USE OF HAMMERING TO DETERMINE COMETARY NUCLEUS MECHANICAL PROPERTIES

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Abstract

An original insertion device for the MUPUS–TP (thermal probe) experiment on board the Rosetta Lander *Philae* was designed to insert a 40 cm long penetrator into a cometary nucleus in almost gravity–free environment. The device uses a hammer, the energy of which can be chosen from four settings, and whose operation is controlled by the experiment's autonomous FORTH program. The hammering process is monitored by depth sensor measurements that provide useful information not only about the insertion progress, but also about material properties, in particular crushing strength and compression strength. As the crushing strength of the cometary surface layer is practically unknown (estimates vary from 0.01 MPa up to 10 MPa), the data to be obtained on the comet after landing will certainly narrow this range and may help in evaluating other physical properties, e.g. thermal conductivity. The tests of hammering that were performed showed very strong dependence of the insertion progress on material strength properties. The challenges encountered during tests were caused by the almost gravity–free environment (rebounds) and by uncertainties of the position reference to the Lander. Such inaccuracies may be caused by to the relatively weak coupling to the tubular boom manipulator to the penetrator. We summarize the results of the many test measurements performed during and after the development period of the MUPUS experiment in order to provide a useful data base that may serve both for the interpretation of the data expected from the measurements at the cometary surface and as input and control data for the development of more sophisticated numerical models.

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1 Introduction

Comets are among the most primitive bodies of the Solar System, in fact they are relics from its formation phase. The determination of the chemical composition of comets will throw light on physical conditions in which cometary nuclei arose. Physical investigation of a comet, on the other hand, can help in revealing the evolutionary changes of the nucleus from the moment of its birth. The Rosetta mission, on its way to the target comet Churyumov–Gerasimenko, is expected to be the next turning point (after the Deep Impact mission) of our knowledge about cometary matter. The mission is well–equipped, and several scientific instruments onboard *Philae* will make *in situ* complementary investigations.

One of the instruments called MUPUS (*MUlti PUrpose Sensor package*) is devoted to study thermal properties of the cometary surface and sub–surface layers down to almost 40 cm depth. In the MUPUS–TP (*Thermal Probe*) shown in Figure 1, frequently called the MUPUS penetrator, thermoelectric sensors and heaters are incorporated into a cylindrical hollow rod inserted by a hammering device.

Figure 1: The MUPUS penetrator in its stowed configuration, FS model.

Among the parameters measured are the thermal diffusivity, conductivity and temperature profile along the inserted probe (MUPUS proposal, 1995; Spohn and Seiferlin, 1999; Knollenberg et al., 2000; Ball et al., 2000; Kömle et al., 2002; Spohn et al., 2007).

Another realized task of MUPUS is the determination of the cometary nucleus' mechanical properties, especially its strength parameters. For that purpose, miniature piezoelectric shock accelerometers (ANC–M) are located inside each of the two anchoring harpoons of the Lander. The deceleration history of the anchoring projectile as it penetrates the cometary soil, immediately upon touchdown of the Lander, will be used to derive information on the strength of the sub–surface layers, down to the depth at which the anchor finally comes to rest (Kömle et al., 1997; Kargl et al., 2002). Data obtained by this impact penetration method will be interpreted with penetration models. It is worth remarking that data obtained from the anchor will also provide advance information about cometary nucleus mechanical properties. According to the current operation scenario, a few days after landing the MUPUS thermal probe will be inserted at a distance of about 1 m from the Lander balcony edge and 1.5 m away from the anchor. The penetrator will be driven by a mechanical insertion device based on hammering action (Grygorczuk et al., 2007). Basic measurement differences between use of the anchor and the penetrator are shown in Table 1.

