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Lunar Meteoroid Ejecta Engineering Model

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2.1 Porosity

The lunar regolith porosity is related to the amount of free space between individual grains. The greater the porosity, the more void space is present. Table 3.4.2.3.4-1 of the DSNE gives values of the porosity as a function of depth down to 60 cm derived from Apollo core measurements (copied from Table 9.5 of the Lunar Sourcebook) and shown here in Table 1.

Table 1: Porosity for various depths.

Depth Range (cm)	Average Porosity, n (%)
$0 - 15$	52 ± 2
$0 - 30$	49 ± 2
$30 - 60$	44 ± 2
$0 - 60$	46 ± 2

2.2 Density

The bulk density (ρ) of the lunar regolith is defined as the mass of material in a given volume, which relates the particle density (ρ_p) and porosity (n) to the bulk density as (see Section 3.4.2.3.1 of the DSNE or Chapter 9 of the Lunar Sourcebook)

$$\rho = \rho_p(1 - n). \tag{2.1}$$

The DSNE suggests using $\rho_p = 3.1$ g/cm^3 for the average particle density over the entire Moon. Otherwise, the typical highlands particle density is $\rho_p = 2.75 \pm 0.1$ g/cm^3 whereas the typical mare particle density is $\rho_p = 3.35 \pm 0.1$ g/cm^3.

The bulk density[1] as a function of depth, fit to Apollo data, is given by

$$\rho(z) = 1.92\frac{z + 12.2}{z + 18}, \tag{2.2}$$

where z is the depth in cm and ρ is in units of g/cm^3. At the surface ($z = 0$), the density is 1.30 g/cm^3, and increases to 1.92 g/cm^3 for large depths. This expression is fairly reasonable down to 3 m (the limit reached by Apollo drill core samples). In order to get an up-to-depth average of the bulk density, take

$$\rho_{avg,depth}(z) = \frac{1}{z}\int_0^z dz'\rho(z'), \tag{2.3}$$

[1] Follows the average particle density of 3.1 g/cm^3 for all depths with a porosity depth dependence following Table 1, see the *porosity of lunar soil* paragraph on page 492 in the Lunar Sourcebook.

which gives (compare with the equation for d_m on page 494 of the Lunar Sourcebook)

$$\rho_{avg,depth}(z) = 1.92\left[1 - \frac{5.8\ln\left(\frac{z+18}{18}\right)}{z}\right]. \tag{2.4}$$

For example, the average bulk density of the regolith with a depth range of $0 - 60$ cm would be $\rho_{avg,depth}(60)$ = 1.65 g/cm^3.

For a higher-fidelity estimate of the average bulk density sampled by the crater, a volume-average can be used instead of a depth-average, given by

$$\rho_{avg,volume}(z) = \frac{\int dV \rho(z')}{\int dV}. \tag{2.5}$$

Expanding the integral in a cylindrical coordinate system, Equation (2.5) becomes

$$\rho_{avg,volume}(z) = \frac{\int_0^z \int_0^{R\sqrt{1-z'^2/z^2}} \int_0^{2\pi} d\phi r dr dz' \rho(z')}{\int_0^z \int_0^{R\sqrt{1-z'^2/z^2}} \int_0^{2\pi} d\phi r dr dz'} \tag{2.6}$$

$$= \frac{1.92}{4z^3}\left[z(6ab - 6b^2 - 3az + 3bz + 4z^2) + 6(a-b)(b^2 - z^2)\ln\left(\frac{b}{z+b}\right)\right], \tag{2.7}$$

for the volume-averaged density in g/cm^3 with z in cm, where $a = 12.2$ and $b = 18$. Following the example from earlier, the average bulk density of the regolith with a depth range of $0 - 60$ cm would be $\rho_{avg,volume}(60)$ = 1.60 g/cm^3, which is $\sim 3\%$ less than $\rho_{avg,depth}(60) = 1.65$ g/cm^3. The expression given in Equation (2.7) is useful for computing the ejected mass from a crater[2], given a crater depth z.

The expressions for the regolith density at a certain depth z, weighted by depth, and weighted by crater volume are given by Equations (2.2), (2.4), and (2.7), respectively, are compared in Figure 1. The crater volume is approximated as a half-ellipsoid with two of the dimensions scaled by the crater radius R and one dimension scaled by the crater depth z, sliced such that the half-ellipsoid is symmetric about the surface normal. For a given crater, more of the volume is near the surface so that more weight is given by bulk densities that originate near the surface. In contrast, the depth-averaged bulk density takes the bulk density at each depth equally. This results in the volume-averaged bulk density to be slightly less than the depth-averaged bulk density, as shown in Figure 1 .

[2] In an iterative fashion, since the crater radius depends on the regolith density.

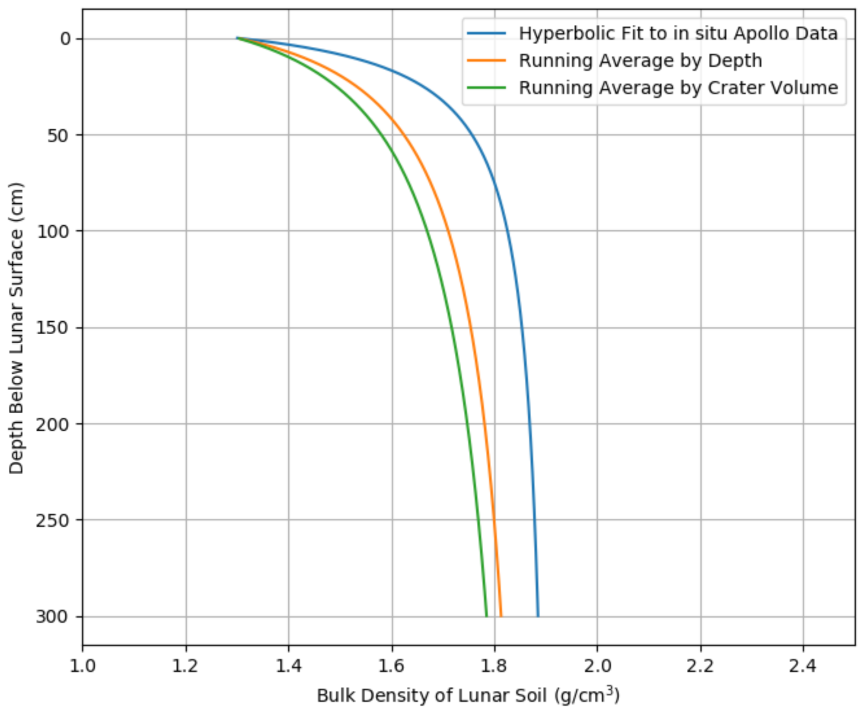

Figure 1: A comparison of the regolith bulk density for a certain depth depth (blue), the depth-averaged bulk density (orange), and the volume-averaged bulk density (green). See also, Figure 9.16 of the Lunar Sourcebook.

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