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Research Paper

Relationships between rut depth and soil mechanical properties in a calcareous soil with unstable structure

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ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form
23 November 2013
Accepted 9 December 2013
Published online

For proper management of soil-machinery interactions, it is essential to know the mechanical strength (i.e. pre-compaction stress, σ_{pc}) of agricultural soils. However, there is little information linked directly to soil sinkage in the field to σ_{pc}. This research was conducted to explore the relationships of rut depth (d_R) with σ_{pc}, penetration resistance (CI) and dynamic drop-cone resistance (DCI) in a calcareous clay loam soil with unstable structure. The σ_{pc}, CI, DCI, and d_R were determined before and after single or multiple wheelings with two tractors under different soil conditions. Average ground pressure (σ_g) applied by the tractors was also determined. The σ_{pc} was determined using large undisturbed soil samples which were taken from the 0–15 cm layer in the wheel track. The CI, DCI and d_R were measured simultaneously along the tyre centreline. When σ_{pc} values before each wheeling were compared with d_R values after wheeling, it was found that σ_{pc} was approximately a threshold value between reversible and irreversible deformations. The results indicated that when the σ_{pc}/σ_g is well above 1 (e.g. 1.6), soil sinkage is essentially negligible. However, for the ratios <1.6, soil sinkage is irreversible and significant. These findings and published documents show that some physico-empirical safety factor greater than 1 is needed as a criterion for field traffic in structurally-unstable soils. Similarly, two-region trends were also observed between d_R and CI or DCI. As soil trafficability criteria, soil properties such as CI and DCI, which are easily and quickly measurable, might be used for practical purposes.

1. Introduction

Nowadays, trafficking of off-road vehicles and agricultural machinery with continuous increasing weight, power and size is the important factor that threatens soil quality leading to soil degradation. Mechanised agricultural production is highly dependent on farm machinery traffic for tillage, planting, and harvesting operations. Soil damage caused by field traffic may be obviously visible on the soil surface or might be invisible when it occurs in the subsoil layers; both will impose negative effects on crop production (Adam & Erbach, 1995). When

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http://dx.doi.org/10.1016/j.biosystemseng.2013.12.006

internal or external forces exerted on the soil are greater than soil mechanical resistance, the soil will be compacted and/or deformed. Soil compaction is one of the factors limiting plant growth and crop yield in arable soils. Soil compaction reduces total porosity and substantially affects the soil air and water permeability and water infiltration (Soane & van Ouwerkerk, 1994, 662 pp.). It could also affect soil pore size distribution, macropores and saturated hydraulic conductivity (Schaffer, Attinger, & Schulin, 2007).

In mechanised agriculture, soil compaction is generally determined by two factors: 1) applied load, which depends on the characteristics of agricultural machines, and 2) soil mechanical strength, which depends on intrinsic soil properties (e.g. texture and organic matter), transient properties (water content and bulk density) and soil structure (Raper, 2005). Soil water status is the most important property controlling soil behaviour during trafficking. The obvious and most visible index of the compressibility of the surface soil is rut depth (sinkage) in the wheel tracks of tractors and agricultural machinery. Soil sinkage due to wheeling would depend on initial soil conditions before wheeling, axle load, tyre inflation pressure and number of passes (Botta, Jorajuria, Rosatta, & Ferrero, 2006). Sinkage occurs when soil mechanical strength is lowered due to tillage operations and/or high soil water content. The number of traffic passes might influence severity, extent and distribution of loading induced by agricultural machinery. Compared to a single pass, Liu, Ayers, Howard, Anderson, and Kane (2011) found that soil deformation and compaction increased with increasing number of passes. Multiple passes by vehicles resulted in rut depth increases in the range 65–548%.

An important soil mechanical property often used as a criterion to assess soil compressibility is called pre-compaction stress (σ_{pc}). The concept of σ_{pc} is based on non-significant reversible or elastic strain in the stress range 0–σ_{pc} and significant irreversible or plastic strain when stress $> \sigma_{pc}$ (Alexandrou & Earl, 1995). The σ_{pc} is considered as an index of soil compactibility (Keller, Arvidsson, Dawidowski, & Koolen, 2004), the maximum pressure a soil has experienced in the past (i.e. soil management history) (Defossez & Richard, 2002), and the maximum major principal stress a soil can resist without major plastic deformation and compaction (van den Akker & Schjønning, 2004).

