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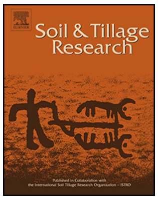

Stress transmission coefficient: A soil stress transmission property for a loading process

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ABSTRACT

Predicting soil stress with analytical models requires proper selection of the models' concentration factor. But due to the insufficient knowledge about the effects of soil conditions on stress transmission, little is known about how the concentration factor varies with soil states and loading conditions. Thus there is a need to supply specifically defined parameters with clearer physical meanings for soil stress transmission while easily being measured with simple laboratory setups. The function of the concentration factor was transformed and a dimensionless factor standing for soil-induced attenuation on the stress transmission between two points, $(\sigma_O\text{-}\sigma_Z)/\sigma_O$, was derived, which complement, σ_Z/σ_O, is the soil stress transmission coefficient and is denoted as STC. Since soil stress transmission property is affected by soil states and loading conditions, a modified oedometer testing setup with a soil stress sensor was used to evaluate controlled soil properties on STCs. Totally 15 soil states were tested by controlling 5 soil water contents and 3 bulk densities. Correlation analysis were performed between measured STCs and soil state parameters, i.e. water content, bulk density and soil strength. The concentration factor was then back-calculated from the acquired STCs.

The highly linear correlation between soil stress and applied surface stress indicates a stable STC for each particular soil state, suggesting that the theoretically derived STC could be used as a specific mechanical property to quantify soil stress transmission. In general, a high soil water content leads to an increased STC, meaning that wetter soils are more effective in transmitting the stress to deeper places. STC was also found both linearly decreased with dry bulk density and precompression stress. A higher soil strength imposes an improved shielding effect on soil stress transmission. The back-calculation of concentration factor from measured STCs illustrates that the proposed solution for soil stress transmission provides a means to define concentration factor for each soil state with measured result. Concentration factor varied from 2.64 to 12.39, being in agreement with the past reports. But the detail of how the concentration factor is affected by the changed states of soils is provided.

1. Introduction

Soil compaction, a major process of soil degradation worldwide (Soane and van Ouwerkerk, 1995; Flowers and Lal, 1998; Hamza and Anderson, 2005; Nawaz et al., 2013), is resulted from stress transmission within a soil due to agricultural traffic. Stress transmission is therefore of major importance as it is a primary process leading to changes in soil functions (Keller et al., 2014). Soil stress can be calculated with stress transmission models, using either FEM or analytical tools (Défossez and Richard, 2000). These models can be used to calculate stress propagation and soil failure in the soil profile under particular loading conditions and soil states, which results may help farmers and advisors in planning and making decisions about specific traffic situations in the field (Keller and Lamandé, 2010).

Analytical soil compaction models have been widely used. They are simple to use, require few input parameters and are robust (O'Sullivan et al., 1999; Arvidsson et al., 2001; Trautner, 2003; van den Akker, 2004; Keller et al., 2007; Keller and Lamandé, 2010; Moslem and Hossein, 2014; Rücknagel et al., 2015). Most of these analytical models were rooted from Boussinesq equation, with a presumption that stress is distributed within a homogeneous, linear elastic, isotropic, semi-infinite solid mass under a point load applied on a soil surface (van den Akker, 2004). However, because soils react neither elastically nor completely plastic, but showing elasto-plastic or even visco-elasto-plastic properties (Fröhlich,

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1934; Smith et al., 2000), the Boussinesq equation was therefore modified with a concentration factor ν for a more precise description of stress distribution in soils (Smith et al., 2000). Assuming a homogenous and isotropic soil volume, the vertical stress distribution below a point load is calculated by:

$$\sigma_z = -\frac{\nu P}{2\pi}\cdot\frac{z^{\nu}}{r^{\nu+2}} \tag{1}$$

Where P is the point load applied on the soil surface (kN); r and z define the radial and vertical distance between the load and the target point within the soil (m), respectively; ν is the concentration factor, which value was set to 3 in the original version of Boussinesq equation. Integrating Eq. (1) gives rise to the stress at a point within the soil volume under a distributed loading condition (e.g. distributed surface stress of a tire-soil interface). In particular, under a uniform stress distribution on a circular area with radius R, the vertical stress at depth z below the center of the contacting surface is calculated as (Smith et al., 2000):

$$\sigma_z = \sigma_0[1-(\frac{z}{(R^2+z^2)^{1/2}})^{\nu}] \tag{2}$$

Where $\sigma_0 = W/2\pi R^2$ is the mean vertical stress at the soil surface (kPa) and W is the total load applied (kN). Several authors have defined the concentration factors for predicting soil compactions as (Smith et al., 2000; Horn and Fleige, 2003):

$$\nu = \frac{2Log[\frac{\sigma_0}{\sigma_0-\sigma_z}]}{Log[(\frac{R}{z})^2+1]} \tag{3}$$

