Soil & Tillage Research 179 (2018) 63–70

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

# Finite element simulation of plate sinkage, confined and semi-confined compression tests: A comparison of the response to yield stress

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ARTICLE INFO

*Keywords:*
Soil compaction
Pre-compression stress
Finite element method
The point of maximum curvature
Casagrande's method

ABSTRACT

Pre-compression stress ($\sigma_{pc}$) has been widely used as a criterion for assessing the susceptibility of soil to compaction. Confined compression (CCT), semi-confined compression (SCCT) and plate sinkage (PST) tests are the most practical procedures to estimate $\sigma_{pc}$. Discrepant estimates of $\sigma_{pc}$ may be obtained from the above tests mainly due to differences in boundary conditions. The aim of this study was to simulate these compaction tests using the finite element method (FEM) to compare $\sigma_{pc}$ estimated from stress-strain curves with the simulated yield stress. It was hypothesized that for a given simulated yield stress, $\sigma_{pc}$ estimated either at the point of maximum curvature or the point of Casagrande's method is not the same as simulated yield stress for different tests. FEM models were developed in ABAQUS with elastic-perfectly plastic law and Drucker-Prager yield criterion for the soil material. Yield stresses of 20, 50, 75, 100, 125, 150, 200 and 300 kPa were examined. The results showed that the stress at the point of maximum curvature was close to the simulated yield stress in CCT but smaller than that in SCCT and PST. Casagrande's method overestimated $\sigma_{pc}$ (averagely by 40%) for all the tests. A more precise estimate of $\sigma_{pc}$ was obtained at the point of maximum curvature than the Casagrande's method in experimental CCT and PST on remolded soils. Cyclic loading-unloading CCT and PST to different stress levels showed that a safe threshold for preventing a severe plastic strain is significantly smaller (with a factor of 0.5 and 0.8 for CCT and PST, respectively) than $\sigma_{pc}$ in either of the tests.

## 1. Introduction

Soil compaction is an ongoing issue of concern which negatively influences many important soil functions, including crop growth and is therefore officially recognized as one of the main threats to soil fertility (Hamza and Anderson, 2005; Batey, 2009). Soil compaction occurs when the applied stress by an external load (e.g. by tire traffic) overcomes the soil compressive strength. Soil strength in relation to compaction is typically expressed by the soil pre-compression stress, $\sigma_{pc}$. The soil deformation is assumed to be elastic and reversible as long as the applied stress is lower than $\sigma_{pc}$ and plastic and permanent when $\sigma_{pc}$ is exceeded (Casagrande, 1936; Lebert and Horn, 1991). Hence, pre-compression stress is a good indicator of overall soil stability and a useful parameter to identify mechanically sensitive areas across a field (Horn et al., 2005). Nowadays, the weights of agricultural machines exceed the bearing capacity of most soils, hence, field traffic is one of the main factors increasing the extent of land degradation by soil compaction (Peth and Horn, 2006), .With a 4-fold mass increase of agricultural vehicles over the past decades, deep soil compaction (subsoil compaction) has become a serious concern which is difficult and expensive to be ameliorated by tillage operations and often even creates a reduced soil stability and trafficability (Peth et al., 2010). Soil strength is impacted considerably by water content, so to increase the timeframe that soil can experience traffic without causing damage, one strategy is to decrease either the applied stress of machinery proportional to the soil water content or to control traffic to tramline (e.g. Bennett et al., 2017).

Several laboratory and in-situ compaction tests have been developed and applied for estimating $\sigma_{pc}$. $\sigma_{pc}$ is generally derived from uniaxial compression test on confined samples where the soil is subjected to stepwise loading. The compaction characteristic is graphically expressed by a soil volume variable (e.g. strain, bulk density or void ratio) versus the logarithm of stress. The standard method for estimating $\sigma_{pc}$ has been the graphical procedure of Casagrande (1936). Although the confined compression test (CCT) does not allow for lateral expansion of the soil which is likely to occur under real field conditions, the technique has been extensively used for assessing the soil compatibility because of its ease and simplicity (Alexandrou et al., 2002). However, it is generally believed that CCT might not represent the soil behavior in the field sufficiently (Mosaddeghi et al., 2007; Keller et al.,

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https://doi.org/10.1016/j.still.2018.02.003
Received 5 August 2017; Received in revised form 2 February 2018; Accepted 3 February 2018
0167-1987/

2004, 2012).

