Experimental Investigation of InSight HP3 Mole Interaction with Martian Regolith Simulant

Jason P. Marshall, Troy L. Hudson & José E. Andrade
Experimental Investigation of InSight HP³ Mole Interaction with Martian Regolith Simulant
Quasi-Static and Dynamic Penetration Testing

Jason P. Marshall¹ · Troy L. Hudson² · José E. Andrade¹

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Abstract The InSight mission launches in 2018 to characterize several geophysical quantities on Mars, including the heat flow from the planetary interior. This quantity will be calculated by utilizing measurements of the thermal conductivity and the thermal gradient down to 5 meters below the Martian surface. One of the components of InSight is the Mole, which hammers into the Martian regolith to facilitate these thermal property measurements. In this paper, we experimentally investigated the effect of the Mole’s penetrating action on regolith compaction and mechanical properties. Quasi-static and dynamic experiments were run with a 2D model of the 3D cylindrical mole. Force resistance data was captured with load cells. Deformation information was captured in images and analyzed using Digital Image Correlation (DIC). Additionally, we used existing approximations of Martian regolith thermal conductivity to estimate the change in the surrounding granular material’s thermal conductivity due to the Mole’s penetration. We found that the Mole has the potential to cause a high degree of densification, especially if the initial granular material is relatively loose. The effect on the thermal conductivity from this densification was found to be relatively small in first-order calculations though more complete thermal models incorporating this densification should be a subject of further investigation. The results obtained provide an initial estimate of the Mole’s impact on Martian regolith thermal properties.

Keywords Penetrator · Regolith · DIC · Dynamic · Quasi-static · Thermal conductivity

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J.E. Andrade
jandrade@caltech.edu

J.P. Marshall
jmarshal@caltech.edu

T.L. Hudson
Troy.L.Hudson@jpl.nasa.gov

¹ Mechanical and Civil Engineering Department, California Institute of Technology, Pasadena, CA, USA
² Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

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1 Introduction

The InSight (Interior Seismic Investigations, Geodesy and Heat Transport) lander currently scheduled to launch in May of 2018 is tasked with geophysical characterization of Mars. One of the primary instruments to be deployed from InSight is the HP3 (Heat Flow and Physical Properties Package), a contribution to InSight from the German aerospace center DLR (Deutsches Zentrum für Luft- und Raumfahrt). The main purpose of the HP3 is to determine the heat flow from the planetary interior \( q \), at the landing site to within \( \pm 5 \) mW/m\(^2\). This quantity will be determined using Fourier’s law of heat transfer, see Eq. (1),

\[
q = -k \nabla T, \tag{1}
\]

where \( k \) is the thermal conductivity and \( \nabla T \) is the temperature gradient (Kömle et al. 2011; Grott et al. 2007; Cornwall and Hagermann 2016). The HP3 will provide measurements of the thermal conductivity and the temperature gradient, allowing Eq. (1) to be solved for the heat flux.

These measurements will be collected by penetrating up to 5 meters into the Martian subsurface with a self-contained hammering apparatus called the “Mole”. The Mole is a cylindrical body with a conical tip, 396 mm in length and 27 mm in diameter. It consists of an internal electromechanical hammering mechanism (motor, gearbox, driveshaft, cam, hammer, and springs), a payload compartment containing tilt sensors, and heater foils embedded in its outer skin. The internal hammering cycle compresses several springs and releases two primary hammering masses periodically, approximately once every 3.1 seconds, see Fig. 1 for a schematic of the hammering cycle. A hammering cycle lasts no more than 200 ms, but multiple downward thrusts occur due to the two hammering masses. This double tap hammering action drives the Mole forward into the granular material at a typical rate of between 0.1 and 1 mm per stroke (slower when deeper). We note that higher penetration rates have occurred during testing, but are not typically seen.

As the Mole penetrates, a science tether (different from the engineering tether, which connects the InSight lander and the HP3 support structure) is pulled behind that provides both power/data to/from the Mole, but is also instrumented with temperature sensors. The Mole’s depth and penetration path are tracked and determined using a tether length monitor and tilt measurement suite that are part of the HP3. The HP3 is instrumented in such a way that it measures the thermal conductivity of the surrounding regolith during rest intervals between each hammering cycle (each cycle aims to increase mole tip depth by 50 cm). A transient hot wire method (Hammerschmidt and Sabuga 2000) will be used to conduct these measurements. Similar methods were used during the Apollo missions and a subsequent analysis conducted by Grott et al. (2010) is particularly relevant to understanding the complexities involved. Following the end of penetration, the temperature sensors remain in the subsurface and monitor the temperature at various depths for 1 Mars year. More details about the measurements and their requirements can be found in Grott et al. (2007), Spohn et al. (2012).

