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Difference in shaking intensity between short and tall buildings: known and new findings

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Abstract

We investigate the influence of building height on the ability of people to feel earthquakes and observe that, in an urban area, short and tall buildings reach different levels of excitation. We quantify this behavior by analyzing macroseismic reports collected from individuals through the Internet, focusing on transitory effects, therefore in the elastic regime during recent earthquakes in Italy in the local magnitude (M_L) range of 3 to 5.9. We find a maximum difference of 0.6 intensity units between the top floors of tall (7–10 stories) and short (1–2 stories) buildings at the highest considered magnitudes. As expected, tall buildings experience greater shaking than short buildings during large earthquakes at large source distances. However, we observe the opposite behavior at close distances when the M_L is less than 3.5. These results can be explained by considering the different spectra radiated by small and large earthquakes and the different fundamental mode resonances of buildings (i.e., shorter buildings have higher resonance frequencies and vice versa). Using idealized building models excited by real acceleration time histories, we compute synthetic accelerograms on the top floors of short and tall buildings, and confirm the trend of the observed differences in felt intensities.

Introduction

Intensity scales and macroseismic surveys are typically used to address large, highly damaging earthquakes. However, the recent diffusion of the Internet and the availability of huge amounts of data have allowed macroseismic analyses to be extended to the study of low intensities, corresponding to weak motions with no permanent effects. The study of transitory effects has enabled "floor" and "building" effects to be quantified, demonstrating that the intensity felt in buildings is affected by the height of the floor (Sbarra et al., 2012). Specifically, the maximum variation in intensity between the highest and lowest floors was determined to be a half degree of the Mercalli Cancani Sieberg (MCS) scale. This is below the expectation of Grünthal (1998) that prescribed "reducing the assigned intensity by one degree for every so many floors". Sbarra et al. (2012) also showed that, regardless of the floor where the observer is, the intensities felt in short (1- and 2-story) buildings at large distances from shallow and crustal earthquakes were significantly lower than the intensities felt in taller (three- to ten-story) buildings.

In this paper, we investigate the origin of the building effect and the role of earthquake magnitude in the shaking differences between short and tall buildings. Systematic variations in building excitation between short and tall buildings are expected, due to their different frequency of the fundamental vibration mode. Observations lead to confirm this behavior. For example, Boatwright and Phillips (2012) observed higher-than-expected intensities far from the earthquake source, in the city of San Francisco, during the magnitude (M) 4.5 earthquake in San Juan Bautista on 12 January 2011. They ascribed this behavior to the high concentration of tall buildings in San Francisco. Here, we investigate whether variations in the frequency content of generated ground motions as a function of the earthquake magnitude and distance lead to differences in the excitation of short and tall buildings. To address this question, we analyzed transitory effects, thus restricting our investigations to the linear regime of building response.

Data

Macroseismic data were obtained from Internet-based questionnaires compiled for earthquakes felt in Italy since June 2007. The "Hai sentito il terremoto" (in English, "Did you feel the quake") database relies on contributions from volunteers and registered compilers, who are alerted via e-mail when a potentially felt earthquake occurs. The questionnaire includes several questions needed to estimate the macroseismic intensity and collects useful information for characterizing where the effects were felt (e.g., the observation floor, the building structure and height, etc.). One question probed whether or not the earthquake was felt, thus providing a set of "not felt" data.

To focus on the role of building height, we selected questionnaires from observers located on the first and second floors of short (1- or 2-story) buildings and on the seventh to tenth floors of tall (7- to 10-story) buildings. Analysis was limited to the uppermost floors where the fundamental mode attains its maximum amplitude. In a previous paper, Sbarra et al. (2014) showed that the variable "situation" (at rest, in motion, or sleeping) has a greater influence on human perception of vibrations than the variable "location" (indoors or outdoors).

As a first step of analysis, we created three plots (Fig. 1) of the ratio between felt and not felt reports ("felt percentage") for different ranges of magnitude versus the hypocentral distance, considering only observers at rest. The felt percentage value was calculated when at least 10 questionnaires were available within an interval of ±10 km around every central distance value (10 km, 30 km, etc.). All of the values in Fig. 1 are overestimated because of the small percentage of people who reported not feeling the earthquake. This overestimation is a common problem with Internet-based macroseismic questionnaires (Boatwright and Phillips, 2012). However, because the sampling method was the same for tall and short buildings, the relative behavior is not expected to be impacted.

For low-magnitude earthquakes (M 2.5–3.4, Fig. 1a) at distances of up to 40 km, a greater percentage of observers in short buildings reported feeling the earthquakes, suggesting a greater shaking of short compared to taller buildings. For higher-magnitude earthquakes (M 3.5–4.4 and M 4.5–5.4; see Fig. 1b and 1c, respectively), tall buildings had higher felt percentages at all distances. The results reveal that the excitation of short or tall buildings depends on the magnitude of the earthquake. This finding is consistent with the expected variation of the frequency content of ground shaking, such that higher magnitudes are associated with a lower predominant frequency of seismic radiation.

To investigate this aspect further, we analyzed the macroseismic intensity felt by individual observers in short and tall buildings, as a function of earthquake magnitude. Following the method described by Sbarra et al. (2010) and refined by Tosi et al. (2015), we automatically assessed the MCS macroseismic intensity for each questionnaire and each municipality. As was done in the previous analysis (Fig. 1), we selected questionnaires from observers located on the top floors of short and tall buildings. We only used data from municipalities with more than 10 questionnaires and with an MCS intensity of III, which is the intensity at which we observed the greatest difference in behavior between short and tall buildings (see Fig. 4 in Sbarra et al., 2012). In this way, we considered the same range of macroseismic intensities at different magnitudes. Distances were small (on the order of 10 km) for the smallest events, but increased to more than 250 km for the largest-magnitude events in the dataset.

