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SCIENTIFIC USE OF THE SAMPLER, DRILL AND DISTRIBUTION SUBSYSTEM (SD2)

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ABSTRACT

Rosetta is the third cornerstone mission of the European Space Agency scientific program "Horizon 2000". Rosetta will be the first spacecraft to orbit around a comet nucleus. It was launched in March 2004 and will reach the comet 67P/Churymov- Gerasimenko in 2014. A lander (Philae) will be released and land on the comet surface for in-situ investigation. One of the key subsystems of the lander Philae is the Sampler, Drill and Distribution (SD2) subsystem. SD2 provides in-situ operations devoted to soil drilling, samples collection, and their distribution to two evolved gas analyzers (COSAC and PTOLEMY) and one imaging instrument (ÇIVA). Recent studies have proven the existence of a correlation between the drill behavior during perforation and the mechanical characteristics of the cometary soil. This outlines the possibility of using SD2 not only as a tool to support other instruments, but also as a scientific instrument itself. In this paper the possibility of using the drill as a quasi-static penetrator is presented. Within this approach, laboratory tests on glass-foam specimens of different porosity show that the drill behavior during penetration can be exploited for cometary soil characterization.

Keywords: SD2, Rosetta Mission, cometary soil.

1 INTRODUCTION

Rosetta is the third cornerstone mission of the European Space Agency scientific program "Horizon 2000". Launched in March 2004, it will reach the comet 67P/Churymov-Gerasimenko in 2014 and will be the first spacecraft to orbit around a comet nucleus. The overall system consists of two elements (see Fig. 1):

- the orbiter, *Rosetta*: a quasi cube of 2.8x2.1x2.0m^3, on which all subsystems and payload equipment are mounted [7];
- a Lander, *Philae*: a pseudo hexagonal prism that will self-eject from Rosetta for a soft landing on the comet nucleus [1].

Rosetta is the first space mission to travel beyond the main asteroid belt relying solely on solar cells for power generation, rather than the traditional radioisotope thermal generators. The new solar-cell technology used on the orbiter two solar panels (32 m tip-to-tip in deployed configuration) allows it to survive over 800 million kilometers from the Sun, where solar radiation is only 4% of that on Earth. Tens of thousands of specially developed non-reflective silicon cells generate up to 8700 W in the inner Solar System and around 400 W during the deep-space hibernation phase (395 W at 5.25 AU [7]).

Figure 1: The orbiter Rosetta and the lander Philae (Credits: ESA).

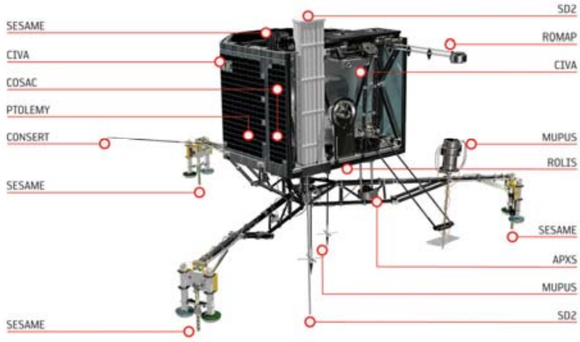

Figure 2: The Rosetta lander Philae (Credits: ESA).

Rosetta will reach 67P/Churyumov-Gerasimenko at about 450 millions kilometers from the Earth, after three Earth gravity assists (GA), one Mars GA and two asteroid fly-bys. During its rendezvous with 67P/Churyumov-Gerasimenko, Rosetta will enter its orbit around the comet and fly with the comet toward the inner solar system. This will enable a close study of the nucleus, as well as the investigation of its evolution throughout its approach to the Sun, by remote sensing techniques. The measurements will provide data to understand the nucleus internal structure, the nucleus nature and the mineralogical, chemical and isotopical composition.

After its arrival on the comet, the lander Philae (see Fig. 2) will perform the first soft landing on a comet nucleus to study in-situ the comet nucleus composition. The lander is provided with all subsystems needed to survive and work alone on the comet. Ten scientific instruments will perform their surface measurements after touch down. The mission goals include the determination of the elementary and mineralogical composition, the identification of traces elements, and isotopic composition of cometary material from the surface and subsurface.

