A SEISMIC RISK FOR THE LUNAR BASE

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Shallow moonquakes, which were discovered during observations following the Apollo lunar landing missions, may pose a threat to lunar surface operations. The nature of these moonquakes is similar to that of intraplate earthquakes, which include infrequent but destructive events. Therefore, there is a need for detailed study to assess the possible seismic risk before establishing a lunar base.

INTRODUCTION

Contrary to the common belief of the pre-Apollo era, a belief that unfortunately is still found in today's popular literature, the Moon is by no means a seismically "dead" planet. It is an observed fact that quakes occur on the Moon. Such moonquakes, if sufficiently large, may damage man-made structures on the lunar surface, may disrupt the activities of the lunar inhabitants, and may cause injury or even loss of life.

From examination of the currently available observational data on lunar seismic activity, we believe that there is sufficient reason to be concerned about a possible seismic risk on the Moon. In this paper, therefore, we will present some basic lunar seismic data relevant to the question of a seismic risk and point out deficiencies in our knowledge on lunar seismicity that need to be resolved before we establish a base on the Moon.

LUNAR SEISMICITY

The data relevant to the seismic environment of the Moon were acquired from 1969 to 1977 during the operational period of the seismic station network established during the Apollo lunar landing missions. Of the two types of seismographs used at each station for covering two different spectral ranges of seismic waves, the long-period seismographs recorded most of the seismic signals relevant to the global seismicity. More than 12,000 seismic events were detected by these instruments (*Latham et al.,* 1970; *Nakamura et al.,* 1982). The majority of these events were tidally induced moonquakes of body-wave magnitude m_b less than 3 (energy release $E < 10^6$ J) deep in the lunar interior. These deep moonquakes are not likely to pose any threat to lunar surface operations. Next in abundance were the seismic events originating from impacts of meteoroids on the lunar surface. The hazard of these impacts and their effects on the lunar base activities require separate consideration and will not be evaluated in this paper.

The most important in terms of seismic hazard is a class of moonquakes that occurs at shallow depths. They are believed to be of tectonic origin and are likely to represent recurrent release of thermoelastic stresses that have accumulated in the outer zone by global cooling and contraction of the Moon (*Nakamura et al.,* 1979; *Binder and Lange,* 1980). Although less frequent than other types of seismic sources, they constitute the most intense seismic events on the Moon. The largest of them detected during the eight years of observation had an estimated body-wave magnitude m_b greater than 5 ($E > 6 \times 10^{10}$ J) (*Nakamura et al.,* 1974, 1979; *Nakamura,* 1977; *Oberst,* 1987).

We assign body-wave magnitudes to moonquakes by equating the estimated total amount of energy released at the source in the same way as for earthquakes: $m_b = (\log E + 1.2)/2.4$ (*Richter,* 1958, p. 365). The effect of a moonquake on the lunar base, however, may be quite different from what would be expected for an earthquake of equal magnitude, as will be discussed later.

OCCURRENCE RATE OF SHALLOW MOONQUAKES

Twenty-eight shallow moonquake events were identified during the eight years of seismic observations. Based on the size distribution of these 28 events and assuming that the shallow moonquakes occur randomly distributed both in time and space over the entire lunar surface, we estimate their occurrence rate to be

$$\log N = -1.8\, m_b + 7.8 \qquad (1)$$

where N is the cumulative number of shallow moonquakes having body-wave magnitudes greater than m_b, occurring within an area of 10^6 km^2 per year (Fig. 1). From this relationship we estimate that the chances for a lunar base at a randomly chosen site to experience a shallow moonquake of, for example, m_b greater than 4.5 ($E > 4 \times 10^9$ J) within a range of 100 km are approximately one in 400 years.

