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Penetrometry of granular and moist planetary surface materials: Application to the Huygens landing site on Titan

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Abstract

The Huygens probe landed on the then unknown surface of Titan in January 2005. A small, protruding penetrometer, part of the Surface Science Package (SSP), was pushed into the surface material measuring the mechanical resistance of the ground as the probe impacted the landing site. We present laboratory penetrometry into room temperature surface analogue materials using a replica penetrometer to investigate further the nature of Titan's surface and examine the sensor's capabilities. The results are then compared to the flight instrument's signature and suggest the Titan surface substrate material consists of sand-sized particles with a mean grain size ~2 mm. A possible thin 7 mm coating with mechanical properties similar to terrestrial snow may overlie this substrate, although due to the limited data we are unable to detect any further layering or grading within the near-surface material. The unusual weakening with depth of the signature returned from Titan has, to date, only been reproduced using a damp sand target that becomes progressively wetter with depth, and supports the suggestion that the surface may consist of a damp and cohesive material with interstitial liquid contained between its grains. Comparison with terrestrial analogues highlights the unusual nature of the landing site material.

Keywords: Titan; Regoliths; Ices, mechanical properties

1 Introduction

On the 14th January 2005, the Huygens probe successfully completed the first landing on the unexplored surface of Titan (Lebreton *et al.* 2005). The probe and Cassini orbiter have since revealed the Titan surface to consist of a wide range of geological features including sand dunes, lakes, mountain chains and dendritic channel networks (Coustenis and Hirtzig, 2009; Jaumann *et al.,* 2008). The probe's scientific instrumentation included the Surface Science Package (SSP) (Zarnecki *et al.*, 1997; Zarnecki *et al.*, 2002), a suite of small sensors primarily aimed at characterising the nature of any solid or possibly liquid surface. This instrument included a penetrometer, designated 'ACC-E' or ACCelerometer-External for historical reasons, as part of its array of sensors. The original intention of the penetrometer was to provide a qualitative identification of a terrestrial analogue material for Titan's surface in the event of a (soft) solid landing (Lorenz *et al.,* 1994). The penetrometer was designed to measure forces ranging from a few newtons up to a limit of 2000 N. Impact loads any higher than this would probably have caused a failure of the probe (Lorenz *et al.,* 1994). No scientific return was expected from the penetrometer in the case of a liquid landing due to the force on the tip being less than the trigger threshold of the sensor (Zarnecki *et al.,* 1997). Additional design details are given in Krysinski *et al*. (2009).

2 Flight sensor and surface signature

[Insert Fig. 1 here]

The ACC-E penetrometer consists of a piezoelectric element sandwiched between a 14 mm diameter hemispherical tip and collar, mounted at the end of a short aluminium pylon (Fig. 1). This element generates a charge proportional to the stress placed on it, thereby acting as a force transducer allowing a direct measurement of the mechanical resistance of the material encountered. Constraints were placed on the positioning and length of the flight penetrometer due to the crystal being located directly behind the probe's heat shield (Lorenz *et al.,* 1994). For electromagnetic compatibility, a mesh screen, through which the penetrometer passed, covered the base of the SSP instrument. The electronics were designed to sample the sensor at a rate of 10 kHz such that at the expected impact speed on Titan of 5 m s^{-1}, a theoretical depth resolution of 1 mm might be obtained. This resolution was intended to allow the possibility of identifying layering in the surface or particle size if the material was granular. The probe landed slightly slower than this at 4.60 ± 0.05 m s^{-1} (Towner *et al.,* 2006; Zarnecki *et al.,* 2005). For an impact under parachutes at this constant vertical speed, the penetrometer force signature can be plotted against depth penetrated as shown in Fig. 2.

[insert Fig. 2 here]

This signature can be considered in four distinct stages; however for the purposes of this analysis only the first three stages are useful, before the addition of strong structural interactions caused by the arrival of the probe foredome at the surface that make the later data (stage 4) unusable. The first stage is a weak but rising force corresponding to a material thickness of 7-8 mm. The second stage is a sudden resistance spike of less than 1 ms duration, equivalent to ~ 2-3 mm penetration depth at the 4.6 m s^{-1} impact speed. This is followed by the longest period of 'clean' penetration before an abrupt rise in force seen in stage 4 which corresponds with the arrival of the Electromagnetic Compatibility (EMC) screen of the Surface Science Package some 55 mm after penetrometer tip entry (Zarnecki *et al.,* 2005). The pre-impact signature by design showed 64 force samples before the triggering threshold. Due to shorter, fixed wiring and better screening, noise levels are lower than those measured with the laboratory equipment, occupying only the least significant bit level of the 8 bit analogue to digital converter (ADC) of the SSP electronics, equivalent to a force of 2 N at Titan surface temperature.

3 Analogue work

Using a replica ACC-E penetrometer and a portable test rig with an electromagnetic release, penetrometry drops were carried out at the probe impact speed both in the laboratory and in the field (for a summary of drops presented in this paper see Table 1). To produce drops comparable to that made by the 200.5 kg probe on Titan, it is only necessary to attach the penetrometer to a small 5 kg mass that provides sufficient inertia to maintain the impact speed for the duration of penetration (Lorenz *et al.,* 1994). The required impact speed was achieved by adjusting the height of the drop, equating the gravitational potential energy lost with the kinetic energy on impact assuming negligible drag. The impact speed for each drop was verified using a laser, photodiode sensor array, and barcode etched mirror attached to the penetrometer weight (Fig. 3). For a fuller description see Atkinson (2008).

The penetrometry in the laboratory was intended to produce impact signatures representative of similar impacts into a semi-infinite planetary surface. In practice, a laboratory target is necessarily bounded by the rigid sidewalls of the target container and the depth restricted by the container floor. Boundaries may lead to spurious effects on the penetrometer signal caused by the confinement and induced order in the target material near the container wall (Zou and Yu, 1995). This leads to a compromise between as large a target as possible, to minimise these effects, and the practicality of producing a target that is manageable in size and not too time consuming to prepare. Boundary effects have been examined extensively and various ‘correction factors’ have been proposed to account for the effects with varying degrees of success (see e.g. Huang and Hsu, 2005).

An analysis of boundary effects is beyond the scope of this study as the effect can be dependent on multiple factors including the type of target material, its preparation, and the sensitivity of the penetrometer. For the purposes of the analogue experiments however, it was not necessary to examine the boundary effects *per se*, but only to establish a target container size of sufficient dimension for them to be negligible. This was done by comparison of the mean force detected between multiple sets of drops into cylindrical targets of varying diameter and depth. The target material was chosen to be 4mm diameter spherical glass beads, as these pack consistently to a narrow range of bulk density, and are easily prepared by pouring. To examine edge effects, three open-bottomed cylindrical containers of internal diameters 104, 152 and 235 mm were placed within a larger 320 mm diameter closed-bottomed cylindrical container. All four containers were filled with glass beads to a depth of 350 mm. Ten drops were carried out into each size container and the mean signature force recorded. Using a one-way analysis of variance (ANOVA) followed by a Tukey Honestly Significant Difference (HSD) multiple comparison test (see e.g. LeBlanc, 2004), a statistically significant increase in mean signature force was measured between the smallest diameter container and the other three containers. To test the effect of the container floor, the 235 mm diameter open-bottomed cylindrical container was set on increasing levels of Foamglas, a rigid but brittle cellular glass insulating material that would crush, avoiding damage to the penetrometer should it not be stopped by the beads. This produced targets of four depths: 350 mm (no Foamglas), 270, 190 and 110 mm respectively. A similar ANOVA and multiple comparison test analysis found the mean penetration force experienced when using the small 110 mm depth container was significantly higher than for the other three containers. These results implied a minimum target container size of ~152 mm diameter and 190 mm depth was needed for boundary effects to be considered negligible. Based on these results, for most experiments the largest container (320 mm diameter, 350 mm depth) was used.

