Earthquake Perception Data Highlight Natural Frequency Details of Italian Buildings

P. Tosi[1], V. De Rubeis[1], and P. Sbarra[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

Corresponding author: Patrizia Tosi (patrizia.tosi@ingv.it)

Key Points:

- Citizen observations, compared with spectral response models, identified the natural vibration frequency of the buildings
- Higher vibration modes are more noticeable for buildings with more than six floors
- The vibration frequency of the basement floors varies with the height of the building.

Abstract

We analyzed more than 286,000 felt/not-felt data to study the effect of building height on earthquake perception. We investigated the boundary distance of perception as a function of magnitude, and we found that as the height of the building increased, observers located on higher floors perceived medium to high magnitude earthquakes progressively better than smaller ones. Comparison of the perception boundary trend with seismic response spectra allowed us to estimate the frequency of vibration perceived by observers located at each floor/building-height case. The results, in agreement with instrumental observation, show that the value of the fundamental period increases with building height for the top floor. In addition, we observed that the height of the building also influences the vibration frequencies of basement floors and that higher vibration modes become more evident for buildings with more than six stories.

Plain Language Summary

As the distance from an earthquake increases, the percentage of observers reporting not having felt it increases too. The average transition distance between 'felt' and 'not felt' depends mainly on the magnitude and depth of the earthquake but also on the observation floor and building height. Indeed, the building, acting as a resonator, can amplify the shaking at specific frequencies. To study this effect, felt/not-felt crowdsourced data were analyzed to find the statistical boundary of perception as a function of the earthquake magnitude. The results show that observers felt medium-to-high magnitude earthquakes progressively better than smaller ones as building height increased, and that the differences between floors are more pronounced for buildings with more than six stories. Comparison with seismic response spectra allowed us to estimate the vibration frequency perceived by observers located at each floor/height combination, highlighting the natural frequencies and vibration modes of the building. In addition, the results show that the height of the building affects the vibration frequencies felt on different floors, including the basement. The general agreement with frequency values provided by instruments and physical models indicates that citizen observations can be reliable.

1 Introduction

Building damage studies have shown the complexity of the problem, indicating the importance of the interaction between ground motion and building response; many variables influence it, including earthquake source, outcropping lithology, damage caused by previous shocks, and building height (Mucciarelli et al., 2004). These variables impact not only damage but also minor effects typical of the lower degrees of the seismic scales. For example, Sbarra et al. (2015), by analyzing municipalities with Mercalli Cancani Sieberg (MCS) intensity = 3, showed that the perception of the earthquake is influenced by building height in a magnitude-dependent way. They have shown that during medium-to-high magnitude earthquakes at large distances from the source, observers on the top floor of tall buildings experience more significant shaking than those in short buildings, but they observed the opposite behavior at close distances from small magnitude events. The different source spectra, coupled with the frequency of the fundamental vibration mode of the building, explain such a result. Macroseismic intensity may not be the most appropriate measure to investigate the phenomenon in more detail. The reason is the inherent complexity of macroseismic intensity, considering the heterogeneous set of effects usually involved in estimating it, as they span from people's perceptions to the consequences of ground shaking on objects and buildings. But each diagnostic has a different behaviour (Lesueur et al., 2013; Sbarra et al., 2020), making macroseismic intensity an averaged measure with minor sensitivity to changes in the several aspects of ground motion. Instead, the analysis of attenuation of individual effects suggested that each of them is an expression not only of the intensity but also of the specific frequency of vibration (Tosi et al., 2017; Sbarra et al., 2021). To obtain this result, Tosi et al. (2017) highlighted the differences between the attenuations through the magnitude-distance scaling ratio, i.e., the ratio of the two key coefficients of each attenuation model, namely that of the logarithm of the hypocentral distance and that of the magnitude. Comparing the corresponding values obtained with the equations for estimating the spectral ordinates of response (Cauzzi and Faccioli, 2008) revealed vibration frequency associated with each effect. This link explains some experimental observations, such as the frequent lack of oscillation of suspended objects in the case of small earthquakes, whose spectrum is poor in low frequencies.

