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Influence of ground motion model selection on seismic hazard for Johannesburg

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Abstract

Selecting ground motion prediction models (GMPM) is crucial in assessing seismic hazard levels in a specific region. This study investigates the influence of ground motion model (GMM) selection on seismic hazard assessment in Johannesburg, South Africa. Most seismic events affecting Johannesburg are related to mining activities and water ingress into the underground mine voids. The most seismically active regions in South Africa include areas around Klerksdorp, Welkom, and Carletonville. These regions experience a significant number of earthquakes, with mining activities being a major factor contributing to seismic events. Ten ground motion prediction equations were selected from regions of similar tectonics setting and were assessed to see if they correspond to the available local data. Six of these were also compared to the ground motions produced by the earthquake of 14 August 2014, which occurred in the Orkney area, one of the mining areas in South Africa. Sensitivity analyses were also carried out to assess the influence of ground motion prediction equations (GMPE) on the seismic hazard of Johannesburg. The results indicate that the choice of GMPM significantly affects the estimation of seismic hazard levels in Johannesburg. Different GMM can lead to varying ground shaking intensity predictions, impacting risk assessments and engineering design considerations. The findings highlight the importance of carefully selecting appropriate GMM tailored to Johannesburg's specific geological and tectonic characteristics. Understanding how different models perform in this region is essential for accurate seismic risk mitigation strategies.

Keywords

seismic hazard assessment, ground motion prediction equations, sensitivity analysis, Johannesburg

Introduction

The ground motion model predicts the distribution of expected ground motions conditional on the occurrence of a given earthquake scenario. Selecting an appropriate ground motion model is a critical aspect of seismic hazard analysis (SHA). Ground motion prediction equations (GMPE) establish a relationship between a ground motion parameter, such as peak ground acceleration (PGA), peak ground velocity (PGV), peak spectral acceleration (PSA), and a series of explanatory variables that describe the earthquake source, wave propagation path, and local soil conditions (Douglas, 2003; Stewart et al., 2015; Akkar et al., 2014). The importance of PGA and various PSA lies in their significance as critical parameters for assessing seismic risk and designing earthquake-resistant structures. PGA measures the maximum acceleration of ground motion during an earthquake, while PSA indicates the maximum acceleration at specific frequencies. These parameters are essential for evaluating how structures respond to seismic events, as different structures have distinct natural frequencies. Every SHA analysis must include a GMPE that accurately models the transmission of ground motion from the earthquake source to the site.

Ideally, it is preferable to use a GMPE derived from local data, but this is only possible in regions of dense station coverage and high seismicity, such as Japan or California (Douglas et al., 2011; Bommer et al., 2015a). In South Africa, the only accelerometric stations installed are in the cluster networks in the mining regions. These stations have been in operation since 2012, and the existing ground motion record dataset does not enable users to derive such a model due to the lack of strong motion earthquakes (Grobbelaar et al., 2017). Although several moderate seismic events (e.g., the December 1976 M5.2 Welkom event, the April 1977 M5.2 Klerksdorp, and the 2005 M5.3 Stilfontein event) have been recorded in South Africa, these were not captured by the accelerometers for them to be used in developing GMPE (Fernandez and Van der Heever, 1985; Durrheim et al., 2006). Although the 1976 event was recorded on accelerometers,

we only had access to the recorded data, apart from that quoted in Fernandez and Van der Heever (1985). In this regard, models from other regions are carefully selected and tested to determine if they fit appropriately with the local data. In actual use in hazard analysis, a ground motion model will be called upon to predict accelerations from the complete range of magnitude and distance scenarios (Shoja-Taheri et al., 2010; Stewart et al., 2015; Midzi et al., 2020). A model that is derived from a dataset that only covers part of this range may not be reliable. This is mainly a problem because the datasets frequently tend to be biased towards small earthquakes at short distances and large earthquakes at long distances (Musson and Sargeant, 2007). This can result in scaling issues when ground motions need to be calculated for parts of the dataset's magnitude-distance domain that require more accurate representation. Otherwise, one must adopt either a relationship in which local data is augmented with data from a broader region or a relationship from anywhere in the world that is considered to be tectonically similar (Cotton et al., 2006; Bommer et al., 2015a; Midzi et al., 2020).

The procedure for selecting the appropriate GMPE for use in the seismic hazard assessment has been well-documented by several authors (Cotton et al., 2006; Scherbaum et al., 2009; Bommer et al., 2010). This process should result in the miniature set of independent models that capture the expected range of possible ground motions in the target region (Cotton et al., 2006). This most miniature set of GMPE will be compared with local data to verify if it capture the local data's uncertainty. Many studies have been devoted in recent years to evaluating the performance and reliability of the GMPE (Cotton et al., 2006; 2008; Shoja-Taheri et al., 2010; Bommer et al., 2003; 2011). Among those, Cotton et al. (2008) investigated the consequences of using them outside their range of validity. It is often the case when predicting spectral ordinates from earthquakes of small-to-moderate magnitude, for which the observed spectral values are systematically smaller. The problem arises because of the scarcity of strong motion data that are necessary to definitively resolve the shape of the attenuation curve. The uncertainty in the selection process is represented in the branches of the logic tree and weighted according to the analyst's relative confidence (Bommer et al., 2005) or degree of belief using available information.

