

Chapter 5

The Role of Site Effects at the Boundary Between Seismology and Engineering: Lessons from Recent Earthquakes

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Abstract This paper summarises the experience gathered on the field following four recent earthquakes: in 2009 at L’Aquila, Italy; in 2010 at Lorca, Spain; in 2011 at Christchurch, New Zealand; in 2012 at Emilia, Italy. These quakes provided useful lessons at the boundary between seismology and engineering, about the difference between what we expected to happen, thanks to more or less simplified models, and what happened in reality. The topics dealt with are: (1) the reliability of “free-field” strong motion recordings, discussing the role of accelerometer housing, spurious transient, city-soil effect, and the possible over-correction of displacements; (2) the mismatch between code provision and observed spectral acceleration due to the role of velocity inversions, the influence of topography, the softening and hardening non-linearity, (3) the importance of vertical component considering the time distribution of phases arrivals and the presence of amplification due to P-velocity contrasts.

5.1 Introduction

In the past 5 years, four moderate magnitude earthquakes caused substantial economic damage and a death toll from dozens to hundreds of casualties each. Namely, they are the 2009 L’Aquila earthquake, Italy; the 2010 Lorca earthquake, Spain; the 2011 Christchurch earthquake, New Zealand; the 2012 Emilia

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earthquake, Italy. All of them happened in densely populated, industrialised area previously subjected to seismic classification.

There were debates following each of those events about the reliability of seismic hazard studies, the implementation of site effects in seismic codes and about the limit of damage that is acceptable by designers but unacceptable (or misunderstood) by population. I had the opportunity, with colleagues of different research groups, to perform field studies in all these areas, noting similarity and differences. This paper tries to summarise the role of the difference between what we expected to happen, thanks to more or less simplified models, and what happened in reality. We all accept that models are a need to simplify theories and make them useful to practitioners, but there is a threshold of disagreement between models and reality that must not be trespassed.

5.2 How Reliable Are “Free-Field” Strong Motion Recordings?

In recent years, it was acknowledged the importance of ground-truthing microzonation maps or V_s30 studies by summarising some lessons learned from large earthquakes and recent earthquake site response studies that utilise earthquake recordings from dense seismic networks or ambient noise measurements (Cassidy and Mucciarelli 2010).

But if we want to consider the instrumental recordings as the truth against which our model should be tested, we must be sure of the reliability of such data. Recent earthquakes have shown that in some cases particular care should be taken before using recorded data. In some cases the owners of an accelerometric network provided to pre-check the strong motion recordings and decided not to disseminate corrupted data. This was the case of the 2009, L’Aquila earthquake when the Italian department of Civil Protection did not distribute the recording of main shock at AQM station. The accelerometer, set to 1 g full-scale, saturated due to a partial detachment of the instrument from the pillar (Zambonelli et al. 2011); In other cases, problems with the recordings were encountered as listed in the following.

5.2.1 *Housing and City-Soil Effects*

The influence of buildings on free-field ground motion recordings has been postulated for the first time more than 30 years ago (Jennings 1970), and confirmed both by experiments and numerical simulations. Ditommaso et al. (2009a, b) showed that the peak and spectral parameters are the most affected, while the integral ones are not so disturbed. This is due to the fact that the presence of the structure has both the effect of a damper (thus reducing the total energy) and of a filter, focusing energy in the band of building eigenfrequencies.

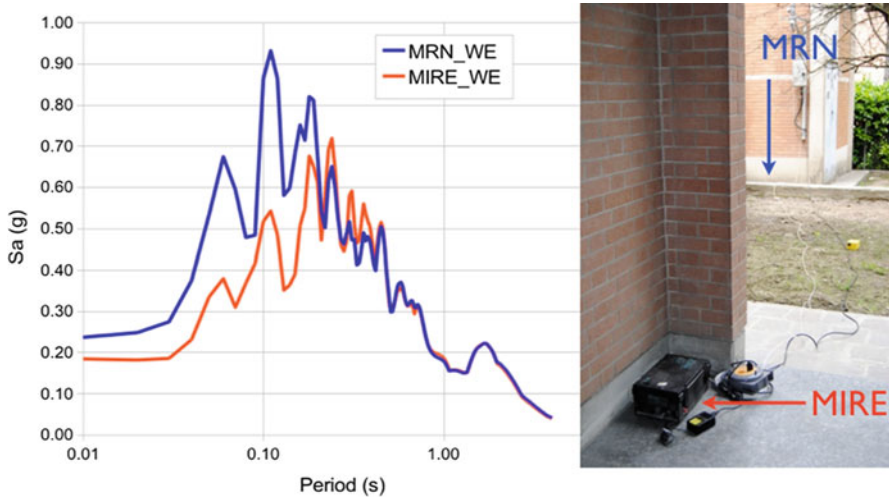


Fig. 5.1 Comparison of ground response spectra inside and outside a building for the 29.05.12, $M = 5.8$ shock in Mirandola, Emilia

During the Emilia sequence, an accelerometer (MIRE) was installed in free-field at 5 m from the existing RAN station, located inside a small electrical substation (MRN). The response spectra of the second strongest shock of the sequence ($M = 5.8$, 29.05.12) showed a noticeable agreement at the two locations (see Fig. 5.1), except that for the short period range, where the recording inside the substation showed peaks much higher than in the free-field station. It is possible that several strong motion recorded in urban areas depend on housing or on the vicinity to oscillating buildings.

