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COMPARING OBSERVED AND MODELLED GROUND MOTIONS USING ADJUSTMENTS FOR SPECIFIC SITES IN THE UK

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Abstract: *Ground motion prediction equations (GMPEs) account for site effects through both elastic amplification, often described by the shear wave velocity of the top 30 m (Vs30), and the near-surface site-specific attenuation modelled by the parameter κ_0. The elastic amplification is included in the site term of many recent GMPEs, whereas the near-surface attenuation is implicitly accounted for in the GMPEs through the data used to derive the equations. Evaluation of these parameters should allow better characterisation of earthquake ground motions and improved seismic hazard estimates. However, Vs30 has only been estimated at a small number of sites in the United Kingdom (UK) and there are no published estimates of κ_0. This work aims to determine both Vs30 and κ_0 estimates for selected sites and evaluate the impact of better site characterisation on the ground motion modelling. We use existing Vs30 estimates for selected seismic strong motion stations from published sources. We estimate κ_0 values for the same stations using seismic ambient noise method. We then use the Vs30 and κ_0 values to make the host-to-target adjustments for a selection of GMPEs and compare the results with observed ground motions. In this work, we also use recently revised magnitude estimates for events in the period 1970 to 1990 to account for new digital phase data. Although the adjustments for Vs30 and κ_0 improve the agreement between the ground motion predictions and the observations, there is still a scatter in the results. This suggests that the chosen GMPEs may not be well calibrated for the source parameters of the UK earthquakes.*

Introduction

The ground motion model (GMM) predicts the ground shaking for an earthquake scenario at a specific site using ground motion prediction equations (GMPEs). These empirical models, which are derived from large datasets of ground motion recordings, provide a probability distribution of the ground motion of interest in terms of median prediction and aleatory uncertainty (e.g. Reiter, 1990; Douglas, 2003; USNRC, 2012). The typical functional form of the median prediction for a generic GMPE consists of three components: source, path, and site terms (e.g. Kaklamanos and Baise, 2011; Douglas and Edwards, 2016). The source term describes the size and source mechanism of the events and the main descriptive variable of this term is the magnitude. The path term describes the propagation of seismic waves from the source to the site and is described by the source-to-site distance as the main variable although some recent GMPEs also include other path parameters such as regionally-dependent attenuation and hanging and foot-wall variables. The site component in ground motion modelling is expressed by two elements: the elastic amplification often described by the time-averaged shear wave velocity of the top 30 m (Vs30) and the near-surface site-specific attenuation modelled by the parameter kappa (κ_0; e.g. Edwards et al., 2016; Douglas and Edwards, 2016). The elastic amplification is included in the site term of many GMPEs published in the last 20 years, whereas the near-surface attenuation is implicitly accounted for in the GMPEs through the data used to derive the equations.

Instrumental monitoring of earthquakes in the UK started in 1969 when a local seismic network consisting of seven stations (LOWNET) was deployed in Central Scotland (Crampin et al., 1970). The seismic network gradually expanded through the 1980s and 1990s reaching a peak in the late 1990s, with over 140 stations. Since then, the number of stations has been reduced and the national seismic monitoring network currently consists of about 70 broadband seismograph stations located across the UK and operated by the British Geological Survey (BGS). Roughly

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half of the stations have strong motion sensors, mostly co-located with broadband sensors. Most of the monitoring stations are uncharacterised in terms of local site conditions and often little information is available on the geological conditions where the stations are located. This may help to explain the discrepancy between ground motion observations and predictions estimated by GMPEs that are valid for active shallow crustal regions (ASCRs; e.g. Mosca et al., 2022).

