A NOVEL TERRAMECHANICS TESTBED SETUP FOR PLANETARY ROVER WHEEL-SOIL INTERACTION

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Abstract

For planetary rovers, demonstration of the overall mobility performance on soft soil is a demand to guarantee for mission success. Since several years, DLR's Institute of Robotics and Mechatronics is strongly engaged in planetary mobile system developments. For the very important wheel-soil interaction a 3D-MBS tool for modeling and simulation of the overall terramechanics behavior, making use of Bekker's well-known terramechnical equations, has been developed. Currently, major applications are followed within ESA's Exomars mission. For the purpose of verification and validation of the 3D-MBS tool intensive hand in hand rover testing in a lab environment is necessary. Therefore, a new facility for planetary locomotion systems including a large testbed and a novel, high-precision bevameter to characterize the soil on which the tests are to be carried out is presented. For precise rover pose estimation inside the testbed a high-level position tracking system is used, and for proper soil surface determination on an in-house developed digital elevation mapping system is relied on. For the Bekker parameter determination, a portable and lightweight bevameter equipped with a state-of-the-art sensor technology is designed. Different design concepts are analysed open minded without any orientation on existing bevameter designs. This leads to a tripod design with electromechanical actuators and sensors integrated in a real-time computing environment to develop own control algorithms. Besides soil testing and soil preparation influence detection, the bevameter is mainly used for identifying soil parameters of the testbed. Finally, for correlation purposes, these parameters are taken as inputs to the 3D-MBS tool for simulating the drive manoeuvres performed inside the testbed. Results obtained from bevameter testing are presented together with the testbed setup design.

Keywords: testbed, bevameter, system level test, planetary rover, wheel, soil contact dynamics, terramechanics, Martian soil simulant, MBS

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1 Introduction

The European Space Agency is currently planning a Mars mission, called ExoMars, equipped with a rover for planetary exploration within the Aurora programme. DLR's Institute of Robotics and Mechatronics contributes 3-dimensional multibody system (3D-MBS) simulations of the locomotion subsystem [1]. Therein a new approach for modeling wheel-soil interaction, based on the well-known equations by Bekker [2] and Janosi [3], is used. In addition to these equations techniques from the computer graphics algorithms are used for soil displacement (for a detailed description see [4]). For the validation of the soil contact model data from external ExoMars system level and single wheel test campaigns are the basis for model improvements and correlation. Processing of the measured test data to correlate them with the 3D-MBS results takes a lot of effort. Furthermore the used test facilities have to be known very precisely for verification and validation of the 3D-MBS in favour of a good modeling approach [1]. To minimize the described problems and for outlook on a mighty and validated 3D-MBS tool usable for navigation, controller or motor design, a novel terramechanics testbed setup is developed. This includes also a bevameter equipped with state-of-the-art sensor technology for characterizing the soil in the testbed.

2 Testbed setup

The complete specifications of the testbed and of the necessary measurement tools are defined by the required inputs and outputs for validation of the 3D-MBS simulation. The designated drive manoeuvres for verification and validation (V&V) contain performance test runs of the rover over hard and soft soil on the whole. The following items define the testbed requirements:

- The testbed has to be large enough to avoid side wall and bottom effects in the system level test (SLT) runs for planetary rovers in the dimension of the actual ExoMars breadboard.
- The testbed setup should allow to divide the soil bin into two parts to cope with two different type of soft soils.
- The testbed has to be equipped with a measuring device to obtain the surface elevation for creating mesh grids of the surface, because the 3D-MBS tool needs a digital elevation model (DEM) of the soil [4].
- For the V&V a position tracking system is indispensable to compare the simulated with the measured rover position at various time samples in the simulation and experiment.
- A soil measurement device is necessary, to characterize the soil with the Bekker parameters and to generate a Bekker parameter map of the testbed area, if it is mandatory.

All these requirements are covered with the actual testbed setup, depicted in Fig. 1. It consists of a soil bin of 5.5 m width, 10 m length and 0.5 m height, a surface 3D-mapping tool (section 2.1), and an optical tracking system (section 2.2). To keep the soil bin expandable in size, flexible in location and robust against the expected side wall soil forces, aluminium parts which are standard in tool design and construction for individual solutions are used for the framework.

