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# A stochastic ground motion accelerogram model for Northwest Europe

Carlos Medel-Vera *, Tianjian Ji [1]

*School of Mechanical, Aerospace and Civil Engineering, Pariser Building, Sackville Street, The University of Manchester, Manchester M13 9PL, UK*

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ABSTRACT

This article presents a stochastic ground-motion accelerogram model for Northwest Europe which simulates accelerograms compatible with seismic scenarios defined by earthquake magnitudes $4 < M_w < 6.5$, distance-to-site 10 km $< R_{epi} <$ 100 km and different types of soil (rock, stiff and soft soil). This model is developed based on Rezaeian and Der Kiureghian (2008, 2010) [1,2] and is a set of predictive equations that define a time-modulated filtered white-noise process. Such predictive equations were calibrated by means of the random-effects regression technique using a subset of the European database of accelerograms. The model is validated in terms of PGA, PGV and spectral accelerations using GMPEs for the UK, Europe and Middle East, and other Stable Continental Regions. This model is the first of its kind for NW Europe.



## 1. Introduction

In order to conduct seismic probabilistic risk analysis (SPRA), it is necessary to perform non-linear time history (NLTH) analysis of a structural model. Ultimately, this will lead to an estimation of the probability of unacceptable performance of the structure for the defined seismic hazard [3–5]. The main obstacle for conducting NLTH analysis of structures is the scarcity of accelerograms able to realistically represent the frequency content, intensity distribution and the strong shaking phase duration of recordings compatible with the scenarios that contribute most strongly to the hazard of the site selected [2]. This is an even more remarkable problem for areas of medium-to-low seismicity because: (i) strong earthquakes rarely occur, and (ii) those areas have limited monitoring networks [6]. For the United Kingdom (UK), which is a zone of relatively low seismicity, seismic hazard cannot be disregarded as strong earthquakes can still occur and may jeopardise the structural integrity of high-risk structures [7]. The paucity of accelerograms has led structural engineers to using techniques based on selecting, scaling and matching procedures applied to available records [8–10]. Even though the legitimacy and applicability of these procedures have been the subject of ample discussion in the literature [11–13], they are widely accepted and used by researchers and practitioners [14–16]. In general, these procedures are intended to match a spectral shape predicted by ad-hoc ground motion prediction equations (GMPEs). Currently, GMPEs play a critical role in seismic hazard and risk analysis and much research effort has been placed on the development of such models. Examples of state-of-the-art GMPEs are: the NGA-West2 Research Project [17], a major long-term project that developed attenuation models for active tectonic regions; and similarly for Europe and the Middle East, a new generation of GMPEs developed using the most recent pan-European strong-motion databank [18]. However, as SPRA requires the direct specification of sets of accelerograms, the use of GMPEs is actually an unnecessary intermediate step towards this objective [19]. Promising trends in earthquake engineering have been developed aiming at the replacement of GMPEs in seismic hazard and risk analysis for more rational approaches [20–22], as the one proposed in this work.

Stochastic generation of artificial accelerograms can be used to overcome the scarcity of ground-motion records. Currently, there are three techniques used to generate artificial accelerograms [23]: (i) mathematical or source-based models based on physical/seismological principles (e.g. Halldórsson et al. [24]; Liu et al. [25]); (ii) experimental or site-based models using measured/experimental data (e.g. Mobarakeh et al. [26]; Rofooei et al. [27]; Sgobba et al. [28]); and (iii) hybrid models that combine both approaches (e.g. Graves and Pitarka [29]). As pointed out by Boore [30], source-based models are mostly developed by seismologists in an attempt to explain the physics behind earthquake generation (e.g. source mechanism and propagation path). On the other hand, experimental models are mainly developed by engineers to obtain accelerograms using fitting techniques. From a structural engineering point of view, the main setback in using source-based

*E-mail addresses:* carlos.medelvera@postgrad.manchester.ac.uk (C. Medel-Vera), tianjian.ji@manchester.ac.uk (T. Ji).

* Corresponding author. Tel.: +44 161 306 2361; fax: +44 161 306 4646.

[1] Tel.: +44 161 306 4604; fax: +44 161 306 4646.

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models is that a profound knowledge of the governing seismological features of the site of interest is needed.

For the UK, the underlying tectonic mechanism that causes earthquakes is not yet fully understood [31] and there is little correlation between the pattern of earthquake occurrence and the structural geology of Britain [32]. Additionally, the database of British earthquakes is mainly composed of accelerograms recorded from small magnitude earthquakes, $M_w$ 2–4.5 [33]. Consequently, the nature of accelerograms (in terms of intensity, frequency content and time duration) is still unknown for stronger earthquakes, say $M_w$ 6, that may occur in the UK [34]. This situation is critical for the British nuclear industry, as such a magnitude is in the order of earthquakes that need to be included in seismic risk analyses, when considering a design basis event of 10,000 years return period [35]. In order to help fill this gap, a site-based model based on Rezaiean and Der Kiureghian [1,2] is proposed that stochastically simulates two-component horizontal accelerograms compatible with any seismic scenario defined by an earthquake of magnitude $4 < M_w < 6.5$, distance-to-site $10 < R_{epi} < 100$ km and different types of soil (rock, stiff and soft soil). These accelerograms can be used to perform SPRA on high-risk structures in the UK and NW Europe. The model is based on a set of predictive equations for parameters that govern a fully non-stationary stochastic process that is used to simulate earthquake accelerograms. The predictive equations are calibrated using regression analysis on a dataset of accelerograms recorded in the tectonic region to which the UK belongs. The simulation of accelerograms is entirely made in the time domain, it essentially involves the generation of random variables and uses a few input data readily available in structural engineering practice. This model is the first of its kind for the general region of NW Europe including the UK. The model is validated through a comparison of estimated peak ground accelerations (PGA), peak ground velocity (PGV) and spectral accelerations with those produced by GMPEs for similar target geographical regions.