The average seismic energy release for the whole Moon from the shallow events is estimated to be about 10^{14} J per year (*Nakamura,* 1980). This is several orders of magnitude lower than the rate of seismic energy released for the entire Earth, estimated to be about 10^{18} J per year (*Kanamori,* 1977). However, this is not surprising, because the overwhelming majority of earthquakes are concentrated along active plate margins, which do not exist on the Moon. In fact, lunar seismicity is very similar to the terrestrial seismicity if the seismically active regions along the plate margins are excluded (*Nakamura,* 1980). The estimated occurrence rate for shallow moonquakes [equation (1)] is indeed very similar to the approximate terrestrial intraplate seismicity for the central U.S. (Fig. 1; *Nuttli,* 1979).

Much about a possible seismic risk on the Moon can be learned from studies of these intraplate earthquakes. Intraplate earthquakes occur preferentially in regions of preexisting weakness in the lithosphere (*Sykes,* 1978). However, because of their long recurrence intervals, they often occur in places where such weakness is unrecognized, and thus large earthquakes are

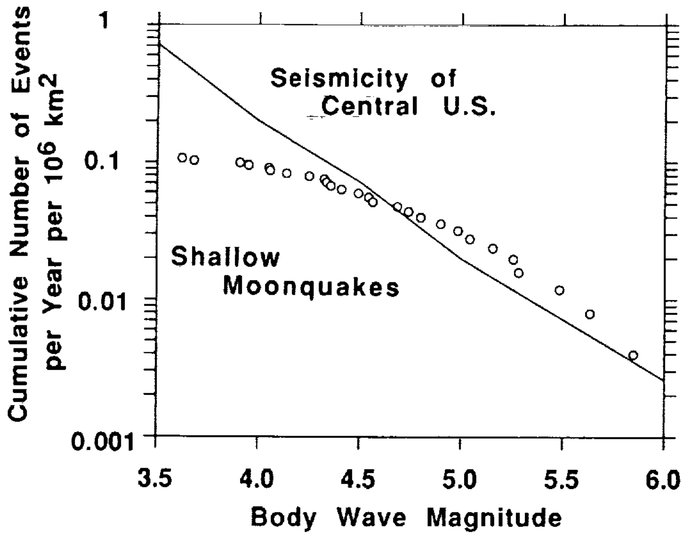

Fig. 1. Magnitude-frequency relationships of shallow moonquakes (open circles) and intraplate earthquakes (line). The moonquake body-wave magnitudes are computed from the estimated energy release of the 28 events observed during the 8 years of operation of the lunar seismic network. The number of observed events has been converted to the rate of occurrence within a unit area and time. Sampling is incomplete at small magnitudes, because amplitudes of small-magnitude events occurring at far distances fall below the detection threshold of the seismometers. The earthquake data are from *Nuttli* (1979).

unexpected. Three of the strongest earthquakes ever reported within the contiguous U.S. did not occur near the margin of the Pacific plate but occurred instead in the Mississippi valley near New Madrid, Missouri, in 1811 and 1812. These unexpected and most devastating intraplate events had estimated body-wave magnitudes of 7.1, 7.2, and 7.4 (*Nuttli,* 1973a). Another large intraplate event occurred in Charleston, South Carolina, in 1886, and had a body-wave magnitude of 6.7 (*Bollinger,* 1983). We cannot rule out the possibility that similar very large seismic events also occur on the Moon but were not detected during the short duration of our observations.

OTHER FACTORS THAT AFFECT SEISMIC RISK

There are several properties of shallow moonquakes other than the rate of occurrence that have direct bearing on the seismic risk. For some of these, direct observational data are still lacking. Moreover, the unique lunar environment that affects the propagation of seismic waves through the Moon also requires special consideration.

Spatial Distribution

We presume that certain regions of the lunar surface are more prone to shallow moonquake activities than others. Such regions may be recognized by statistically significant spatial concentration of observed shallow moonquakes. It is important to identify such regions before we set up a lunar base because the intensity of seismic risk is directly related to the proximity of the base to such concentrations of events.

