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Soil & Tillage Research xxx (2006) xxx–xxx

Soil & Tillage Research

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Estimating precompression stress of structured soils on the basis of aggregate density and dry bulk density

J. Rücknagel *, B. Hofmann, R. Paul, O. Christen, K.-J. Hülsbergen

Agricultural Public Service Centre Rheinhessen-Nahe-Hunsrück, Rüdesheimer Str. 68, Bad Kreuznach, Germany

Received 20 June 2005; received in revised form 14 February 2006; accepted 3 March 2006

Abstract

In soil mechanics, precompression stress is an essential parameter for estimations of the compaction risk of cultivated land. In order to determine this factor, regression equations were developed. They require various input variables of water and air regime, dry bulk density as well as the shear strength parameters c and φ. In this paper, we propose a regression model, which estimates the precompression stress from the two parameters dry bulk density (BD) and aggregate density (AD). The experiments were conducted on various structured arable soils in Germany. Altogether 25 natural soils and seven disturbed substrates were examined with three to seven replications. On all sites, precompression stress ($\log \sigma_P$) was determined by means of stress–strain measurements under drained conditions and a matric potential of -6 kPa. The same samples were used for estimating the dry bulk density. Parallel to this, density measurements of aggregates with a diameter of 8–10 mm were made at a matric potential of -6 kPa. Aggregate density and dry bulk density were put into a relation (AD/BD ratio). This quotient shows the state of the inter-aggregate pore system and thus the load-support strength between the aggregates. A multiple linear regression equation of simple design allows to determine the level of precompression stress using the input variables AD/BD ratio and dry bulk density. Precompression stress rises with increasing dry bulk density. An increasing AD/BD ratio leads to a decline of precompression supposing the density values remain constant. The model produced good agreement with the measured values. The determination coefficient of the regression function was 0.84, the mean absolute error (MAE) 0.12 and the root mean square error (RMSE) 0.14. The index of agreement according to Willmot [Willmot, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63 (11), 1309–1313] was 0.95.

Keywords: Precompression stress; Aggregate density; Dry bulk density; AD/BD ratio

1. Introduction

An important subject in soil-physical studies is the wheeling of heavy farm machines over arable soils and the resulting impact on the soil structure (Alakukku, 1996; Arvidson, 2001; Horn et al., 2003; Schäfer-Landefeld et al., 2004). Often, the intensity of precompression of such soils is compared with measured or estimated loads in order to get information about the risk of compaction (Gysi, 2000; Arvidson et al., 2001; Trautner and Arvidson, 2003; Berli et al., 2004). Precompression stress can be determined in the laboratory using soil compression tests on samples collected with soil cores. Topp et al. (1997) describe that precompression stress is equal to the maximum pressure that affected on the soil in the past. In the topsoil, it is the result of the pressure exerted by machine traffic, soil-loosening operations and aggregation due to drying and shrinking processes, frost impact and biogenic aggregate formation. In the subsoil, precompression strength is caused by the weight of the above soil layers in addition to the pressure exerted by vehicles,

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* Corresponding author. Tel.: +49 345 5522655.
E-mail address: jan.ruecknagel@gmx.de (J. Rücknagel).

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doi:10.1016/j.still.2006.03.004

aggregation processes and sometimes previous glacial load. Precompression stress characterises the load-support stability of the soil.

Regression models for estimating precompression stress were developed by Lebert (1989) and Nissen (1998). The equations by Lebert (1989) (described by Horn and Fleige, 2003) are based on studies on 37 arable sites in Bavaria. Depending on the soil textural class, five regression equations were used for matric potentials of −6 and −30 kPa, respectively. Input variables were: dry bulk density, air capacity, available water capacity, permanent wilting point, saturated water conductivity, organic matter content and the shearing parameters cohesion and angle of internal friction. For a number of textural classes, the shearing parameters can be estimated considering the form of the aggregates. Nissen (1998) developed different regression equations for the soil classes "sands and silts" and "loams and clays". Those equations were base on matric potentials of −6 and −30 kPa on 25 sites all over Germany. The input variables of these equations include the shearing parameters: cohesion and angle of internal friction, dry bulk density, content of organic matter, sand or clay content, permanent wilting point and available field capacity. Test estimates of both regression models in different regions of Germany produced varying and mostly insufficient accuracy levels of precompression stress. While Paul (2004) ascertained good congruence of the measured values of precompression stress and those obtained with the equations according to Lebert (1989) on Thuringian Haplic Phaeozems, Haplic Albeluvisols, Haplic Cambisols and Eutric Vertisols, large deviations were recorded on sites in Bavaria with a great number of different soils (Schäfer-Landefeld and