In this context, the present work aims to investigate the impact of better site characterisation on the GMM for the UK and whether realistic site terms improve the predictions for the UK data by the GMPEs. We use the Vs30 values estimated for selected seismic strong motion stations in the UK in Tallett-Williams (2017) who determine Vs30 using geotechnical methods. We estimate the near-surface site-specific attenuation, described by κ_0, using the seismic ambient noise method of Butcher et al. (2019). From the set of known Vs30 and κ_0 for the selected sites, we adjust the ground motion predictions from a set of GMPEs using the Vs - κ_0 (or host-to-target) adjustment procedure of Al Atik et al., (2014). The comparison between the predicted and observed ground motions is carried out using statistical methods.

UK ground motion dataset

From the BGS instrumentally recorded ground motion database, we select 499 observations from 39 low-to-moderate ($3.3 \leq Mw \leq 5.0$) earthquakes that occurred in the UK between July 1984 and December 2022. Figure 1a shows the location of the 39 earthquakes (yellow stars) and the recording stations (empty triangles), whereas the distribution of the ground motion data as a function of epicentral distances (up to 400 km) and moment magnitude is displayed in Figure 1b. The majority of the data are weak motion recordings for earthquakes of magnitude lower than 4 Mw and distances larger than 50 km.

We use the Vs30 values estimated in Tallett-Williams (2017) who characterises the ground conditions in terms of Vs30 for 14 UK strong motion stations using proxy methods and geotechnical methods (Horizontal to Vertical Spectral Ratio -HVSR-, Multi-Channel Analysis of Surface Waves, and Seismic Cone Penetration Tests). The ground motion dataset reduces from 499 to 181 recordings (coloured circles in Figure 1b) considering only the observations for which the stations have an estimated Vs30 value (coloured triangles in Figure 1a). Triangles and circles in Figure 1 are coloured-coded following the NEHRP (US National Earthquake Hazards Reduction Program) site classification.

We apply the method of Butcher et al. (2019) to compute the kappa parameter using the spectra of ambient noise at these 14 stations. The assumption is made that when there are no transient signals the ambient wavefield is effectively white noise and κ_0 can be found directly by measuring the slope of the noise spectrum (Palacios et al., 2015). For this study, 50 20-second windows of displacement data were taken at random from each of the first 100 days of 2020 for each horizontal component. To measure the slope of only the straight section of the spectra a filter was applied between 5 and 40 Hz. To remove transients, windows with a maximum displacement above 10 nm were rejected. This resulted in between 2500 and 9700 values per station, enough to show a normal distribution and to give a meaningful standard deviation for the measurements.

Figure 2 shows the pairs of Vs30 and κ_0 for the 14 stations. The uncertainty in the Vs30 estimates is of the order of hundreds of m/s in most cases and therefore the Vs30 values for some stations fall into two classes. Our calculations for κ_0 show that the average κ_0 value for NEHRP class B and C is 0.015 s and 0.027 s, respectively. The only station in class D has κ_0 = 0.030 s. The estimated κ_0 for CCA1 is remarkably low for a station on rock conditions but it agrees with the value found by Villani et al. (2019) for the same station. We compare also the estimated κ_0 with the empirical relationship between vs30 and κ_0 derived by Van Houtte et al. (2011). Although the agreement between the κ_0 parameters from the ambient noise method of Butcher et al. (2019) and the empirical relationship of Van Houtte et al. (2011) is relatively good within one standard deviation (Figure 2), κ_0 for the UK stations appear to be slightly lower than the empirical trend suggesting that the average κ_0 for the UK is between Western North America and Eastern North America, i.e. 0.037 and 0.008 s, respectively (Van Houtte et al., 2011).

Workflow to compare ground motion predictions and observations

Considering the GMPEs published before 2021 (e.g. Douglas, 2021) and using the exclusion criteria of Cotton et al. (2006) and Bommer et al. (2010), we have selected 10 GMPEs that are applicable to seismic hazard studies in the UK.