5.2.2 Over-Correction of Displacements

The Emilia second strongest shock provided a lot of strong motion data very close to the epicentre. This posed the problem of correction of accelerometric recordings. Figure 5.2 shows the comparison between the uncorrected and corrected time histories from the vertical component of station MIRE (see Fig. 5.1). The uncorrected data shows a permanent displacement of about 30 cm. INSAR data and modelling from different authors shows that this location suffered a 15 cm static coseismic displacement.

The standard de-trending and filtering procedure could introduce spurious frequencies due to the presence of a real permanent displacement that does not allow for having zero-mean corrected recordings. In the future the availability of high-frequency GPS data co-located with seismic and accelerometric station will provide an unbiased estimate of real ground motion.

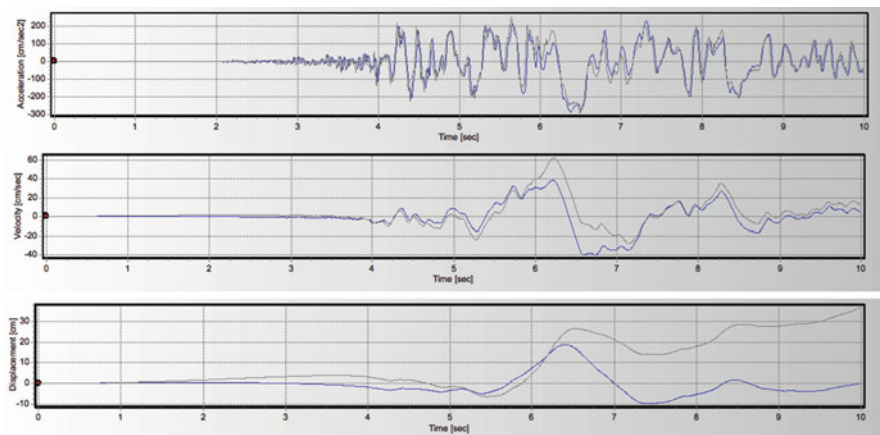


Fig. 5.2 Corrected (*blue*) and uncorrected (*grey*) strong motion recording at MIRE. From *top* to *bottom*: acceleration, velocity and displacements



Fig. 5.3 The accelerometric station in the basement of the old jailhouse, Lorca

5.2.3 Spurious Transient in Strong Motion Recordings

During the 2010 Lorca earthquake, a valuable strong motion recording was available thanks to a station of Red Sismica Nacional located in the historical city centre, very close to the epicentre. The station was installed in the basement of the old jailhouse (see Fig. 5.3).

Fig. 5.4 Application of a band-variable filter (Ditommaso et al. 2012) to the recording of the mainshock in Lorca

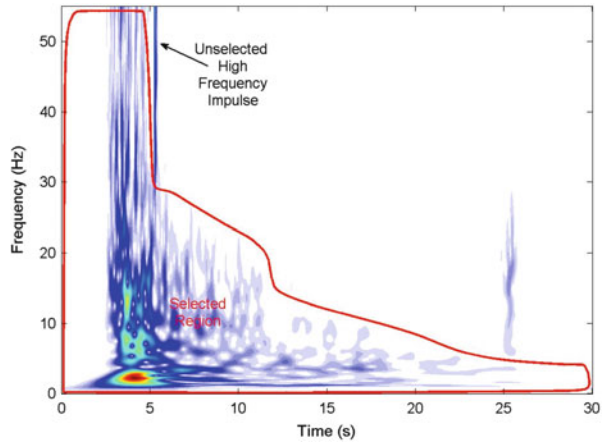
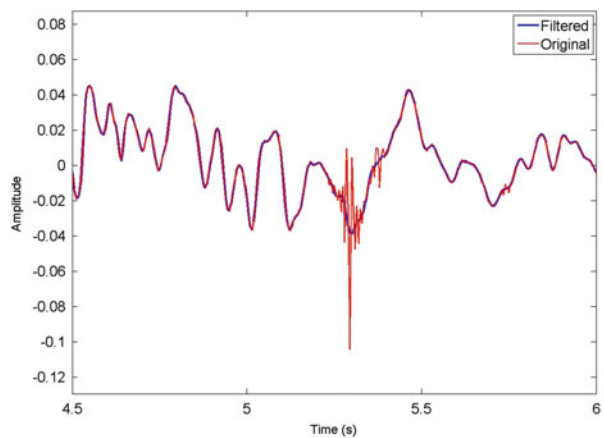


Fig. 5.5 Enlargement of the accelerometric recording of the mainshok in Lorca



During the mainshock, some heavy objects close to the accelerometer fell on the reinforced concrete pillar of the station. This caused a strong, high-frequency acceleration transient in the recording. Using a band variable filter based on Stockwell transform (Ditommaso et al. 2012) it was possible to carefully remove this spurious peak.

