Leveraging Established Principles for Landing and Launching Pad Design. J. Ramirez[1] (ramirez@purdue.edu), A. Bobet[1], A. Sharma[1], S. J. Dyke[1 2], O. Forero[1], C. Holbrook[2], J. Calonge[1] and M. Salmeron[1]. [1]Lyles School of Civil and Construction Eng., [2]School of Mechanical Eng., Purdue University, West Lafayette, Indiana 47907, USA.

Introduction: A future lunar settlement, as envisioned in the Moon-to-Mars architecture [1], with a thriving economy will require reusable and durable launching and landing pads (LLPs). A durable LLP will likely be among the first infrastructure elements to be constructed. Due to its size and expected operational demands, in this paper we explore the design option using ISRU materials. The indigenous materials to be processed to manufacture structural materials and structural elements are expected to exhibit brittle behavior. Based on experience with commonly used indigenous construction materials, such materials often exhibit inherent variability and therefore produce diverse mechanical responses. Civil engineers have learned important lessons on how to design reliable and long-lasting structures using brittle materials on Earth. These lessons must be leveraged and adapted to address the challenges of this extreme and largely unknown environment. Adopting a *build-observe-test-learn approach* to gather the experience required for designing and constructing durable, reusable infrastructure in extraterrestrial environments.

Background: On Earth, engineers have developed methods to analyze soils and design structures that prevent harmful interactions between the ground and the structure. Reliable construction is possible due to: (i) decades of accumulated knowledge of soil behavior and structural mechanics, (ii) the use of standardized tests to verify strength and durability, and (iii) the ability to investigate site conditions both at and below the surface before construction. These observations can then be compared with previously documented failure modes and known performance limits.

In *extraterrestrial environments*, however, the lack of direct experience in situ requires that many current structural and geotechnical design practices be revisited. Specifically, there is a need to return to first principles to understand how such environments and material properties may influence structural and geotechnical formulations. Although multi-physics finite-element methods are powerful tools, reliance on these models without proper validation may obscure potential failure modes and interactions that are critical to achieving safe and efficient designs.

Like typical construction practices on Earth, the final structural and geotechnical design will depend on transportation constraints, construction methods, and the required functionality of the LLP, all of which are part of a broader mission design. For instance, sintered regolith has been proposed as one class of potential construction materials for manufacturing LLPs [2]. However, consistent manufacturing and performance of these classes of materials must still be demonstrated to ensure that they will be effective at large scales and under in-situ Lunar conditions [3].

Design philosophy: When a structure falls outside the range of standard engineering practice, the application of first principles is essential to reliably design and analyze that structural system. Materials, environments, and loadings that are not characterized sufficiently require this treatment. As these structures are realized, in-situ observations and testing will then be critical to validate design assumptions and improve future lunar infrastructure, while also gathering the information needed for better characterization.

Significant knowledge gaps remain that may hinder the design of reliable and reusable Lunar LLPs, and those on other extraterrestrial bodies. Among the most critical information needed are the reliability of materials for structural applications both short and long-term, the geotechnical characterization of the ground below the LLP. Solicitations associated with spacecraft loads, extreme temperature variations, and plume–structure interactions need to be considered. The frictional interaction between the sintered regolith pad and the underlying subbase must also be considered in the structural design.

It is reasonable to assume that these brittle structural materials will exhibit significantly lower tensile strength than compressive strength. Consequently, both the mechanical properties of the LLP material and the characteristics of the supporting subsurface must also be well understood. Thermal effects may also play an important role. For example, temperature variations through the thickness of the slab may occur, where the exposed top surface contracts more rapidly than the bottom during a sudden temperature drop, potentially inducing upward curling of the slab.

Finally, appropriate soil constitutive models are required to represent ground response. An important question remains regarding how sensitive the design is to the selection and complexity of these models.

Due to the current state with very limited engineering knowledge of lunar soil conditions, and the lack of practical experience with various classes of manufactured regolith slabs, any design approach should explicitly account for uncertainty in the soil–structure interaction. In terrestrial slab and pavement design, the modulus of subgrade reaction (k) is often estimated and adjusted based on experience, expected environmental variations, and construction conditions, and the supporting system may be improved through compaction, stabilization, or the introduction of base layers. However, *such experience does not yet exist for lunar conditions*. As a result, the procedure used to determine slab thickness may be highly sensitive to assumptions regarding subgrade stiffness and soil behavior. Designers must therefore evaluate the sensitivity of the LLP design to these parameters while considering the relevant hazards, expected loads and serviceability demands, and acceptable probabilities of failure. To mitigate these uncertainties, early LLP structures could be intentionally designed to reduce sensitivity to variability in native soil support.

