DRAG FORCES ON BOULDERS IN MARTIAN GULLIES FROM FLOW OF VISCOUS CONCENTRATED SALT SOLUTIONS

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Introduction: Almost all flow models for Martian gullies to date have assumed liquids that exhibit viscosities on the order of 1 cP such as pure water [1, 2] and liquid carbon dioxide [3, 4]. However, we have recently characterized the density and viscosity of concentrated aqueous solutions of salts known to be present on Mars [5, 6]. This work was carried out on various solutions of Fe^{2+}, Fe^{3+}, Mg^{2+}, and Ca^{2+} with Cl^- and SO_4^{2-} up to 65% by weight (for $Fe_2(SO_4)_3$) under Martian temperatures, from 273 to 220K. The resulting liquids exhibit densities and, especially, viscosities far in excess of those previously used in gully simulations, either modeling or experimental. This work reports on the results of gully flow modeling using these types of liquids with the expectation that this will lead to the same solutions being studied in our experimental gully simulator to identify geomorphological characteristics that might be observed on Mars [7, 8]. Specifically, in this study we estimate the flow velocity and the drag forces on boulders for these dense and highly viscous fluids in a representative Martian gully. Recent observations of boulders in gullies and gully-like features suggest that they might be a probe of the forces and processes involved in gully formation [9].

Modeling: The gully modeled was V-shaped with a 60° angle, a 15° slope, and an average surface roughness of 0.1 m. The independent variables were kinematic viscosity (10^{-6} to 10^{-2} m^2/s, at the density of pure water this corresponds to 1 to 10,000 cP) and depth of liquid in the gully (1 to 5 m). Gravity was 3.73 m/s^2 and the flow was uniform and steady.

Most equations relating open channel flowrate to gully morphology are semi-empirical in nature and tuned for terrestrial situations. They generally assume turbulent flow and water-like viscosity, and usually employ gentle slopes (<2°) and high width to depth ratios. In order to circumvent these limitations, our model was a more general Bernoulli energy balance relating potential energy supplied by the 15° slope to energy dissipated by friction against the wetted perimeter. To validate this approach, we compared our results to those of a standard open-channel logarithmic velocity model utilizing the Chezy coefficient, as shown in Figure 1. The two models agree very well in the turbulent region, with the Bernoulli modeling also showing a region of laminar flow (Reynolds number < 2300) at high viscosity and low liquid loading in the gully.

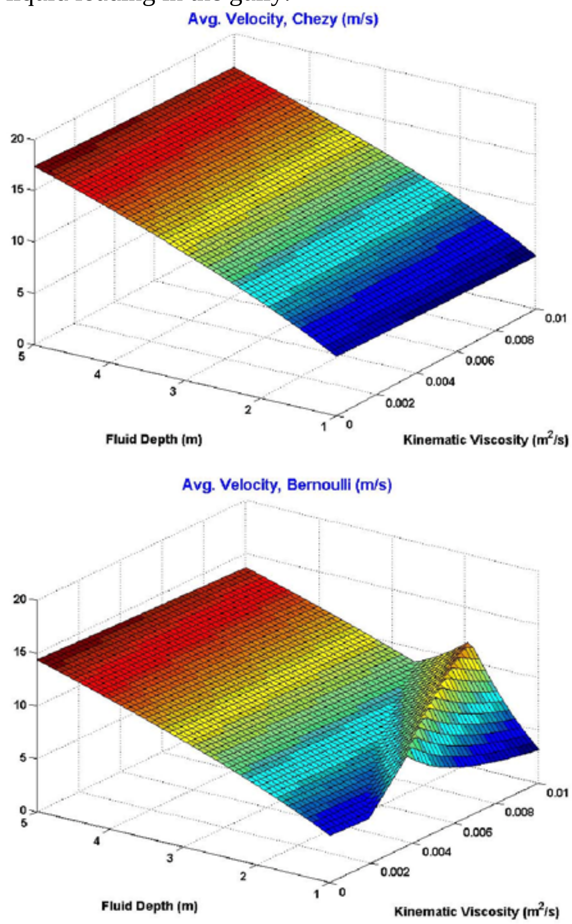

Figure 1. Comparison of estimated average velocities in Martian gullies from a standard terrestrial gully model and our adapted Bernoulli approach.

Pure water would lie on a line along the left-front edge of the data. In regions of turbulence, the flowrate is a very weak function of viscosity. While this may seem counter-intuitive, it is well known in highly-turbulent flow through rough pipes. At very high Reynolds number, in excess of about 10^5, and in any type of conduit (gully or pipe) with a roughness-to-diameter ratio exceeding about 0.01, the flow is “fully turbulent”. This means that increasing the flowrate does not appreciably change the average velocity profile, which is quite flat at high degrees of turbulence. Increasing the flow only amplifies the random eddy motion without changing its scale. It is the average velocity profile, not the random fluctuations, that dominates the frictional losses against the walls and sides.

