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IDENTIFICATION OF THE FORCES BETWEEN REGOLITH AND A RECIPROCATING DRILL-HEAD:
PERSPECTIVES FOR THE EXPLORATION OF MARTIAN REGOLITH

Thibault Gouache
Surrey Space Centre, University of Surrey, United-Kingdom, t.gouache@surrey.ac.uk
ISAE, Institut Clément Ader, Université de Toulouse, France, thibault.gouache@isae.fr

Yang Gao
Surrey Space Centre, University of Surrey, United-Kingdom, yang.gao@surrey.ac.uk

Tom Frame
Surrey Space Centre, University of Surrey, United-Kingdom, t.e.frame@surrey.ac.uk

Pierre Coste
ESTEC/European Space Agency (ESA), The Netherlands, pierre.coste@esa.int

Yves Gourinat
ISAE, Institut Clément Ader, Université de Toulouse, France, yves.gourinat@isae.fr

The large success of Mars exploration missions, such as the NASA Mars Exploration Rovers, Pathfinder and Viking I and II, have allowed a widespread access to the top layer of Martian regolith. However, no exploration deeper than the few centimetres allowed by the scoop of Phoenix has been conducted on Mars. The potential discoveries that will follow from access to the Martian sub-surface (for example, the presence or absence of extinct life forms and of resources for future human exploration; a better understanding of Martian and Solar System history) require the development of new tools and a better understanding of their interaction with regolith to increase their performance and reliability. A promising new drilling methodology, dual reciprocating drilling (DRD), was tested in regolith and showed higher penetration than static penetration. DRD is conducted by two half-cone drill-heads, with back-ward facing teeth, moved back and forth in opposition one to another (no rotation). To gain a better understanding of the forces acting on each half-drill-bit and the influence of slippage on drilling performance, a mono-block drill-head, with the same shape as the DRD drill-head, was tested in static and alternating penetration in two different regolith simulants. The forces acting on it were measured. These novel experimental observations allowed to revise the penetration model of DRD in regoliths and to illustrate the importance of lateral forces in the drilling process. To complement the experimental campaign and to gain a better insight on the regolith kinematics around the reciprocating drill-head, numerical simulations were developed. The discrete element method was chosen to simulate the complex behaviour of regolith. It was implemented within the commercial software Impetus-AFEA. The advantage of using this platform is its ability to use the power of graphical processing units (GPU) to cope with a very large number of elements within reasonable computation times. These numerical simulations allowed to confirm the importance of the lateral forces in DRD. They are also one of the first DEM simulations with more than one million particles on a single desktop computer and pave the way to highly efficient numerical simulations.

I. INTRODUCTION

Despite the large success of robotic missions on the Martian surface, very few explorations of the Martian subsurface have been conducted. The deepest investigations lead have been conducted by digging small trenches with scoops or wheels [1]. This is explained by the high difficulty of drilling on Mars. Creating a Martian borehole is very difficult for two main reasons. The first one is the high level of autonomy required by the drilling system due to the communication time between Earth and Mars.

The second reason is the lack of normal thrust on the tool drilling in a Martian environment. Indeed, Martian gravity is one third of Earth’s gravity. Secondly, robotic exploration missions, like all space missions, are highly mass constrained. Low gravity and low mass combined lead to Martian rovers or exploration platforms that can not push intensively on the drilling tool. Indeed, if the desired push on the tool reached values above the product of exploration-platform-mass times local-gravity, the platform would be lifted off the ground [2].

The most widely used drilling technique on Earth is rotary drilling. Rotary drilling has been used on the Moon by the Apollo astronauts and the Russian Luna missions [3]. The Russians also used it on Venus. However, rotary drilling requires high levels of weight on bit, which limits its performance in an extraterrestrial environment. Thus new solutions are being developed. Systems using percussive action alone (like moles [4]) or combined with rotary drilling [5] are studied. Ultra-
Sonic drilling is also being developed [6]. A European Space Agency (ESA) study also identified possible bio-inspired solutions. Amongst these new solutions, the authors have studied the drilling mechanism inspired by the wood wasp [7]. Such a drilling system is called Dual Reciprocating Drilling (DRD).