Table 1: Basic measurement differences between the anchor and the penetrator

	Anchor	**Penetrator**
1. Principle of measurement and insertion idea	Real time deceleration measurement during penetration generated by a single shot	Measurement of penetration depth progress between strokes, and step by step insertion
2. Applied sensor	accelerometer	depth sensor
3. Depth range limits	Depends on soil strength and maximum depth limited by the cable length of 2.5 m	Depth of almost 40 cm limited by the penetrator rod length

To examine the possibility of mechanical measurements by the penetrator, we describe in the following sections:

- the principle of operation of the penetrator in the near-absence of gravity
- its design features
- the insertion process supported by a manipulator (deployment device) and a depth sensor measurement
- insertion tests

To determine mechanical properties of the cometary nucleus, and in particular its strength properties (crushing, compression, shear), one can try:

- to derive unknown values from the energy spent per unit volume penetrated during the hammering insertion;
- to estimate soil mechanical parameters by comparison of recorded insertion progress on the comet to progress in calibration materials;
- to build an analogue of the Churyumov–Gerasimenko surface according to the data received from scientific instruments onboard *Philae* (possible in 2014–2015) and carry out a comparison experiment with the flight spare model of the MUPUS penetrator. In case of good agreement with insertion progress data obtained at the comet surface, this would be a verification and confirmation test.

In this paper we describe only the second mentioned method. The first method of determining cometary nucleus mechanical properties will be developed in the near future and the third one may be realized (if someone finds it useful) after 2014. Calibration test results of the hammering insertion in known materials would create a valuable reference data base for understanding the mechanical properties of the cometary soil.

2 Principle of operation of the penetrator in low gravity conditions

Considering a self–driven penetrator working under micro–gravity conditions, it has to be taken into account that:

- it will be inserted in many cycles (tens to hundreds) with small portions of energy;
- during each single stroke, the force will act not only towards the ground (principle of conservation of momentum) but also in the opposite direction, i.e. trying to pull out the penetrator.

Under real insertion conditions the penetrator must be guided and supported through a manipulator (deployment system) from the Lander. Initiating insertion without such support is impossible. The operating principle of the penetrator, illustrated in Figure 3, employs three masses: the inserted rod, the hammer and the counter–mass. The counter–mass is coupled with the hammer and the rod with elastic suspensions. The counter–mass provides inertial support and its mass has to be several times larger than the mass of the hammer. The supporting joint from the Lander to the rod terminates with a bushing. That bushing is needed for gripping and linear guiding of the penetrator, and partially damps rebounds by friction.
The operational cycle of the penetrator consists of five phases (Figure 2).

- **Phase 1** — the hammer and the counter–mass are accelerated by a force generator (different solutions are feasible), the hammer towards the rod and the counter–mass backwards. Due to high mass asymmetry, much more energy is transferred to the hammer.

- **Phase 2** — the hammer hits the rod, transfers its energy and somewhat recoils. The countermass still moves backward.
- **Phase 3** — hitting of the rod provides an insertion progress.
- **Phase 4** — the counter–mass reaches the end of backward travel (zero momentum and energy). This configuration exerts a maximum pull out effect by the suspension spring 2. Retracting of the rod is braked by the anchoring properties of the tip equipped with two rows of sharp barbs, and friction resistance of the soil and guiding bushing.
- **Phase 5** — energy storage in the suspension spring 2 auses a reverse movement of the counter—mass towards the tip.

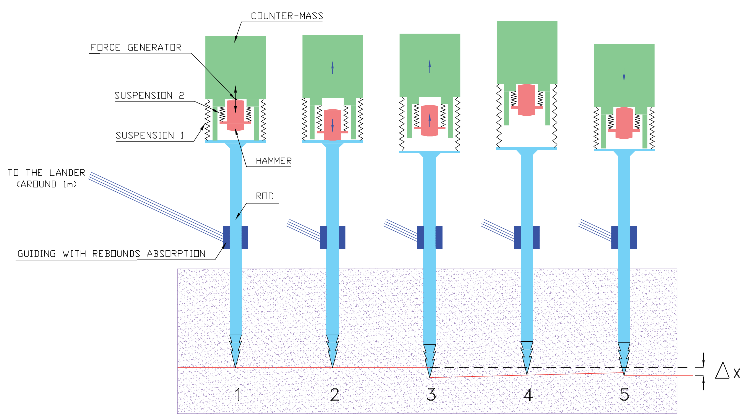

Figure 2: Five phases of the operational cycle of a self–driven penetrator.