The specifics of the HP3 and Mole’s deployment on Mars can be described in several distinct phases (Spohn et al. 2012).

1. The HP3 support structure is placed on the Martian surface by a deployment arm on the InSight lander, in the process releasing the engineering tether with its power and communication connections.
2. The Mole with the integrated HP3 sensors and heaters is released from the HP3 support structure and drops under Martian gravity, slightly embedding itself into the surface.
Fig. 1 A single penetration cycle of the Mole is shown. Penetration occurs during two main hammering events caused by different masses $m_1$ (green component) and $m_2$ (blue component). These masses are raised by springs within the Mole and strike the outer hull in step 3 for $m_1$ and step 7 for $m_2$. The result is a double tap hammering action that propels the entire Mole into a granular material. The specific details of the full hammering cycle can be found in Lichtenheldt et al. (2014).

3. The Mole’s internal hammering mechanism is used to penetrate the surface 50 cm pulling the science tether with it.

4. The Mole rests for a period of time to allow thermal equilibrium before injecting a known quantity of heat with thermal foil heaters within the hull of the Mole. Using the known heat input from the heater foils and the subsequent change in temperature measured, the thermal conductivity can be calculated.

5. Steps 3 and 4 are repeated until the Mole reaches its target depth of 5 meters (or until downward penetration is no longer possible).

6. Upon achieving the final depth, the trailing sensors will monitor the temperature at various depths.

At the end of the deployment cycle, the HP$^3$ will have provided measurements for the thermal conductivity of the Martian regolith along the path of the instrumented tether. These conductivity measurements will also be independently calculated and validated using thermal diffusivity measurements obtained from the attenuation of the annual temperature wave, similar to approaches used during Apollo missions (Langseth et al. 1976). The temperature gradient along the tether will then be monitored for up to 1 Mars year (the duration required...
to reach the desired gradient accuracy will depend on the ultimate penetration depth below the influence of the annual thermal wave). This data will be used to achieve the scientific objective of calculating the heat flux at the landing site. The results of this work will lead to a better understanding of Mars’ formation; radioisotope inventory; crustal thickness and mantle evolution; and climate history (Banerdt et al. 2011; Dehant et al. 2012; Lorenz 2015).

The Mole’s hammering action, while enabling penetration, also affects the in-situ properties of the regolith into which it burrows. Specifically, the density of the granular material surrounding the Mole can be altered due to the Mole’s penetration since it works by pushing material out of the way of its advancing nose and body, rather than excavating it to the surface. The density of the regolith is important as it can both influence the rate of penetration (Seweryn et al. 2014a; Hansen-Goos et al. 2014) and can affect the thermal properties that the HP3’s sensors seek to measure. As the Mole penetrates into regolith, the granular material already passed collapses. The re-collapsed material will likely possess a different density than the native regolith as it rests against the tether and its embedded thermal sensors. As the tether sensors are passive monitors, this density change from native regolith density along the tether will not affect the long-term gradient measurements after equilibration. However, the active thermal conductivity measurements performed by the mole body itself during the penetration phase are transient in nature and will be directly influenced by regolith density differences around the mole body.

Thermal conductivity in granular materials is a highly environmentally dependent quantity depending on many factors. These factors include atmospheric pressure (Huetter et al. 2008), density (Abu-Hamdeh and Reeder 2000; Chen 2008), water or moisture content (Al Nakshabandi and Kohnke 1965; Chen 2008), salt concentration and organic content (Abu-Hamdeh and Reeder 2000), granular mineralogy (Chen 2008), stress state (Pilbeam and Vaišnys 1973), and particle size distribution (Chen 2008; Huetter et al. 2008; Jakosky 1986). In the context of the Mole’s penetration into Martian regolith the most likely factors affected are the density and stress state of the regolith. This work primarily focuses on the affects from the change in density during penetration. However, the change in stress state of the regolith from the Mole could have a non-negligible increase or decrease on the thermal conductivity (Pilbeam and Vaišnys 1973) and warrants further investigation.

