Wheel-Soil Interaction Data Generation and Analysis on Characterized Martian Soil Simulants

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Abstract

The design as well as the operation of rovers for planetary exploration requires information on the locomotion capabilities of the vehicles on the substrates that can be encountered. A major challenge in planetary exploration robotics is to create representative and well characterized test conditions on Earth, to provide accurate data for validating simulation tools and ultimately to increase rover mobility, which is necessary to provide access to a wider range of exploration targets.

Especially in the presence of severe mass and power constraints the tractive performances are limited and the possibility exists of mission degradation or failure due to immobilization of the rover as a result of excessive sinkage in a terrain which properties are only partly known. In order to mitigate these risks, simulants of planetary soils need to be defined and characterized to enable the production of test data, to gain a better understanding of the complex wheel-terrain interaction processes and to characterize the tractive performances of particular vehicle designs.

In the frame of our SWIFT and EXPERTISE R&D activities, four representative Martian soil simulants have been selected, procured and characterized. After having defined the conditions required for performing wheel-soil interaction tests, the performance of a set of flexible and rigid wheels was measured with a dedicated single wheel test facility.

The results illustrate that it is necessary to have a proper specification of soil materials as used in the tests, notably for advanced modelling of soil-wheel interaction. Information on the bulk mass density and on the character of the solids in the soil is indispensable for comparison of test results among published findings.

1 Introduction

A rover in a planetary exploration mission has to carry a scientific payload on an unknown terrain to a predefined target, usually in a power- and energy-constrained environment.

Our activities aim at improving the understanding of small to medium-sized rigid and flexible metallic wheels interacting with soils in order to estimate rover locomotion performances on other celestial bodies like Mars or Moon. Those activities require accurate single wheel test data on well characterised soils essentially for validating simulation tools.

Concerning soil characterization, it is known that the packing density of granular soil material has a significant effect on locomotion, as many occasions of stuck and of sliding vehicles on earth and elsewhere illustrate. As a wheel drives over a soil surface the compaction changes, i.e. densely packed soil can loosen upon disturbance and loosely packed soil can densify. It is also known that the stress level in a soil determines much of the soil behaviour: the well-known “angle of internal friction” expresses only a part of this stress dependence. In order to be able to come to suitable estimates for locomotion performances, these conditions have to be incorporated in soil-wheel tests and need to be considered in simulation tools. In this paper, results are given for soil mechanical parameters and locomotion parameters determined in soil-wheel tests on granular soils with a relative density of 60 %. The soil mechanical parameter values are presented for 10, 80 and 150 kPa total stress, and locomotion parameter values for 3 wheel load values in the soil-wheel tests, with a range of slip values.

2 Soil Simulants Description

Based on a set of required key soil characteristics as well as the practicalities related to their procurement, characterization and use, a procurement specification was established for four materials, with the aim of covering the range of typical soil-like substrates that are anticipated for a rover in a surface exploration mission on Mars. These soils are respectively:

(i) ES1 is very fine-grained, very porous, and compressible material, occurring often in the form of patches of "drift deposits" or as a thin veneer on top of other materials.

(ii) ES2 is a fine, silty to fine sandy soil, appears to be a very common soil type for dunes and dune fields.

(iii) ES3 is a coarse sandy to gravelly material occurring in scree, polymodal surficial lags and local coarser aeolian accumulations. The coarse scree and aeolian accumulations can occur in terrain with rocky escarpments.

(iv) ES4 is a dense stiff soil type considered to be the most prevalent type of soil in overall flat and gently sloping terrain outside dune areas, and for which bearing capability and shear strength are not an issue. It is characterized by a somewhat higher cohesion, resulting from weak brittle cementation, which is obliterated upon disturbance.

For all above mentioned soil types, specification in terms of particle size distribution, particle shape, hardness and surface activity, notably with respect to affinity to water, have been established and materials which meet these specifications have been identified and procured.