Table 1
Description of the test sites

Site no.	Site and depth (cm)	Taxonomy[a]	Texture ($g\ kg^{-1}$)		BD (g/cm^3)	AD (g/cm^3)	AD/BD ratio	log σ_P
			Clay	Sand				
1	Marienborn 19–22	Haplic Phaeozem	210	90	1.39	1.58	1.14	1.87
2	Marienborn 33–36	Haplic Phaeozem	220	90	1.31	1.51	1.15	1.68
3	Hechtsheim I 19–22	Chernozem	150	110	1.33	1.52	1.14	1.73
4	Hechtsheim I 33–36	Chernozem	180	80	1.35	1.44	1.07	1.85
5	Hechtsheim II 19–22	Chernozem	150	150	1.21	1.51	1.25	1.38
6	Hechtsheim II 33–36	Chernozem	170	90	1.27	1.44	1.13	1.66
7	Buttstädt I 2–5	Eutric Leptosol	460	170	0.99	1.31	1.32	1.02
8	Buttstädt I 19–22	Eutric Leptosol	460	170	1.36	1.40	1.03	1.87
9	Wöllstein 19–22	Eutric Cambisol	310	230	1.50	1.60	1.07	2.20
10	Wöllstein 33–36	Eutric Cambisol	290	260	1.38	1.55	1.12	2.07
11	Sprendlingen I 19–22	Calcaric Regosol	490	60	1.38	1.37	0.99	2.13
12	Sprendlingen I 33–36	Calcaric Regosol	450	70	1.32	1.31	0.99	2.06
13	Hemleben 19–22	Chernozem	500	120	1.33	1.42	1.07	2.04
14	Hemleben 33–36	Chernozem	530	120	1.30	1.38	1.06	2.14
15	Bad Kreuznach I 19–22	Haplic Luvisol	240	230	1.50	1.62	1.08	1.90
16	Bad Kreuznach I 33–36	Haplic Luvisol	360	200	1.48	1.54	1.04	2.00
17	Bad Kreuznach II 19–22	Haplic Luvisol	240	230	1.31	1.63	1.24	1.34
18	Bad Kreuznach II 33–36	Haplic Luvisol	290	210	1.46	1.63	1.12	1.70
19	Bernburg I 19–22	Chernozem	210	120	1.41	1.57	1.11	1.85
20	Bernburg I 33–36	Chernozem	210	110	1.45	1.56	1.08	1.95
21	Bernburg II 19–22	Chernozem	180	100	1.24	1.55	1.25	1.12
22	Bernburg II 33–36	Chernozem	180	80	1.45	1.56	1.08	1.93
23	Bernburg III 19–22	Chernozem	210	120	1.47	1.64	1.12	1.94
24	Bad Lauchstädt I 19–22	Chernozem	210	110	1.38	1.62	1.17	1.46
25	Bad Lauchstädt II 19–22	Chernozem	210	110	1.33	1.57	1.18	1.40
26	Bernburg IV 15–25	Chernozem	200	100	1.27	1.63	1.28	0.97
27	Bernburg IV 15–25	Chernozem	200	100	1.37	1.63	1.19	1.44
28	Bernburg IV 15–25	Chernozem	200	100	1.51	1.67	1.11	2.07
29	Bernburg IV 15–25	Chernozem	200	100	1.66	1.71	1.03	2.06
30	Bernburg IV 15–25	Chernozem	200	100	1.41	1.71	1.21	1.68
31	Buttstädt II 15–25	Chernozem	290	280	1.50	1.64	1.09	2.08
32	Halle 15–25	Luvic Phaeozem	80	660	1.70	1.85	1.09	2.16

BD, bulk density; AD, aggregate density; log σ_P, logarithm precompression stress at −6 kPa matric potential.

[a] FAO (1998).

Brandhuber, 2001) and North-Rhine/Westphalia Stagnic Luvisols (Weyer et al., 2003) between actual values and those simulated with the two regression models.

In view of the uncertainty involved by the available equations and the necessity of having up to eight input variables, a regression model has been developed for a number of structured soils with a matric potential of −6 kPa that considers only the parameters aggregate density and bulk dry density.

