

SOIL STRENGTH PROPERTIES DERIVED FROM SCRAPING AND DUMPING ACTIVITIES AT THE INSIGHT LANDING SITE ON MARS. E. Marteau¹, M. Golombek¹, C. Vrettos², P. Delage³, N.R. Williams¹, and V. Ansan⁴. ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (eloise.marteau@jpl.nasa.gov); ²Technical University of Kaiserslautern, Kaiserslautern, Germany; ³Ecole des Ponts ParisTech, Paris, France; ⁴Université de Nantes, Nantes, France.

Introduction The NASA InSight lander [1] arrived on Mars on November 26, 2018, touching down in the Elysium Planitia region. InSight is equipped with a 1.8 m-long four degree-of-freedom robotic arm [2], two color cameras (one mounted on the robotic arm and one mounted on the lander), and science instruments. The science instruments include the SEIS seismometer, and the HP³ heat probe, both of which were deployed onto the surface using the robotic arm. Observations at the InSight landing site suggest a subsurface geological structure consisting of dust (microns), underlain by unconsolidated sand (~1 cm), over duricrust (7-20 cm) [3], with a fined grained regolith layer of unconsolidated sand and sparse rocks underneath [4,5]. The robotic arm end-effector includes a scoop that has been used to interact with the Martian soil. Specifically, the robotic arm and its scoop have been used to apply pressure on the ground, as well as scrape, scoop and dump the loose surface material.

Soil mechanics experiments aiming at characterizing the mechanical failure properties (i.e., the cohesion and internal friction angle) have been previously performed on Mars. Of particular interest are the investigations conducted by the Viking and Phoenix lander robotic arms [6,7]. At the InSight landing site, cohesion estimates have been obtained from the experiments performed on Sols 240 and 250 in which the scoop was used to apply pressure near an open pit that formed around the HP³ mole during initial hammerings. By applying three-dimensional slope stability analysis with measurements of robotic arm forces at the scoop and images, a cohesion value of 5.8 kPa has been estimated assuming an internal friction angle of 30° [3].

In this work, subsequent scraping and dumping activities performed with the robotic arm and its scoop are used to further study the soil characteristics at the InSight landing site.

Observations obtained from scraping and dumping experiments On sol 673, two overlapping 12-cm long scrapes were commanded to bring regolith from the far side of the HP³ pit towards the lander. The scrapes created two piles near the HP³ mole by bulldozing mounds of particles. From the elevation profiles extracted from the sol 673 digital elevation model (Figure 1), we find that the slopes of the bulldozed mounds of regolith can be as high as 38-39° on the upstream side, where the particles have been pushed by the scoop. Once the scoop is no longer in contact with

the regolith, particles likely cascade down the slope. On the downstream side, the slopes of the piles are between 49 to 53°. The walls formed by the sides of the scoop have steep slopes with values of 78° and 70°.

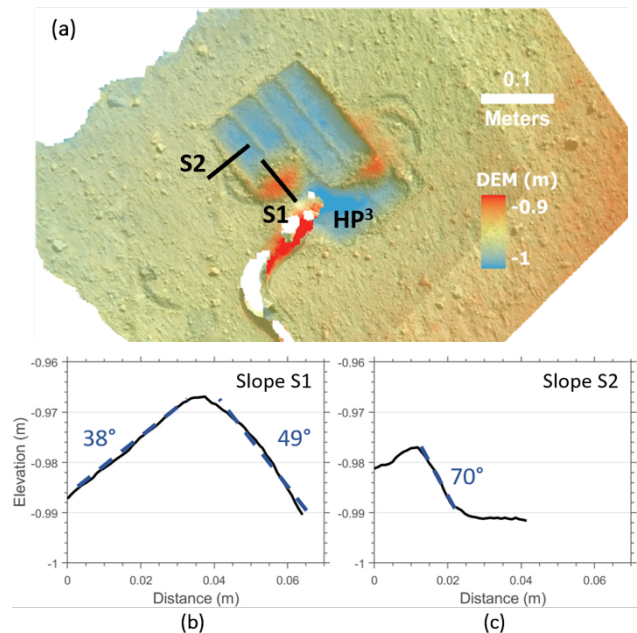


Figure 1: (a) Digital elevation model of the HP³ pit based on the stereo pair taken on Sol 673 after scraping (b) Elevation profile S1 of the scraped pile (c) Elevation profile S2 of the scraped wall

Starting on Sol 803, the arm and scoop were used to bury the SEIS tether by creating a large number of scrapes, scooping and dumping the scraped regolith. Burying the tether was decided in link with CNES (the French Space Agency) in an attempt to get a better thermal insulation of the tether, so as to reduce the glitches and the noise that affect the data of the SEIS seismometer. The arm scraping activities created several piles of regolith and walls along the side of the scoop on the relatively flat surface between the HP³ and SEIS instruments. Elevation profiles were obtained from digital elevation models acquired between Sols 803 and 822 to measure the slopes of the scraped piles and walls. The average slopes of the regolith mounds are between $42^\circ \pm 2.7^\circ$ (with a range from 40° to 45.8°). The side walls scraped by the vertical sides of the scoop have slope value of $54.7^\circ \pm 6.6^\circ$ (with a range from 46° to 63°).