Multiple studies of Martian thermal conductivity have occurred (Jakosky 1986; Fountain and West 1970; Huetter et al. 2008; Presley and Christensen 1997a,b,c, 2010a,b; Presley and Craddock 2006), with a typically assumed form of \( k = k_g + k_s + k_r \), where \( k_g \) is the conduction by the gas between particles, \( k_s \) is the conduction within a particle and between contacting particles, and \( k_r \) is the thermal radiation within and between particles (Presley and Christensen 1997a). The radiation term is proportional to the temperature cubed and its contribution is dominated by the other terms in the low temperature environment encountered on Mars (Watson 1964; Presley and Christensen 1997a). Additionally, due to heat build up between particle contacts, \( k_s \) is significantly reduced with respect to the gaseous conduction term, \( k_g \) (Presley and Christensen 1997a). The end result is that \( k_g \) becomes the dominant mechanism for thermal conduction in granular media. This is particularly important for Martian thermal investigations, because of the atmospheric composition and low pressure. Thus, the bulk thermal conductivities of Martian regoliths are expected to be much lower than the conductivities of terrestrial soils. However, there is still a great deal of uncertainty about Martian thermal conductivity in the absence of actual measurements. Even with measurements, interpreting results can be quite challenging as highlighted by the examination of thermal experiments conducted during the Apollo missions by Grott et al. (2010). In this paper, we assume a thermal conductivity function from Presley and Christensen (1997a) to get a rough estimate of what to expect on Mars and to investigate the impacts that a change
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![Image](image-url)

**Fig. 2** (a) Front view of penetrator tip embedded into regolith simulant in the testing setup. A) Backfilling caused after penetrator has passed. B) Mole penetrator with 2D representation of actual cylindrical geometry. The narrow neck simulates the back end of the mole and the trailing tether. This is important due to the backfilling that occurs during penetration. C) Martian regolith simulant. (b) 3D isometric view of penetrator used during testing. D) Side of penetrator that will be embedded in sand. E) Front of penetrator that will abut against the plexiglass face of the experimental setup, which can then be imaged.

In density due to the Mole’s penetration could have on the thermal conductivity. We note that quantifying the impact on the actual thermal conductivity measurements is beyond the scope of this paper due to the subtleties of how the measurements will be conducted.

In addition to investigating the influence on thermal conductivity from the change in density, we also investigate the impact of penetration by the Mole on the mechanical properties of a granular material. Numerical simulations and analyses of the Mole’s penetration are available (Kömle et al. 2015; Lichtenheldt et al. 2014; Seweryn et al. 2014b), but experimental results, specifically regarding regolith force resistance and deformation, appear to be more limited in availability. In the remainder of this paper, we detail the experimental setup developed and the results of the effects of penetration on regolith thermal conductivity and force resistance.

## 2 Experimental Setup

The penetrator experiments were conducted on a hydraulic uniaxial load frame. All tests were displacement controlled with the hydraulic push rod. Forces were captured by mounting an external 1.3 kN load cell directly to the push bar. The penetrator was mounted to the load cell with an aluminum connector bar and guide rails to prohibit rotations. The actual HP³ Mole is a 396 mm × 27 mm cylinder with a mass of approximately 900 g. The Mole moves forward during penetration cycles that occur approximately every 3.1 seconds. In the experiments conducted, we used a penetrator that was a shorter 2D representation, see Fig. 2, of the full 3D cylindrical shape. The cross-sectional shape of the penetrator was machined to match the curvature of the actual penetrator tip. A narrow neck was used above the penetrator tip to approximate the effect of both a trailing tether during the Mole’s deployment and allowing for borehole collapse.

We used dry Ottawa 20–30 testing sand as a Martian regolith simulant for all tests. The sand was contained in a 445 × 394 × 152 mm aluminum box with a 13 mm-thick plexiglass face. In all tests, the face of the penetrator was exactly aligned with the plexiglass to not
allow any sand between them. Ottawa 20–30 testing sand is classified as round with dry densities, $\rho$, between 1520 and 1765 kg/m$^3$ (Cho et al. 2006). The sand is uniformly graded between 650 and 850 micrometers following ASTM C778 (2013). This testing sand was chosen primarily for its imaging properties, i.e. large enough particle size and a mix of black and white grains. Additionally, the sand’s density range almost exactly overlaps the densities at the Viking and Pathfinder landing sites (Seiferlin et al. 2008) and the density range at the InSight landing site of 1600 and 1800 kg/m$^3$ assumed by Plesa et al. (2016). We do note that the density is on the higher side of many Martian regolith simulants (Hansen-Goos et al. 2014). One difference between the testing sand and the expected Martian regolith is the particle size distribution, where a less uniform distribution is expected on Mars. In this work, we only test Ottawa 20–30 sand, though future work will investigate the importance of different particle size distributions and other granular properties.

