Pre-compression Stress Concept and Physical Qualities of Soils from Central Iran

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Abstract

The concept of pre-compression stress is important to the compressive behavior of unsaturated agricultural soils under quick compression since additional soil compaction might occur only when applied stress exceeds the pre-compression stress. This concept is based on non-significant elastic or significant plastic strain of the soil. This study was conducted in order to examine if the pre-compression stress can be linked to soil physical qualities, such as air permeability ($K_g$). Topoils of five different soil series were collected from Isfahan province in central Iran. Attempts were given to have a range of soil texture and organic matter content. Five soil types, four pF values (2, 2.3, 2.7 and 2.9), three maximum or pre-compression stress values (200, 400 and 600 kPa) and three loading types with two sub-types of loading (cyclic loading with 10 cycles and staircase loading) were used in the experiment. Loading types consisted of confined compression test (CCT), semi-confined compression test (SCCT) and kneading compression test (KCT). For cyclic loading, after reaching a pre-set maximum stress and measuring $K_g$, the loading with the same maximum stress was repeated 9 more times. In staircase loading, the maximum stress was changed between consecutive loading cycles. The effect of loading on void ratio and $K_g$ was affected mainly by soil type and wetness. When reloading of the soils was done several times with the same maximum stress, soil strain was increased more for SCCT and KCT in comparison with CCT. In staircase loading, all the soil types showed a similar response in which, the void ratio and $K_g$ were increased with increasing compression stress. Likewise, the void ratio and $K_g$ at a given compression stress decreased with an increase in soil moisture. Repeated loading on the soils with high water content (pF values of 2 and 2.3) could distort the contractile skin of water menisci around the soil particles. It was found that the repeated loading effect on $K_g$ is more important at lower pF values or higher water contents. This process may not accompany with significant plastic strain since for some cases more than ten times decrease in $K_g$ resulted from the repeated loading. KCT created more homogenization of pore system and resulted in more decrease in $K_g$ when compared with CCT at higher water contents (pF values of 2 and 2.3). On the other hand, for drier conditions (pF values of 2.7 and 2.9), kneading compression formed a more open microstructure i.e. anisotropic arrangement of soil particles, which led to higher values of $K_g$ when compared with CCT though the strains were almost the same. Results from the cyclic loading showed that the pre-compression stress might not be a real critical stress from the view soil qualities (e.g. $K_g$) especially for the soils with unstable structure and high water contents. This is due to the fact that the compressive pore water pressure deteriorates and homogenizes pore system continuities. Moreover, the particles of the unstable soils do not have permanent and stable bonds e.g. by organic compounds or cementation in order to resist the cyclic loading. Therefore, changes of soil physical properties during compaction process imply the fact that bulk properties like bulk density (or void ratio) cannot completely describe the soil physical quality state but additional information about pore continuity properties is necessary.
1. INTRODUCTION

Referring to the concept of pre-consolidation/pre-compression stress (Casagrande, 1936, Horn and Lebert, 1994, Koolen, 1987 and Koolen, 1994), when a soil is pre-compacted, a knee or a sharp change in the slope (pre-compression stress region) is expected on stress-strain curve partitioning the curve into two regions of over-compacted (elastic) and virgin compression (plastic) line (VCL). The concept of pre-consolidation stress originated in civil engineering soil mechanics in relation to slow consolidation of saturated homogenized clayey soils. The concept has also been used for several years in agricultural compaction researches. The concept is important to the compressive behavior of agricultural soils since additional soil compaction occurs only when applied stress exceeds pre-compression stress. It is an important parameter in modeling of soil tillage/compaction problems. Horn (2000) stated that pre-compression stress is the critical stress for changes in physical, chemical and biological properties but the evidence is limited.

This concept is based on non-significant reversible (elastic) or significant irreversible (plastic) strain of the soil (Koolen, 1987 and Horn and Lebert, 1994). However, Koolen and Kuipers (1989) reported that when the stress in the soil is not exceeded the pre-compression stress, there might be significant change of strain (even in over-compacted range of stresses) depending on initial soil properties. They assumed that the concept is more valid for structured dry soil. For structurally unstable soils and sandy soils, however, the sharpness of the pre-compression region is not high. Horn (2002) reported that normal and shear stresses even at constant pore volume will affect the pore size distribution and especially hydraulic conductivity and air permeability are intensely reduced. An important question is, what are the relevant quantities that must be considered to obtain the most useful relationship between compaction and soil physical effect (Koolen, 1994). Thus, it was not clear if we should limit ourselves to strain-related properties as the dependent variable for pre-compression stress assessment, or we should also consider further soil quality attributes. Studies of soil susceptibility to compaction have required extended relationships between pore volume and soil qualities (Lerink, 1990).

The objectives of this work are: i) to use the different compaction tests to assess the response of five agricultural soils from central Iran when compacted at different normal stresses and water contents, and ii) to evaluate if the pre-compression stress is also a critical stress from the view of soil physical quality (air permeability).

