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Experimental Prediction of the Number of Aftershocks of the 1999 Chi-Chi, Taiwan Earthquake

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Abstract

In order to find a practical method to assess forthcoming activity of aftershocks, an attempt was made to predict a plausible range of the number of major aftershocks of the 1999 Chi-Chi, Taiwan earthquake of September 20 (UTC; $M_s=7.7$). Although a method of predicting the probability of aftershocks had been proposed, assuming that parameters in the modified Omori formula would not change during the period of prediction, such an assumption might sometimes be invalid at the time of the especially large aftershocks. For this reason, a range of the number of aftershocks was experimentally discussed between September 22 and November 21 based on the 5-95% or the 0-90% points of the Poisson distribution. As a result, 11 cases were successful among 13 trials, suggesting that a prediction of the range of the number of aftershocks will be available for practical use, at least to some extent.

Key words: earthquake prediction, aftershock, modified Omori formula, Poisson distribution, the Chi-Chi earthquake

1. Introduction

Based on the modified Omori formula and the Gutenberg-Richter relation for aftershock activities, a method of predicting the probability was proposed by REASENBERG and JONES (1989, 1994), and was applied to, for example, the 1984 Western Nagano Prefecture, Japan earthquake of $M_{JMA}=6.8$ by ABE (1991, 1994). The probability $P(M, t_1, t_2)$ that more than one aftershock with a magnitude equal to or greater than M will occur between t_1 and t_2 is,

$$P(M, t_1, t_2) = 1 - \exp\{-N(M, t_1, t_2)\}$$

$$= \begin{cases} 1-\exp[-10^{a-b(M-M_{\min})}\{(t_1+c)^{1-p}-(t_2+c)^{1-p}\}/(p-1)] & (p\neq 1) \\ 1-\exp[-10^{a-b(M-M_{\min})}\ln\{(t_2+c)/(t_1+c)\}] & (p=1), \end{cases}$$

being slightly modified from the formulation of HOSONO and YOSHIDA (1992). Here, K, c, p, a ($=\log K$), and b are parameters in the modified Omori formula and the Gutenberg-Richter relation. $M_{\min}$ is minimum magnitude to be discussed and t_1 and t_2 are the time intervals from the occurrence of the main shock. $N(M, t_1, t_2)$ is the expected number of aftershocks with a magnitude equal to or greater than M between t_1 and t_2. In 1998, based on these discussions, probability predictions of aftershock activities began for official announcement by JMA (Japan Meteorological Agency, Tokyo) when major earthquakes occur in Japan (TSUKAKOSHI *et al.*, 2000).

However, it was discussed that there is an inevitable limitation in this method of probability prediction at the first official announcement for the 1998 Northern Iwate Prefecture earthquake of $M_{\rm JMA}=6.1$. That is, if we intend to apply a probabilistic method for the prediction of especially large aftershocks, the probability may sometimes be underestimated. This is because aftershock activity may be activated just after the occurrence of a large aftershock, and the curve of a cumulative number of aftershocks will vary from the slope expected by the modified Omori formula that is fitted to the data before the large aftershock. Such a discontinuity of the slope of a cumulative curve may also be intensified by possible quiescence which sometimes appears before major aftershocks (e.g. OHTAKE, 1970; MATSU'URA, 1986). Since the method for probability prediction is based on the expected total number of events above the minimum threshold of $M_{\rm min}$ for a certain period, an error in the predicted number would result in the incorrect probability of a large aftershock.

Considering the problem mentioned above, it might be useful to predict a plausible range of the number of aftershocks, in addition to discussing the probability value itself. In order to find practical efficiencies and/or difficulties, a range of the number of aftershocks was experimentally predicted from June 1999. In the next section, a method of predicting a plausible range is discussed. Subsequently, the result of a case study on the 1999 Chi-Chi, Taiwan earthquake ($M_{\rm s}=7.7$) is shown for evaluating the method.

