Ground-Motion Observations and Probabilistic Seismic Hazard: Frequently Asked Questions

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Abstract

Observed exceedances of ground-motion intensity from probabilistic seismic hazard analysis (PSHA), in countries where it is used for structural design, spark significant public attention, rekindle scientific debates, and are sometimes discussed in trials about the accountability for structural failures and other earthquake-related losses. This short article addresses, in a question-reply format, some recurring issues and related research findings that should be carefully taken into account by those who author or face these reasonings. It considers Italy as a reference, yet the discussed issues are common to several other countries worldwide and thus may be interesting at an international level. The arguments provided, mainly stemming from the fact that observed cases of exceedance should not necessarily be considered a failure of PSHA, can possibly help in gaining a more informed perception of seismic hazard assessment and structural design as implemented in building codes.

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Introduction

In countries such as Italy, where ground-motion intensity values for structural design are directly based on probabilistic seismic hazard analysis (PSHA; e.g., McGuire, 2004), arguments based on the comparison of recoded ground motions with those from PSHA are as frequent as moderate-to-high-magnitude earthquakes. This is because, in the Italian code (CS.LL.PP., 2018), design is based on the structure not failing to meet a performance objective for a ground-motion intensity that has a given exceedance return period at the construction site (i.e., a certain probability of exceedance in a given time interval). Observed exceedances of design ground-motion intensities (e.g., Fig. 1; adapted from Iervolino *et al.*, 2018) are, in some cases, accompanied by iconoclastic conclusions about inadequacy of the seismic design codes and, often, of the seismic hazard models and analyses they are based on. In addition to increasing the mistrust in (earthquake) science, these arguments can cast shadows on the safety of the buildings built according to current standards. To help shed some light on these issues, this short article provides replies to questions about some recurring issues and points to related research findings that should be carefully considered by those who author or face these reasonings. More specifically, it is addressed: (1) whether and to what extent exceedances are should not be surprising; (2) that exceedances alone are—in general—not sufficient to question the PSHA results used for design; (3) what kind of performance should be expected by code conforming, as well as precode or lowcode, structures, in case of exceedance; and (4) whether such exceedances could be limited or even avoided by increasing the design ground-motion intensity.

Is It Possible to Avoid Exceedance of Ground-Motion Intensities from PSHA?

No, it is practically impossible to avoid exceedances, for any ground-motion intensity measure (e.g., peak ground acceleration [PGA], pseudo-spectral acceleration [SA], etc.). In fact, modern seismic design codes acknowledge that there is an unavoidable risk that any design intensity is exceeded (and that there is always an inherent risk of structural failure for code-conforming structures). Consequently, design standards (e.g., Comité Européen de Normalization [CEN], 2004; CS.LL.PP., 2018), rather than directly setting a design ground-motion intensity, instead set a tolerated probability that the design intensity will be exceeded at the construction site during the intended service life of the structure. This is equivalent to setting an exceedance return period (the reciprocal of the exceedance rate); for example, if the exceedance return period is 475 yr, then there is a 10% chance that such action will be exceeded in 50 yr, by definition. Once this probability of exceedance has been established, the ground-motion intensity that corresponds to

