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DAMAGE ASSESSMENT ON ELECTRIC POWER FAILURES DURING THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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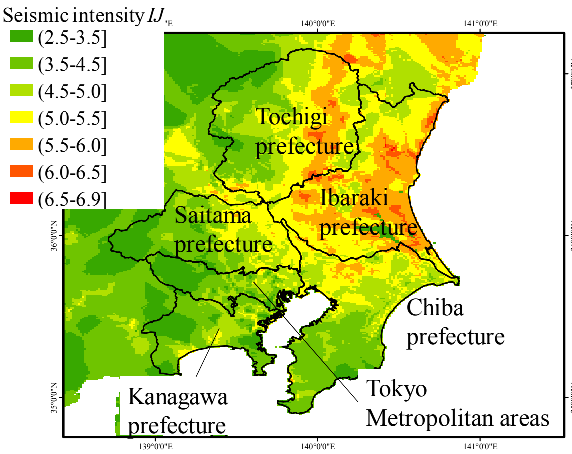
ABSTRACT: We collected the data by surveying the related web sites on power failures during the 2011 off the Pacific Coast of Tohoku earthquake for Kanto areas, and by interviewing to the local government sectors and TEPCO branch offices. We quantify two damage ratios on power failures for subject cities and towns defined by the ratio of the number of affected households and houses at a city by the number of the related households and houses. The dependency of the damage ratios on induced seismic intensities is revealed. The related damage functions with power failures are developed.

Key Words: The 2011 off the Pacific Coast of Tohoku earthquake, electric power failure, damage ratio, damage function

INTRODUCTION

The 2011 off the Pacific Coast of Tohoku earthquake caused severe damage on lifeline systems such as water treatments, energy supply systems, communication networks and transportation facilities. Among them, electric power failures occur at maximumly 4,858,580 houses in the areas offered by Tohoku Electric Power Company as of March 17, 2011 (Tohoku Electric Power Company, Inc. 2011) and at maximumly 4,050,000 houses in the areas offered by Tokyo Electric Power Company as of March 11, 2011 (Tokyo Electric Power Company, Inc. 2011). In the past severe earthquakes, electric power failures occurred: at maximumly 1,600,000 houses in the 1995 Kobe earthquake (Editorial Committee for the Report on the Hanshin-Awaji Earthquake Disaster 1997), at maximumly 280,000 houses in the 2004 Niigata-ken Chuetsu earthquake (Hashimoto 2004), at maximumly 35,344 houses in the 2007 Niigata-ken Chuetsu-oki earthquake (Cabinet Office, Government of Japan 2007), and at 29,320 houses in the 2008 Iwate-Miyagi earthquake (Joint Research Committee of Four Societies in Tohoku Regions on the Iwate-Miyagi Earthquake 2009). The damage assessment for these power failures is significant to implement the associated data for risk assessment on power failures



Ibaraki: 32 cities, 10 towns and 2 villages
Tochigi: 14 cities and 12 towns
Chiba: 36 cities, 17 towns,1 village and 6 wards
Saitama: 39 cities, 23 towns,1 village and 10 wards
Tokyo: 25 cities, 2 towns,1village and 23 wards
Kanagawa:19 cities,13 towns, 1 village and 28 wards

Fig. 1 Subject cities and towns, and spatial distribution of seismic intensity *IJ*

and induced consequences at a hazardous region for the future disaster prevention. From the reason above, we analyze damage on electric power failures during the 2011 off the Pacific Coast of Tohoku earthquake for cities and towns at Ibaraki, Tochigi, Chiba, Saitama and Kanagawa prefectures and Tokyo Metropolitan areas.