We correct the ground motion predictions from the selected GMPEs using the Vs - κ_0 (also called host-to-target) adjustment procedure. This procedure accounts for differences in the effects of elastic amplification due to shear wave velocity structure and near-surface attenuation between the host region from which a GMPE is derived and the target site, i.e. the UK monitoring stations (Douglas and Edwards, 2016). The parameter κ_0 describes the attenuation of shear waves at a given site as a result of the physical properties of the near-surface rocks and soils. We follow the approach of Al Atik et al. (2014) using Inverse Random Vibration Theory to compute $\kappa_{0,host}$ values and adjustment factors for each selected GMPE and nine earthquake scenarios resulting from disaggregation analysis in the high-frequency range, i.e. Mw = 4.0, 5.0, and 6.0, and Rjb = 5, 15, and 25 km. The procedure is described in detail by Mosca et al. (2020). Figure 3a shows the calculated Vs – κ_0 adjustment factors for PGA as a function of κ_0 and Vs30 for the 14 UK stations and the GMPE of Bindi et al. (2014).

Although we compare the ground motion predictions made using the selected 10 GMPEs and the UK ground motion observations using the residual analysis, the log-likelihood (LLH) method of Scherbaum et al. (2009), and the Euclidian Distance-based Ranking (EDR) method of Kale and Akkar (2013), here, we show the results for the GMPE of Bindi et al. (2014), whereas we will give an overview of the results for all the GMPEs at the conference. Figure 3b shows the normalised total residuals as a function of distance for the different NEHRP site classes. The black stars in the figure describe the average values for 50-km distance intervals to highlight if a clear trend exists. Most of the residuals are positive meaning that this GMPE tends to underpredict the recordings. It appears that the residuals for the NEHRP class B are relatively well-centred around 0. Figures 3c and 3d show the normalised between-event (inter-event) and within-event (intra-event) residuals for PGA as a function of magnitude and distance, respectively. The between-event residuals are mostly positive indicating that the source component for this model is not well calibrated for the source parameters of British earthquakes (Figure 3c). The within-event residuals as a function of distance have values between -6 and 7 and the mean residuals are between -1 and 1. For distances smaller than 100 km it seems to have a negative trend suggesting a dependency on regional attenuation (Figure 3d). This may be an artefact due to the small number of recordings.

The results for the LLH and EDR methods are shown for six cases:

- Case 1: Predicted ground motions for the 181 recordings, for which the Vs30 is known, with the Vs - κ_0 adjustments.
- Case 2: Predicted ground motions for the 181 recordings, for which the Vs30 is known, without the Vs - κ_0 adjustments.
- Case 3: Predicted ground motions for the 181 recordings with the Vs - κ_0 adjustments assuming the same Vs30 of 800 m/s.
- Case 4: Predicted ground motions for the 181 recordings without the Vs - κ_0 adjustments assuming the same Vs30 of 800 m/s.
- Case 5: Predicted ground motions for the entire dataset of 499 recordings with the Vs - κ_0 adjustments assuming the same Vs30 of 800 m/s.
- Case 6: Predicted ground motions for the entire dataset of 499 recordings without the Vs - κ_0 adjustments assuming the same Vs30 of 800 m/s.

The summary of the results for these six cases is shown in Figure 3e for LLH and Figures 3f-h for the parameters of the EDR approaches, ie. MDE (Modified Euclidian distance), $k^{0.5}$, and EDR. The variation in LLH, MDE, $k^{0.5}$ and EDR is up to $\pm$43% among the six cases and the lowest LLH and EDR scores are for Case 1. This suggests that a realistic site characterisation in terms of Vs30 and near-surface attenuation results in a reduction of the LLH and EDR scores and therefore improved ground motion predictions of the UK data by the GMPEs. However, there is still a consistent scatter between ground motion predictions and observations.

Conclusions and future work

This work highlights the importance of characterising the first-order local conditions for regional scale monitoring in the UK, although we show the results only for one GMPE. A better site characterisation in terms of Vs30 and near-surface site-specific attenuation for the British monitoring stations will result in better modelling of the ground motion and, ultimately, improve the estimation of seismic hazard in the UK. The remaining difference between ground motion predictions and observations in Figure 3b may be explained by other factors. The most likely cause of this scatter is that the source component for many empirical models for ASCR is not well calibrated for British earthquakes.

