A STUDY ON THE STATISTICAL RELATION BETWEEN MAINSHOCKS AND AFTERSHOCKS IN WEST CHINA AND ITS APPLICATION

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ABSTRACT :

In this paper, research on after-quakes are summarized and spatial and temporal feature of after-quake distribution is revealed by regression analysis based empirical formula between mainshocks and aftershocks, which uses larger portion of samples of earthquake records with magnitude equal to and larger than 5.0 and starting from the time when West China has first modern seismograph, and statistically reliable. This result can be useful for determination of accumulative damage and provide preliminary consideration of main and after-quake motion inputting.

KEYWORDS: main earthquake, aftershock, magnitude, western China

1. INTRODUCTION

The occurrence of an earthquake generally follows a sequence of main earthquake, aftershocks, or just earthquake swarms. Due to lack of sufficient researches at present, there is still no consideration of the further damage caused by aftershocks in the present structural seismic response analysis and anti-seismic design, which only take into consideration of the single main earthquake. Experiences tell us that a great number of aftershocks often follow a main earthquake. According to available seismic damage data, aftershocks often made worse of the damage and sometimes even played a decisive role in the collapse of a construction.

In order to reduce the damage resulting from an earthquake, it is necessary to take into consideration of possible damage caused by aftershocks when a major construction project with possible serious secondary hazards is in its design stage. On the other hand, as an engineering structure will experience cumulative damage effect when under multiple shocks, an anti-seismic design with only the main shock taken into consideration is not only imperfect, but also unsafe. From the perspective of aftershock rescue work, proper consideration of possible damage from aftershocks can make rescue work more fully prepared. Therefore, a research on the characteristics of aftershocks is of vital practical significance to a systematical research on the responsive characteristics and destructive status of the main shock and aftershocks of a major project.

After a strong earthquake occurs, aftershocks in great quantity will follow. However, with the pass of time, the intensity and number of aftershocks will decrease gradually. Some scholars have tried to forecast the occurrence time, intensity, and location of the aftershocks through a number of methods, such as energy computation, mathematical probability statistics, periodic activity estimation, b value variant, forecast through wave velocity ratio change, etc., all of which provide short term forecast, i.e., the aftershocks within several dozen days, in unit of day or month. This paper systematically collected and re-organized data of main earthquakes and aftershocks in Western China since the utilization of modern seismic apparatus and summarized the relation characteristics of main earthquakes and aftershocks, which has provided reference for a forecast of the intensity, incurrence time and location of aftershocks after a strong earthquake.

2. ANALYSIS of RELEVANT RESEARCH RESUTS on AFTERSHOCKS

2.1. Basic Types and Characteristics of Earthquake Sequences

An earthquake sequence refers to a series of earthquakes with different magnitudes, which occur within certain spatial scope and certain period of time and possess inter-related seism incurring mechanism and/or same seismic structure. Earthquake sequences can be classified into the following three types:

1). Main Earthquake Sequence: in this sequence, the main earthquake releases over 90% of the total energy in the sequence. It can be divided into two types: foreshocks-main earthquake-aftershocks, main earthquake-aftershocks, depending upon the existence of foreshocks. The Xinfengjiang earthquake in 1962 with magnitude of 6.1 and the Haicheng earthquake in 1975 with magnitude of 7.3 belong to the sequence of foreshock-main earthquake-aftershock.
2). Earthquake swarms sequence: in the type of sequence, the main energy is released through a number of earthquakes with similar magnitude, among which the biggest earthquake accounts for less than 80 percent energy of the total sequence. This type of earthquake sequences can be divided into double earthquake sequence and swarm earthquake sequence, the former of which is comprised of two consecutive main earthquakes and their aftershock, the latter, a number of aftershocks. This type of earthquake sequences usually decreases in intensity slowly. The following are examples of this type of earthquake sequence: the Xingtai earthquake in March 1966, the Dongchuan, Yunnan earthquake 1n 1966, the Longling earthquake in May 1976, the Bachu, Xinjiang earthquake in February 2003 with magnitude of 6.8.
3) Isolated type: the energy of the main earthquake accounts for over 99.9% of the total and it has very few foreshocks and aftershocks and its intensity declines very fast.
According to related statistics, the main earthquake sequences and the earthquake swarms sequences account for 70% to 85% of all the earthquake sequences with magnitude over 6, which means that in most cases an engineering structure will experience more than one shocks once an earthquake occurs.