It was found that σ_{pc} generally increases with increasing matric suction (Berli, Kirby, Springman, & Schulin, 2003; Mosaddeghi, Hemmat, Hajabbasi, & Alexandrou, 2003), bulk density (Mosaddeghi et al., 2003) and clay content (Imhoff, da Silva, & Fallow, 2004), whereas it decreases with increasing loading time (Horn, Taubner, Wuttke, & Baumgartl, 1994). In addition to soil properties, σ_{pc} might depend on measuring method and loading rate as well (Keller et al., 2004; Mosaddeghi, Hemmat, Hajabbasi, Vafaeian, & Alexandrou, 2006). Initial water content plays an important role in bearing capacity of clayey and loamy soils. In contrast, for sandy soils, the σ_{pc} is less dependent on initial water content but more related to initial ρ_b. Alexandrou and Earl (1998) found that σ_{pc} of a sandy loam soil increased strongly with increasing ρ_b and slightly with decreasing volumetric water content, showing the dominance of frictional resistance within the soil.

Different types of penetrometers have been developed to measure the soil resistance to penetration. The cone penetrometer (Fountas et al., 2013) and dynamic drop-cone test (Godwin, Warner, & Smith, 1991) have been used to quantify soil compaction (Mosaddeghi et al., 2006) and the effect of machinery wheeling on soil (Botta, Becerra, Lastra-Bravo, & Tourn, 2010). Nowadays, cone penetrometers with multiple tips and using GPS have been developed for characterising soil strength profile and its spatial distribution across a large area quickly (e.g. Fountas et al., 2013). However, cone resistance is measured using cone penetrometer, which is relatively expensive, must be inserted through the soil at a constant velocity and is designed for a relatively limited range of soil penetration resistance (ASAE Standards, 2009). Therefore, a less time-consuming, reliable, cheap and repeatable technique has been sought for surface soil strength assessments in the field. Dynamic drop-cone test might be a good alternative (Godwin et al., 1991; Herrick & Jones, 2002), but the relations between the dynamic drop-cone resistance and soil compressive parameters (e.g. σ_{pc}) are not available in the literature.

Although the concept of σ_{pc} is in theory very appealing, whether this transition really occurs in practice is still under investigation. Keller et al. (2004) compared the σ_{pc} values obtained by a field method with those achieved by two laboratory methods. The field tests were conducted using an *in situ* plate sinkage test (PST), whereas, in the laboratory, the undisturbed soil cores were compressed in an oedometer by sequential loading, and at constant displacement speed. They stated that the σ_{pc} did not operate as a threshold value between reversible and irreversible deformations when comparing values of σ_{pc} derived from the different methods with stresses and displacements observed in the field during the wheeling experiments. Even when the observed stress was lower or much lower than the σ_{pc}, a residual displacement was observed. Their study demonstrated that the σ_{pc} is not a distinct boundary value and not only depends on the compression test and determination method, but is also affected by the sampling method/sample distortion. It was reported that compression tests might not accurately represent soil behaviour in the field. A significant relationship between the σ_{pc} and corresponding shear strength values was found by Hemmat, Tahmasebi, Vafaeian, and Mosaddeghi (2009), showing that by the time the soil gets to the pre-compaction point, some plastic deformation may occur.

Keller et al. (2012) examined soil stress (σ)–strain behaviour as measured *in situ* during wheeling experiments on structured soils with a wide range of texture in Sweden and Denmark and related it to the stress–strain behaviour and σ_{pc} measured on soil cores in uniaxial compression tests in the laboratory. In contrast with the concept of pre-compaction stress, they observed residual strain at $\sigma \le \sigma_{pc}$. Residual strain was observed in the field when σ exceeded approximately 40 kPa, and when the ratio σ/σ_{pc} exceeded roughly 0.1, although the residual strain was very small at $\sigma/\sigma_{pc} < 0.5$. On the basis of their findings, they questioned the use of σ_{pc} as a measure of soil strength and called for a re-evaluation of the pre-compaction stress concept. However, Schaffer et al. (2007) investigated the effects of the first use of heavy agricultural machinery on the physical and mechanical properties of a restored soil after the period of restricted cultivation. They

Table 1 – Some physical and chemical properties of the topsoil (0–20 cm) (after Hemmat et al., 2009).

Texture (USDA)	Sand g kg^{-1}	Silt g kg^{-1}	Clay g kg^{-1}	Organic carbon g 100 g^{-1}	$CaCO_3$ g kg^{-1}	PL g kg^{-1}
Clay loam	158	494	348	0.50	377	199

PL: plastic limit.

stated that loads may exceed σ_{pc} for short durations, even in a restored soil that is still far from having re-gained normal strength, without serious damage. Thus, the use of σ_{pc} as a criterion for trafficability was on the safe side in preventing damage to the ecological quality of the soil by compaction, even if the concept did not fully apply to the field reality of the mechanical stress conditions.