2. Materials and methods

2.1. Data acquisition

The background of the studies were 25 samples of natural soils with three to seven replications each, collected in the topsoil and adjacent subsoil layers of cultivated fields (Table 1, nos. 1–14), from tillage experiments (nos. 15–23) and a long-term manure trial (nos. 24 and 25) run in different regions in Germany. The material was complemented by seven disturbed samples with three replications each (nos. 26–32). For the latter, screened soil of <10 mm aggregate diameter was given into the soil core. The investigated soils varied considerably in texture (Fig. 1). The clay content, for example, differed between 80 and 530 g kg^{-1}, the sand content between 60 and 660 g kg^{-1}. On all sites, the skeleton content ranked below 20 g kg^{-1}. Differentiated structural conditions were recorded at dry bulk densities in the range of 0.99–1.70 g/cm^3 and at aggregate densities between 1.31 and 1.85 g/cm^3.

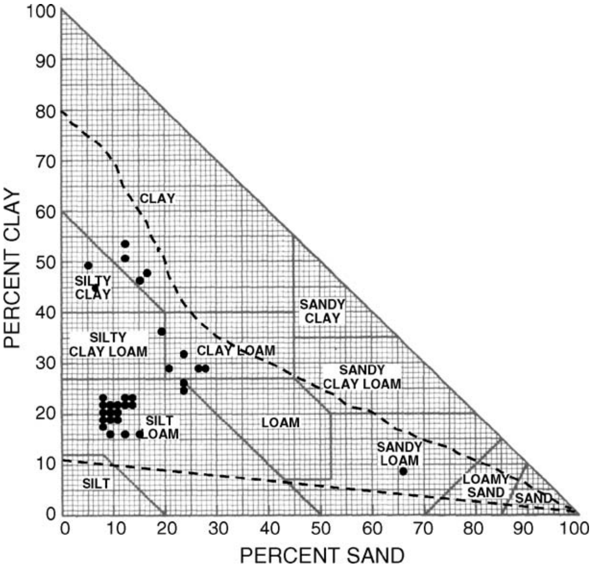

Fig. 1. Particle-size distribution at the test sites and frequent types according to Hartge and Horn (1991) within the broken lines in the USDA classification scheme.

2.2. Soil compression tests

The soil cores used in the compression tests had a diameter of 100 mm and a length of 30 mm. After collecting the soil, the samples got saturated and then adjusted to a matric potential of −6 kPa in a sand box. The applied oedometer (Bradford and Gupta, 1986) was all-automatic, the maximum contact pressure reaches about 600 kPa using a 236 cm^2 loading plate. The settlement was recorded with an accuracy of 0.01 mm. The soil samples in the core were exposed to pressures of 5, 10, 25, 50, 100, 200, 350 and 550 kPa successively. After each loading, a relaxation phase of 1 kPa was observed. Complete relaxation (0 kPa) was not possible for technical reasons. Each loading extended over 180 min with a subsequent relaxation of 15 min. Prolonging the loading time to 540 min on some samples led to minor settlement increases, i.e. by 0.02–0.09 mm. Therefore, settlement can be regarded as largely finished after 180 min. All tests took place under drained conditions. After comparing the settlement (s) after each compression phase with the initial height of the sample in the cylinder (h) and the dry bulk density value (BD) at the beginning of the test, the bulk density after each compression sequence BD_{xi} was calculated.

$$\mathrm{BD}_{xi} = \{(h - s)/h\}^{-1}\mathrm{BD} \qquad (1)$$

The derived equation of the stress/bulk density behaviour of the soil sample served as basis for the determination of precompression stress using the graphic method of Casagrande (1936). According to this method, a tangent and a parallel to the abscissa are drawn at the point of the highest curvature of the stress/bulk density function. The intersection of the bisector of the angle between these two straight lines and the virgin compression line corresponds to the precompression stress, which subdivides the stress/bulk density curve into recompression line and virgin compression line. Slope and position of the straight line can be described by linear equations (Figs. 2 and 3). After drying the sample cores at 105 °C until the sample mass remained constant, the dry bulk density was determined after treatment in the oedometer.