Identification and testing of suitable ground motion prediction equations for Johannesburg

Given its position relative to plate boundaries, relatively low earthquake activity, and the slow rate of crustal deformation, South Africa is generally considered a stable continental region (SCR). According to Malservisi et al. (2013) and Stamps et al. (2018), South Africa's deformation rates are less than 1mm yearly. Therefore, an analogy for this region would be an SCR such as Eastern North America (ENA) and Australia, for which several ground motion models are available. Unlike ENA, however, the current tectonic regime of the southern African region (mainly along the eastern parts) shows evidence of extensional tectonic stresses with dominant normal faulting (Hartnady, 2002; Stamps et al., 2018; Manzunzu et al., 2019; Midzi et al., 2020). Studies by Johnston et al. (1994) show that extensional tectonic stresses are uncommon within SCR, so alternative GMPE from active shallow crust can be selected. Ninety percent of seismicity in South Africa comes from the mining regions, thus motivating for us to identify and select suitable GMPE, preferably derived from induced seismicity. Ground motions from induced seismicity are characterised by high frequencies, which tend to attenuate faster than natural tectonic events (McGarr and Fletcher, 2005; Manzunzu et al., 2017; Zulu, 2018).

Ten pre-selected GMPE from the three tectonic regions mentioned, i.e., SCR, shallow active crusts (SAC), and induced seismicity regions (ISR), were tested on how well they predict ground motion in South Africa using local data for different spectral periods. The information for each GMPE is presented in Table 1. The method of Scherbaum et al. (2004) was applied in order to rank these 10 GMPE. This method is based on a transparent and data-driven process that quantifies the model fit and measures how well the underlying model assumptions are met. Several GMPE in literature were derived from induced seismic events. However, only one, i.e., the relation by McGarr and Fletcher, (2005) is derived explicitly from mining-related events. Most of the other GMPE were derived from geothermal or fracking events. However, the McGarr and Fletcher (2005) relation has been observed to grossly underpredict ground motion for events of MW > 5.0 and distances larger than 10 km (Zulu, 2018). Most GMPE derived from induced seismicity were derived for only one spectral period, i.e., peak ground acceleration (PGA). At the same time, in this study, we needed GMPE that catered for other spectral periods. Hence, they were not tested in this study. The only GMPE from induced seismicity applied in this study was developed by Atkinson (2015) for geothermal sources for spectral periods up to 2 seconds.

A database of 61 seismic events (Figure 1) was compiled from the South African mining Cluster Networks for use in the testing of the GMPE. Our dataset is mainly composed of mining-related events. However, according to Douglas et al. (2013) and Atkinson (2015), ground motion from natural and induced sources are indistinguishable. Therefore, we also included GMPE derived from natural earthquake sources in this study.

Only events with good waveform data regarding signal-to-noise ratio and recorded by at least five stations were included. These contributed 2 018 two-component horizontal acceleration time series within a hypocentral distance range of 0.8 km to 350 km. The magnitude of the events ranged from 3.0 to 5.5. The various magnitude ranges of the events and the number of records associated with each listed magnitude value are presented in Table 2. Hypocentral distance was taken as the distance metric for all comparisons in place of rupture distance. Due to the moderate magnitudes of all earthquakes and shallow depth, the assumption of equality between hypocentral and rupture distance is inferred (Gupta, 2006).

No field investigations were carried out to determine the site conditions at all the seismic stations. Instead, we estimated values based on the surface geology where the stations are located. Given the need for more detailed geological information at all the seismic stations, five site classes based on the National Earthquake Hazards Reduction Program (NEHRP) (FEMA, 2003) site classification were used. The NEHRP site classification forms one of the standard site classifications used in GMPEs (Table 3). The NEHRP site classes are used to categorise sites based on their seismic amplification potential. V_{s30}, representing the average shear-wave velocity to a depth of 30 meters, is a crucial parameter in determining these classes. The V_{s30} values indicate how the ground will respond to seismic waves, with lower V_{s30} values typically associated with higher shaking amplification during earthquakes.

Most of the stations are located on soft rock (Site Class B), followed by stiff rock (Site Class C). This is illustrated clearly in Figure 2, which demonstrates the distribution of earthquake magnitude with hypocentral distance, where each record is linked to the appropriate site conditions.

Table 1

GMPE preselected from different tectonic settings to be used in this study, including the regions (SCR, SAC, and ISR) for which they were developed

	GMPE	Tectonic region	Magnitude range (*MW*)	Distance range (km)
1	Boore and Atkinson (2008) as modified by Atkinson and Boore (2011)	Referenced empirical model for Eastern North America (SAC)	5–8	0–400
2	Atkinson and Boore (2006) as modified by Atkinson and Boore (2011)	Extended stochastic model for Eastern America (SCR)	3.5–8	1–1000
3	Campbell (2003)	Hybrid model for Eastern North America (SCR)	5–8.2	1–1000
4	Rietbrock et al., (2013)	Stochastic model for United Kingdom (SCR)	4.5–7.5	1–1000
5	Frankel et al. (1996) as parameterised by EPRI (2004)	Stochastic model for Eastern North America	5–8	5–8
6	Akkar et al., (2014)	Europe and Middle East (SAC)	4–8	1–300
7	Silva et al. (2002)	Stochastic model for Eastern North America (SCR)	4.5–8.5	1–400
8	Pezeshk et al. (2011)	Hybrid model for Eastern North America (SCR)	5–8	1–1000
9	Toro et al. (1997) modified by Toro (2002)	Stochastic model for Eastern North America (SCR)	5–8	1–100
10	Atkinson (2015)	Small to medium events at short distance (ISR)	3–6	5–40