[Insert Table 1 here]

4 Signal processing path and sensor calibration

The penetrometer front-end electronics consists of a charge amplifier followed by a pseudo-logarithmic amplifier used to accommodate the large range of input signals that could be generated from the possible impact forces. This pseudo-logarithmic amplifier has three linear gain branches selected depending on the input voltage. In the case of the flight data, only the high-gain branch of this amplifier was used, as the force on the penetrometer was at the low (softer impact) end of the range. An anti-aliasing filter is used to remove frequencies above the sensor's Nyquist frequency (5 kHz) before an 8-bit Analogue to Digital converter (ADC). Figure 3 summarises the signal processing paths for the flight and laboratory data.

[Insert Fig. 3 here]

The replica penetrometer was made using a piezoelectric crystal from the same batch as the flight and flight spare penetrometers and constructed in accordance with the original assembly instructions. The charge generated by the piezoelectric crystal leaks away rapidly after the application of a force to the penetrometer tip. For this reason, it is not possible to calibrate the crystal by applying static loads- a known dynamic force must be used instead (Lorenz *et al.,* 1994; Zarnecki *et al.,* 1997). The original ACC-E penetrometers were calibrated using a small pendulum jig to strike the sensor tip with different impactors (Lorenz 1994a; Lorenz *et al.,* 1994). For the replica penetrometer, a different method was used based on a mass moving on a frictionless horizontal linear bearing colliding with the force transducer (Fujii, 2006; Fujii and Fujimoto, 1999). This highly accurate calibration method used an optical interferometer to determine the change in momentum of the moving mass before and after the collision. This change is equal in magnitude to the time integrated impulse acting on a force transducer. Given that this degree of calibration accuracy was not required for the penetrometer, the interferometer was replaced with a suitable accelerometer which allowed a direct determination of the impact force for a known impact mass. The limitations of impacting mass that could be supported on the frictionless linear track used meant only the high gain branch was calibrated. Piezoelectric crystal sensitivity varies with temperature and therefore a conversion factor of 1.83 (Lorenz *et al.*, 1994) was required to account for the reduction in sensitivity of the flight signature returned from Titan's -180°C surface compared to the room temperature analogue signatures.

5 Identifying substrate material grain size

Grain size is of key interest to the Huygens penetrometry investigation due to the strong indication of a sedimentary granular environment at the landing site (Tomasko *et al.,* 2005). One approach to this type of investigation has attempted to reconstruct the grain size distributions of Martian soil analogues from their quasi-static penetrometry signatures by examining frequency content (Kargl *et al.,* 2009). The limitations imposed by the length, the relatively low sampling rate of the ACC-E penetrometer and higher speed of impact meant this technique could not be applied. An alternative method was used to examine laboratory penetrometry drops collected at the probe’s impact speed into targets of glass and plastic spherical beads of known material densities and with diameters between 1 and 8 mm. The amplitude of each peak in the resulting signatures was identified after discarding peaks due to signal noise determined by examining the pre-impact signal. First, to ensure the data were stationary, a moving average was subtracted from each signature. The signature data points were then stepped through and all consecutive rises between sample points summed until a falling value was found. If the sum of the rises was greater than a 95% confidence level of the pre-impact signal (i.e. peak to trough as the penetrometer is falling towards the target), the peak was considered significant and the point was marked as a peak candidate. For this value to be accepted as a peak, an equivalent fall or sum of consecutive falls must follow this candidate point. A similar method was used to find trough candidates (Fig. 4). The mean value of peak to trough height for each target was then determined.

[Insert Fig. 4 here]

During this analysis, a regular enhancement of the penetration force in the first 8-10 mm of target penetration or 'tip entry effect' was evident that considerably affected the mean peak to trough height and variability. This distance corresponds approximately to the length of the ACC-E hemispherical tip as it enters the target surface. In general, the effect was found to be greater for larger beads. One possible explanation is given by comparison of the size of the penetrometer tip to the target beads. Smaller bead targets present more of a smooth continuum surface to the tip with each bead having proportionately less effect on it. However, large beads whose size is comparable to the tip form an uneven target surface with variations in both the number and position of the beads impacted. After the tip has fully entered the target it is completely surrounded and therefore gives a more uniform response. Figure 5 shows the magnitude of the mean peak to trough force plotted against the bead mass after removal of the 'tip entry effect'.

[Insert Fig. 5 here]

A statistically significant empirical relationship between bead mass and the mean peak-trough amplitude, h, was found:

$$h = 37.79M^{0.33} \qquad (1)$$

6 Substrate material properties with depth

The third stage (Fig. 2) of the flight signature lasts 8.3 ms and is unusual due to a significant downward trend; resistance usually increases as the target material becomes compacted in front of the advancing penetrometer, and/or overburden pressure increases the penetration resistance. Several analogues were tested to try to reproduce this trend. One possibility, given the fluvial nature of the surface seen in DISR images, was that the granular material could be size sorted with depth, which might affect the resistance. This effect, known as graded bedding, is due to changes in the flow speed of the liquid transporting the grains and can result in either 'normal grading', where the grain size coarsens with depth, or 'inverse grading' where the material becomes finer with depth.

Artificial graded targets were produced with layers of the four sizes of available glass beads (8, 6, 4 and 1 mm diameter). Whilst some of the inverse graded drops had a downward trend the gradients varied too much to be pursued as a suitable analogue.

Further attempts to reproduce a downward trend using clay targets with added voids were only partially successful in modifying the typically flat clay signature to a slightly downward-sloped one. The gradient of the Titan signature is significantly greater over a short length than seen in a clay void target. Early material catalogue work had shown that some water-wetted sand targets were able to produce a downward signature slope although the amount and distribution of liquid had not been well characterized (Paton, 2005). Examining the effect of water on penetration resistance in soils is often done using penetrometers with combined Time Domain Reflectometry (TDR) probes that measure soil water content *in situ* as they penetrate the soil (see e.g., Vaz *et al.,* 2001). The ACC-E did not have this capability; however by using a ThetaProbe (Delta-T, 1999) to measure the moisture through small sampling points in the target container wall, water distribution could be determined immediately prior to penetrometer impact with minimal target disturbance. Sand targets were prepared in a rigid plastic cylindrical container (diameter 320 mm and sand surface at 350 mm) using a similar method to that used in an investigation to measure elastic wave velocities in saturated sand (Velea *et al.*, 2000). Two target materials were used: well-sorted coarse grained Leighton Buzzard DA 16/30 sand (median grain size, D50 = 614 μm) and well-sorted fine grained RH T sand (D50 = 230 μm) both locally sourced from the WBB Minerals Ltd., Double Arches quarry in Leighton Buzzard, U.K.. The sand targets were poured loosely in the container giving approximate dry bulk densities of 1.51 and 1.57 g cm^{-3} for the LB DA 16/30 and RH T sand respectively. To make a reproducible wet target, water from an external feed bottle was introduced into the sand from below through a perforated hose by capillary action causing minimal disturbance to the sand. The sand was allowed to saturate completely to ensure even settlement and a glass straw (open to the atmosphere) in the feed bottle was set at the required water table level. The sand was then allowed to dry overnight until air in the straw of the feed bottle started bubbling up. At this point, the water table is level with the bottom of the straw in the feed bottle. This produces, by capillary action, a moisture gradient between the water table and the surface that can be controlled by adjusting the depth of water table from the surface (or equivalently its height from the fixed bottom of the target container). Immediately prior to the drop into the target, the water content was sampled at several points along the height of the container using the ThetaProbe that after calibration gave a DC voltage related to the soil water moisture content. Figure 6 illustrates the experimental arrangement used.

[Insert Fig. 6 here]

Drops were carried out into both sands with four water table configurations, at z=150, 200, 250 and 350 mm (saturated sand) where z is the height of the water table measured from the bottom of the target container. Due to the time-consuming target preparation and subsequent necessity to allow each sand to dry completely before it could be used to prepare a new target, only four drops were carried out into each of the two sands. For comparison with the wet sand signatures, several drops were also carried out into the two dry sands at loose and dense compaction states. Representative signatures from these drops are shown in Fig. 7 and Fig. 8.

