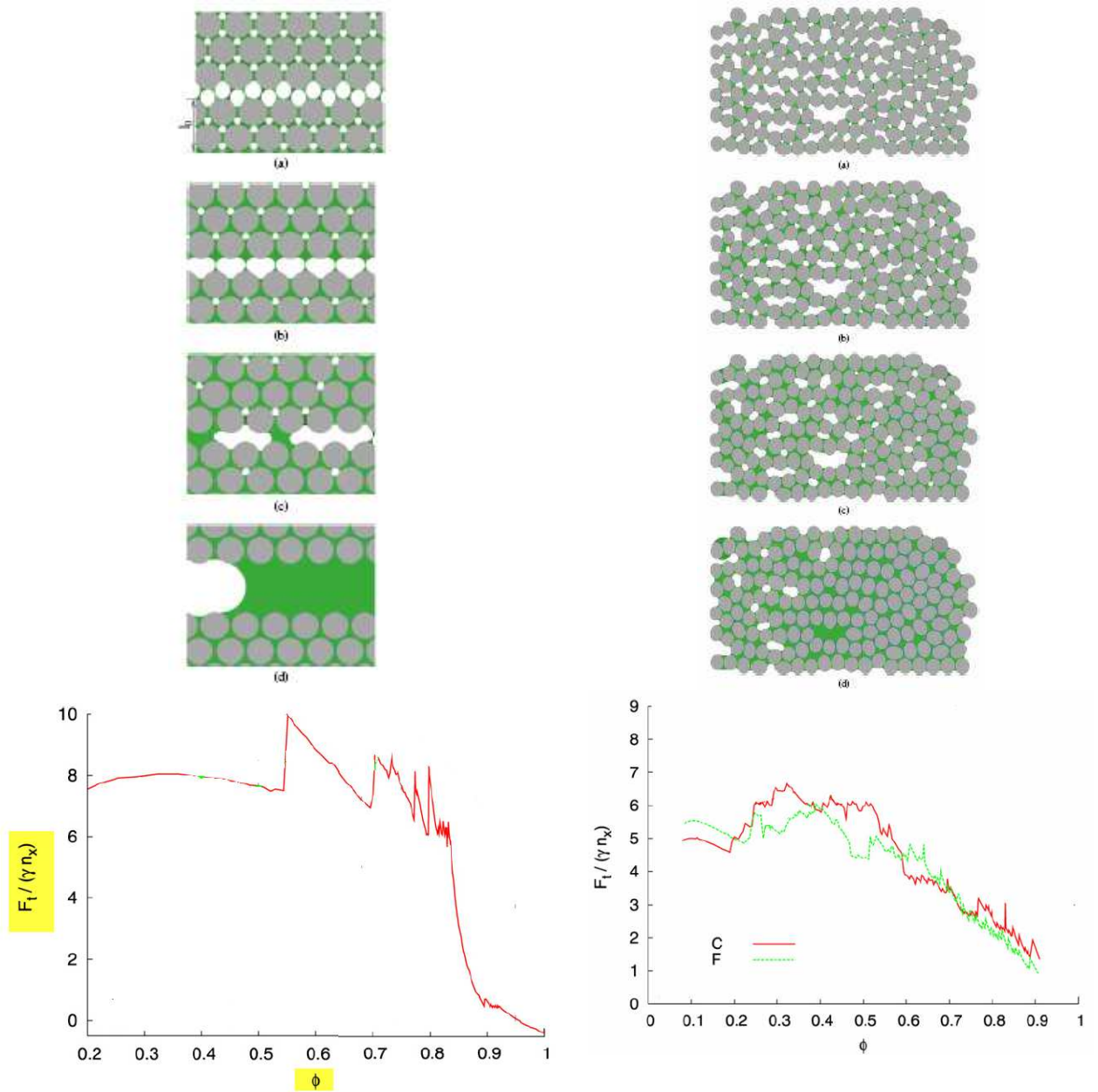


Fig. 4-19 For increasing water content, changes in water location (top) and cohesion (bottom) for grains with two shapes and packing: (left) Hexagonal packing of spherical particles; evolution of tensile force as function of relative liquid content (bottom).(right) Packing of elliptic particles. Initial and maximum tensile force as function of relative liquid content for two different packing realizations (C and F) at different water regime. Details can be seen in (Grof et al., 2008).

1.4.4 Tensile strength and shearing in a wet granular

In a dry granular material, the force chains transmit only compression forces in a way that provides some specific mechanical properties with discrete material. Addition of water induces water bridges that are linking particles and thus provide cohesion to a pile of grains. At the scale of the pile, this cohesion comes from the existence of tensile forces that are able to self sustain the wet pile of cohesionless material (Richefeu et al., 2006; Soulié et al., 2006; El Shamy and Gröger, 2008).

Mathematical simulations have demonstrated that a network of tensile forces coexists with the network of compressive forces (Fig. 4-20 left) and each particle can take on a positive or a negative 'value', *i.e.* can bear compressive or negative forces (Fig. 4-20 right) (Soulié et al, 2006,b; Richefeu et al, 2006,a,b; Radjai and Richefeu, 2009). According to Scheel et al. (2006), the tensile strength is stable on a large range of water content (from 2 to 15 %) (Fig. 4-21).

In the virtual experiment already presented (Fig. 4-13) the displacement and reorganisation of individual grains have been recorded during a small compression. A clear discontinuity was observed (Fig. 4-22): the particles located on the upper and radial part had large displacement (whith colours) when the particles located in the lower and middle part of the cylinder (appearing like a black cone) were quite immobile. This observation indicates that submitted to mechanical compaction, grain motion not generalised but concerns only given category of grains in a well defined geometry and in well defined positions.

Cohesion is the resultant of convergent strengths that tends to maintain the unity of solid elementary constituents. According to Mohr Coulomb criterion, a soil is stable as long as:

$$\tau < \sigma \mu + C$$

with τ the shear stress at failure, μ the coefficient of internal friction and C the cohesion. The coefficient of internal friction is a characteristic of the material and does not change at the time scale of the experiment. The friction angle is almost independent of the

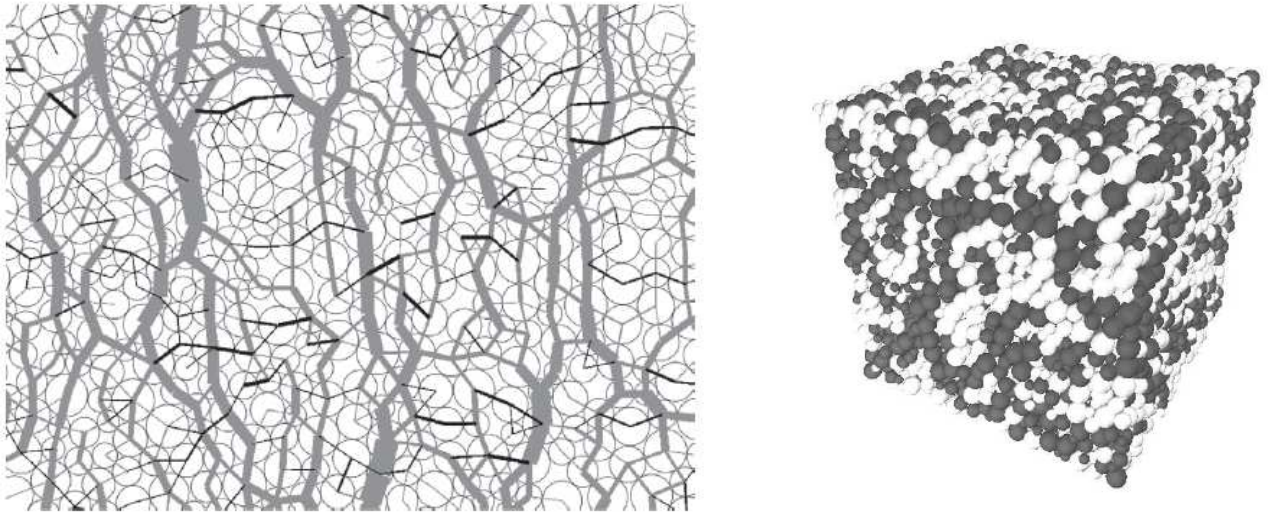


Fig. 4-20 Illustration of stress transmission inside wet granular at pendular regime. **Left:** representation of the compressive (in grey) and tensile (black) forces network; line thickness is proportional to the magnitude of the normal force (from Radjai and Richefeu, 2009). **Right:** according to the forces exerted by contact neighbours, each particles can take on negative (white) or positive (black) pressure (Richefeu et al., 2006).

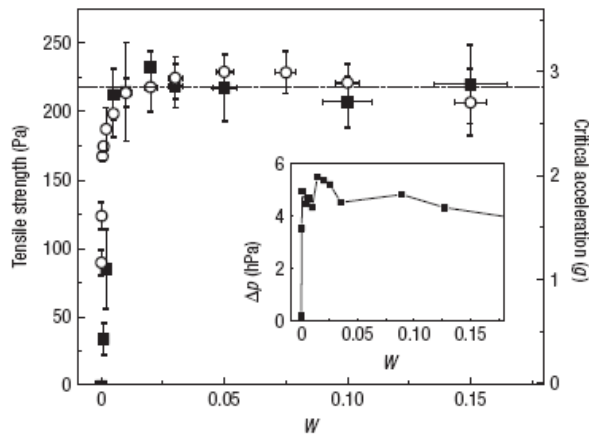


Fig. 4-21 Evolution of tensile strength of a wet granular pile in relation with increasing water content at pendular and funicular regimes; *i.e.* the reorganization of liquid structures. Tensile strength (filled squares), critical acceleration for fluidization (open circles). The dashed horizontal line is a guide to the eye. Inset: Yield stress (Scheel et al., 2006).

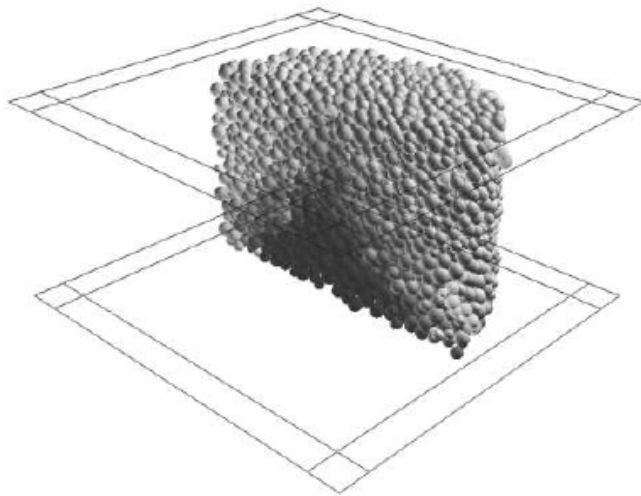


Fig. 4-22 Particle displacement in a thin median vertical layer of the granular packing during the axial-compression test. The particle displacement is proportional to the clearness intensity. The gray levels represent the grain displacements ranging from zero displacement in dark to the largest displacement in white (about 1mm) (Soulie et al., 2006).

saturation degree, whatever the water content (Fig. 4-23) (Herminghaus, 2005; Mitarai and Nori, 2006; Scholtès et al., 2009a; Scholtès et al., 2009b).

According to the Mohr-Coulomb criterion, C is equivalent to the shear stress at zero normal load. By definition, the Coulomb cohesion is the yield shear stress at zero confining pressure in which case the capillary forces are the only forces acting in the material. In this limit, the normal stress σ on the shear plane is simply equal to the average capillary force divided by the sample section S (Richefeu et al., 2006b).

Direct measurements of shear stress are presented on Fig. 4-24 and Fig. 4-25 and indicate that shear stress seems largely independent of water content.

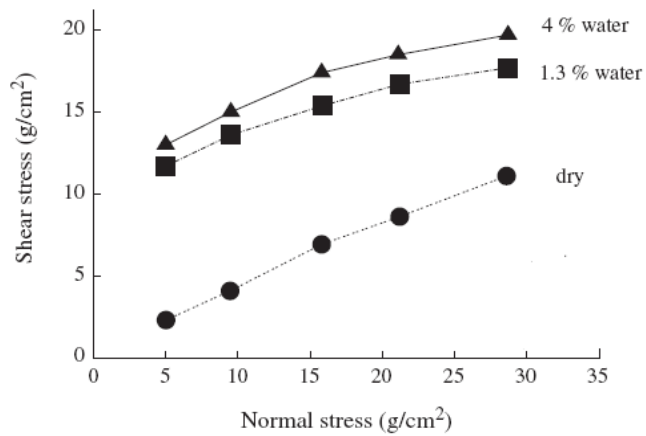


Fig. 4-23 Yield locus obtained by direct shear tests for glass beads (93 μm) : dry (circles), with water and with n-hexadecan (Rahnan et al., 2004).

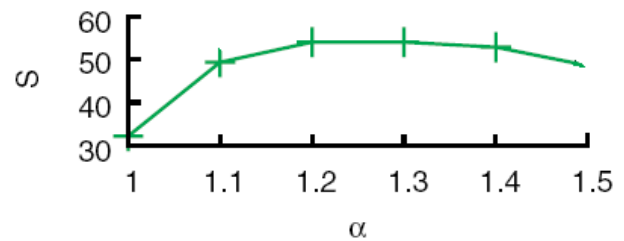
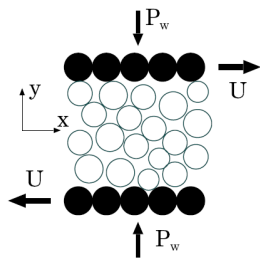


Fig. 4-24 Left: experimental device, Right: S is the shear stress and α : $\alpha = 1$ corresponds to dry granular materials with neither cohesive force nor hysteresis, and α is greater than unity for wet cohesive grains. When $\alpha > 1$, there is a hysteresis in the interaction, and this hysteresis causes dissipation in addition to that caused by the viscous force (Mitarai and Nakanishi, 2009).

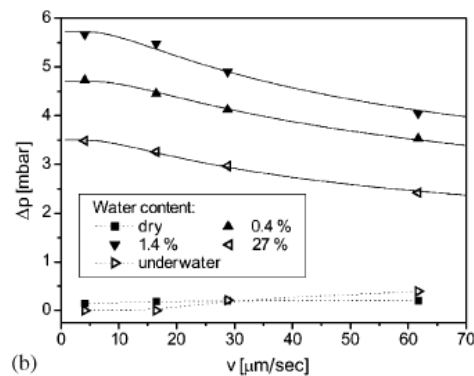
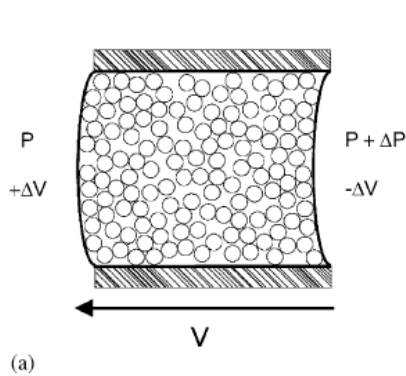


Fig. 4-25 a) Schematic illustration of the measurement of wet granular shear. b) Dependence of the differential pressure on the mean shearing velocity v for glass bead samples (Kohonen et al., 2004).

Conclusion

Cette revue nous montre que, malgré la simplicité de leurs constituants, les milieux granulaires présentent une très grande diversité de comportements. Cette diversité s'observe déjà lors d'un simple mélange entre fractions fine et grossière ; ainsi un élément aussi simple que l'homogénéité du mélange peut avoir une incidence sur la porosité totale. Si l'on étudie non seulement la porosité mais aussi le comportement mécanique d'un empilement de grains secs, la diversité des comportements augmente encore. Cette diversité de comportements provient entre autres de l'histoire de l'empilement, de la dispersion des fractions, de la dureté des contacts, etc... Grâce aux modèles mathématiques, les divers comportements de même que les facteurs qui les déterminent ont pu être reproduits et sont maintenant relativement bien identifiés. Les sols se caractérisent par une très grande dispersion granulométrique mais celle-ci est encore difficilement prise en compte dans les modèles, alors qu'elle a certainement un effet déterminant dans les comportements de matériaux naturels.

Alors qu'un granulaire sec ne comporte que des forces de compression, un granulaire humide se caractérise par la présence de forces de tension. Ces dernières permettent l'émergence d'une cohésion et de propriétés mécaniques nouvelles. Sur le plan théorique, trois régimes de teneur en eau peuvent être définis et modélisés. Le régime pendulaire est facile à définir et modéliser, et les modèles correspondent relativement bien à la réalité. En revanche, le régime funiculaire et plus encore le régime capillaire sont plus difficiles à modéliser dans des empilements de grains monodisperses mais non sphériques et *a fortiori* dans des granulaires polydisperses et des géométries de grains complexes. En effet, plusieurs régimes hydriques peuvent co-exister et donner des réponses beaucoup moins claires en termes de variation de cohésion par exemple.

Cette diversité de comportement des granulaires rejoint la diversité des caractéristiques du slumping décrites dans différents types de sols, sous différents climats et à l'aide de divers outils de caractérisation.

Chapitre 2 Effondrement sous conditions naturelles à l'échelle de la parcelle: experimentations au champ

Ce chapitre présente une expérimentation de terrain menée dans le Nord-est de la Thaïlande sur le plateau sableux de l'Isaan. Cette région a été choisie car les sols sableux ont une très faible teneur en argile et en matière organique et ils ont déjà été décrits comme très sensibles au slumping. De plus, les statistiques climatiques montrent qu'il existe une forte probabilité d'avoir des événements pluvieux à caractère orageux (forte intensité de pluie et total pluviométrique élevé) qui alternent avec des périodes plus sèches. De l'état physique, la variabilité interannuelle rend la date de début de la saison des pluies relativement aléatoire.

Au cours de cette expérimentation nous avons suivi simultanément i) l'évolution des caractéristiques hydriques du sol (teneur en eau et potentiel matriciel) et ii) l'évolution du sol (niveau, microtopographie, profil de densité apparente, de résistance à la pénétration et de cisaillement) sur une période de deux mois. Ces observations se sont faites sous pluies naturelles après travail du sol et aussi lors d'une expérimentation d'irrigation par submersion (flooding) sur microparcelles ($<1\text{m}^2$) préparées manuellement.

Ce chapitre est présenté sous forme d'un article déjà soumis à la revue 'Soil and Tillage Research' (en cours de révision); les principaux résultats ont aussi fait l'objet d'une présentation orale à la 18^e conférence de l'ISTRO (International Soil and Tillage Research Organisation ; Izmir, Turkey, 2009).

Des informations complémentaires sur les protocoles et les résultats obtenus sont présentes en annexe.

Slumping dynamics in tilled sandy soils under natural rainfall and experimental flooding

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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. It has been observed in different soil types, but sandy soils appear particularly prone to this physical degradation. Our objectives in this study were (i) to measure 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 studied the effect of tillage depth and initial water content on slumping dynamic. Plots (9 m×15 m each) 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 m² each) were used for experimental flooding irrigation (similar to measured rainfalls, *i.e.* 100 and 200 mm). Soil bulk density, soil surface elevation, soil water content and matric potential were measured.

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 the flooding experiments, bulk density was higher than after natural rainfall despite similar amounts of water added to the soil.

The existence of a layer with 50 % porosity immediately 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. Slumping was observed during the downward movement of the wetting 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 dynamics and intensity depend on the bulk density at the onset of the rainfall or

irrigation event. It is concluded that the high variability recorded in earlier field trials results 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 such 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 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). Whereas the bulk density increase resulting from mechanical loading has been widely studied, much less attention has been paid to slumping.

For coarse-textured soils, Kemper and Rosenau (1984) suggested that slumping is related to soil 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 yet provided 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 measure 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 for the slumping of sandy soil.

2. Materials 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 ($<2\mu\text{m}$) is less than 10% and contains phyllosilicates (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 ($< 5\text{ g kg}^{-1}$) and high bulk density ($\rho_b \geq 1.6\text{ g cm}^{-3}$) (Table 1 and 2). This field was planted with cassava in 2006 and harvested in February 2007. To minimize the effect of coarse crop residue 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, a 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 therefore 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 ($\pm 1\text{ mm}$ precision) that installed inside the experimental field.

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

		Silt	Clay	Organic			Bulk	RP	SS
Depth	Sand (%)	(%)	(%)	matter	pH	CEC	density		
	50-2000	2-50							
(cm)	μm	μm	$<2\ \mu\text{m}$	(g kg^{-1})		$\text{cmol}_+ \text{kg}^{-1}$	(g cm^{-3})	(kPa)	(kPa)
0-20	87	10	2.8	4.5	4.99	<1	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).

CEC, cation exchange capacity

Table 2 Particle size distribution of soil (g kg^{-1}) at 0-20 cm layer.

	Particle size distribution						
	Clay	Silt		Sand			
	g kg^{-1}						
Size (μm)	2	2-20	20-50	50-100	100-200	200-500	500-2000
Soil	28	39	64	328	434	105	2

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 done using a 120-horse-power tractor equipped with a 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.

Measuring 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 m² 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 cm² 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 (W_c), 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 drying 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 m²) 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 drying 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 had two different W_c during tillage; the treatments were named ‘dry’ (Y) (plots under greenhouse before tillage) and ‘wet’ (W) (plots that were subjected 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 metal rods as “legs” inserted into the soil to 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 W_c 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 deep in the soil (60 cm) to be used as stable benchmarks for recording the level of the soil surface. 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 fell 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 at 5 cm intervals from the 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.

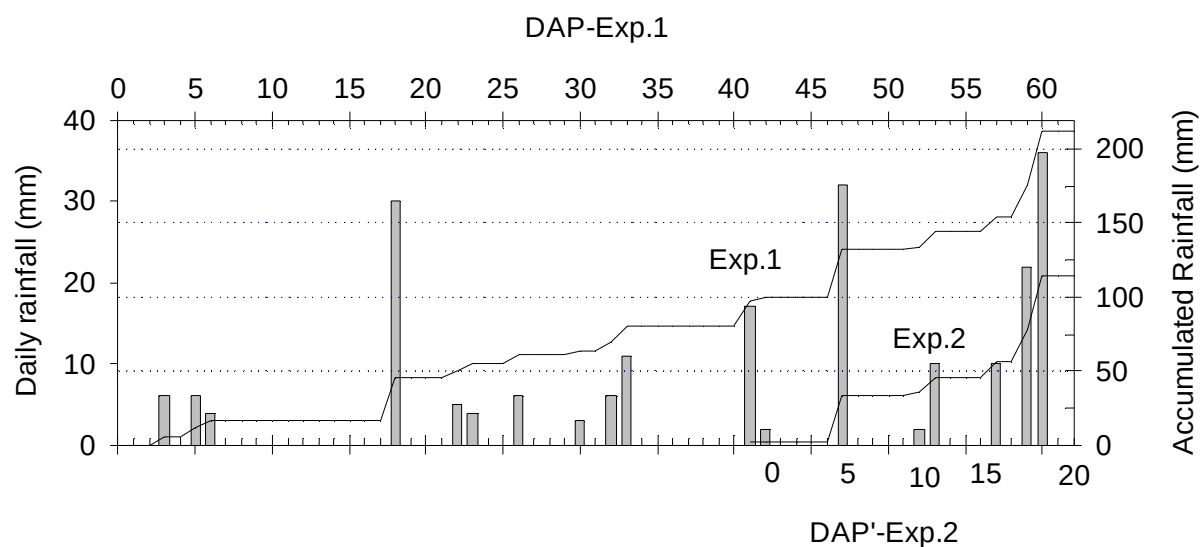


Figure 1 Rainfall distribution and accumulated rainfall (AR) in Exp.1 and Exp.2. DAP is day after tillage for Exp.1, which started from 25 May 2007. DAP' is day after tillage for Exp.2, which started from 6 July 2007.

3.2. Experiments 1 and 2

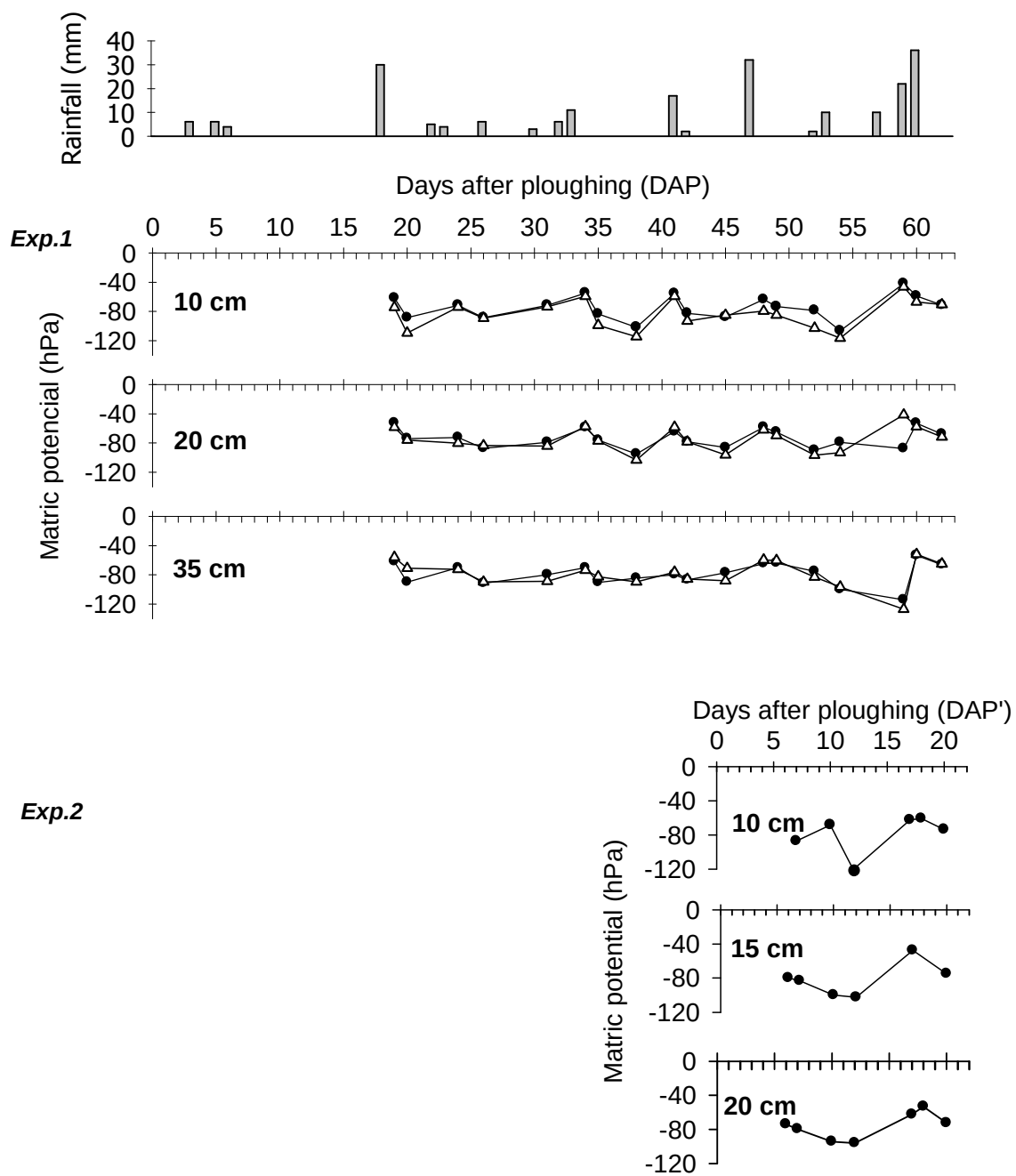
3.2.1. Soil matric potential (ψ) and water content (W_c)

For Exp. 1 and for the Y treatment (dry protected plots) in Exp. 2, W_c was in the range 0.04 to 0.06 g g⁻¹. For the W treatment (unprotected wet plots) in Exp. 2, W_c was significantly higher ($p < 0.05$), ranging 0.08 to 0.10 g g⁻¹ (data not shown).

Matric potential is generally presented as a negative data, thus it is “high” when the value is close to 0 (wet soil) and “low” when the value is getting more negative (dry soil). Fig. 2 presents the matric potential (ψ) measured under furrows and ridges in Exp. 1 (D treatment), and 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 value of 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 measuring: at DAP 59, ψ was recorded a short time (< 1 h) after the rainfall event; while at DAP 60, it was



b)

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

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 large 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 W_c at the tillage depth, W_c 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 statistically-significant difference was found between the 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 greater (0.15 g cm⁻³) showing 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 greater when ploughing was performed at wet conditions. The shift was greater in the top layer than 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 of water, 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 continually (from 0.6 cm with 100 mm input to 0.1 cm with

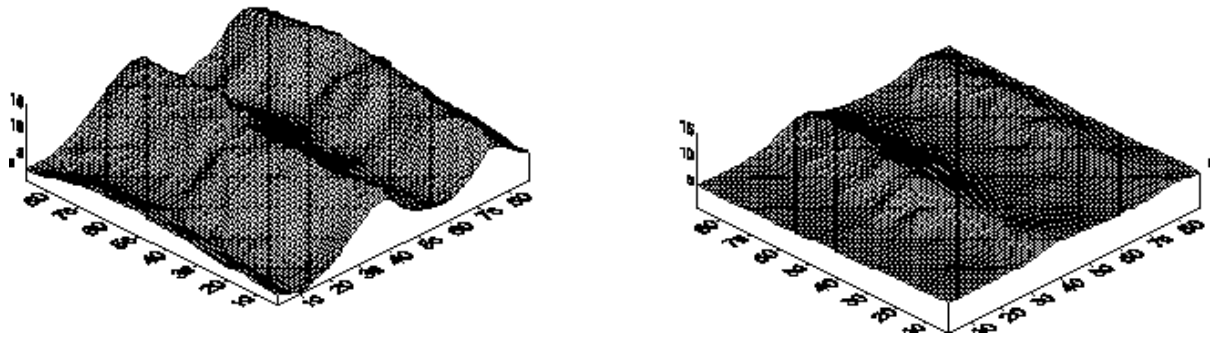


Figure 3 Soil surface level recorded in Exp.1, example of one subplot; left side is DAP4 and right side is DAP60. Measurements were made along a regular grid 5x5 cm (i.e. 361 measurement points).

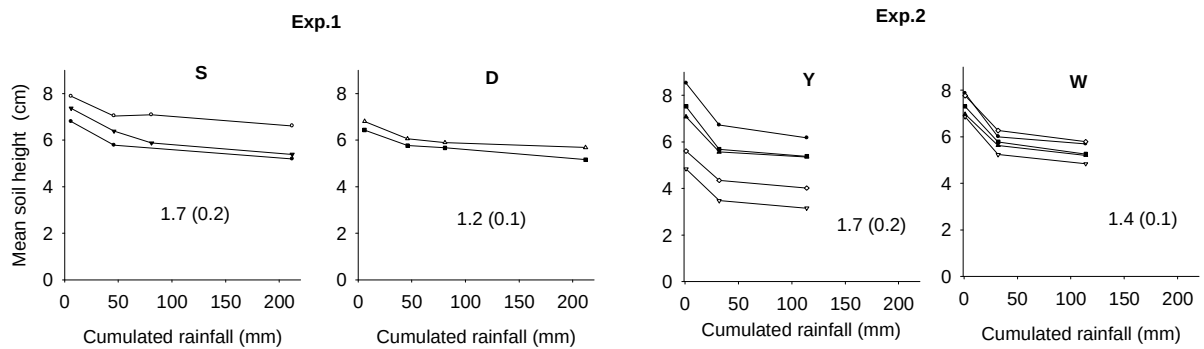


Figure 4 Mean soil height with cumulated rainfall. D and S are Deep (40 cm) and S shallow (20 cm) tillage respectively; W and Y indicate tillage made in wet and dry soil respectively. Each line is one replicate from the subplot. The numbers indicate mean values of level decrease with standard errors 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.

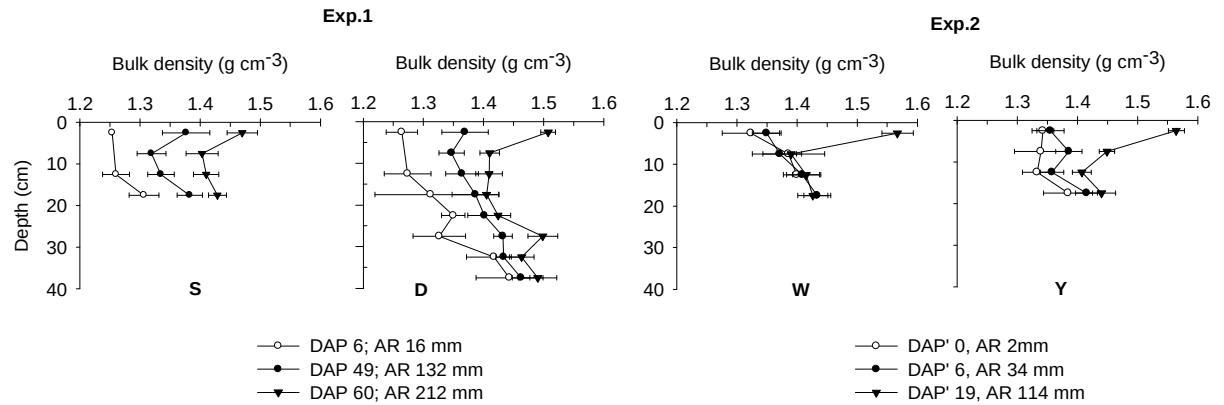


Figure 5 Bulk density collected under furrow after major rainfall events during Exp.1 and Exp.2. D and S are Deep (40 cm) and S shallow (20 cm) tillage respectively (n=5); W and Y indicate tillage made in wet and dry soil respectively (n=9). DAP and DAP' are the number of days after tillage for Exp.1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

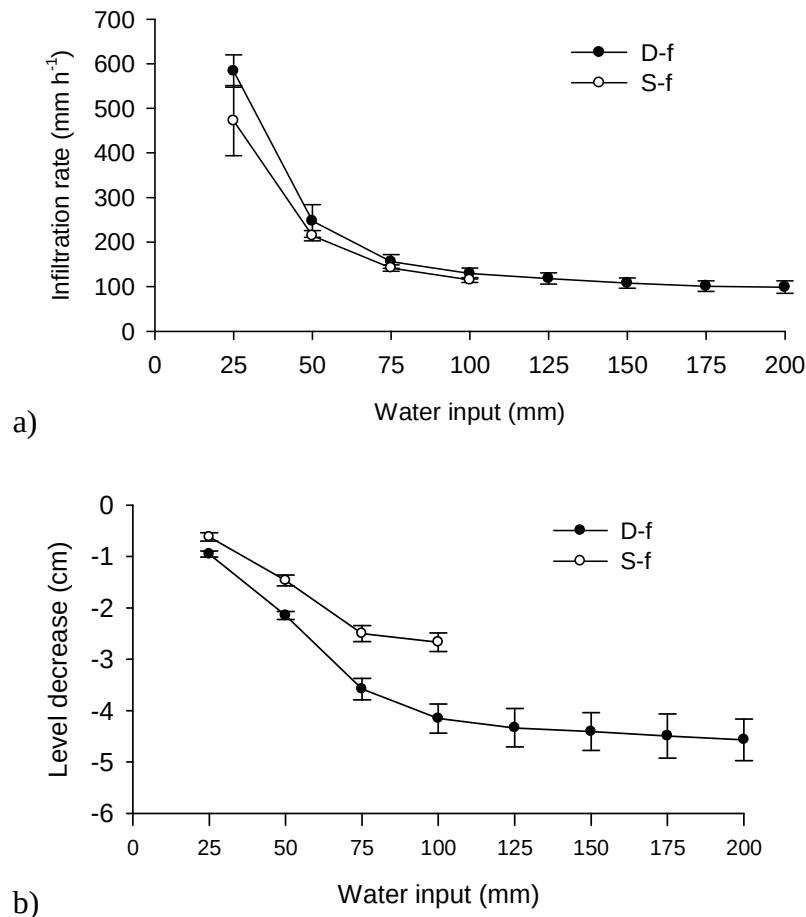


Figure 6 a) Soil infiltration rate decreased with added water amount, b) Soil surface level change with added water amount. The soil was protected from rainfall under plastic before tillage. Error bars indicate standard error of means (n=9). D-f is deep flooding; S-f is shallow flooding.

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 the Df treatment. Just after tillage, ρ_b increased with depth. At the bottom of the tilled layer ρ_b was about 0.3 g cm⁻³ greater than at the surface (Fig. 7). At the end of the experiment, for both Df and Sf, ρ_b shifted to higher values on the entire profile, ρ_b being larger 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 included 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 the surface but also the whole tilled horizon. In the three experiments and whatever the treatment, 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 a decrease in soil surface elevation 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 easily observed by the naked eye even if it is probably a common phenomenon in coarse textured soils, this may explain why it is only rarely described (Wilton, 1964; Young et al., 1991; Moffat et al., 1997; Or and Ghezzehei, 2002). Even if soil sinkage is a relevant indicator of slumping, 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.

This loose packing was created by tillage: the energy developed by the disks lifted up the soils, therefore increasing their potential energy. 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 $W_c < 0.12 \text{ g cm}^{-3}$, 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 before slumping.

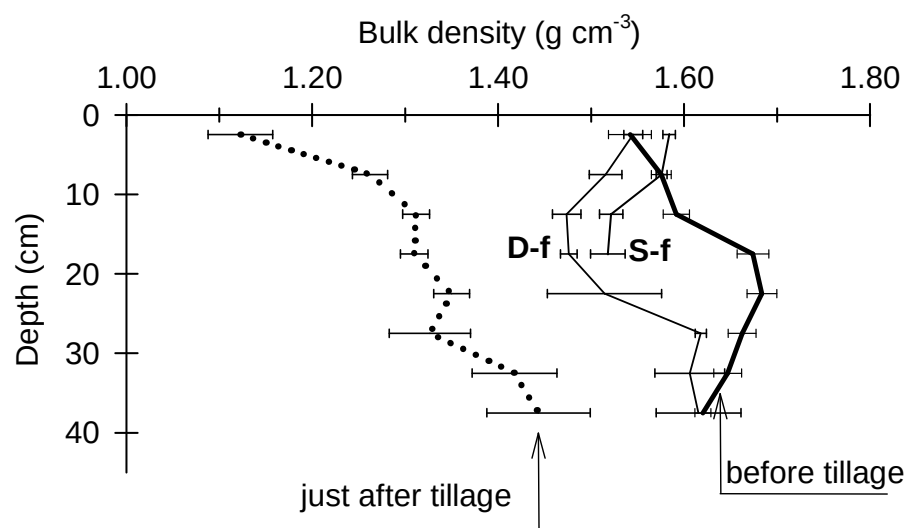


Figure 7 Bulk density after flooding. 200 mm water was added into “D-f” and 100 mm water into “S-f”. Error bar indicates standard error of mean (SEM) (n=9). D-f is deep flooding; S-f is shallow flooding.

4.3. Water characteristics inducing slumping

No relation was found between rainfall amount and slumping characteristics (occurrence, intensity, dynamics): (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 greater 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 ($>1.4 \text{ g cm}^{-3}$ below 10 cm), and (iv) slumping was faster in Exp. 3 compared with 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:

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

where τ is the shear strength, σ is the normal force, μ is the internal friction coefficient and c is cohesion. The cohesion is equivalent to the shear strength 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 usually 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. By contrast, recent developments in the physics of wet granular material (like sandy soils) suggest that slumping could occur before reaching water saturation (e.g., Pierrat and Caram, 1997; Iveson et al., 2002; Mitarai and Nori, 2006).

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 decrease 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. Unlike 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 W_c or ψ that corresponds to a continuous liquid phase in these models and it is not yet possible for real soils. Anyway, the continuity of the liquid phase in sandy material can be seen during fast downward movement of the wetting front that correspond to a locally high W_c 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 lower rates of slumping. Soil and water characteristics (ρ_b , ψ , W_c) were measured manually at intervals of one to seven days; consequently our device could not record any rapid movement of the wetting front. Anyway, structural changes (soil surface sinkage and bulk density increased) were observed only after the limited number of major rainfall events. Similar events occurred 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 downward movement of the wetting front and significant structural changes (surface level decrease, bulk density increase).

In Exp. 3, a steady state was reached earlier for infiltration rate than the decrease of soil elevation (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 information about sand grain rearrangements 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 loosely-packed grains linked together only by capillary water bridges, the first grains to be unbalanced are probably the biggest ones. They are the most strongly pulled by gravity and less strongly held 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 work has shown 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 example, 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 W_c .

