Determination of Pre-compaction Stress of In Situ Tractor Pre-compacted Soil by Plate Sinkage and Confined Compression Tests

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Abstract. Pre-compaction stress ($\sigma_{pc}$) as a direct quantity of bearing capacity has been traditionally measured by quick confined compression test (CCT) for unsaturated agricultural soils. The study was performed on a silty clay loam soil (Typic Haplargids, USDA; Calcaric Cambisols, FAO) in central Iran. The objective was to evaluate the ability of plate sinkage test (PST) vs. CCT in predicting the pre-compaction stress of the topsoil which was pre-compacted by a tractor. The soil was pre-compacted by a JD3140 tractor at water content of 16.4 %w/w. The PST and CCT tests were performed immediately after pre-compaction process on the pre-compacted soil and the value of $\sigma_{pc}$ was predicted by using the stress-strain curves.

Confined compression test and PST underestimated and overestimated the nominal $\sigma_{pc}$, respectively. The soil disturbance during core sampling and the low curvature of critical region on stress-strain curve determined by CCT might be the reason of underestimation. When the cumulative effects of contact stress, uneven stress distribution in the contact area due to lug effect and shear stresses were considered, the calculated value of $\sigma_{pc}$ was close to the PST predicted value. Thus, PST satisfactorily predicted the actual $\sigma_{pc}$ of a soil which was pre-compacted by agricultural tire. Well-known confined compression test (CCT) underestimated the
actual value of $\sigma_{pc}$ of tractor pre-compacted soil. So PST might be recommended as an in situ and reliable method for estimating soil bearing capacity. It is recommended to evaluate the capability of PST and CCT in predicting the pre-compaction stress of different soils at a range of water content.

Keywords. Pre-compaction stress, Plate sinkage test, Confined compression test, Stress-sinkage curve

Introduction

The compaction of soil by agricultural equipment has become a matter of increasing concern. Data in the literature on the compressibility of agricultural soils are limited because of the complexities and difficulties encountered in these soils. Arable soils have to be sufficiently weak for tillage activities, and at the same time they have to be sufficiently strong to carry wheel loads (Earl, 1997). The agricultural soils are almost unsaturated so that the water content (or matric suction) will add to the complexity of their behavior under stresses. Aggregation in agricultural soils creates a complex system in which, the inter-aggregate and intra-aggregate air-water-solid relationships should be determined for quantifications of soil trafficability and workability limits (Aluko and Koolen, 2000 and 2001). Moreover, the strength properties of soil are changing with time after straining (Blazejczak and Dawidowski, 2002).

Pre-compaction stress ($\sigma_{pc}$) is a useful criterion of bearing capacity of unsaturated agricultural soils. It divides the compressive stress-strain curve of the soil into an elastic (over-compacted) region and a plastic (virgin compression) region. The value of $\sigma_{pc}$ has been traditionally measured by quick confined compression test (CCT) for agricultural soils (Koolen, 1987). 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 compactibility assessment due to its easiness and simplicity (Söhne, 1958; Koolen, 1974; Larson et al., 1980; Earl, 1997). Nevertheless, the other methods beside CCT were not often applied for assessing bearing capacity of agricultural soils. Alexandrou and Earl (1995) successfully used plate sinkage test (PST) as a kind of semi-confined compression test to determine $\sigma_{pc}$ of a soil. Dawidowski et al. (2000 and 2001) compared CCT and PST with respect to $\sigma_{pc}$ prediction and reported that there was no significant difference between the two methods.

Selection of a method for determination of soil bearing capacity depends on how much is its capability in prediction of pre-compaction stress of actual pre-compacted soil. Thus, it is worthwhile to compare the different loading types and find a suitable method for $\sigma_{pc}$ determination. There is little information on the capability of different loading methods in predicting $\sigma_{pc}$ of an in situ soil which was pre-compacted by agricultural vehicles. There is an urgent need to study soil behavior in the field and link it to the soil mechanical tests (Keller et al., 2004). This line of research would be very promising to introduce the good method of pre-compaction stress determination.

The objective of this research is to assess the ability of PST and CCT in predicting the pre-compaction stress of a soil which was pre-compacted by tractor.
Materials and methods

Soil properties and study site

The study was conducted in the research farm of Isfahan University of Technology located in Isfahan Province (32° 32´ N; 51° 23´ E; 1630 m a.s.l.), central Iran on a silty clay loam soil (Typic Hapludults, USDA; Calcaric Cambisols, FAO), Khomeinishahr series. The mean annual precipitation and temperature at the station are 140 mm and 14.5 °C, respectively. The soil is formed by the alluvial sediments of the Zayandeh Roud river (Lakzian, 1989), low in organic carbon, and with a history of intensive conventional cultivation and cropping of cereals, hay, and silage corn (Zea mays L.) rotation. According to Lakzian (1989), the dominant clay minerals are in order of micas/illite, smectites, palygorskite and kaolinite.

