The Application and Modification of Geotechnical Engineering Methodologies on the Lunar Surface.

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Introduction: As a permanent lunar base is established on the Moon, it is essential that the geotechnical properties of the lunar surface are well understood. The lunar surface provides a unique environment for geotechnical engineering, as the absence of both liquid water and atmosphere within the regolith results in many terms of terrestrial geotechnical equations becoming negligible By identifying the most important geotechnical relationships of the lunar regolith and how they are altered in the lunar environment, we will be able to better mitigate any negative effects as well as utilize the regolith for purposes such as construction and oxygen production. Here, we review the differences between geotechnical processes on the Earth and Moon, as well as highlight the essential physical relationships for use on the lunar surface.

Fundamental Equations: Much of terrestrial geotechnical engineering is focused on the effects of water within a soil profile, as it complicates relationships such as settlement and effective stress. Since terrestrial sites have large variations in degree of saturation and pore fluid pressure, it is not possible to develop a set of equations that are applicable everywhere across Earth. The Moon provides us with a unique set of conditions that enable the creation of a set of equally unique geotechnical relationships that are potentially applicable across the entire lunar surface. This is primarily due to a consistent lack of pore fluids (e.g., water and air).

To understand the effects of pore fluid absence on the lunar regolith, we must first consider the some of the most fundamental geotechnical equations, which describe Mass-Volume relationships of a soil [1].

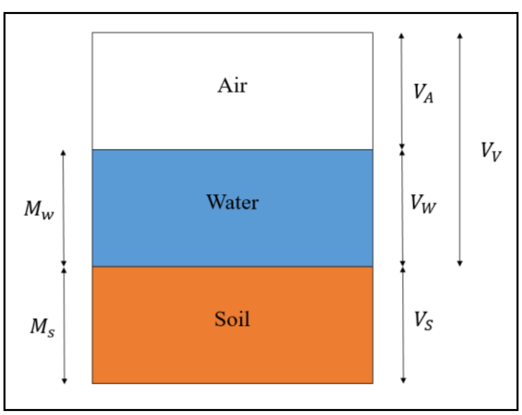

Figure 1. Soil as a Three Phase System

Mass-Volume Equations:

Void Ratio: $e = \frac{V_v}{V_s}$

Porosity: $n = \frac{V_v}{V}$

Saturation: $S = \frac{V_w}{V_v}$

Water Content: $w = \frac{W_w}{W_s}$

Unit weight: $\gamma = \frac{W}{V}$

Dry Unit Weight: $\gamma_{dry} = \frac{W_{dry}}{V}$

Specific Gravity: $G_s = \frac{\gamma_s}{\gamma_w} = \frac{W_s}{V_s \gamma_w}$

Mass-Volume Relationships:

Water Content: $w = \frac{Se}{G_s}$

Unit Weight: $\gamma = \frac{\gamma_w G_s (1+w)}{1+e}$

Dry Unit Weight: $\gamma_{dry} = \frac{\gamma_w G_s}{1+e}$

Dry Unit Weight: $\gamma_{dry} = \frac{\gamma}{1+w}$

Saturated Unit Weight: $\gamma_{sat} = \frac{\gamma_w (G_s + e)}{1+e}$

It can be observed from these equations that there is no one simple way to characterize all of the properties of a terrestrial soil without *in situ* testing. Where previously, void ratio and porosity were dependent on the volume of water and air within a soil, they are now solely functions of bulk density and particle density. This simplification is due to the absence of pore fluids in the void space, as the weight of the sample remains the same no matter its density. Equations measuring water content, saturation, and saturated unit weight are now negligible as there is no water in the regolith. In addition, Unit Weight and Dry Unit Weight are now equal, as the regolith is always dry.