Figure 5.4 shows the area selected for filtering in the time frequency domain, while Fig. 5.5 compares the time histories before and after the filtering, showing the accuracy of the band variable filter in preserving the signal outside the area selected for removal.

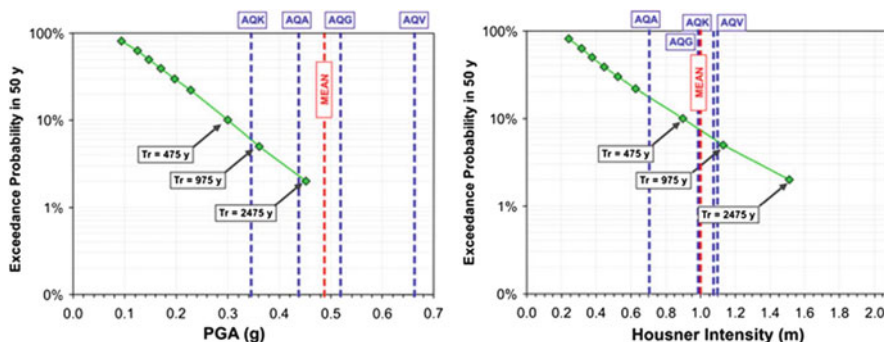


Fig. 5.6 From Masi et al. (2011) Exceedance probability in 50 years at L’Aquila provided by the NTC2008 code for soil class B in terms of PGA (on the left) and Housner Intensity (on the right); the maximum values of the horizontal components recorded at four stations are also displayed (blue dashed lines) together with their mean (red dashed lines)

5.3 Comparison Between Code Spectra and Observed Strong Motion

A careful evaluation of site effects is crucial for the activity of validation of PSHA estimates. Procedures like the one proposed by Albarello and D’Amico (2008) requires to know if the set of recordings to be compared with estimates are obtained on rock or if they have to be deconvolved to a rock-equivalent condition.

The L’Aquila and Emilia earthquakes provided contrasting evidences. For l’Aquila event, the difference between the observed recordings and code provision was mainly due to the choice of parameters used rather than in a bias in base hazard estimates or insufficient description of site effects . After correcting for soil class according with Vs30, Masi et al. (2011) showed that Housner Intensity provided much better results than PGA (Fig. 5.6), and was well correlated with site seismic hazard obtained from the long series of macroseismic data available.

On the other hand, in Emilia it was observed (Gallipoli et al. 2014) that while code provision largely underestimated the recorded values, the convolution of expected motion at a rock site with a 1-d velocity profile down to 120 m instead of Vs30 soil class greatly improved the agreement. This difference it is probably due to the fact that the sediment in the Aterno valley (L’Aquila) are coarse and less than 40 m thick, while in the Po valley (Emilia) the soil is very soft and bedrock is hundreds of meters deep, the condition where Vs30 gives its poorest performances as a proxy of site amplification (Gallipoli and Mucciarelli 2009).

5.4 When Reality Is Far from Models

5.4.1 *Need for Nanozonation?*

During L'Aquila earthquake the variation of damage due to site effects was shown to vary abruptly over a very short distance. The most striking example was observed in the village of San Gregorio. After the microzonation performed following the ICMS08 (Indirizzi e Criteri per la Microzonazione Sismica, Guidelines For Seismic Microzonation) for the basic level, including a new, detailed geological mapping at 1:5000 scale, it was not possible to explain a peculiar damage observed: a three-story, reinforced concrete (RC) building had the first floor collapsed. The remaining two stories fell with a displacement in the horizontal projection of about 70 cm. Buildings located at a short distance had little or no damage reported.

Mucciarelli et al. (2011a) performed a geophysical and geologic survey at the site. The acceleration and ambient noise recordings showed a high amplification in the slope direction. Geo-electrical tomography showed a strong discontinuity just below the building. A very soft material (possibly fault cataclasites) was found in a borehole down to 17 m from ground level, showing a shear wave velocity that starts at 250 m/s, increases with depth and has an abrupt transition in calcarenites at 1,150 m/s. The surface geophysical measurements in the vicinity of the site have not shown similar situations, with flat HVSR curves as expected for a rock outcrop, except for a lateral extension of the soft zone (these results are summarised in Fig. 5.7). The analysis on the quality of the building materials has yielded values higher than average for the age and type of construction, and no special design or construction deficiencies have been observed. A strong, peculiar site effect thus appears to be the most likely cause of the damage observed, extending at a very limited scale, in an area slightly wider than building foundations. This sounds like a warning for anyone that may think to use microzonation studies as input data for design of a specific structure and not for the urban planning aim they are designed for.

5.4.2 *Velocity Inversions*

The EuroCode 8 soil classification in Vs30 classes, adopted following the scheme of NEHRP recommendations, considers a soil-over-bedrock scheme, with mechanical properties improving with depth. The possibility of velocity inversions is not taken into account. The L'Aquila earthquake showed that this kind of geo-lithological situation was more common than previously thought. In some instances, a stratum of well-cemented breccia (conglomerates), even 30 m thick, was overlying softer soil deposits, giving amplification in a situation that could be easily mistaken for a bedrock site. An example of this kind of velocity inversion is given in Gallipoli et al. (2011) for the Poggio Picenze village (see Fig. 5.8).