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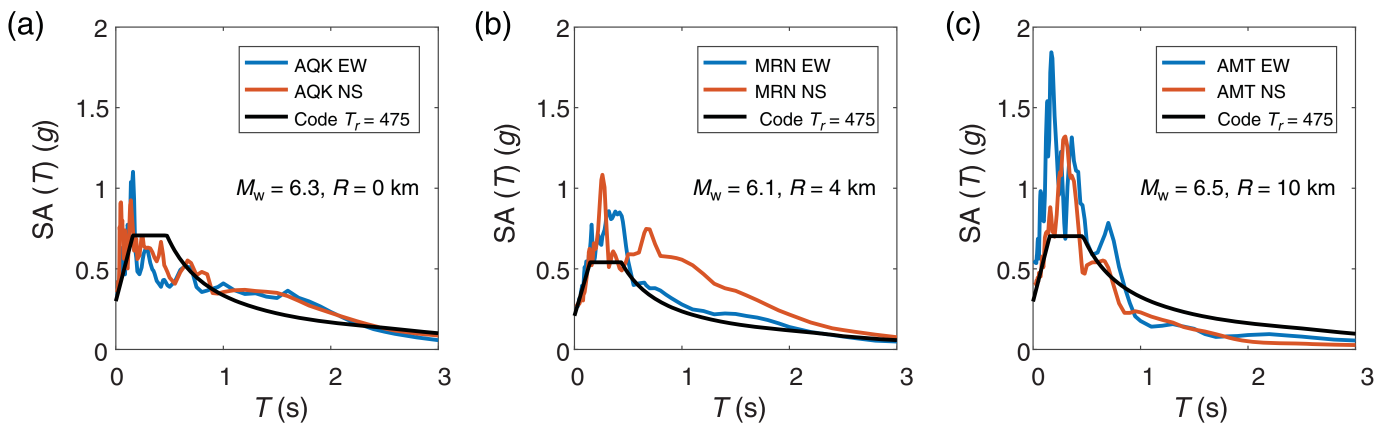

Figure 1. Recorded response spectra and 475 yr design (i.e., uniform hazard) spectra at some sites (where recording stations were present) during three recent Italian earthquakes: (a) L'Aquila downtown (AQK) during (2009) L'Aquila earthquake, (b) Mirandola (MRN) during the (2012) Emilia earthquake, and (c) Amatrice (AMT) during the (2016) central Italy earthquake. Station details and recordings may be found in the Italian Accelerometric Archive (see Data and Resources). Adapted from Iervolino *et al.* (2018).

it, at the construction site, is determined via PSHA. This procedure ensures that the design intensities are consistently different for different sites; that is, they have—for territorial equity—the same probability (risk) of being exceeded (codes consider typical structures, such as buildings, as point-like; thus, in its logic it does not directly consider that a single earthquake can hit multiple sites at the same time).

Given that the design intensity is set based on a probability that it will be exceeded, it is very strange to be surprised by such an exceedance being observed. At most, one can be surprised (i.e., PSHA results can be blamed) if, at the site of interest, the ground-motion intensity being in question is exceeded too frequently (or even too rarely) compared to what is indicated by the hazard analysis; that is, the exceedance return period inferred from observations is much shorter (or much longer) than what predicted by PSHA. However, because typical design return periods are intentionally large, for example, 475 yr, the phenomenon at the site is observed rarely at the site, and intentionally so. Therefore, it is difficult to make convincing empirical assessment of the return period at any site (Iervolino, 2013). In fact, it could be easier to empirically validate the results of hazard analysis considering the observed frequency of exceedance of ground-motion intensities with return periods lower than 475 yr. In other words, the lower the return period the shorter the time needed to collect a sample of observations sufficient for a convincing statistical scrutiny of PSHA results for a given site. However, ground-motion intensities with low exceedance return periods are relatively small and uninteresting to structural engineering. The results gathered for them do not apply, at least not directly, to the intensities corresponding to longer return periods, of larger engineering relevance.

This reasoning should also help to understand that, even if the exceedance of the design ground-motion intensity at a given site is a rare phenomenon, looking at a large territory (e.g., the whole of Italy), whenever there is an earthquake, of moderate-to-high magnitude, it is to be expected that it will cause exceedance at some sites (especially in its epicentral area). This is why exceedances do not seem rare to us: because, by definition, they are rare for a given site, but not for a country as a whole (Iervolino *et al.*, 2019).

Why Not to Consider the Worst-Case Scenario Then?

Because it cannot be defined, at least given current knowledge. Perhaps a worst-case scenario can be defined in terms of maximum magnitude (because seismologist often put a cap on the largest magnitude that can come from the seismic sources the site of interest is subject to) and minimum source-to-site distance (e.g., based on the geometry of the source), but it is not yet possible to put a cap on the resulting ground-motion intensity. This is because the residuals of the ground-motion models used in PSHA are typically modeled by means of unlimited random variables (Strasser *et al.*, 2007). In other words, it is generally very hard, if not impossible, to put a limit on the intensity that could be observed for a given magnitude–distance scenario. In fact, specific studies (e.g., Suzuki and Iervolino, 2017) show that the maximum shaking intensity ever observed is continuously increasing, possibly not because the seismic activity in the world is increasing, rather because the number of recordings, since seismic monitoring started, is very rapidly increasing.

