Paper:

Development of Damage Functions on Road Infrastructures Subjected to Extreme Ground Excitations by Analyzing Damage in the 2011 off the Pacific Coast of Tohoku Earthquake

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Road infrastructure damage due to extreme ground excitations during the March 2011 Tohoku earthquake was assessed and 161 items of damage road structure data were classified into three types of failure modes: road surface and embankment damage items, road surface crack items and road subsidence items. We then compared a damage ratio, which is defined by the number of damage points divided by total road length, to the estimated spatial distribution of JMA instrumental seismic intensity. The maximum damage ratio for the 161 damage data items is 0.0290 points/km compared to a JMA instrumental seismic intensity of 5.8. Last, we developed damage functions for road infrastructures subjected to extreme ground excitations, which describe the relationship between the damage ratios and seismic intensity.

Keywords: the 2011 off the Pacific Coast of Tohoku earthquake, ground excitation, road infrastructure, JMA instrumental seismic intensity, damage function

1. Introduction

Road infrastructures were damaged severely during the 2011 Tohoku earthquake both by tsunamis, and by induced ground excitations. Researchers and practitioners have discussed the relationship between road infrastructure damage and extreme ground excitation indices. For instance, before the Tohoku earthquake, Onishi et al. [1] evaluated the relationship between expressway road damage and ground excitation indices, such as peak ground acceleration (*PGA*), peak ground velocity (*PGV*) and JMA instrumental seismic intensity (*IJ*), by analyzing damage data for four earthquakes, including the 1995 Hyogo-ken Nanbu earthquake. Yamazaki et al. [2] developed damage functions for expressways bridges based on bridge damage assessment for the Hyogo-ken Nanbu earthquake. Yamamura et al. [3] proposed road bridge damage functions dependent on *PGV* by analyzing damage data for 16 extreme earthquakes occurring in the 57 years between the 1946 Nankai earthquake and the 2003 Tokachi-oki earthquake. Maruyama et al. [4] revealed damage ratio features for road embankments for the 2004 Niigata-ken Chuetsu earthquake. Shoji et al. [5] clarified road infrastructure failure modes for the 2011 Tohoku earthquake by analyzing 522 damage data items. Research has been too limited, however, to compare damage to road infrastructures in exceedingly wide spatial areas to ground excitation indices for a huge plate-boundary earthquake such as the Tohoku earthquake. Damage estimation for regional road infrastructures that will be subjected to anticipated extreme ground excitation are therefore urgently required for implementing measures against future seismic disasters.

For the above reasons, we assessed road infrastructure damage in Tohoku prefectures, Tokyo metropolitan areas and six Kanto prefectures based on the extreme ground excitations seen in the 2011 Tohoku earthquake. We compared damage ratios to corresponding spatial distributions of JMA instrumental seismic intensity *IJ*, which is defined as the number of road damage points divided by exposed road length. We then developed road infrastructures damage functions for extreme ground excitation describing the relationship between damage ratio and JMA instrumental seismic intensity.

2. Analytical Method

2.1. Analyzed Data

Table 1 shows information on damaged road infrastructures that are depicted on related web sites by road management authorities and local government sectors. Shoji et al. [5] analyzed these references and made a database consisted of 522 damage data items on road infrastructures, excluding data items due to tsunamis and aftershocks after March 11, 2011, when the Tohoku earthquake hit. Selected road structures include national roads in six Tohoku prefectures, Tokyo metropolitan areas and

Table 1. References in collecting damage data on road infrastructures.

