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Earthquake sound perception

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Abstract

Sound is an effect produced by almost all earthquakes. Using a web-based questionnaire on earthquake effects that included questions relating to seismic sound, we collected 77,000 responses for recent shallow Italian earthquakes. An analysis of audibility attenuation indicated that the decrease of the percentage of respondents hearing the sound was proportional to the logarithm of the epicentral distance and linearly dependent on earthquake magnitude, in accordance with the behavior of ground displacement. Even if this result was based on Italian data, qualitative agreement with the results of theoretical displacement, and of a similar study based on French seismicity suggests wider validity. We also found that, given earthquake magnitude, audibility increased together with the observed macroseismic intensity, leading to the possibility of accounting for sound audibility in intensity assessment. Magnitude influenced this behavior, making small events easier to recognize, as suggested by their frequency content.

Introduction

Sound is one of the most common effects reported during or immediately prior to the onset of felt vibrations caused by earthquakes. Sound is sometime heard prior to shaking, likely because it is mainly produced by P waves [*Hill et al.*, 1976], while perceptible shaking is frequently associated with S waves. In general, earthquake sound is heard within an area surrounding the epicenter, even for very small events. Among the many observations accompanying an earthquake, rumble has frequently been reported, even in the oldest chronicles. The sound heard is generally compared to thunder, roaring, rushing wind, or explosion. In a few cases it has been recorded on tape, adding evidence for frequencies above 20 Hz since tape recorder response typically falls off rapidly below that value. Analyses of experimental results have led researchers to explain earthquake sounds as the acoustic waves generated by seismic waves traveling within the earth. In the context of seismic wave oscillations, soil transfers part of the motion to air producing a sound wave. In this manner soil behaves as the moving diaphragm of a loudspeaker, transmitting sound directly under the observer [*Hill et al.*, 1976]. As suggested by studies of infrasonic waves [*Le Pichon et al.*, 2002], the generation of sound near the epicenter is likely the result of the propagation of air waves produced in the epicentral region due to strong ground motion [*Mikumo*, 1968], the radiation produced from secondary sources such as high mountains [*Young and Greene*, 1982], and the ground coupling to air [*Kanamori*, 1991]. Additionally, considering the factors influencing sound propagation in the outcropping layer is important [*Sbarra et al.*, 2012]; as are others such as the pressure, the temperature variations, and the wind influencing sound propagation throughout the atmosphere [*Ross*, 2000]. Other significant sources of noise, particularly in urban areas, are objects whose movements are amplified by the free surface effect and their non-linear interactions. Also, in urban areas the perception of seismic sound can be disturbed by anthropic noise. However, this aspect of the seismic phenomenon should not be neglected. In fact, although earthquake sound does not cause damage it can give rise to fear and create panic.

From seismometric data we know that earthquakes generally radiate seismic waves mainly in the frequency range of 0.01 to 10 Hz, even if they can generate higher frequencies. To be more precise, the amplitude spectrum shows a plateau for frequencies lower than the corner value, after which the spectrum decays as the inverse of the square of the frequency. The corner frequency is inversely correlated with magnitude. Therefore, small earthquakes have a proportionally greater content of high frequencies. Humans can hear sound waves mainly in the range of 20 to 20,000 Hz. The result is that only seismic waves with the highest pitch (mainly) reside in the frequency range for the lowest audible pitch, as confirmed by recordings of the sound accompanying small earthquakes indicating that the dominant frequencies were in the range of 5 to 60 Hz [*Sylvander et al.*, 2007]. The result explains why not all people in the same place hear seismic sounds and why some animals flee in fear. Much depends on an organism's sensitivity to low pitches. On the other hand, the discrepancy between some observations and ground movement has led to the hypothesis that earthquake sound has a higher frequency content with respect to the seismic signal [*Souriau,* 2006; *Sylvander and Mogos*, 2005], likely due to the influence of non-linear effects that create higher frequencies from lower frequency movements of the surface.