An important limitation of the present work is the small dataset of available ground motion recordings. Therefore, future work will focus on estimating the Vs30 values for the remaining monitoring stations in the UK using the HVSR and proxy methods (note that the κ_0 values for the remaining permanent stations have been already computed but have not been shown here).

Nowadays, the backbone approach is emerging as an alternative approach to the traditional multi-GMPE approach in seismic hazard analysis. The characterisation of the seismic monitoring stations in terms of Vs30 and κ_0 represents a valuable database to develop the backbone approach for the UK.

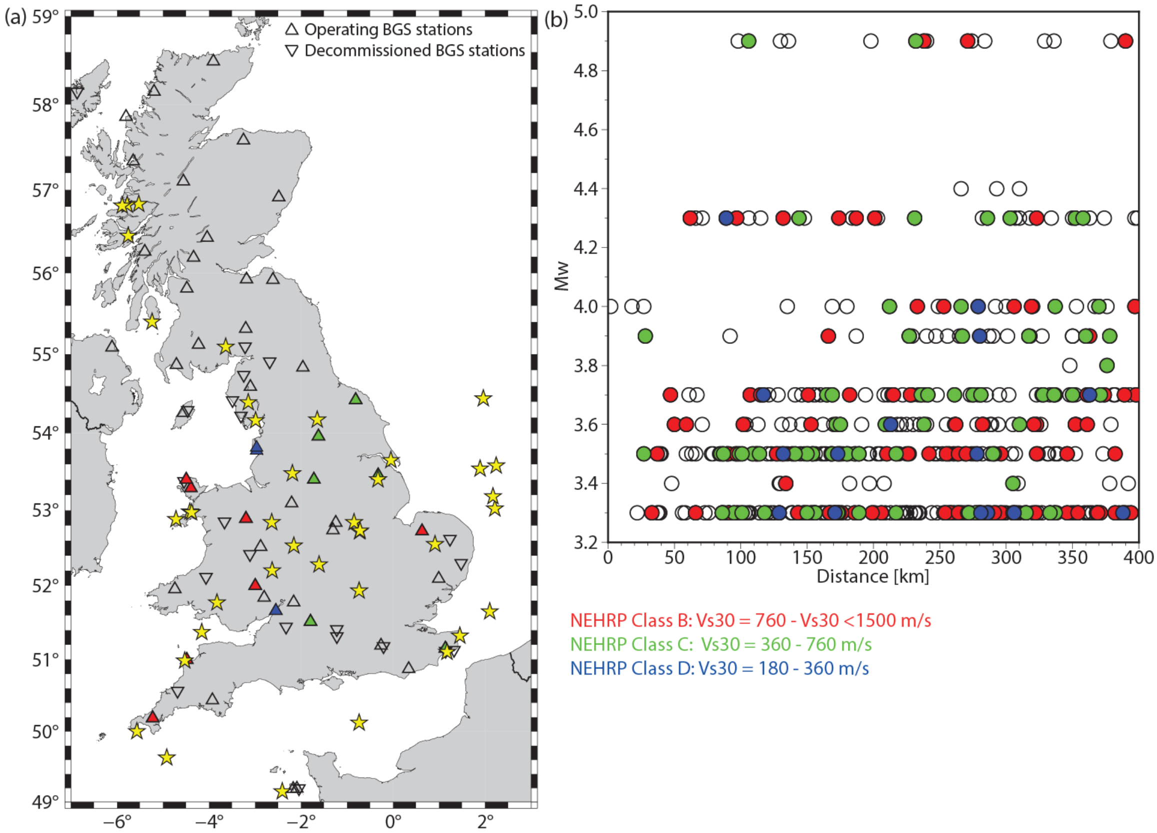

Figure 1. (a) Location of the UK seismic monitoring stations with estimated Vs30 (coloured triangles) and with unknown Vs30 (empty triangles). The colour code of the stations follows the NEHRP classification. The yellow stars indicate earthquakes with Mw ≥ 3.3. (b) Distribution of the UK ground motion data in terms of distance and magnitude (for distances up to 400 km). The coloured circles describe the stations for which the Vs30 value is known and the colour code follows the NEHRP classification.