2.1 DEM

A measurement device to generate a mesh grid of the soil surface is developed to provide a 3D surface elevation grid of the soil. The hardware of this device consists of a linearly movable beam (Fig. 1) above the testbed equipped with five standard cameras. In different poses the linear motion is halted and images are simultaneously taken by the cameras. The digital elevation model is generated with the cameras and intelligent vision algorithms by combining multiple camera images and a Semi-Global Matching (SGM) algorithm, see [5] for further information about the used algorithms. The technology is successfully used to compute digital elevation models from images taken from aircrafts and satellites. The used solution of the soil surface generation has the following performance data:

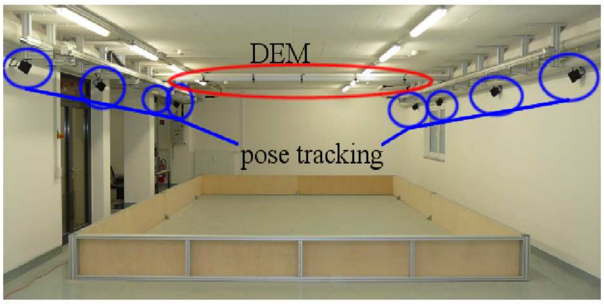


Fig. 1: *Picture of DLR-RM testbed, red ellipses indicate DEM cameras, blue ellipses the position tracking cameras*

- expected resolution of about 1.5 mm in plane and
- expected altitude defect of 2-4 mm.
- Detection of hard rocks and soft soil. This is in favour of simulations performed on different grounds or on Martian like terrain consisting of a combination of rocks on sand.

To improve the resolution in plane and concurrently lower the altitude defect, the number of the used cameras can be increased. Coinciding with the increase of the number of cameras the distance between the positions the linear beam is halted to take pictures has to be decreased. Hence the accuracy of the DEM is adjustable.

2.2 Pose tracking

To achieve an accurate measurement of the actual rover position and orientation a passive optical tracking system, see [6] for further information, is chosen. The system is well-known and used in several applications at different research fields, e.g. telepresence, navigation or minimally invasive surgery. Four tracking camera units are mounted on both sides above the testbed (Fig. 1). A single camera unit consists of a monocamera plus infrared emitting LEDs. The measuring principle is based on infrared optical tracking. Therefore the rover or any other desired target to be tracked has to be equipped with tracking targets. These targets consist of four passive markers, reflecting infrared flashes emitted by the LEDs, integrated in the position tracking camera units. The position and the orientation of the vehicle are calculated from the reflected signals making use of stereo algorithms. The tracking system has the following performance data:

- usage of several targets (consisting of four markers),
- position accuracy less than 3 mm,
- orientation accuracy less than 1 deg,
- 60 frames per second and
- improbable occlusions by the use of 8 cameras.

2.3 Testbed application

A benefit of the chosen testbed setup is that by adding the pose tracking system further states (position and orientation) of the rover are available. Therefore the longitudinal and even lateral slip of the vehicle can be calculated by combining the rotational speed of the rover wheels and the time-derivative of the rover position. A possible scheme for the usage of the testbed to validate the 3D-MBS tool is shown in Fig. 2. After soil preparation and design of a possible terrain in the testbed, the DEM generates a mesh of the soil surface. This mesh could be divided into two parts. One part represents soft sandy soil in the testbed, the other rocks. For soil characterization soil penetration and shear tests are carried out at random positions using a bevameter (see sections 3 and 4). The identified soil parameters from the bevameter measurements are inputs for the 3D-MBS tool as well as the surface mesh and the rover trajectory commands. The simulated and measured results are compared to validate the tool. A comparison of the rover tracks is possible by a further surface mesh generation after the system level test run is completed. An investigation on the rock-wheel interaction in terms of displacing the rocks at the test run can be done also by comparing the surface mesh grids generated before and after the test runs.

