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ORIGINAL PAPER

Classification of road damage due to earthquakes

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Abstract Earthquakes cause massive road damage which in turn causes adverse effects on the society. Previous studies have quantified the damage caused to residential and commercial buildings; however, not many studies have been conducted to quantify road damage caused by earthquakes. In this study, an attempt has been made to propose a new scale to classify and quantify the road damage due to earthquakes based on the data collected from major earthquakes in the past. The proposed classification for road damage due to earthquake is called as road damage scale (RDS). Earthquake details such as magnitude, distance of road damage from the epicenter, focal depth, and photographs of damaged roads have been collected from various sources with reported modified Mercalli intensity (MMI). The widely used MMI scale is found to be inadequate to clearly define the road damage. The proposed RDS is applied to various reported road damage and reclassified as per RDS. The correlation between RDS and earthquake parameters of magnitude, epicenter distance, hypocenter distance, and combination of magnitude with epicenter and hypocenter distance has been studied using available data. It is observed that the proposed RDS correlates well with the available earthquake data when compared with the MMI scale. Among several correlations, correlation between RDS and combination of magnitude and epicenter distance is appropriate. Summary of these correlations, their limitations, and the applicability of the proposed scale to forecast road damages and to carry out vulnerability analysis in urban areas is presented in the paper.

Keywords Earthquake · Damages · Road · Scale · Magnitude · Distance

1 Introduction

Many cities of the world have suffered major economical and social setbacks due to earthquakes. Roads play an important role not only acting as a mere path to transport

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commuters, goods, and vehicles but also as a means to reach and rescue the distressed people during emergencies like natural disasters and wars. Numerous studies have been conducted regarding the damage assessment, damage quantification, vulnerability, and risk analysis of structures. But very limited studies are carried out in vulnerability and risk analysis of road/transport networks. It is an accepted fact that, of all the modes of transport, road transport is the major means of transport to the people. Road network connects all the remote villages in the country. The characteristics of road transport are:

- Roads are used by various types of vehicles, like passenger cars, buses, trucks, two- or three-wheeled automobiles, bicycles, and animal-drawn vehicles unlike other modes of transport.
- It offers flexibility of changes in location, direction, speed, and timings of travel which is unavailable in other means of transport.

Road system is a valuable asset of a city, and road network plays a vital role in emergency operations. Roads play an important role in post-earthquake scenario, i.e., to evacuate dead and injured people. If an evacuation plan is well organized, the number of dead and distressed people can be significantly reduced. Hence, earthquake-induced road damage assessment and post-earthquake damage control studies are important for an effective disaster management plan. To assess the vulnerability, risk of transportation infrastructure, the road damage scale (RDS) plays an important role. At present, the modified Mercalli intensity (MMI) scale is a widely used damage quantification measure for earthquakes. This MMI scale is a measure of earthquake intensity level based on damage caused to buildings by accounting site effects and induced effects. A significant point to be noted here is that structural damage is well defined and quantified using MMI, but no specific reference is made for the damage of roads, even though they play a major role in post-earthquake relief operations (Tung 2004). History shows that major loss of life has been caused due to delay in timely assistance to earthquake victims. Thus, it becomes imperative to study the damage quantification of roads which will help in better disaster management. The importance of risk assessment of transport networks and summary of different methods are given in Kiremidjiam et al. (2007). The major component in the risk and vulnerability assessment of a transportation network is the damage measure (DM), which is basically the level or measure of damage for a given hazard. DM is used to estimate the severity of damage and thereby arrive at a damage ratio. So measure of road damage is important for the risk assessment of road network. In this study, an attempt has been made to propose a new damage scale for roads based on reported road damages, which will help to quantify road damage due to earthquake. Further, a multi-regression correlation between the newly proposed scale and earthquake parameters such as magnitudes, epicenter distance, hypocenter distance, and combination of magnitude with epicenter and hypocenter distance has been developed. The proposed new damage intensity scale gives a very good regression relation and high regression coefficients with earthquake parameters. Summary of proposed correlations, limitations, and suitable regression relations for assessing damage of roads for future earthquakes is presented in this paper.

2 Earthquake damage measures

As mentioned previously, the most popular method among all the methods to assess damage of structures is MMI scale. Intensity ratings are expressed as Roman numerals between I at the lower end and XII at the higher end. The damage scale with intensity level as per MMI scale is given in Table 1 (after Day 2002). The damage due to earthquake in MMI is defined and explained mainly focusing on the damage of building components and factory components. The ground failures and bending of train rails are also discussed in MMI scale. Intensity scale of VIII and above includes different ground damages due to

Table 1 MMI scale (after Day 2002)

Intensity level	Reaction of observers and types of damage
I	Reactions: Not felt except by a very few people under especially favorable circumstances Damage: No damage
II	Reactions: Felt only by a few persons at rest, especially on upper floors of buildings. Many people do not recognize it as an earthquake Damage: No damage delicately suspended objects may swing
III	Reactions: Felt quite noticeably indoors, especially on upper floors of buildings. The vibration is like the passing of a truck and the duration of the earthquake may be estimated. However, many people do not recognize it as an earthquake Damage: No damage, standing motorcars may rock slightly
IV	Reactions: During the day, felt indoors by many, outdoors by few. At night, some people are awakened. The sensation is like a heavy truck striking the building Damage: Dishes, window, and doors are disturbed. Walls make a creaking sound. Standing motorcars rock noticeably
V	Reactions: Felt by nearly everyone, many awakened Damage: Some dishes, windows, etc., are broken. A few instances of cracked plaster and unstable objects overturned. Disturbances of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop
VI	Reactions: Felt by everyone. Many people are frightened and run outdoors Damage: There is slight structural damage. Some heavy furniture is moved and there are instances of fallen plaster or damaged chimneys
VII	Reactions: Everyone runs outdoors. Noticed by persons driving motor cars Damage: Negligible damage in buildings of good design and construction, slight to moderate damage in well-built ordinary structures and considerable damage in poorly built or badly designed structures. Some chimneys are broken
VIII	Reactions: Persons driving motor cars are disturbed Damage: Slight damage in specially designed structures. Considerable damage in ordinary substantial buildings, with partial collapse. Great damage in poorly built structures. Panel walls are thrown out of frame structures. There is fall of chimney, factory stacks, columns, monuments, and walls. Heavy furniture is overturned. Sand and mud are ejected in small amounts and there are changes in well-water levels
IX	Damage: Considerable damage in specially designed structures. Well-designed frame structure thrown out of plumb. There is great damage in substantial buildings with partial collapse. Buildings are shifted off their foundations. ***Ground is conspicuously cracked*** and underground pipes are broken
X	Damage: Some well-built wooden structures are destroyed. Most masonry and frame structures are destroyed, including the foundations. ***The ground is badly cracked. There are bent train rails***, considerable amount of landslides at river banks and steep slopes, shifted sand and mud, water is splashed over their banks
XI	Few if any masonry structures remain standing. Bridges are destroyed and ***train rails are greatly bent***. ***There are broad fissures in the ground***, and underground pipelines are completely out of service there are earth slumps and landslips in soft ground
XII	Reactions: waves are seen on the ground surface. The lines of sight and levels are distorted Damage: Total damage with practically all works of construction greatly damaged or destroyed. Objects are thrown upward into the air

earthquakes such as cracks, liquefaction, and slope failures but none of the MMI scale values focus on the cracks or damages of roads. Hence, in this study, an attempt has been made to propose a new damage scale to classify the road damages due to earthquakes. Road damage depends on the magnitude of vibrations caused by an earthquake, which mainly depends upon the distance of the damaged road from the epicenter and magnitude of the earthquake. Furthermore, road damages are also caused by earthquake-induced effects like liquefaction, landslides, and tsunami which act as major contributors toward road failures. The damage description of roads for earthquake basically should include all the above parameters and condition/usage of pavement after the damage. Damage description has been framed by considering the past earthquake damage scenario and divided into five levels and represented in numbers (i.e., 1–5). The proposed DM is called as "RDS". The proposed scale is applicable to all type of roads generally found in urban and rural area. Table 2 shows the proposed damage scale with description of the damage to roads. The proposed damage scale with failure description is given below:

Table 2 Newly proposed RDS with description

Road damage scale	Damage description	Reported MMI scale
1	Damage is in the form of many minute cracks, one or two moderate cracks not exceeding 20 mm width, slight damage of shoulders and food path. Very little repair work is usually necessary to restore road for full traffic. This damage is seen when roads are of good quality and usually expected in road located away from epicenter for larger magnitudes	XIII
2	Damage is in the form of settlement or moderate cracks, cracks or separation of pavement layers for width of less than 100 mm. Failure of sides and shoulder/footpath of the roads which reduces the road utility. Minor repair works have to be carried out to restore the road to its initial condition	IX
3	A part of the road is damaged. Formation of big cracks and settlement of road is seen. Crack width may exceed more than 100 mm. Many bigger cracks in either one side or both sides of the road. Failure or crack can be attributed by liquefaction, landslide, fault rupture, and failure of subgrade and subbase. Road can be used by limited traffic. Considerable road repair works should be carried out	V, VI, VII, VII, IX, XI and XII
4	A portion of the road is rendered completely useless. Loose soil and debris are found all around. Road layers are washed away or slides. Damaged road can be used only for smooth walking or cycling. Vehicles cannot ply on the damaged stretch of the road and the stretch has to be completely rebuilt	VII, VIII, IX, X and XI
5	Maximum damage occurs to a road during an earthquake. Damage of total width of road, road may not be useful for smooth walking and cycling. The roads are completely rendered useless and are totally inaccessible. Roads are damaged structurally and debris from landslides renders the road totally inaccessible. Complete relaying and rebuilding is needed	VIII, X, XI and XII

2.1 Damage scale 1

The roads are in a satisfactory condition and can be used with minor repairs. The roads coming under this category are completely accessible and can be used for all post-earthquake relief works. Usually, this kind of damage occurs when the roads are of good quality and far away from the epicenter.

