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Comparisons of different procedures of pre-compaction stress determination on weakly structured soils

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Abstract

Compaction is an important component of soil degradation. In this regard, the pre-compaction stress (σ_{pc}) concept is considered useful in mechanized agriculture nowadays. When the external forces exceed the internal strength (σ_{pc}) of soil, soil structure and soil physical quality will deteriorate. This concept was introduced at first for confined consolidation of non-structured, homogenized and saturated subsoils in civil engineering, though it is also suitable for agricultural conditions where the topsoil and subsoil are considered and both are often structured, heterogeneous and unsaturated. The best method for predicting σ_{pc} is by the plate sinkage test (PST) in the field, but it is expensive and time-consuming. This study was conducted to find an alternative laboratory method besides the confined compaction test (CCT) for predicting σ_{pc}. The CCT may not be a good method, especially at higher water contents, and for soils with low organic matter content, because of low sharpness of the critical region on the stress–strain curves. The study was performed on five soil types with a range of soil textures and organic matter content from central Iran using three loading types and three pF (i.e. Log [soil matric suction in cm]) values of 2.3, 2.7 and 2.9 with two replicates. Loading types consisted of CCT, the semi-confined compaction test (SCCT) and the kneading compaction test (KCT) at three maximum (or pre-compaction) stresses of 200, 400 and 600 kPa. The experiment was a completely randomized factorial design. The aim was to determine how accurately each loading type test could predict σ_{pc} of soil pre-compacted by one of the other methods. The applied combinations of CCT–SCCT, SCCT–CCT and KCT–CCT mean that the soil was pre-compacted by the first loading type and evaluated by the second one. The results showed that σ_{pc} and the sharpness of the σ_{pc} region were significantly affected by loading types as well as the soil conditions. The sharpest σ_{pc} region was observed in SCCT and the least sharp in CCT with the overall order being CCT–SCCT > SCCT–CCT > KCT–CCT. The sharpness of the σ_{pc} region was reduced for the soil samples with higher water content and coarser texture. Regardless of the soil and loading conditions, the prediction by SCCT was consistently more accurate than by CCT. The prediction of σ_{pc} by SCCT was more precise in comparison with CCT especially at higher stresses and soil water contents. However, the prediction of σ_{pc} by SCCT was very accurate at pF values of 2.7 and 2.9, and with low σ_{pc} values, when compared with the actual values of the σ_{pc}. For the clay soil at a pF value of 2.3, no pre-compaction region (i.e. zero σ_{pc}) could be determined by CCT at a maximum axial stress of 600 kPa. This was because of the incompressibility of soil water at this near-saturated soil condition at high stress. However, the sharpness of the critical region in SCCT was high enough to predict σ_{pc} satisfactorily. There was no significant difference between the combinations of SCCT–CCT and KCT–CCT in predicting σ_{pc}. The SCCT is a compromise method that lies between CCT and PST. SCCT has the advantage of using a limited and definite soil volume that can be modeled as a soil element. Marginal effects of disturbance caused by coring/sampling as well as pre-test sample preparation seem to have minor effects on the stress–strain curve determined by SCCT in comparison with CCT. Moreover, the soil volume needed for this test is the same as for CCT.

Keywords: Pre-compaction stress; Confined compaction; Semi-confined compaction; Kneading compaction; Sharpness of pre-compaction region; Unstable structure

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1. Introduction

One of the most important factors in soil degradation is soil compaction. The study of constitutive stress-strain curves is very relevant to this. An important point on a soil stress–strain curve is the pre-consolidation stress. The concept of pre-consolidation stress was first defined by Casagrande [1] for consolidating saturated civil soils in confined conditions. Pre-consolidation stress is considered to be a threshold, above which further compaction is considerable and permanent. The concept has entered into agricultural engineering and was named pre-compaction or pre-compression stress (σ_{pc}) of unsaturated agricultural soils [2].

Pre-compaction stress is often used as a criterion for soil susceptibility to compaction. It is an important soil mechanical property that quantifies the soil in terms of compaction history. Pre-compaction stress (σ_{pc}) divides the stress–strain curve into an elastic and a plastic region and may then represent the greatest effective stress that the soil has been subjected to in the past [1]. The concept of σ_{pc} has recently had much interest. It is postulated that by limiting the load to below the σ_{pc}, the risk of additional soil compaction can be minimized and the deformation will be mainly elastic [3]. The concept has been used in soil compaction and tillage researches by using the same method of compaction, i.e. the confined compaction test (CCT), as a simple means of characterizing the behaviour of soil under rapidly increasing principal stress. In an undrained condition of this test, the compaction process will stop when most of the air has been pressed out and the soil has become saturated. In order to simulate the soil behaviour under the wheels, the test must be quick so that sometimes it is named the “quick confined or uni-axial compaction test” [4].

The “sharpness” of the σ_{pc} boundary is a matter of importance. It is important because it can affect the accuracy of σ_{pc} estimation. It seems that this boundary is rather sharp for a structured dry soil, so that the σ_{pc} has a meaningful value. But the boundary may not be sharp for sandy soils and/or soils with low organic matter and low structural stability [5]. When soils are low in organic matter, coarse-textured or weakly structured, bonds between solids are weak in comparison to the inter-granular forces that can be induced by an external compressive load. Under these conditions soil “operations” increase bulk density. The confined compaction test (CCT) is in general close to agricultural practices [4]. However, there is a need to compare other tests in addition to CCT for σ_{pc} evaluation. These tests are kneading tests (like those of Söhne [6] and Lerink [7]), the plate sinkage test (PST) and the triaxial test. In kneading tests, the principal stress directions change, which may have very significant effects for some soil conditions. These direction changes also occur in some agricultural practices. The PST and triaxial test allow soil to be laterally expanded but PST is easier than the triaxial test to perform and can be used in situ.

