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SW—Soil and Water

Plate Sinkage *versus* Confined Compression Tests for *In Situ* Soil Compressibility Studies

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The objective of this study was to evaluate two methods [plate sinkage test (PST) and confined compression test (CCT)] of predicting the compressibility of the *in situ* soil. The study also considered the effects of internal stresses on soil pre-compaction stress σ_{pc}. The experiment was conducted on a Typic Haplargids soil. A quasi-static loading apparatus was used to run the *in situ* PST and CCT. The compressibility tests were performed at different water contents after the second irrigation on the ploughed topsoil and subsoil. The results showed that the values of σ_{pc} measured in the PST were higher than the ones measured in the CCT. This might be related to distortion of stress–strain curve measured in the CCT due to sampling disturbance and the boundary conditions. A strong relationship between σ_{pc} and water content was observed for the topsoil. The compressibility of subsoil was lower than that of topsoil owing to fine texture, higher bulk density and more stable structure of the subsoil. The pre-compaction stress and the effective stress generated by soil matric suction had linear relationship for the topsoil. The σ_{pc} of the topsoil approaches very high values (*i.e.* 500 kPa) upon drying. This implies the dominant effect of effective stress generated by matric suction on the bearing capacity of the topsoil. However, σ_{pc} of subsoil slightly changed with the effective stress. A significant relationship was found between σ_{pc} and cone penetration resistance (C_p) of the topsoil. Slope of the fitted line for the PST was two times of that for the CCT. The relationship between σ_{pc} and C_p was not significant for subsoil. The PST was able to determine σ_{pc} better than the CCT. Internal stresses due to matric suction are important with respect to compaction of the unstable soils in central Iran. Cone penetrometry could be used as a quick method for prediction of pre-compaction stress of the topsoil.

1. Introduction

Development of techniques to identify and quantify the natural and machinery induced compaction in agricultural soils is the first step toward sustainable soil management. Soil compressibility is defined as the ease with which a soil compacts or is related to how a soil will behave under load (Alexandrou *et al.*, 2002). Arable soils have to be sufficiently weak for tillage activities, and at the same time to be sufficiently strong to tolerate wheel loads. Agricultural soils are usually unsaturated so that the water content (or matric suction) adds to the complexity of their behaviour under stresses. Aggregation in agricultural soil creates a complex system in which, the inter-aggregate and intra-aggregate water–soil relationships should be determined for quantifications of soil trafficability and workability limits (Aluko & Koolen, 2000, 2001). Moreover, the strength properties of soil are changing with time after straining (Blazejczak & Dawidowski, 2002).

The pre-compaction stress σ_{pc} as a useful criterion has been used for assessment of compaction in agricultural soils. It is an important soil mechanical property which divides the stress–strain curve into an elastic region and a plastic region (Koolen, 1987). It is postulated that by limiting the imposed stress to below the value for σ_{pc}, the risk of soil compaction (plastic deformation) could be minimised and the deformation will be only elastic (Alexandrou & Earl, 1998).

A well-known technique of soil compressibility and pre-compaction stress determination is uni-axial confined compression test (CCT) (Koolen, 1974). The confined condition in the test does not allow the lateral expansion of the sample which is likely to occur in soil under agricultural vehicles. Increased margins of error through deformation during sampling and unknown amounts of swelling of the sample prior to loading make this technique unattractive for field use. However, the technique has been used extensively for soil compressibility assessment due to its easiness and simplicity (Söhne, 1958; Koolen, 1974; Larson *et al.*, 1980; Earl, 1997). There is insufficient information on compressibility assessment of agricultural soils using methods besides the CCT. Some techniques have been developed for *in situ* assessment of soil mechanical properties (*e.g.* Boon *et al.*, 2005). Plate sinkage test (PST) was employed by Alexandrou and Earl (1995) as a kind of semi-confined test to determine the value of σ_{pc} for the *in situ* soil. Dawidowski *et al.* (2000, 2001) compared the CCT and the PST with respect to σ_{pc} prediction and concluded that there was no significant difference between the two methods.

In Iran especially, in the central parts, the soils are structurally unstable and very low in organic matter. Previous studies have shown that such soils have a very unique behaviour with respect to soil compaction and tillage system effects (Mosaddeghi *et al.*, 2000, 2003a; Shirani *et al.*, 2002). There is little information on the compressibility and bearing capacity of soils containing fibrous minerals (*e.g.* palygorskite) which abound in soils of central Iran.

The objectives of this study were: (i) to evaluate capability of PST and CCT as *in situ* tests in predicting soil compressibility and pre-compaction stress, (ii) to study the effects of wetting and drying processes (internal stresses) on pre-compaction stress and compaction behaviour of the soils, and (iii) to predict soil bearing capacity using easily measurable soil properties.