Therefore, the study of a single diagnostic effect, as opposed to that of macroseismic intensity, may give a better understanding of the influence of other parameters. For example, Leuseur et al. (2013) invoked the natural frequencies of the building to explain the correlation between particular macroseismic effects and seismic response spectrum in the frequency range of 1-10 Hz. Among the various effect, people's perception of the earthquake allowed an in-depth analysis due to the possibility of studying the effect on different locations (higher or lower floors, outdoors) and situations (sleeping, at rest, in motion) of the observer (Sbarra et al., 2014). The problem related to this detailed study is in reducing the data to be considered within the whole dataset. The magnitude-distance scaling ratio method (Tosi et al., 2017) required regression of an intensity prediction equation for each effect and was consequently applied only to cases where a large amount of data were available. Sbarra et al. (2021) proposed an alternative method based on discriminant analysis that proved suitable for application to a smaller dataset, such as observations of those who did or did not feel an earthquake while in a stationary car. Comparison with the response spectra allowed, in this case, to identify the resonant frequency of the car-observer system.

Here, we apply the method by Sbarra et al. (2021) to earthquake perception data from observers indoors to determine the resonant frequencies of 1- to 10-story buildings. The results, being derived from a considerable number of observers distributed throughout the territory, after verifying their agreement with values derived from models and instruments, provide an indication of the average seismic response of Italian buildings to small shaking.

2 Data

HSIT (Hai Sentito Il Terremoto; Tosi et al., 2007) is an Italian service of the Istituto Nazionale di Geofisica e Vulcanologia that includes an online macroseismic questionnaire dedicated to volunteers or site subscribers, listing several questions about earthquake effects, observer location (e.g., inside a building), and observer condition (e.g., at rest or moving). When an earthquake occurs, the automated procedure sends an email requesting information to citizens who may have felt the shaking, chosen in a range depending on magnitude (Tosi et al., 2015). The specific request through the email guarantees the presence of several negative responses to the question: "did you feel the earthquake?". Almost half of the questionnaires received are "not felt," which allows for both assigning the lowest degrees of macroseismic intensity (2 and 3), mainly based on the percentage of felt, and investigating the radius of the felt area. For this analysis, we used Italian earthquake data with a magnitude greater than or equal to 2 that occurred from 2013 to 2020 and more than five archived questionnaires. This criterion allowed us to exclude many small deep or offshore earthquakes and, more in general, to guarantee sufficient data quality. In addition, to solve a problem related to hurry in the selection of the quake for which observations are submitted, particularly evident during seismic sequences, we have also discarded some earthquakes at higher risk of inaccuracy using an automatic procedure (Cameletti et al., 2017). Among the various magnitudes estimated for each event, we used Mw, and when not available, it was derived using ML or Md through the conversion equations of Gasperini et al. (2013).

The data are indoor observers' felt/not-felt responses to single earthquakes. Among these, we selected only those most responsive to earthquake vibration, i.e., those who were at rest (thus excluding those who were moving or sleeping), to prevent the condition from affecting the results (Sbarra et al., 2014). Considering only felt/not-felt data allows for a decrease in the subjectivity associated with people's quantification of shaking. The data selected were more than 286,000, and since the questionnaire includes separate questions on the total number of floors in the building and the observer's one, it was possible to separate the two aspects and study how an observer feels an earthquake in the function of floor and building height. The height investigated is from 1 to 10 stories, plus a generic class including buildings with more than ten stories.

3 Boundary line of perception and vibration frequency

As the distance from the epicenter increases for each earthquake, more and more observers report that they did not feel the quake. The average transition distance between 'felt' and 'not felt' depends mainly on the magnitude and depth. The analysis of the data of all observers indoors at rest plotted (Fig. 1a) as a function of hypocentral distance and magnitude shows that the "felt" give way to the "not felt," which prevail on the right-hand side and bottom of the figure. In this area, there are also several probably erroneous "felt" received, most likely, by observers who have selected the wrong earthquake in the questionnaire, a problem difficult to eliminate even with the applied filters (see data section). Similarly, although not easily visible due to the overlapping symbols, there are also several doubtful "not felt" in the main "felt" area. However, we observed that there are far fewer erroneous reports than reasonable ones, so we rely on statistical analysis to account for the errors on both sides.