There is little information on the sharpness of the σ_{pc} region on the stress–strain curve. Eriksson et al. [8] performed CCT on 21 Swedish subsoils but did not find it appropriate to describe their strength by the σ_{pc}. Salire et al. [9] reported the values of σ_{pc} for eight soils under different traffic systems, although in many cases there was no clear stress limit when the soil changed from reversible to irreversible deformation. Arvidsson et al. [10] were not able to determine the σ_{pc} on a sandy soil because of very low sharpness of the critical region. Arvidsson and Keller [11] reported that even high values of σ_{pc} do not mean a low risk for subsoil compaction on Swedish soils. The results showed a gradual transition from elastic to plastic deformation on the stress–strain curves obtained using CCT. Keller et al. [12] did not find a clear relationship between σ_{pc} and compression method. Pre-compaction stress did not work as a threshold between reversible and irreversible deformation when σ_{pc} values were compared with stress and displacement measured in the field during a wheeling experiment. Even when the stress was lower than the σ_{pc}, a plastic displacement was observed. Therefore, σ_{pc} is not a sharp value and the well-known compression tests might not represent the soil behaviour in the field sufficiently well.

It is also uncertain which procedure should be used in order to measure the σ_{pc} value. A test with long loading times, as carried out in civil engineering, will probably give the most well defined results. However, it does not resemble the short-duration application of load that occurs under tires. Another problem is that no unique method exists for deriving σ_{pc} from the stress–strain curve [1,13,14]. Translation of laboratory results to principal stress situations in the field is complicated by the fact that stress duration, stress path and degree of soil confinement appear to have a substantial effect on the level of compactive obtained. Moreover, the directions of the principal stresses change in a soil–wheel system. The compactive behaviour of a specific soil is determined mainly by the maximum principal stress, the stress path, the stress duration and the degree of confinement it is subjected to [15]. It is necessary to include the simple methods that are more similar to these conditions. In agricultural practices, the soil is partly confined under the load and plastic deformation of the soil occurs easily in wet conditions.

It seems that in spite of the feasibility of the well-known CCT in determining soil compressibility, it does not completely describe soil behaviour in the field. There is a need to compare other tests besides CCT for evaluating σ_{pc}. Koolen [15] stated that two processes named “compaction” and “shear” happen in practice. The first causes a volume decrease of soil, through the expulsion of soil air and the second causes deformation through the rearrangement of soil particles or micro-aggregates. Changes in stress direction lead to compaction as well as shear. Söhne [6] also showed that the effect of different loading conditions depend on soil texture as well as water content. The difference between the compaction obtained with his kneading compaction apparatus and CCT was more pronounced in loamy and sandy soils at moderate water contents. In wet soils, the soil distortion without volume change is more significant under kneading compaction [7,16]. There is insufficient information on agricultural soils pre-compacted by methods other than CCT. Alexandrou and Earl [13] successfully used PST as a kind of semi-confined test to determine σ_{pc} of a soil. Dawidowski et al. [17] compared CCT and PST with respect to σ_{pc} prediction. There are difficulties in combining the σ_{pc} concept with kneading compaction methods. One reason may be the irregular shape of soil compacted in a kneading manner and non-homogeneous compacted soil media. There is an urgent need to design laboratory tests that reflect soil behaviour in the field. Thus, it is worthwhile to compare the different loading types and find a suitable method for σ_{pc} determination.

The objectives of this study, that was conducted on weakly structured soils, are: (1) to compare the sharpness of the σ_{pc} region of soils under confined, semi-confined and kneading compaction tests for different soil types and conditions, (2) to assess suitability of a loading type in predicting σ_{pc} of a soil pre-compacted by another test, and (3) to evaluate the consistency of the prediction methods for different soil and loading conditions.

2. Materials and methods

2.1. Soils

Topsoil from five different soil series was collected from Isfahan province in central Iran to include a range of soil textures and organic matter content. These soils are typical soil series in the region. The mean annual precipitation and temperature at the region are about 160 mm and 16 °C, respectively.

The pre-test samples of topsoils were obtained, air-dried and ground to pass a 2 mm sieve for measuring physical and mechanical properties. Particle size distribution was determined using the pipette method. Organic matter content (OM) was determined using the wet digestion method. Field capacity (FC) and permanent wilting point (PWP) were obtained using the pressure plate method. Atterberg limits (liquid limit; LL, plastic limit; PL and shrinkage limit; SL) were determined by the three-point Casagrande method, the 3 mm rod formation and shrinkage mould techniques, respectively. The differences between LL and PL, and between PL and SL were defined as plastic index (PI) and friability index (FI), respectively. Carbonate content of the soils was determined by the acid titration method. Particle density (PD) was measured using the pycnometer method. Classification and some physical and mechanical properties of the soils are given in Table 1.

2.2. Experimental procedure for sample preparation

The experiment was conducted on the topsoil samples (generally 0–200 mm) in the laboratory. Sufficient soil was collected from the ploughed layer with a suitable water

Table 1
Classification (USDA) and some physical and mechanical properties of the topsoil of the studied soils[a]

Soil No.	Soil classification	Sand ($g\,kg^{-1}$)	Silt ($g\,kg^{-1}$)	Clay ($g\,kg^{-1}$)	Texture	OM ($g\,kg^{-1}$)	LL ($g\,kg^{-1}$)	PL ($g\,kg^{-1}$)	PI ($g\,kg^{-1}$)	SL ($g\,kg^{-1}$)	FI ($g\,kg^{-1}$)	FC ($g\,kg^{-1}$)	PWP ($g\,kg^{-1}$)	$CaCO_3$ ($g\,kg^{-1}$)	PD ($Mg\,m^{-3}$)
1	Aquic haplocalcids	127	348	525	C	20	483	240	243	136	104	293	134	301	2.70
2	Typic haplargids	158	502	348	SiCL	10	306	191	115	86	105	258	102	450	2.73
3	Fluventic haplocambids	240	472	288	CL	14	360	181	179	105	76	269	113	341	2.7
4	Typic torrifluvents	532	301	167	SL	9.3	NP	NP	NP	75	–	155	58	328	2.75
5	Not available	432	396	172	L	8	NP	NP	NP	81	–	171	71	316	2.73

[a] USDA soil textural classification: C, clay; SiCL, silty clay loam, CL, clay loam; SL, sandy loam; L, loam; OM, organic matter content; LL, liquid limit; PL, plastic limit; PI, plastic index; SL, shrinkage limit; FI, friability index; FC, field capacity; PWP, permanent wilting point; PD, particle density.

