Meteoritics & Planetary Science 43, Nr 6, 1021–1032 (2008)
Abstract available online at http://meteoritics.org

A review of penetrometers for subsurface access on comets and asteroids

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(Received 01 March 2007; revision accepted 21 November 2007)

Abstract–The characterization of comet and asteroid interiors will eventually require in situ exploration with drills, penetrators/penetrometers, hypervelocity impactors, excavators or other devices. Because they offer desirable scientific capabilities and relative mechanical simplicity, penetrators and penetrometers, which use only axial force to push beneath the surface, are a good choice for near-term missions. Penetrometers are instruments, generally deployed from a larger vehicle, that measure subsurface mechanical properties and may also contain additional scientific instruments. There are three basic types: "fast" penetrometers are released from above and plunge into the surface. Static and dynamic (collectively referred to as "slow") penetrometers use, respectively, a constant slow penetration speed and periodic hammering impulses. The low gravity environment of asteroids and comets presents a key challenge to instrument deployment and also greatly affects the mechanical properties of surface materials, and in turn penetrometer performance. The Rosetta mission, currently en route to comet 67P/Churyumov-Gerasimenko, will be the next mission to try both fast and slow, dynamic penetrometry, when it arrives in 2014. We present some new concepts of static penetrometers for small body exploration that are adapted to the low gravity environment. The low gravity environment also presents challenges for the testing of penetrometers on Earth and a number of previous solutions are described and new methods suggested. In the next generation of missions to study comets and asteroids, penetrometers could provide important data on their mechanical, seismic, thermal, electromagnetic, and chemical characteristics, as well as sample collection.

INTRODUCTION

Following several centuries of Earth-based study, a handful of spacecraft have had close encounters with asteroids and comets during the past two decades. Such "introductory" missions have vastly increased our knowledge of these small planetary bodies and, at the same time, challenged our notions of them. The opportunity for more capable missions to comets and asteroids in the coming decades places their present study in a similar situation as was the study of Mars four decades ago: in a transition from Earth-based study to in situ examination. With carefully designed missions, the extant physical models of small bodies can be supplemented with higher quality data that will lead to a much greater fundamental understanding of their geophysical makeup. Such models will contribute to knowledge of solar system evolution, make contributions to fundamental solid mechanics, and also play an essential role in the study of impact hazard mitigation.

As has been pointed out in more than one paper, an important next step in their exploration is to examine the geophysics of comets and asteroids directly (Schwehm and Schulz 1999; Asphaug et al. 2002; Binzel et al. 2003). Such reconnaissance of the interiors of these small bodies will eventually require the delivery of scientific instruments and other hardware below the surface. The scientific benefits of doing so might include seismic and ground penetrating radar (GPR) measurements, characterization of mechanical, chemical, electromagnetic or mineralogical properties of the subsurface, thermal analysis, emplacement of locator beacons, and sample collection. There are also engineering benefits from knowing the soil shear strength, bearing strength, and cohesion. The knowledge of these properties would aid in predicting rover trafficability, lander anchoring forces, and, in the more distant future, prospecting for subsurface resources (the so called in-situ resource utilization or ISRU). As with the exploration of other planetary bodies such as Mars, the Moon, and Europa, probing the interior lies

Table 1. Categories of subsurface access technologies.

Method	Description
Drill	Applies torque and axial force to break the formation and also to remove cuttings from the hole.
Penetrator/penetrometer	Applies axial force to compress and displace the formation and create a hole.
Hypervelocity Impactor	Strikes the surface with high velocity and excavates a crater; impactor is destroyed by the collision.
Excavator	Scoops or digs into subsurface

at the high cost and high risk end of the technological spectrum. Therefore, it will only be attempted when it is seen to be absolutely necessary for further scientific advancement and when the technical means of reaching below the surface are within the cost and risk constraints of particular missions. For these endeavors technology development is needed for both the devices that will reach below the surface of comets and asteroids, and the instruments that will be carried inside them.

The possible methods of delivering hardware to the subsurface of a comet or asteroid can be loosely divided into the following categories (described in Table 1): drills, penetrators/penetrometers, hypervelocity impactors, and excavating machines.

Each category has its own inherent merits and disadvantages and all may eventually find use in the subsurface exploration of asteroids and comets. For the near-term, however, penetrators and penetrometers, being generally simpler than drills and excavating machines, yet able to enter the subsurface without the destruction imposed by the even simpler hypervelocity impactors, may represent the most viable technology; this is particularly the case for those bodies with granular or icy surfaces.

PENETRATORS VERSUS PENETROMETERS

The two terms, penetrator and penetrometer, can be easily confused. Penetrometry is the measurement of properties of solid material by means of penetrating probes. Measured properties are usually mechanical (via measurements of force, deceleration, penetration rate, etc.) but can also be other physical properties or composition. Therefore, penetrometers are instruments that constitute sensing payloads supported through a parent platform, while penetrators are vehicles or platforms in their own right, delivering payload to a sub-surface and providing support (power, communications, etc.) to that payload (These definitions, as well as a review of penetrometers and penetrators for space exploration can be found in Ball and Lorenz [2001]). Thus, it is possible for a penetrator, if equipped with certain sensors, to be a penetrometer. Aside from this configuration, penetrometers are generally instruments that are deployed from, and relay their data back to, a host spacecraft. This paper is principally concerned with penetrometers, but many of the concepts herein could also apply to large payload delivery penetrators.

This paper will focus on the various types of penetrometers that might be used on small solar system bodies to fulfill important scientific or engineering functions. It is intended as an introduction for those in the scientific community who are not familiar with these devices. It is only by understanding their functionality that compatible scientific instruments can be designed to travel with them. In addition to the engineering aspects of these technologies, the potential scientific uses of penetrators and penetrometers are also discussed.

