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A simple model to estimate change in precompression stress as a function of water content on the basis of precompression stress at field capacity

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ABSTRACT

Precompression stress is an important criterion in soil mechanics and is often determined at a water content equivalent to a matric potential of −6 kPa. In German-speaking countries, this matric potential corresponds to field capacity. Yet in order to assess the risk of compaction in arable soils, it needs to be known for a wide range of soil water content levels. The site-specific determination of relationships between precompression stress and matric potential or water content is, however, highly labour intensive. Furthermore, previous regression models can only deduce changes in precompression stress depending on water content to a limited extent and not for all values. Alternatively, these models do not directly include precompression stress at a matric potential of −6 kPa as the basis of calculation. Thus the derivation and validation of a simple model are to be presented, which can be used to predict any precompression stress for decreasing soil water content levels. This requires only an initial precompression stress for a matric potential of −6 kPa and the respective soil water content as a percentage of field capacity. The model is based primarily on an analysis of numerous studies in which precompression stress was determined for various matric potentials. Relationships between precompression stress at a matric potential of −6 kPa and the relative water content as a percentage of field capacity at a matric potential of −30 kPa were also derived in the laboratory. These data were used to develop a mathematical model for four soil texture classes, as well as "All texture classes" collectively. This model was tested by way of soil compression tests and the determining of precompression stress at 25 sites. All soil compression tests were initially carried out with a matric potential of −6 kPa. Tests were carried out in parallel to this with greater matric potentials (−10 to −1500 kPa). The accuracy of the modelling approach presented here is good, both in terms of the use of systems of equations for "All texture classes" and for differentiated soil texture classes. In comparison to the regression model for all texture classes, calculation according to soil texture class causes a reduction of the mean absolute errors from 0.15 to 0.11 and of the RMSE from 0.19 to 0.14. Simultaneously, the coefficient of determination and the index of agreement (IA) increase, from 0.54 to 0.67 and 0.92 to 0.95 respectively. Calculation according to different soil texture classes is therefore particularly recommended in the case of applications with high accuracy requirements.

1. Introduction

Precompression stress is an important criterion for soil susceptibility to compaction. In numerous studies, it is determined for a matric potential of −6 kPa (e.g. Peng and Horn, 2008; Peth and Horn, 2006). In German-speaking countries, this matric potential corresponds to field capacity. Often the greatest risk of compaction exists at field capacity because this is the condition where the combined influence of buoyancy and capillary cohesion is smallest. As soil water content decreases, thus precompression stress increases and the overall risk of compaction also decreases. Over the course of the year, soil water content may be subject to considerable fluctuations. This means that for assessments of the risk of compaction in arable soils, and of how to manage these soils, estimates often need to be made of precompression stress for various matric potentials.

For the most part, soil compression tests have hitherto been carried out with various matric potentials, identifying site-specific relationships between precompression stress and matric potential (e.g. Arvidsson et al., 2003; Keller et al., 2004). These tests are highly labour intensive and thus only feasible for a limited number of sites. An alternative to this is the application of the regression functions by Horn and Fleige (2003), which permit a calculation of precompression stress for matric potentials of −6 and −30 kPa. These functions do not however include drier conditions, and a derivation for all values is not possible either. Both these methods, i.e. determining site-specific relationships between precompression stress and matric potential and applying the regression functions by Horn and Fleige (2003), are reliant upon the availability of site-specific water retention curves. If, however, as a reference value only the corresponding water content at field capacity (matric potential −6 kPa) is known,

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and if the actual water content is determined gravimetrically, for example using a disturbed soil sample, then this can only be stated as a percentage of field capacity. This practice is applied in agricultural and agrometeorological consulting, or in the carrying out of simple field tests (Schäfer-Landefeld et al., 2004; Wendling, 1986). What is more, commercial water balance models which are available to a wide range of users (such as that of the German Meteorological Service) tend to show water content as a percentage of field capacity or available field capacity.

The regression functions by Saffih-Hdadi et al. (2009) represent another method of identifying any precompression stress depending on water content. Using these, it is possible to calculate precompression stress for five soil texture classes by means of dry bulk density and the gravimetrically ascertained soil water content. However, studies performed by Arvidsson and Keller (2004), Mosaddeghi et al. (2003) and Semmel and Horn (1995) showed that it is not possible to provide a reliable estimate of precompression stress using dry bulk density alone, because the latter does not allow any conclusions to be made concerning the aggregation within the soil. Thus it is better to use precompression stress at a matric potential of −6 kPa as a direct basis for calculation, if it is only a change in precompression stress depending on water content that is to be identified. Furthermore, this is possible because in recent years numerous studies on precompression stress at field capacity have been carried out in various countries, and also because of the availability of comprehensive soil maps (Cavalieri et al., 2008; Horn et al., 2002). Thus there already exists a broad basis of data which can be used. In order to avoid the drawbacks mentioned of previous approaches, this paper shall therefore present the derivation and validation of a simple, innovative model which can be used to calculate any precompression stress for decreasing soil water content levels in various soil texture classes. This requires only the initial precompression stress for a matric potential of −6 kPa (field capacity) and the respective soil water content as a percentage of field capacity.

