EVALUATION OF THE EFFECT OF SURFACE AND MOHO TOPOGRAPHIES ON LUNAR SEISMIC WAVE PROPAGATION. K.Onodera[1,2], T.Kawamura[3], Y.Ishihara[2], T.Maeda[4], and S.Tanaka[2], [1]SOKENDAI (The Graduate University for Advanced Studies), 3-1-1 Yoshinodai, Chuou-Ku, Sagamihara, Kanagawa 252-5210, Japan (onodera@planeta.sci.isas.jaxa.jp), [2]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuou-Ku, Sagamihara, Kanagawa 252-5210, Japan, [3]RISE Project Office, National Astronomical Observatory of Japan, Mizusawa, Oshu, Iwate, 023-0861 Japan, [4]Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo 113-0032, Tokyo, Japan

Introduction: Inner structure of planetary bodies is one of the most important pieces of information to understand their origin and evolution. Looking at the Moon, some 1D inner structure models have been proposed since Apollo lunar seismic data were obtained e.g. [1], [2], [3]. Although each model suggests different structure, for example crustal thickness has variation from 30 to 60 km, each can explain Apollo data. And we cannot assess which model is the best to constrain the lunar origin and evolution. This is one of the most serious problems in constraining the history of the Moon.

To estimate the lunar internal structure, observables read from seismic data will be the key. Generally, three factors below are said to be important. First factor is origin time which is the time moonquake occurs. Second one is source location where moonquake occurs, and the last one is arrival time that is the time the fastest component of seismic wave arrives at seismometer. In the case of natural moonquakes, origin time and source location have large uncertainties because both source and the seismic velocity structure is unknown and in many cases, inverted simultaneously. Also, it is difficult to read arrival times precisely because of low S/N ratio and coda wave caused by regolith layer. On the other hand, artificial impacts whose impactors are S-IVB rocket booster and Lunar Module ascent stage have the advantage of their known origin time and source location. In addition to this, their S/N ratio is much higher than that of natural ones. So, these impacts are often used to determine the internal sturucture, especially crustal structure. However, even if we use the best data, crustal thickness has variation from 20 to 50 km [4]. From this fact, we considered there are other factors which affect the determination of the crustal structure.

Here, we raise lateral variation of surface and Moho topographies as one of those factors. Recent lunar mission, e.g. Kaguya (SELENE) and GRAIL, observed gravity field of the Moon precisely. By analyzing these data, lateral variation of the lunar Moho was obtained [6], [7]. Chenet *et al.* (2006) [8] considered lateral variation, however, they only looked at the variation just below observation points and impact sites. As we considered the lateral variation between seismometer and source location have an influence on the propagation of seismic wave, we calculated its effect using simulation and evaluated how much the variation affects the determination of the lunar crustal structure.

Method: OpenSWPC (an Open-source Seismic Wave Propagation Code) [9] was used for 2D simulation in P-SV system. We assumed two kinds of structure model shown in Figure 1. One is 1D velocity model whose average crustal thickness of all pairs of seismometer and impact site is about 46 km. The other is SELENE moon structure model based on SELENE crustal thickness map [6]. A typical Moho undulation is from 5 to 10 km. And we put a seismic source which radiates P-wave isotropically on the surface to simulate artificial impact. Basical parameters used in the simulation are shown in Table 1 and 2.

We simulated seismic wave propagation of Apollo artificial impacts under these conditions and looked at difference in arrival time between two models. Notice that we removed regolith layer from each structure to evaluate only the effect of surface and Moho topographies. Also, we only considered artificial impacts whose epicentral distance is less than 450 km (15 deg in the lunar coodinates system). Because the calculation was carried out in the Cartesian coordinates system, i.e. the effect of curvature could not be evaluated.

Results & Discussion: Snapshots of the simulation are shown in Figure 2. Figure 2 (a) is snapshots for 1D velocity model and (b) is snapshots for SELENE moon structure model. Each image shows the behavior of P-wave (red colored) and S-wave (green colored) at different time (t=6.0 s, 20.0 s, 60.0 s). The deeper color the wave shows, the stronger the wave is. Compareing the two models, the wave poropagated in the same way before the first reflection at Moho (t=6.0 s). However, after the reflection, the wave started to behave differently (t=20.0 s). At t=60.0 s, we could see that the wave field was disturbed, and that higher energy escaped downward in SELENE moon structure model. As the surface variation is smaller than that of Moho, its effect is more significant at the shorter wavelengths which are comparable to the topographic variation. As a result, higher frequency wave reflected at the surface and higher energy went downward. From this result, we can say that topographical variation of surface and Moho has a strong influence on the seismic wave from the viewpoint of reflection patterns and energy transportation.

However, focusing on the difference in the first arrivals which mainly determine the structure of the crust, the influence of surface and Moho topographies was not so large as we had expected. Figure 3 shows the travel time curves of both models. Travel time in the vertical axis can be calculated by subtracting arrival time from impact time. Inverse of the inclination of travel time curve corresponds to seismic velocity of crust and mantle. In addition to this, bending point of the curve called crossover distance is used to determine the crustal thickness. Drawing attention to the difference in travel time, its variation was less than 1.0 s for almost all cases. That was not large enough to change the inclination of the travel time curve, however, made crossover distance change by about 10 km. And this led to the change in the thickness of the crust by about 3 km. This value is smaller than the wavelength of P-wave, i.e. resolution of the structure. In other words, the influence of lateral variation is buried in error and we cannot resolve it.