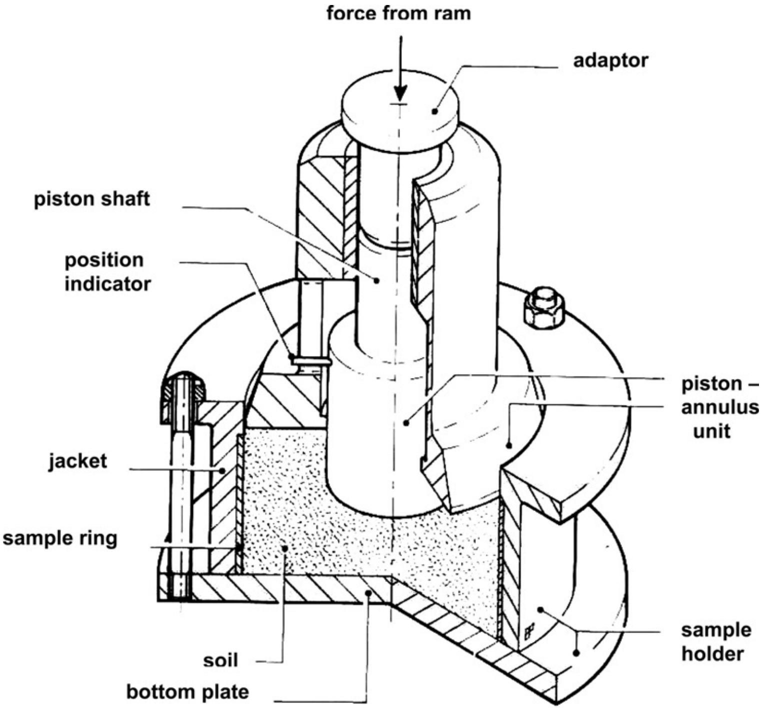

Fig. 1. Schematic diagram of the kneading compaction apparatus (after Lerink [7]).

content (between PL and SL) by composite sampling and great care was taken not to break soil clods and aggregates during sampling. The samples were air-dried and passed through a 10 mm sieve. Soil was poured and knocked lightly into cylinders with diameter and height of 98.6 and 50 mm, respectively. Before soil filling, cloth pieces were tightened by rubber under the cylinders.

The prepared soil cylinders were saturated from the bottom (to prevent air entrapment) for 2 days. Then, the soil cylinders were placed on a sand–kaolin box for adjusting the matric potential to pre-test pF[1] values of 2.3, 2.7 and 2.9 (i.e. matric suctions of 20, 50 and 80 kPa, respectively). The equilibrium time of 5 days was found to be satisfactory. After that, the soil cores were weighed and loaded as defined in the next section. After compaction processes, the soil cylinders were oven-dried for 48 h at 105 °C in order to calculate soil water content and, if necessary, bulk density.

2.3. Loading characteristics

Compaction of the soil cores was accomplished using a Zwick Universal Testing Machine. The machine was fully controlled by a PC through an interface using Xpert software and has several options that can be adjusted for different tests. The master program of Hysteresis and its Staircase loading method were used in order to collect the data on loading, unloading and reloading paths. Pre-load pressure, pre-load speed and loading speed were set, respectively, to 5 kPa, 50 mm min^{-1} and 10 mm min^{-1} for all the tests. It is believed that this strain rate is one order of magnitude slower than strain rates in normal agricultural practices. As a rule of thumb when the loading speed is increased 10 times, a soil mechanical property (e.g. strength) value will increase about 10%. Upper reversal force was pre-set by considering the maximum stress and loaded surface. Three maximum or pre-compaction stress values of 200, 400 and 600 kPa were applied.

Combinations of confined (CCT), semi-confined (SCCT) and kneading (KCT) compaction tests were performed in Lerink's kneading apparatus [7]. A schematic of the apparatus is presented in Fig. 1. It was designed in principle for kneading distortion on wet soil samples without any volume change. It is also possible to conduct the tests by Söhne [6] and Proctor kneading tests, but the degree of deformation cannot be controlled precisely. Moreover, using Söhne [6] and Proctor kneading tests on wet soils does not result in a regular shape of the soil for sampling for further analysis. The aim was to determine the relative accuracy of each method (CCT, SCCT and KCT) in predicting σ_{pc} of the soil pre-compacted by one of the other methods. The applied combinations of CCT–SCCT, SCCT–CCT and KCT–CCT mean that the soil was pre-compacted by the first loading type and evaluated by the second one. The second loading was continued up to 1000 kPa. For CCT, the soil was compacted in the rigid cylinder under a plate fitting inside it until the pre-set σ_{pc} was achieved. The piston stroke of the kneading apparatus was used for SCCT (the loaded area had a diameter of 50 mm in the center of the soil core). Alterna-

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[1] pF = Log[h], where h is the matric suction of the soil with length dimension, i.e. head (cm).

tive strokes of piston and annulus were applied for KCT (see Fig. 2). The strokes of piston and annulus were limited to 20 mm [7], therefore, for some cases of high water content (e.g. a pF of 2.3) and σ_{pc} (e.g. 400 and 600 kPa), it was not possible to apply the exact stresses in one alternative stroke of piston and annulus. Thus, the samples were first brought to a lower stress (e.g. 200 kPa) and then to the desired value of σ_{pc}. For the combinations of SCCT–CCT and KCT–CCT, a Kopecky cylinder (diameter 50 and height 51 mm) was inserted in the center of the soil pre-compacted by the first method (Fig. 2). The reason was due to the fact that the soil in the center (diameter of 50 mm) was mainly compacted [7]. Moreover, reloading by CCT on an uneven surface of the soil pre-compacted by SCCT and KCT was not possible. During the tests, the force was measured as a function of soil sinkage.

From the output of the Universal Testing Machine, stress–apparent strain curves were calculated by dividing the measured force by the loading area and the sinkage by the initial height of the sample. The applied σ_{pc} values were calculated by considering the registered upper reversal force and the loaded area. Since there were two values of σ_{pc} for KCT, the mean value was computed by a weighting formula because the loaded surface of the annulus was three times that of the piston:

$$\sigma_{\text{pc(mean)}} = \frac{\sigma_{\text{pc(piston)}} + 3\sigma_{\text{pc(annulus)}}}{4} \tag{1}$$

where $\sigma_{\text{pc(mean)}}$, $\sigma_{\text{pc(piston)}}$ and $\sigma_{\text{pc(annulus)}}$ are the mean pre-compaction stress and the values of pre-compaction stress under piston and annulus, respectively.

