SIZE AND STRUCTURAL STABILITY ASSESSMENT OF LUNAR LAVA TUBES. A. Modiriasari[1*], A. K. Theinat[1], A. Bobet[1], H. J. Melosh[2], S. J. Dyke[1,3], J. Ramirez[1], A. Maghareh[1], and D. Gomez[1]. [1,*]Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, amodiria@purdue.edu; [2]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907; [3]School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907.

Introduction: Establishment of permanent human settlements outside Earth is gaining attention by Space agencies such as NASA and European Space Agency, as well as by industry, e.g. SpaceX. Existing preliminary conceptual designs for permanent lunar bases mostly focus on above-surface habitat systems and all neglect the largely unexplored needs regarding the habitat and infrastructure required on extraterrestrial bodies. It is imperative to build habitat systems, laboratory or manufacturing buildings that are capable of responding to extreme conditions such as radiation, meteorite impacts and extreme temperatures. Underground habitats are not exposed to those hazards and can potentially serve as secure shelters for future human lunar exploration [1,2].

Data from the Gravity Recovery And Interior Laboratory (GRAIL) support the presence of a network of large, empty caves in the lunar lava flows, with an initially estimated extension of 1-2 km in width [3]. Lava tubes of this size are substantially larger than any known terrestrial examples, which have maximum widths of ~30 m [4]. The presence of such natural lunar caverns is supported by imagery from JAXA's SElenological and Engineering Explorer (SELENE) spacecraft and NASA's Lunar Reconnaissance Orbiter (LRO) that show the existence of uncollapsed pits near the lunar surface (~75 m in height) at locations that are consistent with mass deficits on GRAIL data [5,6]. The key question is whether a lunar lava tube may really attain widths of 1-2 km without collapsing. In this work, we focus on the task of estimating the cross-section area of empty lunar lava tubes on the Moon through analytical and geometrical analyses, given estimated volumes of lava flows and lunar topography. In addition, numerical simulations are presented to analyze the structural stability of lava tubes.

Cross-section area of lunar lava tubes: In this section, we show whether lava tubes may in fact be able to exist at sizes comparable to those inferred from GRAIL data. Our method incorporates knowledge of the parameters of lunar rocks and the mechanics of lava flows.

The effusion rate of lava from a feeder vent provides information about how magma is transported beneath the surface of a planet and is important for determining the extent of a lava tube. Estimation of the effusion rate (Q_E) requires the knowledge of the eruption rate, which cannot be measured directly from past eruptions. Effusion rates may also be estimated using the Gratz number (G_z), which is the ratio between the heat advected during flow to the heat conducted [7]. An estimate of the effusion rate for a single lava flow with Bingham yield stress Y_B, on a surface with average slope θ can be obtained as [7]:

$$Q_E = \frac{\kappa\ A\ G_z}{Y_B} \rho g sin\theta \quad (1)$$

where κ is the thermal diffusivity of the lava composing the flow, A is the area of the lava flow, ρ is the density of the lava, and g is the acceleration of gravity. Effusion rate is probably the major factor controlling the final area of a lava flow [7]. Table 1 lists estimates of the parameters describing lava flows on the moon. κ, G_z, and ρ are assumed as $10^{-6}\ m^2/s$, 30 [7], and 2,790 kg/m^3 (10% less than the solid basalt density of 3,100 kg/m^3 [8]), respectively.

Table 1. Properties of lava flows on the Moon

Bingham yield strength (Pa)	Area (km^2)	Slope (degree)	Effusion rate (m^3/s)
3.8-59151 [9] avg ~1163	0.3-2434 [10] avg ~15.9	0.01-1.4 [10] avg ~0.3	1e(-4)-2e(+6) avg ~10

As shown in Table 1, the estimated range of effusion rate may be up to $2\times10^6\ m^3/s$ (note that here we try to estimate the largest size of lava tubes). Assuming an average velocity of the lava flow of ~1.5-3 m/s [11], the cross-section area of the lava tubes is estimated of order of 7×10^5-$1\times10^6\ m^2$. If we assume that the lava tube has a circular or elliptical (with a width (W) to height (H) ratio of 3:2 or 2:3) cross-section and runs full, the diameter of the tube is ~1 km, which is comparable to the results from the GRAIL data.

