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RAINFALL MAY TRIGGERS LARGE EARTHQUAKES IN TAIWAN (ML>3.0)

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ABSTRACT
This study objectively investigates the potential of rainfall that could trigger the earthquake. The earthquakes and rainfalls from 1995 to 2012 (ML>3.0) were examined. The earthquakes are likely to have significant positive relationship with rainfall after the Chi-Chi earthquake with Chi-Square test. The result revealed a significant difference between the correlations of monthly accumulated rainfall values and earthquake activities both before and after the Chi-Chi earthquake. The significant difference was discussed regarding) changes of crustal conditions after the Chi-Chi earthquake.

KEYWORDS: Ordinary earthquakes, Chi-Chi earthquake, Earthquake activity, Chi-square test).

INTRODUCTION
The topic of rainfall-induced earthquakes has been widely researched and noted. (Husen et al. (2007) reported a series of 47 local earthquakes in the central Switzerland Alps that occurred three days after record rainfall during August 19-23, 2005. In studies conducted in Denver, Colorado, liquid waste was injected into geological faults, resulting in increased seismicity at depths of up to 4 to 5 km. The researcher recorded 1500 minor earthquake events, which subsided after the injections ceased between 1962 and 1966. In this study, a statistical analysis of earthquakes (ML >3.0) in Taiwan island between 1995 and 2012 is used to test whether rainfall triggers earthquakes.

MATERIALS & METHODS
The Chi-square test which is a type of statistical analysis, is conducted to confirm the correlation between two independent data sets (same dimension), and an asymptotic significance value (p-value) is then used to determine significant differences and strong relationships between the two data sets that the p-value is adequately small ($p < 0.05$) (Lawrence *et al*., 2006). The analysis data are listed in Table.1 and Table.2.

TABLE.1 This table lists the earthquake activity related to daily accumulated rainfall values from January 1995 to September 1999 (Source: Central Weather Bureau, Taiwan). Note: The daily accumulated rainfall values are the averages of the rain gauge stations near the epicenters of the earthquakes and the earthquake activity located offshore of Taiwan is not considered.

Year	Month	Earthquake Number	Daily accumulated rainfall values
1995	1	4	22.0mm
1995	2	3	50.0mm
1995	3	2	49.0mm
1995	4	5	70.0mm
1995	5	10	40.0mm
1995	6	4	300.0mm
1995	7	6	70.0mm
1995	8	2	100.5mm
1995	9	1	120.0mm
1995	10	3	20.5mm
1995	11	10	26.5mm
1995	12	6	30.5mm
1996	1	4	10.0mm
1996	2	2	100.0mm
1996	3	5	50.5mm
1996	4	3	48.5mm
1996	5	2	32.8mm
1996	6	1	80.5mm
1996	7	4	90.5mm
1996	8	2	100.5mm
1996	9	4	70.0mm
1996	10	3	40.5mm
1996	11	4	30.4mm
1996	12	3	10.5mm

1997	1	8	60.0mm
1997	2	4	22.5mm
1997	3	4	63.5mm
1997	4	3	68.0mm
1997	5	2	55.0mm
1997	6	6	33.5mm
1997	7	3	35.0mm
1997	8	5	60.0mm
1997	9	3	35.5mm
1997	10	3	40.5mm
1997	11	7	55.5mm
1997	12	3	32.5mm
1998	1	6	34.0mm
1998	2	4	75.0mm
1998	3	3	43.5mm
1998	4	4	41.5mm
1998	5	6	48.5mm
1998	6	3	36.5mm
1998	7	8	47.0mm
1998	8	2	45.0mm
1998	9	5	120.5mm
1998	10	2	100.5mm
1998	11	7	28.5mm
1998	12	5	30.0mm
1999	1	6	20.5mm
1999	2	4	10.0mm
1999	3	2	20.5mm
1999	4	4	70.5mm
1999	5	8	60.5mm
1999	6	3	40.5mm
1999	7	7	12.0mm
1999	8	8	102.5mm
1999	9	90	140.5mm

TABLE. 2 This table shows the earthquake activity related to daily accumulated rainfall values from October 1999 to August 2012 and these data condition is the same as those of Table.1

