Probabilistic aftershock occurrence model based on the 2011 Tohoku earthquake data

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SUMMARY:
After an occurrence of a large earthquake, aftershocks occur subsequently in a wide region. When aftershocks occur, problems arise such as secondary damage or delay of recovery activity. In addition, the region where intensity of shaking due to aftershocks becomes bigger than that due to a main shock exists, which were reported in the past earthquakes. Therefore, it is necessary to evaluate the seismic risk due to aftershocks. In this study, using aftershocks data obtained in the events of the 2011 Tohoku earthquake and of other historical large earthquakes, the spatial and temporal distribution of aftershock occurrence is investigated and modeled based on the Gutenberg-Richter law and the Modified Omori's law. Then, a probabilistic aftershock occurrence model to predict the aftershocks of future large earthquakes is proposed.

Keywords: the 2011 Tohoku earthquake, aftershock, probabilistic model

1. INTRODUCTION

The 2011 Tohoku earthquake occurred on March 11, 2011. Its earthquake magnitude was 9.0, which is the largest magnitude since the modern observation started in Japan. More than ten thousands aftershocks within the wide region following the main shock were observed by the end of June, 2011, including aftershocks with magnitude more than 7.0.
In this study, a new probabilistic aftershock occurrence model is proposed, which can be used for prediction of aftershocks of future large earthquakes. Most of past researches have focused on the risk due to main shocks while few researches have been conducted on aftershock risk. In practice, however, the buildings damaged due to a main shock have the potential to be progressively damaged by a series of aftershocks. Therefore, it is also necessary to evaluate the seismic risk due to aftershocks, which may occur closer to a building site than the main shock occurs. In addition, adequate emergency response and command associated with evacuation or recovery activity during many aftershocks just after a main shock would be one of objectives of this study, which is recognized important during those activities after the 2011 Tohoku earthquake.

2. TWO EMPIRICAL MODELS FOR OCCURRENCE OF AFTERSHOCKS

2.1. The Gutenberg-Richter law

It is assumed in this study that the relationship between the magnitude of aftershocks and frequency of the aftershocks can be expressed by the Gutenberg-Richter (GR) law and the relationship between the time elapsed after the main shock and the occurrence rate of aftershocks follows the modified Omori's (MO) law. Using the above two laws with some necessary modifications, this study constructs a new probabilistic occurrence model of aftershocks based on the aftershock data of past large earthquakes.
It is known that there is less occurrence frequency for larger earthquakes. It can be well expressed by the Gutenberg-Richter law (Gutenberg-Richter, 1944) as follows:

$$\log N = a - bM \quad (2.1)$$

where *M* is the earthquake magnitude, *N* is the total number of earthquakes equal to and more than *M*, and *a* and *b* are constants. *a* is proportional to the occurrence of earthquakes, and *b* describes the size distribution of earthquakes. GR law is mainly used for main shocks, but it is also applied to aftershocks.

2.2. The Modified Omori's law

The modified Omori's law (Utsu, 1969) describes the decay of aftershocks activity with time as follows:

$$n(t) = \frac{K}{(t+c)^p} \quad \left(t[day] = 1, 2, 3 \cdots\right) \quad (2.2)$$

where *t* is the time elapsed after the main shock occurs, *n*(*t*) is the number per unit time of the aftershocks with magnitude *M* or larger, and *K*, *p* and *c* are constants. *K* is the amplitude, *p* is a decay rate of aftershocks, and *c*, the "time offset" parameter, which is assumed 0.1 in this study.

3. EARTHQUAKE DATA

To construct an aftershock model for future large earthquakes, historical earthquakes are compiled, which includes the 2011 Tohoku earthquake, the 2004 Sumatra earthquake and the 2003 Tokachioki earthquake. In this study, aftershock is defined in a limited sense as an earthquake which occurs subsequently within 90 days in the rupture area of a main shock.

3.1. The 2011 Tohoku Earthquake

The fault model by Geospatial Information Authority of Japan (GSI, 2011) is used as an aftershock area of the 2011 Tohoku Earthquake, and hypocenter data of Japan Meteorological Agency is used. The target period is from March 11, 2011. to June 9, 2011. Earthquakes are selected, on the condition that the focal depth is shallower than 100km, and magnitude (M_J) is larger than or equal to 4.0. Spatial distribution of the main shock and aftershocks are shown in Figure 1.