3 Design features

The hammering device was designed as an alternative to a solid thruster (a preliminary concept for the MUPUS penetrator driving system), while observing the constraints of small size and weight. These are key limiting factors for the performance of a small hammer which has to insert a relatively thick (10 mm) nail. Another challenge was to achieve high reliability of the mechanism, comparable to that of a solid thruster. Such reliability can only be provided by a simple system. An important issue concerns executing of sufficiently energetic hammer strokes to penetrate even hard layers of the ground. To solve this problem one requires storage of energy, because the direct electrical power supply of 1.5 – 2 W is insufficient. Following this idea, a capacitor with an electromagnet engine was implemented. The discharge of the capacitor converts its energy through a coil to a magnetic field which forces the hammer to move inside the iron cylinder. This action will close the magnetic circuit. The pre–engineering model of the hammer, used for most of the insertion tests, is shown in Figure 3.

Figure 3: Hammering device (pre–engineering model).

The hammer control electronics board is placed in the housing above the hammering unit among the control boards for the thermal sensors. It contains a DC/DC converter that generates a voltage above 600 V, and the switching element is a thyristor. The hammering insertion is intended for flexible operation able to adapt to some extent to the ground penetration resistance. Therefore there are four power energy settings (PS1 to PS4) for the hammer, arranged in such a way that the capacitor is charged to one of four voltage levels: 180, 330, 460 and 620 V.

The efficiency of the hammer engine is not high, caused by, among other things, the reluctant electromagnetic circuitry (simple and reliable but not efficient). The numerical modeling of optimizing of the magnetic circuit (Demenko et al., 1997; Nowak, 1998) showed that no more than 25–28% of the capacitor energy can be converted to hammer kinetic energy. According to the performed measurements, the initial velocity (V_0) of the non–inserted penetrator rod is: 0.9 m/s for PS1, 1.9 m/s for PS2, 3.3 m/s for PS3 and 4.0 m/s for PS4. Finally the penetrator mass is 480 g, excluding external cables, and its functional three masses correspondingly are: rod (60 g), hammer (30 g), and counter–mass (390 g). Detailed information about the thermal behavior of the hammer can be found in Seweryn et al. (2005).

4 Insertion process and depth measurement

The MUPUS penetrator insertion process begins in the moment when the penetrator has been moved about 1 m away from the Lander and the tip has touched the ground. Such a configuration is provided by an operating scenario realized by the MUPUS manipulator (deployment device) mechanism. It is illustrated in Figure 4.

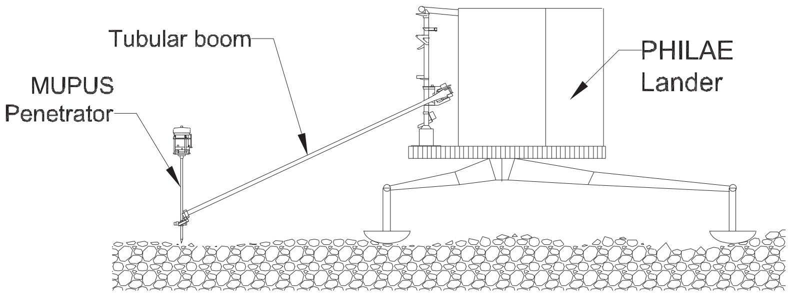

Figure 4: Position of the MUPUS Penetrator just before insertion.

The penetrator rod is held by friction in the grip of the depth sensor device. The grip contains a plastic (electrically isolating) bushing which provides linear guiding for the rod. The force needed to move the rod is about 1N. In addition a small electromagnet was implemented in order to allow release of the depth sensor grip. It is not active during hammering, only after each series of four strokes it is activated to allow relaxation of the tubular boom which connects the penetrator with the Lander. On the outer layer of the rod there is a slightly conductive (10 kΩ) polymer coating. Depth progress is measured just by readout of the change of the electric resistance between two contacts. One is placed in the depth sensor bushing and the second one on the rod attachment. During penetration the distance and the corresponding electric resistance decrease. The depth progress measurement idea is illustrated in Figure 5.

