DATA COLLECTION FOR NON LINEAR SOIL MODEL OF DEM

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Abstract
In order to create a model, input parameters need to be provided. The basic step for obtaining these parameters is the execution of the appropriate experimental tests. Establishing stiffness for the specific soil in relation to its consolidation is one of the important parameters. Soil porosity was observed under various consolidation. Tests were carried out in order to determine the amount of force required to compact the soil to a specific degree of porosity, as well as to determine stiffness and derive the relationship between stiffness and porosity. The individual coefficients can be used to set the model in RockyDEM environment.

Key words: *Stiffness; ball indentation; porosity; soil.*

INTRODUCTION

When creating a mathematical model of a particular substance, a selection of an appropriate contact model between the particles is necessary. Rocky DEM environment *("Rocky DEM Particle Simulator," 2018)* has three particle contact models available. Hysteretic Linear Spring model, Linear Spring Dashpot model and Hertzian Spring Dashpot model *(Obermayr, Vrettos, & Eberhard, 2013; Pasha, Dogbe, Hare, Hassanpour, & Ghadiri, 2013)*. The use of Hysteretic Linear Spring model is advised for creating non-linear soil models. This model was first introduced in the year 1986 *(Walton & Braun, 1986)*. Static and dynamic friction are the fundamental parameters for setting a mathematical model *(Kuře, Hájková, Hromasová, Chotěborský, & Linda, 2019)*. An important parameter for the correct use of the model is Stiffness *(Ucgul, Fielke, & Saunders, 2015)*. Ball indentation method can be used to correctly determine stiffness of a particular substance *(Pasha et al., 2014)*. Principally, it determines hardness of the material. Hardness is defined as the resilience of a material to a plastic deformation. In the case of a loose material, it is possible to determine the stiffness under a specific state of compaction. The aim of this work is to describe the process of determining stiffness, using the ball indentation method, and gaining results for a specific type of soil. These parameters are important in order to create models using the discrete element method.

MATERIALS AND METHODS

This type of soil is located in northwestern part of Prague (Czech Republic). The first step was to determine the soil's moisture. During these tests it is necessary for the moisture to remain at the same value. Moisture of the soil significantly affects its mechanical properties. In order to determine the moisture, a sample was taken, weighted and then left to dry out for 24 hours in a drying room under 105 degrees Celsius (221°F). The moisture was then calculated and determined to be 17%. Another set of tests were performed to determine the dependence of the force affecting the soil in relation to its compaction. A 40mm diameter cylinder was filled with separated soil up to a height of 60mm, followed by a pressure test during which the soil was compressed under constant feed rate. During this test, the force applied to the indentation ball as well as its displacement were observed and recorded (Fig. 1 and 2). In the force/depth of the compaction relation was the force converted to pressure. Deformations were determined from the deformation curve and subsequently a maximal pressures for the soil sample's compaction and consolidation, it is required for the ball indentation test. A size 90x90x60 mm containers were filled with separated soil samples in order to determine its stiffness. Individual load forces were recalculated to the cross section area of 90x90mm. Individual samples were subjected to load forces of 65, 225, 470, 546, 902 and 1841 N. After reaching a specific force load, the samples were hold for 10 minutes in case of soil relaxation and subsequently subjected to the ball indentation test.

The test involves embedding the ball indenter into the sample at a constant deformation rate *(Pasha, 2013; Pasha, Pasha, Hare, Hassanpour, & Ghadiri, 2013)* and then relieving it once again at a constant deformation rate back to the ball's initial position. The test was carried out on a universal tensile machine. The deformation rate was set to 10 mm/min. The force acting on the ball during its retraction is also measured. The cycle is complete after the ball reaches the initial position (Fig. 1). A 25.4 mm diameter Teflon ball was used for the indentation. The result of the test is the dependence of force on the indentation position of the ball into the soil (Fig. 2).