Further possible test cases are mobility investigations for any type of mobile platforms, e.g. crawler or tracked robots, and testing of self-localizing algorithms by comparing position tracking system data with the algorithm outputs. It is also planned to use the testbed for system verification & validation by testing vehicle performance, i.e. without a correlation of the measurement data and simulation.

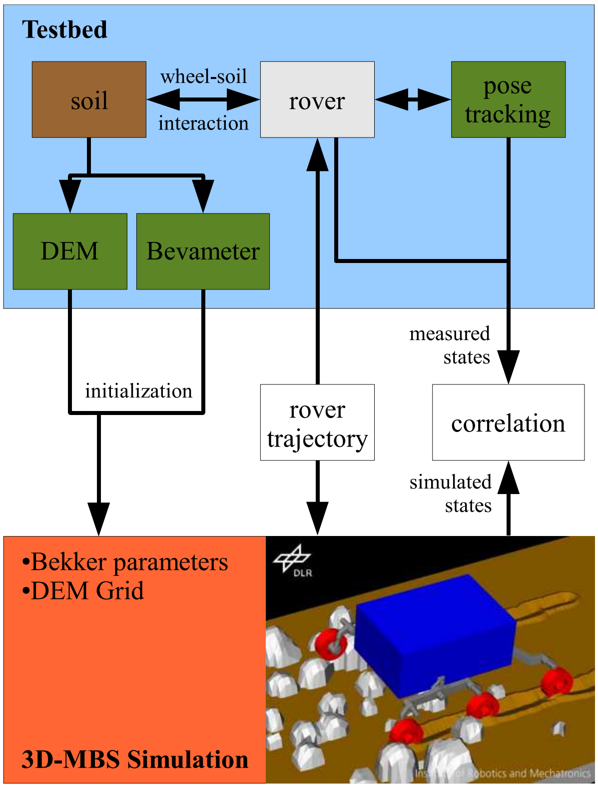


Fig. 2: Usage of the testbed for 3D-MBS tool validation

3 Bevameter

To characterize the soil in the testbed a bevameter is indispensable. Therefore a portable and light-weight bevameter is designed. The first step at the design process is intensive literature review to get an overview of the actual existing bevameters. The requirement specifications are as follows:

- portable and light-weight,
- torque up to 20 Nm,
- normal force up to 500 N,
- extremely stiff system consisting of standard parts,
- fast replacement of penetration plates and shear annuli,
- flexible and intuitive handling,
- fast reacting actuators and
- the data acquisition, data processing as well as the control of the bevameter should be possible with an adequate tool chain.

Currently existing bevameters designs, found in the literature, neither satisfy our specifications nor their structures and setups are unique. Thus a completely new bevameter is developed.

3.1 Design

The result of the study is a tripod design, shown in Fig. 3. The bevameter design consists of three legs mounted on the hexagon cage with the electro-mechanical components. Light weight and stiff standard aluminium profiles constitute the framework. The placing of the main components apart from the framework is in the order from top to bottom as follows:

- linear drive unit to move the tool towards and into the soil,
- harmonic drive unit to rotate the shear annulus,
- a 6 degree of freedom (dof) force-torque sensor, developed at our institute,
- a fast coupling adapter for an easy exchange of the measurement tools and
- a penetration plate or a shear annulus.

Linear guides are added to prevent the system from twisting in case of a shear test. Weights on the legs guarantee that the bevameter does not loose soil contact during the tests, because the linear drive is able to push a sinkage plate into the soil with a force higher than the normal force of the unweighted bevameter. The performance data of the designed bevameter are:

- 500 N maximum normal force,
- 20 Nm maximum torque around the shear axis,
- -60 to 60 rpm rotational speed,
- 4.8 mm/s maximum speed for the linear drive and
- 400 Hz sampling frequency

The demand of a constant normal force at the shear test is satisfied with a force control algorithm implemented in the control model (section 3.2).

