地震災害鏈風險評估及管理研究中心 E-DREM研討會

地震誘發山崩之早期預估

Early Estimates of Landslides After a Major Earthquake

Chyi-Tyi Lee
Graduate Institute of Applied Geology,
National Central University, Taiwan

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INTRODUCTION

This presentation will include two major parts:

- Development of an earthquake-induced **Landslide Prediction Model** for predicting shallow landslides at a general region where the model was trained by using previous EQ-induced landslides, landslide causative factors, and EQ intensity data.

- Application of the model to **Early Estimate of triggered Landslides** after a major earthquake by inputting EQ intensity data, which are estimated from a GMPE for Arial intensity. Suppose earthquake location and magnitude are already known. It will be better if fault rupture information is also known.

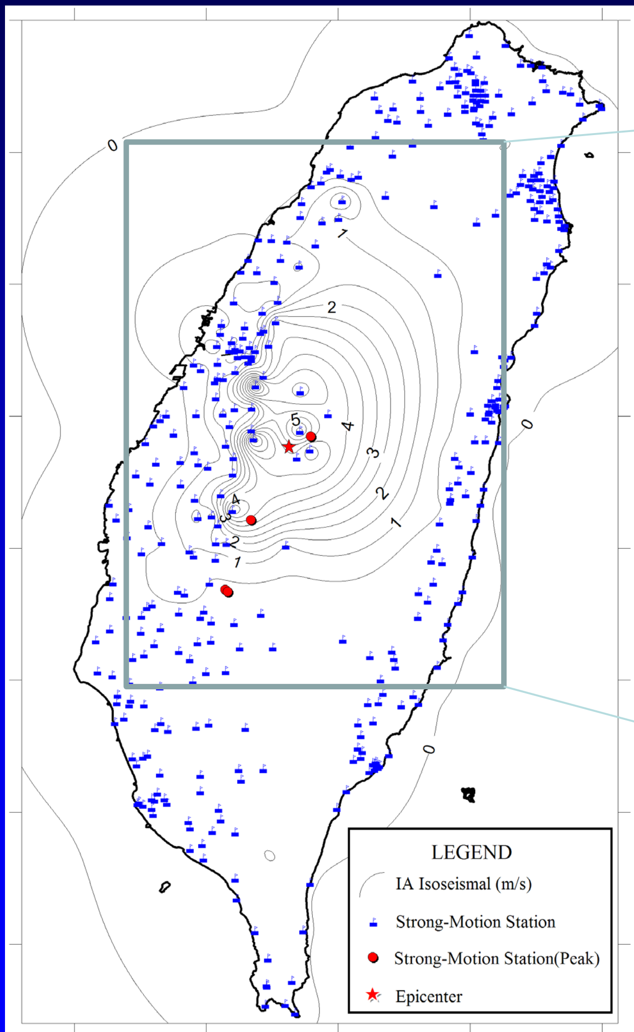
Development of a Landslide Prediction Model

- First, a landslide susceptibility analysis is performed to built a landslide susceptibility model which represents relative grades of slope instability at the region.

- Then, using landslide data, Arias intensity data, and susceptibility values at each study grid, an empirical relationship taking Arias intensity and susceptibility value as two independent variables and the probability of landslide failure as a dependent variable can be developed.

- The empirical formula then can be used as a landslide prediction model, providing the distribution of Arial intensity and susceptibility values at a region are known.

Arias Intensity Map of the Chi-Chi Earthquake



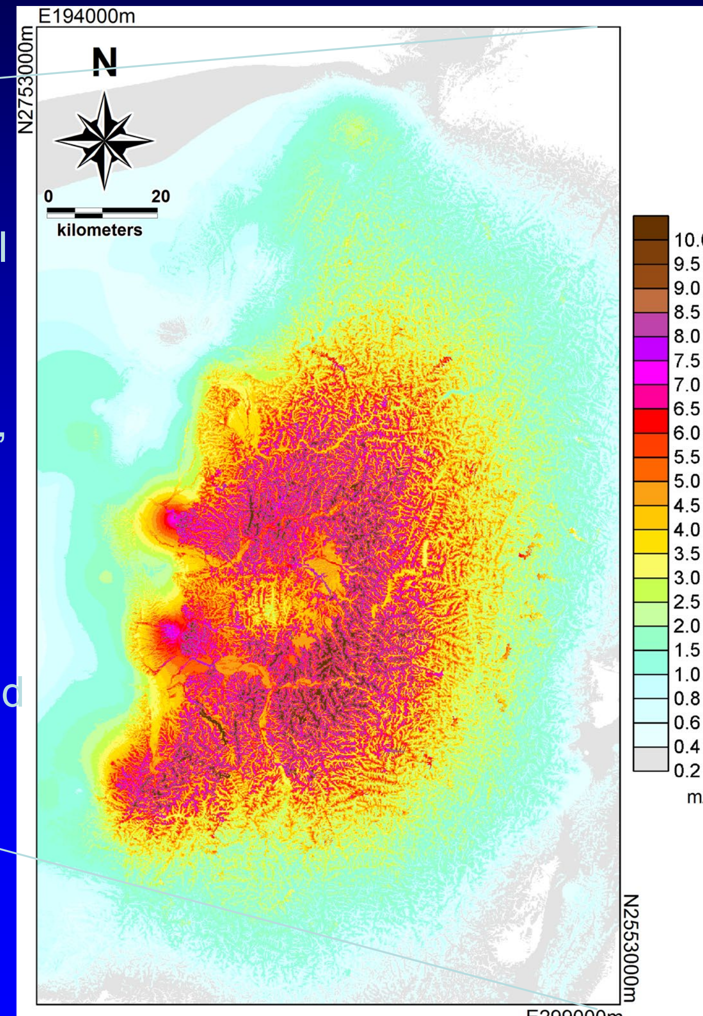
Arias Intensity

The following the empirical formula proposed by Lin and Lee (2003) is used in the topographic correction,