Analyzed questionnaires concerned 1029 earthquakes that occurred between January 2009 and December 2013, with local magnitude (M_L) values ranging from 3 to 5.9 (Fig. 2). To analyze intensities from different earthquakes and towns, and to eliminate the regional attenuation trend, we calculated the macroseismic intensity residuals for every questionnaire. Each residual was computed by subtracting the intensity assessed for the municipality from each questionnaire. We considered the average residuals for each building type (the uppermost floors of short and tall buildings) as a function of earthquake magnitude (Fig. 3). A bootstrap procedure was applied to each average, to calculate the error bars. The large number of data yielded estimates of small, but statistically significant, variations in intensity. At lower magnitudes ($M_L = 3$), the intensity residuals were higher for short buildings, whereas at higher magnitudes ($M_L > 4$), tall buildings had higher residuals (Fig. 3).

Interpretation of results

At an M_L of 3, the difference between short and tall buildings (~0.2 MCS), although small, is statistically significant relative to the error bars. At an M_L of 3.5, small and tall buildings have approximately the same response. At an M_L of more than 3.5, tall buildings have higher intensity residuals than short buildings. This difference increases with magnitude, from 0.1 MCS at an M_L of 4 to 0.6 MCS at an M_L of 5.9 (Fig. 3). The out-of-trend behavior of the data at an M_L of 5.5 is probably due to the small number of observations (only two events, see Fig. 2). The different behaviors of short and tall buildings shown in Fig. 3 confirm the results of felt percentage raw data (Fig. 1). Raw data have the advantage of being free of manipulation, depending on the method used to estimate intensity.

Our results thus show that, at low levels of shaking (MCS intensity of III), the excitation of short buildings is stronger at close source distances and low magnitudes, whereas the excitation of tall buildings is stronger at large source distances and high magnitudes. This observation is expected, given the variation of radiated source spectra for earthquakes of different sizes and the variation of the resonance frequency of fundamental building modes (Fig. 4). High-frequency spectral content predominates during small earthquakes, favoring the greater excitation of short buildings at low intensities. At higher magnitudes, low frequencies predominate and, thus, taller buildings are shaken more intensely. The spectra shown in Fig. 4 are the expected source-radiated accelerations of earthquakes in central Italy (at a reference distance of 10 km), scaled with magnitude according to Calderoni et al. (2013).

To confirm the above interpretation in terms of shaking parameters, we performed simple numerical simulations of building vibrations by considering two building models with different sizes (Fig. 5). The models mimic existing RC frame structures with brick masonry infill panels, which is the most common building typology in Italy. One model represents a low-rise building with one unit per floor (Fig. 5a and c), whereas the other represents a ten-story building with two units per floor (Fig. 5b and d). The grid is composed of 45 joints and 111 frames for the two-story model, and 1760 joints, 818 frames, and 1320 shells for the ten-story model. Mechanical characteristics of the model materials were chosen in the range indicated in the Italian seismic design code (OPCM 3431, 2005) and tuned to reproduce the resonant frequencies corresponding to literature values as a function of building height (Hong and Hwang, 2000; Navarro et al., 2007; Todorovska and Trifunac, 2008; Gallipoli et al., 2010). These papers suggest that the fundamental resonance period is about 0.1 s for 6-m buildings and 0.5 s for 30-m buildings. Elastic parameters were as follows: for concrete, 25 kN/m^3 for the unit volume weight, 28,500 N/mm^2 for the elastic modulus, and 11,875 N/mm^2 for the shear modulus; and for the masonry infill panels, 11 kN/m^3 for the unit volume weight, 2800 N/mm^2 for the elastic modulus, and 1120 N/mm^2 for the shear modulus.

Three-dimensional building models were excited by free-field accelerograms extracted from the Italian Accelerometric Archive (ITACA; see Luzi et al., 2008; Pacor et al., 2011). For modeling, we used the finite element code SAP2000® (see Data and resources section) with linear time history analysis, setting the damping value to 5%. Selected accelerograms included recordings of 12 small-magnitude ($3.0 \le M_L \le 3.2$) earthquakes at short epicentral distances ($10 < D < 17$ km) and 12 moderate-magnitude ($4.8 \le M_L \le 5.2$) earthquakes at large epicentral distances ($84 < D < 127$ km) (Table 1). Both groups corresponded to an MCS intensity of III, according to the attenuation regression

$$\text{Intensity} = -\,2.15 \log R + 1.03\, M_L + 2.31 \qquad (1)$$

where R is the hypocentral distance. Intensity was estimated through the best fit of web-based MCS intensity data in Italy (Tosi et al., 2015). We considered accelerograms from stations located on the most common soils of classes B and C (EC8 site classification), as shown in Table 1.

We applied the largest component of each set of horizontal accelerograms orthogonally to the largest building side (x-axis in Fig. 5a and b) and analyzed synthetic accelerograms corresponding to a receiver in the middle of the top floor. The fundamental resonance periods resulted in 0.10 and 0.57 s for small and tall building models, respectively, in satisfactory agreement with observations by Hong and Hwang (2000) and Gallipoli et al. (2010).