3.2 Control model

The control of the bevameter is realised with Matlab/Simulink, the corresponding Real Time Workshop and its xPC target toolbox [7]. The tool chain is chosen, because it supports an easy filter and control design with several toolboxes and provides a lot of useful functions for data storage and evaluation. In Fig. 4 the scheme of the bevameter control is shown. First the control model of the bevameter is developed on the host computer in Simulink. This model is held as general as possible to match for all potential bevameter test cases. Afterwards the model is compiled and loaded to the target computer. The bevameter measurements are started via a graphical user interface (GUI), shown in Fig. 5, which is developed to keep the tests as user-friendly as possible. During the experiment a visualization of test data is possible in the designated plot windows at the right side of the GUI. Due to the TCP/IP connection between host and target PC a real-time display of the measured curves is not guaranteed. However this does not affect the test data itself, as the

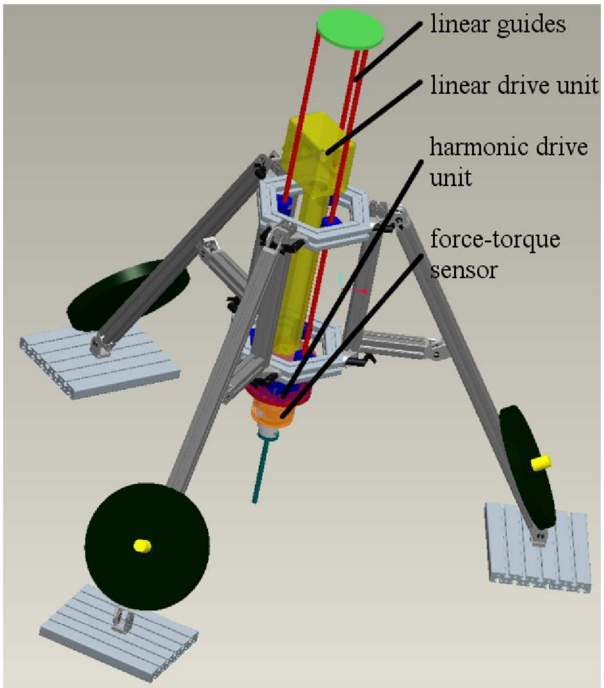


Fig. 3: Bevameter drawing

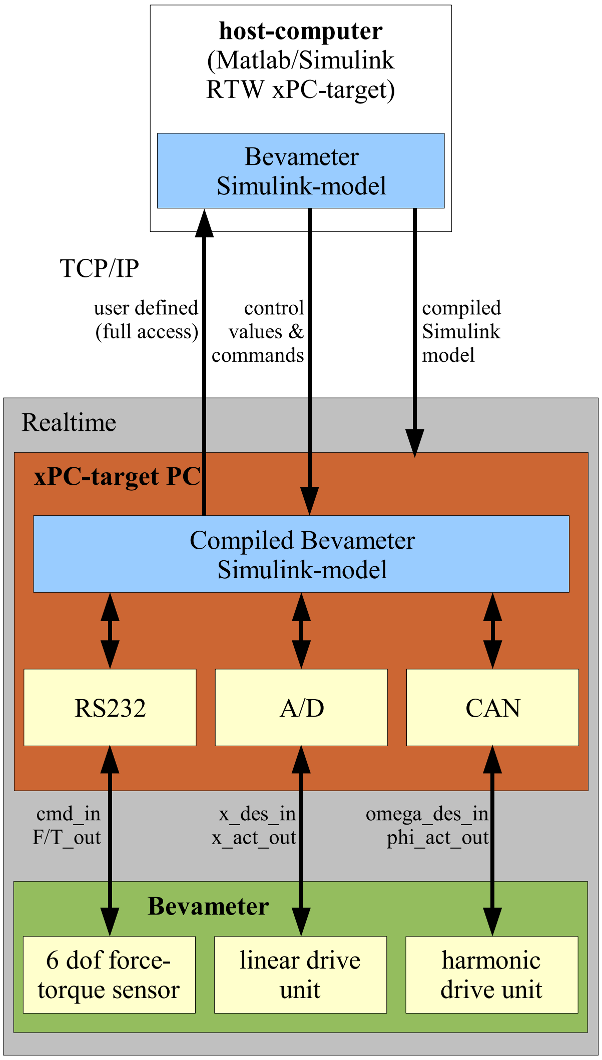
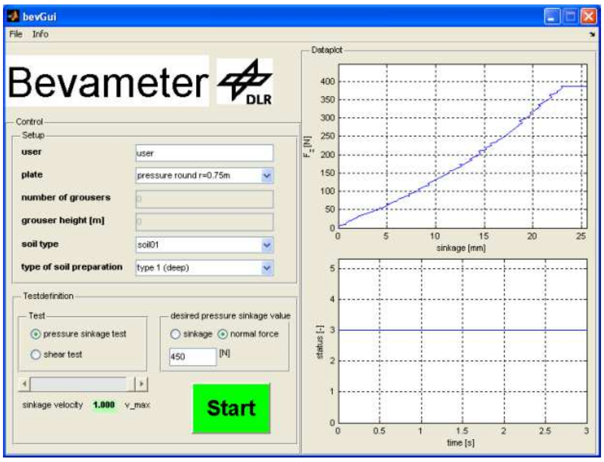