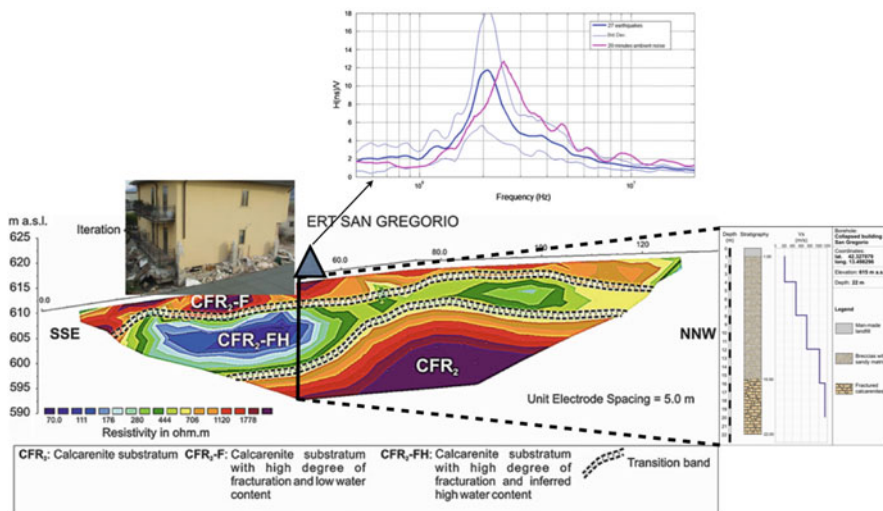


Fig. 5.7 Summary of surveys in San Gregorio from Mucciarelli et al. (2011a), see text for details

In other instances, a further soft stratum was present at the top of the sequence, giving rise to a more complex amplification pattern, that is visible since HVSR measurements have a double peak. This results in amplification of seismic motion over a wider range of frequencies, and was related to damage enhancement as clearly shown for the L'Aquila historical centre (Fig. 5.9) by Del Monaco et al. (2013).

5.4.3 The Role of Topographic Amplification

During the L'Aquila, 2009 seismic sequence, the temporary installation of accelerometric networks provided a test of the Italian anti-seismic provisions about topographic amplifications. Two morphological situations were particularly suitable for the test: Castelnuovo, where two accelerometers located on the same lithology at the hill top and halfway along the slope provided the ideal case to test the proposed rule of linear increment of amplification along the slope, and Navelli, where the combination of code topographic and stratigraphic amplification factors was similar, given a station on a rocky slope and one on a flat alluvial valley. Gallipoli et al. (2013). showed that *“in neither case the observation matches code provisions. For Castelnuovo, there is a frequency dependence that shows as the code is over-conservative for short periods but fails to predict amplification in the intermediate range. For Navelli, the code provision is verified for long periods, but*

