INITIAL RESULTS FROM THE INSIGHT LANDER ROBOTIC ARM SOIL MECHANICS EXPERIMENTS ON MARS

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Introduction InSight landed on Mars on November 26, 2018, in Elysum Planitia [1] and operated until December 21, 2022, acquiring data through 1,440 sols of operations. The InSight lander was equipped with a 1.8 m-long, four degree-of-freedom robotic arm capable of scraping, scooping, dumping, and pushing on the ground using the scoop mounted at the end of the robotic arm [2]. The lander also carried two color cameras (one mounted on the robotic arm and one mounted on the lander), and two scientific instruments deployed onto the surface by the robotic arm, namely the SEIS seismometer and the HP^3 heat probe.

Observations obtained from the InSight lander and instruments suggest a near surface stratigraphy consisting of dust (microns thick), over thin unconsolidated sand (~1 cm thick), underlain by a duricrust (7-20 cm thick) [3], with a fined grained regolith layer of unconsolidated sand and sparse rocks underneath [4,5]. To complement these observations, soil mechanics experiments aiming at characterizing the physical properties of the surface materials were conducted with the robotic arm and scoop. Fig 1 presents an image of the workspace acquired by the lander-mounted camera near the end of the mission on sol 1170 showing were the soil mechanics activities were conducted.

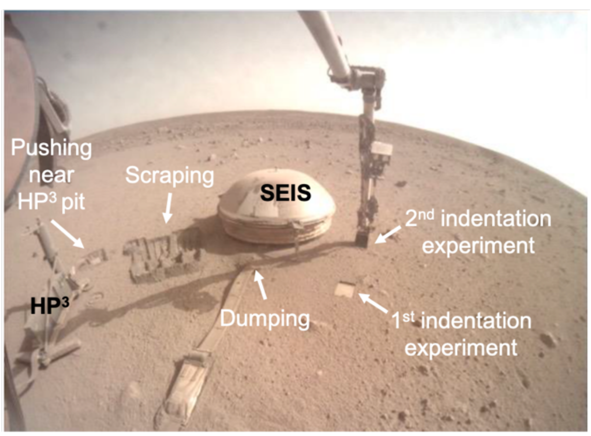

Figure 1: Annotated image of the InSight workspace near the end of the mission on sol 1170

Pushing activities near HP^3 pit Soil cohesion values were obtained from experiments conducted near the open pit that formed around the HP^3 mole during initial hammerings as part of the mole recovery activities [3]. On sol 240, the flat part of the scoop was used to apply pressure at the edge of the HP^3 pit (Fig 2a). Subsequently, on sol 250, the tip of the scoop was pushed into the soil near the HP^3 pit, which resulted in the failure of a 1 cm by 1 cm soil wedge (Fig 2b). By combining three-dimensional slope stability analysis with measurements of robotic arm forces at the scoop and images, a cohesion value of 5.8 kPa was estimated assuming an internal friction angle of 30° [3].

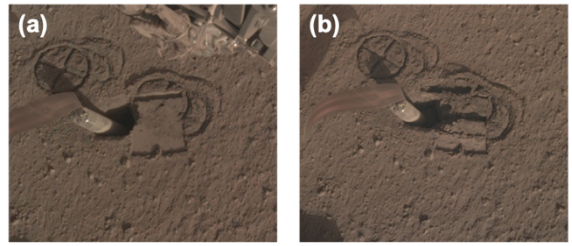

Figure 2: Images of robotic arm scoop interactions with the surface material near the HP^3 mole pit. (a) Flat push on sol 240. (b) Tip push on sol 250.

Scraping and dumping activities The robotic arm and scoop were used to bury the SEIS tether starting on sol 803. This activity created a large number of scrapes on the surface and piles of regolith on the SEIS tether (Fig 3). Elevation profiles were extracted from the Digital Elevation Models to measure the slopes of the scrapped and dumped piles, and walls. The slopes of the bulldozed piles of soil at the end of the scrapes are between 42° ± 2.7° while the walls scraped by the vertical sides of the scoop have slope value of 54.7° ± 6.6°. At its highest point, the dumped pile on the SEIS tether is ~3 cm high and the material rests at slope value of 24.1° ± 6.1°. The difference in slope angles between the scraped and dumped piles are likely due to the different methods used to create them.