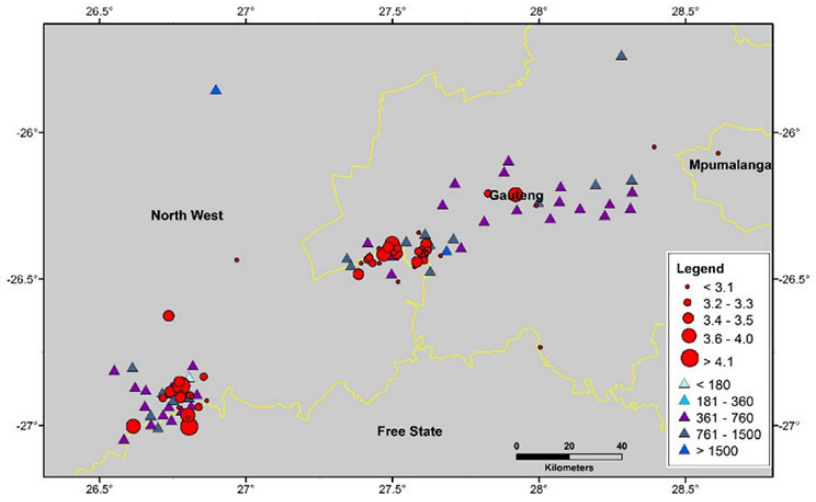


Figure 1—Location of earthquakes used in the testing of GMPE. The figure demonstrates the spatial distribution of the seismic events and the stations. Triangles represent the stations recording the events with each station having a V_{s30} value indicated with the colour; circles are the seismic events

The comparison of observed and calculated ground motion is carried out by calculating residuals. Residuals are generally defined as the difference between the natural logarithm of the observed parameter (Y_{ij}) and the mean calculated parameters ($\hat{Y}$) for a given GMPE, as given by Equation 1 (Shoja-Taheri et al., 2010; Skarlatoudis, 2017). For each observed waveform, the ground motion parameters are extracted at different spectral periods. Each ground motion parameter is compared with predicted ground motion by each individual GMPE at different spectral periods to compute the required residuals.

$$r_{ij} = lnY_{ij} - ln\hat{Y} \quad [1]$$

where lnY_{ij} is the value of the jth record of the ith event and $ln\hat{Y}$ is the mean value of lnY computed using a particular GMPE. The results of the comparison were presented by considering intra-event and inter-event residuals, which are all usually close to zero and represent the residuals related to each individual source and to combined sources, respectively. The intra-event terms presented here were obtained using the whole database of events for all available hypocentral distances in a similar way as reported by Graves et al. (2008). The two residuals are given by Equations, 2 and 3.

$$r_{ij}^{intra} = r_{ij} - \eta_i \quad [2]$$

Table 2

Number of events and recordings in different magnitude range showing the distance range of the recording stations

Magnitude	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.9	4.6	5.5
No. of events	11	13	11	7	3	6	3	1	1	1
No. of recordings	284	424	405	265	130	220	137	41	40	38
Hypocentral distance (km)	1.4–49	2.1–284	0.9–232	1.8–337	0.9–218	1.2–231	2.4–218	4.3–117	4.2–195	4.8–177

Table 3

NEHRP site classification scheme (FEMA, 2003). Vs30 is the shear-wave velocity averaged over the uppermost 30 m

Site Class	Geologic description	Vs30 (m/s)
A	Hard rock	Vs30 > 1500
B	Soft rock	760 < Vs30 ≤ 1500
C	Stiff soil	360 < Vs30 ≤ 760
D	Soft soil	180 < Vs30 ≤ 360
E	Very soft soil	Vs30 ≤ 180

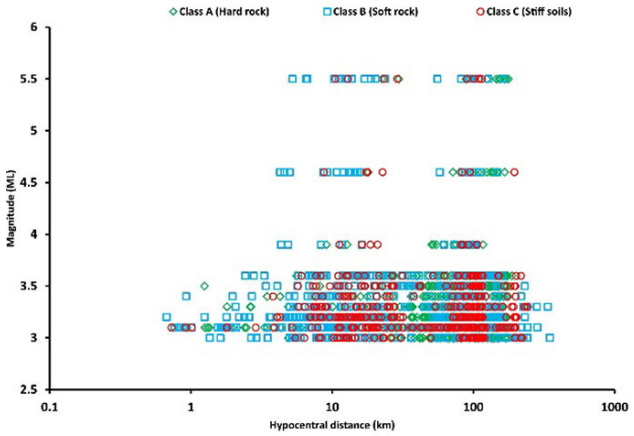


Figure 2—Illustration of site classification of the seismic station records representing different site classes based on NEHRP site classification

$$r_i^{inter} = \eta_i - \frac{1}{N_e}\sum_{i=1}^{N_i}\eta_i \quad [3]$$

where N_e is the total number of events. The mean of the residuals for the i^{th} event with N_i records is defined as presented in Equation 4:

$$\eta_i = \frac{1}{N_i}\sum_{j=1}^{N_i} r_{ij} \quad [4]$$

For each GMPE, the residuals were calculated for 5% damped pseudo spectral acceleration for periods 0.0s (PGA), 0.1s, and 2.0s. In the following section, the results are presented by considering the figures related to the residuals (Equations 2 and 3). Figure 3, Figure 4, and Figure 5 show inter-event residuals for the preselected GMPE (Table 1) and tested with observed data in this investigation for the three spectral periods (PGA, PSA = 0.15s, and PSA = 2.0s).