2.4. Prediction of the pre-compaction stress values

Casagrande's [1] method was used in a software program written in MATLAB and followed the procedure of Dawidowski and Koolen [18]. The software package can filter small fluctuations in the experimental results, reduce the data and determine the data pair for which the smallest radius of curvature of axial strain vs. log axial stress (ε_1–$\log \sigma_1$) has occurred (Fig. 3). Then, it characterizes the bisector line (line C) between the tangential line on the

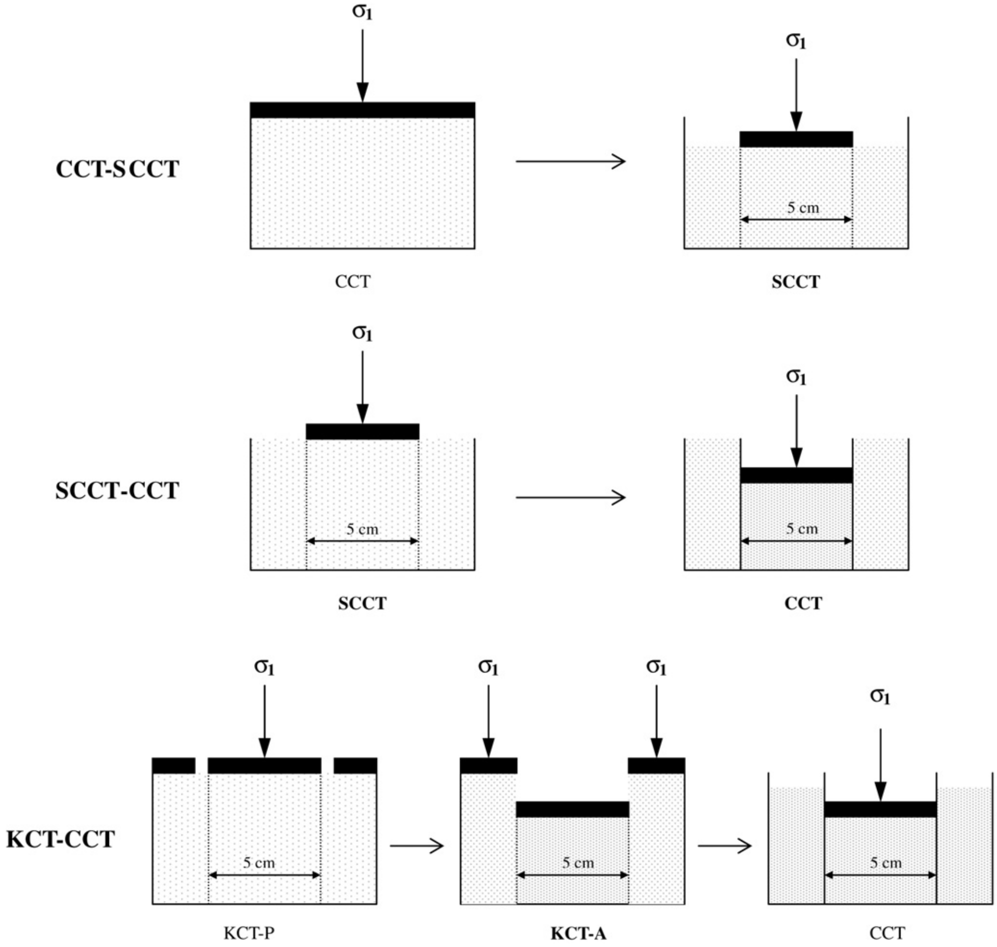

Fig. 2. Schematic of combinations of loading types where CCT–SSCT, SCCT–CCT and KCT–CCT mean that the soil pre-compacted by the first loading type and the pre-compaction stress evaluated by the second one. CCT, SCCT and KCT stand for confined, semi-confined and kneading compaction tests, respectively. KCT-P and KCT-A refer to piston and annulus strokes in KCT.

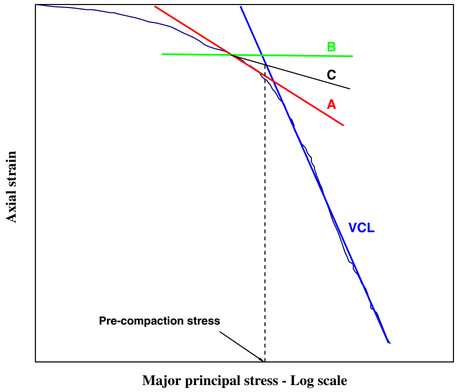

Fig. 3. Determination of pre-compaction stress from the stress–strain curve according to Casagrande [1]. For explanation see the text.

curve at the point of smallest radius (line A) and the horizontal line at this point (line B). Finally, the threshold value (σ_{pc}) can be found from the stress ordinate of intersection of the bisector and the extension of virgin compaction line (VCL).

2.5. Statistical analyses

The experiment was a completely randomized factorial design containing five types of soil, three pF values (2.3, 2.7 and 2.9), three combinations of loading types and three maximum stress or σ_{pc} values (200, 400 and 600 kPa) as the treatments with two replications. Therefore, the total tested soil samples were 240 ($5 \times 3 \times 3 \times 3 \times 2$).

The absolute difference ($\Delta\sigma_{pc}$) between the applied σ_{pc} and the σ_{pc} value predicted by Casagrande's [1] method was used for the analysis of variance. Infact, the value of $\Delta\sigma_{pc}$ represents the prediction error. The mean comparisons were established using the Duncan new multiple range test. All the statistical analyses were undertaken using the SAS statistics software [19].

3. Results and discussion

The analysis of variance showed that the effect of soil type, soil matric potential, maximum applied stress and loading combination as well as their interactions on prediction of σ_{pc} were all very significant ($P < 0.01$). The significant interaction effect of soil type and matric potential implies that the soil intrinsic properties, e.g., texture and organic matter content, might influence the prediction of σ_{pc} at different pF values. Because the soil mechanical properties are not the same among different soils at similar matric potential, the soil type also significantly influenced the effectiveness of loading combinations to predict σ_{pc} at different applied maximum stresses. The interaction between matric potential and loading combination was significant in predicting σ_{pc} due to the dependency of the capability of the loading types on soil water status. Depending on pF value, the maximum axial stress (actual σ_{pc}) has a significant effect on σ_{pc} prediction. Significant interaction between the loading combination and maximum axial stress means that the σ_{pc} prediction by loading combinations depends upon the actual value of σ_{pc}.

