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A systematic approach to reliably characterize soils based on Bevameter testing

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Abstract. *Although there exists a lot of information about soil parameter identification in literature, currently there is no algorithm both making use of state of the art identification methodologies and incorporating statistical analysis. In this paper a state of the art soil parameter identification method is presented including the calculation of their standard deviations and a proper weighting of the objective function. With this algorithm and a Bevameter with advanced sensor and actuator technology a test campaign is started to find a reliable soil preparation which is applicable to a large planetary rover performance testbed. Furthermore the preparation method has to be valid and stable for various types of granular soils, typically used for planetary rover testing in space robotics, since the result of pre-tests show that the soil parameters are highly depending on the preparation. Besides the preparation soil parameters are influenced by different Bevameter test setup variables, too. Thus the effect of the penetration velocity as well as the penetration tool geometry for pressure-sinkage tests on soil parameters is investigated. For shear tests the influence of the dimension of the shear ring is also analysed as the variation of the grouser height, the number of the grousers and the increase of the rotational shear velocity. The results of the extensive test campaign are evaluated by the proposed identification algorithms.*

Keywords. Bevameter, soil parameter, testbed, identification, planetary rover

1 Introduction

Although rover performance and rover mobility testing plays an important role in the ExoMars programme of the European Space Agency (ESA) simulation of the rover performance is a further part for a successful mission, too. With a verified and validated simulation tool special mobility cases occurring during the mission can be examined leading to the best trajectory of the vehicle. Furthermore in early stages of a project simulation has the ability to provide information about the performance of different mobility concepts. An example for such a simulation tool is given by Gibbesch et al. (2010). Therein a soft soil contact model is used to describe the interaction between a wheel and a soft deformable soil (Krenn, 2009). To verify and validate a simulation software, testing and simulation have to go hand in hand. Therefore the test facility described in Apfelbeck et al. (2009) is used with the current ExoMars BB2 breadboard (Figure 1). An essential input for the simulations are the soil parameters identified from Bevameter measurements. However a reliable mechanical characterisation of soft soil by Bevameter testing is a very delicate issue to accomplish, since soil parameter determination depends often to a large extent on several testing impacts like the soil preparation method. Moreover the identified parameters are influenced by several test setup parameters. Using soil parameters identified with improper test setup variables on a soil prepared with an unreliable preparation method as inputs for validation simulations leads to incorrect simulation results and consequently to incorrect validation and correlation results. Therefore an applicable and stable soil preparation method is indispensable as well as information about the effect of the variation of the test setup parameters on the soil parameters. These issues are investigated in an extensive test campaign presented in this paper. Besides the preparation and the test setup the identification algorithm is a further important part of getting stable and reliable soil parameters. The currently known soil identification methods (Wong, 1980; Oravec, 2009) do neither incorporate a statistical analysis of the identified parameters nor consider the nonlinear behaviour of the soil equations directly. Both issues are included in the presented soil identification algorithm presented in this paper.

In chapter 2 the soil parameter identification methods are described. The test results are given in chapter 3, the identification results in chapter 4. Chapter 5 gives a final the conclusion of this paper.

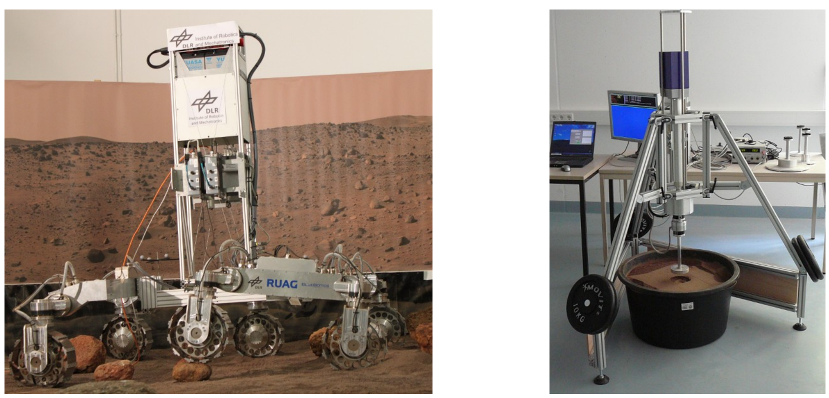

Figure 1: ExoMars BB2 Breadboard (left), Bevameter for soil characterisation (right)

2 Soil parameter identification

In the following a general approach for an identification problem is given. This approach is adopted to the identification of soil parameters using a pressure-sinkage test or a shear test (see sections 2.1 and 2.2). For parameter identification a general minimisation problem is used

$$\min_{\hat{\theta}} E(\hat{\theta}) = \min_{\hat{\theta}} \frac{1}{2} \| \boldsymbol{w_r} \cdot \boldsymbol{e}(\boldsymbol{X}, \hat{\boldsymbol{\theta}}) \|^2 = \min_{\hat{\theta}} \frac{1}{2} \| \boldsymbol{w_r} \cdot [\boldsymbol{y} - \boldsymbol{f}(\boldsymbol{X}, \hat{\boldsymbol{\theta}})] \|^2 \quad (1)$$

The objective function is given by $E(\hat{\boldsymbol{\theta}})$, the error function by $\boldsymbol{e}(\boldsymbol{X}, \hat{\boldsymbol{\theta}})$. The vector $\boldsymbol{y}$ consists of the measured values, $\boldsymbol{f}(\boldsymbol{X}, \hat{\boldsymbol{\theta}})$ is the model function of the identified parameters $\hat{\boldsymbol{\theta}}$ and controlled inputs $\boldsymbol{X}$. The controlled inputs are variables or values the result of the model function is depending on. Furthermore a weighting factor $\boldsymbol{w_r}$ is included in Eq. 1. The solver for the optimisation problem is depending on the chosen model function, i.e. a nonlinear solver (e.g. Levenberg-Marquardt) for a nonlinear objective function or a linear solver for a linear objective function. An overview of solvers for minimisation problems is given in Jarre and Stoer (2004). The quality of the fit is calculated by the root mean square of the identification error over the measured values:

$$\epsilon = 1 - \frac{\sqrt{\dfrac{\sum \boldsymbol{e}\left(\boldsymbol{X}, \hat{\boldsymbol{\theta}}\right)^2}{N-2}}}{\dfrac{\sum |\boldsymbol{y}|}{N}} \tag{2}$$