Road Management Sectors	Damage Information (URL)	Road Management Sectors	Damage Information (URL)
Tohoku Regional Development Bureau Main Office	【Disaster Prevention Information】(Press Release) Tohoku Regional Development Bureau Earthquake Information (15th Version) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1110.htm	Kanto Regional Development Bureau Omiya National Road Office	Road Damage Information in the 2011 off the Pacific Coast of Tohoku Earthquake (1st and 3rd Versions) http://www.ktr.mlit.go.jp/oomiya/04data/kisha/h22.htm
Tohoku Regional Development Bureau Iwate River and National Road Office	Earthquake Information : Iwate River and National Road Office (2nd and 3rd Versions) http://www.thr.mlit.go.jp/iwate/bousai/bousai/index.htm	Kanto Regional Development Bureau Shuto National Road Office	Damage of National Road No. 298 (18:50 on March 11) http://www.ktr.mlit.go.jp/syuto/index.htm
Tohoku Regional Development Bureau Sanriku National Road Office	Sanriku National Road Office Earthquake Information (2nd Version) http://www.thr.mlit.go.jp/sanriku/index.html	Kanto Regional Development Bureau Yokohama National Road Office	Damage Information in the 2011 off the Pacific Coast of Tohoku Earthquake (3rd Version) http://www.ktr.mlit.go.jp/yokohama/report/bn2010.htm
Tohoku Regional Development Bureau Sendai River and National Road Office	【Disaster Prevention Information】 (Press Release) Sendai River and National Road Office Disaster Information (3rd, 13th, and 14th Versions) http://www.thr.mlit.go.jp/sendai/index.html	Aomori Prefecture	Disaster Countermeasures Office about the Damage in the 2011 off the Pacific Coast of Tohoku Earthquake (43th Version) http://www.pref.aomori.lg.jp/
Tohoku Regional Development Bureau Yamagata River and National Road Office	【Disaster Prevention Information】 Yamagata River and National Road Office Earthquake Information (3rd, 4th, 6th, and 7th Versions) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1106.htm	Iwate Prefecture	Situation of Road Traffic Regulation Management due to the Earthquake in Iwate Prefecture on March 11 (As of 9:30 on August 12) http://www.pref.iwate.jp/list.rbz?nd=2974&ik=1&pnp=2974&of=13
Tohoku Regional Development Bureau Fukushima River and National Road Office	【Disaster Prevention Information】Fukushima River and National Road Office Earthquake Information (8th Version) http://www.thr.mlit.go.jp/fukushima/pressedit/disaster_index.html	Akita Prefecture	Earthquake Information (2nd, 4th, 5th, 6th, and 9th Versions) http://www.pref.akita.lg.jp/www/genre/0000000000000/1243242791775/index.html
Tohoku Regional Development Bureau Koriyama National Road Office	【Disaster Prevention Information】 Koriyama National Road Office : Emergency System Response in the 2011 off the Pacific Coast of Tohoku Earthquake (2nd, 8th, and 20th Versions) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1117.htm	Miyagi Prefecture	Traffic Regulation in the 2011 off the Pacific Coast of Tohoku Earthquake (As of 16:00 on May 8) http://www.pref.miyagi.jp/road/kiseinow.htm Damage of Public Facility and Emergency Disaster Recovery Situations in the 2011 off the Pacific Coast of Tohoku Earthquake (Updated August 10) http://www.pref.miyagi.jp/doboku/110311dbk_taiou/index.htm
Tohoku Regional Development Bureau Banjyo National Road Office	【Disaster Prevention Information】 Banjyo National Road Office : Road Disaster Prevention Information Earthquake (5th Version) http://www.thr.mlit.go.jp/bumon/kisya/saigai/sback/zokuhou1132.htm	Yamagata Prefecture	(Press Release) The 2011 off the Pacific Coast of Tohoku Earthquake (3rd and 10th Versions) http://www.pref.yamagata.jp/
Kanto Regional Development Bureau Main Office	Road Division at Kanto Regional Development Bureau Disaster Information of National Road in the 2011 off the Pacific Coast of Tohoku Earthquake (15:00 on March 18, 2011) http://www.ktr.mlit.go.jp/saigai/kyoku_dis00000021.html	East Nippon Expressway Company Limited	Damaged Routes and Sections (List) (March 18) http://www.e-nexco.co.jp/whatsnew/h22.html
Kanto Regional Development Bureau Hitachi River and National Road Office	Hitachi River and National Road Office (Press release) : Announcement for the Damage due to the 2011 off the Pacific Coast of Tohoku Earthquake (10:30 on March 12, 2011) http://www.ktr.mlit.go.jp/kisha/index00000022.html	Metropolitan Expressway Company Limited	(Press Release) Influence and Emergency Response due to the 2011 off the Pacific Coast of Tohoku Earthquake and Response (March 14, 2011) http://www.shutoko.jp/
Kanto Regional Development Bureau Utsunomiya National Road Office	Road Damage Information for the 2011 off the Pacific Coast of Tohoku Earthquake (17:00 on March 11, 18:30 on March 11, 12:00 on March 12) http://www.ktr.mlit.go.jp/utunomiya/bousai/old.htm	—	—

