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NEW GROUND MOTION TO INTENSITY CONVERSION EQUATIONS (GMCIEs) FOR NEW ZEALAND

J. Moratalla [1], T. Goded [2], M. Gerstenberger[3], S. Canessa [4]

[1] *GNS Science, Lower Hutt. j.moratalla@gns.cri.nz*
[2] *GNS Science, Lower Huttt.t.goded@gns.cri.nz*
[3] *GNS Science, Lower Hutt. m.gerstengerber@gns.cri.nz*
[4] *GNS Science, Lower Hutt. s.canessa@gns.cri.nz*

Abstract

Macroseismic intensities play a key role in the engineering, seismological, resilience and loss modelling communities. However, at present there is an increasing demand for instrumental data-based loss estimations that require suitable correlation equations between intensities and strong-motion data.

In New Zealand, there was an urgent need to update the current GMICE from 2007 which was developed prior to a huge dataset including the Canterbury 2010-2011 and Kaikoura 2016 earthquake sequences.

Two main factors now provide us with the opportunity to update New Zealand's GMICE: 1) recent publication of New Zealand's Strong Motion Database, where strong-motion data corresponding to 276 New Zealand earthquakes have been filtered and analyzed individually according to the specific features of each record; and 2) ongoing development of the database of community intensities for the complete set of GeoNet's 'Felt Classic' reports. This corresponds to a total of around 930,000 reports between 2004 and 2019.

To develop the database used in this study, felt reports were grouped in circles of radii of less than 1 km from each strong ground motion station (SMS), and mean Modified Mercalli Intensity (MMI) values were estimated if there was a minimum of three felt reports per circle. Ground motions analysed include peak ground velocity (PGV) and peak ground acceleration (PGA). The intensity database contains 67,572 felt reports from 917 earthquakes, with magnitudes 3.5-8.1, and 1797 recordings from 247 SMS, with hypocentral distances of 5-345km.

Different regression analyses were tested, and the bilinear regression of binned mean strong motion recordings for 0.5 MMI bins was selected as the most appropriate. Total Least Squares regression was chosen for reversibility in the conversions. An optimization algorithm for selecting the regression cut-off point was developed for each ground motion type. As observed in published relationships in other regions of the world, PGV provided the best fitting results. The influence of hypocentral distance, earthquake magnitude, distance to fault rupture and Vs30 on the residuals was also explored in this study.

Keywords: Ground motion to Intensity conversion equations, Earthquake ground motion, Earthquake Intensity

1. Introduction

Macroseismic intensity, and its relationship with ground motion recordings provide a rapid assessment of the effects that population perceive when an earthquake occurs. Previous studies provide relationships for other regions of the world, Worden et al. 2012 [1] defined equations to convert PGA, PGV and three damped spectral accelerations to MMI; a probabilistic approach was selected to develop bilinear regressions for reversible conversion. This study includes the dependence of Magnitude and Distance by residual correction factors of both parameters.

Caprio et al 2015 [2] derived new global relationships, assembling a database from active crustal regions in California, Italy, Greece and global data from the Central and Eastern United States (CEUS) catalogue. They provided a PGV and PGA to Intensity global relationship, obtained by a Total Least Squares bilinear regression. Residual analysis was also developed for Distance and Magnitude terms, without a clear correlation of the residuals. In addition, the authors provided regional correction factors to the global relationships, for Italy, Greece and California, as well as a regional similarities study and associated correction factors for other regions of the world.

Du et al 2018 [3] derived weighted least-squares regressions to convert PGA and PGV data from MMI Western China, as well as regional correction factors for the global relationships proposed by Caprio et al 2015.