2. Method of predicting the range of the number of aftershocks

As shown in the previous section, the expected number $N(t_1, t_2)$ of aftershocks between t_1 and t_2 is well known for any threshold of minimum magnitude as long as we can assume the modified Omori formula as $n(t)=K/(t+c)^p$: ($n(t)$ is the frequency of aftershocks occurred in a unit time interval at the lapse time t after the main shock);

$$N(t_1,t_2)=\begin{cases} K\{(t_1+c)^{1-p}-(t_2+c)^{1-p}\}/(p-1) & (p\neq 1) \\ K\ln\{(t_2+c)/(t_1+c)\} & (p=1). \end{cases}$$

According to this relation, after estimating the values of K, c, and p using data by time t_1, we can obtain the possible number $N(t_1, t_2)$. However, more precisely, it is the average number expected. In some cases, more aftershocks may occur than this estimation. Otherwise, only a small number of aftershocks may occur within the predicted period. Consequently, a plausible range of the number of aftershocks is desirable. Here, there is a problem in that a wide range may be necessary in order to prevent a false prediction, although the range should be narrow for practical use.

The binomial are Poisson distributions are useful for considering the plausible width of the predicting range. Let N be the expected number (i.e. expectance) between t_1 and t_2, and N_0 be a certain large value; e.g., total number expected in the

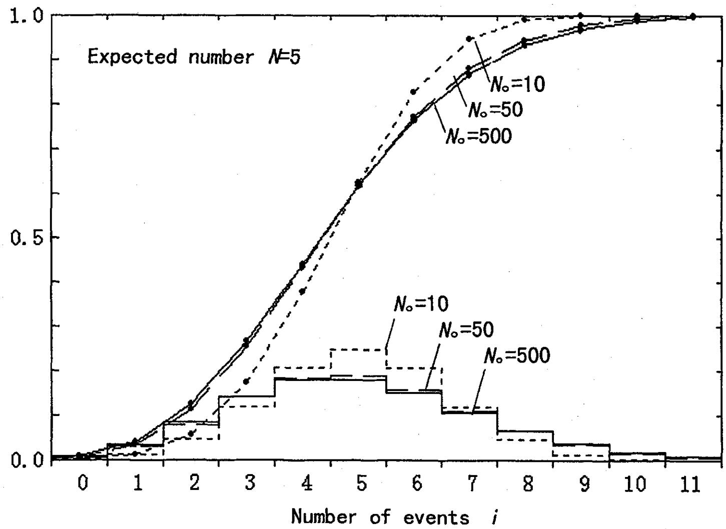

Fig. 1. Calculation of the binomial distributions: Probability densities (bars) and cumulative distributions (circles) that i events will occur among the total number N_o, with an assumption for the expected number $N=5$.

remaining period. Based on a definition of the binomial distribution, a probability $P\,(i;\,N_0,\,N/N_0)$ that i events among N_0 will occur during the interval of t_1 and t_2 is,

$$P\,(i;\,N_0,\,N/N_0)={}_{N_0}\mathrm{C}_i\,(N/N_0)^i\;(1-N/N_0)^{N_0-i}\;.$$

For example, a calculation of $P\,(i;\,N_0,\,N/N_0)$ for $N=5$ is shown in Fig. 1 for different values of N_0. Fortunately, the results are practically identical in spite of the difference of N_0 as long as $N_0 \gg N$, and they converge into the Poisson distribution $P_o\,(i;\,N)$, defined by,

$$P_o\,(i;\,N)=\exp(-N)\,N^i/i!\quad(i=1,\,2,\,\cdots).$$

Alternative explanations will be possible for the binomial and Poisson distributions. Let us divide the time interval between t_1 and t_2 into successive N_0 subintervals with the expected number of N/N_0. If the events are considered to occur independently of each other, a probability $P\,(i;\,N_0,\,N/N_0)$ or rather $P_o\,(i;\,N)$ for $N_0 \to \infty$ can be obtained.

Fig. 1 shows that $i=5$ is the most common, but the range of $i=3$–8 or 2–9 is necessary if we hope to have a successful prediction with a rate of more than 80 or 90%, respectively. Calculations of the 5–95% range of $P_o\,(i;\,N)$ for various values of N are shown in Fig. 2. Exactly 5 and 95% points of the Poisson distribution (Tables 2–3) and their approximate formulae are shown in Appendix. However, if the lower threshold of i is zero, the 5–95% range is in fact identical to the 0–95% range. In such a case, the 0–90% range may be enough to predict a plausible width, as long as the parameters K, c, and p are well determined. Accordingly, the 90% point of the