2.2 Damage scale 2

Less damaged roads can be represented by this scale. The damages may be moderate cracks, failure of sides and shoulder/footpath of the roads. This kind of damage can be expected to occur close to epicenter during moderate earthquakes and away from epicenter for larger earthquakes. The roads are accessible and minor to moderate repair works may be needed for them to function effectively.

2.3 Damage scale 3

This scale is used to represent moderate damage of roads with big cracks due to earthquake-induced liquefaction, landslide, and other effects. Roads partially blocked due to building collapse, land slide, partially washed away due to storm surges, tsunami, etc. These damages may occur due to any magnitude from moderate to high depending upon the distance from the epicenter. This category of damaged roads is partially accessible for vehicle movement. Either one side or both sides of roads may be used, but the damage occurred can be seen distinctly. These roads require moderate to major repair or cleaning work.

2.4 Damage scale 4

This scale demonstrates high damage to roads which render the roads partly inaccessible. Big cracks, failure of pavement layers as block, big holes, and heavy damage at one side of road can be classified as this category. Roads are blocked due to building collapse, land slide, washed away due to storm surges, tsunami, etc. These roads require major repair and reconstruction in some parts of road.

2.5 Damage scale 5

Damage scale of 5 is upper most in the proposed scale. Most of the time, this scale represents very high damage of roads close to epicenter of earthquake and having moderate to major earthquake. The roads are completely rendered useless and are totally inaccessible. One of the major reasons for this is their proximity to epicenters and very high magnitudes of the earthquakes. Complete failure of pavement surface and sublayers due to landslide and liquefaction. These roads require complete reconstruction for effective traffic movement.

3 Road damages due to earthquake

The number of roads that have been damaged due to earthquakes are innumerable; however, limited records are available as proof. The information regarding road damage (description and photo) due to earthquake along with magnitude and epicenter distance is also very limited. The very first road damage that is reported was during the Loma Prieta earthquake that occurred on October 17, 1989. All major transportation networks were closed after this earthquake (Kiremidjiam et al. 2007). Kiremidjiam et al. (2007) has also stated that many roads were closed during past earthquakes, but no details regarding road damage and the earthquake are provided. This section summarizes different road damages due to past earthquakes along with earthquake magnitudes, epicenter distances, and focal depth. The epicenter distance in this paper means the distance of damaged road from the epicenter location. Road damages with photographs and earthquake information like magnitude, depth, and epicenter distances are used in this study. A total of 35 road damages have been identified with required information. Earthquake details such as the moment magnitude, epicenter distance, and focal depth are available for these damaged roads. Table 3 shows the list of earthquakes which have caused road damages and earthquake information such as magnitude, distance, focal depth and reported MMI scale. The distance varies from 1 km to 250 km and magnitude varies from 5.3 to 9 in moment magnitude (Mw). All the road damages reported here have the data of distance from epicenter. The distance range from epicenter is given for few cases and qualitative statement for few cases. For such cases, average distances are used to represent the given distance range, and assumptions are made for data having qualitative statements. Earthquakes from different parts of the world are considered for this study. Road damages reported due to earthquake from 1989 up to date are considered. Summary of past road damages with earthquake details are given below:

3.1 Extensively damaged roads (RDS-5)

Eight roads were damaged extensively due to different earthquakes, and these roads were completely inaccessible. Complete collapse of road structure due to the Great Hanshin earthquake or Kobe earthquake that occurred on January 17, 1995, is shown in Fig. 1. The moment magnitude of earthquake was 6.9, focal depth was 16 km, and the epicenter distance was 20 km from the damage site at Awaji Island. The reported MMI scale is X (Tung 2004). The damage and blockage of a road due to Atico Peru earthquake June 23, 2001, is shown in Fig. 2. The reported earthquake had a magnitude of 8.4 (Mw) and a focal depth of 33 km. The damage site was 25 km from the epicenter and reported MMI scale value is XII (ASCE-TCLEE 2001). The damage to a road in Southern Peru due to the Peru earthquake on August 15, 2007, is shown in Fig. 3. Earthquake magnitude of 8.0 (Mw) and focal depth of 39 km were reported, and the damage site was about 30 km from the epicenter. MMI scale of XI was reported (EERI Special Report 2007). The road embankment failure on the Pan-American Highway due to the Peru earthquake that occurred on August 15, 2007, is shown in Fig. 4. The earthquake magnitude of 8.0 (Mw) scale with a PGA above 0.6 g was reported. The damage road was 190 km from epicenter. The reported MMI scale is XI (MCEER 2007). The road damaged and blocked due to the earthquake at Balakot in Pakistan that occurred on October 8, 2005, is shown in Fig. 5. The reported earthquake magnitude was 7.6 in Mw and a focal depth of 10 km. The damage site was about 30 km to the north from the epicenter. The reported MMI scale is X (Navin and Matthew 2006). This earthquake has also damaged the road (see Fig. 6) located 30 km to the east of epicenter due to the collapse of retaining wall. Thursday, March 24, 2011, a powerful earthquake moment magnitude of 6.8 has rocked far-eastern Myanmar. The quake struck at a depth of 10 km and epicenter located at 20.705°N, 99.949°E, according to the USGS (2011c). This earthquake damaged roads and bridges; Fig. 7 shows

Table 3 List of damaged roads due to earthquake with image and respective earthquake parameters

S. no.	Earthquake description	Moment magnitude (Mw)	Distance (km)	Depth (km)	Hypocenter distance (km)	Reported MMI scale	Proposed RDS
1	Loma Prieta earthquake October 17, 1989	6.9	16	16	22.63	VIII	4
2	Hokkaido Toho-Oki earthquake of Japan, 1994	7.7	2[a]	33	33.06	VII	3
3	Great Hanshin earthquake or Kobe earthquake January 17, 1995	6.9	20	16	25.61	X	5
4	Atico Peru June 23, 2001	8.4	25	33	41.40	XII	5
5	Atico, Peru earthquake June 23, 2001	8.4	225[b]	33	227.41	XII	3
6	Atico earthquake in Peru June 23, 2001,	8.4	250[b]	33	252.17	XII	1
7	Gjilan/Gnjilane Region earthquake April 24, 2002	5.7	2[a]	8	8.25	VII	3
8	Au Sable Forks, New York earthquake April 20, 2002	5.3	8	11	13.60	VI	3
9	Bam City, Iran earthquake December 26, 2003	7	14	6	15.23	VIII	3
10	Miyagi-Oki (Japan) earthquake May 26, 2003	7	1[a]	71	71.01	IX	2
11	Tokachi-oki earthquake September 26, 2003	8.1	250[b]	27	251.45	XII	1
12	Central (Chuetsu) region of Niigata Prefecture earthquake October 23, 2004	6.6	2[a]	16	16.12	IX	3
13	Central (Chuetsu) region of Niigata Prefecture earthquake October 23, 2004	6.6	1[a]	16	16.03	IX	2
14	Balakot in Pakistan, Muzaffarabad earthquake October 8, 2005	7.6	30	10	31.62	X	5
15	Balakot in Pakistan, Muzaffarabad earthquake October 8, 2005	7.6	30	10	31.62	X	5
16	Balakot in Pakistan, Muzaffarabad earthquake October 8, 2005	7.6	20	10	22.36	X	4
17	Peru earthquake August 15, 2007	8	30	39	49.20	XI	5

Table 3 continued

S. no.	Earthquake description	Moment magnitude (Mw)	Distance (km)	Depth (km)	Hypocenter distance (km)	Reported MMI scale	Proposed RDS
18	Peru earthquake August 15, 2007	8	190	39	193.96	XI	5
19	Peru earthquake August 15, 2007	8	220	39	223.43	XI	3
20	Peru earthquake August 15, 2007	8	200	39	203.77	XI	3
21	Sichuan (Wenchuan) Earthquake China May 12, 2008	7.9	5[a]	19	19.65	XI	4
22	MYANMAR (Burma) Earthquake March 24, 2011	6.8	29	10	30.68	X	5
23	Chile earthquake February 27, 2010	8.8	105	35	110.68	VII	4
24	Chile earthquake February 27, 2011	8.8	215	35	217.83	VIII	3
25	Sichuan (Wenchuan) Earthquake China May 12, 2008	7.9	125	19	126.44	VIII	4
26	Canterbury earthquake New Zealand September 4, 2010	7.1	49	5	49.25	IX	2
27	Canterbury earthquake New Zealand September 4, 2010	7.1	26	5	26.48	IX	4
28	Canterbury earthquake New Zealand September 4, 2010	7.1	50	5	50.25	IX	2
29	Canterbury earthquake New Zealand September 4, 2010	7.1	5	5	7.07	VII	3
30	Christchurch earthquake New Zealand February 21, 2011	6.1	8	5	9.43	VII	4
31	Nisqually earthquake Washington February 28, 2001	6.8	24	52	57.27	VIII	5
32	Nisqually earthquake Washington February 28, 2001	6.8	75	52	91.26	V	3
33	Haiti earthquake January 12, 2010	7	10	13	16.40	VII	4
34	Tōhoku earthquake March 11, 2011	9	100	32	105.00	XI	4
35	Tōhoku earthquake March 11, 2011	9	80	32	86.16	XI	4