Comet’s surface strength, density, texture, porosity, ice phases and thermal properties will also be investigated together with soil structure. To this aim, three scientific instruments will analyze comet’s samples:

- COSAC: one of the two evolved gas analyzers onboard Philae, designed to detect and identify complex organic molecules from their elemental and molecular composition;
- PTOLEMY: an evolved gas analyzer designed to perform accurate measurements of the isotopic ratios of light elements;
- ÇIVA: a visible light microscope coupled to an infrared spectrometer to provide data on the composition, texture and albedo of comet samples.

A crucial subsystem to ÇIVA, PTOLEMY, and COSAC activities is the sampling, drilling, and distribution (SD2) device. SD2 is devoted to support their activity by drilling into the cometary soil, collecting samples, and distributing them to the scientific instruments. The design and management of SD2 was committed to Politecnico di Milano and Galileo Avionica by the Italian Space Agency.

2 SD2 DESCRIPTION

The Sampler, Drill and Distribution subsystem is the multifunction device that provides in-situ operations in order to collect and distribute samples to ÇIVA, PTOLEMY, and COSAC.

SD2 is mounted on Philae's baseplate (see Fig. 3), and it is equipped with a drill able to collect several samples of 10-40 mm^3 at different depths (the maximum depth is 230 mm) from the same hole or different ones. It was designed to operate in critical thermo-vacuum environment and to meet the demanding mass/power resources limits of Rosetta mission. To this aim, innovative technological solutions were adopted during the design phase [5]: sampling tube for the drill/sampling operations, composite materials, dry lubrication, stepper motors, medium temperature ovens design.

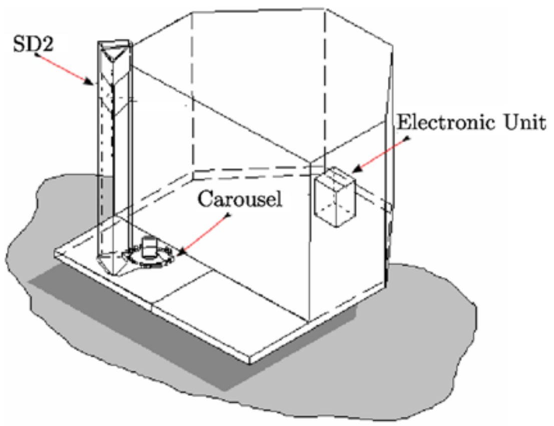

Figure 3: SD2 components distribution on Philae.

Parameters	Range
Soil compressive strength	50 Pa - 50 MPa
Temperature	-140 °C - +50 °C
Pressure	10^{-5} mbar - 1 bar

Table 1: Environmental parameters for SD2 design.

The driving environmental parameters for the subsystem design were comet soil strength, temperature and surface pressure (see Table 1). Parameters ranges, taken into account during the design phase, are wide in order to assure functioning in presence of high uncertainty.
SD2 has a total mass of 5100 g and is composed by a *mechanical* unit (3700 g), an *electronic* unit embedding SD2 software (1000 g), and the *harness* for electrical connection between the mechanical and electronic units (400 g).
The SD2 mechanical unit consists of the Tool Box, the Drill, and the Carousel:

- The Tool Box is built in carbon fiber and avoids drill damages due to vibrations and shocks during launch and landing phases.
- The Drill is made of aluminum alloy, and has a diameter of 12 mm and a maximum extension of 581.6 mm from the lander balcony; polycrystalline diamonds have been used to reinforce the drill bit for hard soil drilling; position, shape and geometry of the bits have been optimized by theoretical analysis, numerical simulations and experimental tests to maximize the cutting capability with a low vertical thrust (200 N) and a low power consumption. The power consumption during operations has a maximum average value of about 20 W. A sampling tube is embedded into the Drill bit and extracted to pick up the sample from the cometary soil. This solution was chosen for its simplicity and flexibility: the collection of the samples is performed by a pressure contact, as well as the release.
- The Carousel is a rotating platform on which some small containers, the ovens, are mounted. The material is picked up and discharged in the ovens. The Carousel task is to