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 ρ_b was finally larger than that of the underlying layers. A different behaviour of the top layer seemed to be related to lateral sand movement from the ridge and accumulation on the surface of the furrow (Exp.1 and 2, Fig. 3). But a 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 (Biielders 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. 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 W_c , even during minor rainfall events. These two specific characteristics can explain why 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 mentioned: slumping was perhaps also influenced by that surface topography, but we have not collected any data that allows us to estimate 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 kinetics, 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 experimental results. The slumping process can be separated into three main steps (Fig. 8):

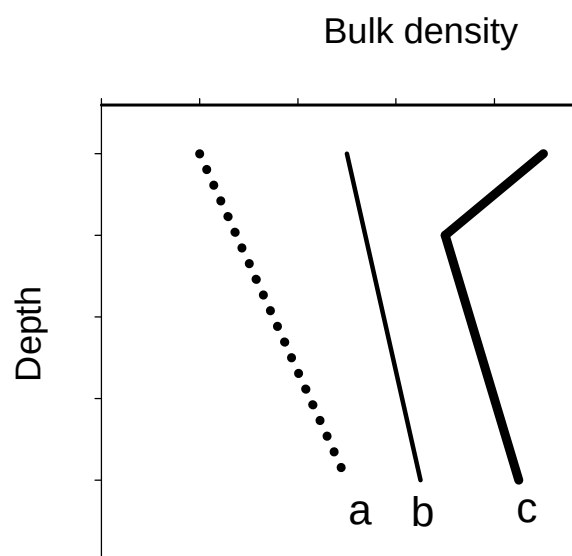


Figure 8 Schematic diagram of possible slumping dynamic profiles in tilled sandy soil. a) just after tillage, b) beginning of slumping, c) with maximum bulk density at surface and deeper layer, d) a comparison profile after mechanical compaction, maximum bulk density occurs in the intermediate layer.

- (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 rapid 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),
- (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).

Because 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, the slumping rate 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 with 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 prediction of the elementary mechanisms of slumping.

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Chapitre 3 Effondrement sous simulation de pluie: le concept de réorganisation des milieux poreux

Ce chapitre présente les résultats d'une expérimentation de laboratoire dont les objectifs et le protocole ont été décidés après analyse des résultats de l'expérimentation de terrain. Cette dernière n'avait pas permis de conclure quant aux facteurs déterminants du slumping ; l'incertitude provenait en particulier du pas de temps des mesures qui était trop long par rapport aux évolutions observées sur le terrain. Il s'agissait donc i) de faire des mesures à des pas de temps beaucoup plus courts afin de suivre de manière précise la dynamique de l'eau et de la structure du sol et ii) d'utiliser des capteurs suffisamment petits afin de suivre des évolutions à des échelles spatiales fines.

Pour reproduire des pluies naturelles dans des conditions proches du terrain, un simulateur de pluies a été utilisé au laboratoire et donc en conditions parfaitement contrôlées. Il fallait un profil de sol sableux labouré. Nous avons donc effectué un travail de mise au point qui est présenté plus en détail dans les annexes de ce mémoire, l'ensemble des résultats se trouve aussi en annexe.

En effet, ce chapitre ne décrit pas l'ensemble de la méthode ni l'ensemble des résultats. Il est bâti sous forme d'un article qui sera soumis à une revue scientifique. Il ne présente donc que les principaux résultats et les principales conclusions.

Slumping of a sandy soil under simulated rainfall: the concept of reorganisable porous media

Introduction

Fast recompaction of soils after tillage is an economical problem and a technical challenge. If porosity created by tillage disappears before it has been colonized by roots of the plants, tillage operations are mainly a waste of time and also of energy. Different options have already been proposed to limit recompaction when caused by heavy loading ([Horn et al., 1995](#); [Arvidsson et al., 2000](#); [Alakukku et al., 2003](#); [Braunack and McGarry, 2006](#); [Adamchuk and Christenson, 2007](#)). But recompaction can also be observed without application of any mechanical constraint, *i.e.* only under the effect of rainfall or irrigation. This phenomenon was studied for the first time several decades ago ([Ghavami et al., 1974](#); [Cassel, 1983](#)), and was formally called ‘slumping’ ([Mullins et al., 1990](#)). But since then, very few studies were dedicated to describe and understand the factors and processes of slumping. Besides, they were mainly consisted in micromorphological observations of surface degradations ([Bresson and Moran, 1995, 2004](#); [Augeard et al., 2008](#)). As a consequence, nowadays, no adapted management technique can be proposed and this water induced degradation is still as unpredictable and severe as in the past.

Sandy soils are particularly affected by slumping in several regions in the world (*i.e.* under various climatic regimes and soil types). It was observed that bulk density increase can be fast but also deep, *i. e.* from the top to the bottom of the tilled layer, whatever the tillage depth ([Mullins et al., 1987](#); [Mullins et al., 1990](#); [Young et al., 1991](#); [Mullins et al., 1992](#)). For example, 60 cm deep in one rainfall ([Meek et al., 1988](#); [Moffat and Boswell, 1997](#)). The fact that slumping can affect deep layers is particularly striking because degradation processes are generally attenuated with depth (*i.e.* crusting, compaction under loading, shearing, etc...). Moreover, fast and deep recompaction (sintering) are particularly worrying from agronomic and environmental point of view because productivity in sandy soils is closely related to the depth of root system development ([Lesturgez et al., 2004](#); [Aggarwal et al., 2006](#); [Ismail and Ozawa, 2007](#)).

Sandy soils have low water and minerals content; thus, optimal biomass production can be reached only if the root system is able to explore a large soil volume, both laterally and vertically, and this exploration seems dramatically reduced for high bulk density ([Kozłowski,](#)

1999; Munkholm et al., 2005; Busscher et al., 2006; Hartmann et al., 2008). Moreover, in intensive agriculture using fertilizers and irrigation, a fast development of the root system could limit nitrate leaching and thus limit underground water pollution (Wong and Asseng, 2007). For these different reasons, control of slumping in sandy soils appears as a highly significant issue for their sustainable management.

Thus it would be useful to have a model soils which allows relevant laboratory experiments. If for silty and clayey soils, elementary aggregates or assemblages of elementary aggregates can easily be used in the laboratory to analyze their physical properties in the field (Shiel et al., 1988; Oades, 1993; Le Bissonnais et al., 1995; Watts and Dexter, 1997; Aluko and Koolen, 2000; Cerd, 2000; Bresson and Moran, 2004; Pinheiro et al., 2004; Le Bissonnais et al., 2005; Lipiec et al., 2007; Abid and Lal, 2008; Daraghmeh et al., 2009) this cannot be applied to sandy soils because their aggregates are usually very poorly developed, mechanically unstable when transported, and not representative of a whole tilled layer. This probably explains the low number of studies which focus on slumping of sandy soils although it is a worldwide physical process of soil degradation and a factor limiting sustainable management of sandy soils in many farming systems. As, by definition, the sand fraction (50-2 000 μm) constitutes most of the weight of a sandy soil, we suggest that a sand material would have the same slumping behavior as a soil and could therefore be an adapted model soil.

In such a context, the aim of this paper is to analyze experimentally under rainfall simulation the slumping process of i) a sandy soil recognized as being highly sensitive to rainfall in the field (Hartmann et al., 2008) and ii) of the sand fraction extracted from this sandy soils. The effect of the rainfall intensity and cumulated rainfall, and the effect of both the water content and suction on the slumping process of the real soil and of the model soil will be detailed. The validity of our model soil and possible alternative management techniques for sandy soils will be discussed.

Materials and methods

Soil sampling and sand preparation

The sandy soil material was collected in the tilled layer (0-15 cm) of a cultivated soil located 30 km south of the city of Khon Kaen (16°10' N, 102°48' E) in Northeast Thailand (Hao et al., submitted). The soil (loamy, siliceous, isohyperthermic Arenic Haplustalf) developed in sandy aeolian deposits covering an alluvial plateau (Bruand et al., 2004; Lesturgez et al., 2004; Hartmann et al., 2008). The sand fraction was extracted from soil by wet sieving at 50 μm after organic matter destruction (H_2O_2) and dispersion (sodium hexametaphosphate); approximately 100 kg of sand was prepared with this method. The subsamples of the soils and sands were analyzed according to standard methods: particle size distribution was measured by sieving and sedimentation, the content of organic carbon was measured by dry oxidation and gaseous chromatography, cation exchange capacity (CEC) was measured by the cobalt-hexamine trichloride method; pH was measured using with a 1:5 soil:water ratio; (see detailed description at http://www.lille.inra.fr/las/methodes_d_analyse/sols).

Cylinders preparation

All the experiments were prepared with wet samples (soil or sand material) having a water content (θ) of 0.10 g g^{-1} ; this corresponds to a soil that have already received some rainfall after tillage. The samples were prepared as follows: several kg of air-dried soil or sand material were poured with the required amount of water and mixed by hand during at least 10 min. Then the resulting soil and sand material was put in sealed plastic bags and stored in a cold room at 4°C until use for the different experiments. Prior to each experiment, water content was checked again (oven drying at 105°C for 24 h).

The sand or soil material was introduced in a transparent plexiglas® column 18.8 cm in internal diameter and 20 cm high (5549 cm^3 in volume). This cylinder consisted in the superposition of ten elementary rings (2 cm high each), bound together externally with an adhesive tape. Each cylinder was prepared at a bulk density of 1.25 g cm^{-3} which is close to the bulk density recorded in the field after tillage. To get such a cylinder, elementary rings were prepared one after the other: 1/10 of the whole sand material required to obtain a bulk density of 1.25 g cm^{-3} was introduced in the ring, a piston (similar size as cylinder) was used to push it down slowly and carefully until a 2 cm high layer was obtained; then, the top surface of this layer was scratched with a knife to avoid a decrease in the hydraulic

conductivity at the limit between the next layers. A fine ring of white glass beads ($\varnothing = 150\text{-}250\text{ }\mu\text{m}$) enabling to observe the collapse process through the transparent cylinder wall was also inserted between each ring. This procedure was thus repeated until the last ring at the top.

Soil and water characteristics measuring

Once the cylinder fully filled, miniature tensiometers (porous ceramic tips of 2 mm in diameter) (SDEC France company) were introduced through the wall of some rings at 1, 5, 9, 13, 15 and 17 cm above the bottom of the cylinder (Fig. 1). The measurement of matric (or capillary) potential is generally achieved through determining the pressure of a fluid phase within the tensiometer, after equilibrium with the surrounding soil has been established. (Hillel, 2005). Tensiometers were filled with de-aired water and were connected to pressure transducers that were first individually calibrated. The matric potential (ψ hPa) was automatically recorded at intervals of one minute during every rainfall experiment by using a data logger. The tensiometer/pressure transducer/data logging system was known to be extremely reliable because it had been used for several years for other soil physical measurement (Dexter et al., 2010).

To measure the volumetric water content ($\theta\text{ m}^3/\text{m}^3$), we used a Time Domain Reflectometry (TDR) probe which convert the travel time of a high frequency, electromagnetic pulse into volumetric water content (Hillel, 2005). It is made with 3 elementary rods (diameter in 3 and 8 cm long) (6510X1 Model, Soil Moisture Equipment Corp., USA). The probe was introduced in the center of the cylinder and was located between 6 and 14 cm above the bottom of the cylinder (Fig. 1). Data were recorded manually at variable intervals (from 1 to 20 min) depending on the variation of water content dynamic. The TDR probe was calibrated with the sand and soil material prior to each experiment.

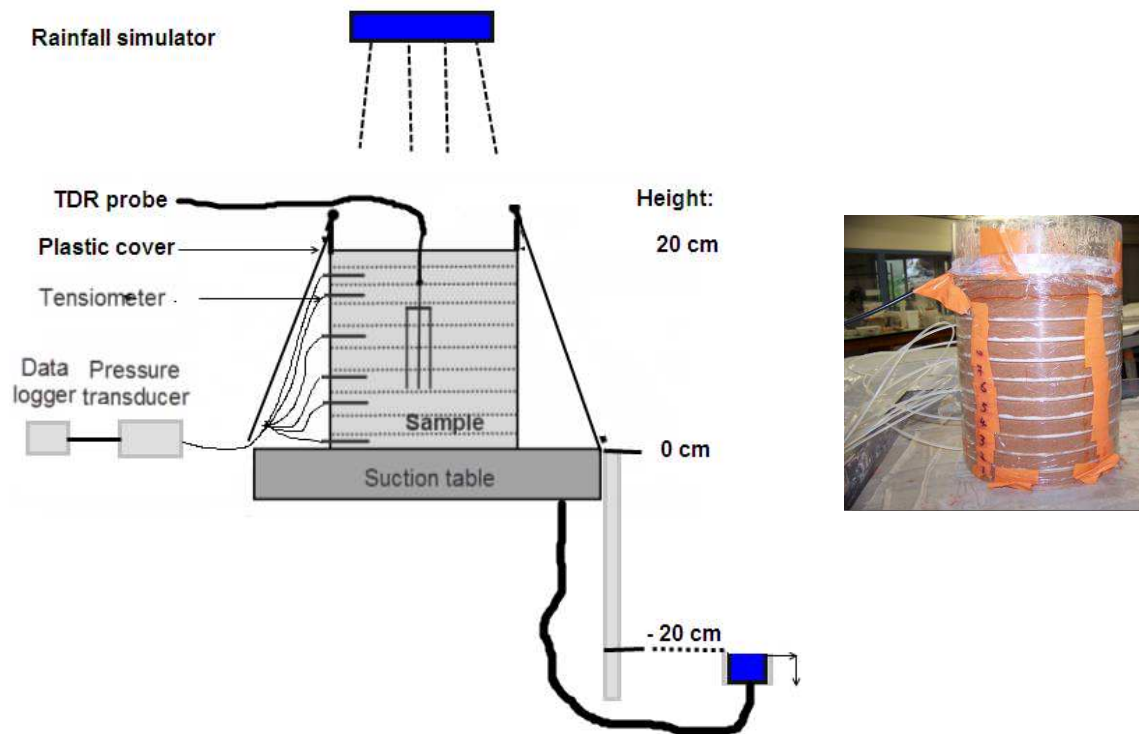


Fig. 1 Schematic presentation of the experimental device.

- a) The surface of the suction table (Soil Moisture Suction Sand Table) was protected from rainfall by plastic cover. The water can be drained out of the cylinder. The height of layers and tensiometers were counted upward from the bottom of the cylinder as 0. The suction was applied by means of a buried porous pipe and an associated sliding control chamber.
- b) a photo of the cylinder with the markers (white glass beads).

To control the water potential at the bottom of the cylinder and therefore the conditions of water drainage, the cylinder was moved on a suction table. The suction table can apply a given suction to the water remaining in the table (Ball and Hunter, 1988). Prior to rainfall simulation it was abandoned during 12 h to reach equilibrium between the suction table and the cylinder; the surface of the sample was covered with a plastic sheet to prevent evaporation. A aluminum plate was put under between the cylinder and the suction table, so that the water from suction table will not affect the material inside the cylinder by capillary force. Then were removed one minute before the starting of simulated rainfall. Another plastic sheet was put on the suction table to prevent water accumulation during the rainfall event and therefore to maintain the suction at the bottom of the cylinder during all rainfall simulation.

Rainfall simulation procedures for soil and sand samples

Simulated rainfall events were produced using an oscillating nozzle located 4.5 m above the samples as described in Foster et al. (1979); the nozzle size was chosen depending on the drop size and rainfall intensity requirement (Spraying Systems Co., Wheaton, Illinois, USA. Veejet type 6550). The intensity was controlled by adjusting the sweep frequency and water pressure. Deionized water was used to avoid any physico-chemical effect on the clay fraction (Darboux and Le Bissonnais, 2007). In all treatments, the total amount brought to the soil and sand samples was 87 mm, but rainfall procedures were different for the sand and soil samples and are summarized on [Fig. 2](#); three replicates were normally used for each treatment ($n = 3$).

For the sand samples, we kept constant the suction at the bottom of the cylinder (60 hPa) and the treatments consisted in three successive events of increasing intensities (40, 60, 120 mm h⁻¹, *i.e.* rainfall duration of 130, 87 and 44 min respectively) and a final flooding. The flooding treatment consisted in adding a total of 87 mm of water by steps of 11 mm each (the surface was protected by a tissue). Note that prior to each rainfall event and prior to flooding, the cylinder was left one night on the suction table to allow water draining out and reach new equilibrium.

For the soil sample, the rainfall intensity was kept constant at 40 mm/h (during 130 min) and the treatments consisted in three increasing suction at the bottom of the cylinder: 20, 60 and 90 hPa. Unlike sand samples, different soil samples were used for each treatment ([Fig. 2](#)). Every 5 to 10 min during the rainfall events and the flooding, the total height of the cylinder and the position of each ring of white glass beads was measured using a ruler with a ± 1 mm precision. At the end of each experiment, the material present in each 2 cm plexiglas® ring was removed using a thin and rigid iron plate and was weighted after oven drying at 105°C during 24 h; so that dry bulk density (ρ) could be calculated for each ring.

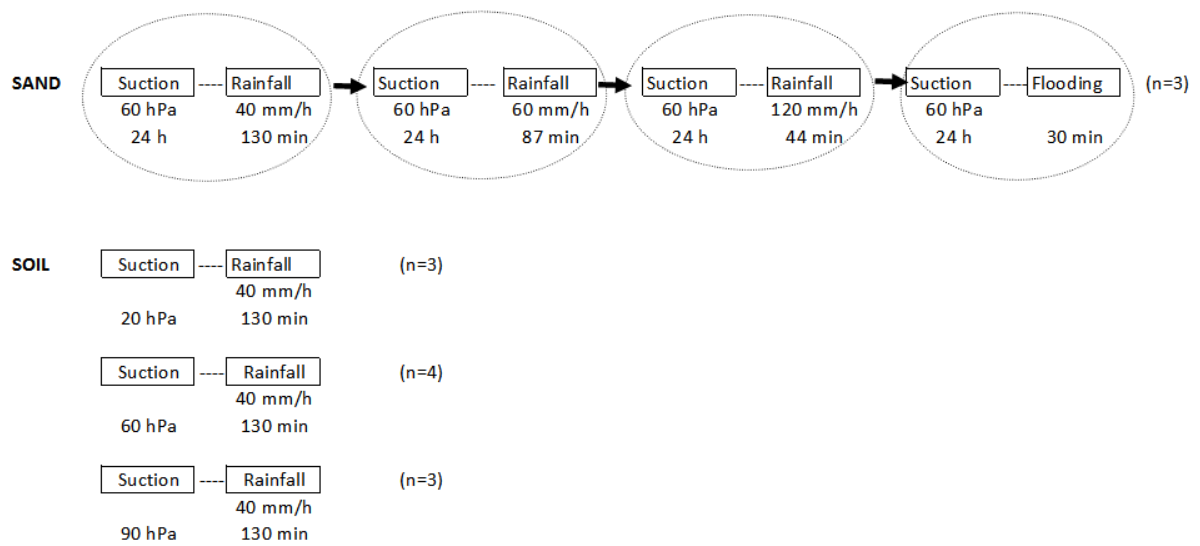


Figure 2 The experiment protocol for sand and soil treatment. Sand samples were submitted to different rainfall intensity with fixed suction (60 hPa) on suction table. Soil samples were submitted to same rainfall intensity (40 mm h^{-1}) with different suction on suction table.

Results

Sand and soil characteristics

Table 1 presents the characteristics of the soil material (collected in the field) and of the sand fraction (extracted from the soil material). The soil material has a low clay and organic matter content, 2.8 and 0.2 % respectively; this explains that CEC is also similarly very low ($< 1 \text{ cmol}^+/\text{kg}$). In the sand fraction, H_2O_2 treatment was efficient as it destroyed 90% of the SOC but dispersion and sieving was not so efficient: 40 % of the clay fraction was still present (1 % in mass); 10% of the fine silt and 50% of the coarse silt. Consequently, the sand sample was not totally pure, it still contained 4 % of fraction $< 50 \mu\text{m}$ (clay and silt), compared to 13% in the original soil. In both soil and sand, the fine sand (50-200 μm) was the dominant fraction as it represented 3/4 of the total mass of the sample.

Table 1. Physico-chemical properties of the soil and sand materials used.

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		Particle size distribution (μm)						SOC	pH	CEC	
		Clay	Silt		Sand						
		g kg ⁻¹						g kg ⁻¹		cmol ₊ kg ⁻¹	
		2	2-20	20-50	50-100	100-200	200-500	500-2000			
Soil		28	39	64	328	434	105	2	2.07	4.99	<1
Sand		10	5	31	329	518	104	3	0.28	6.43	<1

SOC, soil organic carbon

CEC, cation exchange capacity

Surface decrease and water characteristics in sand cylinders

All sand cylinders were put on a suction table with 60 hPa suction; treatments consisted in applying three increasing rainfall intensities (40, 60 and 120 mm/h) and a final flooding. Under rainfall simulation, despite the large porosity of the sample ($> 50\%$), the material inside the cylinder was perfectly stable, even under the highest intensity of 120 mm/h, no surface decrease and no movement of the markers were observed during the rainfall events (Fig. 3a, b, c). Under all intensities, the volumetric water content increased sharply and reached the same stable value of $0.30 \text{ cm}^3 \text{ cm}^{-3}$ (saturation ratio, *i.e.* porosity occupied by water, was $\Phi = 0.57$). The matric potential ranged from -60 to -50 hPa before the rainfall event, and increased also very sharply to reach a steady state of -25 hPa. With the highest rainfall intensity (120 mm/h), the only noteworthy difference was a slightly higher ψ at the bottom compared to the upper layers: -20 hPa compared to -30 hPa.

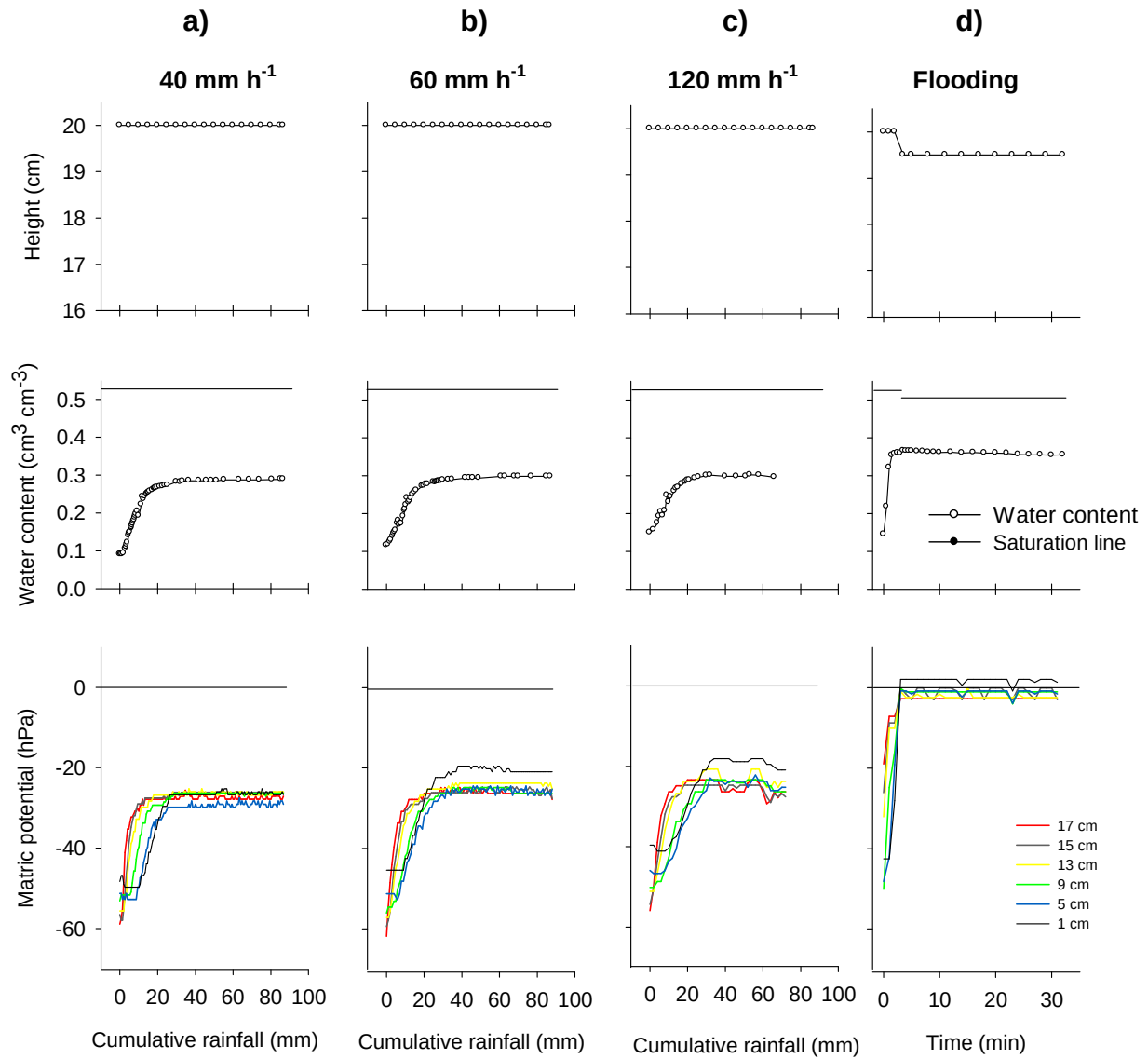


Fig. 3 Height, average volumetric water content and matric potential of sand samples submitted to a series of different rainfall intensity. The suction on suction table was fixed at 60 hPa. One of the three replicates of each rainfall intensity is presented here.

Under flooding conditions, the sample surface decreased by 0.7 ± 0.1 cm (Fig. 3d). This decrease occurred in one time, less than 5 min after the onset of flooding. During that period of time, θ increased up to $0.37 \text{ cm}^3 \text{ cm}^{-3}$ and ψ went up to values around 0 hPa. The value of ψ in the bottom layer (1 cm) was slightly positive (5hPa) when in the upper layers (from 13 to 17 cm) ψ was slightly negative (-5 hPa). The periodic variations of ψ , resulted from flooding procedure (bringing the total water amount by 11 mm steps). It is noteworthy that even during flooding, the sand pile was not saturated and a large amount of air was still present in the system ($\Phi = 0.70$).

Water changes in soil material cylinders

The soil material was submitted to a 40 mm/h rainfall intensity; the three treatments consisted in applying increasing suction at the bottom: 20, 60 and 90 hPa in order to mimic different soil conditions under the tilled layers and therefore to change the drainage conditions. Fig. 4 shows that soil surface decreased in all treatments: 3.0, 2.9 and 2.5 cm for 20, 60 and 90 hPa suction respectively. In all replicates of all treatments, the surface decrease was sharp at the beginning and slower at the end. The only exception was one replicate of the 60 hPa (Fig. 4b). For this sample, a slow decrease was observed before the sharp one occurred. The beginning of sharp decrease was indicated by red vertical line on Fig. 4. At the end of the rainfall event, the decrease in the soil surface seemed stabilized for the 20 hPa treatment; similar stabilization was not observed at 60 and 90 hPa (except for one replicate on three at 60 hPa that presented on Fig. 4b).

The θ was approximately $0.10 \text{ cm}^3 \text{ cm}^{-3}$ after equilibrium on the suction table and immediately after the onset of rainfall simulation it increased sharply and reached a steady state at approximately $0.30 \text{ cm}^3 \text{ cm}^{-3}$ ($\Phi = 0.60$). It is noteworthy that a second significant increase in θ was observed at the same time as the sharp decrease of surface level. The increase in θ is related to the decrease in total pore volume: the volumetric water content was increased due to the reduction of total porosity but the gravimetric water content was probably unchanged. Despite the decrease in total porosity, the saturation rate was still <1 .

The ψ of the top layers also increased immediately and very sharply at the beginning of the rainfall simulations, when the increase was delayed for the deeper horizons (the deeper, the longer delay). For all depths a steady state was observed in matric potential, its value depended on the depth of the layer and, similarly to θ , a second increase was observed for ψ while the soil surface was decreasing. Before the second sharp increase, ψ in the top layers was higher (*i.e.* closer to zero) than ψ in the bottom layers; the contrary was observed after that increase in the 20 and 60 hPa treatment. This change was not observed when the highest suction was applied (90 hPa) because ψ at steady state was the same in all layers; it was -17 hPa and reaches -7 hPa at the end of experiment. For 60 hPa treatment, the matric potential at the end of the experiment was slightly below 0 hPa for the bottom layers and -10 hPa for the top layers. For the 20 hPa, the matric potential was slightly positive (pressure and no more suction) for the two bottom layers, around 0 for the intermediate layers and below 0 hPa (suction) in the top layer (17 cm).

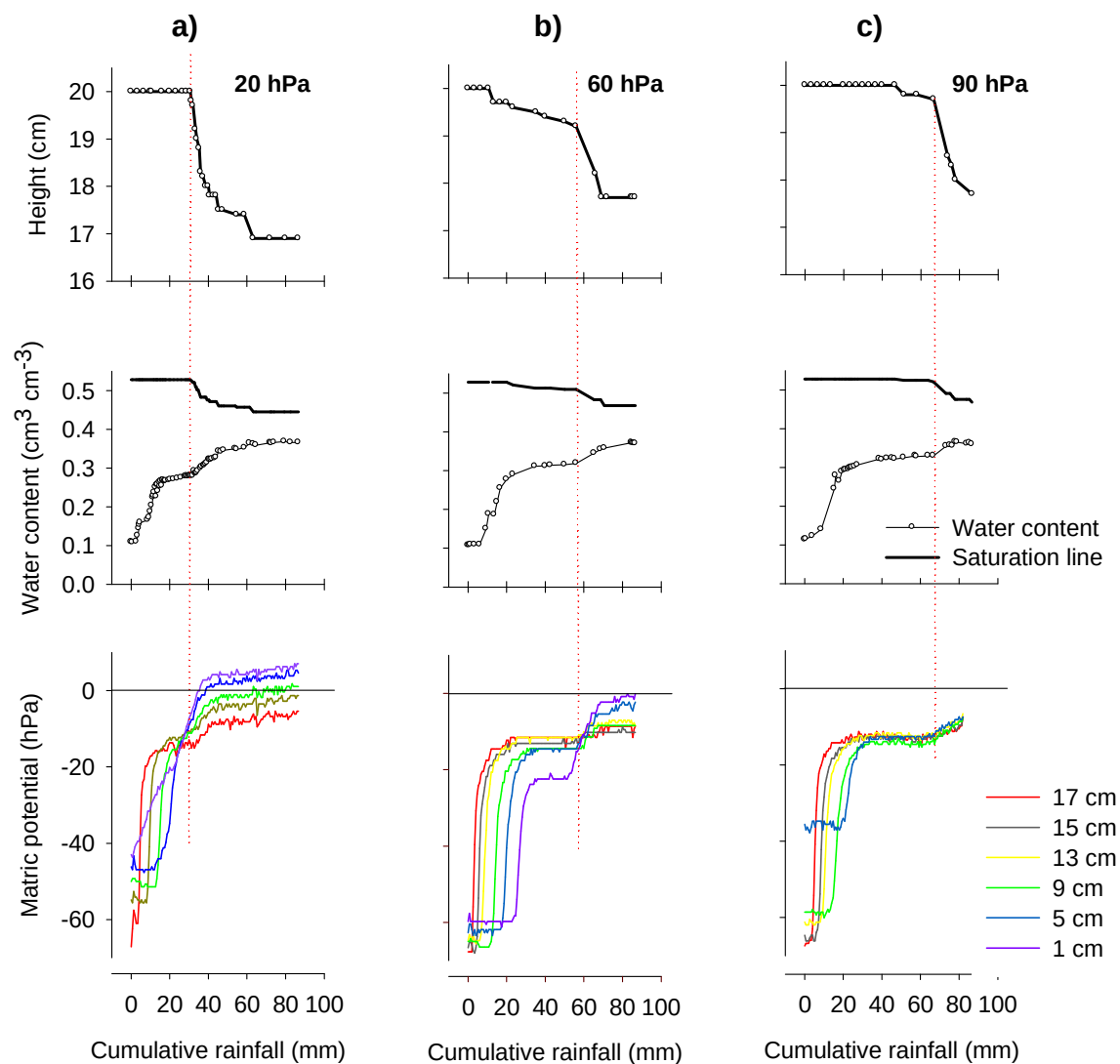


Fig. 4 Height, average volumetric water content and matric potential of soil samples submitted to different suction on suction table. The rainfall intensity was fixed at 40 mm h⁻¹. One of the three replicates of each treatment is presented here.

Slumping dynamic and location in soil material cylinders

For sand material submitted to rainfall simulation, the surface level was stable; under flooding the collapse was very limited (0.7 cm); according to the markers (installed every 2cm) it resulted from small (<1mm) and similar decreases in all layers (data not presented). For the cylinders containing soil material Fig. 5 presents the ρ increase in the different layers measured with two techniques (cutting and markers). Whatever the technique, the same trend was observed in all treatments: at the surface a high bulk density ρ (1.5-1.6 Mg/m³), a sharp decrease in the layers below so that a minimal value is observed and a slight increase until the bottom of the cylinder. With the cutting method, a maximum bulk density is observed on the bottom layer that was not observed with the marker method.

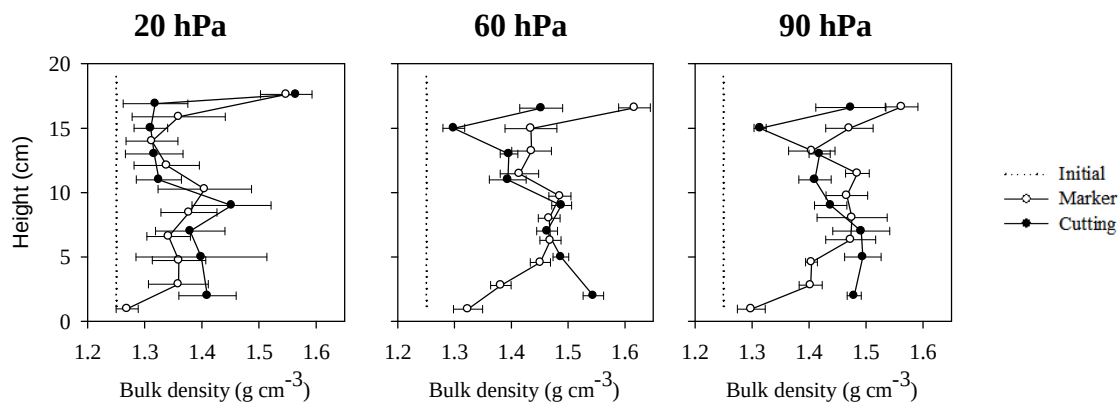


Fig. 5. Averaged bulk density after 87 mm of cumulative rainfall (rainfall intensity of 40 mm h⁻¹ during 130 min) according to the suction applied at the cylinder bottom. The dotted line indicates initial bulk density profile. Two methods are presented here. The bars indicate the standard error (SE) on the averaged bulk density. (n=3).

Discussion

Validity of the experimental device used

Our two hypotheses were (i) slumping of cultivated sandy soils could be triggered by occurrence of either high matric potential (close to zero) or high water content (close to saturation) or both simultaneously, even during a very short time and (ii) if slumping are controlled by the predominance of the sand size particles, it should be possible to consider a pure sand as model for a sandy soil. To test these two hypotheses, laboratory experiments were conducted with detailed measurement of simultaneously changes of compaction and of water characteristics on a model profile created inside a cylinder using wet samples loosely packed (20 cm height, same as one of the tillage depth in field experiment). To reproduce field conditions, a rainfall simulator controlled the amount and the flux of water arriving on the cylinder when a suction table controlled the drainage conditions at the bottom. For the soil samples, the rainfall intensity was fixed (40 mm/h) when the suction at the bottom was changed (20, 60 and 90 hPa); the opposite was done for the sand material: the suction was fixed (60 hPa) and the rainfall intensities was changing (40, 60, 120 mm/h, and flooding).

Under the rainfall experiments, the soil material in the cylinder behaved as the soil material in the field. The top surface collapse recorded within the 20 cm high cylinder was the same as the collapse recorded in the field for a 20 cm deep tillage (*i.e.* from 2 to 3 cm). On the other hand, the ρ profile at the end of the rainfall events was similar to those recorded in the field, *i.e.* a higher increase in ρ just underneath the top surface compared to ρ increase recorded at the bottom of the tilled layer (Hao et al. submitted, Hartmann et al, 2008). Thus, the dimension selected for the cylinders as well as the procedure of the soil preparation can be considered as valid and could be used in future laboratory experiments on sandy or more generally on coarse textured soils.

On the opposite, the sand material did not behave like a soil material, even if it was extracted from the soil of the same field. Surprisingly, the sand material was extremely stable: no collapse was recorded even under three fold higher rainfall intensity (120 mm h⁻¹) compared to soil samples (40 mm h⁻¹). A collapse was observed only during the flooding experiment but it was extremely slighter than in the soil (<1 cm). Moreover, this collapse resulted from closer packing similar in all layers, unlike slumping that is characterized by surface layers always more compacted than deep layers. As a conclusion, the sand fraction extracted from soil sample cannot be considered as a model soil.

The TDR and tensiometers that we selected, as well as the way they were installed, can be considered as satisfactory. The recording of the water content and water potential in coarse textured soil remains challenging because of the discrete nature of the constituents. The size of the elementary particles is not favourable to an appropriate functioning of TDR probes and of tensiometers which affect locally the structural characteristics and thus the structural stability and mechanical behaviors of the soil material. In fact, our different replicates showed that most of the time, we obtained satisfactory water continuity between the tensiometer and the soil. Moreover, neither the TDR probe, nor the tensiometers had significant interaction with the structure and mechanical characteristics as the changes observed on the cylinder are consistent with the changes observed in the field.

Concerning water characteristics, unlike what was expected, saturation by water ($\Phi=1$) and profiles with $\psi=0$ were not recorded before slumping (Fig. 4a). Therefore our hypothesis concerning the determinant factors of slumping has to be rejected and our results need to be detailed to formulate a different and more relevant hypothesis about factors and processes of soil slumping; moreover, we need to explain the surprising higher stability of sand material compared to soil material.

Specific characteristics of wet granular materials

According to Mohr Coulomb criterion, a soil is stable as long as:

$$\tau < \sigma \mu + C \quad (1)$$

with τ the shear stress at failure, μ the coefficient of internal friction and C the cohesivity or cohesion. The coefficient of internal friction is a characteristic of the material and does not change at the time scale of the experiment. Cohesion is the resultant of convergent strengths which tends to maintain the unity of solid elementary constituents; according to the Mohr-Coulomb criterion, C is equivalent to the shear stress at zero normal load. In a standard soil, binding forces result from mineral clays and organic matter. In coarse textured soil, clay content and OM content are generally low, so that cohesion and structural stability are considered as low. But cohesion and therefore stability of coarse textured soils can be dramatically increased by the presence of water, even in small amount. This is observed for sand castle but also in cultivated sandy soils: bulk density as low as 1.1 Mg/m³ were measured immediately in the field after tillage (Hao et al. submitted); this corresponds to an

assemblage where the volume occupied by the pores is higher than the volume occupied by the solid particles.

The binding energy developed by water between two grains results from i) the interfacial tension at the contact line between the liquid and the solid particles and ii) the suction pressure difference due to the curvature of the liquid bridge. The smallest surface/volume ratio is obtained in a sphere, therefore the surface of a liquid will be deformed by an amount quantified by the Young-Laplace equation. This equation describes the pressure difference across a curved surface (capillary pressure) and the atmospheric pressure with:

$$P_c = (2 \gamma \cos \beta) / r$$

where **P_c** is the capillary pressure, γ is the interfacial (surface) tension, r is the radius of curvature of the surface and β is the contact angle. Inside a water bridge linking two solids, the Laplace pressure is negative; consequently the menisci are concave and the surface tensional forces pull the particles together through the liquid bridges.

