ESTIMATION OF THE POTENTIAL EARTHQUAKE PROBABILITIES IN TAIWAN

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ABSTRACT :

Taiwan is located on the boundary between Eurasia Plate and Philippines Sea Plate and earthquakes occur frequently. Since the seismic hazard is inevitable in Taiwan, it is suggested to reduce the seismic hazard. Promotion of seismic hazard mitigation is time-consuming and needs comprehensive resources. Due to limited resources for hazard mitigation, it is suggested to set priority first for regions with high potential of earthquake disaster. In this study, we separated the earthquake source in Taiwan into regional and fault sources, and calculated the potential earthquake probabilities in next 10 to 50 years respectively. For regional source, we analyzed the 13 regions, which used by Taiwan Power Company for Nuclear Power Plant's seismic safety evaluation. We set up the earthquake probability models, and calculate the probabilities for the potential earthquake of each region. As for fault sources, we refer to the active fault parameters investigated by the Central Geological Survey of Taiwan, MOEA, set up the characteristic earthquake probability model, and calculated the probabilities for potential earthquake of each fault. Finally, we estimated the ground motion potential of peak ground acceleration by attenuation relation of PGA for each fault, and the PGA values are improved in prediction by taking into account the site effect. In this study, we can identify the region with high potential earthquake probabilities, these results can be used for seismic hazard prevention and disaster mitigation in Taiwan.

KEYWORDS: Potential Earthquake Probability, Characteristic Earthquake, Attenuation, Site Effect

1. INTRODUCTION

Taiwan island is located on the boundary where the Philippines Sea Plate collides with the Eurasia Plate and earthquakes occur frequently in this area. Many disastrous events brought a lot of loss in human being and property in the past hundred years. The latest event is the Chi-Chi Taiwan earthquake with M_L7.3 in 1999 (Shin and Teng, 2001; Teng et al., 2001) associated with Chelungpu fault ruptures. It is important to prompt the hazard estimation. The earthquakes can be classified into two sources. The first one is earthquakes associated with surface fault ruptures (also called characteristic earthquake), and the other one is from blind fault ruptures (regional earthquake). An earthquake catalogue with uniform local magnitude, M_L, for about one hundred years in Taiwan was developed by Shin (1993) and Yeh et al. (1995) by combining the catalogue of the CWB and the Institute of Earth Science (IES), Academia Sinica. Since 1995, the Science Council (NSC) and the Central Geological Survey (CGS) have started projects of the systematic survey on active fault. Their efforts focus toward investigating the fault trace, long- and short-period slip rate, the potential earthquake magnitude, and the return period, etc.

In this study, we estimate the probabilities of earthquake recurrence in next 10 to 50 years, respectively, for large regional earthquakes and characteristic ones, and then predict its peak ground acceleration (PGA). For regional earthquakes, the earthquakes with $M_L \geq 5$ are selected due to completeness of the catalogue and hazard evaluation. For the characteristic earthquake, we firstly focus on the recurrence of the 13 active faults defined by the CGS. Finally, the ground motions induced by earthquakes are predicted by an attenuation equation which takes site effects into account.

2. PROBABILTY OF POTENTIAL EARTHQUAKE

As mentioned above, the earthquake source can be classified into regional and fault sources. Firstly, we estimate the potential magnitude of earthquake for the 13 regions and for characteristic faults. Secondly, the probabilities of earthquake recurrence in next 10 to 50 years are calculated for earthquake with $M_L \geq 5$, $M_L \geq 6$, $M_L \geq 7$ and the potential magnitudes, respectively. Thirdly, the probabilities of recurrence for characteristic faults are evaluated in next 10 to 50 years.