position the oven and its sample under the scientific ports of ÇIVA, PTOLEMY, and COSAC. The ovens provide the interface between the collected sample and the scientific instrument. According to the scientists requests, two kinds of ovens are on-board: 10 medium temperature ovens with an optical sapphire prism, suited for the analysis by visible I/R microscopes, before heating up for medium temperature experiment (+180 °C), and 16 high temperature ovens suited for high temperature experiments (+800 °C).

The electronic unit is installed into the warm compartment of the lander and incorporates all electronics to control the mechanical unit. The hardware and software installed provide the interface between the mechanical unit and the lander control system, the Command Data and Management System (CDMS) [3]. SD2 is supplied by Philae's power subsystem with a 28 V line from the lander primary bus, devoted to the mechanical unit, and some auxiliary power lines (±5 V, ±12 V) from the lander secondary converters.

3 SD2 FACILITY AT POLITECNICO DI MILANO

A dedicated facility was designed and realized at Politecnico di Milano to test SD2 behavior and assess its performances in different realistic scenarios [6]. The operations that can be carried out at the SD2 facility are listed hereafter:

- mechanical verification of the drilling system; i.e., analysis of the drill structural behavior and assessment of the force and torque transmitted by the drill to the specimen;
- simulation of different comet-like soils and drilling scenarios;
- mechanical and functional verification of the sampling and collecting system;
- assessment of SD2 behavior during mission plan execution;
- identification of the optimal perforation strategies;
- design of the recovery procedures in case of SD2 non-nominal behavior;
- assessment of SD2 power consumption during drilling/sampling activities.

The design of the SD2 facility was accomplished to meet the requirements issuing from the previous tasks. The resulting facility is equipped with (see Fig. 4):

- the SD2 Flight Spare (FS) model, with grease lubrication replacing dry lubrication for operations in air;
- a support structure, designed for easy inspection and replicating the clamping system on the Flight Model (FM);
- an acquisition system used to acquire and process data during tests.

Figure 4: SD2 facility at Politecnico di Milano.

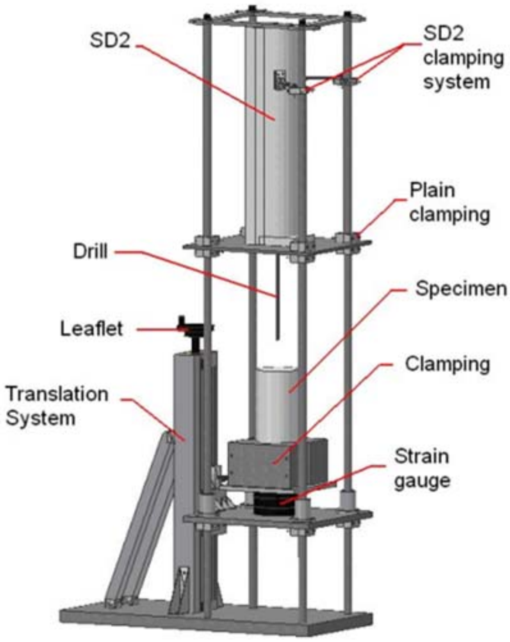

Figure 5: Support structure for the SD2 FS model.

The support structure is composed of (see Fig. 5):

- four tubular beams (2 m high and with a radius of 30 mm);
- three aluminum plates used as baseplate, SD2 FS and sensor system support;
- four beams clamped at the top of the structure to reduce vibrations or distortions during drilling phase.

The plates are clamped to the tubular beams to avoid SD2 FS movements. A translation system allows the sensor system and the specimen to translate to a known position. This decreases the problem of misalignment between the drill and the drilled surface.
The sensor system is composed by a biaxial strain gauge that measures the normal force and the torque applied to the specimen. The strain gauge has

- torque full scale of 25 Nm with a resolution of 0.01 Nm;
- vertical force full scale of 1000 N with a resolution of 1 N.