[a] Assumed distance based on report

[b] Average distance based on report

Fig. 1 Road structure collapse due to Kobe earthquake (Tung 2004)

Fig. 2 Landslide blockage of supply canal (Yashinsky) due to Peru earthquake (ASCE-TCLEE 2001)

damaged road at Tarlay, Burma and this road is about 29 km from the epicenter. Damages also reported in Tachileik, Naryaung, and Monglin (FEWW 2011), but limited details about the road damages are available. Severe damage to moderate damage of roads was reported during 2001 Nisqually earthquake, Washington. The Nisqually earthquake was an intraslab earthquake that occurred on February 28, 2001, and was one of the largest recorded earthquakes in Washington State. Earthquake moment magnitude of 6.8 was reported with MMI of VIII and less. Most of the property damages occurred at a distance nearer to the epicenter (Wikipedia 2010a). Severely damaged road is shown in Fig. 8.

Fig. 3 A damaged road in Southern Peru due to Peru earthquake (EERI Special Report 2007)

Fig. 4 Pan-American Highway damage near the Pacific Ocean due to Peru earthquake (MCEER 2007)

3.2 Highly damaged roads (RDS-4)

From the collected data, it is observed that ten roads were highly damaged which rendered only a part of the road usable. The road damage due to the Wenchuan, China earthquake on May 12, 2008, is given in Fig. 9. The earthquake had a magnitude of 8.0 in Mw with a PGA of above 100 gal. The damage site was reported to be close to the epicenter and reported MMI scale is XI (Zifa 2008). The damage to road due to October 8, 2005, Muzzaffarabad earthquake is shown in Fig. 10. The earthquake had a magnitude of 7.6 in Mw, and the damaged site was at a distance of 20 km from the epicenter. The reported MMI for the same is X (Navin and Matthew 2006). The road damage due to landslide in Yingxiu due to October 17, 1989, Loma Prieta earthquake is shown in Fig. 11. The earthquake had a magnitude of 6.9 in Mw, and the epicenter was at the Forest of Nisene Marks state park in Santa Cruz country which was about 16 km from the damage

Fig. 5 Road blocked due to Pakistan earthquake (Navin and Matthew 2006)

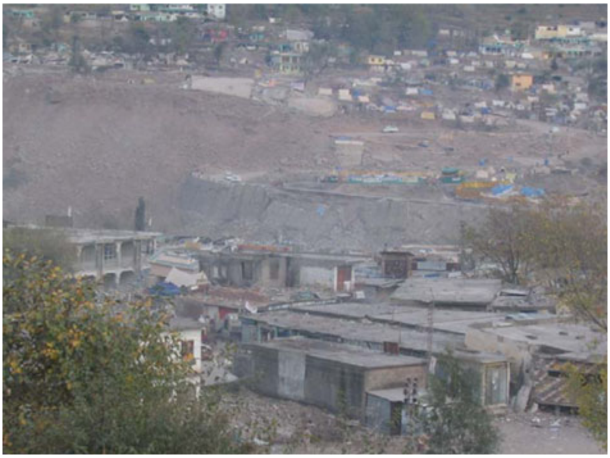


Fig. 6 Collapsed road east of the epicenter due to Pakistan earthquake (Navin and Matthew 2006)

site. The reported MMI is VIII (Marshall et al. 1989). Highly damaged road due to Chile earthquake 2010 is shown in Fig. 12. A moment magnitude of 8.8 occurred on February 27, 2010, at Chile and was called as Chile earthquake. Epicenter location was located off the coast of either the Maule Region or the Biobío Region of Chile (Wikipedia 2011a). This earthquake caused damage of VIII and above in MMI and also triggered a tsunami which devastated several coastal towns in south-central Chile and damaged the port at Talcahuano (Fig. 13). Many roads were damaged and blocked for emergency operation due to tsunami alert. Sichuan earthquake is popularly known as Great Sichuan earthquake or 2008 Sichuan earthquake and also the Wenchuan earthquake. The epicenter was located at 30.986°N, 103.364°E, i.e., 80 km west-northwest of Chengdu, the capital of Sichuan, with a focal depth of 19 km (USGS 2008). Massive landslide was reported at Qingchuan and more than 700 people were dead. A train was buried by a landslide near Longnan,

Fig. 7 Damage of bridge approach road due to Myanmar (Burma) earthquake 2001 (CBC 2011)

Fig. 8 Road damage at Sunset Lake, Tumwater, from the 2001 Nisqually earthquake [Photo: Steven Kramer/University of Washington accessed in Washington DNR (2011)]

Fig. 9 Road damage in Yingxiu due to Wenchuan earthquake (Zifa 2008)

Fig. 10 Damage of road due to Muzaffarabad earthquake (Navin and Matthew 2006)

Fig. 11 Road damage due to Loma Prieta earthquake (EARTHQUAKES, Marshall et al. 1989)

Gansu. At least 2,473 dams sustained some damage and more than 53,000 km of roads and 48,000 km of tap water pipelines were damaged (USGS 2008). Local news agencies reported that widespread hill slides have blocked many roads in the area including a national highway (Wikipedia 2008). Earthquake moment magnitude of 7.1 struck the South Island of New Zealand at 4:35 a.m. on September 4, 2010 (USGS 2010). The earthquake is called as Canterbury earthquake and also known as the Christchurch earthquake or Darfield earthquake (Wikipedia 2010b). Most of the damage was in the area surrounding the epicenter, including the city of Christchurch, New Zealand's second-largest urban area. Maximum intensity of IX was reported in the Christchurch–Greendale area and felt intensity of VI in much of Canterbury area. Many roads were blocked by debris and damages. Figure 14 shows the damaged road due to Canterbury earthquake 2010. In the same country, another earthquake of moment magnitude of 6.1 struck the New Zealand's

Fig. 12 Damaged road due to Chile earthquake 2010 (Photo: http://news.bbc.co.uk/2/hi/americas/8542112.stm)

Fig. 13 Damaged road due to Great Sichuan earthquake 2008 (Photo: http://www.mirror.co.uk/news/top-stories/2008/05/14/china-earthquake-death-toll-may-reach-50-000-115875-20417082/)

South Island on Tuesday, February 22, 2011 (USGS 2011a). The earthquake was centered 2 km west of the town of Lyttelton and 10 km south-east of the center of Christchurch, New Zealand. Its magnitude was 7.1 (Mw), and 2010 Canterbury earthquake occurred on September 4, 2010. Damaged road due to this Christchurch earthquake is shown in Fig. 15. The 2010 Haiti earthquake was a catastrophic earthquake of moment magnitude 7.0 with an epicenter near the town of Léogâne (Wikipedia 2010c). The earthquake occurred on Tuesday, January 12, 2010, with a focal depth of 13 km. Figure 16 shows the damaged road due to Haiti earthquake 2010. The Tohoku earthquake of moment magnitude of 9.0 occurred on March 11, 2011, near the northeast coast of Honshu, Japan and reported a focal depth of 33 km (USGS 2011b). It was the most powerful earthquake to have hit Japan, and one of the five most powerful earthquakes in the world overall since modern record-

Fig. 14 Damaged road due to Canterbury earthquake 2010 (Photo: http://archive.wn.com/2011/03/07/1400/worldnaturaldisaster/)

Fig. 15 Damaged road due to Christchurch earthquake (Photo: http://eqchch.wordpress.com/2011/02/25/canterbury-christchurch-earthquake-damage-2011/)

keeping began in 1900 (Wikipedia 2011b). The earthquake and tsunami caused extensive and severe structural damage in Japan, including heavy damage to roads and railways as well as fires in many areas, and a dam collapse. Damaged road photo with epicenter distance is shown in Fig. 17a, b.