2.2. Duration of Strong Aftershocks

Once a strong earthquake occurs, the following are two questions which are important reference to anti-seismic activities in the earthquake area: How long the strong aftershocks in the earthquake sequence will last and how to judge the termination of the aftershocks. Generally speaking, the research on aftershocks includes its time series, spatial distribution characteristics and intensity fluctuation. As for time series, as early as in 1894, Japanese seismologist Omori Fusakichi pointed out the frequency of aftershocks against time follows the exponential attenuation rule. Afterwards, T. Utsu gave a revised attenuation formula in which the frequency of aftershocks (N) decreases in a manner like a hyperbolic curve. Professor C.F. Richter also mentioned in his book a phenomenon that late strong aftershocks occur several years after the strong main earthquake. Thereafter, the timing of occurrence of aftershocks also became one of the research topics for earthquake forecast. Gu Jicheng and Wang Biquan discussed the quasiperiodic property of strong aftershocks respectively and Fu Zhengxiang did research on the duration of the activities of strong aftershocks, all of which are very meaningful. As for when the strong aftershocks terminate and how to define the aftershocks after the main earthquake, researchers differed in their opinions.
The continuation time of strong aftershock activities generally refers to the period of time from the time when the main earthquake takes place to the time when the last strong aftershock occurs. According to the statistics from Bath(1973), the strongest aftershock in the earthquake sequence often occurs 2 to 3 days after a main earthquake. T. Utsu provided a formula for correlation between the occurrence time(T) of the strongest aftershock and the magnitude of the main earthquake(M) as following:

$$\lg T = 0.5M - 3.5 \tag{2.1}$$

According to the formula, the strongest aftershock of a main earthquake with magnitude of 6~8 will happen in 0.3~3.2 days after the main earthquake. This is similar with the statistics of macroseisms in China. Some researchers called the biggest aftershocks and other aftershocks which apparently lag behind were called late strong aftershock. Judging from the perspective of time, late strong aftershocks take place in a long span of time, from over 100 days to several thousand days after the main earthquake. In the light of the data available, the peak time for late strong aftershocks is between 100 and 1000 days after the main earthquake. The data from some well-known later aftershocks also shows that majority of aftershocks of earthquakes with magnitude between 7 and 8 occurred within several hundreds after the main earthquake. However, there also exist some exceptions to the above rule. For example, the Haiyuan earthquake with magnitude of 8.5 took place in 1920 and the Xiji earthquake with magnitude of 5.5 happened 50 years after, in 1970; the Mabian, Sichuan earthquake with magnitude of 6.8 happened in 1936,an earthquake with magnitude of 5.8 took place in the same place 35 years later. People’s understanding of the above phenomena is different. These rather late coming earthquakes can be considered as super late aftershocks or just new independent earthquakes.

In summarizing the relevant research results and from the perspective of the practical use in anti-seismic engineering, this paper defines the first 4.5 months after the main earthquake as the possible occurrence distribution of strong aftershocks.

2.3. Strength of Strong Aftershock Activities

The difference between the magnitude of the maxim aftershock and its main earthquake (△M)observes the M. Bath rule, which is in common use:

$$\triangle M = 1.2 \pm 0.5 \qquad (2.2)$$

According to researched carried out by T. Utsu, B.C. Papazachos there are some earthquakes with quite different △M if compared with the resulted obtained through the above formula and this difference is related to the types of earthquakes.

Generally speaking, the earliest strong aftershock is stronger than the later ones. For consecutively occurrence of big aftershocks, the second strong aftershock also often turns out to be stronger than the first strong aftershock, or the early strongest aftershock is similar in magnitude with the late strongest one. The magnitude of the strong aftershocks obtained through mathematic statistics is more direct and more practical.

