Simulation of Soil Compaction by a Tractor Passing

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Abstract. Several methods for agricultural soil compaction evaluation are known. However, there is a lack of knowledge about a soil elasticity, which could be an important factor for final level of compaction. The paper deals with a possibility of evaluation of soil elasticity using automatic computerized oedometer. A simulation of tractor passing was performed as a part of research focused on the monitoring of soil conditions in vineyards. Cyclic loading test of five loading cycles (loading 300 kPa and un-loading 5 kPa) was performed and vertical deflection was observed, which changed in dependency on change of vertical stress. Course of vertical deformation indicates the ability of soil to relax when the load subsides. The paper presents pilot results, that show good potential of using oedometer for soil elasticity evaluating. Information on the elastic behaviour of soil will make it possible to design and apply means for improving soil elasticity and thus help to mitigate the effects of soil compaction.

1. Introduction

Soil compaction caused by passing of agricultural machinery is a problem, which all regions using modern technology in horticulture deal with. The excessive compaction of cultivated soils has a negative effect on crops and soil properties. According to [1] soil compaction can be mitigated by a reduction in the number of passes, driving in ruts, integration of organic matter and optimizing the choice of wheel, tire and inflation of the tires. In order to evaluate the benefits of different arrangements, it is necessary to know the methods for soil compaction determination. A measure of compaction is determined indirectly by monitoring the mechanical and physical parameters of the soil, like penetration resistance, bulk density, porosity and soil water content.

For understanding the impacts of soil compaction on soil functions (reaction), knowledge of the soil deformation process (cause) is needed. A parameter frequently used to suggest the soil loading capacity, and accordingly the compaction risk of cultivated land, is precompression stress [2]. Based on the compaction curve developed by Casagrande [3], precompression stress is the point that divides the compaction curve into two parts. When soil is subjected to stresses smaller than the precompression stress, it deforms and recovers elastically along the recompression curve. However, at stresses greater than the precompression stress, the soil deformation is irreversible. Another definition (mentioned for example in [4]) indicates precompression stress as the maximum effective stress to which the soil has been subjected. According to Cavalieri et al. [5], there are several methods for determining precompression stress, but a different method is suitable for each soil type. This makes it difficult to use the absolute value of precompression stress as a limit for soil stress in order to avoid soil compaction.
Development of numerical simulations allows the creation of different models to predict soil compaction. There are reviewed models based on the finite element method in [6] and discussed some differences between experimental data and model simulations in [7]. Ben Hassen et al. [8] introduced a visualization of soil compaction probability, based on Bayesian networks. The input parameters for the models represent the same quantities as are observed in the conventional determination of soil compaction measure: penetration resistance, bulk density, soil depth, humidity, tractor weight, wheel pressure, or passes number.

Many variables make the soil compaction appraisal time consuming and data intensive. The aim is to simplify the process by finding dependencies between variables, so that the risk of soil compaction can be evaluated on the basis of a smaller number of criteria. Experimental verification of dependencies and critical ranges of soil properties is carried out by Rücknagel (most recently in [9]). It is important to be able to determine the current level of compaction and to propose the necessary measures, but it would be better to be able to prevent these undesirable changes in the soil system. One way to improve soil properties to prevent compaction is to increase the amount of humus, which can be performed by applying a compost. According to [10], increases in organic matter may reduce soil compaction by increasing resistance to deformation and by increasing elasticity.

In this paper, attention is paid to an elastic behaviour of soil and its evaluating in order to note the soil resistance to compaction. The aim is to find out how the soil deforms during a passing of an agricultural machinery, which represents a cyclic loading. Pilot results are presented to confirm that a soil elasticity could be an important factor for the final level of compaction.

2. Material and methods
The behaviour of the soil was monitored in laboratory conditions and therefore it was necessary to best simulate the load acting when passing a tractor. The aim was to find out whether the soil deforms partially elastically and how it relaxes. Automatic computerized Oedometer ACE EmS (Wykeham Farrance, Italy) was used for simulation, which usually serves for determination of oedometric modulus of elasticity in field of soil mechanics in civil engineering.