With increasing θ , location of water inside the grains assemblage is changing and this change affects the development of solid/liquid and air/liquid interfaces, what finally affects the cohesion. The three water regimes generally recognized are (Pierrat and Caram, 1997, Iverson et al., 2002, Mitarai and Nori, 2006):

- the pendular regime: water is located in capillary bridges at contact points between grains (Fig. 6a). Development of interfaces is maximum and compared to the two other regimes, cohesion is the highest. An important feature is that the forces exerted by the bridges are largely independent of the bridge volume, therefore similarly high cohesion is measured for a large range of θ (from 2 to 10 % approximately);
- the funicular regime: with increasing θ , the capillary bridges will coalesce and the excess water will fill the packing voids between neighbouring grains, creating ‘water clusters’ (Fig. 6b) (Scheel et al., 2008; Kudroli, 2008); the cohesion of the material is reduced due to the reduction of air/liquid interfaces;

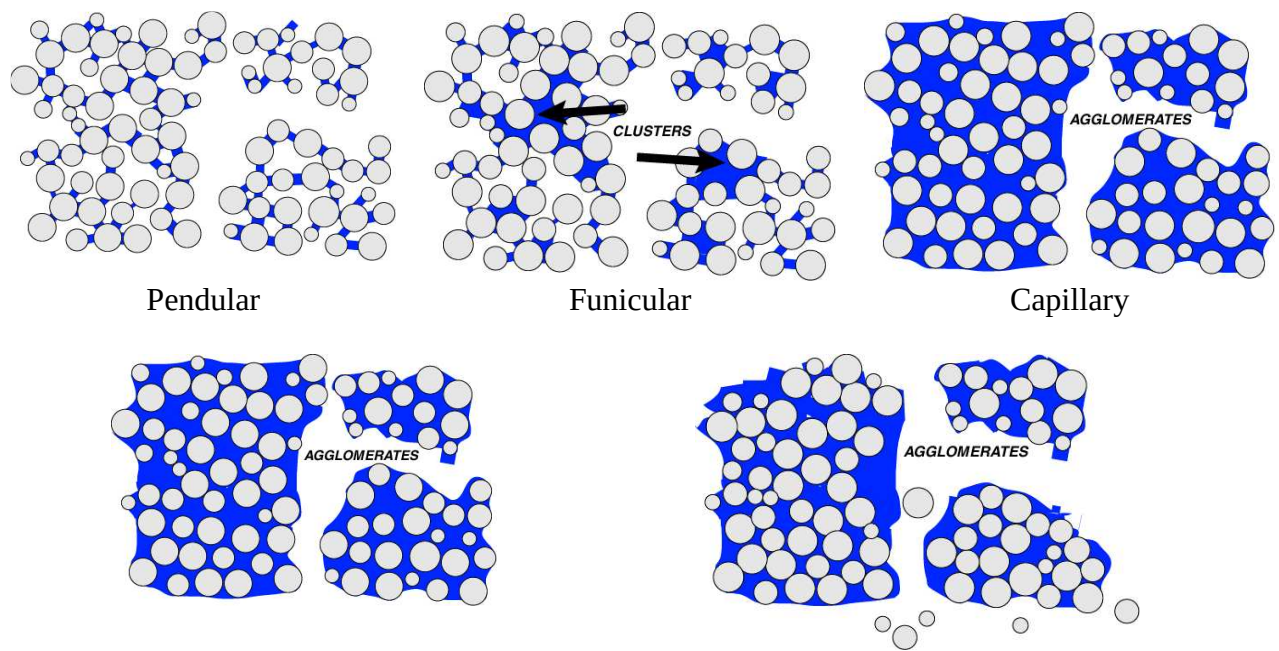


Fig. 6. Top: schematic representation of water location inside a loose granular material at the three regimes. Bottom: when reaching the capillary stage (left) reorganization of grains inside the agglomerates is possible but capillary cohesion still exists maintain agglomerates (right) even if it is under different configuration.

- the capillary regime: finally all clusters will be connected (percolation transition), and some grains will be totally surrounded by water (Fig. 6c). This transition from funicular to capillary regime has dramatic consequences on both hydrological and mechanical characteristics. First, on an hydrological point of view, the water network has such a connectivity that “a paramecium cell would be able to swim from one end of the sample to the other without leaving the water” (Herminghaus, 2005). Second, for grains totally surrounded by water, no capillary force exists anymore to link them with their neighbours and therefore they can potentially move simply under the effect of gravity. Third, this is unlike the grains at the periphery of the agglomerates: they are attracted by interfacial tension of the water which tends at the same time to minimise its extension; thus at the periphery of agglomerates, negative pressure (concave menisci) provides cohesion to the agglomerate but a weak cohesion.

The pendular regime has the clearest definition on a physical point of view; thus it was largely studied (e.g. Groger, 2003, Soulié et al. 2006, El Shamy, 2008, Magias Alguacil, 2009; Scholtès et al, 2009, Radjai et al., 2009) when the funicular and capillary regimes are more

complex and difficult to define and experiment. Thus the latter were studied only recently by puzzling direct observation of water bridges (Scheel, 2008) and on virtual models (Mitarai, 2008, Grof et al., 2008). Moreover, the material used in those experiments and simulation often in ‘close packing density’ and were carefully filled using small amounts of water and long equilibrium time. As a consequence, no reorganisation was observed in the grain packing and only changes in mechanical properties were recorded. Despite those different limitations, the next section will examine our soil material on the basis of these partial information.

Water and solid characteristics at the onset of soil slumping

Just before the rainfall events, $\theta \approx 0.12 \text{ m}^3/\text{m}^3$ and porosity $> 50\%$ in both sand and soil material. To keep standing such loose structures, grains must be connected by strong bonds. This suggests that most of the water was at pendular regime, even if locally some clusters existed as well. At the onset of rainfall, infiltration was fast and whatever the suction at the bottom (soil samples) or whatever the rainfall intensity (sand samples), θ increased more than twofold after only 20 mm of rainfall. Simultaneously, ψ increased (getting closer to zero) indicating a fast evolution from the funicular to the capillary regime. At the onset of slumping, all treatments on sand samples showed a similar ψ and all treatments on soil samples had also similar ψ , but ψ was lower for sand than for soil material: - 30 and - 17 hPa respectively. As ψ reflects the organisation of solid particles, soil and sand samples must be slightly different.

In our original hypothesis we expected that slumping would be triggered when θ and/or ψ would be above some threshold values. Our results demonstrate that the contrary occurred: the top surface collapsed while water characteristics were at steady state; it is the reorganisation in a closer packing of the sand grains that triggered changes in water characteristics. Moreover, for the sand material, no real slumping was observed, only a limited collapse due to small and similar changes in all layers (with $\psi \approx - 5 \text{ hPa}$). Therefore, occurrence of slumping did not result only from specific water characteristics, but was also related to the occurrence of a critical state in the organisation of the solid phase.

Granular materials convey strengths that are heterogeneously distributed; the strength follow force chains (Mueth et al., 1998). A dry granular material conveys only compressive strength when a wet granular material conveys simultaneously compressive and tensile strengths. They follow force chains so that some grains convey only compressive and some grains only tensile strength (Fig. 7).

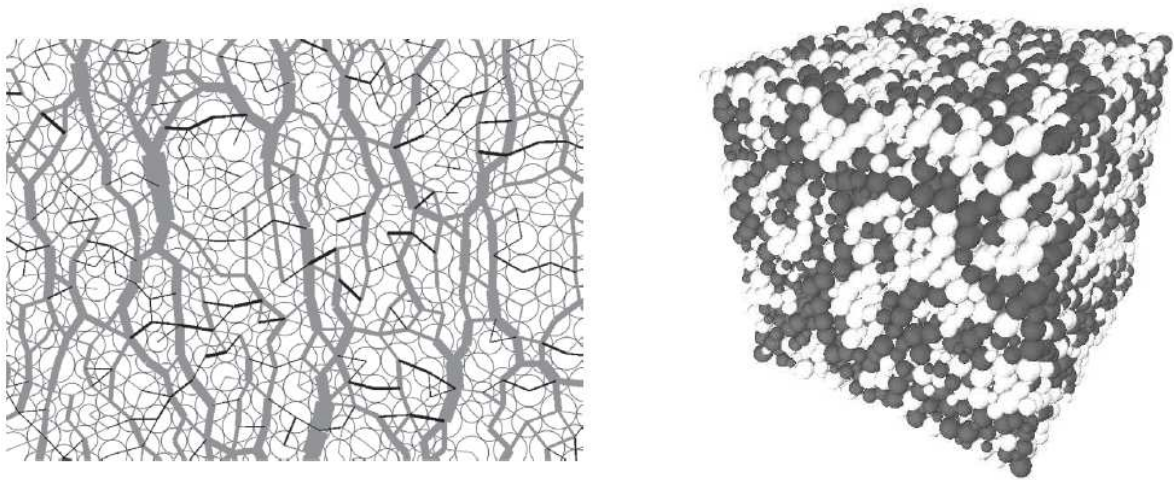


Fig. 7 – Illustration of stress transmission inside wet granular at pendulat regime.
 Left: representation of the compressive (in grey) and tensile (black) forces network; line thickness is proportional to the magnitude of the normal force (from Radjai and Richefeu, 2009).
 Right: according to the forces exerted by contact neighbors, each particles can take on negative (white) or positive (black) pressure (Richefeu et al., 2006).

When reaching the capillary regime, the tensile stress that connected particles together decreased and even disappeared locally inside the agglomerates delimited by water/air interface. At that stage, as already mentioned, the interfacial forces exist at the surface of the agglomerate and a negative capillary pressure develops inside, holding the particles together (like a very soft balloon); but inside the agglomerate under the effect of gravity the grains can potentially change their relative positions. Note that such a change can occur only if it exists at least one pore i) with compatible size and ii) in an accessible position.

Therefore, when reaching the capillary regime, even if a drastic decrease in tensile strength makes local reorganisations possible, macroscopic changes can be observed only when enough small and local reorganisations brought the pile of grain in a critical state so that larger reorganisations can be triggered and become visible. Even once such reorganisation has started, it is only little by little that a new balance can be found; explaining that slumping itself is a time dependent process.

Hypothesis on the stability of the sand material

When similar and even higher intensities of rainfall were applied to sand cylinders, no slumping was observed, the samples remained stable. Such a stability was unexpected because compared to the soil material, the sand had lower content in clay and OM content and the latter are major factors of structural stability; therefore faster and more reproducible slumping was expected, but was not observed. The slight difference in matric potential in sand compared to soil samples is not sufficient to explain a much higher structural stability. Nevertheless, this matric potential difference is an indicator of structural differences that could be a key for explaining the different behaviours. Compared to the soil material, the sand material has not only a lower clay content but also a lower silt content.. Silt grains (2-50 μm) are much smaller than the sand grains of the dominant fraction (200-500 μm) and must be located in the packing porosity between larger grains (Fig. 8). Even if their total weight is low, the number of silt grains is high, and their number of contact is high too. Moreover, silt fraction can have a significant effect on porosity (Fies and Bruand, 1998) and particularly in the sandy soils of this region (Bruand et al., 2004).

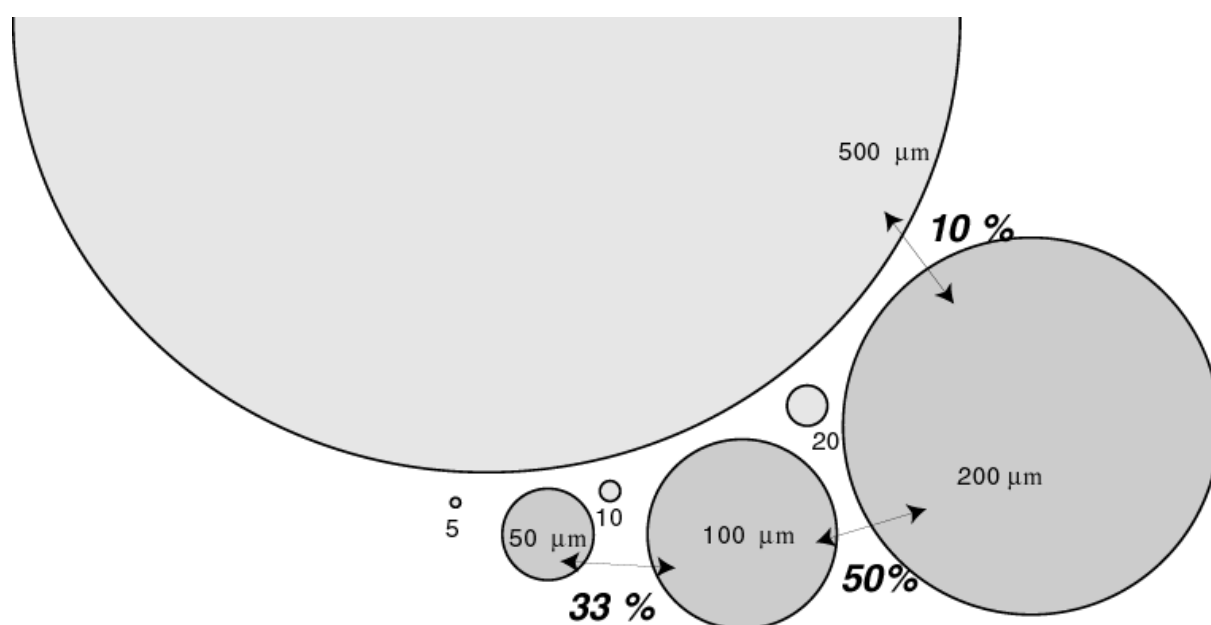


Fig. 8 –The relative diameter of grains from 5 to 500 μm . The percentages represent the data between two diameters. The fraction of silt contains grains between 2 and 50 μm .

Because of the large number of grains, the silt fraction could play a significant role in the development of chain forces at the original pendular regime; but after the funicular/capillary transition, those small grains have a high probability to be in a position from which they can easily move under the effect of gravity when totally surrounded by water. Therefore, the silt fraction might play a significant role in the destruction of the force chains and the macroscopic reorganisation. On the opposite, in the sand material, the absence of this silt fraction the geometry of the grain organisation is slightly different (*i.e.* a closer packing indicated by a lower matric potential) in which the forces chain are conveyed mainly by large grains; the latter cannot be reorganised easily reorganised at capillary because of static constraints, therefore the structural stability was higher in our experimental conditions.

The importance of silt fraction was also mentioned for soil liquefaction processes using grain contact density as a basis explanation ([Thevanayagam and Martin, 2002](#), [Rahman et al. 2008](#)). As processes in granular material are not scale dependant, and despite dramatically different conditions of pressure and porosity, it strengthen the hypothesis that absence of silt fraction could be determinant to explain the stability of the sand material.

Changes during and after slumping: the concept of reorganisable porous media

For the water characteristics: a closer packing of grains will ‘push the water out’ of the aggregates and an increase of ψ (values closer to 0) is measured, and a change in the ‘ranking’ of the different layers.

For the solid phase: When the compaction is increasing during the short time of slumping, reorganisation of grains become more and more difficult ([Clusel et al., 2009](#) ; [Wang and Zhou, 2010](#)). The largest reorganisation will occur if capillary regime is maintained as long as possible, this was observed during the field experiment ([Hao et al, submitted](#)) during which an artificial flooding induced a soil level decrease that was two fold higher than decrease observed under natural rain.

Natural rainfall regime is characterised by infiltration and evaporation periods. As soon as infiltration is stopped, the matric potential will decrease, menisci will appear and probably also induce some reorganisation, if slumping has already occurred or not. After a period of evaporation, the new organisation is probably more stable than before due to the rearrangement under the effect of capillary forces that brings the particles at contact ([El Shamy and Groger, 2008](#)).

As a consequence, slumping intensity depend not only on the amount of rainfall or rainfall intensity, but also i) on the time during which the material was at capillary regime and ii) on the history of the material before reaching the capillary regime. As a consequence, the same duration at capillary regime will not have the same consequences if i) slumping has already occurred before or not, ii) depending on the intensity of previous slumping and ii) depending the number of previous wetting/drying cycles. This explains why high variability can exist in seemingly similar situation and why so different slumping dynamics were described in the literature.

According to our different results, we suggest the concept of ‘reorganisable porous material’. Behaviour of dry granular material depends on their history, the reorganisable porous materials are wet granulars, prepared in a loose packing that can evolve to denser packing and higher cohesion; the characteristics and dynamic of this evolution depends on factors that we have identified but not yet quantified. An improved knowledge of the behaviour of the reorganisable porous materials would allow to suggest adapted management techniques able to maintain high porosity and low mechanical resistance.

Conclusions

The model soil profile (cylinder of 20 cm filled with wet soil, loosely packed) was validated and can be successfully used in other studies on sandy soils. The absence of collapse observed for the cylinder of sand (50-2000 μm) shows that this size fraction can not be a model for sandy soils. Difference in slumping was attributed to the absence of the silt fraction (2-50 μm); more generally, the wide dispersion of mineral fractions for a natural soil must be taken into account to understand its behavior.

Contrary to our hypothesis, the slumping does not need water saturation or zero matric potential ($\psi = 0$). The critical conditions are i) that the wet granular reaches the capillary regime and ii) that it stays at this regime for a time sufficient for the reorganization of the grains to take place; this delay is necessary because of static constraints. Therefore, not only the total rainfall is important but the determinant factor of slumping will be the rainfall pattern, *i.e.* the cycles of rainfall events and dry spells. To efficiently study such materials, we propose the concept of ‘reorganisable porous material’.

Chapter 4 General discussion

The objective of this general discussion is to link all information presented in previous chapters, both the state of the art on the slumping soils and on wet granular theories that the results of our field experiments and laboratory .

This chapter is organized into three sections corresponding to three objectives:

- i) to assess the validity of models of soil profile that we have tested;
- ii) to assess the relevance of theories on granular material in order to use those theories for describing the processes and factors determining slumping;
- iii) to propose a discussion on the structural evolution of sandy soils and on the conditions for integrated and sustainable management of sandy soils and, more generally, of coarse textured soils.

1 – Evaluation of profile and sandy soil models

1.1. Profile model

In soil science, many of the knowledge to the processes of physical degradation of cultivated soils come from laboratory experiments conducted on models of soils and profiles (not only on real soils in the field). The development of these models comprised three main stages:

a-Selection of a representative soil volume

The basic model of these soils is the soil aggregate. For an experiment, their origin, history and status are controlled; they can be collected in fields or made in the laboratory, dried at standard temperature or stored at profile moisture, put at equilibrium with a given water content or potential, treated or not by conditioners, etc. It is also possible to control the aggregate size limit (usually from 10^{-1} to 10^1 mm) and the size distribution between these extremes.

b-Making an artificial profile

The behavior of aggregates can be studied on separate individual aggregates (even when using a population of aggregates, their assembly does not affect the result), as it was done in the case of many tests of structural stability. Sometimes the aggregates are assembled to form a horizontal layer to mimic a bed of aggregates on the soil surface that is subjected to climatic factors of changes (temperature and moisture, rainfall). Aggregates can be assembled to reproduce the characteristics of a plowed profile, in which case they are stacked, usually in columns of varying size (diameter and height).

c-Measurements

To study the physical changes in the aggregates or on the model soil surface or model profile, it was possible to mimic the climatic and mechanical constraints existing in the fields with different devices (rain simulator, oedometer, triaxial cellule, etc ...). On such models, it was also possible to recreate biological activity (e.g., earthworms and termites) or microbiological activity (carbon changes within aggregates, etc.).

We followed a similar approach:

a-Selection of a representative volume

The model of an aggregate assembly can be relevant only if the aggregates represent a dominant fraction, what is not the case in sandy soils where the aggregates are only a minor fraction: the greater part of the soil volume is made of elementary coarse and rigid particles. The aggregation is particularly low when both the clay mineral content and organic matter are low. To study the slumping process, we deliberately selected a soil with i) low clay content and organic matter and ii) in which no fraction $> 2\text{mm}$ existed. In such a soil, the aggregates could not be representative of the whole soil. In absence of grains or aggregates $> 2\text{ mm}$, it was even not necessary to sieve the soil after field sampling. For various reasons it was not possible to keep the soil at field moisture, thus it was air-dried before transport.

b-Making an artificial profile

The disturbed samples collected in the field had to be assembled to reproduce the physical characteristics of a tilled sandy soil, *i.e.* an apparent bulk density of 1.1 to 1.2 g cm^{-3} . A bulk density of 1.1 g cm^{-3} can easily be obtained at the low water content ($\sim 5\%$) that existed during field tillage operation. But with such a low bulk density, heterogeneity within the sample was too large to allow good repeatability of any physical measurement. Thus, a higher value of 1.25 g cm^{-3} was selected; this compromise being subsequently validated as demonstrated by our result. Thus, a water content of 10% was selected because i) apparently created the same cohesion as a water content of 5% , and ii) according the previous studies on granular material, the sample should be at pendular regime for both water content.

When a granular system is limited by some borders, as is the case of our cylinders, the diameter of the cylinder size must be sufficient to avoid edge effects. Cylinders 20 cm in diameter represent 100 times the diameter of the largest grains present in the sand fraction of soil and 200 times that of larger grains present in our sample. At that size, edge effects were negligible as shown by measurements of collapse: The beads on the edge of the system (markers) yielded the same results as the measure of density in the cylinders.

c-Measurement

As the soil or sand cylinders were very fragile, it was not possible to introduce them in any measuring device. After introducing the soil or the sand in the cylinders, they were installed

on the suction table, itself under the rain simulator. This is where the probes (TDR and tensiometers) were implanted into the cylinder. These probes could constitute intruder which might disrupt the evolution of granular, but our results showed that even if disturbances existed, they have not been large enough to influence the behavior of the sample as a whole. Even if it was not necessary in our case, if measurement devices (for example: penetration resistance or shear stress, etc) can be brought near the cylinders, complementary measurements could be made on the cylinders with the procedure suggested above.

As a conclusion, the model of soil profile that we developed was effective in our study and can also validly be used in the study of other sandy soils. So more generally it could be used to study the physical behavior of any coarse textured soils even if it does not allow the full range of characterization usually done on more standard soils.

The knowledge provided by theories of granular materials allows changes in the model so it can be relevant with the particular characteristics that one wants to study. For example, it is possible to make systems more compact, mechanical stresses are applied with care and in a standardized manner to avoid creating force chains of variable or excessive strength in the different layers or in the different replicates.

1.2. Model soil

As the sand fraction (50-2000 microns) is the dominant fraction, it seemed possible to create a model sandy soil by extracting this fraction of the whole soil. But this hypothesis was not validated because the sand fraction does not exhibit the same dynamic evolution of slumping as the soil. Our result suggests that the silt fraction may have a role in the collapse of the structure. The silt fraction represents a large proportion of contacts between particles are created, even if this silt fraction represents only a small fraction in weight.

This hypothesis about the importance of the silt fraction may be checked as follow: after digestion of organic matter with oxygenated water, the soil should be put in contact with dispersant and introduced into a test tube in order to remove the supernatant containing only dispersed clay. The washing procedure must be repeated until elimination of the clay fraction and by the end of the operation it would be easy to collect both sand and silt fraction. Then, this new sample should be used to prepare a cylinder of soil model under standard conditions and submitted to standard rainfall simulation to check if slumping characteristics are similar to those of the whole soil.

If the importance of the silt fraction is confirmed, it will be possible to provide an improved model soil and test the importance of the silt fraction in other physical characteristics (penetration resistance or shear stress for example), compared to a pure sand or to the whole soil.

2 –Physics of granular material to describe slumping

Our field and laboratory results, as well as publications that mention slumping occurrence, and finally our review of current knowledge on wet granular materials, make it possible to propose the following steps and scenarios to describe slumping:

1 - Fragmentation of the compact horizon and the establishment of the tilled horizon

a - Loosening: tillage tools induce soil loosening, i.e. they separate the layer in elementary particles, lift them up from their position, thus providing them potential energy.

b- Particles fall: particles fall back under the effect of gravity. The motion is slow down and hampered by the friction between grains and also by the presence of water (in relation with its interfacial tension).

c - Tilled horizon: the grains are embedded in a loose pile in which compression and tension forces coexist, providing some cohesion and stability despite huge porosity.

2 - Surface rearrangement at the onset of a rainfall event

The kinetic energy of raindrops causes local rearrangements at the scale of the drops, this step was not measured in our study because it does not affect slumping.

3 - Water Infiltration

Our device did not measure the early stages of infiltration, but most probably it was not a homogeneous and horizontal water front going down in the profile, but rather 'in finger', as the soil moisture was at a minimum at the onset of the first rainfall events. It is only after the profile has been wetted, that infiltration can take place along a more homogeneous and horizontal front (Kawamoto et al., 2004).

At that stage, three different scenarios have to be considered (Fig. 1):

Scenario 1: *continuous infiltration*

This is the scenario that we observed in the field experiment under flooding irrigation, under rainfall simulations in the laboratory and probably during the most intense rainfall events under natural rainfall. The laboratory measurements showed i) that after 20 mm cumulative rainfall we reach a steady state for both water content than matric potential, and ii) this steady state is far from saturation and free water (zero or positive matric potential) was not necessarily observed, but most probably the capillary regime was already reached. When the capillary regime was reached, the tension forces decreased as well as the cohesion of the material. Reorganization of local grains was certainly possible within the agglomerates but these reorganizations could not occur instantly. The silt fraction was probably the first that was no longer attached to neighboring grains through the capillary bridges. Once being detached, it could move within the large packing pores under the influence of gravity (as the grain is entirely immersed in water, the hydrostatic pressure is reducing the effect of gravity). These rearrangements changed the balance in the network of force chains. The material was in a increasingly meta-stable state until reaching a critical point for which mass movements were possible. At that moment, the level of the cylinder surface started to decrease. This sinkage was fast at first but it was also quickly slow down: with the local increase of compactness, the reorganization became increasingly difficult because of static reasons; thus new balances and new force chains were continuously set up.

If the water flow was important enough so that the capillary regime was maintained, the material slumping could also be continuous. This is what occurred during the field experiment when microplots were subject to flooding.

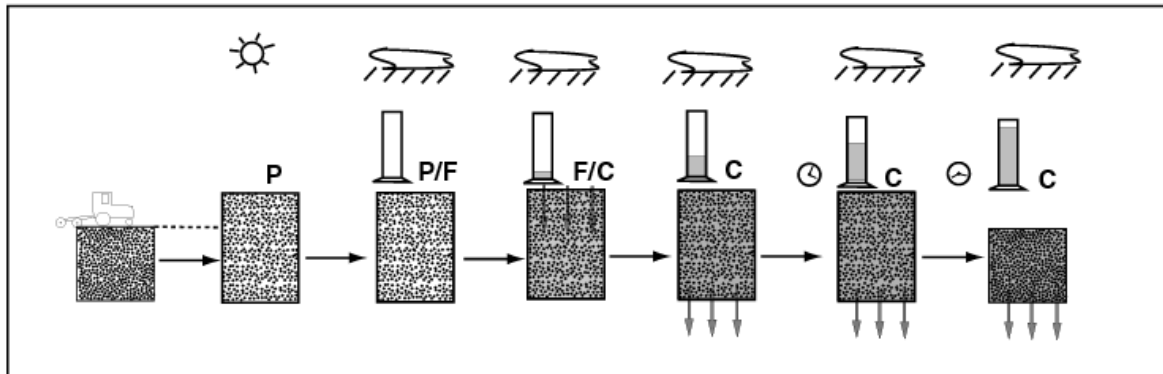
This slumping process did not start at a particular or a specific depth: if the infiltration was sufficient and the capillary regime was reached more or less simultaneously in all the tilled layers, slumping can occur simultaneously in different layers, *i.e.* different depths. This explains why the slumping was observed by several authors from the surface to the bottom of tilled horizons, regardless of the thickness of those layers.

Under natural rainfall, slumping was not as fast, two different scenarios being able to explain this difference.

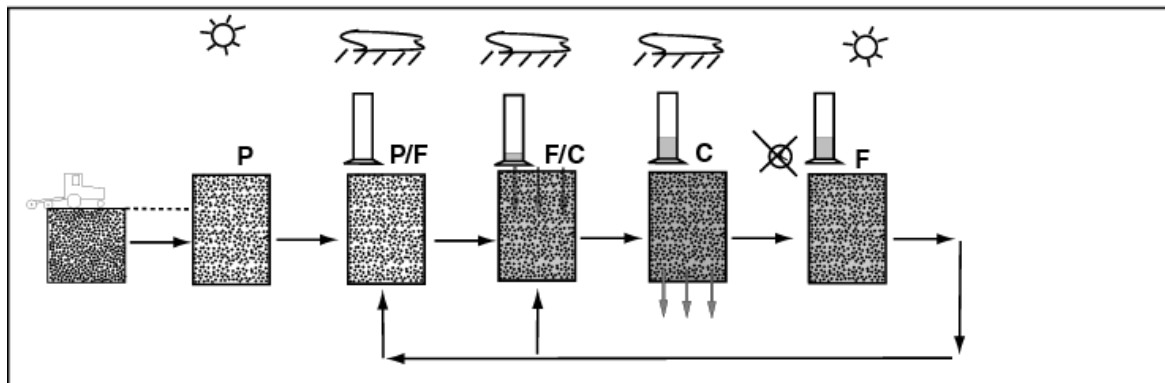
Scenario 2: rain stop after the capillary regime was reached

At the end of rainfall simulation (laboratory), our records show that water content and matric potential decreased very fast, indicating that the material changed also very fast from capillary to funicular regime with associated development water / soil / air interfaces. Larger interfaces increase the cohesion of the material and also restore the capillary forces that exist between particles, blocking any movement of individual particle and therefore blocking any slumping of the material. If the rain stopped when the profile just reached capillary regime, this was certainly what happened, explaining absence of slumping.

Scénario 1



Scénario 2



Scénario 3

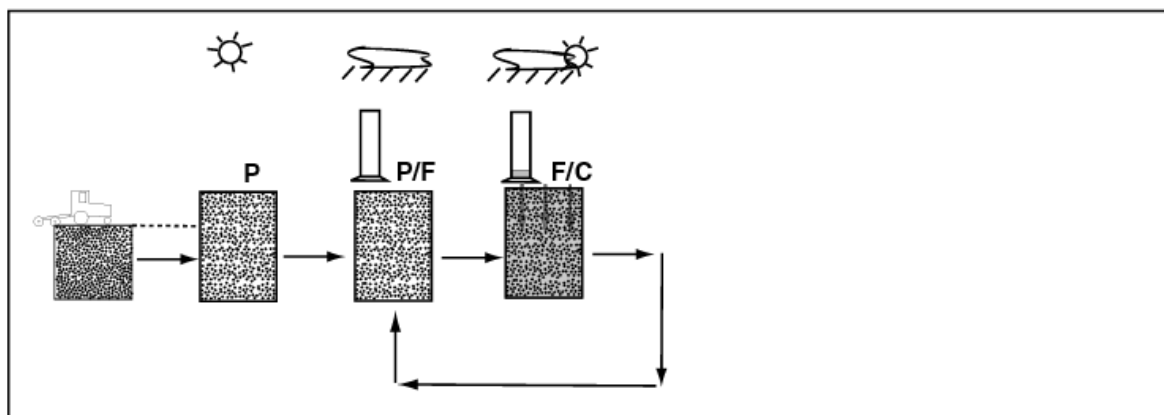


Fig. 1 - Simplified presentation of the three scenarios of soil behavior under rainfall. After tillage and loosening of the dry soil (P: pendular regime), the profile is wetted by rain or irrigation (F: funicular regime). In scenario n°1, the capillary regime (C) is achieved and maintained long enough to observe slumping. In scenario n°2, the capillary regime is reached but not maintained, it comes back to the funicular or pendular regime. In scenario n°3, the rainfall events are too low to overcome the funicular regime. The test tubes give an indication on the amount of water that reaches the soil surface; the clock indicates that time passes by.

Scenario 3: under low rainfall, only the funicular regime was reached

If the intensity of rainfall was not sufficient, even with a high and significant accumulated rainfall total, the soil cannot reach the capillary regime due to simultaneous drainage. Even if some rearrangements occur at very local scale, the critical state can not be reached.

After the field experiments, we hypothesized that only heavy rain had an impact on the slumping. Yet most of the rainfall events were <20 mm, only a few rainfall events were >20 mm. Surprisingly, 20 mm was also the value that we observed in the laboratory under simulated rainfall as a threshold to reach the capillary regime. As a conclusion, we can only notice the good agreement between field data and laboratory, that constitute one more validation of our model profile.

We pointed out the importance of the silt fraction on the destabilization of the material; it is likely that size distributions of sand and more importantly of the silt fraction could have a determinant influence on this threshold. The value of 20 mm rainfall previously mentioned is certainly not universal.

The large differences in slumping dynamic mentioned in different published papers are now easy to understand and to explain as this phenomenon depends on the interactions between rainfall characteristics, the need to maintain a capillary regime for a sufficient time and the importance of the silt fraction. As a consequence:

- with the same total rainfall amount but different rainfall history and pattern, the slumping characteristics can be very different;
- with different silt content, all other characteristics being equal, slumping may also be very different.

It would be necessary to obtain, under various conditions, a better quantification of simultaneous water and soil characteristics so that our conceptual model could become quantitative. Reaching this goal would allow a quantification of slumping risk that is not yet possibly made. Nevertheless, uncertainties that exist in physical systems models are so important, that it is not certain that such a quantification currently possible

3 – The management of the physical characteristics of cultivated sandy soil

Based on our observations and theories concerning granular media, it is possible to make a number of recommendations.

3.1. To predict a sandy soil's behavior needs to characterize its fine fraction

In coarse textured soils, the clay and silt fractions seem negligible if compared to sand fractions. In fact, it seems essential to consider those fractions if we want to understand the whole soil behavior. Because of their limited weight, measuring procedures with high sensitivity need to be developed (laser granulometer for particle size distribution, carbographe to estimate the content in organic matter, etc ...) to obtain accurate description.

3.2. Irreversibility of sandy soils compaction and hampered root development

In the literature, some soils are presented as having a natural tendency to compaction, *i.e.* compaction is observed even in the absence of mechanical stress. The physics of granular media clearly shows that a granular soil type will always move toward the more compact state under the influence of gravity. If there is not a sufficient volume of clay fraction, which can act on this stack over the swelling-shrinkage phenomena, no force can counteract gravity. In these circumstances it is therefore quite logical that the resilience of these soils is very low or even does not exist

In the case of degradation under the effect of a slumping, the rearrangement in closer packing occurs at the scale of individual grains. Therefore, the continuity of the solid phase becomes very high and continuity of the macropores is drastically decreasing with increasing tortuosity. This type of grain packing is a barrier almost impenetrable for roots that can no more find pores large enough to pass by. Thus, root development possibility is related to of grain rearrangement.

These structures also explain the failure of the mechanical tillage as they cannot act at the grain scale. Only biological activity is capable of acting on this scale and to rehabilitate the structure, *i.e.* to increase the soil porosity in a sustainable way.

From our analysis, it seems useful to look at the problems of hardsetting sandy soil with fresh eyes.

3.3. Slumping prevention

Prevention of slumping could be obtained through the limitation of infiltration or by strengthening the stability of the structure. Some techniques can be suggested and tested to limit infiltration (like mulching, spatial localization of infiltration along the furrows between ridges, etc ...). But these techniques must be technically feasible and economically acceptable by farmers. Therefore, they need to be tested in experimental fields and farmers' fields before being recommended for application at large scale.

Strengthening and stabilizing the soil structure could perhaps be obtained through a slight mechanical compaction immediately after tillage, a technical successfully tested by Meek et al. (1992) in a field experiment. Other alternative techniques may be tested on the model profile that we have developed in our work.

Conclusion

Nos résultats ont montré que le slumping peut s'observer sans que le sol soit saturé d'eau et sans qu'il y ait de l'eau libre (potentiel matriciel nul ou positif). Pour que le slumping intervienne il faut que deux conditions soient réunies :

- i) le sol doit être passé en régime capillaire ; à ce régime, les forces interfaciales développées par l'eau et qui assurent la cohésion dans les matériaux granulaires deviennent très faibles ; dans les conditions expérimentales de terrain et de laboratoire que nous avons, ce régime est atteint après un cumul des pluies de 20 mm ;
- ii) le régime capillaire doit être maintenu pendant un temps suffisant pour que les réarrangements locaux passent un seuil critique et qu'un effondrement soit perceptible à l'échelle macroscopique ; le temps nécessaire pour atteindre cet état critique n'a pas pu être établi dans le cadre de nos expérimentations.

Contrairement à l'hypothèse que nous avons émise après l'expérimentation de terrain, il ne semble pas que le slumping se propage de la surface vers la profondeur avec le front d'infiltration ; les mesures de laboratoire ont montré qu'il s'agit bien d'un effondrement dans l'ensemble des horizons de manière quasi-simultanée.

Tous les facteurs qui facilitent l'infiltration de l'eau, donc le passage puis le maintien du régime capillaire seront des facteurs aggravants du slumping. Ainsi, l'irrigation par submersion (flooding) est une technique qui entraîne une forte probabilité d'effondrement.

Jusqu'à présent, seuls les facteurs 'eau' avaient été mis en avant comme facteur explicatif du slumping. Notre expérimentation de laboratoire a montré que des facteurs 'sol' peuvent également intervenir. Une très grande dispersion granulométrique avec une fraction limoneuse minoritaire (environ 10% en masse) à l'intérieur d'une fraction de sable largement dominante est la situation où le slumping semble le plus probable. L'effet déstabilisant des limons avait déjà été observé dans les cas de fluidisation du sol au cours de tremblement de terre. Les horizons labourés ont une extension spatiale et des contraintes mécaniques plus faibles de plusieurs ordres de grandeur, mais des mécanismes similaires pourraient être en jeu. Il s'agit en particulier de nombre de contacts et de risque de déstabilisation des chaînes de force.

Pour limiter le slumping il faut donc jouer sur les deux facteurs ci-dessus : vitesse et intensité d'infiltration. Comme il n'est pas possible de jouer sur la distribution granulométrique (surtout pour retirer la fraction limon) il faut pouvoir renforcer les chaînes de forces afin de les rendre moins sensibles aux déstabilisations entraînées par les limons. Notre profil modèle permettra de tester ces technique.

Sur le plan conceptuel, la théorie des milieux granulaires qui prend en compte l'hétérogénéité du milieu donne un point de vue original qui permet d'expliquer des faits qui semblaient aléatoires ou difficiles à expliquer comme la faible résilience des sols sableux.

Les prochaines études devront donc s'attacher à quantifier et formaliser les relations que nous avons mises en évidence.

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Appendix 1 Detailed materials and methods used in this thesis

Part A. Field experiments

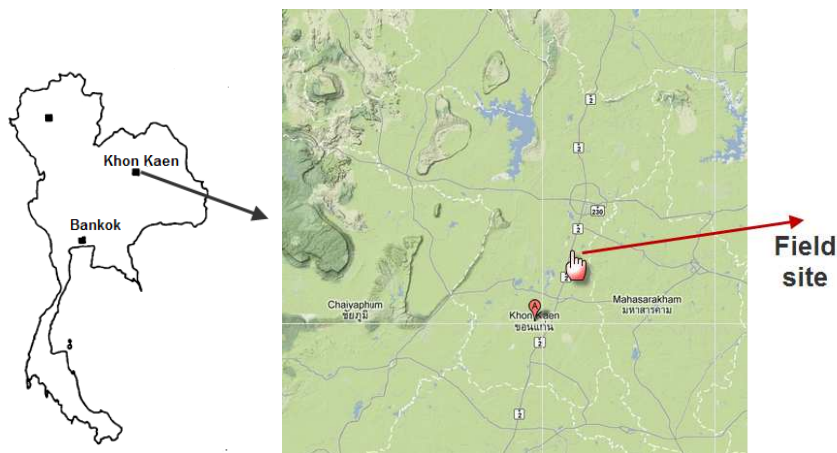


Figure 5-1 The site of the field experiment in Khon Kaen, Northeast of Thailand.

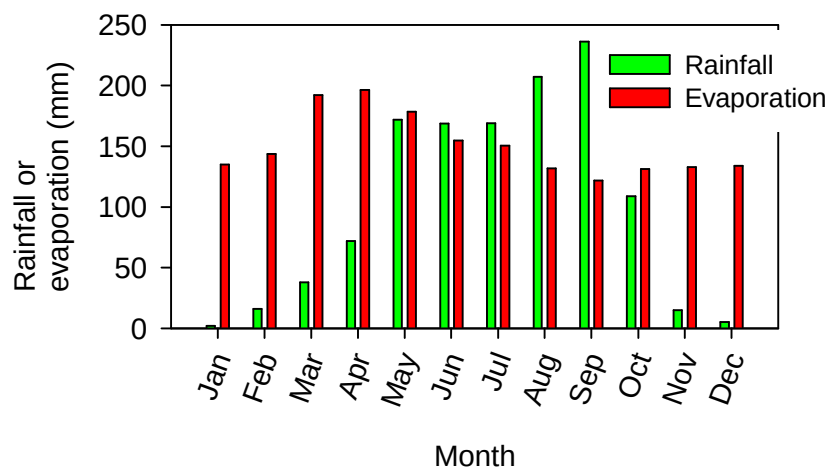


Figure 5-2 The average rainfall and evaporation in each month. These climatologically data are based on the period of 30 years (1971-2000). (Data provided from Siltacho Siwaporn, LDD Thailand).

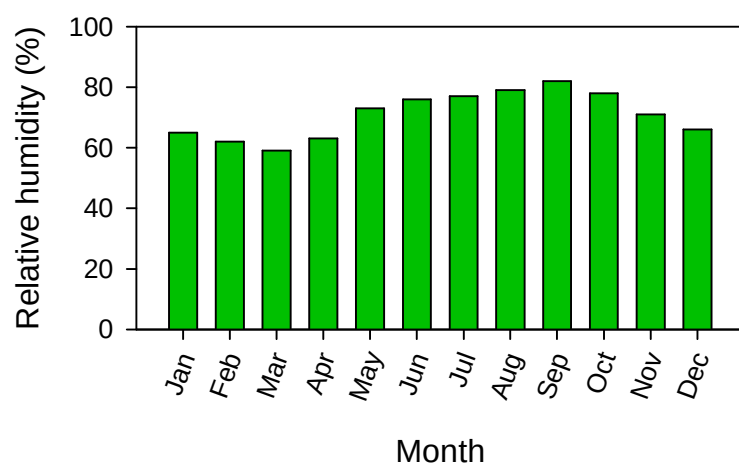


Figure 5-3 The relative humidity for period 30 years (1971-2000). (Data provided from Siltacho Siwaporn, LDD Thailand).