2.4.Spatial Distribution of strong aftershock activities

Researches upon the strong aftershock sequences occurring in mainland China in recent years show that the strong aftershocks usually occur close to the main earthquake or to the nearby region of the ends of the faults. For one-sided fracture structure, strong aftershock often occur at the both ends of the faults of the main earthquake (the main earthquake is at one end of the fault). As for strong earthquakes with fractures at both ends, the epicentre is also one of the locations a strong aftershocks occurs besides the both ends of the fault. After he studied the earthquake distributions in South California, C.F. Richter discovered that the epicentre of the major earthquakes often occurred at one end of the fault, the strongest aftershocks at another end of the fault and the rest of the aftershocks were distributed along the whole fault, mostly at the side of the epicentre of the main earthquake. In recent years, some researchers from Japan and China pointed out in their studies of the distribution of aftershocks that the following three belts basically overlapped with each other: the direct aftershock area, the high intensity epicentre area and the epicentre upheaval zone caused by the breakage of main earthquake. Judging from the locations of the late strong aftershocks, they generally occurred at the edges of the aftershock areas, especially one end or both ends of the aftershock areas, far away from t he epicentre.

At the same time, the activities of the strong aftershocks also moved from one end in the aftershock area to another end, the scope of which is similar with the length of the main fracture belt.

According to the characteristics of earthquakes and the length characteristics of active section of earthquake-incurring faults, the area for possible aftershocks is within 61km in diameter of the epicentre of the main earthquake.

3. METHODS and RESULTS in DATA PROCESSIBG

3.1.Statistics Relations Between the Magnitudes of Main Earthquakes and Their Aftershocks

In order to build up mathematic relationship between the magnitudes of the main earthquakes and their aftershocks, according to the classification and analysis of the historical seismic data, 140 groups of main –aftershocks earthquake sequences were chosen from the macroseism index in Western China from 1912 to the present. All these data conform to the following conditions:

1). The maximum difference in latitude of a main earthquake and its aftershocks is 0.5 degree, the maximum difference in longitude, 0.5 degree, the maximum distance, 60.9km;

2). The greatest time gap is 135 days;

3). As for earthquake sequences with multiple aftershocks, two aftershocks with greatest magnitude are chosen, which are called the first great aftershock and the second great aftershock respectively according to the appearance in time sequence. There are 69 groups belonging to this category.

There is one thing needing to point out that the locations of the epicentres of aftershocks are very complicated, which involves a number of factors. The distance between the epicentres of a main earthquake and its

aftershocks can be very close and can also be very far away. In order to make the statistic results more practical, the following three factors have been taken into consideration: the first one is the distance between the epicentres of the main earthquakes and their aftershocks, which shouldn't be too big; the second one is the historical seismic data for the epicentres of aftershocks; the third is the seismic geological structure in Western China. As the majority of the aftershock activities of earthquakes confined within 1 degree in latitude or longitude, it can reflect the practical situation if we choose 0.5 degree difference in latitude or longitude as the maximum distance between main earthquakes and their aftershocks.
By using regression analysis, the following relation formulae can be obtained:
Based upon statistic analysis of 140 groups of main-aftershock sequences, a statistic formula on the relation between the magnitude of the main earthquake (M) and the magnitude of the first great aftershock (M_{a1}):

$$M_{a1} = 3.08 + 0.332M \quad (\sigma^2=0.196, \quad R=0.518) \tag{3.1}$$

Based upon statistic analysis of 69 groups of main –aftershock sequences, a formula on the relationship between the magnitude of the main earthquake (M) and the magnitude of the second great aftershock (M_{a2}):

$$M_{a2} = 1.896 + 0.529M \quad (\sigma^2=0.263, \quad R=0.616) \tag{3.2}$$

Based upon the analysis of 140 groups of main-aftershock sequence, a formula between the magnitude of the main earthquake (M) and that of the biggest aftershock (M_a):

$$M_a = 2.259 + 0.483M \quad (\sigma^2=0.226, \quad R=0.634) \tag{3.3}$$

Fig.1, Fig.2, and Fig3 are respectively the correlation graph for M and M_{a1}, M and M_{a2}, and M and M_a. The area between dashed lines on all the drawings represents a 95% confidence interval of the population variance in the statistic relationships. From these drawings we can see that the magnitudes of the main earthquakes and that of their aftershocks are positively correlated.