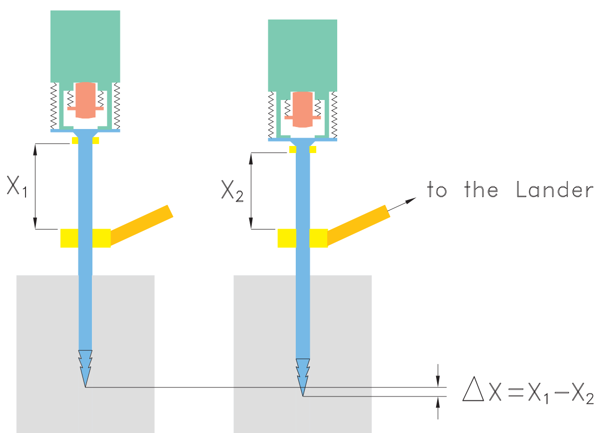

Figure 5: The depth progress measurement concept.

In the insertion process three stages having different influences on the measurement have to be distinguished:

- **Initial insertion phase**: This seems to be the most difficult part. Strong rebounds may appear because they are damped only by friction in the guiding bushing, and with the tip only partially inserted in the soil the probe tends to jump back rather than gain a hold. Thus the depth progress measurement is at this stage confusing and inaccurate. However, from one stroke to another the barbs of the anchoring tip gain better contact with the ground, causing the anchoring to be improved and recoils to be weaker. At a depth of about 30 mm the tip has disappeared in the soil and the initial insertion phase is completed.
- **Main insertion phase**: This stage covers the main part of the penetration and takes place under better defined and more stable conditions. Recoils are negligible and the depth sensor measurement is quite exact. The typical configuration for this stage is shown in Figure 6.
- **Final phase**: The third insertion stage follows at a depth of around 25 cm. According to the operating scenario, at this depth the MUPUS penetrator is mechanically disconnected from the Lander. The depth sensor is separated from the manipulator and the tubular booms are retracted to their stowed position on the Lander balcony. Therefore the position of the depth sensor with respect to the ground becomes undefined. It may move upwards by inertia during strokes and fall down during release of the bushing grip. Furthermore small forces exerted by external cables can affect its position. The configuration for this last insertion stage is shown in Figure 7.

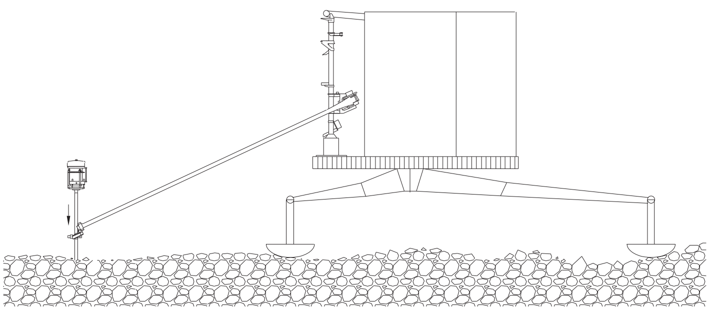

Figure 6: Configuration during the main penetration phase.

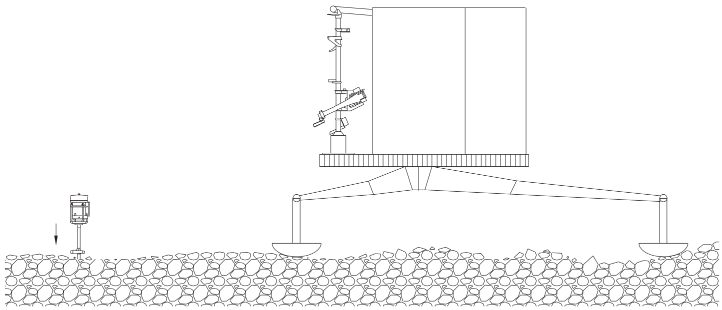

Figure 7: The last stage of insertion without mechanical coupling to the Lander.