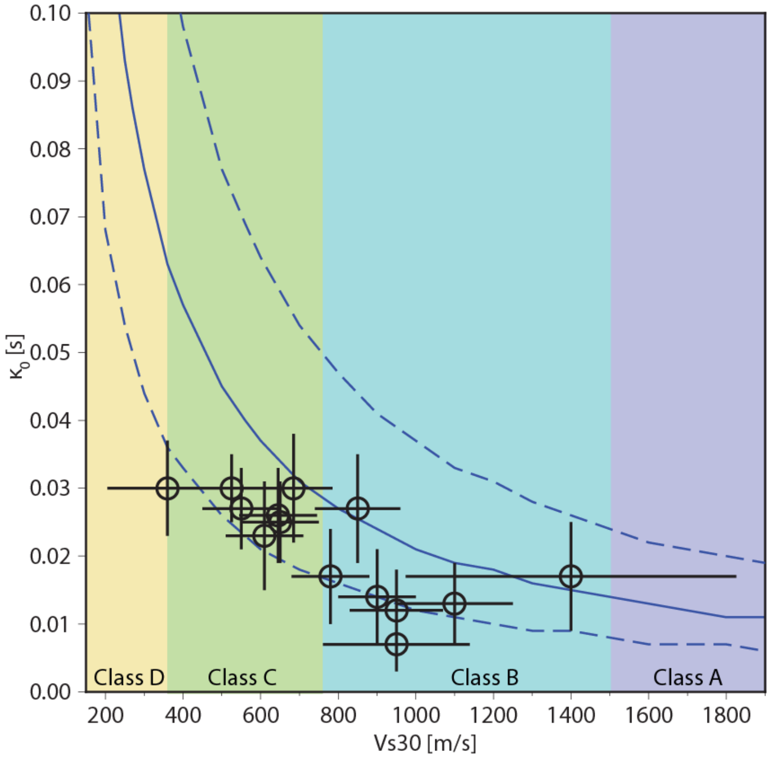

Figure 2. Distribution of the Vs30 versus κ_0 (circles), together with their standard deviation, for the 14 UK monitoring stations for which the Vs30 value was estimated in Tallett-Williams (2017). The solid blue line describes the empirical relationship between Vs30 and κ_0 derived by Van Houtte et al. (2011) within its standard deviation (dashed blue lines).

