Synopsis of the Latest European Seismic Hazard Maps: Case Study from Central Italy - 2016

Cvetan Sinadinovski[1] and Kevin F. McCue[2]

1. Corresponding Author. Canberra, ACT.
   Email: cvetansin@hotmail.com
2. Central Queensland University, Rockhampton, Queensland.
   Email: mccue.kevin@gmail.com

Abstract

A destructive seismic sequence hit Central Italy in 2016 with a series of moderate to large earthquakes that occurred over the period of three months, the largest with magnitudes 5.9, 6.0 and 6.5. It caused human casualties and unusually severe damage for such modest earthquakes. The series of seismic shocks was well recorded by local and regional geodetic, seismological and strong motion networks, as well as on temporary instruments installed by Italian and other European institutions soon after the first event. For seismology, the new data unveil a picture of unexpectedly complex fault interactions and earthquake generation that had not been observed before in Italy. Such a detailed picture contributes towards better understanding of the earthquake processes and regional tectonics. For engineering the lesson is that strong near-source ground shaking is much stronger than expected, the vertical shaking not to be conveniently ignored, magnification in valleys and surficial soils significant, all contributing to the unexpected building damage and collapse. In respect to this new knowledge, the national seismic hazard maps of Europe are undergoing re-evaluation. This experience has lessons elsewhere, including in Australia.

Keywords: seismic sequence, earthquake records, faults, seismic hazard and risk.

1 OVERVIEW:

A destructive complex seismic sequence hit Central Italy in 2016 with a series of moderate to large earthquakes over the period August to October. It started on August 24^{th} with a magnitude M6.0 earthquake located between the towns of Norcia and Amatrice, that ruptured a 20-25 km long fault segment, on a WSW dipping and NNW-SSE striking normal fault, the tear initiating at about 5km depth. Two months later, another event, M5.9, occurred on October 26^{th}, at the northernmost sector of the activated area nearby the village of Visso, rupturing again with a normal-faulting mechanism. Only four days later, the largest shock M6.5, occurred in the center of the activated fault system, causing large surface offsets that occasionally overlapped and exceeded those of the first earthquake of August 24^{th} (Chiaraluce et al, 2017). Figures 1 and 2 show the tectonic setting, interplate, major fault system and earthquake mechanisms.

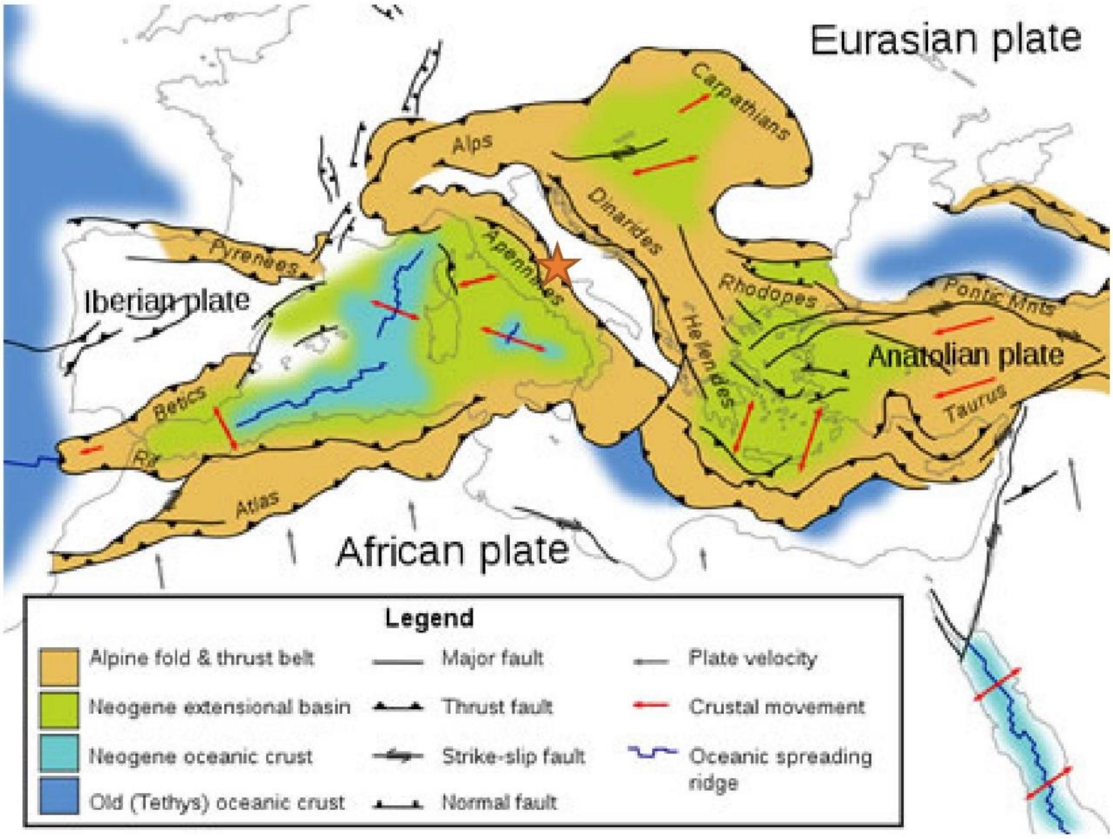
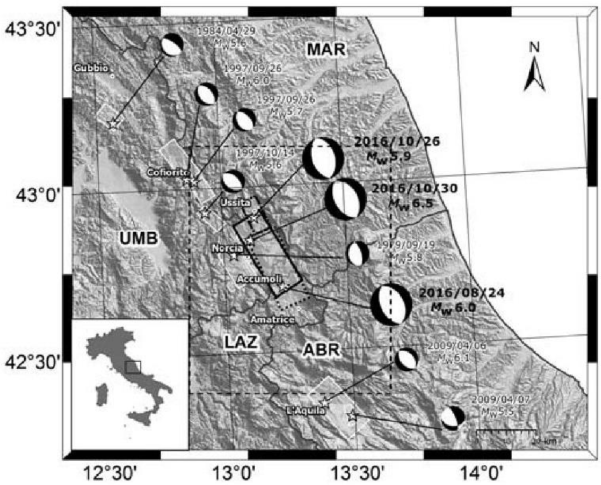