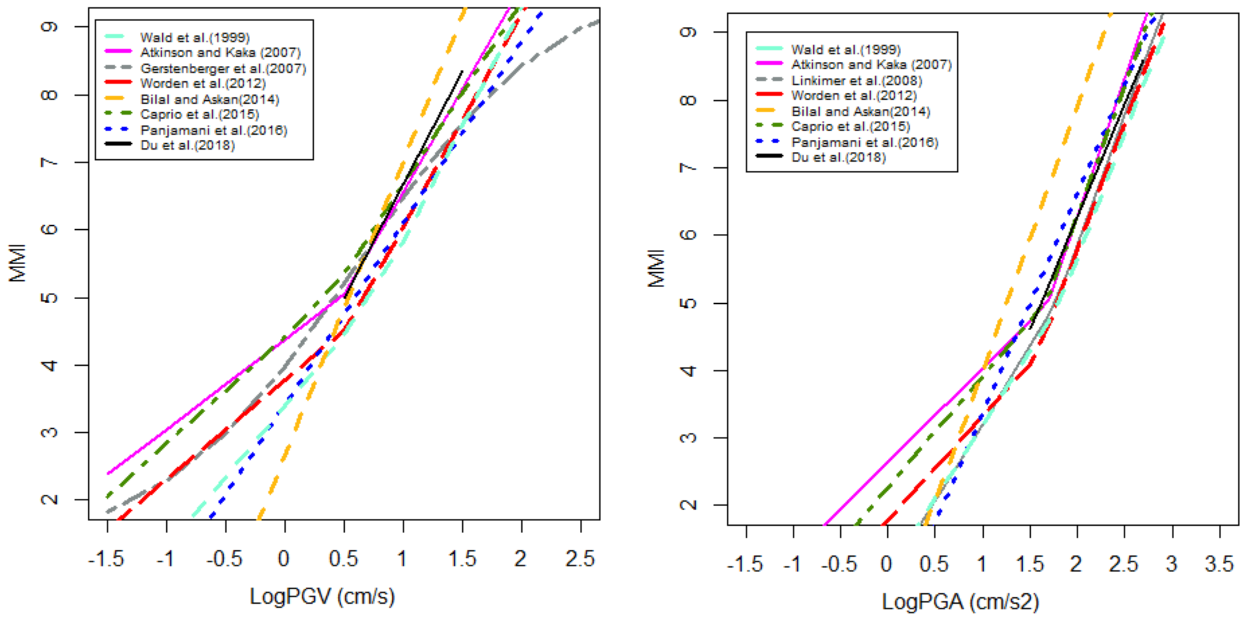

Fig. 1: Published relationships between MMI and Peak Ground Velocity (left) or Peak Ground Acceleration (right).

Gerstenberger et al 2007 [4] developed probabilistic relationships for New Zealand and the US. The New Zealand relationships were based only on PGV and lacked high MMI data. They were developed prior to a large dataset resulting from the Canterbury 2010-2011 and Kaikōura (2016) earthquake sequences. We saw a need to update these relationships given the recent occurrence of large earthquakes (eg Darfield Mw 7.1, 4/9/2010, Christchurch Mw6.2, 22/2/2011, Kaikōura Mw7.8, 14/11/2016) and the corresponding increment in the size of the New Zealand strong motion database, where strong-motion data corresponding to 276 New Zealand earthquakes have been filtered and analyzed individually according to the specific features of each record. In addition, the recent database of community intensities for the GeoNet's 'Felt Classic' and 'Felt

Detailed' online felt reports, comprising a total of around 930,000 reports between 2004 and 2019, provides us with an invaluable opportunity to update the GMICE for New Zealand.

Other ground motion to Intensity Conversion Equations have also been compiled in this work: Linkimer et al., (2008) [5] for Costa Rica, Wald et al (1999) [6] and Atkinson and Kaka (2007) [7], for Central United States, Panjamani et al (2016) [8] for the Himalayan region, Bilal and Askan (2014) [9], for Turkey. Fig.1 shows the compiled GMCIEs.

2. Intensity data

2.1. New Zealand's Community MMI database

In 2004, GeoNet (New Zealand's national geological hazards monitoring service, http://www.geonet.org.nz/) implemented an internet-based questionnaire ('Felt Classic') together with an algorithm (Coppola et al., 2010 [10]) to automatically assign intensity values to each felt report in New Zealand's MMI scale (Dowrick, 1996 [11]; Dowrick et al., 2008 [12]; called "MMI" scale throughout this paper), based on felt information captured from the questionnaire. The questionnaire was similar to the traditional version that had been used for the decades prior to 2004 (e.g., Downes and Dowrick, 2014 [13]). The Canterbury earthquakes of 2010-2012 (e.g., Bannister and Gledhill, 2012 [14]) challenged the facility, which needed to deal with more than 15,000 felt reports for the four major events (Darfield main shock, 4/9/2010, Mw 7.1; Christchurch 22/2/2011, Mw 6.2; Christchurch 13/6/2011, Mw 6.0; Christchurch, 23/12/2011, Mw 5.9).