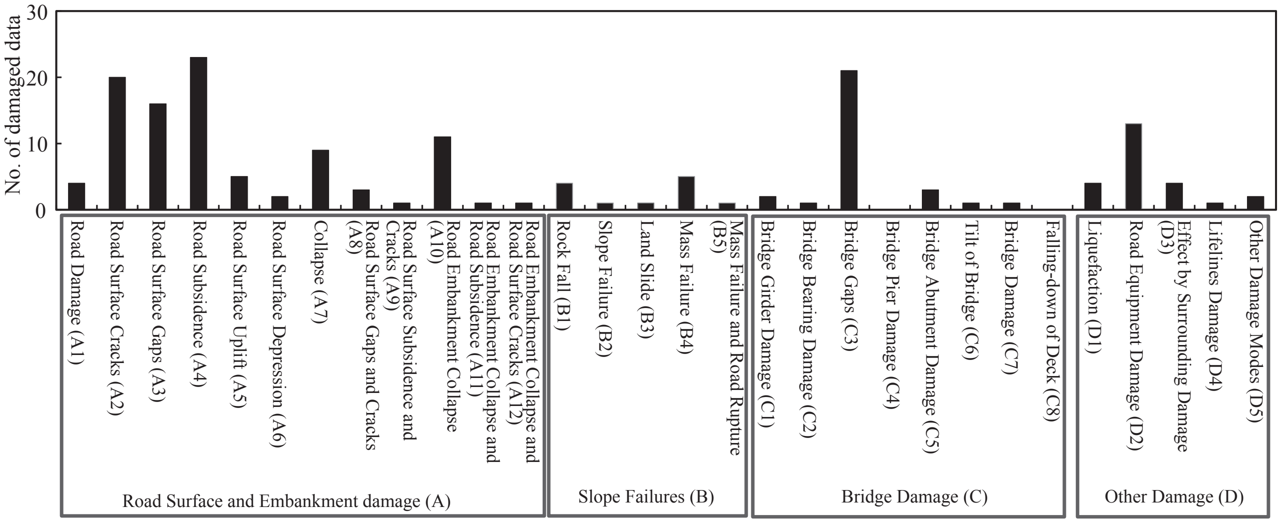
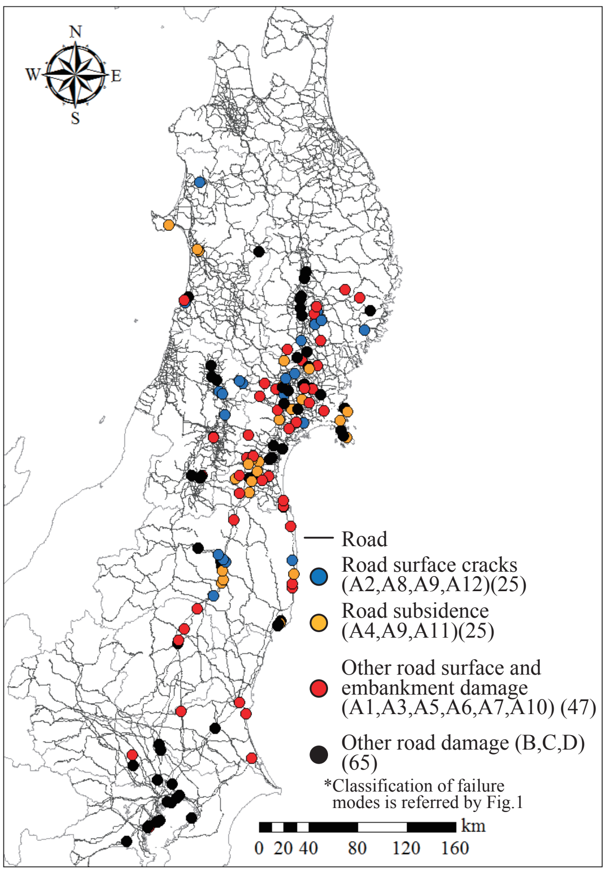
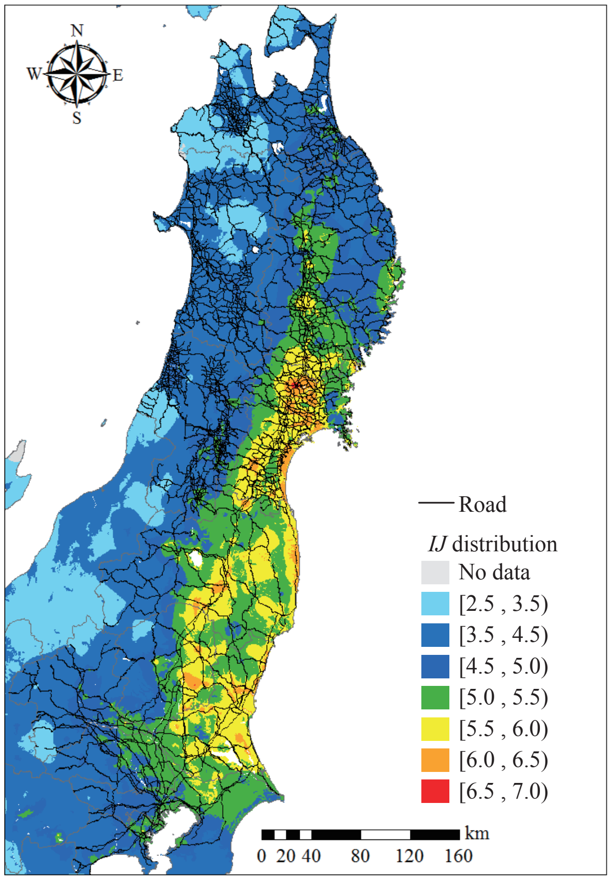