3.3 Moderately damaged roads (RDS-3)

Moderate damage was observed in the eleven roads in the collected data. The damaged road structure in the Pan-American Highway due to August 15, 2007, Peru earthquake is

Fig. 16 Damaged road due to 2010 Haiti earthquake (Photo: http://gallery.usgs.gov/photos/02_24_2010_c28Ja44Yyt_02_24_2010_6)

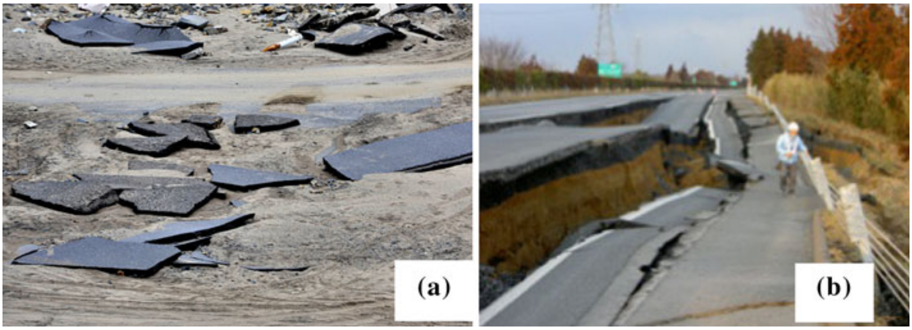


Fig. 17 Damaged roads due to 2011 Tōhoku earthquake, Japan (Photo: **a** http://www.tokyophotographers.com/2011/03/37-frames-great-tohoku-earthquake-tsunami-2011-japan-the-black-mouth-1.html and **b** http://buyjapanese.jp/about-japan/do-you-want-to-know-how-fast-japan-is-recovering-from-the-earhquake/

shown in Fig. 18a, b. The earthquake had a magnitude of 8.0 in Mw and damaged site was located 220 km from the epicenter. The reported MMI scale for the same is XI (MCEER 2007). The damage site (Fig. 18b) was at a distance of 200 km from the epicenter. The reported MMI value is XI (GEER 2008). Partially blocked and damaged road due to rock slide during June 23, 2001, Atico, Peru earthquake is shown in Fig. 19. The earthquake had a magnitude of 8.4 in Mw and epicenter was about 150–300 km from the damaged site. The reported MMI for the same is XII (ASCE-TCLEE 2001). Approach road settlement at Koshino Bridge due to the earthquake on October 23, 2004, at central (Chuetsu) region of Niigata Prefecture is shown in Fig. 20. The earthquake had a magnitude of 7.0 in Mw, and the epicenter was close to the damage site and the reported MMI for the same is IX (Shanmuganathan 2005). Crack on the road traversing the flexural scarp due to the December 26, 2003, Bam City, Iran earthquake is shown in Fig. 21. The earthquake had a

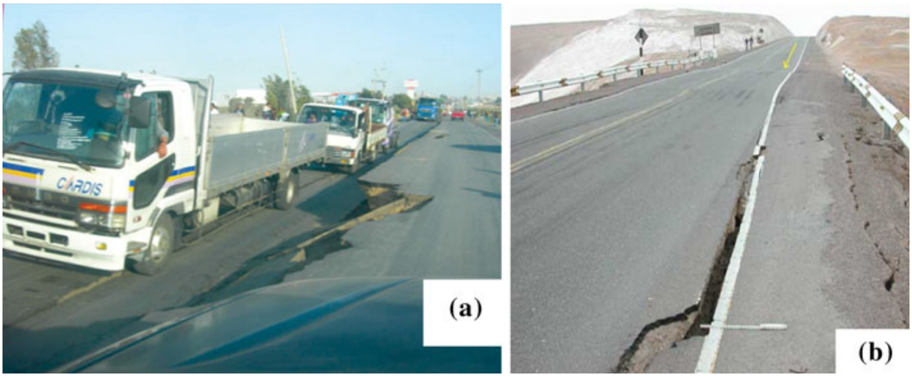


Fig. 18 Damaged roads due to Peru earthquake 2007 (Photo: **a** Pan-American Highway (MCEER 2007) and **b** Highway damage (GEER 2008)

Fig. 19 Road partially blocked due to Atico, Peru earthquake June 23, 2001 (ASCE-TCLEE 2001)

Fig. 20 Approach road settlement at Koshino Bridge due to Chuetsu earthquake (Shanmuganathan 2005)

magnitude of 7.0 in Mw and a vertical motion of over 1 g was observed and the horizontal motion had marked a very high value of 800 gal. The epicenter was about 14 km from the damage site and reported MMI value for the same is VIII (JSCE 2003). Severe defect on

Fig. 21 Crack on the road traversing the flexural scarp due to Bam earthquake (JSCE 2003)

Fig. 22 Severe defect on road surface due to Hokkaido Toho-Oki earthquake (Tung 2004)

road surface due to Hokkaido Toho-Oki earthquake of Japan, 1994, is shown in Fig. 22. The earthquake had a magnitude of 7.7 in Mw and epicenter was reportedly close to the damage site. The reported MMI scale for the same is VII (Tung 2004). The Boston–Jasenovik road was damaged in some parts and ditches were covered with stones and earth due to the April 24, 2002, Gjilan/Gnjilane Region earthquake as shown in Fig. 23. It had a magnitude of 5.7 in Mw and epicenter was close to the damage site. The reported MMI scale for the same is VII (IMC 2002). The road damage due to slumping on Route 9N near Clintonville, Clinton County, NY due to April 20, 2002, Au Sable Forks, New York earthquake is shown in Fig. 24. The earthquake had a magnitude of 5.3 in Mw, and the epicenter was about 8 km from the damaged road and the reported MMI scale for the same is VI (Young Kim 2002). Chile earthquake 2010 caused moderate damage to roads located at 215 km away from epicenter. Figure 25 shows the image of moderately damaged road due to Chile earthquake 2010. Canterbury earthquake 2010 had also caused moderate damage close to epicenter apart from high damage. Figure 26 shows damaged road image close to epicenter due to Canterbury earthquake 2010. Nisqually earthquake 2001 not only caused extensive damage but also moderate damage to many roads. Figure 27 shows image of moderately damaged road due to 2001 Nisqually earthquake.

Fig. 23 Bostan–Jasenovik road is damaged in some parts and ditches are covered with stones and earth (EDARP 2002)

Fig. 24 Road damage due to slumping on Route 9N near Clintonville, Clinton County, NY due to New York earthquake (Young Kim 2002)

3.4 Low damaged roads (RDS-2)

Four figures represent less damage of roads due to earthquake. The road settlement caused due to the October 23, 2004, central (Chuetsu) region of Niigata Prefecture earthquake is shown in Fig. 28. The earthquake had a magnitude of 7.0 in Mw and epicenter was reported very close to the damaged road. The reported MMI value for the same is IX (Shanmuganathan 2005). Cracks on Route 397 in Ohfunato due to the May 26, 2003, Miyagi-Oki earthquake is shown in Fig. 29. Magnitude of the earthquake was 7.0 in Mw with a PGA of 1.1 g at MYG011, 1.0 g at IWT007 stations. The epicenter was reported very close to the damage site and the reported MMI scale for the same is IX (DCRC 2003). 2010 Canterbury earthquake caused moderate to low damages in roads located at a moderate distance (more than 40 km from epicenter). Single crack and moderate damage part of road were reported due to this earthquake. Figure 30a, b shows the images of damaged roads and which can be classified as RDS 2.

3.5 Slightly damaged roads (RDS-1)

Roads suffering low to slight damages are reported in this section. The settlement of bridge approach and cracking of road due to June 23, 2001, Atico earthquake in Peru is shown in

Fig. 25 Road damage due to Chile earthquake 2010 (Photo: http://www.channelnewsasia.com/photosgallery/gallery_20100228095431.htm)

Fig. 26 Damaged road due to Canterbury earthquake 2010 (Photo: http://www.natural-calamity.info/earthquake-destroyed-about-500-buildings-in-chrishchurch/)

Fig. 31. The earthquake had a Mw of 8.4 and the epicenter was at a distance of about 150 to 300 km from the damaged road. The reported MMI value is XII (Nakamura 2000). The damage to road due to the Tokachi-oki earthquake on September 26, 2003, is shown in Fig. 32. The earthquake had a magnitude of 8.1 in Mw and epicenter was about 150 km to 300 km from the damage site. Reported MMI value is XII (Tung 2004).

Fig. 27 Road damage at Sunset Lake, Tumwater, from the 2001 Nisqually earthquake (Photo: http://en.wikipedia.org/wiki/2001_Nisqually_earthquake)

Fig. 28 Approach road settlement at Hurumiya Bridge (Shanmuganathan 2005)

4 Analysis of data

Data collected along damaged roads are earthquake magnitude in Mw, epicenter distance in km, and depth in km, which are listed in Table 3. Table 3 also gives estimated hypocenter distance in km and reported MMI scale. The collected road damages reported for earthquakes magnitude range from 5.3 to 9, epicenter distance ranging from 1 to 250 km and focal depth of 5–71 km. Reported MMI scale in the damaged road locations are listed in Table 3. The comparison between newly proposed scale and range of reported MMI

