Foundation Design Strategies for Lunar Surface Infrastructure

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Disclaimer

This document presents preliminary technical recommendations for lunar foundation design based on current knowledge, published literature, and theoretical modeling. The Moon presents a geotechnical environment for which no complete in-situ data set currently exists. Subsurface behavior, regolith stratigraphy, mechanical properties, and the performance of anchor systems remain subject to significant uncertainty, especially in mascon and fractured terrain.

All design strategies outlined herein must be treated as conceptual and require verification through in-situ testing, robotic reconnaissance, and adaptive engineering during implementation. This Brief Tech does not constitute a construction specification, design and should not be used in place of site-specific analysis or mission-validated data.

Executive Summary

Foundation design for lunar infrastructure represents a paradigm shift from terrestrial practice. On the Moon, the absence of atmospheric pressure, low gravity, severe thermal gradients, and unpredictable subsurface layering reverse typical load assumptions. Instead of bearing compression loads, many lunar foundations must resist uplift, tilt, and tensile stresses, especially for vertical structures such as antennas, power towers, and pressurized modules.

This Brief Tech consolidates practical design strategies and emerging methodologies for constructing foundations on lunar regolith and megaregolith. It incorporates considerations across site types, including mare basalts, highland breccias, and mascon-related crustal structures.

Key recommendations include the use of:

- Deep, prestressed anchors for tension-resisting systems;
- Precast modular foundations with vacuum-compatible grout seams;
- Regolith bag systems for load distribution and ballast;
- High-resolution GPR and gravimetric scanning for site validation;

- Sulfur-regolith casting as a viable in-situ precasting method.

A dedicated section addresses foundation behavior in mascon regions, where uplifted mantle and flexural crust create fractured, anisotropic ground conditions that impact anchor group performance and settlement profiles.

Case studies on Tall Power Towers demonstrate integration of geotechnical strategy with antenna design requirements. The document also summarizes commercial tower variants and recommends interface tolerances, seismic mitigation features, and thermal joint configurations.

This Brief Tech does not offer prescriptive specifications but rather a set of engineering design insights to guide safe, adaptive, and data-informed planning for future lunar surface operations.

1. Scope and Purpose

This Brief Tech outlines foundational principles and design strategies for lunar infrastructure built on regolith and megaregolith. The guidance covers a wide range of structural types, landing pads, vertical towers, buried conduits, habitats, and surface-mounted systems, and reflects the reversal of conventional terrestrial assumptions. On the Moon, foundations are governed by tension and uplift forces rather than compressive bearing.

Given the absence of atmospheric confinement, low gravity, sharp thermal cycling, and seismic activity from moonquakes, lunar foundations demand non-traditional design. This brief presents methods suited for both prefabricated elements deployed from Earth and structures built with in-situ resources.

2. Environmental Context and Load Environment

Lunar surface design must begin by recognizing the operational environment:

- **Low gravity (1.62 m/s^2)** undermines terrestrial bearing assumptions. Structural weight contributes little to resisting uplift or overturning, necessitating alternative foundation anchoring strategies.
- **Vacuum conditions** eliminate atmospheric confinement and prevent the use of water-based binders. However, they increase interparticle cohesion at the surface and impose unique construction chemistry challenges.
- **Thermal cycling** between −230 °C and +120 °C induces severe material contraction and expansion, driving fatigue, joint separation, and subgrade stress fluctuations.

- **Moonquakes**, though infrequent, transmit high-frequency seismic energy through a rigid crust with little attenuation, amplifying loads on shallow foundations, particularly near large-scale crustal boundaries and basin margins.

Surface heterogeneity necessitates locally tailored solutions:

- **Mare regions** contain dense basaltic flows, often with regolith depths of 4–8 m and a relatively uniform bearing profile.
- **Highland areas** expose a thinner, more fragmented regolith (1–3 m), with shallow transition into blocky breccia and megaregolith.
- **Mascon zones**, identified during the Lunar Orbiter and Apollo eras (Muller & Sjogren, 1968), are linked to buried, high-density anomalies beneath major basins like Imbrium, Serenitatis, and Crisium. Key implications include:
    1. **Densities in excess of 3,500 kg/m^3**, interpreted by O'Keefe (1968) as resulting from submerged iron-rich impactor remnants or uplifted mantle blocks.
    2. **Crustal flexure and tension** resulting from isostatic imbalance, introducing radial and vertical fracture systems.
    3. **Gravity gradients up to +300 mGal** across basin centers, potentially affecting orientation and load distribution of extended structures.
    4. **Thin regolith cover** (often <2 m), exposing fractured bedrock that may restrict shallow embedment or require specialized drilling or anchoring techniques.
    5. **Elevated seismic reflectivity and structural anisotropy**, complicating anchor group layout and necessitating post-installation verification.

These conditions demand high-resolution gravimetric surveys, deep GPR scanning, MASW, and Gravimeter and adaptive anchoring systems to ensure stability under tension, vibration, and thermal cycling.

3. Failure Modes and Foundation Demand

Lunar foundations are subject to failure mechanisms that differ substantially from terrestrial structures. The lack of atmospheric damping, reduced gravity, extreme thermal shifts, and uncertain subsurface cohesion expose lunar installations to uplift, tension cracking, and dynamic instability. The following table categorizes key failure modes observed or anticipated under lunar conditions, along with their root causes and typical structural targets. These modes must inform not only the geometry and anchorage method but also the required depth, modularity, and proof testing of all foundation systems.