Figure 5-4 General view of the field before ploughing, and soil profile in the selected experiment field.

Table 5-1 Physico-chemical properties of the soil.

Size (μm)	Particle size distribution (g kg^{-1})							SOC g kg^{-1}	pH	CEC $\text{cmol}_+ \text{kg}^{-1}$
	Clay		Silt		Sand					
	2	2-20	20-50	50-100	100-200	200-500	500-2000			
Soil	28	39	64	328	434	105	2	2.07	4.99	<1

SOC, soil organic carbon
CEC, cation exchange capacity

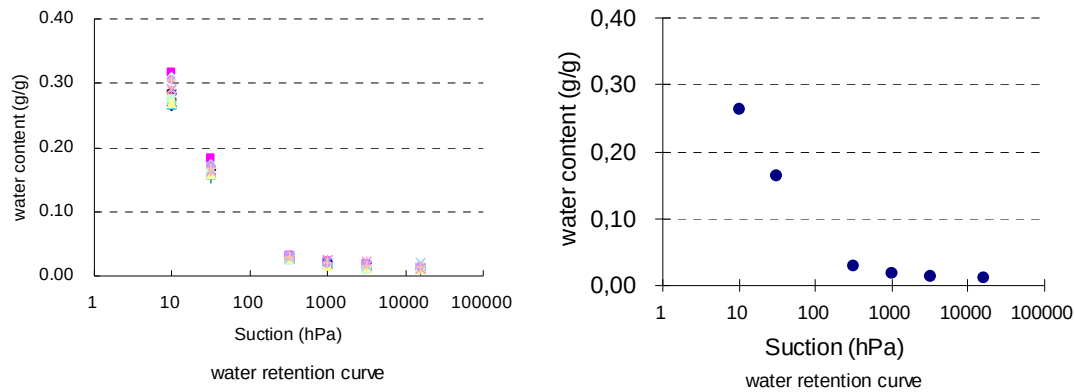


Figure 5-5 Water retention curve of the Thai soil. a) with all data of the four experiments plots. The bulk density ranged from 1.21 to 1.40 g cm⁻³. b) Use only one sample which has a bulk density at 1.25 g cm⁻³. Attention here the water content use g g⁻¹.

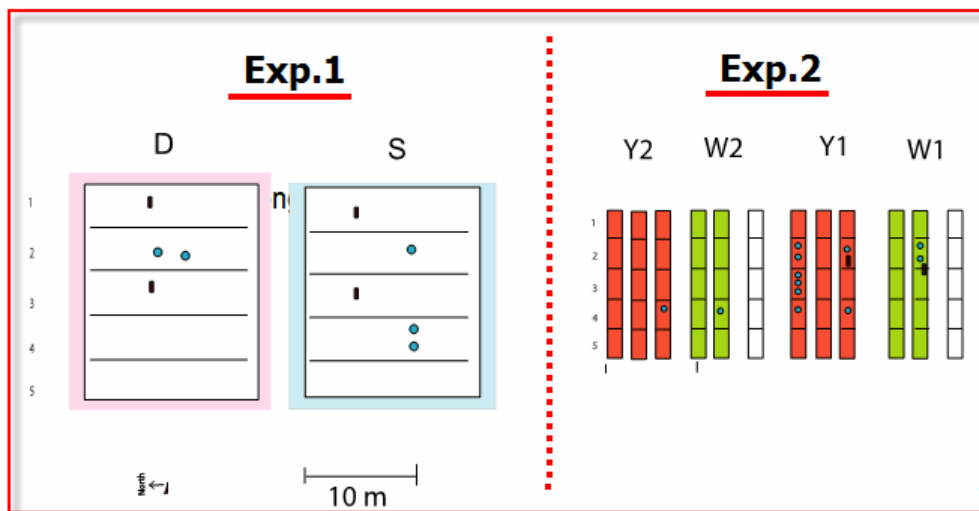


Figure 5-6 Field design, Experiments design. Exp.1 (D and S) was ploughed in 25 May 2007, Exp.2 (E and Y) was ploughed in 6 July 2007. The cycles were where Exp.3 flooding mimic in Ring were conducted, the dark dash showed where tensiometers were installed.



Figure 5-7 In Exp.2, plastic sheet were used to protect the soil from rainfall, therefore, a dry (Y) initial water content was obtained when ploughing.

Field preparation, ploughing, making ridge and furrow



Figure 5-8 Local farmer usually prepare ridges and furrows.



Figure 5-9 Field experiment preparation. a) taking residues out, b) the tractor was used for disc ploughing, c) tractor ploughing, d) making ridge and furrow

Measurement

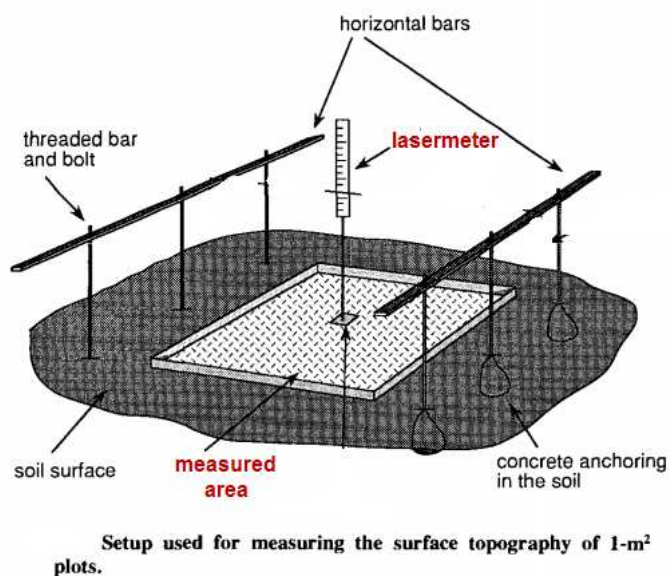


Figure 5-10 Set up for Exp.1 to measure the surface topography and soil height of a 1 m² plot.

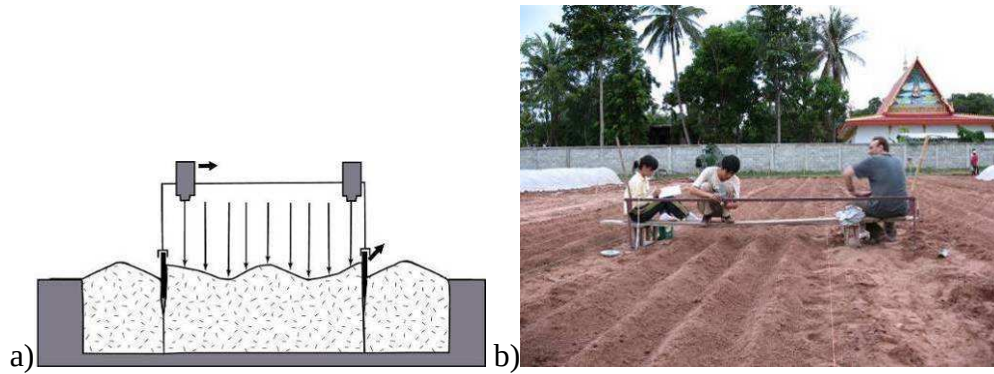


Figure 5-11 Measuring soil surface level by lasermeter in Exp.2. a) schematic figure shows Legs were inserted deep inside the soil 60 cm, which had a stable level, b) an “arm line” was used to measure the soil surface level in Exp.2. Notice during measurement, a “wood bridge” was used to prevent disturbing the soil between the rows.

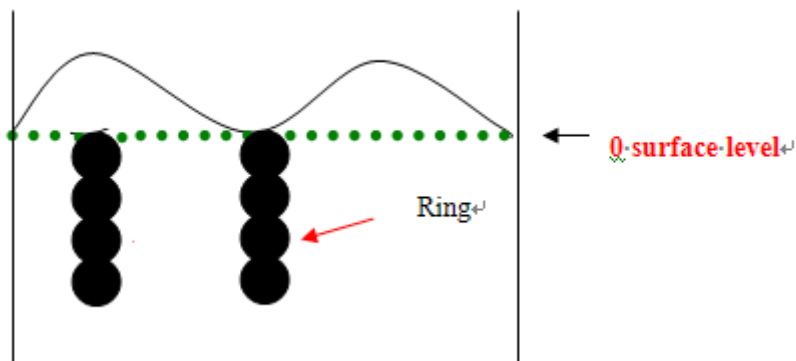


Figure 5-12 Using rings to take soil samples for bulk density and water content at different depth under ridge and furrow. The surface of furrow was used as a reference as 0 level (both for furrow and for ridge).



Figure 5-13 a) Rain gauge was installed in the field to measure rainfall. b) tensiometers were installed to measure soil water potential. Notice when we were working, a “wood bridge” was used to prevent disturbing the soil.

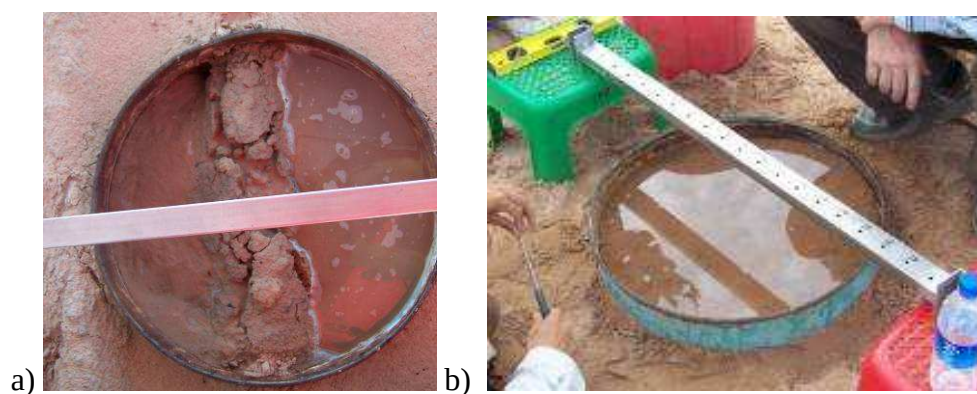


Figure 5-14 Exp.3, the flooding experiment to mimic rainfall: a) without reploughing, the surface with ridge and furrow made water distributed not evenly. Notice there was a hole in the left. b) with reploughing, water was added inside the ring. An “arm” was used to measure the soil surface level from the top.

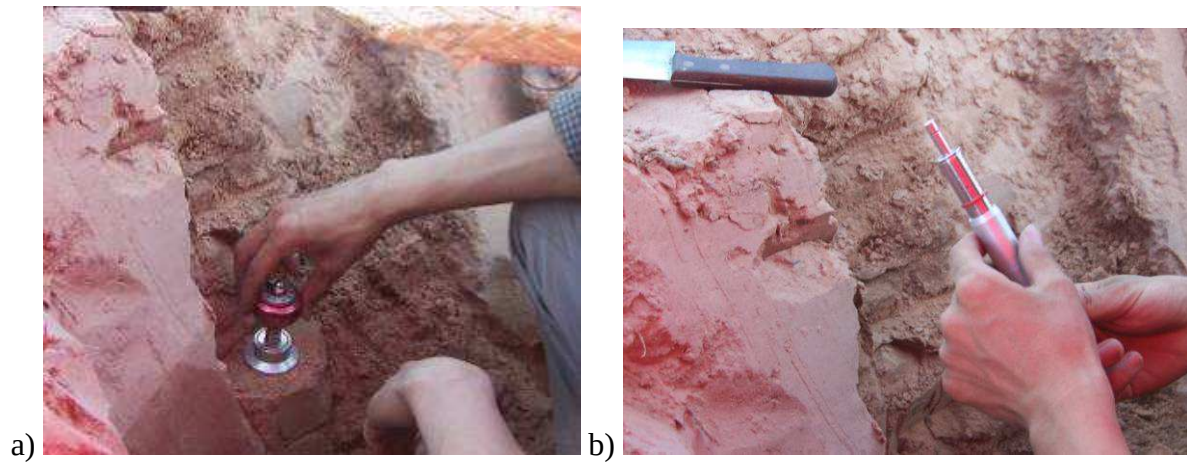


Figure 5-15 Mechanical characteristics measurement. a) measuring shear strength by scissometer, b) measuring resistance to penetration by pocket penetrometer, c) measuring resistance to penetration by datalogger penetrometer.

Part B. Laboratory experiments

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1.1. Preparation of cylinders

1.1.1. The material used: Fontainebleau sand, Thai sand, and Thai soil

Three types of materials were used in our experiments: Fontainebleau sand, Thai sand, and Thai soil.

The Thai soil was from the same field in Khon Kaen, Northeast Thailand, where we have conducted the field experiment. The sand was extracted from Thai soil to get out of clay and organic matter. A sand fraction was extracted by wet sieving at 50 μm after organic matter destruction with H_2O_2 and dispersion with sodium hexametaphosphate. Despite it still has clay, for the convenience we will call it “Thai sand”.

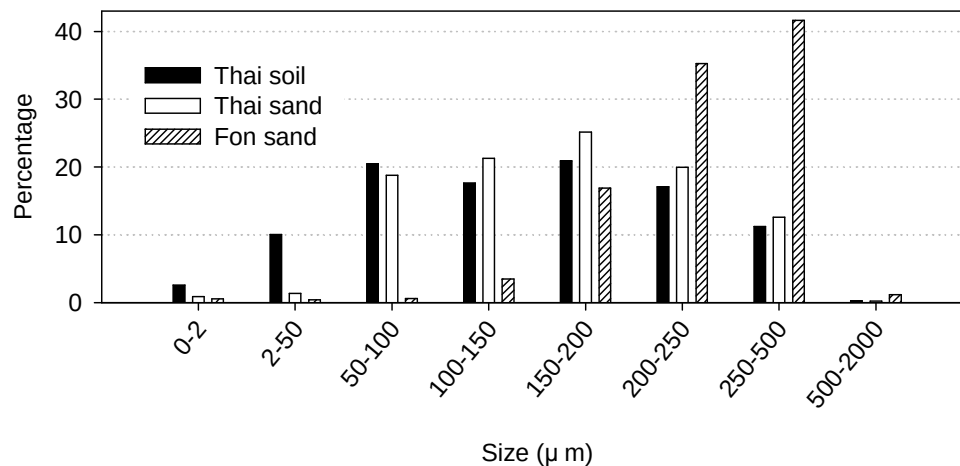


Figure 5-16 Size distributions of Thai soil, Thai sand, and Fontainebleau sand.

1.1.2. Filling by sieve or funnel (point or line filling)

The objectives were: 1) to estimate the influence of different filling methods and columns size on the initial filling structures; 2) to investigate whether we can prepare a homogenous structured soil with standardized initial bulk density. If we can succeed, we can easily reproduce the procedure, and more easily interpret the processes.

Two ways are common when filling sand into cylinders: point filling or line filling. Researches in physical granular material has shown that these two methods produce different distribution of force.

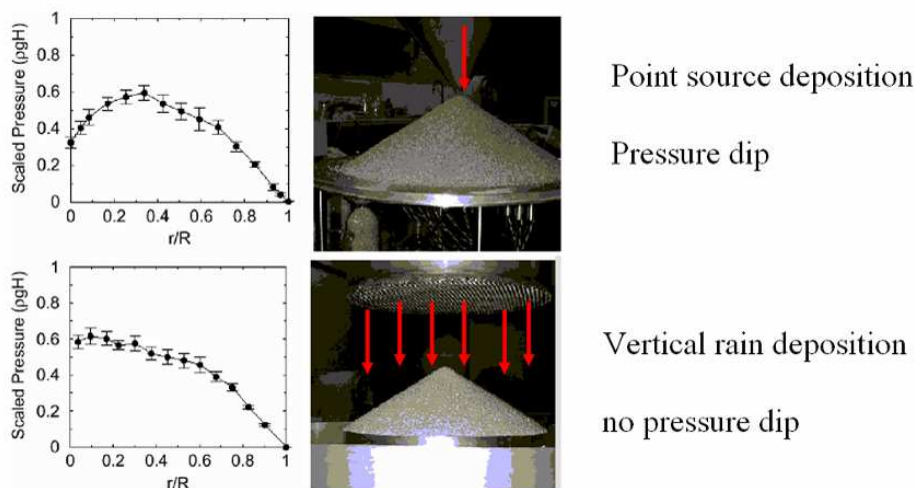


Figure 5-17 The stress distribution was effected by two different filling methods. The figures are plotted as dimensionless normal stress profiles, $P/\rho gh$, vs dimensionless radial distance r/R , beneath conical piles of granular materials of height H and radius R . The construction techniques are illustrated by the accompanying photographs (Vanel *et al.*, 1999).

In our experiments, three methods of filling were used (Figure 5-18):

- Filling directly without anything;
- Point source deposit by funnel;
- Rain deposit by sieves. Different sizes of sieves were used (0.56, 0.71, 1, 2, 3, 5, and 10 mm).



Figure 5-18 Different ways to fill the columns: a) point source deposit with funnel, b) rain deposit with sieve, different sizes of sieves were used.

Fontainebleau sand was used here. Sand was filled into the column by different ways until the column was full, and then the surface was made flat by moving a stick without pressing. In the end the sand was weighted. Since the volume of the column were always the same, bulk density can be calculate by $Bd = m/v$ (Figure 5-19).

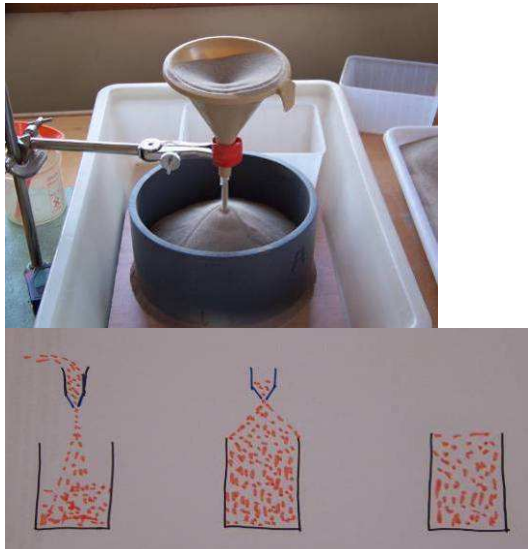


Figure 5-19 The way to fill the column. A funnel or sieve was used, the sand was filled until the cylinder was full, then the surface was cut flat by removing the surplus sand.

1.1.3. The stability of dry sand column: vibrated by tapping

The physicists have been working a lot on dry granular materials (as reviewed in the book of (Duran, 1999). Since the sand particles in sandy soils fell in the range of granular materials, we can borrow the knowledge from them.

Physicists of granular material showed that it is not only the ratio of solid/pore volume is important, but also the way the material is piles up (Vanel *et al.*, 1999). With similar bulk density, it is possible to have very different behaviors. This is because the ‘history’ of piling is important and creates different force network and different pressure at the bottom of the pile. Many other researches also done on the stress response (Serero *et al.*, 2001; Atman *et al.*, 2005).

The objective is to check the stability of sand column, and whether we can get a certain stable structure by vibration. By checking the resistance to disturbance, we can know during doing experiment if any movement or disturbance will affect the initial structure.

Filling

Three kind of filling methods were the same as described before.

To test the kinetic, a larger column was used (diameter $d=18$ cm, height $h=10$ cm). Since the sieve is smaller than the column, they were moved around when filling.

Vibration by tapping

A wood stick was used to tap the wall of the column, then the column was shake gently to be able to get a flat surface, the height was measured at 5 replicates point, mean value was used to calculate the volume as $V = \text{Surface area} \times \text{height}$. The wet sand was dried in oven (105°C) for 24h to measure the dry weight.

A wood stick was used to tap the wall of the column, but as the sand was wet, we could not obtain a flat surface as with dry sand. Besides, the sand was no longer touched the column wall, there was some void space between the sand and the column wall. Therefore, it was not possible to calculate volume. This method can not be used for wet sand.

1.1.4. The preparation of wet sand (tumbler rotating method)

The typical way is to use the mixture method to prepare the wet sand (Kawamoto *et al.*, 2004). The sand and water was mixed together and then they were kept some time (for example 24 h) to let the water mix with the sand more homogenously.

A research (Cook *et al.*, 1997) used wet sand (0.25 volumetric water content) to prepare columns, (49 mm*300 mm), a rubber plunger was used to pack the sand to each 20 mm layer. They got a 1.48, 1.55 and 1.60 Mg m^{-3} bulk densities. It showed that it was difficult to get a real homogenous profile. When they prepared to pack a constant bulk density using the same tamping style, the penetration resistance profiles of the columns showed great variation with depth. It could range from 0.5 to 3.5 MPa in a density value of 1.60 g cm^{-3} . On the other hand, if they want achieve uniform penetration resistance, a greater bulk density was required at both the top and the bottom of the column. To compare, if the columns are packed with moist loamy soil which is more elastoplastic, it is much easier to obtain a uniform penetration resistance with depth by packing to a uniform bulk density. The author explained that in practice, this proved to be difficult because the sand layers were not fully compressed.

The wetting rate and the initial soil water content have been shown to control the degree of aggregate breakdown, so it is perhaps will also have effect on sandy soils even without aggregates (Chan and Mullins, 1994; Bresson and Moran, 2004).

The mixing method

Material: Fontainebleau sand

Depending on the necessary water content, the weight of water and sand was calculated. Add water into the sand, they were mixed manually with a tool. They were then moved into a

plastic bag and kept more than 12 hours in dark place. Replication samples were taken from the same bag to measure the water content.

The tumbler method

The sand from Thailand was used. Designed water content was 0.03, 0.10 and 0.15 g g⁻¹ respectively.

Depending on the necessary water content, the weight of water and sand was calculated. The sand was put inside the tumbler, and the water was adding into the sand. They were totally covered by plastic sheet and adhesive tape to prevent water evaporation. The tumbler was put into a machine to turn upside for 4-8 hours (Figure 5-20). In the end, the Replication samples were taken from the tumbler to measure the water content.

To mimic the slumping process of cultivated soil in field, wet sand will be used in the first step. To get homogenous wet sand, the water was added into the sand, and they were mixed manually. This method produced some aggregates by mixing. A standard method was proposed by using tumbler to mix them. It was aimed to produce sand avalanche inside the tumbler when rotating without producing sand aggregates. After testing, it was found that the tumbler could have different practical problems that will limit its usage.

The objective is to explore if it is convenient to use tumbler by comparing the data of direct mixing method and tumbler method.

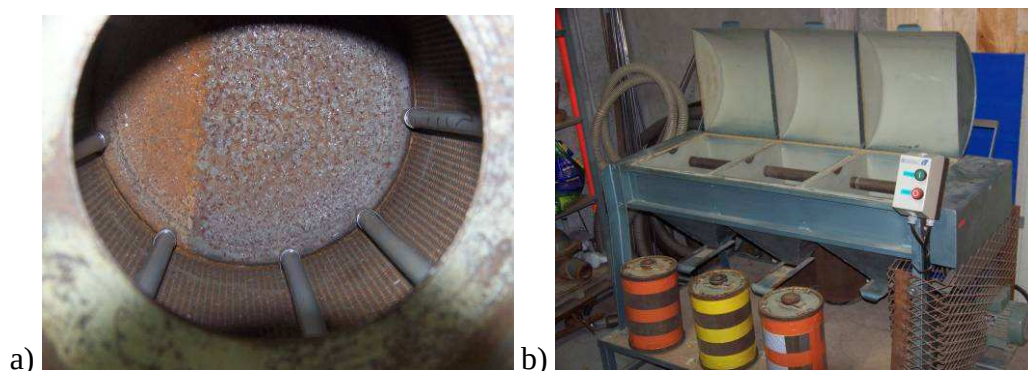


Figure 5-20 Three tumblers in INRA were used to mix sand with water. a) Inside the tumbler, eight sticks were installed, b) the machine can move the tumbler.



Figure 5-21 a) Wet sand stuck to the wall of tumbler even during rotating. b) Some “sand balls” were produced after tumbler rotating. c) At water content 1%, some aggregate was created.

1.1.5. Wetting by capillary force

Capillary rise wetting conditions were used in studies of slumping in hardsetting soils (Bresson and Moran, 1995). Flooding wetting conditions were used in studies of slumping in hardsetting soils (Mullins *et al.*, 1992; Gusli *et al.*, 1994a, b). Nevertheless, in these studies, only wetting of initially air dry soil material has been examined.

Slumping results from processes similar to those involved in crusting (Mullins *et al.*, 1990b), except that overburden pressure is expected to dominate rather than rainfall kinetic energy (Bresson and Moran, 1995, 2004)

Wet sand column affected by capillary force

Water suction table was used. Since the structure is very fragile, so we filled the sand in-situ. A column was put on the suction table, different water content wet sand was filled. Then a given value of suction was used, from $h=0$, -1 , -10 , -20 , -50 hPa.



Figure 5-22 Wet sand column affected by capillary force. a) water suction table, b) wet sand after 2 days in suction table with $h=0$, c) dry sand can not be totally wetted by capillary force at $h= -1$ hPa.

1.1.6. Preparation cylinder with wet sand, its stability

Summary

To prepare wet sand column, we mixed dry sand with water, and filled them inside column. To test their stability, the wet sand column was compacted by wood with hand, or wetted by capillary rise on water suction table at different potentials. The bulk density was very similar with water content from 1% to 10 %. All of them got a very loose structure at the bulk density of 1.0 g cm^{-3} , but it was too loose to mimic the ploughed soil layer we obtained in the field experiment. By tapping bulk density could reached higher value such as 1.5 g cm^{-3} , which was too high to mimic the ploughed soil layer we obtained in the field experiment.

Introduction

To mimic the field experiment, we need 1) to prepare wet sand with homogenous water content; and 2) homogenous structure with the preparation can be repeatable.

Objective

To estimate the ways of getting a structure with different bulk density and their repeatability.

Material and methods

Dry sand was mixed with given amount of water to get wet sand, then they were tried in two ways: 1) they were filled inside the column with a sieve, bulk density then be calculated as the minimum value; 2) tapping and hitting was used to see if a homogenous higher value could be obtained;

Sand

The same Fontainebleau sand was used.

Wet sand preparation

To get a certain amount of water, the sand weight was calculated. They were put in balance, and water was sprayed into the sand until the designed value was reached. They were mixed as thoroughly as possible by hand. They were kept in dark place for at least 15 hours before using.

During filling column, wet sand samples were taken for measuring water content. Three replicates were taken in the different time of filling (beginning, middle, and end).

Filling methods for column

When the sand was wet, it has some aggregates created by mixing. Then they could not pass through the funnel, and they could not pass the sieve smaller than 20 mm. By filling directly, they could have some kinetic energy. Therefore, a sieve with 20 mm holes was used during the experiments.

The wet sand was filled into the column through a 20 mm size of sieve until the column was full. Then the surface of the column was made flat by taking off the surplus sand. In the end, the sand was weighted. The dry sand can be calculated according to the water content value.

1.1.7. Direct filling: the effect of overburden pressure on bulk density

Some researches have mentioned the role of overburden pressure in the slumping processes (Mullins *et al.*, 1990b; Mullins *et al.*, 1992; Bresson and Moran, 2004). But unfortunately, we can still not directly separate the role of overburden pressure from the external force (such as tractor compaction).

Objective

To test how overburden pressure can affect initial bulk density. Use sand from Thailand.

Thai sand, with a distribution described in Exp.1. It was wetted by mixing manually, and the sand was kept more than 12h before using.



Figure 5-23 Cylinders were connected by adhesive tape. An iron plate was used to penetrate each layers.

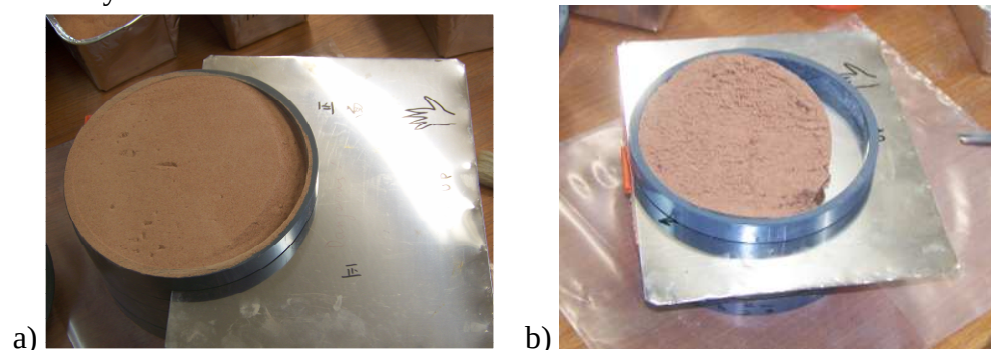


Figure 5-24 The frictions make the sand surface not flat after cutting due to friction. a) Dry sand; b) 5% wet sand.



Figure 5-25 A 2 cm-hole sieve was used to let the wet sand pass by. It produced a loose structure.

Columns with 2 cm height were connected together until 20 cm by adhesive tape. The internal diameter is 18.4 cm. A 20 cm-diameter sieve that has 2 cm holes was used to let the wet sand pass through. When the aggregate of wet sand and soil could not pass the sieve completely by its own gravity, a force was used to push the sand to pass through the sieve. When the column is full of sand, a flat ruler was used to take out the superfluous sand to get a flat surface.

Filling

The sand was filled into columns with different height by a sieve (2 cm). A 6, 10, and 20 cm high column was used respectively. To check if the different layer is homogenous, two 5 cm was banded together to get a 10 cm height column. After filled with wet sand, a very thin aluminum plate was used to separate the two layers.

Different layer measurement

After the sand is filled, the tape was taken out little by little. An iron plate was used to cut from the common boundary of different layer. One must cut the two layers carefully without disturbing other layers. The plate must be thin enough to penetrate the boundary easily. It also must be resistant enough to separate the boundary with a flat shape; otherwise, the upper layer soil can lead to a non-flat shape due to the own pressure. The soil in each 2-cm columns was weighted to calculate dry weight. The final water content and bulk density can be calculated.

1.2. Thai Soil experiment

The objective of these experiments was to investigate the slumping characters of a cylinder under different factors: 1) rainfall intensity, 2) suction of water table, and 3) rainfall amount.

Dry soil preparation

Original soil from the same field of Thailand was taken from 0-15 cm depth. They were oven-dried before import to the lab. All the soil passed through 2 mm sieve. The visible residue material such as root was taken out. As it was observed that the clay from the soil could leached out after rainfall through water suction table, which means the clay decreased. Therefore, the soil was used only once under rainfall simulator. **New soil was used for each cylinder.**

Wet soil preparation

Each time 3000.0 g dry soil was mixed with 300.0 g water to give a water content value with 0.10 g g^{-1} . After mixing thoroughly, they were stored in closed plastic bags and were stored in cold room at 4°C before use. Water content was checked when the wet soil was used. The soils were thoroughly mixed once more before use

Soil cylinder preparation

A set of 2 cm height transparent PVC cylinder were connected with adhesive tape. An iron plate was put in bottom to support the soil and prevent the soil moisture evaporate. The final cylinder was 20 cm in height and 18.8 cm in diameter.

To prepare a cylinder with bulk density value 1.25 g cm^{-3} , 1520.0 g wet soil with water content value of 0.10 g g^{-1} (1387.3 g dry soil) were added. Then a piston was used to push the soil in 4 cm height. In the end, plastic film was used to cover the entire cylinder to prevent water evaporate before rainfall application. During the rainfall, this plastic file was kept to prevent the water and soil goes out from the connection area. The soil height was counted from the top in this experiment, i.e., the top is considered as 0 cm.

The vertical water movement between two layers can be disturbed if the interaction layer is too smooth. To get very good connection between each two layers, a knife was used to dig some small holes (mimic ploughing).

For experiments on 60 hPa and 90 hPa, white marker was used to observe the profile dynamic. At each layer, white glass beads with diameter 150-250 μm were used as markers. To prevent the marker leach throw the holes in the border, the border area was made a little bit harder with figures to had good contact. The markers were spread in the border. Even after rainfall, it still clear to see through the transparent cylinder. White sand has been tried, but when it becomes wet, the color is not so clearly different from the wet soil.

The soil cylinder was kept 12h to get equilibrium. Like the later figure shows, the total water potential goes similar, while the matric potential increase in the bottom (more wet), which means the water moves from the top to the bottom.

Simulated rainfall

The cylinder was put on a water table, which can apply a fixed suction. 20 hPa, 60 hPa, and 90 hPa suction was used respectively.

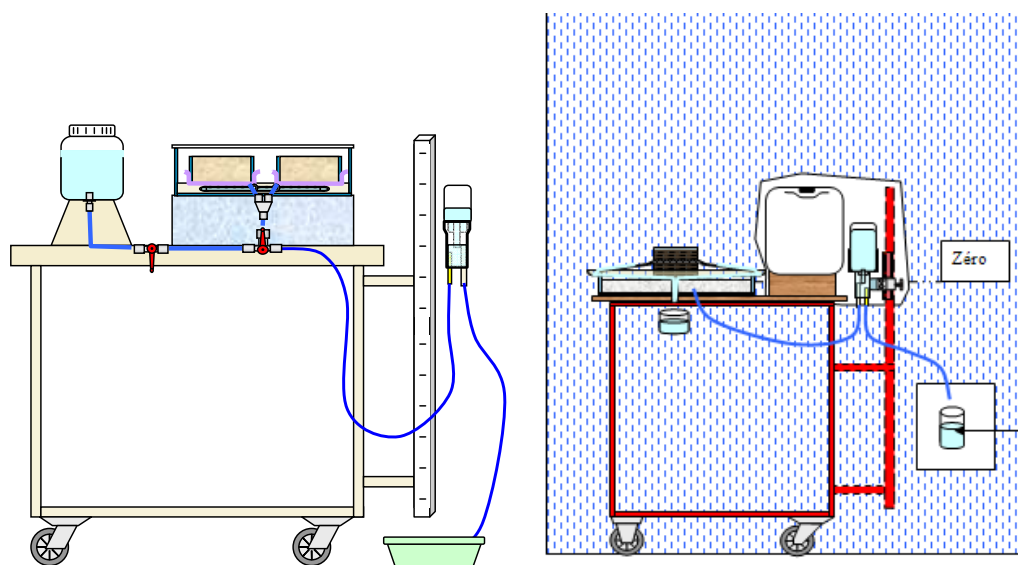


Figure 5-26 Schematic shows the cylinder on suction table.

A rainfall simulator (INRA Orleans) was used to produce rainfall with different intensity. The water EC (electrical resistance) was between 25 to 50 μs . The water suction table was set at one suction (20, 60 or 90 hPa). As the rainfall intensity under the simulator varied at different position, so a fixed position was used for different replicate. Two cups were put around the cylinder to control the rainfall intensity. Because the water from the suction table can wet the soil inside the cylinder by capillary force, the plate was taken out only around two

minutes before the beginning of rainfall. To prevent the rainfall accumulate on the water suction table and saturate the soil cylinder from the bottom, plastic was used around the cylinder to prevent the rain fall down on the surface of suction table. To get the same amount of rainfall, different range of time was applied depend on the rainfall intensity. That's to say, 260 minutes rainfall for 20 mm h⁻¹ intensity, 130 minutes rainfall for 40 mm h⁻¹ intensity, 40 minutes rainfall for 130 mm h⁻¹ intensity.

The rainfall simulator, similar to the one described in Foster et al. (1979), was equipped with oscillating nozzles (Spraying Systems Co., Wheaton, Illinois, USA. Veejet type 6550). The water was used from de-ionized water production unit. The distance between the simulator and the top of the soil cylinder sample was 4.5 m (Darboux and Le Bissonnais, 2007).

1.3. Thai Sand experiment

The preparation and measurement was the same as in soil experiment (see previous section 1.2), except the procedure of simulated rainfall was different.

Rainfall simulation with different intensity

The cylinder was put on a water suction table to apply a fixed suction at the bottom of the cylinder. The water suction table was set at pressure of -60 hPa. To avoid variations under the simulator, a fixed position for cylinders was used for different replicates of the same rainfall intensity. Two cups were put around the cylinder to control the rainfall intensity.

Because the water from the suction table can wet the sand inside the cylinder by capillary force, the plate was taken out only around two minutes before the beginning of rainfall. To prevent the rainfall accumulate on the water suction table and saturate the sand cylinder from the bottom, plastic sheet was used around the cylinder to prevent the rain fall down on the surface of suction table. To get the same amount of rainfall for each rainfall event, different range of time was applied depend on the rainfall intensity. Different rainfall intensities were used successively: 40, 60, 103 and 120 mm h⁻¹.

Cylinder flooding and saturation

Sand cylinder was also wetted using different procedures than rainfall simulation. Flooding was made according to the following procedure: potential in the water table was set at -60 hPa and water added by steps of 22 mm water (610.4 g water for this cylinder with diameter of 18.8 cm). As soon as the free water at surface was totally infiltrated, another 22 mm water were added. Totally 198 mm water was added.

1.4. Measurement for simulated rainfall

1.4.1. Average bulk density by height

The average bulk density in cylinder was measured during each treatment of rainfall events, flooding and saturation. Average bulk density of the cylinder can be calculated by dividing the weight of sand by its volume. The diameter of the cylinder was constant, and the height of sand surface inside the cylinder was recorded using a ruler. The error is one mm. The measurement was made every few minutes.

The maximum bulk density of sand was estimated in saturated and dry conditions respectively. First, for saturated conditions, the sand was saturated by immersion in water. A cylinder (6.4 cm in diameter, 10.5 cm in height) with initial bulk density of 1.25 g cm^{-3} was prepared, using sand with initial water content 0.10 g g^{-1} . Then the cylinder was put on a plastic box, water was added to rise from the bottom until the top. No vibration was made during the wetting process. The height after collapsing was measured to calculate the final bulk density. Second, for dry conditions, the oven-dry sand (24h at 105°C) was filled into an aluminum cylinder (5.8 cm in diameter, 4.8 cm in height). Then the cylinder was vibrated until a stable level reached. No additional sand was added, the final height was measured to calculate the bulk density.

1.4.2. Soil water content measurement by TDR

Volumetric water content was measured with a Time Domain Reflection (TDR) system (Type 6510X1, Sand Moisture Equipment Corp., USA). The 20-cm long sensor being too long for our cylinder, we used an 8-cm long sensor. The TDR probe was made with 3 elementary sticks ($\varnothing = 3 \text{ mm}$ each and 8 cm long).

As the sand surface will decrease few centimeter during the rainfall, so the sensor was inserted 10-11 cm below the sand surface. Water content recording was made manually at intervals of approximately 2 minutes in the beginning to 20 minutes in the middle. The gravimetric water content was calculated from volumetric water content using the bulk density values.

Water content was determined in a flexible time step with TDR probes. They were measured in a variable time step, depending on the speed of slumping.

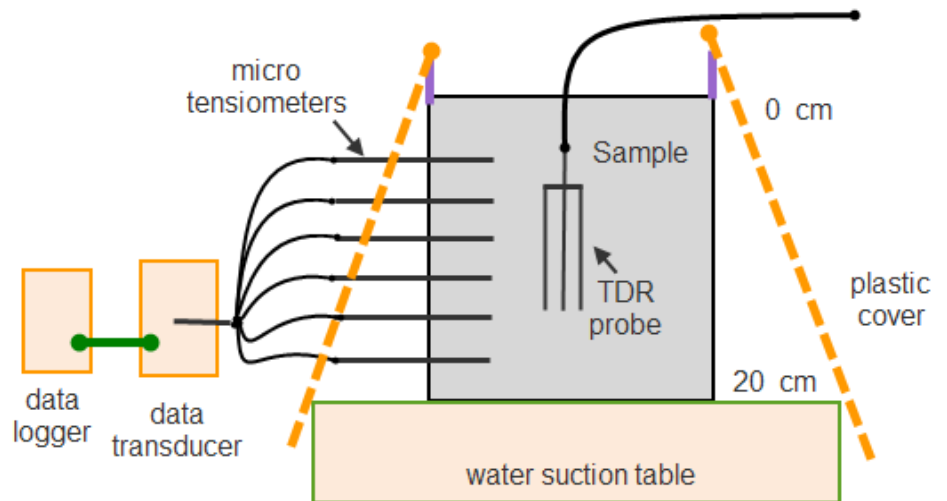


Figure 5-27 Schematic presentation of the experimental devices. To prevent the rainfall accumulate on the water suction table and saturate the sand cylinder from the bottom, plastic sheet was used around the cylinder to prevent the rain fall down on the surface of suction table. TDR and micro tensiometers were used to measure soil moisture and water matric potential respectively. A maximum of six tensiometers were installed, inserted in a hole made in the middle of individual cylinders. To prevent the rain splash outside the cylinder, a 5 cm higher cylinder was added at the top of the cylinders.

1.4.3. Water matric potential by micro tensiometer



Figure 5-28 Micro-tensiometers were inserted in different layers (1, 5, 9, 13, 17 cm counted from the bottom).

Tensiometers record the matric component of the water potential ψ , which is negative in unsaturated soil. Here we also use the pore water suction, h , where $h = -\psi$.