'Felt Classic' (FC) questionnaires were operative between October 2004 and August 2016. During this period, GeoNet received more than 914,000 felt reports from 27,688 different earthquakes. From August 2016, two different surveys have been conducted on GeoNet website: 1) 'Felt Detailed' (FD) is GeoNet's new questionnaire, very similar to 'Felt Classic' with similar questions and answers plus some additional questions related to tsunami evacuation and social science (by 2 July 2019, FD database contained 14,185 felt reports); and 2) 'Felt RAPID' (FR) is a questionnaire available on internet and mobile devices where the public chooses from a set of cartoons (each corresponding to a different MMI level) depicting their experience of the earthquake. The purpose of FR is to obtain quick and numerous responses from the public using a simplified questionnaire. FR is mainly used by the media and GeoNet as a public communication tool. The results in this paper refer to FC data for the 2004-2016 period and to FD data between November 2016 and July 2019.

GeoNet's automatic algorithm assigns an intensity to each felt report. However, intensity values applied to single locations are not consistent with the way traditional MMI are estimated, by measuring the seismic impact at a regional scale. Thus GeoNet's MMI do not provide information on the geographical damage distribution, essential in seismic hazard and emergency planning. This is being carried out with the use of "community intensities" (CMMI) (Goded et al., 2018 [15]), which estimate the intensity based on multiple responses over a region. They are essential to create intensity maps to be used to inform local authorities and emergency planning agencies.

Goded et al. (2018) developed a method for assigning "community" intensities (where community corresponds to a town in rural areas or a suburb in cities) from GeoNet's FC and FD questionnaires, using the most recent New ZealandMMI scale (Dowrick *et al*., 2008 [12]). It is an expert-based method based on the one developed by the *Instituto Nazionale de Geofisica e Vulcanologia* (INGV, Italy (Sbarra *et al.*, 2010 [16], Tosi *et al.*, 2015 [17]), and applied in New Zealand using the GeoNet FC and FD questionnaires and MMI scale (Dowrick *et al*., 2008). With this method, community intensities (CMMI) are assigned to New Zealand FC and FD data. This provides a method to evaluate the geographical distribution of shaking intensities following an earthquake, instead of simply assigning an intensity per location/report, as in previous studies (Coppola *et al.*, 2010).

Community intensities using the matrix method have been calculated for the complete set of GeoNet FC data, and FD data until July 2019, comprising a total of 914,000 felt reports from around 30,000 different earthquakes, resulting in a database of intensity and strong-motion data for the 2004-July 2019 period, the first of its kind in New Zealand. The database contains around 87,000 CMMI values for communities with five or more felt reports. The database contains CMMI derived from the felt reports, data from the closest strong-motion station to the centre of each community, and MMI derived from Gerstenberger *et al*. (2007) [4] and Worden *et al*. (2012) [1] GMICEs. In addition, for completeness of the database, strong-motion data relevant to this project have been extracted from the New Zealand Strong-Motion database (Van Houtte *et al*., 2017 [18]).

2.2. Traditional intensities (MMI_{trad})

Community intensities have been compared to traditional intensities, assigned manually by a seismologist using the New Zealand MMI scale. This has been carried out for three moderate-to-large earthquakes in New Zealand: M_w 7.1 4/9/10 Darfield (7564 reports, 317 communities), M_w 6.2 20/1/2014 Eketahuna (10885 reports, 331 communities) and M_w 7.8 14/11/16 Kaikōura (3509 reports, 164 communities) earthquakes.