There is little information linking directly soil sinkage in the field (i.e. visual index of compactibility) to pre-compaction stress (σ_{pc}) and other soil mechanical properties. This study was conducted to explore the relationships of rut depth (d_R) during wheeling in the field with σ_{pc} and mechanical parameters such as cone penetration resistance (CI) and dynamic drop-cone resistance (DCI) in a calcareous clay loam soil with unstable structure in central Iran. Our main objective was to present an easy and reliable index as a trafficability criterion for practical purposes.

2. Materials and methods

2.1. *The study site and soil*

The study site (32° 32′N; 51° 23′E; 1630 m above sea level) was at the Isfahan University of Technology Research Station Farm in Isfahan (central Iran). The soil has a clay loam texture with unstable structure. The soil is classified as: fine-loamy, mixed, thermic Typic Haplargids (USDA system) and Calcaric Cambisols (FAO system). It was formed on the alluvial sediments of the Zayandeh Roud river (Lakzian, 1989) initially low in organic matter, and with a history of intensive conventional cultivation and cropping of cereals, hay, and silage corn (*Zea mays* L.) in rotation. According to Lakzian (1989), the dominant clay minerals of the soil, which were measured qualitatively, are mica/illite, palygorskite, kaolinite, chlorite, quartz, with a trace of smectite, and the dominance of palygorskite and chlorite.

Some physical and chemical properties of the studied soil were measured. Soil texture was determined by sieving for sand particles (0.05–2 mm) and sedimentation (hydrometer technique) for silt (0.002–0.05 mm) and clay particles (<0.002 mm) (Gee & Bauder, 1986). Organic carbon content (OC) and calcium carbonate content ($CaCO_3$) were measured using the wet-oxidation and back-titration methods, respectively (Page, Miller, & Keeney, 1992, pp. 325–340). Soil plastic limit (PL) was measured using the 3 mm-thread method (Campbell, 2001). The soil physical and mechanical properties are given in Table 1.

2.2. *Experimental treatments*

Experiments were conducted in a 150 m × 40 m field. Experimental plots were 10 m long and 3 m wide. We intended to have a range of soil conditions and water contents for deriving reliable relations between soil physical and mechanical properties and parameters. Therefore, experimental treatments were: 1) two tractor types (MF285; light and 2WD: MF6290; medium and 4WD (Table 2) with/without implement attached to three-point hitch, 2) traffic frequency (0, 1, 2 and 3 tractor passes in the same tracks), 3) two initial soil conditions (ploughed and unploughed), and 4) three soil water contents (0.9 PL, 1 PL and 1.1 PL, where PL is plastic limit). The soil was wetted by sprinkler irrigation to a depth of 30 cm. Then the soil was allowed to dry to each level of soil water content and then the traffic treatment was applied. For the ploughed treatment the soil was mouldboard ploughed to a depth 30 cm and then tilled with a power harrow at an average depth of 15 cm, after crop harvesting. The soil remained undisturbed after harvesting in the unploughed treatment. Soil water conditions varied in a range from semi-solid to plastic states. The 0.9 PL is generally accepted as optimum water content for tillage (Dexter & Bird, 2001; Mosaddeghi, Morshedizad, Mahboubi, Dexter, & Schulin, 2009), the PL might be considered the upper tillage limit (Dexter & Bird, 2001) and 1.1 PL is in the plastic range. Tractor speeds during all experiments were 4.5 km h^{-1}. The treatments were laid out in a split–split plot arrangement within a randomised complete block design with three replicates.

Tyre/soil contact area of the tractors was measured in the same experimental field by tracing the area around the front and rear tyres using chalk powder. The average ground pressure (σ_g) was calculated by dividing total axle load by the tyre/soil contact area of both tyres on the same axle. The average σ_g values are presented in Table 3.

Several soil physical and mechanical properties were determined during the wheeling experiments. The soil surface micro-relief was carefully smoothed and/or trimmed for soil samplings and measurements before the tractor passes. The wheel-lug effect was gently scrapped away after each pass for soil samplings and measurements. All the soil physical and mechanical properties were determined before wheeling, immediately after the first, second and third passes in the

Table 2 – Tractor specifications.

Specification	MF285 (Light) 2WD	MF6290 (Medium) 4WD
Engine power (kW)	53	97
Tyre size, front	7.5–15	10.00–16
Tyre size, rear	18.4–34	16.9R–38
Inflation pressure (kPa), front tyre	204	170
Inflation pressure (kPa), rear tyre	102	102
Total weight (kN)	31.6	56.8
Front weight (kN)	8.7	26.6
Rear weight (kN)	22.9	30.2

Table 3 – Average ground pressures (kPa) of the tractors in the experiment treatments.

Tyre	Relative water content	MF285		MF6290	
		Ploughed	Unploughed	Ploughed	Unploughed
Front tyre	0.9 PL	66.4	60.4	72.0	66.5
	1.0 PL	57.5	50.5	63.3	57.8
	1.1 PL	46.5	42.3	55.0	50.6
Rear tyre	0.9 PL	50.0	41.1	58.1	53.0
	1.0 PL	42.5	34.5	50.3	47.2
	1.1 PL	35.5	29.1	41.8	38.7

PL: plastic limit.