Figure 1: Tectonics of the Italian region showing the normal fault system along the Apennines and the major plates in the region orchestrating movement on those faults. The orange star shows the approximate position of the seismic sequence.

Since August 2016 several Italian and international institutions have conducted seismic microzonation surveys of the most affected areas. A large amount of different data were gathered: geological and geomorphological (from field trips and photo-geological interpretation), geophysical measurements (geo-electric, seismic refraction), and continuous seismic recordings from the network of temporary seismic stations and arrays equipped with both seismometers and accelerometers. They recorded many earthquakes, including the strongest M6.5 of October 30, 2016.

Eight months after the beginning of the seismic sequence in Central Italy, a special session was held at the European Geosciences Union assembly in Vienna. It provided an overview of the multi-disciplinary data analyses and interpretation models of the ruptures processes and of the seismicity by using the latest geological, seismological and geodetic information. Such a comprehensive approach contributes towards better understanding of the earthquake process and the strong ground shaking that resulted in widespread building damage and collapse.



Figures 2: The causative fault mechanisms of the mainshocks displayed here, obtained from Time Domain Moment Tensor technique and implemented at Istituto Nazionale di Geofisica e Vulcanologia (INGV) National Earthquake Centre, feature pure normal faulting, in agreement with the prevailing extensional regime of the central Apennines and with the mechanisms of the previous L'Aquila earthquake.

In respect to those new facts, the committee responsible for the national Seismic Hazard maps (European) are undertaking their re-evaluation. Italy had a reference seismic hazard model in accordance with the Prime Minister Ordinance since 2006, which was based on their 2004 seismicity map. The basic elaboration to be considered for update was the seismic classification of municipalities and the determination of the design spectra in the Italian building code. Other participating European countries, for example Macedonia, also prompted processes in 2017 for the Seismic Hazard and Risk assessment, that might have wider implications in the regions with similar situation and seismotectonic regimes, such as parts of Australia (Sinadinovski and M^{c}Cue, 2013).

2 FIELD SURVEYS:

Site selection was performed according to the following criteria: the geological conditions of the hamlets that experienced a damage level greater than intensity VII MCS scale, optimization of the network geometry for array analysis, bedrock reference sites, safety and accessibility (Hofer et al., 2016). Photo-geology and field investigations allowed the construction of a detailed geotechnical map of the area, characterised by special features, namely the transformation between bedrock and Quaternary deposits (alluvial terraces and fans, landslides) and morpho-structural features (faults, folds, and beddings).