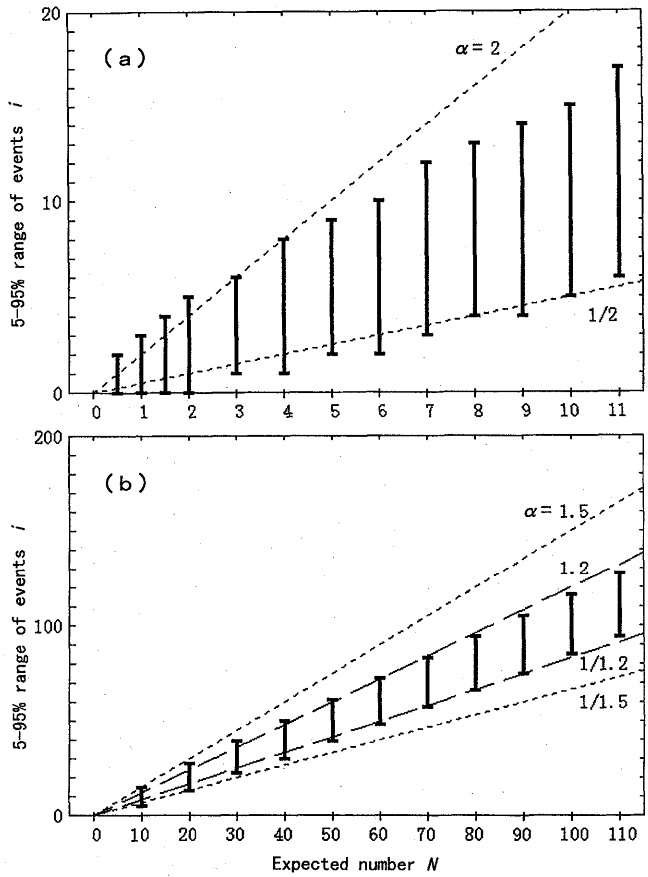

Fig. 2. 5–95% range of the number of events i for the Poisson distribution. The horizontal axis is the averaged number N for (a) N=0.5 to 11 and (b) N=10 to 110. Ranges of 1/2–2, 1/1.5–1.5 and 1/1.2–1.2 times of N are also shown by broken lines.

Poisson distribution is also shown for small values of N in Appendix (Table 4). As shown in Fig. 2, the 90% range (i.e. the 5–95% or 0–90% range in a cumulative distribution curve) will be achieved by, approximately, 1/2–2 times of N for small values of N up to around 5 (omit fractions for the lower boundary; ranges for N=0.2 and 2.0–2.2 are not reliable), and 1/1.5–1.5 times of N for N=20–30.

In the actual earthquake activity, however, the data fluctuate from the ideal relation; i.e., the modified Omori formula. In addition, a lack of data may also exist in the available earthquake list, especially soon after the earthquake occurrence. Therefore, the parameters K, c, p, and thus the expected number $N(t_1, t_2)$ may include errors that are not so small. At the time of a prediction, such errors should also be considered for a plausible range.

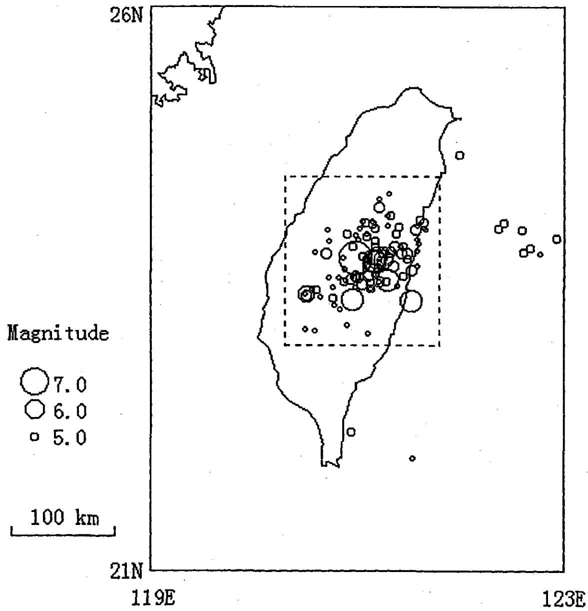

Fig. 3. Earthquakes at a depth of less than 100 km during September 20 and November 30, 1999 (UTC) after USGS. Events within a dotted square are regarded here as aftershocks of the Chi-Chi, Taiwan earthquake of September 20, 1999.

3. Case study for predicting the Chi-Chi, 1999 Taiwan aftershocks

Worldwide earthquake lists are available from NEIC (National Earthquake Information Center at Golden, Colorado) of USGS (United States Geological Survey) with time lags of zero to one day (Near Real Time Earthquake List) or a few days (List of Recent Earthquakes). Based on these data, aftershock activities of the 1999 Chi-Chi, Taiwan earthquake (Fig. 3) were predicted unofficially. The current experience is shown in both Table 1 and Fig. 4 for events with a magnitude of 5.0 or larger. Here, all activities around the main shock were regarded as aftershocks as shown in Fig. 3, even if some of them might have occurred outside the main fault region.