Furthermore, even if it may be argued about setting a maximum possible intensity value (e.g., Andrews *et al.*, 2007), it is not granted that design and construction technologies exist to be sure that such an earthquake would not lead the structure to fail. In other words, even if a worst-case scenario could be defined, to guarantee zero structural risk would not be possible. It must also be recalled here that common ground-motion intensity measures used for design (e.g., pseudo-spectral accelerations) have a limited explanatory power of with respect to seismic response of nonelastic and nonlinear structures with many degrees of freedom (i.e., real structures); see, for example, Chopra (2007).

Is the Exceedance of PHSA-Based Ground-Motion Intensities Evidence of Fallacy of Hazard Analysis?

Observed exceedances do not necessarily provide evidence of fallacy of PSHA. In fact, fallacy of PSHA should not be the first suspicion to come to mind when exceedance is observed. One should first think that exceedances of design intensity from PSHA, especially in epicentral areas, are more likely a confirmation, rather than disproval, of hazard analysis results. As discussed earlier, one can think that a country (e.g., Italy) is a target, and earthquake exceedances can be considered as arrows thrown at such a target at a given rate. Because the target is large, each point on it will rarely be hit (say with a return period of 475 yr), but the arrow hits a point at any shot. Therefore, looking at the whole target, the rate of exceedance will be determined by the shooting return period (the reciprocal of the shooting rate), which is much shorter than 475 yr.

It is very easy to demonstrate analytically that, looking at the intensities have a 10% chance of being exceeded in 50 yr at all sites, one should expect that 10% of the Italian territory (i.e., the ensemble of sites) to have experienced at least one exceedance in 50 yr. In this sense, rather than denying the hazard analysis, the exceedances confirm it, unless—as we said earlier—it is shown that the exceedances are too many, that is they are observed in a fraction of sites much larger, on average, than 10% of the territory in 50 yr periods (or too few; i.e., exceedances involve, on average, much less than 10% of the territory in 50 yr). However, neglecting other issues related to the trend of increasing uncertainty in ground-motion models and complexity PSHA study, this assessment is hard to make if several 50 yr intervals of observations are not available. Although this may appear discomforting at first glance, even letting someone to think that "anything can happen", this is typical of rare phenomena and can only be addressed in the short term by more widespread seismic monitoring and experts' continuous effort in improving earthquake modeling for PSHA (Erto *et al.*, 2016).

Finally, answering this question also allows us to return to one of those previous. Although the exceedances observed so far are not in general enough for a verification of the frequency of exceedance site by site, they may enable an overall assessment of the exceedances in countries such as Italy; however, so far even these calculations have never convincingly denied PSHA results (Iervolino *et al.*, 2017).

Given That Exceedance Cannot Be Avoided, When Is It Most Expected to Occur?

It has been discussed earlier that design ground-motion intensities are probabilistically controlled via hazard analysis so that it is rare that such actions are exceeded at the site of construction (for example on average every 475 yr, that is, with 10% probability in 50 yr). Consequently, by definition, they can be exceeded, even if with a programmed probability. Research has shown, and it is also intuitive to guess, that such exceedance is likely to occur when the site is located near the source of an earthquake from a certain magnitude onward. For example, the current seismic hazard model of Italy (Stucchi *et al.*, 2011) inherently predicts that, whatever the construction site in Italy, if it is located near (e.g., within 5 km) the source of an earthquake of magnitude at equal or larger than (about) six, it is expected that the PGA (but also other spectral ordinates) with a return period of 475 yr will be exceeded. These seismic events that if occurring close to the site will cause exceedance of the design spectral ordinates, can be called strong earthquakes because—by definition—in their epicentral area the code-conforming structures are expected to be subject to seismic actions larger than those accounted for in design. As an example, Figure 2 (adapted from Cito and Iervolino, 2020b) reports the map of "strong earthquakes" for Italy. As already mentioned, this does not contradict the hazard analysis, but it is an intrinsic characteristic thereof. In other words, the fact that the site is located in the epicentral area of an earthquake of magnitude from six onward is something that happens—roughly speaking—on average, much more rarely than 475 yr, for any specific site.