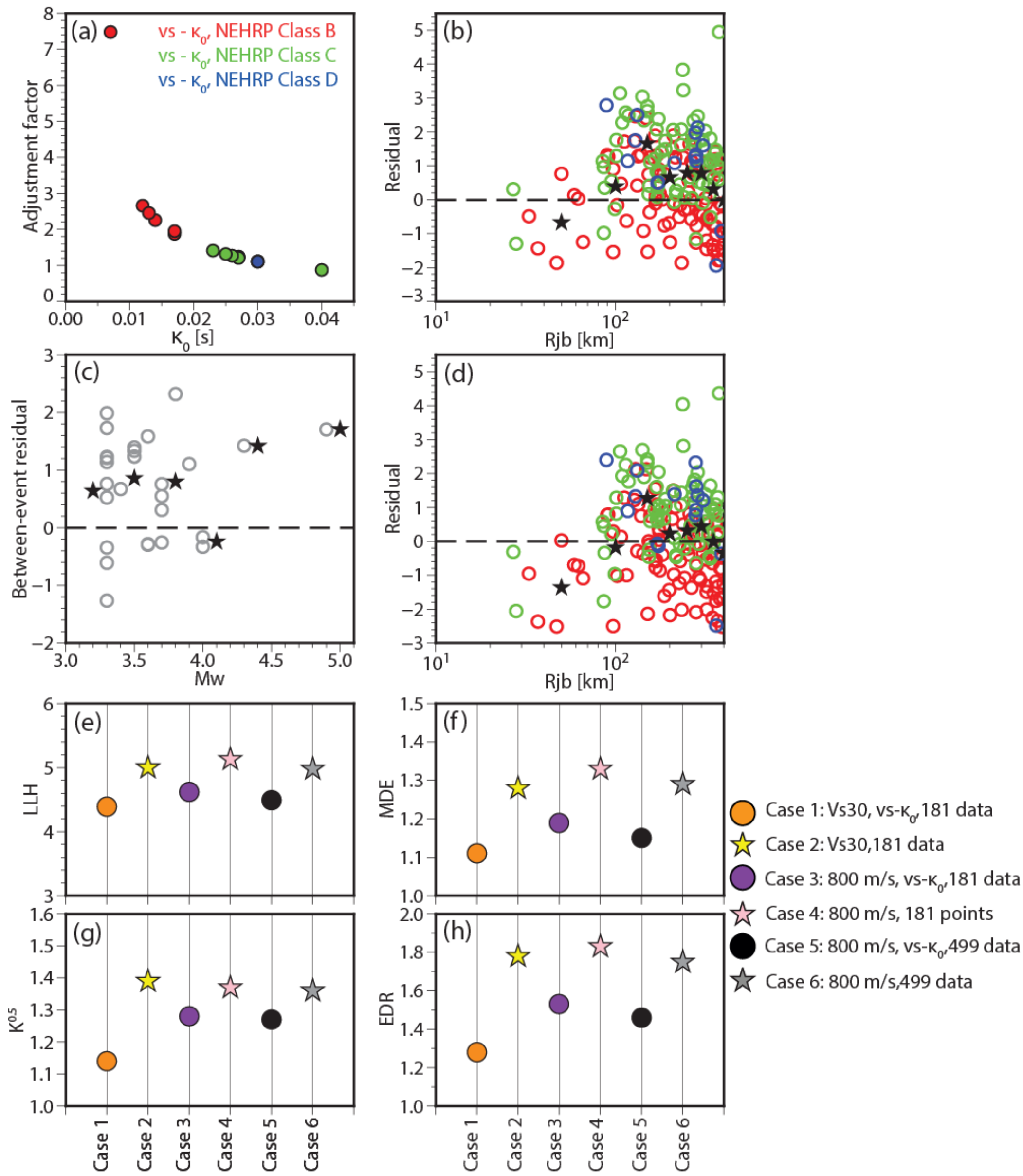

Figure 3. (a) Vs – κ_0 adjustment factors as a function of κ_0 for Bindi et al. (1014) and the 14 stations whose Vs30 is estimated in Tallett-Williams (2017) and κ_0 is calculated using the noise spectrum method of Butcher et al. (2019). (b) Normalised total residuals as functions of Joyner-Boore distance between the 181 UK strong motion data and the PGA predictions for Bindi et al. (2014). The black stars represent the average residuals for distance bins of 50 km. (c) Normalised between-event residuals for PGA between the 181 UK strong motion data and the predictions for Bindi et al. (2014). The black stars represent the average residuals for magnitude bins of 0.3 Mw. (d) Normalised within-event residuals for PGA between the 181 UK strong motion data and the predictions for Bindi et al. (2014). The black stars represent the average residuals for distance bins of 50 km. (d) Log-likelihood (LLH) values for six cases using the GMPE of Bindi et al. (2014). (f) Modified Euclidian distance *(MDE), (g) $k^{0.5}$, and (h) Euclidean Distance Rank (EDR) values for six cases using the GMPE of Bindi et al. (2014). The circles in (a-b, d) are colour-coded based on the NEHRP site classification. The dashed black line in (b-d) describes the ideal case, i.e. when the residuals are zero.*

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