The strain gauge must measure load contributions given by the drill during perforation (maximum load of 200 N), the specimen, and the clamping system (220-500 N). The interface between the strain gauge and the structure is composed by eight screws, each of them tolerating a load range of 20-65 N. A current sensor is added to measure SD2 FS power consumption during operation.

4 SD2 SCIENTIFIC CONTRIBUTION

Recent investigation suggests the possibility of correlating the drill behavior during perforation with the mechanical properties of the cometary soil. This outlines the opportunity of using SD2 not only as a tool to support ÇIVA, PTOLEMY, and COSAC, but also as a scientific instrument itself. To this purpose, a correlation between SD2 telemetry data and the cometary soil characteristics must be identified [6].

The problem of using SD2 as a scientific instrument can be stated as follows

Control variables

- Translation torque level C_t in the range 1-7 (corresponding to a range of commanded current from 75 mA to 600 mA);
- Rotation torque level C_r in the range 1-7 (corresponding to a range of commanded current from 250 mA to 2000 mA);
- Translation velocity level V_t in the range 1-31 (corresponding to the translation velocity range 0.01-19.20 mm/min);
- Rotation velocity level V_r in the range 1-31 (corresponding to the rotation velocity range 5-135 rpm).

Constraints

- The available telemetry is limited to (i) the position of SD2 drill bit (SD2-DB) during the perforation (ii) flag for drill failure (the drill gets stuck), and (iii) SD2 power consumption.
- Drill rotation and translation is commanded with stepper motors: the variation of power consumption cannot be used as an indicator of a variation of the soil characteristics. In fact, a stepper motor works with a fixed current value for each imposed speed value (see [4] for more details).
- The available energy for the long-term science is very limited, thus the number of perforations needs to be minimized.

From the above-mentioned constraints, it is apparent that the working zone approach proposed in previous works [6] is not a viable option due to the large number of perforation required and consequently the high need of energy consumption. Consequently, an alternative strategy is needed.
In this work we propose the use of SD2 as a quasi-static penetrator in order to estimate the resistance of the soil to drill penetration. The strategy implies using only drill translation to a commanded depth for increasing values of C_t. The cometary soil penetration resistance can then be estimated by finding the minimum value of C_t for which the translation succeeds. The advantages of the proposed strategy with respect to the working zone approach are the following:

- As the drill rotation is not used, power and, consequently, energy consumptions are reduced;
- In the worst case the number of drill movements is limited to 7 (all the possible values of C_t), with a further reduction of energy consumption;
- There is no need to rotate the lander as drill movements are always performed in the same hole and always at the same depth;
- The strategy is independent from drill translation velocity; thus, energy consumption can be reduced by selecting high value of V_t;
- There is a direct relation between the strategy output and the soil mechanical properties.

On the other hand, the strategy shares the same risk of the working zone approaches, i.e. when SD2 translation fails, a large force (hundreds of Newton) can be exerted back to the lander, potentially causing the lift of the lander. In the following sections, all the laboratory tests carried out for the implementation of the proposed strategy are summarized.

4.1 Drill characterization

Drill translation is activated by a stepper motor selecting C_t in the range 1-7. The first step for elaborating the proposed strategy is to correlate the translation torque C_t to the forces applied to the soil. This is done by commanding different values of C_t and measuring the force applied on an iron specimen (iron is selected so that the drill gets stuck at the specimen surface). The achieved results are plotted in Fig. 6, where a linear fit of the data is used. (Note that laboratory tests are performed for C_t from 1 to 3 to avoid damaging SD2 motors and mechanisms; results for $C_t > 3$ are extrapolated). From this figure, the range of forces that the drill bit can transmit to the soil are estimated for each value of C_t. These are fundamental data needed for the proposed strategy.

