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Updated intensity attenuation for the UK

Earth Hazards and Systems Programme

Open Report OR/13/029

BRITISH GEOLOGICAL SURVEY

EARTH HAZARDS AND SYSTEMS PROGRAMME

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Foreword

This report updates the preferred intensity attenuation model for the UK published in Musson (2005).

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FIGURES

Summary

For many purposes, including seismic hazard and risk calculations, it is useful to be able to estimate the expected intensity value at a place as a function of magnitude and distance. Such a model was published by Musson (2005), relating intensity to local magnitude and hypocentral distance, based on a dataset comprising 727 isoseismals from 326 British earthquakes, including both modern and historical events, up to 1 October 2002, though for the preferred equation only a subset of this dataset was used. This update adds more data from earthquakes that have occurred since then, up to 1 June 2013. More importantly, the model is recast in terms of moment magnitude. The preferred result is

$$I = 3.50 + 1.28\ Mw - 1.18 \ln R$$

This is derived from a subset of the total dataset, discarding data for intensity 2 (poorly constrained) and using only earthquakes with at least two isoseismals.

1 Introduction

Intensity attenuation is relatively little studied compared to the attenuation of physical measures of ground motion, due to the fact that ground acceleration can be used for engineering design, while intensity cannot. However, intensity has other uses, including the estimation of effects (including damage) of future earthquakes, and hence, at least in a general way, the study of earthquake risk. Knowledge of intensity attenuation is also useful in calibrating hazard models against historical experience. A study by Musson (2005) evaluated the attenuation of intensity in the UK from a data set comprising 727 isoseismals from 326 British earthquakes, including both modern and historical events. Best results were obtained by restricting the data set to events contributing at least two isoseismals. The preferred equation was

$$I = 3.31 + 1.28\ ML - 1.22 \ln R \qquad (1)$$

where I is intensity (European Macroseismic Scale), ML is local magnitude, and R is hypocentral distance.

The purpose of this study is to update Musson (2005), including data from more recent earthquakes up to 1 June 2013, and to express the results in terms of moment magnitude (Mw).

2 The data set

The data used for this study is drawn from Musson (1994), with revisions, and continued to the present day in the BGS earthquake database. The data set was confined to earthquakes with at least two isoseismals as per the recommendation in Musson (2005), as these events contain information on intensity decay for that event. This gave a total of 173 earthquakes and 552 isoseismals.

It may seem surprising to be using isoseismals, when other similar studies in recent years have used the original intensity data points (IDPs), for instance, Bakun and Scotti (2006). The problem with using IDPs is that they are strongly influenced by population distribution. This is illustrated in Figure 1. In this figure, the epicentre of an earthquake is shown by the star, and idealised areas affected by intensity 5 and 6 are plotted. The symbols represent places where intensity 5 was actually reported. The IDP distribution will result in seemingly higher attenuation to the west than the east, just because the towns in the west are closer to the epicentre. Intelligent drawing of isoseismals can take this into account and correct it.

Isoseismals are currently unfashionable because of the subjectivity employed in drawing them, and it is true that different seismologists will draw them in different places (Cecić 1992). However, the overall isoseismal areas will probably vary much less. Also, in this study the isoseismals have all been drawn in a consistent way, with the same degree of smoothing.

Since an isoseismal marks the limit of the area at which the intensity was consistently a given value, it follows that an equation such as (1) will return a value equal to the integer intensity (e.g. 4.0 for intensity 4) at a distance corresponding to the 3D isoseismal radius, when the calculation is done using isoseismals. When the calculation is made on IDPs, it will reflect the mean distance from the epicentre to IDPs of a given intensity value, which is probably not so desirable for forward modelling, and is also likely to have a much higher aleatory variability, also unwanted. This is discussed at greater length in Musson (2005).