2. MATERIALS AND METHODS

2.1. Study Site and Soils

The topsoils from five different soil series were collected from Isfahan province in central Iran. Attempts were given to have a range of soil texture and organic matter content. These soils are typic soil series in the region. The mean annual precipitation and temperature at the region are about 160 mm and 16 °C, respectively. Classification and some general properties of the soils are shown in Table 1.

Table 1: Classification (USDA system) and some general properties of the topsoil of the studied soils

<table>
<thead>
<tr>
<th>Soil No.</th>
<th>Soil classification</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Texture*</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aquic Haplocalcids</td>
<td>127</td>
<td>348</td>
<td>525</td>
<td>C</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Typic Haplargids</td>
<td>158</td>
<td>502</td>
<td>348</td>
<td>SiCL</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Fluventic Haplocambids</td>
<td>240</td>
<td>472</td>
<td>288</td>
<td>CL</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Typic Torrifluvents</td>
<td>532</td>
<td>301</td>
<td>167</td>
<td>SL</td>
<td>9.3</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>432</td>
<td>396</td>
<td>172</td>
<td>L</td>
<td>8</td>
</tr>
</tbody>
</table>

* USDA textural classification, C= Clay, SiCL= silty clay loam, CL= Clay loam, SL= Sandy loam, L= Loam and OM= organic matter content
2.2. Experimental Procedure

The experiment was conducted on the topsoil (often 0-20 cm) samples in laboratory. Enough amount of soil was collected from the ploughed layer in suitable water content (between plastic limit and shrinkage limit) by composite sampling and great care was taken not to crush soil clods and aggregates during sampling. The samples were air-dried and passed through 10 mm sieve. Soil was poured and knocked slightly into cylinders with diameter and height of 9.86 and 5 cm, respectively in order to achieve a uniform initial dry bulk density of 1.2 Mg m\(^{-3}\). Cloth pieces were supplied and tightened by rubber under the cylinders before soil filling. It was assumed this packing state and size range are ideal for a seedbed after primary and secondary tillage practices.

The prepared soil cylinders were saturated from bottom (to prevent air entrapment) for 2 days and weighed for saturation percentage (SP). Then the soil cylinders were placed on sandbox (pF range 0-2) or sand-kaolin box (pF 2.3-3) for adjusting the matric potential of the soils to pre-test pF values of 2, 2.3, 2.7 and 2.9 (i.e. matric suction of 10, 20, 50 and 80 kPa, respectively). The equilibrium time of 2 and 5 days were found to be satisfactory for sandbox and sand-kaolin box, respectively. After equilibrium time, the soil cylinders were weighed and loaded while tightly fitted in sample holder of a kneading apparatus (Lerink, 1990). After compaction processes, the soil cylinder were oven-dried for 48 hr in 105\(^\circ\)C in order to calculate soil water content and dry bulk density. Thus, the experiment contained five types of soil, four pF values (2, 2.3, 2.7 and 2.9), three maximum stress or pre-compression stress values (200, 400 and 600 kPa) and three loading types with two sub-types of loading (cyclic loading with 10 cycles and staircase loading) and two replicates. Therefore, total tested soil samples were 240 (5 \(\times\) 4 \(\times\) 3 \(\times\) 2 \(\times\) 2).

2.3. Loading Conditions and Measured Properties

Compaction of the soil cores was accomplished using a Zwick Universal Testing Machine. The machine was fully controlled by PC through an interface with software of Xpert and has several options that can be adjusted for different tests. The master program of Hysteresis (he006.zpv) was used in order to collect the data on loading as well as unloading paths. Pre-load, pre-load and loading speed were set to 5 kPa, 50 and 10 mm.min\(^{-1}\) for all the tests, respectively. These values were found to be the best based on some preliminary tests on a loamy soil with moderate water content. It was demonstrated that loading speed of 10 mm min\(^{-1}\) is the highest one that does not cause noise or change of stress during constant cyclic loading. Upper and lower reversal points in both cyclic and staircase loadings and increase per cycle in staircase loading were adjusted to 200 or 400 or 600 kPa, 5 kPa and 200 kPa, respectively.

Confined (CCT), semi-confined (SCCT) and kneading (KCT) compression tests were performed in Lerink’s kneading apparatus. The apparatus is fully described in Lerink (1990). For the confined compression test (CCT), the soil was compacted in the rigid cylindrical sampler under a steadily downward-moving plate fitting inside it until a certain pre-compression stress. The piston stroke of Lerink’s kneading test was used for semi-confined loading (SCCT). Alternative strokes of piston and annulus were applied for kneading compression test (KCT). During the tests, the force was measured as a function of sinkage and exported to EXCEL. For the constant cyclic loading, the maximum stress (200 kPa) was constant for the “first” ten cycles and was increased to 400 and 600 kPa for the “second” and “third” ten cycles, respectively. In staircase loading, the maximum stress was increased between consecutive loading cycles (i.e. 200 to 400 and then to 600 kPa).