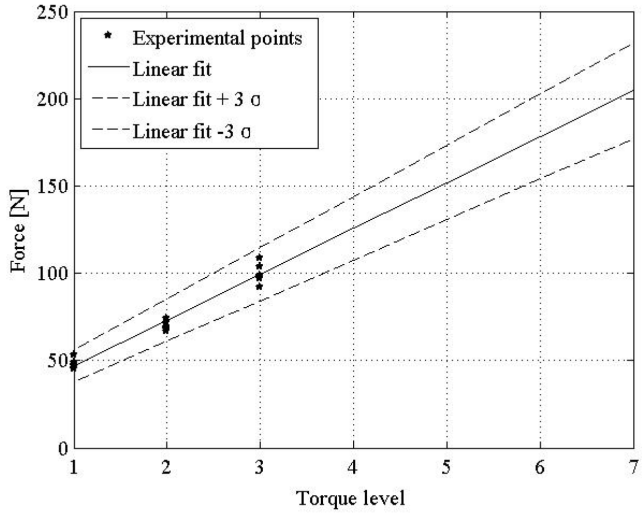

Figure 6: SD2 C_t vs applied force.

4.2 Cometary soil simulant: Foamglas

Foamglas is an industrially fabricated glass-foam normally used to protect buildings against moisture and to act as a thermal insulator. It exhibits several features that resemble some properties of what is generally believed to be ‘cometary crust’ material [2][9]: (i) low bulk density and high porosity, (ii) a compressive strength similar to those of icy sinter crusts observed in various comet simulation experiments [8] and [11], and (iii) it is brittle on a small scale and deforms by the crushing of cell walls rather than by large-scale plastic deformation — a property it may have in common with sintered ice-mineral mixtures at low temperatures. According to the data sheets, the density and the lower bound for the compressive strengths of these materials are reported in Table 2.

Foamglas type	Density [kg/m^2]	Compressive strength [MPa]
F+W	100	≥ 0.4
T4+	115	≥ 0.6
S3	130	≥ 0.9
F	165	≥ 1.6

Table 2: Foamglas material properties.

4.3 SD2 applied pressure

To better characterize Foamglas materials and to study the behavior of SD2 drill bit (SD2-DB) when penetrating specimens, laboratory tests are performed using the material-testing machine MTS Mini Bionix II, shown in Fig. 7.

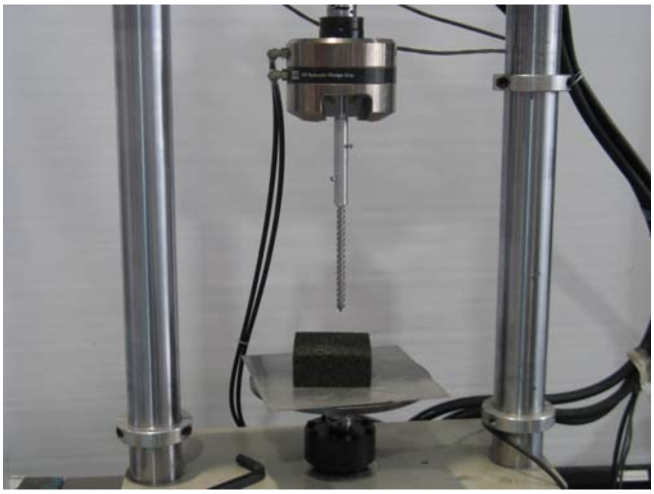

Figure 7: Material testing machine MTS Mini Bionix II.

Two testing tools are used for the tests:

- An exact copy of SD2-DB (shown in Fig. 7);
- The penetration testing tool (PTT) of Fig. 8, which has a disk-shaped bit (right-hand of the tool) with a diameter equal to that of SD2 drill bit (12 mm).

Figure 8: Penetration Testing Tool.

The tests performed in the laboratory consist of commanding a 30 mm penetration in the specimen (with translation velocity of 0.15 mm/s) and measuring the resistance force offered by the materials. Several tests are made for each material; the results (one for each material) are plotted in Figs. 9-12, where polynomial fits of the data are reported too. Note that the large fluctuations of forces are due to the fact that the tool advances by crushing the material cell walls.
The increasing force profile obtained with SD2-DB is mainly due to the increase of the penetration area with depth, whereas the profile obtained with the PTT shows the typical behavior of cellular materials (linear increase of force until crushing, plateau followed by an increase of force due to densification [10]). From the tests performed with the PTT, it is possible to estimate the average penetration resistance of the Foamglas materials, reported in Table 3.

