Geoderma 320 (2018) 115–125

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Models for prediction of soil precompression stress from readily available soil properties

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Pedotransfer function
Bulk density
Matric potential
Soil texture

ABSTRACT

Compaction of the subsoil is an almost irreversible damage to the soil resource. Modern machinery exerts high mechanical stresses to the subsoil, and a range of studies report significant effects on soil functions. There is an urgent need for quantitative knowledge of soil strength in order to evaluate sustainability of current field traffic. The aim of this study was to identify the most important drivers of soil precompression stress, σ_{pc}, and to develop pedotransfer functions for prediction of σ_{pc}. We revisited previously published data on σ_{pc} for a silty clay loam soil at a range of soil matric potentials. σ_{pc} was estimated from the original stress-strain curves by a novel, numerical method for estimating the stress at maximum curvature, assumingly partitioning the curve into elastic and plastic sections. Multiple regression was used to identify the drivers best describing the variation in σ_{pc} data. For the plough layer, σ_{pc} increased with bulk density (BD), which explained 77% of the variation. For the subsoil layer just beneath the ploughing depth, the model best describing σ_{pc} data included the drivers BD and pF, with pF defined as the log to the negative matric potential. The model was strongly significant with $R^2 = 0.90$. The same trend was found for three subsoil layers from 0.35–0.95 m depth, but the model accounted for only 16% of the variation in σ_{pc}. A model involving samples from all soil layers and including BD, pF and soil clay content accounted for 38% of the variation. This model predicted σ_{pc} to be constant at pF ~2 across soil clay contents for a given soil BD. For $\text{pF} < 2$, σ_{pc} was predicted to be higher for sandy soils than for soils rich in clay. In contrast, σ_{pc} increased with clay content for dryer conditions ($\text{pF} > 2$). Model predictions correlated well with measured data in two independent data sets from the literature. However, the predictions were approximately double those of one of the data sets. This may relate to the longer stress application used in laboratory compression tests for these data compared to the other calibration data set and to the procedure used in this study. We encourage further studies of the effect of stress application procedures in compression tests. The prediction equations established in this investigation have to be verified based on measurements of σ_{pc} for a range of soil types, soil horizons and soil moisture conditions.

1. Introduction

Soil compaction has turned into one of the most important threats to soil quality and ecosystem services (Chamen et al., 2015; Schjønning et al., 2016b). This is caused by the steady increase in the weight of machinery used in agriculture (e.g., Vermeulen et al., 2013). The size of tyres has increased simultaneously, but the net effect is a significant increase in the stresses reaching the subsoil (Schjønning et al., 2015). A number of studies have documented considerable levels of vertical stress reaching deep subsoil layers (e.g., Arvidsson et al., 2002; Keller et al., 2002; Keller and Arvidsson, 2004; Lamandé and Schjønning, 2011a, b, c, 2018). Soil strain from machinery loads in the field has been quantified for a range of measurements as summarised by Keller et al. (2012). It turned out that considerable residual (plastic) deformation was frequently observed for soil depths from 0.3–0.7 m. These studies all took place at a water content close to field capacity and included soils with clay contents ranging from 0.18–0.67 kg kg^{-1}. Modelling approaches have also demonstrated that subsoils are at risk of persistent deformation during typical farming operations at moist to wet conditions (e.g., Arvidsson et al., 2003; Duttmann et al., 2014; Gut et al., 2015). It is thus likely that a range of ecosystem services including crop production and mitigation of environmental impacts from agriculture are threatened by modern farming practices (e.g., Berisso et al., 2012; Etana et al., 2013; Schjønning et al., 2013, 2017a).