The inter-event terms show similar variation with distance for most of the equations. For most GMPE, the residuals are negative, with the lowest at about -0.01 and smaller at long periods, where residuals are less than -0.005 (and 0.005 where positive) for periods

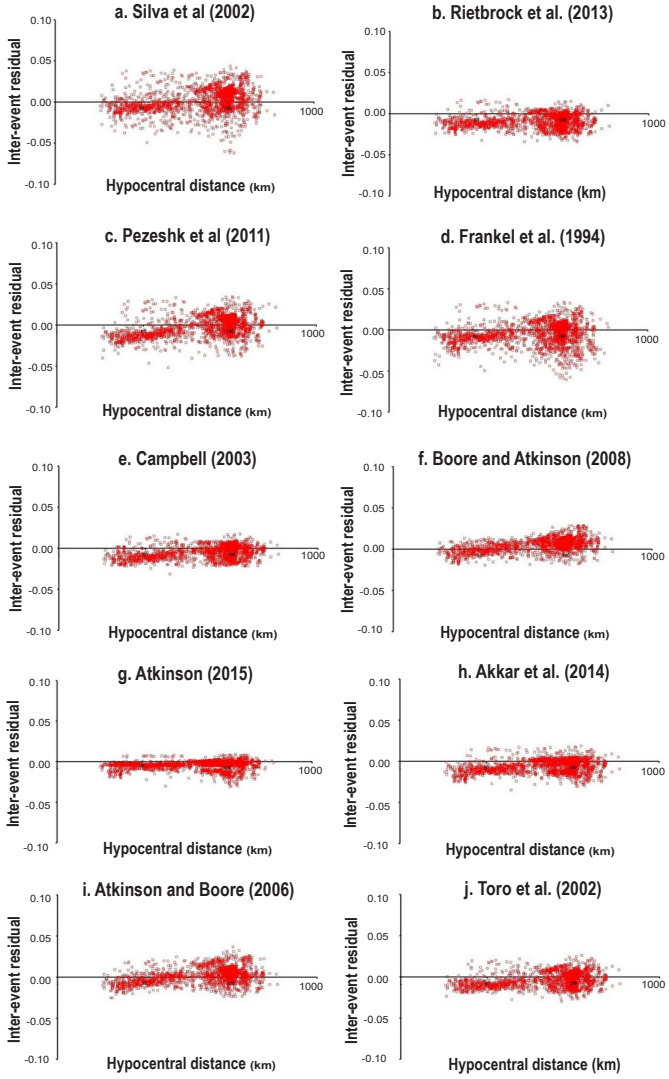


Figure 3—The inter-event residuals of all GMPE for PGA (T = 0.01s) spectral acceleration versus hypocentral distance

greater than 1.0 seconds. The inter-event residual distribution implies that most of the models, in particular Rietbrock et al. (2013), Campbell (2003), Atkinson (2015), and Toro (2002), overestimate the observed ground motion. The residuals for PGA are large for Silva et al. (2003), Pezeshk et al. (2011), Frankel et al. (1994), and Atkinson and Boore (2006) GMPE (Figure 3). For spectral period T = 0.15s, Atkinson (2015), Akkar et al. (2014), Campbell (2003), Rietbrock et al. (2013 and Pezeshk et al. (2011) GMPE have negative residual values, while Boore and Atkinson (2008) and Atkinson and Boore (2006) have positive values (Figure 4). All GMPE slightly overestimate with distribution very close to the zero-residual line (Figure 5).

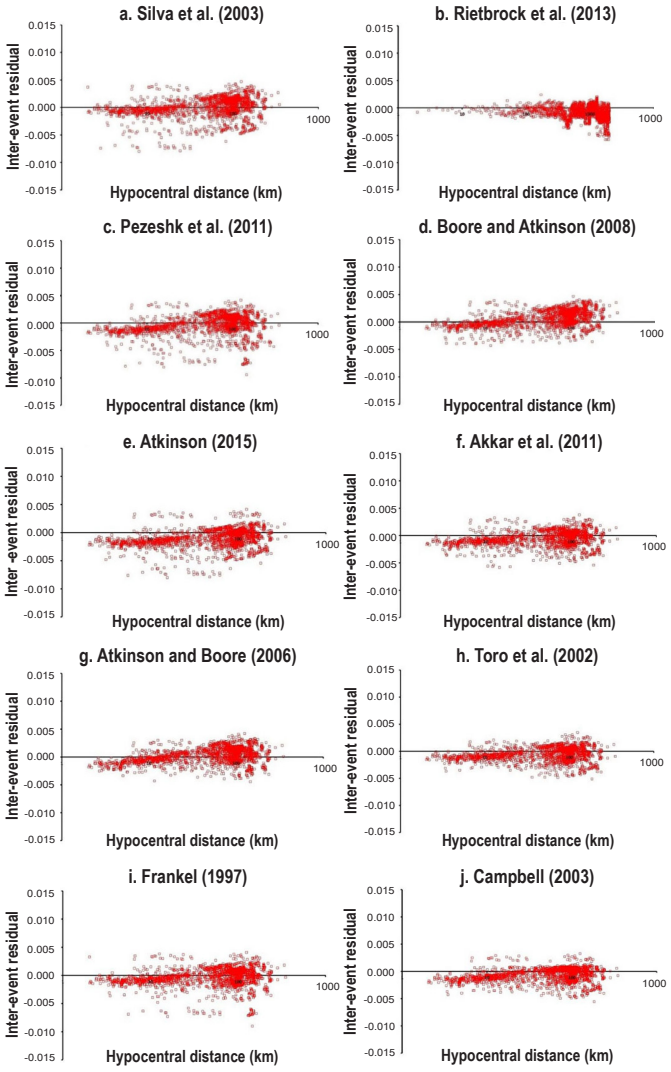


Figure 4—The inter-event residuals of all GMPE for PSA (T = 0.15s) versus hypocentral distance