We use relative density, $D_r$ (Holtz and Kovacs 1981), a measure of compaction state which is the ratio of the current density to the maximum and minimum densities (see Eq. (2)), to quantify the initial state of the sand.

$$
D_r = \frac{1/\rho_{\text{min}} - 1/\rho_{\text{current}}}{1/\rho_{\text{min}} - 1/\rho_{\text{max}}} \times 100 \% \tag{2}
$$

Tests were conducted with sand prepared in a loose state with a relative density of approximately 18% obtained via emplacement by pouring and in a denser state obtained via post-emplacement tamping (tamping occurred from the top surface six times or approximately every 60 mm of deposited material) with a relative density around 82%. It is important to note that the chosen regolith simulant has a narrow density range with a difference of less than 300 kg/m$^3$ between the maximum and minimum densities. Martian regolith is expected to be more poorly sorted, resulting in a larger relative density range. Additionally, the loose sample’s 18% relative density is lower than values typically seen in naturally deposited granular material including several Mars regolith simulants (Perko et al. 2006). Hence, while the loose sample has a bulk density that could realistically be found on Mars, the low relative density is unlikely to be seen.

There were two types of loading profiles employed in these experiments, quasi-static and dynamic. The quasi-static loading profiles, where the penetrator was pushed at a constant rate of displacement, were similar to traditional penetrometry tests and were simpler to perform and understand. The dynamic loading profiles comprised short-duration, high-velocity displacements that approximated the Mole’s motion and the introduction of impulse energy into the regolith. Teflon sheeting was placed on the penetrator face during quasi-static loadings to minimize frictional forces with the plexiglass. Frictional forces were measured during this loading profile with no sand present and were 4.5 N or less at all times. The teflon sheeting could not be used during dynamic loadings, causing the frictional forces to increase in addition to higher inertial effects. These larger frictional and inertial forces were captured without sand present and subsequently subtracted from the forces obtained with sand present (see Sect. 3 for more details). In total, this setup allowed capturing of the 2D deformation of the sand on the plexiglass face with a camera for subsequent analysis. Figure 3 shows the complete setup.

The quasi-static loading profile consisted of a single downward penetration to 102 mm at a constant rate of approximately 6 mm per minute. Digital images were taken every 2 seconds for analysis of the penetration; see Fig. 2 for a sample image. The dynamic experiments consisted of 21 cycles of a double-tap displacement validation loading profile (Lichtenheldt et al. 2014), as shown in Fig. 4. While the input displacement profile was reasonably replicated it was not exact as the hydraulic testing machine was pushed to its control limits. The
Fig. 3 Penetrator experimental setup. 
a) 13.3 kN hydraulic load frame. 
b) Displacement controlled push bar. 
c) Guide rails to prevent rotation of penetrator. 
d) 1.3 kN load cell. 
e) Penetrator (this is not the actual penetrator used in the experiments). 
f) Sand box with plexiglass windows for imaging. 
g) Support base with attached guide rails.

The total displacement for the combined 21 cycles was just over 105 mm. The individual cyclical loading profile was similar to the expected displacement of the Mole in granular material, but was not the expected profile on Mars because of a higher kickback after the initial downward strike and larger penetration depths. This kickback height is the positive displacement peak that can be seen in Fig. 4(a). While the penetration per cycle is larger than expected on Mars, the dynamic loading profile serves as close to an upper bound, most likely maximizing the impact of dynamic loading. Further investigation is needed on a range of dynamic loading profiles, potentially augmented with penetration data from the tether length monitor during deployment on Mars. We do note that we were able to achieve the correct time scale for Mole penetration with a full cycle taking approximately 150 milliseconds. Each of the 21 cycles were captured using a high speed camera with a frame rate of 2000 frames per second. In all experimental tests the force on the penetrator and the downward displacement of the penetrator tip were recorded at a frequency of 1024 Hz.

3 Analysis

Images captured during quasi-static penetration were analyzed using digital image correlation (DIC). Specifically, we used VIC-2D, by Correlated Solutions, Inc for the analysis. This method tracks the changes in speckle patterns within a series of images. For solid materials, like metals, the speckle pattern is typically painted on, while in our case the different colors of sand grains provide the speckle pattern when a black and white image is taken. The method then calculates 2D strain fields from the deformed speckle patterns, which we subsequently used to calculate volumetric and maximum shear strains. More information about DIC can be found in Sutton et al. (1983) or Sutton et al. (2009). The instantaneous density, \( \rho \), was also calculated using the strain fields and the standard continuum expression.
Fig. 4 Dynamic displacement loading curves. (a) A single dynamic displacement loading cycle of the penetrator from hydraulic load frame. Both the input validation curve (Lichtenheldt et al. 2014) and resulting curve are shown. It is important to note that this displacement loading cycle is similar to, but not exactly the expected displacement profile in Martian regolith. The curve has a higher penetration depth and kickback, which serves as an upper bound to maximize the impact of dynamic loading. (b) Collection of 21 repetitive dynamic displacement loading cycles (Mase et al. 2009),

\[ \rho = \frac{\rho_0}{\det(I + \text{grad}(\mathbf{u}))}, \]  

where \( I \) is the identity tensor, \( \text{grad}(\mathbf{u}) \) is the displacement gradient, and \( \rho_0 \) is the initial density, which we assumed to be spatially uniform. Thus, subsequent analysis allowed the calculation of the change in density and the area of influence due to the penetration.