From the output of the Universal Testing Machine, stress-strain curves were calculated by dividing the measured force by the loading area and the sinkage by the height of the sample. From the final soil sample height and soil wet and dry weights, void ratio and water content were calculated. Soil sample height and air permeability (K\(_g\)) were measured by caliper and the constant pressure method proposed by Kmoch (1961), respectively. Because of heterogeneity of compaction processes under SCCT, K\(_g\) was not measured in this test. In this method, the soil core in the cylinder was exposed to a constant air pressure generated by weight of a metal chamber floated over water reservoir. The soil sample height and K\(_g\) were determined before the compaction process, between the first and the second cycles and after the tenth cycle of each ten cycles in cyclic loading. For the
3. RESULTS AND DISCUSSION

3.1. Effect of Soil and Loading Conditions on Void Ratio and Air Permeability

In staircase loading, all the soils showed a similar response in which, the void ratio and $K_g$ were decreased with increasing compression stress. Likewise, the void ratio and $K_g$ at a given compression stress decreased with an increase in soil water content. It appears that the effect of loading is determined mainly by soil type and wetness (Fig. 1). During the compression especially in CCT at high water content (e.g. pF 2 and 2.3), volume decrease will be hampered due to incompressibility of the water and the required load will rise dramatically. The air pressure is built up in air bubbles as compaction continues and is propagated in the soil water, eventually changing soil water tension (negative) into compressive stresses (positive). The compression events in which such phenomenon occurs are said to involve “wet” compaction, as opposed to the “dry” compaction. The soil microstructure will be damaged by this process, which may not coincide with the decrease in soil volume (Fig. 1). Even if soils are kneaded (e.g. KCT) in the presence of excess soil water, more deterioration of the structure takes place.

When reloading of a soil was repeated several times, soil strain increased a little on each load repetition. Any loading repetition increases strain somewhat, although the increase diminishes with an increasing number of loading cycles. When reloading of the soils was done several times with the same maximum stress, soil strain increased more for SCCT and KCT in comparison with CCT.

![Graph showing void ratio and air permeability](image)

Fig. 1. Void ratio and air permeability of Soil 1 as affected by the mean axial stress in staircase loading of the confined compression test (CCT) at the pF values of 2.3 (left) and 2.9 (right).

3.2. Void Ratio and Air Permeability as Affected by Cyclic Loading

The cyclic loading (i.e. constant pre-compression stress) on the soils with high water content (pF values of 2 and 2.3) could significantly decrease $K_g$ although the change of void ratio was not significant (Fig. 2). It seems that the repeated loading distort the contractile skin of water menisci around the soil particles. Since water is high enough to act as a lubricant during repeated loading, the fine clay particles will flow and be squeezed between larger silt and sand particles. It is more likely to happen under conditions that soil particles do not have permanent and stable bonds e.g. by organic compounds or cementation as in the studied soils. These processes finally lead to complete homogenization of pore systems and extremely low soil quality and may not accompany with
significant plastic strain since for some cases more than ten times decrease in $K_g$ caused by repeated loading. Thus, LKT created more homogenization of pore system and resulted in more decrease in $K_g$ if compared with CCT at higher water contents (pF values of 2 and 2.3). On the other hand, for drier conditions (i.e. pF values of 2.7 and 2.9), kneading compression form a more open microstructure i.e. anisotropic arrangement of soil particles, which leads to higher values of $K_g$ when compared with CCT though the strains are almost the same.

The $\log K_g$-$\log$ stress lines of the first and tenth cycles of repeated loading are shown in Fig. 3. Comparisons of the graphs show that the effect of repeated loading with the same maximum stress (pre-compression stress) on $K_g$ is more obvious at lower pF values. Thus, repeated loading effect on soil physical quality such as $K_g$ is more pronounced at lower pF values or higher water contents. As a conclusion, bulk density or void ratio is less important for assessing soil qualities as affected by loading especially at high water contents. However, $K_g$ is extremely depending on soil structure and connectivity of air-filled pores and can evaluate the resultant soil structure.

Fig. 2. Void ratio and air permeability of Soil 1 as affected by the mean axial stress and number of cycles in cyclic loading of the confined compression test (CCT) at the pF values of 2.3 (left) and 2.9 (right).

Fig. 3. $\log$ air permeability ($K_g$)-$\log$ axial stress ($\sigma_n$) lines of Soil 1 as affected by cyclic loading in the confined compression test (CCT) at pF values of 2.3 (left) and 2.9 (right).
4. CONCLUSIONS AND RECOMMENDATIONS

All the soil types showed a similar response in relation to void ratio and $K_g$, which decreased with increasing compression stress (staircase loading). Also, void ratio and $K_g$ at a given compression stress decreased with an increase in soil water content. Results of repeated loading with the same maximum stress showed that the pre-compression stress may not be a real critical stress from the view soil qualities e.g. air permeability especially in low pF values for the studied soils. This is because of the effect of compressive pore water pressure that deteriorates pore system continuities. The results of this study showed that changes of soil physical properties during compaction process imply the fact that bulk properties like bulk density cannot completely describe the soil physical quality state but additional information about pore continuity properties and intensity properties is necessary. Microstructure studies such as thin section preparation technique are very useful methods to confirm our hypothesis concerning the pre-compression stress and soil physical quality. In agricultural soils, characterization of the compaction history may not be completely accounted by a single bulk property like strain, void ratio or porosity.

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REFERENCES