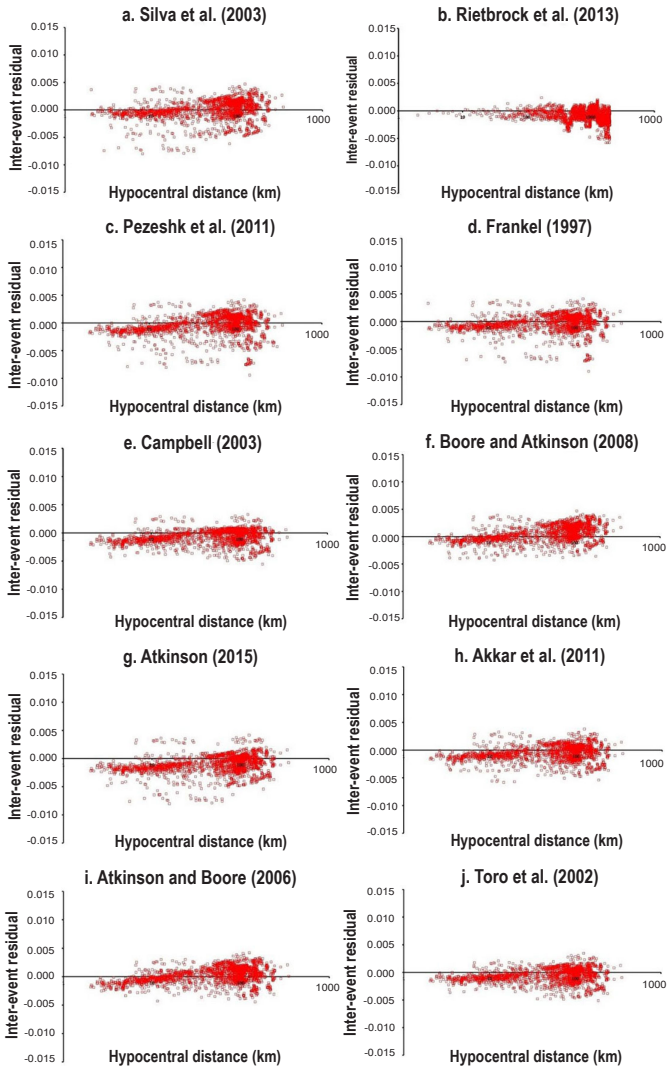


Figure 5—The inter-event residuals of all GMPE for PGA (T = 2.0s) versus hypocentral distance

Analysis of intra-event residuals shows larger residuals (between -0.2 to 0.2) compared to inter-event residuals (Figure 6, Figure 7, and Figure 8). High scattering at low magnitudes is consistently observed for all the spectral periods. The scattering improves at high magnitudes but changes from positive to negative residuals with increasing periods. Large residual values seen in Figure 6 and Figure 7 might be due to the use of GMPE outside their range of applicability. Silva et al. (2003), Rietbrock et al. (2013), Frankel et al. (1994), and Atkinson (2015) have large scatter for PGA compared to other GMPE. The scatter is more significant for small-magnitude events than for moderate ones. For the spectral period T = 0.15s, all the GMPE had residuals of less than 0.1, although they seemed to follow the trend of PGA. At spectral period 2.0s, the residuals are lower than ± 0.05, although they seem more negative.

Negative residuals are obtained where the GMPE overestimate the ground motion and underestimate where they are positive. In general, all the GMPE overestimate the ground motion parameters. Using these GMPE will result in hazard values that are slightly higher than observed values. Much of the observed scatter is at lower magnitudes and larger distances, meaning small events recorded at longer hypocentral distances resulted in large errors. Mining-related seismicity attenuates fast, and with increasing hypocentral distance can also contributed to this. The selected GMPE cover a large spectrum and will represent the uncertainty in GMPE for our region.

Large variations of the residuals are observed for the Atkinson and Boore (2006) model, which appears to underestimate ground motion at short periods but overestimates at long periods at all distances. Considering the trends observed, the models by Campbell (2003), Toro et al. (2002), Boore and Atkinson (2008), Akkar et al. (2014), Rietbrock et al. (2013), and Atkinson and Boore (2006) consistently appear to match observed data better than the other GMPE. Akkar et al. (2014) over predicts for all spectral periods. Pezeshk et al. (2011), tend to over predict for short periods and under predict for longer periods. Variations in residuals might be because the GMPE were used outside their derived magnitude range since most of the events used in this study fall outside the applicability range of most GMPE. Only the Atkinson (2015) model for induced seismicity was derived for short distances (less than 40 km) and can only be used for induced seismic sources.