3.2. The 2004 Sumatra Earthquake

The fault model by Geospatial Information Authority of Japan (GSI, 2008) is used as an aftershock area of the 2004 Sumatra Earthquake. Earthquake list provided by U.S. Geological Survey (USGS) is used. Earthquakes are selected, on the condition that it occurred from December 26, 2004 to March 26, 2005, and the focal depth is shallower than 100km, and target magnitude (M_w) is greater than or equal to 4.0. Spatial distribution of the main shock and aftershocks are shown in Figure 2.

3.3. The 2003 Tokachioki Earthquake

The fault model by Yagi (2004) is used as an aftershock area of the 2003 Tokachioki Earthquake, and hypocenter data of Japan Meteorological Agency is used. The target period is from September 26, 2003 to December 25, 2003, and the focal depth is shallower than 100km, and target magnitude (M_J) is larger than or equal to 4.0. Spatial distribution of the main shock and aftershocks are shown in Figure 3.

3.4. Other Earthquakes

The aftershock area of other earthquakes is assumed to be a circular region in which centers on the main shock hypocenter. And earthquakes which occur in aftershock area of the Equation (3.1) within 90 days after main shock occur are used as aftershocks of the other earthquake, and hypocenter data of Japan Meteorological Agency is used.

$$\log A = M_m - 3.2 \tag{3.1}$$

And the focal depth is shallower than 100km, and target magnitude is 4.0 and more. Spatial distribution of the main shock and aftershocks are shown in Figure 4.

