Maximum Intensity Map of the Conterminous United States

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Abstract

Maps of maximum historical intensity in the 50 United States are prepared by review of published isoseismal maps for 72 historical events and by generation of circular isosiesms for 2,284 events of maximum intensity VI or greater. Modern attenuation relations are used to correlate intensity to threshold acceleration as a function of earthquake magnitude. The relations developed by this method are used to incorporate historical siesmicity into a comparative model for short-return interval seismic hazard analysis. The maps demonstrate that earthquakes are a national problem and are common enough to be under constant consideration in the formation of national policy.

Introduction

Intensity, as applied to earthquakes, is a quantity determined from the effects on people, manmade objects, and the Earth's surface (landslides, offset, ground fissures). An earthquake in a populated area will generally have a different intensity than that determined for a sparsely populated or barren area. However, intensity scales have the advantage that they in a sense take site effects and other complexities of actual attenuation of strong ground motion implicitly into account; that is, an isoseismal map derived from an earthquake's effects may have a higher resolution of, for instance, ground-level response acceleration than any attenuation relation currently available can provide.

A failure of intensity scales in one sense is that their values will change over time as populations shift and change, and as building codes and practices are developed to minimize earthquake damage; the same motion that destroys an un-reinforced brick and masonry structure may have no effect on a more recently built double-walled and reinforced brick building.

Intensities in the United States are generally assigned according to the descriptions listed in the Modified Mercalli Intensity (MMI) Scale of 1931. (Coffman, 1978) Although the MMI is in many instances inadequate for present-day requirements, the scale has been used by NOAA and USGS and will continue to be so used until a new scale has been devised and has acceptance in the engineering and seismological communities. We suspect that any new attempt at defining an intensity scale will show similar boundaries of damage and effects, for historical continuity, but will be determined by different specific criteria more suited to modern structures, experiences, and populations.

The most complete modern treatment of national intensity data was prepared by R. J. Brazee in 1976. Brazee compiled several relevant maps including a map of maximum intensity for the conterminous US by contouring point values taken from historical records and directly from public responses to earthquake questionnaires, compiling a database of locations and their maximum intensities. Brazee reasonably states that published isoseismal maps are limited in their accuracy by a variety of factors, including varying assumptions and limited data. Reports used by Brazee were collected from 1928 to 1973, about 100,000 reports. (Brazee, 1976) The method of contouring may be more meaningful than the strict adherence to circular isosiesms, however the small historical sampling used eliminates most moderate earthquakes and several great ones from the database. Without a clear and accepted method of relating physical phenomena to felt area at each intensity, the maps produced by this method are misleading in their limited demonstration of historical earthquake effects. Because recorded US history (the earliest earthquake is 1638) may correspond to short return-interval events (roughly 15-20% probability of recurrence in 50 years), the significance of this earlier period should not be underestimated.

This study attempts to develop a method for inclusion of historical earthquakes and extend our picture of earthquake effects into Alaska and Hawaii.

Methods

Base Map

The familiar and mathematically simple Polyconic map projection was used for the basis for presentation of this study. However, it should be noted that the basic methods - location of x,y coordinates and generation of circles representing isoseismal radii for each epicenter, could be applied to any projection. See Appendix 1 for discussion of the mathematical use of this projection.

Earthquake Database

The database of earthquakes for this study is a compilation of earthquake records obtained from the USGS National Earthquake Information Center (NEIC), and from the publication Seismicity of The United States, 1568-1989 (revised). The former contains several earthquake databases which can be accessed via an internet search engine (see Bibliography and Appendix 2). The latter publication was required for several significant historical earthquakes to which generally accepted magnitudes have not been assigned. The database is presented in Appendix 3.

