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What is an exceptional earthquake?

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What is an exceptional earthquake?

Introduction

On 8 September 2020 the Italian media reported that the Court of Rieti (central Italy) found guilty with imprisonment between five and nine years the five defendants for the collapse of two public housing buildings and the death of 18 people, following the 24 August 2016, M_w 6.0, Amatrice earthquake; the first of a long-lasting earthquake sequence featuring nine M_w >5 events, the largest being a M_w 6.5 near the town of Norcia (Figure 1b, 1c). The court rejected a claim of exceptionality of the ground shaking put forward by the defendants and stated that the collapse was caused by "... *well-identified design and building flaws, violating specific legal provisions and technical construction standards*...".

Similarly to the L'Aquila Trial (Cartlidge, 2014; Stucchi *et al.*, 2016; Imperiale and Vanclay, 2019), which followed the 6 April 2009, M_w 6.1, L'Aquila earthquake (Figure 1a), the Amatrice Trial is bound to become a landmark in the history of earthquake-related jurisprudence. After the publication of the 500 pages-long sentence on 9 February 2021, the national media revealed that in early September 2020 the lawyer of some of the defendants had deposited an *ad hoc* report signed by the current president of Istituto Nazionale di Geofisica e Vulcanologia (INGV). Based on that report, in a TV interview of 3 September 2020 (see *Data and Resources*), five days before the verdict, the same lawyer stated that[1] "... *indisputable and objective data obtained by INGV show that ground accelerations were four times larger than those allowed by the regulations*...". He added that "... *Any building would have collapsed, regardless of its conditions*...": an especially strong statement implying that the earthquake was *exceptional* – an adjective recurring forty-two times in the verdict – based on the actions it generated. This claim was eventually rejected by the court, but it has been resubmitted for the appeal.

This stance has been repeatedly put forward, at least in recent Italian earthquake history. Following the 31 October 2002, M_w 5.8, San Giuliano di Puglia (southern Italy) earthquake, lawyers invoked the *unforeseeable, extraordinary and exceptional nature of the event* to justify the collapse of an elementary school and the death of 27 kids and one teacher (e.g. Maffei and Bazzurro, 2004). Similarly, *vis maior* (force majeure) was invoked to justify the collapse of a student dorm and the death of 11 people in downtown L'Aquila, following the 6 April 2009 earthquake (Alexander and Magni, 2012; Mulas *et al.*, 2013). In both cases, however, the court stated that the collapsed buildings had been poorly built or inappropriately modified.

The L'Aquila, Amatrice and Norcia earthquakes were indeed quite severe as the measured shaking intensities were among the largest ever observed in Italy. According to the ITACA database (D'Amico *et al.*, 2020), they were recorded by accelerometers located very close to the source – that is, above it or within a distance comparable to the size of the causative fault – and caused horizontal PGAs between 0.66 g (L'Aquila) and 0.95 g (Norcia: Figures 1a, 1c). Nevertheless, a simple calculation for the Amatrice event, based on recent Ground Motion Prediction Equations (GMPEs; see Bindi *et al.*, 2014), shows that the observed PGAs fall within 1.7 sigma of the predicted values for the given magnitude and source-to-site distances.

[1] Original statement: "Dato incontrovertibile e oggettivo ricavato dall'INGV ci dice che le accelerazioni al suolo erano quattro volte superiori a quelle consentite dalla norma. Qualsiasi edificio sarebbe crollato in qualsiasi condizione questo si fosse trovato."

Earthquake Exceptionality Through History

So, can the Amatrice earthquake be claimed *exceptional*? This question will inevitably resurface in the appeal to this trial and in other ongoing trials concerning the effects of the 2016 earthquakes.