3 Soil Simulant Characterization

3.1 Procedure

For all four chosen materials, the mechanical properties have been determined with high accuracy triaxial cell tests, which are tests with well-defined procedures and methods of analyses in soil mechanics. A cylindrical soil sample in a fluid tight membrane is radially loaded by an incompressible liquid in a stiff container. In the test the fluid exerts a radial pressure on the sample and an axial load is applied by a piston on the sample. The deformations (volume and vertical) and forces and pressure applied on the sample are measured as the stress on the sample changes by changing the fluid pressure and the force on the piston. Initially the stresses in the axial and radial direction are applied and are equal, (i.e. 'total stress'). The axial stress is then increased in the actual loading phase of the test. The values for the swelling index and compression index are determined after application of the initial stress by unloading to 50 % and reloading to 100 % of the total stress levels of 10, 80 and 150 kPa. For the very stiff materials, at dense packing and high consolidation stress levels, the volume change has been very small and only an approximate estimation of the κ and λ parameter values was possible. The E_{ur} Young's Modulus has been determined by unloading at 2 % axial strain to 50 % of the then existing axial stress and reloading to the original existing axial stress. The grain size distributions (Fig. 1) of the materials have been determined by dry sieving and the so-called pipette method for the fraction < 63 µm after CEN ISO/TS 17892-4 [4], since not all materials are quartz dominated. Grain mass density ρ_g is determined using a gas pycnometer for volume determination

3.2 Results

Results in this section are provided for the soil simulant ES3 "OMR Dry" (without admixed gravel) procured from Sibelco that has a minimum density of 1360 kg/m^3 and maximum density of 1680 kg/m^3 as determined by common soil mechanical test methods. During the ExoMars LSS testing, gravel with known size distribution was mixed in ES3 soil and comparative single wheel tests results are presented in this paper. The grain size distribution in Figure 1 shows both the base material OMR Dry and the delivered ES3 with gravel.

The values for the soil mechanical parameters for ES3 without gravel are given in Table 1 for a bulk density of 1531 kg/m^3, which corresponds to a relative density of 60%, as was used during the single wheel testing. For some parameters in Table 1 two or three values are given, corresponding to a total stress level of respectively 10 kPa, 80 kPa and 150 kPa total stress.

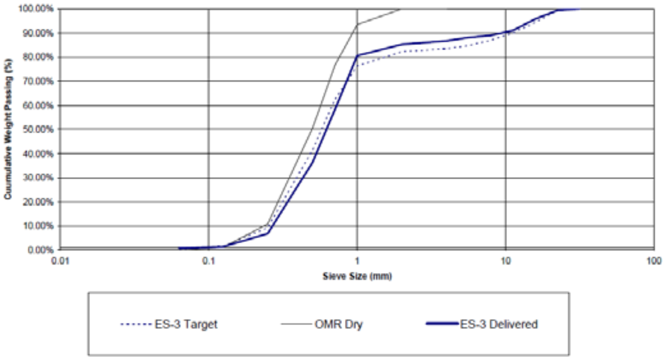

Figure 1. Grain size distribution of ES3 OMR Dry with and without admixed gravel

Table 1. ES3-OMR soil parameters determined at 60% relative density, with values listed for respectively 10, 80 and 150 kPa initial total stress.

Param	Value	Description
E	32 116 172	Young's modulus [MPa]
ν	0.25	Poisson's ratio [-]
ρ_d	1531	Bulk (dry) density [kg/m^3]
ρ_g	2600	Particle density [kg/m^3]
e_0	0.73	-
c	0	Cohesion [F/L^2]
φ_{cs}	37 33 32	Friction angle at critical state [°]
κ	- 0.0015 0.0010	Swelling index [-]
λ	- 0.0043 0.0015	Compression index [-]

3.3 Drucker-Prager Cap Model Material Parameters

In the context of the SWIFT activity an advanced Finite Element Method using a Drucker-Prager Cap model for soil behaviour is applied, as an extension of previous Deltares work reported in [2] and [3]. The parameter values for this model are determined from the Critical State Model parameter values derived from the triaxial cell tests. The Critical State Model requires parameters that describe the load-deformation behaviour of soils for a specific range of packing densities, and specified initial consolidation loads on the samples.