3.1. Sharpness of critical region as affected by soil conditions and loading types

The sharpness of the σ_{pc} region is important in determining the σ_{pc} value of a soil. If the sharpness of the critical region is low, determination of the point of maximum curvature [1], and consequently the tangential line at that point, is difficult and the possibility of prediction errors is high. The results showed that the σ_{pc} and the sharpness of σ_{pc} region were significantly affected by loading types as well as soil conditions. The sharpest σ_{pc} region was observed in SCCT and the least sharp in CCT (Figs. 4 and 5). The sharpness of critical region was in the order of CCT–SCCT > SCCT–CCT > KCT–CCT. Results of Dawidowski et al. [17] also showed that VCL for PST is steeper than CCT but there is no difference between them in swelling index (elastic part). Keller et al. [12] reported a higher value of compression index for PST compared to CCT. An index of sharpness could be defined as the quotient of compression index (slope of VCL) to swelling index (slope of over-compacted region). A soil pre-compacted by KCT and reloaded by CCT caused a reduced sharpness of the critical region when compared with a soil pre-compacted by SCCT followed by CCT (Fig. 4). This might be due to a more compact arrangement of the soil under KCT, which will not be compacted significantly during reloading.

In general, the sharpness of the σ_{pc} region reduced when soil water content was higher and soil texture was coarser (see Fig. 5). The sharpness of the critical region was lower for CCT at higher water contents and maximum axial stresses. Thus, no or very low values of σ_{pc} could be defined by CCT especially for high water content and high maximum axial stress because of the extremely gradual change of plastic strain during reloading. This is due to the fact that while compaction is taking place in a confined condition, there is a large increase of stress as the reduction in height approaches a limit imposed by the maximum potential bulk density of the soil. Moreover, confinement of the soil in CCT and the incompressibility of water do not permit more compaction during reloading. In such conditions, little change or an error in the measurement of the stress–strain curve may lead to a large difference in predicted σ_{pc}.

The critical region in SCCT was almost sharp independently of the soil water content (see Fig. 5) and maximum axial stress. This may have been because of the semi-confined condition, which let lateral movement and freedom of the soil particles to rearrange during loading. Furthermore, it will not cause a build-up in the pore water pressure. As shown in Fig. 5, even for the coarser soil at a pF of 2.3, the sharpness of the σ_{pc} region is high when compared with a pF of 2.9. Even with a linear scale of the stress, the σ_{pc} for SCCT can be determined (see the method

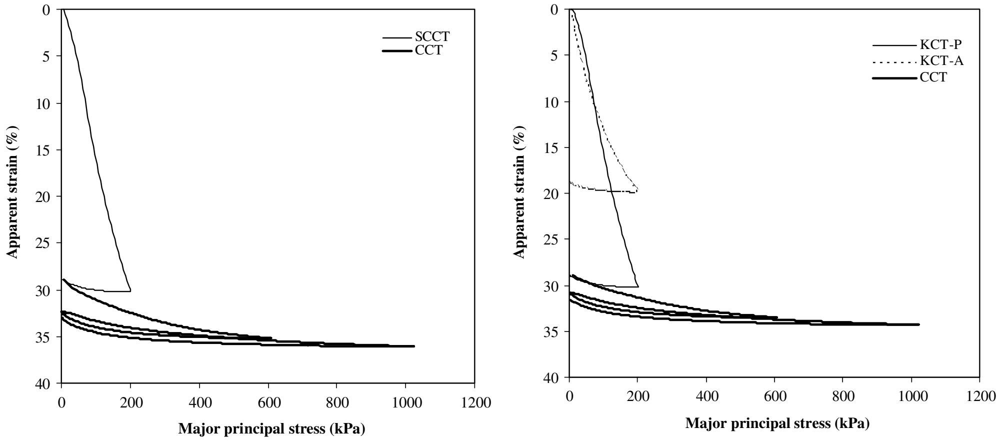

Fig. 4. The sharpness of pre-compaction region as affected by combination of loading types for Soil 1 at pF value of 2.3. KCT-P and KCT-A refer to piston and annulus strokes in kneading compaction test (KCT) and CCT and SCCT stand for confined and semi-confined compaction tests, respectively.

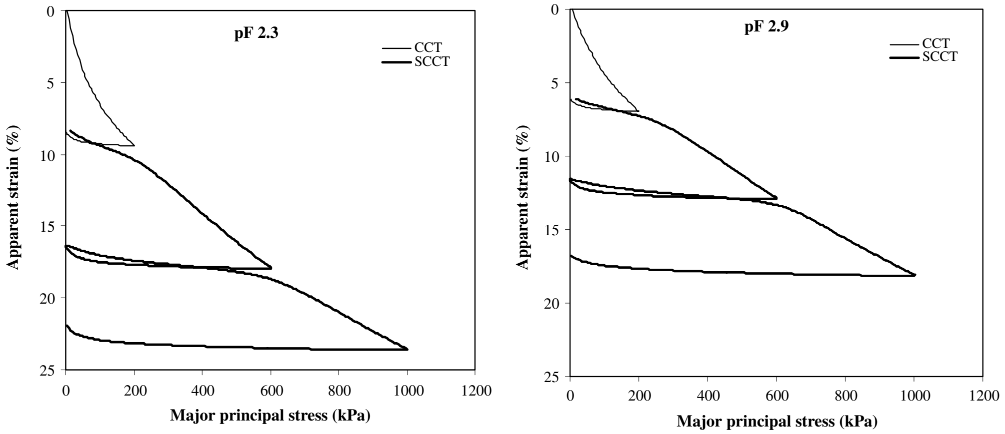

Fig. 5. Combination of loading types for Soil 4 at pF values of 2.3 and 2.9. CCT and SCCT stand for confined and semi-confined compaction tests, respectively.

of Alexandrou and Earl [13]). The problem with Casagrande's [1] method is the fact that a logarithmic scale for stress is rather insensitive and a small error in measuring strain will lead to inaccurate predictions of σ_{pc}.