Fig. 29 Cracks of Route 397 in Ohfunato due to Miyagi-Oki earthquake (DCRC 2003)

scale is also given in Table 2. MMI scale of XII is used to refer minor, moderate and high road damages. This may happen because no proper definition has been given in MMI scale. Damaged roads due to past earthquake (in Table 3) are reclassified considering newly proposed RDS in this study by taking into account of damages noticed in the image (Figs. 1–32) and description in the reports. Road damages showed in Figs. 1–8 (S. no. 3, 4, 14, 15, 17, 18, 22, and 31 in Table 3) come under the damage scale of 5. Figures 9–17 (S. no. 1, 16, 21, 23, 25, 27, 30, 33, 34 and 35 in Table 3) come under damage scale of 4. Figures 18–27 (S. no. 2, 5, 7, 8, 9, 12, 19, 20, 24, 29 and 32 in Table 3) come under damage scale of 3. Figures 28 and 30 (S. no. 10, 13, 26 and 28 in Table 3) come under damage scale of 2, and Figs. 31, 32 (S. no. 6 and 11 in Table 3) come under damage scale 1. Assigned damage level of each damaged road is listed in Table 3. The newly proposed RDS and existing MMI scale have been plotted with earthquake magnitudes, epicenter distance, and hypocenter distance. Figure 33a, b shows the MMI and new RDS versus the reported earthquake magnitude in Mw. The reported MMI scale in roman letter is represented by respective equal number to prepare plot of MMI versus earthquake magnitude, epicenter distance, and hypocenter distance. It is noted that the whole data does not follow any trend with magnitude. However, RDS follow some trend if the data is grouped in some fashion (see closed polygons in Fig. 33b). It is interesting to note that earthquake magnitude less than 6.5 can also cause damage level up to 4. Figure 34a, b shows the MMI and new RDS versus the epicenter distance, i.e., distance of damaged road from the epicenter. It can be seen that MMI and RDS data does not follow any trend as a whole, but the figure gives an idea that RDS can follow some trend with epicenter distances (see closed polygons in Fig. 34b). Meanwhile, it is necessary to highlight that there is no reported road damage data in between epicenter distance of 130–185 km. Combined plots of MMI and

Fig. 30 Low to moderate damaged roads due to 2010 Canterbury earthquake (Photo: http://en.wikipedia.org/wiki/2010_Canterbury_earthquake)

Fig. 31 Settlement of bridge approach and cracking of road. Only one lane is open for traffic (Nakamura 2000)

new RDS with hypocenter distance for whole data are shown in Fig. 35a, b. Whole data of MMI and RDS does not follow any trend with hypocenter distance, but grouping RDS and hypocenter data in some fashion will give a trend (see Fig. 35b). But it is difficult to group MMI data easily to get some trend. It can be clearly noticed that comparing figures "a" and

Fig. 32 Minor cracks on road surface due to Tokachi-Oki earthquake (Tung 2004)

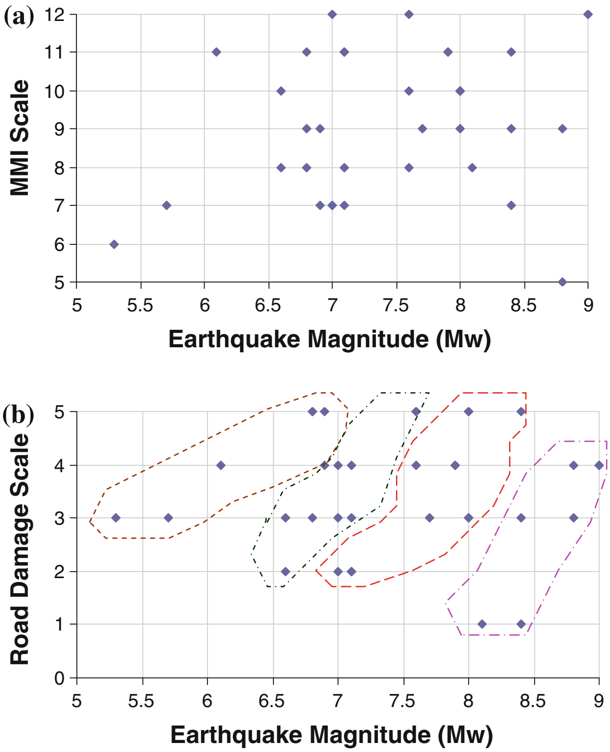


Fig. 33 **a**, **b** MMI and new RDS with reported earthquake magnitudes

"b" (Figs. 33, 34 and 35), existing MMI scales does not follow any grouping or trend with magnitudes, epicenter, and hypocenter distances. Reason for this is well known that MMI scales are not developed for roads. But these are widely used to represent damage of roads.

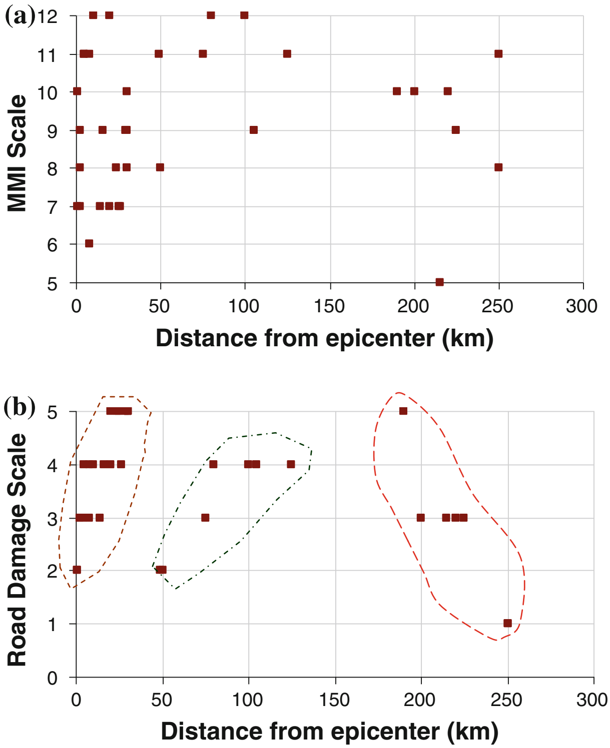


Fig. 34 **a**, **b** MMI and new RDS with reported distance from epicenter

Analysis of the Figs. 33b, 34b, and 35b shows that newly developed RDS does not follow any trend with magnitudes, epicenter, and hypocenter distances as whole data. But RDS follows some trend as marked in Figs. 33b, 34b, and 35b if data are divided or grouped in some fashion. Grouped data shown in these figures are further analyzed separately to develop correlation between RDS to magnitude, epicenter, and hypocenter distances and are presented in the next section.

5 Relation between RDS to magnitudes, epicenter, and hypocenter distances

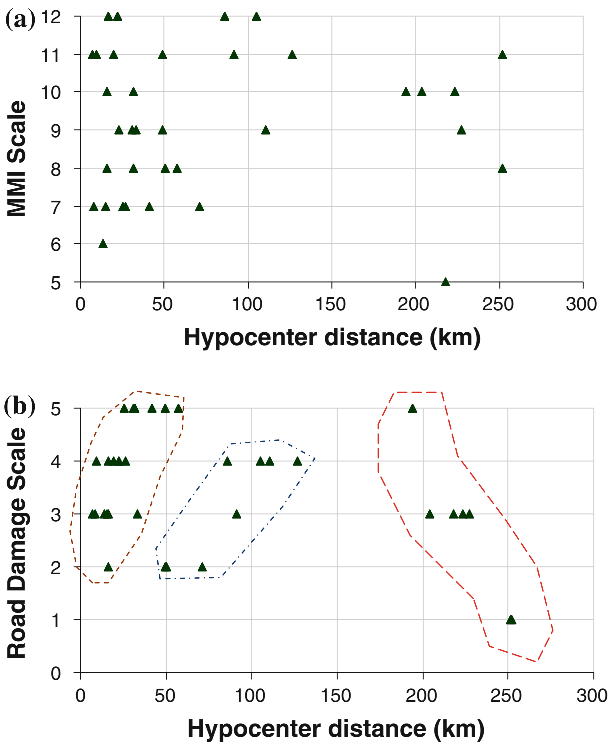
Newly proposed RDS is correlated with the earthquake parameters like magnitude, epicenter, and hypocenter distances. Summary of earthquake parameters causing road damages and respective RDS is listed in Table 3. Each datum contains magnitude in Mw, distance from epicenter in km, focal depth in km, and classification of damaged road considering newly proposed damage scale in this study. As shown in Figs. 33b, 34b, and 35b, new road damage scale follows some trend with magnitude (Mw), epicenter distance (ED), and hypocenter distance (HD) if these are grouped in some fashion. Two types of simple regression equations are followed to develop correlation considering grouped data, which are given below

$$\text{Road Damage Scale (RDS)} = a\,(\text{paramter})^{b} - \text{Power regression equation} \quad (1)$$

$$\text{Road Damage Scale (RDS)} = a\,(\text{paramter}) + b - \text{Linear regression equation} \quad (2)$$

where “a” and “b” are regression coefficients and parameter is magnitude (M) or epicenter distance (ED) or hypocenter distance (HD) or combination of magnitude and ED or HD

Fig. 35 **a**, **b** MMI and new RDS with hypocenter distance



(M + ED or M + HD). Power and linear regression are performed for each data set grouped in Figs. 33b, 34b, and 35b, and equation of best fit with highest correlation coefficient (R^2) is only presented here. Correlations are obtained for specific group of data, and hence, range of values considered to develop correlation is given in Table 4. Coefficients "a" and "b" corresponding to 90% confidence intervals are also obtained and given in brackets (see Table 4, column 6 and 7) in addition to original correlation coefficients.