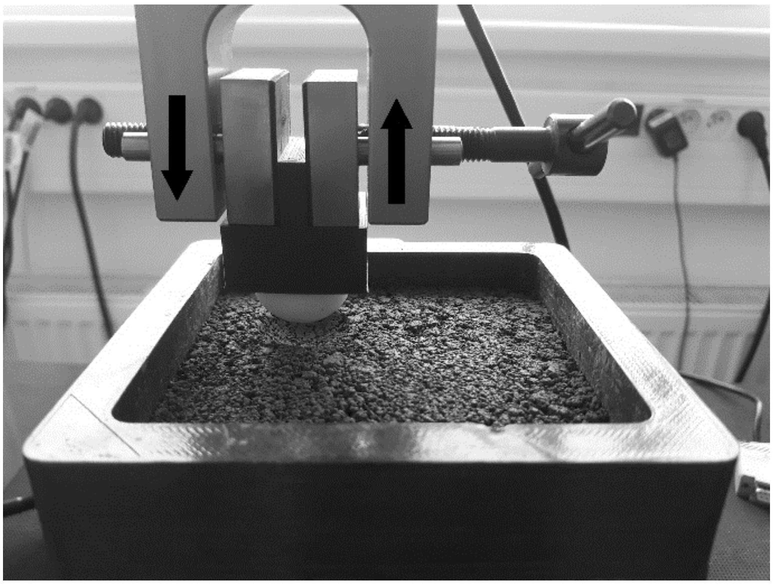

Fig. 1 Cycles of ball indentation into compacted soil

Figure 2 shows the schematic penetration diagram of the test of the test. The graph shows Elastic energy (EE), which indicates the area below the unload curve. Plastic Energy (PE) is the area below the load curve that, at the same time, does not excluded the unload curve. Calculation of areas from the measured data is expressed by equations (1) and (2).

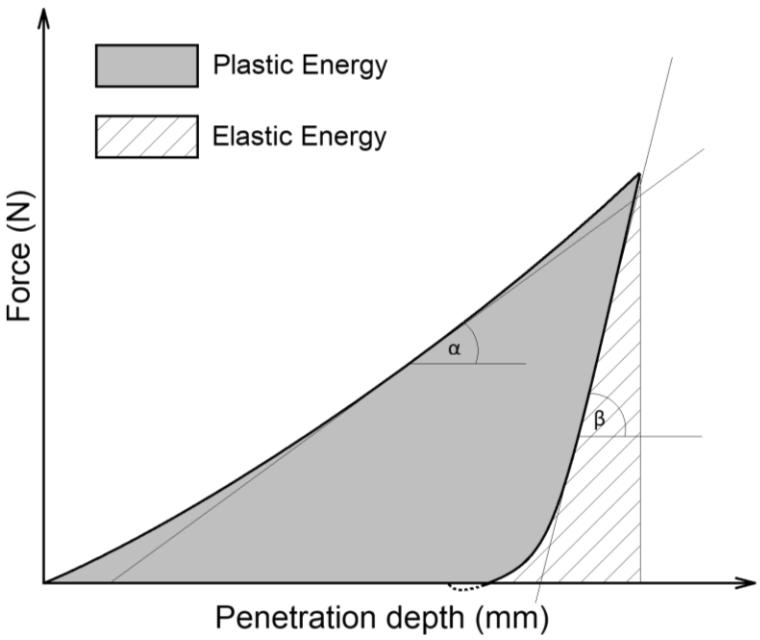

Fig. 2 Loading-unloading curve of ball indentation test

$$\mathrm{EE} = \sum_{1}^{i}\left(\frac{(d_i-d_{i-1})*(\mathrm{Fl}_i-\mathrm{Fu}_{i-1})}{2} + (d_i - d_{i-1})\cdot \mathrm{Fu}_{i-1}\right) \quad (1)$$

where *EE* is Elastic Energy (N.mm, *d* is displacement (mm) and *Fu* is Force of unloading (N)

$$\mathrm{PE} = \sum_{1}^{i}\left(\frac{(d_i-d_{i-1})*(\mathrm{Fl}_i-\mathrm{Fl}_{i-1})}{2} + (d_i - d_{i-1})\cdot \mathrm{Fl}_{i-1}\right) - EE \quad (2)$$

where *PE* is Plastic Energy (N.mm), *d* is displacement (mm) and *Fl* is Force of loading (N)