Summary: We performed 2D simulation to evaluate how much surface and Moho topographies affect the determination of the lunar crustal structure. Although we could confirmed the intense disturbance of wave field, the variation of crustal structure is smaller than the resolution of the structure. As a conclusion, our results derived so far indicate that the effect of the lunar surface and Moho topographies is too small when considering the basic structure of the lunar crust.

References: [1] Nakamura Y. et al. (1982) *Proc. LPSC*, 13th, 117-123. [2] Lognonné P. et al. (2003) *EPSL*, 211, 27-44. [3] Garcia R. F. et al. (2011) *PEPI*, 188, 96-113. [4] Onodera K. et al. (2017) *IAG-IASPEI*, 2017, S19-2-05. [5] Toksöz M. N. et al. (1974) *RGSP*, 12, 539-567. [6] Ishihara Y. et al. (2009) *GRL*, 36, L19202. [7] Wieczorek M. et al. (2013) *Science*, 339, 671-675. [8] Chenet H. et al. (2006) *EPSL*, 159, 140-166. [9] Maeda T. et al. (2017) *EPS*, 69:102. [10] McGarr A. et al. (1969) *JGR*, 74, 5981-5994.

Table 1. Parameters used in the simulation

Dimension	Mesh (km)	Source Depth (km)	Rise Time (s)	Seismic Moment (J)	Frequency (Hz)
2D	0.3	0.0	1.3	3.35e6 - 4.71e7	0.01-1.5

We referred to [5] to give seismic moment and assumed 0.1% as a conversion efficiency [10].

Table 2. Parameters of each layer

Layer	Density (g/cm^3)	Vp (km/s)	Vs (km/s)	Qp factor	Qs factor
1st Layer (Crust)	2.762	5.50	3.30	6750	6750
2nd Layer (Mantle)	3.360	7.80	4.46	3375	1500

We referred the values of density from [6] and collected the rest values from [3].

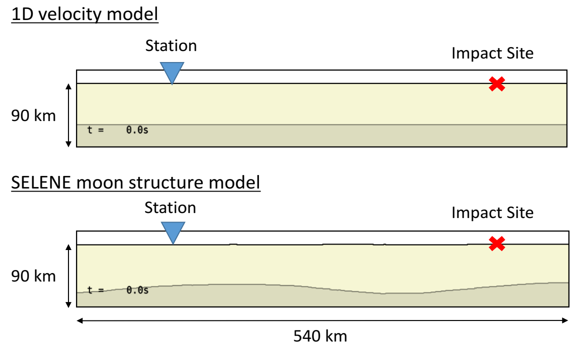

Figure 1. Structure models used in the simulation
The case of the pair of Apollo15 S-IVB impact and Station12 are shown. Upper model is 1D velocity model. Lower one is SELENE moon structure model basd on [6]. First layer correspond to crust and second to mantle. The boundary between two layer represents the lunar Moho.

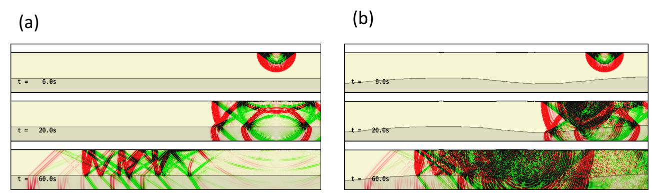

Figure 2. Snapshots of P and S wave
Snapshots of (a) 1D velocity model, (b) SELENE moon structure model. Three snapshots at different time are shown from top to bottom respectively (t=6.0 s, 20.0 s, 60.0 s). Red wave corresponds to P wave and green wave to S wave.

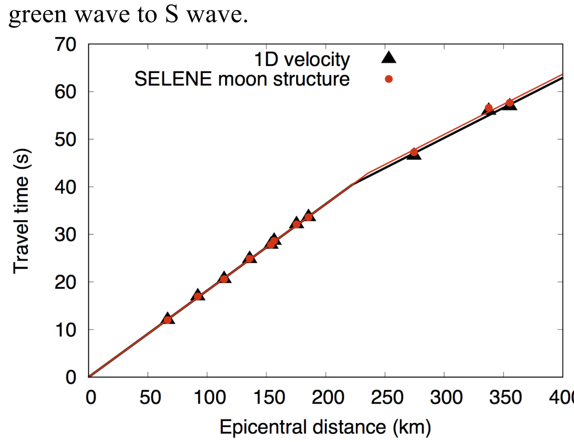

Figure 3. Travel time curves of two models
Horizontal axis shows epicentral distance and vertical axis shows travel time. Black color corresponds to 1D velocity case and red color to SELENE moon structure case. Colored plots are the travel time data derived through the simulation. Each solid line shows the best fit of travel time curve, which determines the characterictics of crust.