[Insert Fig. 7 here]

[Insert Fig. 8 here]

The coarser grained LB sand has a higher penetration resistance than the finer RH T sand and, as expected, the compacted state of each sand type has greater mechanical strength than the loose state. Once water is introduced into these sands even in small quantities, their penetrometry signatures change considerably. Figure 9 shows the RH T sand signatures for the four configurations tested. With the exception of the drop into sand with the lowest water table (d), the characteristic dry sand shape is not seen; the initial tip entry peak of the sand has gone. The other signatures are similar to that of cohesive clay, with a gradual rising slope followed by an essentially constant resistance plateau. This plateau seems to vary in force depending on the height of the water table. The saturated sand, (a), has the lowest resistance, only slightly higher than that of the same sand when dry and in a loosely packed state (Fig. 7). In contrast, the sand with the lowest water table at z=150 mm, (d), has a much greater resistance with a plateau phase nearly twice that of the same sand in the dry dense state. The tip entry peak also returns in this signature. The entry rise of each signature also varies with the moisture content of the sand. The sand with the lowest water table and therefore driest surface, (d), has the sharpest rising force. As the water table is raised and the moisture content of the sand near the surfaces increases, this entry rise becomes increasingly gradual.

[Insert Fig. 9 here]

Coarser LB sand in the same wet drop configurations produces different results (Fig. 10). A drop into saturated sand (a) shows a considerably reduced tip entry peak compared with drops into the same sand when dry, followed by a constant resistance plateau similar to that seen in the wet RH T sand. In subsequent drops, (b) and (c), as the water level is lowered the initial tip entry peak increases in resistance but falls gradually producing a downward gradient similar to that seen in the Huygens signature. Finally, in drop (d) with the saturation level 200 mm below the target surface, the sand starts to behave as if in the dry state again, with a slightly more pronounced tip-entry peak and a gradual increase in resistance with depth in the plateau phase. These signatures again show how the addition of small quantities of water between the grains of sand can modify the penetrometry signature even over a short penetration distance and, in some cases, more than double the average penetration resistance compared to the same sand in the dry state.

[Insert Fig. 10 here]

7 Comparison of laboratory analogue results to the Huygens landing site signature

The laboratory analogue penetrometry work can be compared with the signature returned by the ACC-E penetrometer from the Huygens landing site and some of the findings described previously can be applied. Although the first two stages of the flight data are of extremely short duration, the closest match suggests that the penetrometer's first contact with the surface may have been into a thin coating on the substrate material with weaker mechanical properties than terrestrial snow (Fig. 11). At a 4.6 m s^{-1} impact speed, this putative coating has a thickness of ~7mm. One possibility is that this layer is a loose covering of deposited atmospheric aerosols and tholins. However, recent models of Titan's atmosphere indicate a surface deposition rate of 0.01 µm yr^{-1} (Soderblom *et al.*, 2007), which would suggest that this coating has been deposited over a period greater than 700,000 years. This would seem to be at odds with the current picture of a dynamic Titan surface at the Huygens Landing site. Alternative origins for this layer may be aeolian or fluvial in nature.

[Insert Fig. 11 here]

In previous analogue work (Zarnecki *et al.*, 2005), the force spike seen in the second stage was reproduced by impacts with small pebbles or with hard crusts; however, the images of the surface taken with the DISR cameras suggest a surface shaped by fluvial processes (Tomasko *et al.*, 2005) with rounded pebbles 10-15 cm in diameter lying on top of a darker, grainy substrate material, making an impact with the first of these analogues seem more likely.

Although the presence of water ice at the Titan landing site has yet to be confirmed (Keller *et al.*, 2008), impacts at the Huygens speed were carried out into spherical water ice particles of various masses frozen in liquid nitrogen, to reproduce the peak seen in stage 2 of the Titan signature. While not conclusive, due to the difficulty in controlling the exact point of impact between the penetrometer and ice particle, two drops into the smallest mass particle (~2g) produced a signature peak of similar magnitude to that seen in the signature. This mass corresponds to a spherical particle of approximately 16 mm in diameter, far smaller than the scattered pebbles imaged on the surface by the DISR camera. Given that the accelerometer on the SSP registered a small precursor peak of approximately 0.6 g in magnitude prior to the penetrometer triggering, this would suggest that the probe foredome may have impacted a larger pebble before the first contact of the penetrometer with a granule from the substrate material.

The downward pointing DISR Medium Resolution Imager (MRI) also separately imaged the granular substrate material. Due to the limiting resolution of this imager, the smallest size of grain that can be measured from the images is 3 mm. However, applying the results of the laboratory bead drops, that the grain mass affects the amplitude of the peaks, an estimate of the substrate material grain size can be made assuming spherical grains that consist only of water ice which, at Titan's surface temperature, has a density of 0.93 g cm^{-3} (Collins, 2005). Measuring the amplitudes of the peak to trough forces in stage 3, identifies 21 peaks of which 11 are above the assumed 1-bit noise level of the penetrometer electronics. These excursions have a mean amplitude of 5.53 N which, using the empirical relationship found earlier gives a mean particle mass of 0.003g. Using the relationship between particle diameter, $d_{particle}$, and particle mass, M, together with the water ice grain density, ρ,

$$d_{particle} = 2\left(\frac{3M}{4\pi\rho}\right)^{\frac{1}{3}} \qquad (2)$$

gives a mean grain diameter of ~2 mm. This is a reasonable estimate given the very limited quantity of flight data available and characterizes the grains as 'sand' according to the Udden-Wentworth classification scale (Wentworth, 1922). Other work (Paton, 2005) using a different technique based on peak frequency finds a mean diameter of ~5 mm for dry particles.

Considering next the downward trend in this third stage, Fig. 12 shows the closest matching analogue to the Titan substrate material in both gradient and smaller scale undulations. This is coarse wetted LB sand (D50 = 614 μm) with a water table 150 mm below the sand surface (i.e. z=200). Here the signature has been shifted horizontally, but not rescaled in any way, to align with the third stage of the Huygens signature on which it is overlaid.

[Insert Fig. 12 here]

To demonstrate how unusual the downward trend seen in the Titan surface material is compared with the terrestrial analogues tested, a material identification map is shown in Fig. 13. Two signature parameters, the mean force of peak to trough undulations and the gradient of the signature were used to classify 17 types of analogue.

[Insert Fig. 13 here]

The identification map shows that even the closest terrestrial analogue match for this substrate material, a gradient wetted coarse sand, while close to matching the mean peak-trough undulations in the signature caused by granularity, is still some way from matching the degree of loss of strength with depth. This cannot be explained by Titan's reduced gravity compared to penetrometry drops carried out on Earth, as the flight data's signature gradient is negative. Gravity acts to increase overburden pressure with depth and compress underlying material, which would cause a positive signature gradient (and, for the small depth penetrated the effect of overburden pressure would be negligible). It must be noted that these wet analogues used water as their interstitial fluid, which at room temperature has a ~5 times greater viscosity and a surface tension four times that of liquid methane on Titan's surface. Liquid methane at 95K has dynamic viscosity of 2×10^{-4} Pa s and surface tension 0.018 N m^{-1} (Ghafoor and Zarnecki, 2000; Keller *et al.*, 2008). On the other hand, the viscosity of liquid ethane at Titan surface temperatures is a little higher than water (e.g. Lorenz *et al.*, 2010). Thus, while we acknowledge that fluid properties and the currently unknown contact angle between water ice and liquid hydrocarbons at Titan surface temperature may be different from those in our experiments, our analogue could in fact be rather similar. Nevertheless, carrying out penetration experiments into ice particles mixed with liquid methane/ethane under Titan's surface temperature and pressure conditions may help constrain the quantity of liquid present between the grains. However, the cost and complexity of producing a sufficiently large environmental chamber within which to perform such experiments would be prohibitive.

8 Other Huygens data that support the penetrometer findings

That the substrate material was damp is supported by the measurement of a 40% increase in the level of methane detected by the Gas Chromatograph Mass Spectrometer (GCMS) two minutes after landing while the detection of nitrogen remained constant (Niemann *et al.*, 2005). Modelling of the thermal environment of the inlet supports this possibility, indicating that the heated inlet may have evaporated a small quantity of methane in the local material (Lorenz *et al.*, 2006). This suggests that liquid methane may be mixed with the surface material and was evaporated by the GCMS inlet line heater until the liquid became depleted. Detection of a possible dewdrop (Karkoschka and Tomasko, 2009) falling from the descent imager baffle is also consistent with methane moisture being sweated out of the ground by the 20W surface science lamp.

