CONSTRUCTING A PRELIMINARY PROBABLISTIC SEISMIC HAZARD ANALYSIS FOR THE MOON

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Introduction: Global coverage with high resolution images and altimetry data from the Lunar Reconnaissance Orbiter (LRO) spacecraft have allowed detailed mapping of tectonic features on the Moon, including lobate scarps, wrinkle ridges, and graben [1–7]. Lobate scarps are widely distributed, small-scale contractional tectonic landforms, interpreted to be surface expression of thrust faults [1–4]. To date, over 3,500 of these fault scarps have been identified using Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) images (Fig. 1).

The location of young fault scarps can now be combined with our understanding of:

- Impact crater production rate
- Evidence for and characteristics of recent activity along faults
- Newly developed lunar seismic ground motion scenario shakemaps (Fig. 2) [1]
- Data from the Apollo-era seismic network on the nature of the subsurface [8–10]

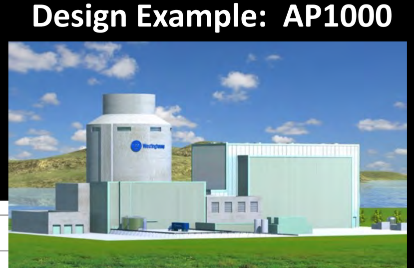
These data collectively offer the components needed to develop a preliminary probabilistic seismic hazard analysis (PSHA) for the Moon.

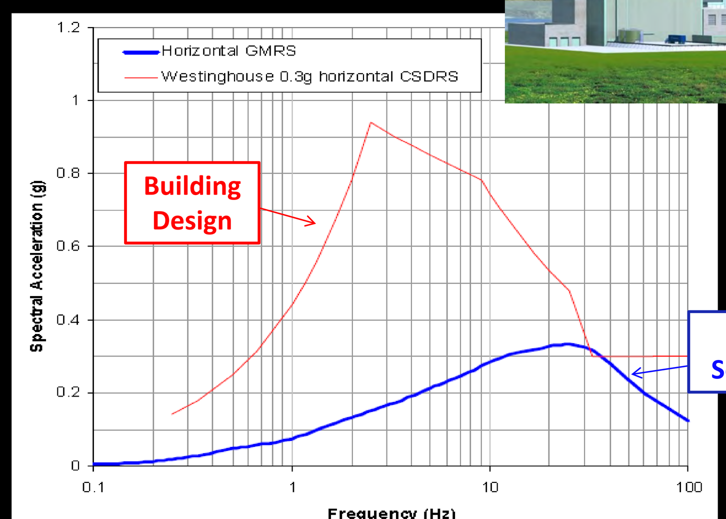
What is the moonquake and impact crater ground motion hazard on the Lunar surface operating environment?

GOAL: In this study we explore the application of PSHA methods utilized in the nuclear industry [11–12] (and more broadly) to selected test sites on the Moon. These methods may provide a useful resource for evaluating seismic hazards on the lunar surface. Such a hazard evaluation is essential to support the future design and construction of structures, systems, and components (especially possible nuclear-based power source options) that are being explored. Such hazard evaluations are particularly timely in lieu of renewed interest in the lunar surface operating environment and NASA's Artemis lunar exploration program. The results of this study will also aid in exploring the development of future lunar seismic monitoring networks.

Example – Seismic Hazard vs. Building Design

Design Example: AP1000





Traditional PSHA Methods: Traditional PSHA calculations involve integrating information regarding the location and magnitude of possible seismic sources and their estimated frequencies of occurrence (seismic source model), estimates of ground motion attenuation (ground motion model), and the effect of the near-surface on the amplification of ground motions (site response), to estimate the probability and severity of expected ground motion at a site of interest on the surface.