To be used successfully on a comet or asteroid, any method will have to operate under conditions of very weak gravity and, in the near term, with a high uncertainty about the mechanical properties of the subsurface. This paper will also delve into those challenges, as well as the task of testing penetrating technologies during their pre-flight development.

From the point of view of spacecraft operations, penetrating below the surface of an asteroid or comet has much in common with the task of landing on the body. It is important to note that, as of this writing, there have been only four attempts to land on a small body: the landers of the Soviet Phobos project, the parent spacecraft of which were lost before deployment of the stationary landers and "hopper"; the successful landing of the NEAR-Shoemaker orbiter on asteroid Eros (Veverka et al. 2001); the brief touchdowns of Hayabusa (Yano et al. 2006), and the failed attempt of the MINERVA robot as part of the Hayabusa mission (Normile 2005; Asphaug 2006). A third mission that also deserves mention in this context is Deep Impact, which did not attempt to land but did deliver hardware into the subsurface of a comet by hypervelocity impact (A'Hearn 2005; Mastrodemos 2005). Finally Philae, the Rosetta mission lander, which will rendezvous with 67P/Churyumov-Gerasimenko in 2014, has two instruments that are designed to penetrate into, and deliver scientific sensors to, the subsurface; if successful, the mission will be the first test of non-destructive penetrating technologies on a small body (Biele 2002).

Penetrometers typically have a long aspect ratio and a pointed end, and they enter the subsurface with a purely axial force, making a hole not significantly larger than the diameter of the penetrometer (A hypervelocity impactor, on the other hand, makes a much wider crater and the impactor is destroyed during the impact).

The downward axial force exerted by a penetrometer (which may be generated by a reaction force from the host spacecraft or by deceleration of the device) is countered by two reaction forces from the subsurface: the base resistance, which pushes against the tip, and the skin friction, which acts on the lateral surface (see Fig. 1). The Second Workshop on

Penetrometry in the Solar System (Kargl et al. 2008) divides penetrometers into the categories of "fast" (also called kinetic or impact penetrometers and "slow." Fast penetrometers are released from above the surface and strike it with enough kinetic energy to pierce into the subsurface, coming to a stop after a very short time period (<<1 s). Slow penetrometers are deployed from the surface and penetrate beneath the ground via the application of a downward force provided by some force generating mechanism, taking seconds to hours to complete their penetration. Slow penetrometers can be further subdivided into two groups that have been delineated by geotechnical engineers: (quasi-)static penetrometers, which produce a steady penetration force, and dynamic penetrometers, which apply a periodic impact (i.e., hammering) force.

CHALLENGES OF THE LOW GRAVITY ENVIRONMENT

In applications for planetary exploration, what fast and slow penetrometers have in common is that they both involve orienting with the surface of, and landing on, their target body. In the very low gravity environment of comets and asteroids, this presents particular challenges. Depending on its mass and size, the gravity field on an asteroid or comet can vary from 0.03 g (1 g being Earth's gravitational acceleration of 9.8 m s^{-2}) for Ceres, the largest main belt asteroid[1], to 10^{-3} g for a medium sized (40 km) asteroid (Britt et al. 2002), to as little as 10^{-5} g for an asteroid that is only hundreds of meters in diameter (Asphaug 2006).

The strength of the gravity field has important implications for navigation and orientation with respect to the small body. For a fast penetrometer, released from some distance above the surface, a weak gravity field will not provide much downward acceleration. The lack of an atmosphere and the negligible gravity-gradient torques also make it difficult to stabilize the orientation of the penetrometer with respect to the surface. These two factors would necessitate an acceleration mechanism and a dedicated attitude control system. Not all the effects of a weak gravity field are negative; as exemplified by the experience of the NEAR mission (Veverka et al. 2001), low gravity can be very conducive to soft landings, because little fuel is consumed in decelerating and because the danger of excessive impact overloads on landing is reduced. Once landed on the surface, however, very low gravity makes deployment of any mechanisms very difficult, because even small downward forces can cause an opposite reaction force on the mass, even to the point of exceeding the body's escape velocity, which can be as low as a few cm s^{-1} (Asphaug 2006). Therefore, the penetrometer, at least initially, must be deployed from an anchored platform. Finally, in the more distant future, if penetrometers become capable of traveling deep into the interior, the low gravity will make it very difficult to sense which way is "down," thus making subterranean navigation very challenging.