2.1 Probability for Regional Earthquake

2.1.1 Scaling of magnitude and frequency

The earthquake catalogue released by CWB over the period of from 1900 to October 2007, in which the earthquakes with $M_L \geq 5$ are selected in this study. Based on the criteria of seismic zoning of the Taiwan Power Company for Nuclear Power Plant's seismic safety evaluation, 13 regions are analyzed. In Figure 1, the circle denotes the distribution of earthquakes at a period spanning from 1900 to October 2007, while the solid lines depict the 13 regions with codes as S001, S002, etc. The statistic of seismicity following *G-R* law (Gutenberg and Richter, 1944) describes the relationship between magnitude and frequency in form of Eqn. 2.1.

$$\log N(m)=a-bm,\ m_o \leq m \leq m_u \qquad (2.1)$$

In Eqn. 2.1, m represents the magnitude, and $N(m)$ expresses the frequency of earthquake with magnitude larger and equal to m. Meanwhile, the constants of a and b can be calculated from best fit of Eqn.2.1. Under the consideration of seismology and earthquake engineering, we take m_o as lower limit for hazard estimation, and m_u as upper limit for the potential earthquake in a specific region. As mentioned above, the m_o is set to 5 in following evaluation. Figure 2 is an example and shows seismicity of region S011. As shown in Figure 2(a), the earthquakes with various magnitudes occur with time from 1900 to October 2007, and it is observed that earthquakes with $M_L \geq 6$ occur repeatedly every 10 to 20 years. Figure 2(b) shows an example of magnitude and frequency relationship (solid circles), which follows the *G-R* magnitude and frequency relationship, and the solid line is the best fit in form of Eqn. 2.1, where a=5.40 and b=1.06.

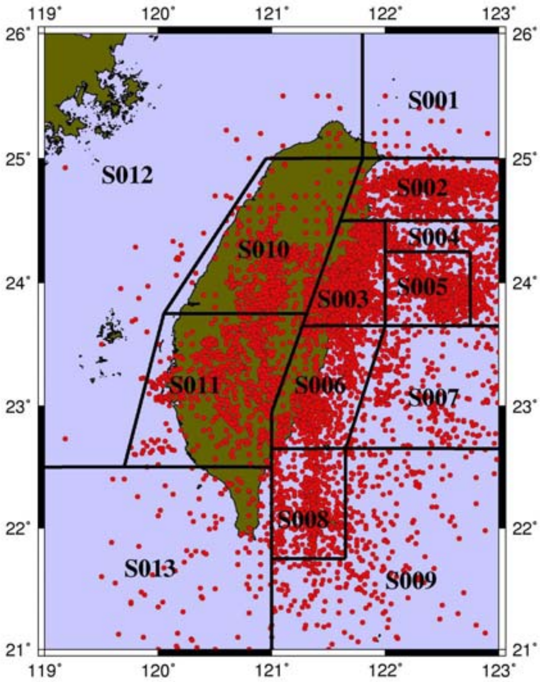

Figure 1 The distribution of earthquake with $M_L \geq 5$ at a period of from 1900 to October 2007.

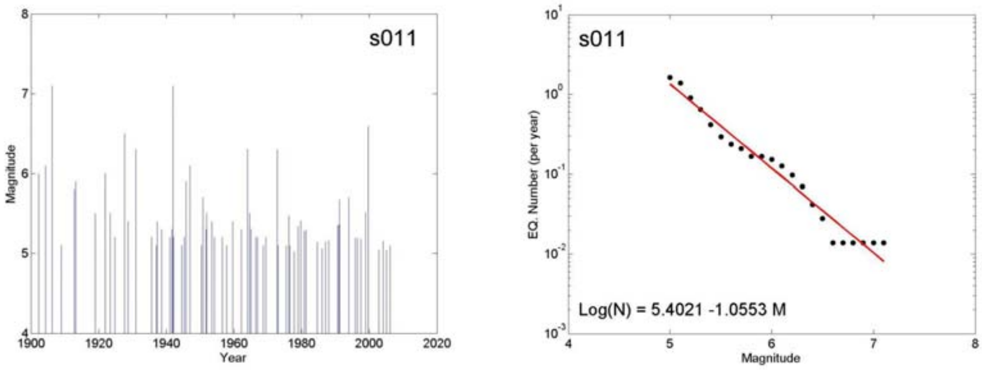

Figure 2 (a) Earthquakes occur from 1900 to October 2007 in the region S011. (b) The solid circles show the magnitude and frequency relationship in the region S011 and the solid line is the best fit.