Once the cylinder fully filled, miniature tensiometers (with porous ceramic tips of 2 mm in diameter) (SDEC France company) were introduced in the cylinder at 1, 5, 9, 13 and 17 cm from the cylinder bottom. They were inserted through the wall of the cylinder through holes of 2 mm in diameter. These were filled with de-aired water and were connected to pressure transducers using rigid plastic tubing. The pressure transducers were individually calibrated. The matric potential was recorded at intervals of one minute during every rainfall experiment

by using a data logger. The tensiometer/pressure transducer/data logging system was known to be extremely reliable because it had been used for several years for other soil physical measurement (Dexter et al., 2010).

1.4.4. Bulk density in each layer by cutting and marker method



Figure 5-29 When cutting, a “spirit level” horizontal ruler was used to check if the cutting is flat.

A fine ring of white glass beads ($\varnothing = 150\text{-}250\ \mu\text{m}$) enabling to observe the collapse process through the transparent PVC cylinder wall was also inserted between each ring.



Figure 5-30 Fill a certain amount of soil in each 2 or 4 cm cylinder.



Figure 5-31 Push by a plate until the certain height.



Figure 5-32 Use a plat to plush, make the surface flat.



Figure 5-33 There can be some holes in the border, need to be filled carefully with finger. Otherwise, the white marker (glass beads) can leach from these holes.



Figure 5-34 Apply white marker around the border of the cylinder.



Figure 5-35 Between each two layers, the soil surface was reploughed a little bit, in order to increase the water flow, and prevent the “border effect” (water accumulate in the surface).



Figure 5-36 A final prepared cylinder, with marker in every two centimeter layer.

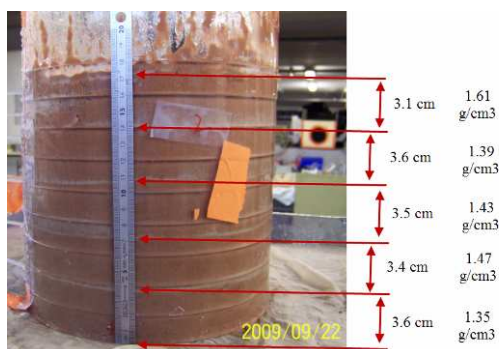


Figure 5-37 Bulk density can be calculated by measuring the corresponding height of each layer after rainfall.

Appendix 2 Detailed results of field and laboratory experiments

Part A. Field experiments

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Experiment 1

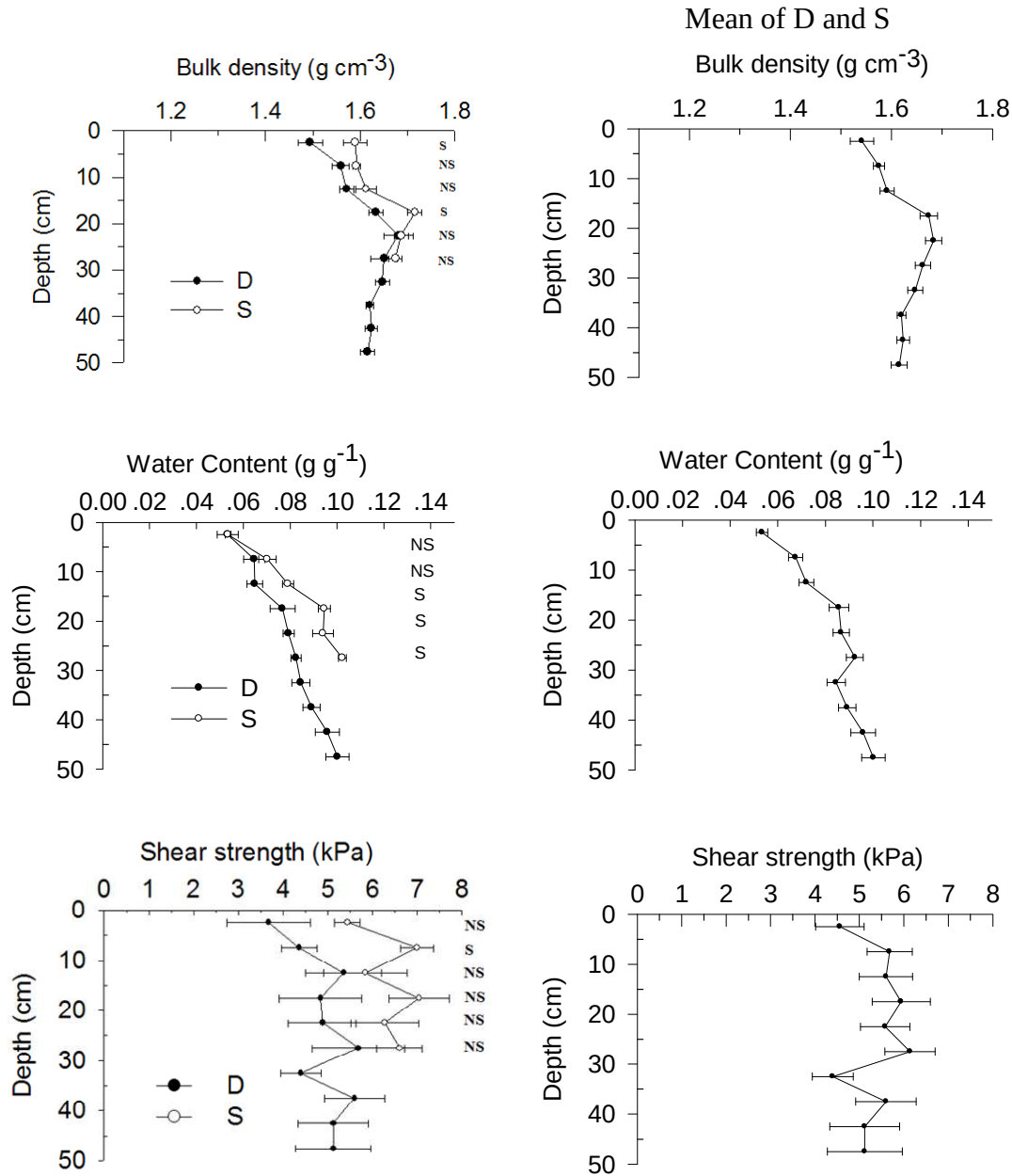


Figure 6-1 Initial (1 day before ploughing) soil characteristics in Exp.1: (a) bulk density, (b) water content, (c) shear strength (measured by scissometer). Left: (D) deep ploughing (40 cm) and (S) shallow ploughing (20 cm) ($n=5$); Right: mean value of D and S ($n=10$). Error bars indicate standard error of mean (SEM). NS indicates there was no significantly difference between D and S in the same depth ($p<0.05$). All of the factors were measured in the same pit.

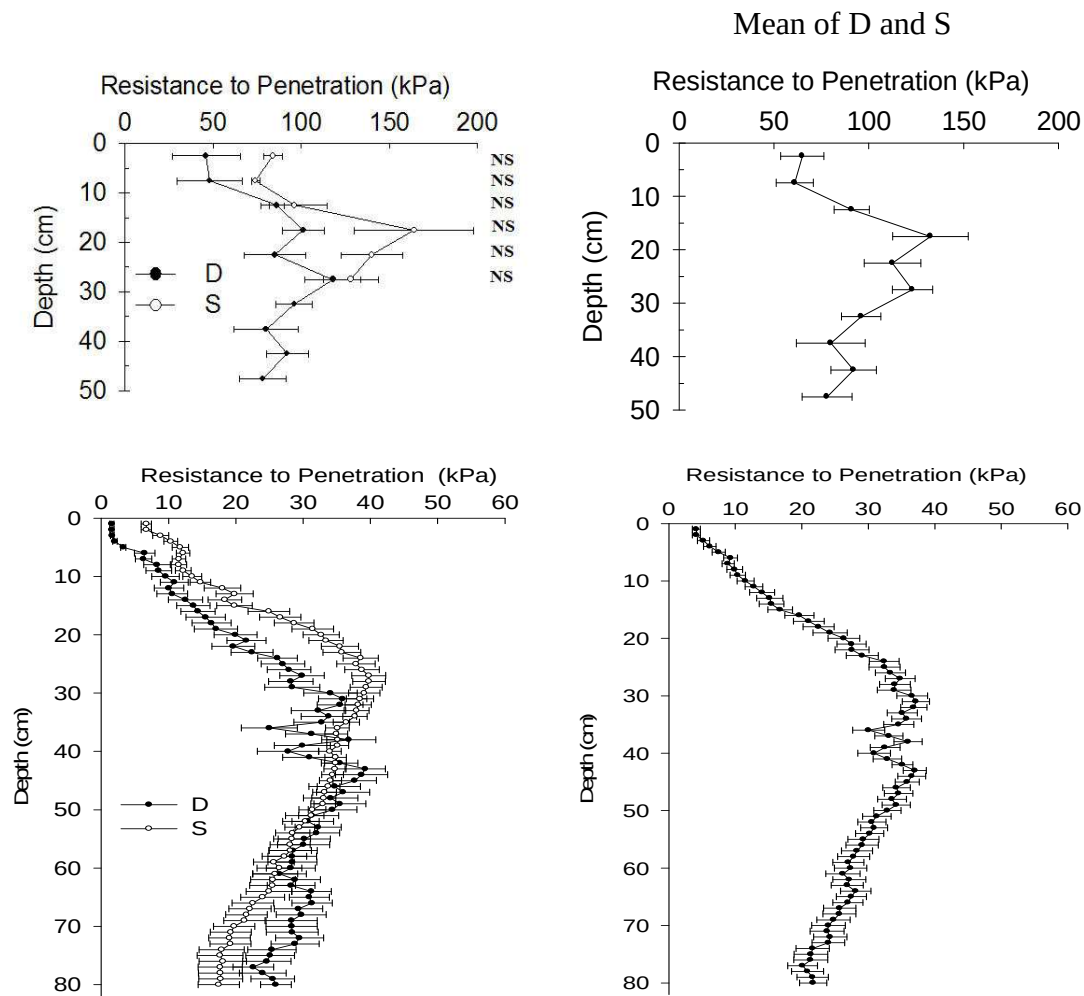


Figure 6-2 Initial (1 day before ploughing) resistance to penetration in Exp.1: (a) by Pocket penetrometer (n=5) measured from the pit, (b) by Penetrometer with data logger measured from the soil surface until 80 cm depth. (n=15). Left: (D) deep ploughing (40 cm) and (S) shallow ploughing (20 cm); Right: mean value of D and S (n=30). Error bars indicate standard error of mean (SEM).

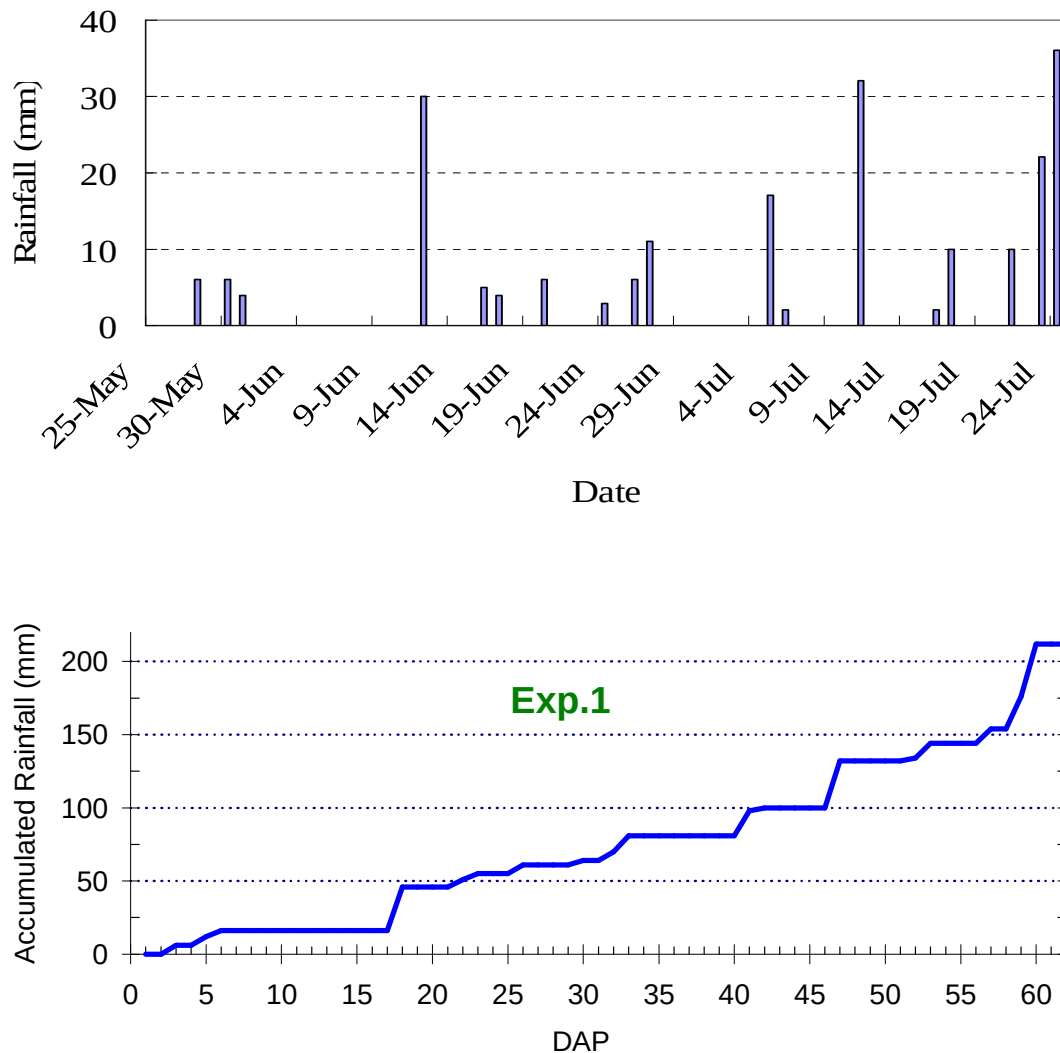
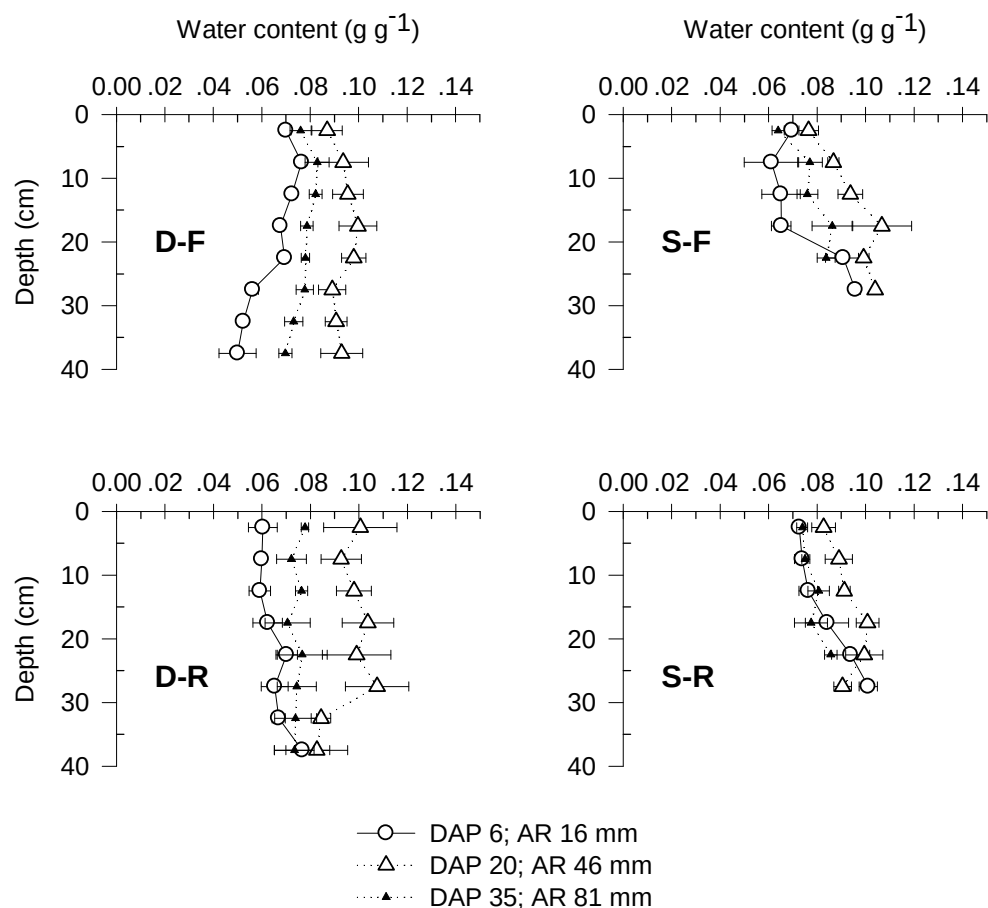


Figure 6-3 Rainfall distributions for Exp.1 (day 0 to day 60). Top: daily rainfall (mm). Arrows indicate rainfall events after which soil characteristics (bulk density etc) were measured. Bottom: accumulated rainfall for Exp. 1 (day 0 to day 60). DAP means days after ploughing.

Table 6-1 Detailed Rainfall events after ploughing for Experiment 1

DAP (Day after ploughing)	Time	Rainfall (mm)	Accumulated rainfall (mm)
3	20070528	6	6
5	20070530	6	12
6	20070531	4	16
18	20070612	30	46
22	20070616	5	51
23	20070617	4	55
26	20070620	6	61
30	20070624	3	64
32	20070626	6	70
33	20070627	11	81
41	20070705	17	98
42	20070706	2	100
47	20070711	32	132
52	20070716	2	134
53	20070717	10	144
57	20070721	10	154
59	20070723	22	176
60	20070724	36	212

a



b

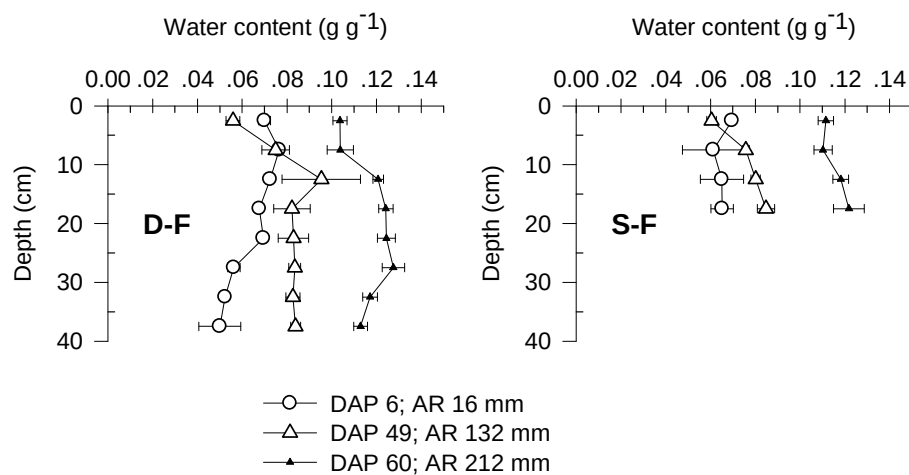


Figure 6-4 In Exp. 1, water content evolution at different time after major rainfall under Furrow (F) and Ridge (R): (a) is DAP after two small rainfall, (b) is DAP after two major rainfall. Left is Deep ploughing 40 cm (D) and right is Shallow ploughing 20 cm (S) ($n=3$). Error bar indicates standard error of mean (SEM). DAP means day after ploughing in Exp.1, AR means accumulated rainfall from day of ploughing.

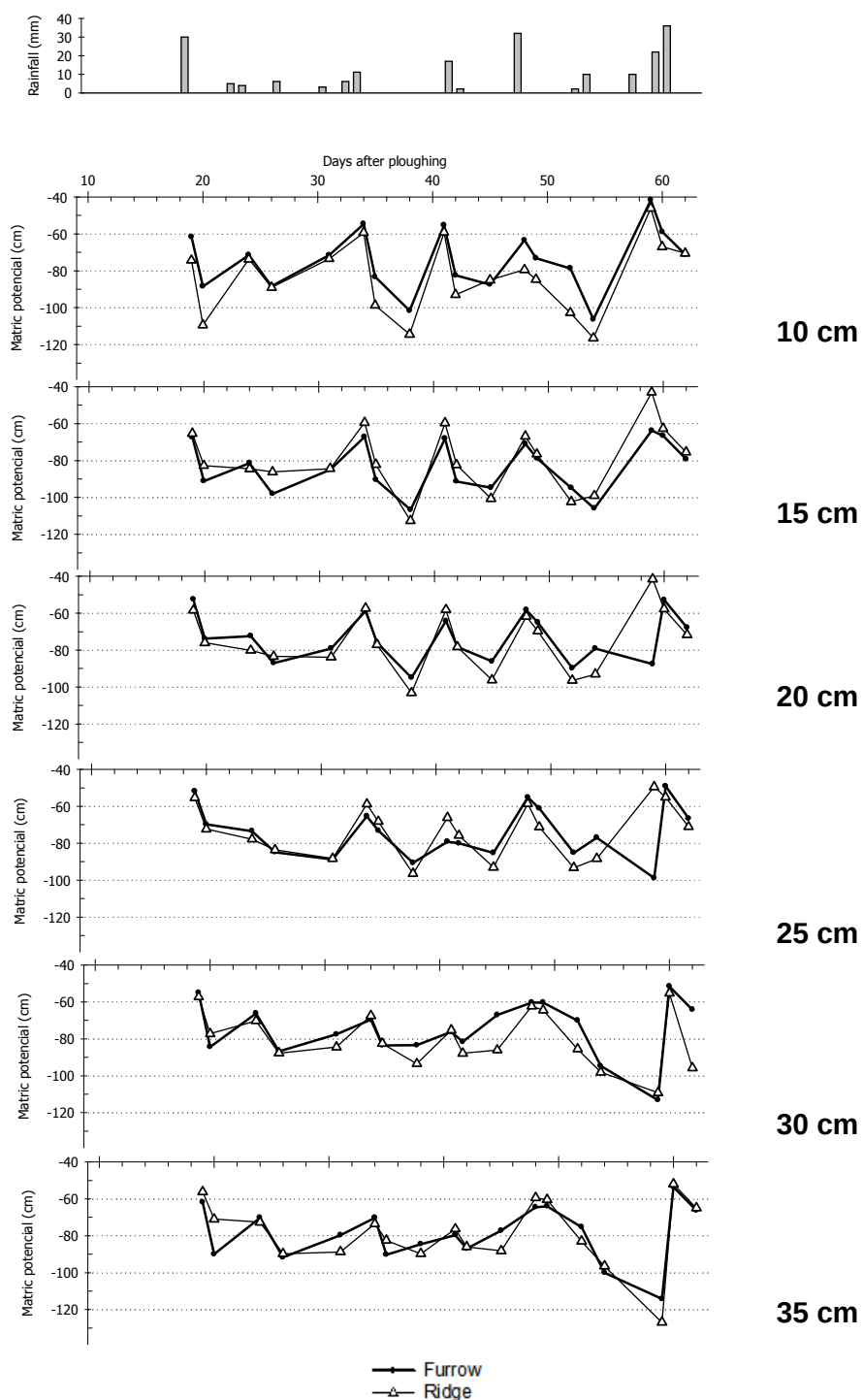


Figure 6-5 Rainfall events (top) and soil matric potential (hPa, or cm H₂O) variations with time under furrow (●) and ridges (Δ) for treatment D (ploughing to 40 cm deep) in Exp. 1; measurements were made with tensiometers installed at six depths (10, 15, 20, 25, 30 and 40(?) cm) below the initial soil surface level (after ploughing). DAP means day after ploughing in Exp.1, AR means accumulated rainfall from day of ploughing.

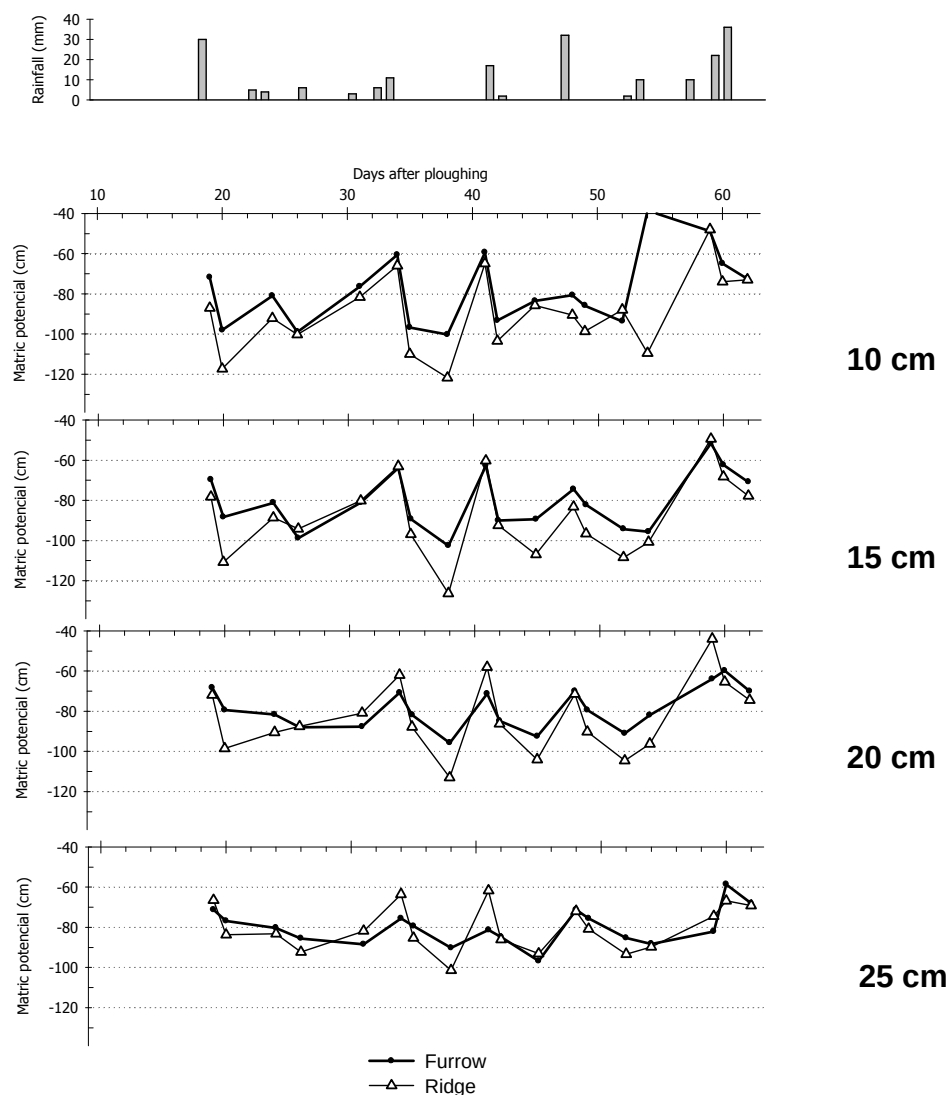


Figure 6-6 Rainfall events (top) and soil matric potential (hPa, or cm H₂O) variations with time under furrow (●) and ridges (Δ) for treatment S (ploughing down to 20 cm) in Exp. 1; measurements were made with tensiometers installed at four depths (10, 15, 20, 25 cm) below the initial soil surface level (after ploughing). DAP means day after ploughing in Exp.1, AR means accumulated rainfall from day of ploughing.

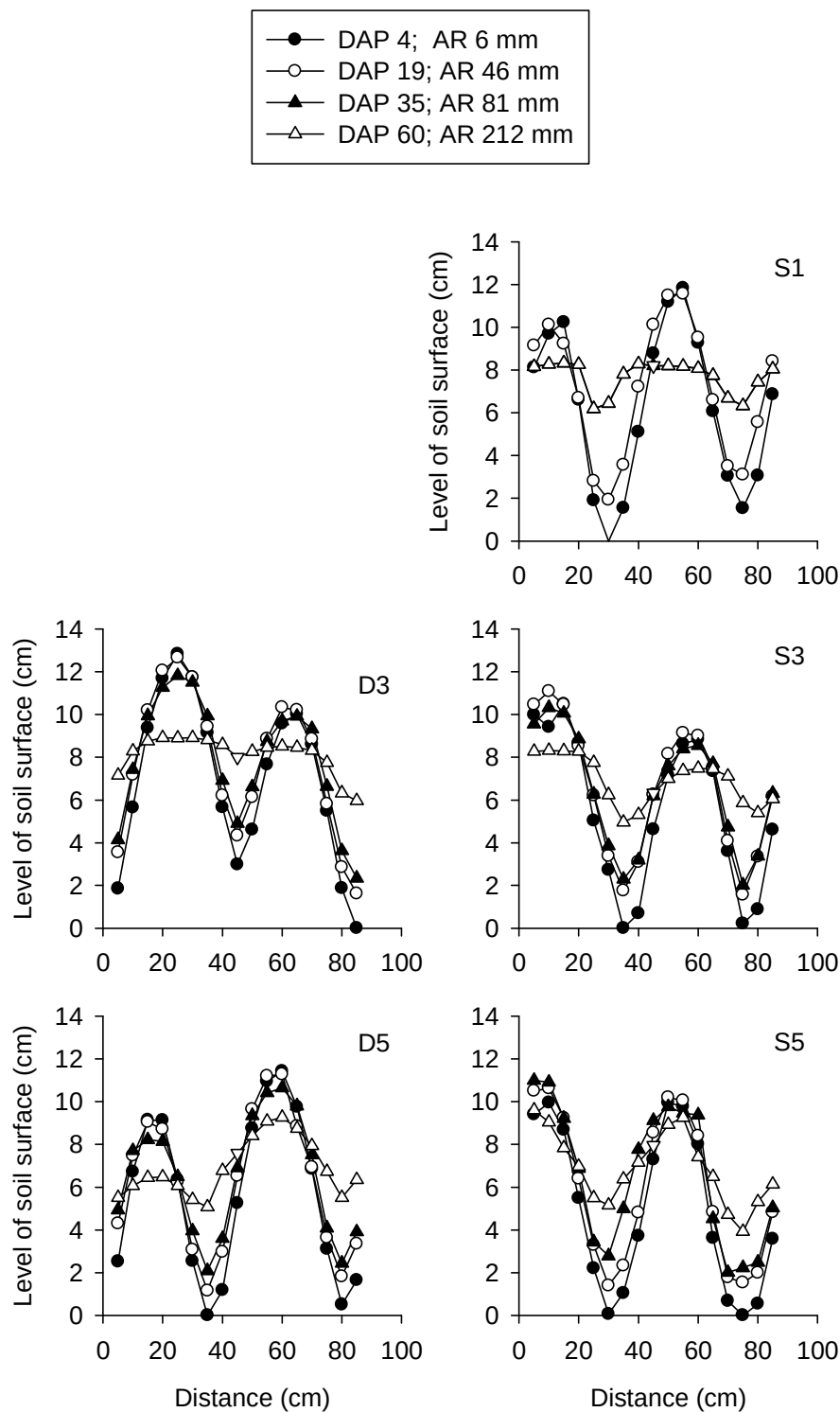


Figure 6-7 Level of soil surface change in Exp.1, D (Deep ploughing, 40 cm) and S (Shallow ploughing, 20 cm). Each point was the average value of 17 replicates. DAP means day after ploughing in Exp.1, AR means accumulated rainfall from day of ploughing. SE (Standard error) was very small therefore was not presented here. All of the CV<3%.

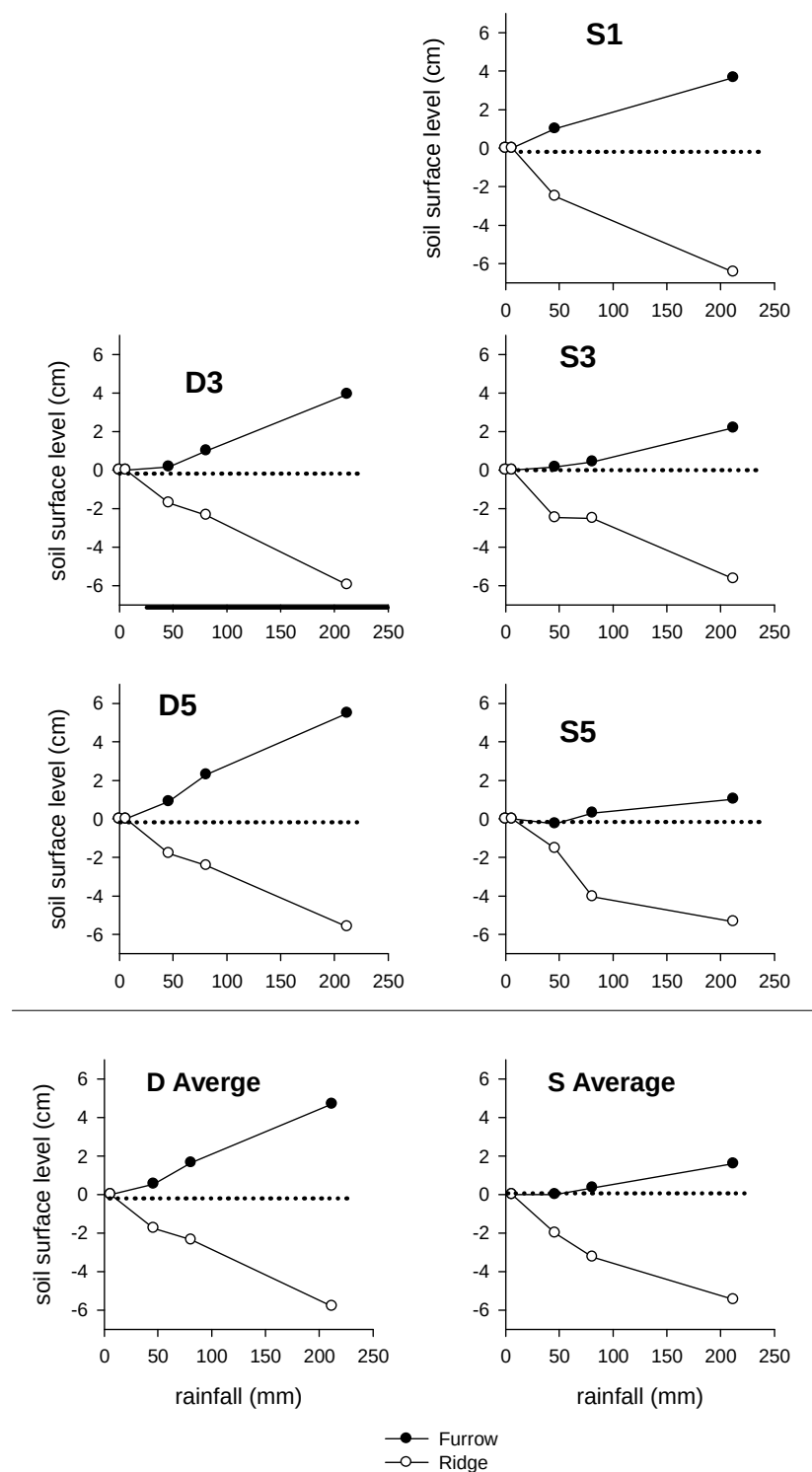


Figure 6-8 Soil surface level increase in furrow (—●—) and decrease in ridge (—○—). Top is different replicates, bottom is average value.

Table 6-2 Level of soil surface increase in F (Furrow) and decrease in R (Ridge). Δ means the absolute value difference between F and R. DAP means day after ploughing in Exp.1, AR means accumulated rainfall from day of ploughing.

			DAP 4			19			35			60		
			AR (mm) 6			46			81			212		
			F	R	Δ	F	R	Δ	F	R	Δ	F	R	Δ
D (cm)	D3	0	0.2	-1.7		1.0	-2.3		3.9	-6				
	D5	0	0.9	-1.8		2.3	-2.4		5.5	-5.6				
	Average		0.6	-1.8	-1.2	1.7	-2.4	-0.7	4.7	-5.8	-1.1			
S (cm)	S1	0	1.0	-2.5					3.7	-6.4				
	S3	0	0.2	-2.5		0.4	-2.5		2.2	-5.6				
	S5	0	-0.2	-1.5		0.3	-4.0		1.0	-5.3				
	Average	0	0.3	-2.2	-1.8	0.4	-3.3	-2.9	2.3	-5.8	-3.5			

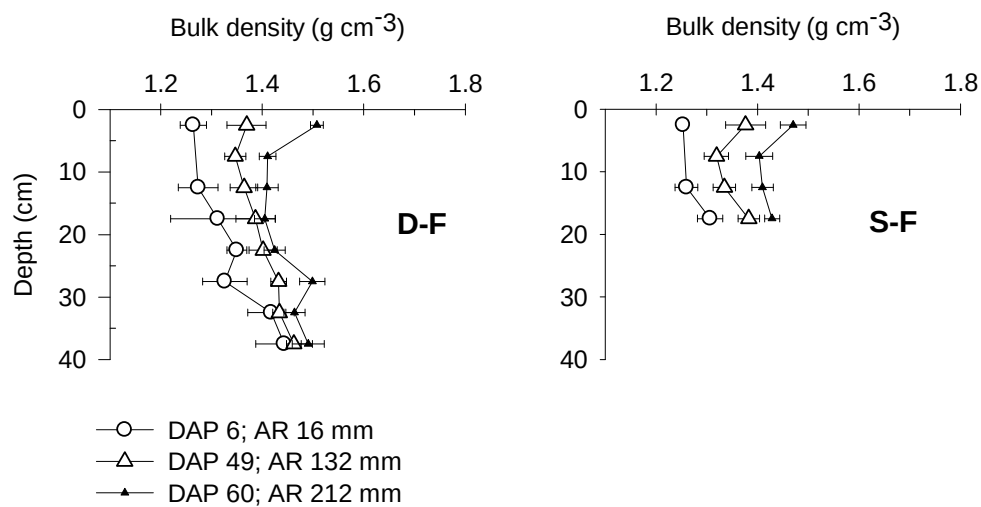
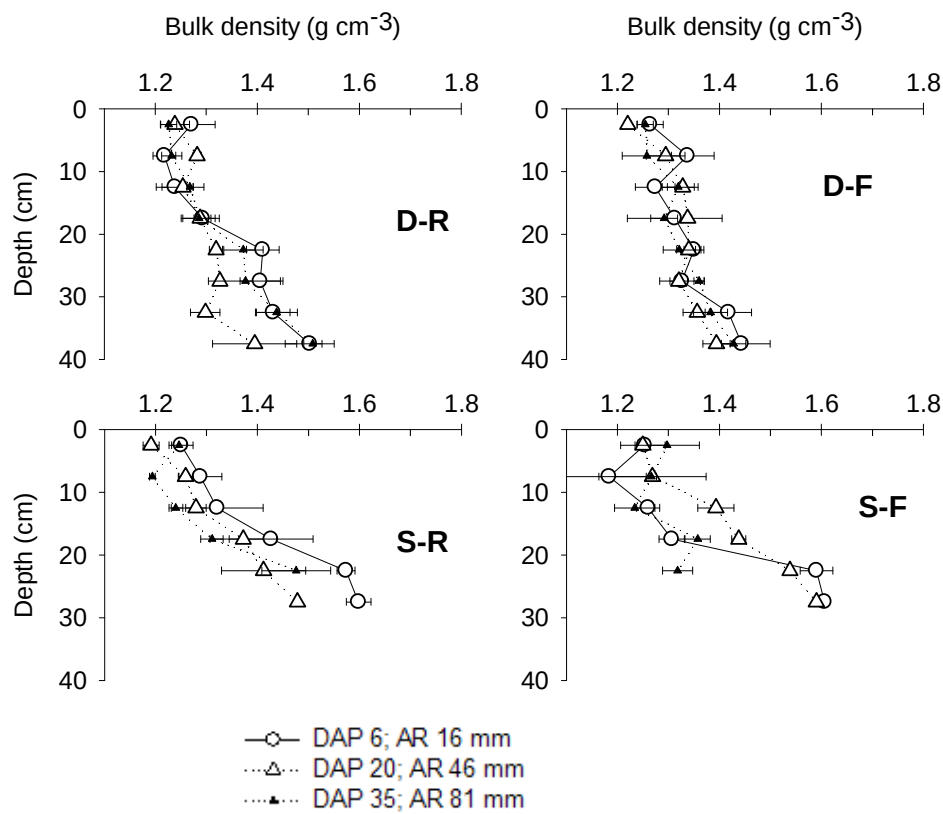


Figure 6-9 Bulk density evolution at different time after major rainfall events in Exp. 1 under furrow (F). (a) is DAP after two small rainfall, (b) is DAP after two major rainfall. Left is Deep ploughing 40 cm (D) (in Black dot) and Right is shallow ploughing 20 cm (S) (n=5). Error bar indicates standard error of mean (SEM). DAP means day after ploughing for Exp.1, AR means accumulated rainfall from day of ploughing.