5 Insertion tests

A number of insertion tests have been carried out with the MUPUS penetrator, which was improved from one development model to another. Many tests were performed with the aim to understand the performance of the penetrator in various test materials. A reasonable number of tests focused on determining the depth progress characteristics as a function of hammering energy (setting PS1 to PS4) and insertion depth in selected test materials. The most valuable tests for the future evaluation and interpretation of cometary soil mechanical properties are the those performed with a few well–defined, homogenous, analogue materials, which are thought to have some similarity with the expected cometary nucleus surface materials.

Extensive insertion tests were done in several laboratories: mainly at SRC–PAS in Warsaw, but also at Caltech in Pasadena, at the Technical University in Munich, and at IWF in Graz. For most of those tests, the pre–engineering model of the penetrator was used. This model represented very well the performance of the flight unit. The first series of insertion tests confirmed what had been previously expected, namely that the hammering device quite easily penetrates non–consolidated media like sand or snow and is effective for brittle and highly porous structures such as a foamed glass. In the case of high porosity samples, their structure is crushed by the hammer strokes and the crushed fragments (often in the form of rough powder) are collected in the pores. In consolidated structures with small porosity, e.g. ice/snow mixtures, porous ice hardened by sintering, or perlite–gypsum, the hammer energy is spent not only on crushing the medium but, first of all, on compressing the material ahead of the penetrator tip.

Penetration of compact materials like solid ice, is not possible. The same is true for elastic sponge and soft rubber materials. Those materials can be quite easy penetrated by static penetration forces, but a hammer stroke cannot do it because its energy is completely consumed by elastic rebounds. Fortunately, no one expects such cometary nucleus properties. The tests performed at Caltech confirmed the penetrator's ability to move through porous ice samples in a cold room environment. Those tests are fully described in a separate report (Killion et al., 1999). In Table 2 only three selected results are listed.

Table 2: Chosen results of tests performed at Caltech (1999).

Test No.	**Material**	**Temp. [K]**	**Porosity [%]**	**Strength [MPa]**	**No. of strokes**	**PS level**	**Distance moved [mm]**
1	Porous ice	210	33	2.0	152	4	95
2	Porous ice	205	33	4.2	156	4	75
3	Porous ice	105	34	3.8	56	4	20

From the tests described above it can be concluded that the hammer penetrates porous ices at temperatures as low as 105 K quite well. However, in this case it had to be switched to power setting 4 (the maximum one) and the depth progress was slower, some 0.35 – 0.62 mm per stroke. A similar test was performed later on for the MUPUS penetrator and the anchor of the Rosetta Lander *Philae* in a thermal vacuum chamber at the Technical University in Munich. Both insertion tests were similarly successful. Calibration tests were carried out with a special set–up (Figure 8), in order to simulate the absence of gravity in the driving direction. The penetrator was suspended horizontally on long (around 1.5 m) threads that almost entirely eliminated the influence of the gravity force.

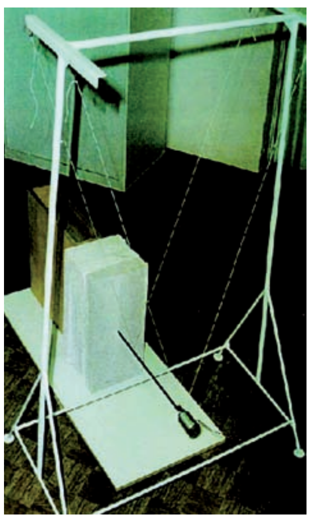

Figure 8: Special calibration set-up.

Looking for room temperature analogues of icy sinter crusts obtained in comet simulation experiments (Kochan et al., 1989; Thomas, 1992), N. Kömle (IWF Graz) identified industrially fabricated foamed glass blocks, Foamglas types T4 and F. They are brittle and have low bulk density and high porosity. They are homogenous enough to be used as calibration material. The SRC Warsaw also found another material with very similar structure, but somewhat harder, which was suitable for testing as well. In Table 3 the basic mechanical parameters of those three calibration materials, taken as nominal from the data sheet (Foamglas T4 and F) or being measured (SRC foam block) are listed.

Table 3: Calibration materials properties.