The existing test standard [11] is not suitable for our purposes. In agriculture, it is desirable for the soil to deform elastically (temporary deformation), in contrast to the requirements of building founding, where elastic deformation is undesirable and the effort is to compact the foundation soil as much as possible before construction to reduce settlement during service life of the building. For our oedometric test, the loading steps were set to simulate the passage of a tractor between the rows of a vineyard.

2.1. Characteristics of soil sample
Soil samples were taken from vineyard located in South Moravia (48°52'45.52"N, 16°52'59.02"E). In this region, the average annual temperature is 8 - 9 °C, the average annual rainfall is 500 - 550 mm and the average relative humidity is around 80 %. According to the Taxonomic Classification System of Soils in the Czech Republic, the soil type is dominated by modal chernozem and pellic chernozem. Physical properties are classified in table 1. Undisturbed soil samples were taken at a depth of 0.05 m from three different locations (A, B, C) spaced approximately 20 m apart. Three samples were taken from each location, for a total of 9 samples were tested.

| Table 1. Physical properties of investigated soil before compression. |
|-----------------|-----------------|----------------|
| Depth (m)       | Bulk density reduced (g/cm3) | Porosity (total) (%) |
| 0 – 0.1         | 1.03             | 60.49          |
| 0.1 – 0.2       | 1.26             | 51.51          |
| 0.2 – 0.3       | 1.30             | 49.87          |
2.2. Soil compression tests

The soil cores used in the compression tests had a diameter of 50.47 mm and a height of 20 mm. The size of the load and the length of the loading steps were chosen in an effort to approximate an actual course of the load during the multiple passage of the tractor in the intermediate row of the vineyard. We assume, that the tractor goes through the intermediate row more than once when performing one work operation. In the soil compression test, two situations alternate: the load step of compression the soil, which simulates the load of the tractor wheel, and the load step of decompression, which simulates a split time before the tractor returns to the same place. A duration of the individual step depends on a speed of the tractor and on a total length of a row. A total of 10 steps were designed for the experiment: 5 steps of loading and 5 of unloading.

The magnitude of the applied stress for the loading step corresponds to the estimated stress under the tractor wheel and was set to 300 kPa. This value was calculated for standard tractor and it corresponds to measured soil stresses in [12] and [7]. A light load of 5 kPa was applied during the unloading step, as complete unloading would make it impossible to monitor the deformation of the sample. It should be noted that compression and unloading also occurred between the individual loading steps, when the vertical stress reached the required value of 300 kPa or 5 kPa.

The actual course of the test was preceded by pre-loading of the test specimen by 5 kPa and zeroing of the displacement. The first loading step followed, when a load of 300 kPa was applied for 1 min. In the second loading step, a load of 5 kPa was applied for 10 minutes, in the third step a load of 300 kPa for 1 minute, and so on until the tenth step, in which a load of 5 kPa was applied. Vertical deflection of soil sample was measured on the beginning and on the end of each loading step.

2.3. Statistical analysis

Using statistical analysis, a correlation between measured deformations within the loading steps was looked for. Results were reported as averages and standard deviation. Analysis of variance (ANOVA) and Tukey’s honestly significant difference (HSD) tests were conducted to determine the differences among averages, using the software package “Statistica 12.0” (ver. 12.0, 2017). Analysis of variance was conducted, and the results were compared using Tukey's multiple range assay at a significance level of $\alpha = 0.05$.

3. Results and discussion

Three soil samples (1,2,3) were taken from each of three locations in vineyard inter-row (A, B, C) and were tested in oedometer in order to simulate the tractor passing during working operation. Changes in sample height were measured during the test. When a load of 300 kPa was applied, the sample was compressed and during the unloading step (5 kPa load) the sample partially relaxed (Figure 1).

The behaviour of soil samples is similar, it differs in initial point, which is the sample height after first loading (in time 60 s). It can be seen from Figure 1, that the first load applied caused the main compression. It corresponds with results of Elaoud and Chehaibi [1], who stated that the first passage of wheel traffic of the tractor affects more than the second passage.