Comparison of the Orkney earthquake strong-motion data with preselected GMPE

The strike-slip *MW* 5.5 Orkney earthquake of 5 August 2014,

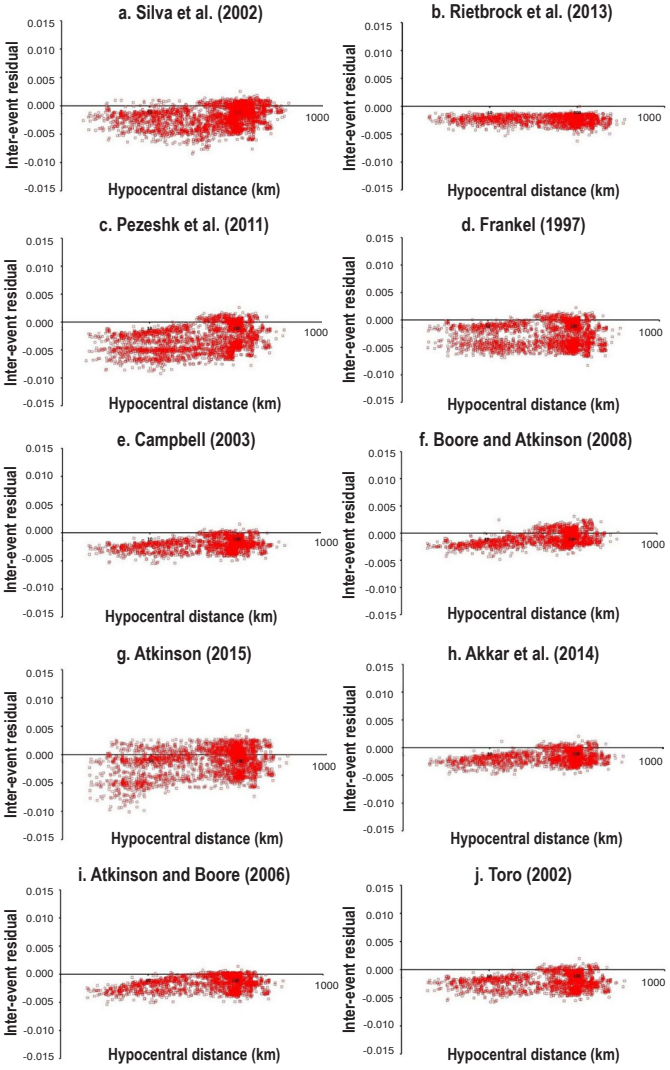


Figure 6—Inter-event terms, also referred to as the mean residual, for the 10 GMPE for PGA

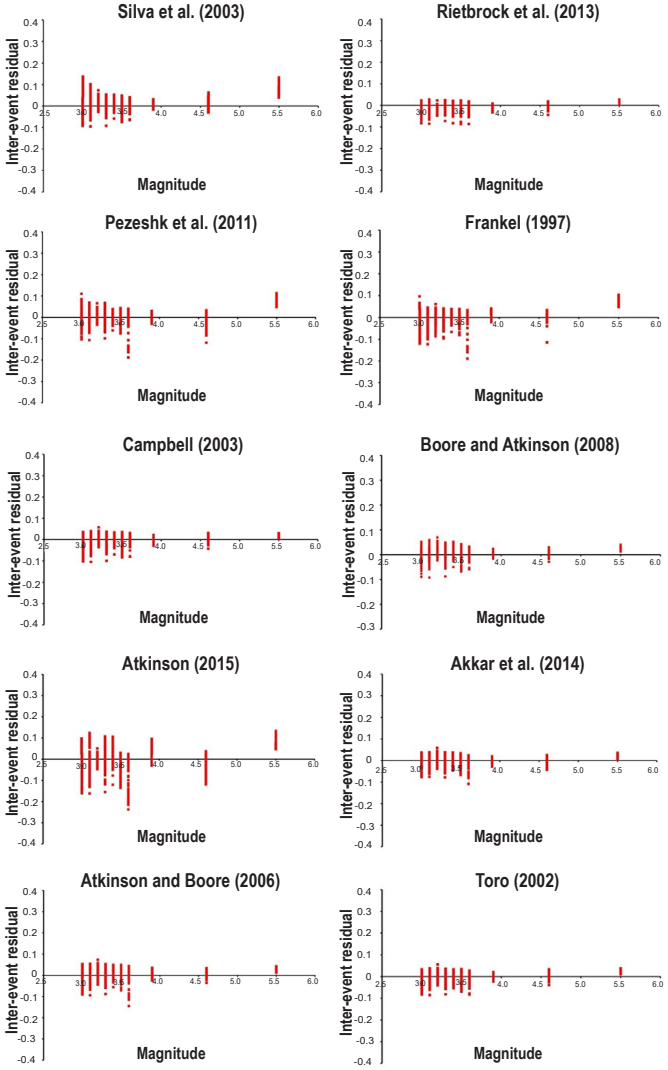


Figure 7—Inter-event terms, also referred to as the mean residual, for the 10 GMPE T = 0.15s spectral period

which occurred in the North West province, South Africa, at approximately 10:22 GMT, was recorded by the SANSN and the cluster network in the mining regions. This earthquake falls within the range of magnitude values used in deriving most of the pre-selected GMPE. Thus, we separately compared its observed ground motion parameters, as recorded by the cluster network of stations, to the predicted values. In Figure 9 we compare the predictions of the ten GMPE preselected for this study to the observations. Rietbrock et al. (2013) and Akkar et al. (2014) predictions fit the data on all the spectral periods analysed, while Atkinson (2015) overpredicts all the spectral periods. Due to its short distance of applicability, the Atkinson (2015) model was not used for further analysis. Toro et al. (2002) and Campbell (2003) mainly overestimate most spectral periods whilst fitting well on others. Silva et al. (2002) and Pezeshk et al. (2011) mainly underestimate ground motion although they sometimes overestimate it. Atkinson and Boore (2006) sometimes overestimate (lower spectral periods <0.1 sec) and sometimes fit the observations well (high spectral periods > 0.1 sec). Boore and Atkinson (2008) fit well up to spectral periods of 0.5 seconds, then it overestimates. For PGA, most of the GMPE overestimate the observed ground motion, except for Rietbrock et al. (2013) and Akkar et al. (2014), which fit well with the data, while Pezeshk et al. (2011) predict lower values. For 0.05 seconds, Rietbrock et al. (2013), Akkar et al. (2013), and Boore and Atkinson (2008) fit the data while the rest of the GMPE overpredict.