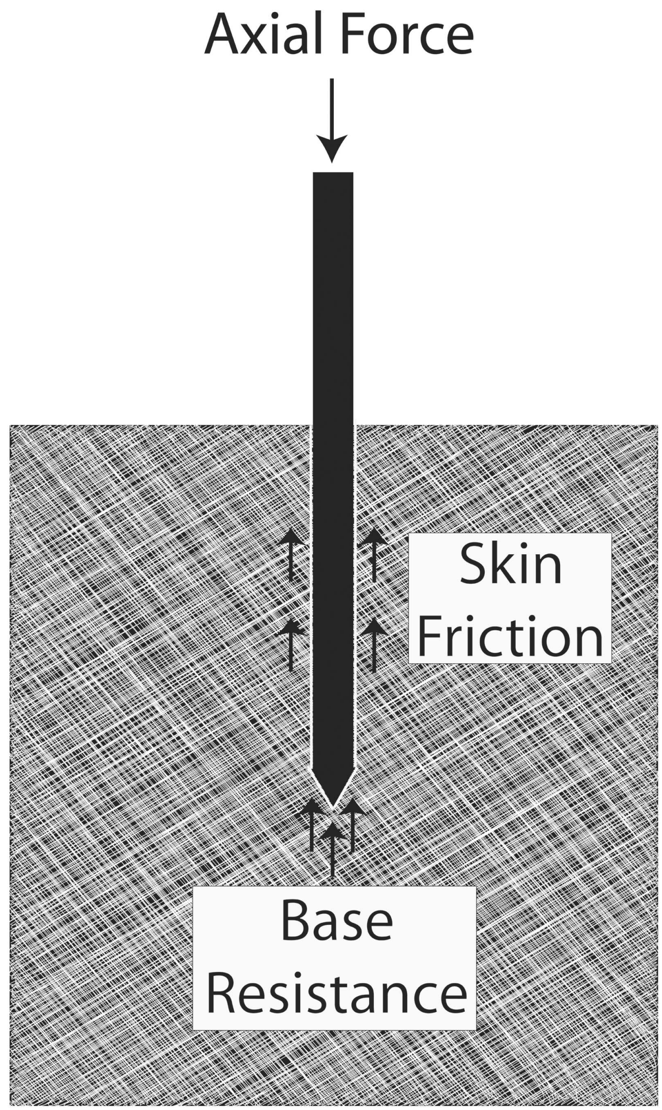

Fig. 1. Forces experienced by a penetrometer.

The gravity field will also affect the mechanical properties of the subsurface. In the case of weak, non-cohesive regoliths, such as may be found on an asteroid, pile driving theory states that base resistance and skin friction are approximately proportional to the overburden pressure, and thus to gravity (Richter 2002). If such materials dominate the near-surface of small bodies, the force required to penetrate, even to very great depths, into the subsurface of a small "rubble pile" asteroid could be quite small when compared to Mars or the Moon. In the case of comets, some evidence from the Deep Impact mission, which indicate extremely soft material on comet Tempel 1 (Kerr 2005) also suggest that penetration to great depths may be possible.

[1]Calculated based on published values for Ceres' mass (8.7×10^{20} kg) and diameter (945 km) (NASA 2004).

UNCERTAINTY OF SUBSURFACE MECHANICAL PROPERTIES

Much of the risk associated with the deployment of any penetrometer comes from the lack of knowledge about the surface properties of target bodies. Great effort has been made to model the interiors of comets and asteroids, but such models can only constrain surface properties to a limited extent, and in some cases they may turn out to be quite inaccurate. Particularly for a first reconnaissance mission, any penetrometer must be designed to function within the best available constraints. As will be described below, some types of penetrometers are more suitable for poorly constrained material properties, while others can provide higher resolution data if the surface properties are somewhat known beforehand.

FAST PENETROMETERS

Released from some distance above the surface, fast penetrometers plunge into the surface via their high kinetic energy and relay scientific data to their host vehicle, an orbiting or hovering spacecraft. They may also be used for sample collection. With some of the larger asteroids, the gravity may be strong enough such that they can be released from an altitude of tens of kilometers and achieve enough speed for proper penetration (60–300 m s^{-1}) (Lorenz and Ball 2001). However, in the majority of missions to asteroids or comets, the gravity will not be sufficient for a free fall release. Possible methods of accelerating small projectiles include compressed gas, explosive charges, spring releases, and passive ballistic trajectories inherited from a host craft. Another technological issue is the need for all instruments and electronics inside the penetrometer to survive the high g decelerations upon impact. Significant progress has been made in this area and it does not appear to be an insurmountable problem (Reynolds et al. 1998; Faber et al. 2005).

In addition to achieving a high enough speed, fast penetrometers may be required to impact at a targeted location, and, for optimum performance, must also impact at an angle as close to 90° as possible with respect to the local surface. The further from the surface the projectile is released, the more difficult these last two requirements become, with the possible need for a guidance system. Thus, there is a trade-off between simple fast penetrometers that must be released from closer range (adding risk and expense to orbital/hovering operations) and more complex instruments that cost more and have more risk, but relieve orbital operations.

No such penetrometers have yet been developed to a high Technology Readiness Level (TRL) for small bodies, but the Lunar-A penetrators and the anchors on the Philae, the Rosetta cometary lander have much in common with them. Primarily designed for an engineering task, the anchor design is a barbed, fluked harpoon that will be shot into the surface from very close range, with pyrotechnically generated, compressed gas. The harpoon will achieve a velocity of 60 m s^{-1} and, depending on the nature of the cometary material, is expected to penetrate anywhere from several cm to 2.5 m into the ground (Kömle et al. 2001).

The use of explosive charges to accelerate a kinetic penetrator has also been suggested and has actually been used for testing prototype lunar penetrators (Faber et al. 2005). One innovative concept would use a small explosive charge to deploy, and then retrieve, a small penetrometer/sample collector. A single charge would simultaneously drive the penetrometer into the surface, while a second mass, tethered to the first, is accelerated in the opposite direction. After the penetrometer comes to a stop, the upward-traveling mass reaches the end of its tether and yanks the penetrometer out of the ground. The two masses can be retrieved via a second tether connected to the host spacecraft. Finally, another type of fast penetrometer makes use of the kinetic energy of a landing spacecraft. The lunar Surveyor missions had strain gages integrated into the landing legs and collected data upon landing (Ball and Lorenz 2001), and the Huygens probe had a small, centrally located penetrometer that was used to ascertain some of the mechanical properties of Titan's surface (Lorenz et al. 1994; Zarnecki et al. 2005).

Fast penetrometers may have a bright future in the "budget conscious" exploration of comets and asteroids. Equipped with miniature, low-cost electronic sensors to measure acceleration, seismic waves, or temperature, an individual spacecraft could be outfitted with multiple penetrometers, each released to a different chosen location. The burden of cost and risk here is shifted away from the penetrometers themselves, to the operation of guiding and orienting the host spacecraft close enough to the landing target before releasing each penetrometer. This is not a trivial exercise, as demonstrated by the failure of the Hayabusa spacecraft to release the MINERVA hopping robot onto the correct trajectory (Normile 2005).

