# Development of a leveling and loosening mechanism for fine sediments on a test track for planetary robots

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**Abstract**. Planetary robots must be extensively tested before they can be sent on a mission. Especially on loose soil, there is a need for tests with repeatable surface and soil properties to simulate the planetary use and to obtain reliable results for each test run. To achieve this, a leveling and loosening mechanism for a robotic test track is presented. By leveling and loosening in one motion, it enables easy and fast test preparation. Bio-inspired bear claws were designed and tested as loosening tools, which allow loosening with minimal resistance and a loosening effect of about 45%. The modular design allows the attachments to be easily interchanged to adapt the mechanism to different requirements or add additional functions like measurements of the soil properties. The paper provides details on the design and evaluation of the leveling and loosening mechanism.

## 1. Introduction

The history of planetary exploration shows an increasing tendency towards the use of robotic systems. Due to the difficult soil conditions on planets, robots must possess a high degree of mobility. Thus, the robots must be extensively tested on earth before they can be sent on planetary missions. One of the challenges on a planetary surface is fine-grained loose soil, which can cause the robot to get stuck and endanger the whole mission, which NASA had to painfully discover with their Spirit Rover [1]. Therefore, during the preliminary testing, the robot should move over a representing soil several times, with repeatable surface and soil characteristics each time to make different approaches comparable or confirm the results.

In the project NoStrandAMust (Learning Ground Interaction Models to Increase the Autonomy of Mobile Robotic Exploration Systems), the focus is on testing the locomotion behavior of various robotic systems on different soils and identifying the behaviors in the context of the surfaces, to generate ground interaction models. These models will then be used to increase autonomy in planetary exploration. To train the models, robotic systems developed at DFKI for planetary applications, such as four- to six-wheeled rovers (Artemis, Coyote III, SherpaTT) and four- to six-legged walking robots (Charlie, CREX, Mantis) [2], are being tested on a test track. The test track consists of four different substrates, from firm, smooth ground to lava structure to loose gravel and fine sand. [3]

For the test track, a fine sand with a grain size of 0-1 mm was selected, which corresponds to the sand chosen for the Space Exploration Hall at DFKI [4] and is oriented to the lunar soil simulant EAC -1A [5]. To achieve repeatable tests on the fine sand and reliably train the ground interaction model, the ground should be leveled and loosened before each run. In this way, increasing compaction of the sand as the number of experiments increases and an associated change in the properties can be avoided. As a result, the fine sand is as close as possible to reality, where most of the ground has remained untouched until now. For this, a leveling and loosening mechanism was developed, which will be integrated into the test track to allow repeatable experiments on the fine sand.

## 2. Development

### *2.1. Concept*

The area of the test track that should be leveled and loosened consist of 3000x3000 mm fine sand with a depth of 300 mm. The goal of the mechanism is to result in a repeatable surface and prevent compression of the sand, while being easy and quick to use, so that the preparation of the test track is not too time consuming.

An example of an approach to level and loosen a fine-grained soil is a mechanism used on a DLR test bed [6]. In that case, depending on the size of the testbed, several passes over different lanes with different tools are needed to cover the whole area. It is also used for a powder like simulant (DLR-RMCS13), where compression plays an even bigger role compared to the fine sand used for this test track.

This paper presents an approach, where the loosening and leveling functions are combined in one mechanism and the sand can be prepared in one movement forth and back. By this the repeatable preparation of a large area of 3000x3000 mm can be accomplished with low effort, which optimises the experiment procedure. This is possible by placing a loosening tool in front of a levelling tool. In this way, the loosening tool breaks up possible compaction to a certain depth and, at the same time, the leveling tool levels the surface at a certain height (Figure 1, b). The two directions of movement are necessary, in order that the leveling mechanism is not blocking the test track when stopping after the first movement in one direction. The structure of the mechanism is kept simple with aluminium profiles, resulting in a modular design where different attachments can be easily exchanged. It also includes a lifting mechanism, so that for the movement in one direction the sand cannot be moved into the prior part of the test track (Figure 1, a). This is realized through joints that are movable in one direction and blocked in the other. With wheels on the side of the mechanism and rails on the test track it can be lifted for one way and drops down for the way back. The linear movement of the mechanism can be realized by linear modules (Figure 1, c) which are driven by a Parker-Hannifin MH 105 30 06 (400 VAC) servo motor.

