Influence of observation floor and building height on macroseismic intensity

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Introduction

The perception of an earthquake depends on whether the observer is located on a lower or upper floor within a building. It is well known that perception of transitory effects is quite dependent on the observer's location. Inside a building, *ceteris paribus*, there are some specific factors that increase the perception of macroseismic effects. Macroseismic scales propose only a qualitative approximate description of the varying effects felt, as they refer only to the lower or upper floor where the observation is made. For example, the Mercalli-Cancani-Sieberg (MCS) (Sieberg, 1930) and the Modified Mercalli Intensity (MMI) scales (Wood and Neumann, 1931) describe the second degree as "Felt only by a few people, extremely susceptible, in perfectly quiet situations, almost always on the upper floors of buildings." The European Macroseismic Scale (EMS) (Grünthal, 1998) describes the seventh degree as "Many find it difficult to stand, especially on upper floors." Moreover, the recommended practice is "To discount all reports from observers higher than the fifth floor when assigning intensity" (Grünthal, 1998). These descriptions highlight the influence of upper floors that are expected to enhance the effects of an earthquake compared with the lower floors and consequently recommends the exclusion of data coming from upper floors. Another effect reported in literature is the different behavior of buildings depending on the structure height in relation to the frequency content of the seismic wave (Drimmel 1984, Kanai 1957, Celebi 2000, Balendra et al. 2002). To analyze the role of observation floor and building height on earthquake perception and to quantify these effects, we analyzed over 36000 macroseismic questionnaires, collected in Italy, reporting transitory effects. Unlike research by other authors dealing with skyscraper structures, in which effects are more pronounced (Brownjohn et al., 2001), our investigation focuses on buildings that are no higher than ten stories.

Questionnaire data and macroseismic intensity assessment

This analysis has been conducted using the questionnaires collected in the database of the web-based macroseismic questionnaire managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), and available at www.haisentitoilterremoto.it ("hai-sentito-il-terremoto?" means "did you feel the quake?"). The analyzed questionnaires pertain to 284 earthquakes located in the Italian territory from December 2008 to November 2010, occurred at a depth of less than 50 km (Figure 1). Most of the events (277) had a local magnitude M_L between 3 and 5, and a few (7) had a magnitude greater than or equal to 5, including the L'Aquila mainshock ($M_L=5.8$, 6 April, 2009). Through an automated procedure, described in Sbarra et al. (2009), the effects reported on the questionnaires were statistically analyzed to extrapolate a probabilistic estimate of MCS intensity for that observer. Assigning the intensity to a single questionnaire, we assume that the compiler belongs to the category of "many" of the MCS scale, the wider and thus the most probable category of people. The intensity is assessed using additive scores that are associated with each answer. A answer concerning an observed effect adds scores to pertinent intensity degrees; the observation of one effect typically refers to one or few degrees. Every answer has a total score equal to 100 and if an effect is present in more than one macroseismic degree, the score is equally divided among all considered intensities. An answer pointing to a lack of a specific effect adds scores to degrees that exclude that effect; unanswered effects, on the other hand, do not produce scores. Scores pertaining to each answer are then added, resulting in a total score for each degree. The maximum value of the distribution should point to the most probable intensity, but there can be more than one macroseismic degree with similar high scores. The intensity degree assigned to each questionnaire is thus calculated through a weighted average of the degrees with a score higher than 75% of the maximum score for that questionnaire. Finally an automated procedure controls the reliability of the questionnaires through a comparison with a regional attenuation law (Gasperini, 2001), therefore excluding those exceeding 2.5 MCS degrees over the intensity calculated from the epicentral distance and magnitude of each earthquake.

In order to discriminate different floors of the same building we discard damage cases, thus analyzing only questionnaires reporting low MCS intensities (less than or equal to VII with the majority being III and IV, Fig. S1 available in the electronic supplement to this article) based on transient effects. The discarded questionnaires of greater intensity constituted only a small fraction of the database, and almost all of them came from the 6 April, 2009 L'Aquila earthquake.