Fig. 4: Bevameter control scheme



user: user
plate: pressure round r=0.75m
number of grousers: 0
grouser height [m]: 0
soil type: soil01
type of soil preparation: type 1 (deep)

Test: ● pressure sinkage test ○ shear test
desired pressure sinkage value: ○ sinkage ● normal force
450 [N]
sinkage velocity 1.000 v_max

Fig. 5: Bevameter control GUI

data is loaded on the host computer when a test is completed.

4 Initial Bevameter tests

To demonstrate the correct operation of the measurement setup and to show that the developed bevameter is ready to use, the bevameter is set on a base frame to test different soils in buckets, usually used by bricklayers (Fig. 6).

4.1 Calibration

Before starting the tests, the reliability and the repeat accuracy of the linear drive unit are analyzed. Therefore the linear drive is moved in several positions from the initial position. In a second experiment the position is altered by increasing it stepwise. Both tests have to be repeated several times for statistical reasons. To get the actual position a mechanical gauge with a precision of 0.05 mm is used. The nonlinearity of the potentiometer for measuring penetration depth is determined by these tests, too. Thus the potentiometer signal is recorded during the repeat accuracy tests. The stored data is used to calculate the accuracy of the potentiometer, which is less than 0.075 mm and is precise enough for the designated tests.

The 6-dof force-torque sensor is checked as well. Although it is calibrated, the temperature drift is not exactly known. This drift leads to a changed offset due to higher temperature, after a certain time in operation. Hence two different masses are mounted on the cold sensor in succession. After several hours in operation this procedure is repeated. The offset observed by this procedure is compensated by a null compensation before each measurement. Using the compensation the sensor is accurate enough for measurements with an error less than 0.3 N.

4.2 Pressure-Sinkage tests

When the calibration of the sensors is accomplished the bevameter can be used reliably for experimentation. Dry quartz (see Fig. 13) sand is chosen as soil material. According to Bekker [2] it is the “easiest” soil material concerning a reproducible soil preparation method.

The first step is to find an appropriate soil preparation method which is reproducible with a certain scatter and also applicable to the large area in our testbed. The best soil preparation method is useless, if the preparation of the testbed consumes large time, i.e. days or even a week. Therefore the method proposed by Bekker [2] to reproduce the soil by sieving it from constant height into the soil bin is improper. Several tests with different tools (small gardening shovel, small and big rake) to loose the soil show that the soil preparation using a big rake is the best. The soil is leveled after loosening. It is obvious that with the described preparation method the soil in the bin is not homogeneous, due to the preparation of the upper soil layer only, as demanded by Bekker [2] to apply the well-known pressure-sinkage relationship to the penetration tests:

Fig. 6: Actual bevameter setup with soil in bucket

$$p=\left(\frac{k_c}{b}+k_\Phi\right)\cdot z^n. \qquad (1)$$

The pressure p on a pressure plate is calculated from the plate penetration depth z with the exponent of soil deformation n, cohesive modulus of soil deformation k_c and the frictional modulus of soil deformation k_Φ. The width of a rectangular penetration plate or the radius of a circular penetration plate are represented by b. Nevertheless Eq. (1) appears appropriate for a description of soil reaction of the measured pressure-sinkage curves, depicted in Fig. 7. The respective log-log curves are shown in Fig. 8. The used tools in these tests are circular pressure plates with the following radii: 0.025 m, 0.05 m and 0.075 m.