Here N is the number of data points used for the identification which is equal to the length of vector $\boldsymbol{y}$. If the identification is perfect, ϵ is equal to one otherwise less than one. This equation is adopted from Wong (1990) and kept more general in order to be applicable for problems with negative measurement values. However such an evaluation of the identification quality allows no statement about existing deviations of the identified parameters. Therefore, for a nonlinear problem, the calculation of the standard deviation σ , according to Seber and Wild (2003), of the identified parameters is included in the identification

$$\boldsymbol{\sigma} = \sqrt{diag\left(\boldsymbol{Cov}\left(\hat{\boldsymbol{\theta}}\right)\right)} \quad , \tag{3}$$

with the covariance matrix

$$\boldsymbol{Cov}\left(\hat{\boldsymbol{\theta}}\right) = \frac{1}{N - N_p} \cdot \boldsymbol{e}\left(\boldsymbol{X}, \hat{\boldsymbol{\theta}}\right)' \cdot \boldsymbol{e}\left(\boldsymbol{X}, \hat{\boldsymbol{\theta}}\right) \cdot \left(\boldsymbol{J}' \boldsymbol{J}\right)^{-1} \quad . \tag{4}$$

The number of identified parameters is denoted by N_p ; $\boldsymbol{J}$ is the Jacobian given by

$$\boldsymbol{J} = \frac{\partial\left[\boldsymbol{w_r} \cdot \boldsymbol{e}\left(\boldsymbol{X}, \hat{\boldsymbol{\theta}}\right)\right]}{\partial \hat{\boldsymbol{\theta}}} \quad . \tag{5}$$

For a linear problem the standard deviations of the identified parameters are calculated according to Papula (2008).

2.1 Pressure-sinkage test

The quantity describing the relationship between the penetration depth of a plate into soil and its reaction is pressure. Therefore the measured force has to be transformed to the needed quantity, since the Bevameter is equipped with a force/torque-sensor:

$$p_m = \frac{F_m}{A} \quad . \tag{6}$$

The "measured" pressure p_m is calculated by the measured force F_m acting perpendicular to the penetration plate with its area A . The relationship between pressure and penetration depth is either given by the Bekker equation (Bekker, 1969)

$$p = \left(\frac{k_c}{b} + k_\phi\right) \cdot z^n \tag{7}$$

or by the Bernstein equation (Bernstein, 1913)

$$p = k \cdot z^n \quad . \tag{8}$$

In both equations z denotes the penetration depth and n the soil deformation exponent. The soil deformation modulus k in Eq. 8 is replaced by a combination of b , k_c and k_ϕ in Eq. 7. Here b is either the width of a rectangular plate or the radius of a round plate, k_c the cohesive modulus of deformation and k_ϕ the frictional modulus of deformation. Eq. 8 is used if different tool shapes have to be compared between each other. Applying Eq. 6 and 7 to Eq. 1 leads to the following objective function for soil parameter identification

$$\min_{\hat{\theta}} \frac{1}{2} \left\| \boldsymbol{w_r} \cdot \left[\boldsymbol{p_m} - \boldsymbol{p}\left(\boldsymbol{X}, \hat{\boldsymbol{\theta}} \right) \right] \right\|^2 \quad . \tag{9}$$

Here the vector of the identified parameters is composed by

$$\hat{\boldsymbol{\theta}} = \left(k_c, k_\phi, n \right)^T \tag{10}$$

and the input matrix by the different plate sizes and measured penetration depths

$$\boldsymbol{X} = \begin{bmatrix} b_1 & z_1 \\ \vdots & \vdots \\ b_{Ns} & z_{Ns} \end{bmatrix} \quad . \tag{11}$$

For solving Eq. 9 data of at least two pressure-sinkage tests with penetration plates having a comparable shape and different dimensions are needed. Furthermore a certain number of test repetitions leads to a more stable identification result since the soil preparation and the soil itself introduce some scatter in the measurements. The same number of repetitions for each test has to be used to have equal influence of all used plates on the identification result. For each single test a certain number of data points, each consisting of the sinkage z_i , the plate dimension b_i and the measured force perpendicular to the penetration plate F_i , are taken. Those data points are equidistantly spaced over the measured penetration depth. For example, for the identification with two different plates, ten tests for each plate and 100 data points for a single test are taken. This leads to 2000 number of samples Ns for soil parameter identification.

If the range of pressure is not equal for each test, the identification results are influenced in a stronger way by tests with a higher maximum pressure. This is among other things the case if tests from penetration tools with different areas for the same range of penetration depth are used. Therefore, a weighting factor $\boldsymbol{w_r}$ is regarded for identification. For a similar weighting of each single test it is suggested to normalize pressure data with the maximum pressure of each single test by setting the reciprocal of this value in the weighting vector. This means that pressure values of each single test vary between zero and one. Therefore the influence of the quantity of the measured pressure for different penetration tools is avoided. The standard deviations of the soil parameters can be calculated according to the method given in Eq. 3 to Eq. 5. This leads to a more realistic soil description since soil has some random characteristic. With the standard deviations the variation of the soil parameters is given. This can be regarded for simulating the rover performance. Furthermore the standard deviation indicates the repeatability of tests. The described identification method using the Bekker equation (Eq. 7) is also applicable for the Bernstein equation (Eq. 8).

The proposed method does not have the problem of an improper excessive weighting of values at low sinkage as it is the case in standard soil parameter identification (Wong, 2010). In these algorithms the logarithm of the pressure and sinkage is taken and the identification is transformed to a linear regression. However this does not represent the original identification problem. To overcome this problem Wong proposes a weighting with the square of the pressure for the logarithmised values. In Figure 2 a comparison between the identification method proposed by Wong and the method proposed in this paper is given. For the identification the Bernstein equation, Eq. 8, is used. Both methods lead to very good identification results. However it can be seen that the proposed algorithm is better (see the values given for ϵ).