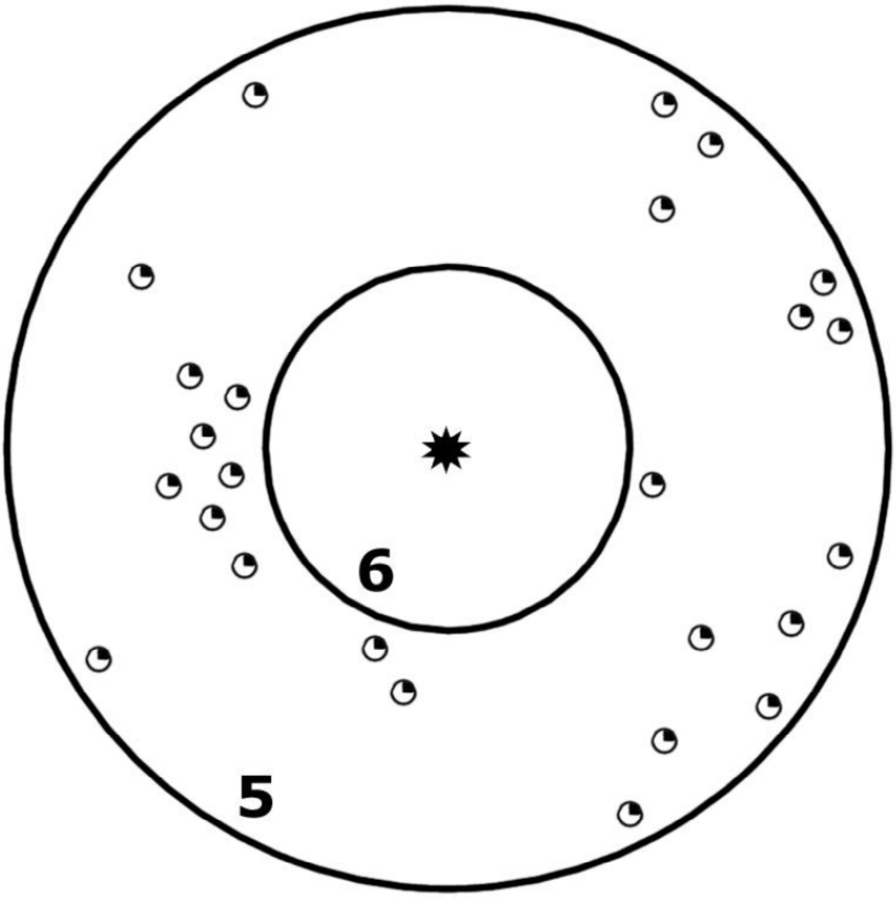

Figure 1 - Effect of population distribution on IDP distribution (from Musson 2005).

2.1 MAGNITUDES

The magnitudes used for the calculations are ML values from the BGS earthquake database converted to Mw. There are several options for performing this conversion, and the choice of which to use is not straightforward.

One candidate formula is derived from a large, well-constrained data set from Central and Northern Europe from Grünthal et al. (2009):

$$Mw = 0.53 + 0.646\ ML + 0.0376\ ML^2 \quad (2)$$

This formula and its predecessor from Grünthal and Wahlström (2003) has already been used for ML to Mw conversion in various UK hazard projects, including Musson and Sargeant (2007).

A recent published formula derived from purely UK data by Sargeant and Ottemöller (2009) is:

$$Mw = 0.70 + 0.70\ ML \quad (3)$$

This has since been updated by Sargeant and Ottemöller (2013) to:

$$Mw = 0.23 + 0.85\ ML \quad (4)$$

Equation (4) relates to recalculated ML values using an adjusted ML scale for the UK. Sargeant and Ottemöller (2013) report that the new ML values are slightly smaller than those previously published for events > 2 ML between 1990-2011. It seems impossible at present to infer the relationship between Sargeant and Ottemöller's (2013) version of the ML scale and ML values calculated for UK earthquakes (a) calculated from historical seismograms 1900-1969, or (b) from BGS stations 1970-1989. For the purposes of this study, it will be assumed that this is parity, but this will need to be checked in due course.

Musson (2005) included an equation derived from a small UK dataset from unpublished work by MEA Ritchie:

$$Mw = 0.26 + 0.91\ ML \quad (5)$$

Also, comparison can be made with surface wave magnitude (Ms). It has been found by Bungum et al. (2003) and Grünthal and Wahlström (2003) that Ms determined for UK and Scandinavian earthquakes by NN Ambraseys (e.g. Ambraseys 1985a) closely agree with Mw values where these are available. Marrow (1992), using Ambraseys (1985a) obtained:

$$Ms = -0.05 + 0.91\ ML \quad (6)$$

However, there are some variations in the magnitudes given for some events between Ambraseys (1985a), Ambraseys (1985b) and Ambraseys (1988). For the purposes of this report, Marrow's regression was repeated using the events and magnitudes from Ambraseys (1988) on the basis that the last values should be the preferred ones, though there is no recognition in Ambraseys (1988) that some values have changed by up to 0.3 magnitude units over the earlier publications.

This now produces:

$$Ms = -0.42 + 0.99\ ML \quad (7)$$

The regression is shown in Figure 2. In this equation one can tentatively substitute Mw for Ms.