2.3. Intensities by strong motion station (MMI_{bySMS})

In this study, intensity data have been regrouped as circles at 500m, 1000m and 200m form the strong-motion stations (SMS). The MMI_{bySMS} values mentioned in this paper will refer to the community intensity data used in this study, where communities are circles around the SMS. The distance of 1000m has been chosen as the most optimal distance to have enough felt reports and to consider similar soil characteristics between the SMS and the location of the felt reports. The intensity database contains 67,572 felt reports from 917 earthquakes, with magnitudes 3.5-8.1, and 1797 recordings from 247 New Zealand strong-motion stations (SMS), with hypocentral distances of 5-345km. Only suburbs with three or more responses are used to calculate MMI_{bySMS}.

3. Method

As a primary step we stablished a maximum distance of 1 kilometre from the ground motion station to constrain the strong motion – Intensity data pairs. Other studies ([2,6]), used a distance of 2km to associate strong motion-Intensity data pairs but due to the rapid lithological and geomorphological variation across New Zealand, we reduced this distance to 1km to reduce the uncertainty associated to this. A minimum of 3 felt reports was applied as a limitation for inclusion of each data pair. We did not consider a maximum distance to source limitation in this study.

A visualization of the MMI by SMS data pairs, and a comparison with data from other regions of the world with similar expected results (as those from Worden et al 2012 for California, [1]) was made. We observed that our data overestimated the Intensities for low ground motions (PGA<0.3cm/s2 and PGV<10 cm/s) and underestimated large intensities (PGA> 0.3 cm/s2 and PGA> 100 cm/s2).

As explained above, traditional MMI (MMI_{trad}) was available in our database for three main earthquakes that occurred in the last 10 years: Kaikoura 2016, Darfield 2010 and Eketahuna 2014. We compared it with our Community MMI data, also available for these three earthquakes, and derived a relationship based on 767 data-pairs. For each Traditional MMI value, we computed the mean of the corresponding Community MMI values, and then computed the least-squares linear fit of Traditional MMI on the mean Community MMI. Fig. (2) shows the relationship and the data.

$$MMI_{trad} = 1.539\ CMMI - 2.164 \quad (1)$$

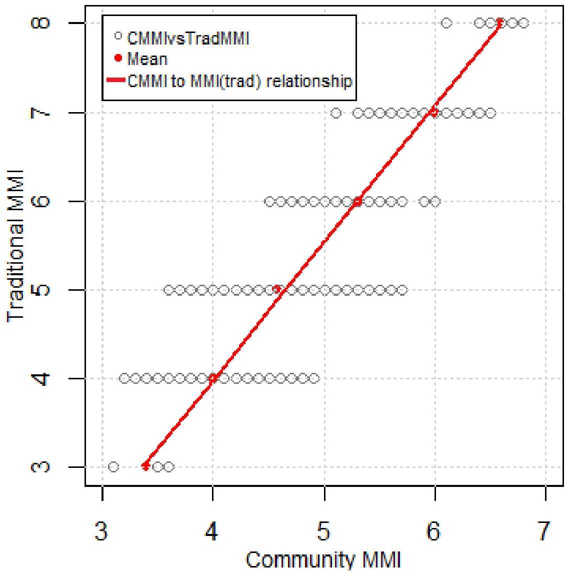

Figure 2: Relationship between the traditional MMI and the Community MMI. Data corresponds to Mw7.8 Kaikoura 2016, Mw7.1 Darfield 2010 and Mw6.2 Eketahuna 2014 earthquakes.