Our sample contains data coming from both near and far fields, as our web-based macroseismic survey permits us to have many questionnaires that refer to low intensities. The epicentral distances covered with a sufficient data number reach 200 km (Fig. S2 available in the electronic supplement to this article).

The distribution of building heights show that about 90% of the data pertains to buildings of less than five stories (Table 1), while the category of buildings of 10 or more stories has been disregarded, due to the scarcity of data. More than 50% of the data come from observers on the first or second floors. It is important to note that in Italy reinforced concrete is the most common building material.

Observer location: method

Firstly we examine the influence of observer floor position to detect possible variations related to earthquake magnitude, depth and hypocentral distance.

In order to analyze intensities coming from different earthquakes and towns a stacking procedure was necessary. We thus calculated the macroseismic intensity residual for every questionnaire. Each residual was computed by subtracting the intensity assessed for its municipality from each questionnaire. The municipality intensity was calculated by averaging the questionnaire intensities coming from that municipality. To evidence the floor effect for this average we selected only questionnaires that referred to the lowest floors (from basements to second floors), as these are the references used by Mercalli in his definition of the macroseismic scale. This procedure has been done separately for each earthquake to eliminate the regional attenuation trend.

Data coming from municipalities with less than 3 questionnaires were excluded in order to avoid poor assessment of the average intensity assigned to those towns. We also excluded data coming from municipalities having average MCS intensities of less than II-III, corresponding to those that were reportedly not felt. Other questionnaires that were excluded from the analysis were those that pertained to effects felt in the city of Rome that were caused by earthquakes belonging to the L'Aquila earthquake sequence. This decision was motivated by several factors. Defining a meaningful stable intensity for the whole city is problematic due to the size of the urban area. In fact, intensity data coming from several locations in the same city presented differences, due not only to local factors but also different epicentral distances, which should be accounted for by a proper attenuation law (Sbarra et al., 2011). Moreover, more than 7,000 questionnaires were received from the Rome municipality; this abundance could bias the results, giving too much weight to the bin corresponding to the distance from the epicenters of the L'Aquila sequence to the center of Rome, with respect to all other represented distances. Having applied all these procedures, we selected 36533 questionnaires from the original whole database of over 180,000 reports pertaining to approximately 3000 earthquakes.

Observer location: results

In Figure 2, we show the results obtained by averaging intensity residuals for distance bins as a function of hypocentral distance. Each plotted bin, resulting from a 20 km wide moving window shifting of 10 km, contains at least 30 questionnaires and an average of 850. Higher floors (from 5 to 10 stories) are grouped to have a sufficient number of cases in each distance bin. The most remarkable result from Figure 2 is that the residuals increase directly with the observation floor. Therefore, as stated in the macroseismic scales, the effects felt inside the lower floors of a building are of a lower intensity than those felt inside higher floors.

The residuals show a negligible variation with hypocentral distance for the lower floors, whereas for the higher floors residuals show a scattered variation. To statistically determine the significance of these differences among the residual averages of each floor, a Student's t-test was applied using average and standard deviation for every distance bin (Tables S1-S4 available in the electronic supplement to this article). The results indicate that floors from -1 to 4 have a statistically different behavior up to 110 km from the hypocenter with a probability less than 5% (Figure S3 available in the electronic supplement to this article). For longer distances the t-test result is not significant because the number of data in each bin is small. In order to have better statistics and to consider the small variation of residuals with distance, we averaged residuals inside a single distance bin (0-200 km), searching for eventual variations with earthquake magnitude and source depth (Table 2). In Figure 3 results show that first and second floors have a residual near 0, in a general increase of macroseismic intensity residuals with observation floors. It is worth noting the negative values associated with the ground and underground floors. For observation floors lower than 5, earthquake magnitude and depth have a little influence on residuals, while for 5th to 10th floors residuals are in proportion to magnitude and in inverse relation to depth. To give a general intensity correction for the observation floor, we calculated the residual average without regard to magnitude and depth (values marked with * in Table 2, square symbols in Figure 3).