The soil characterization is described in terms of Mohr-Coulomb parameters for the soil shear failure (the friction angle *φ* and cohesion *c*) and in terms of the Critical State parameters for the soil compaction (parameter λ*). These parameters are translated to Drucker-Prager cap model parameter values (Table 2).

The material is considered to show plastic behaviour when specific stress conditions are exceeded, which are specified with the cap plasticity, and cap hardening parameters in the Drucker-Prager Cap model. The plastic behaviour includes compaction and shear failure. The soil is considered to show linear elastic behaviour, below these specified stress conditions, when it is not compacting or experiencing shear failure, and the soil behaviour is then determined by the Young's modulus *E* and the Poisson's ratio ν.

Table 2. ES3-OMR parameters of the Drucker-Prager Cap hardening model corresponding to 60% relative density

Elastic	Value	Description
E	80	Young's modulus [MPa]
ν	0.25	Poisson's ratio [-]
Soil	**Value**	**Description**
λ*	0.0027 0.0038	Soil compaction [-]
φ	34.2 33.0	Friction angle [°]
Cap Plasticity	**Value**	**Description**
d	0.20	Cohesion [kPa]
β	54.1 53.1	Friction angle [°]
R	0.83	Cap eccentricity
α	0.01	Transition surface radius parameter[-]
$\varepsilon_{vol}^{pl}\big\|_0$	0	Initial cap yield surface position
K	1.0	Ratio of triaxial tension to stress triaxial compression. K is 1.0 in Explicit [-]
Cap Hardening		
$p_i, \varepsilon_{vol,i}^{p}$	list of values	Pairs of increasing hydrostatic pressure yield stress and corresponding volumetric plastic strains. [F/L^2], $\varepsilon_{vol,i}^{p}$ [-]

The soil mechanical parameter values listed in Table 2 are used in FEM simulations that are capable to simulate soil-wheel interaction in considerable detail, as shown in Figure 2, and with good estimates of actual locomotion parameter values.

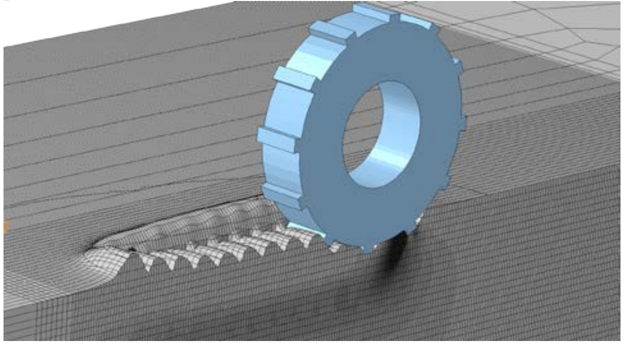

Figure 2. Example of part of an advanced numerical simulation using a Drucker-Prager Cap model, with a rigid wheel on ES3-OMR at 50% slip ratio

3.4 Material Parameters for Other Models

The soil mechanical properties are determined for use in soil mechanical models. For approximations for soil wheel interaction such as after Bekker/Wong and others (see [5]), the test results and the values derived from the triaxial cell tests can be used to estimate suitable characterization values for the materials, such as an appropriate “angle of internal friction”, slip shear behaviour, and indications on sinkage.

4 Single Wheel Testing

4.1 Test Facility

The single wheel test facility is described in [1] and an overview is shown in Figure 2. This facility controls the wheel slip ratio and records forces and torques applied at the wheel centre in all directions, as well as hub displacement.