Experiment 2

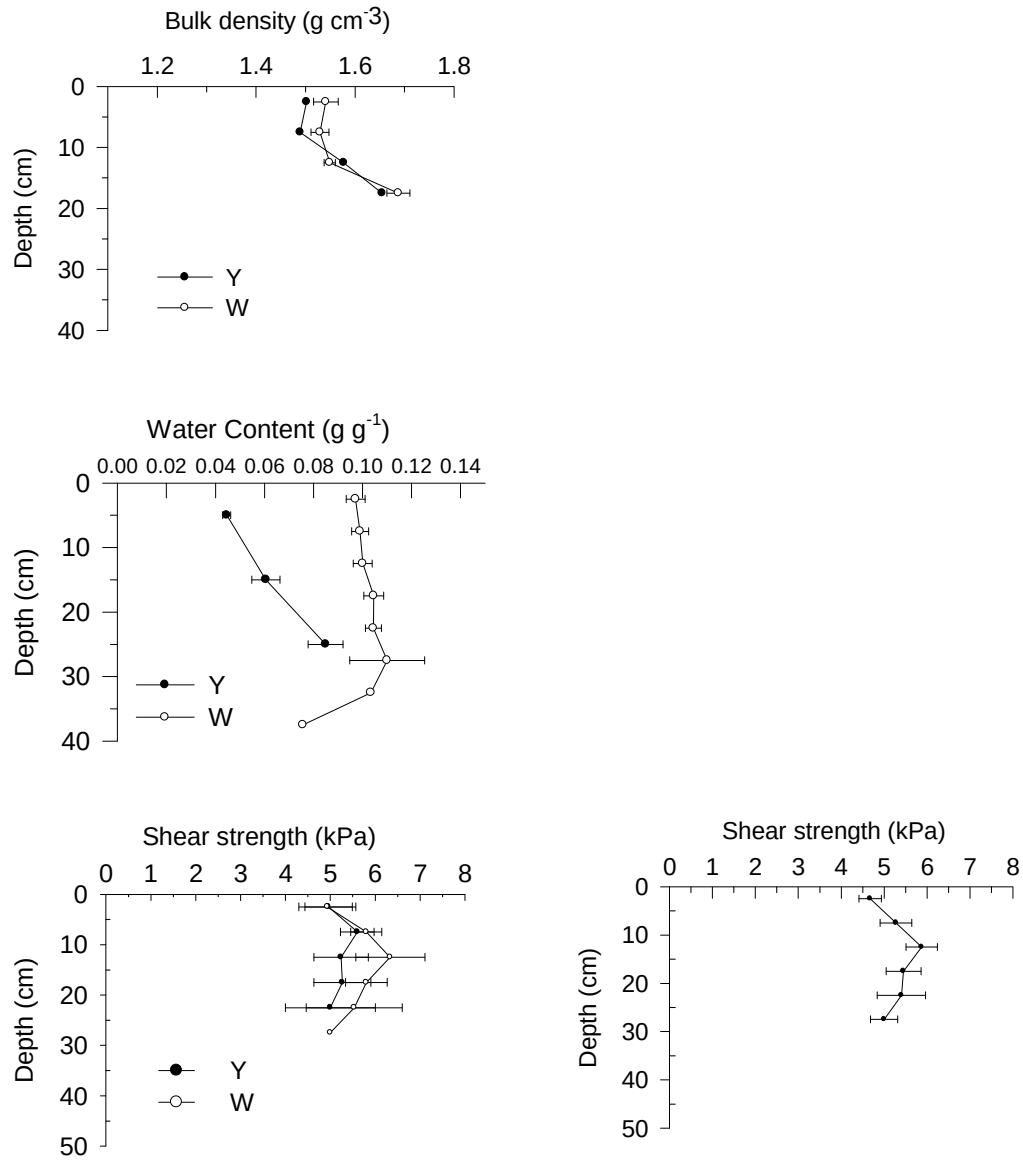


Figure 6-10 Initial soil characteristics in Exp.2 before ploughing: ploughing during dry conditions (Y) (in Black dot) and ploughing during wet conditions (W), both were ploughing 20 cm (S) (n=5); (mean value + SE)

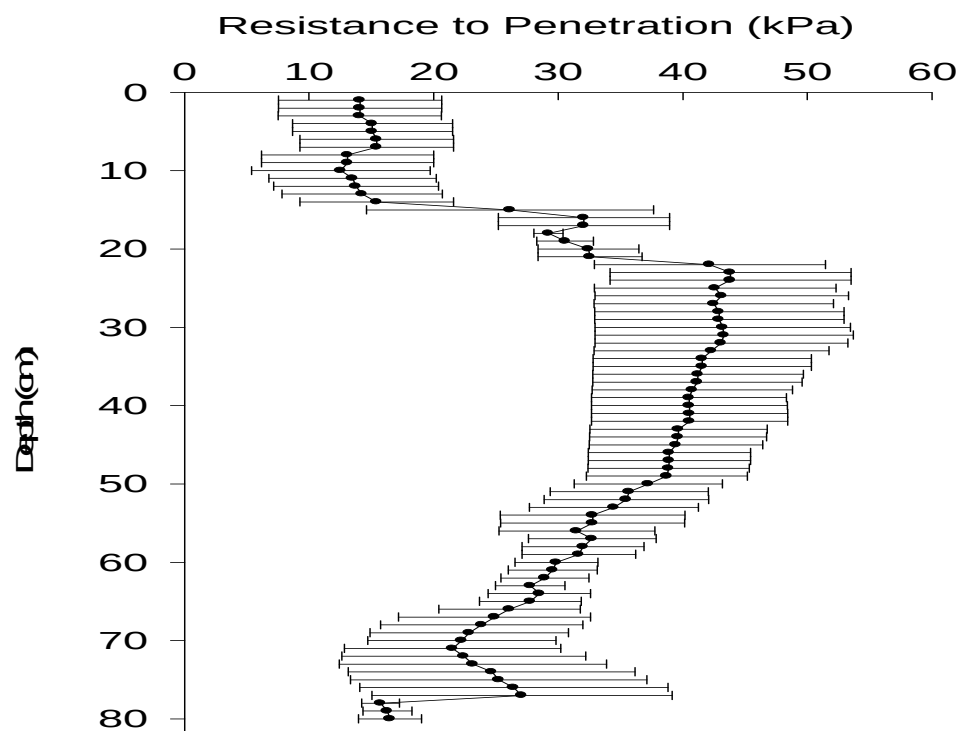


Figure 6-11 In Exp.2, initial (before ploughing) resistance to penetration by Penetrometer with data logger measured from the top of the soil. (n=3). Measured in W (wet conditions). Error bar indicates standard error of mean (SEM).

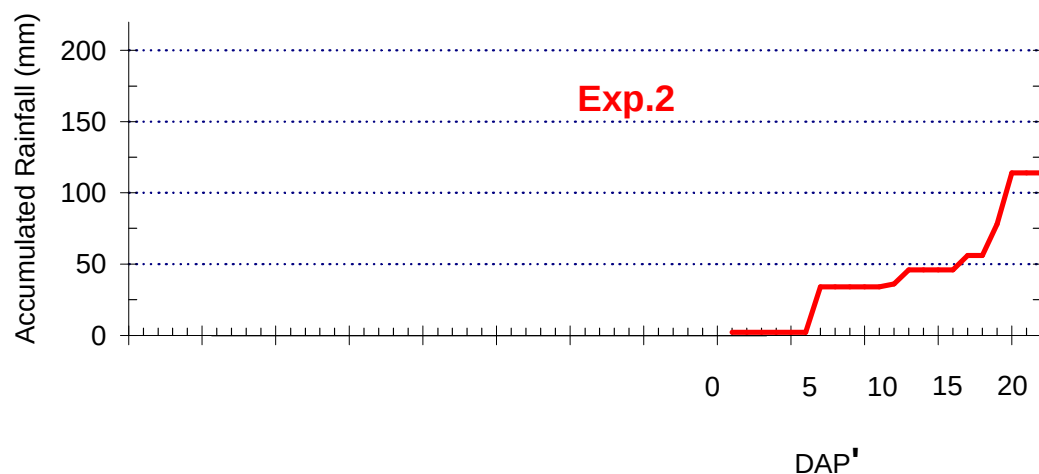
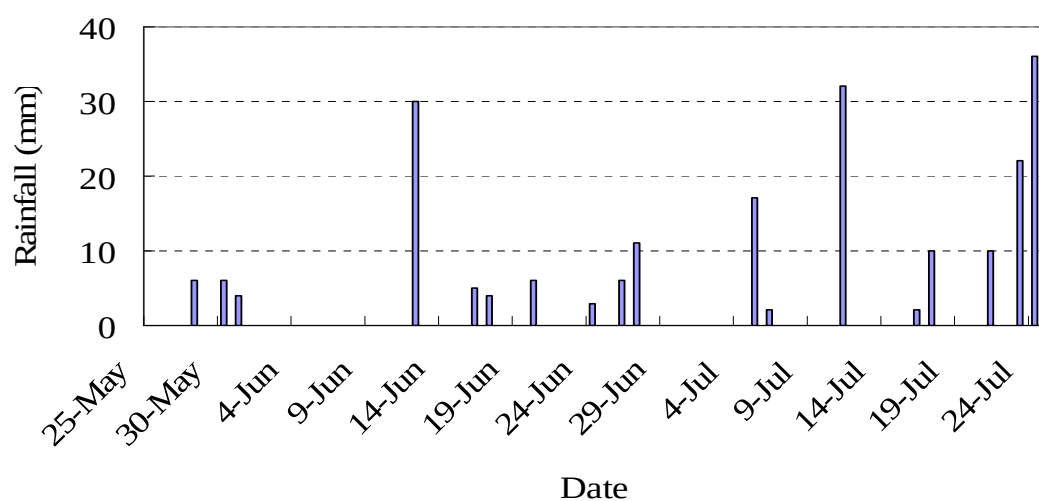


Figure 6-12 Rainfall distributions for Exp.1 (day 0 to day 60). Top: daily rainfall (mm). Arrow indicates major rainfall events after which soil characteristics (lasermeter, Bulk density etc) were measured. Bottom: accumulated rainfall for Exp. 2: (day 41 to day 60, DAP 0 to 20). Arrow indicates after which major rainfall, soil characteristics were measured. DAP' means days after ploughing for Exp.2.

Table 6-3 Detailed Rainfall events after ploughing for Experiment 2

DAP' (Days after ploughing)	Date	Rainfall (mm)	(AR) Accumulated rainfall (mm)
0	20070706	2	2
5	20070711	32	34
10	20070716	2	36
11	20070717	10	46
15	20070721	10	56
17	20070723	22	78
18	20070724	36	114

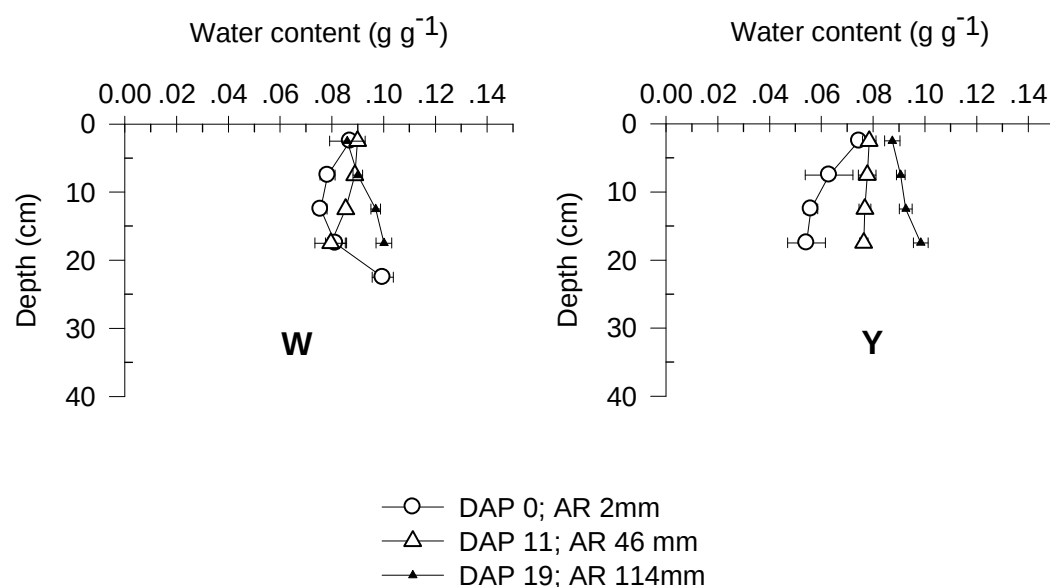


Figure 6-13 In Exp. 2, water content evolution at 3 times under Furrow (F). Left is ploughing during wet conditions (W) and ploughing during dry conditions (Y), both were ploughing 20 cm (S). Error bar indicates standard error of mean (SEM). (n=9). DAP' means days after ploughing for Exp.2, DAP' means day after ploughing for Exp.2, AR means accumulated rainfall from day of ploughing.

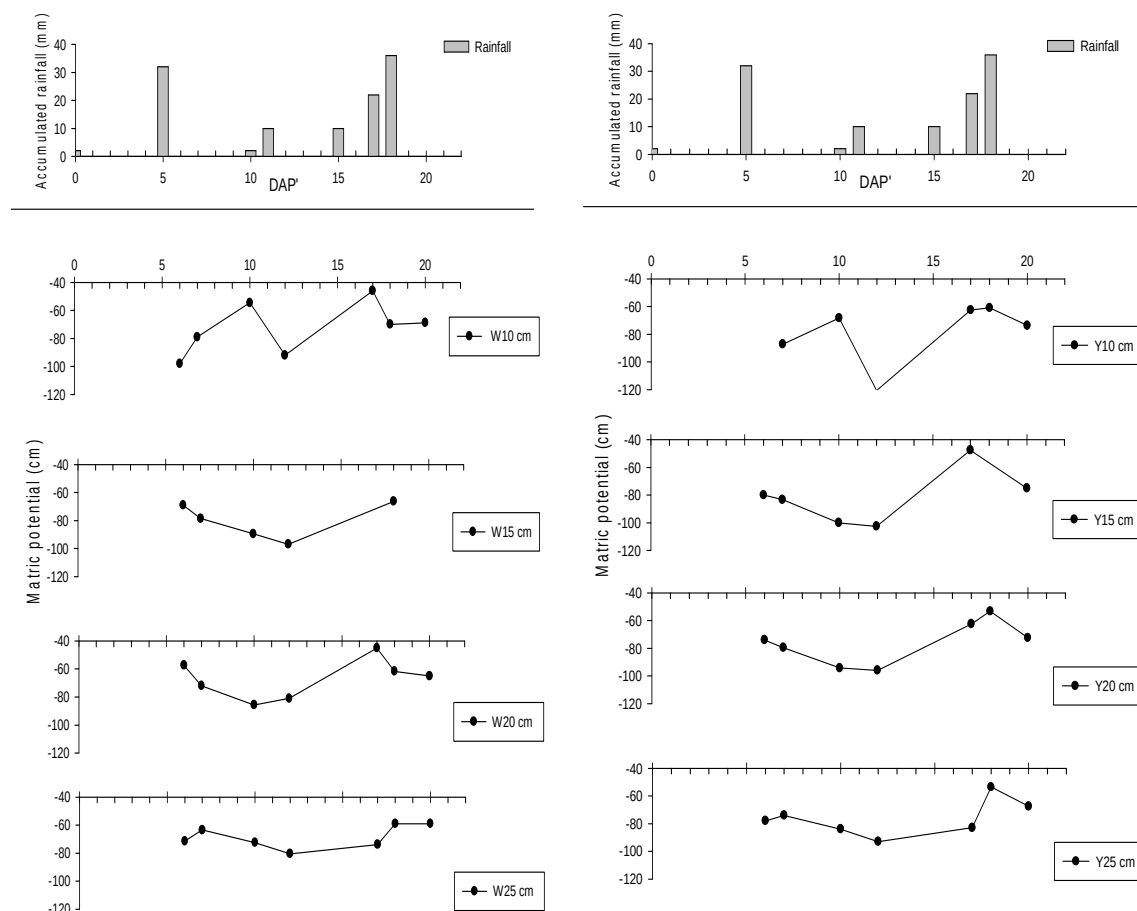


Figure 6-14 Soil water matric potential (cm) in W (Wet) and Y (dry) at different time. DAP' means day after ploughing for Exp.2, AR means accumulated rainfall from day of ploughing.

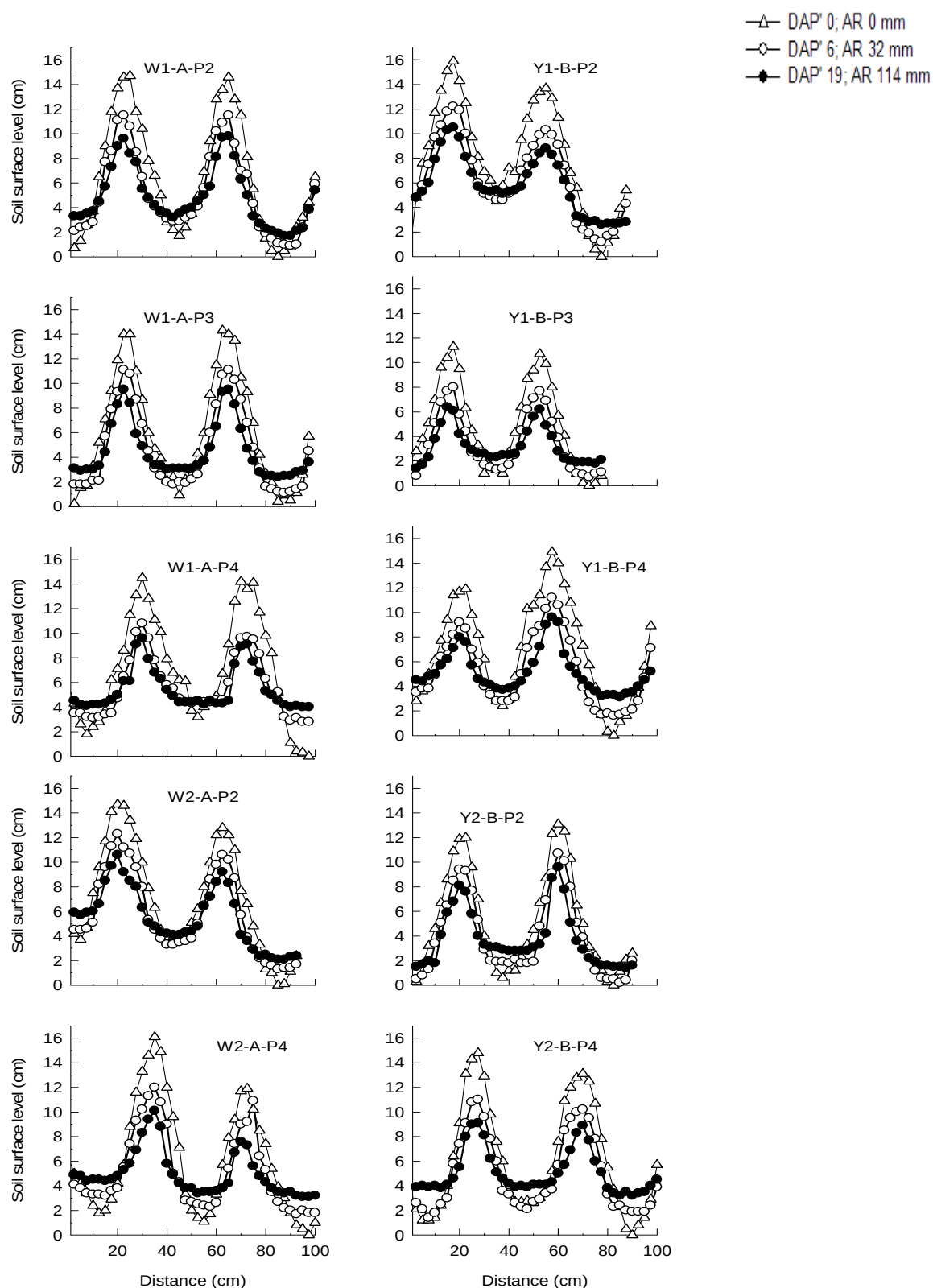


Figure 6-15 Level of soil surface change after two major rainfall events in Exp.2. Measured by lasermeter. Wet (W) is ploughing when initial water content was wet; Dry (Y) is ploughing when soil was dry, ploughing 20 cm. DAP' means day after ploughing for Exp.2, AR means accumulated rainfall from day of ploughing.

Table 6-4 Level of soil surface increase in F (Furrow) and decrease in R (Ridge). Δ means the difference between F and R. DAP' means day after ploughing for Exp.2, AR means accumulated rainfall from day of ploughing. (n=5).

		DAP	0	6			19		
				34			114		
		AR	0	F	R	Δ	F	R	Δ
W	W1		0	2.8	-4.6		4.0	-6.4	
	W2		0	2.0	-3.6		2.9	-5.6	
	W3		0	1.7	-4.5		2.7	-6.3	
	W4		0	1.3	-3.4		2.1	-5.4	
	W5		0	1.8	-4.6		3.1	-6.2	
Average			0	1.9	-4.1	-2.2	3.0	-6.0	-3.0
SE				0.2	0.3		0.3	0.2	
Y	Y1		0	3.6	-3.7		3.8	-5.4	
	Y2		0	0.8	-3.7		1.9	-5.3	
	Y3		0	1.6	-3.7		3.3	-5.7	
	Y4		0	1.3	-3.2		2.3	-5.2	
	Y5		0	1.9	-4.0		3.2	-5.7	
Average			0	1.8	-3.7	-1.8	2.9	-5.5	-2.6
SE				0.5	0.1		0.3	0.1	

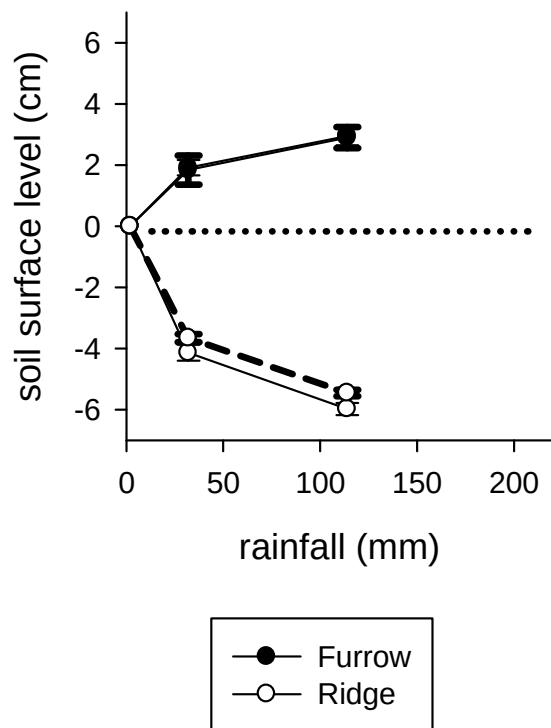


Figure 6-16 Soil surface level average change after two times rainfall in W (wet, straight line) and Y (dry, dotted line). (n= 5).

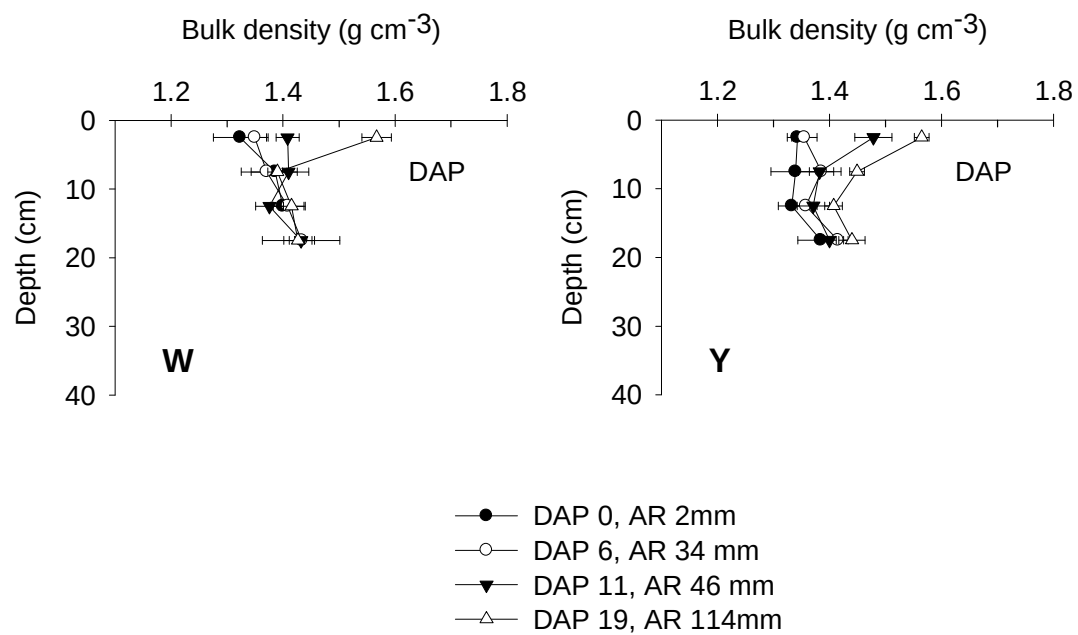


Figure 6-17 Bulk density evolution at different time after rainfall events in Exp. 2 under furrow (F). Left is W (Wet) and Right is Y (Dry) (S) (n=9). Error bar indicates standard error of mean (SEM). DAP' means day after ploughing for Exp.2, AR means accumulated rainfall from day of ploughing.

Experiment 3

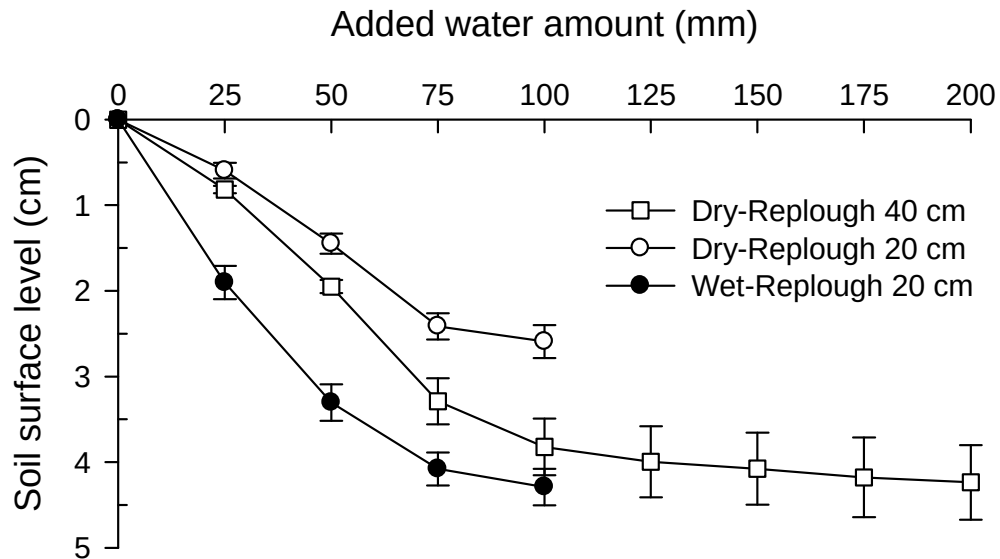


Figure 6-18 Soil surface level decrease after adding water inside the ring of flooding experiment. Error bars indicate standard error of mean (SE). (n=3 for Dry-Replough 40 cm and Dry-Replough 20 cm, n=4 for Wet-Replough 40 cm).

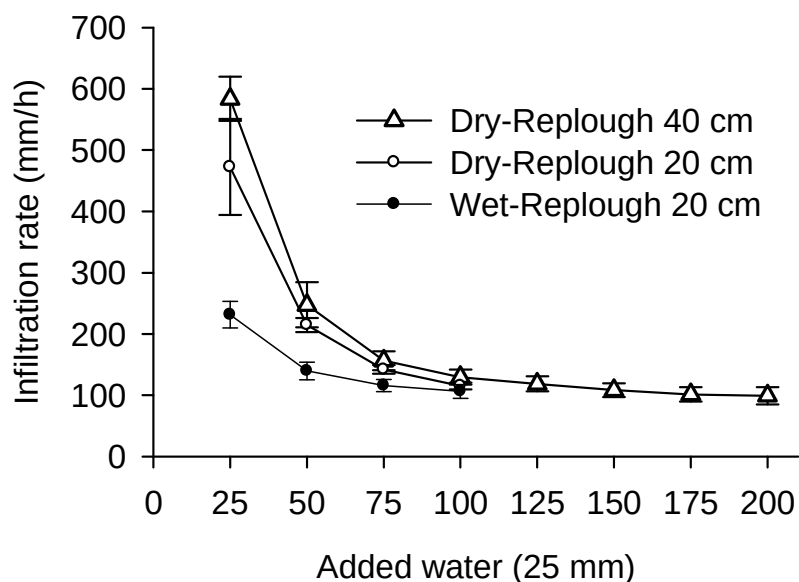


Figure 6-19 Infiltration rate (mm/h) after adding water inside the ring of flooding experiment. Error bars indicate standard error of mean (SE). (n=3 for Dry-Replough 40 cm and Dry-Replough 20 cm, n=4 for Wet-Replough 40 cm).

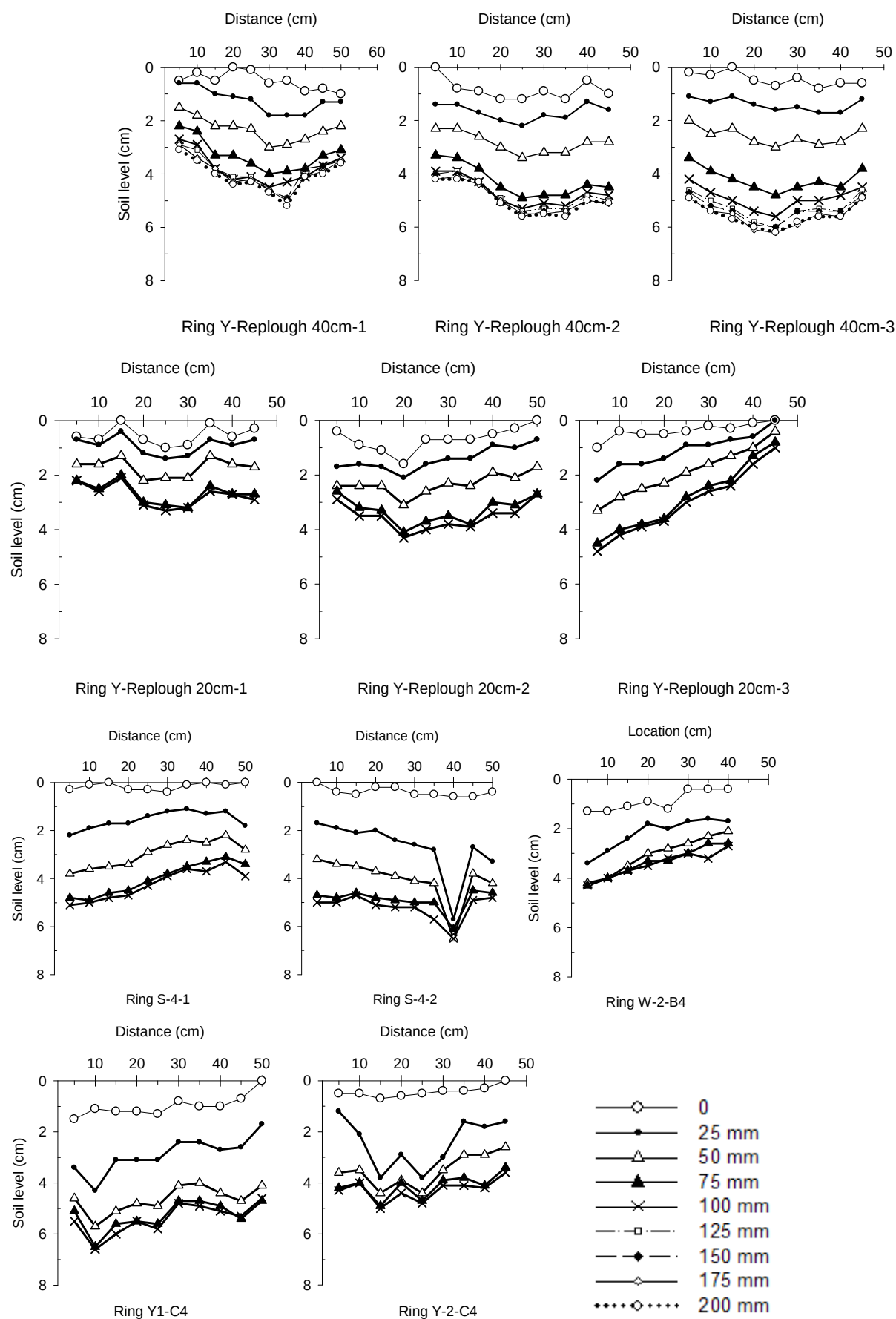


Figure 6-20 Soil level change in ring experiment, after each time add 25 mm mimic rainfall, wait until water totally infiltrate.

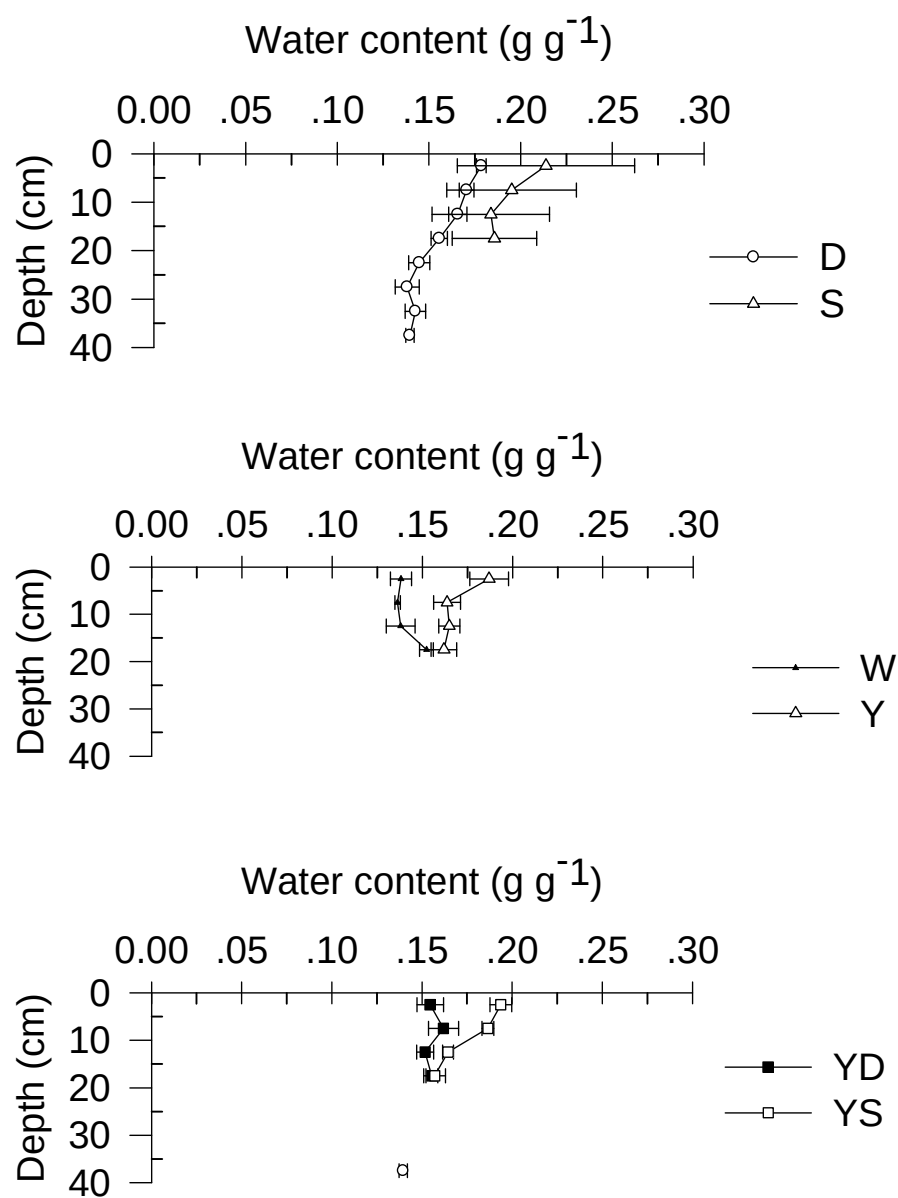


Figure 6-18 Final water content in ring experiment. They were measured 20 min to 1h after adding water. Error bars indicate standard error of mean (SEM).

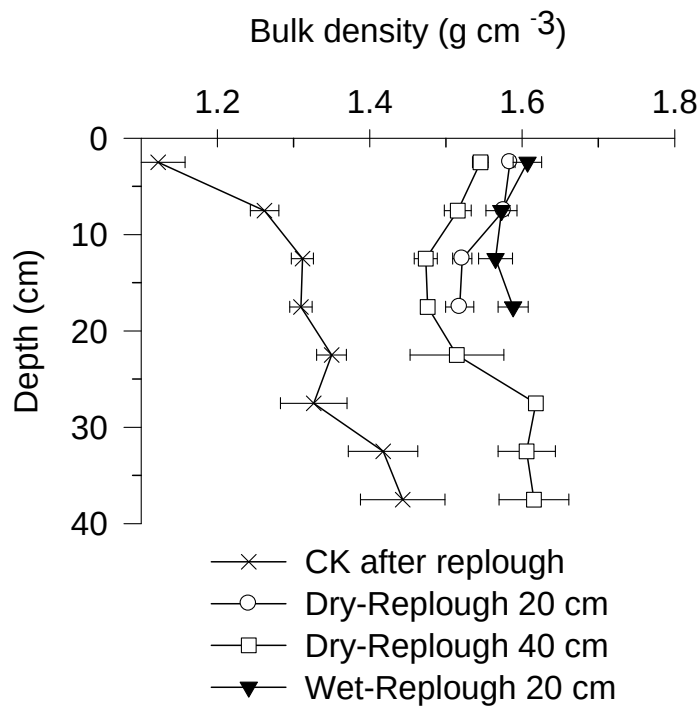


Figure 6-19 Final bulk density after mimic flooding. CK was the initial bulk density just after reploughing. We put 200 mm water in D (each time 25 mm), and 200 mm water in S (each time 25 mm). We add in a 25 mm step until finish. Each step we wait until the water totally infiltration, then immediately put another 25 mm. Error bar indicates standard error of mean (SEM). (n=9)

Part B. laboratory experiments

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1.1 Preparation of cylinders

1.1.1 Effect of filling method: filling by sieve or funnel

The difference between sieve and funnel, and different sieve sizes

Figure 6-20 shows bulk density in column after filling by different methods. The method of direct filling had the same effect as by funnel. Both of the bulk density was 1.35 g cm^{-3} . For different size of sieves, the bigger of the size of sieve, the smaller the bulk density it produced. With 0.71 mm sieve size, a highest value of 1.55 g cm^{-3} was got; with 10 mm sieve size, a lowest value 1.28 g cm^{-3} was got.

Different filling methods had different effect on the bulk density, so if one to prepare the dry sand column in the lab, one should take care of the filling methods.

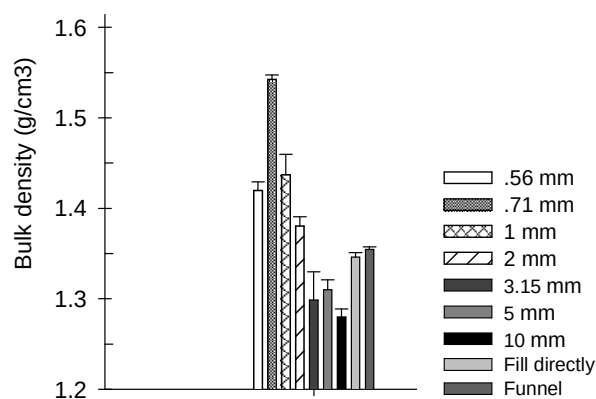


Figure 6-20 Bulk density in column after filling by different methods. The size of column was $\varnothing=7.4 \text{ cm}$, height $h=8.2 \text{ cm}$. The bars indicate standard error (SE), $n=3$.

The stability

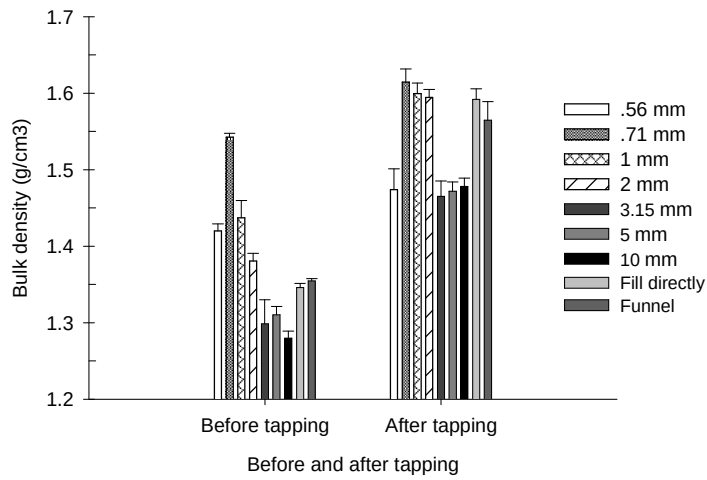


Figure 6-21 Final bulk density in column before and after tapping. It was tapped more than 200 times by a wood stick. The size of the column was $\varnothing=7.4$ cm, height $h=8.2$ cm. The bars indicate standard error (SE), $n=3$.