Year	Month	Earthquake Number	Daily accumulated rainfall value
1999	10	93	40.0mm
1999	11	34	20.0mm
1999	12	17	30.0mm
2000	1	13	45.0mm
2000	2	10	3.0mm
2000	3	17	20.0mm
2000	4	14	20.5mm
2000	5	50	300.5mm
2000	6	59	320.5mm
2000	7	60	434.0mm
2000	8	70	481.5mm
2000	9	51	294.0mm
2000	10	84	500.5mm
2000	11	29	20.5mm
2000	12	40	20.0mm
2001	1	30	100.0mm
2001	2	40	150.0mm
2001	3	25	26.5mm
2001	4	15	28.5mm
2001	5	15	11.8mm
2001	6	60	324.5mm
2001	7	15	12.5mm
2001	8	23	28.5mm
2001	9	33	95.0mm
2001	10	21	15.5mm
2001	11	20	30.4mm
2001	12	23	40.5mm
2002	1	14	3.0mm
2002	2	10	30.0mm
2002	3	36	40.5mm
2002	4	50	408.0mm

2002	5	60	320.0mm
2002	6	40	300.5mm
2002	7	19	45.0mm
2002	8	37	267.0mm
2002	9	27	47.5mm
2002	10	71	300.5mm
2002	11	17	50.5mm
2002	12	19	40.5mm
2003	1	18	24.0mm
2003	2	21	65.0mm
2003	3	16	23.5mm
2003	4	21	340.5mm
2003	5	20	40.5mm
2003	6	38	60.5mm
2003	7	24	30.0mm
2003	8	22	15.0mm
2003	9	24	29.5mm
2003	10	25	22.5mm
2003	11	21	28.5mm
2003	12	80	470.0mm
2004	1	26	44.5mm
2004	2	28	50.0mm
2004	3	21	34.5mm
2004	4	17	110.5mm
2004	5	47	290.5mm
2004	6	13	30.5mm
2004	7	17	120.0mm
2004	8	19	90.0mm
2004	9	16	80.5mm
2004	10	20	40.5mm
2004	11	28	70.5mm
2004	12	9	4.5mm
2005	1	43	70.5mm
2005	2	67	390.0mm
2005	3	50	370.5mm
2005	4	77	389.0mm
2005	5	106	397.5mm
2005	6	52	140.0mm
2005	7	29	133.0mm
2005	8	22	50.5mm
2005	9	20	22.0mm
2005	10	33	4.0mm
2005	11	20	6.0mm
2005	12	21	20.0mm
2006	1	37	43.0mm
2006	2	29	50.0mm
2006	3	24	120.0mm
2006	4	81	400.5mm
2006	5	17	49.0mm
2006	6	36	49.0mm
2006	7	21	33.0mm
2006	8	35	46.0mm
2006	9	19	28.5mm
2006	10	27	43.0mm
2006	11	29	40.0mm
2006	12	47	204.5mm
2007	1	31	200.0mm
2007	2	44	240.5mm
2007	3	50	30.0mm
2007	4	37	200.0mm
2007	5	26	40.0mm
2007	6	40	200.0mm
2007	7	31	220.0mm
2007	8	37	190.0mm
2007	9	40	345.0mm
2007	10	29	240.0mm
2007	11	28	13.0mm
2007	12	28	20.0mm
2008	1	22	30.0mm

2008	2	49	100.0mm
2008	3	32	90.5mm
2008	4	50	254.5mm
2008	5	37	59.0mm
2008	6	39	50.0mm
2008	7	45	250.5mm
2008	8	58	300.5mm
2008	9	26	30.0mm
2008	10	29	40.5mm
2008	11	47	100.0mm
2008	12	30	90.5mm
2009	1	49	100.5mm
2009	2	31	80.0mm
2009	3	40	100.0mm
2009	4	27	100.0mm
2009	5	27	50.0mm
2009	6	130	480.0mm
2009	7	119	367.0mm
2009	8	57	400.0mm
2009	9	29	200.5mm
2009	10	62	100.0mm
2009	11	60	80.0mm
2009	12	92	100.0mm
2010	1	26	20.5mm
2010	2	20	46.0mm
2010	3	69	280.0mm
2010	4	48	300.0mm
2010	5	31	180.0mm
2010	6	39	100.5mm
2010	7	40	400.0mm
2010	8	47	270.0mm
2010	9	73	300.0mm
2010	10	93	330.0mm
2010	11	76	200.0mm
2010	12	35	18.5mm
2011	1	38	12.5mm
2011	2	52	300.5mm
2011	3	71	500.0mm
2011	4	53	220.0mm
2011	5	54	40.0mm
2011	6	49	50.0mm
2011	7	91	600.0mm
2011	8	45	200.5mm
2011	9	53	90.0mm
2011	10	46	80.0mm
2011	11	56	120.0mm
2011	12	45	130.0mm
2012	1	107	400.0mm
2012	2	60	280.0mm
2012	3	60	370.0mm
2012	4	39	60.0mm
2012	5	56	50.0mm
2012	6	160	900.0mm
2012	7	49	500.5mm
2012	8	70	100.5mm