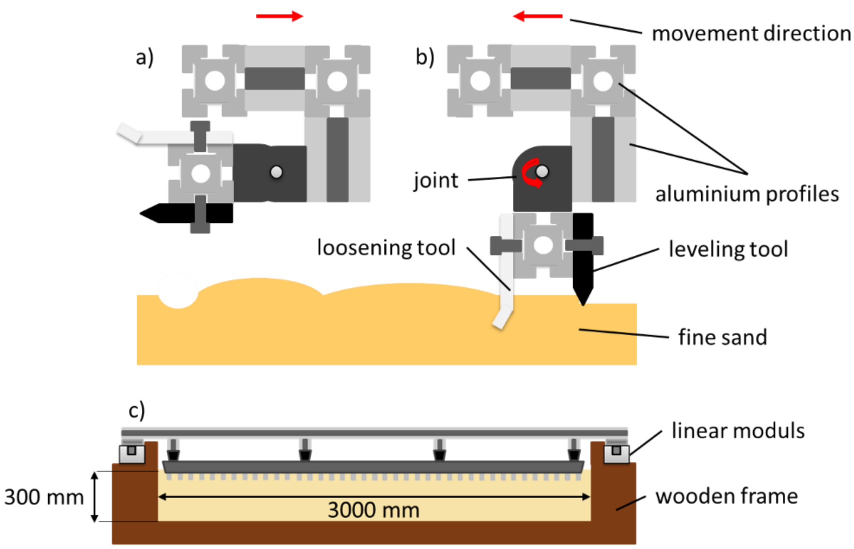


*Figure 1: Concept of the mechanism; **a)** Movement forth with mechanism lifted; **b)** Movement back with tools in the sand for leveling and loosening; **c)** Mechanism attached on the test track.*

As an additional function, a driven penetrometer can be attached to the mechanism, which can measure the resistance of the sand for different depths by pressing a tip into the soil and measuring the resistance via a force sensor. It is powered via a power bank and can be controlled wireless. With this the mechanism can loosen and level the ground and validate its function by measuring properties of the sand.

### 2.2. Tools

For the loosening, pulling the mechanism through the sand should, with minimal resistance, produce a maximum loosening effect. Therefore, various attachments and holders for loosening are devised. In Figure 2 the different holders (1-8) and attachments (A-C) are shown. There are eight different holders with two to eight prongs, gap distances from 12 to 135 mm, thickness from 3 to 8 mm and sinking depths for the attachments from 150 to 300 mm. The different 3D-printed attachments are wedges with various widths, a model inspired by a conventional plough and bioinspired geometries. The wedges (B) are geometries to divert the sand around the front area of the holders, to have less resistance. The plough inspired geometry (A) is based on applications used in agriculture to prepare fields for seeding. The bioinspired attachments (C) are based on the geometry of the claws of American black bears, which also use them to dig for food in the earth [7]. The positive effects of this geometry were proven by previous studies [8].

For the leveling tools, rigid aluminium sheets with different thickness (5 mm and 8 mm), as well as a version with an L-shaped sheet attached to increase the ground contact, will be tested.

