TOWARDS AUTOMATED SOIL PREPARATION FOR PLANETARY ROVERS - METHODS FOR REPRODUCIBLE MEASUREMENTS IN REGOLITH SIMULANTS

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ABSTRACT

Testing and qualification of planetary rovers most times require the interaction with soil simulants. In order to yield comparable results, nimble and accurate soil preparation is required. Unfortunately state of the art preparation methods feature either bad reproducibility and/or take most of the time of the test campaigns. This often leads to fewer, less reliable data in the narrow time frame of planetary exploration missions, as many tests need to be repeated. The problem gets stronger the softer the simulant gets - thus worst-case scenarios, crucial for rover missions, are least reliable. Hence in this article methods to automatically prepare soil simulants will be presented and evaluated. Furthermore an outlook to fully automated testbed preperation and testing is given using DLR's robotic terramechanics laboratory TROLL.

Key words: soil preparation; test bed; terramechanics; planetary rover; soil interaction;.

1. INTRODUCTION

In order to design and later qualify a mobile robotic system like a planetary rover for space exploration, excessive test runs are needed. For in-situ exploration of planetary bodies, the interaction of mobile systems and regolith is a key feature and thread at once. Thus tests exhibiting this interaction have to be carried out.
Given the rapid development in dynamic simulations and soil mechanics, in the near future more and more of these tests will be supplemented by simulation runs using validated models. However to validate these models and for final hardware tests, physical tests will always possess their right to exist.
In these tests reproducibility is a major issue, as granular materials react differently based on their load history and the environmental conditions. Where the latter can be held constant, the former is tackled by rather complex, manual procedures to ensure consistent soil conditions. Mostly these methods tend to compress softer soils towards states, which are not worst-case scenarios anymore. While this is valid for basic verification campaigns on simpler models, it is not suitable for models that aim at covering the full variety of possible soil states, including worst-case and qualification tests. Thus the aim of the paper is to consistently prepare the soil to any desired state possible. The preliminary manual soil preparation often needs more time than the measurements themselves, making measurement campaigns time and cost intensive. The rising number of tests due to poor reproducibility amplifies the problem.
Due to these issues, the article will feature investigations on soil preparation and comparison of the resulting soil density using a simulant (DLR-RMCS13) with high sensitivity to preparation, ranging from a worst case powdery state to a compacted easy to travers state.

2. THE SIMULANT: DLR-RMCS13

DLR-RMCS13 is a simulant designed as a worst-case soft soil simulant, especially for the locomotion of planetary rovers. The simulant has mostly been inspired by MER rover spirits destiny [1] and the afford to free it.

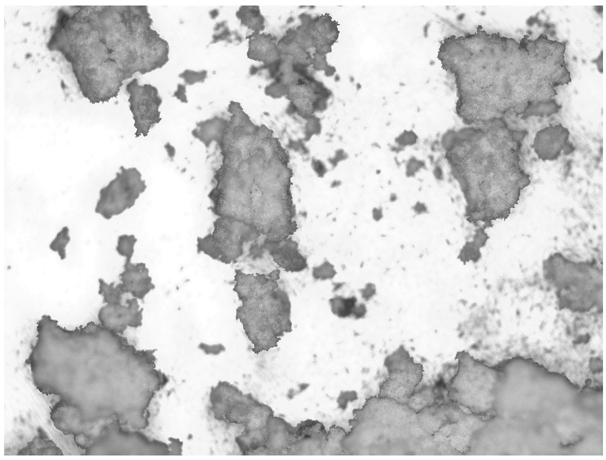

Figure 1. DLR-RMCS13 grain clusters in bright-field microscopy.