Soil may deform plastically at isotropic stress or when subject to shear stress (Keller et al., 2007; Koolen and Kuipers, 1983). This depends on the stress components at any point in the soil profile. The full stress field is extremely difficult to measure, especially for soil in an

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https://doi.org/10.1016/j.geoderma.2018.01.028
Received 7 November 2017; Received in revised form 12 January 2018; Accepted 21 January 2018
0016-7061/

undisturbed condition (Horn et al., 1992), and hence our knowledge is meagre. Most risk assessments for agricultural soils are based on a comparison of the vertical stress component with some estimate of soil strength deriving from uniaxial, confined compression tests. Based on civil engineering soil mechanics, a sharp bend of the stress-strain curve from such tests is expected (Hartge and Horn, 1984). The stress at this point is typically labelled the precompression stress, σ_{pc}. According to theory, the strain at stress levels lower than σ_{pc} is supposed to be elastic, while strain above σ_{pc} is plastic. It should thus be safe to expose soil to stresses less than σ_{pc}, and higher stresses should be avoided in order not to affect soil functions (Lebert and Horn, 1991).

Some studies of soil compressive behaviour have used structurally remoulded and - to a variable degree - homogenised soil in uniaxial, confined compression tests (e.g., An et al., 2015; Saffih-Hdadi et al., 2009). This may decrease the variation among replicate samples tested in the laboratory and hence make it easier to identify the driver soil properties regulating σ_{pc}. However, in line with Dexter et al. (1988) we consider the influence of the undisturbed soil matrix as crucial for soil mechanical strength. Quantitative expressions of soil strength for prediction purposes – especially for the subsoil – should thus be based on measurements on minimally disturbed field soil.

Studies have indicated that the laboratory loading characteristics as well as the procedure for calculating σ_{pc} from the stress-strain curve may influence the estimates (Cavalieri et al., 2008; Keller et al., 2004; Rücknagel et al., 2010). This may be one reason why plastic strain and effects on soil pore functions have been observed at stress levels less than σ_{pc} estimated by compression tests in the laboratory (e.g., Keller et al., 2004, 2012; Mosaddeghi et al., 2007). Nevertheless, knowledge of the loading capacity of agricultural fields is urgently needed. Thus, σ_{pc} has received considerable interest as a predictor of threshold mechanical stress in field traffic (e.g., Arvidsson et al., 2003; Duttmann et al., 2014; Horn and Fleige, 2009; Lebert et al., 2007; Rücknagel et al., 2015).

Some studies have tried to predict σ_{pc} using other soil properties (e.g., Lebert and Horn, 1991). However, to be operational, such pedotransfer functions would need to include only readily available soil properties. Some knowledge exists on the influence of basic soil properties. Generally, σ_{pc} is found to increase with soil density (e.g., Lebert and Horn, 1991; McBride and Joosse, 1996; Salire et al., 1994). Berli et al. (2015) reviewed a range of studies that documented increases in σ_{pc} with decreasing matric potential. Compression tests for estimation of σ_{pc} are labour-demanding. Hence, most studies considered above include only few observations and a limited range in density and matric potential. Rücknagel et al. (2012) developed an empirical procedure for estimating σ_{pc} from the soil water content relative to that at -6 kPa matric potential, but knowledge of σ_{pc} at -6 kPa matric potential is often not available.

We recently developed a novel strategy for quantifying σ_{pc} from stress-strain curves with no need to assume any specific mathematical relationship between stress and strain (Lamandé et al., 2017). We showed that this new numerical method provides estimates better reflecting soil's loading history than the typically applied Gompertz approach suggested by Gregory et al. (2006). In the present study, we revisited previously published data on σ_{pc} (Lamandé and Schjønning, 2011c) adopting this new approach. The data include soil samples with a relatively high variation in clay content, density, as well as soil water content/matric potential. The data set thus seems suitable for estimating the relative influence of these soil properties on σ_{pc}. The aim of this study was to acquire new knowledge about the drivers for variation in σ_{pc} as estimated by the new method.