Fig. 1 – Locations of all soil measurements in the tractor rut: (▭) cone penetration test, (△) drop cone test, (⬭) rut depth measurement and core sampling for soil compressibility tests (○) soil sampling for bulk density and water content determination.

centreline of the tractor wheels. The soil sampling and measurements were obtained in a limited zone and as close as possible to each other (Fig. 1).

2.3. Water content measurements

Water content was measured by taking soil samples within the control and trafficked zones after 1, 2 and 3 passes using stainless cylinders (with diameter of 5.3 cm and height of 5.5 cm) at ds was determined. The water content values of the two layers were averaged and reported as the values for 0–15 cm layer.

2.4. Penetration resistance measurements

Soil penetration resistance was measured using two methods/instruments: a standard cone penetrometer and a dynamic drop-cone device. Soil penetration resistance, cone index (CI), was measured using a standard cone penetrometer (model Rimik CP20) having cone-tip angle of 30° and cone base diameter of 12.8 mm (ASAE S313.3 Standard) driven into the soil at a constant rate 2 mm min^{-1}. Twenty penetrometer readings were taken at 2 cm intervals over the depth 0–30 cm. The mean CI for the 0–15 cm layer was used in this study because it is assumed that the tractive devices (i.e. wheel) obtain their thrust from the strength of this layer (ASAE D497.5 Standard).

A dynamic drop-cone device (Fig. 2) was designed and constructed to measure the dynamic drop-cone index (DCI) quickly. This apparatus consisted of a stainless steel cone with a weight of 2 kg and cone-tip angle of 30°, together with a cone-guide tube (1 m height) and an electromagnet for releasing the cone. This apparatus could be attached to the three-point hitch of a tractor. It was put on a metal rail path which could move horizontally, in order to make the measurements in the trafficked and non-trafficked counterparts. When the cone falls in the guide tube, almost all of the kinetic energy due to drop-cone weight (i.e. $W = mgh$) would help its tip to penetrate into the

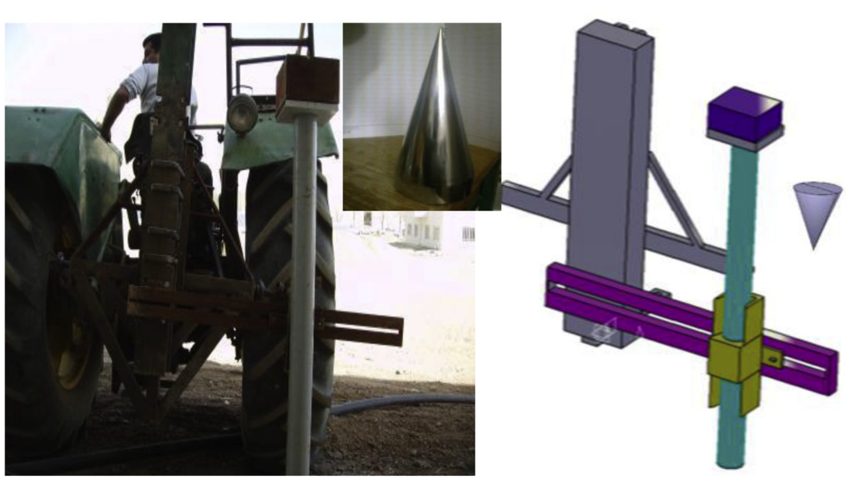

Fig. 2 – Dynamic drop-cone device which was used in this study.

soil. The following equation was used to calculate the DCI in kPa (Vanags, Minasny, & McBratney, 2004):

$$\mathrm{DCI} = \frac{mgh}{A\Delta z} \quad (1)$$

where m is the cone mass (kg), g is acceleration due to gravity (m s^{-2}), h is the fall height (m), A is the cone basal area (m^2), and Δz is the cone penetration depth (mm) that was measured by a digital caliper (with 0.01 mm accuracy). All the parameters in Eq. (1) are constant except Δz which is inversely related to DCI.

2.5. Rut depth measurement

After each tractor pass, rut depth (d_R) or soil sinkage at the centreline of the tyre track was measured by a digital caliper (with 0.01 mm accuracy) and a rod. The rod was placed horizontally, and perpendicular to the wheeling direction, on the tyre ruts. The caliper was then placed vertically across the wheel track perpendicular to the wheeling direction to measure the d_R accurately.

Due to dryness of the subsoil and the existence of an Argillic horizon combined with a plough pan at the depth of about 30–35 cm (Lakzian, 1989), it was assumed that the rut depth was governed by the deformation of the surface layer. This assumption was confirmed by measuring the relative position of upper boundary of the subsoil which was not changed after wheeling events.