Due to the complex interactions of these factors it is difficult to form a comprehensive model. Additionally, since a network containing a sufficient number of instruments capable of recording sound is not available, experimental analyses for the audibility of earthquake sound are mainly performed using reports from individuals. The possibility of studying a phenomenon using humans as "instruments" may lead to a large margin of error. However, it has the advantage of potentially yielding a great quantity of data. The distribution of reports mainly indicates the following: a decrease in the percentage of respondents hearing the sound at increasing distances from the epicenter [*Davison*, 1938], a correlation between the size of the area of interest with respect to an audible sound and the event magnitude [*Sylvander and Mogos*, 2005], and the specific shape of the area where sound is heard, related to the geometry of the seismic source [*Tosi et al.*, 2000].

In this work, we analyzed data for reported sounds in Italy collected using the online macroseismic questionnaire of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), in order to study variations with respect to distance from the epicenter and earthquake magnitude. To explore the possibility of integrating this effect into intensity estimation procedures, we also searched for characterizations of audibility on the framework of the Mercalli-Cancani-Sieberg macroseismic scale.

1. Data

The data were obtained from web-based macroseismic questionnaires compiled for earthquakes with a local magnitude of $M_L \geq 2$ located in Italy, occurring from June 2007 to June 2011 at a depth shallower than 20 km since Italian seismicity is rarely deeper. The questionnaire, located at http://www.haisentitoilterremoto.it (meaning "did you feel the quake"), mainly relies on contributions from ordinary volunteers, but also on the contributions of a group of registered permanent compilers that are alerted via e-mail. The questionnaire asks the questions necessary for estimating the macroseismic intensity adverted in a municipality and other questions useful for describing the possible audible effects of an earthquake. The presence of a question directly asking if a seismic sound was or was not heard provides us with a set of unambiguous data, especially when excluding questionnaires that have this question unanswered. One of the questions asks whether the noise was heard before, during, or after shaking. Among the people that replied to this question, 42% reported the first option, 54% the second option, and the remaining percentage (5%) reported the occurrence of noise following motion. Explaining the last observation was difficult when the model for p-waves converted into air waves directly under the observer was employed. For such cases it is likely that confusion existed regarding the relationship of the seismic sound to other noises such as those produced by the building. Another explanation could be that the sound perceived was generated by strong ground motion in the epicentral area and was propagated in the air, resulting, for long distances, in a delay of a few minutes with respect to the local ground shaking. In this case, audibility is influenced by atmospheric refraction, weather and terrain variations [*Ross*, 2000]. To reduce the role of these factors, we neglected the reports of sound perceived after the earthquake shaking. Using these criteria, out of a total of 190,000 macroseismic questionnaires we selected approximately 77,000, for which “yes” and “no” were almost equally represented.

2. Earthquake sound attenuation

As a general rule, the percentage of respondents hearing the earthquake sound was high near the epicenter, and decreased with distance. We analyzed our data in order to determine more quantitative relationships relative to epicentral distance and magnitude. Instrumental source parameters (magnitude and epicentral location) are always available since the data-base is composed of recent earthquakes. We calculated the percentage of “heard” in a moving window of 20 km wide, stacking together all earthquakes of a fixed magnitude range. The percentage of respondents was correlated with the level of acoustic intensity, as a high level was more likely to be heard by a greater portion of the population. The results are shown in Figure 1. A point was plotted only if the number of questionnaires for the considered distance window was greater than 40. The graph indicates how the percentage of respondents, hearing the rumble, decreased with distance and increased with magnitude. Within a distance of 10 km from the epicenter, 66% of respondents were able to hear a small quake (M_L = 2.5-3.0), while the percentage increased to 97% during a M_L = 5.5 event (Figure 1). Assuming that sound is heard by a population if it is perceived by more than 50% of respondents, we observed that for magnitudes less than 5, the audibility reached 30 km, while for magnitudes from 5.5 to 6 it reached 90 km. For each magnitude interval, as shown by the example dashed line in Figure 1 that fits points corresponding to a magnitude of 5-5.5, the corresponding plot approximately followed a logarithmic decay. Logarithmic decay with distance was in accordance with the behavior of macroseismic attenuation for the Italian territory [*Pasolini et al*., 2008], as shown with a black dotted line in the figure for an earthquake of magnitude 5. In order to find a comprehensive law for the audibility attenuation by taking into account the magnitude, we prepared an additional graph (Figure 2) by calculating the detected sound percentage inside a moving window on the distance and magnitude dimensions. Distances (*d*) were considered on a logarithmic scale. For this variable the non-overlapping moving box was 0.1 $\log_{10}$ d wide, while for magnitude variable the box was 0.24 M_L wide. The results, as shown in Figure 2, confirmed the logarithmic decay observed in Figure 1. In fact, using the logarithm for distance it appears as if there was an almost uniform decreasing slope. We fit this data using a first-degree polynomial function, by obtaining the following:

$$H = -54 \log d + 13 M_L + 73 \quad (1)$$

where *H* is the heard sound percentage in a municipality and *d* is the epicentral distance in km. Relationship (1) resulted in a correlation coefficient significantly different from zero, with a probability of failure of less than 0.001. As a percentage, H was only defined between 0 and 100, the relationship saturated at 100, and was verified only within the magnitude and the distance ranges shown by colored pixels in Figure 2. The fitted plane of equation (1) was plotted in Figure 2 using contour lines, indicating that earthquakes with different magnitudes behave in the same manner, just shifting audibility to longer distances.

3. The correlation between audibility and macroseismic intensity

Earthquake noise is never mentioned on macroseismic scales. Nevertheless, as both macroseismic intensity and noise audibility decay with the logarithm of epicentral distance, there could be a relationship between them. Furthermore, even if earthquake sound does not contribute to estimations of macroseismic intensity, it can cause a human reaction such as fear, and the subsequent overestimation of intensity [*Mäntyniemi*, 2004].

Using the procedure described by *Sbarra et al.* [2010], all of the effects reported on the questionnaires were statistically analyzed in order to extrapolate a probabilistic estimate of the Mercalli-Cancani-Sieberg (MCS) macroseismic intensity for an observer. We used the MCS scale because it is widely used in Italy, for historical reasons. In the procedure the intensity was assessed using additive intensity scores that were associated with the answers. The macroseismic intensity for a municipality was assessed by adding the intensity scores for all of the questionnaires coming from it and by determining the mode. The method was based on the procedure described by *Sbarra et al.* [2010], upgraded for a better estimation of macroseismic intensity using the mode instead of the average. To avoid a poor assessment of the intensity, we excluded municipalities with less than 10 questionnaires.

The MCS macroseismic intensities for each municipality are shown in Figure 3 in relation to the percentage of respondents hearing the seismic sound (*H*). From the figure it is clear that earthquake magnitude (in color) plays a fundamental role in the relationship between the intensity and heard sound, according to the plotted averages of the percentages. When the earthquake magnitude was small it was easier to hear the associated sound, particularly for weak shaking. The result is in accordance with the data of *Gold and Soter* [1979] who, considering the human perception threshold, found that, at frequencies greater than 17 Hz, small earthquakes could be detected more readily by sound than by vibration. The feature can be explained by the relative higher frequency content of small quakes that allows hearing the associated seismic sound.

