EVALUATION OF UNTREATED REGOLITH BERM GEOMETRIES FOR LUNAR EJECTA MITIGATION. Z. Khademian[1], R. Garvey[2], and N. Goudarzi[3] [1]Blueshift, LLC DBA Outward Technologies (155 Commerce St, Broomfield, CO 80020 – zkhademian@outward.tech), [2]Blueshift, LLC DBA Outward Technologies (155 Commerce St, Broomfield, CO 80020 – rgarvey@outward.tech, [3]Blueshift, LLC DBA Outward Technologies (155 Commerce St, Broomfield, CO 80020 – ngoudarzi@outward.tech

Introduction: Plume-Surface Interaction (PSI) during lunar landings creates high-velocity ejecta threatening infrastructure. This study uses the Lunar Landing Pad Design Tool (LLPDT) to evaluate untreated regolith berm geometries for minimizing ejecta kinetic energy.

Berm Design and Modeling: To optimize the use of In-Situ Resource Utilization (ISRU), berm construction designs emphasize bulk regolith. The focus of untreated regolith berms includes landing pad radius, berm height, and internal/external berm slope angles. A Discrete Element Method (DEM) based LLPDT numerical modeling tool was implemented to simulate these structures accurately while observing their effects when exposed to high-speed ejecta. Advanced contact models, including an Elastic Plastic Spring-Dashpot (EPSD) rolling resistance model, were implemented to simulate the complex response of regolith.

Porosity and Stability Calibration: Adjusting the bulk density of the berm is critical for both matching lunar conditions and evaluating the effects of loose vs. compacted regolith structures to imposed ejecta. Particles were randomly removed from a 31% porosity bed to reach an intermediate level of 65% before allowing gravitational deposition to settle the bed to a final desired level. By applying rolling resistance vs. friction-only models, two distinct beds were generated with final porosities of 55% (1,395 kg/m^3) and 43% (1,770 kg/m^3). Calibration efforts focused on the berm's angle of repose. Increasing the rolling resistance friction coefficient directly increased the internal slope angle, allowing the berm to reach a stable equilibrium angle of 50.2°.

Ejecta Kinematics and Impact Dynamics: Based on the video photogrammetry of Apollo mission landings, the estimated dust loading in the exhaust plume is approximately 10^8 to 10^{15} particles/m³ [1]. To maintain high fidelity while managing computational costs, we applied mass scaling and velocity calibration to simulate lunar ejecta impacts. The model grouped small particles into larger-mass spheres to reduce the total ejecta count to a manageable 7,800 while conserving the overall volume fraction. Velocities were inversely scaled to conserve the momentum that potentially drives berm damage. Ejecta velocity field was calculated as a function of particle radius and elevation angle following an empirical fit from Apollo Lunar Module CFD simulations [2]. This velocity field, where predicted speeds range from 1,600 m/s for 1-micron particles to 16 m/s for 10-mm particles, ensures the simulation accurately captures kinetic energy transfer and structural damage despite the reduced particle count. Ejecta cloud characteristics were derived from Apollo mission video photogrammetry, indicating typical ejection angles between 1° and 3° above the ground surface [1]. Simulations revealed that secondary collisions within the ejecta cloud—where smaller, faster particles strike larger ones—lead to higher ejection angles than initial velocity vectors.

Comparative Evaluation of Berms: Two primary berm geometries were assessed for their performance during landing events:

Wall Berms: As shown in Figure 3 (top), this design used a trapezoidal cross-section with a flat top as wide as the IPEx wheelbase, wall berms are constructed by incrementally depositing regolith while the excavator traverses the structure's length. Wall berms feature steep internal slopes (50°) and are more mass-efficient for taller requirements; for a 2.5 m height, they require less mass than ramp berms for lengths exceeding 9 m.

Ramp Berms: As shown in Figure 3 (bottom), these are formed perpendicular to the excavator’s path by repeating parallel deposition operations until a target height is reached. While more susceptible to erosion, ramp berms facilitate rover access for maintenance and are mass-efficient for shorter structures, specifically requiring less mass than wall berms for heights under 1.5 m and lengths beyond 33 m.

Berm efficiency and ejecta impacts

To reduce computational complexity and run time, the full 360-degree landing pad and berm geometry was reduced to a 3-degree axisymmetric wedge. The berm height (0.25 m) was solved using the assumed ejecta angle (typically 1°–3° from Apollo data or up to 5° for simulations) and the landing zone diameter of 10 m. The flat-top width of wall berm was 1.25 m based on the operational requirements of the ISRU Pilot Excavator (IPEx). Figure 1 shows the berm and ejecta domain from top view for a wall berm.

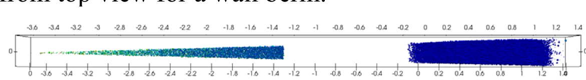


Figure 1: Plan view of the ejecta and berm.