Correlation between RDS and M is generated by considering four groups of RDS and magnitude data set shown in Fig. 33b. Figure 36a–d shows RDS versus magnitude (M) in Mw and respective regression relation with correlation coefficient (R^2). Proposed RDS is well correlated with earthquake magnitudes and gives correlation coefficient (R^2) of above 0.67. Range of magnitude and RDS for each correlation is given in Table 4, Eqs. 1–4. It can be noticed here that two RDS is possible for same magnitudes due to mixing of independent variable while grouping. Similar to RDS and magnitude, correlation between RDS and epicenter distance has been generated and shown in Fig. 37a–c. Regression coefficient (R^2) is above 0.8, which is much more than RDS and magnitude relation. Only one RDS can be obtained for any distance, and there is no mixing of independent variable. Figure 38a–c shows correlation between RDS and hypocenter distance, and good correlation coefficients are obtained for data set in Fig. 38b, c. Twenty sets of RDS and hypocenter distance in Fig. 38a give correlation coefficient (R^2) of 0.42. Lower R^2 value is attributed by two data (see data in the closed polygon). Removal of two data marked in Fig. 38a increases R^2 value considerably and slight changes in the regression coefficients of "a" and "b" (see Eqs. 8 and 9 in Table 4). Even though magnitude, epicenter, and hypocenter distances versus RDS gives good regression, it cannot be directly used to

Table 4 Summary of correlations between RDS and earthquake parameters

Eq. no.	Equation type	Parameter used to relate RDS	Number of data	Coefficients (90% Ci—90% confidence intervals)		Correlation coefficient (R^2)	RDS range	Magnitude range (Mw)	Distance range (km)
				a (90% Ci)	b (90% Ci)				
1	RDS = aM^b	M	7	0.12(±0.23)	1.91(±1.01)	0.81	3–5	5.3–6.9	–
2	RDS = $aM + b$	M	9	2.47(±0.87)	−13.87(±6.13)	0.81	2–5	6.6–7.6	–
3	RDS = $aM + b$	M	12	2.17(±0.87)	−13.27(±6.71)	0.67	2–5	7.1–8.4	–
4	RDS = $aM + b$	M	7	3.41(±1.69)	−26.58(±14.66)	0.77	1–4	8.1–9	–
5	RDS = aED^b	ED	21	2.32(±0.33)	0.22(±0.05)	0.80	2–5	–	1–30
6	RDS = aED^b	ED	7	0.14(±0.22)	0.72(±0.35)	0.87	2–4	–	49–125
7	RDS = aED + b	ED	7	−0.06(±0.02)	15.22(±4.27)	0.88	1–5	–	190–250
8	RDS = aHD^b	HD	20	1.54 (±0.65)	0.30(±0.13)	0.42	2–5	–	7–58
9	RDS = aHD^b	HD	18	1.67 (±0.27)	0.29(±0.05)	0.68	3–5	–	7–58
10	RDS = aHD^b	HD	8	0.07 (±0.13)	0.84(±0.39)	0.80	2–4	–	49–127
11	RDS = aHD + b	HD	7	−0.06(±0.02)	15.88(±4.46)	0.88	1–5	–	190–255
12	RDSRDS = $a(M$ + ED$)^b$	***M* + *ED***	***21***	***1.16*(±*0.34*)**	***0.40*(±*0.09*)**	***0.76***	***2–5***	***5.3–8.4***	***1–30***
13	RDS = $a(M$ + ED$)^b$	***M* + *ED***	***7***	***0.05*(±*0.10*)**	***0.91*(±*0.02*)**	***0.88***	***2–4***	***6.8–9.0***	***49–125***
14	RDS = $a(M$ + ED$) + b$	***M* + *ED***	***7***	***−0.06*(±*0.02*)**	***15.58*(±*0.36*)**	***0.88***	***1–5***	***8–8.8***	***190–250***
15	RDS = $a(M$ + HD$)^b$	M + HD	20	1.06(±0.60)	0.39(±0.16)	0.43	2–5	5.3–8.4	7–58
16	RDS = $a(M$ + HD$)^b$	M + HD	18	1.16(±0.44)	0.37(±0.11)	0.69	3–5	5.3–8.4	7–58
17	RDS = $a(M$ + HD$)^b$	M + HD	8	0.05(±0.09)	0.92(±0.41)	0.82	2–4	6.8–9.0	49–127
18	RDS = $a(M$ + HD$) + b$	M + HD	7	−0.06(±0.02)	16.31(±4.62)	0.88	1–5	8–8.8	193–253

"*a*" and "*b*" are regression coefficients, 90% Ci, coefficient in brackets are regression coefficient for 90% confidence intervals

RDS road damage scale, *M* earthquake magnitude in Mw, *ED* epicenter distance in km, *HD* hypocenter distance in km

Fig. 36 **a–d** RDS correlated with reported earthquake magnitude in Mw

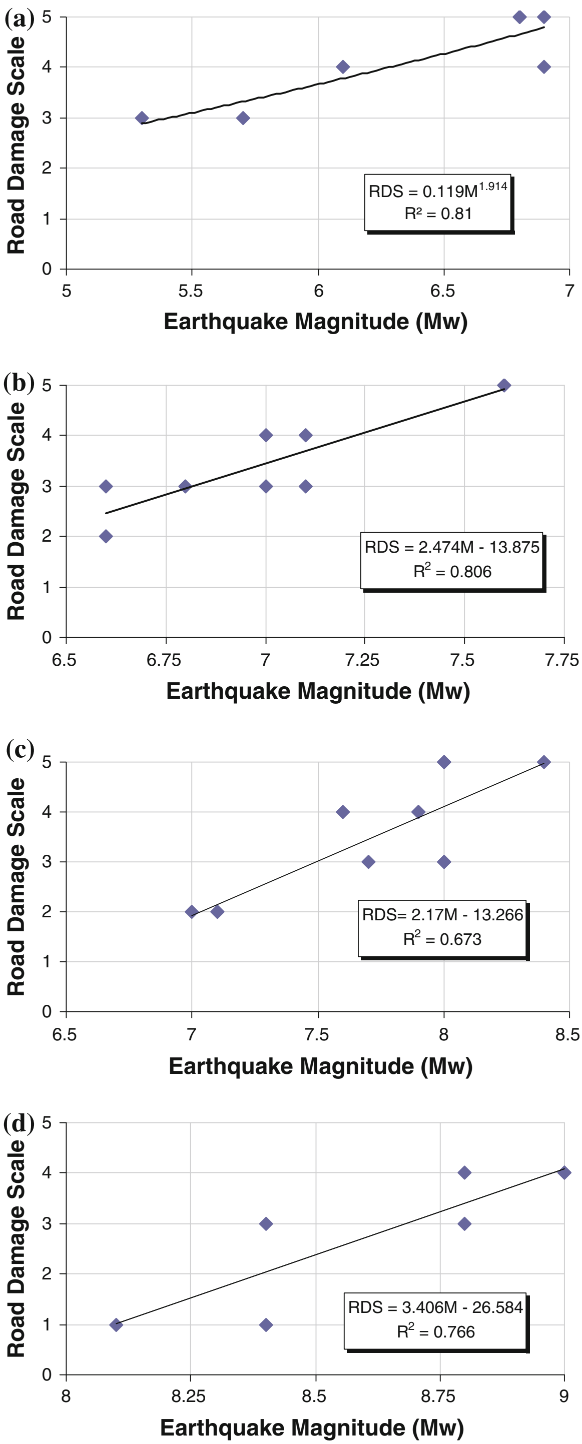
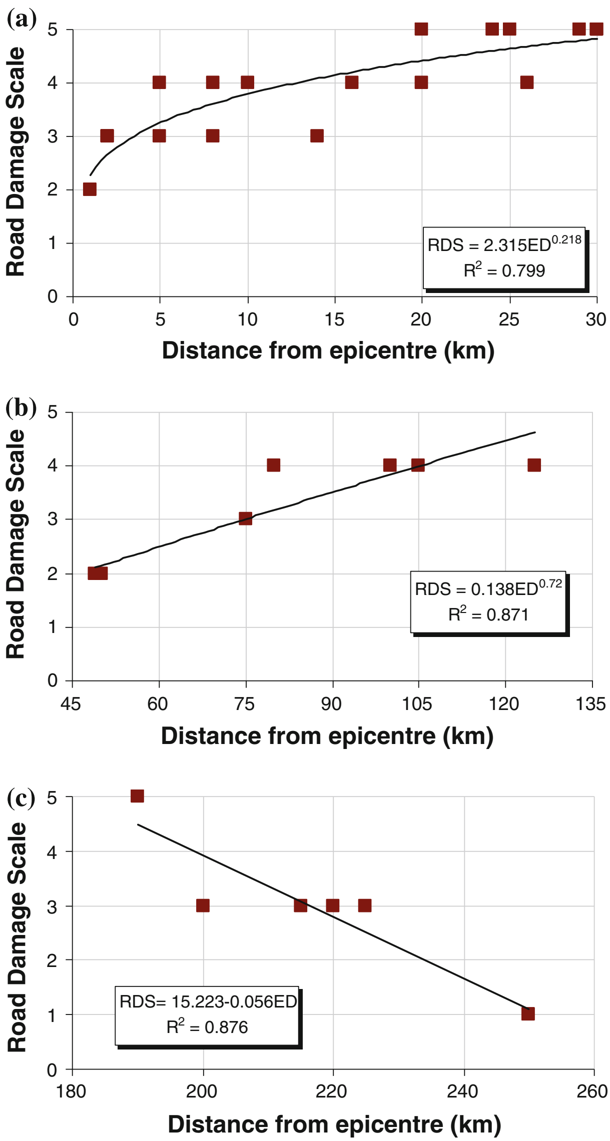


Fig. 37 **a–c** RDS correlated with reported distance from epicenter in km



estimate the RDS for future road damage assessment due to earthquake, because assessing the road damage without the combination of earthquake magnitude and distance is meaningless. Hence, regression is performed by combining magnitude and distances (epicenter and hypocenter) and discussed in next section.