Preparation of Isoseismals

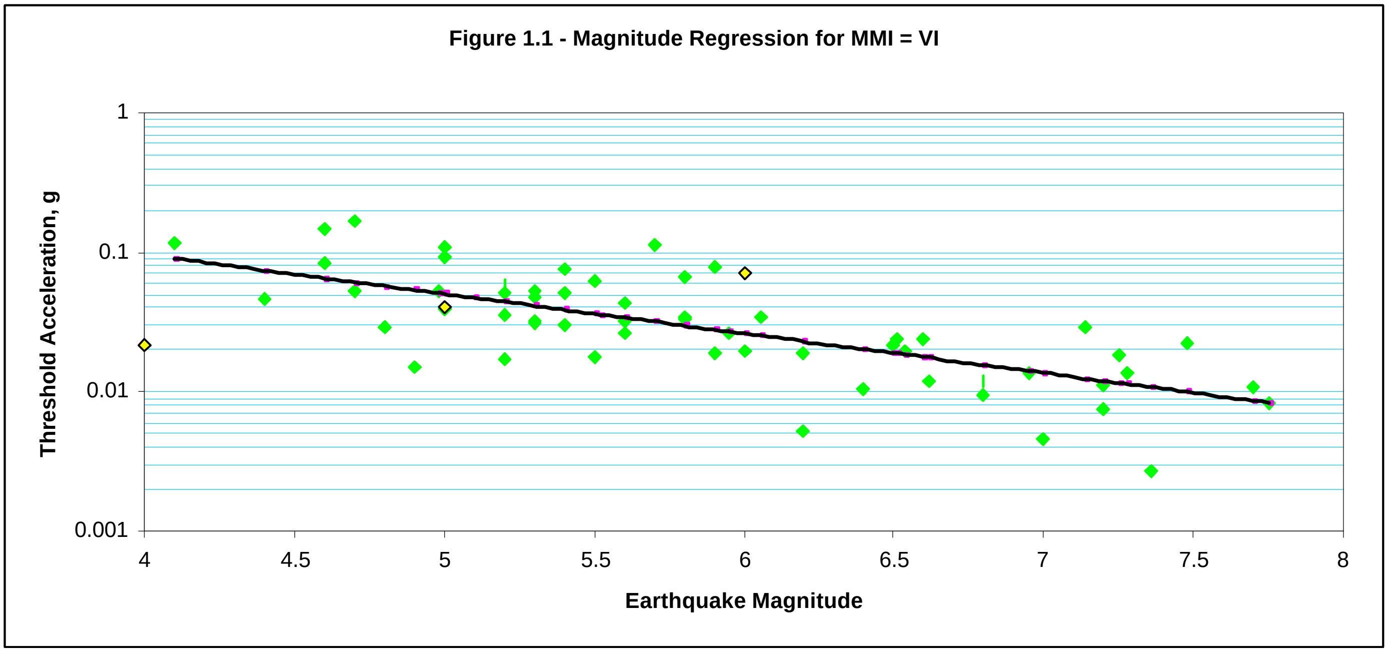
Approximately 41% of the map coverage (72 earthquakes) was taken from published isoseismal maps, primarily from the publications United States Earthquakes and Earthquake History of the United States. The maps were scanned as bitmap files and placed into the base map, and scaled and rotated manually to best line up cities, borders, rivers and other reference points. The isosiesms were then traced. In ambiguous cases, such as an isosiesm for MMI = VI+, with no indication of the location of higher intensities, only the VI - area was enclosed.

Published isoseismal maps represent only a small fraction of the historical earthquakes capable of generating intensities of VI or above. The majority of earthquakes in the database (2,284 events) were generated synthetically by developing empirical equations relating magnitude to felt area for each intensity. Review of existing relations for this purpose suggested that more effort was needed at correlation.

The relation of MMI to peak ground acceleration has been presented by Trifunac and Brady, 1975, including the following relation:

Peak acceleration in cm/s^2 for IV I_{MM} X $\qquad$ $\log a_H = 0.012 + 0.30\, I_{MM}$

Comparison with a larger data set, however, suggests that the peak acceleration which is capable of affecting a certain level of damage may be strongly magnitude-dependent. Using attenuation relations discussed subsequently, the area felt at a given intensity during each of the set of earthquakes given in Appendix 3 was simplified to provide a mean radius. The attenuation relations were solved using this radius and the magnitude of the earthquake to determine the acceleration predicted by the relation at this distance. The results are presented in Appendix 4 and are summarized in Figures 1.1, 1.2, and 1.3.