The pre-test samples of topsoil and subsoil were obtained, air-dried and grounded 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 wet digestion 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 in the order mentioned. 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 through the pycnometer method. The general physical and mechanical properties of the topsoil and subsoil are presented in Table 1.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture</th>
<th>OM</th>
<th>LL</th>
<th>PL</th>
<th>PI</th>
<th>SL</th>
<th>FI</th>
<th>PD</th>
<th>CaCO3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil</td>
<td>494</td>
<td>348</td>
<td>SICL</td>
<td>10</td>
<td>0.306</td>
<td>0.191</td>
<td>0.115</td>
<td>0.086</td>
<td>0.105</td>
<td>2.73</td>
<td>450</td>
</tr>
<tr>
<td>Subsoil</td>
<td>460</td>
<td>460</td>
<td>SIC</td>
<td>7.6</td>
<td>0.357</td>
<td>0.201</td>
<td>0.156</td>
<td>0.095</td>
<td>0.106</td>
<td>2.75</td>
<td>440</td>
</tr>
</tbody>
</table>

* USDA textural classification, SiCL= silty clay loam, SiC= silty clay, OM= organic matter content, LL= liquid limit, PL= plastic limit, PI= plastic index, SL= shrinkage limit, FI= friability index, PD= particle density

An experimental site with the dimensions of 30×30 m was plowed by moldboard plow and disked to a depth of 25 and 10 cm, respectively. The plots were then irrigated twice with 10-days intervals in order to let the soil settle and be ready for the compactibility tests.

Experimental procedure

The ability of PST and CCT in prediction of the pre-compaction stress of the topsoil which was pre-compacted by agricultural vehicles was studied. The topsoil was pre-compacted by a tractor JD3140 at water content of 16.4 %w/w. The tractor speed was 4.5 km hr⁻¹. The plate and confined re-compression tests were performed immediately after pre-compaction process on the pre-compacted soil for six replicates. The dimensions of ellipsoidal ground contact surface of front and rear tires were measured by gypsum powder’s method. The major and minor diameters of the marked delineation of the contact area (ellipse) were measured. The axle loads
on the rear and front axles were also measured at a static condition. The mean ground contact pressure on the front and rear tires were calculated by dividing the load on the corresponding contact area. These values might be considered as nominal pre-compaction stress ($\sigma_{pc(nominal)}$) of the soil. While the soil surface was not flat after pre-compaction due to lug effect, the surface of the soil was carefully trimmed by a shovel. Then, PST was conducted on the pre-compacted soil (Fig. 1). The soil cores were also sampled on the pre-compacted soil for CCT (Fig. 2).

For core sampling from the pre-compacted soil, a core sampler with the diameter (D) and height (H) of 15 cm was pushed vertically into the soil by the hydraulic jack to get undisturbed soil sample (Fig. 2). The internal wall of the cylinder was lubricated with the oil and a plate with diameter of 20 cm was put between the jack and the sampler. In order to achieve the suitable — ratio of around 1.5 (Koolen, 1974 and 1987), the cylinder was inserted to 10 cm into the soil.

Figure 1: The plate sinkage test performed on the soil pre-compacted by tractor.

A quasi-static apparatus was designed and constructed in order to conduct the in situ PST and CCT. It was also used for the core sampling. The apparatus consisted of a mechanical frame, an assemblage of control hardware and a laptop with the controlling software. The mechanical frame was mounted on a JD3140 tractor. A double-acting hydraulic cylinder with 80 cm stroke
was mounted on the frame to apply the load. An EHP load cell (with capacity of 100 kN) and a
digital caliper (with length of 20 cm) were used to measure vertical force and displacement,
respectively. The load cell and digital caliper precisions were 10 N and 0.1 mm, respectively.

The apparatus was fully controlled by a computer. The control software was written in Visual C
and could be run in Windows as user-friendly software. The program consisted of four test
types: constant cyclic loading, stair-case loading, relaxation and creep tests. The stair-case
loading option was used to re-load the tractor pre-compacted soil.

A rectangular steel plate of 1 and 0.5 m length and width and thickness of 1.5 cm was placed on
the firm ground beneath the soil core to perform the CCT. 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. Immediately after the test, the soil was kept in the plastic bag for soil water
content (θm) and bulk density (BD) measurements.

