VALIDATION OF CEMENT CONTACT THEORY TO ESTIMATE MARTIAN REGOLTIH VELOCITIES. Augustus Bates[1], Suniti Karunatillake[1], Juan M. Lorenzo[1] [1]Louisiana State University, Geology and Geophysics (abate15@lsu.edu)

Introduction: Prior workers have hypothesized the various states and stability regimes of regolith-bound H_2O-ice on Mars based on the diffusion of atmospheric water vapor into the porous regolith of Mars [1,2]. Such models rely upon the orbital dynamics of Mars, especially obliquity variations [3], to determine periods of thermophysical stability of ice within the lower latitudes. As the obliquity of Mars changes, the stability regimes for ice change as well, which results in latitudinal transfer of ice through vapor diffusion [2]. However, ice may remain metastable at shallow depths within lower latitudes (~55°) even during low obliquity, as verified by satellite observations [4]. In addition to poorly constrained metastability, the quantity of ice found at lower latitudes exceeds what could have accumulated solely through available atmospheric vapor through the previous ~1.4-2.5 Ma obliquity cycle.

In order to understand seasonal controls and identify key regions of regolith ice growth, future in situ missions must have established methodology to investigate the martian subsurface. A novel and effective, yet non-invasive, method uses high frequency seismic waves, because they reveal subsurface physical properties [5,6]. While many physical parameters of the martian regolith have been constrained [7], no research to date uses these seismic data to define the shallowest velocity structure of the martian regolith with the addition of H_2O in any state. Further, the burgeoning nature of martian near-surface seismology still has many unknowns regarding the physical and chemical parameters that could potentially affect seismic velocity profiles. Before any in-situ seismic surveys are made, we must first understand how known physical properties will affect seismic wave propagation on Mars. We are examining the applicability of terrestrial-based seismic models, such as modified contact theory, to explain the observed velocities [8].

Methodology: Our goal is to successfully model the regolith velocities derived at InSight through the use of terrestrial cemented contact theory models (i.e. 9). Cemented contact theory models provide a method to calculate the shear and bulk moduli of a soil-cement system. The required parameters to calculate these moduli include soil grain density, porosity, shear and bulk moduli as well as the density, shear and bulk moduli of the cementing material [9]. Regolith parameters for martian soil are derived from prior works [7], and we choose to use the parameters from a dense packing model, following the same methodology detailed in [5]. Here we present results using only ice as the cementing material, varying its saturation within the soil through several different trials with the model.

The physical parameters of the soil and cement are used to find the effective shear and bulk moduli of the soil-cement system. We then calculate the density of the 3-part system (cement, soil, and air) and from this, we are able to derive P- and S-wave velocities. We calculate a velocity for each depth interval (25 cm intervals over a total 5 m depth) and compare these results with those found at InSight [5].

Table 1: *This table shows the cement saturation parameters of each trial run, which are all color coded to Fig. 1&2.*

Trial Number	Regolith Porosity Range (ϕ_{max} = 0.36)	Volume of Cement (Pure Ice)	Max Cement volume @ Depth (m)	Grain Density Range (kg/m³)
1	0.2 – 0.001	0.359 – 0.16	5	1300 - 1400
2	0.359 – 0.3	0.06 – 0.001	5	1300 - 1400
3	0.26	0.1	0	1300 - 1400
4	0.26 – 0.001	0.359 – 0.1	0.25	1300 - 1400
5	0.359	0.001	0	1300 - 1400

Results: Here we show our results from various saturation states of ice within the martian soil. Over the course of 5 trials (Table 1), we varied the concentration of the ice within the soil to correspond to cases of extreme saturation (trials 1 & 4), moderate saturation (trials 2 & 3) and low saturation (trial 5). The results of these trails are shown in figures 1 & 2. Overall, velocities for saturation states between 6% and 35.9% of the total regolith porosity show strong resemblance to InSight data (trials 1-4). There is considerable drop-off in velocity once ice saturation decreases to a minimal amount of the total pore space (trial 5). Additionally, there is a large discrepancy in the magnitudes of S-wave velocities between our models and what is observed by InSight. The highly saturated trials show a sharp increase in velocity, which contrasts sharply with the InSight datum. However, our minimally saturated trial has a similarly shaped increase in velocity with depth in comparison to the InSight datum.

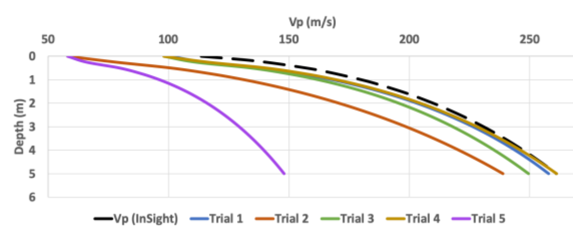

Figure 1: *Vp results for the 5 trial runs with varying saturation states of ice in the regolith. There is strong similarity to the InSight data until ice saturation drops to near 0.*