4. Discussion and conclusion

Earthquake sound audibility is a complex phenomenon inextricably related to the event source (geometry, magnitude, depth, static, and dynamic stress drop); the ground (source distance, geology, attenuation structure, and topography); the air (density profile); the presence of objects (buildings and furniture); and human factors (audibility threshold and anthropic noise). An analysis of 77,000 observer reports indicated that in Italy the heard sound percentage increased with earthquake magnitude and decreased with epicentral distance (Figures 1 and 2). In particular, Figure 2 and equation (1) indicate that the attenuation of experimental audibility was proportional to the logarithm of the epicentral distance and linearly dependent on earthquake magnitude. Audibility, as a physiological effect, was proportional to the acoustic intensity measured in dB, calculated using the logarithm of the acoustic pressure (*P*). Since *P* was directly proportional to the ground displacement, $U \propto M_0/d$, where M_0 is the seismic moment and *d* is the epicentral distance, we determined that the acoustic intensity in dB was, as confirmed using equation (1), as follows: $dB \propto -\log d + M$, where *M* is the earthquake magnitude. Although our results are limited to the Italian region, the reader should note that Italy contains a large variety of tectonic settings and outcropping layers, and is not limited by particular cases. Our results were also in qualitative agreement with a study on the sound of small earthquakes in the French Pyrenees [*Sylvander and Mogos*, 2005].

According to the experimental relationship (1) we found, for a $M_L = 2$ earthquake, that the sound could be heard by at least 50% of a population over a radius of 8 km from the epicenter. For such low magnitudes, it is possible to have, in our data, artificial seismic events caused by quarry blasts. Such seismic events generally have a magnitude smaller than 1.8 and rarely (approximately 0.5% of all earthquakes) larger magnitudes [*Mele et al.*, 2010], thus their influence on our results was minimal. We selected only questionnaires describing effects regarding earthquakes that where instrumentally localized and revised by experts, therefore excluding explosions in air.

Assuming that equation (1) is valid for even much smaller magnitudes, we determined that the radius inside for which audibility was at least 50%, for a $M_L = 1$ reached 5 km. Such events generally pass unnoticed for the shaking effect, supporting the hypothesis that some "*brontidi*" are manifestations of unfelt or feeble earthquakes [*Gold and Soter*, 1979 and references therein], in accordance with *Richter* [1958], suggesting that even weak earthquakes can transfer the energy of the audible frequency from the ground to the air. Therefore, the acoustic effect can be a useful element for better localizing the epicenter of small earthquakes in densely inhabited areas.

For small earthquakes ($M_L < 4$) and relatively long distances (distance > 30 km) the experimental audibility deviated from the fitted function (Figure 2) and was somehow greater than expected. The result suggests that in this magnitude range other variables, such as rock type and focus depth, could have had an influence on audibility. Additionally, the Moho reflection effect could have a role, as occurred in the Po Plain (Northern Italy), where the peak ground acceleration, as well as the macroseismic intensity, were systematically enhanced over distances between 70 and 200 km [*Bragato et al.*, 2011].

For earthquakes with magnitudes greater than 4.5, we suggest the integration of the audibility data into the assessment procedure of macroseismic intensity. As shown in Table 1, there was good agreement between the percentage of people feeling the quake [*Molin et al.*, 2008] and the percentage of respondents hearing the quake sound. For other countries the application must take into account the use of different intensity scales. However, all 12-degree intensity scales have been observed to behave in similar manner, especially regarding low degrees [*Murphy and O'Brien*, 1977; *Musson et al.*, 2010], allowing an extension of the empirical correlation to the European Macroseismic Scale (EMS) and the Modified Mercalli Intensity (MMI).