The main shock occurred at 17: 47 on September 20, 1999 (UTC). An estimation of the parameters in the modified Omori formula was carried out for data 2 hours after the main shock, because many aftershocks might be missing in the catalog just after the main shock. Without using these data, however, it was impossible to estimate a reliable value for the parameter c, which is assumed here to be 0.05 (day) referring to the typical value obtained in Japan (e.g. UTSU, 1999). The value p was also unreliable for estimating in the beginning of activity, and was, if necessary, assumed to be 1.15 referring again to the typical value in Japan (e.g. UTSU, 1999). In the present case study for $M=5.0$ or larger, the expected number $N(t_1, t_2)$ was generally small and the range of the prediction was basically taken to be around

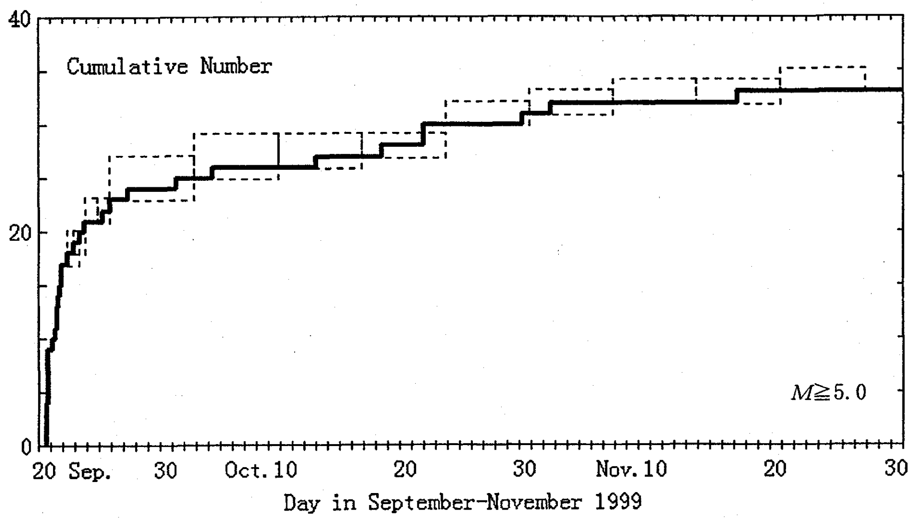

Fig. 4. Cumulative number of aftershocks of the 1999 Chi-Chi, Taiwan earthquake with a magnitude of 5.0 or larger between September 20 and November 30, 1999 (UTC) after USGS. Dotted squares represent the range of the number of experimentally predicted aftershocks.

Table 1. List of the present experimental predictions for a range of the number of aftershocks (M=5.0 or larger) of the 1999 Chi-Chi, Taiwan earthquake. False predictions are shown by ×.

Date of prediction	Period of prediction	Predicted number	Observed number
Sep. 22	1200 Sep. 22–1200 Sep. 23	0–3	1
Sep. 22	Sep. 23	0–2×	3
Sep. 22	Sep. 24	0–2	0
Sep. 22	Sep. 25	0–2	2
Sep. 25	Sep. 26–Oct. 2	0–4	2
Oct. 2	Oct. 3–Oct. 9	0–4	1
Oct. 8	Oct. 10–Oct. 16	0–3	1
Oct. 17	Oct. 17–Oct. 23	0–2×	3
Oct. 26	Oct. 24–Oct. 30	0–2	1
Nov. 1	Oct. 31–Nov. 6	0–2	1
Nov. 7	Nov. 7 –Nov. 13	0–2	0
Nov. 14	Nov. 14–Nov. 20	0–2	1
Nov. 21	Nov. 21–Nov. 27	0–2	0

1/2–2 times of $N(t_1, t_2)$ as shown in the previous section. However, its range was extended to, for example, 1/3–3 or even 1/4–4 according to the degree of the errors in the expected values of $N(t_1, t_2)$.