Amplification of shaking on the top floor was quantified in terms of the horizontal peak acceleration and Arias intensity (Arias, 1970)

$$Arias = \frac{\pi}{2g}\int_{t_1}^{t_2} a(t)^2\, dt \qquad (2)$$

where *a(t)* is the acceleration time series, *g* is gravity acceleration, and t_1 and t_2 are the initial and final times of shaking. Figure 5 shows the accelerogram and the corresponding Husid plot (Husid, 1969) for two example earthquakes, one of small magnitude recorded at a short distance (Fig. 5e–j) and one of moderate magnitude recorded at a longer distance (Fig. 5k–p). Figure 6 reports the geometric means and standard deviations computed over the earthquakes in Table 1. The results are in agreement with macroseismic trends. Short buildings are characterized by higher horizontal peak acceleration and Arias intensity values for small magnitudes at short distances for both types of soil (Fig. 6a and c). For higher magnitudes and longer distances, the peak horizontal acceleration and Arias intensity values of tall buildings exceed those of short buildings (Fig. 6b and d).

To estimate the variation in intensity corresponding to the shaking variation found with numerical models (Fig. 6), we applied Equation (3), which was derived by Faenza and Michelini (2010) to correlate the local MCS intensity with the recorded peak ground acceleration (PGA, in cm/s^2):

$$\text{Intensity} = 1.68 + 2.58 \log \text{PGA} \qquad (3)$$

This equation is intended for free-field acceleration, but it can provide the intensity felt inside a building when the horizontal peak acceleration on the floor of interest is used instead of PGA. This assumption is justified because, for the simulations considered here, the frequency range of the building excitation is the same as the frequency range of human body perception (see Trifunac and Brady, 1975, and references therein).

Averaging the results of all simulations in the case of low magnitudes and short distances, the mean increment of MCS intensity between top and basement is 1.3 MCS for the short buildings, and 0.6 MCS for tall buildings. In the case of moderate magnitudes and large distances, the increment is 1.5 MCS for tall buildings and 0.7 MCS for short buildings. Differences in shaking in terms of simulated intensity are consistent with the experimental macroseismic residuals (Fig. 3). However, the simulations give higher values because they consider only the building vibrations of the uppermost floors, whereas the observations pertain to the first and second floors of short buildings and the seventh to tenth floors of tall buildings.

Conclusions

Because of the availability of large volumes of data for low macroseismic intensities, we are now able to recognize variations in intensity between short and tall buildings. We found that short buildings experience greater shaking than taller buildings during low-magnitude ($M_L < 3.5$) earthquakes at close source distances, whereas the opposite behavior is found for higher-magnitude earthquakes at larger distances from the source. Although the observed macroseismic variations were small (<0.6 MCS), they are well separated and confirmed by the numerical modeling results.

Our results indicate that building height, a parameter never mentioned in macroseismic scales, influences intensity due to the combination of earthquake-radiated spectra and the fundamental resonance mode of buildings. Macroseismic scales account for the floor influence alone, stating that macroseismic effects are greater at upper floors. However, we found that for low-magnitude earthquakes, observers on the second floor of a two-story building feel greater shaking than observers on the tenth floor of a ten-story building. The descriptions of low intensities described in macroseismic scales are usually based on data from the far field of moderate to large earthquakes. Results of this work, based on online macroseismic surveys of low- and medium-magnitude earthquakes, suggest that the building height effect should be considered in the assessment of low intensity degrees.

Data and resources

Macroseismic data used in this paper were collected through the Istituto Nazionale di Geofisica e Vulcanologia (INGV) online questionnaire available at http://www.haisentitoilterremoto.it (last accessed November, 2014). Data assigned to municipalities can be visualized and downloaded through the same site.

Free-field accelerograms were extracted from ITACA available at http://itaca.mi.ingv.it (last accessed June, 2014). Accelerograms were processed and parameter computations performed with the Seismic Analysis Code (SAC 2000, https://seiscode.iris.washington.edu/projects/sac, last accessed November, 2014; Goldstein et al. 2003,).

Building vibrations were simulated numerically by using the SAP2000® software (http://www.csiamerica.com/products/sap2000, last accessed November, 2014). Figure 2 was made with Generic Mapping Tools version 5.1.0 (http://gmt.soest.hawaii.edu, last accessed November, 2014; Wessel et al., 2013).

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References

Arias, A. (1970). A measure of earthquake intensity, in *Seismic Design for Nuclear Power Plants* Hansen R. J. (Editor), MIT Press, Cambridge, Massachusetts, 438-483.

Boatwright J., and E. Phillips (2012). Exploiting the Demographics of "Did You Feel It?" Responses to Estimate the Felt Area of Moderate Earthquakes, 84th Annual Meeting of the Eastern Section of the Seismological Society of America, October 28-30, 2012.

Calderoni, G, A. Rovelli, and S.K. Singh (2013). Stress drop and source scaling of the 2009 April L'Aquila earthquakes, *Geophys. J. Int.* **192** 260–274, doi: 10.1093/gji/ggs011.

Faenza, L., and A. Michelini (2010). Regression analysis of MCS intensity and ground motion parameters in Italy and its application in ShakeMap, *Geophys. J. Int*. **180** 1138-1152.

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

Goldstein, P., D. Dodge, M. Firpo, Lee Minner (2003). "SAC2000: Signal processing and analysis tools for seismologists and engineers, Invited contribution to "The IASPEI International Handbook of Earthquake and Engineering Seismology", Edited by WHK Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger, Academic Press, London.