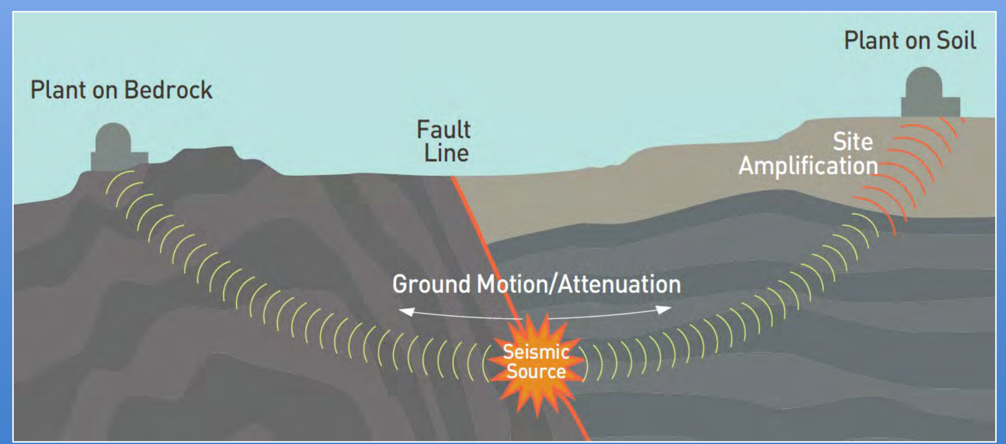


Figure 1: Illustration of PSHA Components; Modified after NRC Information Digest, 2014-2015 (NUREG-1350, Volume 27)

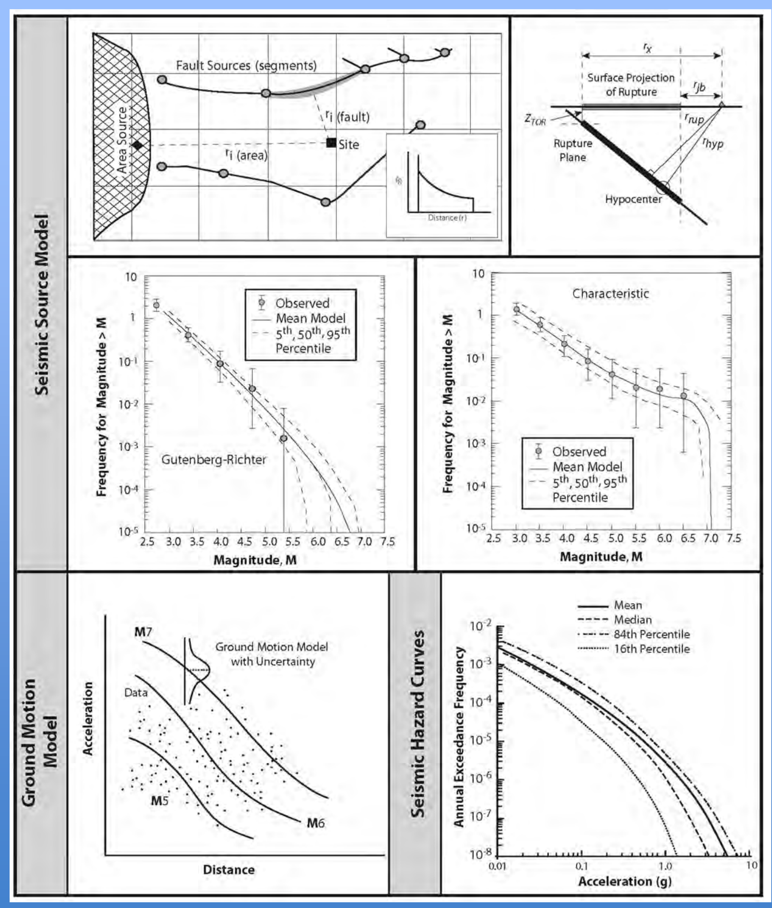
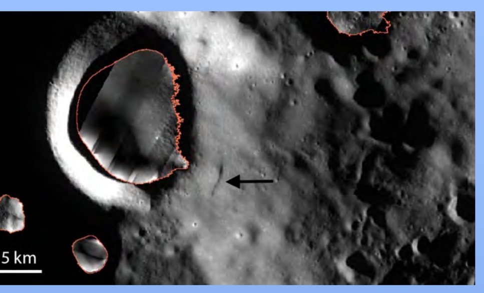


Figure 2: Basic elements of a PSHA; from [4]

Research Vision:

- Analyze the seismic hazard from lobate scarps at high priority landing sites such as in the lunar south polar region near permanently shadowed regions (PSRs) (Fig. 3).
- Integrate seismic source models with ground motion prediction response functions to produce a global seismic hazard map for the Moon (similar to the USGS National Seismic Hazard Maps)

Figure 3. LRO camera (LROC) mosaic showing Shoemaker lobate scarp (black arrow, 86.28ºS, 54.68ºE) [Watters et al., 2015] and nearby PSRs (outlined in orange).