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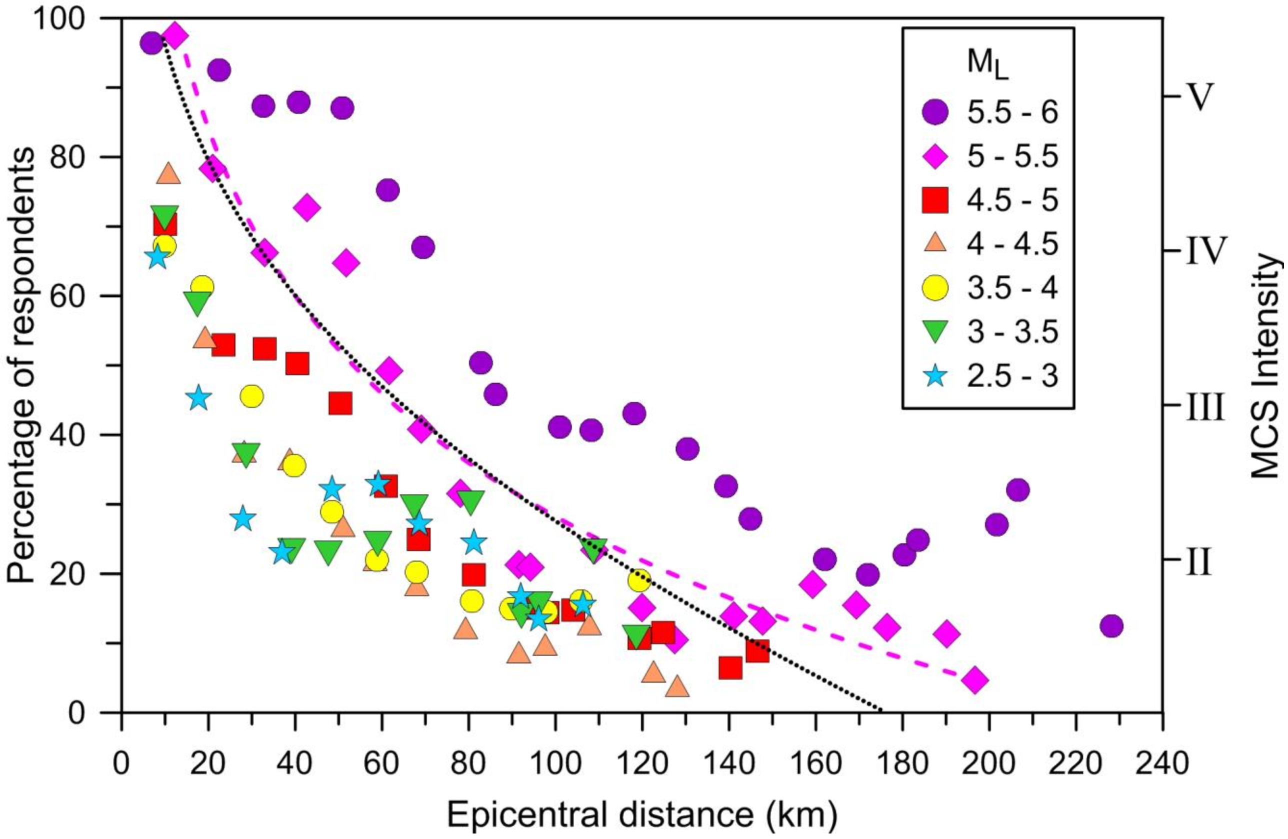

Figure 1 The percentage of respondents reporting earthquake sounds versus distance for different magnitude ranges. The dashed line represents the log-linear fit of the magenta diamonds (M_L = 5-5.5) while the black dotted line represents the macroseismic intensity attenuation function [*Pasolini et al.*, 2008] for M_L = 5.