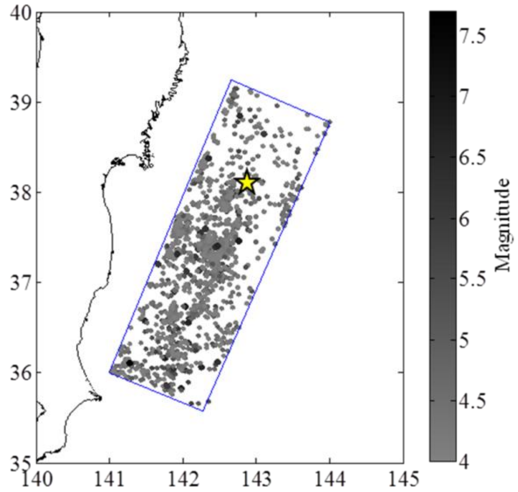

Figure 1. The 2011 Tohoku Earthquake

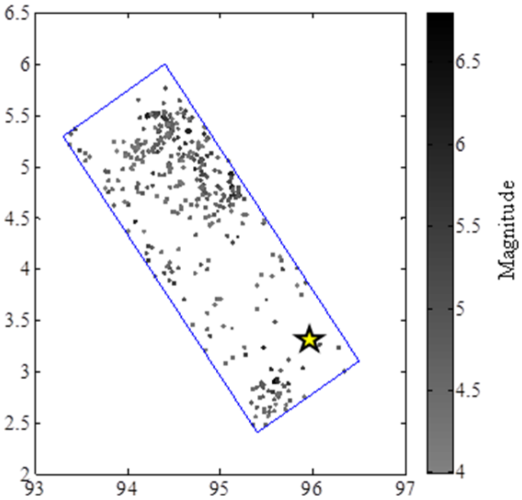

Figure 2. The 2004 Sumatra Earthquake

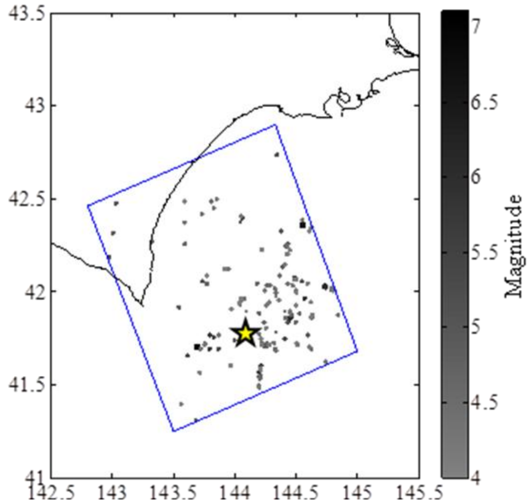

Figure 3. The 2003 Tokachioki Earthquake

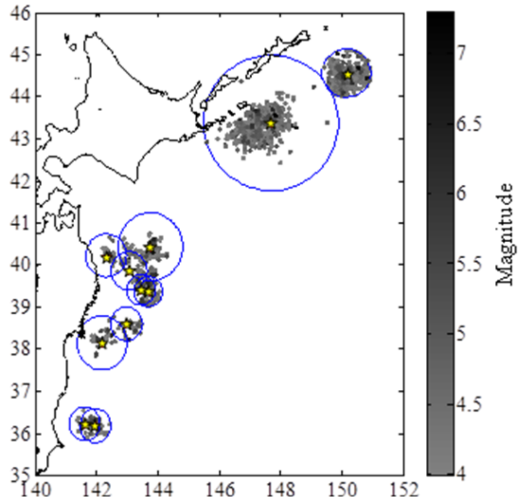

Figure 4. Other earthquakes

4. ANALYSIS OF AFTERSHOCKS

4.1. Application of GR Law and MO Law to aftershocks

Applicability of GR law and MO law to the aftershocks of past large earthquakes is examined, including the 2011 Tohoku earthquake and an occurrence model of aftershock is derived. Aftershocks of the 2011 Tohoku earthquake and aftershocks of the past large earthquakes are modeled by GR law and MO law, and it is shown in Figures 5 and 6. It is confirmed that GR law and MO law are almost applicable to aftershocks from these analysis. The obtained parameters for GR law and MO law are shown in Table 1. Then, the relations of various parameters and the main shock magnitude of a past earthquake are derived, and it is shown in Figures 7 to 10.

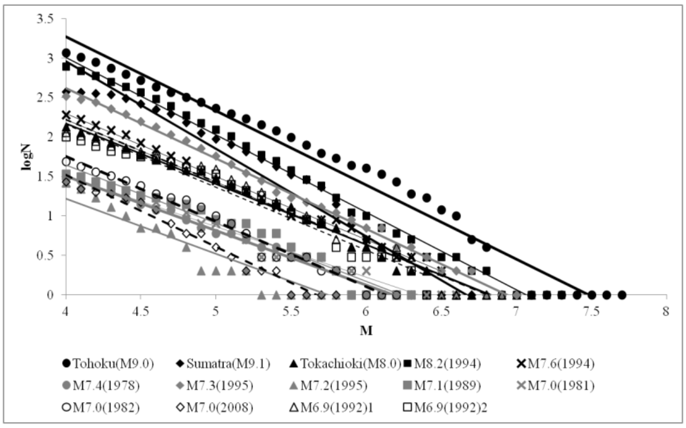

Figure 5. GR law in all aftershock data

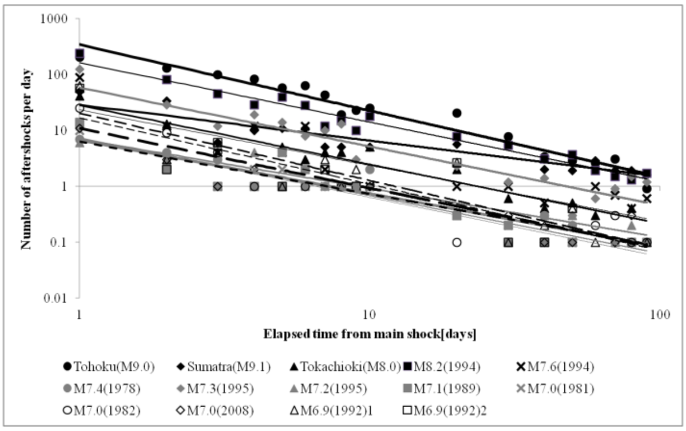

Figure 6. MO law in all aftershock data

Table 1. Parameters of all aftershock data

M	date	N	Hypocenter		GR law			MO law	
			latitude	longitude	*a*	*a*/area	*b*	*K*	*p*
9.0	20110311	1175	142.861	38.108	7.03	2.13	0.94	260	1.13
9.1	20041226	375	95.980	3.300	7.41	2.65	1.11	25.6	0.63
8.2	19941004	780	147.673	43.375	6.95	1.95	0.98	130	1.03
8.0	20030926	134	144.080	41.780	5.25	0.96	0.77	22.3	1.02
7.6	19941228	191	143.745	40.430	5.49	1.09	0.8	19.4	0.97
7.4	19780612	30	142.167	38.150	4.26	0.06	0.69	5.3	0.91
7.3	19951204	329	150.130	44.560	6.19	2.09	0.89	46.6	1.02
7.2	19950107	26	142.306	40.223	4.02	0.02	0.7	5.17	0.82
7.1	19891102	34	143.053	39.858	4.60	0.70	0.74	5.67	0.99
7.0	19810119	26	142.967	38.600	4.05	0.25	0.64	5.6	1.01
7.0	19820723	49	141.950	36.183	5.06	1.26	0.83	8.26	1.02
7.0	20080508	27	141.608	36.228	5.16	1.36	0.91	4.84	0.89
6.9	19920718	115	143.673	39.372	5.38	1.68	0.79	15.5	1.16
6.9	19920718	100	143.433	39.407	5.34	1.64	0.8	12.8	1.15