From the obtained energies, the ratio between them can be calculated. This ratio is marked as Er – energy ratio (3).

$$\mathrm{E}_r = \frac{\mathrm{EE}}{EP} \quad (3)$$

where E_r is Energy ratio (-)

In order to calculate stiffness it is necessary to know the load curve direction and the unload curve direction (4) and (5). The proportion of these two directions (6) expresses the stiffness coefficient.

$$\mathrm{k1} = \tan\alpha \quad (4)$$

where *k1* is slope of load curve ($\mathrm{N.mm^{-1}}$) and α is angle of tangent of load curve (°)

$$\mathrm{k2} = \tan\beta \quad (5)$$

where *k2* is slope of unload curve ($\mathrm{N.mm^{-1}}$) and β is angle of tangent of unload curve (°)

$$\mathrm{stiffness} = \frac{k1}{k2} \quad (6)$$

Soil porosity was determined from density of bulk matter. Volume and weight were determined at maximum compression of the soil sample (at ε = 41.7% deformation). The soil density is therefore 1839 kg.m-3 ± 53 kg.m-3. In order to determine the bulk density, the soil was separated into measuring cylinder to a defined height of h = 60mm. This sample determined weight and volume. The resulting density for the separated soil is 975 kg.m-3 ± 43 kg.m-3. The porosity can be expressed by the relation for each variable deformation ε ranging from 0 – 41.7% using the equation (7).

$$\varepsilon = 0.53 - 1.272 \cdot \mathrm{x} \quad (7)$$

where ε is deformation (-) and *x* is porosity (%)

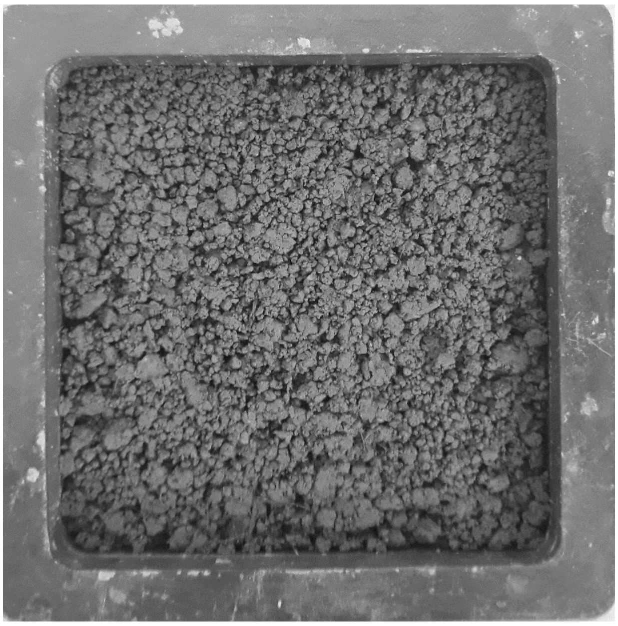

Fig. 3 Compacted specimen soil of 65 N

Once the measuring is done, individual indents can be analysed. The soil must be well spread out before the first load. In case of insufficient separation, larger lumps may occur in the soil. These areas may then distort the result of the test. Fig. 3 shows spread out soil sample after a load of 65 N. Visible pores can be observed between the individual parts of the soil. Fig. 4 shows the same soil sample after the test was carried out. Visible indentations are present in the sample. Measurements were made for a specific maximal load. See Tab. 1 in *Results and discussion* for the measuring parameters. In order to determine the stiffness value, it is important to know the load and unload curve directions. These directions can be obtained from curves for different maximum loads or loading and unloading speeds *(Pasha et al., 2014)*. The measured values were processed and the soil porosity was determined for each load.