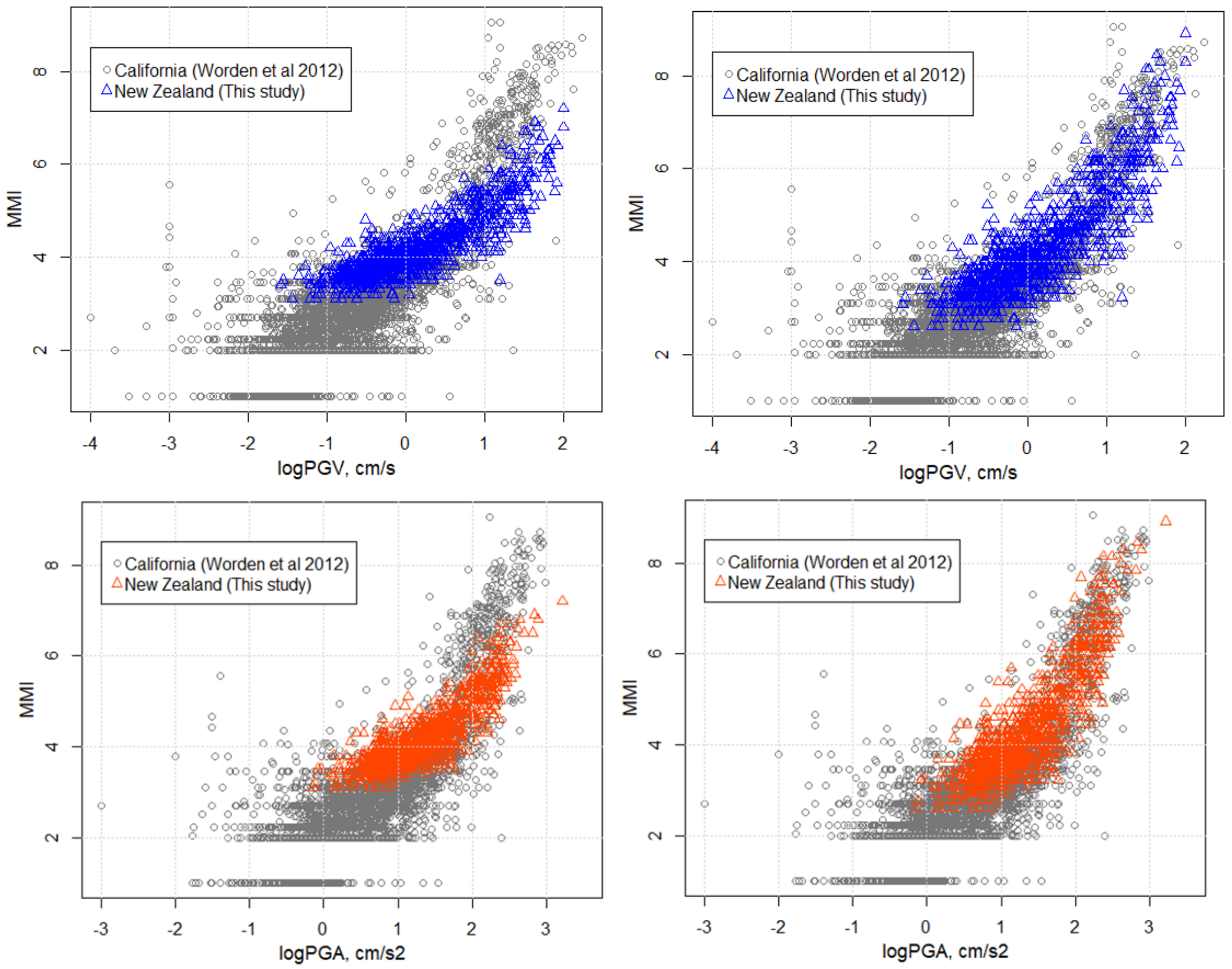

Figure 3: MMI by SMS before (left) and after (right) applying Eq. (1) to the New Zealand database, for PGV (in blue) and PGA (in red). Circles in grey color correspond to data from Western United states ([1]), used as reference.

Using Eq. (1) to convert the complete MMI by SMS dataset to MMI_{trad}, we observed that the previous underestimations and overestimations have been corrected. Fig. 3 shows the comparison with the data from Worden et al 2012 for California before and after the correction, for PGA and PGV.

3. A new GMICE for New Zealand

We selected Total Least Squares (TLS) linear regression, also known as Deming regression (Deming, 1943 [19]), or orthogonal regression, to fit our data and develop the GMCIEs for New Zealand. The Deming regression calculates the residuals as the minimum perpendicular distance from a point to the regression line. It considers the error on both variables, which is an important advantage for making the equations reversible.

Noting the variable number of data points at different MMI levels, we calculated the mean value of logPGV and logPGA for a total of 13 bins with a size of 0.5 MMI, ranging from 2.5 to 9 MMI. The midpoint of each MMI bin was used to develop the regression. This method assures the equal weight of all MMI bins in the regression. Bins with less than three data-points were excluded from the regression analysis.