Building height: method

In order to evaluate if the building height has an influence on the local felt intensity, we corrected the macroseismic intensity value associated to each questionnaire by subtracting the average residual corresponding to the specific floor of the observer (values marked with * in Table 2). In this way it was possible to highlight, through a new analysis of the data, any variation due to the heights of the multi-story buildings The average intensities assigned to every municipality, calculated with the macroseismic intensities of all observation floors, have been recalculated. We then calculated the new residuals for all questionnaires where building height was reported to study the possible effects of this characteristic. The residuals, averaged within distance ranges, inside a moving window 20 km wide and shifting 10 km, are shown in Figures 4 and 5.

Building height: results

From Figure 4 it is evident that structure height does not influence macroseismic intensity for 3 to 10 storey buildings, whereas shorter buildings show a distance-dependent attenuation, noticeable for distances longer that 90 km (Tables S5-S7, Fig. S4 available in the electronic supplement to this article) and earthquake depth in the range 0-25 km. However this behavior is absent for deeper earthquakes (29 events, 25-50 km, Figure 5 Tables S8, S9, Fig. S4 available in the electronic supplement to this article). Probably this behavior is influenced by the few analyzed deep events. In particular felt responses for distance longer than 100 km come from Parma earthquake (23 December 2008, Ml 5.1 depth 26.7 km). The macroseismic field for this event is located in the Po Plain region which is characterized by an anomalous attenuation, due to the Moho reflection, maximized at hypocentral distances between 90 and 150 km (Bragato et al. 2011). Tall buildings were not included in this analysis, as the number of samples was not adequate. The t-test was applied, as before, in order to assess the statistical significance of the estimated differences. The test confirmed that, for shallow earthquakes (Figs. 4, S4, TabsS5-S7 available in the electronic supplement to this article), medium and tall buildings behave equally for the entire distance range, while short buildings exhibited statistically significant differences (at 5% of confidence level) beyond 80 km. For longer distances, the residual associated with shorter buildings was -0.3, comparable in absolute value to the residual of higher observation floors, as shown in Figure 2.

Discussion and conclusion

From the results of our analysis, we have observed that the amplification of macroseismic effects is proportional to the height of the observation floor, while ground level and underground floor slightly attenuate those effects. The maximum variation range between the highest and lowest floors is half MCS intensity degree (Figure 3). This value is well below the correction of "reducing the assigned intensity by one degree for every so many floors" (Grünthal, 1998), that did not find general favor in the macroseismic community. The intensity residual reaches 0.4 for floors higher than 6 and earthquake magnitude between 5 and 6, while for low magnitudes (3 – 4) it is 0.1 (Table 2). Moreover for high floors amplification varies proportionally with magnitude. This behavior could be due to the lower frequency content of earthquakes of higher magnitude causing an increase in shaking of higher floors. In conclusion we have provided the quantification of the macroseismic intensity correction to apply on different observation floors depending on earthquake magnitude and depth (Table 2).

Our results indicate that even the building height has an influence on intensity, although this parameter is never mentioned on macroseismic scales. The shorter buildings (1 or 2 stories) record a progressive lowering of intensity versus distance with respect to the others (Figure 4). The increased intensity attenuation for short buildings (reaching -0.3 MCS at a hypocentral distance of 200 km) is probably related to the high-frequency content of ground-shaking and its amplitude decreasing with distance. We are aware that reducing the building responses based solely on the number of stories and not considering building material, due to the lack of this information in our data, could be an oversimplification. However, the predominance of reinforced concrete buildings in Italy would likely moderate the influence of this limitation.

The presented results on the quantification of floor effects have been possible thanks to the availability of a vast quantity of data. Moreover, for the first time, the building effect has been evidenced using transitory effects rather than damages reports.

The quantification of the floor and building effects derive from averaged values among different conditions, but in particular cases the site effect might cause bigger or lower amplification.