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

Hong, L-L., and W-L. Hwang (2000). Empirical formula for fundamental vibration periods of reinforced concrete buildings in Taiwan, *Earthq. Eng. Struct. Dyn.* **29** 327–337.

Husid, L. R. (1969). Caracteristicas de Terremotos. *Analisis General, Revista del IDIEM (Chile)* **8** 21-42.

Luzi, L., S. Hailemikael, D. Bindi D, F. Pacor, F. Mele, and F. Sabetta (2008). ITACA (Italian ACcelerometric Archive): A Web Portal for the Dissemination of Italian Strong-motion Data, *Seismol. Res. Lett*. **79** 716–722, doi: 10.1785/gssrl.79.5.716.

Navarro, M., F. Vidal, T. Enomoto, F. J. Alcalá, A. García-Jerez, F. J. Sánchez, and N. Abeki (2007). Analysis of the weightiness of site effects on reinforced concrete (RC) building seismic behaviour: The Adra town example (SE Spain), *Earthq. Eng. Struct. Dyn.* **36** 1363–1383.

OPCM 3431, 03/05/2005, Ordinance of the Prime Minister: further changes and upgrade to the OPCM 3274/2003: *Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica*.

Pacor, F., R. Paolucci, L. Luzi, F. Sabetta, A. Spinelli, A. Gorini, M. Nicoletti, S. Marcucci, L. Filippi, and M. Dolce (2011). Overview of the Italian strong motion database ITACA 1.0, *Bull. Earthq. Eng.* **9** 1723–1739, doi: 10.1007/s10518-011-9327-6.

Sbarra, P., P. Tosi, and V. De Rubeis (2010). Web-based macroseismic survey in Italy: Method validation and results, *Nat. Haz.* **54** 563-581, doi:10.1007/s11069-009-9488-7.

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

Sbarra, P., P. Tosi, and V. De Rubeis (2014). How observer conditions impact earthquake perception, *Seismol. Res. Lett.* **85** 306-313, doi: 10.1785/0220130080.

M.I. Todorovska and M.D. Trifunac (2008). Impulse response analysis of the Van Nuys 7-storey hotel during 11 earthquakes and earthquake damage detection, *Struct Control Health Monit*, 15, pp. 90–116.

Tosi, P., P. Sbarra, V. De Rubeis and C. Ferrari (2015). Macroseismic intensity assessment method for web-questionnaires, *Seismol. Res. Lett*. **86** in print, doi:10.1785/0220140229.

Trifunac, M.D. and A.G. Brady (1975). On the correlation of seismic intensity scales with the peaks of recorded strong ground motion, *Bull. Seism. Soc. Am.* **65** 139-162.

Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe (2013), Generic Mapping Tools: Improved version released, EOS Trans. AGU, **94** 409-410.

Table 1

Accelerometric stations.

Station	Event date YYYY MM DD	Depth (km)	Site class EC8	Epicentral distance (km)	M_L
AMT	2004 10 10	14	B	13	3.0
AQM	2004 10 10	14	B	16	3.0
CSN	2006 05 13	1	B	16	3.0
SGV	2007 06 09	4	B	12	3.0
RM07	2009 04 08	10	B	11	3.1
RM09	2009 05 23	9	B	13	3.2
BCN	2007 02 17	11	C	11	3.1
CRI	2010 10 24	13	C	13	3.1
CTL	2009 11 05	8	C	13	3.0
FRE1	2008 03 01	9	C	12	3.1
NOR	2005 11 15	14	C	11	3.1
SPS	2004 11 06	5	C	12	3.0
BRB	2012 01 25	29	B	116	5.0
MDG	2012 06 03	9	B	106	5.1
PIT	2012 01 25	29	B	104	5.0
BRR	2012 05 20	5	B	116	5.0
CNCS	2008 12 23	24	B	120	4.8
SULP	2013 12 29	11	B	90	4.9
FIVI	2012 05 20	5	C	127	5.1
VOLT	2008 12 23	24	C	91	4.8
ALF	2012 05 20	10	C	84	4.9
FAEN	2012 01 25	29	C	126	5.0
SNZ1	2012 05 20	2	C	116	4.8
VOBA	2008 12 23	23	C	123	5.2

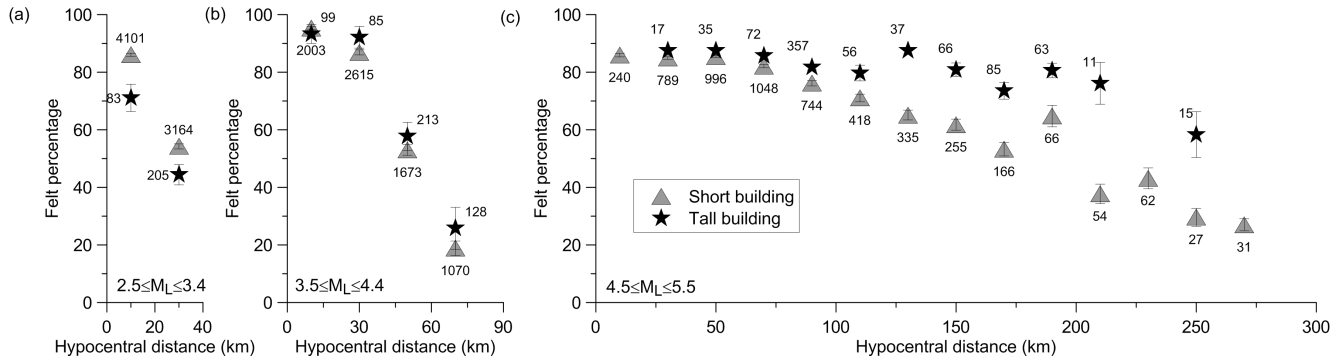

Figure 1. Felt percentage (ratio between "felt" and "not felt" reports) of observers at rest located in the uppermost floors of short (1- to 2-story) and tall (7- to 10-story) buildings for the specified magnitude ranges. Symbol labels indicate the number of questionnaires used to calculate each felt percentage.