Considering a horizontal bining of 0.5 MMi units, we can assume the error associated to the intensity equal to 0.25 (i.e. half of the bin size), for the logPGA and logPGV we used the standard deviation of each bin. Table 1 summarizes the statistical values of each MMI bin. Total Least Squares linear regression requires the variance ratio (i.e. the ratio of their variances) Given the variation in the standard deviations in the horizontal axis (i.e. logPGM), we used the mean value of the variance ratios for the bins.

Table 1: Statistical values for each MMI bin used in the regressions.

	MMI	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**	**8.5**
PGV	**mean**	-0.87	-0.58	-0.31	-0.02	0.27	0.65	0.99	1.13	1.33	1.52	1.58	1.65	1.77
	median	-0.86	-0.59	-0.29	-0.01	0.30	0.68	1.05	1.13	1.34	1.54	1.55	1.64	1.67
	std	0.41	0.39	0.34	0.35	0.41	0.41	0.35	0.27	0.25	0.23	0.25	0.15	0.20
	Max	1.19	0.61	1.16	1.27	1.52	1.62	1.88	1.91	1.83	1.92	1.89	2.00	1.99
	Min	-1.59	-1.36	-0.86	-0.96	-0.52	0.09	0.62	0.73	1.04	1.21	1.49	1.63	1.99
	Var. ratio	0.37	0.42	0.55	0.52	0.37	0.36	0.52	0.85	0.97	1.18	1.00	2.92	1.54
PGA	**mean**	0.42	0.74	0.98	1.20	1.42	1.70	1.96	2.11	2.28	2.33	2.36	2.57	2.79
	median	0.48	0.73	0.99	1.21	1.43	1.71	2.02	2.09	2.30	2.34	2.35	2.56	2.84
	std	0.35	0.31	0.29	0.31	0.31	0.30	0.30	0.20	0.17	0.14	0.16	0.18	0.13
	Max	1.77	1.74	2.05	2.22	2.37	2.38	2.47	2.58	2.56	2.60	2.82	2.89	3.22
	Min	-0.12	0.14	0.36	0.44	0.79	0.97	1.65	1.95	2.00	2.08	2.38	2.65	3.22
	Var. ratio	0.52	0.64	0.74	0.67	0.67	0.72	0.69	1.59	2.29	2.97	2.48	2.01	3.83

Two main trends were observed in the data, with a change in the slope at the intensity range 4.5-6.5. This observation is consistent with other GMCIEs relationships from other authors ([1], [4], [5], [6], [7]). Therefore, we decided to use a bilinear regression to fit our relationships.

The flexion point is the binned value that is common to both linear regressions, where the slope in the points change. It was selected by calculating the t-test of the residuals from the resulting bilinear regression. A p-value larger than 0.05 means that the null hypothesis (the residuals are normally distributed) is accomplished. In order to capture all the possibilities, we performed an iteration of the position of the flexion point. The intersection between the two resulting orthogonal regressions determines the applicability criteria of the derived GMCIEs. The results from the t-test indicate that the best fit is obtained for MMI=5.5, with a p-value of 0.81 for logPGV and 0.67 for logPGA. The change point between the two fitted lines is at logPGV=1.084 and LogPGA= 1.754. The GMICEs equations on MMI from Peak Ground Motion (PGM) are provided in equations (2) and (3).

$$MMI = b_1 \log PGM + a_1 \qquad \text{if } \log PGM < t_{logPGM} \tag{2}$$

$$MMI = b_2 \log PGM + a_2 \qquad \text{if } \log PGM \geq t_{logPGM} \tag{3}$$

Given the reversibility of the equations, the equations for calculating PGM from MMI are:

$$\log PGM = (MMI - a_1)/ b_1 \qquad \text{if } MMI < t_{MMI} \tag{4}$$

$$\log PGM = (MMI - a_2)/ b_2 \qquad \text{if } MMI \geq t_{MMI} \tag{5}$$

Table 2 provides a summary of the parameters in equations (2) and (3), as well as the corresponding standard deviations of the residuals obtained by applying these equations to the complete dataset, for both logPGM and MMI. Fits for PGV and PGA are shown in Figs. 4 and 5, respectively.