2.1.2 Magnitude of the potential earthquake

From the past earthquake, we can derive the potential magnitude of earthquake. Iida (1976) proposed the relation between magnitude and strain energy in form of Eqn. 2.2.

$$\log(E)=12.66+1.4M_L \quad (2.2)$$

In Eqn. 2.2, the E represents the strain energy. The evaluation of the potential magnitude can be done through two lines enveloped the released strain energy cumulated with time. The slopes of the two lines express the energy released constantly in this region and the potential magnitude can be derived from Eqn. 2.2. As shown in Figure 3, we have the energy released in the region S011 over the period from 1900 to October 2007 and the potential magnitude is about 7.2.

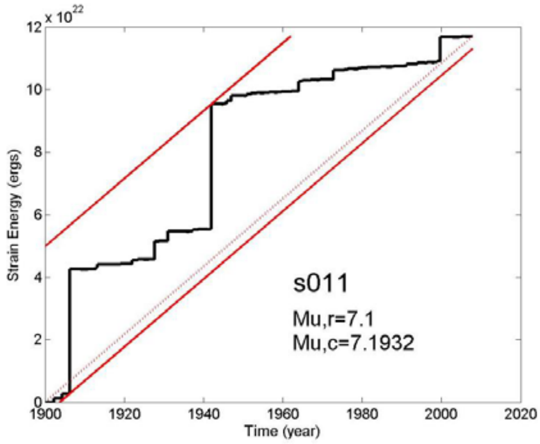

Figure 3 The released strain energy cumulated over the period of from 1900 to October 2007 in the region S011.

2.1.3 Recurrence model and results

In this study, we adopt the recurrence model of lognormal model (Utsu, 2002) based on the concept of the Poisson Process (Angnos and Kiremidjian, 1988). The effect of aftershock is removed from the catalogue through the method proposed by Gardner and Knopoff (1974). Given $f(t)$ as the probability density function (*PDF*), t as the interevent time, the model can be expressed as follows:

$$f(t) = \frac{1}{\sqrt{2\pi}\sigma t} e^{\frac{-(\ln t-\mu)^2}{2\sigma^2}} \tag{2.3}$$

where the σ and μ are mean and standard deviation of *PDF*, respectively. The probability density function can be derived from Eqn. 2.1 for the 13 regions and obtained the values of σ (recurrence time) and μ. Then we take the occurrence time of the last event into account. The probabilities of recurrence of earthquake with $M_L \geq 5$, $M_L \geq 6$, $M_L \geq 7$, and potential magnitude are listed in Table 2.1, Table 2.2, Table 2.3, and Table 2.4, respectively. Asterisk in Table 2.1, Table 2.2, Table 2.3, and Table 2.4 denotes insufficient data to estimate the probabilities. As shown in Table 2.1, the probabilities of earthquake with $M_L \geq 5$ in next 10 are almost 100% for all regions, except for region S001 (77.92%) and S012 (82.59%) due to low seismicity with high standard deviations. The return period for earthquakes with $M_L \geq 6$ are nearly 10 to 20 years, but three regions, i.e., S003 (6.53 years), S006 (7.96 years), and S008 (10.50 years), belong to regions with high seismic hazard (Table 2.2). For earthquakes with $M_L \geq 7$, the most hazardous area is region S003 in the future (Table 2.3). Two regions, i.e., S003 and S006, belong to high probabilities of recurrence for earthquakes with $M_L \geq 7$ (Table 2.4). The highest probabilities of recurrence for potential earthquakes with $M_L \geq 7$ locate at region S003 and exceed 10% in next 10, 20, 30, 40, 50 years.

Table 2.1 Probabilities for $M_L \geq 5$ in next 10, 20 30, 40 and 50 year

Zone	G-R Law		CV	Last event	Probability for T_p years				
	σ	μ			10	20	30	40	50
S001	10.48	6.38	0.61	2003.04	77.92	95.88	99.08	99.76	99.93
S002	1.39	0.91	0.65	2007.01	99.99	100.00	100.00	100.00	100.00
S003	1.26	0.92	0.73	2006.03	99.97	100.00	100.00	100.00	100.00
S004	1.95	2.00	1.02	2004.09	97.86	99.77	99.95	99.99	100.00
S005	1.25	0.79	0.63	2006.06	99.99	100.00	100.00	100.00	100.00
S006	1.32	1.05	0.80	2006.03	99.90	100.00	100.00	100.00	100.00
S007	2.33	1.82	0.78	2006.09	99.41	99.97	100.00	100.00	100.00