The Bernoulli treatment predicts a laminar region at the right-hand corner of the data, as Re drops below 2300. The sudden increase of average velocity is due to the flow profile changing from chaotic turbulence to an organized laminar configuration, resulting in a decrease of energy losses within the liquid phase. Pure water would not be expected to show laminar behavior in any gully size greater than a fraction of a cm across.

Drag Forces on Boulders: One way to experimentally test for the possibility that viscous solutions are responsible for gully formation would be to compare the sizes of spherical boulders that could be moved by these predicted flows to the size of boulders seen to be moved by actual flows on Mars. To get an idea of the factors involved, a force balance was set up between the weight of a boulder immersed in the dense liquid, F_B, and the lateral drag force exerted on the same boulder by the flows from Figure 1, F_D,. The two forces are:

$$F_B = \left(\frac{\pi}{6} d^3\right)(\rho_b - \rho_f)g$$

$$F_D = \frac{1}{2}\rho_f C_D \left(\frac{\pi}{4} d^2\right) V^2$$

The density of the boulder (ρ_b), and the solution (ρ_f) was taken to be 3000 and 1200 kg/m^3, respectively, and the drag coefficient (C_D) was a function of the boulder's Reynolds number, Re. Setting the two forces equal and numerically solving for d (since C_D is a tabulated function of d) gives the diameter of the largest boulder for which the fluid flow past it exerts a force equal to its weight.

While this may seem a fairly arbitrary measure, it is in line with the type of analysis required to determine if large-scale bodies can be moved by such a flow. The force ratio used here is unity, and a different ratio (amounting to a different coefficient of rolling resistance) would be used in practice. We will obtain these from literature or measure them in our gully apparatus. Figure 2 shows the critical boulder diameter for the flows in Figure 1.

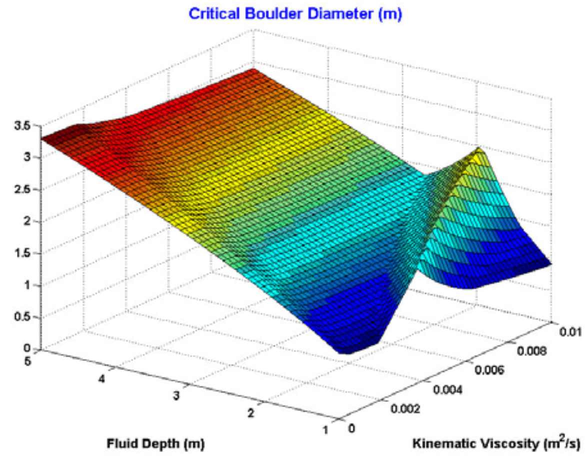

Figure 2. Maximum boulder diameter for which the lateral fluid flow forces equal the weight of the boulder immersed in the fluid.

These results indicate that the expected flow forces are substantial in comparison with the vertical resting force of basaltic boulders immersed in the liquid. This is true for pure water and, interestingly, for more viscous solutions at low liquid loadings due to the increased velocity in the laminar flow region. From these results, boulders with diameters approximately half the liquid depth would experience this much force.

Conclusions: Based on in-situ analyses of unconsolidated surface deposits on Mars, a considerable amount of very soluble salts are present that, when mixed with water, could create viscous and dense solutions under Martian temperature conditions. These liquids could be responsible for the creation of at least some morphological features on Mars such as gullies. Preliminary modeling has revealed the possibility of laminar as well as turbulent flows that may be capable of transporting rocky material large enough to be imaged by HIRISE. The goal of our program is to consolidate laboratory studies of low temperature fluids, numerical modeling, flume-based experimentation and spacecraft images of gullies to determine the physical properties responsible for fluvial features on Mars.

References: [1] Heldmann and Mellon, Icarus, 168. p. 285, 2004 [2] Heldmann et al., JGR, 110, E05004, 2005 [3] Musselwhite et al., GRL, 28, 1283, 2001 [4] Stewart and Nimmo, JGR, 107, p. 5069, 2002 [5] Sears and Chittenden, GRL, L23203, 2005 [6] Chevrier and Altheide, this meeting [7] Coleman et al., 2007. Second International Workshop: Exploring Mars and its Earth Analogs, Trento, Italy, p. 43, 2007 [8] Coleman et al., this meeting [9] McEwen et al., Science, 317, p. 1706, 2007