Table 2: GMCIEs coefficients (a and b), and intersection points (t) in equations (2), (3), (4) and (5). σ values represent the standard deviations of the residuals for the complete dataset.

	a_1	b_1	a_2	b_2	t_{logPGM}	t_{MMI}	σ_{logPGM}	σ_{MMI}
PGV	3.969	1.626	1.571	3.817	1.084	5.731	0.347	0.643
PGA	1.594	1.998	-0.301	3.079	1.754	5.099	0.282	0.616

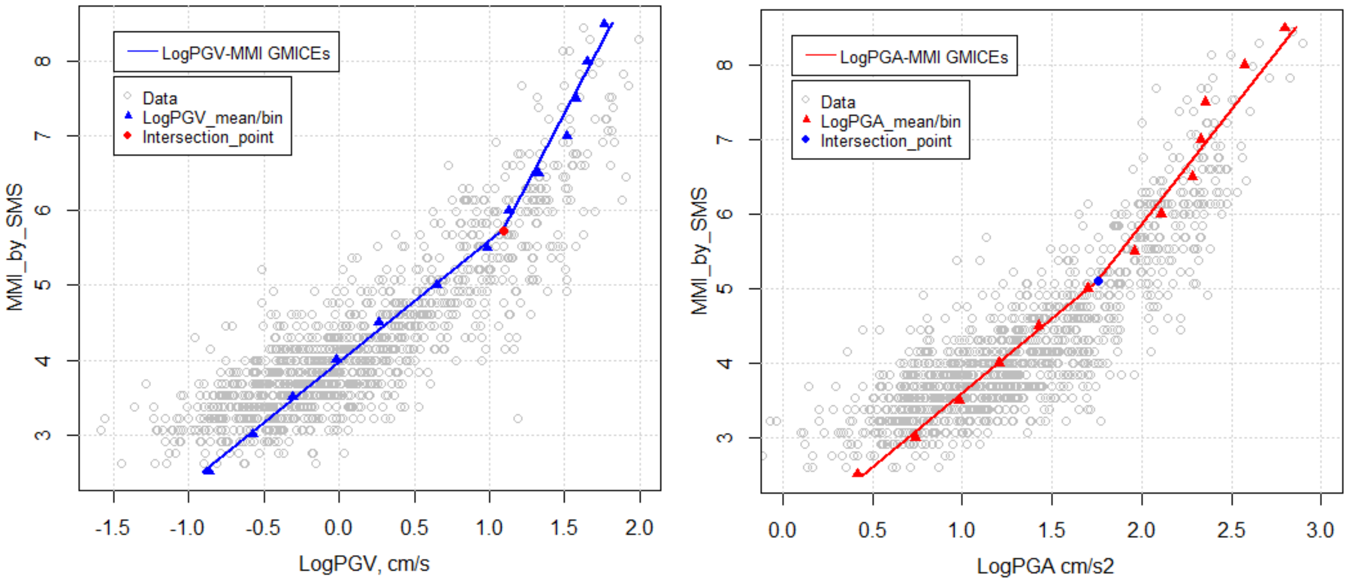

Fig. 4: GMCIEs derived for New Zealand, for logPGV (left) and logPGA(right).

4. Distance correction factor

We explored the effect of hypocentral distances to the Strong Motion Station with the objective of derive a distance correction factor to equations the GMCIEs (Eqs. (2), (3), (4) and (5)). Distances range from 5.2 to 345 km, we divided the dataset into bins of 10 km and calculated the mean of the residuals at each hypocentral-distance bin. Ordinary Least Squares (LS) regression methods were explored to fit both the mean values of each distance bin and the dataset without binning. for both PGV and PGA. The best fit was obtained by applying LS to the binned dataset.

$$MMI_{residuals} = c + d \log(R_{hyp}) \qquad (6)$$

Figure 5 shows the results for both PGV and PGA, and Table 3 the resulting coefficients. Using the new coefficients we included a correction factor to the backbone GMCIEs in Eqs. (2) and (3), as shown in Eqs. 7 and 8.

Table 3: Coefficients of the hypocentral distance correction factors, for PGV and PGA. $\sigma_{MMI\text{-}Rhyp}$ correspond to the standard deviation of the residuals once the correction factor is applied to the dataset.