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Figure Captions

Figure 1. Map of earthquakes considered in this study. The bigger circle corresponds to the M_L=5.8 earthquake occurred in 2009 near L'Aquila, it overlays many smaller circles pertaining to the same seismic sequence.

Figure 2. Observation floor effect: averages of questionnaire MCS intensity residuals from the municipality mean intensity plotted as a function of hypocentral distance. Each curve is computed for a floor range as displayed in the legend.

Figure 3. Plot of observation floor MCS intensity residual averaged for all hypocentral distances less than 200 km.

Figure 4. Building height effect: averages of questionnaire MCS intensity residuals from the municipality mean intensity plotted as a function of hypocentral distance for shallow earthquakes (depth 0-25 km). Each curve is computed for a building height range as displayed in the legend.

Figure 5. Building height effect: averages of questionnaire MCS intensity residuals from the municipality mean intensity plotted as a function of hypocentral distance for deep earthquakes (depth 25-50 km). Each curve is computed for a building height range as displayed in the legend.

Observation floor

Building height	**-1-0**	**1-2**	**3-4**	**5-6**	**6-10**	
> 10	29	101	108	49	128	**415**
6-10	148	786	1007	1305	468	**3714**
3-5	1643	9121	7208	748	-	**18720**
1-2	3618	10481	-	-	-	**14099**
	5438	**20489**	**8323**	**2102**	**596**	**TOT**

Table 1

Number of questionnaires for bins regarding building height and observation floor

Observation floor	M_L	Depth	MCS intensity residuals	Standard deviation	N° of questionnaires
-1 to 0	3-6	0-50	-0.10 *	0.79	5409
1 to 2	3-6	0-50	0.05 *	0.76	20388
3 to 4	3-6	0-50	0.13 *	0.81	8215
5 to 6	3-6	0-50	0.17 *	0.79	2053
7 to 10	3-6	0-50	0.29 *	0.78	468
-1 to 0	3-4	0-50	-0.10	0.72	1817
1 to 2	3-4	0-50	0.07	0.70	6815
3 to 4	3-4	0-50	0.09	0.76	2443
5 to 6	3-4	0-50	0.11	0.72	660
7 to 10	3-4	0-50	0.12	0.65	129
-1 to 0	4-5	0-50	-0.11	0.82	2550
1 to 2	4-5	0-50	0.05	0.77	8766
3 to 4	4-5	0-50	0.14	0.82	3740
5 to 6	4-5	0-50	0.19	0.77	922
7 to 10	4-5	0-50	0.30	0.77	221
-1 to 0	5-6	0-50	-0.08	0.82	1042
1 to 2	5-6	0-50	0.01	0.82	4807
3 to 4	5-6	0-50	0.16	0.87	2032
5 to 6	5-6	0-50	0.22	0.89	471
7 to 10	5-6	0-50	0.44	0.896	118
-1 to 0	3-6	0-25	-0.01	0.75	5632
1 to 2	3-6	0-25	0.05	0.74	19691
3 to 4	3-6	0-25	0.11	0.79	7533
5 to 6	3-6	0-25	0.17	0.79	1757
7 to 10	3-6	0-25	0.31	0.81	327
-1 to 0	3-6	25-50	-0.09	0.82	1010
1 to 2	3-6	25-50	0.05	0.77	4209
3 to 4	3-6	25-50	0.13	0.83	1869
5 to 6	3-6	25-50	0.12	0.76	526
7 to 10	3-6	25-50	0.18	0.71	166

Table 2

Residuals for observation floor averaged for distances 0-200 km. See Figure 4.