Foamglas type	Average penetration resistance [MPa]
F+W	0.4132
T4+	1.1613
S3	1.8745
F	4.5208

Table 3: Foamglas material measured mean penetration resistance.

Once the average penetration resistance (PR) is computed for each material, it is possible to estimate the equivalent penetration diameter of SD2-DB, $d_{SD2\text{-}DB}$, as function of the penetration depth h using the formula

$$d_{SD2-DB}(h) = \sqrt{\frac{4\, F_{SD2-DB}\,(h)}{\pi PR}}$$

where $F_{SD2\text{-}DB}\,(h)$ is the force profile registered when using SD2-DB. The profiles of $d_{SD2\text{-}DB}$ for the different Foamglas types are reported in Fig. 13. It can be seen that the difference among the Foamglas specimen is limited (with the exception of T4+ material); this proves the validity of the presented approach. (Note that in an ideal case $d_{SD2\text{-}DB}$ should be independent from the tested material).

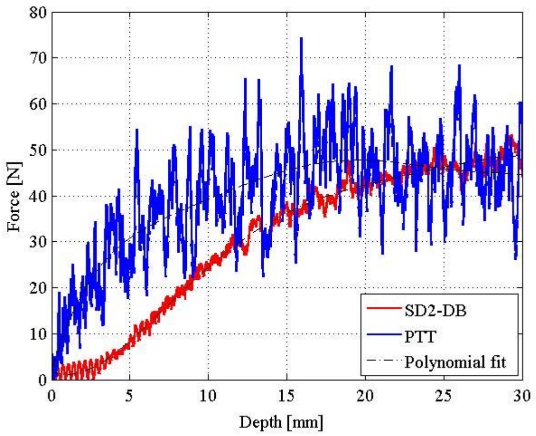

Figure 9: Force vs depth for Foamglas W+F.

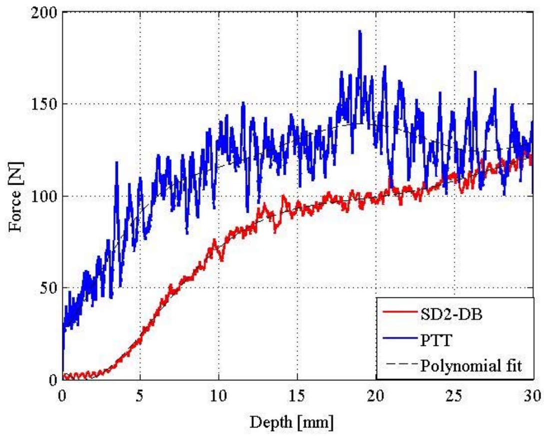

Figure 10: Force vs depth for Foamglas T4+.

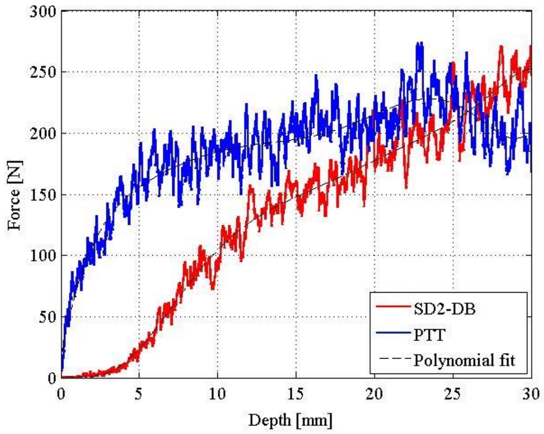

Figure 11: Force vs depth for Foamglas S3.