First, what is the common-language definition of *exceptional*? The Cambridge Dictionary reads: "*Much greater than usual, especially in skill, intelligence, quality, etc.*". The American Dictionary adds "*Not like most others of the same type; unusual.*" The etymology takes us back to *exceptu(m)*, i.e. "except for", the past participle of the Latin verb *exciperĕ* (*to take exception*, or *to object*, in modern English), and to *exceptione*, a semantically clear expression indicating something that falls outside 'normality'. Interestingly, in 14th century Italian this word is attested with a legal meaning (Cortellazzo and Zolli, 1984):

> «A reason that, during a trial, may be used in front of the court to obtain a decision that is different from what was requested (*by the prosecutor*)» [2]

In science, including Seismology, the word *exceptional* necessarily implies a measurement, or a behavior, or a sequence of events standing out from 'normality'; in other words, an *outlier*, for whatever reasons. Defining a *norm* in the experimental domain, however, requires formal, unambiguous criteria based on a sufficient data sample. Fortunately, earthquakes become rarer as their magnitude increases; therefore damaging earthquakes are infrequent, also because since the dawn of civilization, structures were conceived to withstand the most frequently expected shaking levels. As a result, nearly all earthquake catalogues worldwide are made up of *isolated occurrences*, with major exceptions only in subduction zones, where repeating events have been described in the literature (e.g., Mochizuki *et al.*, 2008; Bilek and Lay, 2018; Uchida and Burgmann, 2019). Even the central and eastern Mediterranean earthquake record, one of the longest worldwide (the oldest reported event occurred in 760-750 B.C.: Guidoboni *et al.*, 1994, 2019), hardly reports events that appear to be repeats of previous shocks; i.e., earthquakes generated by the very same seismogenic source. Nevertheless, many historical earthquakes have been considered *exceptional* by witnesses, whose only term of reference was their own living memory.

One of the most debated cases is that of the 365 A.D. earthquake in western Crete. Initially referred to as 'the universal earthquake' by early investigators as it appeared to have involved the entire central and eastern Mediterranean, it was later scaled back following a reappraisal of written and archaeological sources (Jacques and Bousquet, 1984; Guidoboni *et al.*, 1994). As for Italy, most medieval sources report the effects of the 3 January 1117, northern Italy earthquake (estimated M_w 6.8: Figure 2): another presumed giant event, which devastated important cities and monasteries over a 30,000 km^2 large area between Milan, Venice and Modena, one tenth of the whole Italian territory, and was initially held responsible for damage even beyond this region (Guidoboni *et al.*, 2005). The 5 December 1456 earthquake (estimated M_w 7.2), which reportedly devastated a large portion of southern Italy, was shown to include at least three major shocks occurring within a month (Guidoboni and Comastri, 2005; Fracassi and Valensise, 2007). Also the 11 January 1693, southeastern Sicily earthquake (estimated M_w 7.3), which caused extensive damage in Palermo, over 180 km from the epicenter, was deemed extraordinary; and even the catastrophic effects of the relatively

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[2] Original statement: «Ragione che, in un processo, può essere adottata davanti al giudice perché provveda diversamente da come gli è stato chiesto» (1301-1357, notary statement from the city of Arezzo; 1342, *Statuta* of the city of Perugia).

recent 28 December 1908, M_w 7.1, Messina Straits earthquake, were largely unexpected, although the interpretation of archaeological sources revealed the occurrence of a possible predecessor of this event in the 4th century A.D. (Guidoboni *et al.*, 2000).

Modern seismotectonic and paleoseismological evidence (Galli *et al.*, 2008; DISS WG, 2018,) shows that all of these earthquakes, including the 2016 sequence in the central Apennines, have occurred repeatedly in the geological past, but also that their recurrence interval is millenary and they may only appear in the extended geological record. Therefore they are not *exceptional* but simply *rare*, implying that each of them was likely the first of its kind to be witnessed and recounted in writing.

An Instrumental Perspective

The issue raised by the president of INGV and aired by one of the lawyers, however, refers to instrumental observations of earthquake shaking, and hence to presumably objective measures. But, once again, such measures can hardly be brought back to an accepted standard.