Laboratory experiments conducted by Presley and Christensen (1997a) determined estimates of upper and lower bounds for thermal conductivity of Martian regolith as a function of density, see Fig. 5. In this work, we used the upper bound to obtain an estimate of the change in thermal conductivity due to penetration. The specific function, similarly used in Grott et al. (2010) though including the influence of lithostatic pressure, is shown below:

\[ k(\rho) = k_0 + \rho \frac{\partial k}{\partial \rho}, \]  

where \( k_0 = 0.025 \ \text{Wm}^{-1} \ \text{K}^{-1} \) and \( \frac{\partial k}{\partial \rho} = 14 \times 10^{-6} \ \text{Wm}^2 \ \text{kg}^{-1} \ \text{K}^{-1} \). These specific parameter values were also used in related InSight work conducted by Plesa et al. (2016). We note that care needs to be taken when extrapolating the change in thermal conductivity estimates to the measurements that the Mole will perform on Mars, as the actual measurement technique needs to be incorporated in the analysis.

In addition to the digital image analysis, force data was collected for both the static and dynamic loading cases. Due to the force load cell being directly attached to the displacement controlled push bar, inertial forces, while negligible during quasi-static loading, were high in the dynamic loading case. The inertial forces were captured over 3 sets of 21 cyclical loadings to generate an average inertial force profile without any granular material present. These forces were then subtracted from the force data collected when the regolith simulant was present.
4 Results

4.1 Quasi-Static Loading—DIC

Figure 6 shows the DIC results for the quasi-static penetration of the regolith simulant. Videos of all the results can be found in the supplemental information. A couple of key trends were seen in the data. We note that the max shear strain in both the loose and dense samples, while having a similar influence area, have different influence area shapes. The loosely prepared sample had a rectangular influence area in comparison to the more conical shape in the densely prepared sample. This shape led to a larger zone of influence beneath the penetrator tip in the loose sample. Conversely, the denser sample had a much wider zone of influence on the top surface of the particulate material. The denser sample also had surface bulging as expected in a granular material with a high relative density.

Differences between loosely and densely prepared samples were also evident in terms of the relative density. The looser sample showed a much larger increase in relative density as compared to the denser sample as would be expected, but the maximum relative density was not achieved over large areas. Instead a relative density of 50–80% was achieved out to around 3 diameters of the penetrator thickness. We also note that the localized pockets of higher relative density may have been areas where our assumption of a homogeneous initial density was not valid. In the densely prepared sample, while the percentage change was less than the loosely prepared sample, the relative density was higher, and the maximum value was reached for a reasonably large area.

With this updated density, we calculated the thermal conductivity and the change in thermal conductivity in areas next to the Mole. The effect of the penetrator was more pronounced in the loosely prepared sample as a fairly large area of regolith saw a roughly 5% increase in thermal conductivity. This area extended approximately two Mole diameters to either side and did not include any area below the Mole. The densely prepared samples saw very little change in thermal conductivity as there was only a small change in relative density up to the maximum value. It is important to note that due to limitations in the method, the area immediately adjacent to the penetrator cannot be resolved. However, this area is one of the most important regions from a thermal conductivity point of view and warrants further investigation in future work.

We were also able to extract relative density data along a variety of horizontal, diagonal, and vertical profiles (shown in Fig. 7a). Starting with the horizontal profiles, the loose sample increased in relative density at a linear rate from the edge of the field of detection to approximately 30 mm from the penetrator. At that point the relative density plateaued for
Fig. 6 Representative results of quasi-static penetration into a loosely and densely prepared regoliths. The shape of the penetrator is colored in black to clearly denote its position. The area immediately around the penetrator is fictitious due to limitations with the DIC method. This area is colored gray. (a)–(b) Max shear strain. (c)–(d) Relative density. Note that the loose started at 18 % (dark blue), while dense started at 82% (light blue). (e)–(f) Change in thermal conductivity.

