HOW SMOOTH DO WE NEED IT? UNDERSTANDING LUNAR SURFACE PREPARATION REQUIREMENTS. I. Jehn[1], and C. Dreyer[1], [1]Colorado School of Mines, 1310 Maple St., Golden, CO 80401, ijehn@mines.edu.

Introduction: As the cis-lunar economy progresses toward sustained lunar surface operations, significant construction efforts are expected, particularly in preparing the existing regolith surface [1]. On Earth, surface preparation techniques for building sites are grouped into three categories: clearing, grading, and compaction methods [2]. Clearing involves excavation to remove rocks and debris from the site. Grading also relies on excavation to shape the terrain through cut and fill processes, resulting in a level surface. Compaction methods use either static or dynamic forces to consolidate the soil, reducing voids within the granular material before installing any surcharge or developing foundations [3].

The goal of surface preparation of native regolith, using these methods together, is to create a flat, stabilized, and compacted working area [3]. This is essential for providing a dense support for foundation systems, which helps reduce the risk of surface deformation [4]. Terrestrial foundation systems generally depend on an immediate subgrade layer constructed on native soils that offer this support [5]. Projects on the moon will likely utilize regolith within the vicinity of the construction site to form this subgrade layer.

Anticipated foundation deformations largely depend on the quality of surface preparation [6]. Techniques such as clearing, grading, and compacting help reduce the risk of regolith subgrade failure caused by deformations from consolidating the granular matrix. Therefore, it is understandable that significant research effort has been put into densifying regolith. However, recent research at the Center for Space Resources has raised questions about the smoothness requirement of these prepared surfaces.

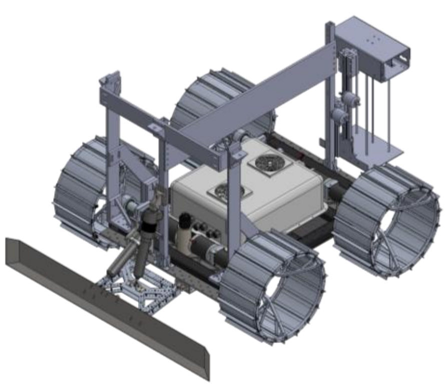

Figure 1: The ASPECT vehicle [10].

Background: Previous research has highlighted the importance of compacting native regolith to minimize potential stress-dependent surface settlement [3,4,6,7,8]. However, less attention has been paid to the smoothness required for these prepared sites to support new foundation systems.

Recently, the authors of this abstract completed the Automated Site Preparation, Excavation, Compaction, and Testing (ASPECT) project, funded by NASA LuSTR21 [10]. This project's goal was to demonstrate lunar surface site preparation using a vehicle equipped with a regolith manipulation "dozer blade" to perform clearing and grading operations, as shown in Figure 1. The platform was designed to clear, level, smooth, and compact a 10 m diameter area within the Mines Lunar Surface Simulator (MLSS) filled with several craters and rocks. For this project specifically, the prepared 10 m area was to support a landing pad foundation system. Many lessons were learned during this project, including applying traditional grading methods to lunar highland simulant. However, a key question became clear: how smooth does the surface need to be to adequately support a foundation system?

The LuSTR requirements specified a final surface smoothness of 1 cm Root Mean Square (RMS). The ASPECT vehicle attempted to achieve this smoothness through back-blading operations, meaning the rover would drive backward with the blade angled approximately 45° to smooth out the grouser tracks and other large amplitude vertical variations. While the team made good progress toward achieving this level of smoothness (see Figure 2), understanding the origin of this requirement became a common topic of discussion.

Discussion: This seems like a situation that could benefit from applying traditional civil and construction engineering experience. For most terrestrial construction projects requiring grading operations to prepare subgrades to receive foundation systems, the primary concerns are the final levelness and slope of the finished grade, rather than its roughness [5]. Typically, a geotechnical engineer will provide a soils report or construction specifications that define the grading requirements for any cut or fill material. However, some relevant construction standards may help provide insight into these requirements.