SLOW PENETROMETERS

Slow penetrometers are deployed from the surface and thus must generate enough pushing force to penetrate. The difficulty of this task inherently limits the size, particularly the diameter, of the device, and thus the complexity of the science payload that it can hold.

Static Penetrometers

Static penetrometers typically use some type of linear actuator to extend the penetrometer into the ground. This means that the anchoring force of the device must be larger than the combined actions of the base resistance and the skin friction. In terrestrial applications this is accomplished by deploying the static penetrometer from a very heavy platform

(There are also manual static penetrometers in which the weight of a single person suffices as a reaction force for soft soils). The low gravity present on small bodies, as well as the high cost per mass of delivering hardware to them, makes this method impractical. An alternative method, which removes the need for a heavy, anchored platform, would be the use of an upward facing rocket booster to provide a downward static force; this method was used by the Soviet Luna 13 mission to penetrate 45 mm into the lunar regolith (Ball and Lorenz 2001) and was originally suggested, but not chosen, for the MUPUS Thermal Probe on the Rosetta mission (Spohn 1995).

The impracticality of translating a terrestrial technology, such as a static penetrometer, to the low gravity environment of an asteroid or comet suggests an alternate way of tackling the problem: view the low gravity as a beneficial tool instead of an obstacle. This approach is exemplified by the design of the MINERVA robot on the Hayabusa mission. Initial designs of a small rover for use on an asteroid encountered the problem of obtaining traction with wheels or legs. MINERVA made use of an internally generated torque to produce an opposite reaction between the exterior of the robot and the asteroid surface. The reaction torque was intended to produce a hopping motion and, as a scientific bonus, to supply information on the friction between the robot and the surface (Yoshimitsu et al. 2003).

Inspired by this design, we present three concepts for non-anchored static penetrometers that would provide mechanical measurements as well as mobility. In the first concept, a small static penetrometer would be extended downwards from an unanchored platform. The resulting reaction forces from the surface and subsurface would tend to accelerate the platform upwards (Fig. 2, left side). The amount of acceleration would be directly proportional to the resistance force experienced by the penetrometer and would therefore provide information about the mechanical properties of the very top layer of regolith. Alternatively, or in addition, a force transducer in the actuator could measure the force directly. By causing the platform to accelerate upwards, this mechanism could simultaneously function as a hopping mobility system, in the same manner as the mechanism of the PROP-F hopper on Phobos 2 (e.g., Kemurdzhian et al. 1989). Unless equipped with a righting mechanism such as that used by PROP-F, a number of penetrometer actuators of this type would have to be arrayed around the exterior of the platform so that the at least one actuator could engage with the surface no matter how the platform were oriented. In this manner, mechanical surface measurements of this kind could be taken at multiple locations.

A second variation of this concept, which follows more closely from the MINERVA design, is shown in Fig. 2 (right side). Instead of an internally generated torque, an internal mass would be accelerated linearly upwards along a rail, causing a downwards recoil force on the body of the robot. If applied via a penetrometer, this force could cause a small amount of penetration, again useful for making mechanical measurements of the top layer of regolith. Accelerating the mass downwards could cause the opposite effect, drawing the penetrator out, and causing the robot to hop. Alternatively, the moving internal mass could also be made to impact either top or bottom internal surfaces, producing the effects of a dynamic penetrometer or mole (see below).

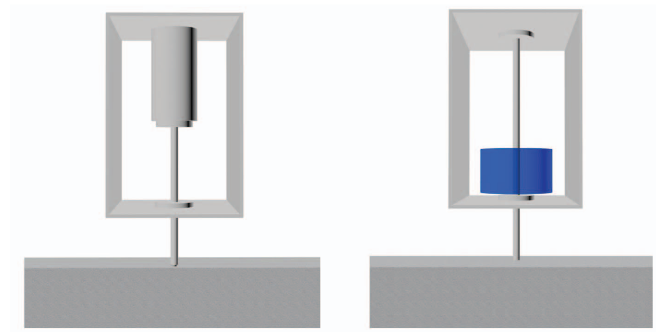

Fig. 2. Conceptual drawings of unanchored static penetrometers that would measure the surface response with accelerometry. Left: A linear actuator would extend the penetrometer, causing a reaction force from the surface. Right: An internal mass would be accelerated upwards, causing a surface-dependent recoil.

Another potential application for static penetrometers concerns the possibility that the interiors of very small "rubble pile" asteroids may have very low cohesion and very low overburden pressures. For example, the central pressure of Phobos has been estimated to be only 2/3 atm (Asphaug et al. 2002). Conceivably, the amount of force necessary to push through the regolith to very great depths would be quite modest. In this case, an un-tethered subterranean vehicle could be used to explore the deep interior of a small asteroid. One way to do this would be with a static penetrometer, made of two segments, that travels in a manner analogous to an inchworm (see Fig. 3): while the anterior segment is pushing forwards, the posterior segment remains fixed in place, due to a set of extended "shoes" that increase the effective skin friction. Subsequently, the two segments reverse their roles, and the posterior segment, with shoes retracted, moves forward, while the anterior segment has its shoes extended. This type of movement can be achieved if the skin friction, or overall gripping force, of the stationary segment is greater than the pushing force of the moving segment. This will be a challenge because, for the same reason that it may be easy to penetrate through the regolith, it may be very difficult to "grip" it.