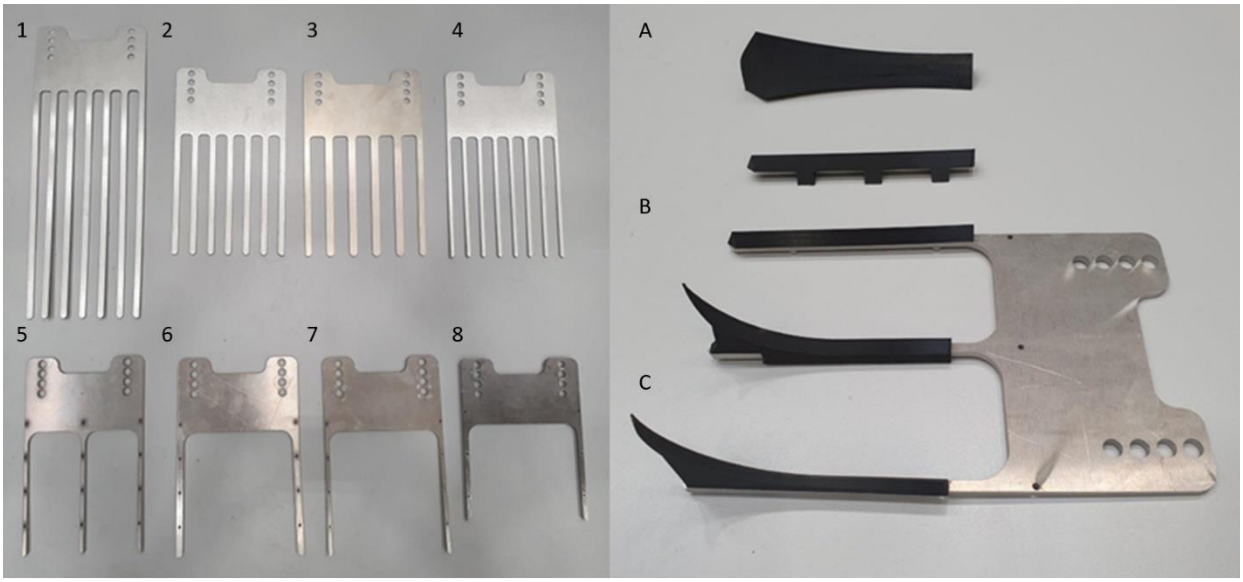


*Figure 2: **Left**: Different holders for the attachments with various number of prongs, gap sizes, thickness and sinking depths (1-8); **Right**: Different attachments, from top to bottom: plough inspired design (A), two different wedges (B) and two bioinspired geometries (C).*

### 2.3. Test bench

A separate test bench was set up to find out which holder/attachment combinations and leveling tools are best suited for the purpose. The test bench consists of a sandbox with dimensions of 1000x450 mm and is filled with fine sand to a height of 300 mm. Linear guides are fitted along its length, which allow the setup with holder and attachments to be pulled through the sand. A joint within the setup ensures that the mounted attachment with the holder sinks into the sand by its own weight during the pulling process. The joint is limited to 90° so that the mount is pulled vertically through the sand. With this it represents the same setup as the final upscaled version for the test track. The test bench including the penetrometer for the loosening experiments is shown in Figure 3.

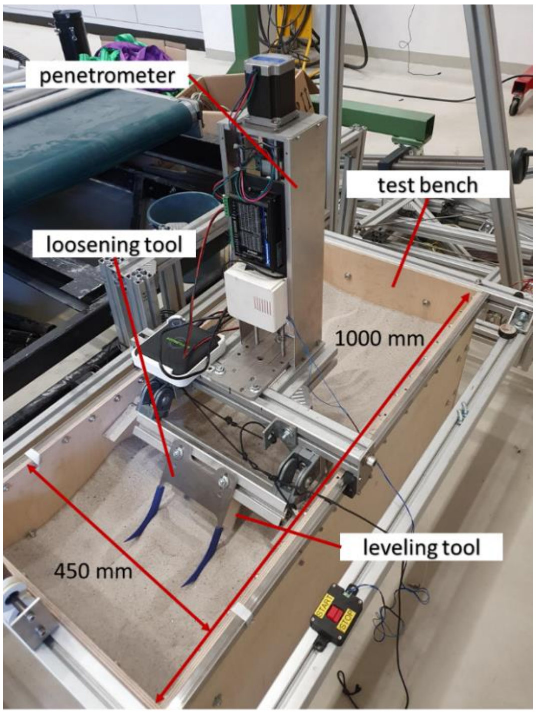

*Figure 3: The test bench with penetrometer.*

## 3. Experiments

For the selection of the loosening and leveling tools, two different experiments were performed. The first one was a mechanical resistance experiment, which was used for a selection of a leveling tool, as well as for a pre-selection of a holder and attachments. The second one was a loosening experiment, to test the loosening capability of the selected attachments.