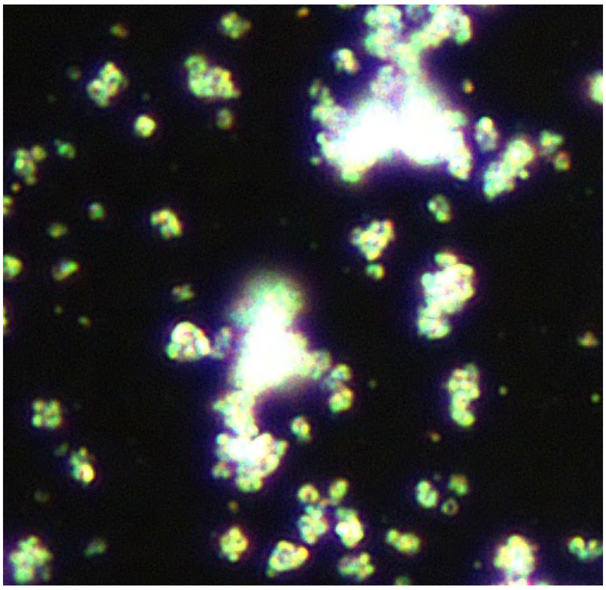

Figure 2. DLR-RMCS13 grain clusters and single grains in dark-field microscopy.

DLR-RMCS13 is consisting of fine CaCO3 powder in the range of sub µm up to tens of µm while being non-toxic. It also shows a tendency of dust clouds to rather sink to the ground quickly than tendencies to float up.
The grains are rounded and mostly of ellipsoidal shape forming clusters due to attractive forces. These clusters then act as "macro grains" which might also break due to external loading (see fig.1). Given the fine grained size as seen in fig.2, the material shows clear cohesional effects and tends to be highly compactable. In non compacted state the material is so soft, that it cannot support the weight of an average person, resulting in knee-deep sinkage. After compaction it is even possible to walk on the material without noticeable sinkage.
Given the wide range of compaction states, the material allows for tests of a wide range of soil conditions in single wheel tests, while using only one material and thus skipping time consuming exchange of soils.

3. STATE OF THE ART SOIL PREPARATION

Nowadays state of the art soil preparation methods are still basically manual work and very labor intensive and make use of standard gardening tools. Nevertheless these procedures have to be robust and less sensitive to the influence of tools, process and individual worker. Therefore even for a precisely defined and followed procedure, a variation of resulting soil properties has to be expected and in some cases can be even traced to the individual worker. Proper soil preparation has to guarantee well defined and repeatable terrain conditions. Continuous monitoring of the soil properties is therefore mandatory for manual soil preparation. The bulk density and the moisture content can be considered as standard measures for soil characterization during preparation. Additional measurement devices like Bevameter or soil penetrometer allow for a more detailed characterization.

Figure 3. Soil loosening and levelling

Planetary soils and soil simulants cover a wide area of soil types and behavior and for each soil type or class a dedicated and individually adapted procedure is desirable. As the resulting soil properties strongly depend on the overall load history standard soil preparation can be subdivided into three major steps:

- Filling in the soil and initial soil preparation
- Elimination of load history and aging effects (typically by loosening and levelling)
- Restoring of desired soil conditions (typically by compression)

Particular attention should be given to the filling of the testbed as direct access to the lower layers is limited later and mostly also affects the upper layers To achieve homogeneous initial soil properties, the soil is therefore typically filled in and prepared in layers. Raining the soil from a certain height leads to a loose uniform sand filling. This free falling method is therefore widely used and very good results are achieved for most standard soil simulants. Different filling methods like pouring and superposition of additional vibrating have also been evaluated successfully [2]. Each soil layer is prepared individually to set the desired soil properties. Typically the soil layer has to be compressed to achieve the desired relative density. To allow final settlement of the soil and dust and to reach equilibrium of the moisture content, a sufficient waiting period shall be implemented. For each test run the soil has to be reprepared accordingly by loosening, leveling and finally compressing it (see Fig. 3 and 4)and has to include the lower layers as well. The main working direction and preparation movements should be parallel to the desired motion direction but can also benefit from crosswise components and complex preparation pattern. Multiple lines shall be prepared with an overlap for the final compaction. Loosening is best achieved by manually plowing (garden hoe, rake) the soil up. Digging over the soil (spade, shovel) is additionally mixing the layers but is the most labor intensive approach. Raking typically just affects the uppermost layer and mainly