Ejecta-Induced Damage Estimation

To evaluate the resiliency of lunar infrastructure, LLPDT incorporates specialized analytical and empirical models to quantify damage based on the impacted material substrate. Damage to brittle materials, such as optical lenses or ceramics, is calculated as pitting volume—a function of spallation radius and cracking depth. Conversely, damage to ductile materials, like metallic structural components, is determined by penetration depth resulting from plastic deformation and indentation. These calculations utilize high-fidelity simulation data, including particle diameter, impact velocity, and density, to generate comprehensive heatmaps that identify safe standoff distances. For landing scenarios using ejecta field velocities offered by [2], with scaled particle mass, and estimated granular micromechanics, results indicate a safe zone starting 10 meters from the berm as shown in Figure 2. Figure 2 is a heat map of damage quantified as the brittle pitting volumes.

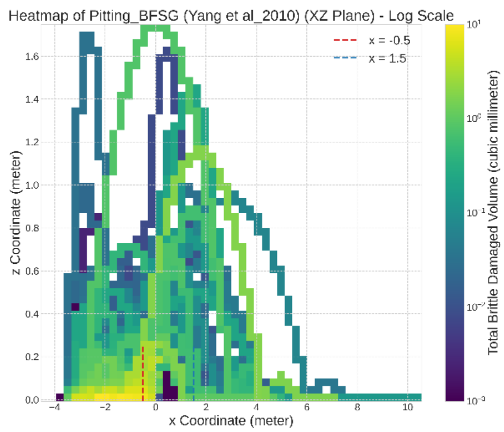


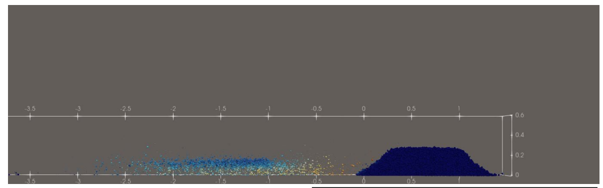
Figure 2: Damage models based on the ejecta velocities from simulation of Apollo landings with the wall berm model.

The berms are shown with dashed lines. The damage calculation in this figure is based on an empirical equation offered by [3].

To test stability limits, ejecta velocity was scaled by a factor of 10. Figure 3 and 3 show the result of the ejecta impact on the berm wall and ramp berms, respectively, with velocities scaled up by a factor of 10. While both berms remained generally stable, the wall berm's active face angle reduced from 50° to 40°, potentially compromising effectiveness for subsequent landings. More damage incurred to the ramp berm with a 10% reduction in the berm height.

Figure 5 shows the damage model based on the same empirical brittle damage criterion [3]. At an elevated velocity with factor 10, the safe distance for sensitive structures increased from 10 m to beyond 200 m. showing there is no linear relationship between velocity and damage zone radius.

Recommendations: Wall berms are superior for immediate shielding and smaller footprints. However, ramp berms are necessary for maintenance access but require broader exclusion zones due to wider potential damage domains. Future work will focus on calibrating micromechanical properties of particles and viscous damping coefficients while evaluating real-scale PSD and duplicating the construction/compaction process to improve modeling capability of LLPDT for berm durability studies.



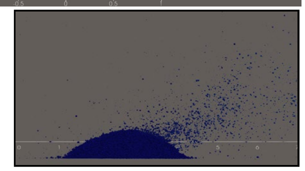


Figure 3: The 10x velocity ejecta impact on a wall berm before and after the impact.

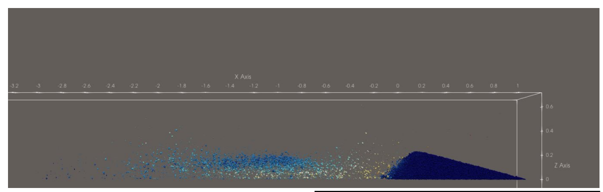


Figure 4: The 10x velocity ejecta impact on a ramp berm before and after the impact.

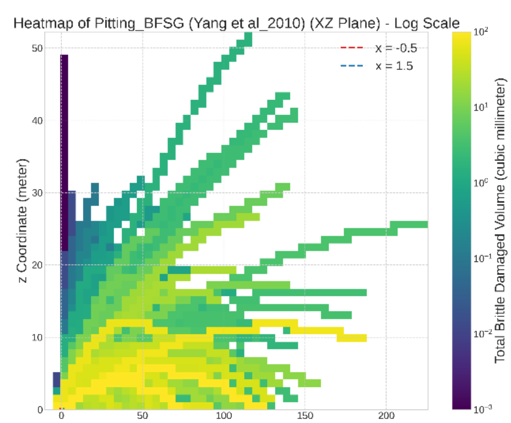


Figure 5. Damage models for the scenario with ejecta velocity of scaling factor of 10 for wall berm.

References: *[1] Immer et al., Earth and Space 2008.*
[2]Lane J. E. et al. (2010) Earth and Space 2010, 134–142.
[3] Jiyun Y. et al. (2010) EPJ Web of Conferences, 6, 39001.