The Huygens probe overall endured a deceleration at impact of about 150 m s^{-2} (i.e. 15 Earth 'g'), the deceleration pulse lasting about 20 ms (Zarnecki *et al.*, 2005; Lorenz *et al.*, 2009). Modelling (Lorenz, 1994b) established the range of target parameters over which the deceleration would be sensitive to the target strength, rather than the deformation of the probe. Indeed, the Huygens landing site was soft enough that probe deformation was minimal (although transient structural 'ringing' is evident in some accelerometer data (Bettanini *et al.*, 2008)). Inspection of the peak deceleration and the rise time of the pulse (Lorenz *et al*., 2009) suggest that the surface material averaged over the base of the probe (~1m^2, as opposed to the ~1cm^2 of the penetrometer) had some cohesion (i.e. bearing strength at zero penetration). This further supports the 'damp sand' model discussed in the present paper. Dry sand has a rather longer rise time than was observed.

Rock counts from the SLI imager (Keller *et al.,* 2008) identify a few gravel-sized particles great than ~5mm in the substrate material, although the majority of the material imaged is finer than this. Nevertheless, sand at the landing site may have been rather coarse – Tomasko *et al*. (2005) note that particles 3mm across (the limiting resolution of the camera) can be identified in the post-impact images.

9 Conclusions

The ACC-E penetrometer made a single direct measurement of the mechanical properties and texture of the surface material at the Huygens landing site. Comparative analysis of the returned signature with those of terrestrial analogues taken together with measurements from other instruments allows an interpretation of the surface material to be made. This work suggests that the penetrometer is likely to have impacted a thin, extremely weak surface coating overlying a small, hard substrate material granule before being driven into a coarse granular sand substrate possibly wet with liquid methane.

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Figure captions

Figure 1. Schematic of the SSP instrument showing the location of the penetrometer at the base of the probe immediately behind the ablative heat shield. Dimensions of the penetrometer and the approximate position of the Electromagnetic Compatibility (EMC) screen are shown. (Upper Image credit James Garry)

Figure 2. ACC-E penetrometry signature returned from the surface of Titan calibrated and processed into force against depth, including correction for the transfer function of the electronics. No smoothing has been applied. The penetration analysis stages are marked.

Figure 3. Free fall drop rig arrangement and data acquisition equipment. For the purposes of comparison with the flight data impact speed of 4.6 m s^{-1}, the drop height of the penetrometer above the target surface was set to 1.07 m. Bottom: schematic diagram of signal and data processing paths for the flight and laboratory data.

Figure 4. Illustration of the peak and trough finding algorithm. The search starts from the beginning of target penetration and identifies candidate peaks and troughs. To be accepted each candidate peak and trough must have a significant rise and fall on either side. The significance is based on the standard deviation of the noise on the signal as the penetrometer falls prior to impact.

Figure 5. Mean peak-to-trough force amplitude plotted against bead mass for 31 drops into plastic and glass bead targets. Standard errors are marked when larger than the data point.

Figure 6. Equipment used to produce a moisture gradient in sand with minimum mechanical disturbance using a siphon principle. Moisture content was measured prior to each drop using a ThetaProbe inserted into the sides of the container. Sampling points were offset to minimise sand disturbance.

Figure 7. Penetrometry signatures for dry RH T (fine grained) sand in two densities, achieved by physical compaction of the target. Impact is at 4.6 m s^{-1}.

Figure 8. Penetrometer signature for dry LB (coarse grained) sand in loose and dense state showing noticeably greater tip entry impact peaks than those seen in the finer RH T sand. Impact speed is 4.6 m s^{-1}.

Figure 9. Penetrometer signature for RH T (fine grained) sand with water: (a) saturated sand (water table height z=350 mm) (b) water table at z = 250 mm (c) water table at z = 200 mm (d) water table at z = 150 mm.

Figure 10. Penetrometer signatures for wet LB (coarse grained) sand: (a) saturated sand (water table height z = 350 mm) (b) water table at z = 250 mm (c) water table at z = 200 mm (d) water table at z = 150 mm.

Figure 11. Penetrometer signature of a drop into loosely packed snow at Huygens impact speed. The signature from the probe (grey) has also been plotted for comparison of the initial entry force (arrowed). The snow signature indicates the variation in density with depth of the material probably caused by packing it into the target container.

Figure 12. Penetrometry signature from Huygens overlaid on the closest analogue match for the third stage (substrate) material, wet Leighton Buzzard coarse sand with a water table 150 mm below the sand surface (i.e. z=200). The flight signature has been shifted horizontally (but not rescaled) to align the third stage with the start of the analogue drop. Penetration speed in both cases is 4.6 m s^{-1}.

Figure 13. Surface material identification using two signature parameters. Parameters exclude the first 1 cm 'tip entry' of signature for comparative purposes with the Huygens third stage of signature. Where multiple drops of an analogue are available averages have been taken and standard errors are shown. There is a marked difference between the flight data's signature gradient compared to the terrestrial analogues.