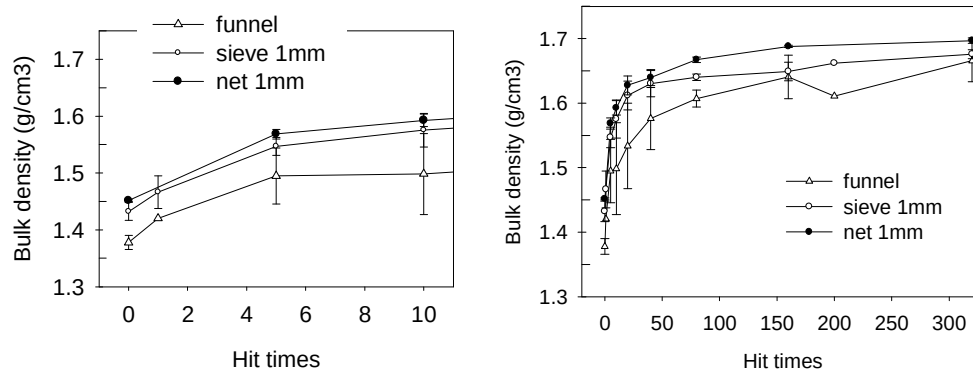


Figure 6-22 Dynamic of bulk density changes as a function of number of hits. The sand columns ($\varnothing=18$ cm, height $h=10$ cm) was filled using a point source deposition (by funnel) or vertical rain source deposition (by 1 mm sieves), The bars indicate standard error (SE), $n=3$.

1.1.2 Wetting by capillary force

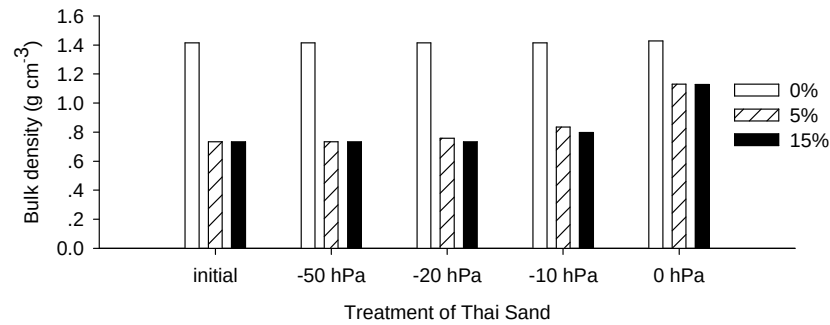


Figure 6-23 The effect of capillary rise water on Thai Sand cylinder with different initial water content (0, 5% and 15% in mass fraction). The cylinders were put on a water suction table with applying incremental matric potential from -50, -20, -10 until 0 hPa. The average bulk density was calculated by measuring the height of sand in the cylinder. At least 48 hours were waiting to get equilibrium for each step of suction.

1.1.3 Direct filling and overburden pressure

Figure 6-24 shows the bulk density value for different treatment. Wet sand (5%) had lower bulk density than dry sand. The bulk density linearly increased with depth for wet sand (5%). In the field experiment, it was found that the soil bulk density was higher in deep layer than in surface. We made the hypothesis that immediately after ploughing, the same loose structure can become denser in deeper layer due to higher overburden pressure. The results here conform to our hypothesis.

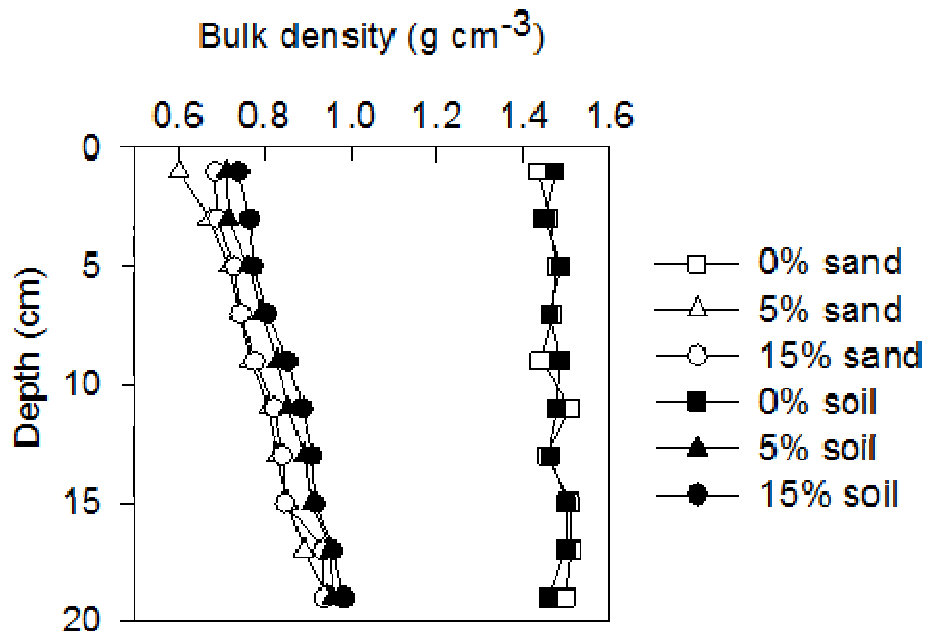


Figure 6-24 Bulk density change with height of soil/sand inside cylinder. They were filled through a 1-cm-hole sieve. The depth was counted from the top of cylinder as 0.

1.2 The factor of rainfall amount

Suction=20 hPa, different rainfall amount (with rainfall 40 mm/h)

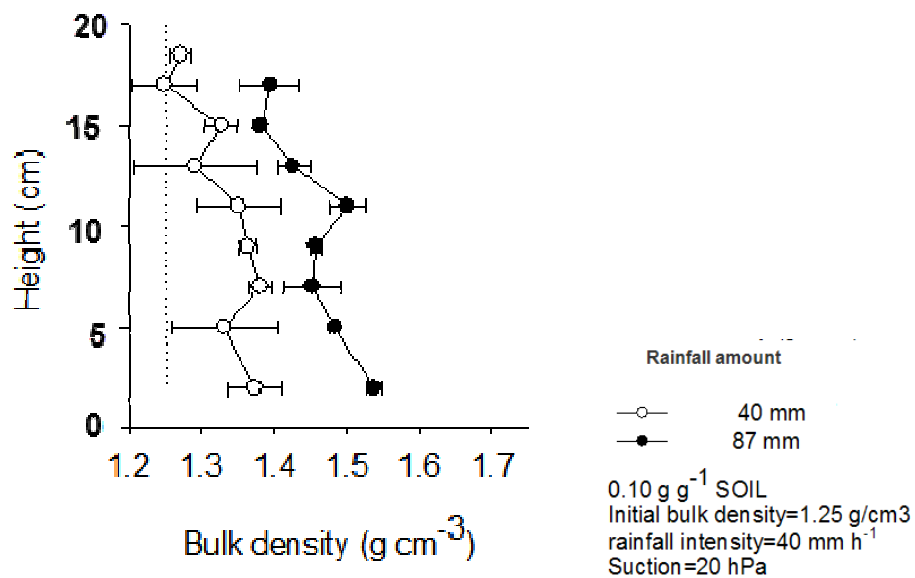


Figure 6-25 The bulk density profile after different rainfall amount: **40 mm and 87 mm** rainfall with same intensity of 40 mm h⁻¹. They were made with cutting methods. The cylinder was put on a suction table with suction as 20 hPa. The dotted line indicates the initial bulk density profile. The error bar indicates standard error (n=3). The height was counted from the bottom of cylinder as 0 and the top of cylinder as 20 cm.

1.3 The slumping of loose structure ($< 1 \text{ g cm}^{-3}$)

Table 6-5 The initial density by filling cylinder and final density after subjected simulated rainfall.

	Water content (g/g)	Rainfall intensity (mm/h)	Rainfall amount (mm)	Initial density (g/cm ³)	Final density (g/cm ³)
Thai soil	0%	520	38	1.46	1.49
	5%	520	29	0.82	1.02
	5%	520	25	0.86	1.14
	10%	120	50	0.85	1.41
	15%	520	21	0.84	1.22
Thai sand	0%	520	54	1.48	1.48
	5%	520	unknown	0.66	1.32
	5%	520	35	0.84	1.40
	10%	520	33	0.81	1.41
	10%	520	23	0.79	0.99
	15%	520	65	0.66	1.46

Note: The simulated rainfall was made with a sprayer.

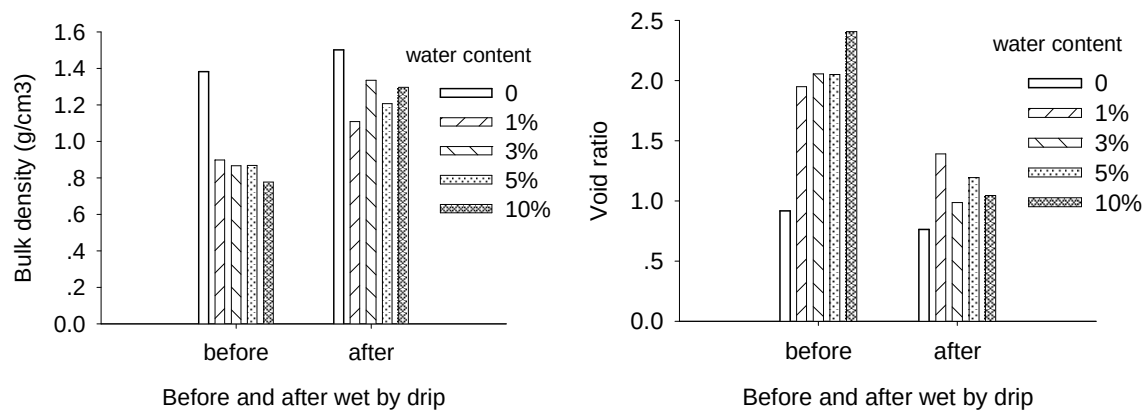


Figure 6-26 Change of Fontainebleau sand before and after subjected to simulated rainfall by drip system. The cylinders were put on dry Fontainebleau sand as border effect. a) bulk density change, b) Void ratio change.

Different slumping profiles

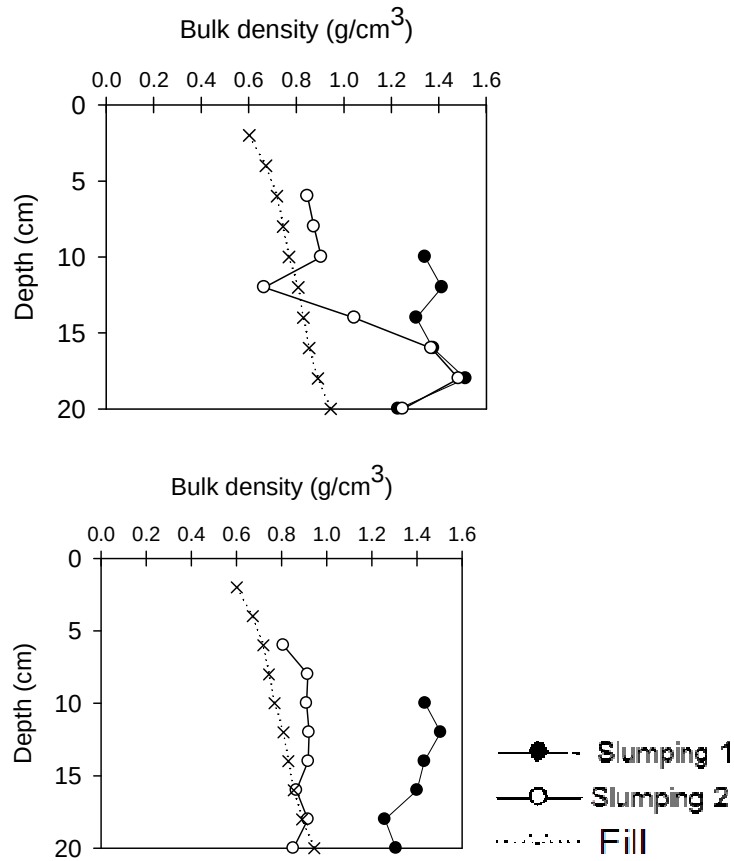


Figure 6-27 The Bulk density profile for totally and partly slumping. Dotted line indicates the initial bulk density just after filling cylinder. a) 5% wet sand, b) 10% wet sand. The suction on suction table was $h=0$ hPa.). After slumping, it was cut in each 2 cm **after waiting 3 h** on the suction table. The depth was count from the top of the cylinder (20 cm). For each figure, two different slumping experiments was made by applying different water. The depth was counted from the top of cylinder as 0.

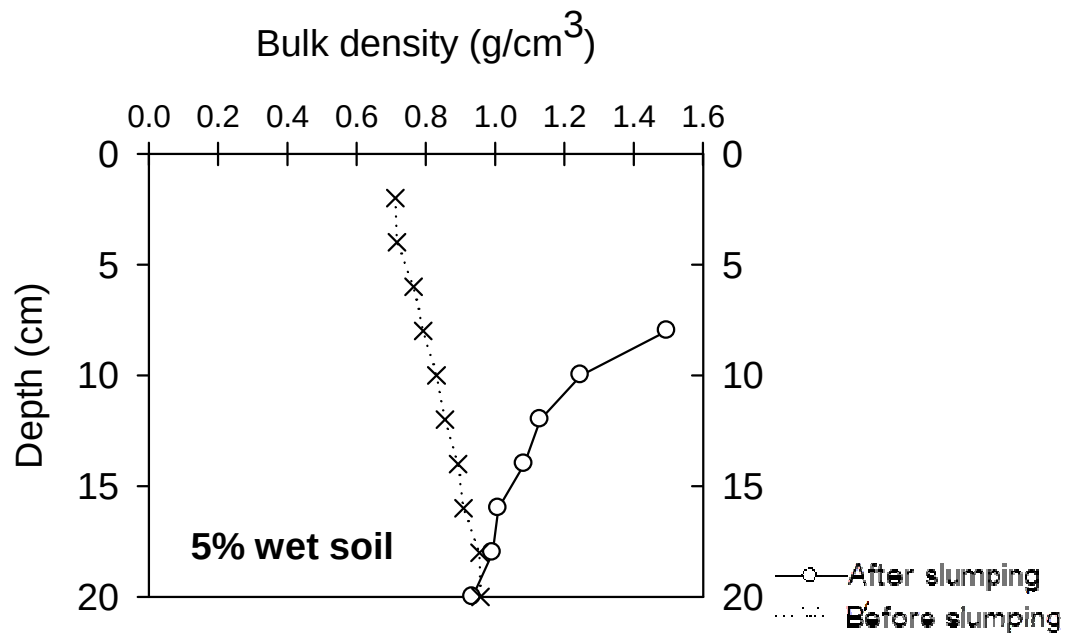


Figure 6-28 The profile of bulk density with 5% wet Thailand soil. It was put on water table with suction=-20 hPa. Dotted line indicates the initial bulk density just after filling cylinder. Solid line indicates the bulk density after slumping. The depth was counted from the top of cylinder as 0.

1.4 The factor of initial structure (bulk density)

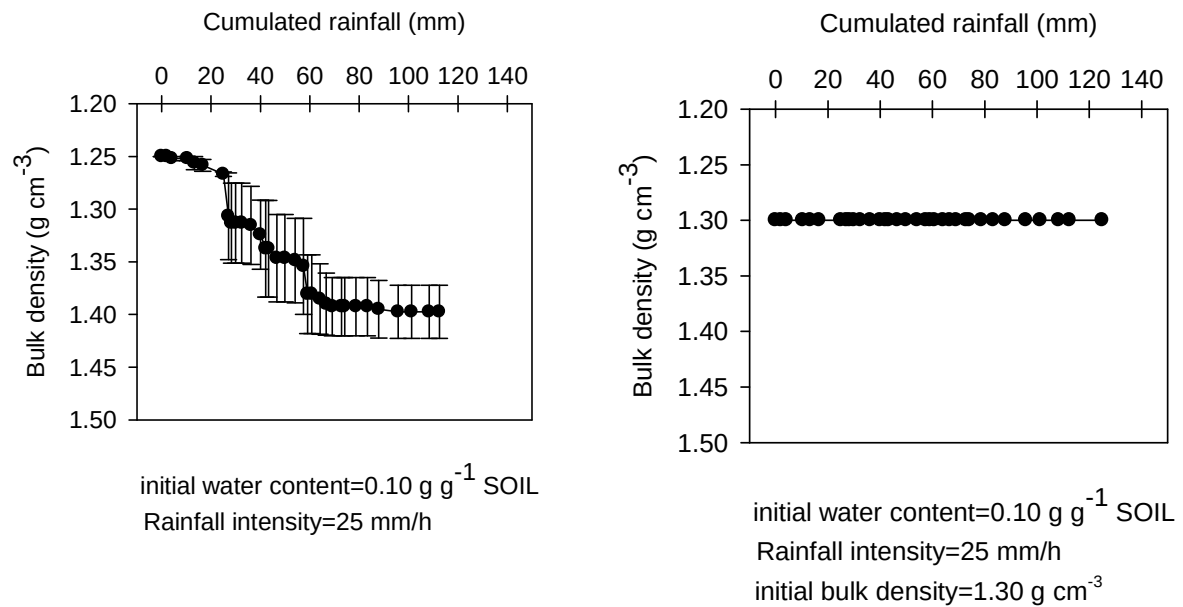


Figure 6-29 Slumping process under rainfall intensity 25 mm/h for different initial bulk density: a) 1.25 Mg m⁻³, b) 1.30 Mg m⁻³. n=3. Error bars indicate standard error of means (SEM).

1.5 Slumping of Thai Soil

1.5.1 The factor of rainfall amount

Suction=20 hPa, different rainfall amount (with rainfall 40 mm/h)

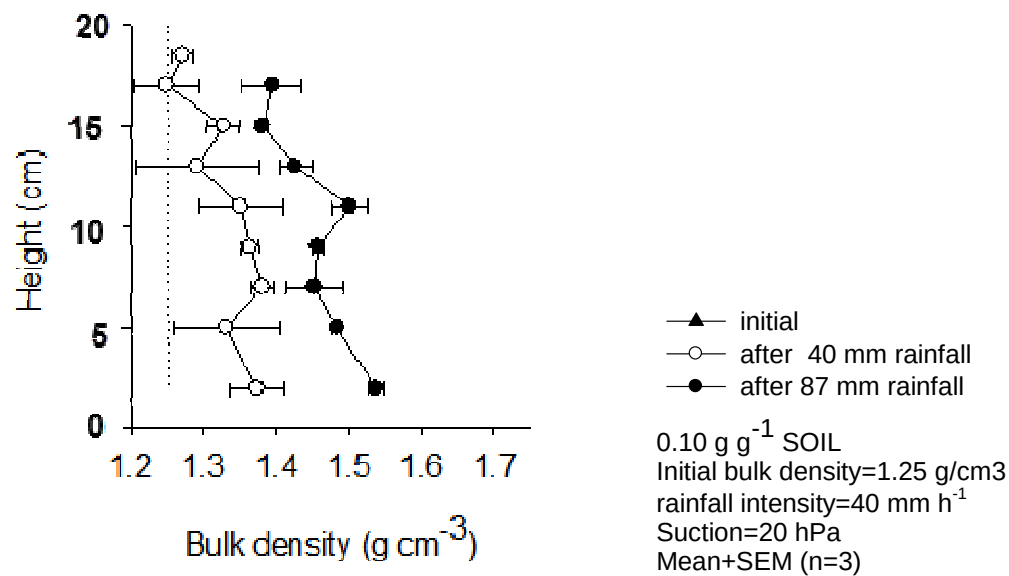


Figure 6-30 The bulk density profile after different rainfall amount: 40 mm and 87 mm rainfall with 40 mm/h intensity. The cylinder were put on a suction table with suction as 20 hPa. The error bar indicates standard error or mean (n=3). The height was counted from the bottom of cylinder as 0 and the top of cylinder as 20 cm.

1.5.2 The factor of rainfall intensity

Different rainfall intensity =20, 40, 130 mm h⁻¹ (Under 20 hPa)

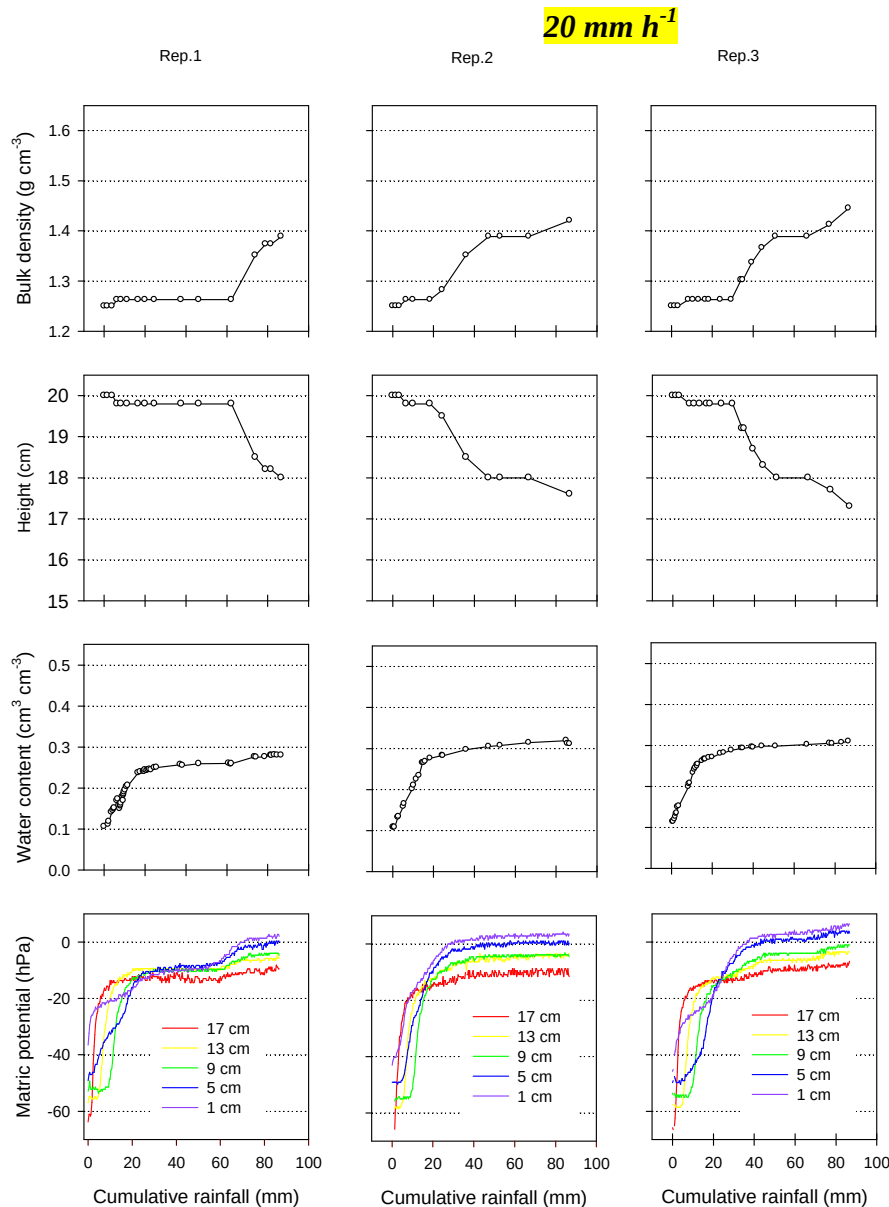


Figure 6-31 Changes during rainfall: a) The average bulk density b) soil height, c) average volumetric water content, d) soil water matrix potential. The cylinder was put on water table with suction at 20 hPa, with rainfall intensity at 20 mm h⁻¹. The rainfall amount was 87 mm. Here three replicates are presented.

40 mm h⁻¹

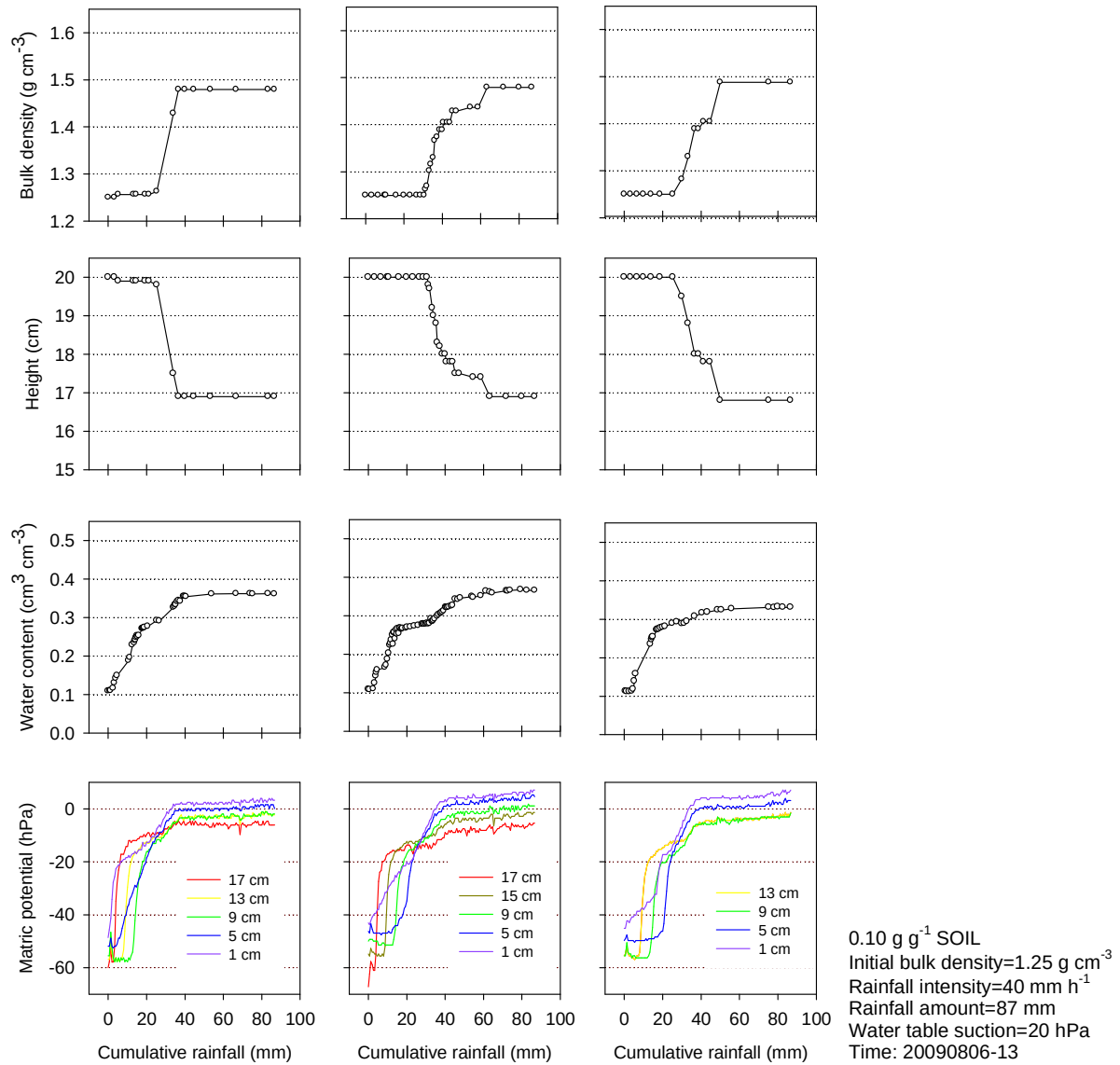


Figure 6-32 Changes during rainfall: a) The average bulk density b) soil height, c) average volumetric water content, d) soil water matric potential. The cylinder was put on water table with suction at **20 hPa**, with rainfall intensity at **40 mm h⁻¹**. The rainfall amount was 87 mm. Here three replicates are presented.

130 mm h⁻¹

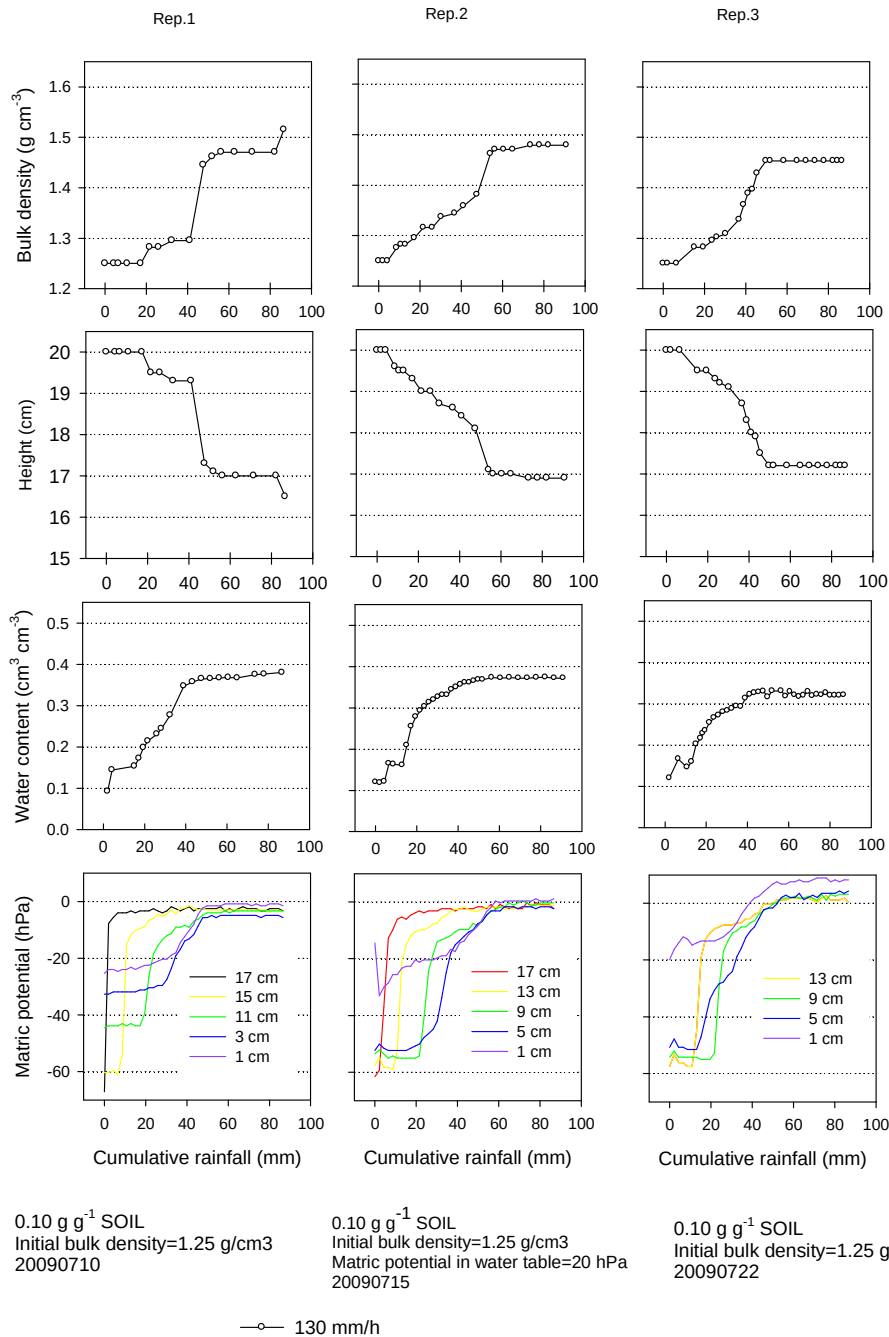


Figure 6-33 Changes during rainfall: a) The average bulk density b) soil height, c) average volumetric water content, d) soil water matric potential. The cylinder was put on water table with suction at **20 hPa**, with rainfall intensity at **130 mm h⁻¹**. The rainfall amount was 87 mm. Here three replicates are presented.

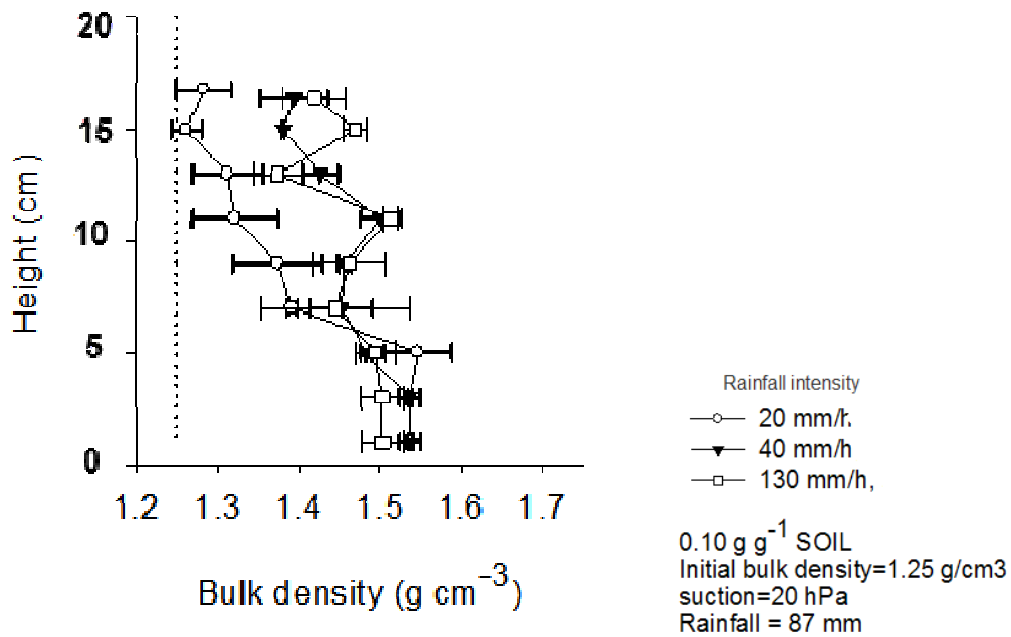


Figure 6-34 Final bulk density profile under different rainfall intensity: 20, 40, and 130 mm/h. They were made with cutting methods. They had been submitted to the same amount of rainfall. The dotted line indicates the initial bulk density profile. The error bar indicates standard error of mean (SEM)).

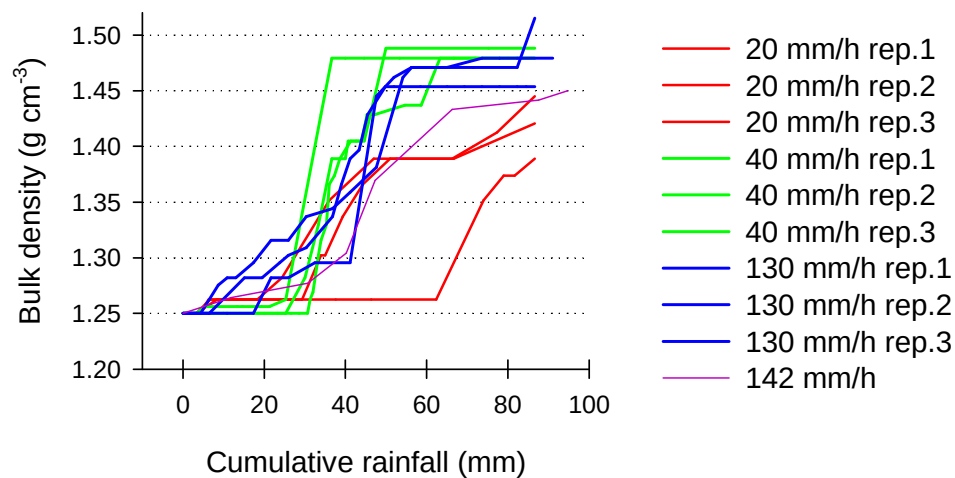
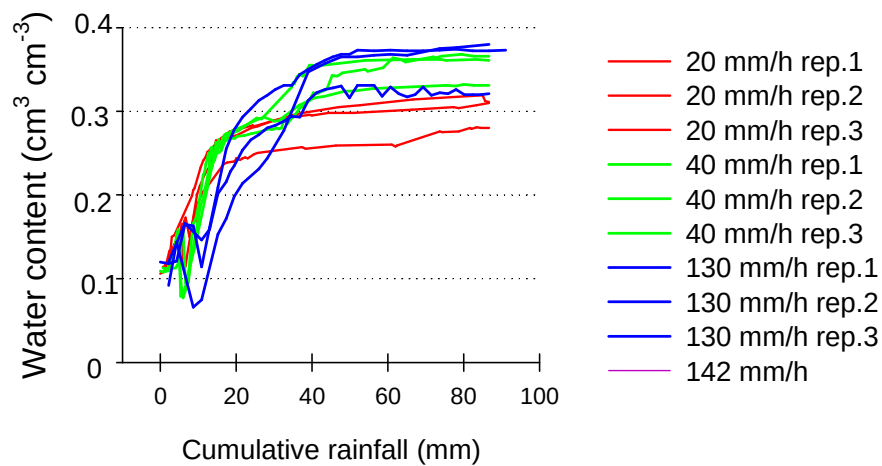
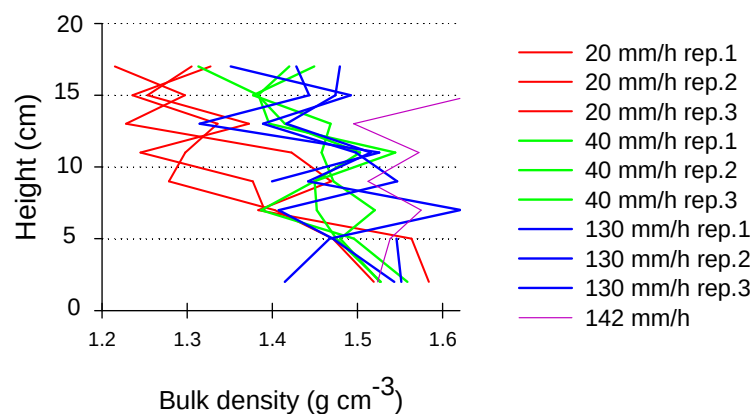


Figure 6-35 The average bulk density dynamic with cumulative rainfall. Different replicates are presented.



0.10 g g^{-1} initial wet Thai SOIL
Initial bulk density=1.25 g/cm^3
Rainfall intensity=20, 40, 130 mm/h
Rainfall amount=87 mm
Suction on suction table=20 hPa

Figure 6-36 The dynamics of average water content value measured by TDR with cumulative rainfall. Different replicates are presented.



0.10 g g^{-1} initial wet Thai SOIL
Initial bulk density=1.25 g/cm^3
Rainfall intensity=20, 40, 130 mm/h
Rainfall amount=87 mm
Suction on suction table=20 hPa

Figure 6-37 The final bulk density at each two centimeters after the simulated rainfall. It was measured by cutting each two centimeter layer and oven-dried. Different replicates are presented.