2.6. Soil pre-compaction stress

For the soil compressibility tests, large undisturbed soil samples were taken prior to the traffic experiment and after the first and second passes, and the measured pre-compaction stresses were assigned as threshold values for the first, second and third passes, respectively. A core sampler (height 15 cm and diameter 27 cm) was pushed vertically into the soil using a hydraulic jack. The internal wall of the cylinder was lubricated with oil and a hard plastic plate was put between the jack and the sampler. The advantage of this sampling procedure was that the soil disturbance was rather low because of continuously vertical application of the load (Mosaddeghi et al., 2006). These large core samples were immediately brought to the laboratory for soil compressibility tests.

The large soil specimens were used for plate sinkage (PST) and confined compression (CCT) tests. These compaction tests are interchangeably used to characterise soil compressibility and pre-compaction stress. The PST has the advantage of simulating semi-confined loading condition of the field soil. However, the CCT as a standard method has the advantages of small volume of soil sample and known boundary conditions (Keller et al., 2004; Mosaddeghi et al., 2006). First, the centre section of the soil specimen was submitted to a 50-mm PST; then immediately one cylindrical sample (with diameter of 5 cm and height of 5.5 cm) was cored for CCT. For CCT, a steel plate having a diameter of a little less than that of the core sampler was mounted between the loading piston and the soil sample. The tests were conducted using a California Bearing Ratio (CBR) testing machine at a deformation rate of 1 mm min^{-1}. During the tests, force and deformation were recorded manually in deformation increments of 0.5 mm. The PST was continued up to a maximum of 20 mm sinkage, whereas the CCT was terminated when water began to be expelled from the bottom of the samples (Koolen, 1974; Mosaddeghi et al., 2003).

From the output of force and displacement gauges of the CBR machine, stress–sinkage and stress–strain curves were obtained for PST and CCT, respectively. Stress and strain were calculated by dividing the measured force by the loading area and by dividing the sinkage by the initial height of the sample, respectively. The stress–sinkage and stress–strain curves were then used for calculation of soil pre-compaction stress (σ_{pc}) values in PST and CCT, respectively. The σ_{pc} was determined using Casagrande's graphical estimation procedure (Casagrande, 1936). Since determinations of the point of maximum curvature and virgin compression line are difficult and subjective, we used a computer program to obtain σ_{pc}. The computer program was written in MATLAB (Mosaddeghi et al., 2003) following the mathematical procedure of Dawidowski and Koolen (1994) based on Casagrande (1936). The strain or deformation *vs.* stress data were also filtered and reduced using the methods of Dawidowski and Koolen (1994) to eliminate noise in the collected data.

2.7. Statistical analyses

In order to obtain different soil sinkage conditions, traffic experiments were conducted. The tests were a combination of four tractor pass conditions (0, 1, 2, 3) with two tractor types, with/without drawbar load, conducted in two soil conditions (ploughed and unploughed) prepared at three soil water contents with three replications. Linear and non-linear relationships between rut depth (d_R) during wheeling in the field and soil mechanical properties including σ_{pc}, CI and DCI (before each wheeling event) were derived. It means that predictors were measured before the tractor pass for which the d_R was determined. All the statistical analyses and linear and non-linear regression were undertaken using the SAS 9.1 package. Bi-linear fitting was performed using Excel Solver. Combined sum of squared errors (pooled SSE) of two segmented-regression lines relating d_R to soil mechanical properties was considered as objective function. The regression coefficients were optimised using the Excel Solver to find the intersection (i.e. critical value) between small (reversible) and large (irreversible) soil deformations.

3. Results and discussion

3.1. Relationships between rut depth and soil pre-compaction stress

The overall relationships between the rut depth (d_R) or soil sinkage and pre-compaction stress (σ_{pc}) values measured by PST and CCT are presented in Fig. 3. It should be mentioned again that the σ_{pc} values were measured before the tractor pass for which the d_R was determined. It is understood from Fig. 3 that as σ_{pc} increases, the d_R decreases. Scatter of the data suggested using a bi-linear regression to derive threshold