Figure 1

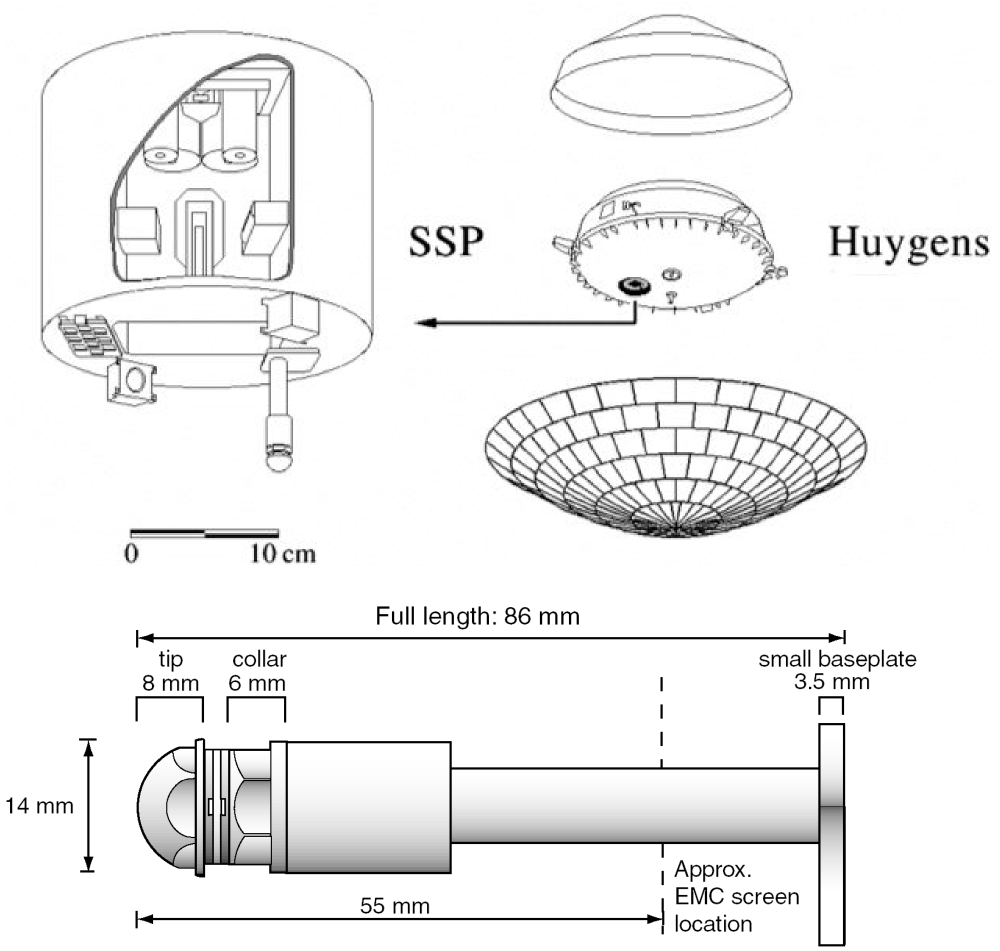
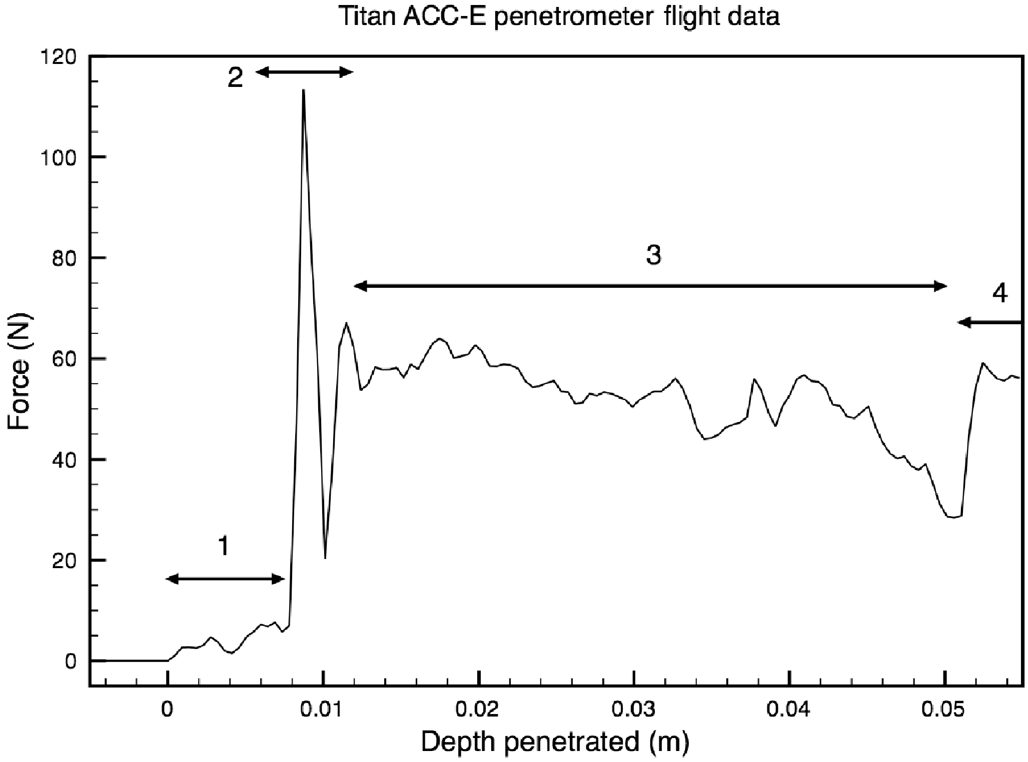
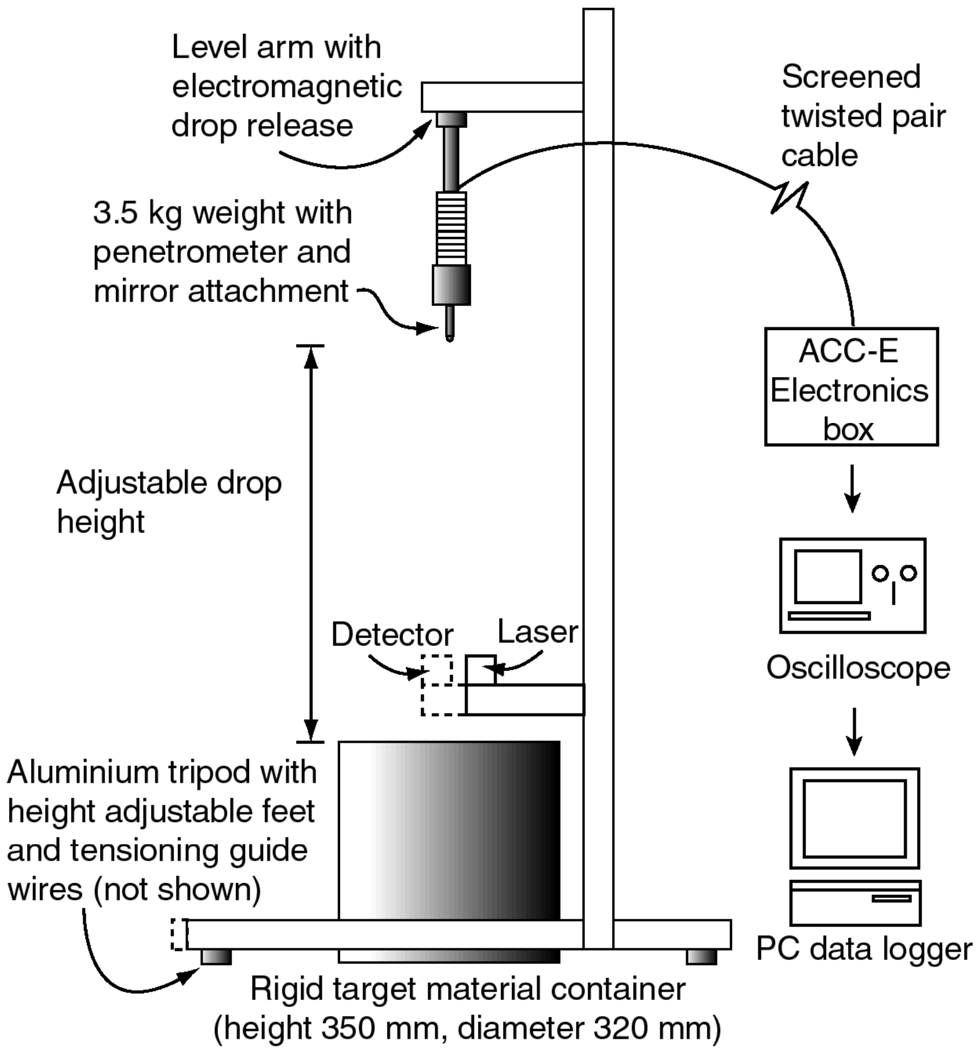

SSP
Huygens
0
10 cm
Full length: 86 mm
tip
8 mm
collar
6 mm
small baseplate
3.5 mm
14 mm
55 mm
Approx.
EMC screen
location

Figure 2



Titan ACC-E penetrometer flight data
Force (N)
Depth penetrated (m)
0
20
40
60
80
100
120
0
0.01
0.02
0.03
0.04
0.05
1
2
3
4

Figure 3


Level arm with electromagnetic drop release
Screened twisted pair cable
3.5 kg weight with penetrometer and mirror attachment
ACC-E Electronics box
Adjustable drop height
Oscilloscope
Detector
Laser
Aluminium tripod with height adjustable feet and tensioning guide wires (not shown)
PC data logger
Rigid target material container (height 350 mm, diameter 320 mm)