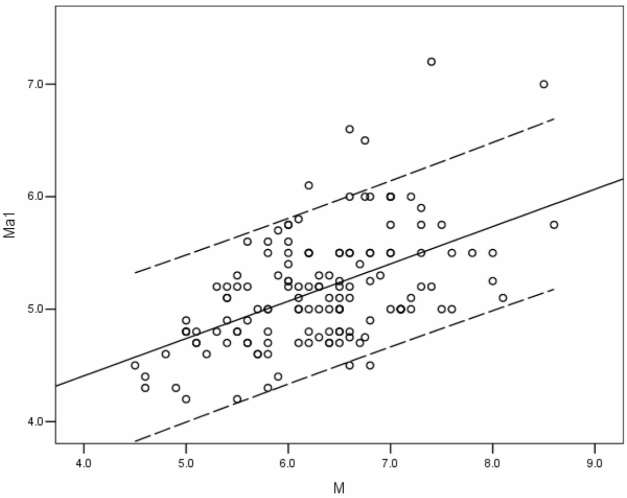


Figure1 Statistic Relation Between M & Ma1

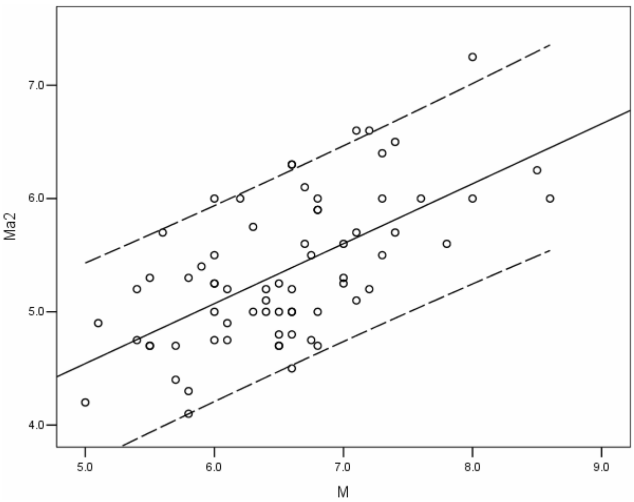


Figure 2 Statistic Relation Between M & Ma2

3.2. Spatial Distribution of Aftershocks

The characteristics of spatial distribution of aftershocks are closely related to the layout of the seismogenic faults, earthquake mechanism, mobility characteristics of the faults. Generally speaking, aftershocks are concentrated around the main earthquakes in the beginning and they will scatter in a wider area with the increase of the magnitude of the main earthquakes. In order to simplify the research, we have carried out statistic analysis of the relative distance between the epicentres of the strong aftershocks and that of their main earthquakes and the results are shown in fig 4 and Table 1, from which we can obtain the following conclusions:
1). The first great aftershock is mainly distributed within 30 km of the epicentre of the main earthquakes, which accounts for 86.4% of the total(0~15km, 54.3%; 15~30km, 32.1%);
2). The second big aftershock is mainly distributed within 35km of the epicentre of the main earthquake, which accounts for 92% of the total (0~10km, 23.2%; 10~20km, 37.7%; 20~35km, 31.9%).

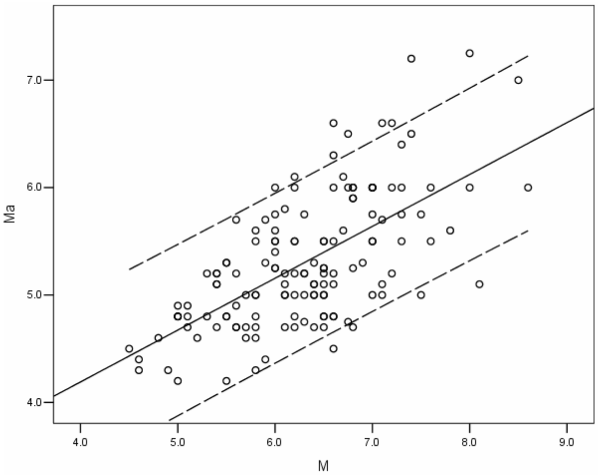
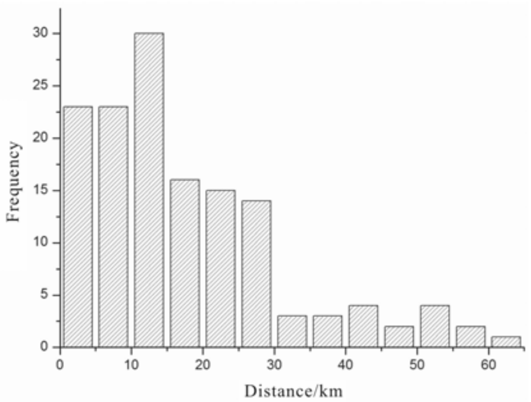


