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Intensity based building damage level prediction model from past Earthquakes for risk assessment

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Abstract

Frequently, the extent of damage i.e. damage level in percentage caused to non-engineered buildings from reported earthquake intensity values is unknown, even though intensity scale defines the building damage relating to a particular intensity. The level of structural damage might help in understanding the effect of great earthquakes and the seismic vulnerability of various buildings in different seismic zones. These are required for precise estimation of seismic disaster and also for planning risk reduction. The main objective of the study is to understand the relationship between the extent of damages to structures and the intensity of the earthquake considering past earthquake data and reported intensity values. In this study, around 80 data are collected from past earthquake reports and open source data files.

Collected data including various types of earthquakes i.e. interplate, intraplate, plate boundary and subduction, the reported magnitude, reported intensities, type and age of building, hypocentral distances are compiled. Collected data has been studied and analysis has been performed to relate amount/level of building damages with reported intensity and hypocentral distance. Correlation between the percentage damage and earthquake parameters like felt intensities, hypocentral distance, type of earthquake along with the building type has been studied. An attempt has been made to obtain relations between these parameters by performing multiple regression analysis and predicted values are compared with reported values.

Keywords: Earthquake, Disaster, Structural Damage, Felt Intensities, Hypocentral Distances.

Introduction

The ground shaking hazard during an earthquake is alone known to account for more than 80% damages to structures[5]. Earthquakes become disasters mainly due to the collapse of buildings and not by directly earthquake as noted by the phrase "Earthquakes don't kill people, Buildings do". The extent of building damage depends on many aspects of the earthquake and the nature of the soil strata the seismic waves pass through such as earthquake magnitude, intensity, duration, frequency of ground motion, site conditions and the engineering parameters of the structure such as natural frequency, building configuration, construction quality etc. If seismic vulnerability of structures i.e. possible extent of damage is known in advance, it may be possible to control and reduce seismic risks.

Intensity is a qualitative measure of the strength of the ground movement at a particular location. Intensity scales do not have a mathematical basis like magnitude scales and instead are an arbitrary ranking based on observed effects. Astroza et al[1] highlighted that correlating the building damage and seismic intensities would prove useful in understanding the effects of historical great thrust earthquakes and the seismic hazard in other seismic zones where this type of earthquake is expected having no prior strong ground motion records of large earthquakes, as in Northern Chile[3] or the Cascadia subduction zone[6].

Most of the earthquakes intensities of different locations soon after an earthquake are reported in various regions of the earthquake affected area but this information is not sufficient to estimate the extent of structure damage to buildings in that particular location. Very little research has been done to assess the damage of non-engineered structures in relation with the earthquake intensities. Hence in this study an attempt has been made to understand the relationship between damage level and intensity by collecting well reported earthquake damages.

Structural damages reported by earthquakes are studied and a particular level of damage has been assigned by qualitatively defining the extent of the damage in this study. The percentage damages assigned to the buildings are in accordance with the damage grades for various building types provided by EMS-98[2] and Architectural Institute of Japan[4]. The assigned damage is related with the reported and estimated hypocentral distance. This relation between the damage of non-engineered structures and the earthquake intensity can be a valuable tool for supplementing seismic hazard assessments for various earthquakes.

Data used in the study: The data compiled consists of 79 locations of structural damages from around the world with epicenters on the seven major tectonic plates. Most of the data obtained are from major earthquake prone areas including San Francisco (San Andreas Fault), Turkey (North Anatolian Fault), Northern India, Japan, Chile etc. Building damages due to the earthquakes from 1906 up to date are

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considered. This data also includes buildings damaged in the recent April 2015 Nepal earthquake. Most of the data is collected from the USGS (US Geological Survey), NGDC (National Geophysical Data Center) and EERI (Earthquake Engineering Research Institute) databases.

The earthquake data includes four major earthquake types including interplate, intraplate, plate boundary and subduction earthquakes for which analysis is done separately. Almost all the data considered have focal depth less than 70 km which are characterized as shallow depth earthquakes. Figure 1a shows the data distribution by each earthquake type in pie chart. It can be noted that there is abundance in data for plate boundary earthquakes and severe lack for intraplate earthquakes. The local intensities in terms of Modified Mercalli units are obtained for all the buildings from the reports. The earthquake records can be characterized as fairly broad in terms of magnitude as data is present between 5.8M_w to 9.5M_w.

Figure 1b shows distribution of data in four magnitude ranges. The buildings considered have hypocentral distances varying between a few kilometers to more than 150 km, and are extensive in the quantity of data near faults and there is a dearth for far field earthquakes. This information is useful in that the amplification of seismic waves when it travels over soil layers at large distances may be ignored, as most of the structures are located near the epicenter and as at the these locations, the time history would contain excess of high frequency components and since it is only lower frequency components of the ground motion which are significantly amplified in soft soil deposits.[7] Figure 1c shows number of data in four distance ranges considered in this study.

There are also wide ranges of non-engineered buildings included in the analysis such as masonry structures, confined masonry structures, reinforced concrete buildings and moment frame buildings which underwent different degrees of damage depending on the building type and distance from the hypocenter. Light to moderate damage is seen in buildings constructed with good quality materials and sufficient reinforcements whereas very high damage is observed in masonry and wooden buildings. The damage percentages to the buildings are assigned as shown in table 1 which is in accordance with the damage grades of EMS-98. The age of few of the buildings is also compiled to check if there is any relationship between the damage of structures and the age of the building. Data collected for the study is enclosed and provided in table 2.

Damage description: The structure (Fig. 2) is a two storeyed storied municipal building in Armenia located at a distance of 96.5 km from the epicenter of the 1999 Armenia 6.2 M_w Earthquake. The reported local intensity was V on the MMI scale. Due to the earthquake, the building suffered slight damages with small cracks seen on its exterior infill walls and spalling of plaster is also seen in some places. Minor damage of the beam column joints is also observed. A damage of 20% (G1) is assigned to the building according to the damage percentages adopted. The structure (Fig.3a and Fig.3b) is a four storeyed moment frame school building in Turkey. It is located at a distance of 17.2 km from the epicenter of the Bingol earthquake 2003 with a local intensity of VIII MMI.