An untethered rotary drilling system, the Inchworm Deep Drilling System (IDDS) that is intended to use radio isotopic power is currently in development (Gorevan et al. 2003). The IDDS has many of the design features mentioned above, except that it is intended to drill through high strength, rocky material. For example, the IDDS has shoes on each segment that extend against the borehole wall to increase the gripping force. In a non-cohesive material, this basic approach could work, but the means by which friction is increased would be

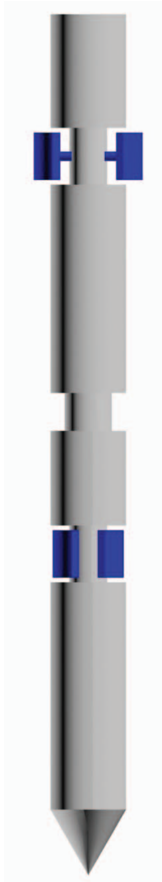

Fig. 3. Concept drawing of an "inchworm" static penetrometer. Alternate gripping and extension of the two segments would create forward progress beneath the surface.

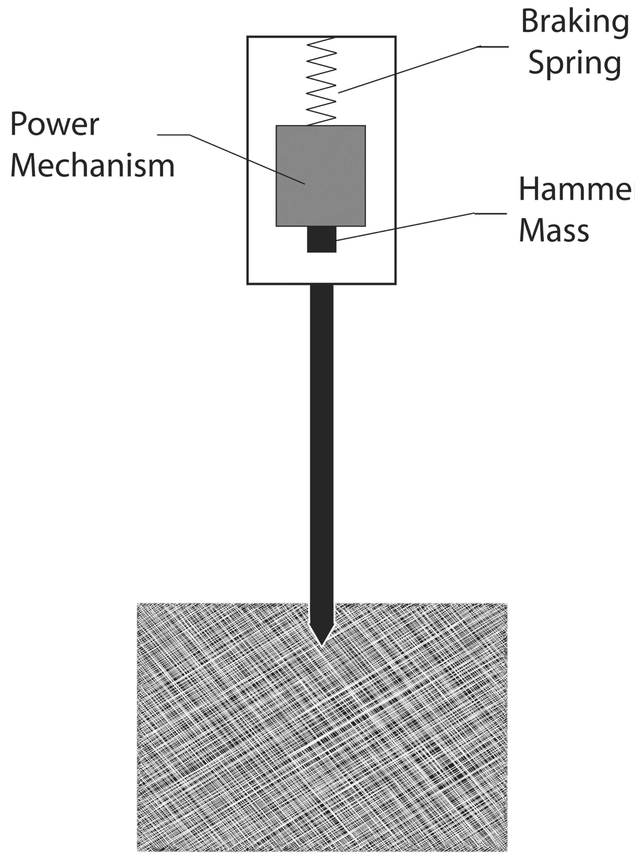

Fig. 4. Schematic of a dynamic penetrometer for subsurface exploration.

more challenging. The development of such a system would not be for the near-term exploration of asteroids, but for some time in the future when power and autonomous robotic technologies have improved significantly, and also when a sufficiently strong scientific or exploratory motivation exists to travel to the center of small asteroids.

Dynamic Penetrometers

Dynamic penetrometers use a hammering force caused by the impact of a downward moving mass (the hammer) against the body of the penetrometer (Fig. 4). The impact between these hard surfaces results in very high peak forces of short (~ms) duration. In accelerating the hammer, a recoil force is also created that would tend to pull the penetrometer out. This recoil force can be reduced by the introduction of a rear braking spring to the rear of the hammering mechanism (Gromov et al. 1997; Pinna 2001a). The braking spring slows down the recoiling mass and, as long as the force used to compress this spring is smaller than the skin friction of the penetrometer, no backwards motion will ensue. The MUPUS Thermal Probe on the Rosetta mission lander functions in this manner. It uses a specially designed solenoid to accelerate a 30 g mass against a very thin composite rod that is supposed to pierce into the surface of the target comet (Grygorczuk et al. 2007, 2008). One limitation of this device is that the diameter of the hammering mechanism is much larger than that of the penetrating rod, so the depth of penetration is limited to the length of the rod.

A device that overcomes this problem is the mechanical mole. Originally invented in Russia (e.g., Gromov et al. 1997), this device has been further developed by the German Aerospace Agency (DLR) (Kochan 2001) and one such instrument, the Planetary Underground Tool (PLUTO), was flown on Beagle 2 mission to Mars (Richter et al. 2001, 2002). A similar but larger mole, the Mars/Moon Underground Mole (MUMM), has been developed by NASA (Stoker et al. 2006). The entire hammering mechanism is encased in a cylindrical shell, pointed at both ends. The mole is deployed from the surface via a tether (which may itself carry sensors), and its depth is limited either by the length of the tether, or by the resistive forces of the subsurface (Kochan 2001). As mentioned above, in the low gravity of small comets or asteroids, the skin friction of non-cohesive regolith could be extremely low, making it more difficult to ensure that the suppressor spring can fulfill its function. This difficulty can be mitigated by making the braking spring as weak as possible and making it long enough to gradually decelerate the recoiling mass. Another solution that has been suggested, identical to that discussed above with the inchworm penetration system, is to artificially increase the skin friction or gripping of the subsurface. This could be done by including unidirectional barbs or similar structures on the surface of the mole, or by having some actuated structures that extend from the mole shell only during the moment of recoil.

The advantage of dynamic penetrometers over static penetrometers is that the peak forces of the hammer impacts are much higher than the recoil or reaction forces. They do not, therefore, require a heavy or firmly anchored platform for their deployment. However, even a static penetrometer must be deployed in the proper vertical position, from a platform capable of generating enough reaction force for its initial penetration. The internal shocks experienced by a dynamic penetrometer are not as severe as the impact of a fast penetrometer, but they are large enough to warrant consideration. For example, the PLUTO mole, flown on the Beagle 2 mission, experienced accelerations of greater than 8000 g for each hammering event (Pinna et al. 2001a). Once it is deep enough, the skin friction provides the necessary reaction force, and the hole made by the penetrometer allows it to maintain its correct orientation. In a low-gravity environment, this initial deployment is not trivial. The Philae lander on the Rosetta mission solves this problem by holding the penetrometer in a telescoping arm that is designed to apply enough downward force to react against the hammering action without transferring unwanted forces to the lander (Grygorczuk et al. 2007). One problematic issue with moles is retrieval from the hole. Generally, a winch mechanism is used to pay out and retract the tether, another operation that would not be trivial in a low gravity environment. Finally, in much the same manner as the inchworm penetration concept, an un-tethered, self-powered mole could potentially be used to explore the deep interior of "rubble pile" asteroids.