Instrumental data have shown that while some earthquakes generate especially large ground motions uniformly (i.e., those having a large inter-event term of the ground motion prediction equations), unusually large motions may occur at selected locations due to a combination of source (e.g. forward directivity), path, and site effects; in this latter case the earthquake is peculiar only at the sites affected by these situations.

Common biases arise mostly from the circumstance that the investigation of earthquake ground shaking is a rather recent branch of Seismology, as the first accelerograms used for engineering purposes are from the 10 March 1933, M_w 6.4, Long Beach (California) earthquake (Figure 3, left). As recalled by seismologist Igor Beresnev (Beresnev, 2019) "*...Prior to the 1971 San Fernando, California earthquake, it was commonly thought that the peak (maximum) ground acceleration could not exceed half of g...*". He noted that the relatively small 22 February 2011, M_w 6.3, Christchurch, New Zealand earthquake, caused accelerations up to 2.2 g: a peak comparable to that caused by the mighty 11 March 2011, M_w 9.1, Tohoku earthquake, causing extreme damage over a proportionally smaller area. This happens because most strong-motion networks provide a very sparse sampling of the ground-motion field, and the largest motions are likely to be missed (e.g. Strasser and Bommer, 2009). But over the past five decades the number of accelerometers has increased enormously worldwide, resulting in a much larger probability that one or more instruments fall close to the source of a large earthquake, and therefore in recorded accelerations that were considered unattainable until recently (Figure 3 right). Along with the records from the recent Italian earthquakes, these extreme accelerations suggest they are all but *exceptional*, and not even too rare. In fact, research shows that they can hardly be proven *exceptional* quantitatively, also with respect to hazard estimates (e.g., Iervolino 2013).

Conclusions

The alleged *exceptionality* of any given earthquake must always be considered against the historical, cultural and scientific backdrop of the time of its occurrence; and, most importantly, it requires a convincing criterion allowing a formal assessment in the context of the purposes for which exceptionality is invoked. In fact, earthquakes have often been interpreted as *exceptional*. Current research in historical seismology allows us to evaluate older events based on their actual effects, not on their perception by contemporaries. Yet, the conflict between the rarity of large earthquakes and the youthfulness of modern instrumental seismology has made also recent events appear *exceptional*: this is generally due to lack of previous experience, limited consideration of historical evidence, and overconfidence in the available knowledge and models.

Nevertheless, seismologists keep learning from experience, based on the progress of instrumental data, of geological and historical data and of interpretative models.

In their turn, structural engineers are progressing in structural design and retrofitting, so that the rate of events causing structural collapse or endangering the life of occupants can be orders of magnitude lower than that at which exceedance of design actions is expected (e.g. Iervolino and Pacifico, 2021). This allows for achievements such as the survival of Norcia (Putrino and D'Ayala, 2019), a magnificent ancient town sitting atop a fault capable of a M_w 6.5 quake.

Within this framework, invoking the *exceptionality* of a modern earthquake implies introducing a deceptive and quantitatively undefined criterion that denies these knowledge advancements, ultimately denying the scientific method itself.

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

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Data And Resources

- TV interview with one of the lawyers of the Rieti Trial (released on 3 Sep 2020, five days before the verdict): https://video.sky.it/news/cronaca/video/sisma-amatrice-riparte-processo-per-crollo-di-due-palazzine-612861
- Sentence of the Italian Supreme Court of Cassation, the highest judicial authority in Italy, concerning the responsibilities for the collapse of an elementary school and the death of 27 kids and one teacher following the 31 Oct 2002, M_w 5.8 San Giuliano di Puglia (southern Italy) earthquake: https://olympus.uniurb.it/index.php?option=com_content&view=article&id=4120:cassazione-penale
- The intensity data and the supporting info for the 3 Jan 1117, M_w 6.8, Veronese earthquake can be found in the Catalogue of Strong Earthquakes in Italy and in the Mediterranean area (http://storing.ingv.it/cfti/cfti5/quake.php?00035EN: Guidoboni et al., 2019).
- The seismogenic sources shown in Figs 2 and 3 were taken from the Database of Individual Seismogenic Sources (DISS), Version 3.2.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas (http://diss.rm.ingv.it/diss/).
- The data and elaborations shown in Figs 1 and 3 were taken from ITACA - Italian Accelerometric Archive v. 3.1 (http://itaca.mi.ingv.it/ItacaNet_31/), and from the ShakeMap Project (http://shakemap.ingv.it/shake4/index.html).