The earthquake had a Moment Magnitude of 6.4 $M_{w.}$ Due to the earthquake, the building suffered minor cracks and spalling of concrete. There was considerable crushing of concrete in the shear walls. A damage of 30% (G2) was assigned. The structures (Fig. 4a, Fig. 4b) are an eight storeyed V-shaped shear wall building in Port-au-Prince, Haiti. It is located at a distance of 24 km from the epicenter of the Haiti 2010 earthquake with a local intensity of VIII MMI. The earthquake had a Moment Magnitude of 7 M_w. This earthquake caused severe damages to life and property. The building shown in the fig. 4 suffered major damages due to the earthquake. Both the structural and non-structural components underwent extensive damage.

Most of the damage is seen in the second and the third floors including shear cracking of columns, failure of concrete cores, damage of column bases and unreinforced non-structural walls etc. A damage of 45% (G4) was assigned. The structure (Fig. 5) is a two storeyed building in Rasht, Iran. It is located at a distance of 40 km from the epicenter of the Northern Iran 1990 earthquake with a local intensity of VI MMI. The earthquake had a Moment magnitude of 7.7. Due to the earthquake, it suffered major damages. The infill walls on both the floors completely collapsed along with cracking of the interior walls. A damage of 70% (G4) was assigned to the building.

The structure (Fig. 6) is a three storeyed residential building in Kathmandu. It is located at a distance of 80 km from the epicenter of the 7.8 M_w Nepal earthquake 2015 with local intensity of IX MMI. Due to the earthquake, the building completely collapsed leading to 100% (G5) damage. Most of the buildings in the surrounding area also suffered similar damage. It is generally noticed that buildings having more than 40% damage are not in a useable condition.

Data analysis and models: Most of the time, engineered structures remain largely undamaged or slightly damaged. Non-engineered structures including mud or buildings constructed using local materials are heavily damaged due to earthquakes. Field investigation of the first author soon after Sikkim 2011 earthquake of magnitude 6.9 Mw found that buildings constructed with traditional techniques using locally available material i.e. wooden floor separated by wooden beam rollers etc. are intact and structures with engineered materials but poor engineering construction i.e. poorly constructed concrete frame structures were affected severely. Figure 7 shows buildings from same location (a) constructed in traditional techniques and locally available material and (b) constructed by modern materials without proper engineering construction practices. Data generated here consist of mud buildings and modern buildings, though non-engineered and are referred cumulatively as non-engineered structures.

It is to be noted that the term non- engineered has been applied to all the structures that have failed during the considered earthquakes within their design life and hence collected data are assigned a level of damage based on damage descriptions. Figure 8 shows complied data for different earthquake types. The general trend shows the intuitive trend of an increase in intensity and increase in damage level irrespective of earthquake type. It is also observed that the damages based on the building types follow a trend except for the most of structures type with moderate positive correlation coefficient.

Structures constructed as moment resisting frames with reinforced concrete do not follow trend with intensity values which may be attributed by the dearth of data. Data complied is also checked for relating the age of the structure with the damage level and in the absence of data proves ineffective. It may be appropriate to report building type with the representative age while reporting building damages due to earthquakes. Similar buildings in the same location with different age may show different seismic damage level. It is also noted here that there are many exogenous variables including time period of the structure, site class, building configuration etc. that effect the response of structures and are not included in this present study.

Data collected for each building consist of location of building, damage description and information about the earthquake such as magnitude (moment magnitude, Mw), epicenter and focal depth. Latitude and longitude data of each building type and earthquake are used to estimate the epicentral distance which are further used to calculate hypocentral distance of each building considering the depth of earthquake (Table 2). Collected data are separated by the earthquake type based on source information and damage levels are assigned to each building based on description in source and photos.

The proposed damage percentages are correlated with the reported intensities and hypocentral distances. The intensities are reported in Modified Mercalli Intensity (MMI) scale and the hypocentral distances are represented in km. Data is studied by plotting intensity and damage level with magnitude (Figure 9) and intensity and damage level with hypocentral distance (Figure 10). It is observed that increase in magnitude shows an increase in the intensity and damage level and at the same time increase in distance shows a decrease in damage level and intensity. It is noted this could be due to the abundance of near field data and lack of far field data where site effects due to the local soil conditions play a major role in aggravating the ground shaking hazard at larger distances.

Figure 9 shows that the earthquake magnitudes range between 5.5 Mw and 9.5 Mw and observed weak correlation between these two parameters. This may be due to the non-consideration of the hypocentral distances of the locations. Similar observation was also noticed in figure 10 when hypocentral distance is plotted with intensity and damage level. Here intensity and hypocentral distance are taken as independent parameters and the damage level is taking as dependent parameter for model development. Linear regression analysis of these parameters are performed for the different type of earthquakes separately and also analysed for all data together to understand relationship between damage level in percentage and the earthquake parameters of intensity (MMI) and hypocentral distance (km) by following below equation form.

$$\text{Damage level \%} = a\,(\text{hypocentral distance in km}) + b\,(\text{intensity in MMI}) + c \qquad (1)$$

where “a”, “b” are regression coefficients and “c” is a constant.

Multiple regression analysis for different earthquake types is done to predict the damage level (in percentage) of structures in terms of local intensities (MMI) and the hypocentral distances and also to find their individual influence on the damage of structures. Coefficients ‘a’ and ‘b’ corresponding to 95% confidence interval are obtained and shown in table 3 for the general form of equation (1) given above. Typical figure for all data showing the variation of the damage level with hypocentral distance and damage level with reported intensity are given in figure 11 and figure 12 respectively. Models for different earthquake type are given in table 3.

This study shows that the data from the intraplate earthquakes show a strong correlation with higher regression coefficient (R^2) value when compared to the other earthquake types. The overall analysis considering all the types of earthquakes gives an average coefficient of correlation value compared to the individual R^2 values. The analysis shows a good correlation between damage level and the local intensities along with the hypocentral distances.

Results and Discussion

The extent of structural damage corresponding to a particular intensity is often not reported or estimated during reconnaissance surveys and post-earthquakes which are very important for structural retrofitting, risk assessment and disaster management in earthquake prone areas. In this study an attempt has been made to estimate the damage level as function of earthquake intensity and hypocentral distance. As no earlier model exists to validate the newly developed relationship, the measured value of damage level is compared with the predicted value in figure 13. Figure 13 shows that model accurately predicts the measured values after a 50 % of damage level within 1:0.7 and 1:1.3. Below 50 % damage level, the model is conservative and predicts higher values than the measured values.