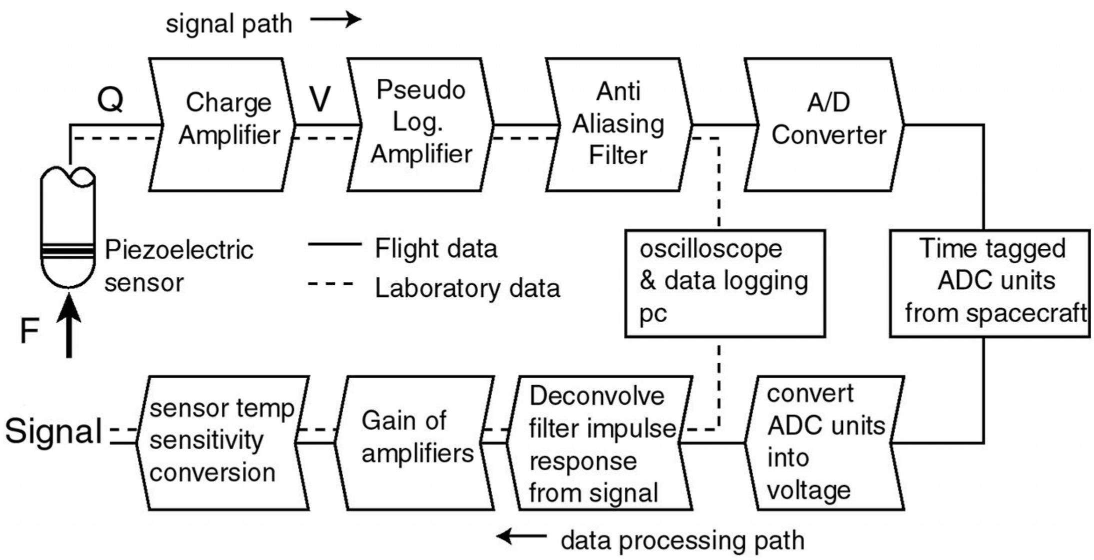
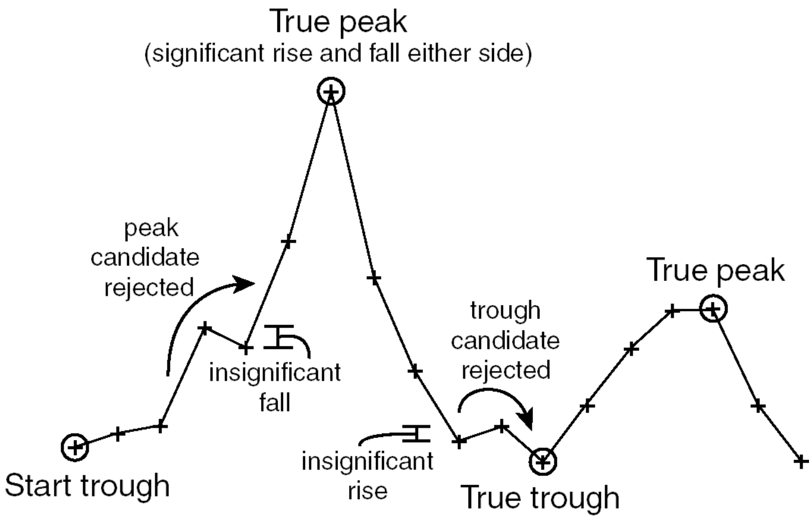

signal path
Q
Charge Amplifier
V
Pseudo Log. Amplifier
Anti Aliasing Filter
A/D Converter
Piezoelectric sensor
Flight data
Laboratory data
oscilloscope & data logging pc
Time tagged ADC units from spacecraft
F
Signal
sensor temp sensitivity conversion
Gain of amplifiers
Deconvolve filter impulse response from signal
convert ADC units into voltage
data processing path

Figure 4



True peak
(significant rise and fall either side)
peak
candidate
rejected
insignificant
fall
True peak
trough
candidate
rejected
insignificant
rise
Start trough
True trough

Figure 5

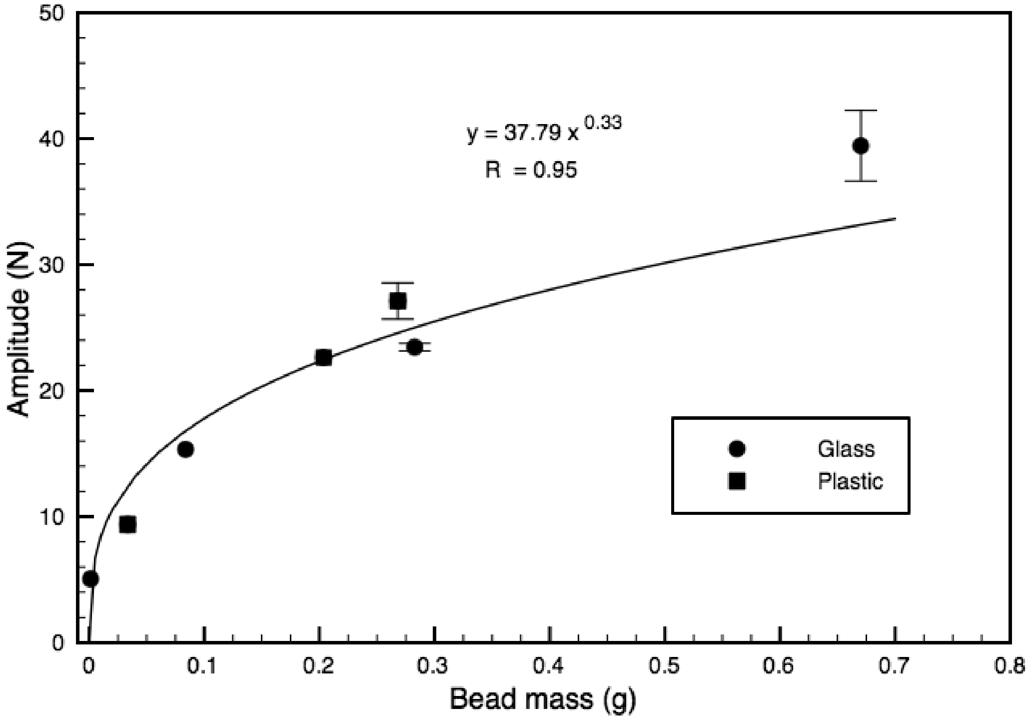

y = 37.79 x 0.33
R = 0.95
Glass
Plastic
Amplitude (N)
Bead mass (g)
0
10
20
30
40
50
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Figure 6

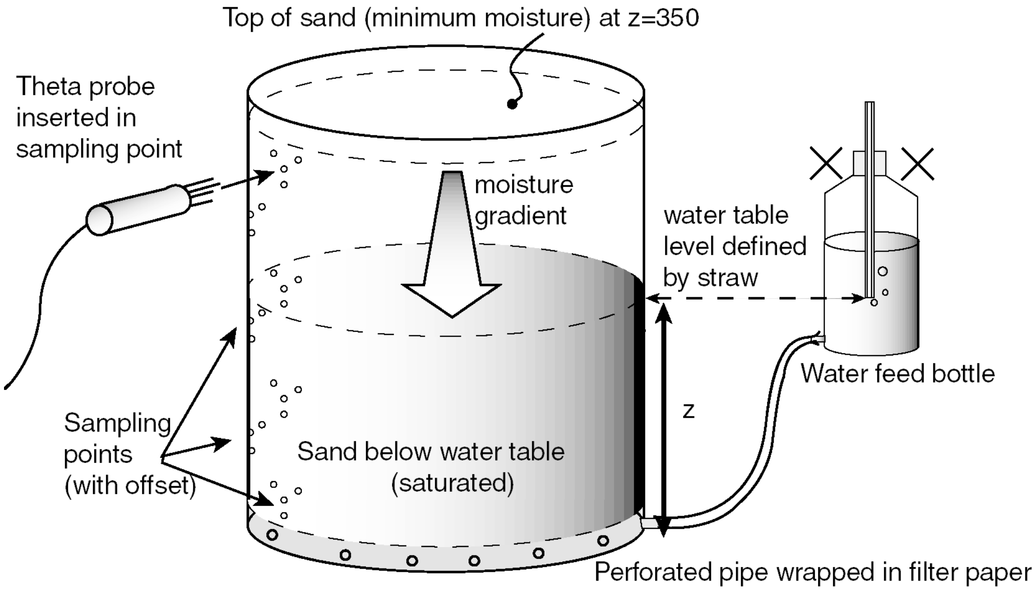

Top of sand (minimum moisture) at z=350
Theta probe inserted in sampling point
moisture gradient
water table level defined by straw
Water feed bottle
z
Sampling points (with offset)
Sand below water table (saturated)
Perforated pipe wrapped in filter paper