It is apparent from these results that the shape of attenuation curves of only one model cannot capture the real behaviour of the data. Therefore, six GMPE were selected to cover the lower (Toro et al., 2002; Boore and Atkinson, 2008), median (Akkar et al., 2014; Rietbrock et al., 2013), and upper range (Campbell, 2003; Atkinson and Boore, 2006) of the ground motion in order to capture the uncertainty associated with GMPE selection. These six GMPE were then used for sensitivity analysis.

Uncertainty analysis related to ground motion prediction equations

The six GMPE (AB06, BA08, AKETAL14, TO02, RIETAL13, and CAM03) selected by comparing with local data were used in this study to demonstrate the effect of choice of the model on the hazard results. The analyses are conducted for six cases, each corresponding to a different GMPE, to illustrate the effect of the chosen GMPE. The sensitivity of the output to variations in the input parameters is quantified using the coefficient of variation (COV), where COV is a measure of relative variability and is related to both the standard deviation (σ) and the mean (μ) through the equation by Cramer (2001a; 2001b; 2002).

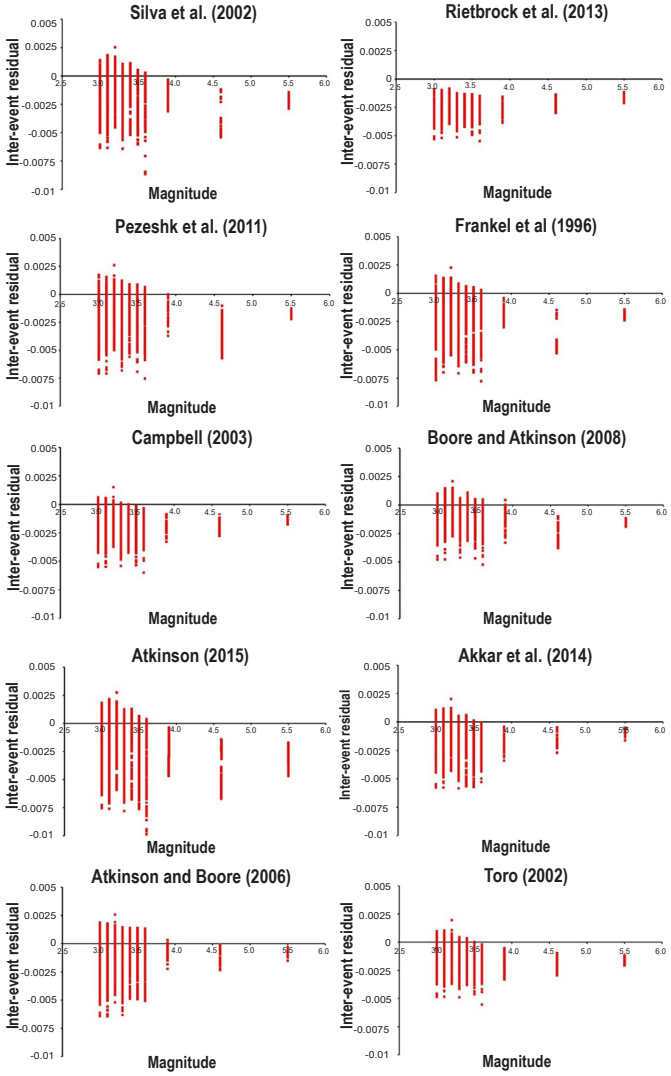


Figure 8—Inter-event terms, also referred to as the mean residual, for the 10 GMPE for T = 2.0s spectral period

$$COV = \frac{\sigma}{\mu} \quad [5]$$

COV is a standardised, unitless measure that compares variability between dissimilar groups and characteristics. A small COV value indicates that the variation in the related parameter does not show large variation in output, while a large COV indicates that the output is susceptible to variations in the parameter under investigation (Gomez and Gomez, 1984; Cramer, 2002; Campbell et al., 2010).

COV results show high values (> 0.3) that indicate large variability in the results (Figure 10). Spatial distribution of the COV values is significantly different for the three spectral periods. High COV values were observed in the central areas for PGA, which decreases north and southwards. For PSA = 0.15s, high COV values are found in the eastern side around Johannesburg CBD while for PSA = 2.0s they are on the west in Soweto. These high COV values for GMPE show that this is an important parameter of which its selection has significant influence on the hazard. Given the uncertainty in the hazard linked to the GMPE, it is necessary that a range of models that cover the epistemic uncertainty associated with the models be selected.

Conclusions

Selecting appropriate GMPE requires a thorough evaluation of local model quality, compatibility with observed data, and consideration of epistemic uncertainties in ground motion prediction. Given the complexity of the seismotectonic setting in the study area, GMPE from various tectonic regimes were chosen for the seismic hazard analysis. To minimise uncertainty in the selection process, ten GMPE were identified and compared with local ground motion data, from which a set of GMPE was selected that best fits the data for the region. Six of these GMPE (Boore and Atkinson, 2008; Campbell, 2003; Akkar et al., 2014; Toro et al., 2002; Rietbrock et al., 2013; and Atkinson and Boore, 2006) were chosen to represent epistemic uncertainty. A sensitivity analysis was conducted to evaluate the impact of GMPE selection on the final hazard estimate.