S008	1.99	1.07	0.54	2007.07	99.98	100.00	100.00	100.00	100.00
S009	2.66	1.67	0.63	2007.03	99.61	99.99	100.00	100.00	100.00
S010	4.00	3.97	0.99	1999.07	87.72	97.26	99.17	99.69	99.87
S011	1.69	1.38	0.81	2006.02	99.71	99.99	100.00	100.00	100.00
S012	8.36	5.33	0.64	1988.05	82.59	96.14	98.97	99.68	99.89
S013	5.72	3.75	0.66	1993.09	90.44	98.59	99.72	99.93	99.98

Table 2.2 Probabilities for $M_L \geq 6$ in next 10, 20 30, 40 and 50 year

Zone	G-R Law		CV	Last event	Probability for T_p years				
	σ	μ			10	20	30	40	50
S001	*	*	*	*	*	*	*	*	*
S002	21.71	14.21	0.65	2002.4	37.90	70.72	86.56	93.63	96.85
S003	6.53	4.74	0.73	2001.5	89.36	98.25	99.61	99.89	99.96
S004	32.45	33.12	1.02	2004.9	24.70	50.09	66.75	77.28	84.06
S005	10.68	6.75	0.63	2006.6	64.62	92.98	98.38	99.56	99.86
S006	7.96	6.33	0.80	2006.3	80.66	96.10	98.95	99.66	99.87
S007	12.77	10.01	0.78	1989.6	65.18	86.25	93.98	97.14	98.55
S008	10.50	5.62	0.54	2002.7	81.41	97.35	99.55	99.91	99.98
S009	12.71	8.02	0.63	2007.1	49.89	87.18	96.53	98.93	99.63
S010	19.55	19.40	0.99	1999.7	49.59	73.45	85.01	91.03	94.36
S011	13.66	11.11	0.81	1999.7	65.03	86.78	94.40	97.39	98.69
S012	*	*	*	*	*	*	*	*	*
S013	45.21	29.63	0.66	1955.3	31.30	52.63	67.09	76.93	83.66

Table 2.3 Probabilities for $M_L \geq 7$ in next 10, 20 30, 40 and 50 year

Zone	G-R Law		CV	Last event	Probability for T_p years				
	σ	μ			10	20	30	40	50
S001	*	*	*	*	*	*	*	*	*
S002	389.88	255.16	0.65	1922.7	0.76	1.74	2.95	4.39	6.03
S003	44.43	32.29	0.73	1957.1	29.52	49.96	64.13	74.02	80.97
S004	*	*	*	*	*	*	*	*	*
S005	145.33	91.85	0.63	1910.7	9.73	18.95	27.52	35.38	42.52
S006	81.20	64.57	0.80	1968.2	14.93	28.51	40.26	50.18	58.45
S007	120.74	94.66	0.78	1979.0	5.80	13.12	21.08	29.06	36.68
S008	96.13	51.52	0.54	1996.7	0.28	2.30	7.50	15.72	25.78
S009	86.62	54.63	0.63	1972.1	11.24	23.62	35.66	46.54	55.97
S010	148.38	147.28	0.99	1999.7	1.57	5.44	10.91	17.16	23.62
S011	176.85	143.80	0.81	1942.0	6.06	12.27	18.42	24.40	30.10
S012	*	*	*	*	*	*	*	*	*
S013	910.48	596.69	0.66	1900.4	0.05	0.12	0.23	0.36	0.54

Table 2.4 Probabilities for $M_{u,r}$ in next 10, 20 30, 40 and 50 year

Zone	G-R Law		CV	Last event	$M_{u,r}$	Probability for T_p years				
	σ	μ				10	20	30	40	50
S001	122.51	74.62	0.61	1907.5	5.8	12.72	24.17	34.33	43.25	51.03
S002	7179.40	4698.60	0.65	1922.7	7.6	0.00	0.00	0.00	0.00	0.00
S003	102.11	74.22	0.73	1951.8	7.3	12.41	23.99	34.42	43.61	51.59
S004	199.03	203.15	1.02	2004.9	6.5	0.25	1.66	4.44	8.27	12.74