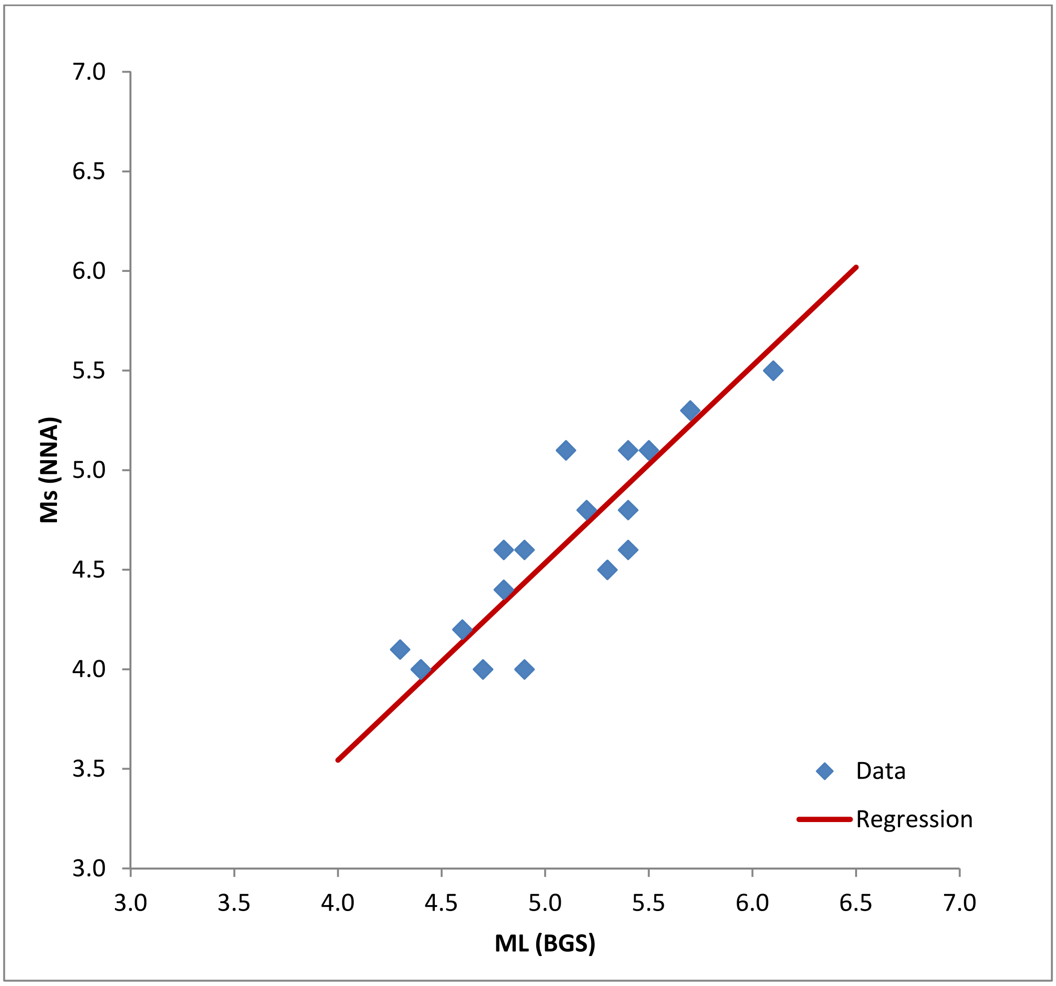

Figure 2 - Ms-ML comparison and orthogonal regression

All these equations are shown in Figure 3, with the exception of (6), which is assumed to be superseded by (7). Figure 3 also plots the data supporting equations (3) and (4), but not the data on which the others are based. Equations (2) and (4) agree well, at least up to magnitude 4, which is the range that equation (4) is largely based on. Equation (3), on the other hand, implies that Mw and Ms diverge significantly at higher magnitudes, which has not been found in Northern Europe; and elsewhere, the divergence is in the opposite sense, i.e. Mw is about 0.7 units higher than Ms for 4.0 Ms and the divergence decreases with increasing magnitude (Scordilis 2006, Bormann et al. 2009, Musson 2010). Equation (4) also agrees with (7) above magnitude 4; the importance of equation (7) is that it is entirely based on events of 4.0 Ms/Mw or higher.