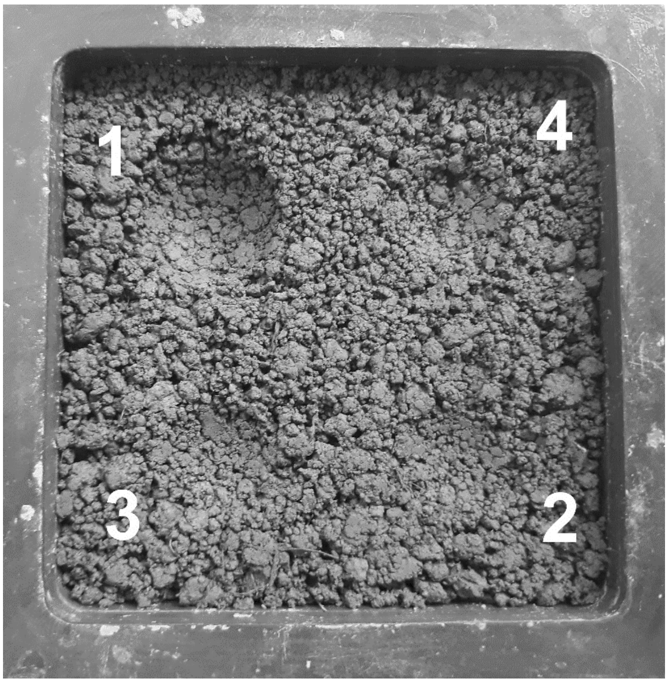

Fig. 4 Soil specimen with dimples

RESULTS AND DISCUSSION

Plastic and elastic energy was determined from the measured curves. EE / PE is defined as the proportion of Elastic energy and Plastic energy, indicated as E ratio. See Tab. 1 for the measured data.

Tab. 1 Energies of ball indentation tests

Pre-load N	Plastic Energy N.mm	Standard Deviation N.mm	Elastic Energy N.mm	Standard Deviation N.mm	Ball maximum force N	E ratio -
65	27.7	1.26	1.52	0.035	10	0.054
225	169	27.6	10.2	0.127	40	0.060
470	88.8	4.17	9.66	0.317	40	0.108
546	83.0	8.94	9.36	0.127	40	0.112
902	56.3	5.54	8.95	0.233	40	0.158
1841	39.0	1.80	8.84	0.116	40	0.226

See Tab. 2 for the measured load-unload directions. The load curve direction is indicated by the coefficient k1, and the unload curve direction by the coefficient k2. The proportion of these directions indicates stiffness.

Tab. 2 Energies of ball indentation tests

Pre-load	k1 slope	Standard Deviation	k2 slope	Standard Deviation	Coefficient of Stiffness	Standard Deviation
N	$N.mm^{-1}$	$N.mm^{-1}$	$N.mm^{-1}$	$N.mm^{-1}$	-	-
65	1.70	0.04	44.3	0.71	0.04	0.0012
225	4.07	1.21	97.9	0.46	0.04	0.0125
470	8.24	0.43	101	2.12	0.08	0.0125
546	9.39	0.96	105	1.75	0.09	0.0076
902	12.8	1.31	106	1.39	0.12	0.0119
1841	17.9	0.83	108	3.31	0.16	0.0068

Fig. 3 indicates the relation between stiffness and Energy ratio expressed from the measured values. Based on this ratio it is possible to calculate the stiffness value from the proportion of the individual energies.