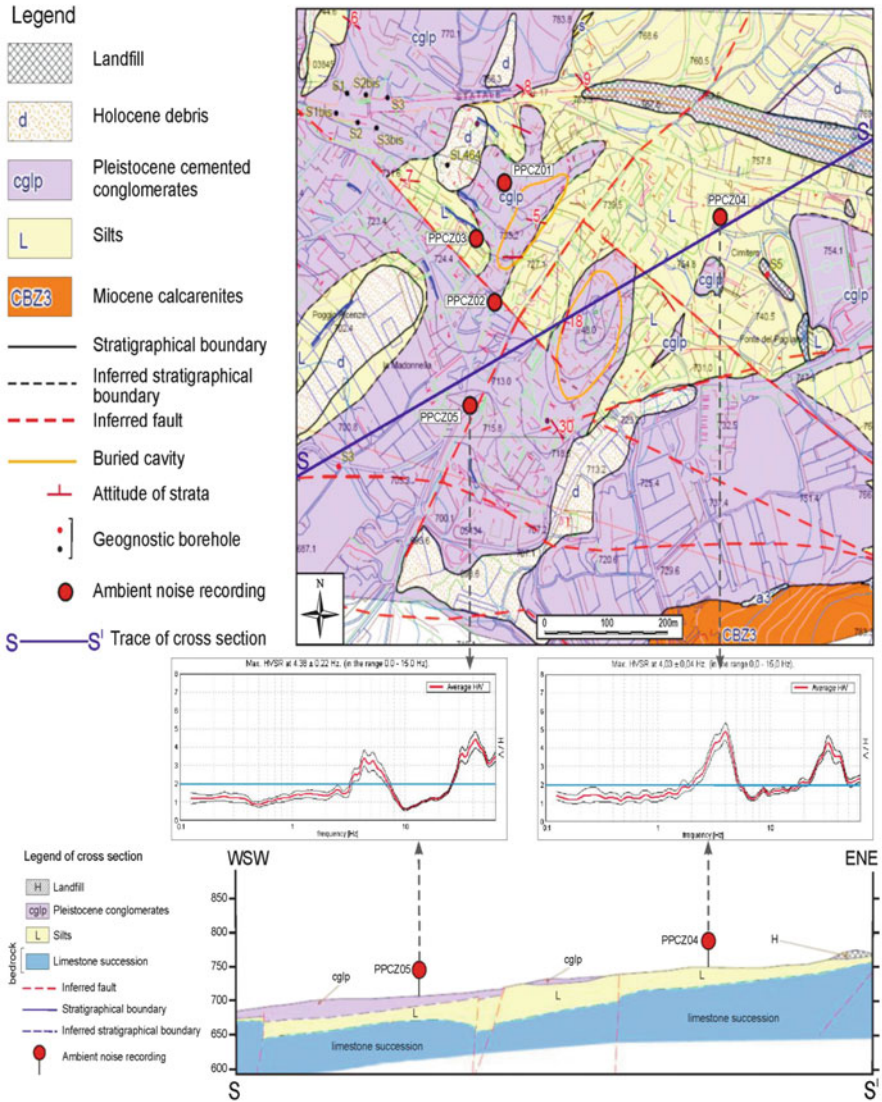


Fig. 5.8 The geological map and geological section with HVNSR (PPCZ04 and PPCZ05) of Poggio Pienze, from Gallipoli et al. (2011)

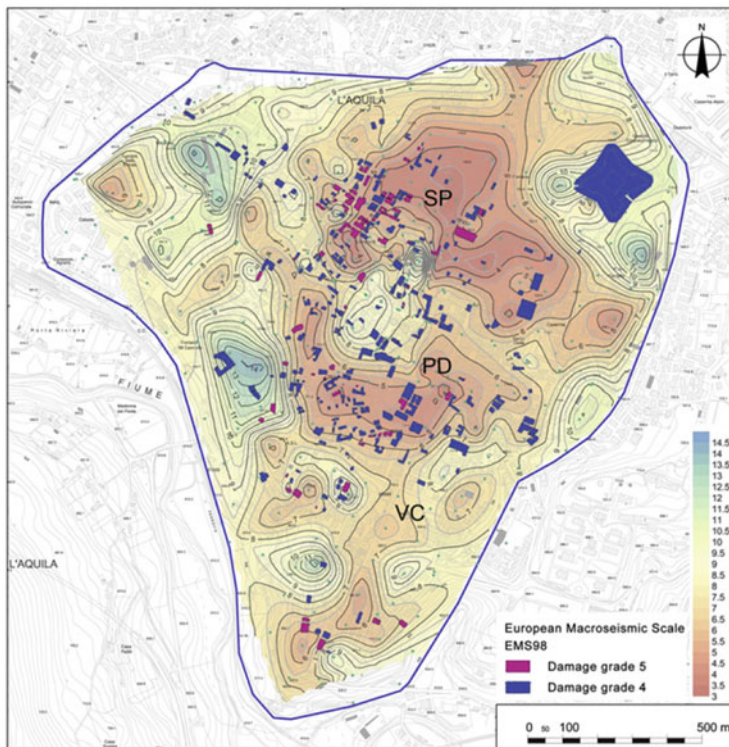


Fig. 5.9 From del Monaco et al. (2013); location of the severely damaged buildings (DG5 and 4 in EMS'98 damage grade, Tertulliani et al. 2011) and contouring of the second resonance frequency peak from HVNSR analysis in L'Aquila historical centre

in the range around the site resonance frequency the stratigraphic amplification proves to be three times more important than the topographic one.”

Figure 5.10 reports the Navelli case.

5.4.4 The Role of Non-linearity

The L'Aquila and the Christchurch earthquake provided interesting evidence about the role of non linearity in seismic response.

The analysis of two arrays in the Upper (L'Aquila) and Lower Aterno valley (Navelli) showed that softening soil non-linearity played a role only of soft, fine and well graded basins like in Navelli. Mucciarelli et al. (2011b) found a few percent decrease in fundamental frequency and amplification between the largest ($M > 4$) aftershocks and lesser aftershocks and noise. On the contrary, Puglia et al. (2011) did not find any evidence on non-linearity in the response of the coarser, inter-digited soils of the Upper Aterno valley.

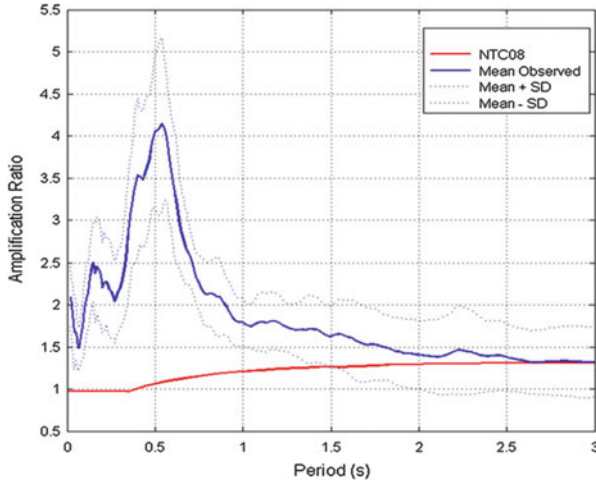


Fig. 5.10 Comparison between code provisions (*red*) and observed amplification ratio (*blue*) in Navelli between closely spaced stations, one on a rocky slope and one on a flat alluvial valley