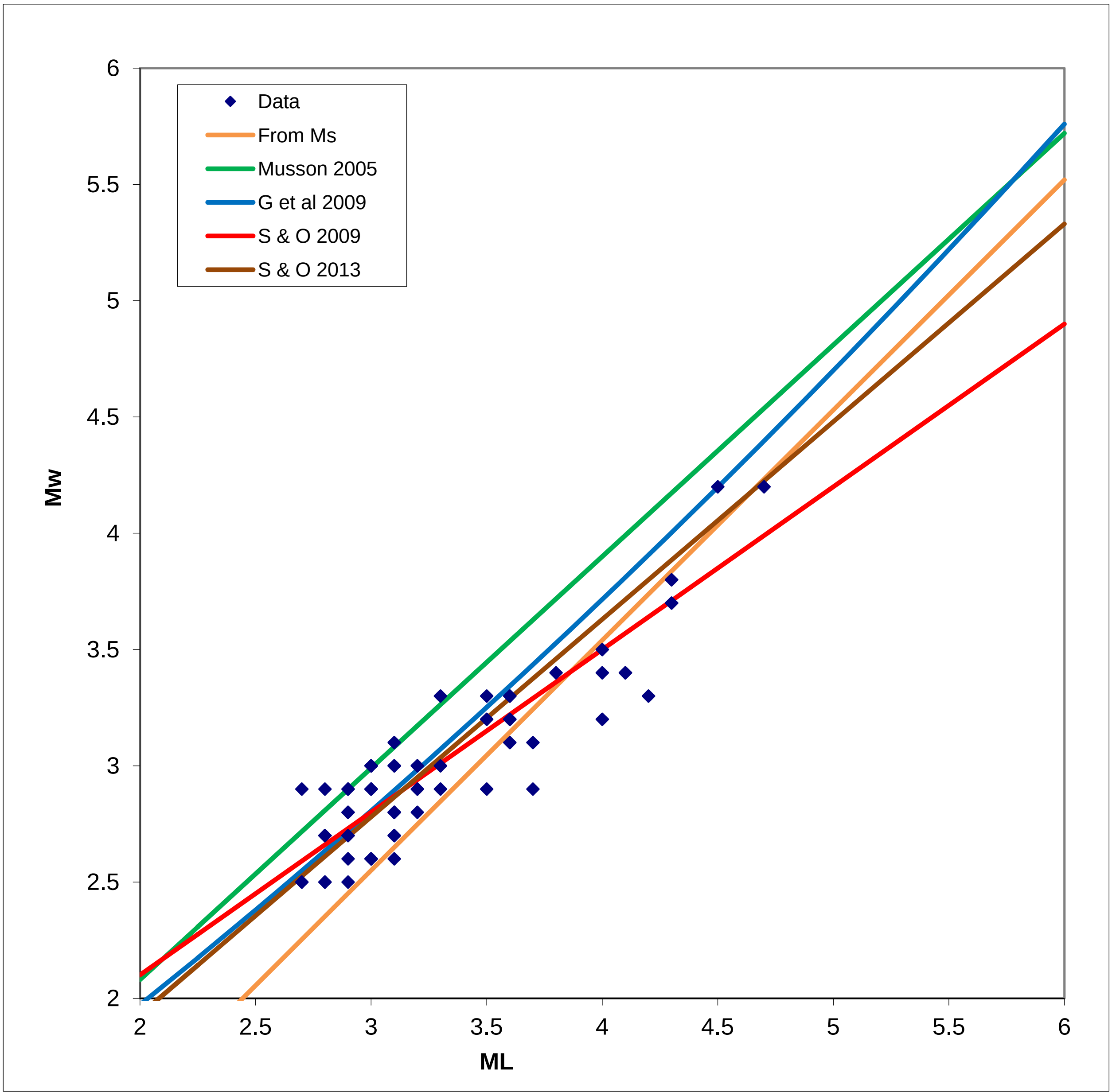

Figure 3 - Alternative ML-Mw conversions

Equation (3), also implies that no onshore British earthquake has ever exceeded 4.5 Mw, in which case one could conclude that seismic hazard in the UK is effectively zero, which would be a comforting but probably not robust conclusion. While it can be accepted that this is extrapolating the equation outside its range of applicability, since hazard studies are concerned almost exclusively with earthquakes larger than 4 Mw, such extrapolation is necessary, or the equation is of no practical use for the hazard analyst. Equation (4) is a distinct improvement. As a quick check, the 5.4 ML Lleyn Peninsula earthquake, the largest onshore British earthquake, would become 4.8 Mw, equal to the 4.8 Ms given by Ambraseys (1988), and a magnitude of 6.1 ML (Musson 1994) for 1931 North Sea translates to 5.4 Mw, compared to 5.5 Ms. These are within the uncertainty of the Ms-Mw equivalence.

For the purposes of this report, both equations (2) and (4) will be used. However, Sargeant (2013 pers. comm.) recommends that equations (3) and (4) are only applicable within the range of the bulk of the data, i.e. below about 4.3 ML, so equation (2) is preferred. There are additional difficulties with equation (4), in that Sargeant and Ottemöller (2013) also recalculated ML for earthquakes post-1990, obtaining slightly different values from those in the database used here; but the new values are not included in the paper. The differences, though, seem to be very slight above 3 ML, judging from Sargeant and Ottemöller's (2013) Figure 7. Since no similar recalculation has been made for events before 1990 (i.e. the bulk of the earthquake catalogue), the only option at present is to assume that applying equation (4) to the entire dataset will not lead to significant errors.

3 Results

The main intention was to follow the preferred equation in Musson (2005) and apply the following constraints:

- Use all data, including historical earthquakes
- Do not use isoseismals for intensity 2
- Use only events with at least two isoseismals greater than intensity 2

The dataset thus reduces from 173 earthquakes to 161, and now contains 446 isoseismal areas instead of 552. The reduced dataset is given in the Appendix. This yields:

$$I = 3.50 + 1.28\ Mw - 1.18 \ln R \qquad (8)$$

The value for sigma is 0.48.

As discussed in Musson (2005), it is debatable whether this involves a circularity, since earthquakes without instrumental magnitudes have magnitudes calculated from isoseismal radii, which are now being used in turn to calculate expected intensity values. The counter-argument is that macroseismic magnitudes are calculated with respect to a correlation between the area of intensity 3 EMS (sometimes 4 EMS) and instrumental magnitude, therefore macroseismic magnitude is a proxy for instrumental magnitude, and is used here to calculate an equation expressing the estimation of all intensities, not just 3 EMS. Also, restricting the dataset to only earthquakes with instrumental magnitude loses a lot of the higher intensity data (including all the earthquakes with an intensity 7 EMS isoseismal).

However, for completeness, the calculation was repeated using only earthquakes with instrumental magnitudes (including events in the 1900-1969 period, which were not used in Musson 2005). This reduced the dataset to 219 isoseismal areas from 80 earthquakes. The equation now becomes:

$$I = 3.93 + 0.99\ Mw - 1.00 \ln R \qquad (9)$$

The value for sigma is 0.52

Repeating the calculations with Mw calculated from equation (4) gives:

$$I = 3.07 + 1.43\ Mw - 1.17 \ln R \qquad (10)$$

using all data and

$$I = 3.59 + 1.11\ Mw - 0.99 \ln R \qquad (11)$$

with only instrumental magnitudes. The sigma values are now 0.49 and 0.53 respectively.

These results are displayed in Figure 4. The x axis is epicentral distance assuming a focal depth of 10 km. The main conclusions are:

- Using equations based on only instrumental data tends to result in lower estimated intensities, possibly due to the presence of more high intensity data in the complete dataset.
- Using equations based on the Sargeant and Ottemöller (2013) conversion produces higher estimated intensities, because any given Mw value is equivalent to a considerably larger ML magnitude. As noted above, though, this conversion is questionable for magnitudes within the range of interest for hazard studies.

