SECED 2023 Conference
*Earthquake Engineering & Dynamics for a Sustainable Future*
14-15 September 2023, Cambridge, UK

# DEVELOPMENT OF A SUITE OF STOCHASTIC GROUND-MOTION MODELS FOR THE UNITED KINGDOM

John DOUGLAS[1], Fleur O. STRASSER[2], Guillermo ALDAMA-BUSTOS[2],
Sarah TALLETT-WILLIAMS[2], Manuela DAVÍ[3] & Iain J. TROMANS[2]

**Abstract**: *Since 1995, various estimates of stochastic ground-motion parameters have been computed for UK earthquakes and a few UK stochastic models proposed. These models have been developed by inverting the available weak-motion data to estimate ranges for the key parameters and using expert judgement and evidence from other regions when data are insufficient. The resulting ground-motion models have been used within site-specific seismic hazard assessments for critical infrastructure and for the 2020 UK National Seismic Hazard Model developed by the British Geological Survey. Often stochastic models have been given a lower weight within these assessments than empirical models from other regions, particularly due to doubts over how the stochastic models scale to larger magnitudes. As part of a broader project to develop a backbone ground-motion model using a hybrid stochastic-empirical method, here we present a summary of analysis conducted using an expanded ground-motion database from the UK and surrounding region to determine stochastic parameters. The ground-motion data have been adjusted to a single rock condition using an approximate technique. We used an approach to determine the stochastic models that is appropriate for their final use, namely within a scaled backbone approach that provides a suite of consistent models with appropriate weights. Due to the trade-off amongst the key parameters (e.g., stress (drop) parameter, geometrical spreading and site attenuation), constraints from the literature and expert judgement are applied. The resulting suite of models captures the uncertainties inherent in the inversion owing to the limited magnitude, distance and structural period range of the ground-motion data. These models will be the basis of a UK ground-motion model due for completion in 2023.*

## Introduction

This article summarises one of the key steps in the development of a new ground-motion model for the UK. We are developing this ground-motion model using the backbone approach (e.g., Atkinson et al., 2014) following the hybrid empirical-stochastic method (HEM) of Campbell (2003). This method uses the ratios between stochastic models (e.g., Boore, 2003) for host and target regions to adjust an empirical ground-motion model for the host region to make it applicable to the target region. For this application, the host region is, in first instance, California and the target region is the UK. The stochastic models for the target region should capture appropriate epistemic uncertainties. These uncertainties are generally larger for the target region than for the host region because of fewer ground-motion records, which are also often of small ($M<5$) earthquakes recorded at large ($R>100$km) distances. Here, we summarise the suite of preliminary UK stochastic models that we currently plan to use to develop the HEM; these models may change.

The approach followed to develop this suite of models is outlined in the next section. This is followed by a summary of the resulting models and graphs showing ground-motion predictions from the stochastic models. The article ends with a brief discussion of the next steps.

## Approach to develop suite of stochastic models

The initial suite of potential models was developed using a literature review of previous stochastic models for the UK and surrounding region (northern France, Belgium, Netherlands and north-western Germany). The stochastic method has been used to predict ground-motions for the UK since the pioneering work of Winter (1995). Key references for this review include Lubkowski et al. (2004), Edwards et al. (2008), Sargeant and Ottemöller (2009), Ottemöller and Sargeant (2010), Rietbrock et al. (2013) and Rietbrock and Edwards (2019). Based on this review, ranges

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[1] Dr, University of Strathclyde, Glasgow, United Kingdom, john.douglas@strath.ac.uk
[2] Dr, Jacobs, London, United Kingdom
[3] Ms, Jacobs, London, United Kingdom

for the key stochastic parameters were estimated using simplicity and physical arguments as well as considering potential trade-offs between parameters.

A database of ground-motion records from the UK (from the British Geological Survey, BGS) and surrounding region (from various seismic networks, e.g., the Réseau Accélérométrique Permanent in France) was compiled, and processed to obtain parameters of engineering interest (e.g., peak ground acceleration, PGA, and pseudo-spectral accelerations, PSA, at various structural periods), by Jacobs in recent UK nuclear-related projects. Given the low-to-moderate seismicity of this region, this database consists of just over 200 three-component records from 26 events with moment magnitudes (Mw) between 3.5 and 5.3 and epicentral distances less than 300km, with most data from epicentral distances greater than 50km. In addition, the site conditions of many of the recording stations are poorly known. The relatively small size of the database, the lack of data from larger magnitudes and closer distances and the limited local site information makes inversion of these data to determine parameters of stochastic models highly non-unique. The time average shear-wave velocities in the top 30m ($V_{S30}$) for all stations in this database were estimated using all available information (e.g., Tallett-Williams, 2017; Villani et al., 2019; local boreholes from the BGS database; horizontal-to-vertical ratios; generalized inversion). These estimates were then used to adjust the Fourier amplitudes of the ground-motion records to a uniform reference of $V_{S30}$ = 900m/s using the site-amplification terms of the ground-motion model of Bayless and Abrahamson (2019). These site-adjusted data were used as inputs to the process to assess the applicability of the initial suite of potential stochastic models. The project team then met in an in-person workshop to propose the final suite, based on expert judgement.