Damage level prediction for each type of earthquake at specific hypocentral distance is compared in figure 14. The damage level was predicted from the model for various intensities (MMI) while keeping the hypocentral distance of the buildings constant (plot has been generated for 25 to 150 km with increment of 50 km). This study shows that intensity of V and above caused damage level of 30 to 50% to non-engineered structures. The extents of damage to buildings are almost similar in shorter hypocentral distances of up to 100 irrespective of earthquake type.

We can also see that for shorter distances (25 km), the damage suffered by buildings in subduction earthquakes is higher compared to the other types and those by intraplate earthquakes are the least. This could be attributed to the high magnitude of most of the subduction earthquakes. Also, for larger distances, the damage suffered by buildings in interplate earthquakes is higher and those by plate boundary earthquakes are the least. Damage level reported by plate boundary earthquakes generally shows lesser damage levels than other earthquake types.

From figure 14 it can also be observed that for almost all the earthquake types due to the high dominance of near field earthquake data, the predicted damage level is decreasing with increase in hypocentral distance of the buildings, for a given intensity value in turn not accounting the site effects at larger distances. It is to be noted that the site effect will play a major role in the modification of the seismic waves through the deposit, but since the intensity is a measure of the felt hazard at the soil stratum, the site effects are assumed to be incorporated while performing the regression to obtain the equation.

This study shows that the intensities (MMI) and hypocentral distances can be effectively used to estimate the damage level of the structures for a particular intensity and location. This model is useful to predict the extent of damage a non-engineered structure undergoes at specific location if intensity is available from intensity attenuation relationship. It can be also noted that the study incorporated a reasonably good number of data for each earthquake type and building type. The accuracy of this damage level prediction could be improved by including large number of data sets in the future.

Table 1
Damage Description and Percentages Adopted

Grade	Damage Description	% Damage	Felt Intensities
0	No damage	0	-
1	Negligible damage (Hair line cracks in walls, columns and beams of frame. Mostly seen in buildings constructed with good quality materials and sufficient reinforcements and also usually located far away from the epicenter of the earthquake)	10-20	IV, V
2	Slight damage (fall of small pieces of plaster, spalling of concrete. This type of damage is observed in Reinforced Concrete and Framed masonry infill buildings with minor repair work required)	20-30	V, VII, VIII, IX
3	Moderate damage (Shear cracks in columns and beams and shear failure of columns. Such damage is observed in Confined masonry and moment frame buildings in areas of moderately higher intensity and considerable repair work is necessary)	30-40	VI, VII, VIII, X
4	Major damage (collapse of columns, buckling of reinforcing bars, serious failure of walls. Buildings are not suitable for living and entire storey or parts of building must be rebuilt)	40-70	V, VI, VII, VIII, IX, X
5	Collapse (collapse of storeys, parts of building or complete structure. This type damage is mostly seen in masonry buildings or those constructed of low quality materials. Also the buildings are mostly very close to the epicenter up to 25km. Complete reconstruction of the building is required)	70-100	VII, VIII, IX, X, XI

Table 2
During damage with intensity reported during earthquake and earthquake magnitude, hypocentral distance of building and damage level (%) assigned in the study)

S. N.	Earthquake Name and Year	Earthquake type	Magnitude (Mw)	Focal depth (km)	Epicentral distance (km)	Hypocentral distance (km)	Reported intensity (MMI)	Building Type based on report	Damage level (%)
1	Java Earthquake, 2009	Interplate	7	46.2	108.3	117.7	5	Precast frame with concrete masonry	15
2	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	7.6	9.7	8	Moment Frame and Shear Wall Combination	60
3	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	7.7	9.7	8	Shear Wallrete	70
4	Peru Earthquake, 2007	interplate	8	39.0	121.8	127.9	7	Frames with Masonry infill	70
5	Nepal Earthquake, 2015	Interplate	7.8	15.0	80.0	81.4	9	Frames with Masonry infill	90
6	Nepal Earthquake, 2015	Interplate	7.8	15.0	80.0	81.4	9	Frames with Masonry infill	100
7	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	7.3	9.4	8	Moment Frame and Shear Wall Combination	60
8	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	7.6	9.6	8	Masonry	100
9	Nepal Earthquake, 2015	Interplate	7.8	15.0	88.0	89.3	8	Masonry	95
10	Kashmir Earthquake, 2005	Interplate	7.6	26.0	60.0	65.4	5	Masonry	50
11	Sikkim earthquake, 2011	Interplate	6.9	19.7	68.0	70.8	6	RC building	70
12	Sikkim earthquake, 2011	Interplate	6.9	19.7	69.0	71.8	6	RC building	50
13	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	6.5	8.8	8	Precast – prestressed and Reinforced Concrete	80
14	Christchurch Earthquake, Newzealand, 2011	Interplate	6.1	5.9	7.4	9.4	8	Frames with masonry infill	95
15	Sikkim earthquake, 2011	Interplate	6.9	19.7	60.0	63.2	7	Frame and Masonry Infill	70
16	Nepal Earthquake, 2015	Interplate	7.3	15.0	2.7	15.2	8	Masonry	85
17	Bhuj earthquake, 2001	Intraplate	7.7	22.0	240.0	241.0	7	Shear wall	80
18	Great Sichuan Earthquake, 2008	Intraplate	7.9	19.0	139.0	140.3	8	Frames with masonry infill	70
19	Northern Italy Earthquake, 2012	Intraplate	6.1	6.3	37.0	37.5	7	Frames with masonry infill	60
20	Bhuj earthquake, 2001	Intraplate	7.7	22.0	60.3	64.2	9	RC building	85
21	Jabalpur earthquake, 1997	Intraplate	6	32.0	9.0	33.2	5	Masonry	30
22	Bohol Earthquake, Philippines, 2013	Intraplate	7.2	12.0	17.9	21.6	8	Masonry	60
23	Bohol Earthquake, Philippines, 2013	Intraplate	7.2	12.0	35.9	37.8	8	Masonry	100
24	Meckering earthquake, Australia 1968	Intraplate	6.9	7.0	2.5	7.4	9	Masonry	80