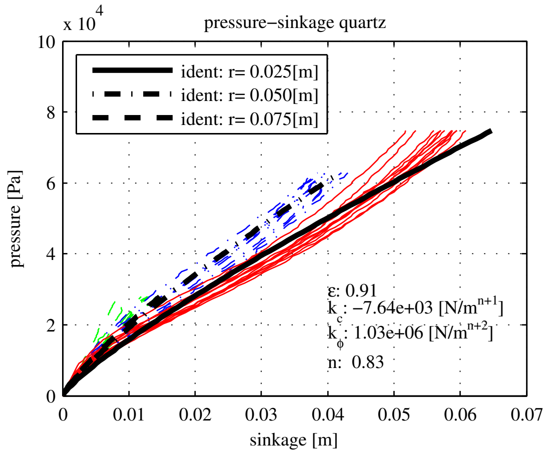


Fig. 7: pressure-sinkage test data for dry quartz sand, red: r=0.025m, blue: r=0.050m, green: r=0.075m

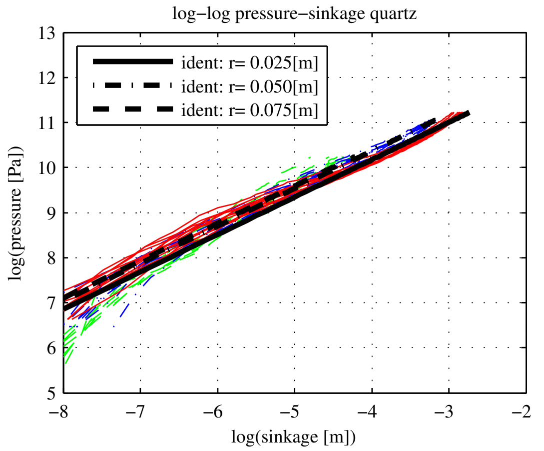


Fig. 8: log-log plot of pressure-sinkage test data for dry quartz sand, red: r=0.025m, blue: r=0.050m, green: r=0.075m

4.3 Identification of Bekker Parameters

To identify the Bekker parameters standard Matlab identification routines for global optimization problems are used for the following problem:

$$\min_{\boldsymbol{x}} \| \boldsymbol{p_c}(\boldsymbol{x}, \boldsymbol{U}) - \boldsymbol{p_m} \|_{2,}^{2} \qquad (2)$$

with $\boldsymbol{x} = [k_c, k_\phi, n]^T$, $\boldsymbol{U} = [\boldsymbol{z}, \boldsymbol{b}]^T$. The vector $\boldsymbol{p_m}$ represents the measured pressure on the penetration plates of all recorded pressure-sinkage curves of a test series, $\boldsymbol{p_c}$ is the calculated vector according to Eq. (1) for the curves. The vectors $\boldsymbol{z}, \boldsymbol{b}, \boldsymbol{p_m}, \boldsymbol{p_c}$ are of the same length representing N data points. For each measured pressure-sinkage curve the same number of samples, uniformly distributed over the measured penetration, is taken into account. Although this does not guarantee that the curves influence the identification results in an equal manner, the results are acceptable. On the one hand data points at lower sinkage values have a stronger influence, because the bevameter is not able to push plates with a larger area deeper into the soil. On the other hand higher pressure values influence the identification result in a stronger way, because the same relative error at higher pressure values is absolute greater than at lower pressure values. To find an optimal weighting of the errors is an important future work. Wong's formula [8] to calculate the root mean square of the pressure error over the mean calculated pressure is modified to evaluate the performance of identification:

$$\epsilon = 1 - \frac{\sqrt{\dfrac{\sum (\boldsymbol{p_m} - \boldsymbol{p_c})^2}{N-2}}}{\dfrac{\sum \boldsymbol{p_m}}{N}}. \qquad (3)$$

If the fit is perfect, ε is one, otherwise less than one. With this method of soil parameter identification a single set of soil parameters can be determined with a much better reliability than Bekker's technique. Bekker's technique is to calculate the mean of the soil parameters identified with two single pressure-sinkage curves measured with plates of different size.