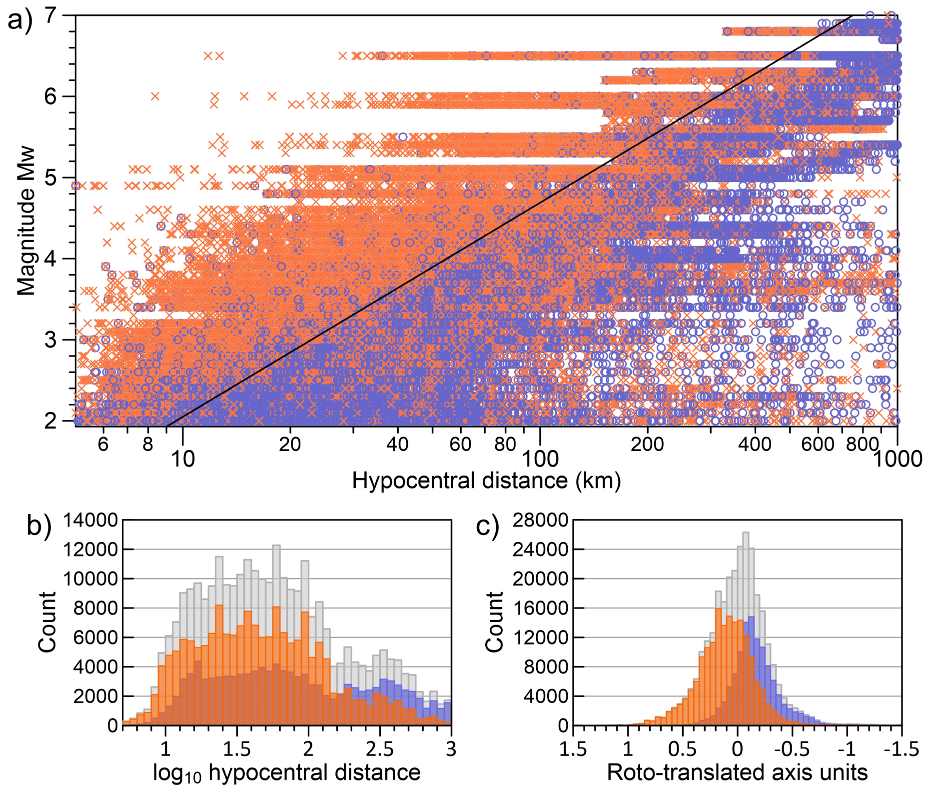

Figure 1. (a) Observers at rest inside a building (without distinction to floor and height of the building) who felt (orange crosses) or did not feel (blue circles) the earthquake, whose magnitude we show in ordinate, as a function of their distance from the hypocenter. We derived the linear boundary of earthquake perception (black line, Eq. 1) by discriminant analysis. (b) Histogram of total data (grey line), felt (orange), and not-felt (blue) data versus hypocentral distance. (c) Histogram of total data (grey line), felt (orange) and not-felt (blue) data projected onto the perpendicular to the discriminant line.

To find the mean perception boundary, we used a method based on the application of discriminant analysis to questionnaire data, evaluated as a function of the decimal logarithm of hypocentral distance (logR) and magnitude (Mw), to find the line that best separates the observers who have from those who have not felt the earthquake (Sbarra et al., 2021). For all the reports, shown in Figure 1a, the discriminant line, with a probability associated with F-test less than 10^{-5}, was found to be:

Mw=2.64 logR-0.59. (1)

The principle on which discriminant analysis is based is shown in Figure 1. The histograms of the number of "felt" and "not-felt" are displayed as a function of hypocentral distance (Fig. 1b) and of the projection on the perpendicular to the discriminant line found (Fig. 1c). In the latter case, the two distributions are best separated, making the discriminant line the boundary of earthquake perception. In this context, the slope of the boundary line highlights the mutual role of distance and magnitude in determining the intensity of ground motion. For this reason, we investigated in more detail the effect of building (total height and observer floor location) on perception by subdividing data shown in Figure 1 and applying the discriminant analysis to the individual subsets corresponding to each floor and building height combination. The discriminant lines found were considered significant if both the number of data exceeded 50 and the probability associated with the F-test was less than 0.005 (Table S1 in Supporting Information). Among the different combinations, only four related to basement floors failed to meet the minimum data and F-test thresholds. In Figure 2, we show line slope significant values as a function of the number of stories of the building.