METHOD OF THE SURVEY

We survey the related web sites on power failures during the 2011 off the Pacific Coast of Tohoku earthquake for cities and towns at Ibaraki, Tochigi, Chiba, Saitama and Kanagawa prefectures and Tokyo Metropolitan areas, and we interview to the local government sectors and TEPCO branch offices. The total number of subject cities and towns is 315: 32 cities, 10 towns, and 2 villages at Ibaraki, 14 cities and 12 towns at Tochigi, 36 cities, 17 towns, 1 village and 6 wards at Chiba, 39 cities, 23 towns, 1 village and 10 wards at Saitama, 25 cities, 2 towns, 1 village and 23 wards at Tokyo Metropolitan areas, 19 cities, 13 towns, 1 village and 28 wards at Kanagawa as shown in Fig. 1.

INDICES FOR THE ANALYSIS

Based on collected data, we analyze whether power failures occurred or not, the number of households and houses affected by power failures at a city i N^{PF}_i and the restoration periods D_{RP}. We quantify the relative frequency f^R_{PF} defined as the ratio of the number of affected cities and towns divided by total number of subject cities and towns at a same class for seismic intensity *IJ*. In addition, we quantify two damage ratios R^h_i and R^c_i at a city i, defined as the ratio of the number of affected households and houses N^{PF}_i divided by the number of households N^h_i and houses N^c_i as the following equations,

$$R_i^h = \frac{N_i^{PF}}{N_i^h} \tag{1}$$

$$R_i^c = \frac{N_i^{PF}}{N_i^c} \tag{2}$$

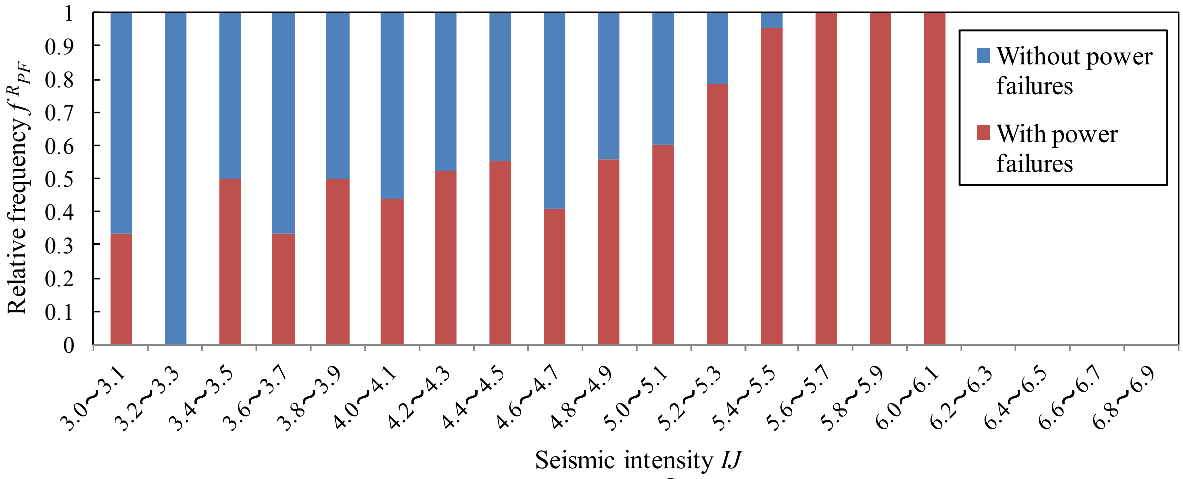


Fig. 2 Relation of relative frequency f^{R}_{PF} with seismic intensity *IJ*

Table 1 Frequency of affected cities and towns by power failures with seismic intensity *IJ* and cumulative probability P_f of occurrence of power failures with *IJ*

Seismic intensity *IJ*	Frequency		Cumulative probability
	With power failures	Without power failures	With power failures
3.5～4.4	19	10	0.34
4.5～4.9	40	29	0.42
5.0～5.4	42	70	0.63
5.5～5.9	6	44	0.88
6.0～6.4	0	37	1.00
6.5～	0	5	1.00
Summation	107	195	-