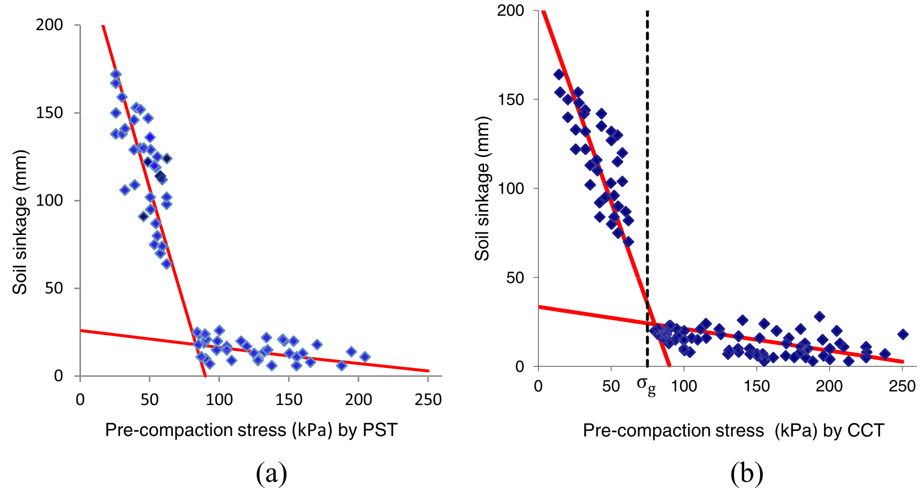

Fig. 3 – Overall relations between soil sinkage (rut depth) and pre-compaction stress for (a) plate sinkage test (PST) and (b) confined compression test (CCT). The intersection of the two fitted lines gives the estimated value of critical pressure (on *x* axis) as (a) 85 kPa and (b) 80 kPa; coefficient of determination (R^2): (a) 0.95 and (b) 0.93; sum of squared errors (SSE): (a) 175,461 and (b) 194,142 mm^2; average ground pressure was shown by vertical dashed line on (b).

value between high (irreversible) and low (reversible) soil sinkages. Bi-linear fitting resulted in highly significant relations between d_R and σ_{pc} ($R^2 = 0.95$ and $R^2 = 0.93$ for PST and CCT data, respectively). The value of critical/threshold stress was obtained between two distinct regions: first region with low σ_{pc} and high d_R values mostly belonged to the σ_{pc} values before traffic and the sinkage values after first pass; and second region with high σ_{pc} and low d_R values mostly belonged to the σ_{pc} values after 1 and 2 passes and the sinkage values after 2 and 3 passes. Critical stress for the CCT data was 80 kPa. The critical stress is much higher than the average ground pressure (σ_g) which was applied by the tractor. It was in the range of 1.10–2.75 times the σ_g depending on soil water content and the tractor type used (see Table 3). The reason is that the contact stresses probably are considerably larger than $\sigma_{g.}$ It might be concluded that, when σ_{pc} is lower than its critical value for that soil, the soil sinkage would be considerable (i.e. soil is in the virgin compression region with plastic behaviour and with irreversible deformation). Similarly, when the soil σ_{pc} is much higher than its critical value, soil sinkage is essentially negligible, i.e. soil is in the over-compacted region with elastic behaviour. However, there is also a possibility that the measured σ_g values may not represent the actual distribution of the contact stresses applied by the tyres (Keller, 2005).

The relationships between soil sinkage and the ratio of pre-compaction stress to ground pressure (σ_{pc}/σ_g) are shown in Fig. 4. When σ_{pc}/σ_g is well above 1.6, soil sinkage is essentially negligible. However, for the ratios <1.6, soil sinkage is irreversible and significant. Horn and Fleige (2003) found for some soils in Germany that the soil structure is unchanged if the ratio of σ_{pc}/σ_g is in the range 1.2–1.5. They found that if the

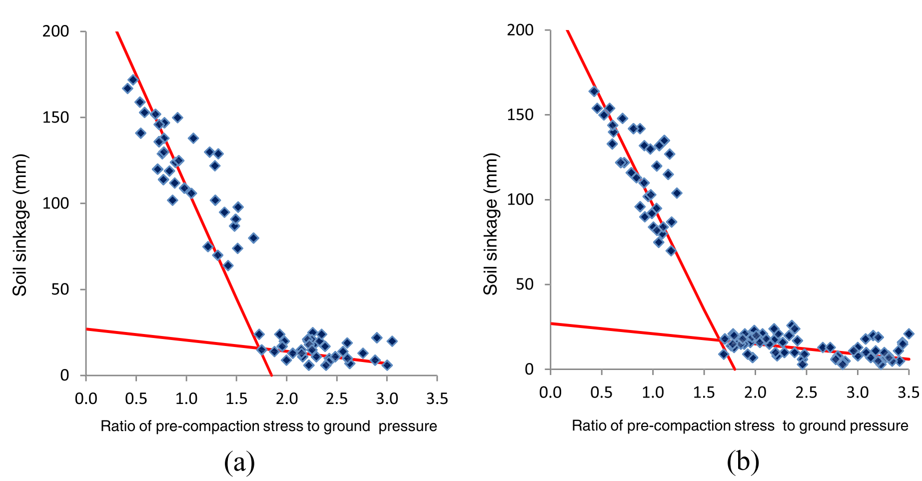

Fig. 4 – Overall relations between soil sinkage and pre-compaction stress to ground pressure ratio for (a) plate sinkage test (PST) and (b) confined compression test (CCT); coefficient of determination (R^2): (a) 0.90 and (b) 0.93; sum of squared errors (SSE): (a) 14,221 and (b) 13,655 mm^2.