25	Virginia Earthquake, 2011	Intraplate	5.8	6.0	9.0	10.8	5	Masonry	15
26	Jabalpur earthquake, 1997	Intraplate	6	32.0	149.0	152.4	7	Masonry	60
27	Duzce Earthquake, Turkey , 1999	Plate Boundary	7.2	12.5	37.7	39.7	8	Moment Frame	80
28	Bingol Earthquake, Turkey, 2003	Plate Boundary	6.4	10.0	13.3	16.6	8	Moment Frame	95
29	Izmit Earthquake, Turkey, 1999	Plate Boundary	7.6	17.0	44.6	47.7	9	Moment Frame	70
30	Izmit Earthquake, Turkey, 1999	Plate Boundary	7.6	17.0	4.9	17.7	9	Moment Frame	85
31	Duzce Earthquake, Turkey , 1999	Plate Boundary	7.2	12.5	13.6	18.5	9	Frames with masonry infill	85
32	Coalinga earthquake, California, 1983	Plate boundary	6.2	10.0	11.0	14.9	8	Frames with masonry infills	80
33	Northern Iran earthquake, 1990	Plate boundary	7.7	10.0	112.5	112.9	6	RC building	50
34	Northern Iran earthquake, 1990	Plate boundary	7.7	10.0	40.0	41.2	6	Frames with masonry infills	70
35	Northern Iran earthquake, 1990	Plate boundary	7.7	10.0	39.5	40.7	6	Frames with masonry infill	60
36	San Fernando earthquake, 1971	Plate Boundary	6.7	8.4	13.0	15.5	9	Frames with reinforced masonry walls	70
37	Duzce Earthquake, Turkey , 1999	Plate Boundary	7.2	12.5	9.1	15.5	9	Frames with masonry infill	95
38	Duzce Earthquake, Turkey , 1999	Plate Boundary	7.2	12.5	9.1	15.5	9	Frames with masonry infill	100
39	Big Bear earthquake, USA, 1992	Plate Boundary	6.5	5.0	13.5	14.4	6	Masonry	50
40	Long Beach earthquake, 1933	Plate Boundary	6.4	10.0	26.0	27.9	8	Masonry	80
41	Northridge Earthquake, 1994	Plate Boundary	6.7	19.0	21.0	28.3	7	Moment Frame and Shear Wall Combination	55
42	Northridge Earthquake, 1994	Plate Boundary	6.7	19.0	40.5	44.7	6	Frames with masonry infill	50
43	Northridge Earthquake, 1994	Plate Boundary	6.7	19.0	40.3	44.6	6	Masonry	65
44	Haiti Earthquake, 2010	Plate Boundary	7	13.0	27.0	30.0	8	Frames with masonry infill	60
45	Haiti Earthquake, 2010	Plate Boundary	7	13.0	27.0	30.0	8	Moment Frame	50
46	Haiti Earthquake, 2010	Plate Boundary	7	13.0	23.0	26.4	9	RC building	90
47	San Francisco Earthquake, 1906	Plate Boundary	8.3	8.0	80.0	80.4	11	RC building	100
48	Loma Prieta earthquake, 1989	Plate Boundary	6.9	18.0	14.0	22.8	6	Masonry	65
49	Loma Prieta earthquake, 1989	Plate Boundary	6.9	18.0	98.5	100.1	4	RC building	20
50	San Francisco Earthquake, 1906	Plate Boundary	8.3	8.0	39.0	39.8	8	masonry	85
51	Loma Prieta earthquake, 1989	Plate Boundary	6.9	18.0	22.5	28.8	6	Masonry	40
52	Loma Prieta earthquake, 1989	Plate Boundary	6.9	18.0	33.0	37.6	5	Masonry	55
53	San Francisco Earthquake, 1906	Plate Boundary	8.3	8.0	39.0	39.8	8	Masonry	60
54	San Francisco Earthquake, 1906	Plate Boundary	8.3	8.0	12.8	15.1	8	RC building	90
55	Sumatra Earthquake, 2009	Subduction	7.6	81.0	61.5	101.7	7	Moment Frame	80

56	Mexico Earthquake 1985	Subduction	8.1	20.0	385.0	385.5	8	Moment Frame	100
57	Mexico Earthquake 1985	Subduction	8.1	20.0	360.0	360.6	8	Frames with masonry infill	70
58	Southern Peru Earthquake, 2001	Subduction	8.4	9.0	306.7	306.8	7	Frames with Masonry infill	65
59	Chile Earthquake, 2010	Subduction	8.8	35.0	105.0	110.7	7	Moment Frame	85
60	Niigata Earthquake, Japan, 1964	Subduction	7.5	57.0	50.0	75.8	8	Moment Frame	85
61	Chile Earthquake, 2010	Subduction	8.8	35.0	105.0	110.7	7	Moment Frame and shear wall combination	85
62	Armenian Earthquake, Soviet Union, 1988	Subduction	6.8	10.0	40.0	41.2	9	Masonry	90
63	Great Hanshin earthquake, Japan, 1995	Subduction	6.9	22.0	20.0	29.7	7	RC building	90
64	Armenian Earthquake, Soviet Union, 1988	Subduction	6.8	10.0	18.0	20.6	10	Stone masonry	90
65	Alaska earthquake, 1964	Subduction	9.3	20.0	120.0	121.7	8	Moment Frame and Shear Wall Combination	80
66	Alaska earthquake, 1964	Subduction	9.3	20.0	125.0	126.6	8	RC building	100
67	Great Hanshin earthquake, Japan, 1995	Subduction	6.9	22.0	17.5	28.1	7	Moment Frame and Shear Wall Combination	85
68	Great Hanshin earthquake, Japan, 1995	Subduction	6.9	22.0	17.5	28.1	7	RC building	95
69	Armenia earthquake, Colombia 1999	Subduction	6.2	17.0	95.0	96.5	5	Frames with masonry infill	20
70	Armenia earthquake, Colombia 1999	Subduction	6.2	17.0	95.0	96.5	5	Masonry	55
71	Helena earthquake, 1935	Subduction	6.2	17.0	1.5	17.1	8	Frames with masonry infills	85
72	Armenian Earthquake, Soviet Union, 1988	Subduction	6.8	10.0	36.0	37.4	9	Frames with masonry infills	90
73	Armenian Earthquake, Soviet Union, 1988	Subduction	6.8	10.0	30.0	31.6	9	Stone masonry	70
74	Armenian Earthquake, Soviet Union, 1988	Subduction	6.8	10.0	16.0	18.9	10	Stone masonry	100
75	Armenia earthquake, Colombia 1999	Subduction	6.2	17.0	95.0	96.5	5	Frames with masonry infill	20
76	Valdivia earthquake, 1960	Subduction	9.5	33.0	101.0	106.3	7	Wooden building	60
77	Alaska earthquake, 1964	Subduction	9.3	20.0	131.0	132.5	8	Concrete and steel combination	50
78	Mexico Earthquake 1985	Subduction	8.1	20.0	363.0	363.6	9	Frames with masonry infill	95
79	Boumerdès earthquake, Algeria, 2003	Subduction	6.8	10.0	45.0	46.1	10	Frames with masonry infill	70