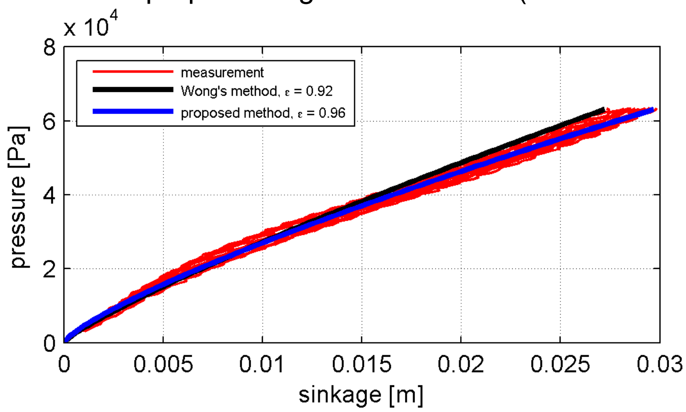

Figure 2: Comparison between Wong's identification method and the proposed method

2.2 Shear test

In case of the determination of the shear parameters the measured torque has to be converted into shear stress. Therefore the equation proposed by Janosi and Hanamoto (1961) is used

$$\tau = \frac{3 \cdot T_m}{2\pi \left(r_o^3 - r_i^3 \right)} \quad . \tag{12}$$

The measured torque is denoted by T_m and the shear stress by τ . The tool dimensions are given by the inner and outer radius of a shear ring (r_i, r_o). The soil shear stress-strain curve is described by the equation (Janosi and Hanamoto,1961)

$$\tau = (c + \sigma \cdot \tan\phi) \cdot \left(1 - e^{\frac{-j}{K}} \right) \quad . \tag{13}$$

Here the soil parameter c denotes the cohesion, ϕ the internal friction angle and K the soil deformation modulus. Input parameters are the normal pressure σ and the soil deformation j calculated from the shear angle α and the tool dimensions:

$$j = \frac{r_o + r_i}{2} \cdot \alpha \quad . \tag{14}$$

By applying Eq. 12 and 13 to Eq. 1 an identification of the soil shear parameters is possible. Shear tests at different normal pressures have to be performed, since the shear stress is depending on the normal pressure. The weighting factor can be calculated according to the method given in section 2.1. The standard deviations of the shear parameters can be calculated according to the method given in Eq. 3 to Eq. 5, too.

In most cases it is sufficient to determine the cohesion and the internal friction angle. It is assumed that the shear motion is static after a certain rotation angle, i.e. there is no change in shear stress even if the shear motion continues. If this takes place Eq. 13 is simplified to the following expression commonly known as Mohr-Coulomb failure criterion

$$\tau = c + \sigma \cdot \tan\phi \quad . \tag{15}$$

Applying Eq. 12 and Eq. 15 to Eq. 1 leads to a linear minimisation problem, which can be solved by the ordinary linear least squares method to determine the values for the cohesion and the internal friction angle from measurement data of the static part. The standard deviations can be calculated according to Papula (2008).

3 Test results

The results of the Bevameter test, both for pressure-sinkage tests and shear tests are given in this chapter.

3.1 Pressure-sinkage tests

With the soil parameter identification methods given in the above chapter it is possible to characterise the analysed soils by means of reliable values according to the chosen pressure-sinkage relationship. Before starting a measurement campaign to identify the influence of the test setup on the soil parameters an applicable soil preparation method leading to reproducible and reliable measurement results has to be found first.

3.1.1 Soil preparation tests

The soil preparation method has to be in line with the following three criteria:

1. It has to be applicable to a 90 liter soil bin for an evaluation of small soil samples as well as to a 10 m to 5.5 m testbed dedicated for rover tests. The best soil preparation is not practicable, if the preparation for the large rover testbed consumes a lot of time.
2. The soil preparation has to be performed by several persons according to a given procedure without leading to any remarkable differences in the recorded measurements.
3. The value for ϵ , see Eq. 2, has to be as close to one for the identification with Bekker equation. This value indicates the quality of the identification. The highest three values are regarded for further investigation.

Different soil preparation methods are identified to be evaluated for soil preparation. They are tested on a dry quartz sand (soil01) using the tools shown Figure 3. The investigated methods vary in the used soil loosening tools and the handling of these tools, e.g. crosswise or parallel raking. The best three methods determined by the evaluation are selected for a further investigation on a different soil (soil02). The result of the evaluation is shown in Table 1. It can be seen that the preparation method 9, 11 and 13 are suited best for soil01. The little hand shovel is used for soil loosening at method 9, the little hand rake at method 11 and the garden rake at method 13. At each method the soil preparation is finished by leveling the soil with the leveling board. The handling of the tools for the rejected preparation methods is more complex than for the selected. These methods include certain sequences of different preparation movements as well as a certain preparation pattern. Therefore these methods are not applicable to a large testbed since they are time consuming and very difficult in handling. Nevertheless they are tested to avoid the disregard of any possible preparation method. The soil loosening tools for the selected preparation methods (9, 11 & 13) can be increased in dimensions and are hence possible tools for a large soil bin. By comparing the effect of a certain soil preparation method by different people a lesson learned from first tests is that an accurate instruction of the use of the tools is indispensable. However the results at using shovels for soil mixing show that the possibility of diverging measured pressure-sinkage curves for such a preparation is clearly available in contrast to preparing the soil with a rake. The criterion 3 is evaluated according to quality of the identification for all tested methods, see Figure 4.

Figure 3: Tools used for soil preparation method testing; leveling board (above), garden rake (left), hand shovel (middle) and little hand rake (right)

	Preparation method												
	1	2	3	4	5	6	7	8	9	10	11	12	13
crit 1	-	-	-	-	-	-	-	-	+	-	+	-	+
crit 2	+	+	+	+	+	+	+	+	-	-	+	+	+
crit 3	-	-	-	-	-	-	-	-	+	-	+	-	+
$\sum$	-1	-1	-1	-1	-1	-1	-1	-1	1	-3	3	-1	3

Table 1: Evaluation of preparation method according to the given criteria

According to the result of the first evaluation the best three methods are selected and tested on a different soil. Since criterion one and criterion two is not effected by the soil, only criterion three is regarded, see Figure 4. It is clearly evident that preparation method 13 is the best method for soil preparation. Therefore at all further investigations the soil is prepared according to this method.