Figure 4. Soil compaction by lawn roller (left) and tilting movements (right)

contributes to levelling. For levelling larger areas a leveling board or similar devices is used. Finally the desired relative density and soil properties are obtained by compressing the loose soil by applying appropriate loads (lawn roller, weights). Using additional boards or metal sheets result in a flatter surface and a more homogenous pressure distribution and resulting bulk density. For loose power like soils like DLR-RMCS13 much better results are observed when applying dynamical loads and tilting movements e.g. by walking along the boards as shown in Figure 4. A systematic approach to selecting optimal tools, preparation movements and methods is given in [3]. To counteract the long term and aging effects (e.g. soil preparation less effective to lower layers and disposal of fine particles) a mixing of the layers is required at larger time intervals.

4. AUTOMATION

Automation in soil preparation does not only lead to lowered cost due to lowered manpower, but also allows for predictable and reproducible test. Whereas compression by body weight always causes difference by deviations in load or load patterns. Thus in the following sections we will present methods to automatically prepare soil simulants using conventional test beds available in most facilities. In order to further improve reproducibility we will introduce our robotic terramechanics testbed TROLL and give an outlook on possible methods for soil preparation.

4.1. Conventional Testbed

In order to provide commonly usable method for automated soil preparation, the techniques have been implemented and tested in the DLR-RMC conventional single wheel testbed (SWT). The following sections deal with the setup of said testbed for semi-automated preparation.

Single wheel Testbed

The single Wheel Testbed of the DLR Oberpfaffenhofen is used to investigate the rover wheel interaction with the soil and rate its locomotion performance. Fig. 5 depicts the testbed and its main components. It features two different drive modes: fixed slip drawbar pull (DBP) and free slip mode. The allowed movements of the wheel are

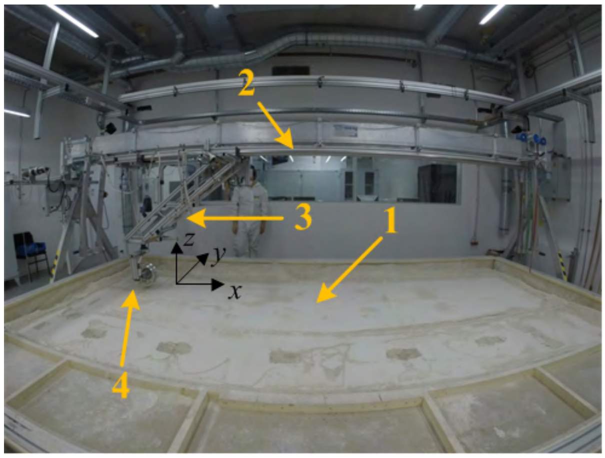

Figure 5. DLR-RMC conventional SWT: 1: Soil bin with the soil simulant 2: mobile rail above the bin 3: Parallelogram suspension linked to the rail thanks to a sliding carriage 4: Rover wheel with motor and force/torque sensor

the rotation around the y-axis (drive) and the translations along the x- and z-axis. After each locomotion test, the wheel is hanging above the soil bin and the trolley is free to translate; a linear cable drive enables it to move it along the rails direction at different velocities.

The tools have been designed such, that they are attached to the SWT sledge directly without interfering with the wheel suspension while being easy to exchange. Furthermore only the tools showing good preparation performance will be shown in this paper for conciseness.

4.2. Method and tools used for the soil preparation

Similar to manual preparation techniques the automated version is split into two steps: loosening and compression of the soil, each featuring an individually taylored tool. A trident-like plow is used to loosen the compacted layers of the soil and a simple sled (Fig. 8) with a load on it was built for the soil compaction. Both tools are inspired by the renowned manual tools and motions to prepare the soil. The displacement of the rail above the soil bin enables to prepare several parallel lanes, allowing for several tests accordingly. The plow is attached to the sliding carriage by means of two metallic bars (see Fig. 6). The height of the tool can be adjusted in order to allow for a shallow first run to lower the forces created by highly compacted soils. There are two different parameters for the soil loosening: the trolleys translational velocity and the depth of the tool in the soil. Moreover it is possible

