Simulations of Lunar Seismic Wave Propagation: Organization of Future Experiment on the Moon and Investigation of Scattering Effects

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1. Introduction

Seismic observation has played an important role in planetary science because of its capability of exploring the planetary interior in various spatial scales. In fact, seismology has been applied to the Moon and Mars so far and will be done on Titan in the 2030s (e.g., [1][2][3]).

The first seismic exploration on the Moon took place during the Apollo missions, where both passive and active seismic experiments were conducted (e.g., [1][4]), paving the way to access the lunar near-surface and deep internal structures. At present, to improve our understanding of the global seismicity and the internal structure and also to search resources for human activities (e.g., water ice), lunar seismology is being paid attention to again, and several missions are planned (e.g., [5]).

In this study, by numerically simulating the lunar seismic wave propagation, I will give (a) new insights into the intense seismic scattering on the Moon as well as (b) implications for future active seismic explorations.

2. Numerical experiment of near-surface imaging with artificially driven seismic signals

2.1 Background

There are some topics related to seismology in the future scopes of lunar exploration, such as hazard assessment and search of water-ice reservoirs. In fact, the LUPEX mission by the Japanese and Indian space agencies (JAXA and ISRO) will investigate lunar water in the late 2020s [6], although seismic exploration will not be performed. Yet, several seismic explorations are being planned or in preparation to be launched in 2026 – 2028 (e.g., [5]), and it is worthwhile giving meaningful proposals to mission plans through numerical studies.

In this theme, by collaborating with one of the JAXA's innovation hub projects (Autonomous seismic survey system based on a minimal source and a seismometer), I have been trying to propose an optimized active seismic experiment on the Moon [7].

2.2 Method

The fundamental idea of this study is to estimate a minimum number of stations to seismologically determine a target structure beneath the lunar surface (down to 100 m) through seismic wave propagation simulations. The workflow is as follows: (a) inserting a dummy interface in the structure, (b) performing a numerical simulation, and (c) reconstructing the input structure by analyzing the simulated signals (Fig 1). An important output (i.e., input for future seismic exploration planning) is to give the minimum number of stations to illustrate the mimicked structure.

For the simulation, I constructed two possible structures in the lunar subsurface: (a) slope-step and (b) dike (right top in Fig 1). Regarding the velocity structure, I used the reference velocity model of the lunar subsurface constructed by a previous study [8]. The numerical simulations were conducted, using the Open-source Seismic Wave Propagation Code (OpenSWPC [9]).

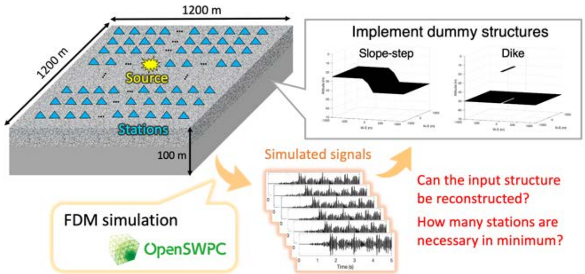

Fig 1. Overview of the project.

2.3 Key results

Here, focusing on the dike model, I present key results obtained so far. Fig 2 shows snapshots of simulated seismic waves seen from (a) the bird view and (b) E-W cross-section, respectively. Obviously, the wavefield is distorted around the dike structure (e.g., the right panel in Fig 2a). Because the wave velocity is higher in the dike (or bedrock) than in the shallower part, such a structure causes a deviation in travel times. Indeed, aligning the waveforms observed at the virtual stations on the surface, I did observe the P-wave arrival time deviation (Fig 3a). Making a 2D color map of the arrival time deviation (Fig 3b) shows a clear negative anomaly (i.e., earlier arrival times) around the dike, implying that the reconstruction of the input structure is possible.

2.4 Future work

As some key simulation results were obtained, I will further proceed the analysis of the simulated data to estimate how many stations are necessary in minimum to determine a target structure and how we can optimize an active seismic experiment, collaborating with members of the seismic exploration project team of the JAXA innovation hub.