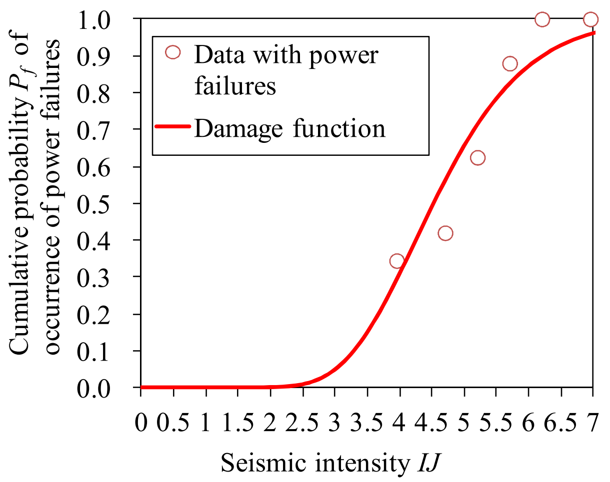


Fig. 3 Damage function on occurrence of power failures

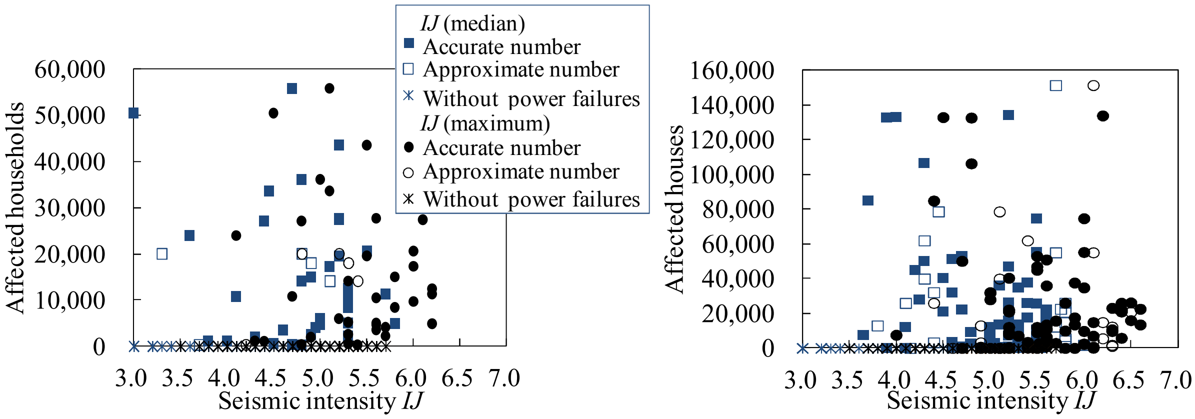
Table 2 Identified parameters of damage function on occurrence of power failures

Inclination	4.09
Intercept	-6.22
Coefficient of determination	0.83
Parameter λ	1.52
Parameter ζ	0.24
Mean μ_x	4.72
Standard deviation σ_x	1.38
Median $\widetilde{m}_x$	4.58

DAMAGE ASSESSMENT ON POWER FAILURES

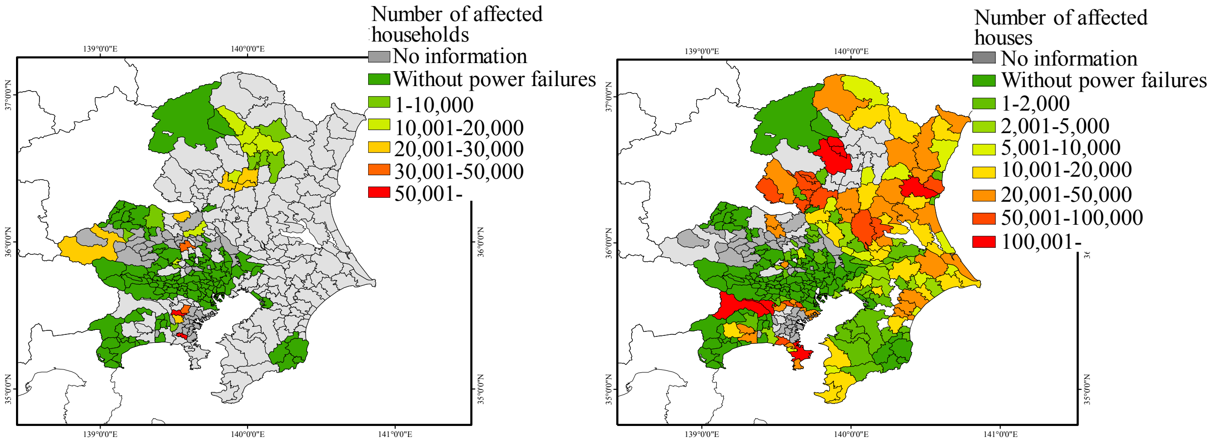
Analysis on occurrence of power failures