A small distance, before an area of low trust with the DIC results was reached. A similar trend was seen in the dense sample, except that the linear increase in relative density occurred approximately 25–50 mm from the penetrator. In the dense sample, the peak relative density was slightly above the maximum theoretical value of 100 % by approximately 5 %.
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**Fig. 7**
The average change in relative density along different profiles for quasi-static loading is plotted. The average was calculated from 3 sets of experiments for both the loose and dense samples. Note the linear increase in the horizontal profiles as compared to the nonlinear increase in the vertical profile. All results were captured after full penetration into the regolith simulant. (a) Profile locations that were analyzed; the dark blue region around the penetrator produces invalid DIC data and is not considered in the profile analysis. (b) Average relative density along horizontal profiles for both loose and dense samples with a linear fit. (c) Average relative density along diagonal profiles at 45° for both loose and dense samples with a linear fit. (d) Average relative density along vertical profile for both loose and dense samples with a 4th order polynomial fit.

This occurred because we assumed a homogeneous average initial density, while in reality the top most layers of the simulant were a little looser than the average value. Hence these layers, corresponding to areas with the horizontal profiles, were able to consolidate to a slightly higher value than the theoretical maximum in our analysis. We also note that a 5% change in relative density over the maximum value is less than 15 kg/m$^3$ in this regolith simulant, a relatively small amount when compared to the theoretical density range of 1520 to 1765 kg/m$^3$. The varying density profile with depth, however, is important for the HP$^3$ thermal measurements and warrants further investigation without assumptions of a uniformly dense material. In addition to the individual results of the loose and dense sam-
ples, it is interesting to note that the rate of increase of the relative density was similar for both.

The results were different for the relative density along diagonal profiles, at a 45° angle from horizontal, starting at the penetrator tip. On these profiles, the relative density of the dense samples remained mostly constant. The loose sample increased at a slower rate than the horizontal profiles before plateauing around 40 mm from the penetrator tip. We do note, however, that the diagonal profiles in the loose samples had much larger error bars than all other profiles.

The relative density along the vertical profile saw little change from the initial values in both the loose and dense samples up to approximately 100 mm beneath the tip. Within 100 mm the relative density rapidly increased in the loose sample at a high, nonlinear rate. The relative density in the dense samples also increased nonlinearly, but at a much lower rate than the loose sample. It is interesting that the relative density increases in a clearly nonlinear way along the vertical profile. This nonlinear increase is in sharp contrast to the linear increase on the horizontal profiles. We note that in both the loose and dense samples there is a slight drop off in the relative density immediately before the artifacts region. We believe this downturn to be a real decrease in density, however, due to the closeness to the artifacts region more data is necessary to fully justify the decrease.

Overall, these results suggest that the changes in relative density during penetration are highly complex spatially with multiple regions of different behavior that are dependent on the initial relative density. We note that all these results assume a uniform initial density in the experimental setup, which adds a level of uncertainty to the results. A uniform density is also not expected during actual Mole deployment on Mars. Instead the density, coming from far away to the surface, is expected to remain fairly constant with moderate decreases up to a few meters below the surface. Within a few meters of the surface, the density is expected to rapidly decrease though the exact profile can only be assumed. Two of these assumed profiles can be found in Grott et al. (2007) and Plesa et al. (2016). The impacts of the expected rapidly varying density near the surface on our results are unknown, but warrant further investigation.

4.2 Dynamic Loading—Traveling Waves

The dynamic loading case provided quite different results from the quasi-static loading. The rapid acceleration of the penetrator created an impulse load on the regolith simulant, inducing a traveling wave. While the presence of a traveling wave was expected, the lack of dissipation in the system was not. Traveling waves captured with the high speed camera could be clearly seen propagating through the system, reflecting off bottom and side boundary walls, and returning to the penetrator and top surface. These traveling waves could help explain the densification that has also been observed during actual mole testing in metal cylinders with similar wave reflecting boundaries. Figure 8 highlights the traveling wave reaching the top regolith surface after reflecting off of boundary walls. Due to the large amount of reflections in the experimental setup acting to settle the granular particles into a densified state, the results reported most likely represent an upper bound on possible compaction. The Mole’s penetration into an unbounded regolith material will result in fewer, if any, wave reflections. However, there may be other factors including penetration depth and overburden pressure that play a different role when the reflections are smaller or absent. The densification during actual mole penetration in a half-space will likely still be less than in this small, self-reflecting volume, but there are subtleties that warrant further investigation in future work.
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Fig. 8 Loosely prepared granular material undergoing 21 cycles of dynamic penetration. Videos of all results can be viewed in the supplemental information. (a) Penetrator and regolith simulant in initial configuration with grid lines at every 40 pixels ($\approx$6.25 mm) for height comparison. (b) Penetrator and regolith simulant after 21 cycles of dynamic penetration with grid lines at every 40 pixels ($\approx$6.25 mm) for height comparison. (c) Example of wave reaching surface and deforming grains. (d) Example of wave reaching surface and launching grains from the surface, at times out of the entire enclosure