6 Relation between RDS to magnitudes + distances

Relation between RDS and magnitude, epicenter distance, and hypocenter distance in previous section shows that newly proposed RDS is well co-relatable with high correlation

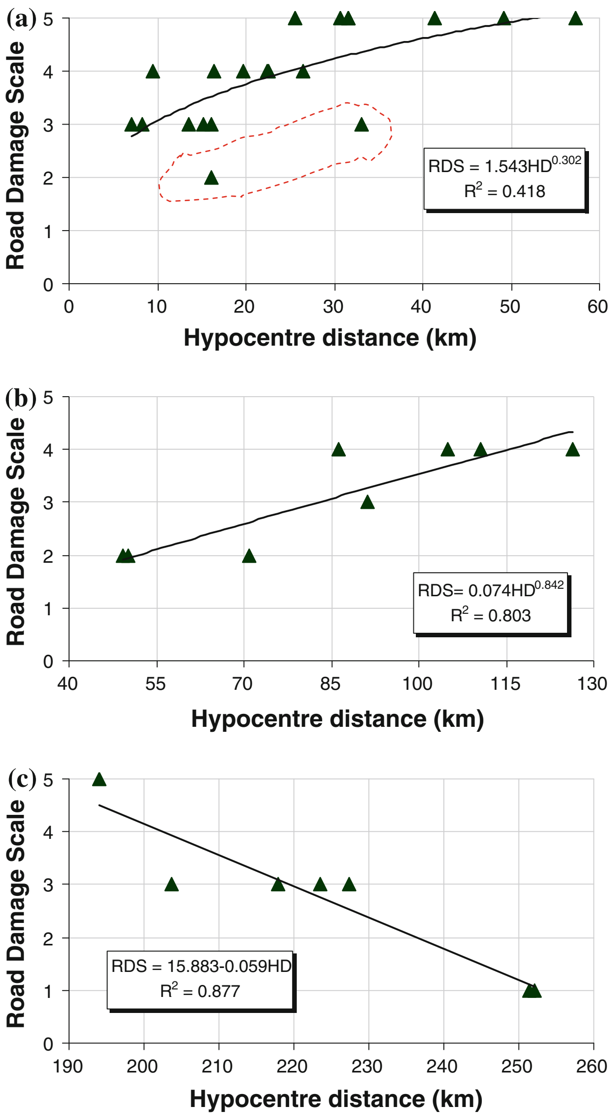
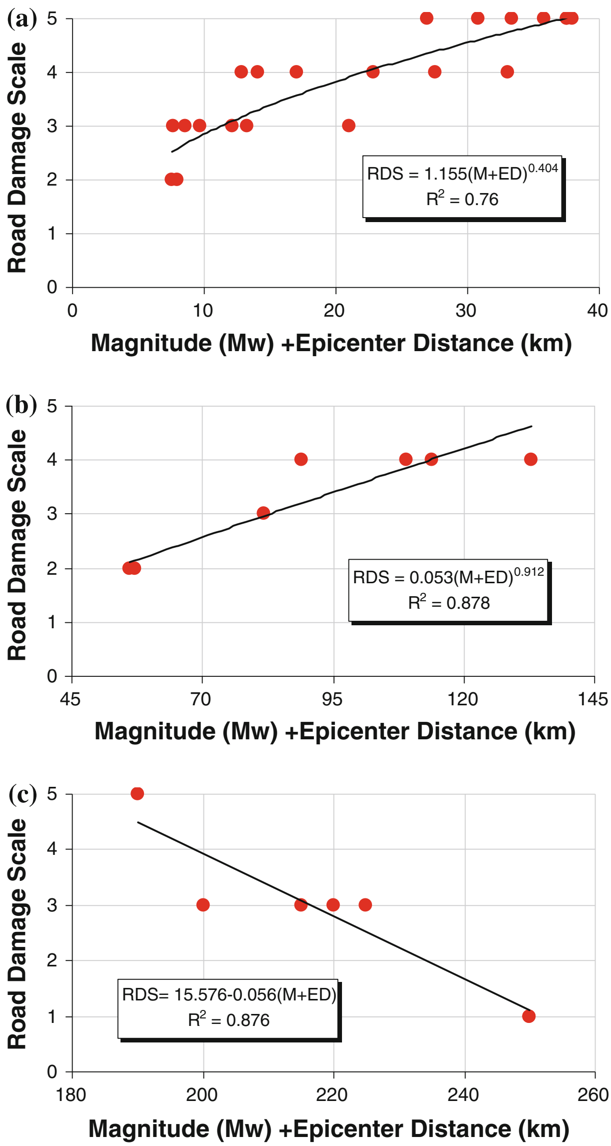


Fig. 38 **a–c** RDS correlated with hypocenter distance in km

coefficient of R^2. RDS versus magnitude and hypocenter distance gives different RDS for the same M and HD due to mixing of independent variables while grouping. RDS and epicenter distance gives very good regression and no mixing of independent variables. Reported road damages are grouped based on epicenter distance and combined with magnitude to relate the proposed RDS. Roads located within 125 km may experience low damage to extensive damage based on site specific condition. In the offense of soil data, distance and magnitude are related to RDS. Magnitude 5.3–8.4 and distance of less than 30 km are combined together and shown in Fig. 39a. Twenty-one data set gives best power regression correlation with correlation coefficient of 0.76. Remaining data experienced similar road damage for epicenter distance of 30–125 km and magnitude of 6.8–9.0. Correlation of these data is shown in Fig. 39b with regression relation and best fitted line.

Fig. 39 **a–c** RDS correlated with magnitude in Mw plus epicenter distance in km



These data sets give correlation coefficient of 0.88. Limited road damage data are available for distance 130–185 km. Roads located in between 190 and 250 km from the epicenter had experienced slight to extensive damage (RDS 1–5). Figure 39c shows data, best fitted line, and regression relation with correlation coefficient of 0.88.

Similarly, hypocenter distance also combined with magnitude and related to RDS. Figure 40a–c shows the relation between RDS and magnitude plus hypocenter distance and best fitted line, correlation and R^2 value. Figure 40a gives less R^2 because of the presence of two data similar to Fig. 38a. After removing these two data marked in Fig. 40a, R^2 value of 0.69 was obtained (see Eqs. 15 and 16 in Table 4). In general, R^2 values for relation between RDS and M + HD are less than RDS and M + ED. Newly proposed RDS is well

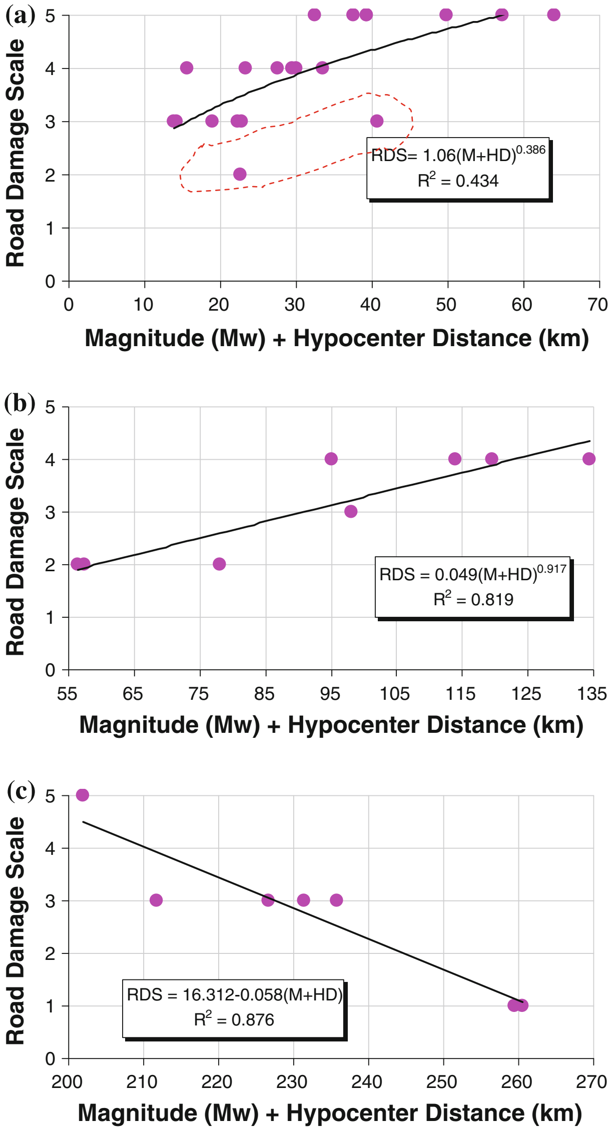


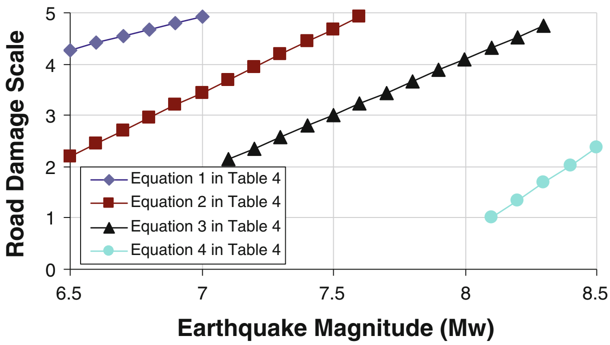
Fig. 40 **a**–**c** RDS correlated with magnitude in Mw plus hypocenter distance in km

correlated with earthquake magnitude and combination of magnitude and epicenter and hypocenter distances.