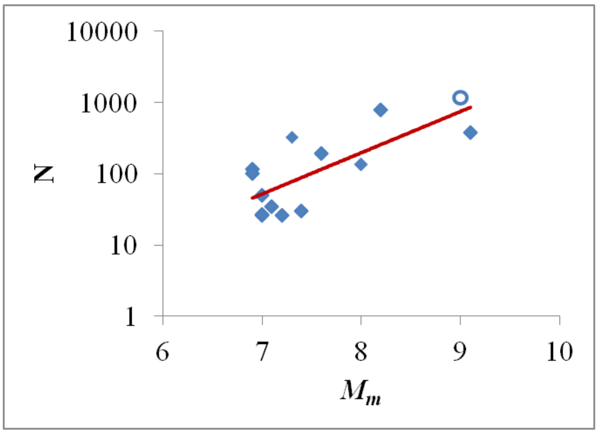

Figure 7. Relation of total number of aftershocks and magnitude of main shock

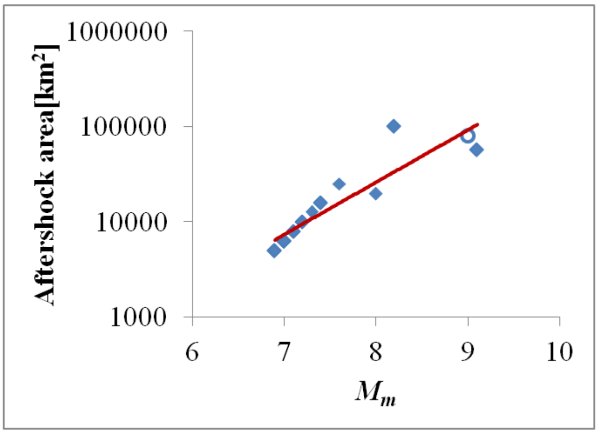

Figure 8. Relation of aftershock area and magnitude of main shock

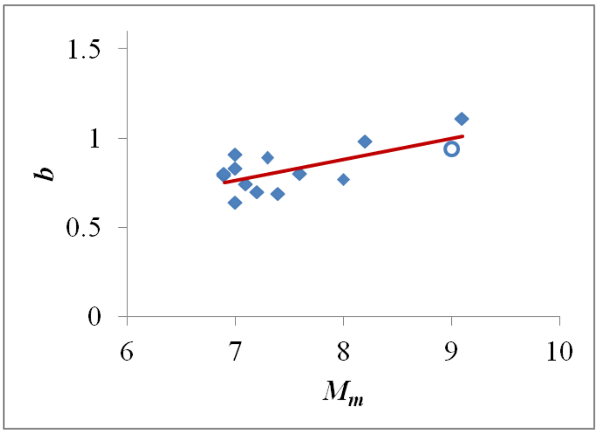

Figure 9. Relation of *b* and magnitude of main shock

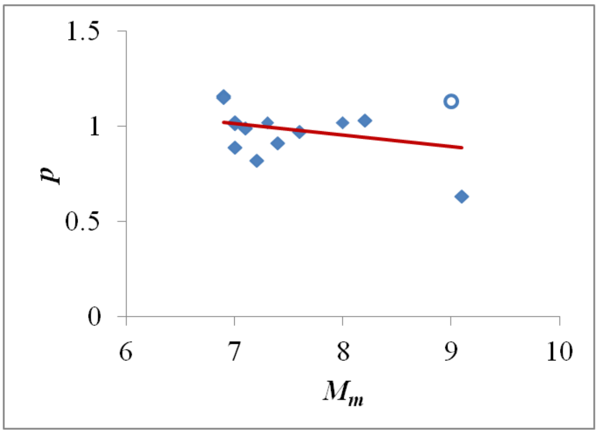

Figure 10. Relation of *p* and magnitude of main shock

The following characteristics of aftershock are obtained from Figure 7 to 10.