### *3.1. Resistance experiments*

The different parameters to compare for the loosening tools consisting of holder and attachment, are the maximum resistance during inserting the attachments into the sand, the maximum resistance during drawing the attachments through the sand and the width of the furrow on the surface after the drawing. The resistance can be measured using a luggage scale that measures the force that must be applied to pull the mechanism through the sand.

For the leveling tool it is important to create minimal resistance resulting in a flat surface.

### *3.2. Loosening experiments*

To test the loosening capability of the selected attachments, the penetrometer was mounted on the test bench (Figure 3) to measure the compaction of the sand at several points up to a depth of 100 mm. Three different rows were selected, each with four measurement points (Figure 4). In two rows (left, right) the direct contact point of the attachment with the sand is measured and in one row (middle) the position exactly in the middle of the contact points. In this way, the loosening effect in all areas can be evaluated. For the experiment, the different attachments were compared with each other, as well as with sand that was not loosened at all. Between the measurements of each row, the sand was recompacted (with a load of 80 kg) and loosened again (loosened only for measurements of the attachments), to avoid any influence of the measurement procedure on the different rows and have the same soil conditions for every attachment. To obtain a significant number of measurements, ten runs were performed, measuring each position for each attachment and the compacted sand.

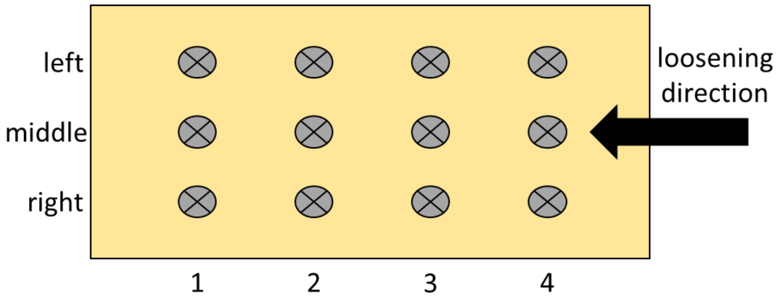


*Figure 4: Description of measurement positions in the test bench for the loosening experiment*

## 4. Results

In this chapter, the results of the two experiments are presented and evaluated. With the results of the resistance tests, a decision was made for a leveling tool, as well as a pre-selection for the loosening tools. The loosening tests decided on the final selection of a loosening tool.

### *4.1. Resistance experiments*

In initial tests, the influence of the leveling tool on the resistance proved to be negligible and all three variants produced the same flat surface. For this reason, the 5 mm thick rigid aluminium sheet was chosen because it was the lightest variant.

A limiting factor that must be considered for selection, is the use of the servo motor in the test track, which can generate a nominal torque of 6 Nm and can achieve a torque of 60 Nm with the help of a planetary gearbox. Therefore, the decision was made in advance to use a holder that would provide results in an acceptable resistance range to meet the requirements of the limited motor power. The most suitable holder for this purpose, which has been found from preliminary tests, is a cut-to-size, 8 mm thick aluminium sheet with two 120 mm long prongs, to attach the attachments and a distance between the two attachments of 135 mm (Figure 2, 8). The experiments were further continued with this holder.