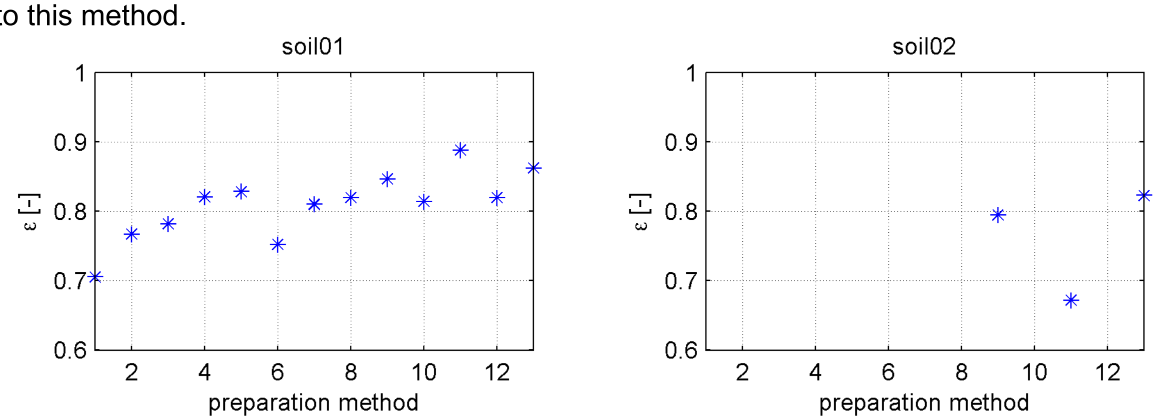

Figure 4: Quality of identification for different preparation for soil01 (dry quartz sand) and soil02

3.1.2 Penetration velocity tests

Although there are some approaches to consider the penetration velocity in Bekker equation (Grahn, 1996), there is almost no information available about its influence on the pressure-sinkage relationship. Therefore the capability of the developed Bevameter to control the penetration velocity is used and tests at different sinkage speeds on different soils are performed. For each soil and each penetration velocity three different circular plates with the radii 0.025, 0.05 and 0.075 m are used. These dimensions span the expected contact area of wheels for rovers up to the size of the planned ExoMars rover. The tests are performed at three different penetration velocities, 0.48e-3, 2.4e-3 and 4.8e-3 m/s. These velocities are the intersection of the maximum possible penetration velocity of the used Bevameter and low speeds of the ExoMars breadboard. Each test is repeated twelve times.

During the evaluation of these tests an influence of the penetration velocity is observed. The less the mean grain size of a soil is, the stiffer is the pressure-sinkage relationship for lower velocities. This is shown exemplarily at measurement results for tool02 in Figure 5. Soil01 is a quartz sand with a grain size distribution from 0-1.5 mm. The mean grain size for soil02 is at 30 µm. A further soil type (soil08) is used, where 83% of the soil have a particle size lower than 2 µm. Since a part of the soils used for rover performance testing and validation of wheel-soil contact models are similar to soil02 and soil08, the determination of the Bekker parameters has to be done very carefully with a penetration velocity which is adequate to the mean rover speed.

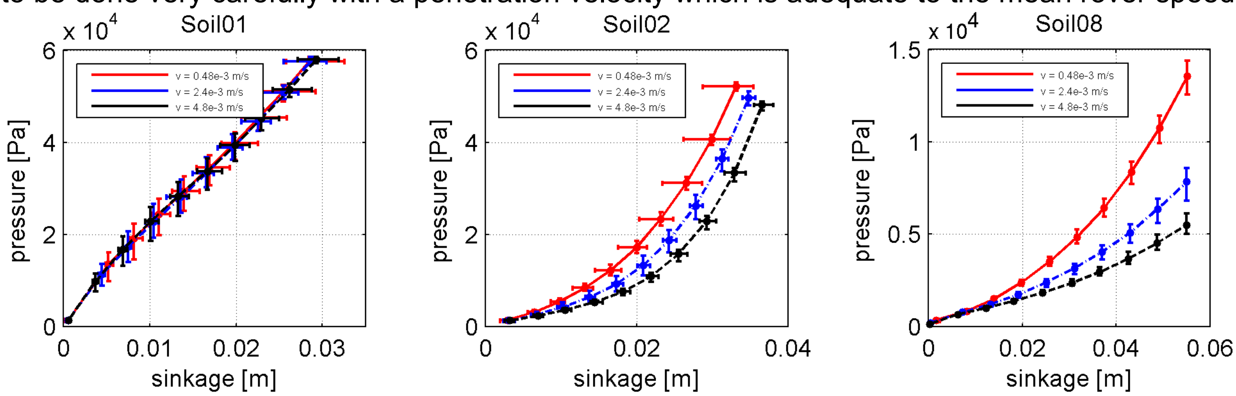

Figure 5: Measurements of pressure-sinkage curves for three different soils at three different penetration velocities with a circular plate (r = 0.05m); the mean grain size for each soil gets lower from left to right; the error bars indicate the statistical spread in the measurement

3.1.3 Influence of tool shape and size

Wong (2010) recommends to use penetration tools being equivalent to the wheel print with respect to the soil for soil parameter determination. A test series with a circular plate and rectangular plates having the same area is performed. The side ratios of the rectangular plates are 1:1, 1:3, 1:5 and 1:7. Reference tools are circular plates with 0.05 m or 0.075 m radii. Penetration velocity is set to 4.8e-3 m/s. The measured pressure-sinkage curves for the soils 1,2 and 8 are exemplarily given for tools with an area of 0.0079 m^2 (equivalent for a circular plate with r = 0.05 m) in Figure 6. It is observable for side ratios of 1:5 or greater, that the pressure-sinkage relationship gets softer for soil01 and soil02.

The measured curves can be explained by the observations for the soil behaviour under a penetration plate given in (Leis, 1961) and (Earl and Alexandrou, 2001). At the first stage of a penetration test pure compaction of the soil takes place. This is shown by the almost identical pressure-sinkage curves at their initial stage. In this stage soil is compacted under the plate only. The curves are not influenced by the tool dimensions. Since soil08 is a very loose one only compaction is observed and the curves do not diverge in the measured range. During compaction the failure zone under the plate is rectangular if the test is only regarded in 2 dimensions, see Figure 7.