S005	217.98	137.76	0.63	1910.7	7.1	4.64	9.56	14.63	19.74	24.81
S006	118.99	94.63	0.80	1968.2	7.1	8.24	17.00	25.64	33.81	41.32
S007	120.74	94.66	0.78	1979.0	7.0	5.81	13.12	21.08	29.07	36.69
S008	494.09	264.80	0.54	1936.6	7.3	0.03	0.08	0.18	0.33	0.56
S009	778.90	491.25	0.63	1972.1	7.5	0.00	0.00	0.00	0.01	0.03
S010	473.62	470.09	0.99	1999.7	7.3	0.02	0.15	0.47	1.04	1.88
S011	264.21	214.83	0.81	1942.0	7.1	2.79	5.95	9.39	13.02	16.76
S012	316.14	201.66	0.64	1920.9	5.9	1.47	3.27	5.37	7.75	10.36
S013	910.48	596.69	0.66	1900.4	7.0	0.05	0.13	0.23	0.37	0.54

2.2 Probability for Characteristic Earthquake

Based on the concept of time-predictable model on the characteristic earthquakes, we can estimate the probability of recurrence for each fault. Young and Coppersmith (1985) used slip rate of faults on evaluation of probability for avoiding the underestimating probability of large earthquake. Table 2.5 shows return period estimated from trenching survey and monitoring of active faults, and averaged return period used in this study. The longest return period is 1500 years for the Hsincheng fault, and the shortest one is 110 years for the Milun fault. Taking occurred time of last event, we can estimate the probabilities of each fault system. Results are listed in Table 2.6. The larger probabilities of Tachienshan-Chukou fault and Milun fault with potential magnitude 7.3 are 5.43% and 9.39%, respectively, in next 10 years.

Table 2.5 Return period for characteristic faults from trenching survey and monitoring of active faults

Fault name	Estimated return period (yr)			Return period used in this study (yr)
	Trenching survey	Monitoring of active fault		
		Long-term	Short-term	
Hsincheng F.	1300~1850	*	167~237	1500
Shihtan F.	*	*	167	
Shenchoshan F.	*	*	138	300
Tuntzuchiao F.	*	*	424	
Chelungpu F. (northern)	341~892	392~980	641~5769	
Chelungpu F. (middle)	298~731	269~476	374~749	375
Chelungpu F. (southern)	408~625	212~532	103~516	
Meishan F.	*	*	409~631	300
Tachienshan F.	*	*	8~390	200
Chukou F.	*	*	*	
Hsinhua F.	*	16~152	20~206	120
Milun F.	*	*	67~178	110
Yuli F.	*	*	625~2187	
Chishang F.	240	*	*	240
Chimei F.	*	*	*	

Table 2.6 Probabilities for characteristic faults in next 10, 20 30, 40 and 50 year

Fault name	Return period	T_e	Last event	M_u	Probability in T_p year(%)				
					10	20	30	40	50

Hsincheng F.	1500	196.0	1811	6.60	0.00	0.01	0.01	0.02	0.02
Shihtan F. Shenchoshan F. Tuntzuchiao F.	300	72.7	1935/4/21	7.10	0.35	0.94	1.82	3.04	4.61
Chelungpu F.	375	8.3	1999/9/21	7.30	0.00	0.00	0.00	0.00	0.01
Meishan F.	300	101.8	1906/3/17	7.10	1.21	2.77	4.70	6.98	9.57
Tachienshan F. Chukou F.	200	100.0	*	7.30	5.43	11.28	17.36	23.51	29.61
Hsinhua F.	120	61.1	1946/12/5	6.10	8.50	18.10	28.03	37.69	46.69
Milun F.	110	56.2	1951/10/22	7.30	9.39	19.99	30.82	41.16	50.60
Yuli F. Chishang F. Chimei F.	140	56.1	1951/11/25	7.30	0.41	1.18	2.44	4.23	6.58

3. Shake map

After estimating the probability of earthquakes recurrence, we can predict the ground motion induced by both of the potential earthquakes and the characteristic ones. The main factors that affect the attenuation relationship are the existence of site effects. It is believed that the systematic bias mainly comes from the site effects. Therefore, it is necessary to take account of the site effects in applying the attenuation relationship of PGA, and the results in estimation of seismic hazard will be improved. Up to date, the sites for stations of the Taiwan Strong-motion Instrumentation Program (TSMIP) deployed by the CWB and Central Mountain Array (CMA) deployed by the Academia Sinica still not been classified explicitly. In this study, we used two steps to predict the best results of PGA shake map.