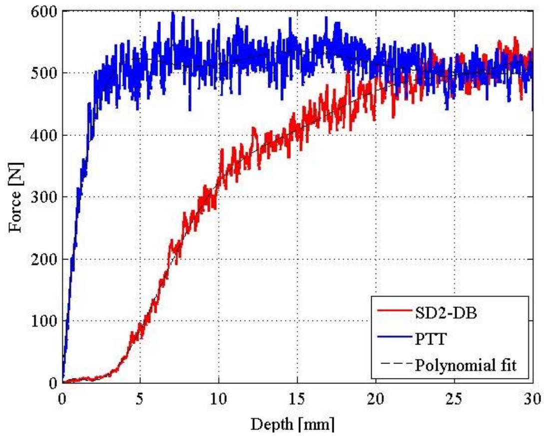

Figure 12: Force vs depth for Foamglas F.

The mean profile of $d_{SD2\text{-}DB}$ is then computed and a polynomial fit of the data is used (see Fig. 14) to find the depth at which $d_{SD2\text{-}DB}$ is equivalent to the drill diameter, i.e. the diameter of the PTT. This value, obtained by inverting the polynomial fit of $d_{SD2\text{-}DB}(h)$, is h^*= 27.86 mm (red dot in Fig. 14). In addition, it is then possible to compute $\sigma_{dSD2\text{-}DB\ (h^*)}$ by evaluating $d_{SD2\text{-}DB}(h^*)$ for each of the tested material.

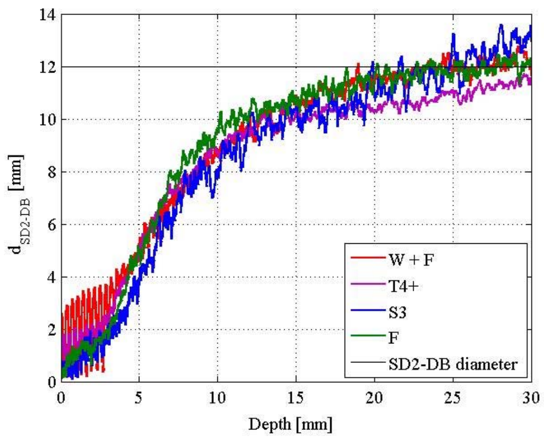

Figure 13: Equivalent drill bit diameter: laboratory tests.

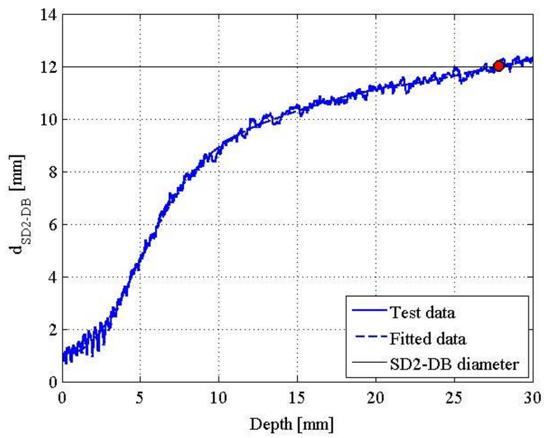

Figure 14: Determination of the h^*.

As the last step, the relation "C_t vs applied force" (Fig. 6) is translated into "C_t vs applied pressure" at the specific depth h^*, for which the value of $\sigma_{dSD2\text{-}DB\ (h^*)}$ is used to obtain upper and lower bounds of pressure. The achieved result is plotted in Fig. 15. This figure can be read in the following way: for any applied C_t, the range of the pressure exerted by SD2-DB when it reaches the commanded depth h^* can be estimated. Note that, as the equivalent diameter of the drill is lower when the depth is lower than h^*, the pressure applied by SD2 before reaching h^* is higher than the value plotted in figure. This means that if the drill is able to penetrate the cometary soil by a depth h^* (for a given value of C_t), then it can be assumed that the maximum penetration resistance of the soil is lower than the lower bound of the applied pressure for a specific C_t.

In Fig. 15, the maximum penetration resistances offered by Foamglas W+F and T4+ materials is plotted as well. (Note that these values are higher than those of Table 3, as the maximum values are plotted.) This allows to make the following prediction: to obtain a successful penetration of SD2, $C_t = 3$ is necessary for W+F material and $C_t = 7$ for T4+. In fact the lower bound of the pressure applied by the drill must be higher that the maximum resistance pressure of the soil.