Subsequently, the IDA scooped and dumped the scraped material from a height of 40 cm on top of the

SEIS tether. The digital elevation model and elevation profiles of the dumped pile obtained on Sol 877 are presented in Figure 2. At its highest point, the dumped pile is ~ 3 cm high and the material rests at slope value of $24.1^\circ \pm 6.1^\circ$ (with a range from 16.6° to 32°).

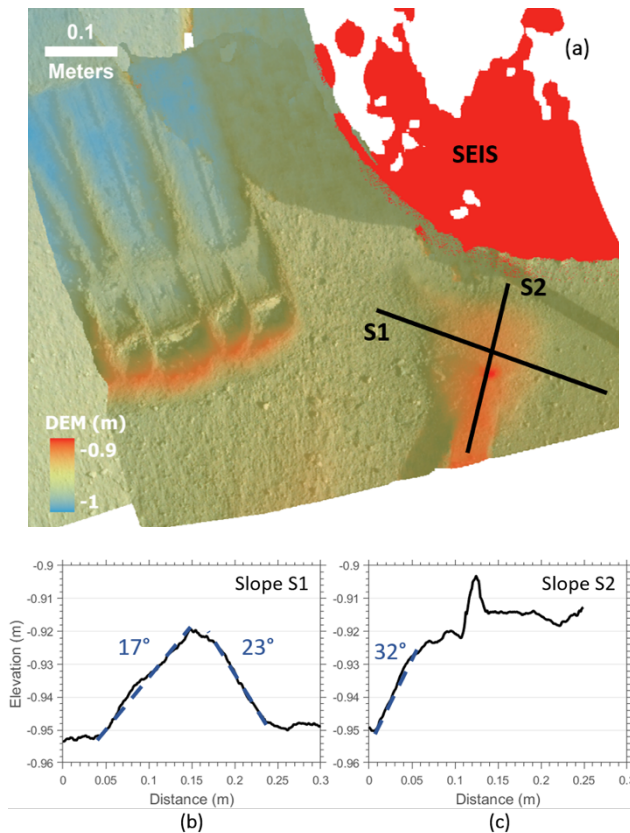


Figure 2: (a) Digital Elevation Model of the surface between HP³ and SEIS based on the stereo pair taken on Sol 877 after scraping, scooping and dumping (b) Elevation profile S1 of the dumped pile (c) Elevation profile S2 of the dumped pile

Analysis of soil characteristics The different slope angles between the scraped and dumped piles are likely due to the different methods employed to create the piles. Piles created by scraping typically yield different geometries and soil bulk densities than piles formed by pouring the loose material from a specified height [8].

The average slope value of 24.1° obtained for the dumped piles corresponds to a lower bound estimate of the angle of repose, which can be considered as a lower bound of the internal friction angle of the regolith in a loose state, resulting from the successive actions of scraping and pouring (estimated around 30° at intact state, [9]). In contrast, the average slope value of 42° obtained from the scraped piles can be interpreted as an upper bound of the internal friction angle of the regolith moved into a denser state, due to the effects of pushing and compacting during scraping.

The slopes of the side walls created by the scrapes are larger than those of the piles. Slope failure was not seen on these walls. This can be explained by the presence of some inter-particle bonding forces that provide some cohesion to the undisturbed soil, which is consistent with the cohesion values reported in [3].

Note also that the average slope value of 42° observed above on the scraped pile is rather high with respect to the friction angle of a sub-rounded/rounded granular material (estimated around 30°). Similar inter-particle bonding forces are also suspected to act here, in link with the low gravity and low atmospheric pressure prevailing at the surface of Mars (see Bromwell's work in lunar conditions [10]).

Conclusion Soil mechanical properties at the In-Sight landing site are derived from the interactions between the surface material and the robotic arm. The observations suggest that the material has an angle of internal friction between 24.1° and 42° and cohesion of around 5.8 kPa [3]. The soil strength values at the In-Sight landing site are comparable to relatively strong, blocky, indurated soil at Viking Lander 2 [6] and are similar to other soil on Mars [11].

References [1] Banerdt W.B. et al. (2020) *Nat. Geosci.*, 12, 183-189. [2] Trebi-Ollennu A. et al. (2018) *Space Sci. Rev.*, 214, 93. [3] Spohn et al. (2021) *Space Sci. Rev.* arxiv.org/abs/2112.04438 [4] Golombek M. et al. (2020) *Nat Commun*, 11, 1014. [5] Hudson T.L. et al. (2020) 51st LPSC, Abstract #1217. [6] Moore H.J. et al. (1987) *U.S. Geol. Surv. Prof. Pap.*, 1389, 222. [7] Shaw A. et al. (2009) *JGR*, 114, E00E05. [8] Jiang et al. (2017) *J. Terramechanics*, 71. [9] Morgan P. et al. (2018) *Space Sci. Rev.* 214, 104. [10] Bromwell L. (1966) *Rep. 7 Earth Phys. MIT*. [11] Golombek et al. (2008) *Cambridge University Press*.