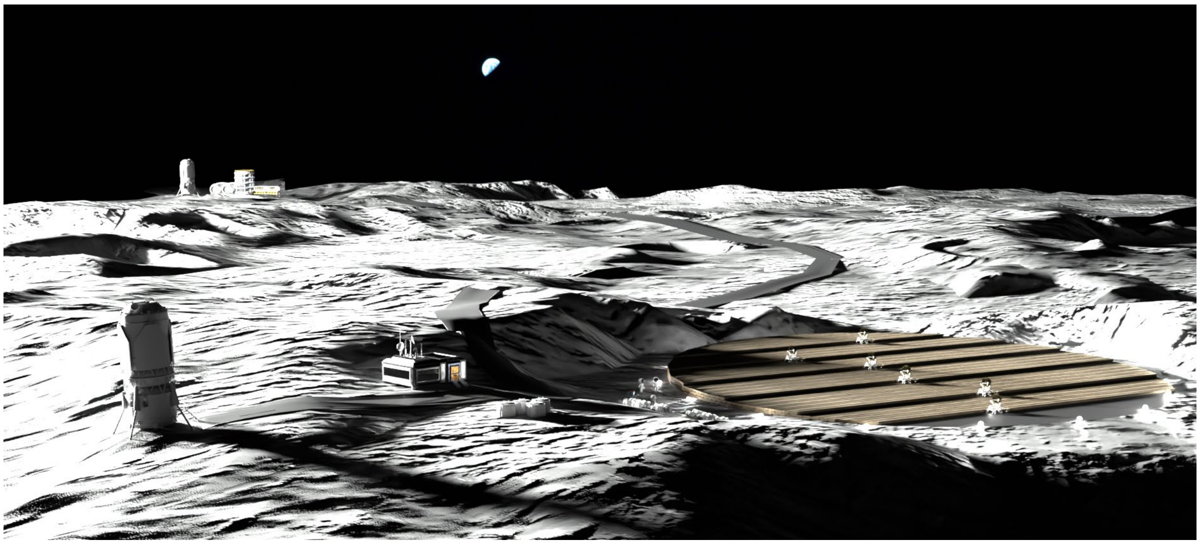

Figure 1. Envisioned LLP design and construction with a **build-observe-test-learn** approach.

Path Forward: These challenges are not new to civil engineers. Structural engineers have the expertise to build safe and reusable structures that can perform as needed on the Lunar surface. Given the significant uncertainties associated with extraterrestrial construction, conservative designs will be required until the necessary data is available for refined designs. Early infrastructure may be designed with a limited service-life while enabling critical steps related to observation and testing. These should be performed both during construction and while in operation. We recommend prioritizing the collection of information that is most critical for developing an initial safe and functional structure.

A robust **build-observe-test-learn** approach is therefore recommended to progressively develop the experience required for constructing infrastructure in extraterrestrial environments. In addition, a *dedicated structural and durability testing facility* for ISRU-based construction materials should be established on the Moon [2, 3]. Such a facility would support the development of engineering knowledge, enable the characterization of variability in manufactured regolith materials, and contribute to the establishment of construction standards necessary for future lunar infrastructure.

Closing: Although many unknowns remain regarding the construction of ISRU-based structures, similar challenges have historically been addressed within the field of structural engineering. Terrestrial construction materials also exhibit significant variability, and design loads are frequently estimated using simplified and imperfect models. Nevertheless, civil engineers have successfully developed safe and reliable structures under such conditions and will continue to do so. These challenges will be addressed gradually as knowledge and experience are accumulated.

References:

[1] NASA, "Moon to Mars Architecture Definition Document, Revision C." 2025. [2] E. Mount et al., "Lunar landing and launching pad design considerations using ISRU materials," *Acta Astronautica*, 240, 165–182, Mar. 2026, doi: 10.1016/j.actaastro.2025.11.071. [3] S.J. Dyke, et al., (2024). "Establishing Standards for Lunar ISRU Structural Materials," *AIAA Journal*, 62(7), 2414-2423, https://doi.org/10.2514/1.J063816.