2.3. Determination of aggregate density

Parallel to core sampling for the oedometer tests, distorted soil samples were collected from the same depths. This field-fresh material was carefully dispersed

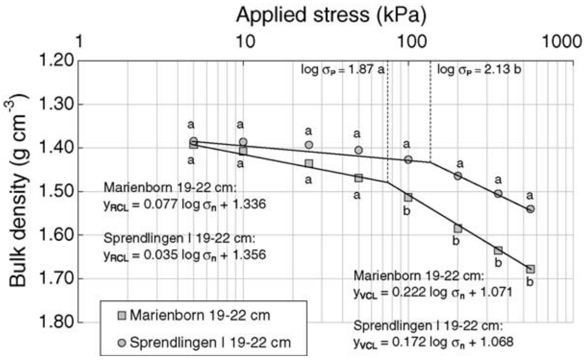

Fig. 2. Logarithm stress/bulk density functions and precompression stress (log σ_P) at two sites of equal dry bulk density and different AD/BD ratios; the different letters for positions and precompression stress indicate significant values $P \leq 0.05$.

through a screen of 20 mm slot diameter, and then the aggregates of 8–10 mm in size were separated. In a sand box the aggregates got saturated and adjusted to the same matric potential (−6 kPa) as used in the samplers of the compression test. In the box, the aggregates were arranged in rings of 50 mm diameter in such a way that each aggregate had contact to the sand. Saturation took place through the capillary suction of the aggregate pores from an about 1 mm thick water film in the sand box. Higher water levels would have increased the danger of aggregate crumbling. When the matric potential was equalized (1 day later), the water content was determined in a portion of each sample (about 10–15 g) by drying it at 105 °C. The second part of the sample (another 10–15 g) was weighed, placed in a fine-meshed screen and dipped in vegetable oil (viscosity 32). The soaked aggregates were spread on filter paper to let excess oil run off. Thus, the aggregate got coated by a thin water-repellent film, with a neglectible effect on the volume. The thus treated aggregates were completely immersed in water. The volume of the displaced water corresponds to their own volume (Archimede's principle). The mass of the displaced water was weighed at an accuracy of 0.01 g. At a water density of 1.0 g/cm^3, it corresponded to the volume of the weighed aggregates.

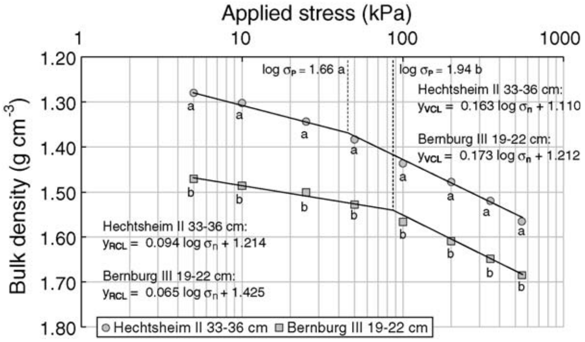

Fig. 3. Logarithm stress/bulk density functions and precompression stress (log σ_P) at two sites of equal AD/BD ratio and different dry bulk density; the different letters for positions and precompression stress indicate significant values $P \leq 0.05$.

Each determination of aggregate density was performed with three replications on a mixed sample of five collections at each site and depth.

2.4. Statistical analysis

The statistical analysis of the data was made by use of the software program Statistica (StatSoft, 2003). The derivation of the regression equation and the determination of the mean value of the replicate measurements based on the log precompression stress, because the test parameter precompression stress displayed a right-leaning frequency distribution if the unit kPa was applied, as shown by the data material of Lebert (1989) and Nissen (1998) (Fig. 4). Executing the calculations in kPa may lead to an overrating of the arithmetic means vis-à-vis the logarithm means or to the occurrence of wider deviations with increasing precompression values when different precompression stress values are to be compared. For evaluating the prognostic accuracy of the developed model, the mean absolute error (MAE), the root mean square error (RMSE), the determination coefficient (R^2) of the regression function and the index of agreement according to Willmot (1982) were used.

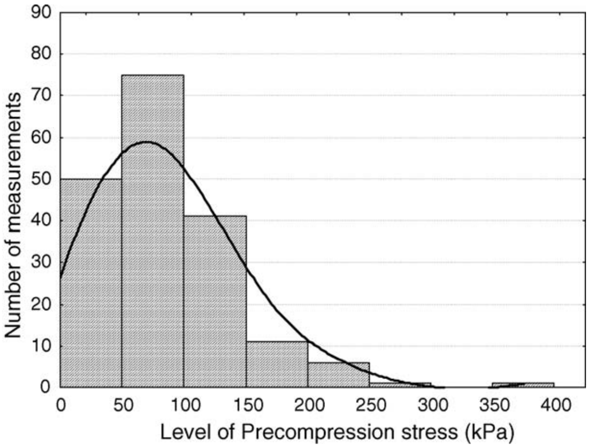

Fig. 4. Frequency distribution of precompression stress in kPa at a matric potential of −6 kPa (measured by Lebert (1989) and Nissen (1998)).

