TOWARD A LUNAR BUILDING CODE: DEVELOPMENT OF SEISMIC DESIGN CRITERIA FOR LUNAR INFRASTRUCTURE. N. Caluk[1], T. Williams[2], I. Jehn[3]; [1]Skidmore, Owings & Merrill, 300 Clay St, San Francisco, CA 94111, nerma.caluk@som.com, [2]Slate Geotechnical Consultants, 5940 College Ave Ste A, Oakland, CA 94618, twilliams@slategeotech.com, [3]Colorado School of Mines, 1310 Maple St, Golden, CO 80401, ijehn@mines.edu

Introduction: Centuries of accumulated engineering knowledge, hard-learned lessons, and societal evolution have shaped the robust framework of building standards that governs construction on Earth today. Organizations such as American Society of Civil Engineers (ASCE), American Concrete Institute (ACI), American Institute of Steel Construction (AISC), International Organization for Standards (ISO), among many others, have developed numerous codes, standards, and guidelines that span the terrestrial built environment. Building codes such as ASCE-7, International Building Code (IBC), Eurocode, and their regional equivalents serve as more than technical documents; they function as social contracts between the engineering profession and the public. When a person enters a building, they do so with an implicit assurance that it was designed and constructed to meet the minimum safety threshold, accounting for its intended occupancy, use category, and local environmental demands. These frameworks did not emerge overnight; they are the product of generations of research, failure analysis, and iterative refinement.

As humanity prepares to establish a sustained presence on the Moon, a parallel challenge is present: how do we ensure the safety and integrity of structures built in an environment for which no such tradition exists? Lunar construction demands its own engineering framework, one that defines the boundaries of current knowledge, quantifies design load under conditions radically different from those on Earth, and identifies the data gaps that must be addressed before that knowledge can mature into fully codified practice.

In response to this need, research conducted through a NASA STTR Phase I solicitation had to the development of the first ever lunar seismic load criteria. This work, conducted by members of the ASCE Aerospace Division's Technical Committee on Space Engineering and Construction (SEC), provides the technical foundation for quantifying seismic demands on the lunar surface. These criteria have been integrated into the Lunar Infrastructure Engineering, Desing, Analysis, and Construction (LIEDAC) guidelines, an initiative by the SEC committee to establish a foundational lunar building code. This abstract focuses on the methodology behind seismic development, the scope of its applicability, and the framework it provides for safeguarding lunar infrastructure.

Proposed Lunar Seismic Loads: The seismic criteria developed through the NASA solicitation establish a preliminary methodology for lunar structural design, drawing parallels to terrestrial seismic philosophy while accounting for the Moon's unique geophysical environment. Central to this framework is the requirement for lunar structures to possess lateral and vertical force-resisting systems with sufficient strength, stiffness, and energy dissipation capacity to withstand moonquake ground motions.

To accommodate varying levels of structural complexity, the following two seismic analysis methods regularly used for terrestrial structures are also proposed for the lunar structures: Equivalent Lateral Force (ELF) method and Response Spectrum Analysis (RSA). The ELF method offers a simplified, static approximation of seismic demands by converting dynamic ground motion into an equivalent set of lateral forces applied across the height of the structure. This approach is well-studied on regular, low-complexity terrestrial structures. RSA, by contrast, is a dynamic analysis procedure that characterizes the structural response through its individual vibration modes, combining their contribution through established modal combination rules to capture the full dynamic behavior of the system. RSA is recommended for structures assigned to higher risk categories or those exhibiting significant dynamic complexity, where a single-mode approximation would be insufficient to capture the true distribution of seismic demands.

Two seismic shaking levels are defined to establish performance objectives at different severity thresholds. The Design Basis Moonquake (DBM), intended to establish the primary design demands, targets performance objectives consistent with life safety and limits structural damage under expected seismic events. The Maximum Considered Moonquake (MCM), representing a more severe shaking level, is used to verify collapse prevention and ensure overall structural integrity under extreme lunar seismic events. The framework also introduces a pathway for performance-based design. While current limitations in global data preclude the development of region-specific Ground Models, this approach allows for tailoring of seismic source characterization as site-specific data becomes available. By refining the source characteristics for a given area, engineers can significantly reduce uncertainty in the resulting hazard analysis, which is a critical step as lunar site data matures over the coming decade.

Equivalent Lateral Force Method: The seismic demand for the ELF procedure is anchored by a minimum base shear equation specifically adopted for the lunar environment. The proposed formulation is:

$$V = 0.6 * I * W \quad (1)$$

In this equation, V represents the minimum base shear, I is the importance factor, and W is the effective seismic weight of the structure under lunar gravity (1.62 m/s^2). While this formulation follows familiar terrestrial conventions, the underlying research derived the 0.6 scaling factor to account for the unique relationship between lunar gravitational acceleration and predicted seismic demands. This technical derivation, including the geophysical assumptions and safety margins established during the initial study, has been formally documented within the Commentary section of LIEDAC Chapter 6 to provide engineers with the necessary theoretical background for its application.

Response Spectrum Analysis: The dynamic behavior of lunar structures is captured through response spectra developed specifically for this framework, as exemplified by the spectral integrated into the LIEDAC documentation. These spectra were generated using a probabilistic seismic hazard analysis (PSHA) based on a Poisson process model. The methodology accounts for the rate of exceedance of ground motion, which may result from multiple seismic events, rather than the exceedance of a single moonquake. This hazard calculation integrates the rate of moonquake occurrences with the probability that any given event will cause ground motions to exceed a specified threshold. Using a standard design life of 50 years, the research computes ground motions associated with various probability levels of exceedance. As detailed in the development criteria, the appropriate probability of exceedance and ground motion fractile (selected as either the mean or 95th percentile) are determined based on the structure's risk category. This ensures that the selected ground motion intensity remains consistent with the required performance objectives for lunar infrastructure with higher risk categories.

Vertical Ground Motions: To address vertical seismic demands, the framework provides a standardized scaling approach for the development of vertical response spectra. Horizontal response spectra for each shaking level and risk category are scaled by a factor of 2/3 at each corresponding period. Rather than an arbitrary adaption of terrestrial standards, this scaling factor was validated through the analysis of available lunar seismic data, providing a rational and consistent basis for design. This approach ensures that vertical ground motions are adequately represented even in the absence of site-specific vertical data, maintaining structural safety against the multi-directional nature of moonquakes.

Geotechnical Investigation Report: Given the inherent uncertainties of the lunar subsurface, the developed criteria emphasize the necessity of a local geotechnical site investigation for all structures, regardless of their seismic design category. These investigations are critical for identifying and mitigating risks such as seismic slope stability, seismically induced total and differential settlement, and other geotechnical hazards that may be triggered or amplified by moonquake ground motions. The framework acknowledges that lunar site conditions are not yet fully understood on a global scale. Therefore, responsible design practices must account for this uncertainty through rigorous subsurface investigation whenever feasible. By prioritizing localized data collection, engineers can ensure that structural foundations are robust enough to handle the unique physical properties of the lunar regolith and the specific seismic demands of the deployment site.

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