The prediction included 13 trials from September 22 to November 21. Among

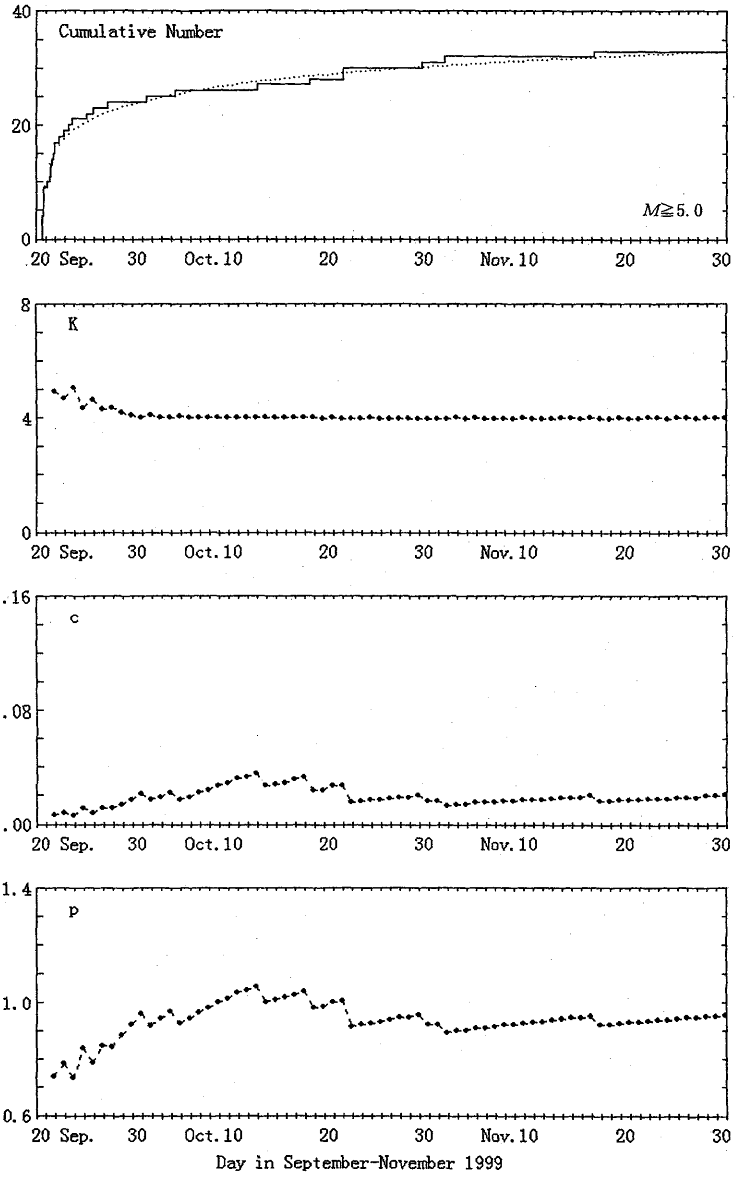

Fig. 5. Cumulative number of aftershocks of the 1999 Chi-Chi, Taiwan earthquake, and re-determined parameters K, c (in day) and p of the modified Omori formula for the events with magnitude M=5.0 or larger. The continuous curve in the figure for the cumulative number is the modified Omori formula fitted to all the data by November 30. The values of K, c, and p are plotted at the end of the analyzed period.