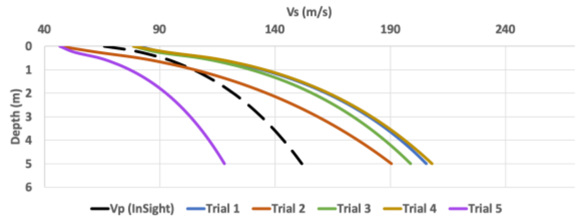

Figure 2: *Vs results for the same 5 trial runs. In contrast to Fig. 1, our Vs results aren't similar to InSight until ice saturation drops to near 0.*

Discussion: We find that a velocity increase with depth, as predicted through contact theory, is a valid model for the martian regolith, through comparisons with recent InSight findings (Figs. 1 & 2). In addition, cement contact theory appears to provide a robust characterization of the regolith system in P-wave space. However, its applicability to S-wave space remains unclear. We performed an internal validation of our model (Figs. 3 & 4) with previously published data [i.e. 10] in an attempt to better understand the causes of our S-wave velocity discrepancy. This validation showed that our model's P-wave velocity estimations are good, but estimations of S-wave velocities are systematically off by ~200 m/s. Initially, this suggests a problem with our reconstruction of these models, but further examination of the work from [10] reveals that they made use of both effective medium theory and cement contact theory to estimate their velocities. This makes comparisons between our results difficult, as we adhere strictly to cement contact theory. In addition, researchers from [10] don't make it explicitly clear how the compaction state of the soil changes with depth, a phenomenon which we incorporate into our models. There are other reasons why our S-wave velocities are inconsistent with InSight, one being that cement contact theory is generally better suited to estimating P-wave velocities [9]. Another, more likely reason, is that the regolith at InSight is uncemented, meaning its shear strength is substantially lower than that of a cemented regolith. Comparisons between the two should show inconsistencies because of this reason alone.

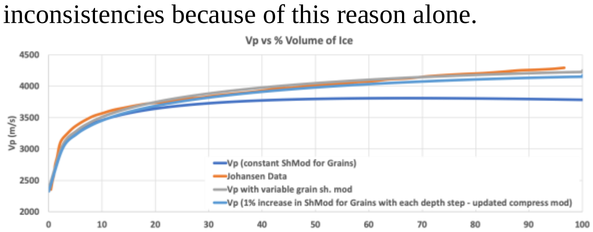

Figure 3: *Comparison of our model's Vp with the results from [10]. An increase in grain shear strength is required in order to match data from [10].*

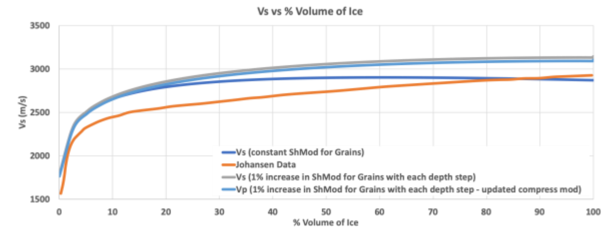

Figure 4: *Comparison of our model's Vs with the results from [10]. There is a systematic offset below 50% saturation of ~200 m/s. The results do converge near maximum saturation.*

Overall, it seems that cement contact theory is a valid model for estimating the P-wave velocity of a cemented martian regolith. Ongoing research will reveal the effectiveness of this model in estimating the S-wave velocity of cemented martian regolith.

References: **[1]** M. T. Mellon, W. C. Feldman, T. H. Prettyman, The presence and stability of ground ice in the southern hemisphere of Mars. *Icarus* **169**, 324–340 (2004). **[2]** M. T. Mellon, B. M. Jakosky, The distribution and behavior of Martian ground ice during past and present epochs. *J. Geophys. Res.* **100** (1995). **[3]** B. M. Jakosky, B. G. Henderson, M. T. Mellon, Chaotic obliquity and the nature of the Martian climate. *J. Geophys. Res.* **100**, 1579–1584 (1995). **[4]** C. M. Dundas, *et al.*, Exposed subsurface ice sheets in the Martian mid-latitudes. *Science (80-.).* **359**, 199–201 (2018). **[5]** P. Lognonné, *et al.*, Constraints on the shallow elastic and anelastic structure of Mars from InSight seismic data. *Nat. Geosci.* **13**, 213–220 (2020). **[6]** B. Knapmeyer-Endrun, M. P. Golombek, M. Ohrnberger, Rayleigh Wave Ellipticity Modeling and Inversion for Shallow Structure at the Proposed InSight Landing Site in Elysium Planitia, Mars. *Space Sci. Rev.* **211**, 339–382 (2017). **[7]** P. Morgan, *et al.*, *A Pre-Landing Assessment of Regolith Properties at the InSight Landing Site* (Springer Nature B.V., 2018). **[8]** J. Dvorkin, G. Mavko, A. Nur, The effect of cementation on the elastic properties of granular material. *Mech. Mater.* **12**, 207–217 (1991). **[9]** G. Mavko, T. Mukerji, J. Dvorkin, *The Rock Physics Handbook*, 1st Ed. (Cambridge University Press, 1998). **[10]** T. A. Johansen, P. Digranes, M. van Schaack, I. Lønne, On seismic mapping and modeling of near-surface sediments in polar areas. *Geophysics* **68**, 1–8 (2003).