First step, we got the first PGA of each site by attenuation relationship of PGA (Jean, 2001), which used more than 3000 seismic records from 59 earthquake events to study the attenuation relationship of PGA, which follows the model proposed by Campbell (1997). The attenuation equation can be expressed as follows:

$$Y_{att} = 0.00369e^{1.75377m}[R+0.12220e^{0.78315m}]^{-2.05644} \quad (2.4)$$

where Y_{att} is predicted PGA value and R is the closest distance to the source.

Second step, the site correction of each station of the TSMIP and CMA can be simplified by the following law:

$$\ln(PGA_{obs})_S = C0 + C1 \times \ln(Y_{att})_S \quad (2.5)$$

where $(PGA_{obs})_S$ is the observed PGA value, and $(Y_{att})_S$ is the predicted PGA value obtained by the attenuation relationship law. In Eqn. 2.5, the values of C0 and C1 are the site-dependent parameters for corrections on site effects. The selection criteria for earthquakes are $M_L > 4.0$ and focal depth < 50 km. All seismograms are well recorded by the Taiwan Rapid Earthquake Information Release System (TREIRS) system, TSMIP system and CMA system. The results reasonably agree with the surface geology from published maps.

Figure 4 shows two example of the shake map for two high hazardous faults, i.e., (a) Tachienshan-Chukou Fault with potential magnitude M_L7.3 and recurrence probability 5.43% in next 10 years, and (b) Milun Fault with potential magnitude M_L7.3 and recurrence probability 9.39% in next 10 years.

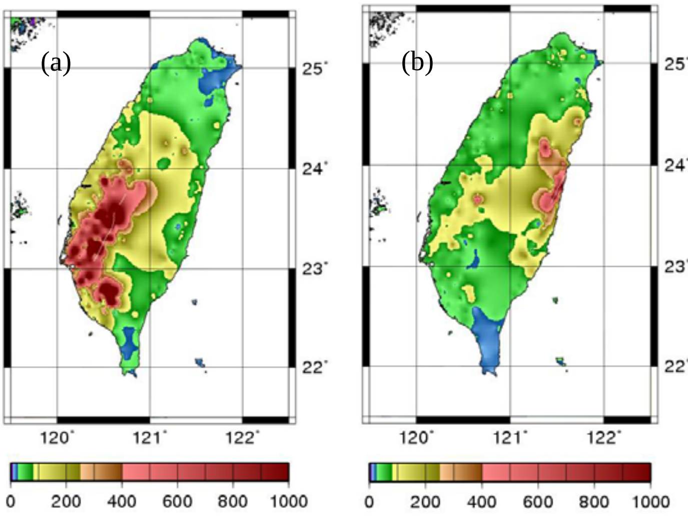

Figure 4 Three examples of shake map for (a) Tachienshan-Chukou Fault (M_L=7.3, 5.43% in next 10 years) and (b) Milun fault (M_L=7.3, 9.39% in next 10 years)

4. SUMMARY

From Tables 2.1, 2.2, 2.3, and 2.4, four regions, i.e., S003, S006, S008, and S009 belong to high seismic potential high hazards. On the contrary, the regions, i.e., S001, S004, and S012 are low seismic hazards. Compared with the tectonic of Taiwan area, it shows regions close to collision zone between plates with high seismic hazards, and far away from collision with low ones. The probabilities of Tachienshan-Chukou fault and Milun fault with potential magnitude 7.3 are 5.43% and 9.39%, respectively, in next 10 years. According to shake map of Tachienshan-Chukou fault with M_L7.3, the shake intensity reaches sixth degree for large area with high population and should pay more attenuation.

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