What Should Happen to Code-Conforming Structures in Case of Exceedance of the Design Intensity?

State-of-the art seismic design is such that other safety margins for the structure should be expected, for example, because of precautionary material strength used in the design process or specific design approaches such as capacity design (Fardis, 2018), in addition to the rarity of the exceedance of the design intensity. Therefore, it is expected that if the structure is designed for ground-motion intensity with a given return period, for example 475 yr, the return period of the structural failure is larger than 475 yr, possibly by a significant amount. Moreover, the structure is designed in such a way that failure, that is the violation of the design performance, occurs prior to collapse by a large margin; that is, the design failure is not tantamount to complete loss of load-bearing capacity. Instead, the failed structure still possesses some safety against collapse, and this is an additional caution. However, it must be said that, because of the classical approach of modern seismic codes (i.e., unless risk-targeted design is implemented, to follow), the structural safety (the return period of failure) implied by code-conforming design is not generally known to the

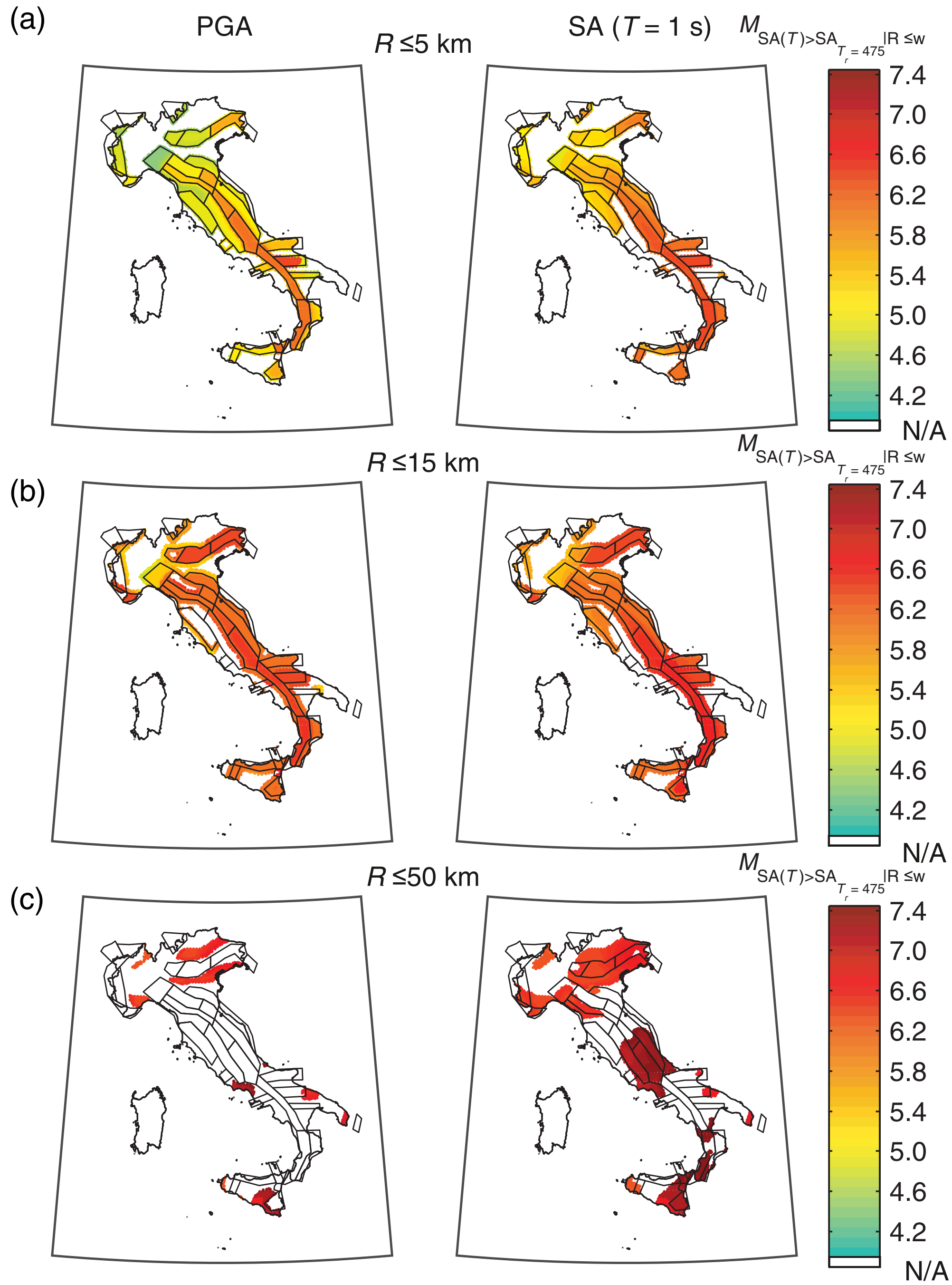

Figure 2. Map of strong earthquakes for Italy according to the current hazard model of Italy (Stucchi *et al.*, 2011); that is, the minimum magnitudes with a probability larger than 50% of exceeding two spectral ordinates with a return period of the exceeding equal to 475 yr, if the earthquake occurs within (a) 5 km, (b) 15 km, and (c) 50 km from the site. Adapted from Cito and Iervolino (2020b).