Figure 7

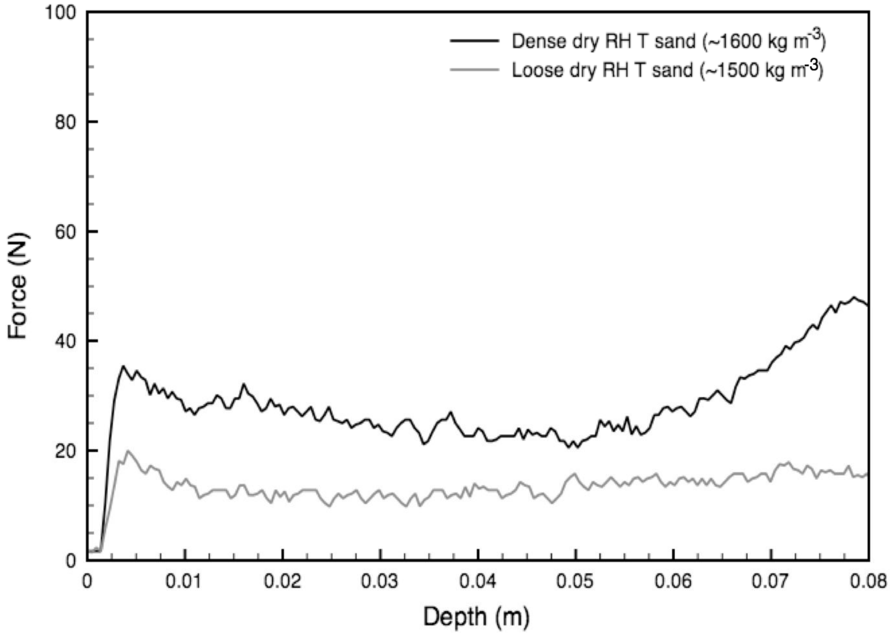

Dense dry RH T sand (~1600 kg m^{-3})
Loose dry RH T sand (~1500 kg m^{-3})
Force (N)
Depth (m)
0
20
40
60
80
100
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

Figure 8

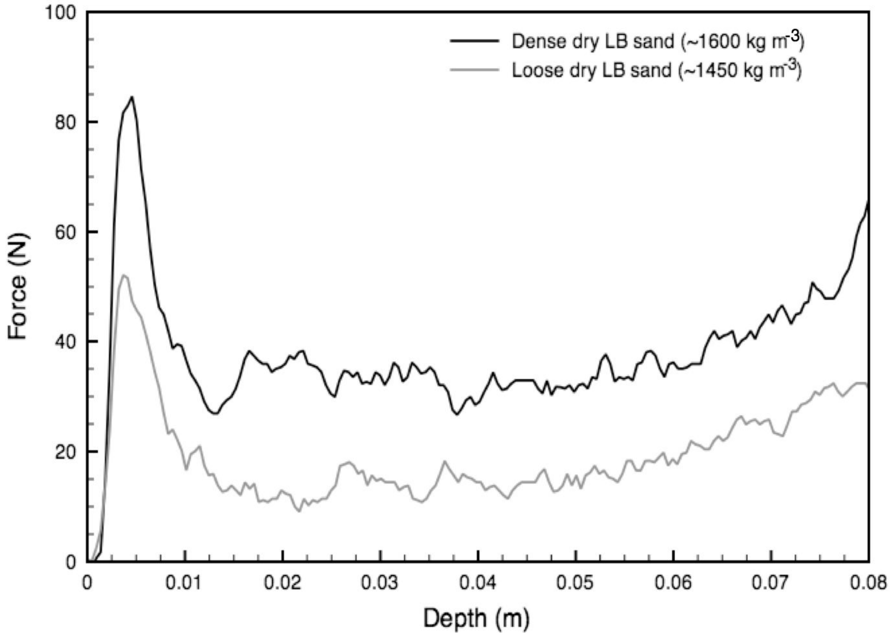
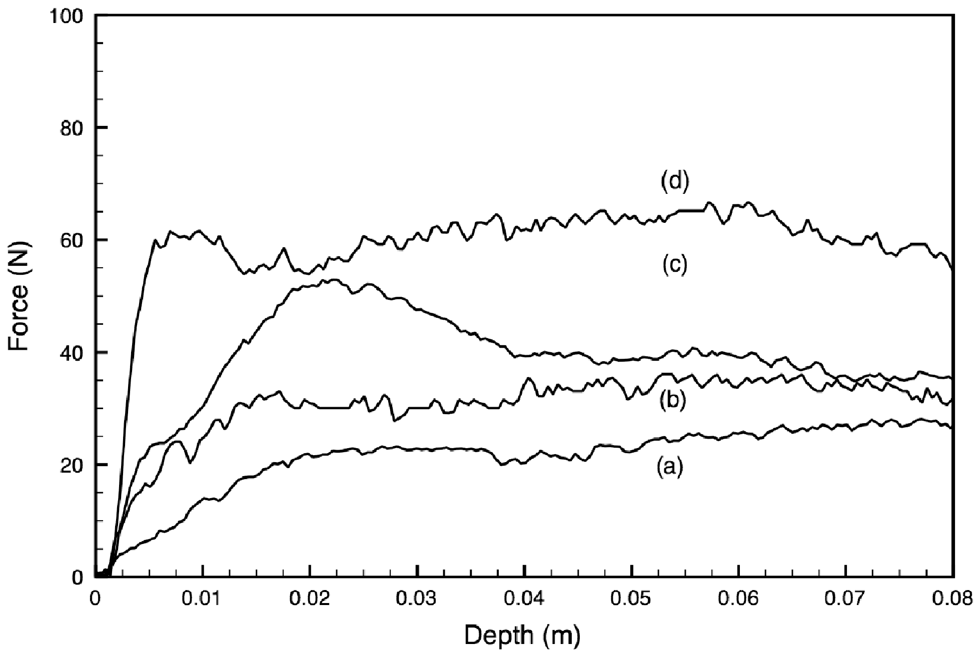

Dense dry LB sand (~1600 kg m-3)
Loose dry LB sand (~1450 kg m-3)
Force (N)
Depth (m)
0
20
40
60
80
100
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

Figure 9



100
80
60
40
20
0
Force (N)
(d)
(c)
(b)
(a)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
Depth (m)

Figure 10

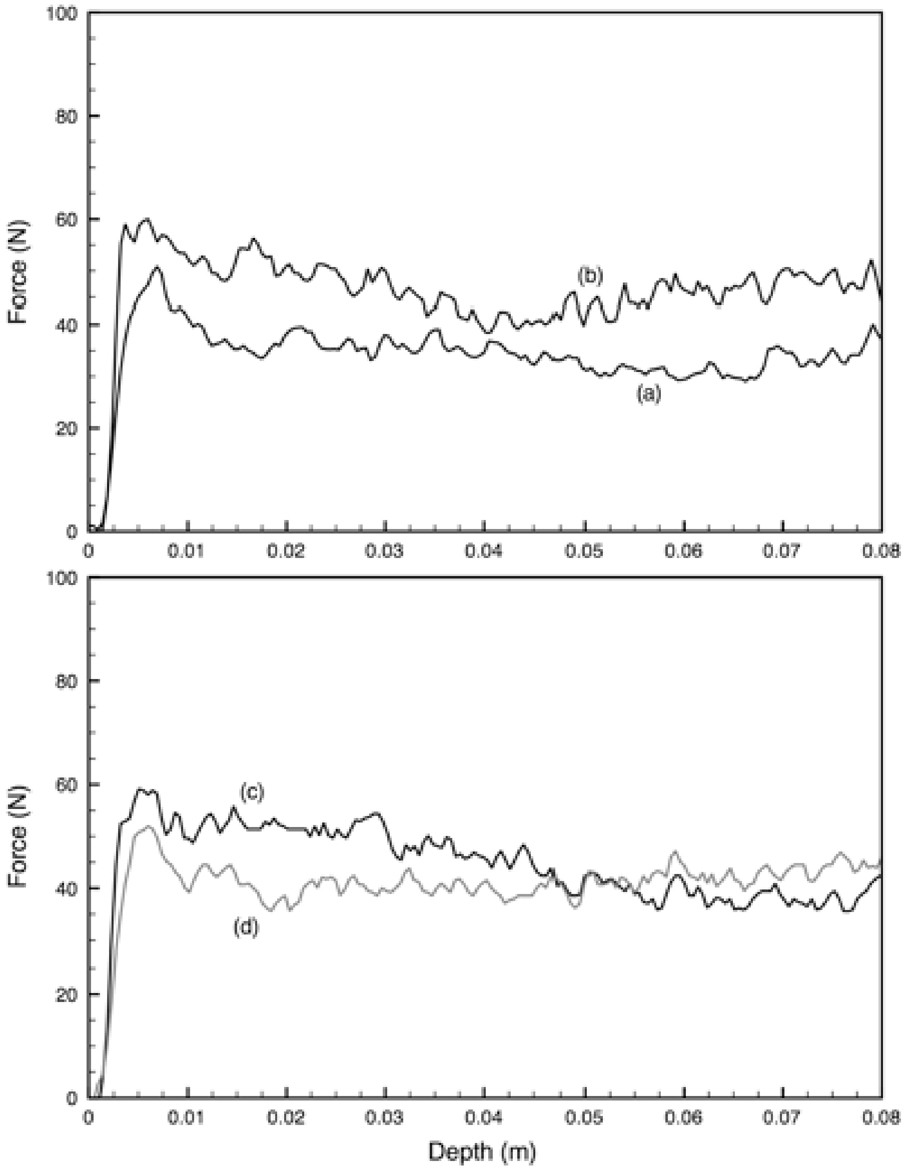

Force (N)
Depth (m)
(a)
(b)
(c)
(d)
0
20
40
60
80
100
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08