Unfortunately, while the high speed camera was necessary to capture deformations at the correct loading timescale, the resolution was not high enough to accurately use DIC methods to quantify the compaction. However, massive amounts of densification occurred, especially in the loosely prepared sample, where the change in height of the sand surface from the beginning to the end of loading could visibly be seen. Representative start and end heights are shown in Fig. 8(a)–(b). While spatially quantitative results were not possible with DIC, the full sample’s average density was roughly calculated upon completion of all loading cycles. Both the loose and dense cases were near the maximum relative density at the end of loading, with the average relative density for the loose sample increasing from 18 % to approximately 92 % and the average relative density for the dense sample increasing from 82 % to approximately the maximum density at 1765 kg/m$^3$. However, further investigation is needed with absorbing boundary conditions to minimize wave reflections. More accurate boundary conditions will lead to a more accurate representation of the response of an unbounded regolith to the Mole’s hammering action.

4.3 Quasi-Static and Dynamic Loading—Forces

Force results were captured for both quasi-static and dynamic loading. During quasi-static loading there were some distinct differences in the force resistance between the loose and dense samples, as shown in Fig. 9. In the loosely prepared sample, the resistance was almost completely linear, while the resistance in the denser sample was more non-linear though not to a high degree. Additionally, the slope of the resistance line was about 3.5 times as steep.
Fig. 9 Force resistance to quasi-static penetration. Note how the dense and loose sample force curves neither overlap nor converge for the quasi-static loading case, in contrast to the dynamic case shown in Fig. 10. (a) Force resistance of loosely prepared samples. (b) Force resistance of densely prepared samples. (c) Averaged and smoothed force resistance for both types of prepared samples.

in the densely prepared sample versus the loosely prepared sample. It is interesting to note that the dense and loose sample force curves neither overlap nor converge. This is in direct contrast to the dynamic case discussed below.

Force resistance results were also captured for the dynamic loading cases. We subtracted the inertial forces from tests without granular material from tests with granular materials. We then investigated two areas of the loading curve for the dynamic penetrations: the peak striking force on the penetrator and the elastic residual force of the regolith simulant after a hammering cycle. In the first, the peak striking force on the first downward plunge in a penetration cycle is plotted versus the tip displacement, as shown in Fig. 10. A couple of trends were noted in the data. The loosely prepared sample had an initial portion, where there was very little resistance to the loading. This occurred because of the large amount of densification occurring in the system. After around 5 cycles, the resistance started to increase. In the densely prepared sample the initial portion of the curve with little resistance only occurred for the first cycle or two, before increasing. The slopes of the increasing portions of the curve for both the loosely and densely prepared samples were similar. This suggests that the density of the regolith simulant converged to similar values in both the dense and loose samples. This density value is expected to roughly be the maximum relative density as suggested by the results in Sect. 4.2.

The second measure of dynamic force resistance captured was the elastic force exerted by the compressed regolith on the penetrator tip after a loading cycle, shown in Fig. 11. These values were captured by averaging 50 force measurements (sampled at 1024 Hz) taken immediately before a dynamic loading cycle occurred. Both the loosely and densely
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4.4 Dynamic Loading—Force Curve Offset in Loose Samples

In the previous results section, similar trends were seen in the dense and loose samples for both the peak and residual force resistance during dynamic loading. However, in both cases the loose samples had a longer flat portion at the beginning of the curves. We suspect that this occurred because of the large amounts of densification occurring in the system during the first few cycles. This large amount of densification led to a corresponding decrease in the penetration depth of the tip due to the drop in the average surface height. We define the penetration depth as the distance from the tip to the average surface height. The end result was that the penetration depth of the loose samples was offset several cycles when compared to the dense samples, as seen in Fig. 12. This resulted in a corresponding shift in the loose force resistance curves and a longer initially flat portion in comparison with the dense curves.
Fig. 11  Residual force resistance before each dynamic loading cycle. The linear portions of both the dense and loose curves appear to increase at similar rates, however, the loose sample increase starts several cycles later than the dense sample. (a) Residual force resistance of loosely prepared samples. (b) Residual force resistance of densely prepared samples. (c) Averaged residual force resistance for both types of prepared samples with linear fits for portions of the data.

Fig. 12  Penetrator tip depths during dynamic loading cycles. Note that the loose average is offset by several cycles from the dense average. (a) Penetrator tip depth during dynamic loading cycles. (b) Example of penetrator tip depth measurement.

5 Conclusions

The results outlined in the previous section lead to several conclusions and interesting scenarios to investigate in future work. The relative density of the granular material clearly...
plays an important role in mechanical interactions with the Mole. This importance is apparent under both quasi-static and dynamic loading.