Fig. 1. Failure modes based on road damage data due to ground excitations.



(a) Road networks and road damage points assessed



(b) Roads and *IJ* spatial distribution

Fig. 2. Spatial distribution of analyzed data.

six Kanto prefectures managed by the Tohoku Regional Development Bureau, Kanto Regional Development Bureau, East Nippon Expressway Company Limited and Metropolitan Expressway Company Limited, together with prefectural roads in five Tohoku prefectures by local government sectors excluding Fukushima prefecture. Of 522 data items, the exact locations of 361 data items indicated by East Nippon Expressway Company Limited cannot be clarified because these items show the number of damage points between interchanges, so we omitted the 361 data items above and reconstructed 161 dataset items to be analyzed.

Figure 1 shows failure modes for 161 datasets. These modes are classified into independent 4 types of datasets:

96 road surface and embankment damage datasets, 12 slope failures damage datasets, 29 bridge damage datasets and 24 other damage mode datasets. In the next section, these 161 data are analyzed for computing damage ratio $\hat{R}_N$ and constructing damage functions. The 96 data road surface and embankment damage datasets are then focused on to clarify the dominant failures such as failure mode for road surface cracks based on a total of 25 data items unified dependently by road surface cracks (A2), road surface gaps and cracks (A8), road surface subsidence and cracks (A9) and road embankment collapse and road surface cracks (A12). A total of 25 data items is similarly unified dependently by road subsidence (A4), road surface subsidence and cracks (A9) and road embankment collapse and road subsidence (A11) are clarified as failure road subsidence mode, so the 96, 25 and 25 datasets are dependent on each other.

Exposed road networks including these road damage points are also modeled by Shoji et al. [5] for a total length of 29,655 km. Among exposed model networks, network data items in inundated areas [6] and managed by East Nippon Expressway Company are not considered for analysis. The total length of analyzed roads is 26,764 km. **Fig. 2** shows the spatial distribution of road networks analyzed.

2.2. Computation of Seismic Intensity *IJ* Spatial Distribution

In the analysis below, we use JMA instrumental seismic intensity IJ as a ground excitation index. **Fig. 2(b)** shows estimated spatial distribution with the 250 m mesh of IJ, based on simple kriging and derived by analyzing 573 waveforms observed by K-NET and KiK-net [7], 43 waveforms observed by JMA [8], 134 waveforms observed by NILIM [9], and 364 waveforms observed by JMA [8], including the 14 local government sectors of Aomori, Iwate, Miyagi, Yamagata, Fukushima, Ibaraki, Tochigi, Gunma, Saitama, Chiba, Kanagawa, Niigata, Yamanashi and Nagano prefecture. To estimate JMA instrumental seismic intensity IJ_b at a base layer with shear wave velocity V_s of 500 m/s, we use mean values derived by a parameter-fitted equation form in the same way as the equation describing the attenuation relationship proposed by Si and Midorikawa [10]. To estimate the amplification factor of seismic intensity IJ on the ground surface with seismic intensity IJ_b, the formulation proposed by Suetomi et al. [11] is used. We refer to the methods used by NIED [7], AIST [12] and Sakurai et al. [13]. We also verify our spatial distribution of IJ derived from the above procedures by using the same spatial distributions computed by NIED [7], JMA [8], Suetomi and Fukushima [14], and AIST [12], and confirmed good agreement among the results of this study and from other research.

