Cross-references

Earthquake, Focal Mechanism
Earthquakes and Crustal Deformation
Earthquakes, Source Theory

EARTHQUAKE SOUNDS

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Definition

Earthquake sounds. Atmospheric pressure waves associated with earthquakes, especially those audible to humans.

Introduction

"... previous to an earthquake, a roaring is usually heard," wrote Lucius Annaeus Seneca, circa 65 CE, in the sixth volume of "Naturales Quaestiones" (translation by Clarke and Geike, 1910). While Seneca's explanations for earthquakes now seem fanciful, this statement remains accurate and historical records of earthquake sounds have been joined over the last few decades by instrumental studies of this phenomenon.

A particularly interesting case of earthquake sounds concerns the long reported noises near Moodus, Connecticut, whose town name is derived from a Wangunk word meaning "where noises come from the ground." Reports of these noises predate the arrival of European settlers who described them as accompanying shaking "as though in an earthquake" (Davis, 1897). Seismographic studies of the earthquakes that accompany the Moodus Noises demonstrate that these sounds are caused by swarms of magnitude −2 to 2.1 events with shallow (less than 2.4 km) hypocenters (Ebel, 1982). Similarly, explosive sounds similar to cannon fire have been documented during earthquake swarms in the lower Rhone Valley of France since 1772 and have now been explained by events with ultra-shallow focal depths of only 200 m. With magnitudes as small as −0.7 many of these events are heard even if the shaking cannot be felt (Thouvenot et al., 2009).

Because human hearing is an effective spectral analyzer, the sonification of seismograms provides a useful educational tool. And because sound is commonly associated with earthquakes, audio can be an effective element of artistic works about earthquakes. This entry reviews the role of earthquake sounds in science, education, and art.

Records of sounds

People have reported hearing earthquakes for as long as we have earthquake reports. *The Earthquake Catalog of the British Association* (Mallet and Mallet, 1858) lists reports of earthquake sounds back to 122 BCE, although these are referenced to histories written by Julius Obsequens in the fourth century CE.

Catalogs of intensity data are good sources of reports on earthquake sounds. Davison (1938) explored a global set of catalogs, including the Mallet and Mallet catalog mentioned above, and the references in his paper provide a guide to these classic sources. Most of his data came from Britain and he classified about 20,000 descriptions into seven classifications that are largely consistent with low rumbling sounds but also include some descriptions of impulsive sounds, which are heard more often at short epicentral distances. A more recent intensity catalog with special emphasis on sounds was collected by Pierre Stahl in the French Pyrenees (Sylvander and Mogos, 2005), and the USGS "Did You Feel It?" catalog of Internet-collected intensity data includes information on sounds in its 1.25 million observations (Wald et al., 1999).

A problem with sounds described in intensity catalogs is that they depend on peoples' ability to describe an ephemeral experience in words. In the 1979 M4.0 earthquake near Bath, Maine, sounds were widely heard and mostly described as high frequency booms (Pulli et al., 1980). Many respondents described the sound in terms of the explosion of a heating system boiler. One exception was a resident who had actually heard a boiler explode and said the earthquake sounded nothing like that. Regardless of the words used to describe the sound, some residents who had previously lived in southern California explained that they were different than the longer-lasting, low frequency rumbles they remembered from earthquakes there. Those descriptions are consistent with Hill et al. (1976) who described earthquake sounds heard in southern California as "ranging from the rumble of distant thunder to the rushing of a wind." The high frequency content of the sounds in Maine could be due to high frequency ground motions created by a combination of shallow hypocenters, low crustal attenuation, and relatively high stress drops in that region (Pulli et al., 1980). The Moodus area shares similar characteristics and thus the shaking should also have substantial high frequency energy. However, many observers there described the noises in 1981 as "distant thunder" (Ebel, 1982). Thus, the subjective observations in intensity catalogs can make interpretation difficult.

The first known recording of earthquake sounds is from 1954 when a recording that was being made inside a two-story wood-frame dwelling in Eureka, California, accidently captured an M6.6 earthquake. It is likely that the recording, which was cut short by a power outage, largely captured sounds created by the building (Steinbrugge, 1974). The catalog of earthquake sound recordings compiled by Steinbrugge is available from the Seismological Society of America. All of these recordings mix together natural earthquake sounds with those produced by man-made structures and human reactions to the shaking. A notable entry in this catalog is a 5-min recording done by Robert Pate during the 1964 M9.2 Alaska earthquake, including his narration of several minutes of felt shaking.

The first purposeful recordings of earthquake sounds away from man-made structures were made in studies of the 1965–1967 Matsushiro swarm in Japan (Japan

Meteorological Agency, 1968) and the 1975 earthquake swarm near Brawley, California (Hill et al., 1976). Hill et al. recorded the audio on one stereo channel of an audio cassette tape and recorded both a time signal and the seismic sensor on the other channel by using FM multiplexing. Unfortunately, the seismograms recorded by this analog system were clipped and that made some of their analysis more uncertain. Sylvander et al. (2007) made digital audio and seismic recordings in the Pyrenees that stayed on scale.