RESULTS

The Chi-square test is used for the previous period to determine the difference in the correlation between monthly rainfall and earthquake activity before and after the Chi-Chi earthquake. Using the Chi-square test, the p-value is estimated to be nearly 4.86×10^{-12}, which is less than 0.05 and therefore, a strong significant difference exists between the correlations. Figure 1 shows the relationship between the number of the earthquakes in a month (N) and the monthly accumulated rainfalls (R), and the results of the Chi-Square Test. Blue circles and red crosses indicate the N-R relationships before and after the Chi-Chi earthquake, respectively. Three downward curves (lines) covered the blue circles indicate the N-R relationship before the Chi-Chi earthquake and the best fitted equation for the N-R relationship is

$LogN = 2.000 - 0.168 LogR$ (blue line). (1)

Three upward curves (lines) covered the red crosses indicate the N-R relationship after the Chi-Chi earthquake and the best-fitted equation for the N-R relationship is

$LogN = 2.021 + 0.343 LogR$ (redline). (2)

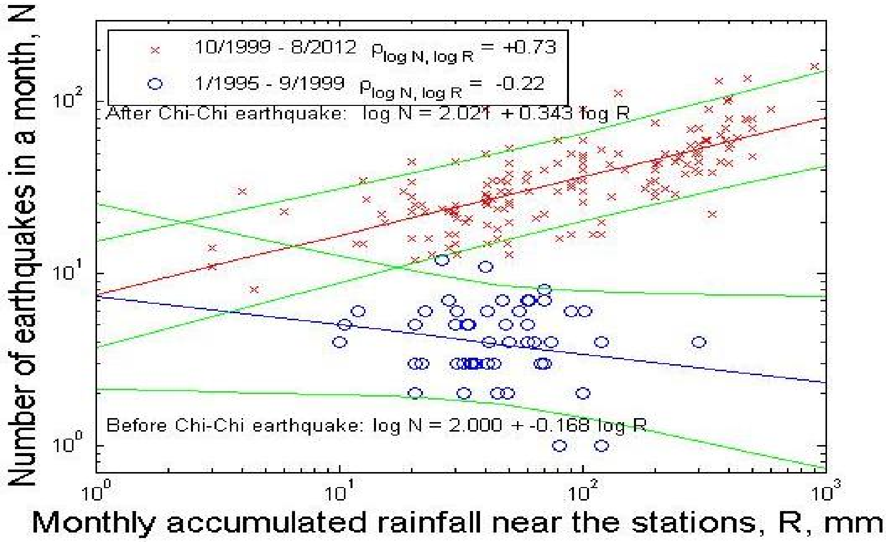

FIGURE 1: shows the correlations between the number of earthquakes (ML>3.0) in a month (N) and the monthly accumulated rainfalls (R) before and after the Chi-Chi earthquake (in log-scale).

The correlation is low, with a slightly negative coefficient of -0.22, before the Chi-Chi earthquake. The N-R relation is approaching the equation (1). Therefore, the earthquake activity has been associated with heavy rainfall during this time period slightly. On the contrary, the correlation is high, with a positive coefficient of +0.73, after the Chi-Chi earthquake, while the N-R relation is approaching the equation (2). During this time period, then, the earthquake activity is increased during periods of heavy rainfall. These results, covering a period from 1995 to 2012, include activity both before and after the Chi-Chi earthquake that may like create significant changes in crustal stress and strain conditions, allowing rainfalls to trigger small ordinary earthquakes.

DISCUSSION

The Chi-Chi earthquake may have resulted in crustal changes in stress and strain conditions throughout Taiwan, forming some blind faults (Tsou et al. 2011) and causing existed faults to become unlocked. Such situation may have then allowed rainfall to trigger earthquakes. Previous results indicate the high likelihood of rainfall-induced earthquakes due to the creation of non-rigid layers after the Chi-Chi earthquake. True cause is arguable; although some possible reasons have been discussed in section one. One potential cause is worth mentioning that level and pressure variances in groundwater due to rainfall (Yeh et al. 2008; Saar et al. 2003). Then water from rainfall may change groundwater levels while simultaneously inducing slight stress and pressure redistributions near the faults according to Mohr-Coulomb failure criterion (Hoek et al. 2002), thereby triggering more large earthquakes although their depths are a little thick.

CONCLUSION

This study found that the correlation between monthly rainfall and earthquake activity, before and after the Chi-Chi earthquake, is significantly different. It is possible that changes caused by the Chi-Chi earthquake made crustal conditions suitable for subsequent rainfall-triggered earthquakes. Potentially, heavy rainfall might have triggered two particular earthquakes observed in this study.

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