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Determination of soil density by cone index data

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ABSTRACT

In this paper a novel soil-density determination method is presented. The classic method (sampling, drying, mass measuring, etc.) can give proper results for the given problem but the standard methodology requires a lot of practical effort. While the soil is generally inhomogeneous, the measured density values of the soil sample applies only for the sample itself. On the entire soil territory this density can be interpreted only with significant errors. For a better mapping of the soil-density distribution expansive measurements are required. The task is complicated by the determination of density distribution in deeper layers of the soil as well. Our work presents a simpler method to determine the soil-density distribution in deeper layers with the use of cone penetration test (CI) results. With this method we can obtain detailed results of the soil-density distribution in deeper layers that may help further calculations for soil deformation analysis such as an exact determination of the soil sinkage below a tire track.

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1. Introduction

Cone penetrologger measurements are widely used in the field of soil investigations. Changying and Junzheng (1998) used the method to investigate the bearing capacity of paddy fields; Hernanz et al. (2000) built an empirical model where cone penetration method was used; the method also helped Mathe and Kiss (2015) in determining rolling losses of a towed vehicle. The cone penetration (also Cone Index – CI) method is also used to determine the bearing capabilities of soil, the quality evaluation of cultivation, for the determination of rolling losses of vehicles, and during the investigations of tire-terrain interaction (Meirion-Griffith and Spenko, 2011). The soil density is directly proportional with CI values, while the resistance of the soil is a smaller value if the soil density is lower. Also the compressed soil with higher density gives higher CI values. However there is no direct method in the literature, which would express the soil density directly from the CI values. The classical soil density defining methodology requires the sampling of the soil. The soil is perturbed during the sampling, and the whole process requires extensive practical effort (the requirements increase in the deeper layers). Also the determination of the density is a lengthy process, where the density may change with the time (see Table 1).

Soil deformation caused by the passing of the vehicle depends on the physical composition of the soil, the dampness (water content), the density, and the initial state of compression. Any lack of initial compression may result in uncertainty of the density calculations. Due to the aforementioned reasons, there is a need for a relation, which may give a precise calculation method to obtain soil density from the CI measurement results.

As shown by Sitkei (1972b, 1997) soil can be modelled as a viscoelastic medium, so rheological approach may be applied for soil calculations as well. A suitable parameter introduction for calculations will be the use of the strain ε, where the compression of the soil can be assumed as a negative elongation.

2. Material and methods

To investigate the relations between the soil density and the CI, soil tank experiments are needed. The soil is more homogeneous in a soil tank than at the field, so fewer measurements are sufficient to obtain correct data. The given homogeneity may also help to define new correlations.

The used soil tank (Fig. 1) had the following dimensions $1.8 \times 1.0 \times 0.7$ m. The dimensions were determined according to the required distance of the measurement point from the side walls. The CI measurements may be affected by both the side wall and the bottom of the track. The filling was performed with sandy adobe stubble, husked stubble and cultivated stubble. The soil to be filled was mesh filtered beforehand to remove any floral resi-

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Table 1
Soil densities.

ρ_1 = 0.9 g/cm^3	ρ_2 = 0.95 g/cm^3	ρ_3 = 1.1 g/cm^3
ρ_4 = 1.25 g/cm^3	ρ_5 = 1.45 g/cm^3	ρ_6 = 1.65 g/cm^3

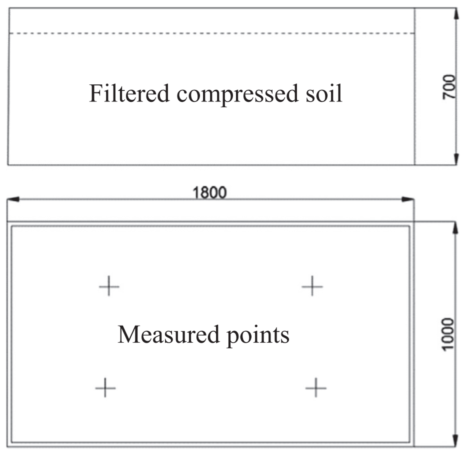

Fig. 1. Dimensions of soil tank.

dues. The tank was filled multiple times, with the same filtering approach of compressed soils of given densities.