Future surface experiments can further inform and constrain PSHA methods.

Examples include:

- Seismometer deployments: individually or in arrays; within craters to understand topographic amplification
- geophone arrays
- seismic surveys: estimate ground motions
- traverses with GPRs: inform near surface fault geometry (i.e. fault dip angle and direction, fault geometry, depth of faulting)

Challenges and Opportunities in Extending Traditional PSHA Methods to Assess Lunar Seismic Hazards

Seismic Source Model

Recent reconnaissance and mapping efforts provide new insights regarding fault locations and surface geometry. However, challenges remain with regard to characterizing the seismic potential of these fault sources. As an initial strategy, gridded seismicity approaches provide an opportunity to distribute (assign) seismicity based on measures of fault density.

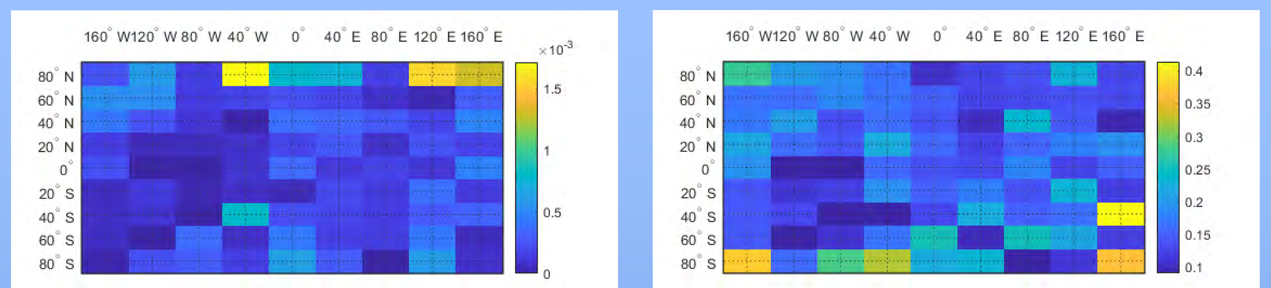


Figure 6. Spatially gridded information (gridded areas of 40 degrees longitude by 20 degrees latitude) providing the total length of faults per unit of gridded area (left) and the average fault length per grid cell (right)

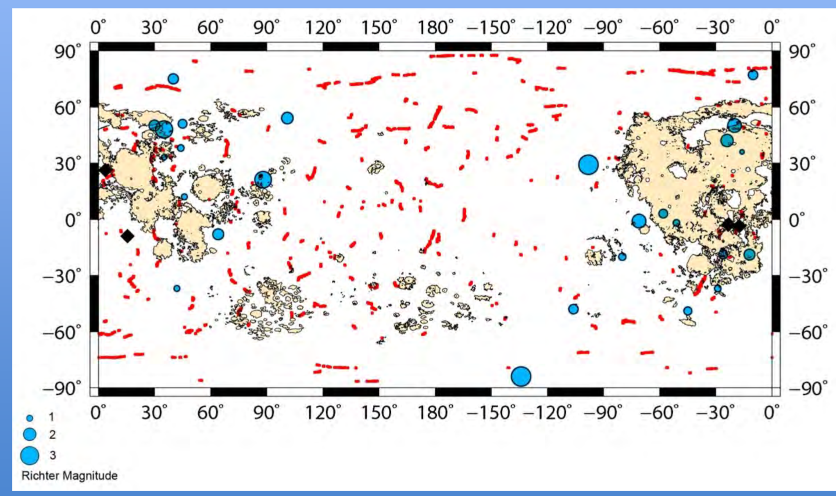


Figure 4. Map of lobate scarp thrust faults on the Moon (red lines), epicentral locations of shallow moonquakes (blue dots), Apollo Seismic Network Seismometers (black diamonds), and mare basalt units (tan polygons) (figure modified from [1]).