Property material	**Foamglas T4**	**Foamglas F**	**SRC foam block**
Bulk density (kg m^{-3})	120	165	285
Porosity (%)	95	93	High (around 87)
Crushing strength (MPa)	0.85	1.7	(5-6)

The measured insertion depth during these tests was in the range from 3 to 25 cm, corresponding to the stable conditions with support from the Lander. The depth progress in the high porosity, foamed materials was not strongly dependent on the insertion depth. This is a consequence of the chosen hammering method, which crushes the brittle material in a cross–sectional area a little larger than that of the penetrator rod itself. This allow the rod to be never in a very close contact with the surrounding sample material, except in the vicinity of the tip. Therefore wall friction does not significantly increase with depth. A more serious obstruction of the penetration with increasing depth is related to the crushed material. Although in high porosity samples most of the debris goes into pores, some of it remains around the cone and the barbs of the tip. In this region the material becomes more and more compressed, as the penetrator moves deeper into the sample. This gives rise to higher dissipation of the stroke energy. Overall, the tests showed that typical depth progress values between 15 and 20 cm depth were around 20% lower than those in the depth range 5 – 10 cm.

During calibration tests each material was penetrated with an appropriate energy setting matched to a depth progress between 2 and 8 mm after each four strokes, the same value which is planned to be used for the power setting control on the comet. The results of the recorded insertion depth progress on depth of 5 – 10 cm range are shown in Table 4.

Table 4: Depth progress values (mm) after a series of 4 strokes.

Foamed material	**Crushing strength [MPa]**	**Power setting / progress [mm]**			
		PS1	PS2	PS3	PS4
SRC block	5	-	-	-	2.0
Foamglas F	1.7	-	2.0	3.8	4.8
Foamglas T4	0.85	2.0	4.2	8.0	-

The obtained results showed very strong dependence of the measured depth progress on the crushing strength of the tested material. Additional tests using materials with similar structure, but different crushing strength, would be useful. Especially important would be to search for softer samples, since the measurement range is estimated from 0.05 to 5 MPa. The lower limit is related to the depth progress produced by a single stroke on the PS1, which might be close to 10 mm (corresponds to 40 mm for 4 strokes).

Another calibration test carried out at IWF Graz (in 2006) on Foamglas–T4 and Foamglas–F confirmed that the calibration results for Foamglas–T4 are very comparable (practically the same) with the values measured at SRC Warsaw a few years ago. On the other hand, unexpectedly, smaller depth progress was recorded while the Foamglas–F was penetrated. A probable interpretation of this result is that this sample of the Foamglas–F was stronger than the SRC ones (by the way received due to courtesy of the IWF). More investigation showed that the bulk density of that stronger Foamglas–F is 178 kg/m^3 instead of the nominal 165 kg/m^3 value, and that a quasi–static penetration resistance for that material varied from 3 to 4.5 MPa (Kömle et al., 2001). In a brittle, highly porous material, the crushing strength should be only a little lower than the quasi–static penetration resistance values. The bulk density of the SRC Foamglas–F sample is 171 kg/m^3. In Table 5 the data related to depth progress in both materials are shown.

Table 5: Comparison of the insertion progress values for two different samples of the Foamglas-F, after a series of 4 strokes.

Foamed material (bulk density)	**Crushing strength (MPa) Nominal (true)**	**Power setting / progress [mm]**			
		PS1	PS2	PS3	PS4
IWF Foamglas F (178 kg/m^3)	1.7 (3.5-4.0)	-	-	2.0	2.6
SRC Foamglas F (171 kg/m^3)	1.7 (2.0)	-	2.0	3.8	4.8

Perhaps the higher strength of the IWF Foamglas–F is a consequence of a heavier, more tough structure than the tested SRC samples. It is also obvious that the hammering method perception clearly revealed this difference.