Table 2
Classification of AD/BD ratios

Classification	AD/BD ratio
Very low	<1.05
Low	1.05–1.10
Mean	1.10–1.15
High	1.15–1.20
Very high	>1.20

3. Results

3.1. AD/BD ratio

The AD/BD ratio was calculated as the quotient of aggregate density and dry bulk density. The ratio is a yardstick for the expression of the inter-aggregate pore system and thus also for the density heterogeneity within the soil structure. A classification of the calculated values is possible on the basis of Table 2. A rough estimation of the AD/BD ratio can be obtained by a morphological characterization of the soil structure (Table 3). Very close AD/BD ratios are often coupled with distinct signs of harmful compaction. They occur also in soils with edged and smooth surfaced aggregates (e.g. blocky structures), whose sides face each other. Roundish aggregates (e.g. subangular aggregates) lead to larger AD/BD ratios. They may, however, also be very large in soils that had been intensively operated with loosening implements, irrespectively of the form of soil aggregates. Sometimes, values up to 1.30 have been recorded. Omitting loosening narrows the AD/BD ratio markedly, especially in the lower topsoil.

3.2. Influence of dry bulk density and AD/BD ratio on precompression stress values

The undistorted samples differed clearly in their physical properties. The latter influence the stress/bulk density behaviour and the extent of precompression stress. Two essential effects were observed. In the first case, a similar bulk density of 1.39 and 1.38 g/cm^3, respectively (Fig. 2), was ascertained for the test sites ‘‘Marienborn 19–22 cm’’ and ‘‘Sprendlingen I 19–22 cm’’. However, the locations differ essentially in their aggregate density, which is 1.58 g/cm^3 at ‘‘Marienborn 19–22 cm’’ and only 1.37 g/cm^3 at ‘‘Sprendlingen I 19–22 cm’’. This led to different AD/BD ratios of 1.14 and 0.99, respectively. While the site ‘‘Marienborn 19–22 cm’’ has a medium inter-aggregate pore system with semi-open to open aggregate positioning, no inter-aggregate pore system is evident in ‘‘Sprendlingen 19–22 cm’’ with its dense aggregate arrangement. Due to these structural differences, ‘‘Marienborn 19–22 cm’’ has a rising slope of the recompression line, which implies an increasing dry bulk density with rising contact load in the recompression sector vis-à-vis ‘‘Sprendlingen I 19–22 cm’’. The virgin compression line for the site ‘‘Marienborn 19–22 cm’’ is dislocated by about 0.10 g/cm^3 towards larger density values. It is mainly this shift that reduces the precompression stress level from 2.13 (‘‘Sprendlingen I 19–22 cm’’) to 1.87 (‘‘Marienborn 19–22 cm’’). In this example, the degree of precompression depended on the AD/BD ratio at equal initial density.

In the second case, a similar AD/BD ratio of 1.13 and 1.12 was obtained for the sites ‘‘Hechtsheim II 33–36 cm’’ and ‘‘Bernburg III 19–22 cm’’, respectively (Fig. 3). Thus, the inter-aggregate pore system showed the same moderate development stage in both locations. However, at the test site ‘‘Bernburg III 19–22 cm’’, dry bulk density and aggregate density was 0.20 g/cm^3 larger, and precompression stress was increased by 0.28 compared to the site ‘‘Hechtsheim II 33–36 cm’’. The higher precompression stress values can again be explained by the position of the virgin compression line. Other than dry bulk density and aggregate density, it