7 Results and discussion

Summary of correlation between newly proposed RDS and magnitude, epicenter distance, hypocenter distance, and combination of magnitude with epicenter and hypocenter distances is given in Table 4. Most of the correlations have the best fit with high correlation coefficient. Correlation between RDS and magnitude has limited application because of

Fig. 41 Range of magnitude values predicts two RDS values



predicting more than one road damage level for a same magnitude in the certain range of magnitude values. Figure 41 shows the plot of four equations developed and magnitude values resulting in two RDS values. Two RDS values can be predicted for the magnitude range of 6.5–7.0 using Eqs. 1 and 2 in Table 4, 7.1–7.6 using Eqs. 2 and 3 in Table 4, and 8.1–8.4 using Eqs. 3 and 4 in Table 4 (see Fig. 41). This happens because of mixing of independent variable while grouping data. Similarly, correlation between RDS with hypocenter distance and magnitude plus hypocenter distance also predicts more than one RDS value for certain range of hypocenter distance and magnitude plus hypocenter distance. Figure 42a, b shows the data set with developed equations predicting two RDS values. Figure 42a shows that three RDS values can be predicated for hypocenter distance range of 40–60 km using Eqs. 8, 9, and 10 in Table 4, if Eq. 8 is omitted even two RDS values are applicable. It can be also noted that RDS values are slightly exceeding the upper limit of 5 for Eq. 8 for hypocenter distance of more than 52 km. Figure 41b shows that three RDS values can be predicted for magnitude plus hypocenter distance range of 55–70 km using Eqs. 15, 16 and 17 in Table 4, if Eq. 15 is omitted even two RDS values are applicable. Here also RDS value of more than 5 is obtained for magnitude plus hypocenter distance of more than 56 km. One should be aware of these limitations while using these relations to predict road damage level for any future earthquake. Relation between RDS and epicenter distance gives one RDS value for all the range of epicenter distance. But predicting road damage level due to earthquake without considering earthquake magnitude is meaningless. Correlation between RDS and magnitude plus epicenter distance is highly recommended for prediction of road damage level due to earthquake. Recommended equations with coefficient 90% correlation confidence intervals in brackets are given below:

$$\text{Road Damage Scale (RDS)} = 1.16\,(\pm 0.34)\,[M + \text{ED}]^{0.40(\pm 0.09)} \tag{3}$$

$$\text{Road Damage Scale (RDS)} = 0.05\,(\pm 0.10)\,[M + \text{ED}]^{0.91(\pm 0.02)} \tag{4}$$

$$\text{Road Damage Scale (RDS)} = 15.58\,(\pm 0.36)\; - 0.06(\pm 0.02)\,[M + \text{ED}] \tag{5}$$

where RDS is to assess road damage level due to earthquake, M and ED are magnitude in Mw and epicenter distance in km. Equation 3 (Eq. 12 in Table 4) has been developed for earthquake magnitude (Mw) of 5.3–8.4 and epicenter distance up to 30 km. This equation can be used for combined M and ED value of 45, and RDS values should be rounded to nearest single digit. Equation 4 (Eq. 13 in Table 4) has been developed for earthquake magnitude (Mw) of 6.8–9.0 and epicenter distance of 49–125 km. This equation can be used for combination of M and ED value 45–150, and RDS values should be rounded to

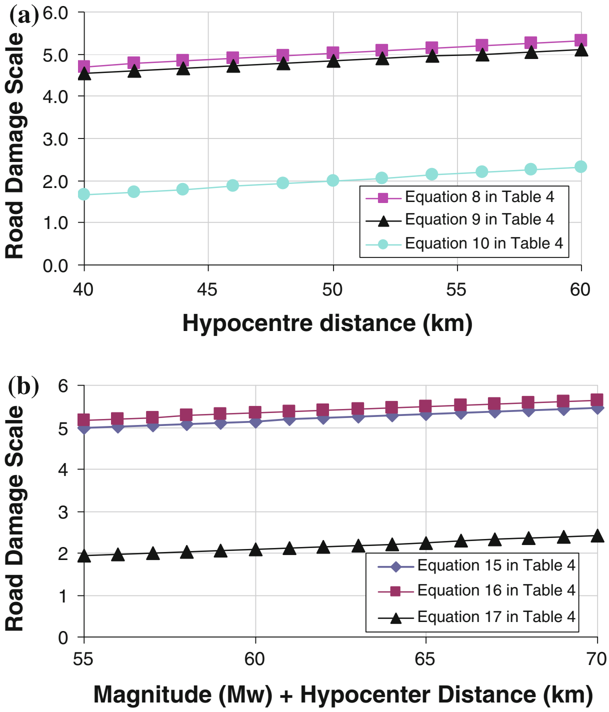


Fig. 42 **a**, **b** Range of hypocenter and magnitude plus hypocenter predicts two RDS values

nearest single digit. Equation 5 (Eq. 14 in Table 4) has been developed for earthquake magnitude (Mw) of 8.0–8.8 and epicenter distance of 190–250 km. This equation can be used for combination of *M* and ED value 180–270, and RDS values should be rounded to nearest single digit.

Newly proposed RDS can be used to define road damage level due to any earthquake. Damaged road details with photo and earthquake magnitude, epicenter distance, depth, and reported intensity value in MMI scale were collected for past earthquakes since 1989 to up to date. Past road damages due to earthquake are classified according to proposed RDS value. Proposed RDS follows a trend with earthquake magnitude, epicenter distance, and hypocenter distance if data set is grouped in some fashion. Correlation between RDS and magnitude in Mw, epicenter distance in km, hypocenter distance in km, magnitude plus epicenter distance, and magnitude plus hypocenter distance has been developed using available collected data. Correlation between RDS and magnitude plus epicenter distance is more reliable when compared with other relations. These correlations (Eqs. 3–5) can be used to assess the damage level of road for the forecasted earthquake. This will help to assess the vulnerability and risk of transportation networks and identify the optimum route for disaster handling and management soon after the earthquake. The correlations developed in this study are based on available data and newly proposed RDS, by assuming all the roads are having same structural features and quality. If the quality of road is considerably poor, estimated damage level may be upgraded to one or two higher damage scale levels based on the field road quality assessment. Separate detailed analysis may be carried out in future to study behavior of various types of subsurface soil and pavement properties for different earthquake parameters.

8 Conclusion

This paper presents different past road damages due to the earthquakes and MMI scale for these damages. The study shows that MMI scale has limited application to classify damaged road due to earthquake. Further, a new RDS has been proposed to classify the damaged road due to earthquakes. The proposed scale has been called as RDS, which has five levels of damage description based on various parameters and reported past earthquake damages. The lowest level of RDS is one, which defines the slight road damage such as minor cracks due to earthquakes and these roads are usable for post-earthquake relief work. The highest damage level is five where the road is completely inaccessible due to extensive damage/blockage. Available damaged roads with image and earthquake parameters have been collected. About 35 road damage cases were available with earthquake information and failure images. The past earthquake damaged roads are reclassified using newly proposed scale and compared with MMI scale. Study clearly shows that MMI scale is not capable of defining road damages. MMI scale does not follow any trend with earthquake magnitude, epicenter distance, and hypocenter distance for collected data. Newly proposed RDS follows some trend with earthquake magnitude, epicenter distance, and hypocenter distance if the data are grouped in some fashion. Collected data have grouped based on trend and have been used to generate correlation between RDS and earthquake parameters of earthquake magnitude in Mw (M), epicenter distance in km (ED), hypocenter distance in km (HD), magnitude plus epicenter, and hypocenter distance (M + ED and M + HD). Study shows that proposed RDS correlates well with earthquake parameters with good correlation coefficient (R^2). Table 4 gives the summary of these correlations with 90% confidence intervals coefficients. Correlation between RDS and M, HD and M + HD has to be used with caution because some range of values of these correlations give two RDS values. Correlation between RDS and ED cannot be used to predict road damage level, due to absence of earthquake magnitude. Correlation between RDS and M + ED is reliable with high R^2 values. Further to forecast the road damages due to earthquakes, regression correlation between the new RDS and earthquake magnitude plus epicenter distance can be used. These correlations are more useful for vulnerability and risk assessment of roads and transportation networks.

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