- As M_m increases, the number of aftershock increases.
- As M_m increases, the aftershock area increases.
- As M_m increases, the *b* value increases.
- As M_m increases, the *p* value decreases.

5. PROBABILISTIC AFTERSHOCKS OCCURRENCE MODEL

5.1. Probabilistic Occurrence Model of Aftershock

From GR law and MO law, one can obtain a model (Reasenberg & Jones, 1989) that describes the rate of aftershocks of magnitude *M* or larger, at the time *t* following a main shock of magnitude M_m, may be expressed as follows:

$$\lambda(t, M, M_m) = \frac{10^{a(M_m) - b(M_m)M}}{(t+c)^{p(M_m)}} \tag{5.1}$$

where *a*, *b* and *p* are function of M_m, which is discussed in the next section.

5.2. Parameters of the Suggestion Model

Using equation (5.1) and Figures 7 to 10, a probabilistic aftershock occurrence model is suggested. In equation (5.1), parameter *a*, *b* and *p* are used, we can obtain the parameter by regression of Figures 7 to 10.
The *b* value increases as the magnitude of the main shock increases as follows:

$$b(M_m) = 0.12M_m - 0.063 \tag{5.2}$$

The *N* value is obtained by regression of Figure 7 as follows:

$$\log N(M_m) = 0.58M_m - 2.34 \tag{5.3}$$

Using equation (5.2) and (5.3), the *a* value is expressed as follows:

$$\begin{aligned} a(M_m) &= \log N(M_m) + M_0 b(M_m) = (0.58M_m - 2.34) + M_0(0.12M_m - 0.063) \\ &= (0.58 + 0.12M_0)M_m - (2.34 + 0.063M_0) \end{aligned} \tag{5.4}$$

where M_0 is the minimum magnitude of target aftershock.
The *p* value on magnitude of main shock is obtained by regression of Figure 10 as follows:

$$p(M_m) = -0.06M_m + 1.44 \tag{5.5}$$

5.3. Application of a Proposed Model

The probabilistic aftershock occurrence can be modeled by equation (5.1), parameter $a(M_m)$, $b(M_m)$ and $p(M_m)$. Using this proposed model, the probabilistic aftershock occurrence rate (M_m=9.0) is calculated and it is shown in Figures 11. The aftershock occurrence rate in each elapsed time from main shock (day) and aftershock magnitude is estimated using this result.
Furthermore, using the ground motion attenuation relation together with the proposed model, the ground motion caused by aftershocks can be calculated and then an aftershock hazard can be estimated.

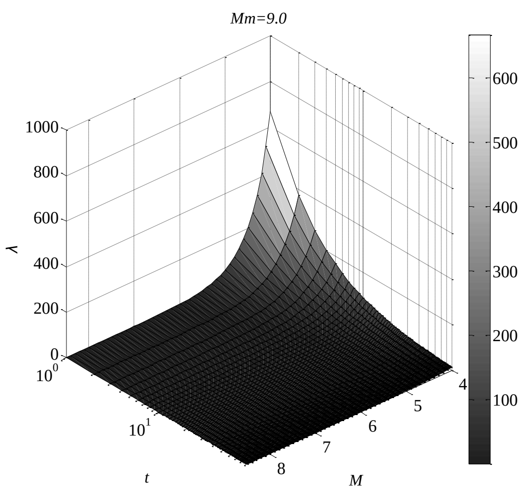

Figure 11. An example of proposed model

6. CONCLUSION

The aftershock data of the 2011 Tohoku earthquake were modeled by the GR law and the MO law. A space and time dependence model for aftershocks was proposed. Parameters of the GR law and the MO law are obtained, and the relations of the magnitude of main shocks and the parameters are derived. This study shows that *a* value of the GR law is dependent upon the earthquake magnitude of the main shock, while *b* value is larger when the magnitude of main shock is larger, and *p* value is smaller when the earthquake magnitude of the main shock is larger. Using these parameters, the probabilistic aftershock occurrence model for future large earthquakes is constructed that is combination of the GR law with the MO law. Probabilistic assessment of building damage due to aftershocks will be conducted using the proposed model.

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