2. Materials and methods

2.1. *Apparatus designed for soil compressibility tests*

A quasi-static loading apparatus was designed in order to conduct the *in situ* PST and CCT. The apparatus consisted of a mechanical frame, an assemblage of control hardware and a laptop computer with the controlling software (*Fig. 1*). The mechanical frame was mounted on a John Deere 3140 tractor. A double-acting hydraulic jack with 80 cm stroke was mounted on the frame to apply the load. A load cell with a capacity of 100 kN and a digital caliper were used for measuring vertical force and displacement, respectively. The resolutions of the load cell and digital caliper were 10 N and 0·1 mm, respectively. A DC motor was mounted on a power screw to activate a directional control valve to control the direction of force application. The caliper was connected to the jack piston by an interface and placed on a stand over the ground to avoid the errors in displacement measurement due to the tractor uplifting during loading.

The control hardware was interfaced among the computer, the force and displacement sensors and the DC motor. The software commands for the DC motor were altered to analogue signals by a digital to analogue (D/A) interface. The sensor analogue signals were also converted to digital signals by an A/D interface and were sent to the laptop computer. The apparatus was fully controlled by the laptop computer. The control software was written in Visual C and could be run in Microsoft Windows as user-friendly software. The program consisted of four test types: constant cyclic loading, staircase loading, relaxation, and creep tests. The maximum stress of the consecutive loading cycles was changed in the ‘staircase’ loading. The ‘staircase’ loading was used in this study to apply loading, unloading and reloading paths on the soil.

2.2. *Soil properties and study site*

The study was conducted on the topsoil and subsoil of a Typic Haplargids (USDA) soil at the Research Farm of Isfahan University of Technology located in central Iran. Some physical and mechanical properties of the soil are presented in Table 1.

2.3. *Experimental procedure*

A site with dimensions of 30 m by 30 m was cultivated by a mouldboard plough and discs to a depth of 25 and 10 cm, respectively. To avoid the machinery-induced compaction on soil especially at high water contents, the width of the plots was 1 m which was less than the tractor tread. Then, the soil was surface irrigated for two cycles in order to settle and be ready for the compressibility tests.

The compressibility tests were conducted at different water contents after the second irrigation. Two types of loading in the PST and the CCT were applied at different water contents for the topsoil and subsoil. In