In computing exposed road length and road damage points, we use spatial distribution at 0.1 intervals of IJ. Compared to exposed road length, minimum IJ is 2.5 and maximum IJ is 6.7 at Kurihara city in Miyagi prefecture.

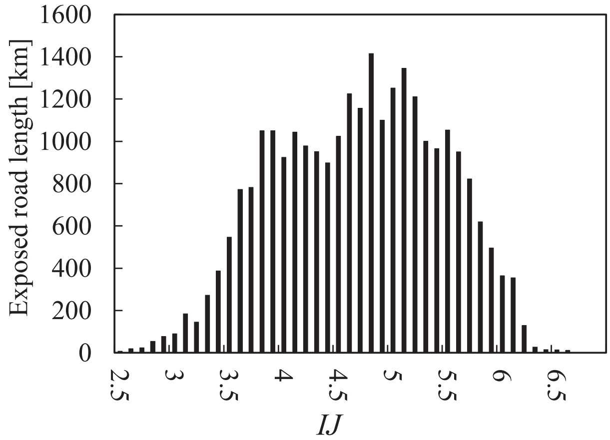


Fig. 3. Exposed road length compared to seismic intensity *IJ*.

Fig. 3 shows the relationship between exposed road length and IJ. The longest length is 1,415 km with IJ of 4.8. The exposed length for a seismic intensity scale of 4 is 9,002 km, 5,992 km for a scale of 5-lower, 5,775 km for 5-upper, 3,943 km for 6-lower, 893 km for 6-upper, and 28 km for 7.

2.3. Road Damage

We quantified road infrastructure damage by extreme ground excitations defined by ratio R_N [points/km] of number of road damage points N_p [point] divided by exposed road length L [km] as described in the following equation.

$$R_N = \frac{N_p}{L} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

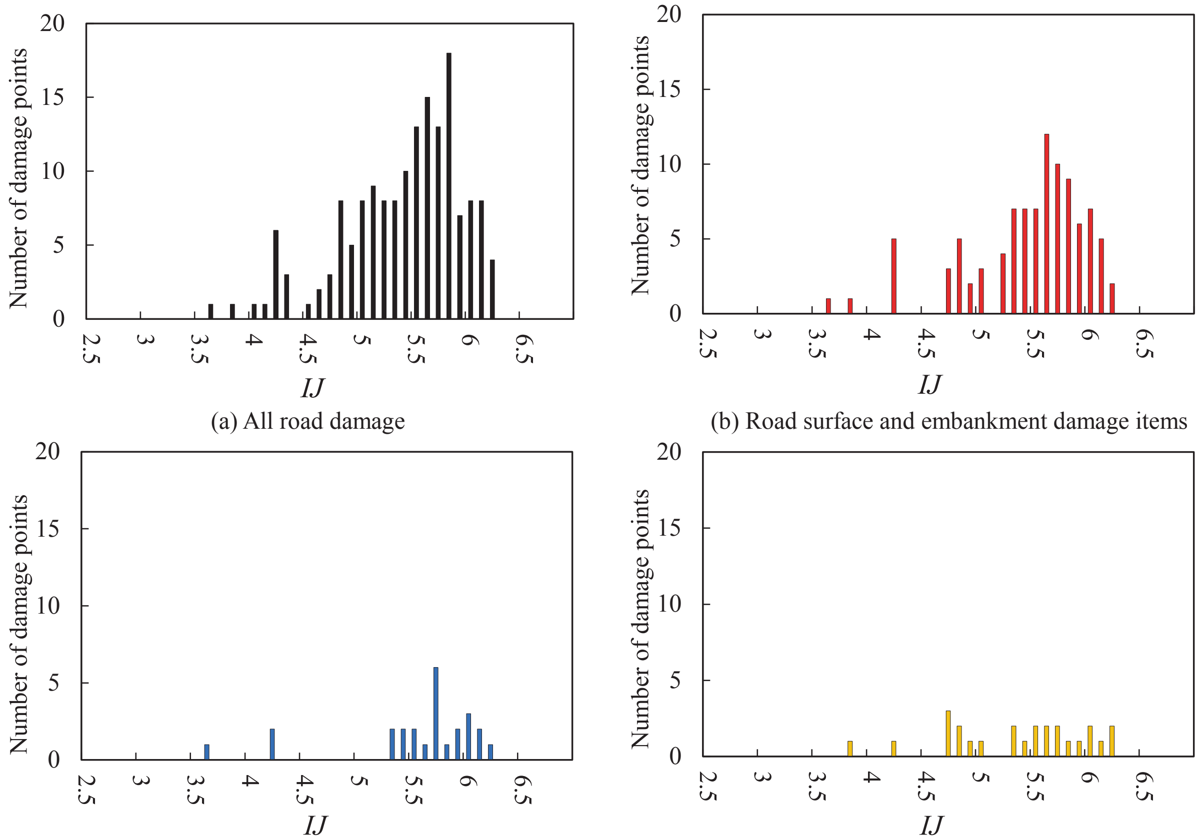
When damage ratio R_N was computed, datasets of N_p and L for each IJ class associated with L of less than 0.5% (equal to 133 km) compared to a total exposed road length of 26,764 km were removed from analyzed datasets because we use reliable data to compute damage ratio.