CHALLENGES OF TESTING PENETROMETERS

How can the various penetrometer technologies that may be useful on asteroids or comets be tested here on Earth? The low gravity environment is difficult to simulate, as are the properties of the subsurface materials. The MINERVA robot was tested in a drop tower, which provided eight seconds of free fall, during which MINERVA's hopping movement was videotaped (Yoshimitsu 1999). The Touch-and-Go Sampling System (TGSS), a rotary blade excavator intended for use on the proposed Discovery-class Hera mission to an asteroid, was tested in a KC-135 parabolic flight. This testing method was found to have aided in the proofing of the TGSS concept, but numerous moments of negative gravity made it difficult to truly test performance of the mechanism (Sears et al. 2002). The MUPUS penetrometer was tested by hanging it horizontally and having it penetrate into a simulated cometary material (Grygorczuk et al. 2008). This method simulates zero gravity, but it would be more difficult to test with a non-cohesive material. Another method that has been used to test mechanisms under simulated low gravity is to hang them from a pulley system with counterweights that reduce the effective weight of the mechanism (e.g., Kemurdzhian et al. 1993; Jagganathan et al. 1995). In a gross sense, this does simulate low gravity, but any internal mechanical components would still be operating under terrestrial gravity. Computer simulations are also essential tools to assess the performance of possible configurations in a number of scenarios, as was done for Philae landing dynamics (Hilchenbach et al. 2000).

Another possibility is to perform tests in a LEO environment, such as the International Space Station. Although such testing would be very costly, it could be justified as part of a broad effort to develop new technologies for the in situ exploration of comets, asteroids, and small moons such as Phobos. A host of technologies need to be developed for these endeavors, including those for navigation, orientation, landing, anchoring, sample collection, and subsurface exploration.

SCIENCE ENABLED BY PENETROMETERS

Since any penetrometer technology will introduce greater cost and risk to a mission, when compared with remote sensing of the subsurface of an asteroid or comet, it would pay to identify the most important potential uses in the near-term for the various types of penetrometers that were described above.

Measurement of Soil Mechanical Properties

The measurement of soil and ice/snow/permafrost mechanical properties has an extensive history behind it and a multitude of laboratory and field instruments and procedures have been created for this task. Owing to the complexity and heterogeneity of these materials, quantification of their mechanical properties is not a trivial task. For penetrometers alone, dozens of different types have been developed all over the world (Sanglerat 1972). Additionally many empirical, analytical and numerical models have been created to interpret the data gathered by geotechnical instruments, and such models are not always in agreement.

When terrestrial soil is characterized for geotechnical purposes, generally measurements from multiple instruments are combined. For example, data from a dynamic cone penetrometer might be combined with soil classification (including particle size analysis) and a determination of moisture content. Or, shear strength measurements are combined with those for density (Das 1998). It is also important to note that terrestrial soil mechanics is highly influenced by the presence of liquid water in most soils

(Craig 2004), a major factor that will be absent in most, in not all, surface materials on comets and asteroids. When transferring this knowledge to extraterrestrial studies, the difficulty is compounded by our fundamental lack of knowledge of the materials and the constraints of what type and how many instruments we can send there. In spite of these limitations, a general approach, and one that has already been widely used in planetary exploration, will be to make use of as many measurement modalities as possible in order to arrive at the best possible conclusions. In other words, any penetrometer data must be supplemented with various other measurements and observations from other spacecraft instruments.

Fast Penetrometers

The deceleration profile of a kinetic penetrometer, measured with an accelerometer, can provide a coarse measurement of subsurface mechanical properties and layering. Extensive studies of such measurements, intended for cometary material, were performed in the development of the Philae harpoon anchor, which has an integrated accelerometer. In the preparation of this instrument for flight, the anchor was fired into a variety of materials representing the strength regime (hundreds of Pa–10 MPa) and porosity thought possible in a comet (Kömle et al. 2001). As pointed out by these authors (Kargl et al. 2001), there are a number of potential sources of error in such accelerometer measurements. Without independent verification, the depth measurement obtained from integrating the deceleration signal twice was within 15 percent (Kargl et al. 2001). The usefulness of frequency analysis of the accelerometer data was also investigated by this group. It is thought that, if the vibration modes of the penetrator are sufficiently well known, then the superimposed effect of the measured frequencies during the impact could provide information, for example grain size. The Philae anchor has a very complex geometry and thus doesn't lend itself well to such characterization, but a dedicated fast penetrometer would have a simpler geometry. The authors also suggested that a faster sampling rate (>200 KHz) would be more likely to gather information about grain sizes. One potential way to gather the very useful data on final penetration depth would be to have a small aft body, of large surface area, that is left at the surface when the penetrometer plunges in. A thin filament would pay out from the penetrometer, allowing for an accurate depth measurement.

Qualitatively, the deceleration profiles from the laboratory tests of the Philae anchors matched quite well with the resistance profiles obtained with a quasi-static penetrometer, indicating that the harpoon anchors will be able to show any layering in the near surface of the comet (Kömle et al. 2001). A number of different models were used to obtain strength parameters from the deceleration data, including those based on classical soil mechanics, and another that numerically simulated cohesive bonds between particles. The former worked better with porous ices, which exhibit some plastic behavior upon impact, and the latter showed promise with very brittle, porous materials. In order to know which models to apply on data from the actual mission, information from other sources, such as the on board camera, a sonar sensor, a sampling drill, and the MUPUS Thermal Probe (a dynamic penetrometer), will supplement the accelerometer data in interpretation.