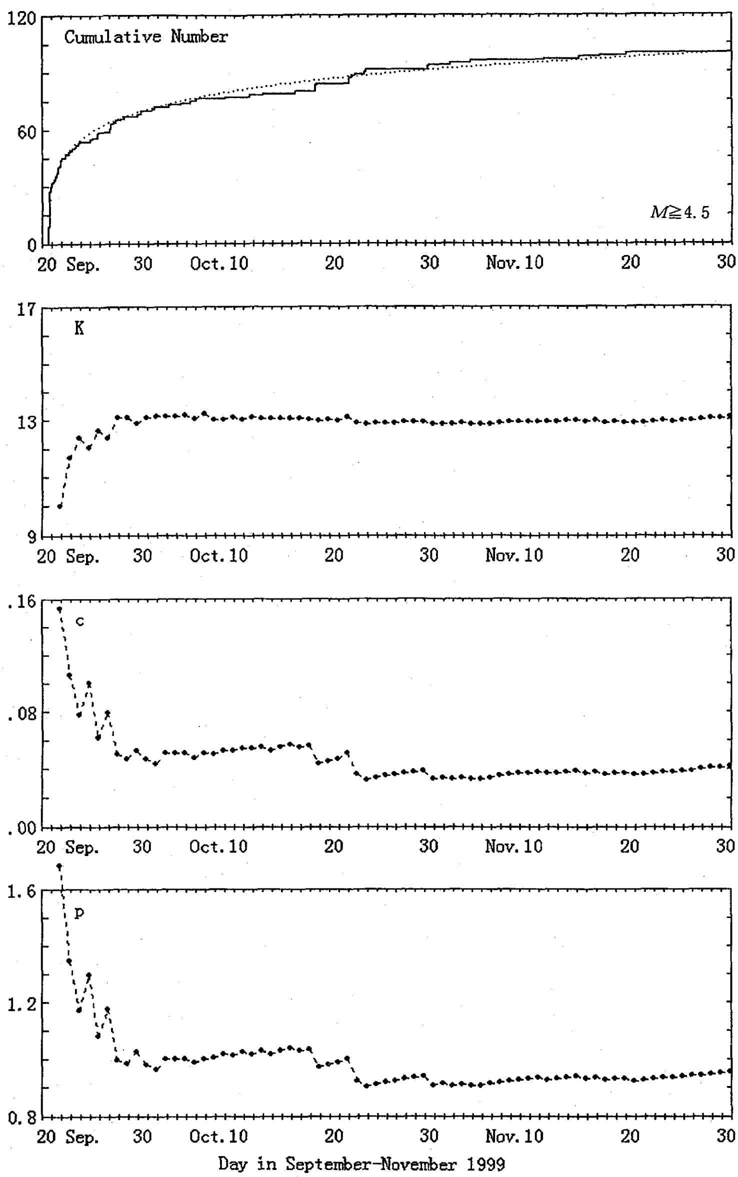

Fig. 6. Cumulative number of aftershocks of the 1999 Chi-Chi, Taiwan earthquake, and re-determined parameters K, c (in day) and p for the events with magnitude $M=4.5$ or larger. The explanations are the same as in Fig. 5.

them, 85% were successful, but underestimations occurred twice. One of the false predictions occurred on September 23. In this case, 0–2 events were expected. Against this, however, 3 events were reported by USGS. Considering the uncertainty of the expected number $N(t_1, t_2)$, a wide range should have been needed in this case. On October 22–23, a new activity of $M_w=5.9$ occurred southwest adjacent to the previously active region. Including this extended activity, observed events in the week from October 17–23 totaled 3 against the predicted number of 0–2. As shown in these cases, the present simple method is not of course perfect, and results in false predictions in some cases with a small probability.

Incidentally, the parameters of K, c, and p are re-examined based on all data prepared six months after the main shock (Figs. 5–6). For events with $M=5.0$ or larger, K, c, and p were found to be 4–5, 0.01 or less, and 0.7–0.8, respectively, in the first several days using a maximum likelihood method (e.g. OGATA, 1983). Hereafter, K, c, and p were relatively stable at 4, 0.02 and 0.9–1.0, respectively. In this calculation, however, the total number of $M=5.0$ or larger were only about 20–30, suggesting a possible lack of confidence in the reliability of the estimated values. In the magnitude range of $M=4.5$ or larger, K, c, and p varied widely around 9–13, 0.06–0.16, and 1.1–1.7, respectively, up to September 26. Subsequently, K, c, and p became about 13, 0.03–0.06, and 0.9–10, respectively. The results suggest a question over the first several days, but proved that c was commonly small to be 0.02–0.06 and p was 0.9–1.0 throughout the total period of 60–90 days. Among them, small but marked step-downs in the values of c and p were caused by the activity on October 18 and 22–23. Prior to October 18, a relative quiescence was recognized in the curve of the cumulative number of aftershocks (Fig. 6). Such a quiescence and a possible recovery on October 18 ($m_b=5.0$ and others) might have been a precursor to forthcoming activity; i.e., the $M_w=5.9$ event on October 22. Unstable results obtained in the first several days suggest a lack of data, especially in the magnitude range of less than $M=5.0$.

4. Additional comments and conclusions

Considering that events of less than $M=5.0$ seem to be incompletely listed in the catalog of USGS, an experimental prediction for $M=4.0$ or larger was carried out based on the catalog of JMA. As a result, the number of successful predictions was almost identical to that of $M=5.0$ or larger. However, this is omitted in this paper because it was proved that the list of JMA was also incomplete in this region located outside the Japanese seismic network, and that magnitudes of $M=4$–5 were, in many cases, slightly smaller than those determined by USGS.