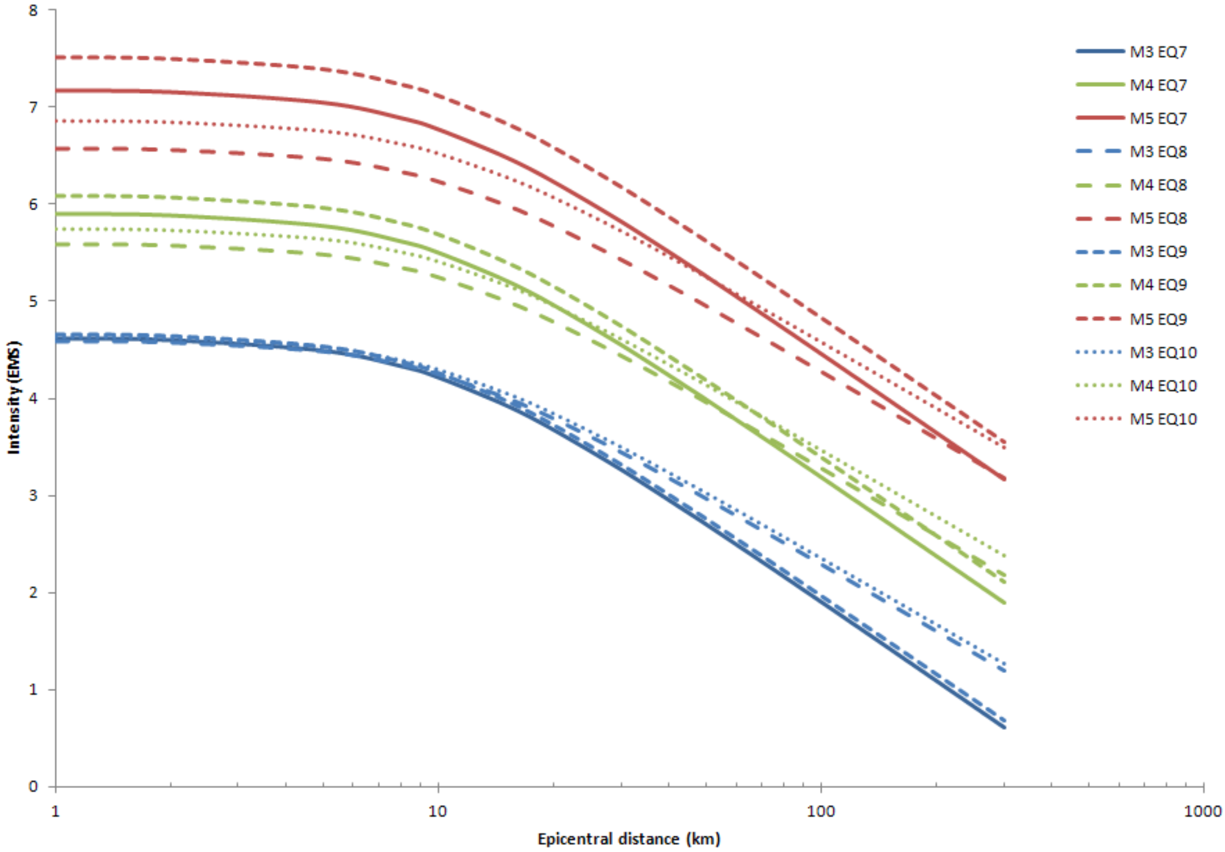

Figure 4 - Comparison of the four equations for three magnitude values

If one does use the entire data set including intensity 2, equation (7) becomes:

$$I = 2.96 + 1.50\, Mw - 1.358 \ln R - 0.00023\, R \qquad (12)$$

The sigma value is now 0.58.

Figure 4 compares the average RMS value for each isoseismal area in the data set, compared to the expected area from equations (8), (9) and (12), arranged by intensity. It will be seen that values from equation (12) do not fit intensity 2 data very well, which is a good justification for not using intensity 2 values, which are by their nature poorly determined. Equations (8) and (9) are consistent in having lower residuals for intensity 4 than for other intensities.

Further analysis of residuals was undertaken, this time for equation (8) alone, which is the favoured version. Figure 6 plots residuals against time. The value for each earthquake is the mean of the RMS values for each isoseismal, plotted against year. Data before 1700 is excluded for clarity; there are only two data points for the period 1300-1699. There is no clear trend of increasing or decreasing residuals with time, and while there are more high-residual events after 1950, there are simply more events altogether. The worst fitting event of all is the very anomalous 1965 Barrow earthquake, the magnitude of which may be underestimated. The only other event with a mean RMS above 1.5 is the 1950 Dover Straits earthquake, which was rather poorly reported at the time. The worst-fitting recent earthquake is the 2010 Coniston event, for which the isoseismal 5 is likely to be overestimated.

Figure 7 plots residuals against magnitude, and there is clearly no discernible bias.