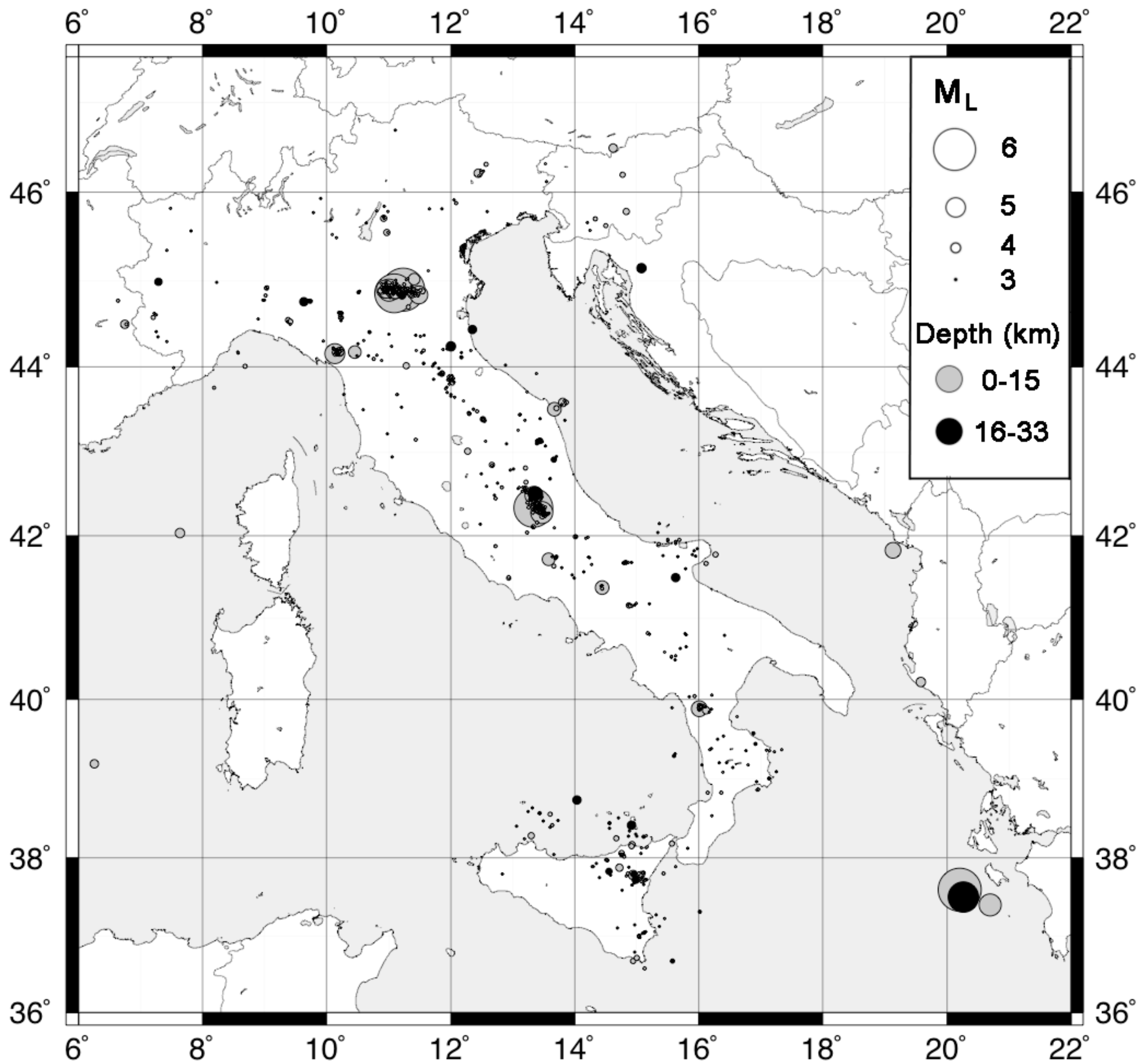

Figure 2. Map showing the location of earthquakes used for the intensity residual estimation.