6 Interpretation of the expected cometary surface data

Bearing in mind which mechanical properties of the soil might be determined by the MUPUS penetrator during its driving into the cometary nucleus, first of all it has to be stated that throughout insertion a soil penetration resistance occurs. This is not a simple duplication of the quasi–static penetration resistance. The basic difference is that the penetrator is driven dynamically by strokes delivered in small portions of energy 0.03 – 0.5 J during each hammering cycle. Also a different interval of 1–10 s appears between the strokes, depending on the energy setting. Finally, the tip is not a simple cone, but rather a tip of complicated shape, with barbs designed for acting as an anchor. Moreover, the diameter of the rod is 10 mm (rather thin in comparison with other penetrators). Taking all that into account it should be noticed that the MUPUS–PEN measures soil penetration resistance in a unique way. Already a qualitative analysis of the cometary data taken from the penetration characteristics may provide answers on:

- whether there are harder and softer layers in certain depth ranges, or if the cometary nucleus near the surface is rather uniform;

- what is approximately the mechanical crushing strength of the surface material;
- whether or not other penetrators with a certain diameter and power, just studied or developed for use in a planetary environment, could be successfully inserted.

For a more precise determination of the soil mechanical properties from *in situ* penetration data hopefully obtained after the comet landing in 2014, it will be essential to have the following support:

- comparison with the acceleration data from two anchor shots and their interpretation;
- extracting from the other *Philae* experiments all available data related to density, temperature, thermal conductivity, diffusivity, etc., which would supply valuable information on the cometary nucleus density, temperature, porosity, grain size, etc. Fortunately, some of those parameters will be in addition measured as a function of the depth;
- developing a new penetration model taking into account a specific insertion by hammering;
- to build and test (after 2014) an analog of the Churyumov–Gerasimenko soil for verification purposes.

Finally we discuss an example which show that the interpretation of penetration resistance in terms of material strength is not as straightforward as one might think at first glance. Among different tests which have been performed with the hammer, we have tested as well insertion into dry and wet sand. The grain size was 0.3 – 0.8 mm. The obtained penetration results for the completely wet sand showed, that the single depth progress per single stroke (taken as average after each 10 strokes was: 1.0 mm on the PS2 and 2.0 mm on the PS3, with very little dispersion within the measured depth range 7 – 17 cm. Comparing the depth progress obtained for the wet sand with the values given in Table 4 for Foamglas–T4, there are 4 mm on the PS2 and 8 mm on the PS3 (i.e. 1 mm/stroke on PS2 and 2 mm/stroke on PS3). This shows that that the penetration resistance is the same for these two very unlike materials, namely the wet sand and the Foamglas–T4. The wet sand is still a loose material with only some adhesion between particles due to the surface tension of the added water, while the Foamglas–T4 has a brittle (but consolidated cells) structure and is a lightweight, highly porous material. The density of the sand is 14 times higher than the bulk density of the foam.

The above example testifies that penetration resistance is not a unique measure for the “strength” of a material. In the case of the glass foam the resistance is caused by cohesive forces between individual solid structures inside the medium, while in the wet sand medium it reflects the work to be done by the re–arrangement of individual dense sand grains. In this case the resistance force is caused by the overburden pressure of the sand grains and by the internal friction among the sand grains when they are pushed aside by the penetrator. Fortunately for a comet a good number of material properties combinations can be ruled out by our general knowledge, the data received from the other instruments, additional tests, simulations and modelling. Taking this into account we may still expect that the penetration test will supply reliable information on the strength properties of the soil on the comet's surface.

7 Summary and conclusions

Technically, the MUPUS penetrator was developed for insertion of a rod with thermal sensors into a cometary nucleus. The process of hammering penetration is monitored by a depth sensor. This information, in combination with known technical data, can be used to extract information on the mechanical resistance of the penetrated layers as a function of depth, because both the geometry of the tip and the energy spent per hammer stroke are known parameters. The penetration will evidently supply data about the nucleus layering and its strength. This is by itself a practically useful information for engineering purposes. Deriving the particular mechanical properties of the soil from their penetration resistance demands additional data from other *in situ* experiments as well as more advanced theoretical modelling and further calibration tests in well–known materials. Nevertheless the laboratory calibration tests carried out till now proved the usefulness of the MUPUS penetrator for determining material strength parameters. Furthermore the insertion data may also help in evaluating other physical properties linked to material strength and texture, e.g., thermal conductivity.

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