A similar problem was also found in the preliminary catalog of CWB (Central Weather Bureau, Taipei). In this case, the magnitudes were systematically larger than those of USGS. For example, 1.6 times of events of $M=5.0$ or larger were listed by CWB compared to the data of USGS.

In conclusion, a range of the number of aftershocks was experimentally predicted for the 1999 Chi-Chi, Taiwan earthquake. When an expected number N between t_1 and t_2 was obtained after estimating the parameters in the modified Omori formula, a plausible range was obtained from; e.g., the 5 and 95% points of the Poisson distribution. If we approximate the range by $1/\alpha$–α times of N, α will be around 2 for $N=5$ or less, and 1.5 for $N=20$–30, in order to achieve the probability of a successful prediction around 90%. In addition, when the estimation of N is not so convincing, the value of α should be increased, for example, to 3 or 4.

In the present test, the rate for successful predictions is 85%, which is close to the expected value of 90%. This proves that a method for predicting a range of the number of aftershocks can be put to practical use. Although the predictions included a not so small range, it is still useful to know an outline of forthcoming aftershock activity for the people in the epicentral area, especially for the staff of offices involved with disaster prevention. Rapid and reliable data obtained by near real-time monitoring of earthquakes is desirable to develop the present prediction efforts.

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Appendix: 5 to 95% range of the Poisson distribution

The 5 and 95% points of the cumulative values of the Poisson distribution are calculated for the expected number $N=0$ to 15 (Table 2), and for N up to 1,000 (Table 3). In addition, the 0 and 90% points are shown in Table 4 for N up to 2.99.

Although the cumulative distributions can be easily computed from the notation of the Poisson distribution, explicit formulations for the 5 and 95% points will also be useful. For large N, the Poisson distribution is well known to be approximated by the χ^2 distribution and thus the normal distribution, after a certain transformation of the parameters (e.g. YAMAUCHI, 1972). Let $x_{0.05}$ and $x_{0.95}$ be the 5 and 95% points for the Poisson distribution, respectively. Then,

$$x_{0.05}=[\{(-u_\alpha+\sqrt{u_\alpha^2+4N}\ )/2\}^2-0.5]$$

$$x_{0.95}=[\ \{(u_\alpha+\sqrt{u_\alpha^2+4N}\ )/2\}^2\ -0.5].$$

Here,

$$u_\alpha=z-(a_0+a_1z)/(1+b_1z+b_2z^2),$$

$$z=\sqrt{-2\ln(1-\alpha)}\ ,\ 1-\alpha=0.05,$$

Table 2. 5 to 95% range of the Poisson distribution

The 5 and 95% points of the Poisson distribution $P_o\ (i;N)$ are defined by the minimum value of x satisfying,

$\sum_{i=0}^{x} P_o\ (i;N) \geqq 0.05$ and $\sum_{i=0}^{x} P_o\ (i;N) \geqq 0.95$,

respectively. Expected number is the expectance N, and $N=0.05$ in the first line, for example, does not necessarily include 0.051. Similarly, $N=0.06$ in the second line does not necessarily include 0.059. Values in parentheses are calculated using proposed approximate formulae.

Expected number (appr.)	5–95% range	Expected number (appr.)	5–95% range
0.00–0.05 (0.00–0.05)	0– 0	7.69– 7.75 (7.70– 7.76)	3–13
0.06–0.35 (0.06–0.35)	0– 1	7.76– 8.46 (7.77– 8.46)	4–13
0.36–0.81 (0.36–0.82)	0– 2	8.47– 9.15 (8.47– 9.16)	4–14
0.82–1.36 (0.83–1.38)	0– 3	9.16– 9.24 (9.17– 9.24)	5–14
1.37–1.97 (1.39–1.98)	0– 4	9.25–10.03 (9.25–10.03)	5–15
1.98–2.61 (1.99–2.63)	0– 5	10.04–10.51 (10.04–10.52)	5–16
2.62–2.99 (2.64–2.99)	0– 6	10.52–10.83 (10.53–10.83)	6–16
3.00–3.28 (3.00–3.30)	1– 6	10.84–11.63 (10.84–11.63)	6–17
3.29–3.98 (3.31–3.99)	1– 7	11.64–11.84 (11.64–11.85)	6–18
3.99–4.69 (4.00–4.71)	1– 8	11.85–12.44 (11.86–12.43)	7–18
4.70–4.74 (4.72–4.74)	1– 9	12.45–13.14 (12.44–13.15)	7–19
4.75–5.42 (4.75–5.43)	2– 9	13.15–13.25 (13.16–13.24)	8–19
5.43–6.16 (5.44–6.17)	2–10	13.26–14.07 (13.25–14.06)	8–20
6.17–6.29 (6.18–6.30)	2–11	14.08–14.43 (14.07–14.44)	8–21
6.30–6.92 (6.31–6.93)	3–11	14.44–14.89 (14.45–14.88)	9–21
6.93–7.68 (6.94–7.69)	3–12	14.90–15.70 (14.89–15.70)	9–22