How are sounds produced?

The existence of earthquake sounds is hardly surprising given that seismic waves from the solid earth will refract, albeit weakly, into the atmosphere. This was first demonstrated by Ewing, who considered the simple case of a P-wave in a body of water being transmitted into the atmosphere (Ewing, 1883).

As described by Seneca and in the observations cataloged by Mallet and Mallet (1858) and Davison (1938), earthquake sounds are often heard slightly before the shaking is felt. Because people often feel the stronger, but later arriving S-wave, this suggests that the sounds are produced by the P-wave. The instrumental studies referenced above used collocated seismometers and microphones to demonstrate that the sounds coincide with the arrival of the P-wave. The coincidence of the sounds with the arrival of the P-wave demonstrates that the onset of the sounds is generated by transmission of the seismic waves into the atmosphere very close to the listener. This is consistent with Davison's conclusion that the audible sound and the felt shaking travel at the same velocity. Hill et al. (1976) extended the simple analysis done by Ewing and explored the transmission of sound from a realistic shallow crustal structure to the atmosphere, the frequency content of the shaking from the seismic source, and the sensitivity of human hearing. That analysis showed that the higher frequencies of the seismic shaking (up to 50 Hz) overlap with the lower range of human hearing (over 20 Hz) and are transmitted into the atmosphere with sufficient amplitude to be heard.

Thus, what people hear is in the frequency range of 20–50 Hz. These low frequency sound waves have wavelengths much longer than the size of a human head and therefore people cannot localize the source of such sounds. The description of earthquake sounds as distant is based on association with other low frequency sounds that actually are distant, despite that the earthquake sounds are generated close to the listener. It is noteworthy that because earthquake sounds are at such low frequencies, humans are at least as sensitive to these sounds as many animals (Hill, 1976).

At Brawley, the later and stronger S-wave arrival was not associated with an audio signal while at Matsushiro and in the Pyrenees the S-wave was coincident with sound in some cases. The relative rarity of sound associated with the stronger S-wave shaking can be explained by the attenuation of higher seismic, and therefore audible, frequencies in the S-wave (Hill et al., 1976).

Applications of sounds

Mallet's classic study of the Great Neapolitan earthquake of 1857 includes many reports of people hearing the earthquake and he devotes Part III, Chapter VIII, titled "Of the Sounds that Attended the Shock," to discussing these observations and attempting to interpret them in terms of a finite source model by drawing an analogy to a long line of troops firing their rifles in succession (Mallet, 1862).

Davison's (1938) study of earthquake sounds attempted to relate his seven classifications to the maximum intensity on the Rossi–Forel scale, the distance from the event, and the region within which the event occurred. He found that earthquakes were heard over the entire felt area for small earthquakes but only half of the felt area for larger events and that at greater distances the sound was described as being smoother and more monotonous. The smoother and more monotonous sound with increasing distance is consistent with the attenuation of high frequency shaking at greater distances from the event. Due to this attenuation, low frequency motion from large earthquakes is felt at distances beyond the point where shaking in the higher frequency human hearing range is transmitted. Thus, for large earthquakes the area of felt shaking is larger than the area where the earthquake can be heard.

In a more recent study, Sylvander and Mogos (2005) developed relationships between the locations of sounds heard, earthquake magnitude, and epicentral distance and considered sound as a factor in human detection of small earthquakes. Souriau (2006) also explored relationships between heard sounds and shaking and points out that sound may be responsible for waking people and thus could contribute to intensity values at the low end of the scales. That builds on Hill et al.'s (1976) observation that the sound can be audible even when the P-wave is not felt. Tosi et al. (2000) examined whether records of sounds could be used to infer focal mechanisms. Partially because the sound observations do not include polarity information, they concluded that the uncertainties were too large to use such data to infer unknown focal mechanisms.

Despite these efforts, it is not clear that earthquake sounds make a significant contribution to the analysis of pre-instrumental earthquakes beyond helping us understand how such sounds contribute to observations of lower intensities. As noted above, there are problems with interpreting subjective reports of sounds that mix together both the natural transmission of shaking into the atmosphere and the shaking of man-made objects. These objections could be removed for future earthquakes by making audio recordings, which could easily be integrated into existing digital seismic acquisition systems (Sylvander et al., 2007). Unfortunately, audio recordings may not be a very useful addition to the collocated seismograms because little of the seismic energy is transmitted into the atmosphere and because audio captures only a scalar recording of the 3-component ground motion.

While microphones may not be an effective way to record seismic data, seismometers can produce useful records of acoustic waves in the atmosphere that are strong enough to shake the ground. For instance, seismic records of acoustic waves have contributed to forensic seismology investigations into the 1995 Oklahoma City bombing (Holzer et al., 1996), the 1998 truck bombing of the American embassy in Nairobi (Koper et al., 1999), a chemical plant explosion in Nevada (Ichinose et al., 1999), and a pipeline explosion in New Mexico (Koper et al., 2003).

