# Dynamics of Soil Structure as a Function of Hydraulic and Mechanical Stresses

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## Abstract

The dynamics of soil structure is driven by hydraulic and mechanical stresses. Hydraulic stress causes soil swelling and shrinkage during natural wetting and drying. Mechanical load results in soil compaction. In this paper we combined the hydraulic and mechanical stresses by considering shrinkage, moisture release and compaction concurrently. The volume of rigid pores compacted by mechanical stress do not alter soil pore shrinkage capacity. Their shrinkage curves are parallel to each other with an identical coefficient of linear extensibility (COLE) and shrinkage slope, although their structural shrinkage phases narrow with an increase in compaction stress. With different shrinkage properties of rigid and non-rigid pores, we proposed numerical methods to illustrate the bundle of the $e$-$\vartheta$-$\sigma$ relationship as affected by mechanical stress stemming from tillage management, and to model the loaded soil shrinkage behavior. The similarity of soil shrinkage behavior before and after tillage management can be easily assessed regarding the dynamics of soil structure during natural wetting and drying cycles.

## Key Words

Soil shrinkage, soil compaction, water retention curve, soil tillage

## Introduction

For a nonrigid soil, soil porosity (e.g. void ratio, $e$) changes not only with mechanical stress ($\sigma$) but also soil moisture (e.g. moisture ratio, $\vartheta$). The relationship between $e$ and $\vartheta$ is well defined as soil shrinkage behavior, which has in general been studied under load-free conditions. The relationship between $e$ and $\sigma$ is often cited as the soil strain-stress, commonly used in both agricultural and geotechnical engineering to derive soil mechanics parameters. Baumgartl and Köck (2004) summarized the three relationships of $e$-$\vartheta$, $e$-$\sigma$ and $\vartheta$-$\psi$, and addressed a similar behavior between soil deformation and soil moisture release due to hydraulic stress $\psi$ or mechanical stress $\sigma$. However, knowledge of soil shrinkage as affected by soil loading conditions, which involves a bundle of shrinkage curves under mechanical stress, is still unclear. The mechanical stress from tractors occurs rapidly and is removed as soon as the tillage operation is complete. Thus, the soil becomes load-free again after the removal of the stress. Soil pores can be intensively compacted by a heavy agricultural machine in which structural pores or macropores are most susceptible but textural pores remain unaffected. Soil shrinkage is principally induced by the textural pores derived from active clay, rather than by the structural pores. Thus, we hypothesize that this tractor load does not modify soil shrinkage behavior.

## Theory

### Soil volume change by hydraulic stress

The soil volume (e.g., void ratio, $e$) can vary either with hydraulic stress or moisture ratio ($\vartheta$) or with mechanical stress ($\sigma$). The relationship between the change of soil volume and hydraulic stress is defined as soil shrinkage and swelling, generally presenting a sigmoidal curve. In this study, we used a modified van Genuchten equation to fit the relationship between void ratio ($e$) and moisture ratio ($\vartheta$):

$$e(\vartheta) = e_{\mathrm{r}} + \frac{e_{\mathrm{s}} - e_{\mathrm{r}}}{\left[1 + (\chi\vartheta)^{-p}\right]^{q}} \qquad 0 \leq \vartheta \cdot \leq \vartheta_{\mathrm{s}}, \qquad (1)$$

where $\chi$, $p$ and $q$ are dimensionless fitting parameters. Parameter $p$ in Equation 1 is always a positive value. $e_{\mathrm{s}}$ and $e_{\mathrm{r}}$ are the saturated and residual void ratios, respectively, which can be obtained either by measurements or by fitting. In this paper, we used the measured data. $\vartheta_{\mathrm{s}}$ is the saturated moisture ratio. If combining $\chi$, $p$ and $q$ parameters, Equation 1 can be simplified as:

$$e(\vartheta) = e_{\mathrm{r}} + (e_{\mathrm{s}} - e_{\mathrm{r}})k(\vartheta), \qquad (2)$$

where

$$k(\vartheta) = \frac{1}{[1 + (\chi\vartheta)^{-p}]^{q}}. \qquad (3)$$

As discussed in Peng and Horn (2005), $k(\vartheta)$ describes a basic shape of soil shrinkage, depending on the type and the amount of active clay.