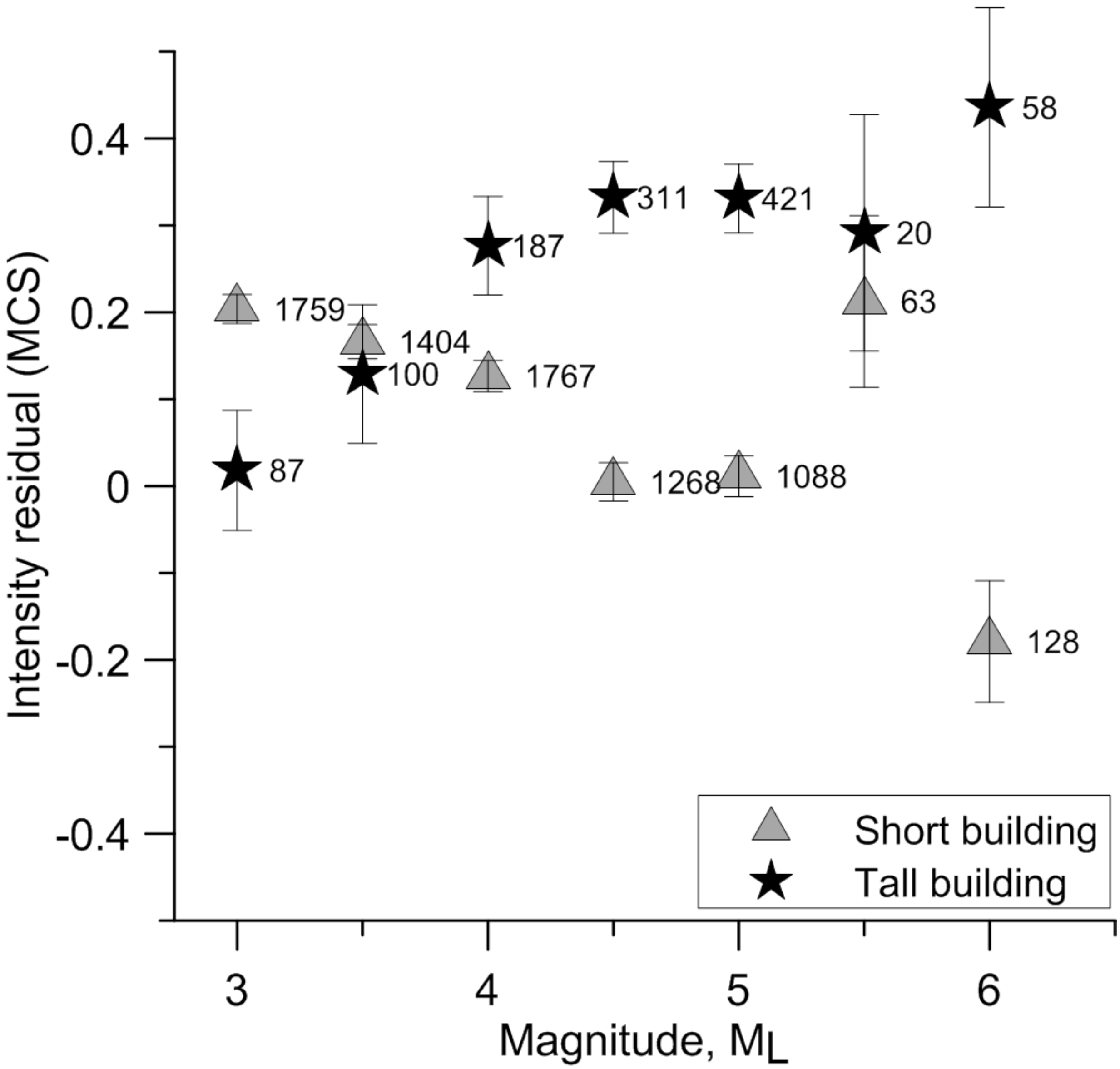

Figure 3. Average of intensity residuals versus magnitude for observers located in the uppermost floors of short (1- and 2-story) and tall (7- to 10-story) buildings. Symbol labels indicate the number of questionnaires used to calculate each intensity residual average.