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Figure Captions

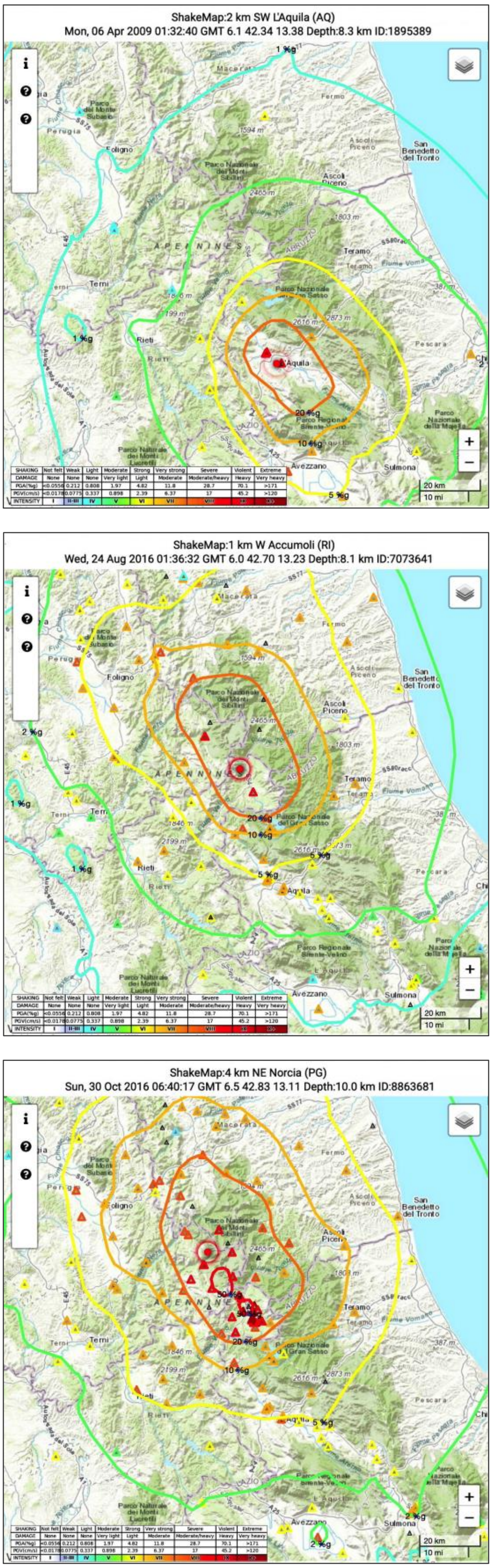
Figure 1 - ShakeMap computed for the 6 April 2009 L'Aquila, 24 August 2016 Amatrice (Accumoli) and 30 October 2016 Norcia earthquakes, using INGV's ShakeMap project (Michelini *et al.*, 2020): the ground motion intensity measure is horizontal Peak Ground Acceleration (PGA). The effects of the first two events, which share a similar M_w (6.0-6.1), seem quite comparable, whereas the 30 October event exhibits larger ground motion intensity, in keeping with its larger M_w (6.5). PGA is only one of the available ground motion intensity measures, yet it is often used to compare the effects of different earthquakes. Nevertheless, ShakeMap comparisons using other intensity measures show similar results.