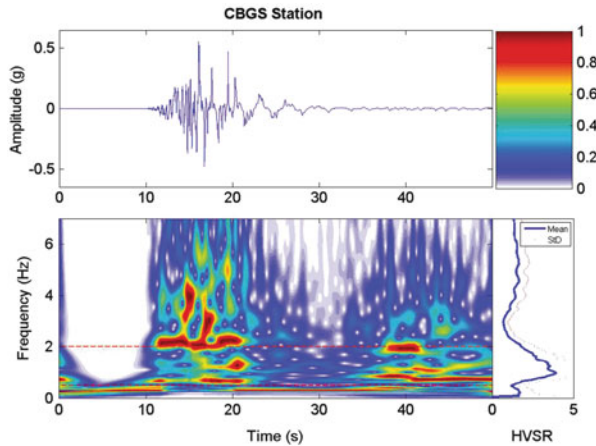
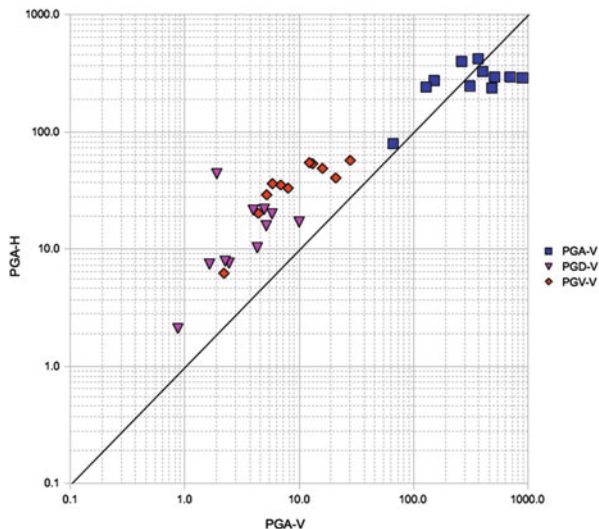


Fig. 5.11 Comparison between normalized S-transform and HVSr at GeoNet CBGS accelerometric station

In Christchurch it was possible to observe hardening non-linearity in action. Mucciarelli (2011) analysed jointly noise and accelerometric recordings, using the S-transform. The result (Fig. 5.11) shows that the energy of the largest horizontal component for coda waves is at frequencies lower than the fundamental one determined by HVSr, but in an earlier phase, the time-domain trace and the S-transform show high-frequency acceleration peaks, the evidence of the hardening non-linearity first described by Bonilla et al. (2005), due to hysteretic dilatant behaviour of non-cohesive, partially saturated soils.

Fig. 5.12 comparison between horizontal and vertical component of the peak parameters of ground motion PGA, PGV, PGD in the near field of Emilia, 2012 earthquake. The units are respectively cm/s^2 , cm/s and cm



5.4.5 Vertical Component and P-Wave Amplification

The Emilia sequence had two similar magnitude main events separated by 9 days. While there was only an accelerometric station active during the first shock, several organisation (INGV; CNR-IMAA, OGS, RAN) installed temporary network in the epicentral area. When the second shock occurred it was thus possible to have a large number of near field recordings. Figure 5.12 summarises the relationship between horizontal and vertical component of the three peak parameters of ground motion (PGA, PGV, PGD). It is possible to see that while for velocity and displacement the horizontal peak is always larger, for acceleration the majority of near-field peaks is larger in the vertical component. These large vertical accelerations are overlooked by present day Italian seismic code.

5.4.6 Time Distribution of Seismic Actions

Some important lessons from these recent earthquakes came from the time-domain representation of data.

Analysing the previously described data from the Christchurch earthquake using the cumulative Housner intensity, calculated from $T=0$ for incrementing time intervals, it possible to evaluate the importance of the transition from linear behaviour in the beginning to hardening non linearity in the middle and softening non-linearity at the end (Fig. 5.13).

It is possible to see that during the hardening non-linearity phase the Housner intensity recorded is enough to cause damages corresponding to the VIII EMS