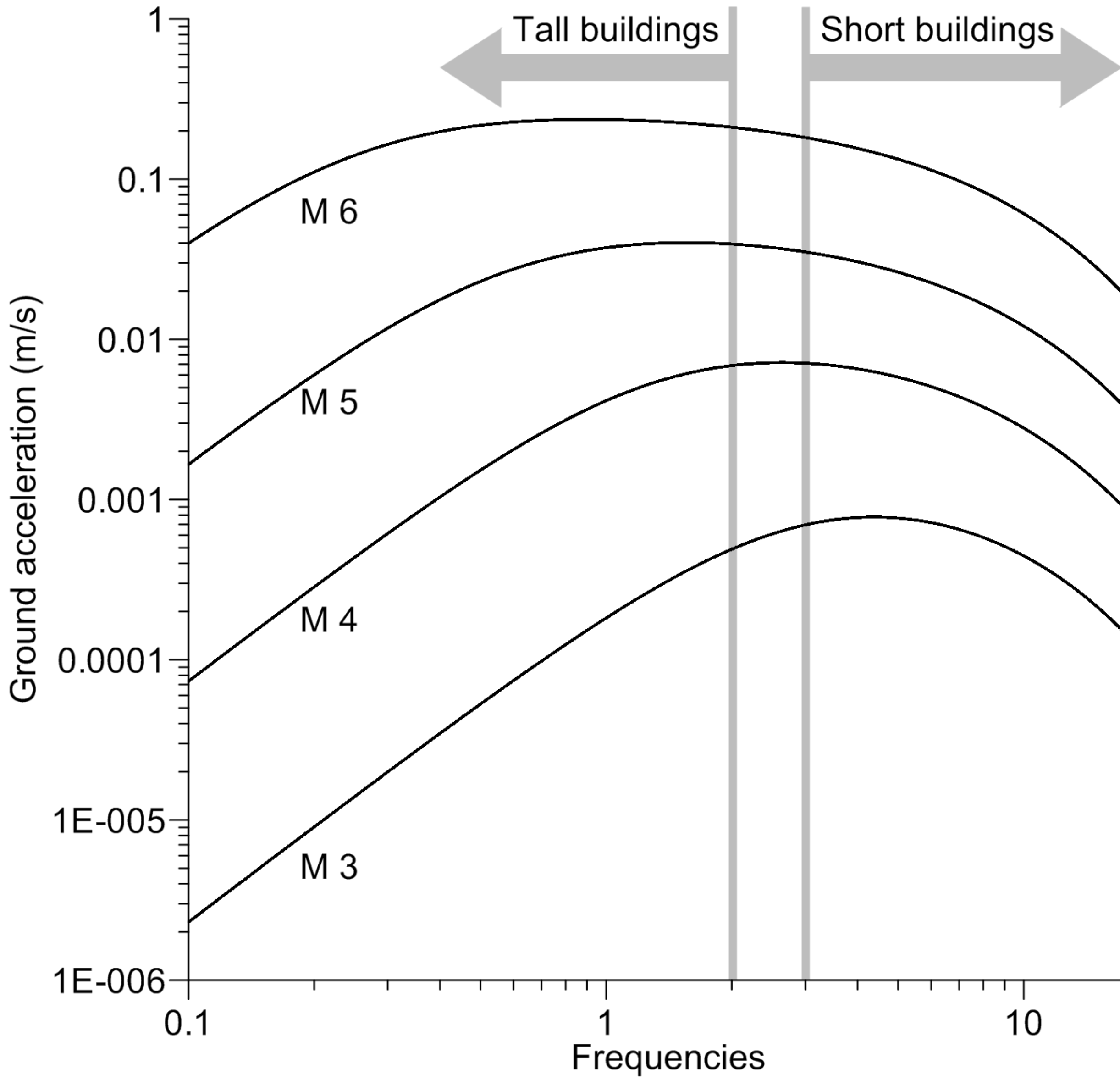

Figure 4. Idealized scheme of source-radiated accelerations versus magnitude (according to Calderoni et al., 2013) and separation of fundamental frequencies between tall and short buildings.