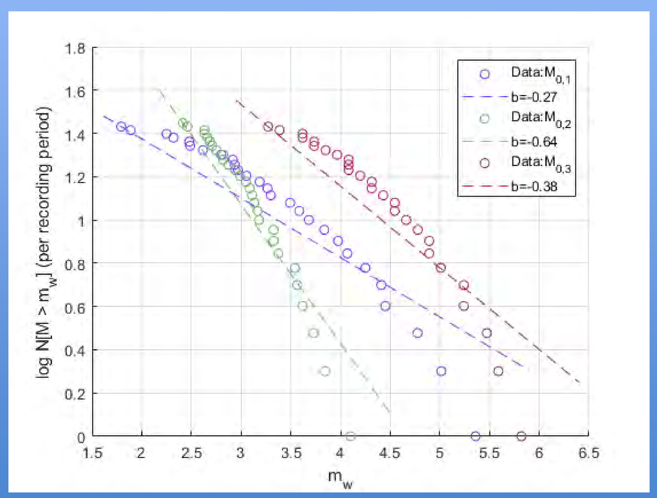


Figure 5. Preliminary exploration of M-R relationship estimating global number of events with moment magnitude $M > m_w$ over Apollo-era seismic data recording period, considering multiple strategies for event magnitude assignment

The Apollo-era seismic stations (Figure 9) recorded ground motion data from 28 shallow moonquakes. This provides information to estimate a "global scale" magnitude-recurrence (M-R) relationship. However, analysis shows that the estimated parameters of the M-R relationship change depending on the measure of magnitude used and method used to assign an estimated of magnitude to each event. Strategies are also needed to account for uncertainty arising from the limited time period for which recordings are available, uncertainty in event magnitudes, and "missed events." Theses issues are not addressed in the preliminary estimates provided in Figure 5. Further, physically-informed heuristics are needed to distribute and attribute this "global scale" M-R information across the lunar surface area.

Ground Motion Model

Traditional PSHA uses empirical ground motion prediction equations built using strong motion data to predict ground motion as a function of earthquake magnitudes and location (source-to-site distance). However, the limited quantity of available information from the lunar seismic stations makes such an empirical approach challenging to implement. High-fidelity numerical models, coupled with a growing knowledge of fault characteristics and lunar topography, provide an opportunity to model ground motion for moonquakes. The computational cost of these high-fidelity models makes it impractical to perform the large number of event simulations needed for PSHA. Machine-learning derived surrogate modelling techniques present an opportunity to balance computational costs and prediction capabilities.

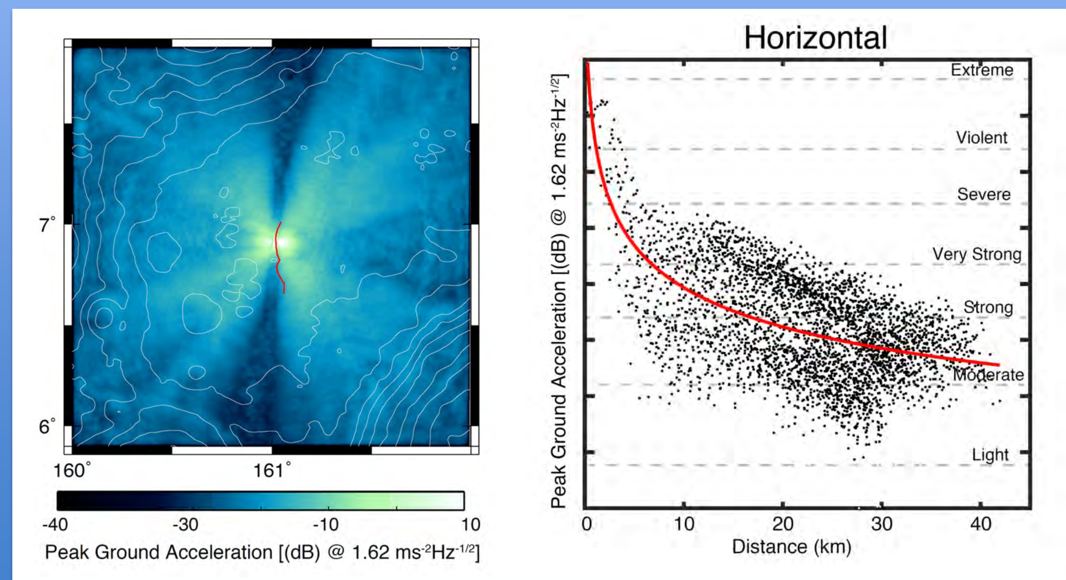


Figure 7: Shakemap (left panel) and expected peak ground acceleration (right panel) for a moment magnitude (Mw) 6.36 slip event on a lunar thrust fault (red line, right panel) in the Mandel'shtam cluster (6.90°N, 161.02°E) (figure modified from [1]).

