### Introduction:
Mass movement is a collection of gravity-driven processes that act to move materials down a hillslope. Depending on particle size, unconsolidated hillslope materials have a variety of properties that may allow them to resist this gravitational pull downslope, which are known collectively as the shear strength. The relationship between gravity and shear strength is dependent on many variables that are independent of gravity. Nevertheless, the lower gravity on Mars is expected to produce some systematic changes in mass movement behaviors that may in turn create morphological features that are observably different from their terrestrial counterparts. Here we examine how the lower gravity field on Mars is expected to affect the behaviors of unconsolidated slope materials and subsequent landforms. Future work will utilize this detailed understanding of the behavior of unconsolidated materials on Mars to investigate potential processes acting on hillslopes.

### Angle of Repose:
The angle of repose describes how steep a slope made of unconsolidated materials may become; once this critical angle is exceeded, slope failure will occur. The angle of repose also dictates how steep a regolith mantle may become on a bedrock slope. If we set aside the effects of gravity-independent properties such as cohesion, the forces acting on a grain on the slope of a sand pile at the angle of repose can be expressed as the sum of the resisting (frictional) and driving (gravitational) forces (Fig. 1). Friction is both a function of gravity and also the intrinsic properties of the slope material. This intrinsic component is expressed as the static coefficient of friction \( \mu \), which is an empirically derived, dimensionless quantity. The total force felt by a grain on the slope can be expressed as

\[
F = mg \sin \theta - \mu mg \cos \theta \quad (1)
\]

where \( m \) = mass of the grain; \( g \) = acceleration of gravity; \( \theta \) = critical angle of the slope (angle of repose); and \( \mu \) = coefficient of friction. In the case where material is at the critical angle of repose, the forces on the grain are equal:

\[
mg \sin \theta = \mu mg \cos \theta \quad (2a)
\]

or

\[
\mu = \tan \theta \quad (2b)
\]

Equation (2b) shows that the coefficient of friction \( \mu \) is not dependent on gravity but rather on the angle of the material. Thus, for a particular cohesionless granular material, the angle of repose will be the same regardless of gravity.

The angle of repose generally increases with particle size, but this relationship is size-limited; in very fine-grained materials, the angle of repose begins to increase again as particle sizes decrease [e.g. 2]. This is the result of cohesion between grains produced by van der Waals forces. While this cohesion is often the result of thin films of water between grains, it may also occur in the absence of moisture in very fine-grained materials. As gravity is reduced, the apparent strength of the van der Waals forces increases in relation to the weight of a particle. As the weight of the particle increases, cohesion decreases. However, under martian gravity the weight of the particle is less than that of the same size grain on Earth. As a result, the total weight force felt by the grain is less on Mars than on the Earth, thus cohesion is a relatively larger force in the system.

If cohesion \( C \) is added to the model shown in Fig. 1, Eq. (1) now becomes

\[
mg \sin \theta = \mu mg \cos \theta + C \quad (3a)
\]

or

\[
\sin \theta - \mu \cos \theta = \frac{C}{mg} \quad (3b)
\]

When cohesion is taken into account, the gravity term remains; now the angle of repose may be increased in a cohesive material in a lower gravity envi-
environment. Thus, on lower-gravity Mars, fine-grained materials may have a higher angle of repose than they would on Earth if sufficient moisture is available or if grain sizes are small enough.

**Shear Strength**: Shear strength is the maximum strength of a material to resist deformation or yielding. Both friction and cohesion provide shear strength to an unconsolidated material. The shear strength \( \tau \) of a slope material is the summation of resisting forces (friction and cohesion) and driving forces, and can be described with the Mohr-Coulomb model:

\[
\tau = \sigma_n \tan \varphi + C
\]  

where \( \sigma_n \) = effective normal stress (normal force); \( \varphi \) = angle of internal friction; and \( C \) = cohesion. As in Eq. (3a), which describes the total force acting on a grain at rest on a slope, the angle of internal friction (\( \varphi \)) here is equivalent to the angle of repose when cohesion \( C = 0 \).

Once a critical amount of intergranular water is present, van der Waals hydrogen bonding is no longer effective and the water acts to push grains apart. This pore pressure acts against the normal force, which holds materials together. Equation (4) can be modified:

\[
\tau = (\sigma_n - \mu_p) \tan \varphi + C
\]  

where \( \mu_p \) is pore pressure.

Because gravity is a component in the normal force, shear strength decreases with a decrease in gravity. However, recall from Eq. (3a) that when a particle is at rest on a slope, the resisting forces are equal to the driving forces. If Eqs. (3a) and (5) are combined, we can see that

\[
mg \sin \varphi = (\sigma_n - \mu_p) \tan \varphi + C
\]  

Gravity is a term on both sides of the equation and will cancel out; and so even as shear strength decreases, the pull of gravity will be proportionally smaller. However, both cohesion and pore pressure are independent of gravity, and so a change in gravity will lead to these factors having a greater effect on the system. Thus, cohesion in unconsolidated materials may lead to steeper slopes on planets such as Mars that have lower gravity fields than Earth. By the same token, pore pressure may act to weaken slopes more on Mars than would be expected on Earth.

**Implications**: The lower gravity on Mars will allow for steeper slopes in fine grained (< 0.5 mm) materials, even when dry. No change in angle of repose is expected for larger particles. An increase in soil moisture content (e.g., pore pressure) on Mars is expected to weaken unconsolidated slope materials more than the same moisture content in a similar terrestrial slope (Eqn. 6). As a result, rates of creep for a particular soil moisture content may be expected to be somewhat greater for soils on Mars. Similarly, the action of frost heave is expected to have a greater effect on downslope transport of slope materials on Mars than it does on Earth. Processes triggered by saturation such as debris flow may also occur at lower pore pressures, suggesting that less liquid water is needed on Mars for these processes to occur. Additionally, a lower driving force (gravity) should lead to shorter runout lengths for rapid mass movements if cohesion remains the same. This has been observed in large landslide deposits on Mars, which have larger ratios of height of drop/length of runout (H/L) than landslides of similar volumes on Earth [3]. A lower gravity will also cause overland flow to exert a proportionally lower shear stress on slope materials than similar flows on Earth (see [1] for a more detailed discussion of overland flow in extraterrestrial environments), suggesting that proportionally smaller sediments will be transported downslope for the same volume of water.

**Future work**: With this understanding of how unconsolidated hillslope materials are expected to behave under martian conditions, it is possible to combine observed hillslope morphologies with particle size information to evaluate the types of processes that may have acted on a particular hillslope, as well as whether or not liquid water may have a role. Thermal infrared remote sensing data has been used successfully on Earth and Mars to identify sediment types and sizes [e.g. 4, 5]. Previous work by [6] has identified several locations on Mars in which debris flow deposits appear to be present based on observed morphologies. Preliminary examination of nighttime thermal infrared data from the THERMAL EMission Imaging System (THEMIS) of these locations [6] indicate that variations in thermal inertia (which can be related to sediment size or degree of induration) are discernible between gullied hillslopes and the adjacent terrain. Future work will focus on understanding sediment size distributions and slope gradients on these and other gullied crater hillslopes.

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