Strong evidences of the effect of the vertical ground motion in reinforced concrete (RC) buildings were the symmetrical buckling of reinforcement, compression damage and crushing at mid-height and in other parts of columns, undamaged windows and unbroken glass panels as well as partial collapse of the buildings that usually occur along the vertical axis within the plan of the building. On the other hand, relatively flexible structures such as castle and bell towers in Arcuata del Tronto and Amatrice respectively were not affected by the vertical ground motion (Fig. 3)

Figure 3: An areal view showing the damage after the first main shock in the Amatrice centre with the bell tower still standing (AP).

During the action of the vertical component of the ground motion in Amatrice affected area, stationary waves were formed vertically in the observed structures resulting in the collapse of one or more floors at any level of the buildings (Fig. 4)

Figure 4: The main street through Armatrice before and after the August 24th 2016 earthquake (AP)

At the same time, the overlying or underlying adjacent floors were completely horizontal and the corresponding parts of the building remained practically intact as if the partial collapse had not taken place. In partially collapsed buildings, the remaining still-standing parts were almost undamaged, that leaded to consider the effect of a strong vertical component. The intact parts of the buildings prove that they had a quite satisfactory lateral behaviour and the unbroken windows show modest horizontal actions. Moreover, collapsed load-bearing and infill walls in unreinforced masonry and RC buildings respectively were symmetrically thrown away around the vertical axis of the buildings as if they were blown out by an explosion suggesting the predominance of vertical powerful actions over horizontal displacements. The damage described above suggested the predominant effect of the vertical component of earthquake ground motion typical for a shallow near-field earthquake.

3 GROUND SHAKING:

Different methodologies were used to estimate and investigate the ground shaking experienced over a large area comprising the source region and extending throughout central Italy (Fig. 5). The main aim of the investigation was to understand the origin of the very diversified strong ground motion observed for the three main shocks and compare with previous research (Ambraseys, et al., 1996, Meletti et al., 2016).

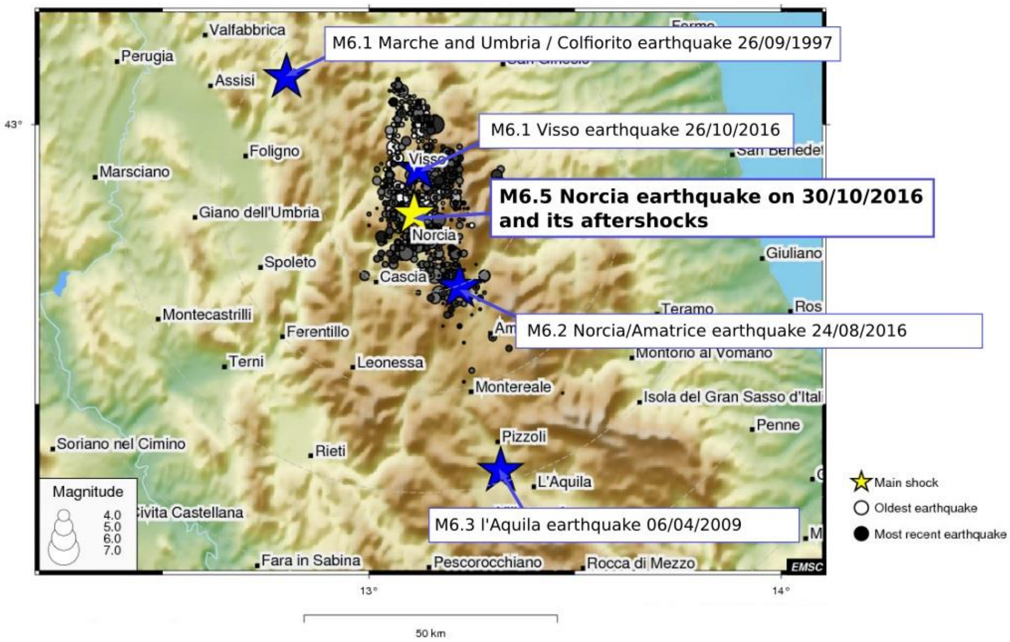


Figure 5: Epicentral map of the 2016 Central Italy sequence (EMSC); stars denote the strongest earthquakes in the last 20 years.