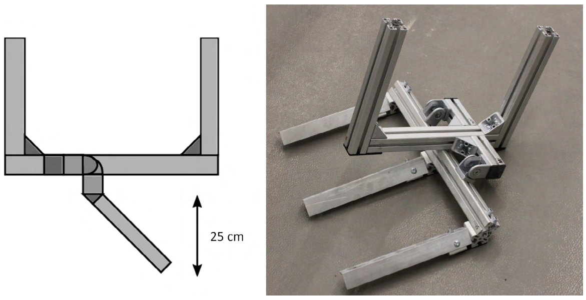

Figure 6. Plow used to loosen up the soil for the total testbed depth: principle (left) and prototype (right)

to do multiple passes with the plow in the same lane by reversing. The plow was tested in several configurations featuring different numbers of rakes. Thereby the qualitative loosening, rated by few measurements of bulk density, as well as the load on the tool were criteria for the final choice. Operation and effect of the three pronged plow is shown in Fig. 7 The shape of the sled is a flexible half cylinder, thus the sled can translate equally in x or -x direction. Due to its shape the sled does not only compact the soil but also levels the testbed, as it pushes soil excess via bulldozing. It is linked to the trolley by means of two sliding metallic bars (see Fig.9), this way the sled can translate in vertical direction to overcome obstructions. As a second setup a suspension via a parallel kinematic has been tested, but does not perform as well as the first setup. There are two different parameters for the soil compaction: the trolleys translational velocity and the load (additional 10, 20 or 30 kg) on the sled (see Fig.9). Similarly to the plow, multiple passes may be performed to allow for higher compaction rates. In order to test the performance of those tools and the semi-automatic preparation itself, a test campaign was carried out. In particular the influence of the different parameters on the resulting bulk density have been studied.

Figure 7. Plow loosening up the soil using the DBP actuator

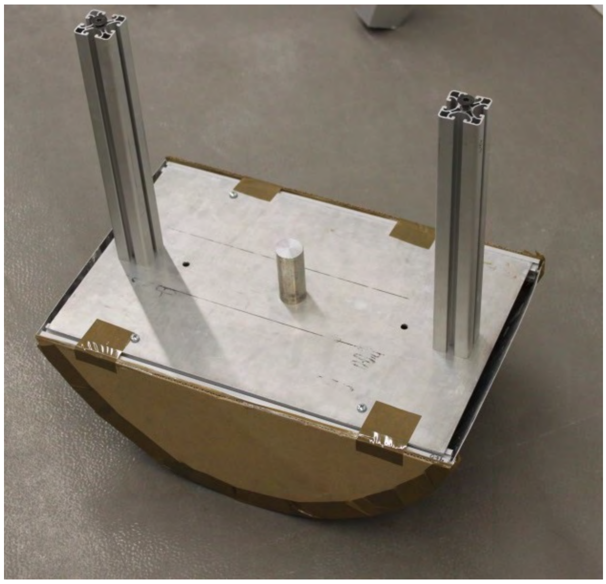

Figure 8. The sled is used to compress the soil and level it in one step. It is mounted instead of the plow.

Figure 9. Usage of the sled to compress and level the soil. Weight and the number of repetitions of the process yield different compression levels.

4.3. Results

In the following sections results on the preparation methods will be shown, Therefore the measurement methods and measured values will be explained in advance.

4.3.1. Measurement of the bulk density

Before and after each soil preparation the bulk density was measured at different places along the lane. Thereby measurements have been taken in the middle of the lane, right where a wheel would run. A special tool was built to sample the soil without changing its bulk density (see Fig. 10 on the right). Each sample was then weighted to calculate the bulk density. It has to be noticed that because of the handling of the soil sample this kind of measurement introduces uncertainty: the relative measurement uncertainty was evaluated to be $\pm 2.5\%$ and is represented in the plots below.