Figure 11

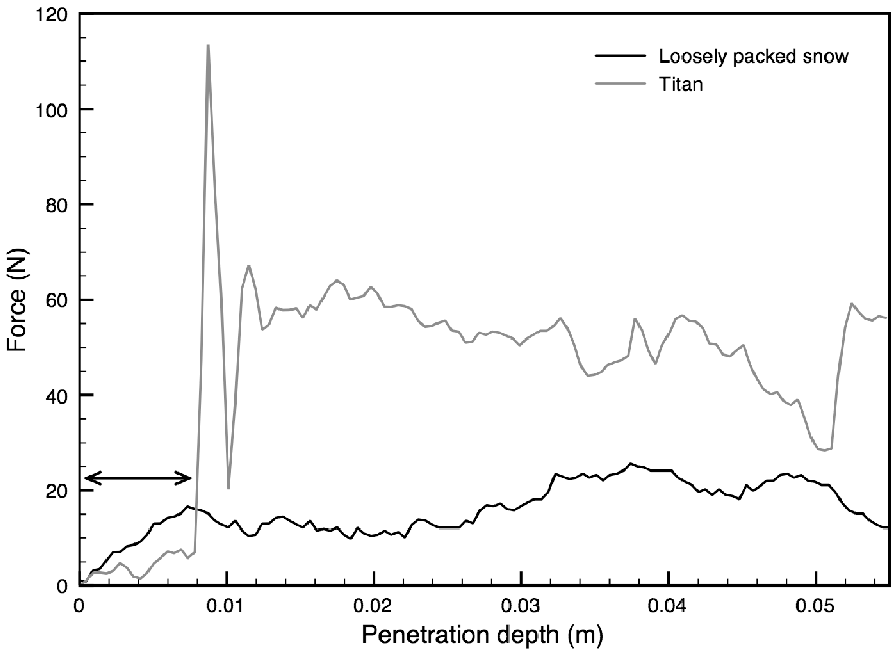
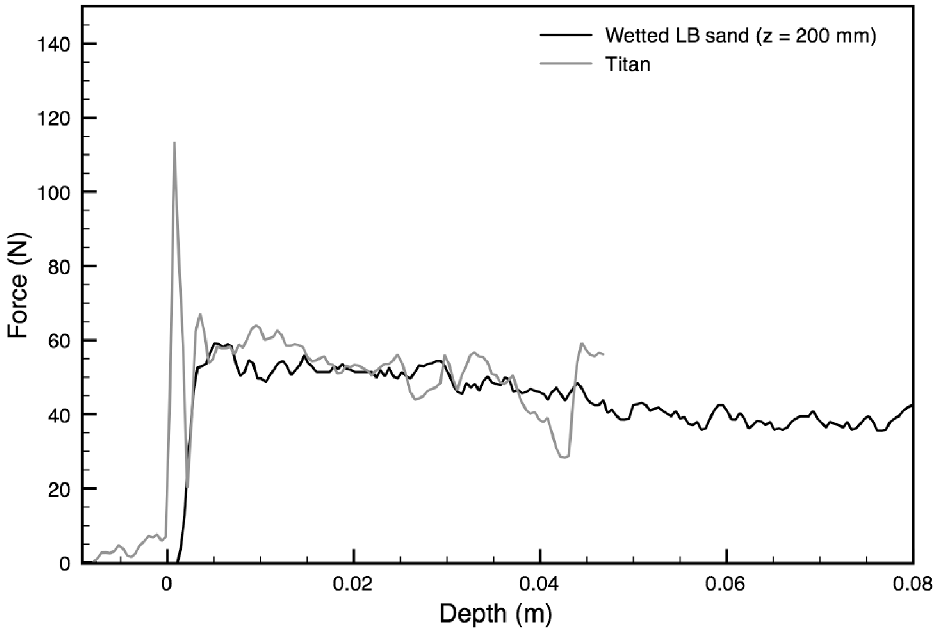
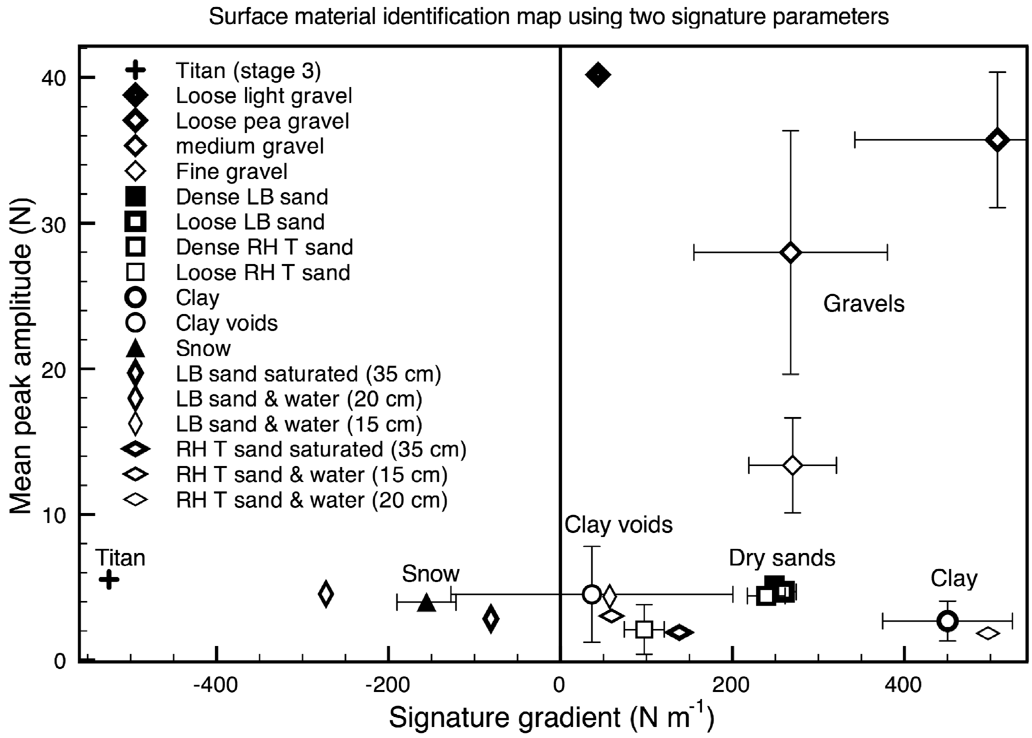

Loosely packed snow
Titan
Force (N)
Penetration depth (m)
0
20
40
60
80
100
120
0
0.01
0.02
0.03
0.04
0.05

Figure 12



Wetted LB sand (z = 200 mm)
Titan
Force (N)
Depth (m)
0
20
40
60
80
100
120
140
0
0.02
0.04
0.06
0.08

Figure 13


Surface material identification map using two signature parameters
Titan (stage 3)
Loose light gravel
Loose pea gravel
medium gravel
Fine gravel
Dense LB sand
Loose LB sand
Dense RH T sand
Loose RH T sand
Clay
Clay voids
Snow
LB sand saturated (35 cm)
LB sand & water (20 cm)
LB sand & water (15 cm)
RH T sand saturated (35 cm)
RH T sand & water (15 cm)
RH T sand & water (20 cm)
Gravels
Clay voids
Dry sands
Clay
Titan
Snow
Mean peak amplitude (N)
Signature gradient (N m-1)
0
10
20
30
40
-400
-200
0
200
400