Under quasi-static loading, there were clear differences in the deformed area and the force response. The deformed areas, while being similar in size had different shapes with the loose sample being rectangular and the dense sample being conical. Additionally, both the loose and dense samples saw increases in the relative density, though the end results were different. The loose sample increased to roughly 50–80% relative density, while the dense sample increased to the maximum over a large area. We also extracted relative density profiles along horizontal, vertical, and diagonal profiles around the penetrator. These results were spatially complicated with multiple regions of differing behavior. Interestingly, the relative density increased non-linearly along the vertical profile, but linearly on the other profiles, especially the horizontal ones. The horizontal profile relative density results are particularly relevant to HP3 thermal conductivity measurements since the cylinder of regolith surrounding the mole body will play a larger role than regolith around the nose and aft-end caps in the transient hot wire technique (Hammerschmidt and Sabuga 2000) used. These relative density results motivate further work on the impact of penetration on the Mole’s thermal measurements. We were also able to use the density results to calculate the change in thermal conductivity in areas surrounding the penetrator, which saw up to a 5% increase over a fairly large area in the loose sample. This area extended approximately two Mole diameters to either side. Conversely, the change in thermal conductivity was minimal for the dense sample, due to the small change in relative density. These first order estimates of the impact of compaction on thermal conductivity are significantly smaller than the factor of 2–3 found in Grott et al. (2010) in their study of the Apollo missions. However, this is not unexpected as the dependence of thermal conductivity on density is quite different between the Moon and Mars (Fountain and West 1970).

Under dynamic loading, both the loose and dense samples approached the maximum relative density, though this is likely due to the large number of traveling wave reflections in the system producing similar results. Further evidence of both samples approaching similar relative density states was seen in the force resistance data, where both the peak and residual forces showed similar rates of increase in the loose and dense samples. We note that these reflections will likely be smaller or non-existent in the Mole’s penetration into an unbounded Martian regolith and such convergence may be less significant or absent in such an environment. However, it is important to note that during actual Mole deployment there will be potentially thousands of dynamic penetration cycles. These repetitive load cycles could cause compaction to the same maximum relative density even without reflecting traveling waves.

We can also say something about the magnitude of impact on the regolith’s thermal conductivity around the Mole due to dynamic penetration. If we can assume that the wave-reflective test setup used here represents an upper bound on the change in density, a dynamic penetrator such as the Mole would result in at most a 7.5% increase in the thermal conductivity in areas around the Mole for the regolith simulant tested. This increase is easily calculated by inputing the minimum and maximum relative densities into the thermal conductivity relation from Presley and Christensen (1997a) to generate minimum and maximum thermal conductivities. We note that the maximum increase could be higher with a different simulant, especially one more representative of Mars’ regoliths with a less uniform size distribution.

In general, both the thermal conductivity change and the axially varying density profile around the Mole have the potential to influence the measurements made by the Mole. To fully understand the degree of influence these properties have on Mole thermal conductivity...
measurements, further work modeling the Mole’s transient hot wire method in a material with a spatially varying density is needed. Particular emphasis needs to be placed on investigating areas close to the Mole. A simple calculation of the heated region size using the heat diffusion equation, \( d \propto \sqrt{\kappa * t} \) (Gustafsson et al. 1979), with the diffusivity, \( \kappa \), equal to \( 4 \times 10^{-8} \text{ m}^2/\text{s} \) and the time, \( t \), equal to 24 hours results in a region size, \( d \), just under 6 cm wide. Thus, the heated region is just over two Mole diameters away, warranting further investigation with increased focus in these areas.

6 Future Work

Planned future work is laid out in several phases. In the first phase, improvements to the experimental setup will be made including the following.

- Inclusion of semi-circular penetrator in testing
- Higher resolution imaging during dynamic testing to enable the use of DIC
- Higher resolution imaging during quasi-static testing to investigate areas immediately adjacent to the penetrator
- Testing of additional displacement loading profiles of Mole penetration in Earth soils and Martian regolith simulants
- Development of wave absorbing boundary conditions to minimize reflections

In the second phase, a wider range of particle size distributions and regolith simulant types will be tested and compared to each other for analysis. This will enhance estimates of the amount of densification that could occur on Mars, depending on the type of regolith encountered. Lastly, Martian regolith has some cohesion due to a variety of potential reasons including moisture and salt content (Kömle et al. 2017). This cohesion could have an impact on the Mole’s passage and affect the thermal conductivity measurements. We plan on testing this impact by adding small amounts of water to the testing sand to mimic the expected cohesion of Martian regoliths.

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