designer. This is relevant in this discussion, because although it is not legitimate to directly expect collapse upon exceedance of design seismic actions, the remaining margin against collapse each structure can resist in case of such an exceedance, is not explicitly controlled, unless very accurate ex-post (i.e., forensic) engineering analyses of the structural performance are carried out.

A large research project in Italy has found that that this margin changes with the structural typology and with the hazard of the construction site for reasons that are now well understood (Baltzopoulos *et al.*, 2021). In this sense, it is difficult to determine whether and to what extent this additional margin can be relied upon, even for perfectly code-conforming structures; therefore, this is a very sensitive issue as it involves liability (Valensise *et al.*, 2021).

Having clarified the difference between the known risk of exceedance of design intensity and the unknown risk of structural failure given exceedance, it can be concluded that probabilistic seismic hazard maps are often questioned precisely because they are clear in their probabilistic meaning (at least for those who understand the basics of PSHA), while the rest of the structural safety is less transparent. In fact, one can argue that, to help design practice to evolve, earthquake engineering should work on making the rest of the safety margins equally explicit, rather than continuously focusing on the hazard.

Could It Be Appropriate to Increase the Return Period of the Design Intensity, at Least Close to Known Faults?

This is a question that is legitimate to ask, but this is a much more complex issue than it appears. If the return period of the design intensity is the same everywhere, either for a site near a known fault or for a distant one, in principle there would be no need to differentiate between the two. However, it is not currently possible to know all the faults (at least in countries with complex geology such as Italy) and for this reason PSHA often relies on seismic source zones that, in fact, enable not explicitly