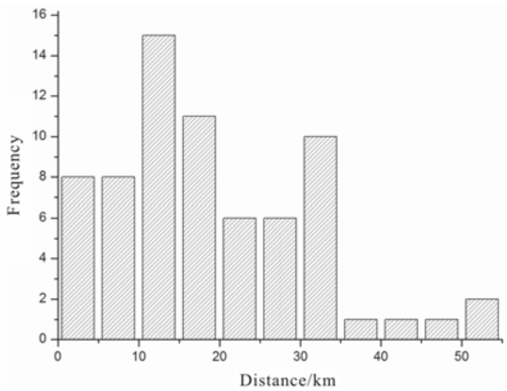
Figure 3 Statistic Relation Between M & Ma

3). The greatest aftershock is mainly distributed within 30km of the epicentre of the main earthquake, which accounts for 84.3% (0~20km, 65.0%, 20~30km, 19.3%)

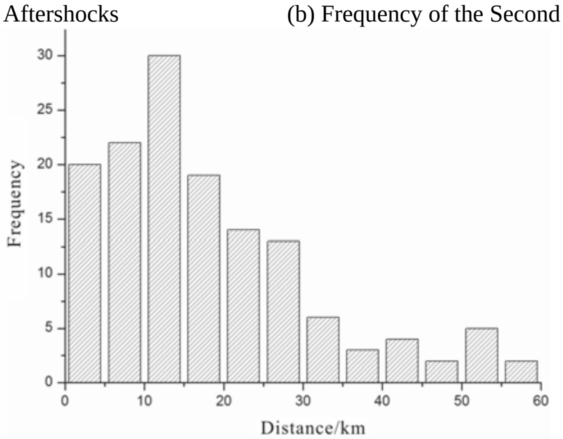
Therefore, in studying dynamic responsive characteristics of engineering structure under the influence of the main-aftershocks, we should concentrate our attention on the influence of strong aftershocks within 30km of the epicentre of the main earthquake and, in combination with the properties of the seismic structure, forecast potential locations of aftershocks and their influences upon engineering structures.



(a) Frequency of the First Great Aftershocks



(b) Frequency of the Second Great Aftershocks



(c) Frequency of the Greatest Aftershocks

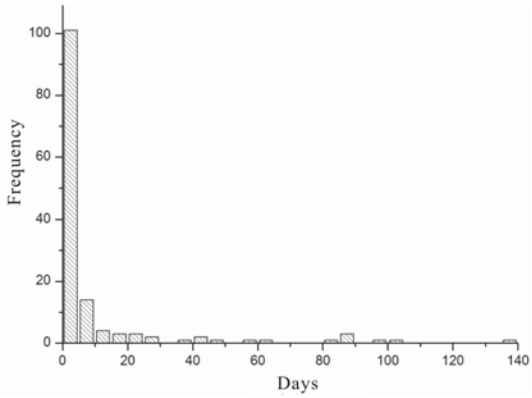
Figure 4 The Distribution of Distance of Strong Aftershocks to Epicenter of Main Earthquakes

Table 3.1 Statistic Result of distance of Aftershock Epicenters to the main shock

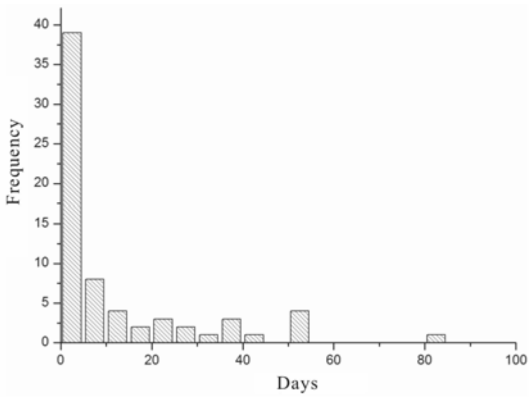
Distance /km Frequency		0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60	60-65
The first great aftershocks	Frequency	23	23	30	16	15	14	3	3	4	2	4	2	1
The second great aftershocks	Frequency	8	8	15	11	6	6	10	1	1	1	2	0	0
The largest aftershock	Frequency	20	22	30	19	14	13	6	3	4	2	5	2	0