This article is organised as follows: Section 2 gives a full description of the target geographical region of interest and defines the dataset of accelerograms selected for this work. The explanatory variables selected to perform regression analyses for the predictive equations are also discussed in this section. Section 3 provides the stochastic process to simulate accelerograms and gives an example of simulation using a single record from NW Europe as the target accelerogram. This section also reports predictive equations for the parameters that govern the stochastic process and their regression coefficients, as a function of earthquake magnitude, distance-to-site and type of soil. Section 4 provides the procedure to simulate accelerograms and validates such simulations against recorded accelerograms from NW Europe and GMPEs. Such attenuation models are from three main regions: the UK, Europe and the Middle East, and other Stable Continental Regions (SCRs) whose tectonic behaviour is expected to be similar to NW Europe's. Section 5 discusses further aspects regarding the calibration and use of the model proposed, its validity, its limitations and its constraints imposed by traditional attenuation relations. Finally, the conclusions from this work are summarised in Section 6.

## 2. Target geographical region and model parameters

The United Kingdom (UK) is considered to be an intraplate region with moderate-to-low seismicity levels [32]. In seismological terms, it is part of one of several Stable Continental Regions (SCRs), possessing unique tectonic features. These features are mostly linked to the timing and nature of crustal deformation. Johnston et al. [36] reported a comprehensive study on the tectonic character and seismicity of SCRs worldwide. They defined nine major and some minor SCRs that cover approximately 2/3 of all continental crust (and 1/4 of all crust: continental, oceanic and transitional); however, they are only responsible for 0.22% of the global seismic moment release rate. This reflects the relatively low seismicity levels in SCRs (such as the UK) compared to tectonically active zones (such as California and Japan). In spite of this fact, seismic hazard in the UK is non-negligible, as strong ground motions capable of compromising the structural integrity of strategic facilities can still occur [7]. In terms of magnitudes, two of the most significant known earthquakes which occurred in the UK were in 1382 and 1580 in the Dover Straits area. Both events were of magnitude approximately $M_L$ 5.75 [32]. This magnitude is close to the largest known earthquake occurred in the UK: an event $M_w$ 5.8 occurred in the English Caledonides region of the North Sea in 1931 [37]. Additionally, in a study by Musson [38], it was suggested that a major earthquake $M_w$ 7 could have occurred offshore in recent geological times in the NW European passive margin near Britain. Examples of the latest moderate earthquakes which have occurred in the UK are: (i) a $M_L$ 4.7 event in September 2002 in Dudley, West Midlands [39] (ii) a $M_w$ 4 event in April 2007 in Folkestone, Kent [40], and (iii) a $M_L$ 5.2 event in February 2008 near Market Rasen, Lincolnshire [41]. The current state-of-the-art knowledge on the seismicity and seismic hazard zoning of the UK is reported in Musson and Sargeant [42].

Several problems arise when developing predictive models in zones that are not tectonically active. The database of British earthquakes is mainly composed of accelerograms recorded from a few small magnitude earthquakes. The use of such information, in the prediction of accelerograms of moderate-to-strong earthquakes, can produce unreliable and unrealistic results [42]. It is also not entirely consistent to make predictions based on accelerograms recorded in different SCRs from the region of interest. Even though all SCRs share the same fundamental crustal features, there is no overall agreement whether such regions are similar in terms of their earthquake generation and attenuation mechanisms [34]. Therefore, the predictive model proposed in this work is based on the assumption that the nature of accelerograms (intensity, frequency content and time duration) of strong magnitude earthquakes in Britain would be similar to those strong earthquakes occurred in the same SCR to which the UK belongs, namely NW Europe. This assumption effectively avoids both the use of small-magnitude records to predict moderate-to-large accelerograms and the inclusion of earthquakes from other SCRs or other intraplate regions.

### 2.1. Definition of Northwest Europe

A systematic description of the boundaries of NW Europe was needed. Various definitions have been reported in the literature, for example, Goes et al. [43] defined it as a relatively small area excluding the UK and the Scandinavian peninsula, whereas Ambraseys [44] defined it as a more expanded area including the UK and most of Norway and Sweden. The approach used in this work to define boundaries for NW Europe, was the Flinn–Engdhal (F–E) regionalisation scheme [45], comprising the countries and areas indicated in Table 1 and shown in Fig. 1. Such a definition of NW Europe is within the limits of the European SCR defined by Johnston et al. [36]. Hence, it can be considered as a subset of the SCR of interest, possessing relatively uniform tectonic features.

Regarding the size of the dataset, it is acknowledged that current databases of accelerograms have experienced a particularly rapid expansion in recent years to reach several thousands of available earthquake recordings [17,46]. Such an expansion has led a fast development of GMPEs: Douglas [47] showed that more