Fig. 2 shows the relation of relative frequency f^{R}_{PF} with seismic intensity *IJ*. Now, we use median of



(a) Affected households (b) Affected houses

Fig. 4 Relation of the number of affected households and houses N^{PF}_i at a city *i* with seismic intensity *IJ*



(a) Affected households (b) Affected houses

Fig. 5 Spatial distribution on the number of affected households and houses N^{PF}_i

seismic intensity *IJ* for a city *i*. f^R_{PF} shows 0.33 at *IJ* of 3.0 - 3.1. f^R_{PF} increases to 0.50 - 0.60 at *IJ* of 3.2 to 5.1 although f^R_{PF} shows zero at *IJ* of 3.2-3.3, 0.33 at *IJ* of 3.6 - 3.7 and 0.44 at *IJ* of 4.0 - 4.1. f^R_{PF} increases to 0.78 - 1.00 at *IJ* of 5.2 to 6.1.

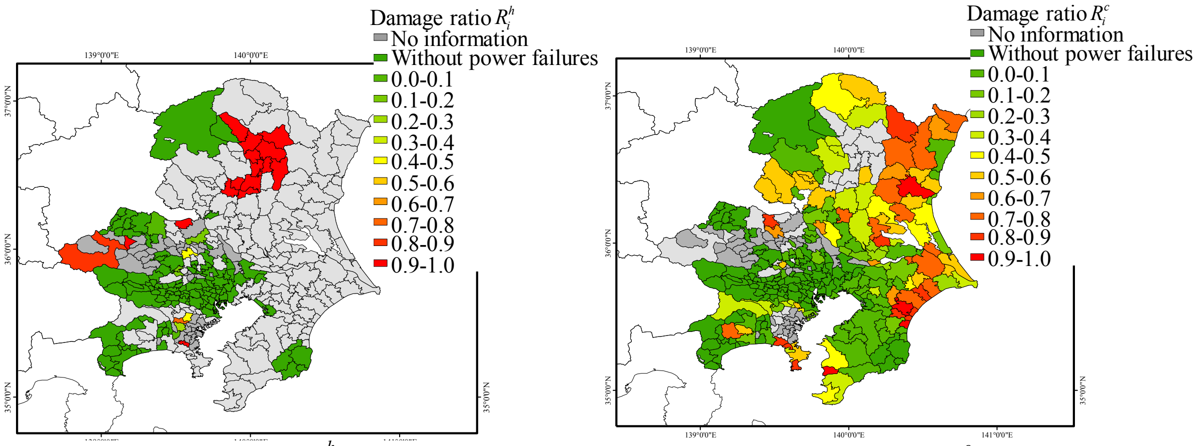
Table 1 shows the frequency of affected cities and towns by power failures with seismic intensity *IJ* and cumulative probability P_f of occurrence of power failures with *IJ*. Based on the data, we derive the damage function idealized by logarithmic distribution as shown in the following equation,

$$P_f = \int_0^x \frac{1}{\sqrt{2\pi}\cdot\zeta\cdot x}\exp\left\{-\frac{1}{2}\left(\frac{\ln x-\lambda}{\zeta}\right)\right\}dx \qquad (3)$$

where λ and ζ are parameters describing logarithmic distribution. Random variable *X* is a seismic intensity *IJ*. Fig. 3 shows the derived damage function and Table 2 shows the related parameters.