Fig. 5.13 Cumulative Housner Intensity at GeoNet CBGS accelerometric station

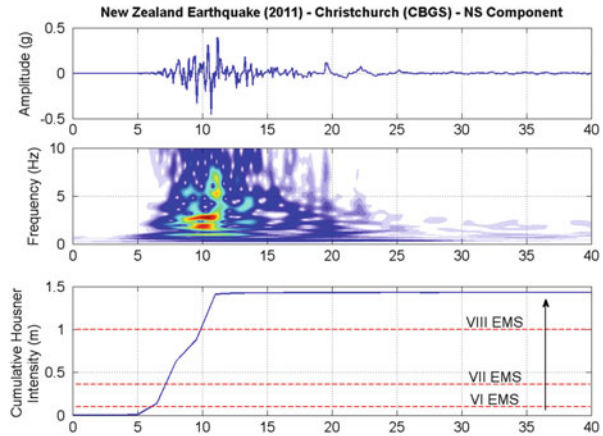
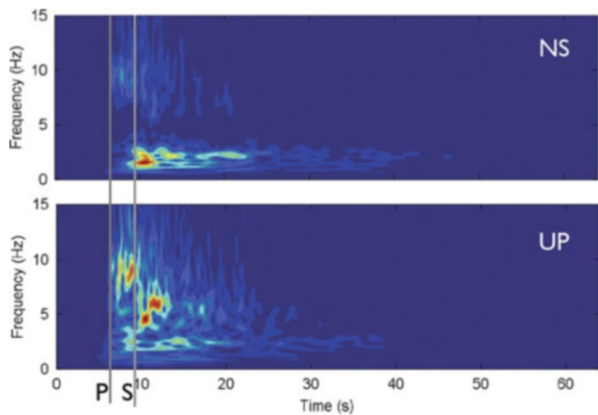


Fig. 5.14 S-transform of the 29 May earthquake at MIRE station



degree. When finally there is the onset of softening non-linearity, the Cumulative Housner intensity is already more than 90 % of the total. This should induce care when using simplified 1-d linear-equivalent models for site seismic response that do not take into account hardening non linearity and are not able to reproduce correctly in time-domain the onset of softening non-linearity.

Another lesson learned from frequency-time domain during the Emilia earthquake is the role of the combination of vertical and horizontal strongest phases. A peculiar kind of damage of this earthquake was the failure of several pre-fab industrial facility. Most of damage was caused by the fact that the beam were not connected to pillars, but the contact was pure friction. A loss of vertical load could have caused the reduction of friction and subsequently the collapse of the beams.

A look to the frequency domain representation of the recordings at MIRE stations (Fig. 5.14) shows that there is, as expected, a strong phase of vertical motion connected to the arrival of the P waves, when the horizontal motion is

minimal. Unexpectedly there is also a strong pulse in the vertical component practically synchronous with the arrival of S-waves. This could have been the cause of many observed collapse of industrial facilities.

5.5 A Look to the Future

Three main field of activity are envisaged for the future.

1. A federation of accelerometric borehole arrays in Italy. The motivation of this project arises from the need of improving existing installations, provide uniform site characterisation of sites (Fo, velocity profiles, etc.), bring together the owners in order to share good practices and finally to provide a web portal for the public dissemination of results. The availability of well characterised sites where the absolute site amplification is known, beside improving GMPEs could also be a resource for hands-on training of practitioners that could test their skills and their equipment against the available knowledge.
2. The consideration of building soil-resonance. The importance of resonance was highlighted for the Emilia quake by the striking case of two twin buildings whose different damage was caused by the different fundamental frequency of foundation soil even at close distance (Castellaro et al. 2014). During the L'Aquila earthquake it was possible to determine the frequency decay due to different level of damage on a large set of buildings (Ditommaso et al. 2013). The availability of these data made possible the study of the relationship between height, damage and fundamental frequency. Since the microzonation studies will provide in few years iso-frequency maps of the most hazardous municipality, it will then be possible to map the resonance-prone buildings, both for elastic and post-yield frequency.
3. A move toward a two-parameters soil classification. As in other parts of Europe (see, e.g. Pitilakis et al. 2013) also in Italy similar studies are carried on (Luzi et al. 2011). It is now time to implement these study into seismic code abandoning the Vs30 classification scheme.