Note: Outlined values are for Regions III and IV (Eastern United States)

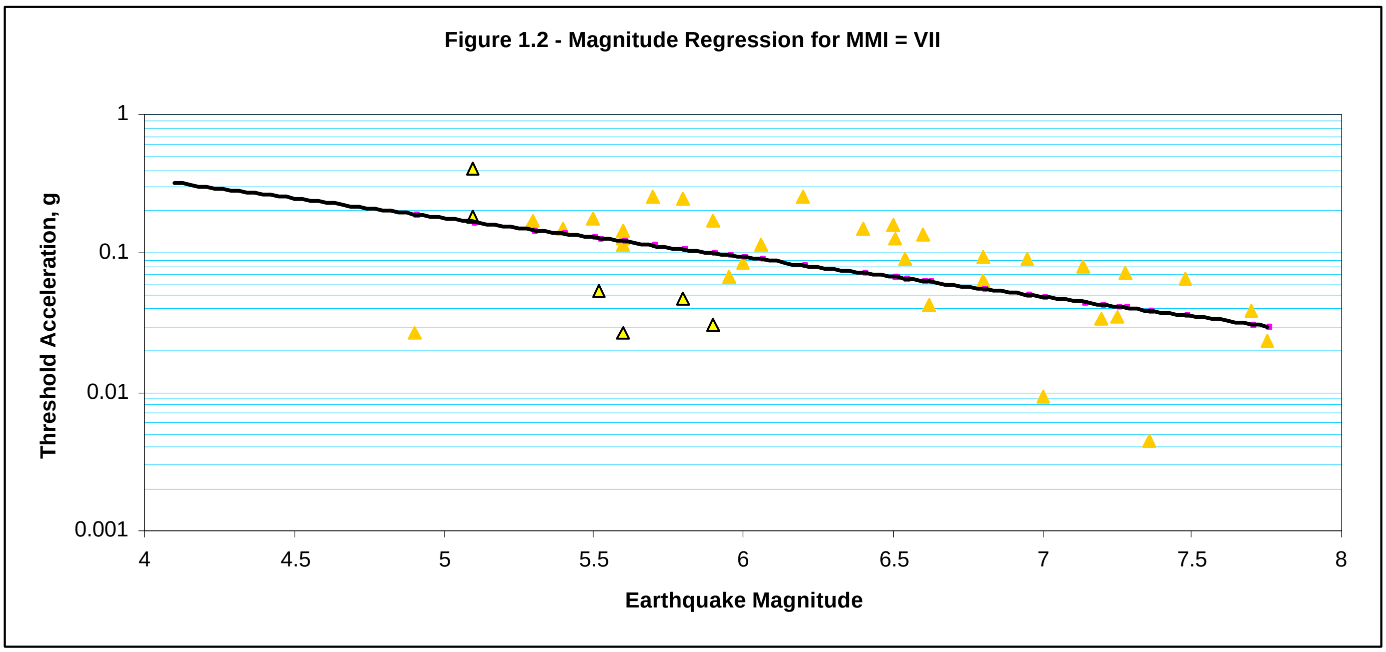
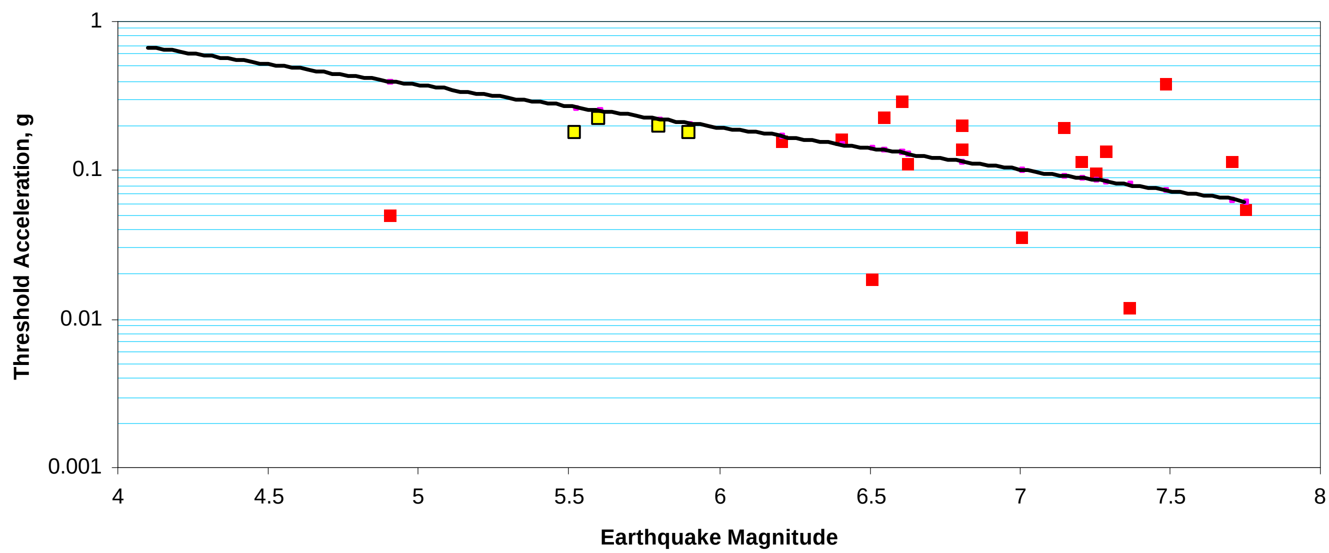


