Predicted Penetration Performance of the InSight HP^3 Mole. H..Hansen-Goos[1] (Hendrik.Hansen-Goos@dlr.de), M. Grott[1] (Matthias.Grott@dlr.de) , R. Lichtenheld[2], C. Krause[3], T.L. Hudson[4], T. Spohn[1], [1]DLR Institute for Planetary Research, Berlin, Germany, [2]DLR Institute of System Dynamics and Control, Oberpfaffenhofen, Germany, [3]DLR Microgravity User Support Center, Cologne, Germany, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA

Introduction: NASA's discovery class mission InSight [1] is scheduled to launch in March 2016, and will deliver a geophysical lander to the surface of Mars in September of the same year. The primary payload of the mission consists of a seismometer [2] and the HP^3 heat flow probe [3], the latter of which will access the martian subsurface to a depth of up to 5 m to emplace a string of temperature sensors into the ground. These sensors will measure the thermal gradient in the regolith, and together with a determination of the thermal conductivity by means of an active heating experiment, the geothermal heat flow at the landing site will be determined.

The HP^3 instrument is a self-penetrating probe, which will be deployed onto the martian surface by the lander's robotic arm. After deployment, HP^3 will penetrate into the regolith by means of its hammering mechanism (termed the 'mole'), which delivers 0.3 J of hammering energy at 3 second intervals. In the following, we will apply the cavity expansion model to estimate the penetration performance of the instrument as a function of regolith parameters (density ρ and internal friction angle ϕ) as well as compaction state D_R.

Theory: We apply the cavity expansion model [4,5] for cone penetration to model the penetration performance of the HP^3 instrument. The model calculates the stresses needed to create a cylindrical cavity at the tip of the mole by establishing a relationship between shear failure of the soil and the horizontal stress state [6]. To first order, the resistance to penetration q_c is given by:

$$\frac{q_c}{p_A} = 1.64 \cdot e^{[(0.1041\,\phi + (0.0264 - 0.0002\,\phi) D_R)]} \times \left(\frac{\sigma_h}{p_A}\right)^{0.841 - 0.0047\,D_R} \qquad (1)$$

where p_A = 1 MPa is the reference stress, σ_h is the horizontal stress, ϕ is the regolith's angle of internal friction, and D_R its relative density [5]. Note, that the approximation in Eq. 1 is only valid for friction angles between 29 and 36°. The advance of the hammering probe per stroke is known as the dynamic cone penetration index (DCPI), and given the penetration resistance q_c, hammering energy E, and hammering efficiency α (an empirical parameter), DCPI is given by:

$$DCPI = \frac{4\alpha E}{q_c \pi d^2} \qquad (2)$$

where d = 2.64 cm is the diameter of the mole.

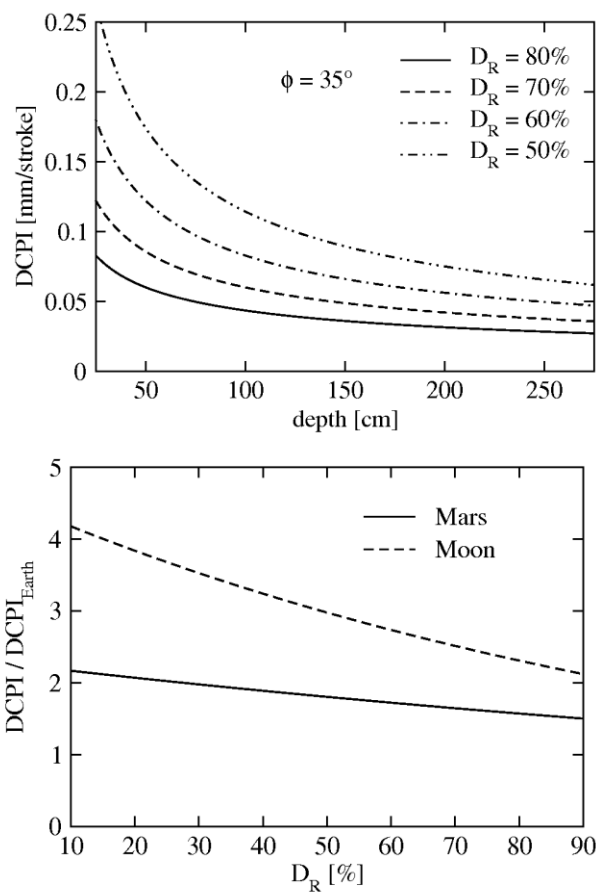

Figure 1: Top: DCPI as a function of depth z for a mole hammering energy of 0.3 J under Earth gravity. Bottom: DCPI on Mars and Moon relative to that on Earth as a function of soil compaction. DCPI scales approximately with the inverse of the square root of gravity.