The graph in Figure 1 also shows that the elastic part of the deformation is lost during unloading. Supporting evidence is supplied by Peth et al. [13] who, after observation soil deformation under dynamic loading conditions concluded that soil deforms elastic, if stresses remain below the pre-compression stress. In our paper, pre-compression stress was not determined. As mentioned in the introduction, opinions differ on the effect of pre-compression stress on soil behaviour under load. For example, results in work of Gubiani et al. [14] do not confirmed the assumption that pre-compression stress represents a transition from elastic to plastic soil behaviour.
Figure 1. Measured height of the soil sample during compression test

It can be noticed in the graph that the slope of the lines representing the change of vertical displacement within one loading or un-loading step seems to be the same for all tested samples. Statistical evaluation was performed, which showed a correlation between loading steps. The SA1 sample was excluded from the set, in which the slope differed from the other samples. It is evident from table 2, that there are no significant differences, except for the first loading step, when the maximum compression occurred. In the un-loading steps, the soil relaxed. For all samples, the vertical displacement (compression of sample) at the end of the 10th step was smaller than after the first loading step. The results of the statistical analysis show a correlation between the deformations at the individual un-loading steps and the correlation between the deformations at the loading steps. This corresponds to the similar slope of the curves in Figure 1.

These results are in good agreement with results of Peth et al. [13], who performed cyclic loading tests with 100 loading cycles (loading and un-loading sequence), with vertical stress 80 kPa applied by pneumatic multistep oedometer and two different loading times of 30 and 240 s. Even after 100 loading cycles soil deformation did not completely cease, similar to the typical creep behaviour of clayey soils.

There are neglected shear effects as well as the pore water pressure influences in laboratory conditions. However, we believe that this method could be sufficient to compare the tendency of soil to compaction at different compost applications.
Table 2. Compression during the loading step (mm), L = loading, U = un-loading

| Loading step | SA2 | SA3 | SB1 | SB2 | SB3 | SC1 | SC2 | SC3 | Average value of compression or decompression (mm)* |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|---------------------------------|
| 1 L          | 0.24| 0.625| 0.433| 0.585| 0.429| 0.431| 0.425| 0.419| 0.448±0.117c                  |
| 2 U          | 0.231| 0.345| 0.17| 0.246| 0.202| 0.207| 0.274| 0.293| 0.246±0.056b                |
| 3 L          | 0.11| 0.254| 0.14| 0.201| 0.15| 0.225| 0.19| 0.169| 0.18±0.047ab                |
| 4 U          | 0.222| 0.232| 0.096| 0.163| 0.133| 0.18| 0.243| 0.242| 0.189±0.055ab                |
| 5 L          | 0.095| 0.184| 0.101| 0.114| 0.091| 0.153| 0.137| 0.127| 0.125±0.032a                 |
| 6 U          | 0.248| 0.22| 0.09| 0.148| 0.102| 0.151| 0.206| 0.213| 0.172±0.058ab               |
| 7 L          | 0.076| 0.149| 0.083| 0.088| 0.075| 0.128| 0.124| 0.109| 0.104±0.028a                |
| 8 U          | 0.253| 0.272| 0.085| 0.122| 0.099| 0.219| 0.181| 0.213| 0.18±0.071ab                |
| 9 L          | 0.064| 0.14| 0.067| 0.078| 0.052| 0.116| 0.096| 0.109| 0.09±0.030a                 |
| 10 U         | 0.256| 0.31| 0.082| 0.13| 0.083| 0.188| 0.182| 0.185| 0.177±0.079ab              |

*Different letters within the column indicate significant differences (P < 0.05) according to the Tukey test

4. Conclusions
The main purpose of the paper was to find out, what is the behaviour of soil during cyclic loading, which is in reality represented by agriculture mechanization. Vertical stress was applied to the soil sample in oedometer and vertical deflection was measured during cyclic changes of stress. The course of deformation confirmed the partially elastic behaviour of the soil and supported the idea of monitoring the soil elasticity depending on the time to reduce the risk of soil compaction.

Presented results will be used in research that deals with the application of compost in vineyards and their effects on soil quality and production. In the next phase of the research, attention will be paid to the effects of organic matter addition into soil on the course of vertical displacement during cyclic loading.

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