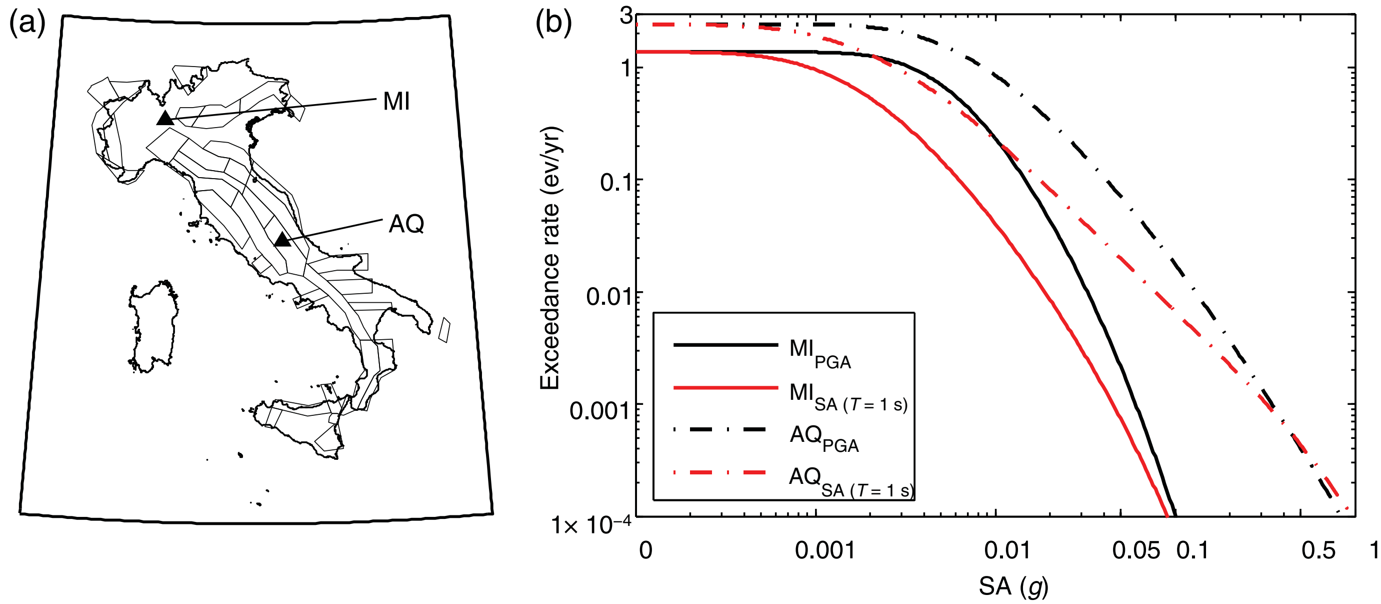

Figure 3. (a) Milan (MI) and L'Aquila (AQ) and the source zone model for the hazard assessment of Italy (Stucchi *et al.*, 2011). (b) Hazard curves (on rock) in terms of two spectral ordinates. Adapted from Cito and Iervolino (2020a).

modelling faults. In addition, engineering seismology research is aware of a so-called near-source effect, that some compare to the Doppler effect in acoustics, that might result in detrimental effects for some structures (see also a following question dedicated to that) and that the classical PSHA does not consider explicitly (i.e., it does so only in an average sense). Therefore, rather than increasing the design return period, it would be more appropriate to refine the source models based on faults.

This allows us to come back to the safety of code-conforming structures, which is still dependent on the seismic hazard of the site, even if the design intensities are defined to have the same exceedance return period at all sites. It happens, in countries such as Italy, that the accelerations with exceedance return periods beyond (i.e., rarer) those considered for design are, at high-hazard sites, disproportionately larger than those at low hazard sites. In other words, the ratio of the acceleration with a return period larger than 475 yr divided by that corresponding to 475 yr is much larger in L'Aquila, that is one of the highest hazard sites in Italy, than the ratio of the accelerations corresponding to the same return periods in Milan, which is a low-hazard site; see Figure 3 (Cito and Iervolino, 2020a).

This means that the risk of failure, to which a code-conforming structure in L'Aquila is exposed, is much larger than that of a structure of the same type designed in Milan, despite the return period of the design ground-motion intensity being the same at both sites. This has nothing to do with PSHA, but with the fact that current (i.e., state-of-the-art) design only considers a limited number of return periods (and other issues), while what happens for larger return periods still affects structural safety. Perhaps this issue can be at least mitigated with the mentioned risk-targeted design that consists in designing by setting a period of return of failure, rather than of the design intensity. Obviously, even in this case PSHA results are used, yet in a different manner.

We Are Mostly Talking about Italy Here. What about the International Debate on the Topic?