The comparison between before and after preparation provides information about the loosening and compaction rates. The comparison between the bulk densities at different places along the lane provides information about the homogeneity of the preparation. Furthermore qualitative measures have been taken into account to complement quantitative data and to allow a rating even under the difficult conditions in terms of reproducibility. These measures will be given in the conclusion.

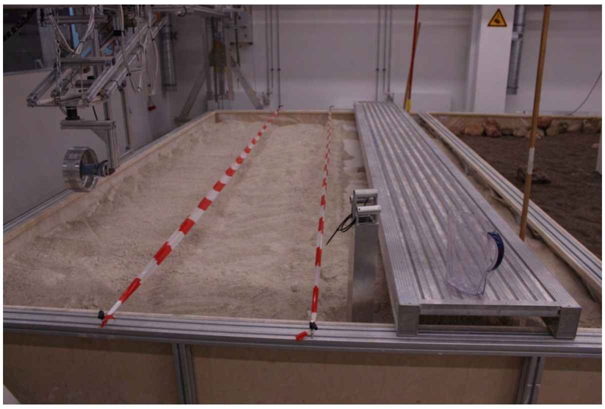

Figure 10. Lane before preparation (between the two with and red lines), Density measurement tool (right of the lane)

4.3.2. General results and best choice parameters

Concerning the soil loosening using the plow, a high translational velocity and multiple passes are required for the method to sufficiently loose the soil. As it was noticed that only the tracks of the trident-like plow were loosened, for the whole lane a translation of the tool before a second pass enables to improve the soil loosening. Furthermore the tool needs to be deep enough to reach all the layers of the ground. In order to loosen up very compacted soil specimens several runs in different depths should be taken into account.
Concerning the soil compaction using the sled, lower translational velocity and multiple passes are required. The influence of the load on the compaction is small, which is probably due to the fact that the link between the sled and the trolley is featuring friction and thus not perfectly sliding. Hence the pressure exerted on the ground was limited by the link's frictional forces. The resulting compaction is lower compared to the manual board walk although the pressures on the ground were similar in both cases. Possible reasons may be vibration caused by the board walk or the multi-dimensional nature of the board walk motion. Alongside the improvement of the guidance in z direction these points should be subject to further research. The caused difference in compaction compared to the manual preparation ($\approx$ 1.2..1,35 kgm^3) is not a problem, as the achieved bulk density of $\approx$ 1,26 kgm^3 is still sufficient for SWT. Using different numbers ob compaction passes density can also be set to different values during the automated preparation process.

The test campaign enabled to find the best combination among the parameters mentioned previously, based on both the homogeneity, ease of use and the bulk density measurements. Thereby a fast (16 $\frac{\text{cm}}{\text{s}}$) and a slow velocity (2 $\frac{\text{cm}}{\text{s}}$) have been tested, alongside different versions of the procedure. Selected parameters and experimental results are presented below.

State of the art preparation

In order to allow comparison to state of the art manual soil preparation, the automated methods are compared to loosening by deep raking and board-walk compression. Fig. 12 shows the density results for loosening of the soil. In order to achieve it the soil has been raked down to the ground to break up any clodding material. The mean and

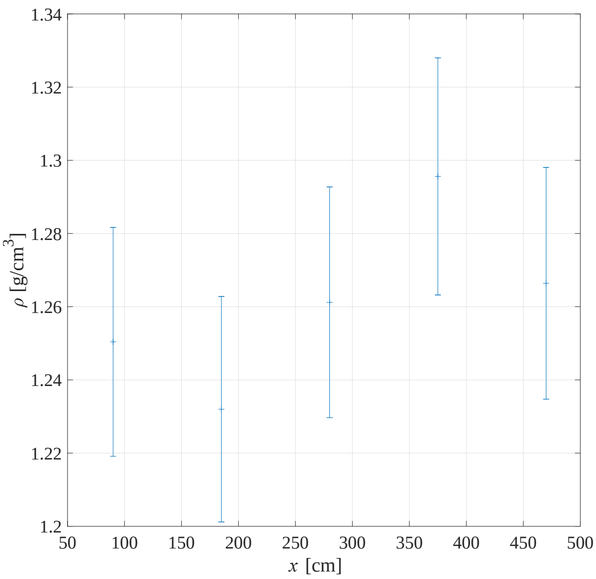

Figure 11. Density after loosening at different parts of the testbed for manual deep raking.