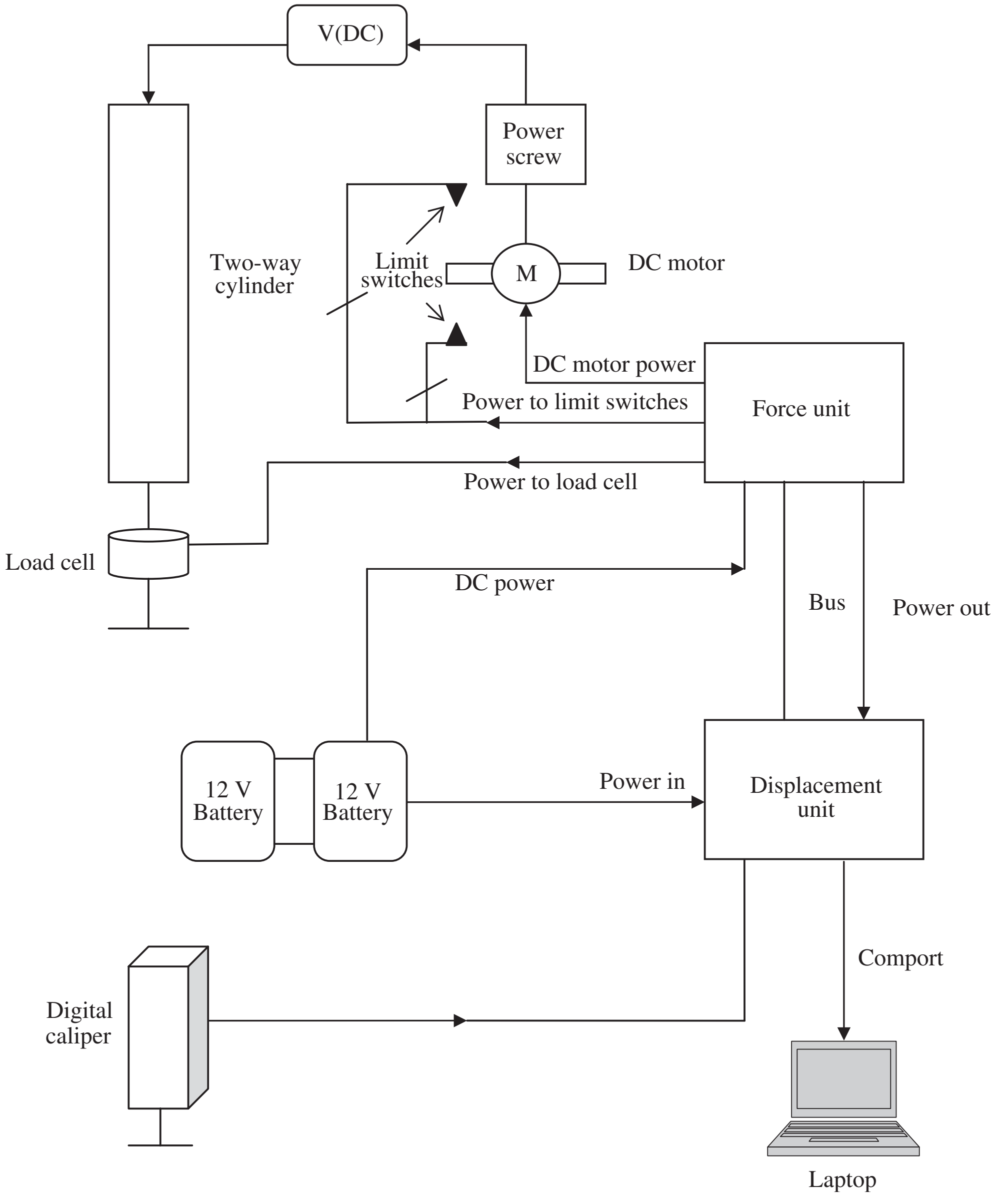

Fig. 1. Block diagram of the in situ soil compressibility tester

Table 1
Some physical and mechanical properties of the soil

Horizon	*Topsoil*	*Subsoil*
Sand, g kg^{-1}	158	80
Silt, g kg^{-1}	494	460
Clay, g kg^{-1}	348	460
Texture (USDA classification)	Silty clay loam	Silty clay
Organic matter, g kg^{-1}	10	7·6
Liquid limit, g kg^{-1}	306	357
Plastic limit, g kg^{-1}	191	201
Field capacity, g kg^{-1}	258	195
CaCO$_3$, g kg^{-1}	450	440

order to increase the applied force range, the rear tyres of the tractor were filled up to half with water. The plate test on the topsoil is illustrated in *Fig. 2*. The plate was made of iron and had diameter and thickness of 150 and 15 mm, respectively. Before starting the test, the soil surface was levelled carefully by a shovel to prevent stress concentration on lumpy points of the soil surface under the loading plate. For applying load to the subsoil, a shaft was used between the jack and the plate to increase the effective stroke of the jack (*Fig. 3*).

For the CCT, a core sampler (with the diameter, height and wall thickness of 150, 150 and 3 mm, respectively) was pushed vertically into the soil by hydraulic jack to get an undisturbed soil sample. The internal wall of the cylinder was lubricated with oil and a plate with diameter of 200 mm was put between the jack and the sampler. In order to achieve the suitable diameter to height ratio of around 1·5 (Koolen, 1974, 1987), the sampling depth was set to 10 cm. The advantage of this sampling procedure was that the soil disturbance was rather low because of continuously vertical application of the load. A rectangular steel plate (with dimensions of 1 m by 0·5 m) was placed on the firm ground beneath the soil core for the CCT (*Fig. 4*). It was assumed that the error due to deflection of the plate was negligible in comparison with the soil deformation in the cylinder under the load. A rod was adapted between the loading ram and the loading plate. Immediately after the test, the soil was kept in a plastic bag for soil water content and bulk density measurements.

Fig. 2. Plate sinkage test on the topsoil

Matric potential component ($-\chi\psi_m$) was used as effective stress σ' generated by internal stresses where χ was assumed to be equal to the degree of saturation and ψ_m represented soil matric potential. Matric potential was found indirectly by matching the field soil water content on the soil water characteristic curve. The soil water characteristic curve was determined on the undisturbed soil cores with diameter and height of 5 cm using a pressure plate extractor (Klute, 1986).

Casagrande's (1936) method for pre-compaction stress determination was used in a package written in MATLAB using the procedure developed by Dawidowski and Koolen (1994). The pairs of values for sinkage *versus* stress for the PST and the CCT were used

Fig. 3. Plate sinkage test on the subsoil

Fig. 4. In situ confined compression test

to obtain the value of σ_{pc} for the soil. Cone penetration resistance C_p was measured by a digital cone penetrometer (Model Rimik CP20, Agridry Rimik Ltd, Queensland, Australia) along a transect in nine points with horizontal distances of 4 cm on the soil near where the PST was conducted. The penetration resistance was measured in 2 cm intervals to a depth of 50 cm. The average values of 0–25 and 25–50 cm depths were used for the penetration resistance of topsoil and subsoil, respectively.

