The Past and Future of Ground-Motion Models: A Review on Uncertainty

Sanjay Bora
GNS Science, Lower Hutt, New Zealand.

ABSTRACT

The ground-motion models (GMMs) are an integral part of a seismic hazard analysis; moreover, they are crucial for earthquake early warning, shake maps and earthquake rapid response applications. In the last two decades, the empirical GMMs have undergone significant development and benefitted from the abundance of instrumentally recorded data on regional and national scales. This has allowed various components of the GMMs to be constrained by the data, such as the recent developments in partially non-ergodic and fully non-ergodic GMMs in certain regions across the globe. However, current non-ergodic GMMs heavily rely on the availability of recorded data. Thus, it remains a challenge to constrain epistemic uncertainty in such non-ergodic terms particularly for regions like New Zealand. Moreover, constraining the scaling of ground-motions for larger magnitude and complex ruptures has remained a challenge.

In this study, we present a historical review of GMMs from the perspective of constraining uncertainties. It will also include discussion of current challenges and opportunities in the context of future development of GMMs. The focus will be on the partially ergodic and fully non-ergodic GMMs. Particularly, how well such non-ergodic path and site terms can be constrained form the instrumentally recorded observations. For example, discussion related to constraints on the epistemic uncertainty in such terms (adjustments) in regions with high potential seismic hazard but without sufficient observations of engineering interests. In this context, the role of physics-based numerical simulations will also be discussed.

1 INTRODUCTION

Ground shaking forecast models typically called ground-motion models (GMMs) are critical component of any seismic hazard analysis. A GMM provides a probabilistic description of ground-shaking in terms of a median and an aleatory uncertainty (also called sigma) model. It essentially represents a conditional distribution of shaking given the earthquake magnitude, distance and site condition information. In probabilistic seismic hazard analysis (PSHA) studies a full probabilistic description of shaking is considered that involves both median as well as the sigma models. In the recent past abundance of recorded data in certain regions has allowed certain scaling components of the GMMs to be well constrained by the empirical data. For example, the distance scaling from small-to-moderate magnitude earthquakes and the linear component of site amplification. In the last one decade, there has been increasing focus towards regional GMMs which are often referred as non-ergodic GMMs in purely statistical terms. However, in data-scarce regions such as New

Zealand (NZ) and some other regions, the major challenge is availability of the recorded data to constrain such regional effects for earthquakes of engineering interest.

Figure 1 Hazard ratio maps for peak ground acceleration (PGA) and spectral acceleration, SA (1s). The ratio is defined as GMCM-2022/GMCM-2010 keeping SRM-2010 common, for VS30 = 250 m/s. a) and c) The ratios for 10% probability of exceedance in 50 years. b) and d) The ratios for 2% probability of exceedance in 50 years.

Another major challenge we face globally is the availability of observed earthquake data for scenarios that often dominate hazard. It is particularly challenging for NZ where the hazard is dominated by large magnitude earthquakes particularly along the eastern coast of the North Island as identified in the recent revision of NZ national seismic hazard model (NZ NSHM 2022) (Gerstenberger et al., 2024). Bora et al. (2024) demonstrated that the major change in hazard along the eastern cost of the North Island was because of the update in ground-motion characterization modelling (GMCM) scheme (Figure 1). Figure 2, clearly shows the larger impact of change in GMCM scheme on the hazard curves mainly in high hazard regions such as Wellington. In Figure 2, the comparison of hazard curves are shown between NZ NSHM 2010 and hazard curves obtained by just updating the GMCM scheme keeping the seismicity rate model identical to NZ NSHM 2010. It is well known that ground-shaking at low annual probability of exceedance levels is affected by sigma of the GMMs. As discussed in later sections the sigma of the GMMs used in NZ NSHM 2022 remains high. Thus, it is crucial to better understand the uncertainty in median and sigma models of the GMMs particularly for rupture scenarios that dominate hazard in a specific region and at a site. In this study, we provide a comprehensive review of the GMMs from the uncertainty perspective.