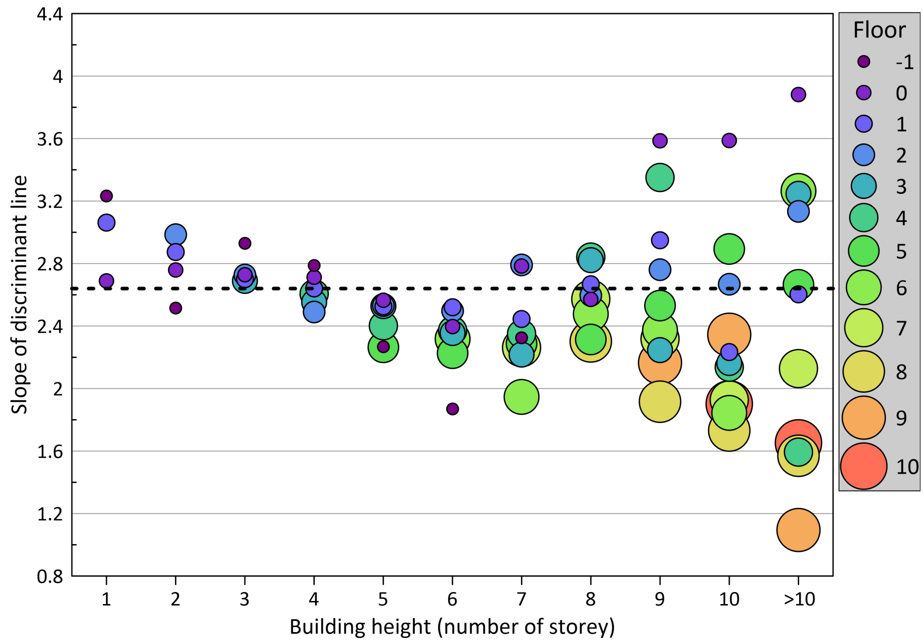

Figure 2. Slopes of the linear boundary of earthquake perception for observers located on different floors, plotted as a function of the building height. The black dashed line marks the slope value (2.64) of the discriminant line calculated from the total data of observers at rest inside a building (Eq. 1).

It is interesting to note that for 1 to 6-story buildings, the slope of the discriminant line has a general decrease, while for individual floors of buildings with more than six stories, the slope values are distributed over an increasing range as the height rises. We remind here that the slope of the boundary line of perception reflects the different attenuation of shaking as the magnitude varies. In particular, a decrease in slope reveals a more significant difference in the mean perception distance for small and medium-to-high magnitude earthquakes.

As shown by Sbarra et al. (2021), the slope of the discriminant line is a value that embodies the same concept represented by the scaling ratio defined by Tosi et al. (2017), i.e., the ratio of the coefficient of the logarithm of the hypocentral distance to that of the magnitude in the equation estimating the perception of shaking in the form:

$P_E = a_1 + a_2 M + a_3 \log R$ (2)

where P_E represents the ratio between the number of ”felt” and a total number of questionnaires (both ”felt” and ”not-felt”). To test this equivalence, we applied the method of Tosi et al. (2017) to the whole set of earthquake perception data (Fig. 1a). A large amount of data allowed the application of the Tosi et al. (2017) method, involving the regression of Eq. (2) on the attenuation of the rate of people who perceived the earthquake. We calculated the rate PE, stacking data of all earthquakes having the same magnitude (with the accuracy of one decimal place) inside a window 0.02 logR-wide. Through least squares regression, we estimated Eq. (2) as:

$P_E = 0.78(\pm 0.02) + 0.31\ (\pm 0.01)\ Mw - 0.83(\pm 0.03) \log R$ (3)

leading to a scaling ratio value $S = -a_3/a_2 = 2.68$. In Tosi et al. (2017), the same method applied to perception data from all observers located within a building yielded a slightly lower value (S=2.32). Nevertheless, comparison with the case presented here is not straightforward because the databases analyzed differ in both temporal range and reference magnitude (Ml for the former). The major difference is likely due to the selection, in the case presented here, of only those observers who were at rest, thus excluding moving and sleeping ones. In fact, the observer’s activity can significantly influence the perception of earthquakes (Sbarra et al., 2014). However, given the confidence limits, the S value calculated here (2.68) shows good agreement with the slope of the discriminant line (2.64) estimated on the same data set, thus supporting the possibility of comparing the values derived from the two methods.