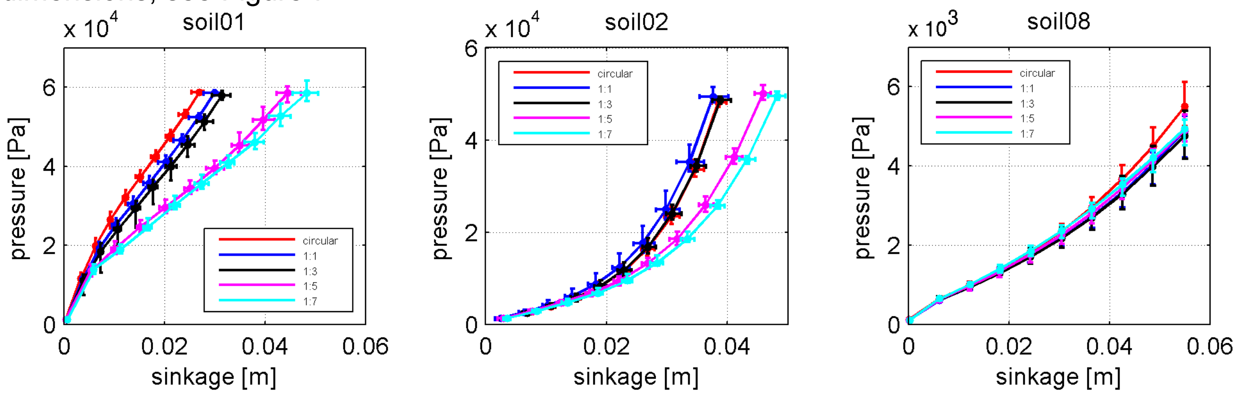

Figure 6: Measured pressure-sinkage relationship for a circular penetration plate (r=0.05m) and rectangular plates with the same area and different side ratios for different soils

By increasing the penetration depth the lower corners of the rectangular failure zone round off and the failure zone transforms from a rectangular shape via a truncated cone to a fully formed cone. If the failure zone starts to transform towards the cone also lateral soil compression and flow commences. At this stage the pressure-sinkage curve gets softer according to Earl and Alexandrou (2001). This is also visible in the measured curves for soil01 and soil02 at side ratios of 1:5 and 1:7. This effect is rather recognised for thiner plates because the transformation of the soil failure zone into a cone tends to be faster than for plates with larger side ratios. This effect is not observed in Figure 6 (soil01 and soil02) for the plate with side ratio 1:3 as well as for soil08 since only compaction takes place in the measured range. It is assumed that the missing of these effects is caused by the limits of the Bevameter used for the measurement.

Summing up, the tool dimensions effect the measurements. For a soil characterisation in terms of determining Bekker parameters for a wheel with a certain dimension the use of a circular plate with the same or almost the same size than the wheel print is adequate.

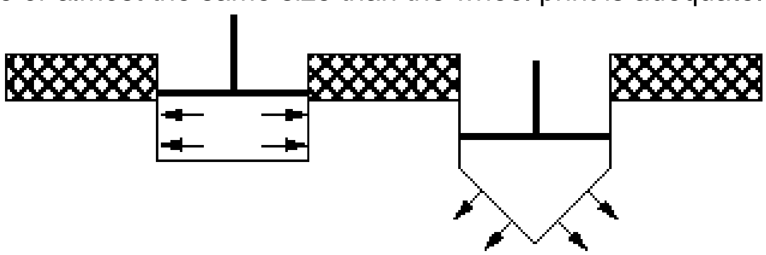

Figure 7: Schematic 2D illustration for the soil behaviour under a pressure plate during a pressure-sinkage test; pure soil compaction with a rectangular failure zone (left); lateral soil compaction and soil flow with a cone as failure zone (right)

3.2 Shear test results

In the previous section different effects on the measured pressure-sinkage curves are given. For a complete description of the wheel-soil contact the shear parameters are needed, too.

Therefore the Bevameter is used again. The Bevameter control subsystem includes a control algorithm that adjusts the sinkage of shear tool for holding the normal force constant. Only tests results for soil01 and soil02 are presented, because therein is enough information about the influence of the altered setup parameters on the soil shear parameters.

3.2.1 Variation of tool size

For an investigation of the influence of the tool size two tools, depicted in Figure 8, with different dimensions are used. The rotational velocity is set to 0.1 rpm for both tools to reach almost static conditions. An overview of the tool dimensions is given in Table 2. The results are shown in Figure 9. It is visible that a thiner shear ring leads to a higher cohesion and internal friction angle. Therefore the appropriate tool dimensions for soil characterisation in order to get the parameters for a wheel-soil contact model have to be found by a further test campaign including single wheel testing and simulating the tests.

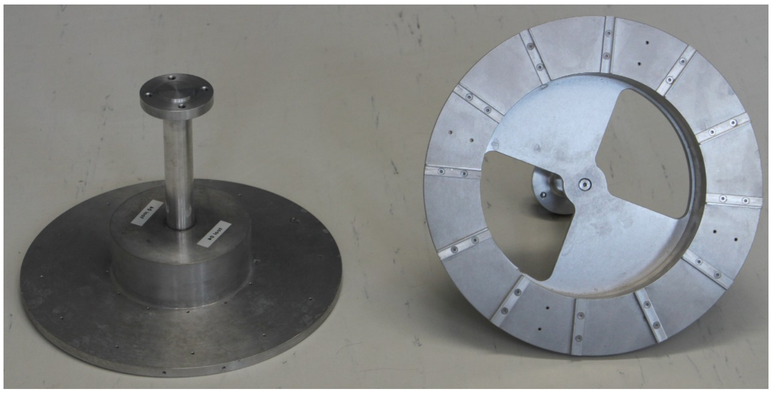

Figure 8: depicted shear tools, tool04 left, tool07 right

	Tool04 (t04)	Tool07 (t07)
inner radius r_i [m]	0.05	0.1
outer radius r_o [m]	0.15	0.15
nr of grousers [-]	12	12
grouser height [m]	0.005	0.005

Table 2: Dimensions of the shear tools

3.2.2 Variation of number of grousers

In a further test series the influence of the number of grousers on the soil parameters is investigated. For these tests tool07, see Table 2 for its dimensions, is used. The grouser height is set to 7.5 mm. The rotational velocity of the tool is set to 0.1 rpm. The measurements are taken with 6, 8 or 12 equally spaced grousers on the shear tool. The results are shown in Figure 10. It is clearly visible, that the number of grousers does not affect significantly the shear stress over the normal pressure in the measured range. Decreasing the number of grousers to two or even zero has certainly an effect on the measurements. However such a test setup is not a realistic representation of a wheel shear motion. Thus these tests are omitted.