The experience of the penetrometer on the Huygens probe illustrates an alternate approach to collecting penetration data, and also demonstrates the practice of combining data from various sources. The landing of the probe on Titan occurred at a velocity of only 4.6 m s^{-1} (Zarnecki et al. 2005), but it was also propelled by the inertia of the 200 kg probe behind it. Instead of an accelerometer, the penetrometer had a piezoelectric force transducer in contact with its tip. However, the probe itself was equipped with two axially oriented accelerometers that provided auxiliary measurements. Optical and sonar imaging of the surface also added information about the terrain and the presence of ice cobbles on the surface, which ended up being very important for the interpretation of the penetration data. The force transducer data indicated a penetration resistance of 250 kPa, while the accelerometer data (applied to the deceleration of the entire probe as it impacted the ground) pointed to a significantly lower value. One interpretation of this discrepancy is that the probe landed on a number of ice cobbles (seen in photographs looking to the side of the probe). The authors concluded that the combined accelerometer and force transducer data indicate a surface material that is either, "solid, granular material having either low or zero cohesion, or a fluid component. The mixture resulting from the latter possibility would be analogous to a wet sand or a textured tar/ wet clay" (Zarnecki et al. 2005).

The two above examples show that data from fast penetrometers can indeed be very challenging to interpret. With the addition of other sensors, a fast penetrometer could have significantly more capability and still remain fairly small (i.e., less than 2 kg). The addition of an optical sensor and/or a camera in the body wall of the penetrometer could provide complementary data on layering and grain size. A small shear vane or static penetrometer (see below) could also be extended laterally from the wall, to provide mechanical measurements complementary to the deceleration profile.

Another potentially important use of fast penetrometers lies in their ability to deliver small sensors beneath the surface to provide data over extended periods of time. This could include seismic, thermal, electrical, chemical, or mineralogical sensors, as well as location beacons. Unless tethered, the main challenges here are long lasting electrical power and a means of communicating with the host orbiter or a lander. One of the greatest potential benefits of fast penetrometers would be the deployment of multiple units around a small body to create simple networks that can gather data from several different locations.

Perhaps the most important of these is seismology, an essential tool for studying the internal structure of a body. There is some debate over whether seismic sensors can be left on the surface, or whether they must be deployed below it (Binzel 2003; Walker et al. 2006). If this debate concludes in favor of subsurface deployment, then fast penetrometers should be considered as front runners for this application.

Slow Static Penetrometers

One common terrestrial standard, the cone penetrometry test (CPT), uses a 60° cone with a cross-sectional area of 1000 mm^2 (36 mm diameter) with a force sensor behind it, and a sleeve with area of 150 cm^2 above the cone that has its isolated force measured by another force sensor (Craig 2004). The cone penetrometer is inserted into the soil at a constant rate of 22 mm s^{-1}, generally with a hydraulic mechanism. From this arrangement, two independent measurements, the cone penetration resistance, q_c (equivalent to the base resistance described above), and the frictional resistance, equivalent to the skin friction, f_s, both measured as force per area. Both the values of q_c and the "friction" ratio f_s/q_c are used to broadly classify soils. Also, an empirical relation has been determined relating q_c, the effective overburden pressure, and the shear strength parameter (Craig 2004). Theoretically, this could be scaled down for use on small bodies, but, as described above, static penetrometers are not very feasible in a low gravity environment. However, the data that they provide, an unambiguous measurement of penetration resistance, bears further examination on the use of the technique. The static penetrometers used by the Apollo astronauts and the Soviet robotic lunar missions represent the best extraterrestrial use of penetrometers to date. Mitchell et al. (1974) attested to the utility of static penetrometers for obtaining information on the strength, porosity, and density of the lunar regolith. The rocket propelled versions are interesting, but, in the initial stages of study, it might be undesirable to release so much gas, contaminating the environs of a small body. As mentioned above, a small static penetrometer could be extended laterally from a submerged fast penetrometer.

The small, unanchored static penetrometers described earlier in this paper could provide data on penetration resistance of the very top layers of a small body. If some of the penetrometer/actuators are very slender and others have a less extreme aspect ratio, then information on friction versus base resistance could be gleaned by comparing their behavior. Downward facing cameras would also be a must, to record particle size and distribution at the surface and to record the surface deformation/alteration caused by the penetrometers. Small sensors requiring intimate surface contact or shallow penetration could also be incorporated, for example electrical permitivity, magnetic susceptibility or various types of spectrometer for compositional measurements. A small hopping rover equipped with these actuators/sensors could travel around an asteroid or comet, and take multiple measurements of the top few cm of the surface. A similar precedent for such a series of measurements was taken by the Soviet Lunokhod rovers, each of which was equipped with a small "cone vane" penetrometer that reached a depth of 100 cm and also rotated to make shear measurements with the incorporated vane. Between the two rovers, more than 1000 measurements were taken over distances of many kilometers (Ball and Lorenz 2001).

Slow Dynamic Penetrometers

The principal measurement taken by a slow dynamic penetrometer (or a mole) is a "penetration index" which is defined as the number of hammer blows per depth of penetration. In the case of one common standard in the U.S. for the Dynamic Cone Penetrometer (DCP), its penetration index has been correlated empirically with an older standard called the California Bearing Ratio (CBR), which incidentally, is determined with a static penetration test. Such empirical indices will not be useful for non-standard instruments used on exotic materials in a very low gravity environment. There has been some work done on extracting the actual mechanical properties of soil with a DCP. Nazarian et al. (1999) developed two experimental versions of the DCP, for transportation civil engineering, that were tested in pavement bases and subgrains. A "Seismic DCP" (SDCP) was outfitted with a 3-axis accelerometer in the cone tip. After driving the penetrometer into the ground, a shock hammer was tapped on a piece of metal at ground level at a known distance from the penetrometer. The time of impact of the hammer was recorded in relation to the arrival of shear and compression waves and the processed data was used to back out the shear modulus and the Poisson's ratio of the soil. One could envision this same experiment being performed by a robotic lander, creating a small shock event at the surface that would be measured by a mole below. Of course, the same seismic sensor could also be used to collect more global seismic data if a suitable larger seismic pulse could be produced over a larger distance.