In this paper, the concept of DRD is recalled and previous studies are synthesized. A new experiment setup, designed to measure the forces on a simplified DRD head in regolith is presented and the main results obtained are highlighted. Based on these new results, revised penetration processes are proposed for DRD in regoliths and the importance of lateral movements are highlighted. To complement the experimental work, numerical simulations using Discrete Element Method (DEM) were setup. To correctly model DRD in regoliths, more than one million particles were required. Such a simulation was conducted thanks to the computation power of Graphical Processing Units (GPU) on a single desktop computer. Without GPU technology, a computer farm would have been required for such a simulation. The simulations confirmed the importance of lateral forces.

II. DUAL RECIPROCATING DRILLING

II.1 The bio-inspired concept

DRD or dual reciprocating drilling is the name given to the drilling technique inspired by the wood-wasp. This insect (1-cm long body) uses its ovipositor (a long and thin appendix) to drill into wood to lay its eggs. The drilling mechanism used by the wood wasp was identified by Vincent and King [8]. The ovipositor is split into three parts that slide one against each other, each one with back-wards facing teeth. For the drilling procedure only two parts or valves are considered. When one is being pushed on and is penetrating, the other is pulled on and recedes. The receding valve, thanks to the back-wards facing teeth, is able to generate a reaction of the substrate that is used by the insect to drill. This force puts in tension and stabilizes the receding valve that in turn stabilizes the penetrating valve. The insect can thus drill with larger forces than its ovipositor’s buckling limit. A given valve is alternatively the penetrating valve and the receding valve. Figure 1 is an illustration of the drilling concept.

The ability for a drilling system to generate a reaction force that can be used to drill is highly valuable. Indeed it was envisaged that the drilling forces required to penetrate could be balanced by the forces generated by the receding valve. The valves would thus penetrate without the need for an exterior push [9].

![Fig. 1: Illustration of DRD concept.](image)

II.2 Concept demonstration

A first prototype was thus developed and tested in low unconfined compressive strength rocks (chalk, mortar and non-fired clay). It proved the ability of DRD to generate a borehole (though the maximum depths reached were around 5 cm). This demonstration is described in [9]. Outside of the field of planetary drilling, DRD has fostered a novel brain probe development [10].

II.3 DRD in regoliths

DRD was then tested extensively in extraterrestrial regolith simulants. These tests are reported in [11] and Figure 2 is a picture of the DRD head. These tests showed that DRD enables deeper penetration than static penetration under the same exterior load in regoliths. High levels of slippage were observed as were some slight lateral movements. Based on the recorded data and the visual observations during these experiments, penetration mechanics were proposed: local compaction in low relative density regoliths and local and lateral shearing in high relative density regoliths [11].

To improve the modelling and understanding of the interaction between DRD and regolith a new experiment was designed to measure the forces between a DRD head and regolith. Its results are reported in the next section. It was designed specifically to measure the influence of slippage and to control lateral movements.
III. FORCES ON DRD

III.I Experimental setup

Because of the complexity of DRD and the two halves sliding one on each other, it is very difficult to measure the force on the penetrating half and on the receding valve separately. It was thus decided to simplify the drill-head for this experiment. Instead of making two halves, a full mono-block drill-head was manufactured. A picture of such a manufactured mono-block drill-head is shown in Figure 3. To reproduce the reciprocation movement of a half DRD drill-head, the full drill head was reciprocated. Figure 4 is an example of the displacement imposed on the mono-block-drill-head.

To impose such a displacement, a hydraulic ram is used. The regolith container is set on a support table above the hydraulic ram. A frame is used to go up and around the support table and regolith container, up to the mono-block drill head. A force sensor is placed between the frame and mono-block drill-head. The displacement of the mono-block drill head is measured by a displacement sensor. Figure 5 is a schematic of the setup and Figure 6 is a picture of the setup.

III.II Experimental values tested

\( a, s, \) and \( v \) (amplitude, slippage and speed) were varied during the experiments. The values adopted are reported in Table 1. The slippage values \((s)\) where chosen to span a large variety of possible slippages. Two values close to 100 \(\%\) were chosen since very high levels of slippage where observed in [11]. The values of amplitude \((a)\) and speed \((v)\) were chosen to be similar to the experimental conditions encountered in [11]. The chosen values are reported in Table 1.
Fig. 6: Picture of experimental setup.