3. Road Damage Assessment

Figure 4 shows the frequency of the number of damage points compared to seismic intensity IJ for all road damage and for each dominant damage mode. **Fig. 5** shows the relationship between the damage ratio and IJ in modeling damage functions as derived in the section below.

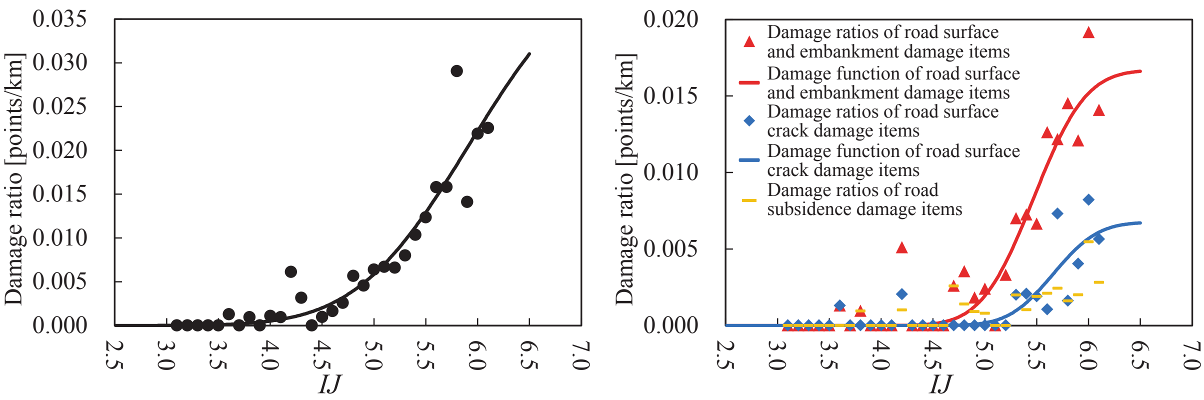
Figure 4(a) shows for all road damage that damage point N_p with IJ of less than 3.6 is 0.0. Damage point N_p with IJ of 5.8 shows the largest of 18 and N_p with IJ of 5.6 shows the second largest value of 15. **Fig. 5(a)** shows that actual damage ratio $\hat{R}_N$ with IJ of less than 4.2 has low value with less than 0.0011 [points/km]. Damage ratio $\hat{R}_N$ with IJ of 5.7 increases rapidly to 0.0158 [points/km] and $\hat{R}_N$ with IJ of 5.8 has the largest value of 0.0290 [points/km].

Figure 4(b) shows for 96 damage data points associated with road surface and embankment that damage point N_p with IJ of less than 3.6 is 0.0. Damage point N_p with



(a) All road damage
(b) Road surface and embankment damage items
(c) Road surface crack damage items
(d) Road subsidence damage items

Fig. 4. Frequency of the number of damage points compared to seismic intensity *IJ*.



(a) All road damage
(b) Each damage mode

Fig. 5. Relationship between damage ratio and seismic intensity *IJ*.