3.3.Time Distribution Characteristics of Aftershocks

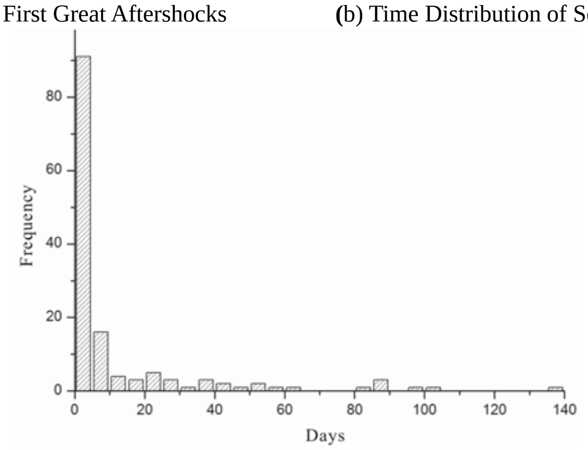
The frequency of aftershocks is great within 5 days of the occurrence of their main earthquakes, during which period of time energy is released in big amounts and weakened very fast. Most of the strong aftershocks also took place during this time. Table 2 to Table 4 and Figure 5 show respectively the occurrence time measured in days after the main earthquakes of the first great aftershocks, the second great aftershocks and the greatest aftershocks. From the above information, we can see that 101 out of the total 140 first great aftershocks(72%); 39 out of 69 second great aftershocks(57%) and 91 out of 140 greatest aftershocks(65%) all took place within 5 days of the occurrence of their main earthquakes. Therefore, the peak time for strong aftershocks is 5 days after the main earthquakes. Late strong aftershocks occurred in relatively wider range, not as concentrated as the early ones. So the first 10 days after the main earthquakes is the most important period of time that effect of strong aftershocks should be taken full consideration.



(a) Time Distribution of First Great Aftershocks



(b) Time Distribution of Second Great Aftershocks



(c) Time Distribution of Greatest Aftershocks

Figure 5 Time Distribution of Strong Aftershocks after their Main earthquakes

Table 3.2 Frequency Distribution of First Great Aftershocks

Days	0-5	5-10	10-15	15-20	20-25	25-30	35-40	40-45
Frequency	101	14	4	3	3	2	1	2
Days	45-50	55-60	60-65	80-85	85-90	95-100	100-105	135-140
Frequency	1	1	1	1	3	1	1	1

Table 3.3 Frequency Distribution of Second Great Aftershocks

Days	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	50-55	80-85
Frequency	39	8	4	2	3	2	1	3	1	4	1

Table 3.4 Frequency Distribution of Greatest Aftershocks

Days	0-5	5-10	10-15	15-20	20-25	25-30	35-40	40-45
Frequency	91	16	4	3	5	3	1	3
Days	45-50	55-60	60-65	80-85	85-90	95-100	100-105	135-140
Frequency	2	1	1	1	3	1	1	1

4. CONCLUSION

Strong earthquakes, especially strong earthquakes with shallow origin, are very destructive and have a larger number of aftershocks and slow attenuation in intensity, all of which will enhance the intensity of earthquakes and pose greater danger to engineering structures as well as human activities. Experiences from earthquakes in the past also showed that damages caused by aftershocks are very significant. Based upon a large number of samples chosen by their statistic significance, this paper has provided empirical formulae between the magnitudes of main earthquakes and that of their aftershocks and disclosed the characteristics of spatial distribution and time distribution. With regard to major important construction projects in seismic area, full attention should be paid to the combined effects of the input of main earthquakes and aftershocks and to the responsive characteristics and the cumulative destructive effect of the main-aftershocks upon engineering structures so as to disclose the regularity of aggravation of seismic damage under aftershocks and to provide scientific basis for a safe ant-seismic design of engineering structures.

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