$$I_a' = f I_a ,$$

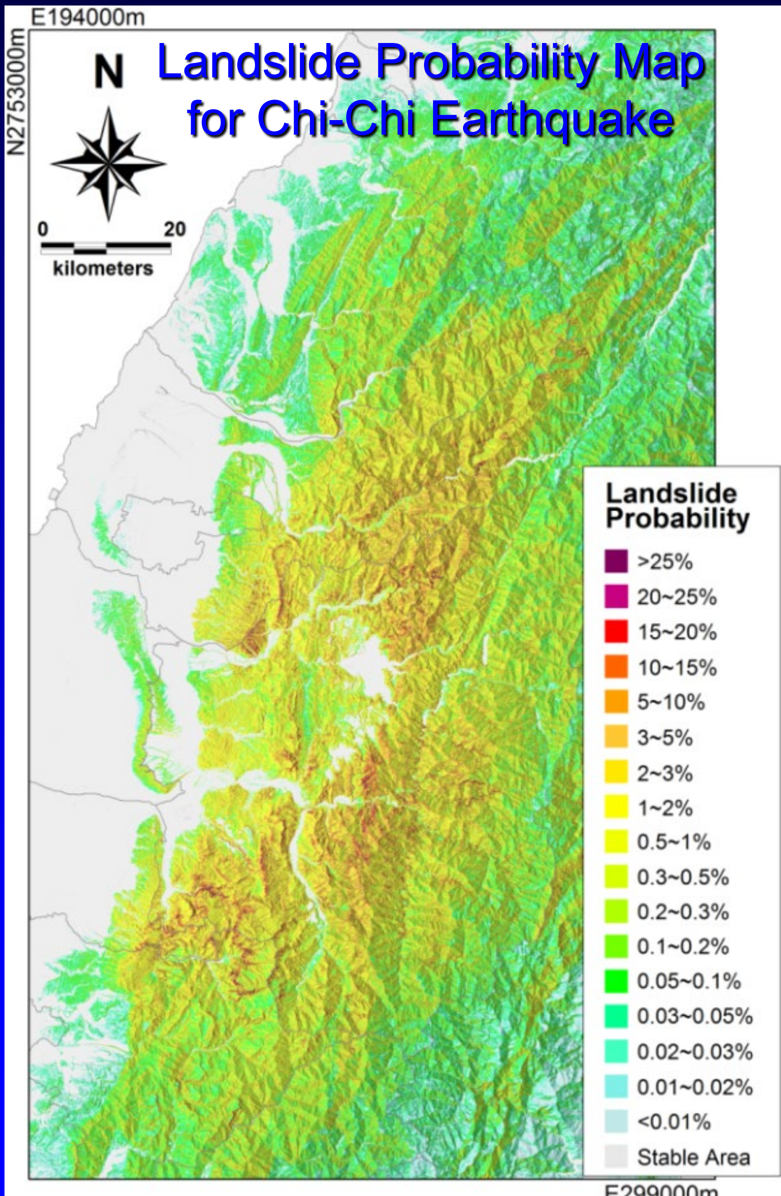
$$f = \sqrt{h / 93.8 + 0.287} + 0.464$$

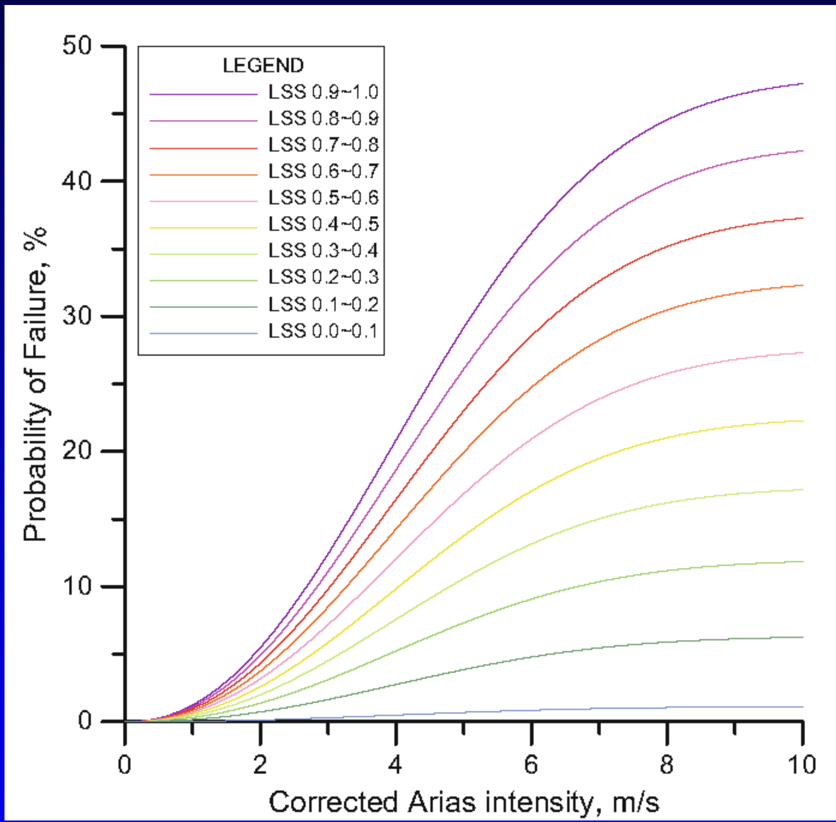
where I_a is the Arias intensity; I_a' is the corrected one; f is the amplification factor; and h is the height relative to riverbed in meters.