Table 3
AD/BD ratios related to aggregation morphology, aggregate size 8–10 mm

AD/BD ratio	Topsoils (15–25 cm) and subsoils (30–45 cm)
<1.05	Clear coherent aggregation without obvious aggregate forms; closed positioning of blocky structure; signs of severe morphological compaction
1.05–1.10	Blocky structure with semi-open to open aggregate positioning; partially coherent aggregation; subangular aggregates with closed positioning, often occurring in soils whose topsoil was not loosened over many years (reduced tillage)
1.10–1.15	Blocky structure with semi-open to open positioning; subangular aggregates with semi-open positioning, often occurring in the topsoil of soils not loosened for many years (reduced tillage)
>1.15	Blocky structure with open positioning; subangular aggregates with semi-open to open positioning; mostly in soils after intensive mechanical loosening

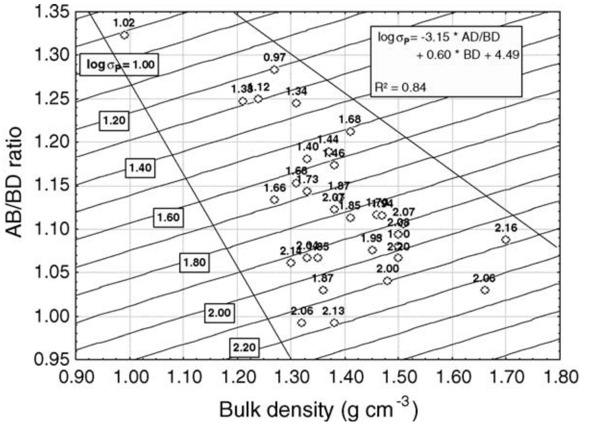

Fig. 5. Determination of precompression stress on the basis of dry bulk density and AD/BD ratio (the area within the broken lines is the defined sector of the tests; the values correspond to logarithm of the measured precompression stress).

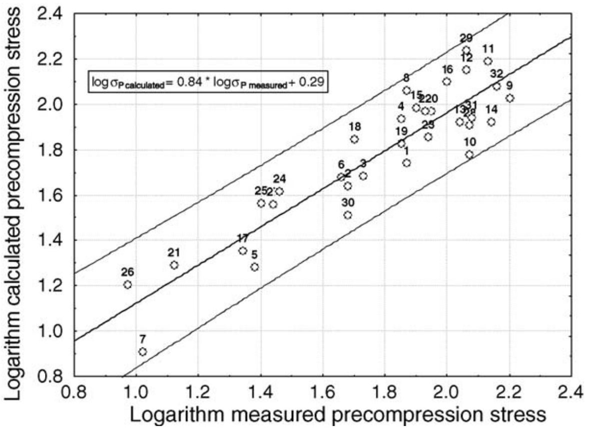

Fig. 6. Measured precompression stress and values calculated with function (2). The number indicates the site. The area between the broken lines shows the calculated values at 95% probability.

was dislocated towards increased density values by some 0.12 g/cm^3 only. The example underlines that increasing dry bulk density involves a rise in precompression stress, even in the case of an equal AD/BD ratio and thus similar positioned aggregates.

3.3. Regression model for estimating precompression stress

When the described effects of dry bulk density and AD/BD ratio are coupled with each other, the precompression stress at the tested sites can be described by use of a simple linear model (Fig. 5; Eq. (2)):

$$\log \sigma_P = -3.15\,\mathrm{AD/BD} + 0.60\,\mathrm{BD} + 4.49, \quad R^2 = 0.84 \tag{2}$$

Increasing AD/BD ratios mean decreasing precompression stress, but increasing dry bulk density at a constant AD/BD ratio stand for a rise in precompression stress. However, the effect of the two input variables is differently strong. While a 0.70 g/cm^3 increase in density throughout the entire data material raises precompression stress by 0.42 only, an enhancement of the AD/BD ratio by up to 0.32 reduces precompression stress by 1.00. In Fig. 6, estimated values have been compared with measured figures. The estimation of precompression stress using Eq. (4) considers the measured values with a mean absolute error (MAE) of 0.12 and a RMSE of 0.14. The index of agreement according to Willmot (1982) is 0.95. The functional curve runs slightly under the assumed 1:1 line. The defined section of the regression model lies within the range of dry bulk density and AD/BD ratio, which is separated by the broken line in Fig. 5. It can be applied to the following soil classes: silty loam, silty clay loam, clay loam, silty clay and clay (Fig. 1). The measured precompression stress ranked between 0.97 and 2.20.

4. Discussion

Precompression stress is a important mechanical parameter, which is often used as a criterion for soil susceptibility to compaction.