Table 3
Summary of correlations between damage level (%) and hypocentral distance, local intensity

Earthquake Type	**Regression constant (95% CI)**			**Regression Coefficients**
	a	**bb**	**cc**	
Interplate	0.021(±0.10)	14.62(±3.34)	-36.43(±27.54)	0.633
Plate Boundary	-0.153(±0.097)	9.257(±1.53)	5.91(±13.25)	0.668
Subduction	0.0082(±0.032)	9.648(±2.55)	1.1724(±20.56)	0.394
Intraplate	0.084(±0.057)	15.22(±3.13)	-53.36(±23.46)	0.789
Overall	0.0179(±0.02)	11.35(±1.17)	-14.83(±9.17)	0.553

D – Damage %, HD – Hypocentral Distance (km), MMI – Local Intensity

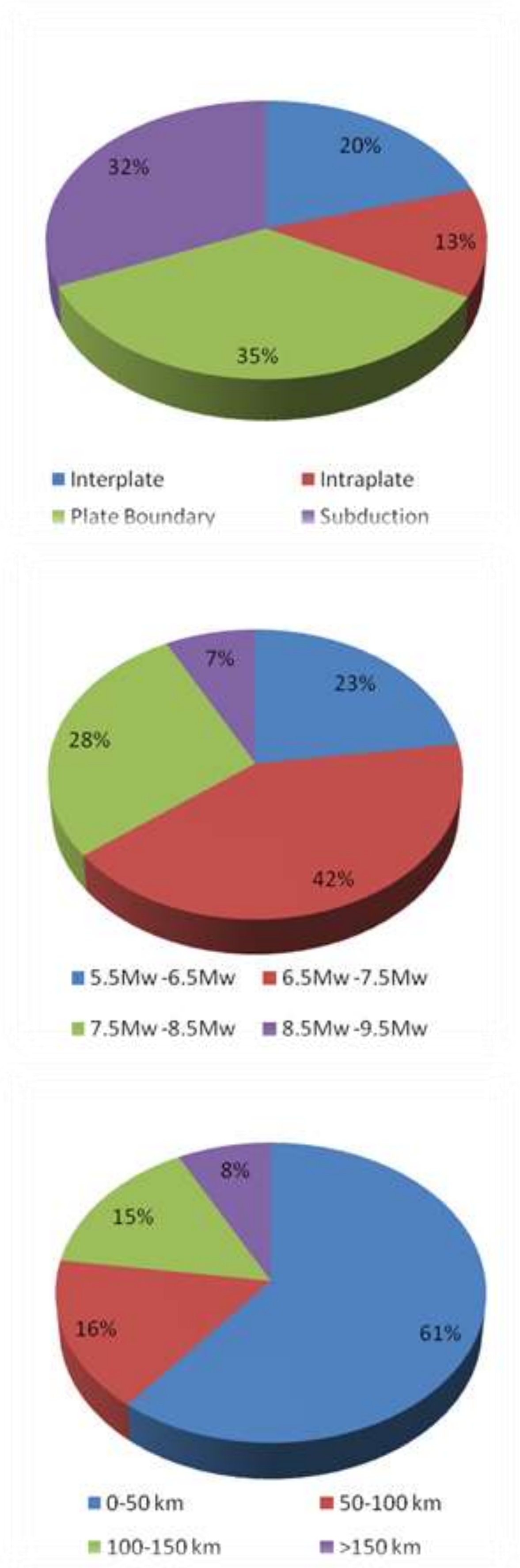

Fig. 1: Data considered for the study

Fig. 2: Municipal building in Armenia, Colombia (http://www.ngdc.noaa.gov/hazardimages/picture/show/824)

Fig. 3a: Back view of the school building, Turkey

Fig. 3b: Concrete crushing in shear wall due to Bingol 2003 Earthquake (http://db.concretecoalition.org/building/133)

Fig. 4a: Exterior damage to the teleco building, Haiti

Fig. 4b: Damage of the column base (http://db.concretecoalition.org/building/144)

Fig. 5: Building in Rasht, Iran (http://www.ngdc.noaa.gov/hazardimages/picture/show/288)

Fig. 6: Complete collapse of a residential building due to Nepal 2015 Earthquake

Fig. 7: Buildings status soon after Sikkim 2011 earthquake; (a) Constructed in traditional techniques and locally available material and(b) Constructed by modern material without engineering considerations

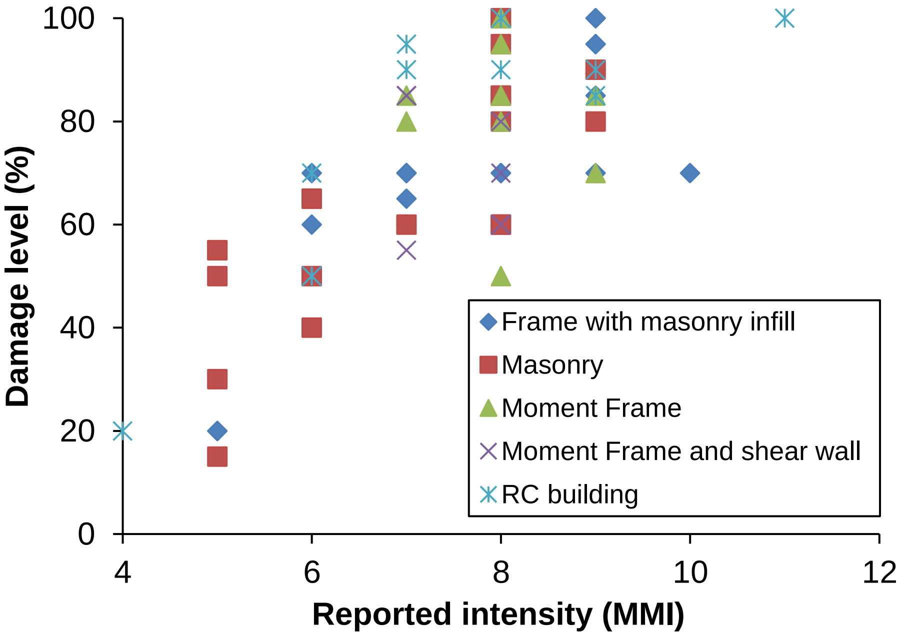

Fig. 8: Data considered in the study for different building type.