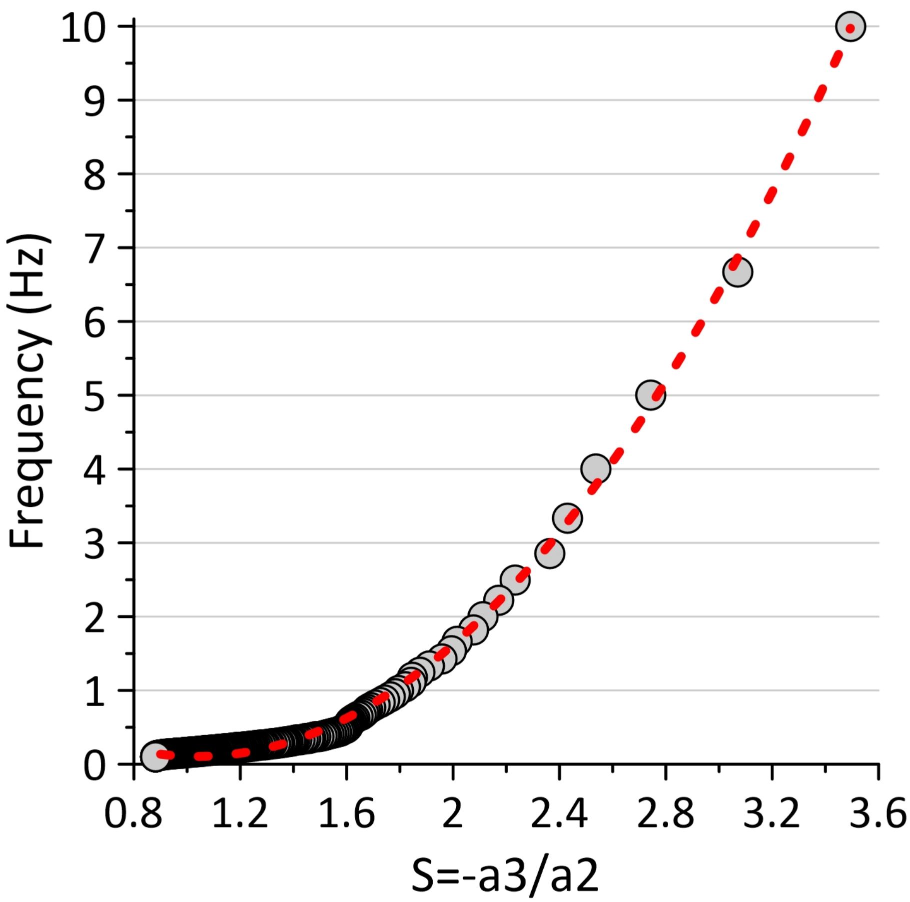

Figure 3. Scaling ratio values (S, ratio of the coefficients in Eq. 2) and corresponding frequencies for the models of spectral ordinates of response by Cauzzi and Faccioli (2008). The red line represents the interpolation of the points by Eq. (4).

We compared the slopes of the perception boundaries shown in Figure 2 to S values derived from the equations of a ground motion model. In particular, we chose the 5% damped horizontal response spectrum model of Cauzzi and Faccioli (2008) because it has the same functional form as Eq. (2), giving the possibility of obtaining a value of S for each frequency considered (Fig. 3). The variation of S as a function of frequency (F), shows a simple trend inside the range 0.1-10 Hz, highlighted by the second-degree least squares regression curve

$F=1.63(\pm 0.05)\ S^2 - 3.39(\pm 0.23)\ S + 1.86(\pm\ 0.23)$ (4)

that interpolates the points. To derive a stable regression, the very high number of points at the left of the plot has been reduced and substituted with a moving average data set. The sole purpose of Eq. (4) was to make it easy to find the frequency of the response spectrum to which a particular value of S corresponds. For this reason, we considered frequency as the dependent variable in the regression. Each slope value of the discriminant line (Fig. 2) was thus associated, through Eq. (4), with the natural frequency of the harmonic oscillator whose oscillation amplitude attenuates with the corresponding scaling ratio S. The resulting Fig. 4 shows that the general decrease in the discriminant slope, going from 1- to 6-story buildings, corresponds to a lowering of the frequency.