$$a_0=2.30753,\ a_1=0.27061,\ b_1=0.99229,\ b_2=0.04481.$$

$[x]$ represents the maximum positive integer or 0, which does not exceed x. u_α is the approximation of the cumulative distribution of the standard normal distribution proposed by HASTINGS *et al.* (1955). In order to improve the approximation for small values of N; i.e., especially for $N \leqq 10$, a correction term is proposed empirically as follows,

$$x_{0.05}=[\{(-u_\alpha+\sqrt{u_\alpha^2+4N}\ )/2\}^2-0.5+1.72\exp(-1.22N^{0.32})]$$

$$x_{0.95}=[\{(u_\alpha+\sqrt{u_\alpha^2+4N}\ )/2\}^2-0.5-3.29\exp(-1.61N^{0.19})].$$

Approximate values obtained from these relations are compared with exact values of x_α in Table 2.

Table 3. 5 to 95% range of the Poisson distribution

Expected number	5-95% range	Expected number	5-95% range
0.15	0- 1	15	9- 22
0.2	0- 1	20	13- 28
0.3	0- 1	30	21- 39
0.4	0- 2	40	30- 51
0.5	0- 2	50	39- 62
0.6	0- 2	60	48- 73
0.7	0- 2	70	57- 84
0.8	0- 2	80	66- 95
0.9	0- 3	90	75- 106
1.0	0- 3	100	84- 117
1.5	0- 4	150	130- 170
2	0- 5	200	177- 224
3	1- 6	300	272- 329
4	1- 8	400	367- 433
5	2- 9	500	464- 537
6	2-10	600	560- 641
7	3-12	700	657- 744
8	4-13	800	754- 847
9	4-14	900	851- 950
10	5-15	1000	948-1052

Table 4. 0 to 90% range of the Poisson distribution

Expected number	0-90% range	Expected number	0-90% range
0.00-0.10	0-0	1.11-1.74	0-3
0.11-0.53	0-1	1.75-2.43	0-4
0.54-1.10	0-2	2.44-2.99	0-5

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1999年台湾集集地震の余震数予測の試み

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1999年9月20日（世界時）に発生した台湾集集地震について，想定した期間にある大きさ以上の余震が何回起こるか，試験的な予測を試みた．予測が当たる確率を上げるためには適当な幅を考える必要があるが，ここでは90％くらいの確度を想定して，ポアソン分布の5％および95％点を予測数の上下限の幅として考えた．ただし，下限値が0に減少したときには，ポアソン分布の0〜90％点をとれば十分かもしれない．また，期待値が5以下のときはその1/2〜2倍くらい，期待値が20〜30のときはその1/1.5〜1.5倍くらいの範囲をとると，ある程度近似できる（その際，下限値を求めるときは小数点以下を切り捨てる）．観測された余震のデータを改良大森公式にあてはめてその係数を定めれば，任意の期間に起こる余震数の期待値を求めることができる．これをもとに予測回数の幅を推測するが，期待値に誤差が見込まれるときは，それに応じて予測の幅を広げる必要が生じる．今回の台湾の余震活動では，9月22日〜11月21日までの2カ月間，初めは1日ごと，その後は1週間ごとにマグニチュード5.0以上の余震数を予測した．合計13回の予測の結果をみると，11回が予測幅の範囲内に収まり，2回が予測幅をそれぞれ一つ超過した．地震発生直後に入手できる地震データは不完全な場合が多く，具体的に予測の作業を行うときは，それによる不確かさも考慮しなければならない．このような難しさもあるが，今回の試行では，85％程度の成功率を得た．どのくらい活発な余震活動がこれから先に見込まれるか，本稿のような方法によってある程度の目安が得られれば，それなりに役に立つのではないかと思われる．なお，期待値が与えられたときに，ポアソン分布の5-95％幅が具体的にどのような値をとるかを表の形で表し，また，参考までにその値を算出する近似式を示した．