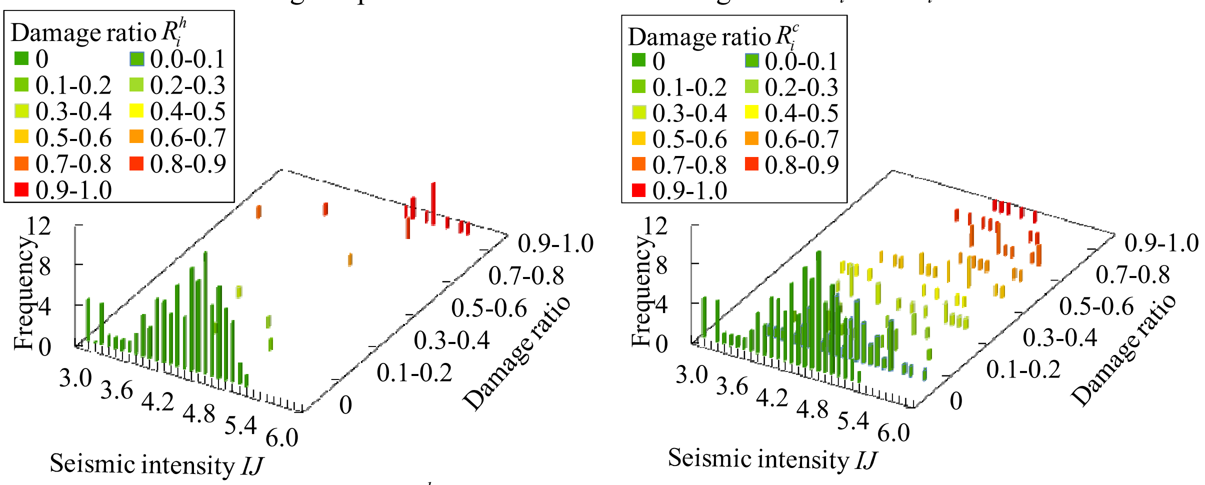
Analysis on the number of affected households and houses

Fig. 4 shows the relation of the number of affected households and houses N^{PF}_i at a city *i* with seismic intensity *IJ*. In analyzing the data, we use median and maximum values of seismic intensity *IJ* for a city *i*. From Fig. 4(a), we select most influenced city and ward for each prefecture: 27,291 households at Moka city (*IJ*=5.2) in Tochigi prefecture, 43,406 households at Kounosu city (*IJ*=5.1) in Saitama



(a) Damage ratio R^h_i (b) Damage ratio R^c_i

Fig. 6 Spatial distribution on the damage ratio R^h_i and R^c_i



(a) Frequency on R^h_i (b) Frequency on R^c_i

Fig. 7 Frequency of damage ratios R^h_i and R^c_i with seismic intensity *IJ*

prefecture and 55,700 households at Midori ward (*IJ*=4.7) in Yokohama city. From Fig. 4(b), we select most influenced city for each prefecture: 151,517 houses at Mito city (*IJ*=5.7) in Ibaraki prefecture, 134,000houses at Utsunomiya city (*IJ*=5.2) in Tochigi prefecture, 47,000 houses at Gyoda city (*IJ*=5.2) in Saitama prefecture, 36,567 houses at Katori city (*IJ*=5.2) in Chiba prefecture, 106,400 houses at Machida city (*IJ*=4.3) in Tokyo Metropolitan areas and 133,037 houses at Yokosuka city (*IJ*=4.0) in Kanagawa prefecture.

Fig. 5 shows spatial distribution on the number of affected households and houses N^{PF}_i. From Fig. 5(a), N^{PF}_i for Midori ward and Sakae ward at Yokohama city show larger values over 50,000 households. From Fig. 5(b), N^{PF}_i for 12 cities and towns at Ibaraki prefecture and 7 cities and towns at Tochigi prefecture show larger values over 20,000 houses. N^{PF}_i for 2 cities at Saitama prefecture and 3 cities and towns at Chiba prefecture also show larger values over 20,000 houses. N^{PF}_i for the boundary regions between Tokyo metropolitan areas and Kanagawa show over 100,000 houses.

