LOW GRAVITY, HIGH STAKES: ENGINEERING SHAKE-RESISTANT LUNAR INFRASTRUCTURE

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Introduction: With NASA's Artemis program paving the way for permanent human presence on the lunar surface and beyond, research into construction methods that harness bulk regolith are needed. Site preparation and infrastructure development are needed to increase reliability and facilitate a permanent human presence. Leveraging industry experience and established design practices in civil engineering can accelerate the development of sustainable lunar infrastructure and shape effective construction strategies [1].

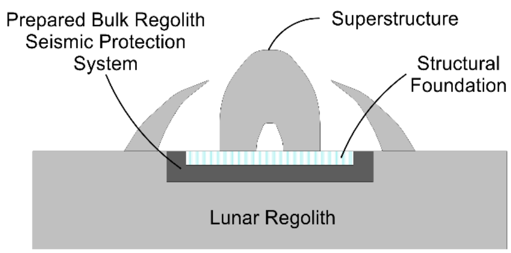

Figure 1. Example of Bulk Regolith Dampening Seismic Protection System

The anticipated lunar infrastructure stated in the Artemis vision will rely on prepared and compacted regolith surfaces, engineered to withstand expected loads with adequate safety margins. Ensuring the protection of these structures from seismic activity is crucial for system survival, human safety, resilience, and mission success. Key infrastructure components under consideration include vertical takeoff and landing pads, pressurized habitats, unpressurized shelters, tall towers, and protective structures, with an example of Starship HLS shown in Figure 2.

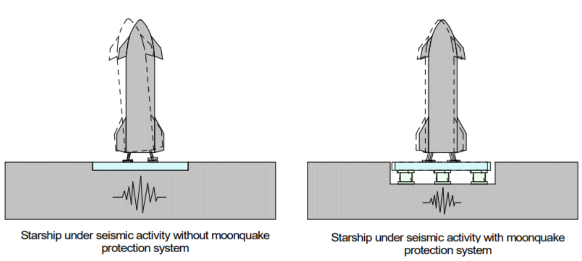

Figure 2. Simplified Seismic Structural Foundation Analysis Model Representation for Starship HLS

Slate Geotechnical Consultants (Slate), Colorado School of Mines (CSM), and Skidmore, Owings and Merrill (SOM) are working together towards furthering the knowledge of bulk regolith surface preparation construction Concepts of Operations (ConOps), foundation requirements, and establishment of preliminary seismic loading criteria, through NASA Small Business Technology Transfer Program (STTR) grant.

Moonquake Ground Motion Model (GMM): The collaborative work was initiated by the development of a lunar specific Ground Motion Model (GMM) that is representative of the seismic wave properties of shallow moonquakes by Slate. Physics-based simulations were conducted using limited lunar properties and a point-source stochastic model. To account for uncertainty in the medium and sigma GMM, Slate has used a set of moonquake parameters based on various publications, adjusted to best fit the available lunar data. An example of generated Probabilistic Seismic Hazard Analysis, depicting the mean and fractile hazard curves for frequency of 10 Hz can be seen in Figure 3. Figure 3 also demonstrates the large epistemic uncertainty in the Spectra Acceleration values computed given large uncertainty in the GMM and the simplified Seismic Source Model (SSM).

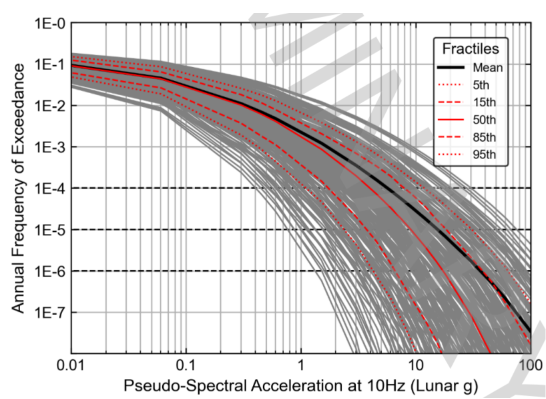

Figure 3. Mean hazard curve and fractiles at 10 Hz

The intention is to apply the developed lunar GMM modal towards the initial studies of lunar infrastructure, until more, site-specific data is obtained, while also identifying knowledge gaps to be addressed through future missions.

Geotechnical Assessment of CSM-LHT: CSM has worked towards determining the relationship between regolith density and surface preparation requirements to understand stress-based surface deformation behavior for lunar foundation systems. This involved determining the compressibility index and other geotechnical properties of CSM lunar highlands simulants to evaluate the fidelity in relation to actual lunar highlands regolith and mid-TRL testing environments inside the new CSM testbed. These geotechnical. These geotechnical properties can be used to inform modeling and testing efforts for scaled foundation systems when anticipated lateral loading is applied from Moonquakes. Results from this work can establish requirements for lunar surface preparation compaction levels for efficient system requirements, including foundations for infrastructure and building structures. Comparing this to terrestrial-based construction site compaction requirements can address potential cost savings in excavation depth and lunar surface preparation needs while also promoting both the safe operation of lunar foundation systems and minimizing construction costs.

Structural Analysis of Lunar Structures: SOM has taken a task of identifying potential lunar structural systems that are anticipated to require foundation systems. Eight prospective construction materials and five sets of lunar structural systems were identified, each having a subgroup of archetypes. For this phase of the project, two defined structural systems have gone through preliminary structural design and analysis: Tall Lunar Tower (TLT) and unpressurized catenary dome. TLT global geometry was based on the design parameters obtained from the research done by NASA Langley Research Center, as part of the Advanced Exploration Systems (AES) Polaris Project, [2,3]. The unpressurized catenary dome, considered due to its efficient load transfer, is assumed to act as an equipment shelter, with two ingresses.

By leveraging the results obtained from the lunar shallow moonquake assessment, simulant geotechnical testing, and compacted bulk regolith analysis, structural design efforts were investigated to provide for an initial foundation and seismic protection system, considering the site conditions, loading scenarios and environmental factors. The TLT and catenary dome models can be seen in Figure 4.

After developing conceptual seismic hazards and site preparation parameters, two predefined structures were further investigated using finite element analyses to evaluate their structural responses. These simulations accounted for the effects of reduced lunar gravity and moonquake-indued ground motions. The analyses investigated key structural behaviors, including stress distributions, modal frequencies, and deflection. Based on the results, different seismic mitigation approaches were considered, either by enhancing the structural system's strength and stiffness, or by incorporating seismic protection systems such as base isolation, viscous damping, or other energy dissipation devices to improve performance and resilience under moonquake events.

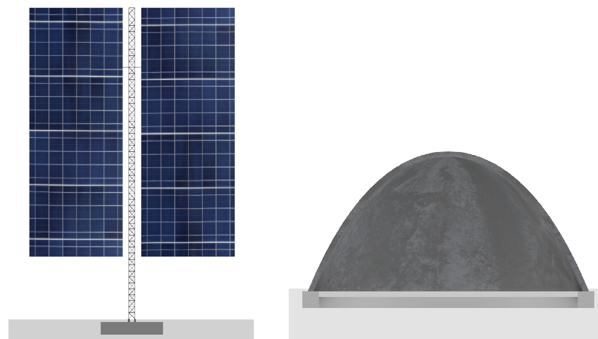

Figure 4. Potential Foundation Systems: Mat Foundation for Tall Lunar Tower (left) and Ring Beam Footing for Catenary Dome (right)

Next steps: Future studies intend to address additional lunar structural systems and archetypes, geotechnical properties of the site, and fatigue concerns. Shake table testing will be conducted utilizing anticipated seismic hazards determined through the GMM work.

References:

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