Both absolute single event, and event-to-event relative measurements of analysis were used. The results indicated a prevalent amplification of the ground shaking along the NW-SE axis of the Apennines and, in particular, towards the N of the epicentral area. The majority of the site effects were coincident with the local basins characterised by soft shallow velocity layers, and a consistent part of that relative amplification was attributed to source directivity effects. Beside those, the observed amplification could also be attributed to velocity/attenuation structural complexities occurring north of the seismic sequence active area. Overall, the important outcome of the analysis was that source directivity seems to be a common and widespread feature of the M≥4.0 events (Lombardi, 2016).

4 OBSERVED VS SEISMIC DESIGN GROUND MOTIONS:

The ground motions recorded during the sequence were compared with the values used for design, according to the Italian seismic code. Because the design spectra are de facto uniform hazard spectra (UHS) from probabilistic seismic-hazard analyses (PSHA), this can also be presumed as a comparison between the ground motions recorded during the sequence and the reference values from PSHA.
Four events with magnitude larger than 5 were considered. The stations with the largest horizontal PGA for each event were selected: Amatrice AMT for the M6.0, CMI for the M5.4 and 5.9, and T1213 (temporary station) for theM6.5 earthquakes. The observed PSAs, at 5% of critical damping, were compared with the elastic design

spectra provided by the code for two different return periods, 475 and 2475 years. The spectra were computed for the Eurocode 8 soil categories; for example, soil class B for AMT, soil class C for CMI, and soil class A for T1213. Only the AMT station recorded all four named events.

Comparisons are presented in Figures 6 and 7. It can be seen that in the 0 to 0.8s period range (of biggest interest in structural engineering), records exceed the design spectra, even at a return period of 2475 years. Spectral ordinates rapidly fall as the period increases, which is expected for moderate magnitude events recorded close to the source.

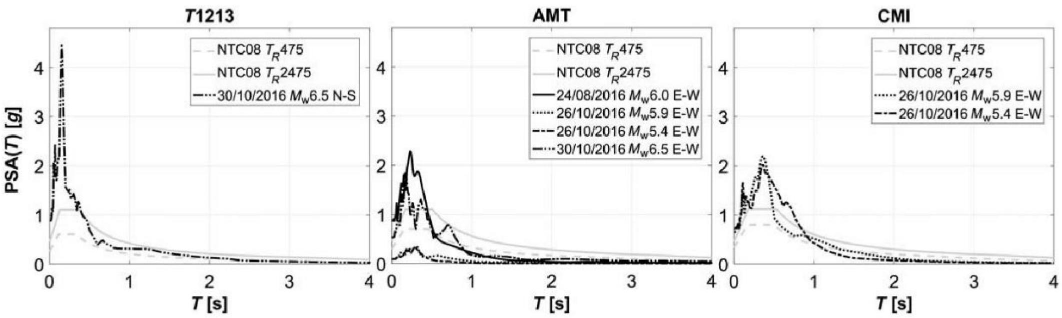


Figure 6: Comparisons between the code design spectra and elastic spectra from the recording station with the highest PGA in each event.