3.2. Assessment of different loading types to predict pre-compaction stress at different soil conditions

Capability of a loading type in predicting σ_{pc} of a soil pre-compacted by another one was assessed. Table 2 shows mean comparisons of pre-compaction stress prediction among the treatments. The differences ($\Delta\sigma_{pc}$) between the applied and predicted σ_{pc} values were higher for the fine-textured soils (Soil Nos. 1, 2 and 3) when compared with the coarse-textured soils (Soil Nos. 4 and 5). At similar pF values, the degree of saturation of clay soils is higher than sandy soils which could reduce the sharpness of the critical region on stress–strain curves. It is due to lower hydraulic conductivity and generated effective stress in compacted clay soils. A high difference ($\Delta\sigma_{pc}$) or error

Table 2
Mean comparisons of pre-compaction stress prediction as affected by soil type, pF value, loading combinations and maximum axial stress[A]

Soil No.	$\Delta\sigma_{pc}$ (kPa)	pF value	$\Delta\sigma_{pc}$ (kPa)	Loading combination	$\Delta\sigma_{pc}$ (kPa)	Maximum axial stress (kPa)	$\Delta\sigma_{pc}$ (kPa)
1	209.3^{a}	2.3	246.1^{a}	CCT–SCCT	66.6^{b}	200	85.9^{c}
2	205.4^{ab}	2.7	184.6^{b}	SCCT–CCT	254.2^{a}	400	184.0^{b}
3	188.1^{c}	2.9	133.5^{c}	KCT–CCT	243.4^{a}	600	294.3^{a}
4	146.9^{d}						
5	190.6^{bc}						

[A] Means with the different lower-case letter in each column are significantly different at $P < 0.05$. $\Delta\sigma_{pc}$ represents the absolute difference between actual (applied) and predicted pre-compaction stress values.

was determined for Soil No. 2 which has an unstable structure and very low organic matter content (see Table 2). Arvidsson et al. [10] also found that they could not determine σ_{pc} on a sandy soil because of very low sharpness of the critical region. Koolen and Kuipers [5] also believed that the critical region is rather sharp for structured dry soils but the boundary may not be sharp for sandy soils and/or soils with low organic matter and weak structure.

With increasing pF value (decreasing matric potential), the accuracy of prediction increased significantly (see Table 2). At high matric potential or water contents, incompressibility of water might lead to a low sharpness of the critical region under "quick" loading, i.e. the stress induced by the quick loading of wet soil will in the majority be born by the pore water and will significantly reduce soil compression. Indeed, at high water contents very low effective stress is experienced by particles and the real σ_{pc} would be much lower than the applied maximum stress.

The interaction effects of the treatments on σ_{pc} prediction are illustrated in Tables 3 and 4. The tendency of $\Delta\sigma_{pc}$ variation with soil type and matric potential shows that for finer soils (Soil Nos. 1, 2 and 3), the accuracy of σ_{pc} prediction increased significantly with increasing pF value (see Table 3). Since the water content of clay soils is higher than sandy soils at similar pF value, the decrease of water content with increasing pF value improves the σ_{pc} prediction. On the other hand, the accuracy was not greatly increased with the decrease of water content for sandy soils (Soil Nos. 4 and 5) and there was no significant difference between pF values of 2.7 and 2.9 (see Table 3). This was because the water content was low enough at a pF value of 2.7 to prevent pore water pressure development upon loading. In general, the prediction was better for coarse-textured soils than fine-textured soils. The prediction at a pF value of 2.7 for sandy soils was not significantly different from the prediction at a pF value of 2.9 for clay soils (see Table 3). At a pF value of 2.9, there was no significant difference among the soils with respect to σ_{pc} prediction. This was because the water content of all the soils was low enough at this pF value to

Table 3
Mean comparisons of pre-compaction stress prediction as affected by interactions of soil type and pF value, soil type and loading combination, and soil type and maximum axial stress[A]

Soil No.	pF value	$\Delta\sigma_{pc}$ (kPa)	Soil No.	Loading combination	$\Delta\sigma_{pc}$ (kPa)	Soil No.	Maximum axial stress (kPa)	$\Delta\sigma_{pc}$ (kPa)
1	2.3	262.1^{ab}	1	CCT–SCCT	88.7^{f}	1	200	96.2^{f}
1	2.7	224.0^{cd}	1	SCCT–CCT	266.0^{abc}	1	400	186.7^{de}
1	2.9	142.8^{ghi}	1	KCT–CCT	273.2^{ab}	1	600	345.0^{a}
2	2.3	271.9^{ab}	2	CCT–SCCT	64.8^{fg}	2	200	95.9^{f}
2	2.7	200.6^{de}	2	SCCT–CCT	272.7^{ab}	2	400	194.0^{cd}
2	2.9	143.7^{ghi}	2	KCT–CCT	278.7^{a}	2	600	326.4^{a}
3	2.3	248.4^{bc}	3	CCT–SCCT	50.5^{g}	3	200	92.2^{f}
3	2.7	191.2^{ef}	3	SCCT–CCT	259.4^{abc}	3	400	176.2^{de}
3	2.9	124.7^{i}	3	KCT–CCT	254.3^{abcd}	3	600	295.8^{b}
4	2.3	165.7^{fg}	4	CCT–SCCT	42.6^{g}	4	200	55.3^{g}
4	2.7	150.8^{ghi}	4	SCCT–CCT	226.4^{d}	4	400	163.4^{e}
4	2.9	124.4^{i}	4	KCT–CCT	171.8^{e}	4	600	222.1^{c}
5	2.3	282.3^{a}	5	CCT–SCCT	86.4^{f}	5	200	89.9^{f}
5	2.7	156.6^{gh}	5	SCCT–CCT	246.3^{bcd}	5	400	199.7^{cd}
5	2.9	132.9^{hi}	5	KCT–CCT	239.0^{cd}	5	600	282.1^{b}

[A] Means with the different lower-case letter in each column are significantly different at $P < 0.05$. $\Delta\sigma_{pc}$ represents the absolute difference between actual (applied) and predicted pre-compaction stress values.