Fig. 6 shows spatial distribution on the damage ratios R^h_i and R^c_i. From Fig. 6(a), R^h_i for eastern areas in Tochigi prefecture show higher values over 0.9. R^h_i for western areas in Saitama prefecture show higher values over 0.7. R^h_i for Midori ward and Sakae ward in Yokohama city show higher values over 0.7. From Fig. 6(b), R^c_i for 21 cities and towns in Ibaraki prefecture and 12 cities and towns at Chiba prefecture show higher values over 0.6.

Fig. 7 shows frequency of damage ratios R^h_i and R^c_i with seismic intensity *IJ*. We use median of seismic intensity *IJ*. From Fig. 7(a), frequency of R^h_i of 0.0 to 0.4 becomes high at *IJ* of 3.0 to 4.5 whereas frequency of R^h_i of 0.7 to 0.8 becomes low at the same range of *IJ*. Frequency of R^h_i over 0.8 becomes high at *IJ* over 4.7. From Fig. 7(b), frequency of R^c_i of 0.0 to 0.6 becomes high at *IJ* of 3.0 to

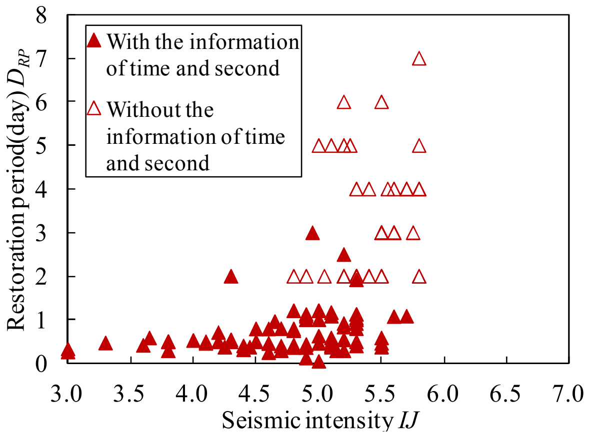


Fig. 8 Relation of the restoration periods D_{RP}

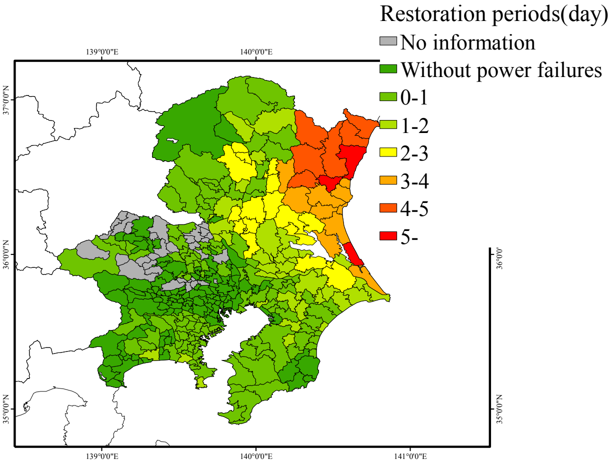


Fig. 9 Spatial distribution on restoration periods D_{RP} with seismic intensity IJ

Table 3 Frequency of affected cities and towns for restoration periods D_{RP} with seismic intensity IJ and cumulative probabilities on restoration periods D_{RP} with IJ