RMS are $\rho_{\text{mean}} = 1,11\text{g/cm}^3$ and $\varepsilon_{\text{rms}} = 0,016\text{g/cm}^3$, resulting in a relative error of $\approx 1\%$.
Compression has been carried out using the board-walk compression method, which has proven itself useful is test campaigns. In Fig. 12 the bulk densities measured are shown. Given the relative error the homogeneity is already suitable but still shows potential to be improved. The mean and RMS are $\rho_{\text{mean}} = 1,26\text{g/cm}^3$ and $\varepsilon_{\text{rms}} = 0,023\text{g/cm}^3$. This equals a relative error of 2%.

Semi-automated soil loosening

The parameters of the method have been chosen as followed to reach best results:

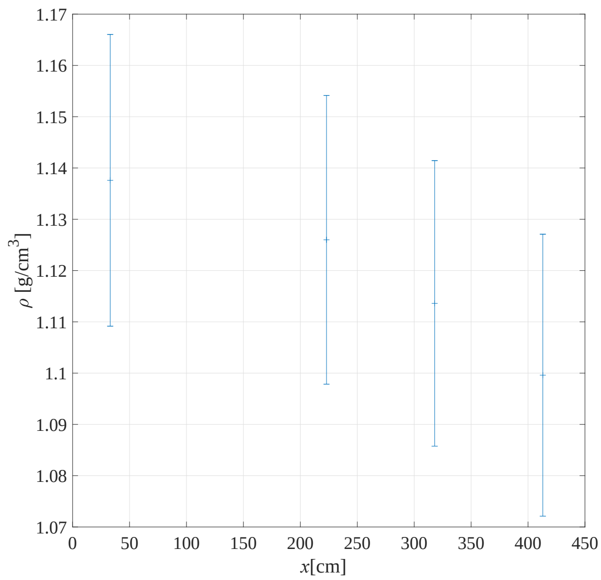

Figure 12. Density after compression at different parts of the testbed for manual board walk compression.

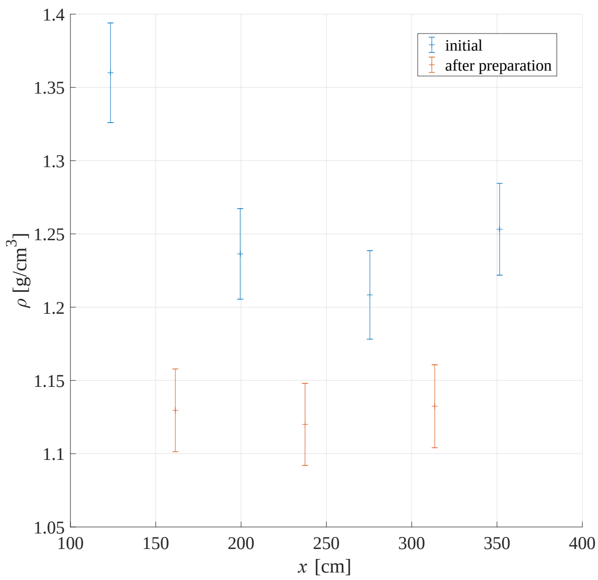

Figure 13. Density before and after loosening at different parts of the testbed.