Infrasound

Very low frequency acoustic waves known as infrasound can travel great distances through the atmosphere, although with frequencies below 20 Hz these waves are not audible to humans. Bolt (1964) demonstrated that micropressure recordings after the 1964 Mw 9.2 Alaska earthquake included acoustic waves with periods of 20–40 s (frequencies of 0.025–0.050 Hz) generated near the earthquake and recorded 3,100 km away at Berkeley, California. Donn and Posmentier (1964) further explored these recordings and showed that earlier infrasound arrivals were generated near the recording station by the passing Rayleigh waves. Away from the earthquake, infrasound can also be generated when surface waves travel through mountainous regions. A good review of these mechanisms is Mutschlecner and Whitaker (2005) and the references therein. More recently Le Pichon et al. (2006) suggested that infrasound could be used to study the amplification of ground displacement by topography, especially in regions with inadequate seismic networks. And Green et al. (2009) demonstrated that coastal cliffs could also be a source of infrasound. While infrasound arrays have recorded many earthquakes, their primary applications continue to be the study of atmospheric phenomena such as meteorites and the study of explosions whether chemical or nuclear tests.

Sonification, education, and art

Sonification is the process of producing sound from nonauditory data. Most seismic data contains frequencies below human hearing and the simplest way to sonify seismograms is to speed them up, which increases the frequency content, and play them back through an audio system. Steinbrugge (1974) mentions that, in 1952 or 1953, Hugo Benioff and Cook Laboratories (Stamford, Conneticut) used this method to produce an LP record with one side called "Earthquakes of this World." Many seismologists have followed in Benioff's footsteps and this has become particularly easy now that digital seismograms can be converted to audio files using common software such as MatLab.

The human ear is an excellent spectral analyzer and most people are more used to listening to music than looking at seismograms. Therefore, sonification of seismograms can be an effective educational tool. Michael (1997) (http://earthquake.usgs.gov/learn/listen/index.php) developed a set of audio playbacks of seismograms that explores how the frequency of shaking varies with source dimension, epicentral distance, and site geology. This Web site includes a recording of the 1992 M7.3 Landers earthquake recorded at Mammoth Lakes where local earthquakes were triggered by the passing seismic waves. The local earthquakes are easily heard in the raw sonified seismogram but required filtering to be detected visually in the plotted seismograms (Hill et al., 1993). This demonstrates that audio can be a powerful educational tool.

Sound is a common part of experiencing earthquakes and so naturally it is part of artistic explorations of seismic events. The seismograms from the above site were used as the basis for my Earthquake Quartet #1 for Trombone, Cello, Voice, and Seismograms (Michael, 2000) which is available online at http://earthquake.usgs.gov/learn/music/. Earthquake Quartet #1 starts by describing the earthquake cycle and then explores the idea that society and culture, including music, take place with the earthquakes as an often-ignored backdrop. The earthquakes play the role of percussion because they have abrupt beginnings and broad, nonharmonic, spectra.

Another musical approach was taken by Loos and Scherbaum (1999) in a CD titled "Inner Earth, a seismosonic symphony" which used many different methods of shifting, converting, and transposing seismograms to make them audible. They produced music with harmonic properties that is purely based on seismograms but sounds nothing like the ones that have simply been sped up.

Overlaying a seismogram on a musical staff provides a form of graphical musical notation that can then be played back using synthesized instruments. Some seismograms from the Mt. Etna volcano can be heard as piano music at http://grid.ct.infn.it/etnasound/page4/page8/page8.html. The goal of that project was to provide a way to detect changes in the behavior of the volcano by hearing changes in the sonified seismograms (http://grid.ct.infn.it/etnasound/) and it also extended into the arts.

The "Great California ShakeOut" earthquake preparedness drills (Jones et al., 2008) use audio combining synthesized earthquake sounds with sounds of damage occurring and sirens to simulate an earthquake experience at the start of the drills. These files can be downloaded from http://www.shakeout.org/drill/broadcast/index.html.

"Memento Mori: an internet based earthwork" by Goldberg et al. (1999) used live seismic data to trigger non-seismic audio in a dark installation that also included a visual display of the seismic particle motion. This approach was later used for "Ballet Mori: a ballet conducted by the earth" performed by Muriel Maffre at the San Francisco Ballet to commemorate the centennial of the 1906 earthquake (Goldberg et al., 2006). Video of the dance can be seen at http://goldberg.berkeley.edu/art/Ballet-Mori/.

In 2009, the Parkfield Interventional Earthquake Fieldwork (PIEQF) (Rogers, 2010), and online at http://pieqf.allshookup.org/, consisted of a large shake table whose motion was triggered by earthquakes throughout the state of California. Both the table itself and a set of rods mounted on the table created noise when an earthquake occurred. This mechanical amplification of the shaking replaced the natural "roaring" discussed by Seneca with a clatter that allowed the viewers to hear distant seismic activity in a way that is not possible through natural shaking and sounds.

Summary

Earthquake sounds form an important part of the earthquake experience, and thus are a large part of artistic explorations of these events, but their study forms a small niche within seismology. The last few decades have produced the data necessary to finally understand this phenomenon along with its role in the study of earthquakes and explosions.

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Cross-references

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