Söhne (1953) found that v increases with increasing soil moisture content and hence recommended a value of 4, 5 and 6 for ‘hard’, ‘firm’ and ‘soft’ structured soils, respectively. Ram (1984) tried to determine concentration factors experimentally with remoulded soils under controlled densities and moisture contents. The concentration factor was found decreased from 5.4 to 1.5 as soil bulk density increased from 1.24 to 1.63 $\mathrm{Mg\,m^{-3}}$. This trend was in agreement with the findings by Söhne (1953). However a significantly lower value was observed for hard soils. Thus, in well-aggregated soils, the concentration factor values are smaller than in the same but homogenized soils (Smith et al., 2000). Horn (1993) and Horn et al. (1995) determined the concentration factor values for structured and unsaturated soils as a function of internal soil strength. As long as the stress applied to the soil doesn't exceed the internal strength (e.g. precompression stress) the concentration factor is smaller as compared to the behaviour in the virgin compression load range. In this case the concentration factor value can even obtain values of 6–9. In other cases, a large variation of v, ranging from 2.0 to 14.3 and relating to structured soils, was also reported (Horn and Fleige, 2003; Keller and Lamandé, 2010; Lamandé and Schjønning, 2011a,b,c). The theoretically or laboratory acquired values of the concentration factor were inconsistent and could not be convincingly accounted. Moreover, the trend of v variations was reportedly non-uniform. For example, Horn and Fleige (2003) and Rücknagel et al. (2015) observed an increased v for weaker soils, while a contrasting result was reported by Trautner (2003), who noted a greater v for stronger soils.

The concentration factor is a coupled result from both loading conditions and the soil environment (Söhne 1953; Horn et al., 1995; Défossez et al., 2003; Horn and Fleige, 2003). Despite the widely use of analytical soil stress models, little is known about their key parameters, v, in terms of how it varies with soil type and loading conditions (Keller et al., 2014). In many occasions v is determined by calculating from surface stress σ_0 and measured soil stress σ_z (Smith et al., 2000; Horn and Fleige, 2003; Keller and Lamandé, 2010). But upon trying to do so, it immediately loses its significance for predicting soil stress from given loading conditions.

Keller and Lamandé (2010) asserted that soil stress calculation would be unattainable due to the insufficient knowledge about the coupled effects of both soil states (e.g. soil type, structure, moisture, density, etc.) and loading conditions on the concentration factor. Therefore, it would be much helpful in quantifying soil stressing processes once a pure soil property, i.e. stress transmission coefficient (STC), is available, and which is independent of boundary conditions and loading states. The aim of this paper is thus to investigate whether STC can be derived from existing models (Eqs. (1)–(3)) and if the derived STC is an easily measurable pure soil parameter applicable for quantifying soil stress transmission properties.

2. Theory

Due to the widely observed deviation of the predicted decay pattern of soil stress from empirically observed results (Söhne, 1953; Smith et al., 2000; Keller and Arvidsson, 2004), the concentration factor was introduced to provide a means of modification on the predicted soil stress, allowing the measured stress decay patterns to be theoretically reproduced with classical theory of elasticity (Selvadurai, 2014). Under a controlled loading condition, i.e. loading contact area or tire geometry, a general equation for the concentration factor can be derived from Eqs. (1)–(3):

$$v(\sigma_0,\sigma_z,R,z) = \frac{2Log[\frac{\sigma_0}{\sigma_0-\sigma_z}]}{Log[(\frac{R}{z})^2+1]} = \frac{2Log[\frac{1}{1-\sigma_z/\sigma_0}]}{Log[(\frac{R}{z})^2+1]} \tag{4}$$

Eq. (4) can be further rephrased as:

$$v(\frac{\sigma_z}{\sigma_0},R,z) = \frac{2Log[\frac{1}{1-\sigma_z/\sigma_0}]}{Log[(\frac{R}{z})^2+1]} \tag{5}$$

This simplified form of Eq. (5) illustrates that the concentration factor is governed by the loading conditions (R and z) and a dimensionless factor, $(\sigma_O\text{-}\sigma_z)/\sigma_O$ or $1\text{-}\sigma_z/\sigma_O$, which is purely a soil-induced attenuation on the stress between two points, denoted as η. Then the complement of η, i.e., $1\text{-}\eta$, is the soil stress transmission coefficient, denoted as STC. Eq. (5) is then rephrased as:

$$v(STC,R,z) = \frac{2Log[\frac{1}{1-STC}]}{Log[(\frac{R}{z})^2+1]} \tag{6}$$

Eq. (6) illustrates that, under controlled loading conditions, concentration factor ν is a simple function of STC, i.e., the sensitivity of soil stress transmission being defined as the ratio of soil stress σ_z with respect to the applied surface stress σ_O.

3. Materials and method

The above equations (Eqs. (2)–(6)) assume that soil medium is semi-infinite (Smith et al., 2000). However the evaluation of soil stress transmitting process has to be performed with simple laboratory settings, e.g., uni-axial compression test with remolded soils. Enormous efforts have been made to monitor soil stresses with sensor-based laboratory constructions (Smith et al., 2000; Arvidsson et al., 2001; Abu-Hamdeh and Reeder, 2003; Keller and Arvidsson, 2004; Lamandé et al., 2007; Keller and Lamandé, 2010; Lamandé and Schjønning, 2011a,b,c). Soil stress sensors can be readily applied to quantify the interrelationship between soil stress(σ_z) and the applied surface stress (σ_0) (Lamandé et al., 2015).