- Translational velocity: $16\ \frac{\text{cm}}{\text{s}}$ (each pass)
- Direction: $-\vec{x}$ (each pass)

The procedure was altered to find the most loose and homogeneous soil conditions. It was carried out in four steps as follows: In the first pass a pre-loosening run in a depth of 5 cm is performed. Thereafter a second pass at full depth of 25 cm is performed. Next the translation of the rail is set to 11,5 cm in $\vec{y}$-direction followed be a second full depth run. Last the rail is moved back to its initial position and the top 5 cm are raked again in order to pre-level the soil in preparation of compaction. The quantitative results on bulk densities are shown in Fig. 13. The mean and rms of the measurements along the prepared lane are $\rho_{\text{mean}} = 1,13\text{g/cm}^3$ and $\varepsilon_{\text{rms}} = 0,01\text{g/cm}^3$, resulting in a relative error of 1%. Compared to the manual preparation, the density is slightly higher by $0,02\text{g/cm}^3$, which is negligible. Given the lower RMS, the homogeneity is similar to the results of the manual preparation and thus sufficient.

Semi-automated soil compaction

The parameters for soil compaction show best results for a first pass at $2\ \frac{\text{cm}}{\text{s}}$ and $16\ \frac{\text{cm}}{\text{s}}$ at the second pass. Thereby direction is reversed after the first pass. The load is set to 20 kg for all passes. Compression may be increased or deacreased using different numbers of passes. Given this procedure the bulk density results in Fig. 14 are obtained. It has to mentioned, that for this compression experiment the homogeneity in loosening is not as good as in other experiments, but still within in acceptable range. This is due to the fact, that homogeneous loosening of soil is more difficult in general. However, even with the slightly higher deviation in loosening densities the compression homogeneity is satisfactory. This is due to the fact The mean and rms of the measurements along the prepared lane are $\rho_{\text{mean}} = 1,26\text{g/cm}^3$ and $\varepsilon_{\text{rms}} = 0,005\text{g/cm}^3$, resulting in an relative error of $0,4\%$. Compared to manual compression, the same level of compression is reached. Regarding homogeneity, the RMS is significantly lower than the one of the manual preparation, yielding in reproducible and homogeneous soil conditions. However the maximum density of the material was not possible to be reached via semi-automated preparation, but by its manual counterpart. Thus, to reach higher compaction rates further parameters have to be varied in future alongside with tests of new tools.

4.4. Terrramechanics Roboticts Locomotion Lab

The Terramechanics Robotics Locomotion Lab (TROLL) at the RMC uses an force controlled, ingress protected industrial robot to conduct terramechanical locomotion experiments. Each Cartesian axis is either force controlled or follows holonomic constraints. The main task is to conduct single wheel experiments. A configuration for this task is shown in Fig. 15. By combining different force or holonomic constraints it is possible to generate all common single wheel test procedures. To increase productivity and repeatability it is necessary to implement an automated soil preparation procedure.
The previously shown preparation procedure can be directly implemented on the TROLL. The tools for loosening and compression will be mounted on a separate tool, which replaces the testing tool. A common tool changer will be used to switch tools in between testing an

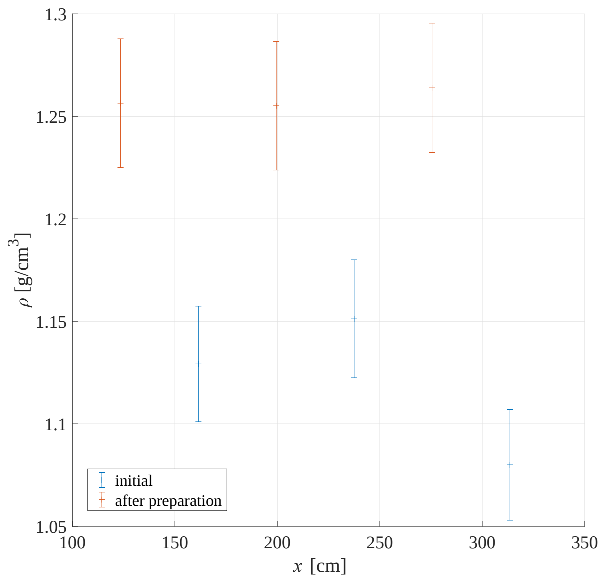

Figure 14. Density before and after compression at different parts of the testbed.

preparation. By changing the tool's orientation between testing (a) and preparation (b) it is possible to use a single robot tool for both compression and loosening (see Fig. 16). The force torque sensor can be directly used to evaluate the preparation progress.