## Suite of proposed stochastic models

In this section the suite of stochastic models developed for this project are summarised. It should be noted that we are assuming standard choices for the other input parameters to the stochastic method (e.g., source duration and radiation pattern factor). Changing these fixed parameters within a range of possible values has a negligible impact on the predicted ground motions.

### *Source spectral shape*

The source spectral shape most applicable for UK earthquake ground motions has not been studied in detail in the literature. Edwards et al. (2008) found that the single-corner omega-squared Brune (1970, 1971) spectral shape clearly fits the observed spectra from 33 near-source local magnitude (ML) 2.0 to 3.0 records better than two other single-corner spectral shapes. They use this shape for the rest of their analysis. Other UK studies also use this classic spectral shape, as do many studies for other regions. Double-corner spectral shapes (e.g., Joyner, 1984) imply a breakdown in the 1:1 scaling relation between seismic moment and fault dimensions (i.e., a fault aspect ratio no longer equal to 1.0). Given the relatively small earthquakes that occur in the UK and its relatively thick seismogenic layer (~25km), we do not think it necessary to use a more complex spectral shape, which would also increase the number of free variables that need to be determined. Figure 1 shows that the single-corner omega-squared Brune (1970, 1971) spectral shape matches the observed spectra closely. Hence, all our stochastic models assume a single-corner omega-squared Brune (1970, 1971) spectrum.

### *Geometric spreading*

A number of models of the geometric spreading (decay) of seismic waves in the UK have been proposed. Many models include a 1/R branch (spherical spreading) for near-source distances and then often a $1/\sqrt{R}$ branch (cylindrical spreading) for far-source distances (e.g., Lubkowski et al., 2004). The most important difference, for ground-motion prediction, between these models is whether they include a middle branch with little or no decay to model the arrival of critical reflections off the Mohorovičić discontinuity (Moho). In addition, the distances at which the transitions between the different branches occur also varies between models.

The depth of the Moho below the UK is 33±5km according to CRUST1.0 (Laske et al., 2013). Using this information, the ratio between the shear-wave velocities above and below the Moho (about 0.8), the probable focal depths for UK earthquakes (between 5km and 25km) and Snell's law, it is possible to estimate that reflections off the Moho would occur between about 40 to 75km. The Edwards et al. (2008), Rietbrock et al. (2013) and Rietbrock and Edwards (2019) models use 50km for the start of this flat branch. A distance of 100km has been used as the start of the cylindrical spreading branch by multiple UK models.

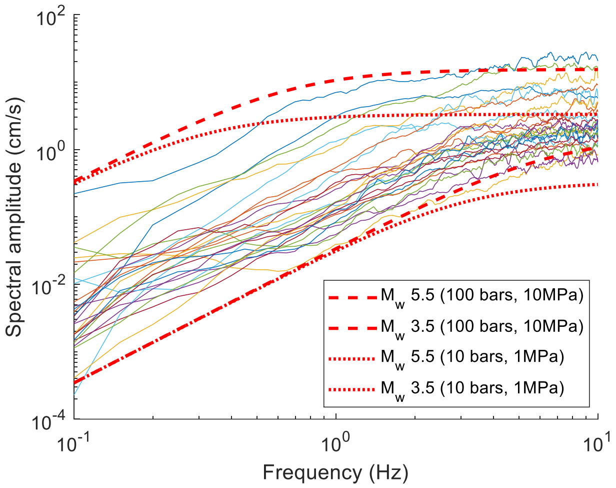

*Figure 1: Acceleration source spectra for the UK ground-motion data. Also plotted are Brune spectra for Mw 3.5 and 5.5 for stress (drop) parameters of 10 bars/1MPa (dotted lines) and 100 bars/10MPa (dashed lines).*

Based on this information the following three models are proposed:

- 1/R to 100km and then 1/√R for larger distances (lower model)
- 1/R to 75km and then 1/√R for larger distances (central model)
- 1/R to 50km, no decay until 100km then 1/√R for larger distances (upper model)

The decay of the site-adjusted data binned into 0.5 unit magnitude bins is shown in Figure 2. These plots show evidence for the Moho reflections at distances from about 50 to 100km and slower decay at larger distances. It should be noted that the ground motions at larger distances will be increasingly affected by anelastic attenuation (Q) and not just geometrical spreading.