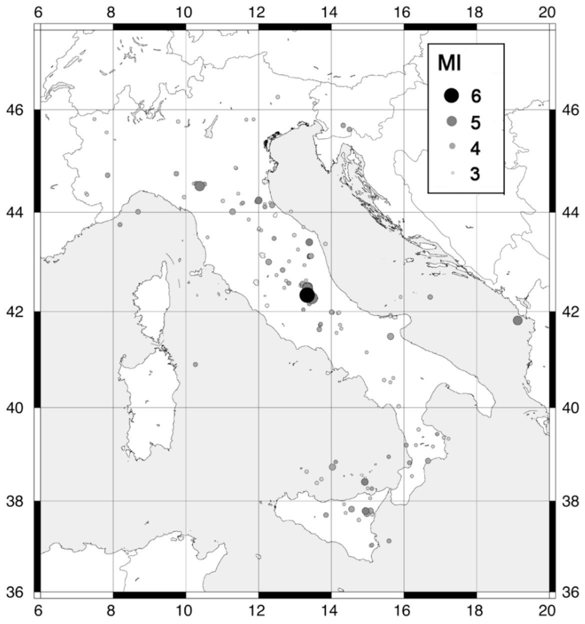

Figure 1

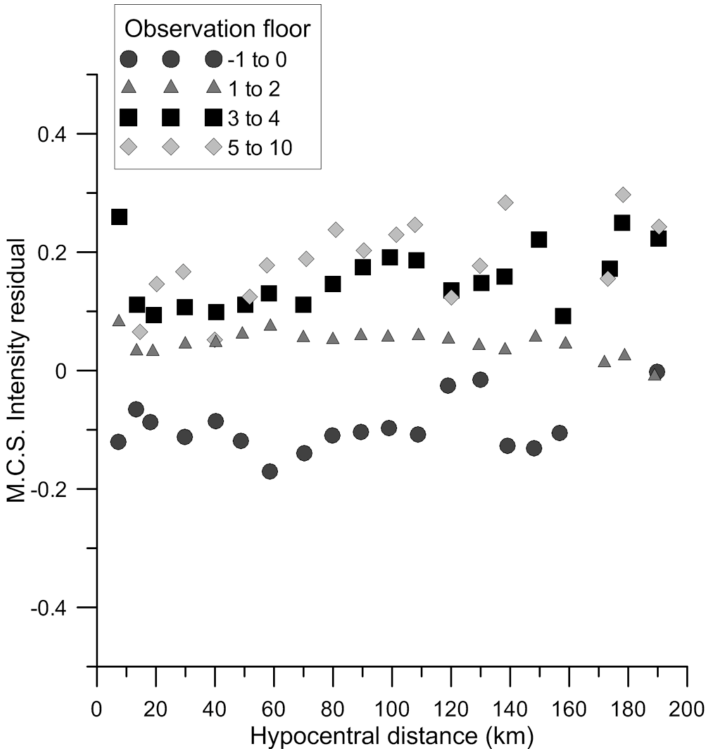

Figure 2

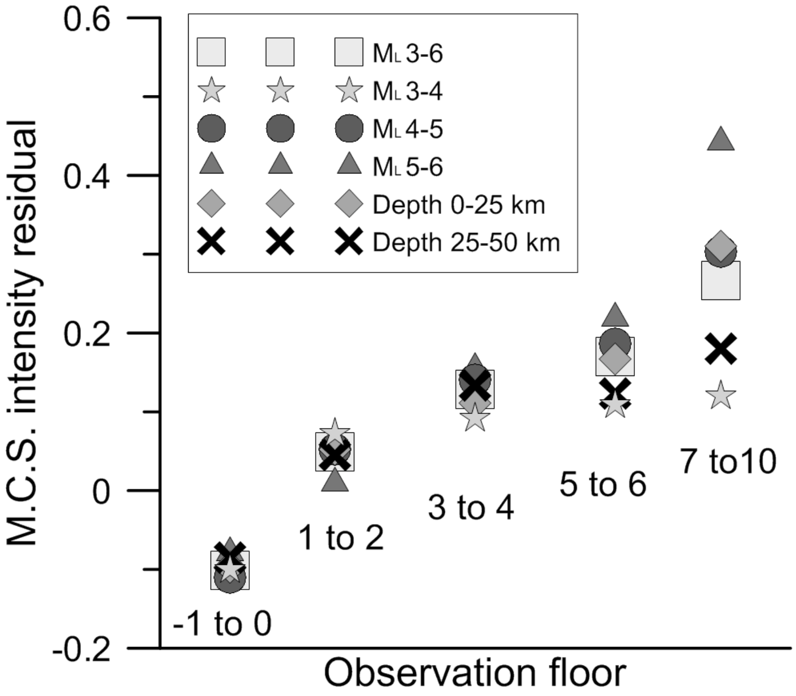

Figure 3

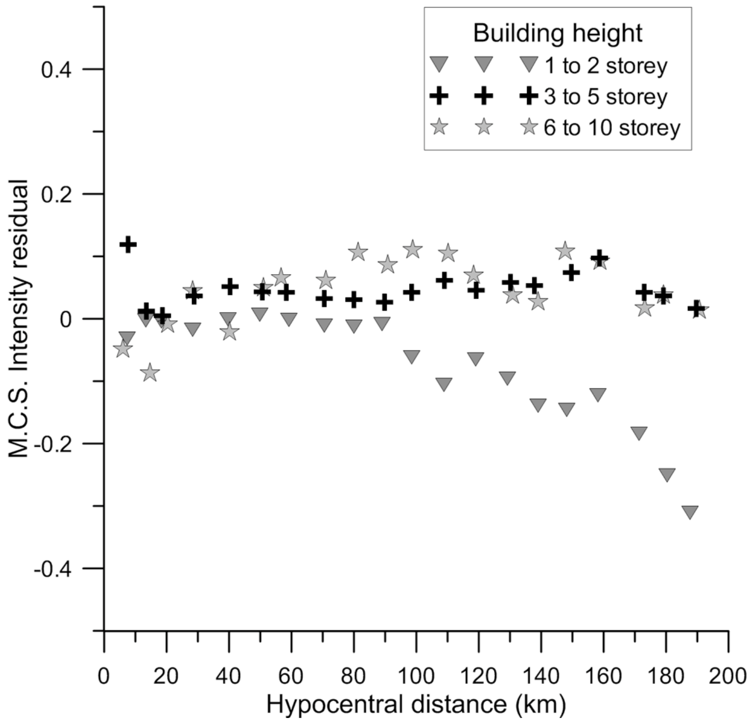

Figure 4