The plough inspired design (Figure 2, A) showed too much resistance at an early stage, so it was not pursued further. The highest inserting resistance was found in the tests for the bear claws. However, since this is well below the maximum drawing resistance, it can be neglected. There are no major differences for the drawing resistance, the bear claws nevertheless show the least resistance with an average maximum drawing resistance of 8,13 kg. Meanwhile the measured average furrow width for the bear claws is with 68,3 mm significantly higher than the value for no attachments (38,3 mm) and the wedges (37,7 mm), as it is shown in Table 1. This suggests a higher influence of bear claws on a loosening effect with a slightly lower mechanical resistance. Since this result was relatively quickly recognizable, three experiment runs were enough to select. For further loosening experiments two variants of the bear claws are used. A big bear claw enclosing the holder and a small bear claw covering only the front surface of the holder (Figure 2, C). This allows the influence of the width on the loosening area to be tested.

*Table 1: Results of the resistance experiments for no attachments, small wedges and bioinspired bear claws. The values are given with the standard deviation.*

| Attachment | Inserting resistance | Drawing resistance | Furrow width |
|---|---|---|---|
| | in kg | in kg | in mm |
| No Attachement | 2,36 ± 0,05 | 8,53 ± 0,54 | 38,3 ± 9,7 |
| Wedges | 2,33 ± 0,05 | 9,34 ± 0,57 | 37,7 ± 3,1 |
| Bear Claws | 4,67 ± 0,12 | 8,13 ± 0,09 | 68,3 ± 2,4 |

*4.2. Loosening experiments*

After the pre-selection for the attachments was made, in this experiment the loosening effect of the small bear claw, the big bear claw and compressed sand was compared. When analysing the data, it was possible to validate a loosening of the soil by both attachments, as a clear difference in density of about 30% is visible compared to the compressed sand (represented in the experiment by the resistance of the sand to penetration in kg, measured over the penetration depth). While this represents the average loosening effect over the depth of 100 mm, the measured average loosening effect at a depth of 75 mm, which represents the depth of the loosening attachments in these tests, is even higher at about 45% (Figure 5, a).

If additionally, the error for the measurements is given, a high error is visible, especially with increasing depth, where the error lines partly overlap (Figure 5, b). This is mainly due to differences between the measurements of the individual columns. Thus, as the number of the measured column increases (Figure 4), the density in the deeper measurement range increases significantly (Figure 5, c). This could be since, when the experiment was carried out, the loosening only started shortly before the beginning of the fourth column, as it was not possible to do otherwise due to the space constraints of the penetrometer. Thus, some of the sand next to column four was compressed with each run, but never loosened up. In contrast, the sand to the left of the first column was completely loosened with each pass. Accordingly, it can be assumed that the sand to the right of the measuring points had a negative influence on the measuring areas closer to it, which explains the increase in resistance with increasing number of columns. This also shows that loosening has a positive effect on the deeper area that the attachments cannot reach. The loosening depth of the bear claws of 75 mm can be seen in all graphs by the increasing slope from this point (Figure 5). However, this slope is noticeably lower in the first columns where the 75 mm depth was fully loosened, compared to the last columns where there are influences from the not loosened areas. Accordingly, regular loosening makes also sense in order to prevent excessive compression in deeper areas. Looking at only one column, for example column 2, the error is recognizably lower, which supports the previous assumptions (Figure 5, d).