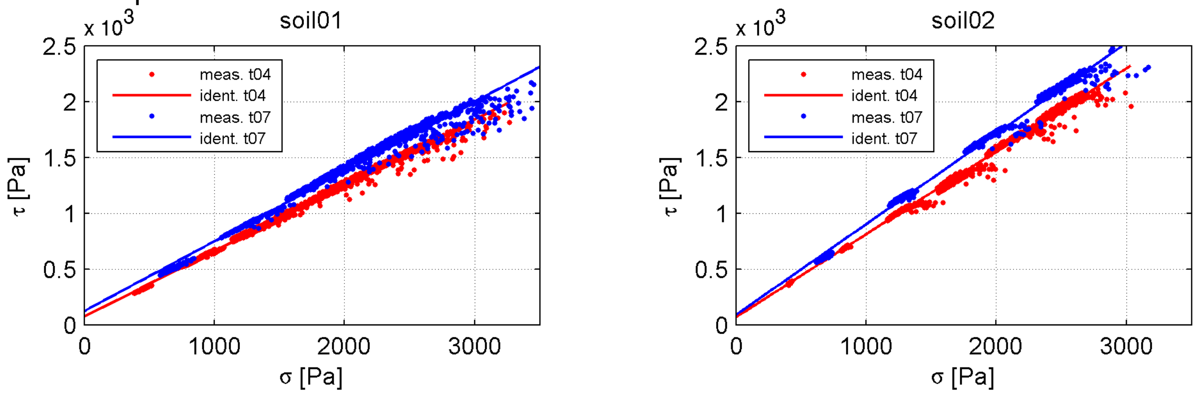

Figure 9: Shear test results for different shear rings for two soils

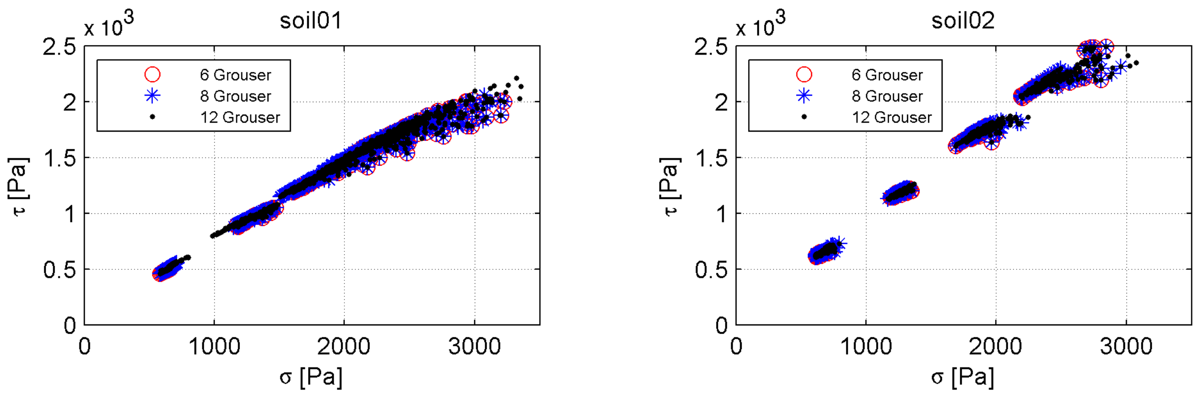

Figure 10: Measurement data from tests with different numbers of grousers for two soils

3.2.3 Variation of grouser height

The influence of the grouser height on the soil parameters is investigated, too. Tool07 is used for these tests. The number of grousers is 12. The rotational velocity is 0.1 rpm. The grouser height is altered from 2, 5, 7.5 to 10 mm. The results are shown in Figure 11.

Increasing the grouser height leads to a higher shear stress for the same normal pressure. In section 4.2.3 a detailed investigation in terms of shear parameters identification is given. It can be stated, that for a proper soil parameter determination the usage of grousers similar to the grousers on the wheels is best suited.

3.3.4 Variation of shear velocity

A further feature of the used Bevameter is to vary and to control the rotational shear velocity. In a test series the influence of the rotational speed on the shear parameters is investigated. Tool07 with 12 grousers and a grouser height of 7.5 mm is used for the tests. The rotational velocity is set to 0.1, 0.2 and 0.3 rpm. The results are shown in Figure 12. No significant influence on the shear parameters is observed in the test.

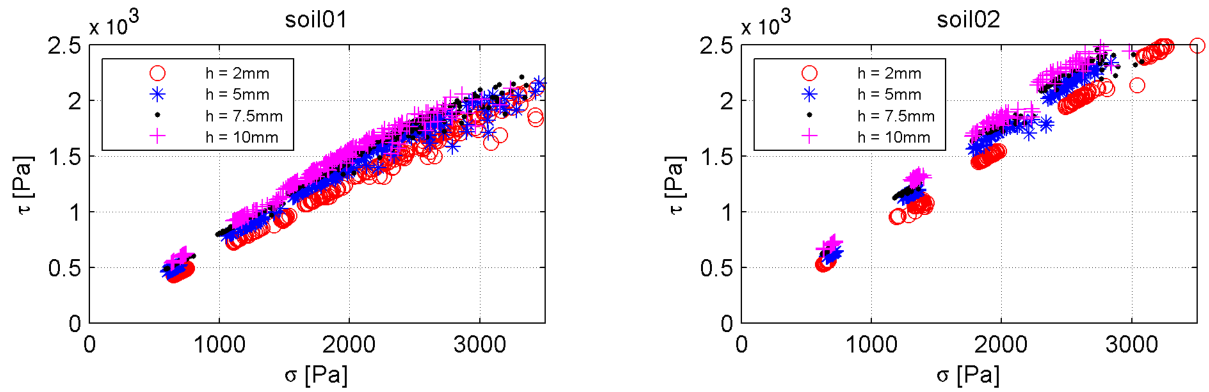

Figure 11: Measurement data from tests with different grousers heights for two soils