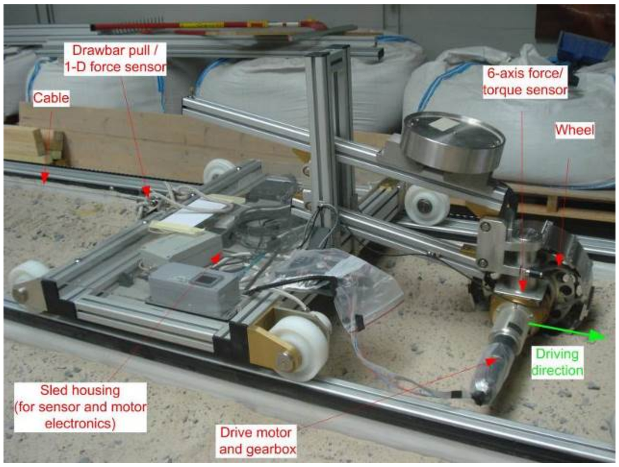

Figure 3. RUAG Single Wheel Testbed (SWT) filled with Martian soil simulant ES3-OMR with gravel

4.2 Tested Wheels

Two flexible wheels, developed in the context of the ESA ExoMars locomotion subsystem program phase B by DLR and RUAG Space, were tested. Both wheels are shown in Figure 3 and their main properties can be found in Table 3.

In addition, ESA provided a set of rigid wheels with diameters 250 mm, 300 mm and 350 mm. Each wheel is adjustable by width (50 mm, 100 mm, 150 mm), grouser height (2 mm, 5 mm, 10 mm) and number of grousers.

Table 3. Flexible wheels specification

EXMB1	EXMB2	Description
250	250	Diameter w/o grousers [mm]
100	112	Width [mm]
9.5	13.8	Wheel radial stiffness [N/mm]
12	12	Number of grousers
4	9	Grouser height [mm]

Figure 4. Left EXMB1 wheel; right EXMB2 wheel

4.3 Soil Preparation

The soil characteristics are dependent not only on the environment like air pressure, temperature, and notably humidity, but also on the condition of the soil, which depends upon the soil preparation method. For accurate repeatable measurement of the wheel-soil interaction characteristics, such as required for validation of the simulation tool, the soil has to be highly homogenous. Soil preparation techniques were investigated and adapted for each soil to create a specified bulk density, which for ES3-OMR, was at a relative density of 60%.

4.4 Test Cases

For this study, a comparison is made based on locomotion performance measurements in a set of tests with a range of slip values for various combinations of soil and wheel parameters. The performance parameter values are measured for the slip ratios and an interpolation function is used to provide values for the entire slip ratio range from 0 to 100 %.

Due to the number of parameters that can be varied, a dedicated test case approach was set up in order to limit the number of tests to a reasonable value.

Experience gained with measurement data demonstrates that drawbar pull versus slip up to 80% can be approximated by a polynomial function of degree 3, thus only four tests run would be necessary. However, in order to improve the quality of the interpolation function, tests were performed at six slip ratio values: near 0, 10, 20, 40, 60, 80 and 85% slip.

Testing a wheel under various passes (i.e. multipass) on a horizontal bin does not necessarily correspond to the same conditions as rover level testing on significant slopes. The reason is that on significant slopes, soil disturbed by a wheel could slide downhill. Therefore multipass testing was limited to slip values that were anticipated for slopes up to approximately half of the soil's angle of internal friction.

Tests have been performed with different wheel loads, representing the different conditions experienced by a planetary exploration rover on uneven terrain. Wheel loads tests of 70, 180 and 300 N were performed. When necessary, interpolation is used in order to estimate the locomotion performance for other load case. Tests were also performed with 30 N wheel load but do not produce meaningful results on most of the soils due to very low drawbar pull.

Variation of angular velocity does not significantly influence wheel-soil interaction parameters with the exception of tests at very high slip. This assumption was verified through exploratory tests and therefore most of the tests are performed with a single rolling velocity (i.e. product of angular velocity with the undeformed wheel radius) of 11 mm/s.