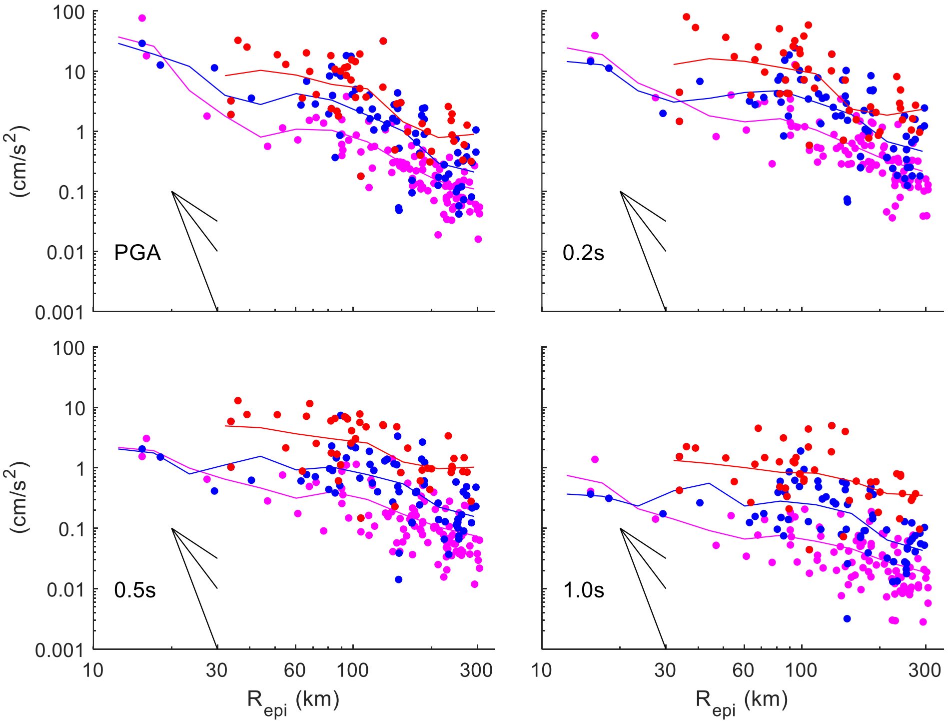

*Figure 2: Site-adjusted accelerations [PGA, PSA(0.2s), PSA(0.5s) and PSA(1.0s)] from events with Mw 3.5-4.0 (magenta), Mw 4.0-4.5 (blue) and Mw 4.5-5.0 (red) against epicentral distance. Also shown are piece-wise linear fits within log-spaced intervals. Black lines indicate, from top to bottom, 1/√R, 1/R and $1/R^2$ slopes.*

### *Path attenuation*

Three main models for UK anelastic attenuation (Q) have been proposed in the literature. Based on previous analyses that showed a close match with observations, **we have adopted the**

Sargeant and Ottemöller (2009) relationship, $Q = 266\,f^{0.53}$ as our central model. This model is also simpler than the two alternatives by Edwards et al. (2008) and Rietbrock et al. (2019), which propose a depth-dependent but frequency-independent model. The simplicity of the Sargeant and Ottemöller (2009) relationship makes it easier to implement within SMSIM and also reduces the chances of unexpected trade-offs with other stochastic parameters.

Sargeant and Ottemöller (2009) identify consistent regional dependency within the UK (their Figure 8). The minimum and maximum values of $1/Q_{Lg}$ shown in Figure 8 of Sargeant and Ottemöller (2009) are used to construct two alternative models to capture the regional variations in Q and also epistemic uncertainty. The extracted values and the central model are plotted in terms of Q on Figure 3. Based on these values lower and upper Q models have been estimated by eye to capture the observed trend in these minimum and maximum estimates: $230f^{0.5}$ (lower) and $330f^{0.6}$(upper). These Q models are also similar to the models for the UK by Rietbrock and Edwards (2019), for France by Campillo and Plantet (1991) and for southern Netherlands by Goutbeek et al. (2004). The UK clearly has higher attenuation (lower Q) than Scandinavia, as estimated by the model of Kvamme et al. (1995).