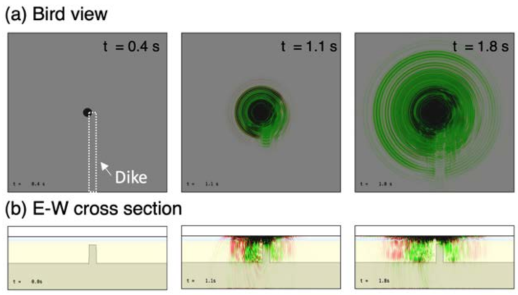

Fig 2. Snapshots for the simulation of dike structure model in (a) bird view and (b) E-W cross section. The red wave indicates P-wave, and the green wave does S-wave.

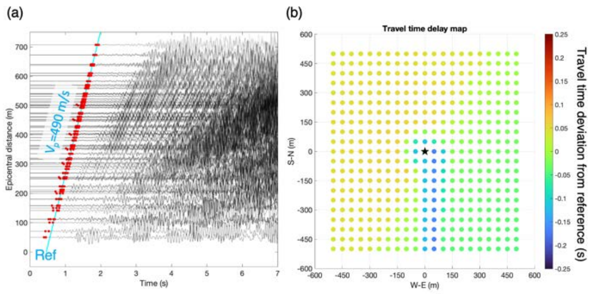

Fig 3. (a) Waveforms aligned with epicentral distance. The red dots indicate the P-wave arrivals. (b) 2-D Travel time delay map for P-wave. The color indicates the time deviation from the reference travel time (cyan line in panel (a)) at each virtual station. The stations are located with a 50 m interval.

3. Study on seismic scattering caused by lunar megaregolith and mantle plug

3.1 Background

One of the characteristics of the lunar seismic signal is a spindle-shaped waveform, which indicates that seismic waves are highly scattered. Such scattering is considered to be attributed to the structural heterogeneity in the lunar crust (e.g., [10]-[12]). In previous studies, the influence of megaregolith (a fractured rock layer in the upper crust) was mainly focused on, and the scattering intensity was assessed at the Apollo landing sites (e.g., [12][13]).

On the other hand, it is known that seismic scattering can be caused by topography (e.g., [14]), which has been scarcely investigated in lunar seismology. Since the Apollo landing sites are relatively flat, the seismic scattering by topography has been considered much smaller than that by megaregolith. On the other hand, future lunar seismic exploration missions plan to go to the far side/polar regions, where complex topographic features are expected both on the surface and at the crust-mantle boundary.

In this theme, I have been investigating the combined effects of megaregolith and topographic features on lunar seismic wave propagation, helping us predict or interpret future observation data.

3.2 Method

As a case study, I selected the Szilard crater, located on the far side (34°N, 106°E) and hosts many craters on the surface and a mantle plug underneath (Fig 4). The idea is to compare numerically simulated signals between stations at different azimuths and distances. In this report, I will focus on two stations shown in Fig 4 (S1 and S2).

For simplicity, I put an explosive source on the surface, which is an analog of a meteorite impact. The velocity structure model was constructed based on the model by Onodera et al. [12], where the average thickness of megaregolith (scattering layer) in the target region is about 20 km. Under these settings, I conducted wave propagation simulation with OpenSWPC [9].

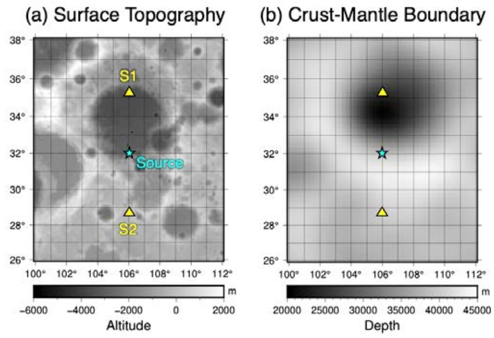

Fig 4. (a) Surface topography and (b) crust-mantle boundary map around Szilard crater. The original data were provided by Barker et al. [15] and Wieczorek et al. [16].

3.3 Key results

To assess the scattering by topography and random media, two cases were considered: (Case-a) only topography and (Case-b) topography and random media (i.e., velocity fluctuation).