The second variation created by Nazarian et al. (1999) the "Instrumented DCP," was outfitted with a high speed load cell and a single axis accelerometer at the top of the penetrometer rod (where the drop hammer impacts it). The accelerometer was used to determine the time versus velocity and depth data (by single and double integration respectively) and the load cell measured the dynamic force. Analysis of the accelerometer data showed the effect of compressive and tensile waves that passed through the penetrometer following each hammer impact. By calculating the kinetic energy of the of the rod as it traveled in the soil following each impact, and subtracting this quantity from the energy in the rod when traveling through a material of negligible resistance, the researchers were able to measure the energy transmitted to the soil. Finally, the soil resistance was determined as the energy dissipated per volume of soil penetrated. This final calculation was based on the assumption that all of the energy was dissipated at the cone tip (none by friction with the smaller diameter rod). No details on reduction of the load cell or accelerometer data (or the sampling frequencies) were given, but it is also expected that the deceleration regime of this type of penetrometer is less extreme than for a fast penetrometer and perhaps less prone to large errors.

Pinna et al. (2001b) conducted similar experiments with the PLUTO mole, in which an axial accelerometer was integrated for some penetration tests. The PLUTO team was principally concerned with the ability of the mole to penetrate to a depth on Mars adequate for the science requirements of the Beagle 2 mission. Equations from pile driving theory for both non-cohesive soils (e.g., sands) and cohesive soils (those with clay) were used to model the soil resistance as the sum of the base resistance and the skin friction. The impact dynamics of the mole mechanism are much more complex than those for the DCP, which is simply a standard mass dropped from a standard height. The PLUTO team created a dynamic model based on energy transfer in the mole hammering mechanism, the pile driving theory mentioned above, and data collected from laboratory tests, including those with an accelerometer. The accelerometry data had to be prepared by adding theoretical values for small forces (those below the measurement capacity of the accelerometer) and after these corrections were added, the singly and doubly integrated accelerometer data matched independent depth measurements very well. From the point of view of "backing out" soil mechanical properties, this would be done by using accelerometer data to get displacement per blow, and, knowing the energy outputs from the performance model, the total soil resistance could be calculated. Alternatively, the inclusion of a force sensor behind the penetrometer tip would make it possible to separate skin friction from base resistance.

The MUPUS Thermal Probe on the Rosetta lander is also a dynamic penetrometer. Its primary function is the deployment of thermal sensors below the cometary surface, but it also has a depth sensor and, since the impact energy of the solenoid will be known beforehand, meaningful data on subsurface mechanical properties can be obtained. The solenoid hammer has several power settings which will allow the hammer impact force to be adjusted depending on the actual strength of the cometary material.

Dynamic penetrometers may be the best tool for obtaining high resolution data about the strength and layering of regolith on an asteroid, or the icy surface of a comet. If the MUPUS Thermal Probe is successful in 2014, this would be an excellent indicator of the usefulness of dynamic penetrometers on such missions. A next step might be the deployment of a mole on a comet or asteroid, to penetrate to depths of one meter or more.

Slow dynamic penetrometers, moles in particular, are well suited to housing instruments in their body. The PLUTO mole had a temperature sensor, and a larger mole, a progenitor of PLUTO, the MMUM mole is equipped with a Raman spectrometer that peers through a sapphire window in the side of the mole housing (Stoker et al. 2007). Cameras are another possibility, as are seismic instruments.

CONCLUSION

Penetrometers are promising tools for physical access below the surfaces of comets and asteroids. There exist a wide range of potential configurations, with extensive (decades) heritage in some aspects from terrestrial and/or planetary exploration. Operating in the low gravity environments of small bodies represents a significant technological challenge, however. Fast penetrometers, which are released above, and plunge into, the surface, have the advantage of not requiring a soft landing. Due to their inherently high kinetic energy, they are capable of penetrating into a wide variety of strength regimes, making them a good choice for initial reconnaissance missions. However, their data is of lower resolution and very challenging to interpret. Slow penetrometers, which are deployed from the surface, must be deployed from an anchored, stabilized platform but they can provide higher resolution data. This extra technological burden may make them a better choice for second and third generation missions, although the eventual success of the MUPUS penetrometer may obviate that conclusion. Slow penetrometers include static penetrometers, which use a steady pushing force, and dynamic penetrometers, which use a repeating hammering impact.

The preferred configuration of any penetrometer system depends to a large extent on the deployment and operational requirements of the intended scientific measurements, in terms of lateral coverage (sequential or simultaneous), maximum depth, depth resolution and measurement duration, may usefully opt for a combination of lateral mobility, affording shallow subsurface access, with fewer subsurface devices, affording deeper access, at particular locations. Non-anchored static penetrometers may fill the former need, while dynamic penetrometers (stationary, or of the mole variety) could fill the latter need.

Acknowledgments—D. L. Glaser and K. A. Zacny wish to thank the organizers and sponsors of the Recon 2006 workshop.

A. J. Ball wishes to thank the organizers and sponsors of the Recon 2006 workshop for financial support, and the UK's Particle Physics and Astronomy Research Council (PPARC) for postdoctoral fellowship funding.

Editorial Handling—Dr. Louise Prockter

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