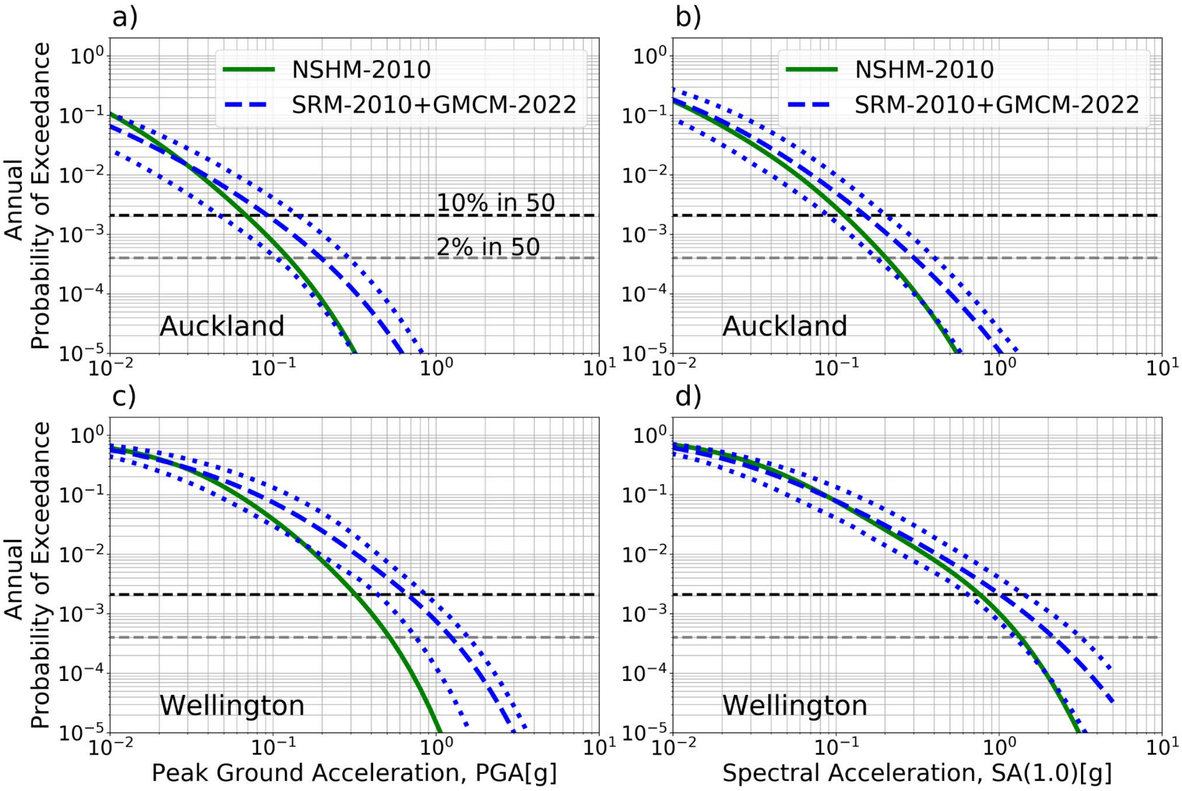

Figure 2 Hazard curves comparison from 2010 NZ NSHM and those from by just changing the GMCM to 2022 GMMs keeping the seismicity rate model (SRM) identical to 2010. The hazard curves are shown for VS30 = 250 m/s.

2 GROUND MOTION MODELS AND UNCERTAINTY

As noted in the introduction of this article, GMMs provide a conditional distribution of ground-shaking as a function of magnitude, distance and site condition information. The distribution is represented by a log-normal distribution of a chosen ground-motion intensity measure (IM) such as peak ground acceleration (PGA). It is described in terms of a median (or mean in log) and a sigma. Figure 3 uses a simple cartoon to demonstrate the concept median and sigma. Assuming that the median has captured the current state of knowledge in terms of magnitude and distance scaling, the sigma is referred to as aleatory uncertainty reflecting randomness in the nature of ground-shaking. Modern GMMs prescribe sigma models as a function of magnitude, distance and site condition information in addition to the median models. Given that our knowledge of earthquake processes and wave propagation is limited and also the recorded data used to calibrate the GMMs is not complete, there is always some uncertainty associated with our estimation of median and sigma from a GMM. This uncertainty is often referred to as epistemic uncertainty. However the separation of aleatory and epistemic uncertainty is not absolute, it is always model and context dependent. For PSHA studies, uncertainty in both the median as well as sigma models is important.

Figure 3 A representative cartoon depicting the concept of median model and aleatory uncertainty in ground-motion models.