The model was deliberately developed to be a simplified, empirical model which would causally link the correlations described in the following sections with each other. As a result, it does not follow the customary mechanistic approach. Overall we feel that an empirical model is more robust. It should be available for use in practical applications, and indeed the model presented here is already widely used, in the REPRO software programme (Rücknagel and Christen, 2009) module concerning the analysis of the risk of soil compaction, as well as in parts of the CANDY C/N simulation model (Franko et al., 2007) and in a testing concept used across Germany to detect the actual risk of compaction in agricultural soils (Lebert, 2010).

2. Materials and methods

2.1. Analysis of data from previous studies

The model is based primarily on an analysis of various scientific literature (e.g. Arvidsson, 2001; Arvidsson et al., 2003; Berli et al., 2003; Horn, 1986; Keller et al., 2004; Lebert, 1989; Nissen, 1998) where precompression stress was determined for a total of 160 samples of natural soils, of varying texture, at matric potentials of −6 and −30 kPa. This analysis serves to help determine the differences in precompression stresses between these two matric potentials.

2.2. Relationships between matric potential and water content

As well as for soil texture classes in the analysis of scientific literature, relationships were derived between precompression stress at a matric potential of −6 kPa and relative water content as a percentage of field capacity at a matric potential of −30 kPa, so that the change in precompression stress could be contrasted with a relative change in water content. The corresponding precompression stress levels were calculated according to Rücknagel et al. (2007) using dry bulk density and aggregate density. Examples shown in this paper are the results for a “Silt Loam” (240 g kg^{-1} clay, 230 g kg^{-1} sand), a “Sandy Loam” (80 g kg^{-1} clay, 660 g kg^{-1} sand) and a “Clay” (460 g kg^{-1} clay, 170 g kg^{-1} sand).

2.3. Soil compression tests

Soil compression tests at 21 sites with natural soils (Table 1) form the basis of the model validation. They come from the topsoil and the subsoil of normal arable land (site code 6.1.–15.2.) and two soil tillage experiments (site code 18.1.–19.3.). These are supplemented by four disturbed samples (site code 21.1.–24.1.). For these, the soil core samples were filled with sieved, field-wet soil of <10 mm aggregate diameter. In the model tests, the clay content varies between 10 and 550 g kg^{-1}, while the sand content ranges between 30 and 960 g kg^{-1}, thus covering a very broad range of texture classes, even if the primary focus is on the soil texture class “Silt Loam”. This is due to the prevalence of the soil texture class “Silt Loam” in the soils from the regions studied.

The soil compression tests were initially performed for each sample at a matric potential of −6 kPa. Tests were carried out in parallel to this with greater matric potentials (−10 to −1500 kPa). The corresponding water contents are given as g kg^{-1} and as a percentage of field capacity (% FC) (Table 2). The loading steps 5, 10, 25, 50, 100, 200, 350 and 550 kPa (and in some cases 1200 and 2500 kPa) were applied in succession to the soil core samples. A relaxation phase occurred after each step. The tests took place in drained conditions with a loading time of 180 min per loading step and relaxation phases lasting 15 min. In previous tests on soils of similar texture classes, for loading times of up to 540 min in comparison to 180 min only very slight increases in settlement were measured. Therefore, settlement can be regarded as largely finished after 180 min. However, how matric potential changed during the soil compression tests was not measured. The stress/bulk density functions served to help numerous independent testing persons

Table 1
Description of the test sites for model validation.

Site code	Site and depth (cm)	Texture (g kg^{-1})			Texture class[a]	SOM (g kg^{-1})
		Clay	Silt	Sand		
6.1.	Neurath III 45–48	150	800	50	Silt Loam	24
7.1.	Fortuna IV 32–35	160	810	30	Silt Loam	22
7.2.	Fortuna IV 55–58	170	790	40	Silt Loam	22
7.3.	Fortuna IV 85–88	130	830	40	Silt Loam	22
9.1.	Pesch 40–43	120	850	30	Silt Loam	7
10.1.	Quellendorf 10–13	110	290	600	Sandy Loam	16
11.1.	Herrengosserstedt I 18–21	220	650	130	Silt Loam	–
11.2.	Herrengosserstedt I 32–35	240	630	130	Silt Loam	–
11.3.	Herrengosserstedt II 12–15	440	440	120	Silty Clay	–
11.4.	Herrengosserstedt II 25–28	550	370	80	Clay	–
12.1.	Uchtdorf 19–22	30	140	830	Loamy Sand	19
12.2.	Uchtdorf 35–38	10	30	960	Sand	4
13.1.	Lossa 2–5	150	690	160	Silt Loam	17
14.1.	Hemleben I 9–12	460	370	180	Clay	–
15.1.	Rothenberga I 14–17	60	830	110	Silt	22
15.2.	Rothenberga II 17–20	130	820	50	Silt Loam	22
18.1.	Lückstedt I 17–20	40	210	750	Loamy Sand	13
18.2.	Lückstedt II 17–20	40	210	750	Loamy Sand	12
19.1.	Buttelstedt I 15–18	310	640	50	Silty Clay Loam	32
19.2.	Buttelstedt I 45–48	270	650	80	Silty Clay Loam	10
19.3.	Buttelstedt II 15–18	310	660	30	Silty Clay Loam	34
21.1.	Halle I 15–25	80	260	660	Sandy Loam	21
22.1.	Hemleben II 15–25	500	380	120	Clay	36
23.1.	Niestetal 15–25	130	800	70	Silt Loam	16
24.1.	Seehausen 15–25	120	450	430	Loam	22

SOM — soil organic matter.
[a] USDA classification scheme (Gee and Bauder, 1986).