Corrected Arias Intensity

The Landslide Prediction Model





$$y = 43.928\lambda(1 - e^{-11.956\lambda^{0.994}})(1 - e^{-0.020x^{2.669}})$$

x: corrected Arias intensity,

y: probability of failure,

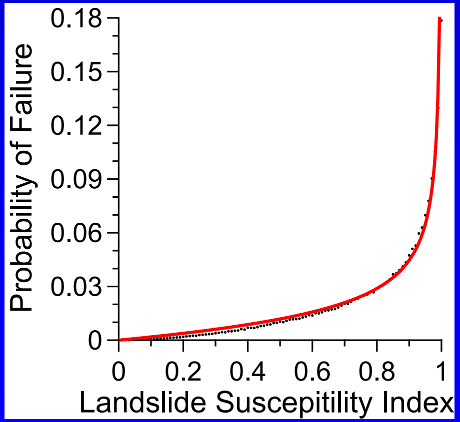
λ: event-independent susceptibility.

Early Estimate of triggered Landslides

- The application requires a scenario earthquake or a return period earthquake, an **Arias intensity map**, and a **landslide susceptibility map** of the region. The output is a **probability of landslide failure map**.

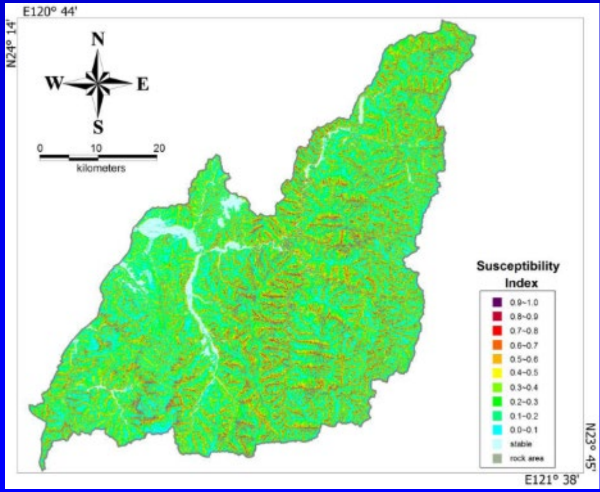
- The probability of landslide failure at a study grid is a spatial probability of landslide occurring at the grid.

The probability of landslide failure is calculated at each susceptibility bin and each Arias intensity bin, and is the ratio of failure grids divided by total grid.

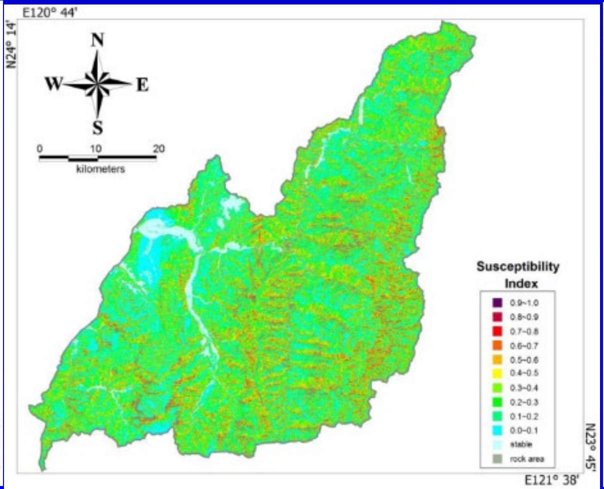


Early Estimate of triggered Landslides

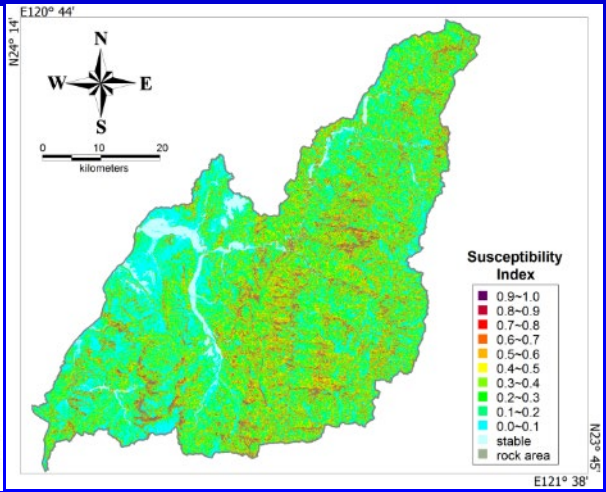
- The landslide susceptibility map could be built from a **multi-temporal landslide inventory** of the region with no restriction of earthquake triggered ones, or it is trained from an **event-based landslide inventory** of earthquake-induced or rain-induced (Lee, et al., 2008a,b).