Nakamura et al. (1979) note that moonquakes appear to occur preferentially near the margins of large mare basins, which may represent zones of weakness in the lunar lithosphere. In contrast, *Binder and Gunga* (1985) and *Binder and Oberst* (1985) suggest that shallow moonquakes are associated with young thrust fault scarps in the lunar highlands. Unfortunately, the number of detected shallow moonquakes to date is not large enough to make a statistically meaningful correlation with any topographic or selenologic feature.

Focal Depths

The severity of ground motion and, consequently, the potential danger to a lunar base of a shallow moonquake depend directly on focal depth. Unfortunately, the observational data do not provide accurate focal depths of any of the detected shallow moonquakes. This is because all shallow moonquakes detected to date occurred far outside the seismic network, while accurate determination of focal depth requires observations at near ranges. Once we identify any region of high seismic activity on the Moon, we need to set up local seismic stations in order to determine precisely the focal depths of individual shallow moonquakes there.

Character of Ground Motion

Even on Earth it is difficult to predict the level of ground motion for an earthquake of given magnitude occurring at a given range (see *Heaton and Hartzell,* 1988, for a review). The difficulty is further compounded for the Moon because of the vastly different environment. The observed lunar seismic data clearly show that the character of ground motion caused by a shallow moonquake is significantly different from that of an earthquake of equal magnitude at equal range for several reasons.

The source spectra of shallow moonquakes generally contain much more energy at high frequencies than those of earthquakes of comparable total energy release (*Oberst,* 1987). Since the response of some man-made structures to the ground motion near the epicenter is highly dependent on frequency, a significant difference in potential damage to the structures is expected between earthquakes and moonquakes.

Seismic waves are much less attenuated in the Moon than in the Earth (*Nakamura and Koyama,* 1982). As a result, seismic energy from a moonquake is likely to spread much farther from the epicenter, thus affecting a wider area of the Moon than would be expected for an earthquake of comparable magnitude. Such a difference is observed between earthquakes occurring in the eastern and western parts of the U.S. At a given magnitude, earthquakes near the east coast are often felt over an area up to 100 times larger than those in the western U.S., since in the east the more stable tectonic setting allows more efficient transmission of seismic waves (*Nuttli,* 1973b).

Another distinct difference between the lunar and the terrestrial seismic environment is the more intense scattering of seismic waves in the highly fractured near-surface zone of the Moon than on Earth. Seismic signals on Earth are relatively short and impulsive. In contrast, seismic signals from moonquakes show a very gradual increase of intensity within the first several minutes followed by an extremely slow decay, often lasting for several hours. The dispersion of seismic energy over a very long time span may reduce potential structural damage to the lunar base.

The intense seismic scattering in the near-surface zone and the consequent destruction of coherent surface reflections prevent efficient long-range propagation of surface waves on the Moon.

Since surface waves, which decay more slowly with distance than body waves, are often primarily responsible for earthquake damage, the absence of surface waves may be of benefit to the lunar base.

CONCLUSIONS

In spite of considerable scientific literature on lunar seismicity, the general public is not fully aware that the Moon is tectonically quite active. The seismic data now available suggest that shallow moonquakes may pose a significant risk to the operation of the lunar base. Studies of the seismic environment are common practice before starting important construction projects such as bridges, dams, and power plants on Earth. Such a study may also be indispensable for the Moon before establishing a base there.

The currently available data are not sufficient to firmly establish the seismic risk for the lunar base. In particular, further studies are needed in two general areas: (1) a better characterization of the shallow moonquake sources, including their focal depths and spatial distribution; and (2) the effect of the moonquake ground motion, which is significantly different from earthquake ground motion, to structures and inhabitants. For the former, establishment of a global network of seismic stations deployed by, for example, penetrators or soft landers may be required. Seismic observations during the initial phase of the lunar base operations will be beneficial for furthering our knowledge on the seismicity and seismic risk.

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