3. Results and discussion

3.1. *Predicting soil pre-compaction stress*

Pre-compaction stress values of *in situ* soil measured by the PST and the CCT are illustrated in *Fig. 5*. The values of σ_{pc} measured in the PST were higher than the ones measured in the CCT. This might be obvious because the boundary conditions of the soil under the plate in the PST were different from those of the soil in confined compression. In the PST, there are vertical and lateral soil deformations, whereas in the CCT, the soil deformation is mainly vertical. The friction among soil particles and internal wall of the cylinder in the CCT were also different from the internal friction between the particles in the imaginary cylinder under the loading plate in the PST. In addition, the soil under the PST is undisturbed but sampling as well as swelling of soil

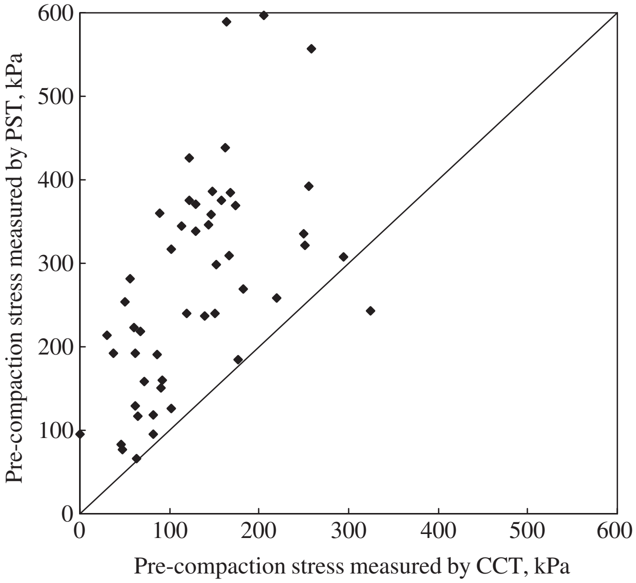

Fig. 5. Pre-compaction stress of in situ topsoil and subsoil measured by plate sinkage test (PST) versus confined compression test (CCT)

during or after sampling would disturb the soil and affect (distort) the measured stress–strain curve and pre-compaction stress in the CCT. The soil disturbance could reduce the sharpness of the critical region (*i.e.* pre-compaction stress region) on the stress–strain curve and consequently decrease the value of σ_{pc} (Dias Jr & Pierce, 1995; Schmertmann, 1955).

Dawidowski *et al.* (2000, 2001) applied a specific normal stress level (defined pre-compaction stress) on a soil and then reloaded the pre-compacted soil up to a higher stress in the PST and the CCT. The reloading curves were used for determination of pre-compaction stress of the pre-compacted soil. The actual and predicted values of σ_{pc} were compared. They reported that the measured values of σ_{pc} in the PST were higher than those measured in the CCT but the difference was not statistically significant. So, they concluded that the results of confined and semi-confined (plate) compression tests can be used to identify the range of the first stage of soil compaction where the changes from elastic to plastic behaviour (pre-compaction stress region) takes place. They reasoned that pre-compaction stress should occur within the initial stage of compaction where the mode of soil deformation is more or less similar under confined and semi-confined conditions. However, the results of this study demonstrated that the measured values of σ_{pc} in the PST were two to three times higher than those measured in the CCT (*Fig. 5*). Since the soil under study was pre-compacted by drying and wetting processes (internal stresses), the arrangement of soil particles was probably more isotropic and random when compared with the anisotropic arrangement of soil particles under external vertical stress. The isotropic arrangements of the soil particles reduce the sharpness of the pre-compaction stress region on the stress–strain curve and allow a soil to deform significantly even in the over-compacted region. The low sharpness of the critical region causes difficulty in determination of the point of maximum curvature and the possibility of error is high. Mosaddeghi *et al.* (2003b) reported that the drying and wetting cycles between loading cycles distort the real shape of stress–strain curves. In the case of the PST, the virgin compression line (VCL) is much steeper than that for the CCT. This could be due to the fact that when compression is taking place in a rigid cylinder (*i.e.* CCT), there is a large increase in stress and the reduction in soil sample height approaches to some limit which is determined by maximum potential bulk density of the soil. Whereas, the compression in a semi-confined condition (*i.e.* PST) consisted of lateral and vertical deformations of the soil under the plate. Therefore, the extension of the VCL that is used for determination of σ_{pc} by Casagrande's (1936) method was steeper for the PST. So the curvature of the critical region was higher in the case of the PST and the values of σ_{pc} determined from the PST were higher than those found from the CCT (*Fig. 5*).