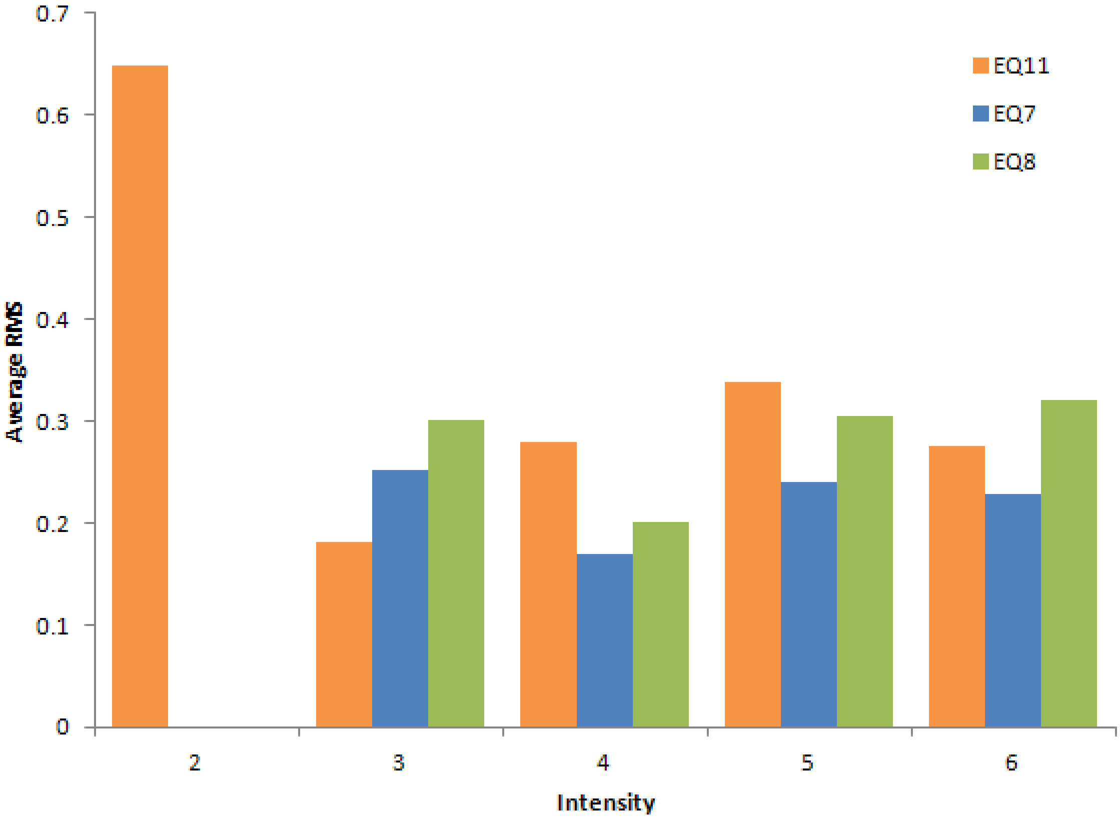

Figure 5 - Average residuals as a function of intensity

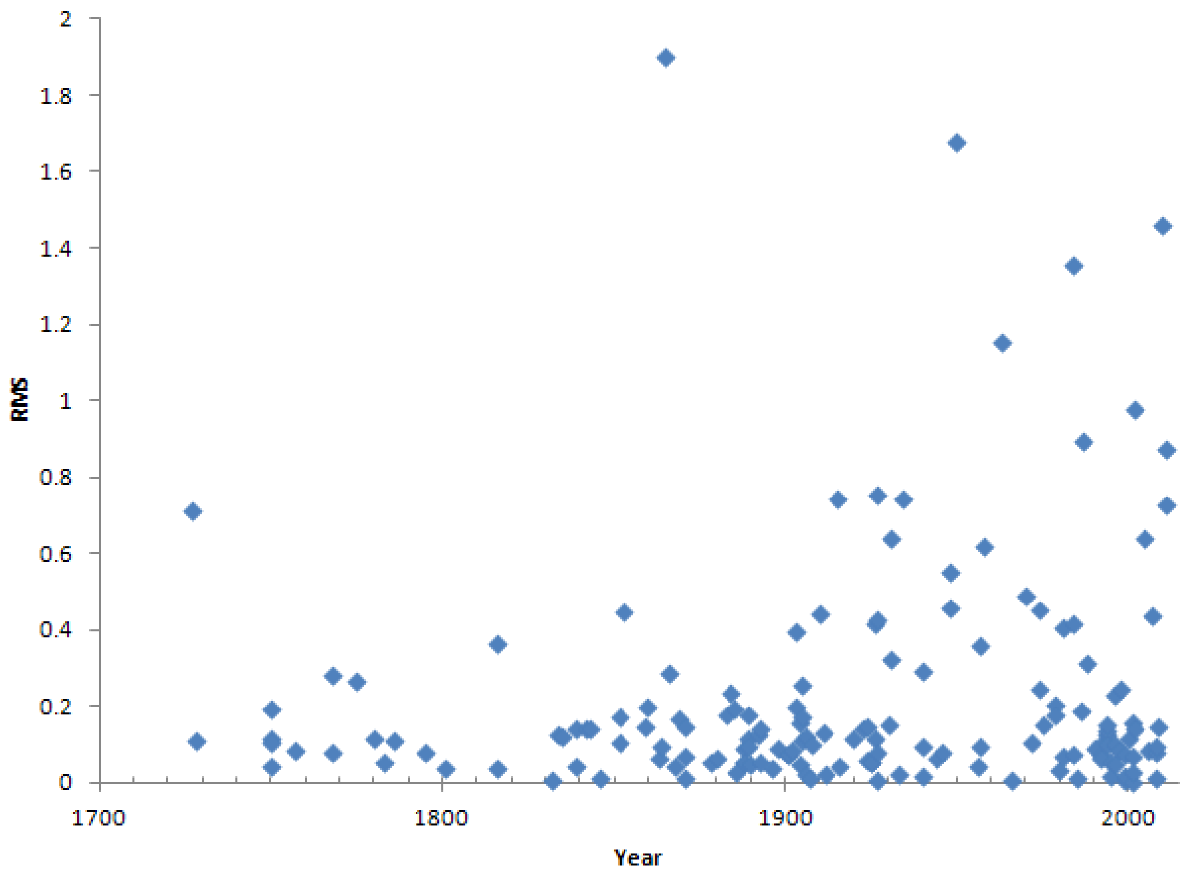

Figure 6 - Residuals by year

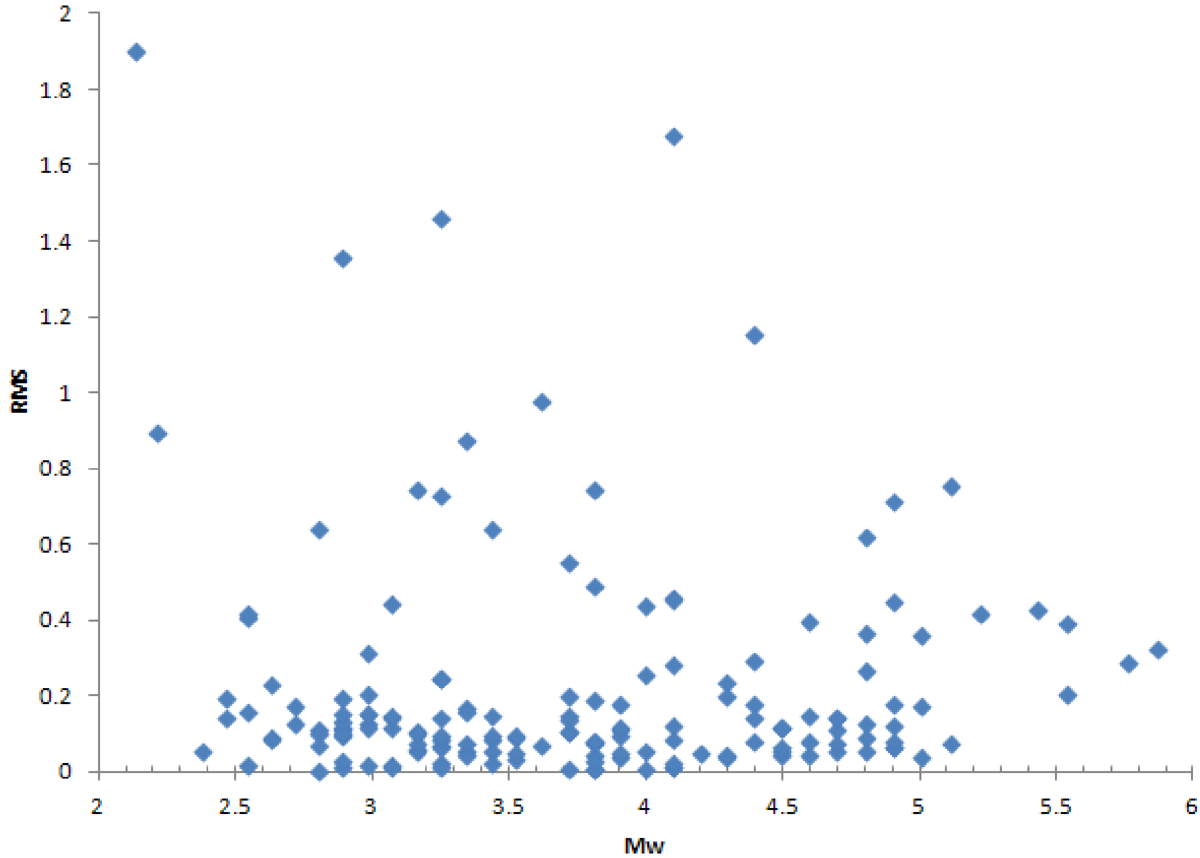

Figure 7 - Residuals by magnitude

4 Conclusions

Given present availability of UK earthquake data, the preferred equation for estimating EMS intensity as a function of magnitude and hypocentral distance is equation (8) in this report.

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Appendix 1 Data used

Date	*h*	*Mw*	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*
13820521	25	5.5			350000	96000	17000		
15800406	22	5.5			335000	145000	30000	1800	
17270719	25	4.9		157000		67000	6000		
17280301	21	3.9		20000	2000				
17500208	2	2.5		470	170	30			
17500308	3	2.9		1700	400	80			
17500402	10	3.7		11000		800			
17500930	5	3.8			4500	1500			
17570715	15	4.1		30000	8000	230			
17680515	17	4.1		26000		4300			
17681221	10	3.8		15000	5000	1400			
17750908	19	4.8			81000	23000			
17801209	21	4.5		74000	34000	650			