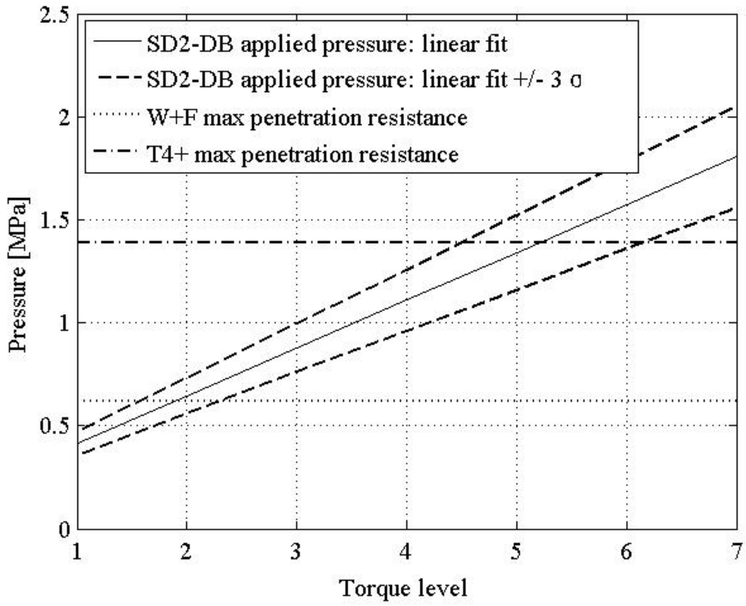

Figure 15: SD2 C_t vs applied force.

This conclusion is validated by performing SD2 pure translation tests on Foamglass specimens in the facility described in Section 3. The tests are run on each Foamglas specimen by:

1. commanding a penetration depth of h^*
2. progressively increasing C_t from 1 to 7
3. registering the minimum value of C_t for which the penetration is successful
4. comparing the corresponding lower bound of the SD2 applied pressure with the maximum resistance pressure offered by the specimen.

Laboratory tests confirm the results expected from Fig. 15, although in some cases SD2 penetrates in W+F material with $C_t = 6$. This result can be explained by the little difference between the lower bound of the pressure applied by SD2 at $C_t = 6$ and the maximum penetration resistance of the material. Furthermore, note that SD2 is not able to penetrate Foamglas S3 and F specimens with pure translation. This result is again expected, due to high penetration resistances of these materials.

4.4 SD2 scientific strategy

Based on the analyses illustrated in the former sections, the proposed strategy for the scientific use of SD2 in the long-term science can be summarized as:

1. Command a drill translation to penetrate into the cometary soil by $h^* = 27.82$ mm;
2. Start with $C_t = 1$ and increment progressively C_t until the commanded depth is reached;
3. Estimate the maximum soil penetration resistance through Table 4.

C_t	Estimated maximum penetration resistance [MPa]
1	<0.36
2	[0.36, 0.56]

3	[0.56, 0.76]
4	[0.76, 0.96]
5	[0.96, 1.16]
6	[1.16, 1.36]
7	[1.36, 1.56]
none	>1.56

Table 4: Range of soil penetration resistances that can be estimated using SD2 as quasi-static penetrator (data obtained from Fig. 15).

5 CONCLUDING REMARKS

A new strategy for the scientific use of SD2 has been presented. The strategy is based on the use of SD2 as a quasi-static penetrator. Laboratory tests using Foamglas materials as cometary soil simulants have shown that, with a limited amount of drill translations (maximum 7), it is possible to estimate the penetration resistance of the cometary soil within 8 ranges. The strategy avoids the large number of drill movements required by the working zone approach, enabling both a drastic reduction of energy consumption and a better correlation with soil mechanical properties. As a drawback, no distinctions between materials with penetration resistance either lower than 0.36 MPa or higher than 1.56 MPa can be made. Additional laboratory tests are planned to prove the effectiveness of the proposed approach on different cometary soil simulants.

6 ACKNOWLEDGEMENTS AND REFERENCES

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