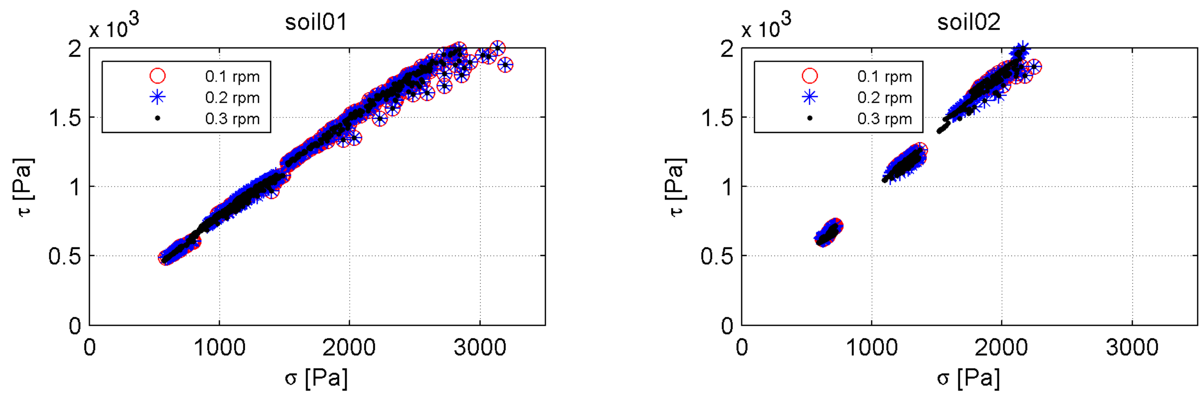

Figure 12: Mohr-Coulomb lines from the identified shear parameters from tests with different shear velocity for two soils

4 Identification results

The identified results of the test campaign measurement data are given in the following chapter.

4.1 Identification for the pressure-sinkage test case

For the identification of the pressure-sinkage tests the methods as described in section 2.1 are used. The weighting factor is calculated according to the description given in section 2.1.

4.1.1 Penetration velocity tests

The identified Bekker parameters including their standard deviations for the penetration velocity are given in Table 3. It can be seen that for almost all parameters the standard deviations is below 10 % relative to the identified values. For the parameter n it is below 1 %. This result confirms the applicability of the chosen soil preparation method. The values for soil01 are constant for different penetration velocities. This is obvious, since their pressure-sinkage curves do not vary for different sinkage speeds as shown in Figure 5. For soil02 and soil08 the values are different. However there is no trend identifiable, as for example an increase for the value of n at higher penetration velocities. This is among other things caused by the numerics of the identification algorithm. The used algorithms find the best solution for the given minimisation problem (Eq. 9). Therefore a glance on the soil parameters does not suffice for a comparison of different soils. There has always to be a comparison of the pressure-sinkage curves for a detailed analysis.

		soil01	soil02	soil08	Penetration velocity [m/s]
k_c	$[N/m^{n+1}]$	$-9.8e3 \pm 4.6e2$	$-1.4e6 \pm 1.1e5$	$-1.5e4 \pm 4.6e2$	4.8e-4
k_ϕ	$[N/m^{n+2}]$	$1.2e6 \pm 3.1e4$	$1.0e8 \pm 7.0e6$	$3.0e6 \pm 8.2e4$	
n	[-]	0.80 ± 0.01	2.14 ± 0.01	1.82 ± 0.01	
ϵ	[-]	0.82	0.81	0.88	
k_c	$[N/m^{n+1}]$	$-1.2e4 \pm 5.0e2$	$-3.2e7 \pm 2.0e6$	$7.3e3 \pm 1.9e2$	2.4e-3
k_ϕ	$[N/m^{n+2}]$	$1.2e6 \pm 3.3e4$	$1.9e9 \pm 1.1e8$	$5.7e5 \pm 1.4e4$	
n	[-]	0.81 ± 0.01	3.02 ± 0.02	1.57 ± 0.01	
ϵ	[-]	0.81	0.83	0.89	
k_c	$[N/m^{n+1}]$	$-9.8e3 \pm 4.6e2$	$-1.8e8 \pm 2.2e7$	$7.0e3 \pm 1.6e2$	4.8e-3
k_ϕ	$[N/m^{n+2}]$	$1.2e6 \pm 3.4e4$	$1.0e10 \pm 1.2e9$	$2.2e5 \pm 5.0e3$	
n	[-]	0.82 ± 0.01	3.59 ± 0.03	1.45 ± 0.01	
ϵ	[-]	0.81	0.82	0.88	

Table 3: Identified Bekker parameters and their standard deviations for different soils and different penetration velocities

4.1.2 Influence of tool size and shape

For determination of the influence of the tool size and shape on a mathematical representation of the pressure-sinkage relationship Eq. 8 is applied to Eq. 1. The Bernstein equation is used here since the tool shapes are varying and for an easier comparison of the identified parameters. The identified soil parameters relative to the soil parameter of the circular plate and also the quality of the fit are depicted in Figure 13. The quality of the fit is good, the values for the relative standard deviations are below 12 % for k and below 2 % for n . The identified soil parameters k and n are depicted with their standard deviations. All values are relative to the parameters of the circular plate. It can be seen, that there is no clear trend in the identified parameters. As mentioned above for a comparison of tests a look at the pressure-sinkage curves can not replace a pure look on the identified numbers.

4.2 Identification for the shear test case

The identified values for the shear tests are given in this chapter. For shear soil parameter identification Eq. 15 is applied to Eq. 1. The weighting is set to one.

4.2.1 Variation of tool size

As depicted in Figure 9 the tool size has an influence on the shear measurements. The identified values with their standard deviations for the test are given in Table 4. Furthermore the relative difference between the identified parameters are listed therein. For the cohesion the difference is quite high. However due to their little effect for values around and below 100 Pa on the wheel performance the influence of the tool dimension on the cohesion is neglectable. Moreover the relative increase of about five to six percent of the internal friction angle influences the wheel performance much stronger. Mohr-Coulomb lines calculated from the identified values are plotted in Figure 9. It can be seen that the calculated lines are matching to the measurement data. A consequence of this result is that the used shear ring has to be appropriate for the rover wheels for a correlation of rover performance tests and simulations.