Snapshots for the respective cases are shown in Fig 5ab, where the bird view plane and N-S cross section are displayed at different lapse times. Looking at the middle and right panels in Fig 5a, the wave propagates anisotropically, influenced by surface topography. That resulted in focusing or defocusing of Rayleigh wave energy depending on its path. On the other hand, it does not seem that the crust-mantle (Moho) boundary affects wave propagation so much because of the low-velocity layer in the lunar upper crust.

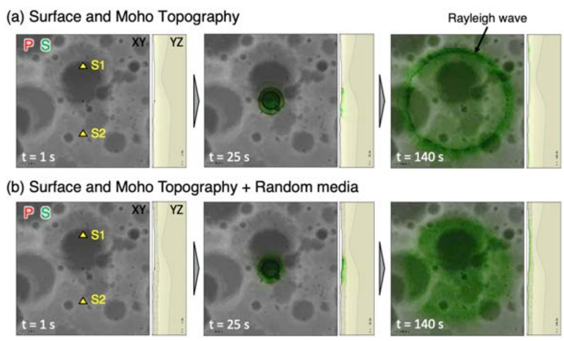

Fig 5. Snapshots of wave propagation simulations including (a) only topography and (b) topography and random media. In each panel, XY plane and YZ cross section along S1 – S2 line is shown.

Turning into Fig 5b, the wave pattern gets more diffusive because of intense scattering, and a clear difference in Rayleigh wave propagation can no longer be seen visually. Thus, the first key point is that impact-induced seismic waves are dominantly characterized by random media (i.e., megaregolith).

Fig 6a compares the waveforms observed at S1 and S2 for Case-a and Case-b, respectively. As visually observed in Fig 5, clear differences can be seen in both waveform and spectra between S1 and S2 for Case-a (blue and red profiles in Fig 6ab), which should reflect scattering effects from different topography along each path. On the other hand, including random media (Case-b) made the waveforms of Case-a more diffusive and featureless (cyan and orange profiles in Fig 6a). This means we would not see clear differences depending on paths in a real situation because the scattering by megaregolith is far more dominant. Nevertheless, there are some differences in body wave energy ratio (e.g., P/S) between S1 and S2 (Case-b in Fig 6a). Further analysis using other virtual station data may give us some idea to separate the topographic effect from that of megaregolith.

Although this study is still in progress, I have confirmed that the simulation gave me highly scattered waveforms (similar to the Apollo lunar seismic signals), which will help me discuss future seismic exploration plans more realistically.

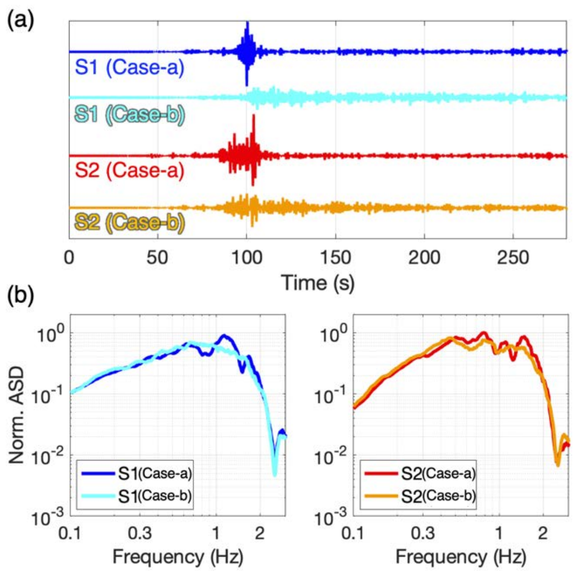

Fig 6. Comparison of (a) relative waveforms and (b) amplitude spectral density for Case-a and Case-b observed at S1 and S2. The waveforms and ASDs were normalized with the maximum amplitude of S2 (Case-a).

2.4 Future work

In the next year, I will continue to analyze the simulated waveforms for hundreds of stations in addition to S1 and S2. Also, simulations for different source conditions, such as source mechanism and source depth, to observe how these factors affect the resultant waveforms.

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