Lunar Regolith Mass-Volume Relationships:

Particle Density = ρ_s

Void Ratio: $e = \frac{V_v}{V_s} = \frac{\rho_s - \rho_{bulk}}{\rho_{bulk}}$

Porosity: $n = \frac{V_v}{V} = 1 - \frac{\rho_{bulk}}{\rho_s}$

Saturation: $S = 0$

Water Content: $w = 0$

Unit weight: $\gamma = \gamma_{dry} = \frac{W}{V}$

Effective Stress: One of the most essential properties of a site for infrastructure development is its effective stress, which is the stress at a depth in the soil profile due to both the weight of the material above, and the pore pressure from below. In terrestrial conditions, effective stress is subject to changes throughout the year as water tables rise and fall. This variability is not a concern on the Moon, as there is no water table.

Effective stress on the Moon is simplified to only the weight of the material above a point, a linear relationship. While any attempt to estimate effective stress on Earth requires field testing and sampling, due to the relative homogeneity of the Moon we can estimate the lower and upper bounds of lunar effective stress through our knowledge of mineralogy and regolith density.

Assuming a range of regolith density from 1000-2000 kg/m^3 as seen in Carrier et al. (1991) [2], we can calculate effective stress end cases at any depth. This is shown below:

$h_1 = Dry\ depth$
$h_2 = Saturated\ depth$
$Effective\ Stress\ on\ Earth\ (\sigma') = (\gamma h_1 + \gamma_{sat} h_2) - (h_2 \gamma_w)$
$Effective\ Stress\ on\ \text{The}\ Moon\ (\sigma') = \gamma h = \rho g d$

$$\gamma_{low} = 1000\,\frac{kg}{m^3} * 1.625\,\frac{m}{s^2} = 1.625\ \frac{kN}{m^3}$$
$$\gamma_{high} = 2000\,\frac{kg}{m^3} * 1.625\,\frac{m}{s^2} = 3.250\ \frac{kN}{m^3}$$

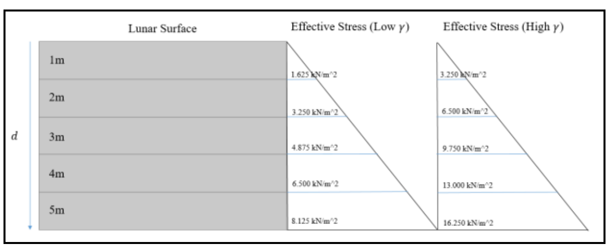

Figure 2. Effective Stress at a depth on the Lunar Surface

Assuming the upper and lower limits of bulk density for lunar regolith are known, this simplification of effective stress reduces the amount of site testing required, saving both time and energy required for geotechnical characterization.

Effective Stress: The settlement of a soil profile is a critical aspect of geotechnical engineering, as excessive or uneven settling can damage a structure. The three main types of settlement are: immediate settlement, primarily settlement, and secondary settlement. Immediate settlement is the reduction of void space without a change in moisture content, whereas primary and secondary settlement are dependent on pore water. Due to the lunar regolith having a negligible water content, only immediate settlement is applicable. Settlement within the lunar regolith depends only on the porosity of lunar regolith and its potential to compress further. This potential is limited by the regolith's relative density, as bulk density cannot exceed grain density. Settlement calculations are greatly simplified by this, as much of the complexity on Earth comes from the variability in pore water leaving the soil over the life of a structure.

Additional modeling and testing are required to determine the estimated settlement of lunar regolith, as it is dependent on relative density which changes with depth. With a deeper understanding of both the pre-existing density of subsurface lunar regolith as well as the reduction of void space due to a load, it will be possible to characterize the maximum settlement at any site on the lunar surface.

Conclusion: The lunar surface provides a unique opportunity to consider the reasoning behind geotechnical characterization, as well as determining differences in extraterrestrial environments. Due to the lack of pore fluids within the lunar regolith, both effective stress and settlement can be simplified into relationships that remain consistent across the Moon. These basic physical relationships form the foundation for understanding the geotechnical processes in extraterrestrial environments.

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References:
[1] Das, B. M., & Sobhan, K. (2018). Principles of geotechnical engineering (Ninth Edition)
[2] Carrier et al. 1991 *Lunar Sourcebook* pg. 497 Table 9.7