17830810	9	3.3		5000	1600	60			
17860811	16	4.7			41000	16000	650		
17951118	10	4.4			22000	4500	1000		
18010907	9	4.3			16000	4000			
18160317	5	3.9			6500	1400	300		
18160813	18	4.8			73000	31000			
18321230	5	4.0			7500		250		
18340123	4	3.0		2000	700				
18350820	11	4.1		30000	12000	3700			
18390901	9	3.3		4100	600				
18391023	9	4.5			26000	7000	400		
18420217	3	2.5		550	260	60			
18430317	17	4.7		108000	40000	15500			
18461124	8	4.1			11000	2000			
18520812	5	3.2		3200	1800	300			
18521109	24	5.0		208000	98000	32000			
18530401	21	4.9		170000	104000	46000	6500		
18591021	7	3.7		12000	5800	1700			
18600113	8	3.7		13000	9600	1600			
18631006	25	4.9		189000	87000	12500	800		
18640821	4	2.9		1600	600	130			
18650215	1	2.1		200			50	15	
18660309	31	5.8		1000000	500000	250000			
18681030	24	4.6		97000	33000	2000			
18690315	5	3.3		5000	2000	800	65		
18710317	10	3.6		10000	4000				
18710317	21	4.6		80000	36000	11000			
18710415	2	2.9			600	100			
18780128	16	4.7		115000	35000				
18801128	25	4.9			83000	4500			
18830625	11	3.9		18000	8900	2800			