Remarkably, not only the 30 October earthquake was not considered *exceptional*, but the extraordinary performance of Norcia's historical center, rebuilt following the large 1703 earthquake and retrofitted at least twice following major shocks in 1859 and 1979, is regarded by many as a benchmark in seismic resilience (e.g. Valensise *et al.*, 2017).

Figure 2 - Despite its age, the 3 January 1117 earthquake is very well documented by contemporary sources and by evidence for damage repairs in cathedrals and churches, some of which are still visible today. It is the largest known earthquake of northern Italy (see main figure), but it was initially believed to have caused damage from central Europe to Tuscany. This event was later interpreted in the light of many contemporary sources of various typology, which made it possible to identify two additional minor shocks: in southern Germany, 12-15 hours before the mainshock in Italy, and in the Tuscan Apennines, perhaps in the following days (Guidoboni et al., 2005: see inset on the left). The intensity reports are from the Catalogue of Strong Earthquakes in Italy and are shown here along with Individual Seismogenic Sources (from DISS WG, 2018). The area affected by intensity VII and larger encompasses most of the Po Plain, a region that features the largest concentration of population and economic activities countrywide. A repetition of this earthquake would be catastrophic, but certainly not exceptional.

Figure 3 - Left) History of largest recorded values of horizontal PGA, in Italy and worldwide, and cumulative number of accelerometric records available for Italian earthquakes (from Suzuki and Iervolino, 2017, redrawn). Since the 10 March 1933, M_w 6.4, Long Beach (California) earthquake, the maximum recorded ground motion intensity has been increasing at an exponential pace. This effect is unlikely to reflect a systematic trend in worldwide (and Italian) seismicity, but is primarily a result of the fast increase in the density of seismic monitoring networks.

Right) Current distribution of accelerometric stations (blue triangles) in the area hit by the 23 November 1980, M_S 6.9, Irpinia (southern Italy) earthquake: the red boxes are the surface projection of its presumed causative ruptures (from the DISS database: DISS WG, 2018). The stations that recorded the event are shown in red: they all reported relatively small accelerations (0.06 to 0.32 g), reflecting the circumstance that no station occurred in the near-field of that event. The largest acceleration was recorded at Sturno (STR), 14 km NW of the closest edge of the fault, probably also as a result of northwestward rupture directivity. Today the same earthquake would be recorded by as many as 15 accelerometers lying directly above the rupturing faults.



a)

b)

c)