Examples of stress–strain curves obtained in the PST and the CCT are shown in *Figs 6 and 7* for topsoil and subsoil, respectively. The sharpness and change of soil

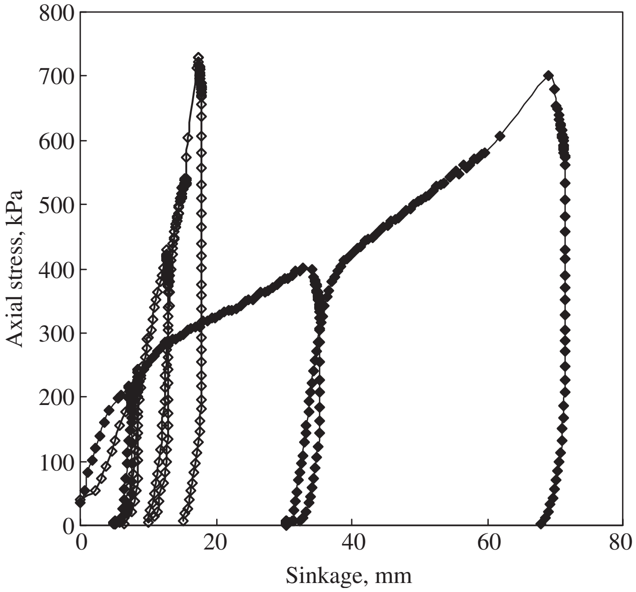

Fig. 6. Stress–strain curves of topsoil measured by plate sinkage test (–◆–) and confined compression test (–◇–) at water content of 11·5% w/w and bulk density of 1·43 Mg m^{-3}

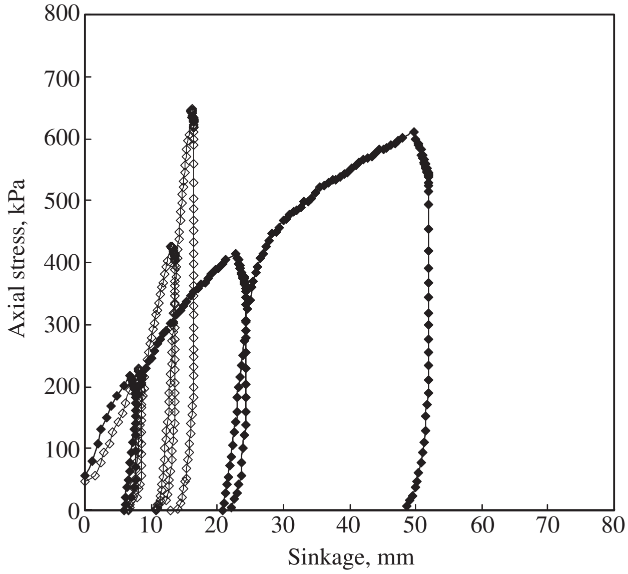

Fig. 7. Stress–strain curves of subsoil measured by plate sinkage test (–◆–) and confined compression test (–◇–) at water content of 17·9% w/w and bulk density of 1·58 Mg m^{-3}

behaviour from elastic to plastic in the critical region was clear for the PST even where the normal scale of stress was used. The problem with the Casagrande's (1936) method is the fact that a logarithmic scale for stress is rather insensitive and a small error in measuring strain will lead to inaccurate determination of σ_{pc}. At the compaction point as defined by Earl (1997), the stress–strain curves of the PST and the CCT diverge. In confined compression, the deformation process is due to pure compaction, whereas for semi-confined compression in the PST, the deformation consists of vertical and lateral compaction and movement of the soil under the plate. It is theoretically expected that the stress–strain curves and modes of soil deformation in the PST and CCT are similar for the stresses lower than the compaction point. However, it has to be pointed out that the initial parts of both curves do not exactly coincide (*Figs 6* and *7*). This could be owing to the differences in friction when soil particles are moving during the compaction. There is cohesion and friction between soil particles in the PST, while during confined compaction, friction between soil particles and the internal wall of cylinder may play an important role in the process (Earl, 1997). The disturbance of the soil core to be used for the CCT might be the cause of higher compressibility (slope of stress–strain curve) of the soil at stresses lower than the compaction point, too. The elastic part of loading–unloading paths could be used for calculation of *in situ* modulus of stiffness.

Dawidowski *et al.* (2000, 2001) believed that pre-compaction stress takes place at stresses far lower than the compaction point so that the PST and the CCT might be used for determination of pre-compaction stress interchangeably. However, it seems that depending on the water content and soil condition, the pre-compaction stress might occur at stresses lower or higher than the compaction point (*Figs 6* and *7*). Our results are similar to those found by Alexandrou *et al.* (2002).

Comparing *Figs 6* and *7* shows that the compressibility of subsoil is lower than topsoil though the water content of subsoil was higher. The texture of subsoil was finer and more compacted and its structure was more stable and less affected by annual loosening/ploughing. The overburden load, stresses resulting from agricultural vehicles, drying and wetting processes and ageing effect in long-term might be the reason of higher strength and lower compressibility of subsoil.