**Determination of pre-compaction stress**

Casagrande’s (1936) method was used in a package written in MATLAB and followed the
procedure of Dawidowski and Koolen (1994). The pairs of sinkage vs. axial stress from the re-

Figure 2: Soil sampling on the soil pre-compacted by tractor for confined compression test.
loading process on the pre-compacted soil were used to calculate the pre-compaction stress of the soil. Following the procedure, the package can reduce and filter the data in order to cope with ever-present small fluctuation in the experimental results and determine the data pair for which the smallest radius of curvature in the semi-log plot (sinkage vs. logarithm of axial stress) has occurred. Then, it characterizes bisector line between tangential line on curve in point of smallest radius and horizontal line. Finally, threshold value ($\sigma_{pc}$) can be found by stress ordinate of intersection of the bisector and the extension of the virgin compression line (VCL).

**Results and discussion**

The previous work (Mosaddeghi, et al., 2003a) on the same soil showed that the soil is self-compactive, so that the pre-compaction stress of 100 kPa is generated by the internal stresses (matric suction) at water content of 16.4 %w/w. However, the external stress resulting from the load applied by tractor tire was higher ($\sigma_{pc(nominal)}$ of about 243 kPa) and compressed the soil on the virgin compression line (VCL) to the higher pre-compaction stress. The static ground contact pressures were calculated about 135 and 243 kPa for rear and front tires, respectively. Although the axle load of rear axle was higher but because of lower contact area of front tires, the contact pressure was higher for the front tires. The nominal pre-compaction stress was assumed to be equal to the higher applied stress (243 kPa) which was imposed by front tires.

The ability of PST and CCT in predicting the $\sigma_{pc}$ of the soil pre-compacted by tractor is illustrated in Fig. 3. Confined compression test underestimated and PST overestimated the $\sigma_{pc(nominal)}$ of the pre-compacted soil. The soil disturbance during core sampling and the low curvature of critical region on stress-strain curve determined by CCT might be the reason of underestimation. The soil disturbance would distort the real shape of re-compression curve. In this regard, Horn and Hartge (1990) reported that CCT measured lower values of $\sigma_{pc}$ when compared with the ground contact pressure (i.e. actual $\sigma_{pc}$). Mosaddeghi et al. (2003b) also concluded that the change of elastic to plastic deformation would be gradual under reloading by CCT and the accuracy of $\sigma_{pc}$ prediction was low.

Plate sinkage test overpredicted the nominal value of $\sigma_{pc}$ (Fig. 3). The cumulative effects of contact stress, tire carcass, uneven stress distribution in the contact area due to lug effect and shear stresses due to tractive force generation by drive tire would appear in the value of $\sigma_{pc}$ measured by PST. Thus, it is reasonable that the measured (actual) value of $\sigma_{pc}$ be higher than its nominal value. As a first approximation, it is assumed that uneven stress distribution could increase the stress to 1.5 times of its average value and shear stresses causes 10 % increase in pre-compaction stress (Koolen and Kuipers, 1983). So the actual pre-compaction stress ($\sigma_{pc(actual)}$) can be calculated as:

$$\sigma_{pc(actual)} = 1.5 \sigma_{pc(nominal)} + 0.1 \sigma_{pc(nominal)} = 1.5 \times 243 + 0.1 \times 243 = 389 \text{ kPa}$$

The calculated value of $\sigma_{pc(actual)}$ is close to the PST predicted value (351 kPa). The preparation of the surface of pre-compacted soil for re-loading by PST might be the reason of the lower predicted value when compared with the calculated value of $\sigma_{pc}$. Therefore, pre-compaction stress of a soil pre-compacted by tractor was better predicted by PST when compared with CCT. Mosaddeghi et al. (2003b) reported that a semi-confined method was always a suitable method for prediction of $\sigma_{pc}$ on pre-compacted soil independent of the loading or soil conditions. Dawidowski et al. (2000 and 2001) reloaded the pre-compacted soil by PST and CCT and
concluded that the predicted values of $\sigma_{pc}$ by PST were higher than those predicted by CCT but the difference was not statistically significant.

Figure 3: Prediction of pre-compaction stress of the tractor pre-compacted soil by plate sinkage test (PST) and confined compression test (CCT).

The $\sigma_{pc}$ prediction difference between PST and CCT might be also interpreted by the difference in the boundary conditions of the soil under PST and CCT. The confining stress in CCT was higher than its value for in situ soil under the loading plate. The friction among the soil particles and the internal wall of the cylinder in CCT were also different from the internal friction between the particles in the imaginary cylinder under the loading plate in PST.

**Conclusions and recommendation**

Plate sinkage test (PST) satisfactorily predicted the actual pre-compaction stress of a soil which was pre-compactad by agricultural tire. Well-known confined compression test (CCT) underestimated the actual value of pre-compaction stress of tractor pre-compacted soil. It is recommended to evaluate the capability of PST and CCT in predicting the pre-compaction stress of different soils at a range of water content. It would be useful to recommend PST as an in situ and reliable method of estimation of soil bearing capacity.
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References