The plate sinkage test (PST) is the most used procedure to evaluate the soil compactibility in-situ. In terrain-vehicle mechanics, PST has been used as a first step towards a comprehensive set of soil-vehicle relationships which can handle traction elements (Earl and Alexandrou, 2001a). The compaction behavior of soil under plate sinkage resembles the soil behavior under tire/track passage. The soil under PST is free for lateral strain which is the main difference with CCT. Earl and Alexandrou (2001a, b) proposed a theoretical approach to predict the extent of soil deformation under PST based on the experimental observations. They suggested that soil behavior during compression under a sinking plate passes through three phases: (i) the soil is directly compacted with a constant lateral stress immediately after applying the plate pressure, (ii) the lateral stress starts to increase until exceeding the confining stress of the soil surrounding the disturbed area and (iii) a cone of soil is formed beneath the plate and moves down with it causing the soil to be further compacted.

Running PST in the field is time-consuming, labor-intensive and needs a bevameter which is costly to be developed and may not be readily available. Alternatively, the semi-confined compression test (SCCT) has been proposed and evaluated as a laboratory method (Mosaddeghi et al., 2007; Hemmat et al., 2009). In SCCT, the diameter of loading piston is smaller than that of soil cylinder. It is hypothesized that the semi-free lateral strain for soil under compression in SCCT causes a more realistic behavior of soil compaction to be attained. SCCT has the advantage of using a limited and definite soil volume that can be modeled as a soil element. Marginal effects of disturbance caused by coring/sampling as well as pre-test sample preparation seem to have minor effects on the stress–strain curve determined by SCCT in comparison with CCT (Mosaddeghi et al., 2007).

Numerous studies can be found that compared the different compaction tests. Keller et al. (2004) showed slightly larger $\sigma_{pc}$ with PST in comparison with stepwise CCT. The results by Mosaddeghi et al. (2004) showed that PST overestimated and CCT underestimated the nominal pre-loads. Mosaddeghi et al. (2006) showed that the values of $\sigma_{pc}$ measured in the PST were higher than the ones measured in the CCT. This was discussed to be related to distortion of stress–strain curve measured in the CCT due to sampling disturbance and the boundary conditions. The study by (Hemmat et al., 2009) indicated that CCT resulted in $\sigma_{pc}$ values much larger than the nominal pre-loads whereas accurate $\sigma_{pc}$ was obtained by PST. Excessive pore water pressure was discussed as a potential reason for overestimation of $\sigma_{pc}$ by CCT.

For many years, the standard method of estimating $\sigma_{pc}$ from stress-void ratio or stress-strain curves has been the graphical Casagrande's method (Casagrande, 1936). The intersection of the bisector between the tangential and horizontal lines at the point of maximum curvature with the virgin compression line when plotting void ratio versus log stress gives an estimate of $\sigma_{pc}$. Several simpler regression methods have also been evaluated for estimating $\sigma_{pc}$ which often resulted in significantly smaller $\sigma_{pc}$ as compared to the Casagrande's method (Arvidsson and Keller, 2004). The study by Gregory et al. (2006) with CCT tests on repacked soil samples indicated the point of maximum curvature of the log stress-void ratio curve as the most accurate estimate of $\sigma_{pc}$.