3.2. *Effect of soil drying and wetting processes on pre-compaction stress of in situ soil*

Pre-compaction stress changes upon drying are shown in *Figs 8* and *9* as a function of soil water content for topsoil and subsoil, respectively. The strong relationship between σ_{pc} and water content of topsoil reflects the dominance of cohesion rather than friction on soil strength as reported by Alexandrou and Earl (1998) for

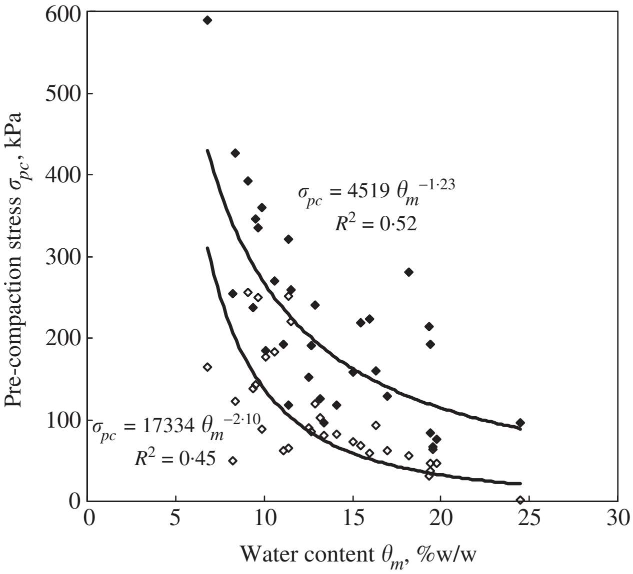

Fig. 8. Pre-compaction stress determined by plate sinkage test (◆) and confined compression test (◇) versus soil water content for topsoil; R^2, coefficient of determination

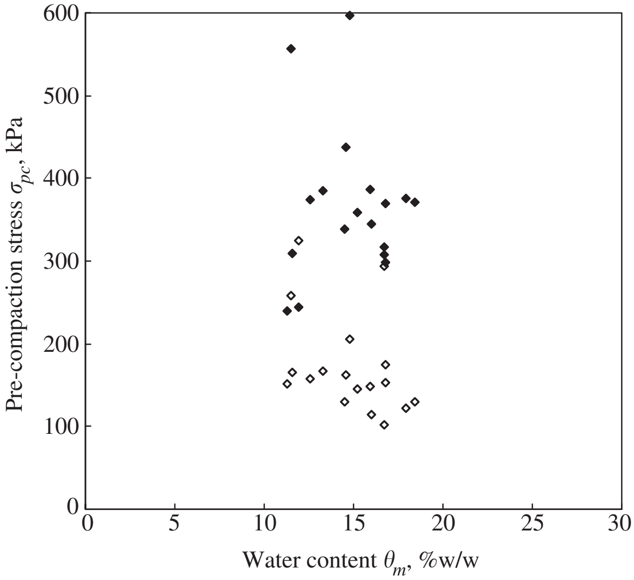

Fig. 9. Pre-compaction stress determined by plate sinkage test (◆) and confined compression test (◇) versus soil water content for subsoil

clayey soils. Mouazen *et al.* (2002) also observed a decreasing trend of cohesion of a sandy loam soil with moisture content. The relationship could be utilised for easy and quick prediction of soil pre-compaction stress if the water content is available. Despite the linear relation reported by Alexandrou and Earl (1998), our results (*Fig. 8*) showed a logarithmic relationship. This might be due to intrinsic soil properties. Since the topsoil was structurally unstable, an abrupt change of strength as a result of soil drying was expected. However, studies by Dias Jr (1994) on structurally stable soils with high organic matter under long-term tillage treatments showed a slight change in the value of σ_{pc} with water content. The power coefficient of the relation was dependent on the method of compression (*Fig. 8*). Comparing the results with the relation derived from a pot experiment on the same soil (Mosaddeghi *et al.*, 2003a) revealed that slope of soil strength changes with water content upon drying was higher in the pot experiment. It implies that the shrinkage and increase of soil strength upon drying was higher in pots due to different boundary conditions of the soil.

The value of σ_{pc} for the subsoil was higher (*Fig. 9*) when compared with the topsoil (*Fig. 8*) at the similar water contents. It might be due to stable structure and undisturbed condition of the subsoil. There was a tendency of increase in subsoil strength upon drying (*Fig. 9*), but the rate of change was lower than that of the topsoil (*Fig. 8*). It seems that the compacted and structurally stable subsoil was less affected by internal stresses. The other reason might be the smaller range of water contents for subsoil which was studied.