4.5 Locomotion Parameters

The drawbar pull (DP) is a key parameter for performance comparison as this provides the net pulling force in the direction of motion (soil thrust, H, minus motion resistance, R). This parameter is provided by the test facility by measuring the pulling force on the cable with a correction for considering the sled resistive force.

The wheel input torque (T) is the torque the drive actuator has to provide for the given motion and therefore wheel designs requiring lower torque for the same drawbar pull are advantageous.

The wheel sinkage represents the vertical displacement of the wheel sinking into the soil. This value depends on the nature of the soil, wheel load and the amount of slip. As this value reduces the ground clearances, minimising the sinkage is of importance. For rigid wheel, the sinkage is equivalent to the hub vertical displacement and is measured by the facility. For flexible wheel, the sinkage is measured manually on the wheel track using a laser telemeter. The sinkage has a major influence on the other locomotion parameters.

5 Test Results

The mean values for the locomotion parameters of each individual test, for a sufficiently long duration, and taken during the stable phase of a test run is used for the subsequent analysis. The transient phase, during which the wheel is accelerating / decelerating in the horizontal direction or sinking, is not considered.

5.1 Flexible vs Rigid Wheel

Compared to rigid wheels, flexible wheels have an outer structure deformation that allows increasing the wheel-soil contact area when loaded, producing higher friction and decreasing sinkage, and therefore should produce better performances than a rigid wheel of same dimension. To confirm this assumption, comparative testing was performed on different soils allowing to trade-off, from a locomotion point of view, rigid versus flexible wheels.

The performances of the flexible wheel EXMB2 is compared with a rigid wheel of same dimension. For a given slip ratio, the drawbar pull is significantly higher on both soils ES1-S6 and ES3-OMR than for the rigid wheel as shown in Figure 5 for a nominal wheel load of 180N.

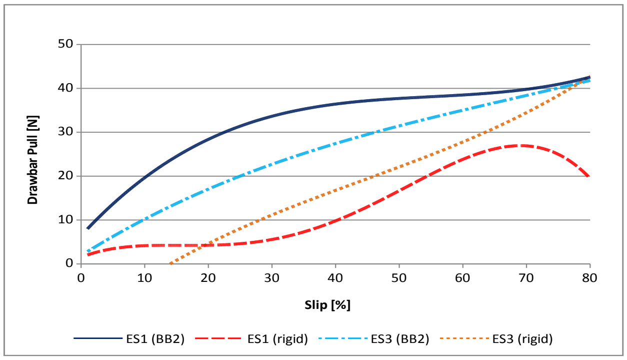

Figure 5. Drawbar pull for flexible EXMB2 and similar rigid wheel

The wheel torque vs slip curve is relatively identical for both wheels and on both soils. The torque increases relatively linearly from ca 4 Nm at 5% slip ratio to reach 15Nm at 80%.

The sinkage is also reduced for the flexible wheel. However, in this case, hub vertical displacement is more appropriate for aspects of wheel comparison, for which results are reported in Figure 6. Due to its radial flexibility (i.e. low stiffness), the flexible wheel EXMB2 has a vertical displacement of 13mm under the 180N wheel load on rigid ground. This behaviour penalised flexible wheel on relatively "hard" soils like ES3-OMR compared to a rigid wheel.