2004 Typhoon Mindulle



Multi-temporal inventory



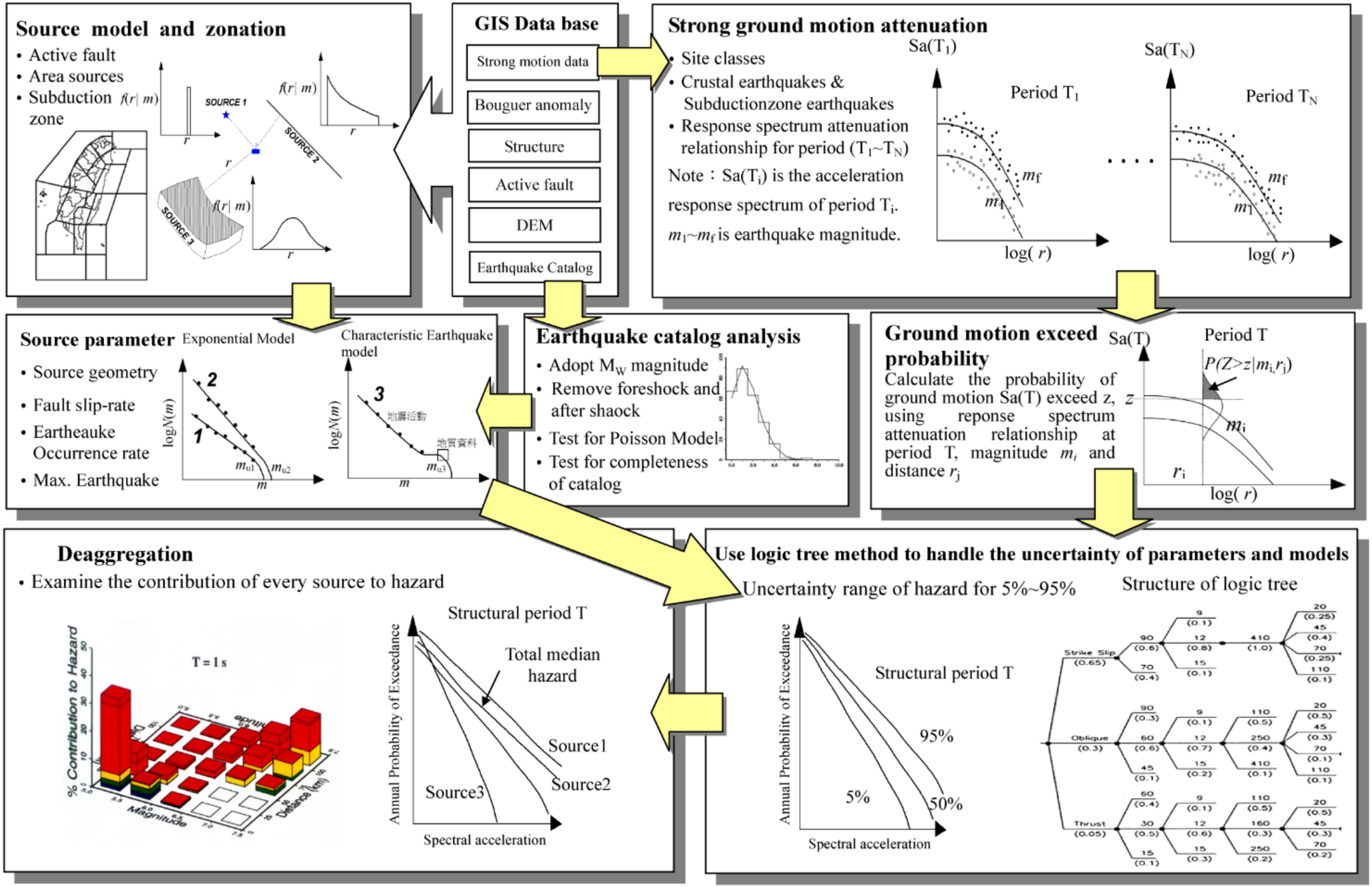
1999 Chi-Chi EQ

Early Estimate of triggered Landslides

- The **Arias intensity map** could be estimated from a scenario earthquake or from a probabilistic seismic hazard analysis (**PSHA**).