The relationships between σ_{pc} and effective stress ($\sigma' = -\chi\psi_m$) generated by matric potential ψ_m are shown in *Figs 10 and 11* for topsoil and subsoil, respectively. The trend of soil strength changes with the effective stress was linear for the topsoil. The pre-compaction stress of the topsoil approaches very high values upon drying (*Fig. 10*). This implies the dominant and controlling effect of effective stress generated by matric suction on the bearing capacity of topsoil. The dominant effect of effective stress on soil strength means that the soil structure is very unstable and behaves like hardsetting soils. Hence, pre-compaction stress of the topsoil was increased from the values near zero for the loose and ploughed soil to value of 500 kPa just due to wetting and drying processes. So sufficient attention should be paid to the effect of internal forces on the physical and mechanical properties of such soils.

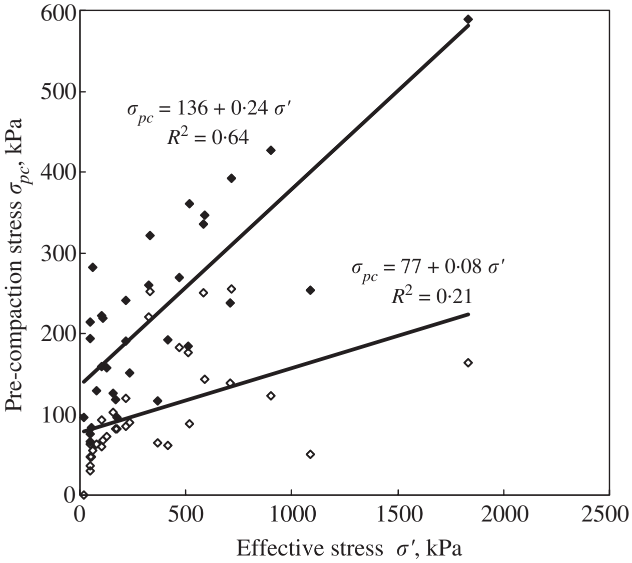

Fig. 10. The relationship between pre-compaction stress of topsoil as determined by plate sinkage test(◆) or confined compression test (◇) and effective stress; R^2, coefficient of determination

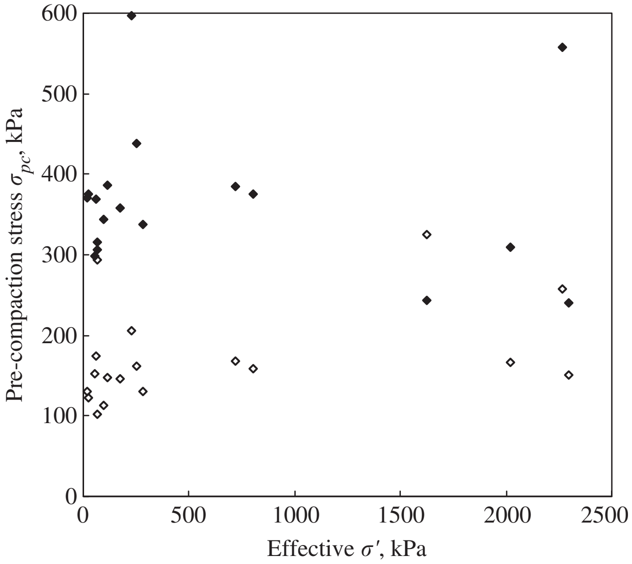

Fig. 11. The relationship between pre-compaction stress of subsoil as determined by plate sinkage test (◆) or confined compression test (◇) and effective stress

It was interesting that the value of σ_{pc} for the subsoil slightly changed with effective stress. The subsoil has high values of σ_{pc} independent of effective stress (*Fig. 11*). The subsoil is equal to the argillic horizon which was reported in the profile of the soil by Lakzian (1989) together with a plough pan at the depth of 28 cm. It can be assumed that the high clay content and stable structure of the subsoil, and wetting and drying processes and ageing during years caused higher soil strength which was slightly affected by effective stress generated by matric suction. Blazejczak and Dawidowski (2002) reported that pre-compaction stress of the remoulded soil samples at constant water content was increased by age-hardening (thixotrophy). It is also believed that dense agricultural subsoils are usually caused by secondary compression (realignment of clay particles during long time periods under constant overburden pressures) occurring simultaneously with primary compression under increased effective stress from desiccation (Hartge, 1986).