Restoration period D_{RP} (days)	Frequency(Seismic intensity IJ)					Cumulative probability			
	IJ=7	IJ=6 higher	IJ=6 lower	IJ=5 higher	≤IJ=4.9	≥IJ=6.5	≥IJ=6.0	≥IJ=5.5	≥IJ=5.0
0～0.25	0	0	8	42	59	0.00	0.00	0.07	0.46
0.25～0.5	0	1	7	19	16	0.00	0.02	0.19	0.63
0.51～1.0	0	3	12	0	1	0.00	0.19	0.94	0.94
1.01～1.5	1	2	4	4	0	0.09	0.27	0.64	1.00
1.51～2.0	0	6	10	4	0	0.00	0.30	0.80	1.00
2.01～2.5	0	1	0	0	0	0.00	1.00	1.00	1.00
2.51～3.0	0	10	1	0	0	0.00	0.91	1.00	1.00
3.01～3.5	0	0	0	0	0	–	–	–	–
3.51～4.0	0	7	3	0	0	0.00	0.70	1.00	1.00
4.01～4.5	0	0	0	0	0	–	–	–	–
4.51～5.0	4	1	1	0	0	0.67	0.83	1.00	1.00
5.01～5.5	0	0	0	0	0	–	–	–	–
5.51～6.0	0	2	0	0	0	0.00	1.00	1.00	1.00
6.01～6.5	0	0	0	0	0	–	–	–	–
6.51～7.0	0	1	0	0	0	0.00	1.00	1.00	1.00
Summation	5	34	46	69	76	–	–	–	–

4.7 whereas frequency of R^c_i of 0.6 to 0.9 becomes low at the same range of IJ. Frequency of R^c_i over 0.6 becomes high at IJ over 4.8

Analysis on the restoration periods D_{RP}

Fig. 8 shows relation of the restoration periods D_{RP} with seismic intensity IJ. Fig. 9 shows spatial distribution on the restoration periods D_{RP}. We use median of seismic intensity IJ. From Fig. 8, D_{RP} for cities and towns at IJ of 3.0 to 4.5 show 0.3 days to 0.7 days, that is nearly half a day. D_{RP} for Funabashi city and Sakura city in Chiba at IJ over 4.5 show 1 day, D_{RP} for Oamishirosato town in Chiba at IJ of 4.7 shows 2 days and D_{RP} for Daigo town in Tochigi at IJ of 5.0 shows 5 days. Moreover, we select most influenced city and town for each prefecture: 7 days at Kashima city (IJ=5.8) in Ibaraki, 4 days at Mogi town (IJ=5.8) in Tochigi, 0.6 days at Kounosu city (IJ=5.2) in Saitama, 3 days at

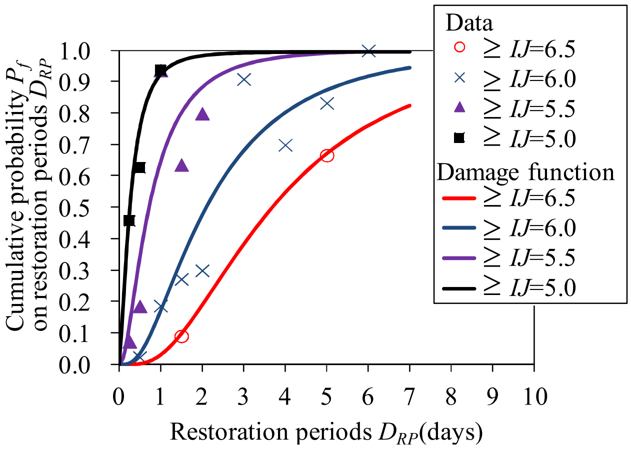


Fig. 10 Damage function on restoration periods D_{RP} with seismic intensity IJ

Table 4 Identified parameters of damage function on restoration periods D_{RP} with seismic intensity IJ

	≥ IJ=6.5	≥ IJ=6.0	≥ IJ=5.5	≥ IJ=5.0
Inclination	1.47	1.33	1.20	1.18
Intercept	-1.94	-1.01	0.31	1.40
Coefficient of determination	1.00	0.86	0.42	1.00
Parameter λ	1.32	0.76	-0.26	-1.19
Parameter ζ	0.68	0.75	0.83	0.85
Mean μ_x	4.70	2.85	1.09	0.44
Standard deviation σ_x	13.02	6.22	1.19	0.20
Median $\tilde{m}_x$	3.73	2.15	0.77	0.30

Katori city (IJ=5.2) in Chiba, 0.5 days at Machida city (IJ=4.3) in Tokyo Metropolitan areas, 2 days at Miura city (IJ=4.1), Kamakura city (IJ=3.7), Hayama town (IJ=3.7) and Hiratsuka city (IJ=4.7) in Kanagawa.