The Federal Aviation Administration's (FAA) *Standard Specifications for Construction of Airports* is a widely used document for federally funded airport projects. It provides clear smoothness and grade tolerances for prepared subgrade layers. For example, a cement-treated subgrade layer placed before runway paving must achieve a surface tolerance that "shall not vary more than ± 1/2 inch (12 mm) when tested with a 12-foot (3.7 m) straightedge applied parallel with and at right angles to the centerline," with a final grade measured on a 50-foot grid "shall be within ± 0.05 ft (15 mm) of the specified grade" [11].

Figure 2: MLSS post infill(top), and post flattening (bottom) operations.

Another example is the Department of Defense's *Unified Facilities Guide Specifications* (UFGS). Within the standard Earthwork specification (UFGS 31 00 00), "all the surface of the subgrade for buildings and pavements must not show deviations greater than 15 mm (0.05 foot) when tested with a 4 meter (12-foot) straightedge applied both parallel and at right angles" [12].

Thus, it is clear that the LuSTR requirements may have been influenced by these other federally produced specifications, although the units of measure appear to follow those typical in aerospace and mechanical engineering. The point here is not that a smooth surface for receiving a foundation is unimportant; rather, there should be a more informed discussion within the lunar construction industry to ensure these requirements are practical and make sense within both construction timelines and budgets.

The authors of this abstract argue that surface smoothness should be guided by a foundation engineering approach, based on both past terrestrial construction experience and state-of-the-art analysis of regolith behavior. Every bit of energy invested in constructing systems on the lunar surface will cost significantly more than traditional construction [13]. These smoothness requirements are not for aesthetic purposes but to control dynamic load amplification, ensure full bearing contact, minimize stress concentrations, and verify subgrade uniformity [5]. Localized subgrade surface irregularities reduce the effective contact area with the foundation, increase bearing stresses, and cause transient load pathing during operation [6].

For example, on a lunar landing pad where landing leg forces act on an engineered pad material, vertical geometric deviations in the subgrade can create localized stress concentrations and cracking. This may lead to required maintenance or a shorter operational life of the pad [6]. Therefore, smoothness tolerances may be a mechanics-driven requirement in this case to ensure adequate load transfer and structural performance of the landing pad material.

Thus, it is not as simple as applying a general standard for all construction projects on the moon as the construction industry does on Earth. It will be crucial to determine smoothness requirements during the design phase of the specific foundation system. Some systems can likely bridge and accommodate vertical variations in the regolith surface more than others, leading to significant savings in construction costs.

Conclusion: This abstract was submitted to encourage a wider discussion with the industry on how to address this smoothness requirement. A meaningful conversation could happen through a presentation at this year's SRR, where members of the public and private sectors, as well as academics from various engineering fields, can share their perspectives, insights, and experiences from previous work.

References: [1] Moses R. & Mueller R. (2021) *Earth and Space 2021*. [2] Mamlouk M. & Zaniewski J. (2017) *Pearson Education*. [3] Jehn I. et al. (2023) *ASCEND 2023*. [4] Jehn I. et al. (2025) *Space and Planetary Resources, 1(1), 5*. [5] Das B. M. (2004) *Thomson/Brooks/Cole*. [6] Jehn I. & Dreyer C. (2025) *Acta Astronautica, 231, 175–192*. [7] Carey C. et al. (2023) *ASCEND 2023*. [8] Chen C. et al. (2016) *Advances in Space Research, 58(1), 145–154*. [9] Scott B. et al. (2023) *ANZ2023*. [10] Dreyer C. et al. (2026). *Earth & Space 2026*. [11] FAA (2018) *AC No: 150/5370-10H*. [12] NAVFAC (2023) *UFGS 31 00 00*. [13] Metzger P. & Autry G. (2022) *arXiv*.