3.3. *Prediction of pre-compaction stress of in situ soil by cone penetrometer*

A strong and significant relationship was found between pre-compaction stress and cone penetration resistance C_p of the topsoil. The slope of the fitted line depended on the loading method; the slope for the PST being two times of that for the CCT (*Fig. 12*). It seems that the disturbance of soil during sampling for the CCT and the other causes stated in Section 3.1 might be the reason of lower value of pre-compaction stress determined by this method. By measuring cone penetration resistance, the bearing capacity of the soil could easily be predicted. Abedin and Hettiaratchi (2002) demonstrated that cone penetration resistance could be linked to a state parameter of critical state soil mechanics in an unsaturated agricultural soil. Therefore, cone penetrometry as a quick and simple method with high reproducibility could be used in soil compaction and compressibility studies.

The relationship of pre-compaction stress with cone penetration resistance of subsoil was not as strong as the one for topsoil (*Fig. 13*). Since the C_p of subsoil was continuously measured from the soil surface, the measured C_p value of subsoil might be affected by the friction between penetrometer rod and the topsoil while inserting the rod. However, as it was stated in Section 3.2, the strength of subsoil was almost independent of water content and had high values.

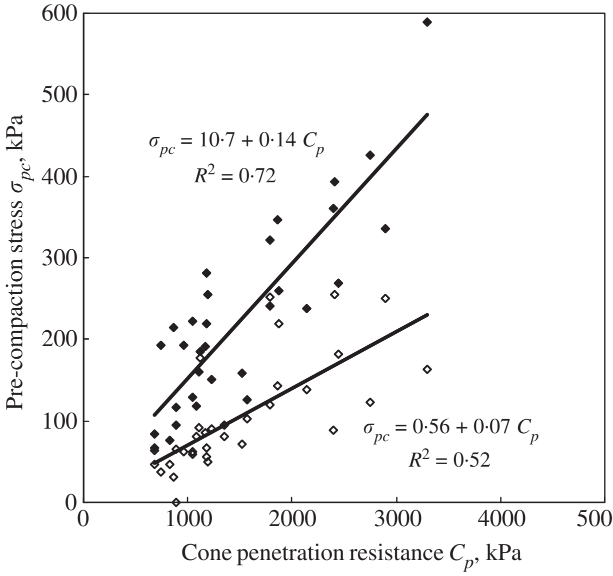

Fig. 12. The relationship between pre-compaction stress of topsoil as determined by plate sinkage test (◆) or confined compression test (◇) and cone penetration resistance; R^2, coefficient of determination

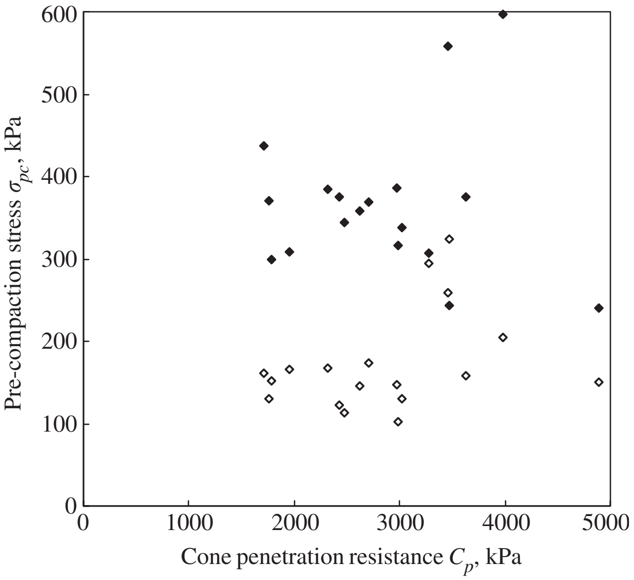

Fig. 13. The relationship between pre-compaction stress of subsoil as determined by plate sinkage test (◆) or confined compression test (◇) and cone penetration resistance

4. Conclusions and recommendation

In situ plate sinkage test (PST) and confined compression test (CCT) on topsoil and subsoil of an important soil series in Isfahan Province, Iran showed that PST is able to measure pre-compaction stress better than CCT did. The effect of wetting and drying processes could be monitored by the PST. The effect of effective stress generated by matric suction on pre-compaction stress was more pronounced for the topsoil. Internal stresses (matric suction) are important with respect to soil compaction and pre-compaction stress of the unstable soils in central Iran. So sufficient attention should be paid to the effect of internal stresses on physical and mechanical properties of structurally unstable soils. The subsoil was more stable and less affected by the effective stress generated by matric suction. Cone penetrometry could be used as a quick method for prediction of pre-compaction stress.

The results of PST can be used in sustainable management of the soil in the region in terms of trafficability and the effect of different management/tillage systems on soil behaviour. It is recommended to measure pre-compaction stress-water content/cone penetration resistance relationships for the important soil series in the region and include the soil maps for practical applications. The study is recommended for different soils in order to interpret compressibility tests correctly. It is also recommended to include pre-compaction stress measurements in tillage/compaction studies in the region.

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