Figure 1.3 - Magnitude Regression for MMI = VIII



The approximation of threshold peak horizontal accelerations were found to be of the form:

(1) $a_H = C_1 \exp[C_2 M]$

The constant C_2, the slope of the line, was held constant to compensate for limited data for Intensity VII, and was found by matrix methods to be -0.6026 for all cases, with C_1 is a function of the desired intensity, as follows:

Table 1 - Magnitude/Intensity Relation Coefficients			
Modified Mercalli Intensity	**6**	**7**	**8**
C_1	0.918329	3.47919	6.98874
Logarithmic Standard Deviation	0.0768	0.1258	0.2079

Attenuation relations presented in Seismological Research Letters V.68 N.1 by Abrahamson and Silva, Toro et al., and Sadigh, et al. were used. The more fault-specific relations by the former authors were unsuited to this study for two reasons. First, the number of earthquakes investigated and historical nature of many preclude knowledge of fault geometry, geologic nature of the surroundings, and other refining parameters that are accounted for in their papers. In addition, the relation given by Sadigh et al., in modeling with a second exponential function of magnitude, is capable of generating negative numbers when solved for distances. This eliminates the complication of every M4 earthquake generating MMI values of 8 for the first few meters around the epicenter. This condition may *strictly* be accurate, but it violates the nature of the intensity scale by imposing very high levels of damage on a region where there may have been no structure or observer. Therefore, the form given by Sadigh et al. was used exclusively as the modeling equation:

(2) $\ln(y) = C_1 + C_2M + C_3(8.5M)^{2.5} + C_4\ln(r_{rup} + \exp(C_5 + C_6M)) + C_7\ln(r_{rup} +2)$

for PGA, C_3 and C_7 are 0.00, and the equation can be solved for r_{rup} as:

(3) $r_{rup} = \exp[(\ln(y) - C_1 - C_2M)/ C_4)] - \exp[C_5 + C_6M]$

where r_{rup} = the minimum distance to the rupture surface, y = the spectral acceleration at 5% damping (in this case only PGA), M = earthquake magnitude, the equation having been developed for moment magnitude M_W, but here used for all scales when moment magnitude is unavailable, and C_1-C_6 are empirical constants as presented in Table 2.

The Sadigh et al. relation was prepared from California strong motion data, and was used for Regions 1 and 2. Following the geographical divisions used by Toro, et al., Regions 3 and 4 were established generally for the states east of the Rocky Mountains, Region 3 representing the northern states, and Region 4 the Gulf states.

The form of the Sadigh et al. relation was extended to include these areas by comparison with other relations for the Eastern US. The equation given by Toro, Abrahamson, and Scheider for Central and Eastern N. America is as follows:

(4) $\ln Y = C_1 + C_2(M-6) + C_3(M-6)^2 + C_4\ln(R_M) - (C_5 - C_4)\max\{\ln(R_M/100),0\})$

$- C_6R_M + \varepsilon_e + \varepsilon_a$

Solving the Sadigh et al. Relation simultaneously with equation (4) and relating constants gives the following summary of constants for equation (2) for each region. Graphical and tabled comparison of the results of this constants relation are presented in Appendices 5 and 6 for Regions 3 and 4, respectively.

Table 2 - Attenuation Relation Coefficients

Region	C_1	C_2	C_4	C_5	C_6
1 - CA, WA, OR and W. NV					
M<6.5	-0.624	1.00	-2.10	1.29649	0.250
M>6.5	-1.274	1.10	-2.10	-0.48451	0.524
2 - NV-Continental divide					
M<6.5	-0.624	1.00	-2.10	1.29649	0.250
M>6.5	-1.274	1.10	-2.10	-0.48451	0.524
3 - Northeastern, N. Central					
M<6.5	-0.22	1.00	-1.98	-0.4800	0.620
M>6.5	-0.19	1.00	-2.04	-0.4800	0.530
4 - Southeastern, S. Central					
M<6.5	-0.22	1.00	-2.06	-.6200	0.580
M>6.5	-0.20	1.00	-2.07	-.4800	0.480

By using this two-step approach (a threshold acceleration for a given magnitude coupled with an attenuation relation for peak acceleration, we expect that this model may be improved upon with future developments in either analysis, in contrast to attempting a pure attenuation of intensities themselves, which has been historically problematic.