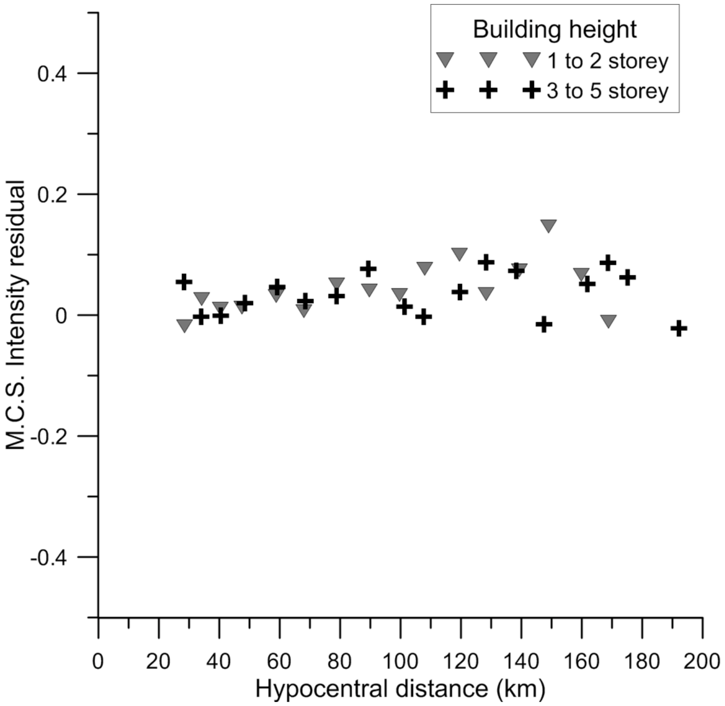
Building height
1 to 2 storey
3 to 5 storey
M.C.S. Intensity residual
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
100
120
140
160
180
200
Hypocentral distance (km)

Figure 5