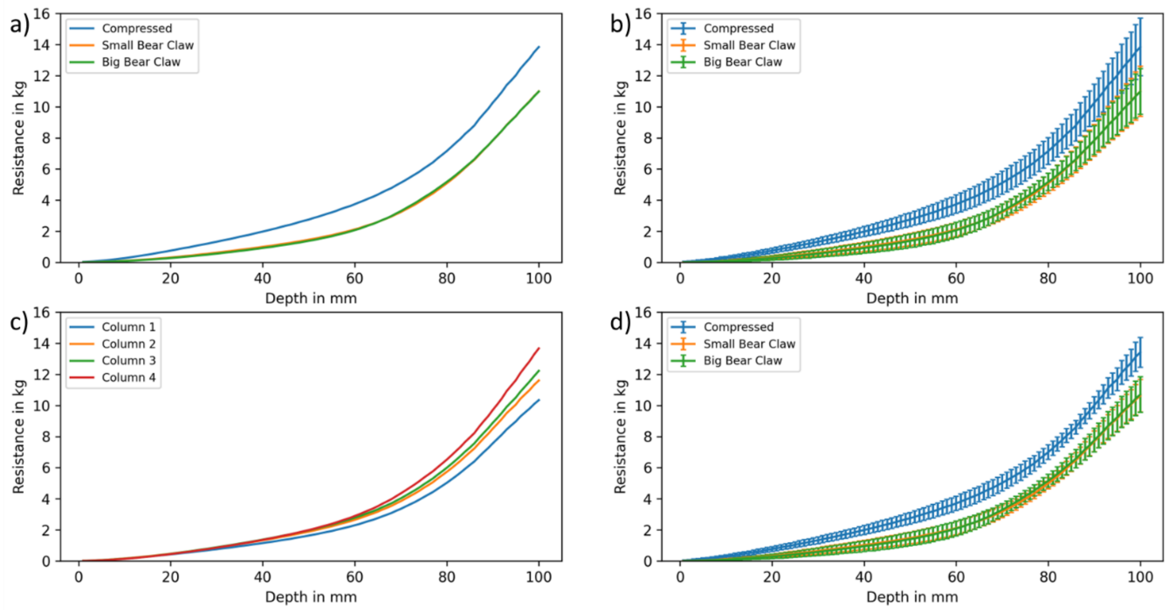


*Figure 5: **a)** Comparison of all mechanisms; **b)** Comparison of all mechanisms with error; **c)** Comparison of different columns; **d)** Comparison of all mechanisms in column 2 with error*

After the loosening effect of both attachments was validated and no significant difference could be found between the two variants (Figure 5), it was also checked whether the wider/bigger bear claw has a greater influence on the middle measurement row. The evaluation (Figure 6, b, c) showed that the loosening effect is generally better in the rows on the left and right than in the middle area, which was expected. However, when comparing the big and small bear claws, there was no discernible difference between the two variants (Figure 6, d). For this reason, the small bear claw was finally selected, since it has the same loosening effect but causes less resistance due to a smaller surface area.

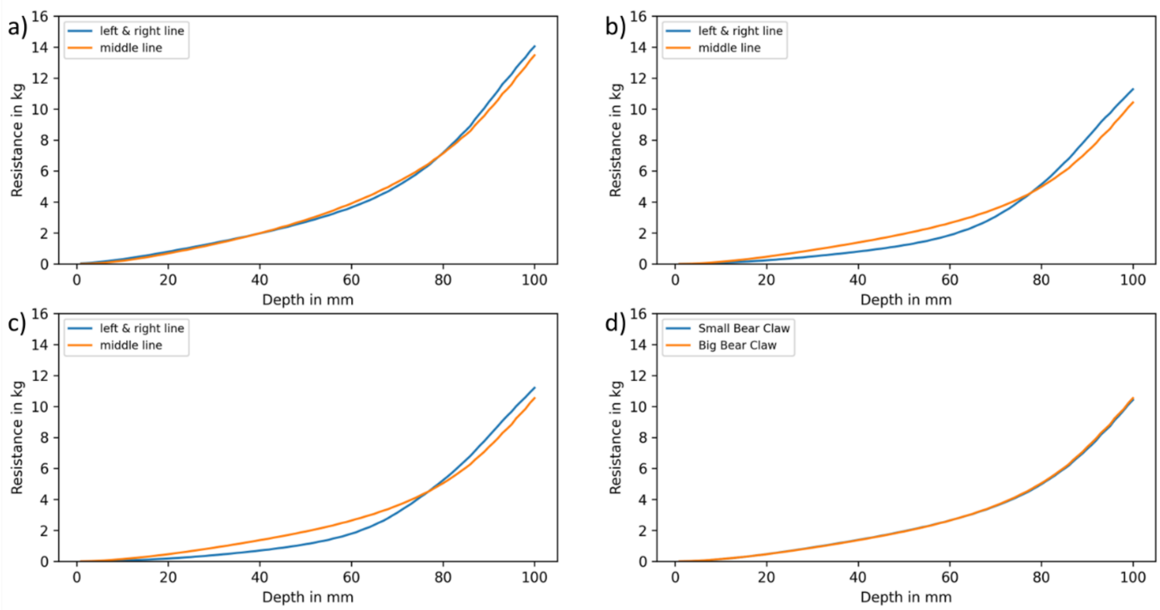


*Figure 6: **a)** Outer and middle line for compressed sand; **b)** Outer and middle line for small bear claw; **c)** Outer and middle line for big bear claw; **d)** Middle line for small and big bear claw*