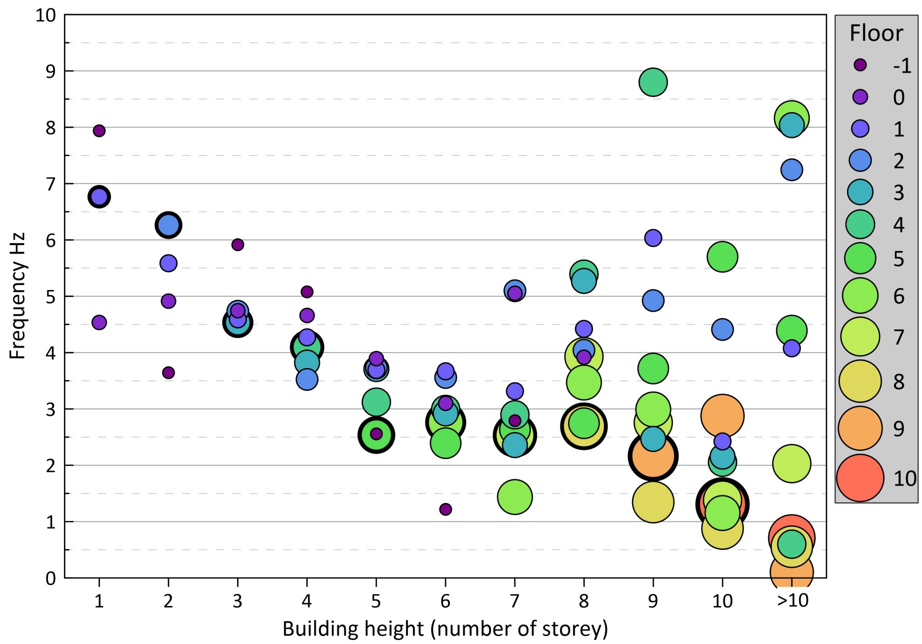

Figure 4. Natural frequencies corresponding to the slope of the linear earthquake perception boundary (Eq. 4) for observers located in different floors, plotted as a function of building height. Data are limited to the values for which the Eq. (4) is defined (0.1-10Hz); for this reason, some symbols about the ground floor in tall buildings (3 violet points in Fig. 2) are missing. The bold circles help to identify the top floors.

In contrast, the spread of points for taller buildings shows an increase in vibration frequency values. This experimental observation is in agreement with a simple model of an oscillating building where the frequency of the dominant mode decreases with increasing height. At the same time, the increase of vibration modes explains the spreading of frequency values for buildings with more than six stories. In this case, the higher modes contribute substantially to the motion of the middle and lower floors. In any case, the highest floors of these buildings are associated with lower frequency as their dominant modes have a longer period range. The latter is a general phenomenon. The top floors of all the buildings (highlighted by a bold circle in Fig. 4) display a rather continuous frequency lowering. The presence of different vibration modes in the taller buildings allows observers inside them to perceive both low frequencies, typical of long distances from major earthquakes, and high frequencies, present in the vicinity of small earthquakes.

4 Discussion

The natural frequency of a building, when compared to a standard oscillator, depends on its mass and stiffness, but the variety of building types means that it depends on many other parameters, including height, building typology, and geometry. Moreover, both structural and non-structural components have a significant effect on natural frequencies. Since it is complicated to calculate the natural frequency of a building directly, it is preferable to use simplified models or experimental observations.

Sbarra et al. (2015), simulating a three-dimensional model of a 2-story and a 10-story building, evidenced a natural period of 0.10s and 0.57s (frequencies of 10Hz and 1.8Hz). These two values confirm that tall buildings have lower natural frequencies than low buildings and are similar to the corresponding ones we found for the top floor, where fundamental mode reaches its maximum amplitude (6.3Hz and 1.3Hz).

A collection of measures made using horizontal to vertical noise spectral ratio on the top floor of 96 Italian buildings of various types and years of construction (Gallipoli et al., 2020) shows, as expected, that the first vibrational frequency value decreases with the increase of the number of floors and that the values are close to those we found for the top floors. In particular, our values are between the 25th and 75th percentiles of the natural frequency values distribution for each building height (from 2 to 7 stories, Gallipoli et al., 2020). Only for the 5-story building is our value (2.5Hz) slightly lower than that (3Hz) of the corresponding distribution.

The regression of a simple linear experimental relationship through the origin between fundamental period (T) in seconds estimated at the top floor with our data and building height (h) in meters computed from the number of stories N (h=3.5 N +1) gave the equation:

$T=0.017\ (\pm 0.001)\ h$ (5),

having a coefficient of proportionality very similar to that found in other studies (Gallipoli et al., 2010; 2020 and references therein).