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References

- Albarello D, D'Amico V (2008) Testing probabilistic seismic hazard estimates by comparison with observations: an example in Italy. *Geophys J Int* 175(3):1088–1094
- Bonilla LF, Archuleta RJ, Lavallée D (2005) Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: field data observation and modeling. *Bull Seismol Soc Am* 95:2,373–2,395
- Cassidy JF, Mucciarelli M (2010) The importance of ground-truthing for earthquake site response. In: Proceedings of the 9th U.S. National and 10th Canadian conference on earthquake engineering, Toronto, Ontario, Canada, 25–29 July 2010. Paper no. 758
- Castellaro S, Padrón LA, Mulargia F (2014) The different response of apparently identical structures: a far-field lesson from the Mirandola 20th May 2012 earthquake. *Bull Earthq Eng*. doi:[10.1007/s10518-013-9505-9](https://doi.org/10.1007/s10518-013-9505-9)
- Del Monaco F, Tallini M, De Rose C, Durante F (2013) HVNSR survey in historical downtown L'Aquila (central Italy): site resonance properties vs. subsoil model. *Eng Geol* 158:34–47
- Ditommaso R, Parolai S, Mucciarelli M, Eggert S, Sobiesiak M, Zschau J (2009a) Monitoring the response and the back-radiated energy of a building subjected to ambient vibration and impulsive action: the Falkenhof Tower (Potsdam Germany). *Bull Earthq Eng*. doi:[10.1007/s10518-009-9151-4](https://doi.org/10.1007/s10518-009-9151-4)
- Ditommaso R, Mucciarelli M, Gallipoli MR, Ponzo FC (2009b) Effect of a single vibrating building on free-field ground motion: numerical and experimental evidences. *Bull Earthq Eng*. doi:[10.1007/s10518-009-9134-5](https://doi.org/10.1007/s10518-009-9134-5)
- Ditommaso R, Mucciarelli M, Ponzo FC (2012) Analysis of non-stationary structural systems by using a band variable filter. *Bull Earthq Eng* 10(3):895–911. doi:[10.1007/s10518-012-9338-y](https://doi.org/10.1007/s10518-012-9338-y)
- Ditommaso R, Vona M, Gallipoli MR, Mucciarelli M (2013) Evaluation and considerations about fundamental periods of damaged reinforced concrete buildings. *Nat Hazards Earth Syst Sci* 13:1903–1912
- Gallipoli MR, Mucciarelli M (2009) Comparison of site classification from Vs30, Vs10, and HVSR in Italy. *Bull Seismol Soc Am* 99:340–351
- Gallipoli MR, Albarello D, Mucciarelli M, Bianca M (2011) Ambient noise measurements to support emergency seismic microzonation: the Abruzzo 2009 earthquake experience. *Boll di Geofisica Teorica ed Appl* 52(3):539–559. doi:[10.4430/bgta0031](https://doi.org/10.4430/bgta0031)
- Gallipoli MR, Bianca M, Mucciarelli M, Parolai S, Picozzi M (2013) Topographic versus stratigraphic amplification: mismatch between code provisions and observations during the L'Aquila (Italy, 2009) sequence. *Bull Earthq Eng* 11(5):1325–1336
- Gallipoli MR, Chiazzi L, Stabile TA, Mucciarelli M, Masi A, Lizza C, Vignola L (2014) The role of site effects in the comparison between code provisions and the near field strong motion of the Emilia 2012 earthquakes. Submitted to *Bull Earthq Eng*. doi:[10.1007/s10518-014-9628-7](https://doi.org/10.1007/s10518-014-9628-7)
- Jennings PC (1970) Distant motion from a building vibration test. *Bull Seismol Soc Am* 60:2037–2043
- Luzi L, Puglia R, Pacor F, Gallipoli MR, Bindi D, Mucciarelli M (2011) Proposal for a soil classification based on parameters alternative or complementary to Vs,30. *Bull Earthq Eng* 9:1877–1898. doi:[10.1007/s10518-011-9274-2](https://doi.org/10.1007/s10518-011-9274-2)
- Masi A, Chiazzi L, Braga F, Mucciarelli M, Vona M, Ditommaso R (2011) Peak and integral seismic parameters of L'Aquila 2009 ground motion: observed vs. code provision values. *Bull Earthq Eng* 9:139–156
- Mucciarelli M (2011) Ambient noise measurements following the 2011 Christchurch earthquake: relationships with previous microzonation studies, liquefaction, and nonlinearity. *Seismol Res Lett* 82(6):919–926
- Mucciarelli M, Bianca M, Ditommaso R, Vona M, Gallipoli MR, Giocoli A, Piscitelli S, Rizzo E, Picozzi M (2011a) Peculiar earthquake damage on a reinforced concrete building in San Gregorio (L'Aquila, Italy): site effects or building defects? *Bull Earthq Eng* 9:825–840. doi:[10.1007/s10518-011-9257-3](https://doi.org/10.1007/s10518-011-9257-3)

- Mucciarelli M, Bianca M, Ditommaso R, Gallipoli MR, Masi A, Milkereit C, Parolai S, Picozzi M, Vona M (2011b) Far field damage on RC buildings: the case study of Navelli during the L'Aquila (Italy) seismic sequence, 2009. *Bull Earthq Eng* 9:263–283. doi:[10.1007/s10518-010-9201-y](https://doi.org/10.1007/s10518-010-9201-y), ISSN: 1570–761X
- Pitilakis K, Riga E, Anastasiadis A (2013) New code site classification, amplification factors and normalized response spectra based on a worldwide ground-motion database. *Bull Earthq Eng* 11:925–996. doi:[10.1007/s10518-013-9429-4](https://doi.org/10.1007/s10518-013-9429-4)
- Puglia R, Ditommaso R, Pacor F, Mucciarelli M, Luzi L, Bianca M (2011) Frequency variation in site response as observed from strong motion data of the L'Aquila, 2009 seismic sequence. *Bull Earthq Eng* 9(3):869–892. doi:[10.1007/s10518-011-9266-2](https://doi.org/10.1007/s10518-011-9266-2)
- Tertulliani A, Arcoraci L, Berardi M, Bernardini F, Camassi R, Castellano C, Del Mese S, Ercolani E, Graziani L, Leschiutta I, Rossi A, Vecchi M (2011) An application of EMS98 in a medium-sized city: the case of L'Aquila (Central Italy) after the April 6, 2009 Mw 6.3 earthquake. *Bull Earthq Eng* 9:67–80
- Zambonelli E, de Nardis R, Filippi L, Nicoletti M, Dolce M (2011) Performance of the Italian strong motion network during the 2009, L'Aquila seismic sequence (central Italy). *Bull Earthq Eng* 9(1):39–65