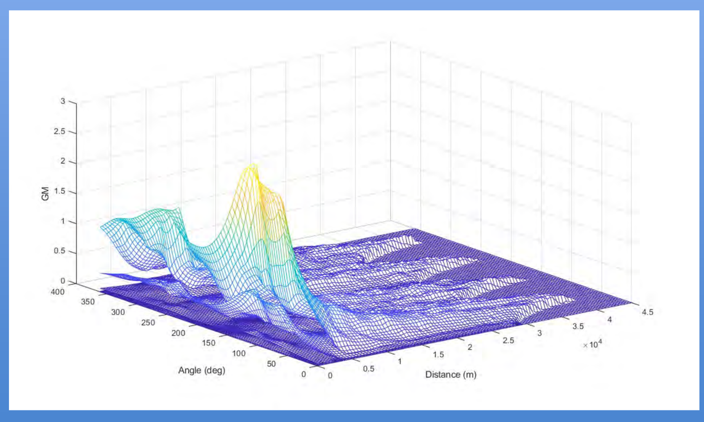
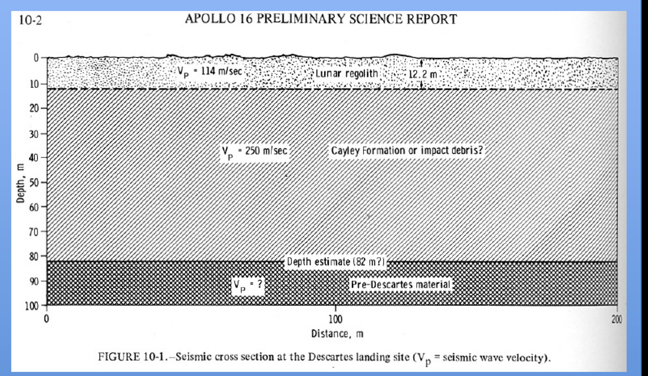


Figure 8: Example of ground motion response function derived using machine-learning methods and information from high-fidelity numerical model input-output pairs

Site Response Model

Data from moonquakes recorded by the Apollo-era seismic stations offer some information on the shear-wave velocity of layers in the near-surface needed for the site response component of the PSHA.



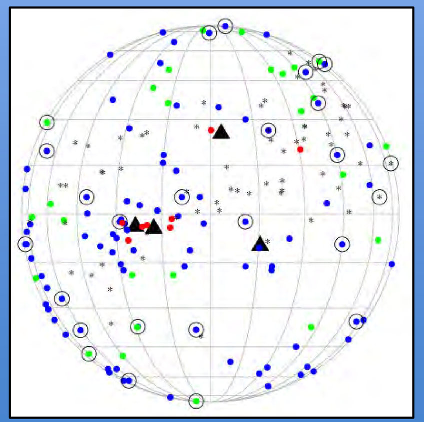
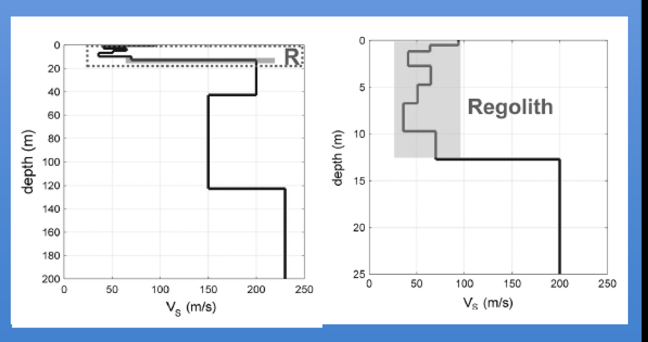


Figure 9. Apollo-era seismic recording stations (triangles) and recorded moonquakes (dots)



Moro (2015) near-surface Velocity profiles using the HVSR method

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