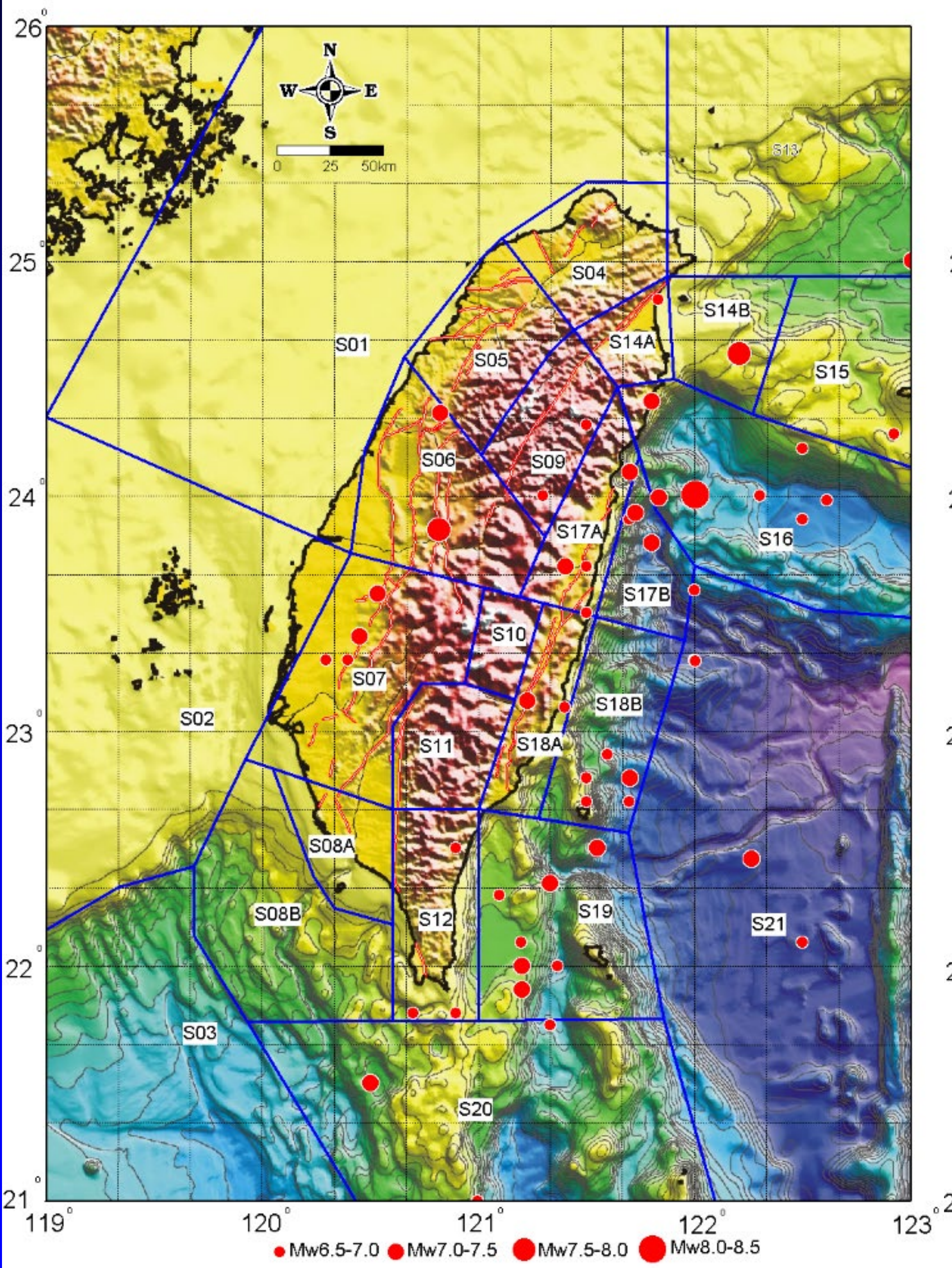
The following slides introduce how to develop a return-period Arias intensity may form PSHA and then used in developing a return-period landslide probability map.

