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Fifty years of ground-motion models

John Douglas^{1,*}

¹BRGM (French Geological Survey), 3 avenue C. Guillemin, BP 36009, 45060 ORLEANS Cedex 2, France; *Author for correspondence, e-mail: j.douglas@brgm.fr

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Abstract

It has now been over fifty years since the first model for the prediction of earthquake ground motions accounting for both magnitude and distance dependence was derived directly from strong-motion data (Esteva and Rosenblueth, 1964). These models are commonly known as: ground-motion models, ground-motion prediction equations (GMPEs) or attenuation relation(ship)s. They are one of the key components of seismic hazard assessment since they predict the median ground motion at a site and its variability given the occurrence of a particular earthquake at a certain distance. A summary of the history of GMPEs and suggestions for future developments are presented here.

1. Introduction

GMPEs are currently published at the rate of more than one a month and at the last count the total number of equations for the prediction of peak ground acceleration (PGA) was more than 400 (Douglas, 2014). The purpose of this paper is to summarize the current state of the art in the field of GMPEs. The improvements made since the first GMPEs were developed in the 1960s are highlighted in terms of, for example: the increase in the quantity and quality of ground-motion data used; the increase in the complexity of the models; and improvements in the derivations methods. Progress in ground-motion modeling is highlighted based on a meta-analysis of the recent GMPE compendium of Douglas (2014).

2. Recent developments

Douglas (2003) provided a review of empirical GMPEs published until the early 2000s for PGA and linear elastic response spectral ordinates. In the decade since then, GMPE developers have concentrated on: improvements in the estimation of the ground-motion variability (standard deviation, σ) associated with their models and its components, including estimating single-station σ (Atkinson, 2006); a move away from simple regression-based curve fitting; attempts at using non-parametric

techniques; the use of much more and better (e.g. in terms of site characterizations) data; attempts at including additional independent parameters to reduce σ ; a better appreciation of epistemic uncertainty (multiple models by same developer or by various teams using the same master database); extensions of spectral models to shorter (<0.1s) and longer (>2s) periods using individually-processed records; a more careful consideration of how the models perform at small ($M_w < 5$) and large ($M_w > 7$) magnitudes; and making the models easier to use within PSHA. In addition, until the early 2000s the vast majority of published GMPEs were for PGA and elastic response spectral ordinates but, as shown by Douglas (2012), there has been a growing interest in developing models for other intensity measures, e.g. peak ground velocity and displacement, Arias intensity and various duration measures.

3. Epistemic uncertainty

As shown by Douglas (2010, 2012) average predicted ground motions for scenarios close to the barycentre of available data ($M_w \sim 6$, $R \sim 20$ km) have remained roughly constant over the past few decades despite improvements to GMPEs. However, predictions for scenarios closer to the edges of available observations (e.g. $M_w > 7$ and $R < 10$ km) demonstrate larger differences. As strong-motion networks become denser the average number of stations that record a given earthquake increases (e.g.

singly-recorded events are rarer), which means that model source terms (e.g. style-of-faulting factors) and the inter-event variability (τ) are better constrained in recent GMPEs. Similarly a modern station generally records more earthquakes leading to better estimates of site terms and single-station σ . Site terms are now less biased since fewer stations contribute a large proportion of records to strong-motion databases, although the number of records per station remains highly variable. The reduction of epistemic uncertainty (differences in predictions among models) remains a considerable challenge. It is vital that this uncertainty is not artificially reduced but seismic hazard assessments correctly account for the true uncertainty in ground-motion prediction.

4. Aleatory variability

Following Douglas (2003), Strasser et al. (2009) observe that σ associated with GMPEs has shown little or no decrease since the 1970s despite the increasing complexity of models. This fact and the importance of σ on the results of probabilistic seismic hazard assessments, especially at long return periods, has encouraged attempts to increase the complexity of models to account for other effects than simply magnitude, distance and site class. To date these attempts have not led to significant reductions in σ since GMPEs remain simple representations of complex physical phenomena. However, one of the major areas of engineering seismology research in the past decade has been in separating σ into its different components (Al Atik et al., 2010) and using the appropriate components when conducting a hazard assessment (e.g. Walling and Abrahamson, 2012).

5. The future

Some recent authors (e.g. Field et al., 2003; Atkinson, 2012) have argued that GMPEs will soon be replaced by numerical simulations of earthquake shaking. Such simulations do provide a much richer representation of the earthquake hazard to engineers (full time-histories rather than simply intensity measures) and they allow source- and site-specific calculations. Although ground-motion simulations show significant advances with the advent of high-performance computing and developments of better procedures (e.g. Douglas and Aochi, 2008), GMPEs are likely to remain a key component of hazard assessments for the foreseeable future. This is

because: reliable simulations of short-periods (<1s), generally the most important for engineering studies, remain problematic; defining the required input parameters and their variability is difficult and prone to large uncertainties; and ground-motion simulations remain time-consuming and expensive. In consequence, even if it is unlikely that GMPEs will continue to be a key component of hazard assessments for all of the next fifty years they will remain so for the next decade or two.

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