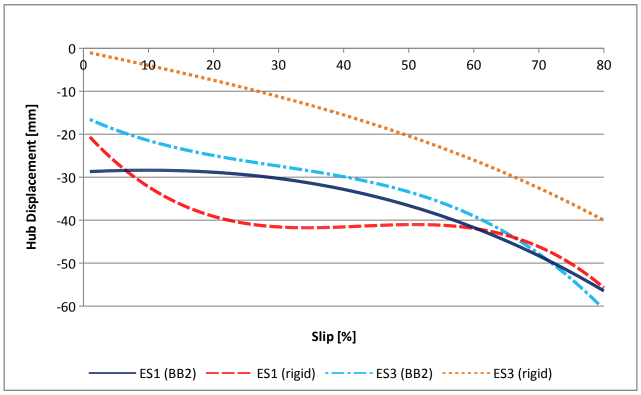

Figure 6. Hub displacement vs. slip for flexible and rigid wheel

The comparative tests demonstrate that flexible wheels reduce the soil resistive forces, and therefore can produce more drawbar pull at a given slip ratio while requiring similar amount of wheel torque than a rigid wheel. It has to be noted that similar increase in drawbar pull can be obtained by doubling the number of grousers as reported in the next section.

5.2 Effect of Grousers

The impact of the number of grousers is investigated for a rigid wheel of dimension d250x100mm on soil ES3-OMR. As is visible on Figure 7, doubling the number of grousers from 6 to 12 and then 24 has a positive effect on the drawbar pull. The difference in performance between 6 and 12 grousers is very significant. The difference between 12 and 24 grousers is less significant but comparable to an increase in wheel width from 100mm to 150mm. Beyond this number, the distance between two adjacent grouser is critical as gravels or soil can be stuck in it and therefore 24 grousers is considered to be the optimal value for this wheel diameter.

It is noted that the spacing between the grousers is about 120 mm, 12 x the grouser height of 10 mm, for the wheel with 6 grousers, about 60 mm for the 12 grousers wheel and 30 mm for a 24 grousers wheel. In the latter case action of individual grousers will strongly overlap in the soil, creating more or less, a single shear surface surrounding the grousers. For the 0.25 m diameter wheel with 12 grousers of 10 mm this is not yet the case at 50% slip, as is indicated by the extend of the shaded dark grey area in the soil at the grouser in Fig. 2.

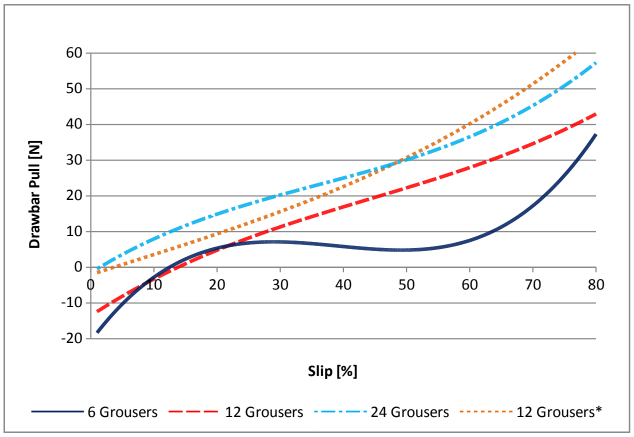

Figure 7. Drawbar pull vs. slip for a d250mm rigid wheel with different number of 10mm height grousers. *wheel width of 150mm instead of 100mm

5.3 Effects of Soils

The current projects have a relatively similar general test matrix for the four types of soils. For future activities and for the development of simulation tools, it is useful to study the influence of the soil parameters and conditions (e.g. relative density). Results in terms of drawbar pull and vertical hub displacement are presented in Figure 8 and 9 for three types of soils.

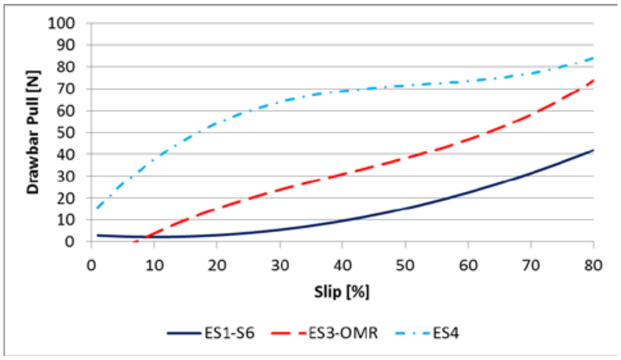

Figure 8. Drawbar pull vs. slip for a d300x150mm rigid wheel on different soils at 180N wheel load