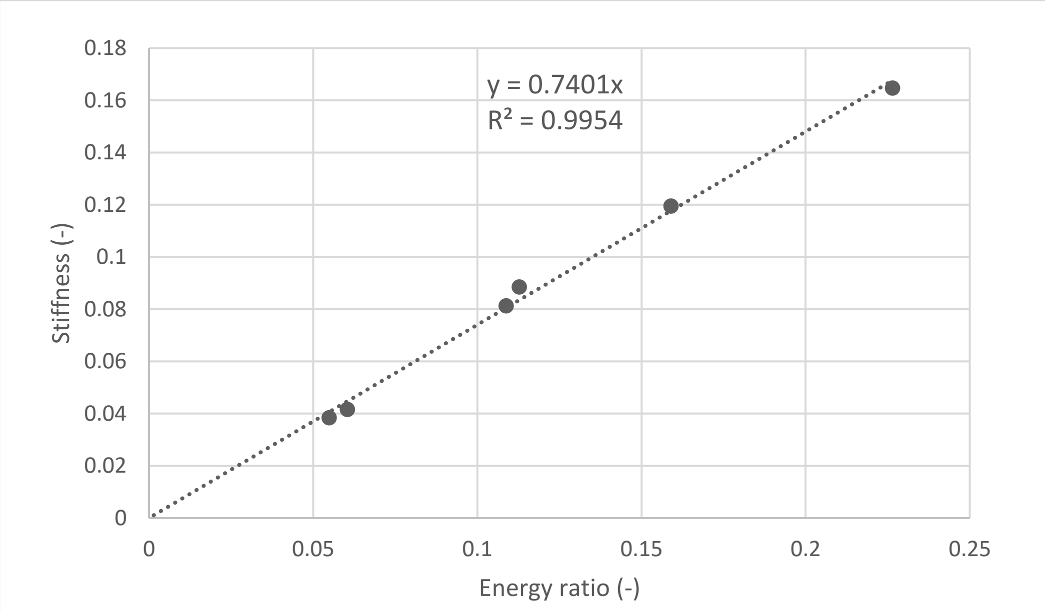

Fig. 5 Curve of stiffness and energy ratio

Tab. 3 shows the relations between energies, stiffness and porosity, which were obtained from the measured data. Equations 1) and 2) express relation between energy and porosity. Equation 3) shows the relation between stiffness and porosity. Knowing these relations, it is possible to calculate individual values for different degrees of porosity.

Tab. 3 Ratio between porosity elastic energy, plastic energy and stiffness where x is porosity

	Equation	
1)	$EE = 15.043 \cdot x^2 + 1.5719 \cdot x + 8.8433$	$R^2 = 0.964$
2)	$EP = 1784.4 \cdot x^2 + 4.6881 \cdot x + 43.815$	$R^2 = 0.916$
3)	$Stiffness = 0.7756 \cdot x^2 - 0.6388 \cdot x + 0.1619$	$R^2 = 0.975$

Stiffness values range, in the case of this soil type, from 0.04 to 0.16. This is a considerable interval within the model setup. Porosity of the material depends on its separation. There is, however, a dependence between porosity and other properties such as Elastic energy, Plastic energy or Stiffness. The porosity was calculated from 0 when reaching the maximum soil pressure. Deformation of the soil is therefore dependent on its porosity. Stiffness value also fundamentally changes based on the type of soil.

In comparison, stiffness values of a sandy soil are lower than those of other types of clay soil *(Chen, Munkholm, & Nyord, 2013)*. The maximal value of stiffness that can be used in the model equals 1. The individual parameters depend on the moisture content *(Ucgul, Fielke, & Saunders, 2015)*. Moisture content was obtained and maintained at 17% throughout the test.

CONCLUSIONS

The measured values indicate that the value of stiffness is directly proportional to the Energy ratio. Stiffness is a very important parameter when creating models using the discrete element method. The measurement method used is a fundamental solution for obtaining important values needed for preparation and usage of a mathematical soil model. Soil porosity affects the stiffness value. With increasing porosity of soil, the stiffness value decreases. In the case of Plastic energy and Elastic energy with increasing porosity of soil, the energy values also increase. However, the Energy ratio decreases with the increasing soil porosity.

ACKNOWLEDGMENT

This study was supported by the Internal Grant 31200/1312/3102 of the Faculty of Engineering, Czech University of Life Sciences in Prague with the name: Influence of Input Parameters of Agricultural Bulk Matter on the Accuracy of Solution Using Discrete Element Methods.

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