Results: Results of the calculations are shown in Figure 1, where DCPI is shown as a function of penetration depth z for a regolith with density 1500 kg/m^3. The degree of compaction D_R is varied between 50 and 80%, and the soil's friction angle is 35°. Depending on overburden pressure (depth), the probe advances between 0.2 and 0.05 mm per stroke. An increase of relative density by 20% divides penetration speed roughly in half. Dependence of results on internal friction angle is also quite pronounced, and a decrease of ϕ to 30° increases penetration performance by a factor of ~1.5 (not shown).

Given the dependence of penetration resistance on $\sigma_h = K_0\rho g z$, where K_0=0.45 is the consolidation ratio, scaling of penetration performance for different gravitational accelerations g can be computed. Results of these calculations are also shown in Figure 1, where the ratio of DCPI on Mars and the Moon to that on Earth is shown as a function of relative density. In essence, penetration performace roughly scales with the squareroot of gravity, such that for intermediate compaction (70%) penetration performance is increased by a factor of 1.6 and 2.5 on Mars and the Moon as compared to Earth, respectively.

Soil	ρ [kg/m^3]	ϕ [°]	$z_{max,0.3J}$ [m]	$z_{max,0.8J}$ [m]
MMS Sand[7]	1400-1800	33-35	1.78-2.18	3.40-4.17
			2.47-3.03	4.73-5.80
MMS Dust[7]	1000-1600	35-37	1.64-2.17	3.14-4.15
			2.28-3.02	4.37-5.77
MMS Mix[7]	1550-1950	31-33	1.95-2.37	3.73-4.54
			2.71-3.30	5.19-6.32
Mars Sand[8]	1100-1300	30	2.67-2.83	5.12-5.41
			3.72-3.94	7.12-7.53
Mars C. C.[8]	1100-1600	30-40	1.37-2.83	2.63-5.41
			1.91-3.94	3.66-7.53
Mars B. I.[8]	1200-2000	25-33	1.93-3.70	3.70-7.08
			2.69-5.15	5.14-9.85
Moon[9]	1500	45	1.04	1.99
			1.92	3.67

Table 1: Maximum penetration depth achieved in different regoliths and analogue materials, characterized by their bulk density ρ and friction angle ϕ. Upper row gives results for penetration under Earth gravity, second row gives the gravity scaled depth (Mars and Moon). Extreme values of ρ and ϕ, as well as D_R = 70% have been assumed in the calculations. In addition to the results for a hammering energy of 0.3 J, results for 0.8 J are also given. Note that results for lunar regolith are only given as a rough estimate, as the friction angle of 45° is outside the applicability of Eq. 1. MMS: Mojave Mars Simulant. C.C.: Crusty to cloddy soil. B.I.: Blocky, indurated soil.

As is evident from Figure 1, penetration speed levels off as a function of depth, and we have calculated the maximum depth achieved by the probe by integrating Eq. 2 with respect to time, and assuming a maximum hammering time of 24 h, and a hammering energy of 0.3 J, which is the energy stored in the HP^3 prototype's hammering mechanism. Results of these calculations are shown in Table 1, and values for Mars analogue materials, Mars regolith parameters as determined in situ, and lunar regolith parameters as determined from lunar samples have been considered. In addition, results for a hammering energy of 0.8 J are also shown.

Results presented in Table 1assume a mole diameter of d = 2.64 cm, corresponding to that of the HP^3 prototype. For intermediate compaction (D_R = 70%), penetration performance scales with ~ $(1/d)^{4/3}$, and an increase of the diameter by 10 and 20 % decreases the maximum achieved depth by 12 and 22%, respectively.

Discussion: For the present hammering energy of 0.3 J in the HP^3 prototype, instrument penetration performance generally falls short of the 3 m penetration depth required for the heat flow measurement. Therefore, the strength of the hammering mechanism for the HP^3 flight unit needs to be improved. The new design to be implemented in the flight instrument will compress the hammering springs by 15 mm, resulting in a total hammering energy of 0.83 J for a spring constant of 7.4 N/mm. With this energy, the instrument should reach the target depth of 5 m for most expected regolith parameters, and safely fulfill the depth requirement of a 3 m minimum penetration depth.

References: [1] Banerdt, W.B., et al., LPSC, abstract #1915 (2013). [2] Dandonneau1, P-A., et al., LPSC, abstract #2006 (2013). [3] Spohn, T., et al., LPSC, abstract #1445 (2012). [4] Salgado,R., J.K. Mitchell, M. Jamiolkowski, J. Geotech. Geoenviron. Eng., 123, 344 (1997). [5] Salgado, R., M. Prezzi, Int. J. Geomech., 7, 251 (2007). [6] Houlsby, G.T., R. Hitchman, Géotechnique, 38, 39 (1988). [7] MMS testing was performed by Braun Intertec on contract of JPL. Density was determined according to ASTM D-4253 and ASTM D-4254. Angle of friction was determined according to ASTM D-3080. [8] Golombek, M.P. et. Al, The Martian surface, Chapter 21, Cambridge University Press (2008). [9] The Lunar Sourcebook, Table 9.1.