The agreement between the results found with very different methods showed that the perception data provided by citizens yielded consistent results, despite the problems associated with collecting this type of data, which are due not only to the subjectivity of perception but also to the accuracy of the information provided. In this specific case, the numbering of floors in Italy is understood in different ways, as usually, the floor at street level is called the ground floor, and the floor above it is referred like the first. Nevertheless, the 1st floor is sometimes treated as synonymous with the ground floor, leading to confusion. Moreover, other variables on which perception depends, besides the observer's condition of stillness or movement, should be considered: position (standing, sitting, lying down) and attention. On the other hand, asking people for such detailed information could discourage them from filling out the questionnaires, resulting in the further splitting of data and reduced reliability. For the analysis of this type, the availability of a substantial amount of data is crucial. Indeed, in our previous works (Sbarra et al., 2012; 2014; 2015; 2021), we decided to analyze the observer's situation or location alternately to obtain consistent results.

However, in all cases, our analyses showed variation as a function of magnitude and distance, which is why we emphasize the importance of the frequency content of the vibration for earthquake perception. The same is true for other macroseismic effects. Tosi et al. (2017) showed that diagnostic effects of low degrees of macroseismic scales occur at different resonant frequencies. As an example, the oscillation of suspended objects occurs preferentially at low frequencies (<0.5 Hz), unlike the vibration of doors and windows (~2.5 Hz). Therefore, the occurrence of effects depends on coupling between the natural frequency of objects and buildings, besides the frequency content of the ground motion. For these reasons, to correctly assess the macroseismic intensity, a large enough amount of data is essential to ensure a broad sampling of the various situations, places, and buildings, especially on MCS degrees 2 through 5, based on the perceptions of people and effects on objects.

5 Conclusions

In the present work, we compared the variation of distance, within which observers placed on various floors of buildings of different heights perceived the earthquakes of different magnitude, with the prediction equations of the response spectra. Such comparison indicates the vibration frequency that may be the primary cause of perception in each considered location. This approach was based on a large number of observations and represented aspects, such as the human perception, that are difficult to achieve with a few instruments. In any case, the agreement with natural frequency values provided by instrumental data shows the potential and reliability of citizen observations.

The results (Fig. 4) show the gradual decrease in the frequency of the first natural mode for buildings from 1 to 6 stories and the increase in the contribution of higher frequency vibration modes for taller buildings. The latter aspect is crucial because it indicates a greater possibility of coupling between the natural frequencies of building and soil and thus a greater risk of resonance effect (Gallipoli et al., 2020).

Another result is the variation of vibration frequencies of basement floors for buildings of different heights. This variation suggests that the whole building shaking also has an appreciable effect on the foundation. We should use caution, therefore, in evaluating the response of the building considering the basement instrumental recording as the free field excitation (Hong and Hwang, 2000).

As a final remark, we would like to emphasize the importance of knowing the position of the observer in order to correctly assign macroseismic intensity since ground motion frequencies and building resonance can influence any diagnostic effect, including earthquake perception. To give an application example, we cite the European Macroseismic Scale (Grünthal, 1998), which recommends neglecting observer reports above the fifth floor (interpreted as fifth above the ground floor by Brüstle et al., 2020). However, considering the vibration frequencies (Fig. 4), we observe that floors above the fifth/sixth floor do not deviate much from the range of values found, while the ground floor of buildings taller than eight stories exhibit the most unusual behavior. We found that the discriminant line for these cases has a high slope, and, although it cannot be associated with a frequency value within the limits shown in Figure 3, it indicates that observers on the ground floor of tall buildings are not likely to perceive high magnitude distant earthquakes. Therefore, for reliable estimation of intensities 2 to 5, it is more reasonable to exclude observations on the ground floor of tall buildings than those made on floors above the fifth.

Acknowledgments

We thank Diego Sorrentino for maintaining the HSIT site and database.

Open Research

Data from the database of the Hai Sentito Il Serremoto system (Tosi et al., 2007) were used in the creation of this manuscript. Data are available in an open-access repository (Sbarra et al., 2021).

References

Brüstle, W., Braumann, U., Hock, S., & Rodler, F. A. (2020), Best practice of macroseismic intensity assessment applied to the earthquake catalogue of southwestern Germany. In: *Historical Earthquakes, Paleoseismology, Neotectonics and Seismic Hazard: New Insights and Suggested Procedures*, 7-35. doi:10.23689/fidgeo-3864.

Cameletti, M., De Rubeis, V., Ferrari, C., Sbarra, P., & Tosi, P. (2017), An ordered probit model for seismic intensity data. *Stochastic Environmental Research and Risk Assessment, 31,* 1593-1602. doi: 10.1007/s00477-016-1260-4.

Cauzzi, C., & Faccioli, E. (2008), Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records, *Journal of Seismology,12,* 453–475. doi:10.1007/s10950-008-9098-y.