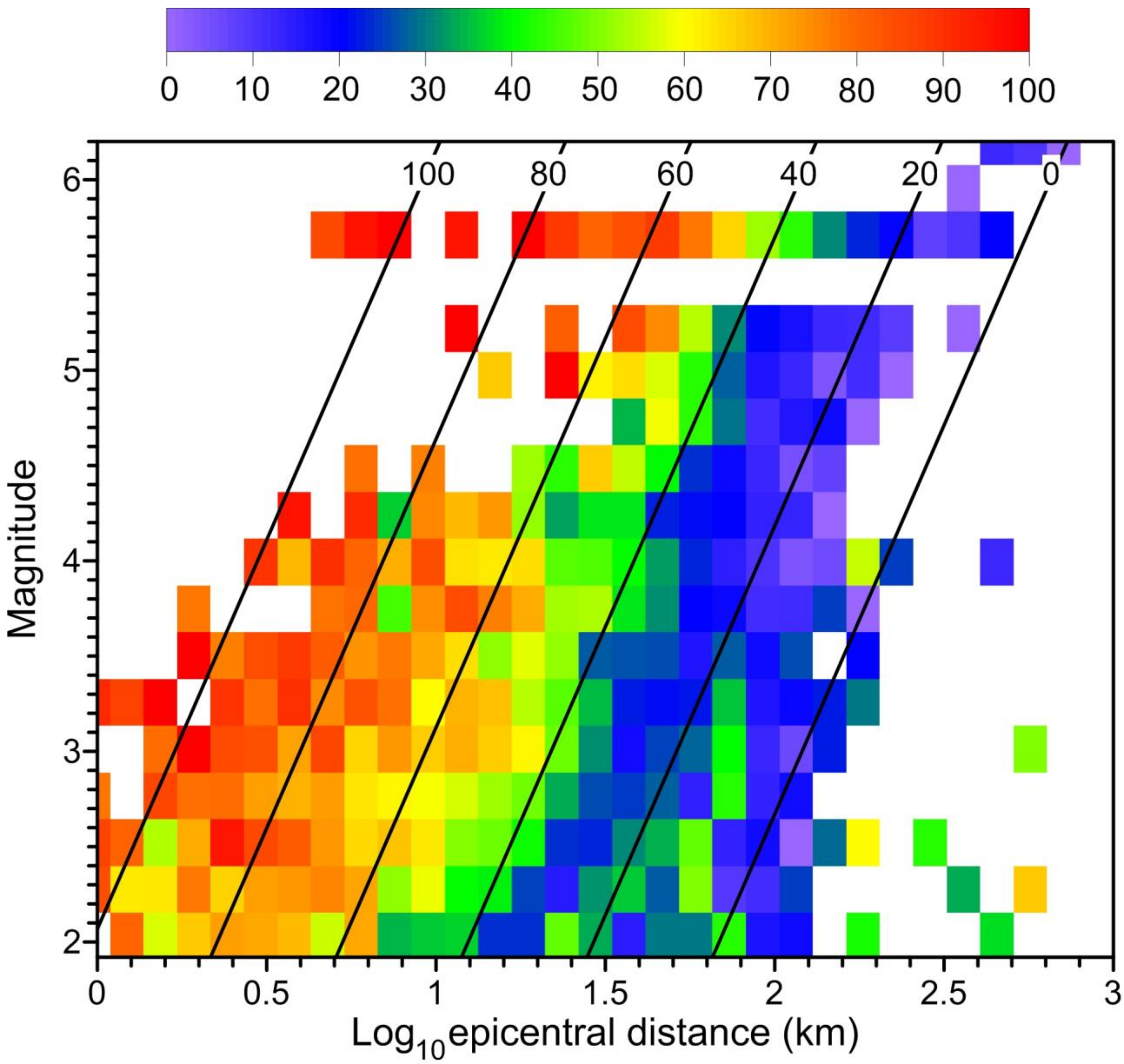

Figure 2 The percentage of respondents reporting earthquake sounds as a function of epicentral distance and magnitude. The black contour lines represent equation (1).