Seismic Hazard Analysis Procedure

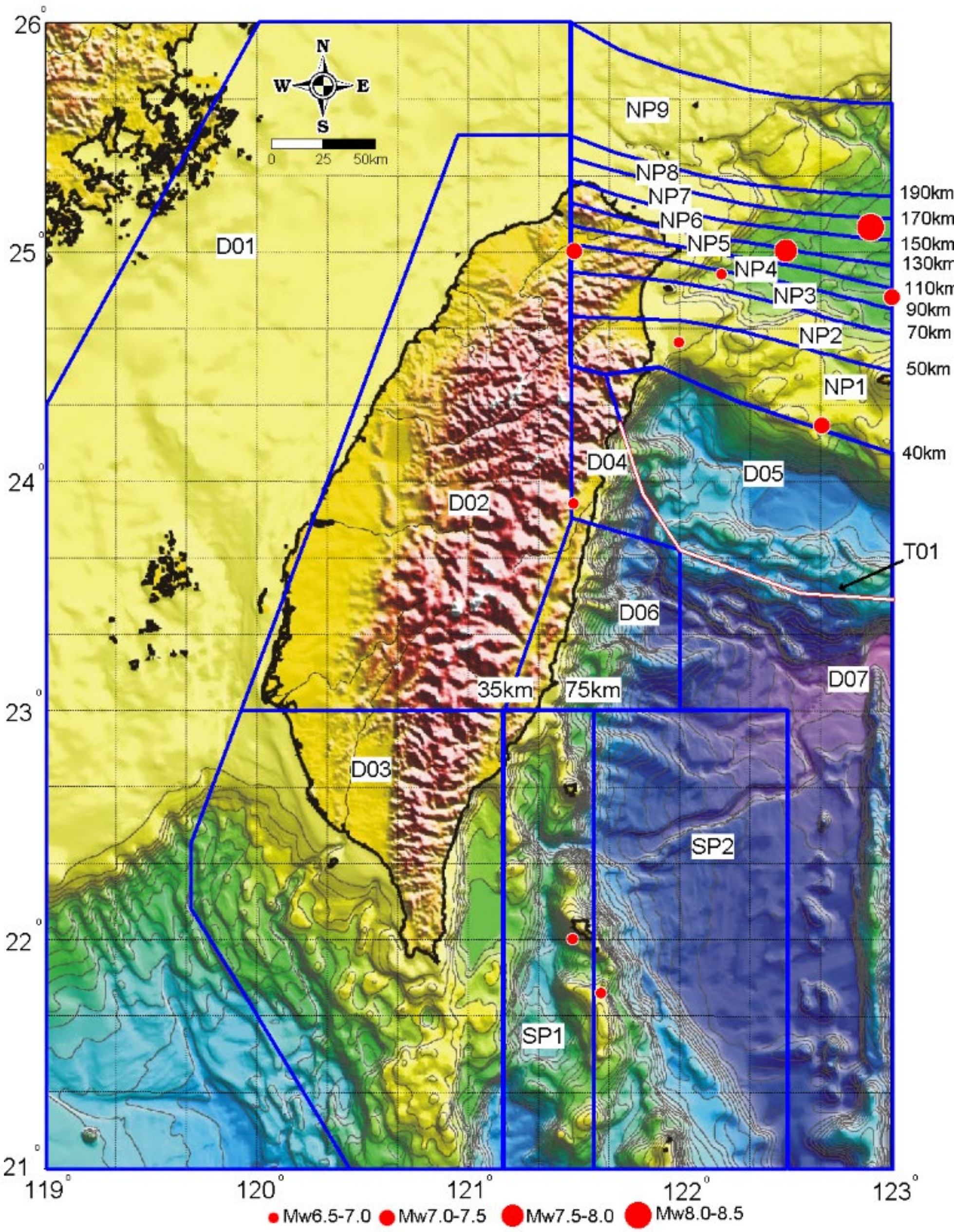


Source Model

Regional Source（Depth≦35km)

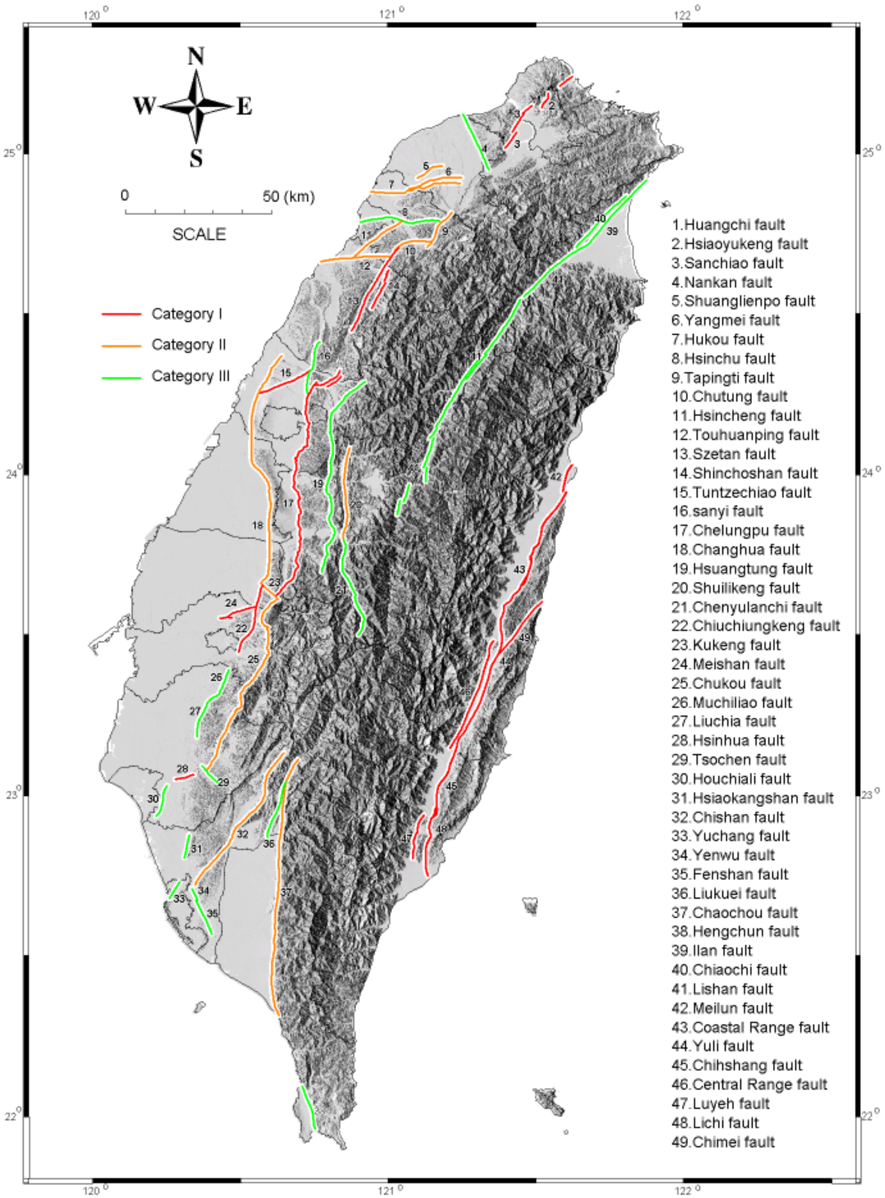


Regional Source（Depth>35km)



