IMPACT OF REGOLITH AND VARIABLE GEOMETRIES ON LUNAR LAVA TUBES STABILITY.

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Introduction: There is strong evidence supporting the presence of lava tubes on the Moon [1]. Their potential large sizes would make them ideal shelters against surface hazards such as temperature variations, radiation, and micrometeoroids. From this perspective they are promising alternatives for future human and robotic activity on the Moon. In this context, the stability of potentially very large lava tubes becomes an important issue for assessing their presence because safety will be the prime importance for eventual use in future exploration. In this regard, a recent stability analyses for variable lava tube cross-section geometries [2] have shown that consideration of variable shapes causes significant decrease in lava tube stability with respect to circular or elliptical shapes (e.g., [3, 4]).

Our primary focus involves the regolith layer consideration in lunar lava tube stability assessment to further making it more realistic for safety analysis. For simplicity, a single cross-section of variable geometry is selected and a detailed analysis of regolith impact on its stability is demonstrated.

Methods: Stability assessment of variable cross-sections are performed via Finite Element Limit Analysis (FELA), for which commercially available software OptumG2 was used in conjunction with the in-house MatLab procedure [2]. FELA is an implementation of lower- and upper-bound theorems of limit analysis (e.g., [5]) capable to provide bounded estimates of the true collapse load by searching a statically admissible stress field (the lower bound of limit load) and kinematically admissible velocity field (the upper bound of limit load). The setting used here provides the lowest solution for the upper bound and the greatest for the lower bound in terms of gravity multiplier ($\mu_G$), which means how many times the lunar gravitational acceleration must be increased to observe the collapse. Figure 1 shows the upper bound stability results for 500 randomly generated cross-sections as a function of ratio between the maximum extent of the collapse and width of the tube [2]. The introduction of variable shapes causes significant decrease of stability with respect to ideal circular cross-section (for which the upper bound is denoted by the solid horizontal line in Fig. 1). The results are obtained for Mohr-Coulomb material, rock density 3100 kg/m³, unit weight of rock 5.028 kN/m³, cohesion 4.2 MPa, and friction angle 37°; variable shapes are obtained by adding a random noise to the circular shape of diameter 800 m (the scale of fluctuation is 200 m, the standard deviation of geometry variations is 20 m, for more details see [2]).

Regolith impact on lava tube stability: The case of variable geometry for which the lowest gravity multiplier is obtained is shown as the red dot in Fig. 1 and represented in Fig. 2. Note that earlier results [2] and these presented in Fig. 1 do not consider the presence of lunar regolith; therefore in Fig. 2 the geometric characteristics for the scenario with regolith are presented. Uniform regolith parameters are assumed; density 1900 kg/m³, unit weight 3.082

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**Figure 1.** Stability results for variable lava tube geometries.

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**Figure 2.** Model used for regolith consideration.
kN/m$^2$, cohesion 5 kPa, and friction angle 40° [6]. Due to its significantly smaller cohesion, the presence of a regolith layer decreases the lava tube stability. To assess this effect all analyses were performed for the cross-section shown in Fig. 2 for a variety of regolith thickness and rock thickness configurations. The scenarios for which the regolith layer is considered on the top of the rocky roof are shown in Fig. 3, where the bar thickness denotes the difference between the lower and upper bound estimates. The red bar denotes gravity multipliers for the reduced rock tensile strength (tension cut-off is 0.697 MPa [2]). For both cases lava tube stability decreases for increasing regolith thickness, and greater relative decrease is observed for the thinner roof scenario (see right panel in Fig. 3). The discussed results illustrate the regolith influence on the lava tube stability, however it does not fully represent the lunar case, where due to aging of lunar surface the thickness of intact rocks decreases in favor of an increasing layer of regolith and highly fractured rocks. This effect is reflected in the results shown in Fig. 4, where the minimum distance from the top of the ceiling to the lunar surface is constant, but the proportions of intact rock and regolith thicknesses are varied. For reference, in Fig. 4 dashed lines denote the gravity multiplier obtained only for a rock thickness of 5 m (with or without reduction in tensile strength). It is seen, that when decreasing rock thickness and substituting it by a weaker regolith layer, a stronger decreasing tendency in gravity multipliers is obtained in comparison with a constant rock thickness and increasing regolith layer (compare Fig. 4 with Fig. 3). This suggests that aging processes may significantly reduce the lava tube stability over time, which is especially important for relatively thin lava tube roofs. Examples of such collapse may be observed in the case of Schlüter and Southwest Fecunditatis pits [7]. For presentation purposes, we considered regolith thickness ranges larger than the Moon’s estimated average values [8].

![Figure 3. Gravity multipliers as a function of regolith thickness for cross section shown in Fig. 2 and two rock thicknesses, i.e., 50 m (left) and 15 m (right).](image1)

![Figure 3. Gravity multipliers for different proportions between regolith and rock thicknesses.](image2)

**Conclusions:** The presence of a regolith layer may significantly decrease the stability of lunar lava tubes, where those with relatively thin roofs are most vulnerable to collapses due to lunar surface aging. To more precisely estimate the decrease of stability over time the knowledge of lunar surface aging will be employed in future studies. It is demonstrated that consideration of regolith layer together with variable shapes significantly reduce the stability estimates with respect to earlier studies (e.g. [3, 4]), where ideal cross-section geometries were considered. This means that gravity driven collapses are more probable when considering the discussed aspects. However, it is noted that if the lava tube ceiling is perpendicular to the gravity vector, there is a higher chance of collapse, potentially leading to the preservation of more resistant shapes during the tube formation.