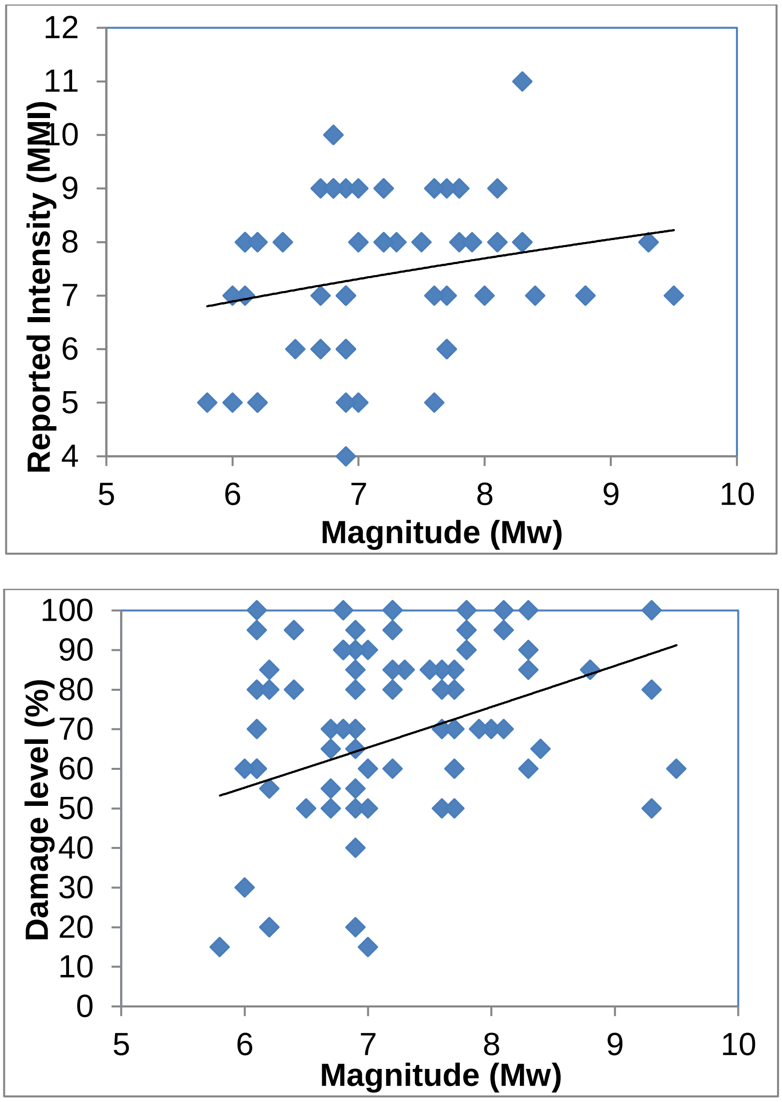

Fig. 9: Intensity and damage level versus magnitude of data used in the study

Conclusion

About 80 data consisting of buildings damaged in many earthquakes from around the world is studied in this paper. The buildings are assigned different damage percentages based on the observed failures and are reported. The effects under each grade of damage are described and the corresponding felt intensities are noted down in MMI. Also, other earthquake parameters corresponding to each building are compiled. Multiple regression analysis is done to predict the damage suffered by buildings based on the local intensities and the hypocentral distances.

These correlations are generated considering different sets of data relating to Interplate, Intraplate, Plate boundary and Subduction type of earthquakes. The damages to the structures with respect to different building types like masonry, framed masonry, RC buildings etc., are also studied to understand the extent of damage suffered by each type. It is observed that the buildings constructed out of weak materials like wooden buildings, masonry buildings etc. suffered a severe damage compared to the RC and moment frame buildings. The summary of the correlations between the damage level of structures (%) and the Local intensities (MMI) along with hypocentral distances is shown in table 3. Also, the correlation coefficients corresponding to 95% confidence interval are also shown.

The study shows that these results are reliable to a certain extent to predict the damage suffered by buildings corresponding to different intensities (MMI). These correlations are more useful for vulnerability and risk assessment of buildings and their retrofitting for better earthquake resistance. But a better accuracy may be achieved by considering many other parameters which affect the behavior of structures during earthquakes. These parameters include earthquake magnitude, duration, frequency of ground motion, site conditions and construction quality etc.