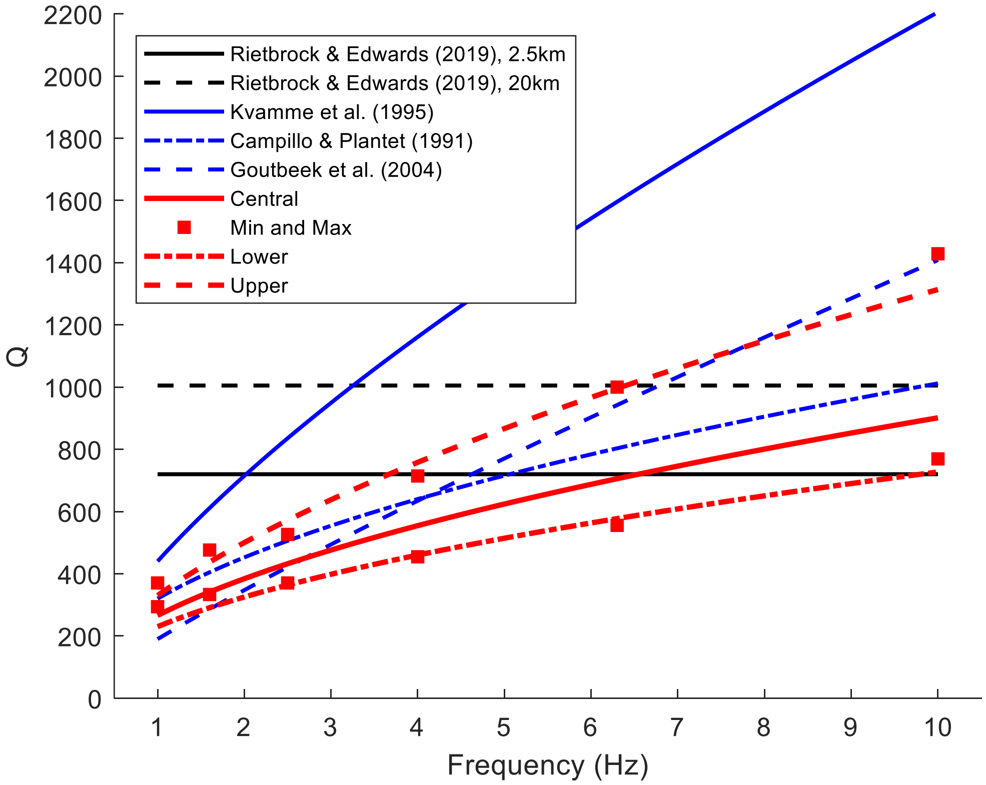

*Figure 3: Lower, central and upper Q models of the UK stochastic models. 'Min and Max' are the maximum and minimum Q estimates from Figure 8 of Sargeant and Ottemöller (2009). Also shown are Q models for the UK (Rietbrock and Edwards, 2019) for two depths, Scandinavia (Kvamme et al., 1995), France (Campillo and Plantet, 1991) and southern Netherlands (Goutbeek et al., 2004) for R>25km.*

### *Site amplification*

There is considerable uncertainty and spatial variation in shear-wave velocity ($V_S$) profiles (even within a relatively small country such as the UK). Rather than using different $V_S$ profiles to capture this, we decided to assume a single $V_S$ profile representative of a generic site with outcropping chalk in southern England. The values of $V_S$ with depth can then be used to adjust the site amplification in the resulting ground-motion model, if needed for a particular application. Based on experience from various site-specific hazard studies (Tromans et al., 2019; Aldama-Bustos et al., 2023), we believe that the adopted profile is applicable to rock sites in the Avalonian/Gondwana crustal block of southern Britain (e.g., Figure 1 in Sargeant and Ottemöller, 2009). Excluded are hard rock sites that occur in northern England, much of Scotland and Wales.

Several $V_S$ profiles for UK sites, particularly those with resolution in the upper 2km, from the literature were examined. These include profiles used by the BGS for locating earthquakes; profiles reported in articles on specific earthquake sequences; and oil-prospecting profiles in the public domain. We used the functional form of the Poggi et al. (2011) profile to parameterise the $V_S$ profile (Equation 1, where z is depth from surface). The coefficients in the Poggi et al. (2011) function were varied to find the best visual fit to the available profiles. The final coefficients chosen were: $b_1 = 1.1$, $b_2 = 150$, $V_{Smin} = 873$m/s and $V_{Smax} = 3{,}700$m/s, which correspond to the surface $V_S$ and $V_S$ at 10km. The $V_{S30}$ of the final profile is 900m/s.

$$V_S(z) = (V_{Smax}-V_{Smin})\left[1-b_1^{-z/b_2}\right]+V_{Smin} \tag{1}$$

Figure 4 compares the proposed $V_S$ profile and corresponding site amplification to two other profiles for similar $V_{S30}$. This comparison shows that there are considerable differences in the modelled amplifications, although much of the difference will be reduced by the site attenuation.