2. Materials and methods

2.1. Soil and field experimentation

An experimental field located at Årup, Denmark (56°28′N, 09°43′E) was used for the studies of stress transmission in the soil profile reported previously (Lamandé and Schjønning, 2011a, b, c). The soil is a silty clay loam developed on diluvial clay and classified as a Stagnic luvisol according to the WRB (FAO) system. The textural composition of the plough layer (0–0.2 m) consisted of ~15% clay (< 2 μm), ~35% silt (2–63 μm), and ~50% sand (63–2000 μm) combined with ~3% soil organic matter (SOM). Generally, soil clay content increased with depth, reaching ~28–40% at 0.9 m depth (Lamandé and Schjønning, 2011a). Due to its geological origin, the Årup soil has no stones. This was one reason for choosing the location for the studies of stress transmission (Lamandé and Schjønning, 2011a). The lack of stones is also beneficial to studies of soil σ_{pc} as it has been shown to be affected by particles > 2 mm (Rücknagel et al., 2013).

As part of the previously reported studies, field plots at different water contents were subjected to experimental traffic. Some plots were tested in the spring at field capacity water content. These were labelled "wet/wet" in Lamandé and Schjønning (2011c) to indicate the generally moist conditions throughout the profile. Other plots were subjected to a period of drought during growth of winter barley (*Hordeum vulgare* L.). Half of these were irrigated with an amount of water sufficient to wet the upper part of the soil profile but not the whole profile (labelled "wet/dry"). The other half of the dry plots was tested with both the topsoil and the subsoil in a dry condition ("dry/dry").

2.2. Sampling and laboratory measurements

Simultaneously with the field traffic experiments, 100-cm^3 soil cores (61 mm inner Ø, 34 mm height) were sampled from the 0.08–0.12, 0.25–0.29, 0.35–0.39, 0.60–0.64 and 0.90–0.94 m depths of uncompacted soil (Lamandé and Schjønning, 2011c). This included eight plots (four plots in each of two field blocks: two plots for the 'wet/wet' treatment and one plot each for the 'wet/dry' and 'dry/dry' treatments). Four cores per depth and treatment were taken to a uniaxial, confined compression test at the field-sampled water content. A strain-controlled stress application was applied as suggested by Koolen (1974) using the technique described by Schjønning (1991). Each compression test contained between 250 and 280 measured points, equidistant in a logarithmic stress scale, to a maximum applied stress of 1000 kPa.

Eight additional soil cores were sampled from each depth. They were saturated with water on tension tables and used for determination of the soil water characteristic with a standard technique at 0.4, 1, 2, 5, 10, 20, 50, 150 and 1500 kPa matric potentials. We revisited this data set (Lamandé and Schjønning, 2011c) for estimating the matric potential of the soil when sampled. For each soil core, the water retention curve was interpolated using a piecewise function composed of a set of polynomials of degree three (Akima, 1970). The soil matric potential at field volumetric water content was derived from the interpolated curve.

2.3. Calculations

Soil water content was expressed by the volumetric water content, θ ($m^3\,m^{-3}$) and the dimensionless water ratio, $WR = \theta / (1 - \Phi)$, where Φ is soil porosity ($m^3\,m^{-3}$). We used Eq. (10) of Schjønning et al. (2017b) to estimate soil particle density from soil content of clay and SOM. Next, Φ was calculated from soil bulk density and soil particle density. WR relates the volume of water-filled pores to the volume of soil solids. It is analogous to the void ratio, expressing the total volume of pores to that of solids. WR has also been labelled the liquid ratio (Hillel, 1980). The soil matric potential was expressed through the pF variable, $pF = \log_{10}(-\psi)$, where ψ is the matric potential in hPa.

In the original article by Lamandé and Schjønning (2011c) σ_{pc} was estimated using the Gompertz model described by Gregory et al. (2006). In this study, we revisited the raw data from all uniaxial confined compression tests and applied the recently developed numerical method to estimate σ_{pc} (Lamandé et al., 2017). This method consists of