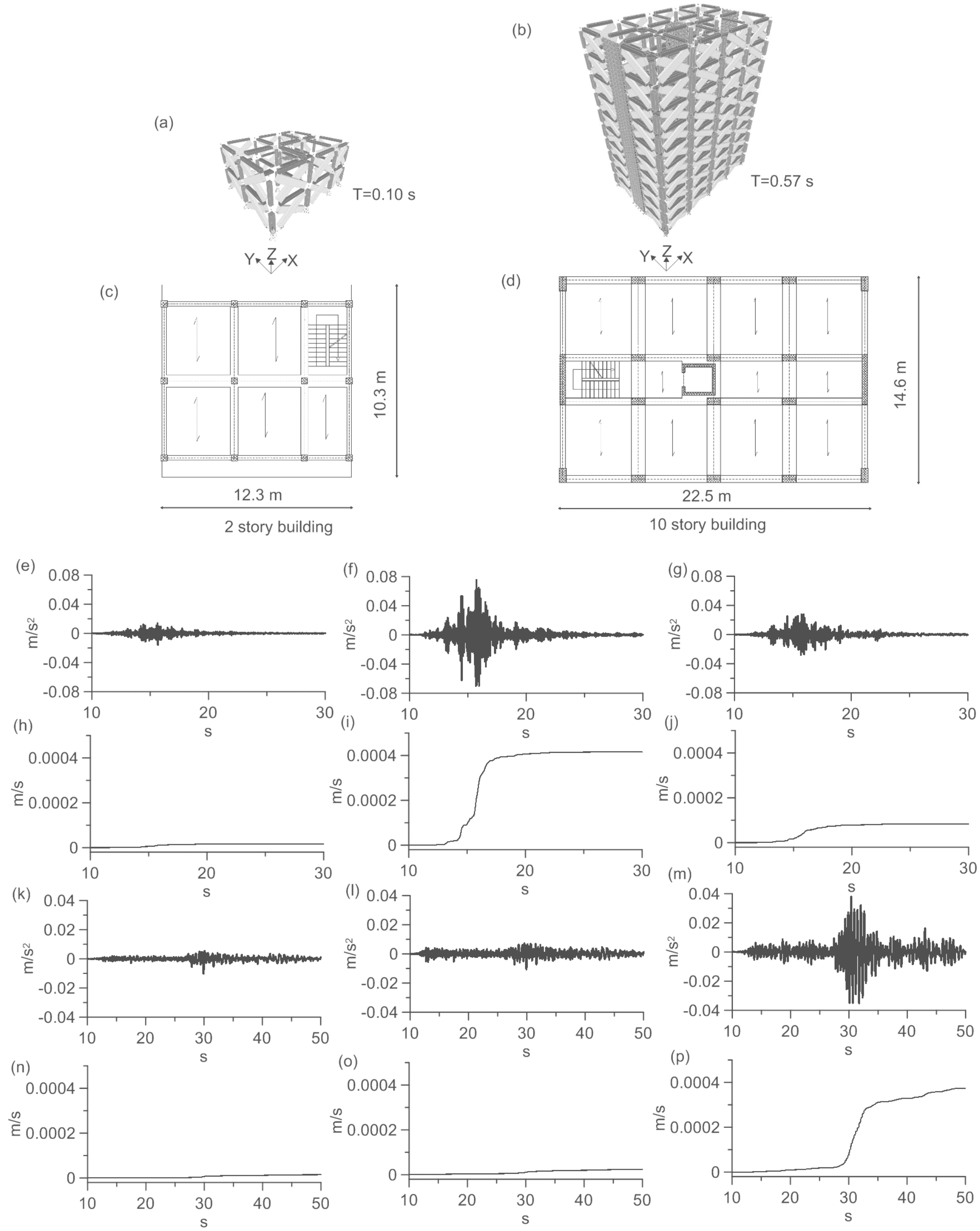

Figure 5. Three-dimensional models of (a) two-story and (b) ten-story buildings, with (c) and (d) showing these buildings in the geometry plane view. Acceleration time series of station AQM (Table 1) for a short-distance, small-magnitude earthquake (e) in free field, (f) on the uppermost floor of the two-story model, and (g) on the uppermost floor of the ten-story model. Similarly, (h), (i), and (j) show the Arias intensities of the same stations. Panels from (k) to (p) repeat the scheme of (e) to (j) for the acceleration time series of station BRB during a higher-magnitude, longer-distance earthquake (Table

1).

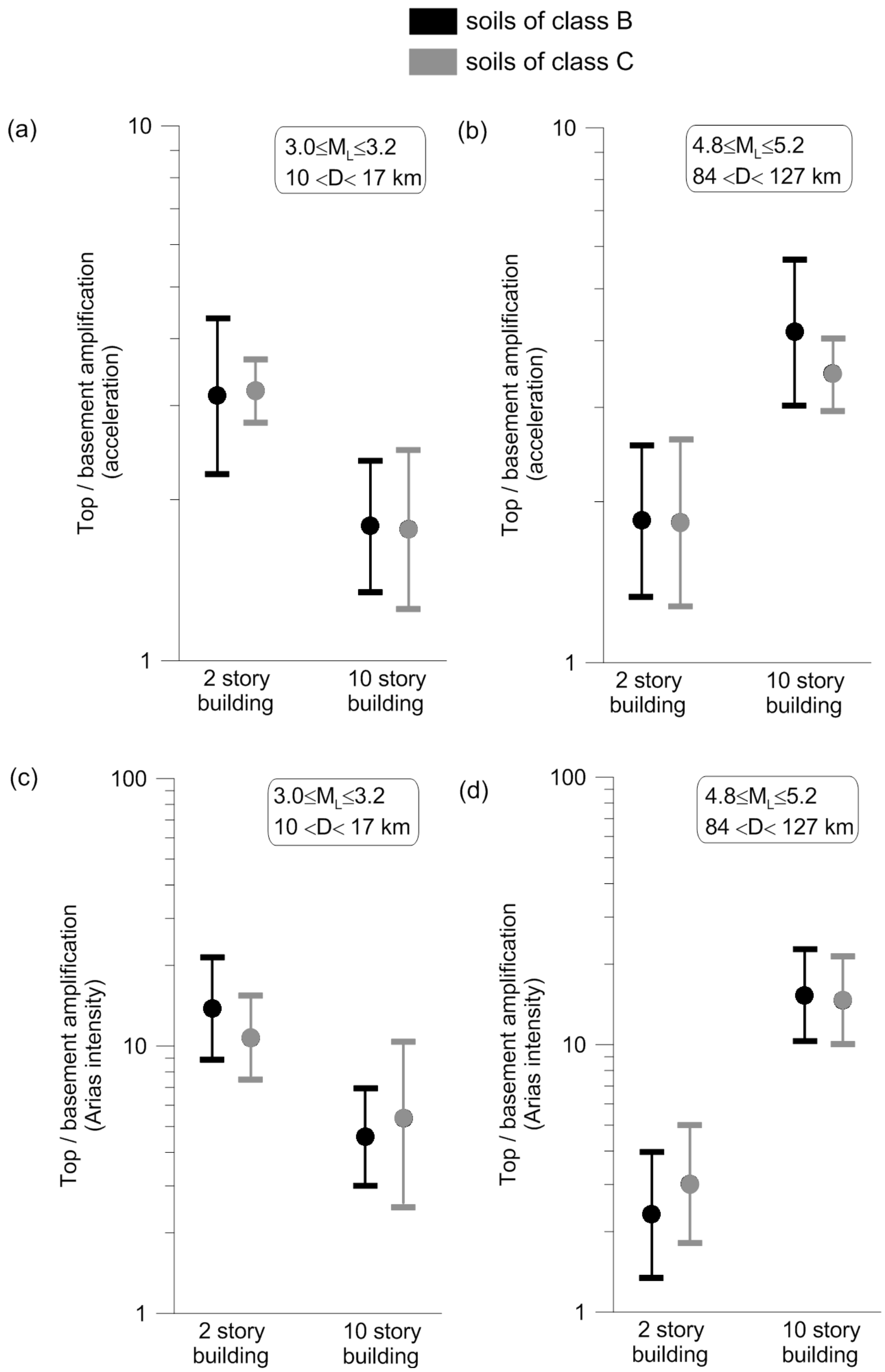

Figure 6. Amplification of the uppermost floor (mean ± 1 standard deviation of the top/basement ratio) in terms of (a and b) horizontal peak acceleration and (c and d) Arias intensity, where (a) and (b) are relative to short-distance, small-magnitude earthquakes and (c) and (d) to longer-distance, higher-magnitude earthquakes. Soil classes B and C are defined according to the EC8 site classification.