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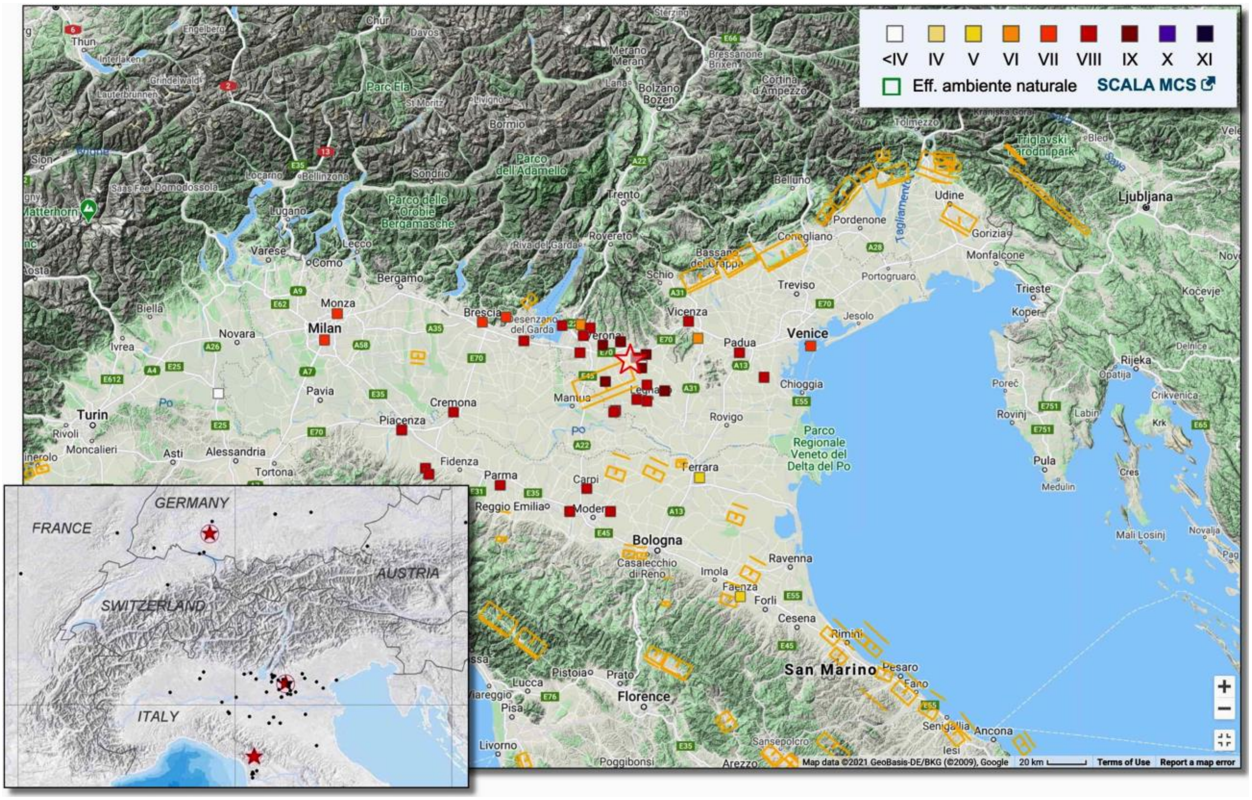

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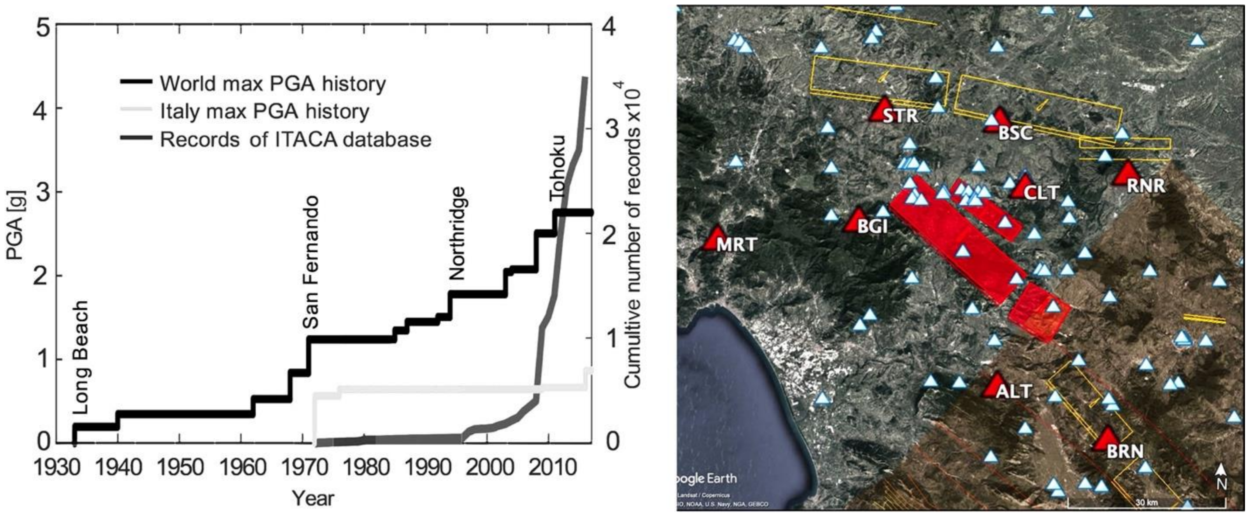

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