The nature and condition of the soil influences the locomotion. Tables 1 and 2 list soil mechanical parameter values for the ES3-OMR soil material at 3 initial total stress levels. The ES3 material is a rather stiff coarse sandy material experiencing relatively little compaction on static loading, whereas the ES1 material, a fine powder, compacts easily upon loading. With increasing slip these effects become more pronounced as shown in Fig. 9.

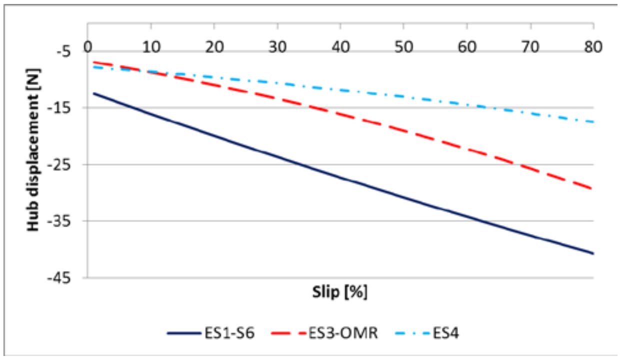

Figure 9. Hub displacement vs. slip for a d300x150mm rigid wheel on different soils at 180N wheel load

Sinkage, including entrenchment of the wheel in the soil, has a major bearing on the locomotion efficiency. Energy is lost by compaction and trenching, but higher compaction can generate a higher reaction force of the soil. Figure 9 shows that hub displacement increases rapidly with slip for the ES1 material, while the drawbar pull remains limited to about 40 N in the tests. The hub displacement for the ES3-OMR and ES4 material increases less, while the resulting drawbar pull reaches 75 N, respectively 85 N. The higher angle of internal friction of ES1 does not result in higher drawbar pull in this test series. The compaction behaviour dominates the locomotion performance in this case.

Even at high slip values there is only little sinkage for a wheel with 180N load in the very stiff ES4 material, as Figure 9 shows. The drawbar pull is high for the material as Figure 8 shows. The Critical State angle of internal friction of this soil is very high. However, the very high compaction stiffness of this soil appears to also have a dominant effect on locomotion performance.

5.4 Effect of Gravel

For the soil characterisation and the development of wheel-soil interaction tool, soil ES3-OMR without about 10 % (M/M) admixed gravel has been considered, and the potential impact of gravel was investigated. Comparative tests were performed with the flexible wheel EXMB2 and results in terms of drawbar pull are shown in Fig. 10.

The tests indicates that the presence of gravel in the soil increases the drawbar pull at a given slip ratio for wheel loads of 180 N and above. This effect is reduced for multipass level 1, 2 and for lower wheel loads.