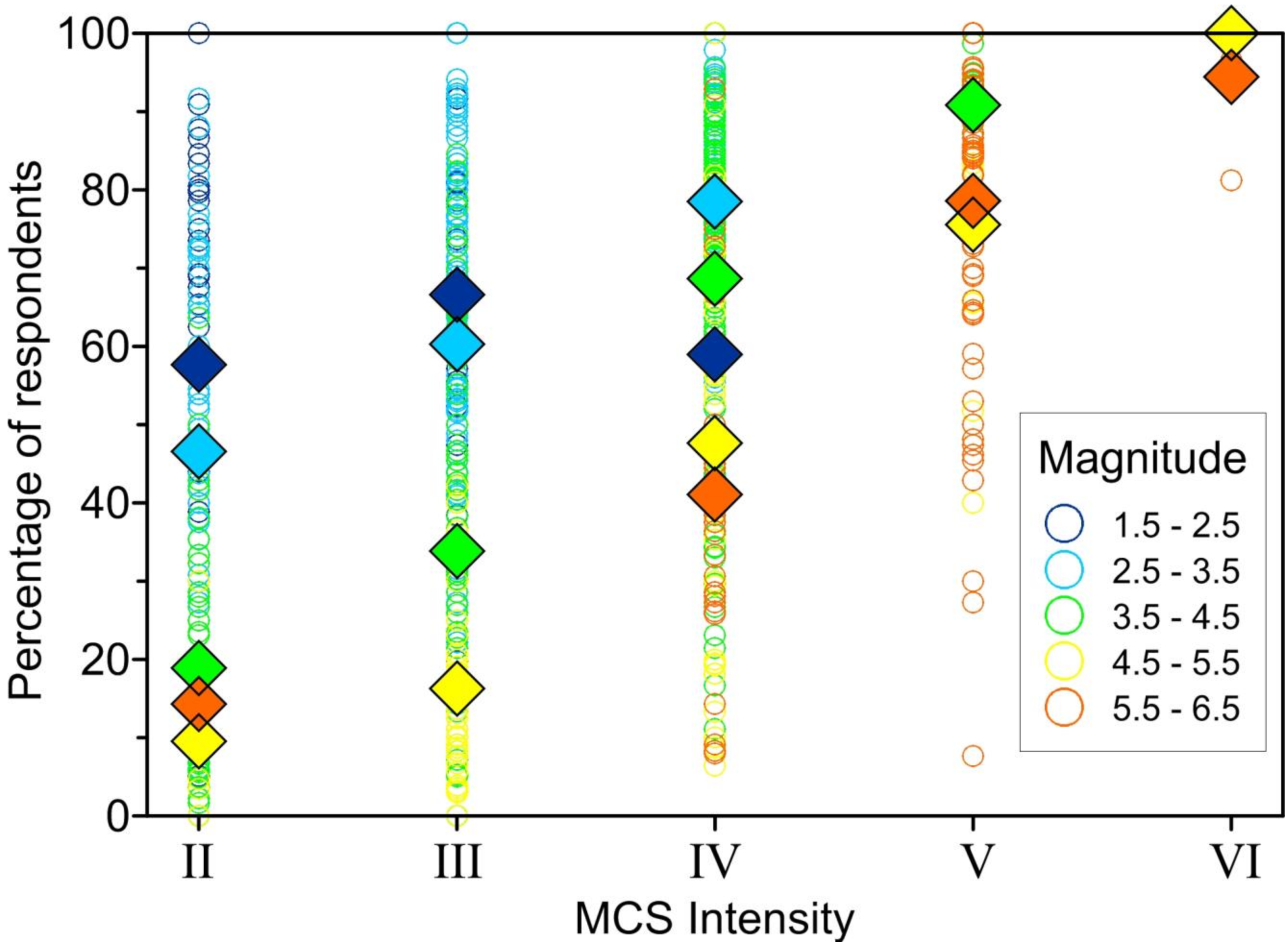

Figure 3 Percentage of respondents reporting earthquake sounds for each municipality (circles) as a function of the corresponding macroseismic intensity on the MCS scale and the earthquake magnitude (in color). Diamonds indicate percentage averages calculated for each MCS intensity and magnitude range.

Table 1 Percentage of people feeling earthquake and hearing sound.

MCS intensity	People earthquake was felt by (qualitative descriptions):	Percentages assigned to qualitative descriptions [*Molin et al.*, 2008]	Percentage of respondents hearing sound
II	individuals	5	10
III	a few	25	16
IV	many	50	45
V	most	75	78
VI	all	100	96