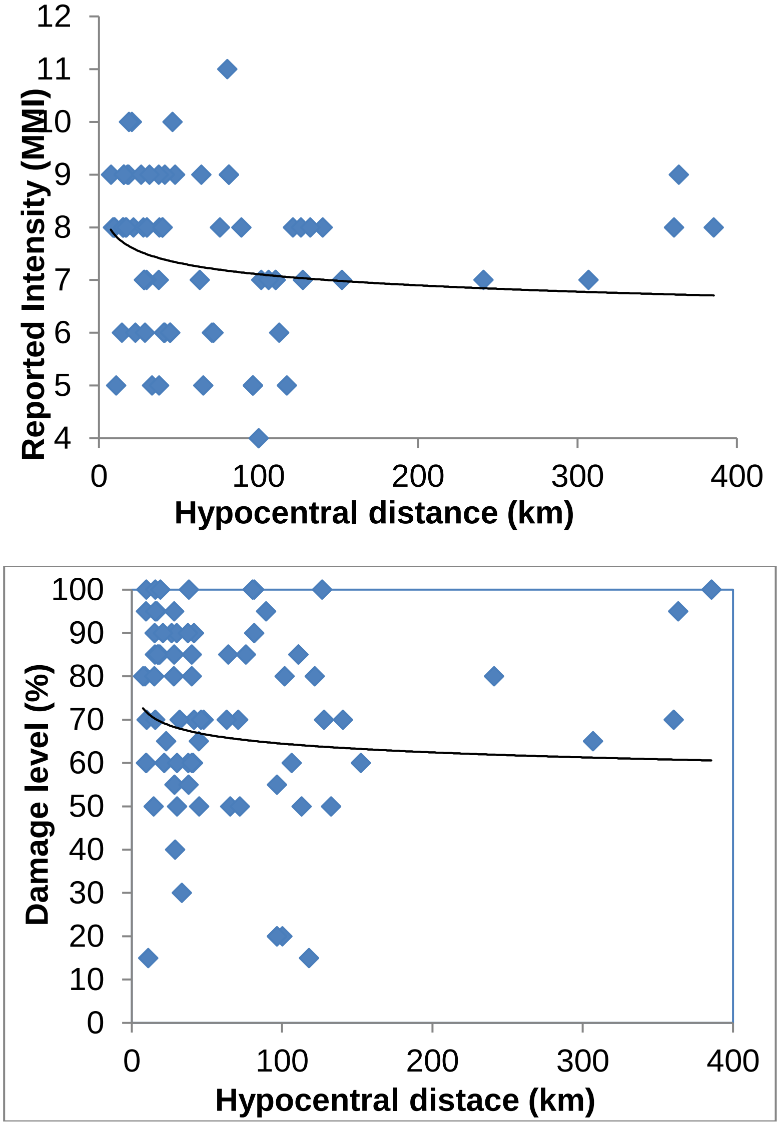

Fig. 10: Intensity and damage level versus hypocentral distance of data used in the study

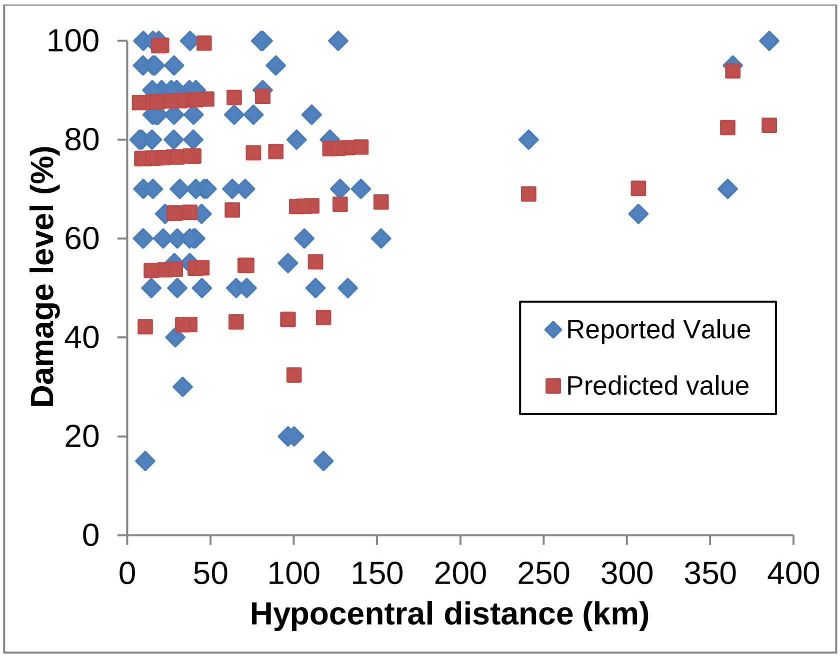

Fig. 11: Typical plot of data and predicted model plot – All data damage level with hypocentral distance.

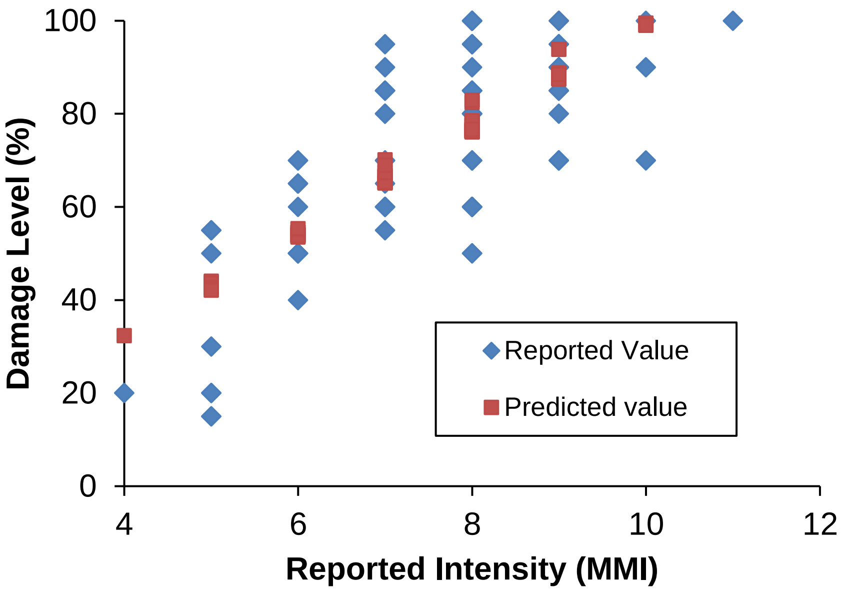

Fig. 12: Typical plot of data and predicted model plot – All data damage level with reported intensity