Structural stability of lunar lava tubes: Oberbeck et al. (1969) estimated the maximum possible width of lunar lava tubes to be ~385 m, assuming a lunar basalt density of 2,500 kg/m^3 and a roof thickness of 65 m [12]. Their results underestimate the maximum width of the tubes since it was assumed, in the calculations, that the roof could be approximated as an elastic beam. However, arched structures like lava tubes should be able to support much larger stable spans [8]. Previous work using numerical methods and reasonable estimates of the lunar rocks properties has shown that lava tubes may in fact be able to remain stable at sizes comparable to those inferred from

GRAIL data [8]. We can show that lava tubes with the sizes estimated from the analytical analysis and GRAIL data may be structurally stable, which is consistent with the findings from Blair et al. [2017].

For the analyses, we have created a series of finite element models using the commercial software ABAQUS [13]. All of the models assume plane-strain conditions and are symmetric about a vertical plane following the lava tube's longitudinal axis. A lunar basalt density of 3,100 kg/m^3 is used in the models that is a rough mean of the values found in Apollo mare samples [14]. The stresses in the rock are due to the self-weight of the material while the lateral boundaries have the vertical displacements constrained. This represents situations where the rock has not been able to relax the differential stresses after deposition. A Poisson initial stress states, assuming a Poisson ratio of 0.25, is assumed in the models. A Mohr-Coulomb plastic failure envelope is used for the constitutive model of the lava (Young's modulus of 30 GPa, unconfined compressive strength of 100 MPa, friction angle of 43^0, dilation angle of 29^0, cohesive strength of 7.2 MPa, Geological Strength Index (GSI) of 70, and material constant of 20 [8] are used in the models).

Two series of simulations are conducted. In the first series, we vary the roof thickness (T) of the lava tube for a tube width of 4 km, assuming that the void space inside the tube is a half-ellipse with a W:H ratio of 3:2. This cross-section shape mimics the general shape of terrestrial lava tubes [15]. In the second series, the effect of the shape of the lava tube's cross-section on its stability is analyzed. Both circular and elliptical cross-sections (with a W:H ratio of 3:2 and 2:3) are used. The stability of a lava tube is assessed by observing the volume of rock in the overburden that is yielding. If there is not yielding at all, then the tube is stable; if the yielding is less than 50% the thickness of the overburden, then it is considered quasi-stable; if the yielding is larger than 50%, then it is unstable. The stability results of a lava tube with 4 km width are shown in Table 2, and are comparable to the numerical results by Blair et al. [2017]. As shown in Table 2, the maximum stable (or quasi-stable) size of a lava tube strongly depends on the tube's roof thickness. A lava tube with ~4 km width is stable with a roof thickness of 50 m.

Table 2. Lava tubes stability from this study and comparison with the results from Blair et al. [2017]

W (m)	H (m)	T (m)	Stability	Results in Blair et al. [2017]
4000	1333	200	quasi-stable (8%)	quasi-stable
4000	1333	100	quasi-stable 10%)	quasi-stable
4000	1333	50	quasi-stable (25%)	quasi-stable
4000	1333	20	unstable (70%)	unstable

Figure 1 shows the results of the second series of simulations. As shown in Figure 1, the shape of the cross-section has a significant influence on the results, with smaller yielding in the overburden for circular cross sections or for ellipses with the long axis oriented vertically.

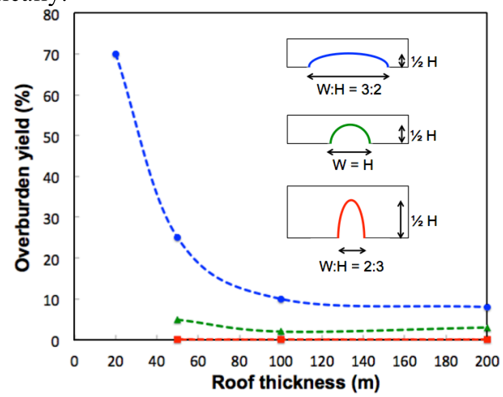

Figure 1. Lava tubes stability with different cross-sections

Discussion: Our results from analytical analysis support the interpretation that GRAIL gravity observations could represent very large vacant sublunarean lava tubes (several kilometer-wide) under lunar conditions, if such tubes were able to form initially. Our numerical simulations indicate that lava tubes with even 4 km width may be able to remain stable with roofs as thin as ~40 m with both elliptical and circular shapes if the material does not contain a fatal defect (i.e. the cooling process does not induce significant cracking in the rock or large tensile strains, and the assumption of a continuous medium is acceptable). The analyses show that these tubes could be more than two orders of magnitude wider than the largest known terrestrial lava tube. This might be due to reduced gravity and different volcanic environment on the Moon than on the Earth, with e.g. higher eruption rates on the Moon and different cooling conditions and cooling rates.

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