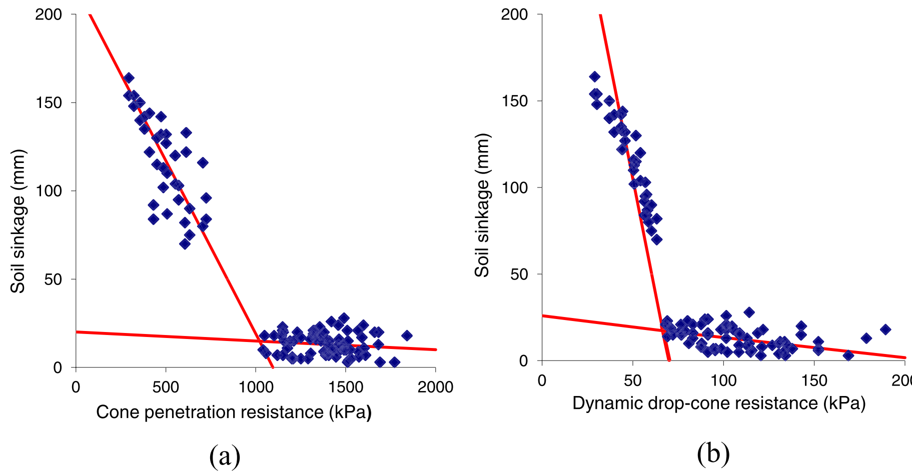

Fig. 5 – Overall relations between soil sinkage and (a) cone penetration resistance and (b) dynamic drop-cone resistance; the intersection of the two fitted lines gives the estimated value of critical stress (on *x* axis) as (a) 1050 kPa and (b) 69 kPa; coefficient of determination (R^2): (a) 0.95 and (b) 0.96; sum of squared errors (SSE): (a) 14,354 and (b) 10,816 mm^2.

ratio is 0.8–1.2, the soil will deform irreversibly. Mosaddeghi, Koolen, Hajabbasi, Hemmat, and Keller (2007) found that σ_{pc} might not be the real critical stress for soil physical quality indices such as soil air permeability, especially at high water contents, for five soils in central Iran. More recently, Keller et al. (2012) observed residual strain in the field when the ratio of σ_{pc} to applied stress, σ, was roughly smaller than 10, although residual strain was very small at $\sigma_{pc}/\sigma > 2$.

These findings and published documents show that some physical or empirical safety factor greater than 1 is needed as a criterion for field traffic in calcareous clay loam soils with unstable structure. However, one possibility is that measured σ_g under static condition might not be a good estimate of contact stress during wheeling (i.e. dynamic condition). Carcass stiffness, uneven stress distribution in the contact area, lateral movement of the soil and shear stresses in the contact area might play a role in the traffic-induced soil stresses which are not considered in static ground stress calculations (Koolen & Kuipers, 1983, 235 pp.). Mosaddeghi et al. (2006) demonstrated that the PST results can be used for sustainable soil management, soil trafficability and for studying the effect of management and tillage practices on soil mechanical behaviour. Dias Junior, Leite, Junior, and Junior (2005) investigated the traffic effects on soil preconsolidation pressure due to eucalyptus harvest operations. They reported that the traffic effects on σ_{pc} in the dry season indicated that the soil compaction process was neither evident nor important while in the rainy season, the traffic effects on σ_{pc} indicated that the operations performed with harvester and forwarder caused greater soil compaction than those with motorised saw and manual transport. Keller et al. (2004) reported that the σ_{pc} did not work as a threshold stress between reversible and irreversible deformation when comparing σ_{pc} derived from different methods with stress and displacement observed in the field during wheeling experiment. They also demonstrated that even when the observed stress was lower or much lower than the σ_{pc}, a residual displacement was observed. Similar to studies of Keller et al. (2004) and Dias Junior et al. (2005), results of our study showed that the σ_{pc} measured using two methods (i.e. CCT and PST) cannot be used as a threshold stress for excessive soil compaction in calcareous clay loam soils with unstable structure.