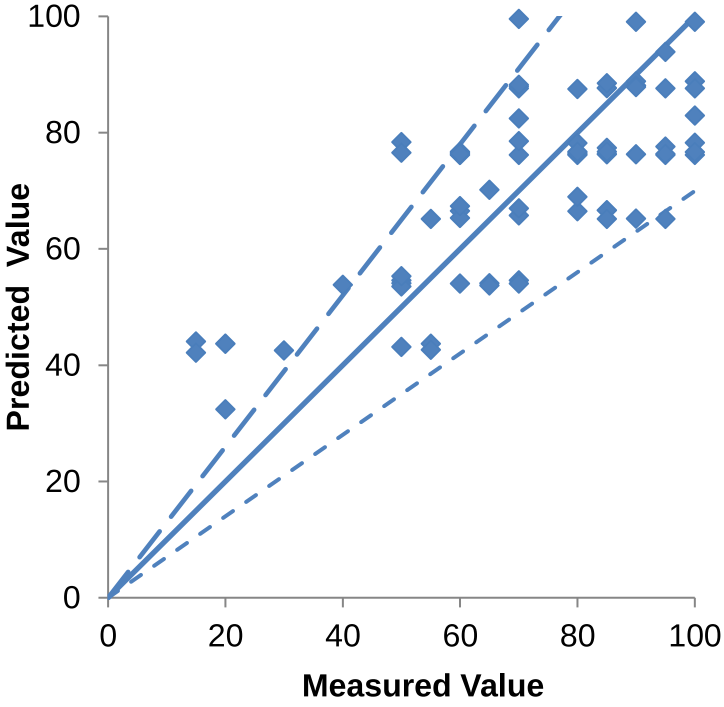

Fig. 13: Typical comparison of measured and predicted damage level for all data set

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References

1. Astroza M., Ruiz S. and Astroza R., Damage assessment and seismic intensity analysis of the 2010 (Mw 8.8) Maule Earthquake, *Earthquake Spectra*, **28(S1)**, S145-S164 **(2012)**

2. Grünthal G., Ed., European Macroseismic Scale 1998 (EMS-98), Cahiers du Centre Européen de Géodynamiqueet de Séismologie 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 99 **(1998)**

3. Kelleher J., Rupture zones of large South American earthquakes and some predictions, *J. Geophys. Res.*, **77**, 2087–2103 **(1972)**

4. Okada Shigeyuki and Nobuo Takai, Classifications of structural types and damage patterns of buildings for earthquake field investigation, Proceedings of the 12th world conference on earthquake engineering (paper 0705), Auckland **(2000)**

5. Tsang H.H., Lo S.H., Xu X. and Sheikh M.N., Seismic Isolation for Low-to-Medium-Rise Buildings using Granulated Rubber-Soil Mixtures: Numerical Study, *Earthquake Engineering and Structural Dynamics*, **41(14)**, 2009-2024 **(2012)**

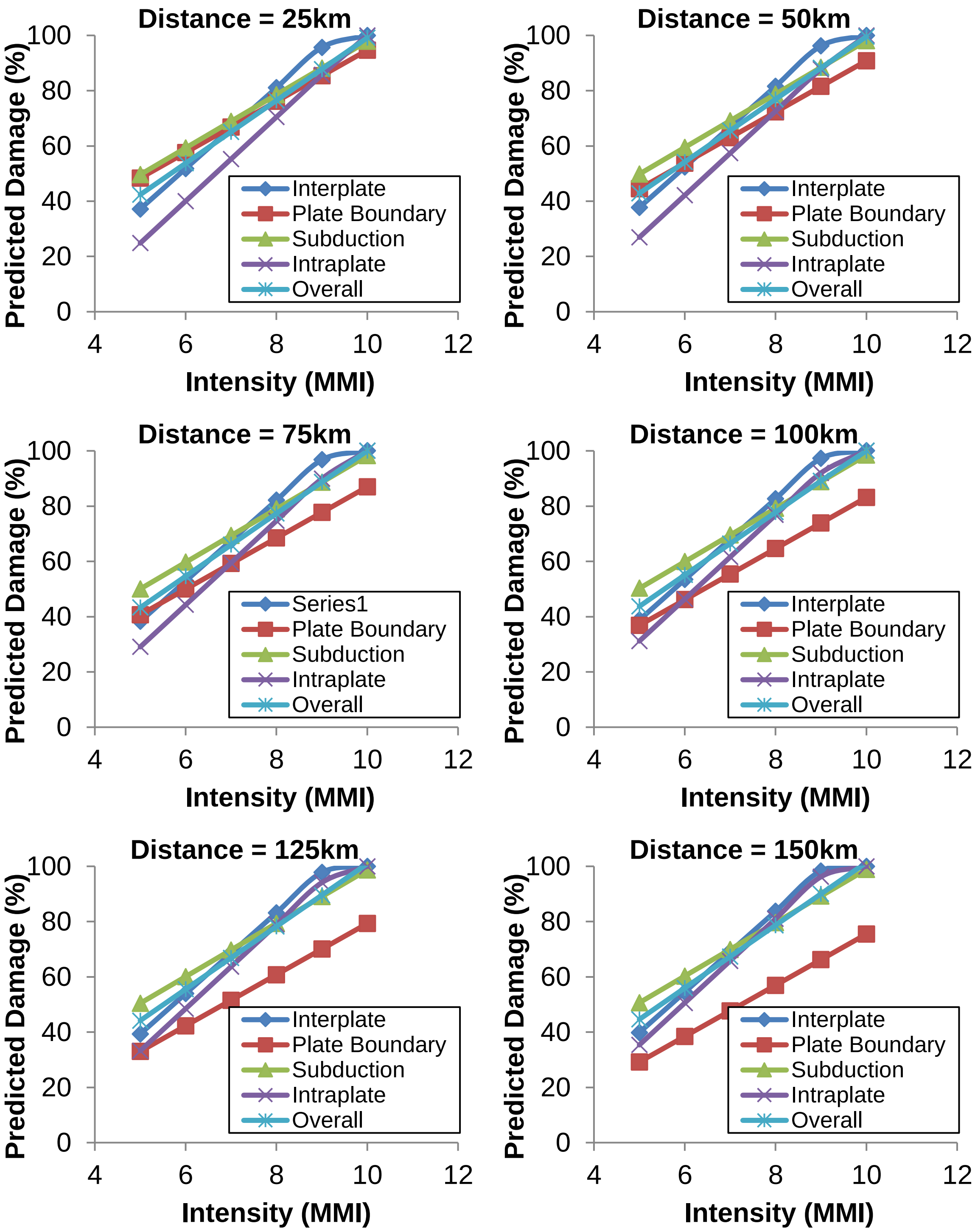

Fig. 14: Comparison of damage level for different type of earthquake by varying intensities and hypocentral distance

6. Heaton T.H. and Hartzell S.H., Seismic hazards on the Cascadia subduction zone, *Science*, **236**, 162–168 **(1987)**

7. Kramer S., Geotechnical Earthquake Engineering, Pearson Education **(2003)**.

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