A loosening tool with a geometry similar to the one shown in the sections above will be moved linearly through the ground to loosen the soil. By slowly increasing the depth in each pass the soil can be loosened without excessive load on the robot, tool or force torque sensor. The sensor will be used to evaluate the processes of loosening. This process will be based on pure holonomic constraints but still be protected by the force limits. To increase the effectiveness, additional movements can be overlaid onto the linear base motion. To decrease the transport of soil the passes will alternate in direction.

The compression tool is planned to be similar to the sled shown in this paper. It will combine the functions for a force controlled compression and a position controlled leveling of the soil. During the compression step the tool will be moved over the ground while maintaining a constant vertical load. The load, the number of passes as well as the horizontal velocity will define the compression. After the soil is compressed a final leveling pass will be executed.

The expected loads for both compression and loosening are well in range of the robot's and force torque sensor's specifications. Especially for the loosening process it is possible to reduce the number of spikes on the rake and increase the number of passes to further decrease the load. A detailed analysis and design of the tools and methods are part of ongoing work.

Figure 15. Terramechanics Robotics Locomotion Lab in its current configuration for single wheel tests.

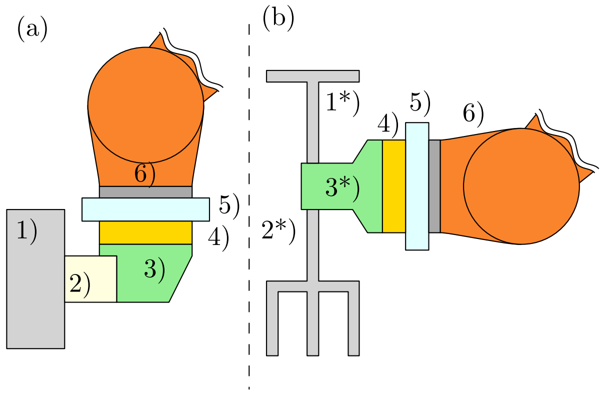

Figure 16. Testing configuration (a) and soil preparation concept (b) with the robot 6), sensor mount 5), force torque sensor 4) adapter 3), drive unit 2), wheel 1), loosening 2) as well as compression tool 1*)*

5. CONCLUSION

The following tables summarize the qualitative results of the test campaign, based on the bulk density measurements and the results of previous test campaigns. In terms

Table 1. soil loosening

	Manual (rake)	Automated (plow)
max. Level of loosening	++	+
Homogeneity	+	+
Reproducibility	-+	+
Ease of use	–	-+
Time/personell needed	–	+

of the loosening rate of the preparation, i.e. the maximum change in density achieved by the proposed semi-automated soil preparation is slightly lower compared to the manual and exhausting, deep raking. Considering the homogeneity both methods are astride, whereby the operator in manual preparation will adapt the number of iterations and thus time used, to the intermediate results achieved after the single iterations. For compression only, homogeneous preparation is almost impossible for manual procedures, as the board walk is highly dependent on the operator.

Regarding reproducibility the automated preparation is highly advantageous. Manual preparation of requires rework, while still featuring significant deviations. Ease of use is still to be improved for the automated preparation, as tools need to be changed and the test stand needs to be manipulated several times. In a global manner, the semi-automatic preparation gave encouraging results. However it showed several limitations:

Table 2. soil compaction

	Manual (board)	Automated (sled)
max. Level of compaction	++	+
Homogeneity	-	+
Reproducibility	-+	+
Ease of use	–	-+
Time/personell needed	–	++

- High loads (compared to the tool strength) required to loosen the soil, especially in case of high bulk density
- Limited action of the tools because only movement in one dimension is possible (translation)
- Even if the semi-automatic preparation is less exhausting, the multiple manipulations of the tools make it still time- and energy-consuming

Thus, even though the required time and personell can be reduced significantly, robotic testbed will improve automation of soil preparation even further, making it an integral part of automated test procedures. Hence usage of robotic testbeds should be a major focus of future research in applied terramechanics.

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