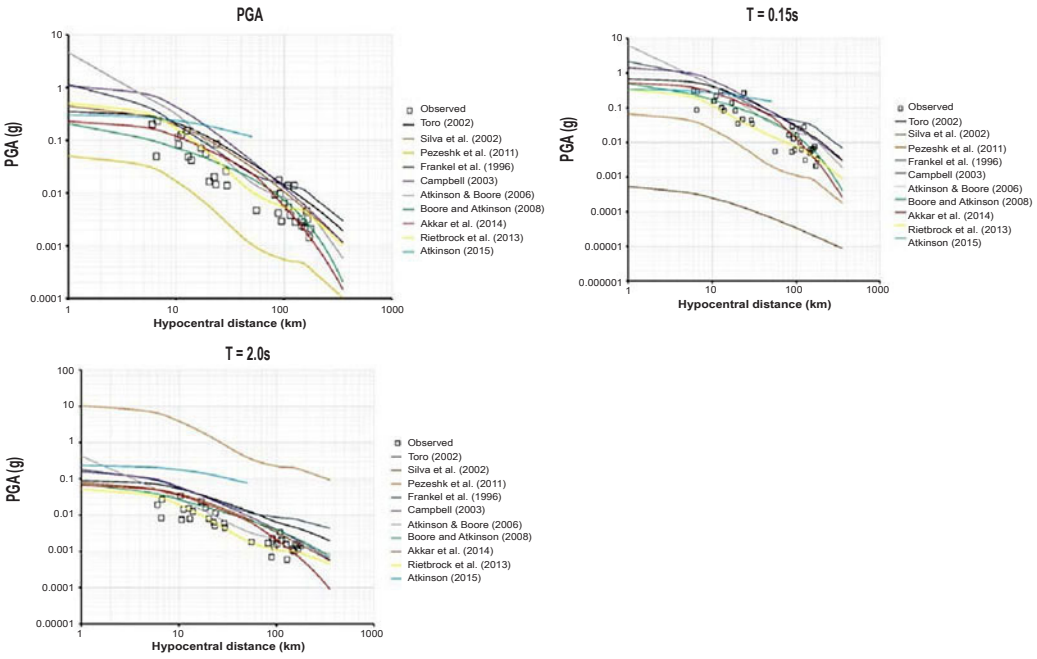


Figure 9—Comparison between the spectral accelerations at three spectral periods recorded during the 2014 Orkney earthquake of magnitude Mw = 5.5 and the predictions obtained with ten preselected GMPE

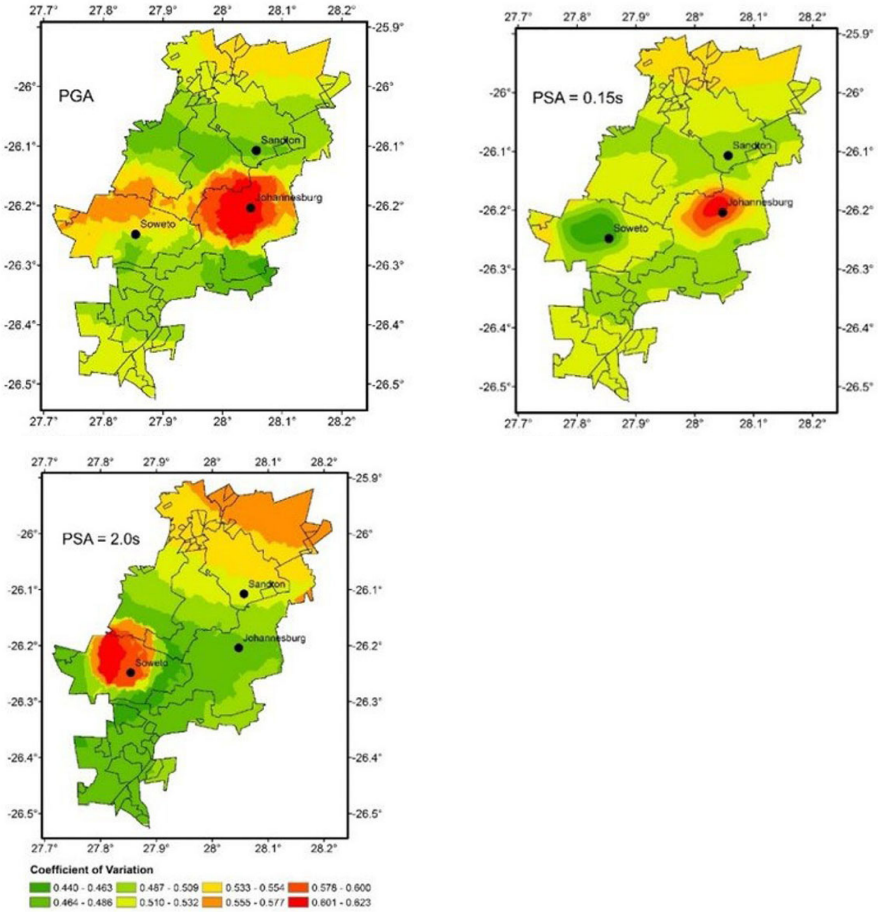


Figure 10—COV results for GMPE seismic hazard sensitivity analysis (a) PGA, (b) PSA = 0.15 s, and (c) PSA = 2.0 s

GMPE based on induced seismicity were excluded, as they did not meet the selection criteria outlined by Bommer et al. (2010), being limited to PGA predictions and not considering other spectral periods. The Atkinson (2015) equation was also excluded because it is applicable only to small magnitudes, whereas seismic hazard analysis focuses on events of moderate to large magnitude that generate ground motions capable of affecting buildings. Comparisons show that when attenuation models are based on a well-assembled database and used within their validity range, they can accurately predict ground motion parameters, especially for short and intermediate structural periods. The methodology adopted in this study aligns with current best practices. Future efforts will be necessary to assess or develop GMPE for this region as suitable strong-motion data from moderate to large earthquakes are recorded.

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Credit

BM: Conceptualisation, methodology, software, investigation, validation, writing, formal analysis, visualisation.
VM: conceptualisation, supervision, software, project management, writing. RJD: supervision, writing.

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