Studies by Arvidson and Keller (2004), Mosaddeghi et al. (2003) as well as Semmel and Horn (1995) have shown that reliable estimations of precompression stress merely on the basis of the dry bulk density are impossible, because the latter allows no conclusions about the internal soil structure. Distinguishing between aggregate density and dry bulk density of the entire soil, however, provides information about the heterogeneity of the soil density. Increasing heterogeneity of bulk density involves a decline in the load-support strength between the aggregates. Hartge and Sommer (1982) explained this by the frequency distribution of the number of grain contacts. In a homogenous and not aggregated soil, frequency distribution has only one maximum number of grain contacts. The mean number of grain contacts is decisive for the mechanical stability of the soil. In aggregated soils, frequency distribution has two maxima, the first represents the number of inter-aggregate contacts, the second indicates the intra-aggregate contacts. In this case, the load-support stability of the soil is only insufficiently characterized by the mean number of grain contacts, because the inter-aggregate stability falls below the stability expected from the mean number of grain contacts.

A validation of the regression model with regard to the results obtained by other authors has not been possible, because they measured aggregate density in dried aggregates (Horn, 1986; Schäfer-Landefeld et al., 2004), or one of the required parameters was not communicated (Werner and Werner, 2001; Horn et al., 2003). Drying the aggregates produce changes in the AD/BD ratio depending on the shrinkage properties (Rowell, 1994).

According to Hartge and Horn (1991), the most frequently observed soil texture is that of loams or more or less pure sands. Sandy soils have either granular or coherent structure, and, other than loam soils, they contain no stable aggregate forms, which makes it impossible to apply the described regression model also to these soils. Further experiments are required to determine the exact range of soil texture for a reliable use of the model.

We hypothesis that different reasons may have led to the deviations between the measured precompression values and those simulated by the multiple linear regression model:

1. The conventional determination of precompression stress by means of the graphical method by Casagrande (1936) is not exact because the point of the stress–strain function to which the tangent is created underlies the subjective rating of the testing person. Attempts have been made to improve the technique by computer-aided evaluations (Dawidowski and Koolen, 1994).
2. Too low a number of replications are insufficient for a reliable description of the test site and thus the determination of dry bulk density, aggregate density and precompression stress. This, however, cannot be accepted because aggregate density, dry bulk density and to a certain extent also precompression stress were determined on different soil samples. Due to the large labour requirement for sampling and soil compression tests, often only two (Trautner and Arvidson, 2003) to five (Gysi et al., 1999) replications were made. Predictions of precompression stress, however, should generally include at least five replications. The same sample cores should be used for measuring also the dry bulk density. Determinations of aggregate density as well should purposefully be made with five replications in each depth and test variant. The collected material can be handled as mixed sample and the aggregate density should be ascertained with three replications.
3. The pore geometry exerts a large influence on the compressibility of soils. Soils with a high proportion of vertically oriented pores are less susceptible to compaction than soils with predominantly horizontal pores (Hartge and Bohne, 1983). The AD/BD ratio reflects this fact only insufficiently, because it does not indicate the distribution of the inter-aggregate pore system. The AD/BD ratio is base on the assumption of an isotropic distribution of aggregates and inter-aggregate pore system within a soil sample. However, this is not always true, and thus large proportions of vertically oriented pores with low compaction susceptibility may involve higher precompression stress than expected from the AD/BD ratio.

The advantages of the introduced regression model compared to those developed by Lebert (1989) and Nissen (1998) lies in the advantage that only two input parameters are required. They can be defined with relatively low consumption of time and monetary resources. Apart from a sand box and a pair of laboratory scales the described method for determining the aggregate density requires no expensive or special devices. Handling the sample and measuring the aggregate density with three replications takes roughly 15–20 min only. For measurements of aggregate density, alternative methods are available (Frede and Meyer, 1983; Sarli et al., 2001). Further improvements of the approach might lead to a practice-oriented method for predicting precompression stress of structured soils. Thus, it would become possible to make small-gridded diagnoses of precompression stress on a large number of sites.

5. Conclusions

The described regression model shows good estimates of precompression stress for a number of structured soils considering dry bulk density and AD/BD ratio at a matric potential of −6 kPa. A prerequisite of the new approach is the determination of the aggregate density at a matric potential of −6 kPa. A large number of replications is recommended for measuring precompression stress, dry bulk density and aggregate density, in order to achieve good agreement of measured and computed values. The applicability under different soil conditions requires further investigations.

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