Source Model

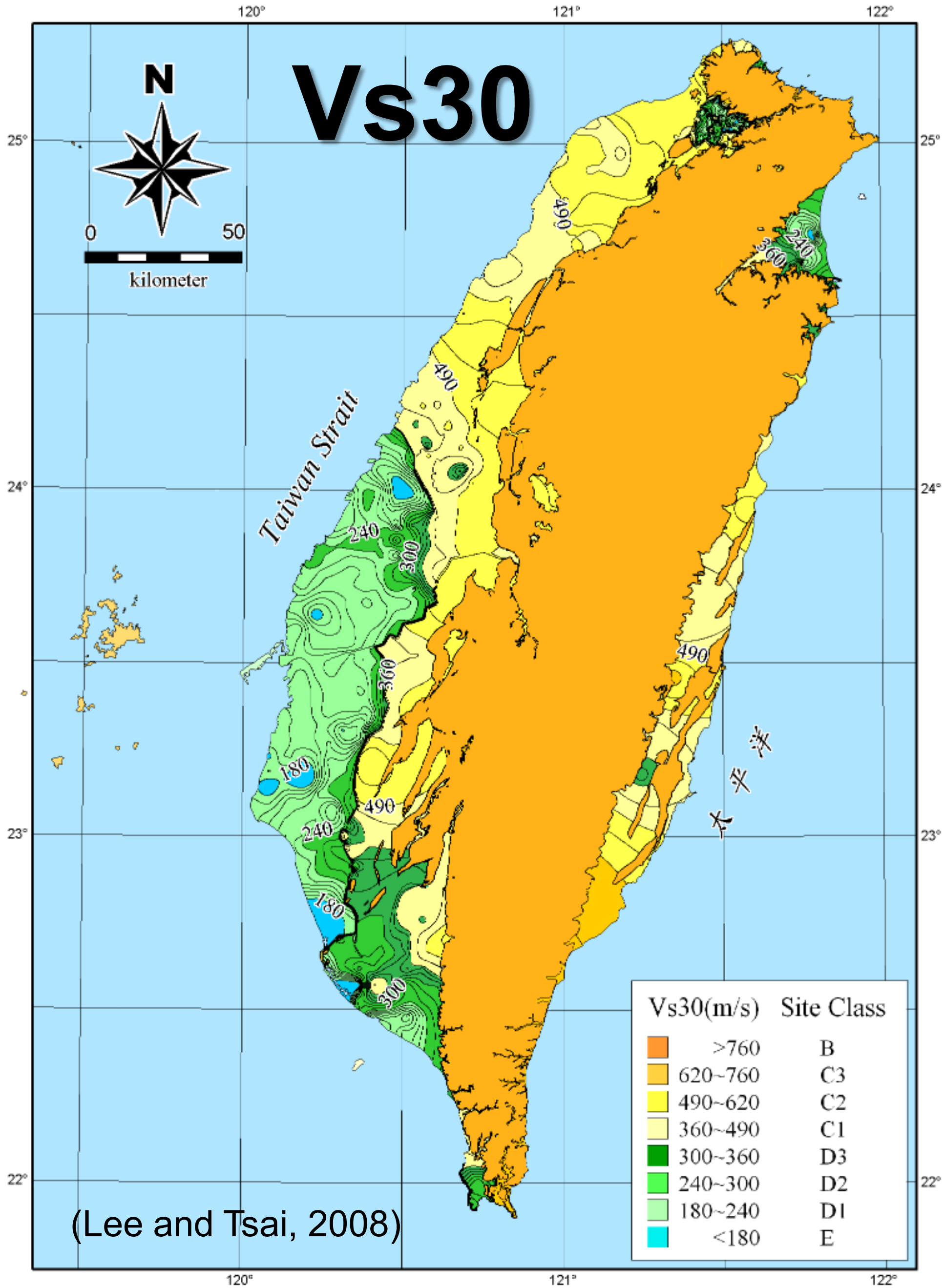
Active faults in Taiwan

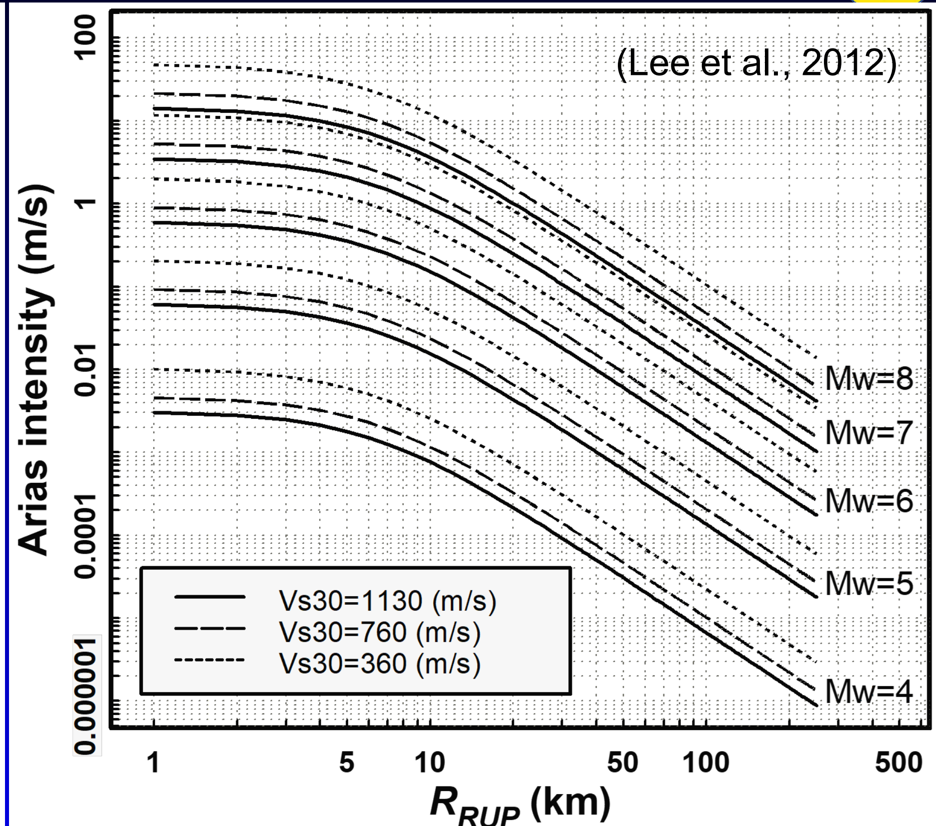


Assessment of Fault Parameters

Fault No.	Fault Name	Strike	Dip (degree)	Fault mechanism	Length (km)	Fault rupture depth (km) Top	Fault rupture depth (km) Button	Fault rupture width (km)	Displacement (m)	Maximun rupture area (km^2)	Slip rate (mm/yr) (weighting)	Maximun earthquake magnitude Mu (weighting)	Recurrence interval (year) Youngs and Coppersmith, 1985	Recurrence interval (year) Matsuda, 1975	Recurrence interval (year) Bolina, 1970
01+02+03	Huangchi+ Hsiaoyukeng+ Sanchiao	NNE	60SE	Norma & Sinistral	36	0	15	17	1.8	624	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.8(0.2) 7.0(0.6) 7.2(0.2)	543	746	568
04	Nankan	NNW	80NW	Normal& Dextral	22	0	10	10	0.7	223	0.2(0.2) 0.4(0.6) 0.6(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	1352	1896	1492
05	Shuanglienpo	ENE	50SE	Reverse	12	2	10	10	0.4	125	0.2(0.2) 0.5(0.6) 0.8(0.2)	6.0(0.2) 6.2(0.6) 6.4(0.2)	567	1036	831
06	Yangmei	ENE	50NW	Reverse	20	2	10	10	0.8	261	0.2(0.2) 0.5(0.6) 0.8(0.2)	6.4(0.2) 6.6(0.6) 6.8(0.2)	1082	1704	1334
07	Hukou	ENE	45SE	Thrust	32	0	12	17	1.5	543	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	733	1362	1041
08	Hsinchu	E-W	45S	Thrust	28	0	12	17	1.4	475	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.6(0.2) 6.8(0.6) 7.1(0.2)	395	832	639
09	Tapingti	NNE	45SE	Thrust	15	0	12	17	0.8	255	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.3(0.2) 6.5(0.6) 6.8(0.2)	653	1378	1080