Gallipoli, M. R., Mucciarelli, M., Šket-Motnikar, B., Zupanćić, P., Gosar, A., Prevolnik, S., Herak, M., Stipčević, J., Herak, D., Milutinović, Z., & Olumćeva, T. (2010), Empirical estimates of dynamic parameters on a large set of European buildings, *Bulletin of Earthquake Engineering, 8,* 593–607. doi:10.1007/s10518-009-9133-6.

Gallipoli, M. R., Calamita, G., Tragni, N., Pisapia, D., Lupo, M., Mucciarelli, M., Stabile, T.A., Perrone, A., Amato, L., Izzi, F., La Scaleila, G., Maio,

D. & Salvia, V. (2020), Evaluation of soil-building resonance effect in the urban area of the city of Matera (Italy). *Engineering Geology, 272*, 105645. doi:10.1016/j.enggeo.2020.105645.

Gasperini, P., Lolli, B., & Vannucci, G. (2013), Empirical calibration of local magnitude data sets versus moment magnitude in Italy. *Bulletin of the Seismological Society of America, 103*, 2227-2246. doi:10.1785/0120120356

Grünthal, G., (Editor) (1998), European Macroseismic Scale 1998 (EMS-98), in *Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 15*, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 1–99.

Hong, L-L., & Hwang, W-L. (2000), Empirical formula for fundamental vibration periods of reinforced concrete buildings in Taiwan, *Earthquake Engineering and Structural Dynamics, 29,* 327–337. doi: 10.1002/(SICI)1096-9845(200003)29:3<327::AID-EQE907>3.0.CO;2-0.

Lesueur, C., Cara, M., Scotti, O., Schlupp, A., & Sira, C., (2013), Linking ground motion measurements and macroseismic observations in France: a case study based on accelerometric and macroseismic databases, *Journal of Seismology, 17*, 313–333. doi 10.1007/s10950-012-9319-2.

Mucciarelli, M., Masi, A., Gallipoli, M. R., Harabaglia, P., Vona, M., Ponzo, F., & Dolce, M. (2004), Analysis of RC building dynamic response and soil-building resonance based on data recorded during a damaging earthquake (Molise, Italy, 2002). *Bulletin of the Seismological Society of America, 94*(5), 1943-1953. doi: 10.1785/012003186.

Sbarra, P., Tosi, P., De Rubeis, V., & Rovelli, A. (2012), Influence of observation floor and building height on macroseismic intensity. *Seismological Research Letters, 83*(2), 261-266. doi: 10.1785/gssrl.83.2.261.

Sbarra, P., Tosi, P., & De Rubeis, V. (2014), How observer conditions impact earthquake perception. *Seismological Research Letters, 85*, 306-313. doi: 10.1785/0220130080.

Sbarra, P., Fodarella, A., Tosi, P., De Rubeis, V., & Rovelli, A. (2015), Difference in shaking intensity between short and tall buildings: known and new findings. *Bulletin of the Seismological Society of America, 105*, 1803-1809. doi: 10.1785/0120140341.

Sbarra, P., Tosi P., De Rubeis V., & Sorrentino, D. (2022), Hai Sentito Il Terremoto (HSIT)—Macroseismic questionnaire database 2007–2021, version 2, (in Italian). doi:10.13127/HSIT/Q.2.

Sbarra, P., Tosi, P., De Rubeis, V., & Sorrentino, D. (2020), Quantification of earthquake diagnostic effects to assess low macroseismic intensities. *Natural Hazards, 104*, 1957-1973. doi: 10.1007/s11069-020-04256-6.

Sbarra, P., Tosi, P., De Rubeis, V., & Sorrentino, D. (2021), Is an Earthquake Felt Inside a Car?. *Seismological Research Letters, 92*, 2028-2035. doi:

10.1785/0220200347.

Tosi, P., De Rubeis V., Sbarra P., & Sorrentino D. (2007), Hai Sentito Il Terremoto (HSIT), (in Italian). doi:10.13127/HSIT.

Tosi, P., Sbarra, P., De Rubeis, V., & Ferrari, C. (2015), Macroseismic intensity assessment method for web questionnaires. *Seismological Research Letters, 86*, 985-990. doi: 10.1785/0220140229.

Tosi, P., De Rubeis, V., & Sbarra, P. (2017), Frequency ranges and attenuation of macroseismic effects. *Geophysical Journal International, 210*, 1765-1771. doi: 10.1093/gji/ggx201.