The practical use of $\sigma_{pc}$ as a reliable threshold for soil plastic strain has been questioned in some recent studies where considerable residual deformation was observed even when the applied stress was much smaller than $\sigma_{pc}$ (e.g. Keller et al., 2004 and Keller et al., 2012). Time-dependency and different boundary conditions were argued as important reasons of relatively large difference between the residual soil deformation observed in the field during wheeling experiments and that in confined uniaxial compression tests in the laboratory. It was concluded that the uniaxial confined compression test with relatively slow loading rate and lateral confinement may generate a poor representation of the (subsoil) deformation behavior beneath a rolling tire (Keller et al., 2012). This may suggest that alternative compaction tests such as PST and SCCT may represent a more comparable response of soil to what happens under tire passage. Therefore, comparison and standardization of the methods of estimating $\sigma_{pc}$ from different laboratory and in-situ compaction tests is urgently needed. The objectives of this study were thus to: (i) simulate the CCT, SCCT and PST using the finite element method, (ii) assess the FE simulated stress-strain/stress-sinkage curves with respect to the simulated yield stress and soil mechanical properties for different tests, (iii) compare the pre-compression stress obtained at the point of maximum curvature and by Casagrande's method with the simulated yield stress for different tests and (iv) carry out cyclic CCT and PST on remolded soils at different water contents and bulk density to evaluate the accuracy of Casagerande's method and the point of maximum curvature for estimating the pre-compression stress and finding the threshold of severe plastic strain with respect to pre-compression stress.

## 2. Materials and methods

### 2.1. FE simulations

Confined, semi-confined compression and plate sinkage tests were simulated in ABAQUS (6.10.1) with the dimensions shown in Fig. 1. The models consisted of two distinct ABAQUS parts: (1) deformable soil, (2) rigid piston. Since the models were symmetric about the central axis, they were simulated axi-symmetrically. The dimensions of the semi-confined and plate sinkage tests were primarily selected from previous studies by Mosaddeghi et al. (2007) and Hemmat et al., (2012). Sensitivity analyses were then carried out to select the proper size of simulated soil to minimize the effect of boundary conditions. This resulted in soil radius/ piston radius and soil height/ piston radius of 1.5 and 1.2 for SCCT and 5 and 3 for PST.

The soil was defined as an elastic-perfectly plastic material with Drucker-Prager yield criterion (Drucker and Prager, 1952). The simple perfectly plastic law allowed for investigating the effect of yield stress (with no hardening or softening) on the resulting stress-strain (for CCT) and stress-sinkage (for SCCT and PST) curves. The Drucker–Prager model is a modified version of von Mises model, considering the influence of hydrostatic pressure in failure. The extended Drucker–Prager models are used to model frictional materials such as soil (e.g. Tekeste et al., 2007; Naderi-Boldaji et al., 2013, 2014). The yield surface of this model can have a linear, a hyperbolic, or a general exponential form (ABAQUS, 2010). The linear Drucker–Prager yield function is defined as:

$$F = t - p\tan\beta - d = 0 \quad (1)$$

where $F$ is the yield function, $t$ the deviatoric stress, $p$ the mean normal stress, $b$ is the Drucker–Prager internal angle of friction and $d$ the $t$-axis intercept in the $p$–$t$ plane. The parameters $b$ and $d$ are analogous (but not identical) to the internal angle of friction (φ) and cohesion (c) of the Mohr–Coulomb yield function, respectively (Naderi-Boldaji et al., 2013). The direction of the plastic strain gradient ($d\varepsilon^{pl}$) with respect to the yield surface is controlled by dilation angle ($\psi$) which introduces two plastic flow rules (i.e. associated and non-associated flow). Associated flow results from setting $\psi = \beta$ (i.e. the direction of plastic strain is normal to the yield surface) that was employed in this study.

The soil geometry was meshed with 4-node bilinear axisymmetric quadrilateral elements CAX4R. The element size was selected based on sensitivity analyses of mesh density which resulted in 4.5 mm as the largest possible size of the elements (i.e. smaller size showed a similar stress-strain curve). The boundary conditions applied were: (1) the side wall of the soil was constrained in lateral direction (i.e. only vertical deformation was allowed), (2) the bottom of soil was set as roller and (3) a 20 mm vertical displacement for the reference node of the rigid piston with a 2 mm/min sinkage rate. The slow rate of 2 mm/min was selected to minimize the inertial effects during soil deformation (Hemmat et al., 2012). The 20 mm vertical deformation ensured that