The soil investigations were performed with different devices and methods: CI determination (Ejkelkamp type penetrologger with (2 cm^2, 60°) type, pointed angle pressure probes), moisture/water content measurement (SMM-1 type soil moisture measuring device), and bulk density with soil sampling.

During the measurements two types of cones were used. One cone had an opening angle of 30° with 2.05 cm diameter (meaning 3.3 cm^2 surface), the other had 60° opening angle with 1.6 cm diameter (meaning 2.01 cm^2 surface). The soil provides different responses for different cones with different opening angles.

2.1. The relationship between soil density and relative elongation

The soil compression below the tire bears not only vertical characteristics. Due to the load, sideway creep is occurring in the soil, underneath the pressure surface. For a given sink of the soil (in percentage values for example), a given percentage of sideway creep can be defined. For cohesive soil, this effect has smaller relevance; for cohesionless soil, the effect is more significant.

Relative vertical deformation can be calculated according to the following. According to the soil bulk density, the porosity, and the moisture content:

$$\rho_v = \rho(1 - n_v) \cdot (1 - X_n). \tag{1}$$

ρ	–	real soil density (ρ = 2.7)	[g/cm^3]
ρ_v	–	the soil density of measured soil	[g/cm^3]
n_v	–	porosity	[%]
X_n	–	water content, for dry basic	[%].

The (1) balanced to n_v, if X_n = 10% ⇒ 0.1 and ρ = 2.7 g/cm^3:

$$n_v = 1 - \frac{\rho_v}{2.4}. \tag{2}$$

The change of porosity n_ε with ε relative strain can be defined with:

$$n_\varepsilon = \frac{n_v - \varepsilon}{1 - \varepsilon}. \tag{3}$$

The (2) and (3) can be used to form an equation defining the relative strain of the soil, with ρ_0 (before compression) and ρ_ε (after compression) bulk density parameters:

$$\rho_\varepsilon = 2.4 - 2.4 \cdot \left(\frac{1 - \frac{\rho_0}{2.4} - \varepsilon}{1 - \varepsilon}\right). \tag{4}$$

(4) in simplified form:

$$\varepsilon = 1 - \frac{\rho_0}{\rho_\varepsilon}. \tag{5}$$

Using Eq. (5) a nomogram can be created to characterize the compression:

Fig. 2 shows how the relative elongation can be determined as a function of soil density, for example: if the soil density before the soil compression is 1.1 g/cm^3, after compression it becomes 1.3 g/cm^3. The relative elongation (which characterizes the compression) can be defined according to the horizontal line originated from 1.3 and the plot starting from 1.1. The X value for the intersection of the horizontal line and the plot will give the Relative elongation, which is approximately ε = 0.15 in this case.

2.2. The relationship between soil density and cone index plot

Figs. 3–5 show the results of penetration experiments for different moisture content. Due to increased moisture the soil becomes more compact, so obtaining data for lower densities was not possible. The resistance of the cone was linearly increasing up until 10 cm depth, then stabilized at a maximal value. The linearly increasing section extends the length of the cone by multiple times. The length of the linear sections decreased with the increase of compression. This phenomenon causes more difficult evaluation of the results, and requires a more complex practical approach to define the densities.

The CI plots and the actual values are depending on the applied cone type. During the measurements the aforementioned cones were used. To process the CI plots, classical Boussinesq formula for point load should be applied:

$$CI = R \cdot \left(\frac{z}{d_k}\right). \tag{6}$$

For the constant section:

$$CI_{max} = R \cdot \left(\frac{z_{max}}{d_k}\right). \tag{7}$$

The increasing linear ramp section can be characterized with R, which depends on the soil density, and according to the measurements, is a negative exponential function:

$$R = Ae^{-\frac{B}{\rho_v}}. \tag{8}$$

where:

CI	–	cone index	[MPa]
R	–	steepness of the steady state section	[MPa]
z	–	depth	[m]
d_k	–	diameter of cone head	[m]
A	–	constant for the soil condition	[MPa]
B	–	constant for the soil condition	[g/cm^3]

The data obtained from soils with different water contents show that the breakpoint position aligns to lower penetration depths, as moisture increases.

Using the Eqs. (6) and (8), the relationship between the CI and the soil density (for the increasing linear ramp section) can be described as follows:

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