<table>
<thead>
<tr>
<th>Values tested</th>
<th>a</th>
<th>5 mm</th>
<th>12 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>30 %</td>
<td>60 %</td>
<td>90 %</td>
</tr>
<tr>
<td>v</td>
<td>4 mm/s</td>
<td>12 mm/s</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Values of experimental parameters used.

The regolith simulants used for the experiments reported here are SSC-1 and SSC-2. Details on these simulants can be found in [12]. They were prepared at two very distinct relative density levels: one very high density level using vibrations to compact the regolith and one very low level through pouring. Details on the preparation methods used can be found in [13].

III.III Raw data obtained

Figure 7 is an example of the raw data recorded during the experiments lead. The displacement of the monoblock drill-head is imposed by the hydraulic ram, based on the levels of a, s and v chosen by the experimenter. The force cell records the force applied to the monoblock drill-head. It is positive when it is being pushed into the regolith (penetration force) and negative when being pulled out (traction force). The traction force is one to two orders of magnitude smaller than the penetration force.

III.IV Experimental results

Figure 8 top presents the evolution of the penetration force versus depth with different levels of slippage in low relative density regoliths. High levels of slippage induce a higher penetration force. Figure 8 bottom presents the evolution of the traction force versus depth during the same experiments. The traction force is one to two orders of magnitude smaller than the penetration force in low and in high relative density regoliths.

III.V Interpretation of experimental results

Semi-analytical model of penetration force

In low relative density regoliths, it was observed that the higher the slippage the higher the penetration force. This is due to the high levels of shearing the regolith in the vicinity of the drill-head is subject to when the drill-head reciprocates with high levels of slippage. The more the regolith is sheared the more it compacts and thus the more difficult it is to penetrate.

Each time a volume of regolith is subject to a cycle, it is sheared. It is possible to quantify the numbers of cycles a portion of regolith is subject to by counting the number of times a tooth or the tip of the monoblock drill-head passes through a fixed control surface, function of the slippage. This is given by Equation 1.
It was thus suggested that the penetration force of a reciprocating drill-head is proportional to Equation 1. When slippage is equal to 0, the penetration is done without any reciprocation. The value of the penetration force is thus equal to the static penetration value. It was thus proposed that the penetration force is equal to Equation 2, with \( Q \) an experimentally derived parameter depending on depth, amplitude and penetration speed and \( F_{SP} \) being the static penetration force, increasing with depth.

\[
\frac{S}{1 - s} \quad [1]
\]

\[
F_{SP} \cdot \left[ 1 + Q \cdot \frac{s}{1 - s} \right] \quad [2]
\]

Figure 9 presents the experimental penetration force values at 150 mm deep versus slippage and the proposed model. As can be seen, the semi-analytical model fits the experimental data very well. However this model is only applicable in low relative density regoliths and can not be used for high relative density regoliths since they do not compact under repeated shearing.

However, they do not explain the difference between the experiments in [11] (increase in penetration depth of more than 100 \% thanks to DRD under the same load as the static penetration reference) and the ones presented here (increase in penetration force with slippage). It is proposed that this discrepancy comes from the lateral movements that were present in experiments presented in [11] and are absent here because of the axial symmetry of the mono-block drill-head.

The following penetration mechanics are thus proposed. In low relative density regoliths, the reciprocation combined with lateral movements compact the regolith on the side of the DRD, thus lowering the penetration force required and enabling deeper penetration. For the mono-block drill-head the purely axial movement induces compaction in front of the drill-head thus increasing the penetration force. This is represented in Figure 10.

In high relative density regoliths, it is proposed that the lateral movements facilitate lateral and local shear. The local shear process is shown in Figure 11. The lateral movements push the regolith up and out of the borehole.
IV. NUMERICAL SIMULATIONS

To confirm this hypothesis, DRD was simulated using the Discrete Element Method (DEM). Due to the teeth like structure on the surface of the DRD head, it is necessary to adopt small enough particles so they are smaller than the teeth. This requires simulating over one million particles. Such simulations generally require large computer farms with parallel computing abilities.

IV.I GPU technology

To cope with such requirements, Graphical Processing Units (GPU) are now being used to propose massively parallel calculations on a single desk-top computer [14]. Impetus-AFEA, a commercial numerical simulation tool has implemented GPU compatible codes [15]. There code was modified to implement DEM solutions and was used for these simulations. It was thus possible to simulate DRD interacting with over one million particles on a desk-top computer.