Table 4
Mean comparisons of pre-compaction stress prediction as affected by interactions of pF value and loading combination, pF value and maximum axial stress, and loading combination and maximum axial stress[A]

pF value	Loading combination	$\Delta\sigma_{pc}$ (kPa)	pF value	Maximum axial stress (kPa)	$\Delta\sigma_{pc}$ (kPa)	Loading combination	Maximum axial stress (kPa)	$\Delta\sigma_{pc}$ (kPa)
2.3	CCT–SCCT	106.9^{d}	2.3	200	98.1^{g}	CCT–SCCT	200	80.1^{d}
2.3	SCCT–CCT	322.7^{a}	2.3	400	255.9^{c}	SCCT–CCT	400	89.5^{d}
2.3	KCT–CCT	308.6^{a}	2.3	600	384.2^{a}	KCT–CCT	600	88.1^{d}
2.7	CCT–SCCT	49.5^{e}	2.7	200	79.9^{g}	CCT–SCCT	200	50.7^{e}
2.7	SCCT–CCT	258.3^{b}	2.7	400	167.0^{e}	SCCT–CCT	400	243.2^{c}
2.7	KCT–CCT	246.1^{b}	2.7	600	307.0^{b}	KCT–CCT	600	258.1^{c}
2.9	CCT–SCCT	43.3^{e}	2.9	200	79.7^{g}	CCT–SCCT	200	68.9^{de}
2.9	SCCT–CCT	181.6^{c}	2.9	400	129.2^{f}	SCCT–CCT	400	429.9^{a}
2.9	KCT–CCT	175.5^{c}	2.9	600	191.6^{d}	KCT–CCT	600	384.0^{b}

[A] Means with the different lower-case letter in each column are significantly different at $P < 0.05$. $\Delta\sigma_{pc}$ represents the absolute difference between actual (applied) and predicted pre-compaction stress values.

prevent the pore water pressure's effect on the compression process.

For the coarse-textured soils, increasing maximum axial stress caused a lower reduction in accuracy of σ_{pc} prediction when compared with fine-textured soils (see Table 3). This might be due to the water retention characteristics of the soils. For the clay soils, the degree of saturation will increase rapidly as the applied stress increases and the prediction of σ_{pc} is poorer. With increasing pF value, the effect of applied stress on σ_{pc} prediction diminished. At an applied stress of 200 kPa, the σ_{pc} prediction was not significantly different among pF values. However, the σ_{pc} prediction depends on matric potential for the applied stresses of 400 and 600 kPa (see Table 4). At low applied stresses, the soils did not have a high degree of compaction and regardless of matric potential, the σ_{pc} prediction was good.

The interaction effect of loading combination and applied stress was significant. At low applied stresses (200 kPa), there was no significant difference between loading combinations but with increasing the applied stresses, a significant difference was realized between loading combinations (see Table 4). This significant difference might be due to the unsuitability of SCCT–CCT and KCT–CCT combinations in σ_{pc} prediction. However, CCT–SCCT predicted the σ_{pc} values satisfactorily regardless of the applied stresses. The results of predicted versus actual values of σ_{pc} are shown in Figs. 6 and 7. Regardless of the soil and loading conditions, the prediction by SCCT is consistently more accurate than CCT. However, the prediction of σ_{pc} by SCCT was better at higher stresses and wetter soil conditions when compared with CCT.

With increasing water content and axial stress, the sharpness and prediction of σ_{pc} by CCT was very poor. For Soil 1 at a pF value of 2.3, no pre-compaction region (zero σ_{pc}) could be determined on the stress–strain curves at maximum axial stress of 600 kPa (indicated by a small

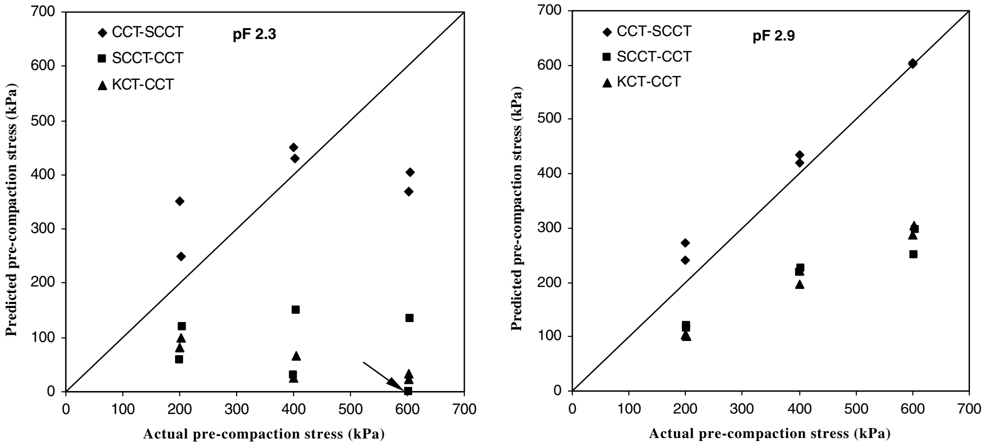

Fig. 6. Predicted versus actual values of pre-compaction stress for Soil 1 at two pF values. CCT, SCCT and KCT stand for confined, semi-confined and kneading compaction tests, respectively. The combinations of the loading types mean that the soil had been pre-compacted by the first method and then predicted by the second one.

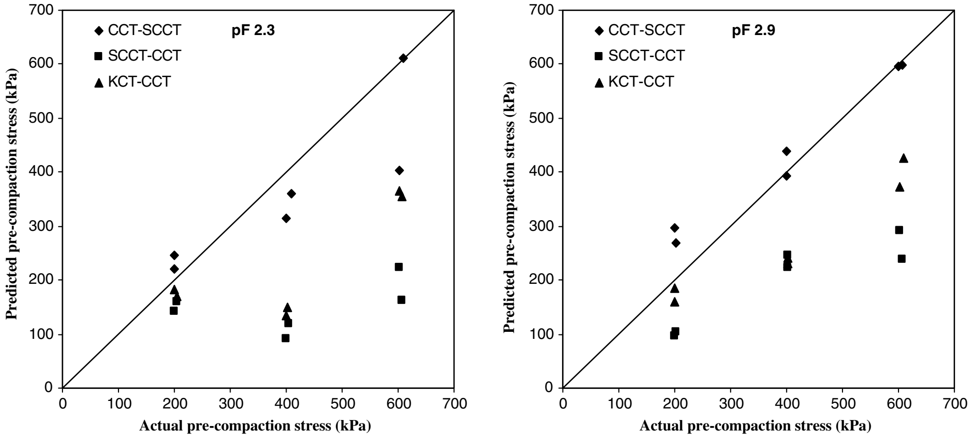

Fig. 7. Predicted versus actual values of pre-compaction stress for Soil 4 at two pF values. CCT, SCCT and KCT stand for confined, semi-confined and kneading compaction tests, respectively. The combinations of the loading types mean that the soil had been pre-compacted by the first method and then predicted by the second one.