*Soil volume change by mechanical stress*

The change of soil volume ($e$) with the mechanical stress ($\sigma$) is termed as soil strain-stress relation or soil compaction in soil science and engineering. The relationship between them is in general a negative exponential as follows:

$$e(\sigma) = e_0 \exp(-b\sigma), \qquad (4)$$

where $e_0$ is the initial void ratio prior to loading. Parameter $b$ is the fitting dimensionless parameter.

*Rigid and nonrigid pores of the soil*

In this paper, we separated total pores ($V_{t.p}$) of a nonrigid soil into rigid ($V_{r.p}$) and nonrigid pores ($V_{nr.p}$) according their shrinkage and swelling capacity.

$$V_{t.p} = V_{r.p} + V_{nr.p}. \qquad (5)$$

Hereby it needs to be pointed out that the 'rigid' of soil pores is not relative to the mechanical stress, but to the hydraulic stress or soil moisture.

*Soil shrinkage under the mechanical stress*

After loading by a mechanical stress, some rigid pores are lost, with macropores being the most susceptible. However, nonrigid pores are less affected, either by regaining structure immediately after stress removal or in the case of a large stress after subsequent wetting under load-free conditions. Therefore, the mechanical stress ($\sigma_i$) from tractor tillage only reduces rigid pores.

$$\Delta V_{t.pi} = \Delta V_{r.pi}. \qquad (6)$$

Then, at a given moisture ratio ($\vartheta$), the loaded void ratio ($e_i(\vartheta)$) is

$$e_i(\vartheta) = \frac{V_{t.p0}(\vartheta) - \Delta V_{r.pi}}{V_s}, \qquad (7)$$

where $V_s$ is the solid volume, independent of stress, $V_{t.p0}$ is the total pore volume of the soil prior to loading. In Equation (7), the subtract component $\Delta V_{r.pi}$ is constant during the entire shrinkage process, because the change of rigid pores is independent of soil moisture. Therefore, the difference of void ratios between the loaded soils before ($e_0(\vartheta)$) and after stress application ($e_i(\vartheta)$) is constant over the whole range of soil moisture.

$$e_0(\vartheta) - e_i(\vartheta) = \frac{\Delta V_{r.pi}}{V_s}. \qquad (8)$$

Owing to no alteration of nonrigid pores, the pore shrinkage capacity ($\zeta$), defined as the first derivative of soil shrinkage, remains identical after loading:

$$\frac{\partial e_i}{\partial \vartheta_i} = \frac{\partial e_0}{\partial \vartheta_0}. \qquad (9)$$

Hereby we introduce the load-shrinkage factor ($\varpi$), defined as the ratio of the loaded to unloaded pore shrinkage capacity at a given moisture ratio. For the tractor-loaded soil, $\varpi(\vartheta, \sigma_i)$ is always 1 over the range of soil moistures.

$$\omega(\vartheta, \sigma_i) = \frac{\zeta_i(\vartheta, \sigma_i)}{\zeta_0(\vartheta, \sigma_0)} = 1. \qquad (10)$$

In Equation (10), the unity $\varpi$ is independent of the mechanical stress and soil moisture. If taking Equation (1) to fit soil shrinkage, an identical shrinkage slope can be defined before and after loaded as follows:

$$(e_{si} - e_{ri})k_i'(\vartheta) = (e_{s0} - e_{r0})k_0'(\vartheta). \qquad (11)$$

In Equation (10), it must be

$$k_i'(\vartheta) = k_0'(\vartheta). \qquad (12)$$

The $k(\vartheta)$, or three parameters of $\chi$, $p$ and $q$, describing the basic shape of soil shrinkage, are independent of the stress. The difference between $e_s$ and $e_r$ is a factor for the magnitude of the pore shrinkage capacity. Their soil shrinkage curves derived from various transient stresses are thus parallel to each other. The only difference between them is a shift of void ratio with a magnitude of $\Delta V_{r.pi}/V_s$. The maximum shift should take place when all rigid pores ($V_{r.p}$) are compacted. Therefore, the loaded soil shrinkage curve can be derived from the load-free soil shrinkage as follows:

$$e_i(\vartheta_i) = e_{r0} - (e_{s0} - e_{si}) + \frac{e_{s0} - e_{r0}}{[1 + (\chi\vartheta_i)^{-p}]^q} \quad 0 \leq \vartheta_i \leq \vartheta_{si}. \quad (13)$$