3.2. *Relationships between rut depth and soil penetration resistances*

Overall relationships between rut depth (d_R) and soil cone penetration resistances (CI) and dynamic drop-cone resistance (DCI) are shown in Fig. 5. The relations between d_R and CI or DCI are quite similar to the conceptual d_R–σ_{pc} relations (Fig. 3). Although the DCI is mainly governed by the soil surface properties (and perhaps a couple of cm depth) while CI is an average of the 0–15 cm layer, both soil cone penetration and dynamic drop-cone resistances (i.e. CI and DCI) can be used as measures of soil bearing capacity and trafficability. Trends in the data in Fig. 5 suggest that the DCI is a superior criterion because scatter of the CI data is greater with lower R^2 for bi-linear fitting. Critical DCI obtained using the bi-linear fitting was 69 kPa. The corresponding critical CI value was 1050 kPa. Therefore, the DCI and CI could be suitable, convenient and fast alternatives instead of σ_{pc} for soil trafficability. This is an important finding since determination of σ_{pc} is usually time-consuming and costly.

Cone penetration resistance (CI) is an easily-measurable soil attribute and was found to have high correlation with σ_{pc} determined by PST (Fig. 6). This relation implies that soil bearing capacity could easily be predicted by CI; the σ_{pc} is equal to about 0.09CI (Fig. 6). Mosaddeghi et al. (2003) and Mosaddeghi et al. (2006) also found that σ_{pc} (determined by CCT) is approximately equal to 0.10CI and 0.14CI in lab and field studies on the same soil, respectively. However, the σ_{pc}/CI ratio was 0.07 when σ_{pc} was measured by PST in the field (Mosaddeghi et al., 2006). Fritton (2008) assessed the σ_{pc}/CI relation in Pennsylvania, USA and also analysed the soil compression data in the literature. He found a linear relationship between σ_{pc} and CI with the σ_{pc}/CI ratio varying in the range 0.046–0.168 for his data and in the range 0.057–0.100

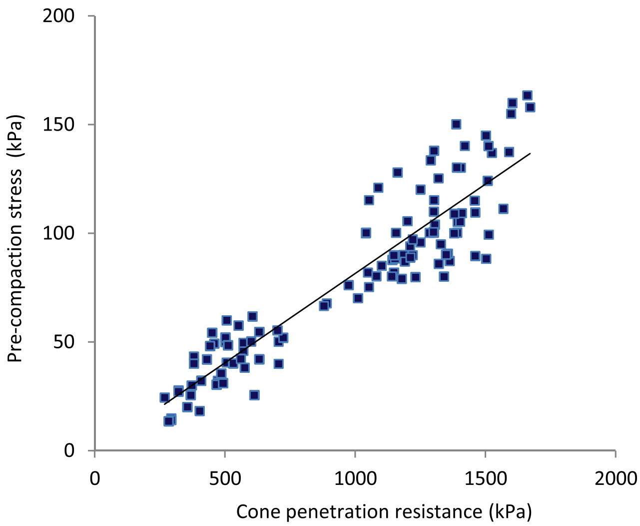

Fig. 6 – Overall interrelation between soil pre-compaction stress and cone penetration resistance (CI); $\sigma_{pc} = 0.092CI - 1.0522$ ($R^2 = 0.87$).

based on the literature data. As a first approximation for practical purposes, it might be concluded that CI is ten times the σ_{pc} (i.e. CI $\approx 10\sigma_{pc}$).

4. Conclusions

1) In an extensive field experiment, we found that there were critical values for soil pre-compaction stress (σ_{pc}), cone penetration and dynamic drop-cone resistances (CI and DCI) which could be good and reliable predictors of soil sinkage (d_R) during field traffic regardless of the tractor type, number of passes, and soil initial tilth and water status. They were able to distinctly separate the regions of low (reversible) and high (irreversible) soil deformations.
2) The results indicated that σ_{pc} cannot be considered as the threshold stress for soil compaction and trafficability in a calcareous clay loam soil with unstable structure. When the ratio of σ_{pc} to average ground pressure (σ_{pc}/σ_g) is well above 1 (e.g. 1.6), soil sinkage is essentially negligible. However, for the ratios <1.6, soil sinkage is irreversible and significant. These findings and published documents show that some physical or empirical safety factor greater than 1 is needed as a criterion for field traffic in calcareous clay loam soils with unstable structure (prevalent in central Iran). However, one possibility is that measured σ_g under static condition might not be a good estimate of contact stress during wheeling.
3) Significant linear interrelations were also observed between σ_{pc}, CI and DCI. Therefore, the DCI and CI could be suitable, convenient and fast alternatives for σ_{pc} in predicting soil trafficability. As a first approximation for practical purposes, CI is ten times the σ_{pc} (i.e. CI $\approx 10\sigma_{pc}$). This is an important and promising finding since determination of σ_{pc} is usually time-consuming and costly, and cone penetrometers with the use of GPS and multiple tips have been recently developed for characterising soil strength profile and spatial distribution of soil strength across a large area quickly. This finding also confirms using a soil-strength property (like CI or DCI) to predict soil deformation in the field.

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