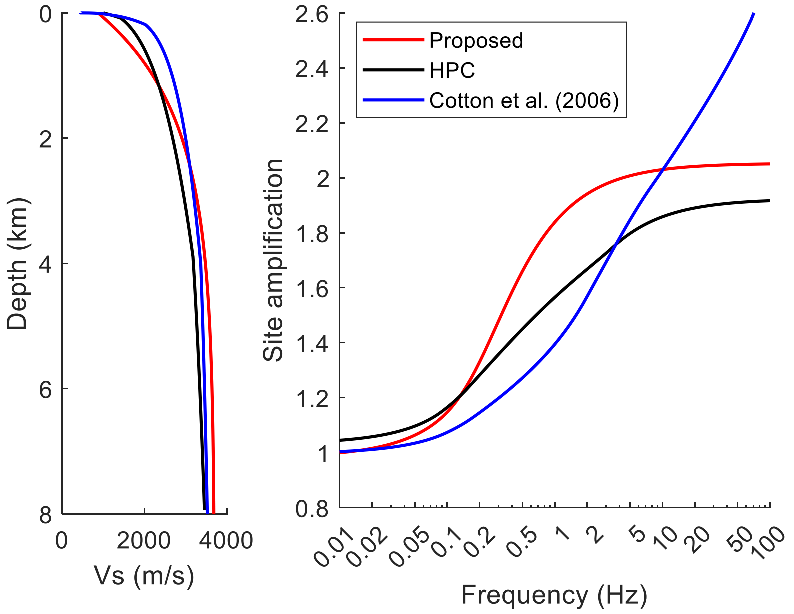

*Figure 4: The proposed $V_S$ profile (left) and the corresponding site amplification (right). For comparison the $V_S$ profile used by Tromans et al. (2019) for the Hinkley Point C (HPC) seismic hazard assessment and the Cotton et al. (2006) profile obtained for a $V_{S30}$ of 900m/s are also shown.*

### *Site attenuation*

The next parameter within the suite of UK stochastic models is the site attenuation, for which we use the standard approach of a kappa filter (Anderson and Hough, 1984). We are assuming that the Q model accounts for path attenuation and so we need to define a range of $\kappa_0$ (kappa at 0km) values appropriate for the (rock) $V_S$ profile and potentially other stochastic parameters.

Villani et al. (2019) and Baptie (2021) provide $\kappa_0$ estimates for various BGS stations. Also, Tromans et al. (2019) and Aldama-Bustos et al. (2023) provide $\kappa_0$ estimates, along with their uncertainty range, for the HPC and Sizewell C (SZC) sites. The $\kappa_0$ estimates for HPC and SZC correspond to similar $V_{S30}$ values to the one proposed for the current study, and in the case of SZC also to similar geological conditions (i.e., chalk). Finally, various analyses of the ground-motion data using the approach of Anderson and Hough (1984) were undertaken.

Based on the above and considering a $V_{S30}$ of 900m/s, (i.e., the $V_{S30}$ of the selected $V_S$ profile), three alternative $\kappa_0$ values are proposed: 0.037s, 0.023s and 0.010s, as the upper, central (i.e., best estimate) and lower estimates.

### *Stress (drop) parameter*

Figure 2 of Rietbrock et al. (2013), showing the estimated stress (drop) parameters for UK events in their database, demonstrates that, as is often observed, the values are relatively low for small UK events. They parameterise this in two models: a) a self-similar (magnitude-independent) model where the median stress (drop) parameter is 1.8MPa (18 bars) for all magnitudes, and b) a magnitude-dependent model where the median stress (drop) parameter is 0.7MPa (7 bars) for $M_w \leq 3$ and increases linearly to 10MPa (100 bars) at Mw 4.5 and then stays constant for larger magnitudes. There are currently no near-source UK ground-motion data from $M_w > 5$. The lack of data from moderate and large magnitudes means that there is uncertainty in what value is appropriate for such events, particularly given the potential Mw-dependency of this parameter.

Due to the trade-off between the inputs to the stochastic model, rather than adopting stress (drop) parameters from other studies we have estimated appropriate values using the following inversion approach. Firstly, we computed predicted PSA from 0.1 to 1s for all site-adjusted ground-motion records using the central branches for the geometric spreading, path attenuation and site attenuation, the single choices of site amplification and spectral shape, and a set of stress (drop) parameters (1, 2, 5, 10, 20, 50, 100 and 200 bars). Secondly, comparing these predictions and the observations enables estimates of the most appropriate stress (drop) parameters for each record to be made using the sum of squares of the deviation between the predictions and observations at each spectral period. The resulting stress (drop) parameter estimates for each record are shown in Figure 5. Overall, the best single stress (drop) parameter is 100bars, although the sum of squares curve is quite flat (Figure 5). Using a broader spectral period range (0 to 5s), which would introduce more recording and processing noise, had little effect on the results.

These results are quite surprising as usually smaller stress (drop) parameters are observed for low magnitude events (e.g., Rietbrock et al., 2013). This could be because of the choice of the other stochastic parameters, in particular the site attenuation (kappa) and the geometric spreading, and the associated strong trade-offs. As a test the upper geometric spreading model was used and the analysis repeated. The results (Figure 6) are similar to using the central model, with 100bars remaining the preferred average stress (drop) parameter.