1.5.3 The factor of suction on suction table

Different Suction=20, 60, 90 hPa (with rainfall 40 mm/h)

20 hPa

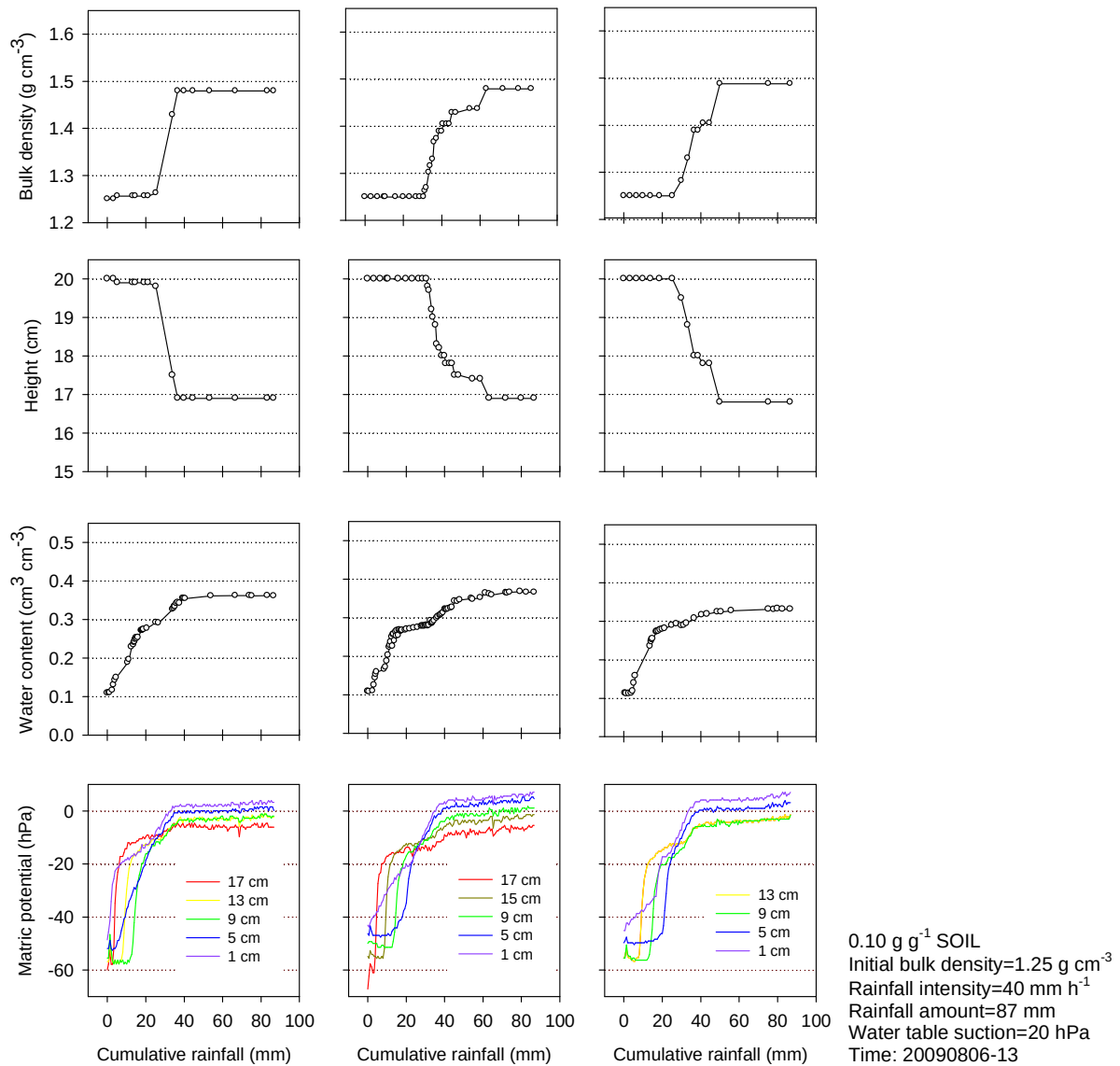
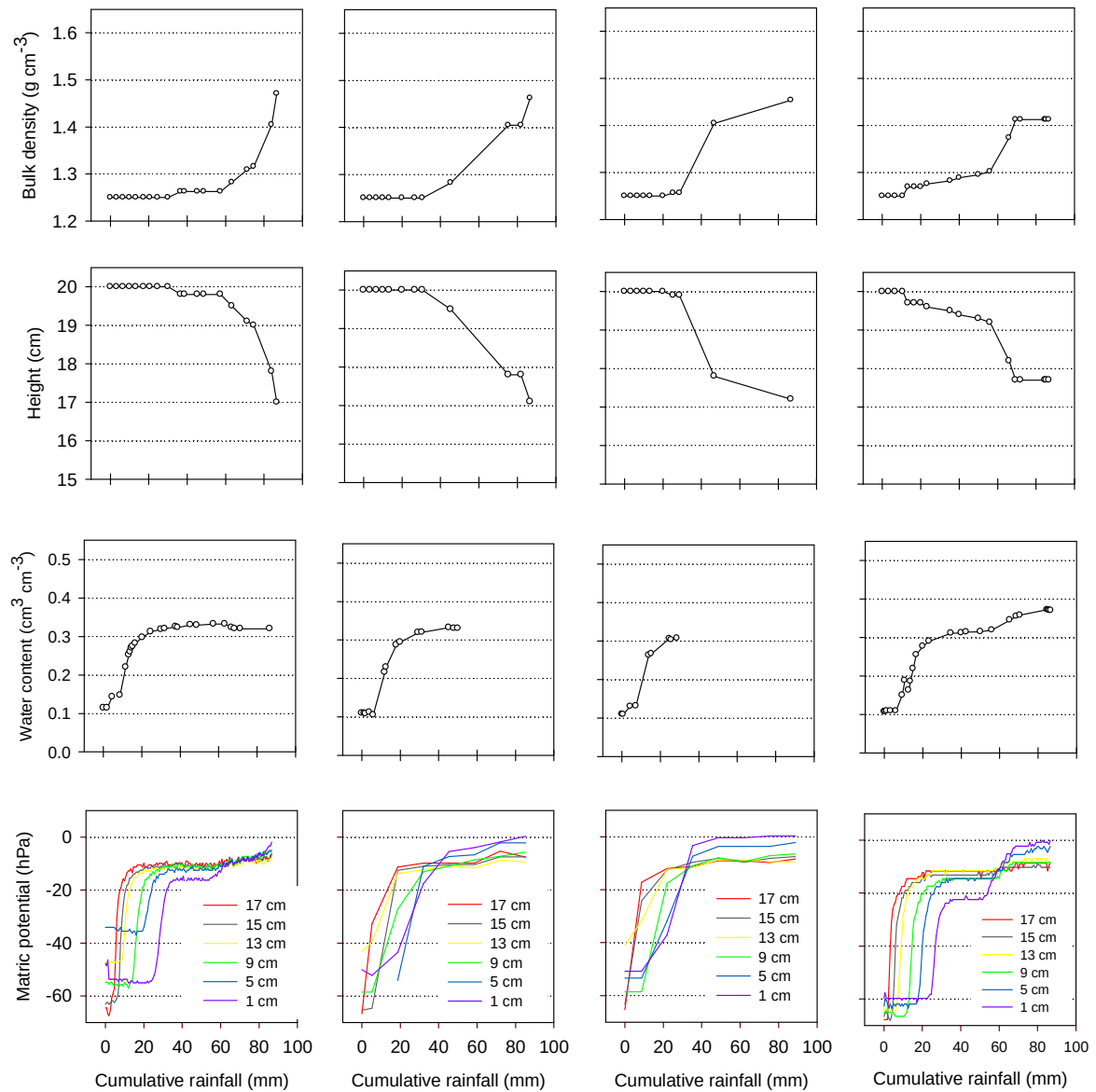


Figure 6-38 Changes during rainfall: a) The average bulk density b) soil height, c) average volumetric water content, d) soil water matric potential. The cylinder was put on water table with suction at 20 hPa, with rainfall intensity at 40 mm h⁻¹. The rainfall amount was 87 mm. Here three replicates are presented.

60 hPa



0.10 g g⁻¹ SOIL
 Initial bulk density=1.25 g/cm³
 Suction in water table=60 hPa
 Rainfall intensity=40 mm/h
 20090922-30

Figure 6-39 Changes during rainfall: a) The average bulk density, b) soil surface level decrease, c) average volumetric water content, d) soil water matric potential. The cylinder was put on water table with suction at **60 hPa**, with rainfall intensity at 40 mm h⁻¹. The rainfall amount was 87 mm. Here four replicates are presented.

90 hPa

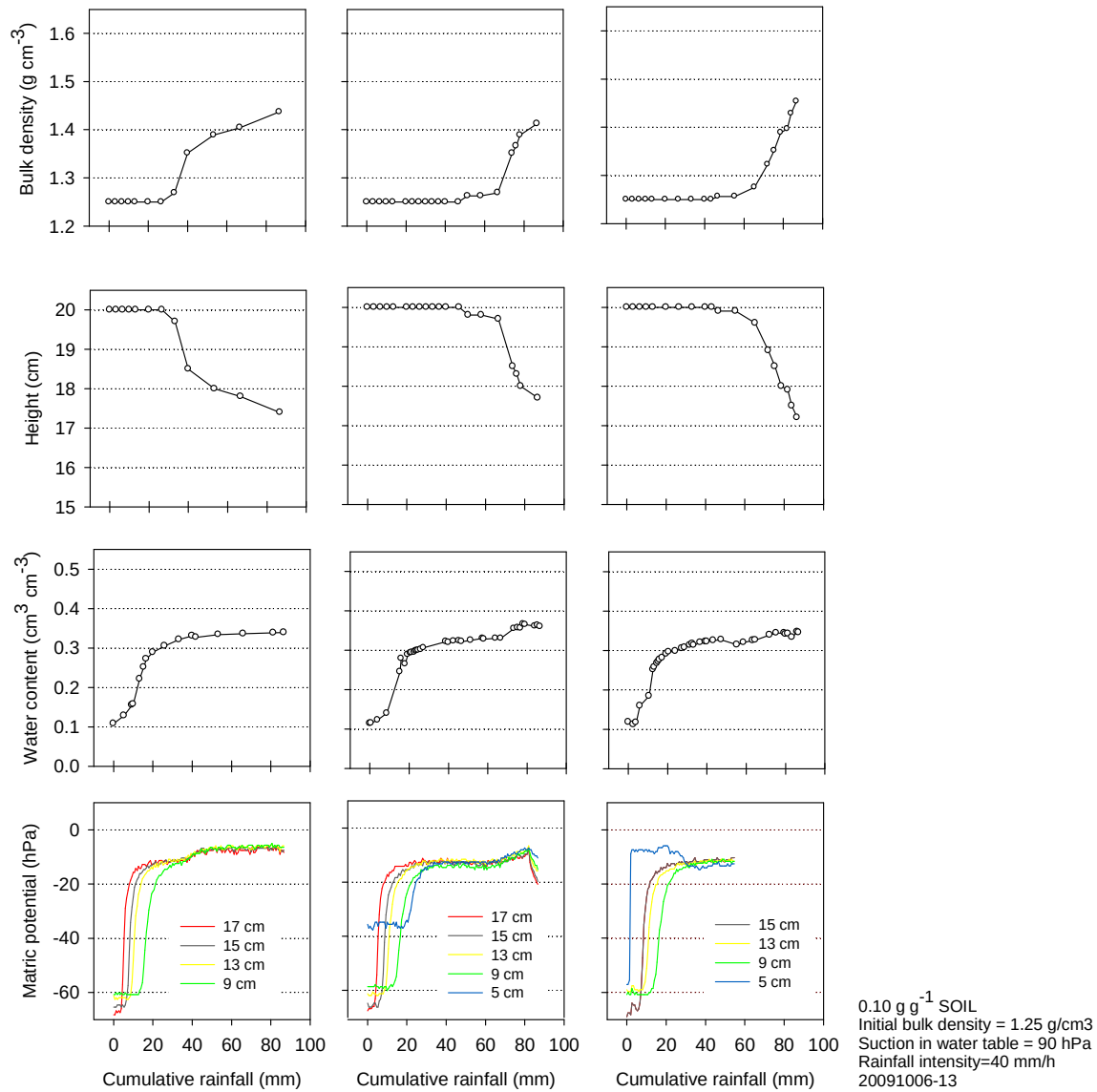


Figure 6-40 Changes during rainfall: a) The average bulk density, b) soil surface level decrease, c) average volumetric water content, d) soil water matric potential. The cylinder was put on water table with suction at 90 hPa, with rainfall intensity at 40 mm h^{-1} . The rainfall amount was 87 mm.. Here three replicates are presented.

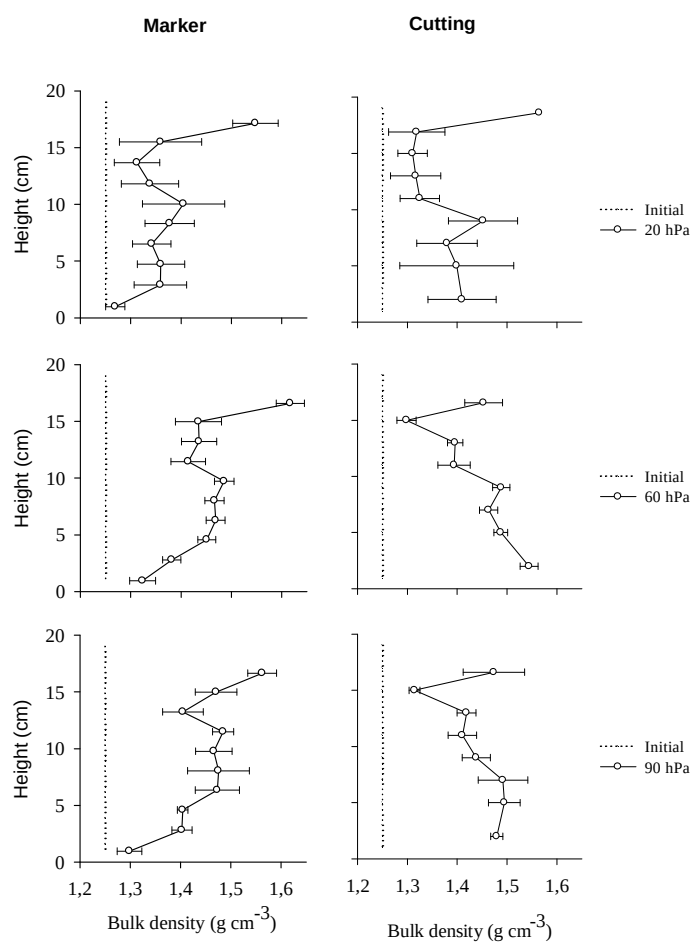


Figure 6-41 The final bulk density at different layers by marker method and cutting method. Error bars indicate standard error (SE) of the means (n=3 for 20 hPa and 60 hPa, n=4 for 90 hPa).

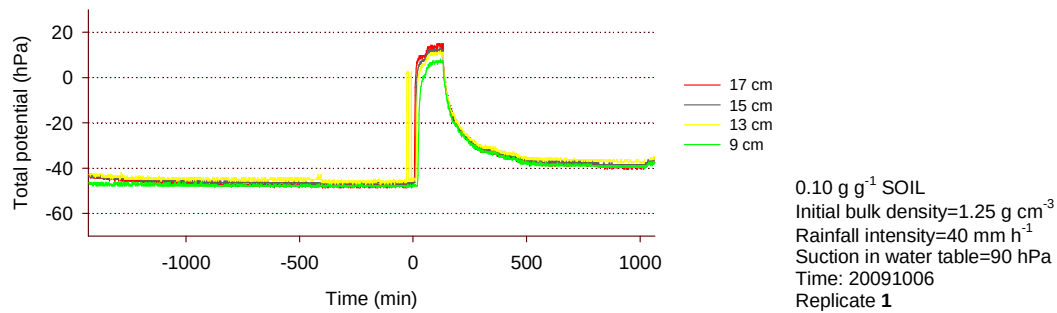


Figure 6-42 The total potential before, during and after simulated rainfall of one replicate on 90 hPa suction table. It demonstrate the equilibrium was reached as the values for different depth were very similar. The total potential is the sum of matric potential and gravitational potential (the arbitrary reference level is set as the bottom of cylinder at 0).

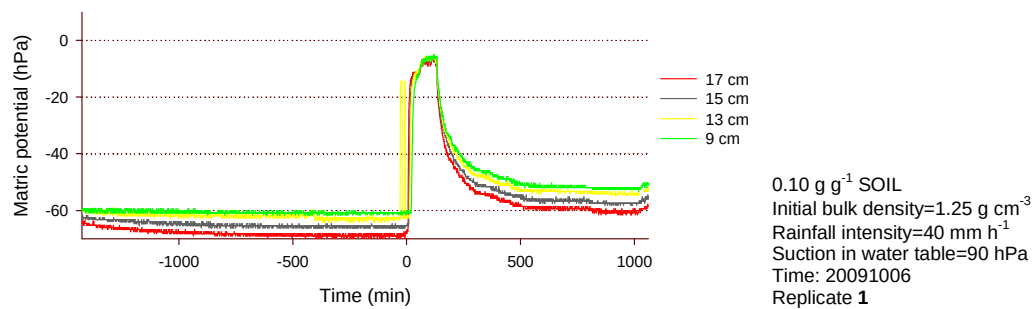
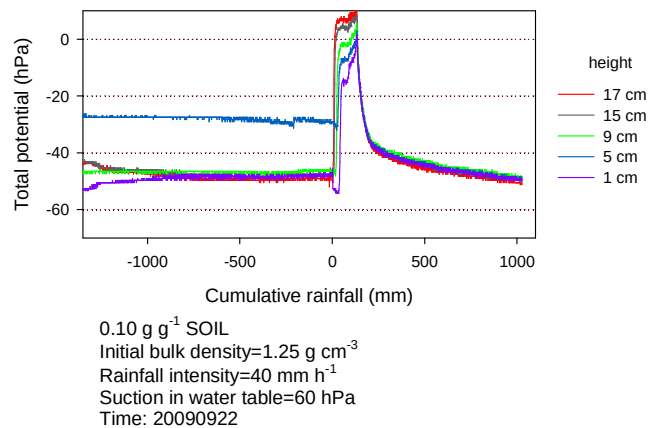
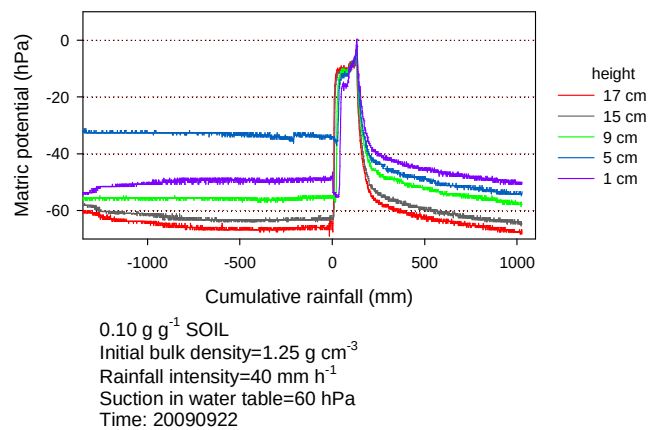


Figure 6-43 The matric potential before, during and after simulated rainfall of one replicate on 90 hPa suction table. It demonstrates the water move from the top to the bottom during equilibrium. The matric potential decrease in the top of 17 cm (more dry), which means the water moves from the top to the bottom.



Height was count from bottom as 0

Figure 6-44 The total potential before, during and after simulated rainfall of one replicate on 60 hPa suction table. It demonstrates the equilibrium was reached as the values for different depth were very similar. The total potential is the sum of matric potential and gravitational potential (the arbitrary reference level is set as the bottom of cylinder at 0).



Height was count from bottom as 0

Figure 6-45 The matric potential before, during and after simulated rainfall of one replicate on 60 hPa suction table. It demonstrates the water move from the top to the bottom during equilibrium. The matric potential decrease in the top of 17 cm (more dry), which means the water moves from the top to the bottom.

Table 6-6 Averaged thickness of the layer (cm) recorded with the marker method and averaged mass of soil material present in each ring recorded with the cutting method (g). (n=3 for 20 and 90 hPa, n=4 for 60 hPa)

Soil material under a rainfall of 40 mm h ⁻¹ submitted at the bottom cylinder to a suction of:							
		20 hPa		60 hPa		90 hPa	
		Average	SE	Average	SE	Average	SE
Averaged total height (H) and associated standard error (cm)							
		18.4	0.5	17.3	0.13	17.4	0.15
Averaged thickness of the layer and associated standard error (cm)							
Marker	Layer (n°)						
	10	1.6	<0.1	1.6	<0.1	1.6	<0.1
	9	1.9	<0.1	1.7	<0.1	1.7	0.1
	8	1.9	<0.1	1.8	<0.1	1.8	<0.1
	7	1.9	<0.1	1.7	<0.1	1.7	<0.1
	6	1.8	0.1	1.7	<0.1	1.7	0.1
	5	1.8	<0.1	1.7	<0.1	1.7	0.1
	4	1.9	<0.1	1.7	<0.1	1.7	<0.1
	3	1.8	<0.1	1.8	<0.1	1.8	<0.1
	2	1.8	<0.1	1.9	<0.1	1.8	<0.1
	1	2.0	<0.1	1.6	<0.1	1.9	<0.1
Averaged mass of soil material and associated standard error (g)							
Cutting method	Ring (cm)						
	18-20	-	-	-	-	-	-
	16-18	401	*	461	*	540	*
	14-16	767	1	730	6	729	6
	12-14	792	12	766	4	787	10
	10-14	833	14	788	15	783	16
	8-10	808	4	827	14	798	16
	6-8	806	21	815	14	828	28
	4-6	823	3	823	10	829	18
	0-4	1706	6	1726	11	1642	7

-: empty ring

*: high variability because the rings were partially filled

Table 6-7 Averaged bulk density (g cm⁻³) calculated by the marker method and averaged bulk density (g cm⁻³) calculated by averaged mass of soil material present in each ring recorded with the cutting method (g).

Soil material under a rainfall of 40 mm h ⁻¹ submitted at the bottom cylinder to a suction of:							
		20 hPa		60 hPa		90 hPa	
Marker method	Layer	Averaged bulk density of the layer and associated standard error (g cm ⁻³)					
	10	1.55	0.04	1.62	0.03	1.56	0.03
	9	1.36	0.08	1.43	0.05	1.47	0.04
	8	1.31	0.05	1.44	0.03	1.40	0.04
	7	1.34	0.06	1.41	0.03	1.48	0.02
	6	1.40	0.08	1.49	0.02	1.47	0.04
	5	1.38	0.05	1.47	0.02	1.48	0.06
	4	1.34	0.04	1.47	0.02	1.47	0.04
	3	1.36	0.05	1.45	0.02	1.40	0.01
	2	1.36	0.05	1.38	0.02	1.40	0.02
Cutting method	1	1.27	0.02	1.32	0.03	1.30	0.02
	Ring	Averaged bulk density of soil material and associated standard error (g)					
	18-20	1.56		-	-	-	-
	16-X	1.32	0.06	1.45	0.04	1.47	0.06
	14-16	1.31	0.03	1.30	0.02	1.31	0.01
	12-14	1.32	0.05	1.40	0.02	1.42	0.02
	10-14	1.32	0.04	1.39	0.03	1.41	0.03
	8-10	1.45	0.07	1.49	0.02	1.44	0.03
	6-8	1.38	0.06	1.46	0.02	1.49	0.05
	4-6	1.40	0.11	1.49	0.01	1.49	0.03
0-4	1.41	0.07	1.54	0.02	1.48	0.01	

:- empty ring

Table 6-8 Water content (cm³/cm³) at which for slumping started with the soil material during the rainfall experiments (rainfall intensity of 40 mm h⁻¹, total rainfall with 87 mm. The suction on the sand table were different.

		Water content (cm ³ /cm ³)		
Suction	Replicate	0.30	0.31	0.32
20 hPa	Rep4	×		
	Rep5	×		
	Rep6	×		
60 hPa	Rep1			×
	Rep2			×
	Rep3	×		
	Rep4	×		
90 hPa	Rep1			×
	Rep2			×
	Rep3			×

Note: 1. X indicate the slumping began.

1.6 Slumping of Thai sand

With different rainfall intensity

40 mm h⁻¹

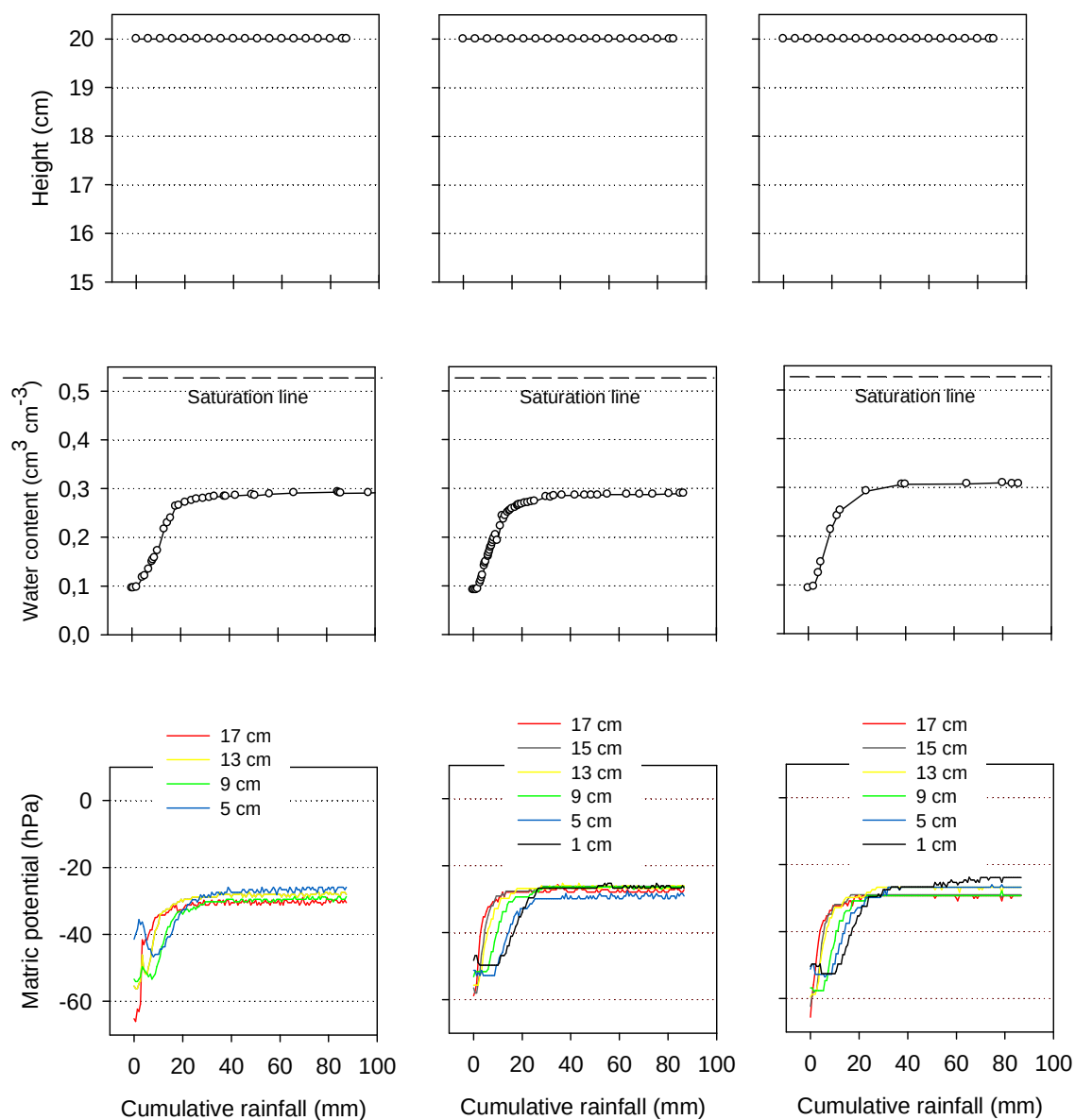


Figure 6-46 Height, water content and matric potential recorded under a rainfall of 40 mm h⁻¹ intensity during 130 min for the triplicate cylinders filled with the sand material and submitted to a bottom suction of 60 hPa. (For Replicate 1, the total rainfall was 200 mm. The data did not change between 87 and 200 mm and therefore was not shown).

60 mm h⁻¹

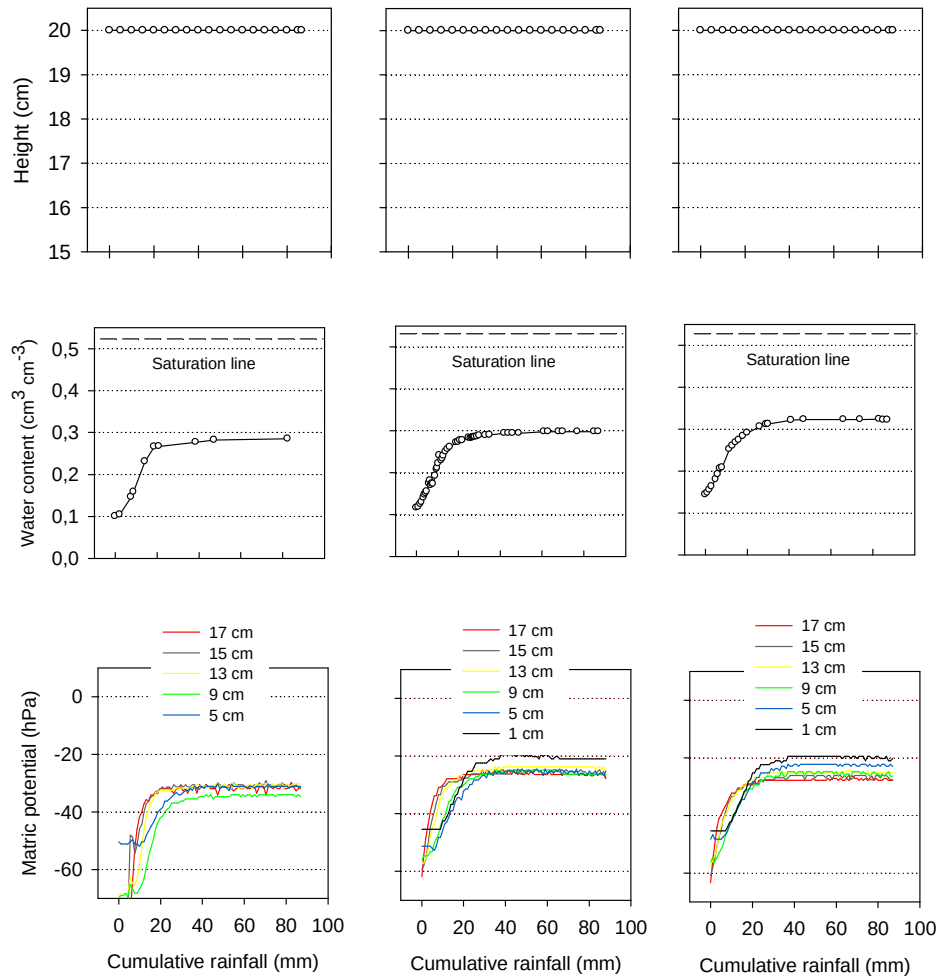


Figure 6-47 Height, water content and matric potential recorded under a rainfall of 60 mm h⁻¹ intensity during 97 min for the triplicate cylinders filled with the sand material and submitted to a bottom suction of 60 hPa.

120 mm h⁻¹

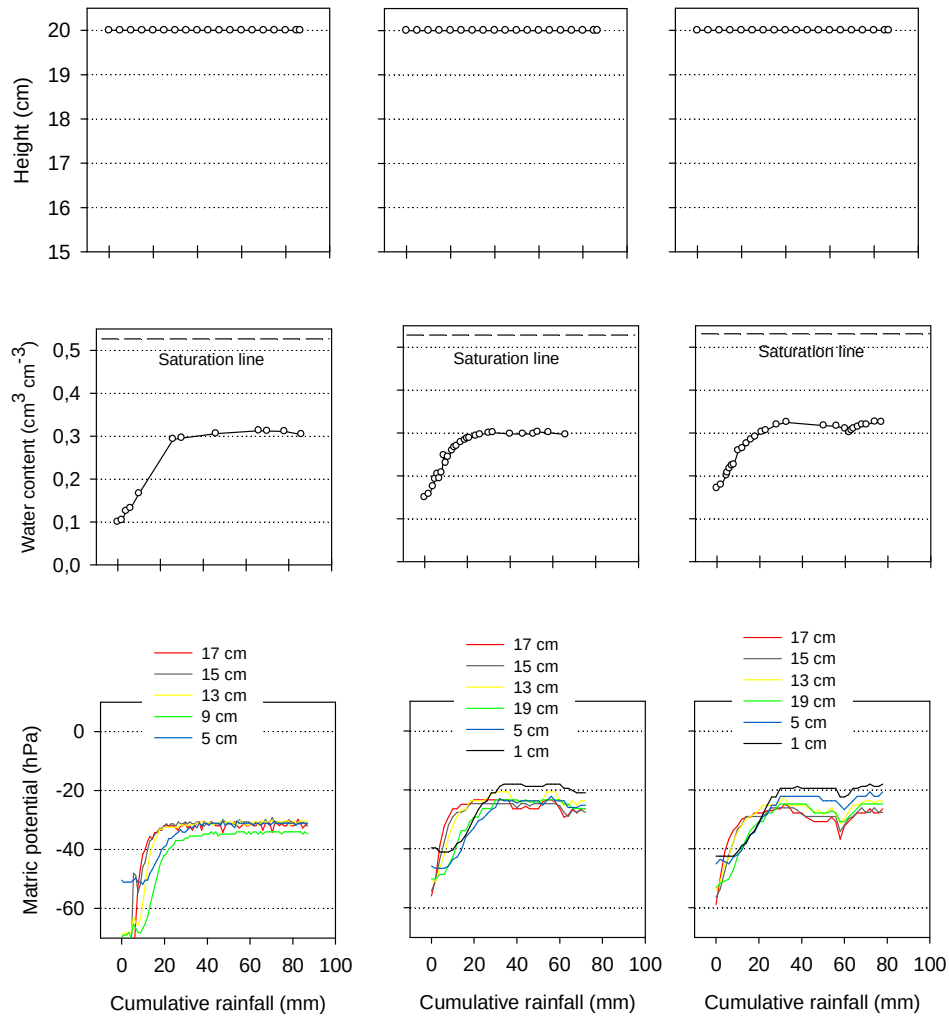
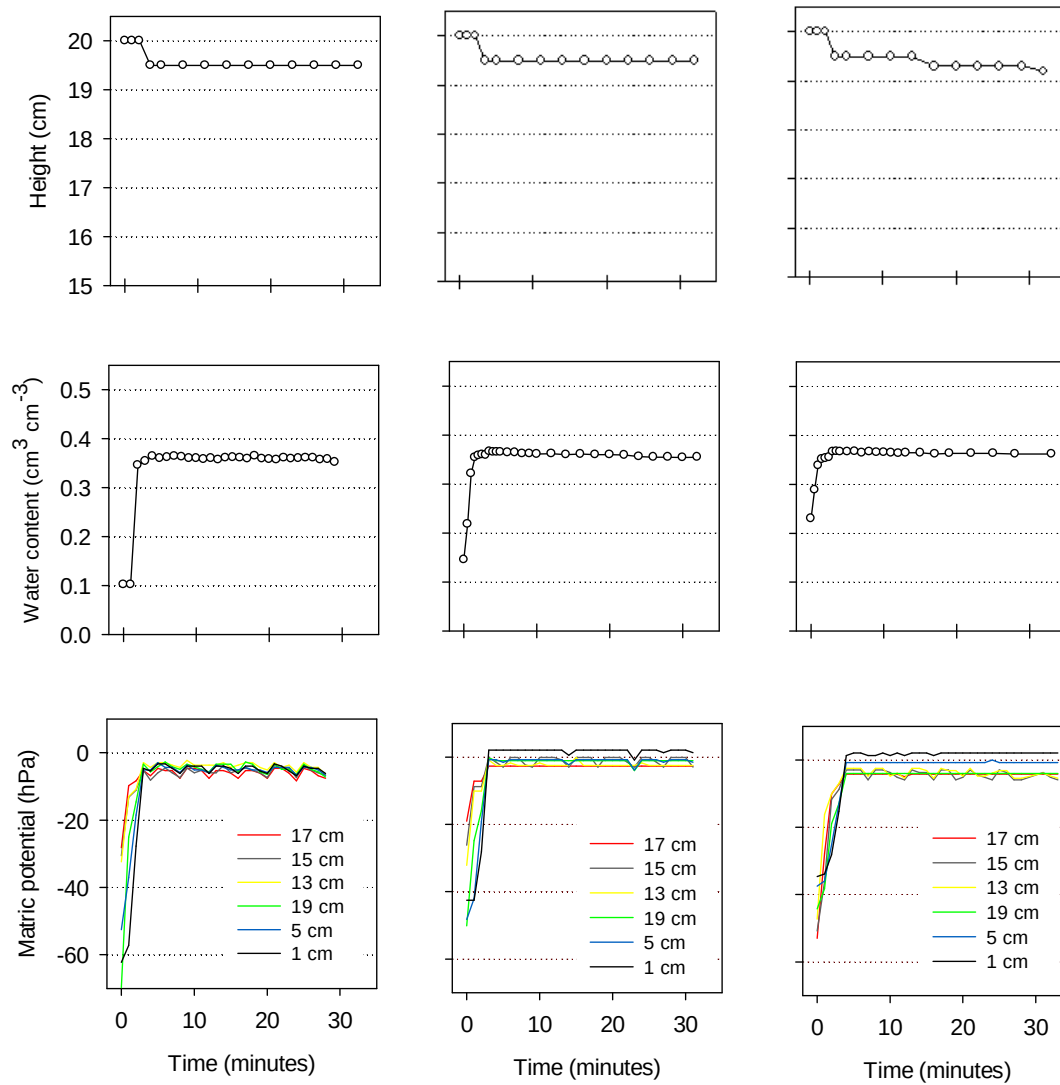


Figure 6-48 Height, water content and matric potential recorded under a rainfall of 120 mm h⁻¹ intensity during 44 min for the triplicate cylinders filled with the sand material and submitted to a bottom suction of 60 hPa.

Flooding



SAND

Initial bulk density= 1.25 g cm^{-3}
 Rainfall intensity=flooding 22 mm× 9 times
 Suction in water table= 60 hPa
 Initial water content=0.1 g/g
 Total adding water=198 mm
 Time: 20091123

Figure 6-49 Height, water content and matric potential recorded during the flooding which followed the three rainfall experiments for the triplicate cylinders filled with the sand material and submitted to a bottom suction of 60 hPa.

Hongtao HAO

Slumping des sols cultivés sableux: processus, facteurs et indicateurs

Résumé

Les sols sableux peuvent constituer une réserve potentielle de sols cultivables mais leur mise en valeur entraîne toujours des dégradations de la structure et une baisse du potentiel agricole. Une dégradation très fréquente est l'affaissement des couches labourées sous l'action de la pluie, ou slumping. Notre objectif était d'identifier les mécanismes et les facteurs déterminants du slumping afin de proposer des techniques de prévention. L'étude a été conduite sous pluies naturelles (au champ) et simulées (au laboratoire). Au champ, la cinétique d'évolution des caractéristiques hydriques et physiques du sol a été suivie après un labour à 20 ou à 40 cm de profondeur, dans un sol sableux tropical Thaïlande. Au laboratoire, un sol cultivé modèle a été élaboré dans un cylindre (h et $\varnothing = 20$ cm) à partir i) du sol prélevé dans le champ expérimental, ii) de la fraction sable ($> 50 \mu\text{m}$) extraite de ce même sol. Les sols modèles ont subi des pluies d'intensité variable (de 20 à 120 mm/h) après mise en place sur une table à succion (20 à 90 hPa).

Le slumping se produit lorsque deux conditions sont réunies: (1) l'eau doit atteindre un potentiel proche de 0 hPa ce qui réduit la cohésion et aboutit à un équilibre fragile du sol comme décrit par la physique des milieux granulaires; (2) ce potentiel doit être maintenu assez longtemps pour qu'une instabilité se produise et entraîne une brusque et importante diminution de la cohésion, donc l'effondrement du matériau. Si la fraction fine ($< 50 \mu\text{m}$) est retirée du sol, aucun effondrement n'est observé, démontrant l'importance de cette fraction limono-argileuse, pourtant minoritaire ($< 10\text{-}15\%$ en masse), dans l'instabilisation et le slumping.

La prévention du slumping et la gestion des sols sableux sont discutées en guise de conclusion.

Mots clés : sol sableux, granulaire, limon, densité apparente, slumping, simulation de pluie, Thaïlande

Slumping of cultivated sandy soils: factors, processes and indicators.

Summary

The sandy soil can serve as a potential reserve for cultivation. However, they are often considered as marginal because prone to have low productivity and problems of structure degradation. One of the degradations is compaction caused by rainfall or irrigation, which is called slumping. Our objective is to identify the processes and factors that affect slumping. The study had been done under natural conditions (field) and simulated conditions (laboratory) respectively. In the field, a tropical sandy soil in Thailand was selected. After 20 cm and 40 cm depth tillage, the dynamic of hydraulic and physical characteristics were measured. In laboratory, a cultivated soil model was build in a cylinder (height and diameter was 20 cm). We used two materials: 1) the original soil from the experiment field site, and 2) the sand fraction ($> 50 \mu\text{m}$) extracted from this soil. These model soils were submitted to rainfalls with different intensity (20 to 120 mm h⁻¹), combined with different suction (20 to 90 hPa) on a suction table which can support the cylinder.

The slumping for soil happens when two conditions were met: 1) the water potential reached a threshold value near 0 hPa. In this value, the soil cohesion decreased and a fragile equilibrium conditions were reached according to granular material theory; 2) the potential value was kept long enough and the cohesion continue decrease until they can no more support the equilibrium, so slumping happens. Surprisingly, in our treatment, when the fine particles ($< 50 \mu\text{m}$) were taken out from the soil, no slumping was observed. This demonstrates the particles of clay and silt are very important to soil stability, even their content were very low as less than 10 percent.

The possible ways to prevent slumping and management of sandy soils are also discussed

Keywords: sandy soil, granular, silt, bulk density, slumping, rainfall simulation, Thailand



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