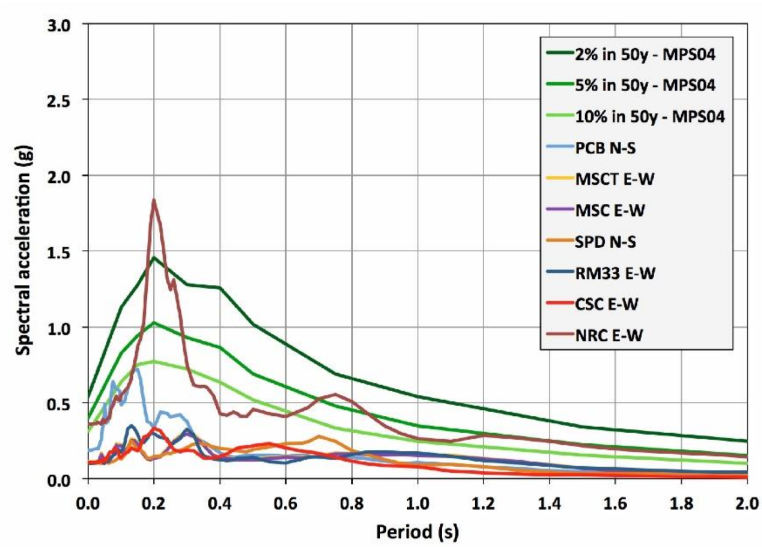


Figure 7: Comparison between the maximum horizontal acceleration response spectra (5% damping) of the Amatrice M6.0 mainshock recorded at the stations located between 16 and 25 km from the epicenter and the UHS of MPS04 for soil class B, at a node located at about 20 km to the southeast of AMT, for 2%, 5% and 10% probability of exceedance in 50 years.

Figure 7 compares the UHS evaluated by MPS04, corrected for soil class B, with the maximum component of the recorded horizontal ground shaking for stations located at epicentral distances less than 25 km. UHS in Figure 7 are computed for a site located at about 20 km to the southeast of Amatrice AMT station. The response spectrum at NRC (Norcia) station, the second nearest station to the epicenter of the August 24th earthquake, shows a sharp peak at 0.2 s that is higher than the UHS for 2475 years and a second peak at ~0.7-0.8 s which exceeds the UHS for 975 years. At the other stations, the maximum horizontal components are always lower than the MPS04 UHS for 475 years return period.

In fact, exceedance of design actions is expected to occur for large earthquakes recorded at near-source stations, because UHS is likely to be exceeded when the considered site is in the vicinity of the seismic source. On the other hand, at larger distances the design spectra are expected to be larger than observations. That is illustrated via statistics of the spectral exceedances of design values recorded during the M6.5 event on 217 stations about 6% of which recorded intensity exceeding the corresponding design values for PGA for both 475 and 2475 years return periods.

Also, pulse-like near-source ground motions may be the result of rupture forward directivity and the radiation pattern of the seismic source (Somerville et al., 1997). More specifically, seismic waves generated at different points along the rupture front may arrive at some site simultaneously leading to constructive wave interference.

5 DISCUSSION AND SUMMARY:

Comparison of the design response spectra of the Italian seismic code with the spectra of the observed ground motion in the epicentral area shows that the latter far exceeded the design actions in the range of short to medium periods, though the actual number of records is relatively small. Near-source ground motions recorded during the strongest events in the sequence revealed evidence of possible pulse-like directivity effects.

The possible reasons for the discrepancy between the expected and recorded values at the near-source area could be the impact of the adoption of different Ground Motion Predictive Equations GMPE on the PSHA assessment. Italy had a reference seismic hazard model MPS04 in accordance with the Prime Minister Ordinance since 2006, which was based on their 2004 seismicity map and the hazard was computed using the same earthquake rate model. A more recent GMPE model called ITA10 (Bindi et al., 2011) shows a strong increase of expected values for both PGA and UHS, thus making the PSHA estimates more consistent with the observations.

The recent GMPEs produce higher hazard estimates due to stronger near source shaking and higher uncertainty (standard deviation) than the earlier ones. Moreover, it has to be emphasised that the ITA10 equation was derived from an Italian strong motion dataset that included also recordings in the near field, that were lacking in previous GMPEs used for the MPS04 model. And the very high accelerations recorded at Amatrice AMT station (the largest PGA ever recorded in Italy) could be due to pulse-like motions in the near field as discussed above although this has also been observed over recent years in New Zealand, over the last 50 years in the US, and in mines when they are monitored.

Any PSHA model, however, has to be considered with respect to the available data and knowledge at the time of its release. MPS04 adopted the best input data available in 2004, and the same applies to projects later. As an example we pointed out how the use of a recent GMPE can change the hazard. For that reason, the Italian reference seismic hazard model is currently under re-evaluation, taking into account state-of-the-art methodological approaches, input data, and computational codes.

In Australia, steps were taken towards a National Seismic Hazard Assessment by a team of experts who worked together on the expert elicitation at Geoscience Australia in March 2017. At the Canberra workshops, different aspects of the seismic hazard calculation were addressed, such as: source modelling and zonation, fault representation, re-evaluation of magnitude-frequency relationships and usage of the uniform earthquake catalogue. Future workshops, hopefully adopting some of the revised GMPE models coming out of the recent Christchurch and Italian experiences, will be used to update the next generation of the Australian Building Code.

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