IV.II Modelling choices

The DEM method as proposed by Cundall and Strack was used [16]. Only perfectly spherical particles were modelled. Particle radiiues range from a minimum radius \( R_{\text{min}} \) to twice this radius. The particles are modelled using the classical linear models: an elastic and a damping interaction in the normal and tangent direction (like in [17]). To give the particles the same behaviour as regolith, the Coulomb law is implemented. The tangent force is limited to \( \mu \) times the normal force with \( \mu \) the coefficient of friction. Additionally all forces are equal to zero when the particles are not penetrating one another.

IV.III Verification of performance on direct shear tests

To test the performance of the DEM method implemented in Impetus-AFEA, Direct Shear Tests (DST) reported in [18] were simulated. A direct shear tests consists in a rectangular box that is cut in half and filled with regolith. The lower part is moved and shears the regolith inside.

The regolith DEM particles were prepared at two different relative densities and sheared under three normal pressures. The results are presented in Figure 12. The DEM clearly reproduces numerous key behaviours of regolith. The final or critical state shear resistance does not depend on the initial density but only on the normal pressure. The critical shear resistance increases with normal pressure. Peak shear resistance is present in high relative density simulations and the higher the normal pressure the higher the peak is. Though the DEM interaction parameters were not optimized to perfectly fit the experimental DST, the behaviour obtained with the simulations is correct.

IV.IV DRD simulations

For the DRD simulation, the displacements of each individual DRD half or valve was imposed. To limit
Fig. 12: Results of DST simulations. The low relative density simulations are plotted with a line and circles, the high relative density simulations are plotted only with lines. The three different normal pressures are represented by the grey scale, the darker the line the higher the normal pressure.

absolute values of the forces can not be compared to the experimental values. However their ratios can be. Figure 13 presents the force applied to the DRD valves, the forces on one valve are in black and the forces on the other one are in grey.

The traction force to penetration force ratio obtained with the simulations is clearly too high compared to the experimental ratio. This is a clear limit of the simulation results presented here. However the traction force is still small when compared to the penetration force.

The lateral force obtained during the simulation is of the same order of magnitude than the simulated penetration force if not higher. This clearly confirms the ability of the DRD to generate important lateral forces. These important lateral forces will induce lateral displacements that are most probably key to understanding DRD performance and penetration in regoliths. This confirms the hypothesis proposed at the end of III: the non axi-symmetric nature of a DRD-half generates a lateral force.

IV V Penetration simulations

A simulation of the penetration experiments reported in this article (III) was also conducted using over one million particles. It was conducted to compare the regolith movements observed experimentally and the ones obtained with the simulation. Figure 14 presents the results of this simulation. The colour scale represents the vertical displacements of the particles, red represents a displacement equal to zero and the blue the highest downwards displacement. It is clear here that a depression is formed around the bore-hole. This was also observed experimentally. This allows to confirm the usefulness of the DEM technique to model DRD-regolith interaction.

V. CONCLUSIONS

In this paper, the novel method DRD (Dual Reciprocating Drilling) has been explored via simplified experiments and DEM numerical simulations. They have showed the importance of lateral movements and forces in the DRD penetration of regoliths that were not taken into account previously.

Indeed the experiments conducted on a full-mono-block drill-head reciprocating in regolith showed that the traction force generated by the receding DRD valve is one to two orders of magnitude lower than the force required to penetrate the regolith. DRD’s extra progression when compared to static penetration can thus not be explained by this traction force. Discrepancies between the experiments presented here
Numerical simulations using the DEM method were set up to show that the geometry of the DRD drill-head naturally induces lateral reaction forces to explain the lateral movements of the DRD drill-head. They were also used to demonstrate the effectiveness for this technology to reproduce regolith deformations during drilling. To do so a GPU compatible code (Impetus-AFEA) was used and allowed a simulation with more than one million particles on a single desktop computer.

For future Martian exploration, DRD designs will now take into account the importance of lateral movements in its progression in regolith. This should enable even higher performance. The use of DEM simulations with more than one million particles running on a desk-top computer will also enable an in depth understanding of the kinematics of regolith during the interaction of a robot and the Martian regolith. Wheel, drill, scope and instrument designs will greatly benefit from such simulations. For an in depth description of all the aspects presented in this paper, please refer to [18].

REFERENCES