After generation of an x,y coordinate and radii for each Intensity for each of 2,284 earthquakes (see Appendix 3), these were plotted using drafting software and exported into the base map.

Discussion

Intensities are a convenient and meaningful tool for the communication of earthquake effects. We expect that the sensory and social consequences of earthquakes - how we apprehend these dramatic occurrences - has a part to contribute to the science of seismology.

The maps prepared in this study are a convincing demonstration that earthquake hazard should be taken into consideration for almost all areas of the country, in that the brief interval of geologic history which we have witnessed has realized significant damage and destruction of property over roughly 40% of the land area of the United States, and has been disastrous in several key regions. The modern conceit of assuming California and Alaska to be the only states with an "earthquake problem" is clearly demonstrated to be shortsighted.

The development of a statistically satisfying method of relating magnitude and peak acceleration to intensity has led to the incorporation of most of US earthquake history. If the data synthesized by these methods were to be formalized into a geographic coordinate system, such as a grid of 1-minute latitude and longitude references, the improved flexibility and application of a maximum felt intensity database could be generated. This model, for which the accompanying maps are a preview, would provide a means of comparison to probabilistic seismic hazard maps, perhaps revealing omissions or overestimations of earthquake hazard and ultimately refining our picture of the siesmicity of the United States.

Furthermore, this historical compilation may provide insight into "seismic gaps" or areas which, though geologically at risk for damaging earthquake events, have not experienced them in our limited time of observance, such as central Utah and the southern borders of Lake Erie and Lake Ontario.

Conclusions

Earthquakes are a national problem, and the limits of human memory should not excuse us from recognizing the significance of seismic hazard in the United States.

Earthquake intensity, though unsatisfactory for several reasons, remains a powerful tool of communication, and is a link to history that has a place in modern seismology.

Intensity can be convincingly related to earthquake magnitude and peak acceleration, and if the methods used in this study prove robust, could regain a place in seismologic analysis.

Acknowledgements

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Appendix 1 - Use of the Polyconic Map Projection

The relevant equations for the spherical earth model, for which the base map was prepared (Espenshade, 1986) are as follows, after Snyder, 1987:

(5) $x = R \cot \phi \sin E$

(6) $y = R[\phi-\phi_O + \cot \phi (1-\cos E)]$

(7) $h = (1 - \cos^2 \phi \cos E)/(\sin^2 \phi \cos D)$

(8) $E = (\lambda - \lambda_O)\sin\phi$

(9) $D = \arctan [(E - \sin E)/(\sec^2 \phi - \cos E)]$

where E and D are constants for use in equations 5-7, R is the mean radius of the Earth, and is used for scaling of the map, ϕ and and λ are the latitude and longitude, respectively, for which an x,y coordinate is desired, ϕ_O is an arbitrary latitude (in this case 40^O) chosen for the origin of the rectangular coordinates at its intersection with λ_O, the central meridian (here -100^O), and h is the scale factor along the meridians, required to compensate for map distortion of true lengths.

Appendix 2 - Record of Search Criterion					
	latitude ϕ		longitude λ		
Region	**minimum**	**maximum**	**minimum**	**maximum**	**Databases Used**
1 - CA, WA, OR and W. NV	27	56	-127	-117	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	5.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)
					California, 1735 -1974
					Canada, 1568 - 1992
2 - NV-Continental divide	22	56	-117	-105	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	5.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)
					Canada, 1568 - 1992
					Eastern, Central and Mountain States of U.S., 1534 - 1986
3 - Northeastern, N. Central	35	56	-105	-62	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	4.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)
					Canada, 1568 - 1992
					Eastern, Central and Mountain States of U.S., 1534 - 1986
4 - Southeastern, S. Central	22	35	-105	-62	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	4.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)
					Eastern, Central and Mountain States of U.S., 1534 - 1986
5 -Alaska	50	75	-180	-130	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	5.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)
6 -Hawaii	15	30	-165	-150	USGS/NEIC (PDE) 1973 - Present
Minimum Magnitude	4.0				Significant Worldwide Earthquakes (2150 B.C. - 1994 A.D.)
					Significant U.S. Earthquakes (1568 - 1989)