2.1 Uncertainty in Median and Sigma

Uncertainty in the median and Sigma models of GMMs mainly stems from the limited recordings available for certain magnitude and distance ranges. Globally observed earthquake records are scarce for events M > 6.5. The situation is particularly challenging for NZ as instrumental recordings from larger magnitude crustal as well as subduction events are rarely available. This results in significant amount of epistemic uncertainty in the ground-shaking forecast for future events. The uncertainty in median is important at all APoEs and the impact of sigma is mainly dominant at lower APoEs (Bommer and Abrahamson, 2006).

In the last two decades, there have been significant efforts to collect and compile instrumentally recorded data that has resulted in significant increase in data repositories in certain regions of the world such as California and Japan. Moreover, there has been significant development in our understanding regarding magnitude and distance scaling of ground-shaking. These combined efforts culminated in more advanced versions of the GMMs such Next Generation of Attenuation (NGA-West1) and NGA-West2 GMMs for active shallow crustal earthquakes. Similar efforts were also made in Europe. As noted by Douglas (2010), there has been significant increase in the number of GMMs in last two-three decades. A major question in this regard is: whether such increase in data and better understanding of earthquake process results in lower epistemic uncertainty the ground-shaking forecast over time? Figure 4 depicts uncertainty in both median and sigma models for three generations of GMMs. Figure 4a shows comparison of standard deviation of median models from GMMs that were developed in 1997, NGA-West1 (2008), NGA-West2 (2014) mainly based on events recorded in California. Similarly Figure 4b shows comparison of standard deviation of sigma models from the same set of GMMs. Both the comparisons are shown for an event M6 at 20 km distance. It is evident from both the figures the uncertainty in both median and sigma has not reduced over time as a result of more data and better knowledge. This becomes rather challenging for events which are rarely recorded such M > 7.5 which is the case for NZ. Figure 5, shows the comparison of Sigma models for active shallow crustal and subduction events for rupture scenarios that dominate hazard in Wellington (Gerstenberger et al., 2024). Clearly, there is significant scatter between the models particularly at short vibration periods. This has been one of the main reasons for increased hazard in Wellington at short periods and at 2% PoE in 50 years.

Figure 4 Plots showing comparison of uncertainty in a) median, b) aleatory uncertainty of GMMs over time.

Figure 5 Plots showing comparison of aleatory uncertainty from GMMs used in NZ NSHM 2022: a) for crustal sources, b) subduction interface sources.

3 NON-ERGODIC GROUND-MOTION MODELS

As noted in the previous section, the increase in the volume of the observed data and better understanding about earthquake processes does not result in lower epistemic uncertainty in both sigma and the median models of the GMMs. This large uncertainty mainly in sigma is attributed to the use of earthquake recordings from multiple regions, sites and source zones with datasets following individual underlying distributions that essentially results in inflated sigma. In other words, there are systematic variations in the ground-shaking between sites, between regions and between source zones. When such systematic biases are not accounted in the data and it gets accounted as random bias that results in larger sigma. In the last one decade availability of earthquake recordings from small-to-moderate magnitude earthquakes in certain parts of the globe has allowed such regional variations to be explicitly accounted in the median models of the GMMs. For example, ample records at various sites allows the site-term to be well constrained and the site-to-site variability to be removed from the sigma such models were called partially ergodic GMMs. Similar concepts hold for source zones and wave propagation that repeatable effects can be modelled in the median models resulting in further decrease in sigma. Such GMMs are called fully non-ergodic GMMs. Clearly, non-ergodic GMMs result in lower sigma however, a major challenge for such GMMs is to constrain epistemic uncertainty in such site-specific, path-specific and source-specific median models. In other words, how well we know that such site and region specific variations in ground-shaking represents the true variation?

4 CONCLUSIONS

In this study, we present a comprehensive review of the GMMs mainly from the perspective of uncertainty. We separately discuss the uncertainty in both median and sigma models of the GMMs because both are important for PSHA studies. Importantly, sigma of the GMMs has larger impact on hazard at lower APoEs. I discuss, the philosophical aspects associated with GMMs that were developed in last two-three decades. Then I provide a perspective from various datasets available so far. In that context, the paucity of recorded data in high hazard regions such as NZ poses a significant challenge for GMM developers. Thus, I will also provide insights how physics-based ground-motion simulations can help in constraining median models for certain regions and sites. Importantly, they can be considered to provide constraint on epistemic uncertainty for rupture scenarios that are never/rarely recorded.

5 REFERENCES

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