arrow in Fig. 6). This can be related to incompressibility of soil water at near-saturated status of the soil at high stress. Koolen [20] also reported that prediction of σ_{pc} by CCT for a heavy silty clay loam in wet condition and at high values of σ_{pc} is not satisfactory. However, the sharpness of the critical region in SCCT was adequate to predict σ_{pc}. An exception was maximum axial stress of 600 kPa at a pF value of 2.3 where the prediction by SCCT was only moderately good. Since the upper limit of normal stresses resulting from agricultural machinery is about 400 kPa [2], this would not be a significant disadvantage for SCCT. There was no significant difference between the combinations of SCCT–CCT and KCT–SCCT in predicting σ_{pc} (see Table 2 and Figs. 6 and 7).

In most of the cases, the σ_{pc} values were to some extent over-estimated by SCCT (see Table 2 and Figs. 6 and 7). This might be interpreted by the well-known friction–cohesion law of Mohr–Coulomb. Since soil-cylinder wall friction for the initial stage of compaction under CCT is low, soil will be compacted easily in this part. On the other hand, in SCCT a specific amount of load must be applied to break the bonds between the soil under the piston and the surrounding soil to start the compaction/sinkage process. The piston load could be assumed as a shear stress on the imaginary cylindrical interface of the piston with the surrounding soil under the annulus. Since sandy soils (e.g. Soil 4) are frictional and cohesionless, this process may not be important, so that the predicted σ_{pc} values are marginally higher than the actual values (see Fig. 7).

Under tires and in wet conditions (e.g. a pF value of 2.3), the induced positive pressure in the free water can act as an isotropic stress in each direction. It causes damage to soil structure as well as a large lateral soil displacement and upheaval of the surrounding soil. It is obvious that during the CCT, the development of positive pressure causes a small soil strain and in reality this cannot happen under tires. It can be said that the positive pore water pressure developed under SCCT or tires is low because of freedom of soil water to move to the surrounding soil volume. Thus, SCCT may be a better simulation of the compaction process under tires.

3.3. Consistency of the prediction methods for different soil conditions

The capability of CCT–SCCT combination in predicting σ_{pc} was higher when compared with the other two combinations (see Table 2). The small and gradual change of soil strain under reloading by CCT might be the reason of the higher error for SCCT–CCT and KCT–CCT combinations. The $\Delta\sigma_{pc}$ (prediction error) increased significantly by the increase of maximum axial stress (applied σ_{pc}) (see Table 2 and Figs. 6 and 7). As the stress increases, the soil compaction approaches its potential maximum bulk density and the degree of saturation increases. Therefore, the change of elastic to plastic deformation will be gradual and the accuracy of σ_{pc} prediction is low, i.e. the virgin compression line (VCL) deviates from the linear trend at high stresses.

The accuracy of σ_{pc} prediction by loading combination improved with increasing pF value (see Table 4). There was no significant difference between pF values of 2.7 and 2.9 for CCT–SCCT. This implies that the capability of CCT–SCCT in σ_{pc} prediction was not decreased with water content increase. The CCT–SCCT provided the best predictions, regardless of the soil type (see Table 3). For the fine-textured soils, there was no significant difference between SCCT–CCT and KCT–CCT, but for the coarse-textured soils, KCT–SCCT prediction was better.

It could be concluded from Figs. 6 and 7 that the semi-confined method (SCCT) is a suitable method for prediction of σ_{pc} on pre-compacted soil independent of the loading or soil conditions. For low stresses and clay soils, SCCT over-estimated the values of σ_{pc} slightly. The prediction by CCT is adequate at low stresses (e.g. 200 kPa) but very poor at higher stresses (400 and 600 kPa) (see Figs. 6 and 7).

4. Conclusions and recommendations

Tractors or other equipment in the field apply loads that are difficult to replicate in the laboratory because they comprise shear and normal stress and result in lateral and vertical soil compaction. The best way of testing soil is the in situ plate sinkage test (PST) in the field. The PST needs labour and complicated loading instruments in the field. Furthermore, the measured properties (i.e. pre-compaction stress, compression index and swelling index) by this test cannot easily be related to a specific layer of the soil.

The results showed that CCT is not a good method for the wet range of water contents and soils with low organic matter content because of the low sharpness of the critical region on the stress–strain curves. The first attempt to find an alternative laboratory method beside CCT has led to the conclusion that the semi-confined compaction test (SCCT) is a compromise method which is between CCT and PST. It has the advantage of a limited and definite affected soil volume that can be modeled as a soil element. Marginal effects of disturbance caused by coring/sampling as well as pre-test sample preparation seem to have a minor effect on the stress–strain curve determined by SCCT in comparison with CCT. The effects of sampling will be greater in the soil volume which is near the internal wall of the cylinder and less in the less disturbed soil in the center of the cylinder. The soil volume needed for the test is no larger than that for CCT. In addition, determining compressibility and stress–strain curves of the soil is possible in the laboratory and can approximately simulate soil behavior under PST, at least for the initial stage of the compaction process where the pre-compaction stress is expected. The soil between the piston circumference and the inner circumference of the sample ring has a volume three times greater than the soil under the piston and permits the soil directly under the load to move laterally. One may argue that the surrounding soil volume is insufficient to allow the loaded soil under the piston move infinitely like in PST. However, the soil cone formation during PST is most likely to happen under wet soil conditions [21]. Inspection of the cross section of soil loaded by SCCT showed that only under conditions of high stresses (400–600 kPa) and when the soil is wet (pF values of 2 and 2.3), is the surrounding soil fully compacted and has an upward displacement. It is more significant for heavier (clay) soil because of the flexibility of smeared clay particles for movement and the incompressibility of soil water. It would be worthwhile, however, to study the effect of different ratios of diameter of piston and annulus on the results of SCCT.

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