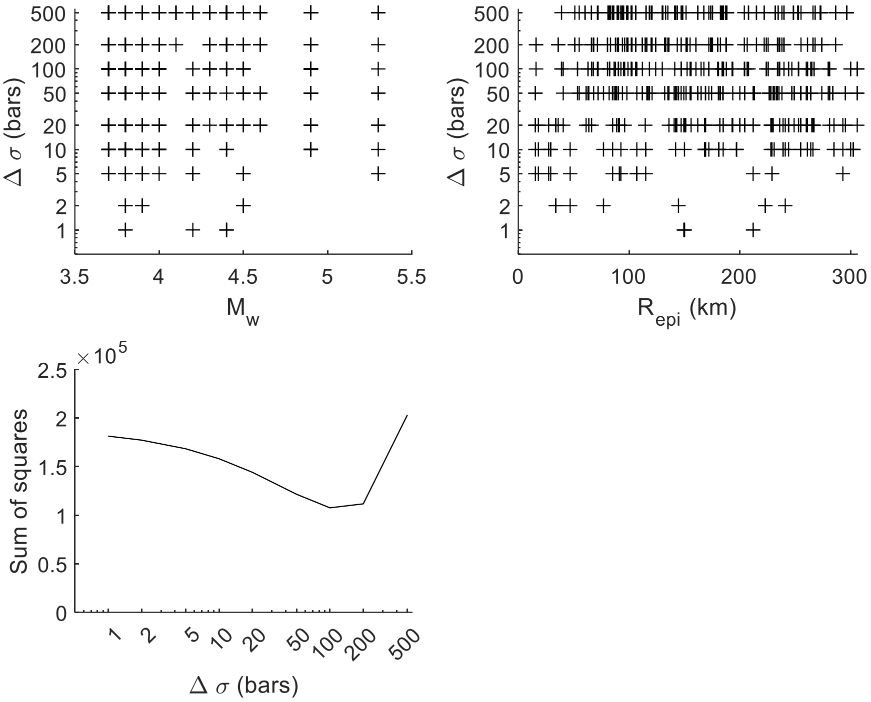

*Figure 5: Stress (drop) parameter estimates against Mw and epicentral distance using central parameters.*

Since these estimated stress (drop) parameters only provide estimates for Mw<5, an approach similar to that used by Bommer et al. (2022) for the Groningen gas field was applied. In this approach, predictions from empirical ground-motion models from other regions for Mw 5.5, 6.0 and 6.5 and a near-source distance (R=20km) where the empirical models are well constrained and differences due to path attenuation are small, are compared to predictions from the suite of predictions from the UK stochastic model for the set of stress (drop) parameters mentioned above. The ground-motion models used by Aldama-Bustos et al. (2023) within their ground-motion model for the SZC, excluding the Rietbrock and Edwards (2019) model as it is not constrained at large magnitudes, were adopted as appropriate choices for this analysis. Constant values of the stress (drop) parameter needed to get the best match between these ground-motion predictions are then chosen. Figure 7 shows the results of this analysis for Mw 6.5 and only stress (drop) parameters of 20, 50 and 100bars as these values lead to the best match.

The conclusion of this analysis is that values of stress (drop) parameter between 20bars [best match to Cauzzi et al. (2015)] and 100bars [best match to Yenier and Atkinson (2015)] provide the closest match to predictions from the empirical models. Three values were chosen: 20bars/2MPa (lower model), 50bars/5MPa (central model) and 100bars/10MPa (upper model). The previous analysis for the UK ground-motion data suggests that these values would also be applicable at lower magnitudes (3.5≤Mw≤5). Hence, the approach followed by Rietbrock et al. (2013) of a transition to smaller stress (drop) parameters at lower magnitudes is not required.