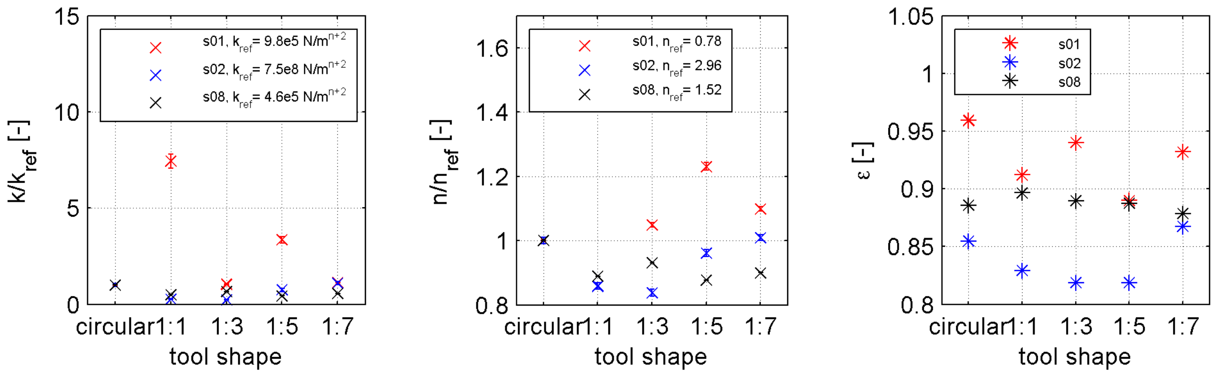

Figure 13: Identified soil parameters and quality of the fit from tools with different tool shapes for different soils

	soil01		soil02	
	c [Pa]	ϕ [deg]	c [Pa]	ϕ [deg]
tool04	71.9±2.2	30.5±0.1	66.5±2.8	36.7±0.1
tool07	122.2±22.9	32.1±0.1	88.3±20.1	39.1±0.1
rel. deviation [%]	70	5.3	32.8	6.5

Table 4: Comparison of shear parameters for different shear rings and soils

4.2.2 Variation of number of grousers

The result of these tests (the measurement data is shown in Figure 10) is that there is no recognisable influence of the number of grousers on the shear parameters. However this statement is only valid for a grouser numbers between 6 and 12. An extrapolation for a higher or lower number of grousers can of course lead to other results. The identified results and their standard deviations are given in Table 5. The values are varying less, as it is expected from the measurement data.

	soil01		soil02	
	c [Pa]	ϕ [deg]	c [Pa]	ϕ [deg]
6 grouser	107.9±12.8	33.3±0.1	131.9±16.3	40.0±0.1
8 grouser	141.9±6.7	33.3±0.1	129.7±9.3	40.1±0.1
12 grouser	128.0±4.6	33.1±0.1	137.0±6.5	39.8±0.1

Table 5: Comparison of shear parameters for different number of grousers and soils

4.2.3 Variation of the grouser height

The measurement data for these tests, depicted in Figure 11, shows an influence of the grouser height. With increasing grouser height the shear stress increases, too. This effect can also be regarded in the identified shear parameters, see Figure 14. An increase in grouser height leads to an increase in cohesion and internal friction angle. A possible explanation of this effect is, that for the transformation of the measured torque into the shear stress a 3-dimensional area has to be regarded. For calculation of the shear stress (Eq. 12), given by Janosi and Hanamoto (1961) only the shear area of the shear ring is taken into account. However there is a certain soil to soil friction on the side of the shear rings. This area depends on the grouser height. First investigations show, that regarding this area also is a promising approach to describe the observed effects. The high standard deviations for the cohesion can be neglected, since the influence of the cohesion on wheel-soil interaction is minor for these values.

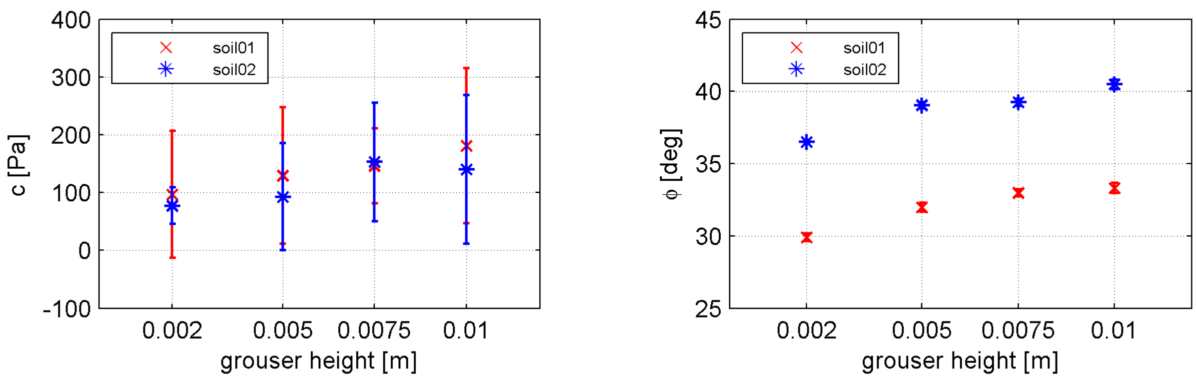

Figure 14: Identified shear parameters including their standard deviations for different grouser heights

4.2.4 Variation of shear velocity

The measurement data, depicted in Figure 12, shows, that the shear velocity does not influence significantly the measurement and thus the identified shear parameters. However an extrapolation of this statement for shear velocities lower than 0.1 rpm or higher than 0.3 rpm has to be handled with care. For identified shear parameters it is referred to the parameters for 12 grousers in Table 5. The rotational velocity of the measurement data for these identified values is 0.1 rpm. The measurement data is the same as used for shear parameter identification to compare the influence of the number of grousers.

5 Conclusion

An objective function for a proper soil parameter identification is presented as well as a calculation of the standard deviation of identified parameters. Combining the presented objective function with a nonlinear solver leads to improved and reliable identification results. Furthermore the influence of the Bevameter test setup is investigated as well as an appropriate soil preparation method applicable for a large testbed is determined. The test results show that there are certain influences on the pressure-sinkage relationship for different penetration velocities and different penetration tool dimensions. It is also shown that the shear parameters depend on the dimensions of the shear tool and the grouser height. Whereas they are invariant against the number of grousers and the rotational velocity. However it has to be stated all results are only applicable for the presented soils or similar ones and can not be extrapolated to broader ranges as the investigated ones without some care. It has to be remarked that the results for the shear test do not diverge for different types of soils. Future work is to find appropriate equations taking into account the tool dimensions, both for pressure-sinkage tests and shear tests including the grouser height. Moreover this work can help one to find the appropriate test setup for a validation of a soil contact model for a certain wheel at defined operating conditions.

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