The pressure-sinkage curves calculated from the identified set of soil parameters show a good correlation with the measured curves of $\varepsilon = 0.91$. However the parameter n for the red curves (plate with radius = 0.025 m) seems to be greater than one at sinkage values lower than 0.04 m. This might be caused by the soil preparation, since the soil is loosened only in the upper layer. In lower layers the soil is not loosened and is therefore more compressed. This leads to a steeper rising of the pressure-sinkage curve.

To conclude, the identification procedure shows a good correlation with the measurements. Hence further tests with two different soils are performed. One of these two soils is the Martian Soil Simulant D (MSS-D) provided by the DLR's Institute of Space Systems (DLR-RY). The other soil is German Eifel lava sand, which is milled to get a grain size distribution similar to the quartz sand used in first tests. Both sands are depicted together with the quartz sand in Fig. 13.

The results of these tests and the corresponding log-log plots are depicted in Fig. 9 to Fig. 12. The quality of the identification for MSS-D and milled lava are above $\varepsilon > 0.8$. This value indicates that the identified set of Bekker parameters is acceptable. It is obvious that the curves calculated with the identified sets of Bekker parameters (black colour) match to the measured set of curves at higher sinkage values better

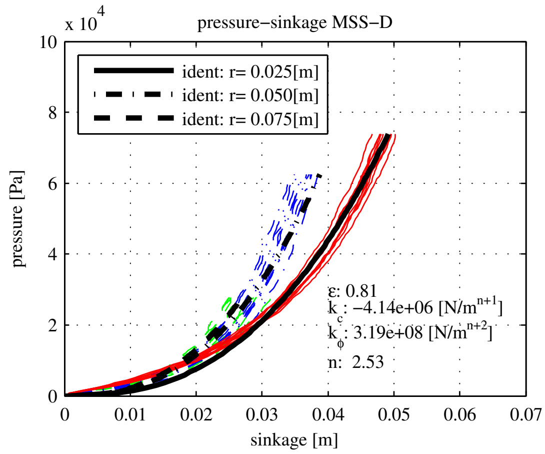


Fig. 9: pressure-sinkage test data for MSS-D, red: r=0.025m, blue: r=0.050m, green: r=0.075m

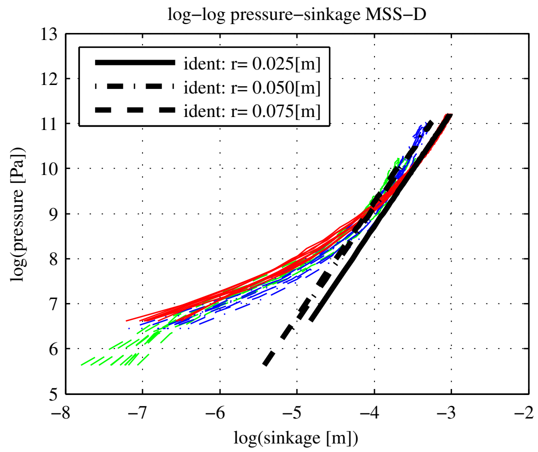


Fig. 10: log-log plot of pressure-sinkage test data for MSS-D, red: r=0.025m, blue: r=0.050m, green: r=0.075m

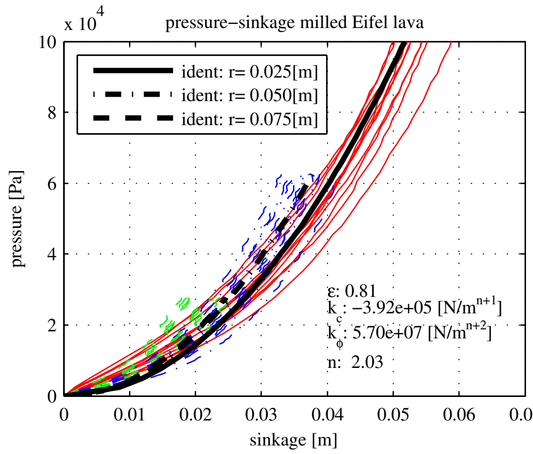


Fig. 11: pressure-sinkage test data for milled Eifel lava, red: r=0.025m, blue: r=0.050m, green: r=0.075m