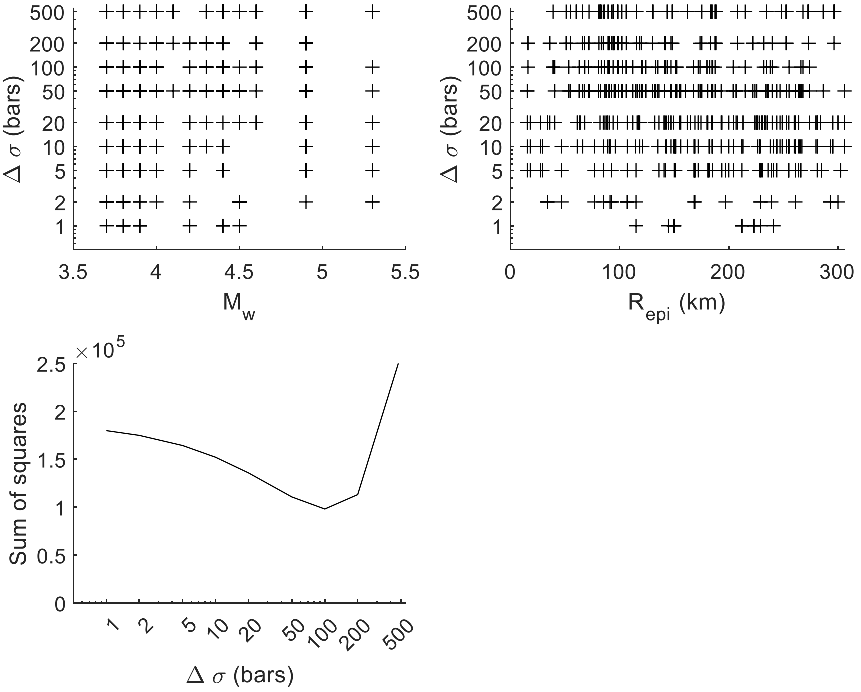

*Figure 6: Like Figure 5 but using the upper geometrical spreading model.*

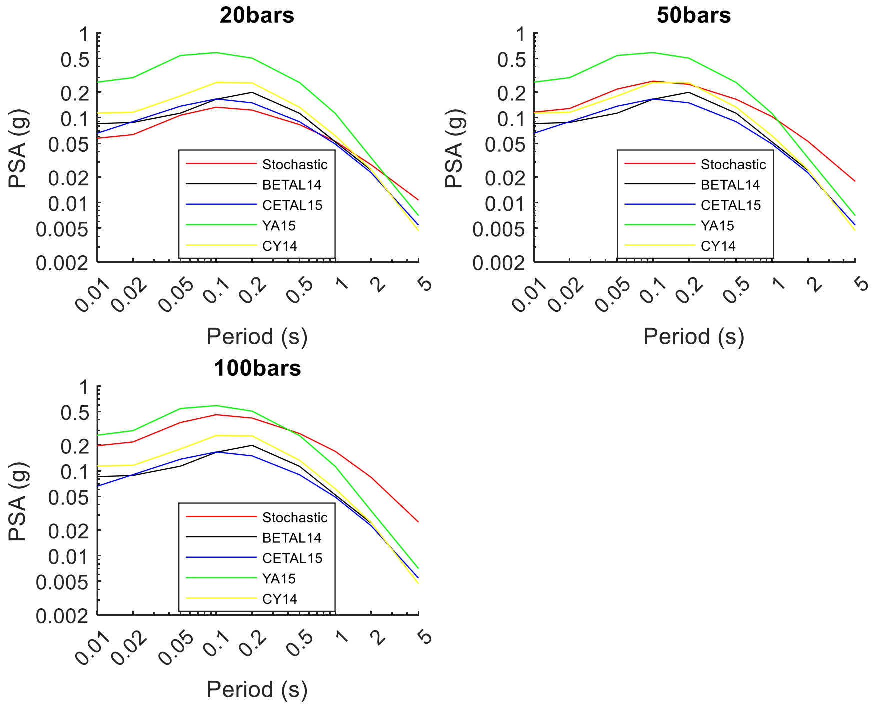

*Figure 7: Comparison of predictions for Mw 6.5 earthquake at 20km from four empirical ground-motion models and predictions from the central stochastic model for the UK. BETAL14 is Bindi et al. (2014), CETAL15 is Cauzzi et al. (2015), YA15 is Yenier and Atkinson (2015) and CY14 is Chiou and Youngs (2014).*

It should be noted this comparison demonstrates that the response spectral shape from the stochastic model is slightly flatter than the shape from the empirical models, which means that choosing a stress (drop) parameter that is appropriate for T<1s leads to over-predicting spectral accelerations for T>1s. Whether this over-prediction is evident after application of the HEM will be carefully studied in the next steps of the project. It may be necessary to modify the stochastic models, e.g. using a double-corner spectral shape, to address this mismatch.

Finally, we note that the approach used here makes the assumption that average near-source ground motions from moderate and large earthquakes in the UK will be similar to those in other regions, which are not necessarily tectonically analogous. Any estimate of the stress (drop) parameter for UK events with Mw>5 would be an assumption given the complete lack of near-source data for this magnitude range. Following discussion, we believe that the assumption that UK ground motion are similar to better observed regions is the most defensible.

## Predictions from proposed stochastic models

Figure 8 shows predictions from the 3 (stress parameter) × 3 (geometric spreading) × 3 (path attenuation) × 3 (site attenuation) = 81 models for Mw 4.5 and for PGA, PSA(0.2s) and PSA(1.0s) and site-adjusted ground-motion data from events with 4.0≤Mw≤5.0. The comparisons demonstrate that predictions from the stochastic models match the observations and the significant epistemic uncertainty on the stochastic models, particularly at short spectral periods.