If the residual void ratio of the loaded soil ($e_{ri}$) is available, Equation (13) can be simplified as:

$$e_i(\vartheta_i) = e_{ri} + \frac{e_{s0} - e_{r0}}{[1+(\chi\vartheta_i)^{-p}]^q} \quad 0 \leq \vartheta_i \leq \vartheta_{si} . \quad (14)$$

In Equation (14), $e_{si}$ is an exponential decay with the applied stress ($\sigma$) (see Equation 4). If combining Equations (4) and (14), the loaded soil shrinkage can be rewritten as:

$$e_i(\vartheta_i, \sigma_i) = e_{r0} - e_{s0}[1 - \exp(-b_i\sigma_i)] + \frac{e_{s0} - e_{r0}}{[1+(\chi\vartheta_i)^{-p}]^q} \quad 0 \leq \vartheta_i \leq \vartheta_{s0} - \frac{\Delta V_{r,pi}}{V_s} . \quad (15)$$

Equation (15) formulates the relation between soil volume ($e$), soil moisture ($\vartheta$) and stress ($\sigma_i$).

**Table 1. Saturated void ratio ($e_s$) of different textural soils after loaded by the mechanical stress.**

| Treatments | Added sand /g kg$^{-1}$ | Clay /g kg$^{-1}$ | Silt + sand /g kg$^{-1}$ | 150 kPa (1.208)[a] | 400 kPa (0.893) | 1400 kPa (0.656) |
|---|---|---|---|---|---|---|
| S 0 | 0 | 649 | 351 | 1.600 ± 0.024[b] | 1.293 ± 0.028 | 1.082 ±0.011 |
| S 1 | 100 | 590 | 410 | 1.522 ± 0.008 | 1.192 ± 0.030 | 0.942 ± 0.017 |
| S 2 | 200 | 541 | 459 | 1.476 ± 0.017 | 1.184 ± 0.022 | 0.930 ± 0.016 |
| S 3 | 300 | 499 | 501 | 1.453 ± 0.009 | 1.144 ± 0.025 | 0.913 ± 0.009 |

[a] Stress followed by the corresponding initial void ratio in parentheses.
[b] Mean saturated void ratio ± standard deviation.

**Materials and methods**
Sieved <2 mm soil samples were added with 0%, 10%, 20%, and 30% clean sand (0.2-0.63 mm) in mass. The four soil-sand admixtures of adding 0%, 10%, 20%, and 30% were defined as treatments of S0, S1, S2, and S3, respectively, in this paper. The soil-sand admixtures were then wetted with distilled water up to a defined water content at the plastic limit. The admixtures were homogeneously repacked by uniaxial compressive loads of 150, 400, or 1400 kPa (Model 5569 series, Instron, UK). It took about 30 sec to reach the desired stress at the speed of 60 mm min$^{-1}$. The stress was released immediately after compacting. Three initial void ratios of 1.208, 0.893, and 0.656 were obtained corresponding to the three stresses (Table 1). Each treatment was in triplicate. During the wetting process, soils swelled to some extent, depending on soil texture and initial void ratio. The addition of sand increased void ratio and decreased swelling (Table 1). The part of swelling soils above the cylinder was cut. The saturated soil samples were then dehydrated successively on ceramic plates at water potential of -3, -6, -15, -30, -50, -100, and -500 kPa. At the water potential more negative than -500 kPa, samples were shifted to air-dry at a room temperature of 20 ± 2°C continuously for 7 d. Measurements were taken on the second day (airdry02), fourth day (airdry04), and seventh day (airdry07). They were then stepwise ovendried at 30, 60, and 105°C. At each step, soil moisture ratios were recorded from mass measurement, and the vertical deformations were measured at 9-points on the soil surface using a caliper gauge. Due to homogeneous samples, the soil-volume changes in this study were assumed to result from isotropic shrinkage. For more details please see Peng *et al.* (2009).