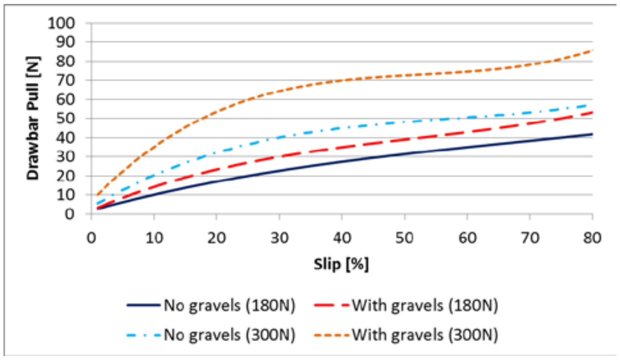

Figure 10. EXMB2 wheel on soil ES3-OMR with and without admixed gravel

It is known that a limited amount of coarse particles in soil does not influence the common soil mechanical parameters much if the size of those particles is small compared to that of the test set up. The size of the gravel particles in the ES3-OMR material, however, is similar and frequently larger than the height of the grousers used in the test. The wheel action concentrates and aligns the somewhat oblate gravel sized particles in the compressed upper zone of the soil, enhancing their effect, and increasing the performance, as if larger grousers are acting. Sinkage is also reduced by the coarse particles, which has a significant effect on the performance parameters. The decrease of the effect of gravel upon multipass, may be due to the armouring effect of the relatively plate-like gravel sized particles, resulting in reduced grip of the wheel on the substratum, and slip over the hard pavement.

Figure 11. EXMB2 wheel track on soil ES3-OMR at 25% slip, left with and right without admixed gravel

6 Lessons Learned

The condition of the soil is not often specified in the existing published literature, which seriously hampers comparison of results of soil-wheel tests. A specification of the nature of the material and notably of the actual packing density, or merely in situ bulk density, used in tests would greatly improve the efficiency of analysis of the various features that are compared and investigated in locomotion performance studies. To do so, soil is to be prepared in a homogeneous way with a well-established preparation method and the achieved relative density measured accurately with an appropriate device.

As a function of soil types, the repetition of test run and the appropriate selection of slip ratios allow to have more accurate results. It is difficult to select a priori the test matrix and therefore an evaluation of test data and optimization of the test definition during the test campaign is essential.

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8 Conclusions

In order to estimate rover locomotion performances, design wheels and drive units, single wheel testing is essential. In order to provide meaningful data, this is to be performed with an accurate facility and on well characterised and prepared soils.

In the context of our activities, approximately 2000 single wheel test runs have been performed on, currently, three different soils. The definition of the test matrix allows studying the impact of wheel flexibility, wheel dimensions and number of grousers. In addition, an interpolation function provides wheel performance values for the full range of load conditions experienced by a planetary exploration rover of the 300 kg class on Mars. Based on it, a software library was developed that provides directly wheel-soil interaction data to a rover simulation tool.

However, engineering soil simulants on Earth do not provide exactly the same locomotion conditions as on Mars and on Martian soil. Therefore the development and validation of computational wheel-soil level interaction tools is necessary. This development and validation has to rely on the single wheel test data. In addition, soil is to be characterised with a methodology compatible with the selected simulation approach. In our activity, a FEM simulation based on a Druger-Prager Cap model is used for which the appropriate soil mechanical parameters are derived from dedicated soil mechanical tests.

Based on all collected test data and complementary FEM simulations, an easy to use simulation tool is under development. The results from soil characterisation campaign, the test database and data-processing tool are the key elements for supporting this activity, necessary to predict accurately wheeled rover locomotion performances on bodies like Mars or the Moon.

References

[1] S. Michaud, P. Oettershagen and T. Oechslin, "Wheel Level Test Data Generation and Utilization to Predict Locomotion Performances of Planetary Rovers and Validate Simulation Tools", Proceedings of i-SAIRAS 2012, Turin, Italy.

[2] J.P. Pruiksma, J.A.M. Teunissen, G.A.M. Kruse, M.F.P. Van Winnendael: "Assessment of Tractive Performances of Planetary Rovers with Flexible Wheels Operating in Loosely Packed Soils", Proceedings of i-SAIRAS 2010, Sapporo, Japan.

[3] J.P. Pruiksma, G.A.M. Kruse, J.A.M. Teunissen, M.F.P. van Winnendael: Tractive Performance Modelling of the ExoMars rover wheel design on loosely packed soil using the Coupled Eulerian Lagrangian Finite Element Technique. ASTRA 2011, ESA/ESTEC, Noordwijk, The Netherlands.

[4] ISO/TS 17892-4, 2004-10: Geotechnical investigation and testing -- Laboratory testing of soil - Part 4: Determination of particle size distribution.

[5] Wong, J.Y. (2008). Theory of Ground Vehicles, Wiley