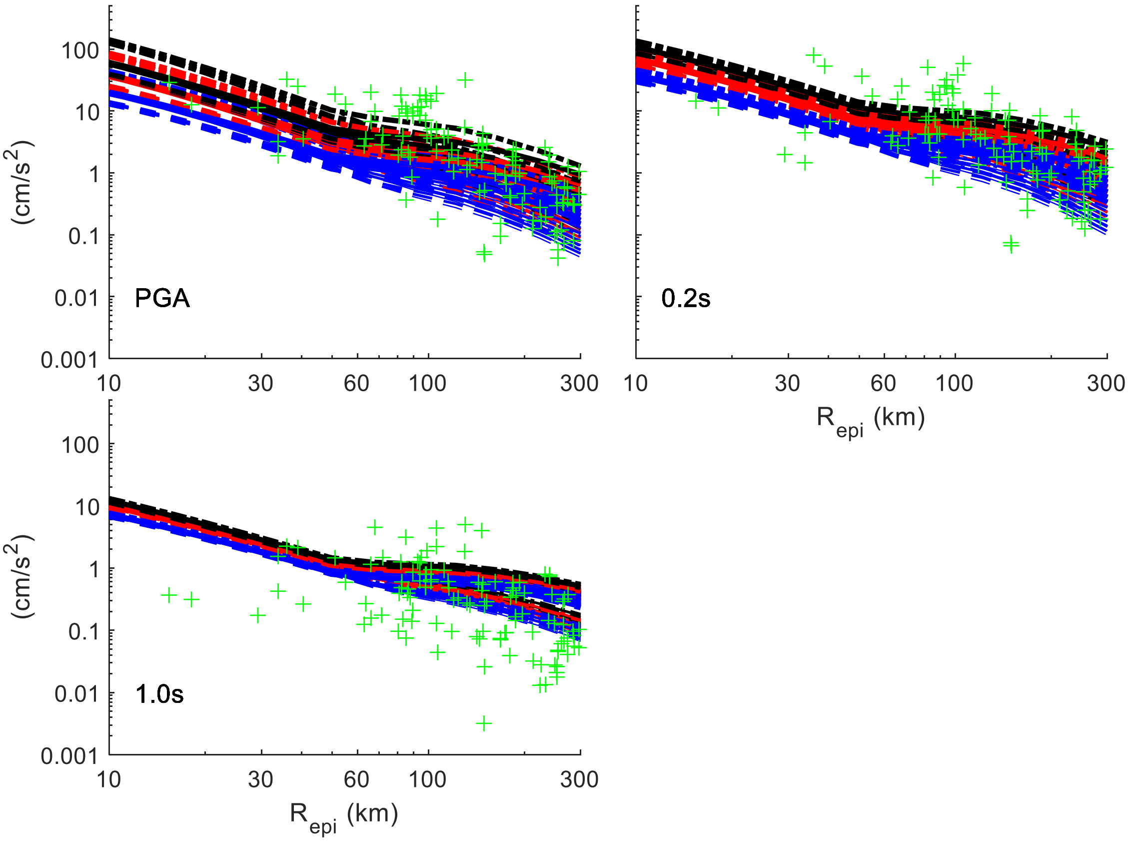

*Figure 8: Predictions from the suite of stochastic models proposed here and the ground-motion data (green) for Mw 4.5 (data from Mw 4.0 to Mw 5.0). Top-left: PGA, top-right: PSA(0.2s), bottom-left: PSA(1.0s)*

## Next steps

As discussed in the introduction, in the coming months a UK backbone ground-motion model will be finalised based on these stochastic models. It should be noted that the stochastic models proposed in this article are only preliminary and are subject to change. In particular, the stress (drop) parameter, and its correlation with other components of the stochastic model, may be refined following more analysis. Once completed, the models derived using the HEM will be compared with existing ground-motion models for the UK and other regions. The instrumental and macroseismic data from the broader region (UK, northern France, Belgium and the Netherlands) will be used to assess the validity of the model. The macroseismic data will be particularly valuable as it provides an independent check on the near-source behaviour of model for Mw>5, where there are no instrumental records. In addition, the impact of this new ground-motion model on assessed seismic hazard will be evaluated using some example locations and existing seismic source models. Finally, the developed model will be disseminated through various channels, including journal articles, computer subroutines and a series of seminars.

## Acknowledgements

The work presented here was supported by a Fellowship held by the lead author and funding from Jacobs. This Fellowship was supported by the Royal Academy of Engineering under the Industrial Fellowships programme. We thank all those who provided comments following the SECED Evening Meeting on 25th January 2023 on this project. We also thank the seismic networks, especially BGS, for providing the ground-motion records used here.

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