**Results and discussion**
All measured soil shrinkage curves are sigmoidal for the four different soil-sand mixtures, although their starting points of the saturated void ratios are different (Figure 1). The stronger the applied stress, the more the saturated void ratio and the total pore volume were reduced. At a given soil texture, the three soil shrinkage curves, derived from three different transient stresses, were parallel to each other. The only difference was that soils loaded by the stronger stress presented a narrower structural shrinkage phase on the moisture ratio aspect. The coefficient of linear extensibility (COLE), which is defined as the one-dimensional variation of soils between wet and dry states, was not significantly different between the three loaded soils (Figure 2). Figure 2 also shows that their slopes at the inflection point of their shrinkage curves fitted by Equation (1) were identical. This similarity demonstrates that the mechanical stress simulating the tractor load does not alter soil shrinkage behavior.

*Effect of stress on soil moisture release*
The rigid pores reduced by the stress were in general macropores, while the micropores were far less susceptible. Therefore, moisture ratios were smaller at less negative water potentials for the soils loaded by higher stress, but they finally tended to converge together with those of the lightly-loaded soils when the water potential reached more negative than -30 kPa (Figure 3). Consequently, hydraulic properties were different at near saturation as affected by the stress, but they were assumed to be same for the pores which were finer than the pore size equivalent to -30 kPa water potential.
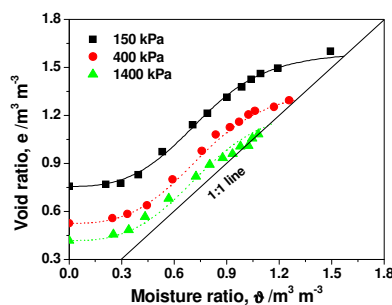
**Figure 1. Example of parallel shrinkage curves loaded by different mechanical stresses (S 0)**
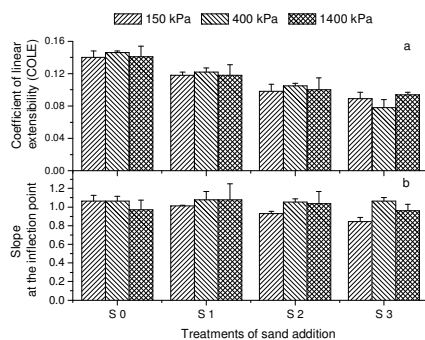


**Figure 2. Effects of mechanical stress on the COLE (a) and the slope at the inflection point (b) of soil shrinkage curves fitted by Equation (1) for the four soil-sand mixtures.**
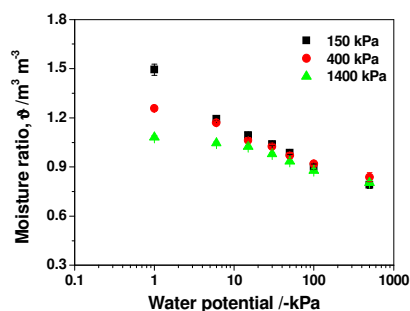


**Figure 3. Example of soil water release curves loaded by different mechanical stresses (S 0)**

## Conclusions

The mechanical stress stemming from tractor tillage management cannot change nonrigid pores but it can compact rigid pores, especially macropores. The change of rigid pores does not modify pore shrinkage capacity, so that the loaded soil shrinkage curves are parallel to each other with identical shrinkage slope and COLE values. Based on these, we developed a numerical model to explain the relationship between soil volume ($e$), soil moisture ($\vartheta$) and mechanical stress ($\sigma$). The soil shrinkage behavior after loading can be predicted. This study improves our understanding of the dynamic of nonrigid soil structure with hydraulic and mechanical stress.

## References

Baumgartl T, Köck B (2004) Modeling volume change and mechanical properties with hydraulic models. *Soil Science Society of America Journal* **68**, 57-65.

Peng X, Horn R (2005) Modeling soil shrinkage curve across a wide range of soil types. *Soil Science Society of America Journal* **69**, 584-592.

Peng X, Dörner J, Zhao Y, Horn R (2009) Shrinkage behaviour of transiently- and constantly-loaded soils and its consequences for soil moisture release. *European Journal of Soil Science* **60**, 681-694.

Richard G, Cousin I, Sillon JF, Bruand A, Guérif J (2001) Effect of compaction on the porosity of a silty soil: influence on unsaturated hydraulic properties. *European Journal of Soil Science* **52**, 49-58.