IJ of 5.6 has the largest value of 12 and N_p with *IJ* of 5.7 has the second largest of 10. **Fig. 5(b)** shows that actual damage ratio $\hat{R}_N$ with *IJ* of less than 5.2 has a low value with less than 0.0051 [points/km] but that $\hat{R}_N$ with *IJ* of 5.8 increases to 0.0145 [points/km] and $\hat{R}_N$ with *IJ* of 6.0 has the largest value of 0.0192 [points/km].

Figure 4(c) shows that for 25 damage data points on road surface cracks, damage point N_p with *IJ* of less than 3.6 has 0.0. Damage point N_p with *IJ* of 5.7 has the largest of 6 and N_p with *IJ* of 6.0 has the second largest of 3. **Fig. 5(b)** shows that actual damage ratio $\hat{R}_N$ with *IJ* of less than 5.5 has a low value of less than 0.0020 [points/km]. Damage ratio $\hat{R}_N$ with *IJ* of 5.7 increases gradually to 0.0073 [points/km] and $\hat{R}_N$ with *IJ* of 6.0 has the largest value of 0.0082 [points/km].

Similarly, **Fig. 4(d)** shows for 25 damage data points on road subsidence that damage point N_p with *IJ* of less than 3.8 is 0.0. Damage point N_p with *IJ* of 4.7 has the largest value of 3. **Fig. 5(b)** shows that actual damage ratio $\hat{R}_N$ with *IJ* of less than 5.7 has the low value with less than 0.0026 [points/km] and $\hat{R}_N$ with *IJ* of 6.0 has the largest of 0.0055 [points/km].

4. Damage Function Development

We developed three types of damage functions for all road damage modes, for road surface and embankment damage mode and for road surface cracks. We modeled observed data for actual damage ratio $\hat{R}_N$ as estimated damage ratio R_N by standard normal distribution function Φ multiplied by parameter C as shown in the following equation:

$$R_N = C\Phi\left(\frac{IJ-\mu}{\sigma}\right) \quad \ldots\ldots\ldots\ldots (2)$$

where C, μ, and σ are regression coefficients determined by iterative least squares estimation with an initial value setting of 1.0 for all parameters with minimizing objective function ε as described in the following equation:

$$\varepsilon = \sum_j \left(R_N^j - \hat{R}_N^j\right) L^j \quad \ldots\ldots\ldots\ldots (3)$$

where j is the number of a class at a 0.1 interval of IJ; L_j is exposed road length for the j $^{\text{th}}$ class of IJ. Last, we developed the damage functions as shown in the following three equations:

(i) For all road damage:

$$R_N = 0.0412\Phi\left(\frac{IJ-5.9}{0.9}\right) \quad \ldots\ldots\ldots (4a)$$

(ii) For road surface and embankment damage:

$$R_N = 0.0166\Phi\left(\frac{IJ-5.5}{0.4}\right) \quad \ldots\ldots\ldots (4b)$$

(iii) For road surface cracks:

$$R_N = 0.0067\Phi\left(\frac{IJ-5.7}{0.3}\right) \quad \ldots\ldots\ldots (4c)$$

Damage functions could not be derived for road subsidence because of the low accuracy of computational convergence for ε by Eq. (3) in higher range of IJ. **Table 2** shows individual damage function parameters.

Table 2. Regressed parameters for damage functions.

	C	μ	σ
All road damage	0.0412	5.9	0.9
Road surface and embankment damage	0.0166	5.5	0.4
Road surface cracks	0.0067	5.7	0.3

5. Conclusions

We have analyzed 161 damage data items on road infrastructures subjected to extreme ground excitations in the 2011 Tohoku earthquake. These 161 data items have been classified into three types of failure modes: road surface and embankment damage, road surface crack damage and road subsidence. A damage ratio that is defined by the number of damaged points divided by total road length has been compared to estimated spatial distribution of JMA instrumental seismic intensity. Based on damage ratio assessment, damage functions of road infrastructures subjected to extreme ground excitations, which describe the relationship between damage ratio and seismic intensity, have been derived for all road damage modes, road surface and embankment damage, and road surface cracks. These damage functions efficiently describe damage to road infrastructures distributed in exceedingly wide spatial areas for a huge plate-boundary earthquake such as the Tohoku earthquake, so we could implement proposed damage functions for estimating damage ratios of regional road infrastructures exposed by anticipated huge earthquakes such as the Nankai trough earthquake.

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