Date	*h*	*Mw*	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*
18840422	3	4.3		47000	10000	3000	800	200	60
18850630	5	2.9		1400	400				
18860104	2	2.9			500	100			
18880202	17	4.5		71000	27000	5000			
18880411	8	3.5		7500	3300	670			
18880719	5	3.2		3400	1200	180			
18890118	4	3.0		2000	500	70			
18890210	10	3.5		7000	1400	130			
18890530	25	4.9		187000	87000	30000	1300		
18901115	10	4.2		32000	11000	1400	100		
18920818	26	4.8		140000	70000	14000	800		
18930804	10	3.4		6000	2000	140			
18931102	24	4.7		102000	64000	8000	900		
18961217	20	5.0		215000	76000	11000	1500		
18980401	3	2.6			350	130			
19010709	7	3.8		13500	6500	750	150		
19010918	11	4.7			45000	5000	200		
19020413	15	3.4		6000	1000				
19030324	8	4.3		21000	9000	2000	130		
19030619	12	4.6		39000	7800	1500	250		
19040303	4	2.5		650	250	70			
19040703	17	3.9		20000	6500	800			
19050120	4	2.7		1100	250				
19050423	15	4.0		36000	24000	3000			
19050921	4	2.9		1500	500	100			
19060627	13	4.9		117000	59000	11000	3000		
19060827	11	3.3		5600	970				
19070117	10	4.1			11000	1200			
19081020	4	2.9		1500	670	80			
19101214	4	3.1		1500	350	20			
19110516	7	2.9		1500	650				
19120503	4	3.4			1800	280			
19151002	17	3.2		12500	7500	200			
19160114	10	4.3		46000	18000	3000	400		
19200902	4	3.1		2500	1200	300			
19231225	3	3.1			1200	450			
19240306	5	3.2			1380	340			
19240404	2	3.1		2600	1100		70		
19250201	25	4.8		146000	35000				
19251223	15	4.0		25000	5500				
19260730	18	5.2		142000	41000	9000			
19260815	17	4.5			46000	6000	400		
19270124	25	5.4		840000	432000	187000			
19270127	7	3.8			4500	700			
19270217	22	5.1		78000	23000	3000			
19271119	22	4.6		72000	20000	4000			
19300825	5	3.0		1850	400	40			
19310503	2	3.4			500	125			

Date	*h*	*Mw*	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*
19310607	23	5.9			740000	190000	63000		
19330114	10	4.1		38000	12500	1600	140		
19340816	14	3.8		45000	24000	6000			
19400202	8	3.1		5000	550	25			
19400716	7	3.4		5500	2000	500			
19401212	12	4.4		28500	8000	1450			
19441230	21	4.5		70000	33000	2000			
19461225	11	3.8		14500	3000	350			
19480528	10	3.7		4000	2000				
19480531	14	4.1		30000	1500				
19500109	7	4.1		4000	1500				
19560110	4	3.3			3000	350			
19570211	13	5.0		83000	27000	5000	1000		
19570212	12	3.9		20000	9000	1700			
19580209	16	4.8		46000	17000				
19631025	12	4.4		9000	4000	300			
19660723	18	3.8		30000	4000	200			
19700809	20	3.8			15000	2000			
19720307	6	3.7		11500	4000	1400			
19740123	8	3.3		4000	400				
19740810	22	4.1		9000		90			
19750116	6	3.0		1850	530				
19790219	6	3.0		1400	600	200			
19791226	11	4.4			45000	7000	500		
19800101	5	3.5		9000	2600	550			
19810225	5	3.3		4900	1100	100			
19810612	15	2.5		2200	750				
19840216	2	2.5		650	100				
19840530	15	2.9		12000	6500	500			
19840719	20	5.1		239000	105000	9000	1200		
19850916	4	3.1		4000	1000	140			
19860929	23	3.8		24000	8600	1100			
19871109	18	2.2		1000	350				
19880912	15	3.0		2700	700	40			
19900402	14	4.8		138000	63000	15500	1500		
19920217	10	3.2		7000	2000	100			
19920729	11	3.3		4000	1300	40			
19930626	8	2.8		2700	760	60			
19940210	14	2.7		2626	517				
19940215	7	3.7		9500	2800	300			
19940317	22	2.9		1056	150				
19940512	16	2.8		1996	447				
19950220	3	2.4		720	240				
19950828	9	2.5		1400	215				
19960307	10	3.2		3052	1154	105			
19960506	3	2.6		926	168				
19961110	8	3.5		14000	5000	400			
19971016	10	2.6		1361	465				

Date	*h*	*Mw*	*A2*	*A3*	*A4*	*A5*	*A6*	*A7*	*A8*
19980503	15	3.3		12000	4000				
19990304	19	3.7		18700	2600				
19990901	6	3.0		3500	600				
19991025	4	3.3		6800	1100				
20000923	4	3.9		14900	4700	700			
20010513	2	2.8		2900	540	110			
20010531	4	3.3		14428	4466				
20011010	7	2.8		1641	321				
20011028	2	3.8		25166	8286	1013			
20020922	14	4.4		126000	44500	1200			
20021021	2	3.6		2540	650	170			
20051210	11	2.8			1100	215			
20061226	7	3.3		3590	1300	230			
20070428	2	4.0		8500	2000	850	150		
20080227	18	4.9		240000	72500	20000			
20081010	13	3.3		10000	2600				
20081026	5	3.3		6400	1450				
20090428	10	3.4			2500	740			
20101221	13	3.3		38000	11000	2900			
20110103	7	3.3		35000	10000	1900			
20110123	13	3.3		21800	7000	1000			