## 5. Conclusion and Outlook

This paper presents a solution for a leveling and loosening mechanism, which can be used for loose soil on a robotic test track, in order to evaluate the locomotion of different robotic systems for a ground interaction model. The design allows a quick and repeatable experiment preparation and with its modular structure an easy adaptability to different requirements by changing the tools or adding new functionalities (e.g. vibrating tools for a potentially improved loosening effect). A bioinspired bear claw attachment was designed and validated with multiple experiments, achieving a loosening effect of up to 45%. The mechanism can additionally be equipped with a driven penetrometer, adding an extra function of measuring soil characteristics.

The integration of the mechanism into the full-size test track is ongoing (Figure 7) and as a next step its function will be validated. Initial tests have shown that the lifting mechanism can be implemented without wheels and only with the resistance of the sand lifting the mechanism during the first movement, which eventually helps to spread the sand over the test track. However, more tests need to be done and the control system needs to be programmed until the mechanism is ready to be used in experiments on the robotic test track.

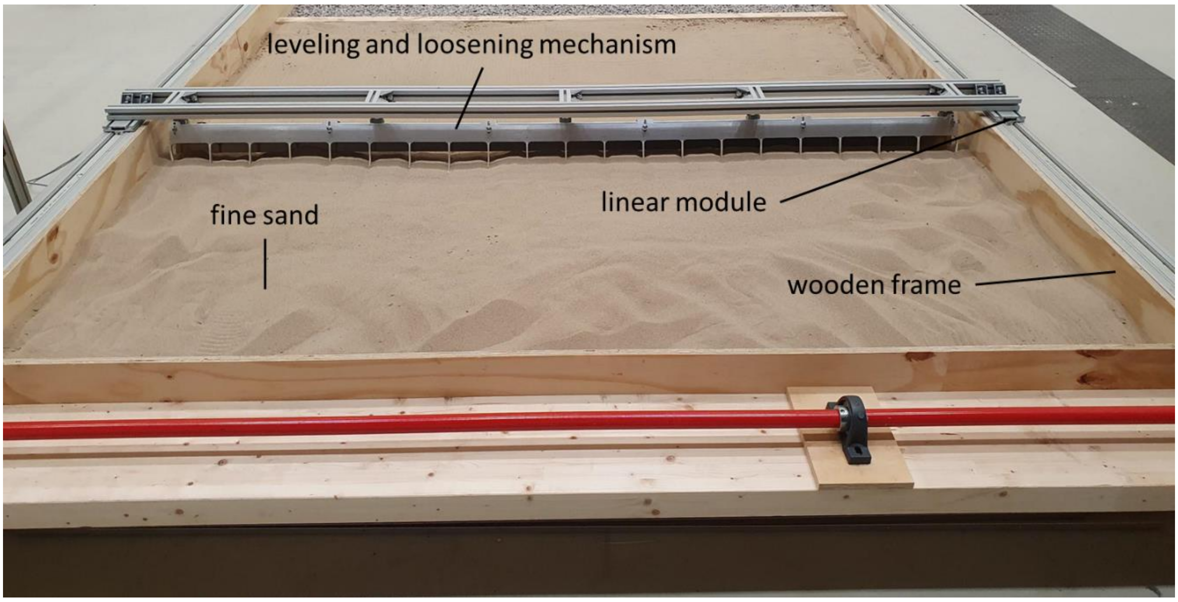


*Figure 7: Ongoing integration of the mechanism into the test track*

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