From Fig. 9, D_{RP} for northern areas and coastal areas at Ibaraki prefecture show over 4 days which is longer than other areas. On the other hand, D_{RP} for the areas at Saitama prefecture and Kanagawa prefecture show within 1 day which is relatively shorter.

Table 3 shows the frequency of affected cities and towns for restoration periods D_{RP} with seismic intensity IJ and cumulative probabilities on restoration periods D_{RP} with IJ. As well as the damage function on occurrence of power failures in Fig. 3, we derive the damage function on restoration periods D_{RP} with seismic intensity IJ idealized by same model as Eq. (3). Fig. 10 shows the derived damage function and Table 4 shows the related parameters.

CONCLUSIONS

We surveyed the related web sites on power failures during the 2011 off the Pacific Coast of Tohoku earthquake for cities and towns at Ibaraki, Tochigi, Chiba, Saitama and Kanagawa prefectures and Tokyo Metropolitan areas, and we interviewed to the local government sectors and TEPCO branch offices. Based on the data, we quantified the relative frequency f^{R}_{PF} defined as the ratio of the number of affected cities and towns divided by the total number of subject cities and towns for seismic intensity IJ. In addition, we quantify two damage ratios R^h_i and R^c_i at a city i, defined as the ratio of the number of affected households and houses N^{PF}_i divided by the number of households N^h_i and houses N^c_i. The following conclusions are deduced.

1) Relative frequency f^{R}_{PF} shows 0.33 at IJ of 3.0-3.1. f^{R}_{PF} increases to 0.50-0.60 at IJ of 3.2 to 5.1 although f^{R}_{PF} shows zero at IJ of 3.2-3.3, 0.33 at IJ of 3.6-3.7 and 0.44 at IJ of 4.0-4.1. f^{R}_{PF} increases to 0.78-1.00 at IJ of 5.2 to 6.1. Based on the trend, we developed damage function on occurrence of power failures.
2) Number of affected households and houses N^{PF}_i for Midori ward and Sakae ward in Yokohama city show large values over 50,000 households. N^{PF}_i for 12 cities and towns in Ibaraki prefecture and 7 cities and towns in Tochigi prefecture show larger values over 20,000 houses. N^{PF}_i for 2 cities in Saitama prefecture and 3 cities and towns in Chiba prefecture also show larger values over 20,000 houses. N^{PF}_i for the boundary regions between Tokyo metropolitan areas and Kanagawa prefecture show the values over 100,000 houses.

3) Damage ratio $R^h{}_i$ for eastern areas in Tochigi prefecture show higher values over 0.9. $R^h{}_i$ for western areas in Saitama prefecture show higher values over 0.7. $R^h{}_i$ for Midori ward and Sakae ward in Yokohama city show higher values over 0.7. Damage ratio $R^c{}_i$ for 21 cities and towns in Ibaraki prefecture and 12 cities and towns in Chiba prefecture show values over 0.6.

4) Restoration periods D_{RP} at IJ of 3.0 to 4.5 show 0.3 days to 0.7 days, that is nearly half a day. D_{RP} for two cities at IJ over 4.5 show 1 day, D_{RP} for a town at IJ of 4.7 shows 2 days and D_{RP} for a city at IJ of 5.0 shows 5 days. Moreover maximum value of D_{RP} for Kashima city in Ibaraki prefecture at IJ over 5.0 shows 7 days. D_{RP} for northern areas and coastal areas at Ibaraki prefecture show over 4 days which is longer than the other areas. On the other hand, D_{RP} for the areas at Saitama prefecture and Kanagawa prefecture show within 1 day which is relatively shorter. Based on the trend, we developed damage function on restoration period D_{RP} with seismic intensity IJ

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