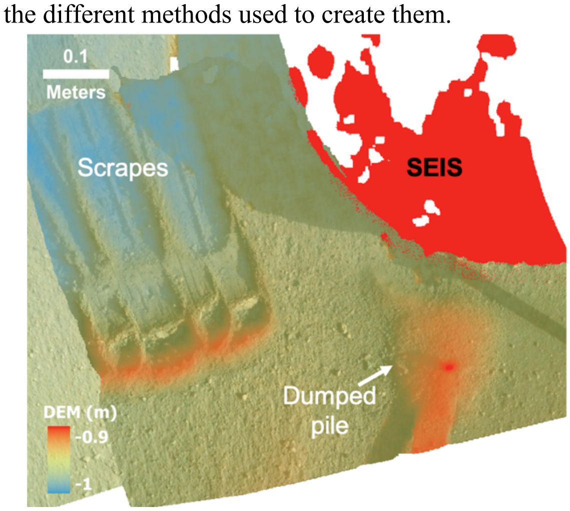

Figure 3: Digital Elevation Model of the surface between HP^3 and SEIS based on the stereo pair taken on sol 877 after scraping, scooping and dumping

The slope value of 24.1° obtained from the dumped pile is interpreted as a lower bound estimate of the internal friction angle of the regolith in a loose state while the value of 42° obtained from the scrapped piles corresponds to the internal friction angle of the soil in a denser state. In addition, the slopes of the walls left by the scoop's scrapes are larger than the slopes of the piles and slope failure was not observed on these walls. This result can be explained by the presence of some cohesive forces in the undisturbed soil, which is consistent with the cohesion values reported above.

Indentation experiments The main scientific goal of the indentation experiments is to characterize the bearing properties of the Martian regolith at the InSight site. The indentation experiments used the flat part of the robotic arm scoop to push on the ground at defined locations. The robotic arm current and torque limits were set to allow maximum downward force, while still preventing damage to the arm. Indentation experiments were performed on Mars at a first location on sol 1074 in which the robotic arm forearm is a vertical position, and on sol 1170 at a second location, in which the robotic arm is extended about 48cm farther away from the first location (Fig 1).

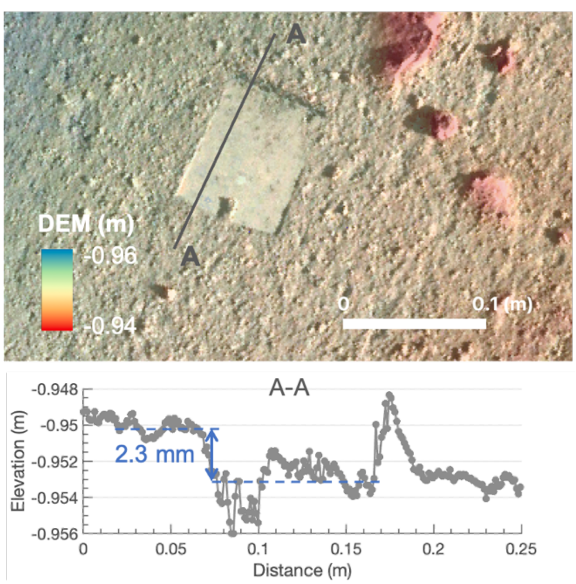

Figure 4: Digital Elevation Model after the push at the first location on sol 1074 and elevation profile of the scoop imprint

Before and after each push, images were acquired by the camera mounted on the robotic arm and subsequently used to create Digital Elevation Model of the scoop imprint from which the penetration depth is measured (Fig 4). Elastic properties experiments were also conducted at the same locations, in which SEIS measured the tilt from the arm pressing on the ground to derive near surface elastic properties. Initial results show that a pressure of 9.4 kPa applied by the scoop results in a sinkage of 2.3 mm at the first location.

Robotic arm force calibration To help interpretation of the data acquired on Mars during the soil mechanics experiments, calibration tests were conducted at JPL using the full-scale replica of the InSight lander and a multi-axis load cell setup. The interpretation of these experiments relies on the measurements of the pressure applied by the scoop to the ground and, hence, on evaluating the force imparted by the scoop. Because the robotic arm is not equipped with a force-torque sensor, the force measurements must be inferred from the telemetry (i.e., motor currents and torques at the joints) and compared with the calibration data. It is worth emphasizing that the force magnitude at the scoop in the x-, y-, and z-direction depends on the arm pose and, thus, different force values are obtained at different workspace locations. The results of the force calibration are tabulated below.

	Mean ± Standard Deviation (N)		
	x-axis	**y-axis**	**z-axis**
Flat push near HP³	59.0 ± 15.9	2.3 ± 2.3	78.4 ± 28.5
Tip push near HP³	63.5 ± 17.1	-0.2 ± 1.4	82.9 ± 27.1
1st Indentation Exp	17.6 ± 3.0	1.9 ± 1.2	61.6 ± 17.0
2nd Indentation Exp	59.0 ± 9.7	2.5 ± 1.6	67.2 ± 12.8

Table 1: Summary of the robotic arm force load cell measurements along the x-, y-, and z-directions at different locations within the workspace

Discussion and conclusion Soil mechanical properties at the InSight landing site are derived from the interactions between the surface material and the robotic arm, in a similar fashion to mechanical measurements with the Viking and Phoenix lander robotic arms [6,7]. These investigations 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 InSight landing site are similar to relatively strong, blocky, indurated soil at Viking Lander 2 [6] and are comparable to other soil on Mars [8].

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. (2022) *Space Sci. Rev., 218, 72* [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] Golombek et al. (2008) The Martian Surface *Cambridge University Press.*