These issues are of global importance (e.g., Stirling and Gerstenberger, 2010; Hanks *et al.*, 2012). In the United States there are attempts to move the design approach, as mentioned, from rules that define the probability of exceeding design ground-motion intensity, which is the same across the country, to vary it by trying to control the probability of failure of the structure; that is, via risk-targeted design. This is the right way, as envisioned many decades ago by the father of PSHA, C. Allin Cornell (McGuire *et al.*, 2008), but this approach also has its own problems, mainly due to the fact that the probability of failure of a structure is very difficult to control during design, if strong assumptions are not made. In Europe, meanwhile, work is being done on the revision of Eurocode 8 (CEN, 2004) for seismic design. However, the approach will be the same as the current one that is based on exceedance return period of the ground motion intensity.

What Are Near-Source Effects and Are They Accounted For in Seismic Design Codes?

Among the various effects that are observed close to earthquake ruptures there is one potentially of interest for structural engineering: the so-called pulse-like ground motions due to forward directivity (Somerville *et al.*, 1997). For specific rupture-site configurations, the velocity recording of the seismic shaking can show a large full-cycle pulse that concentrates most of the energy carried by the signal. This may be particularly relevant (detrimental) for structures with vibration periods in some proportion with respect to the duration of the pulse (Iervolino *et al.*, 2012). This is a phenomenon known for many decades and also observed in relatively recent earthquakes (Chioccarelli and Iervolino, 2010). Although ground-motion models used in classical PSHA are calibrated on databases which likely include pulse-like records, classical PSHA only account for this issue in some average sense, which is not very useful for design. In fact, research has proposed an advancement of hazard analysis to explicitly predict (in a probabilistic sense) near-source effects, but it requires a very accurate knowledge of the faults relevant for the site (e.g., Chioccarelli and Iervolino, 2013). Consequently, design codes, so far, do not take them explicitly into account, if not grossly.

What about Precode, Lowcode, Retrofitted, and Poorly Built Structures?

Poorly constructed structures, as well as precode or lowcode, cannot be addressed in a one-for-all answer. These constructions need case-by-case assessment and discussion. On the other hand, the question of structures built with design codes now considered obsolete or before the adoption of any seismic standard is an important issue. In many countries, for example in Europe and Italy, the vast majority of the building stock is of this kind (e.g., Petruzzelli and Iervolino, 2021). Such structures may have been designed only for gravity loads or with seismic (i.e., horizontal) forces evaluated with conventional methods, that is, not on a probabilistic basis, and with design criteria less effective than those we use today (e.g., without capacity design). In both cases, however, these structures have an inherent seismic safety, even if that is less controlled than that of current-code-conforming structures, and with lower expected margins against collapse (e.g., Jalayer *et al.*, 2011). In other words, all the issues discussed earlier for current-code-conforming structures apply to a greater extent.

Concluding Remarks

In this short article, possible (research-informed) replies were given to some frequently asked questions about the exceedance of design ground-motion intensity from PSHA. The following is worth being finally remarked.

- Exceedances of design intensity alone (i.e., if their frequency and/or extent of exceedance is not empirically evaluated) are more of a confirmation of PSHA rather than a disproval.
- Exceedances are expected to be as frequent as moderate-to-high magnitude earthquakes. In fact, in their epicentral areas exceedance it is more likely than not. This is an intrinsic characteristic of PSHA, which acknowledges that a moderate-to-high magnitude occurring close to any site is a very rare phenomenon.
- Near-source effects, for which classical PSHA only accounts in an average manner, do not necessarily need to be called into question to explain observed exceedances.
- Code-conforming structures are expected to have further safety margins against failure (or collapse) once the design intensity is exceeded. However, currently, such margins are not explicitly controlled in design carried out according to most of building codes; thus, whether and how much such margins can be relied upon remains an open issue.

Data and Resources

All data come from the listed references. The other relevant data to this article were provided in Figure 1 at http://itaca.mi.ingv.it/ (last accessed November 2021).

Declaration of Competing Interests

The author acknowledge that there are no conflicts of interest recorded.

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