Variable	i	c_i	d_i	$\sigma_{MMI\text{-}Rhyp}$
PGV	1	-0.21	0.13	0.654
PGA	2	0.99	-0.53	0.699

$$MMI = b_1 \log PGV + a_1 + c_1 + d_1 \log(R_{hyp}) \qquad (7)$$

$$MMI = b_2 \log PGA + a_2 + c_2 + d_2 \log(R_{hyp}) \qquad (8)$$

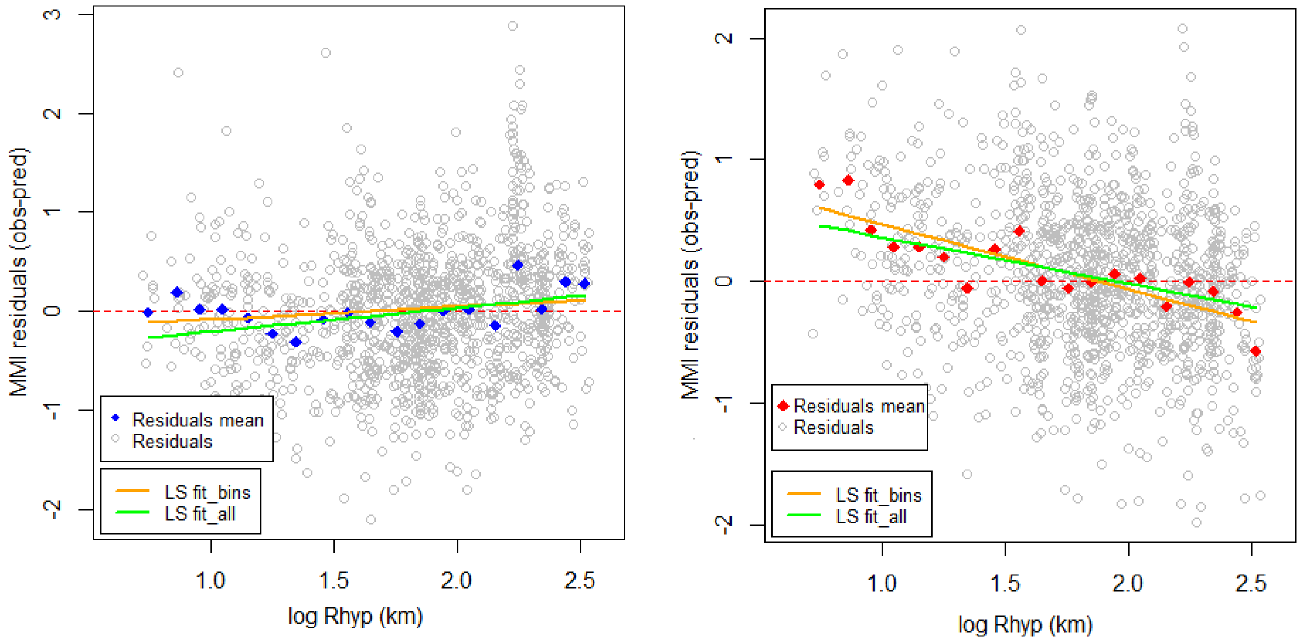

Figure 5: Residual analysis and corresponding Least Squares (LS) regressions for PGV (left) and PGA (right) datasets. LS_fit_bins correspond to the LS fir of the 20km hypocentral distance bins. LS_fit_all corresponds to the LS fit to all the data.

We calculated the MMI residuals for both PGV and PGA using the new equation to guarantee that the distance correction is improving the relationships. The standard deviations of the residuals is larger than the one resulting from the backbone equation by 0.011 for PGV and 0.083 for PGA. Therefore the hypocentral distance correction factor does not improve Eqs. (2), (3), (4) and (5) and we did not include it to the final GMCIEs.

Further research is intended to be done about the effect of earthquake magnitude and the average seismic shear-wave velocity from the surface to a depth of 30 meters (Vs30) at the strong motion station site.

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8. References

References must be cited in the text in square brackets [1, 2], numbered according to the order in which they appear in the text, and listed at the end of the manuscript in a section called References, in the following format:

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