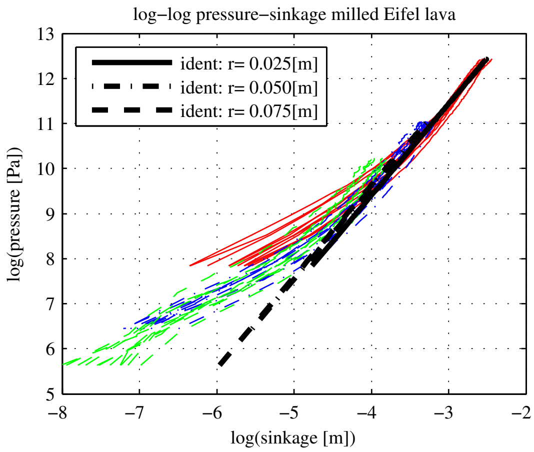


Fig. 12: log-log plot of pressure-sinkage test data for milled Eifel lava, red: r=0.025m, blue: r=0.050m, green: r=0.075m

than at lower sinkage values for the MSS-D and the milled Eifel lava. Regarding the log-log plot it is possible to draw a second straight line representing the soil at higher surface layers. This leads to a soil with two different sets of soil parameters for two soil layers with different compression. Due to the acceptable identification results and to avoid a more complex soil description a sectioning of the soil into two layers is omitted. Since in both soil bins the deeper layers are not loosened by the soil preparation, the measured curves are expected, apart from the layer transition at penetration values at 0.01 m. This is caused by the bottom effect of the lower soil layers, because they possess a very high compression, caused by transporting the soil in the bin over a long distance in case of the MSS-D and filling the soil bin layer by layer over several weeks to dry the soil in case of the lava sand. This inhomogeneity is similar to the conditions expected in the testbed. Although it is a contradiction to the Bekker theory, the identification of Bekker parameters results to acceptable set of parameters. Therefore Bekker theory can be applied to the measured pressure-sinkage curves.

Table 1: Overview of identified soil parameters and the performance of identification for different soils

Soil	k_c [N/m^{n+1}]	k_Φ [N/m^{n+2}]	n [-]	ε [-]
dry quartz sand	-7.64e3	1.03e6	0.83	0.91
MSS-D	-4.14e6	3.19e6	2.53	0.81
milled Eifel lava	-3.92e5	5.70e7	2.03	0.81

Fig. 13: Photos taken from the used soil: dry quartz sand, MSS-D, milled Eifel lava

5 Conclusion

A completely new terramechanics testing facility built up at the DLR's Institute of Robotics and Mechatronics in Oberpfaffenhofen is presented. The testbed will be used for system level tests primarily for the ExoMars project of the European Space Agency for rover performance and mobility tests, but also for future planetary rovers.

Furthermore it is shown, that the expected soil conditions in the testbed can be expressed with Bekker [1] parameters, identified from bevameter measurements taken with a new bevameter equipped with state-of-the-art sensors. The used identification technique differs from the method proposed by Bekker [1]. It has the advantage taking more than two bevameter measurements in account for a single identification. Further work on weighting the error in the identification has to be done as well as to prove that the designed bevameter can be used for shear tests. First shear tests show very promising results. Besides it has to be stated, that an integration of statistics is very crucial for a more realistic soil characterization.

Nomenclature

b	radius of circular pressure plate or shorter length of rectangular pressure plate	[m]
ε	performance of identification	[-]
k_c	cohesive modulus of soil deformation	[N/m^{n+1}]
k_Φ	frictional modulus of soil deformation	[N/m^{n+2}]
n	exponent of soil deformation	[-]
N	number of data points used for calculation of ε	
p	pressure	[Pa]
p_c	calculated pressure	[Pa]
p_m	measured pressure	[Pa]
r	radius of pressure plate	[m]
z	sinkage	[m]

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