10	Chutung	NE	50SE	Reverse	14	0	12	16	0.7	219	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	760	1249	983
11	Hsincheng	N40E	45SE	Thrust	22	0	12	17	1.1	373	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.5(0.2) 6.7(0.6) 7.0(0.2)	267	532	412
12	Touhuanping	E-W	80S	Dextral	27	0	12	12	1.0	329	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.5(0.2) 6.7(0.6) 6.9(0.2)	242	392	304
13	Szetan	N10E	75W	Reverse	35	0	12	12	1.3	435	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	259	471	362
14	Shinchoshan	N10E	60E	Reverse	16	0	12	14	0.7	222	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	180	302	238
14BT	Miaoli blind thrust	N10E	30E	Reverse & Dextral	37	2	15	26	2.6	962	2.5(0.2) 5.0(0.6) 7.5(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	223	397	298
15	Tuntzechiao	N60E	90	Dextral	20	0	15	15	0.9	300	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.4(0.2) 6.6(0.6) 6.8(0.2)	226	368	287
16	Sanyi	NNE	40E	Thrust	22	0	15	23	1.5	513	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1313	1005
17	Chelungpu	N-S	40E	Thrust	90	0	20	31	6.8	2800	8(0.2) 15(0.6) 23(0.2)	7.5(0.2) 7.7(0.6) 7.9(0.2)	182	268	194
18	Changhua	NNS	30E	Thrust	85	2	15	28	5.4	2354	8(0.2) 15(0.6) 23(0.2)	7.4(0.2) 7.6(0.6) 7.8(0.2)	153	226	165
19	Tamoupu- Hsuangtung	N-S	45E	Thrust	70	0	15	21	3.8	1485	0.4(0.2) 0.8(0.6) 1.2(0.2)	7.2(0.2) 7.4(0.6) 7.6(0.2)	2282	3306	2444
20	Shuilikeng	N-S	50E	Thrust	32	0	15	20	1.8	627	0.3(0.2) 0.6(0.6) 0.9(0.2)	6.8(0.2) 7.0(0.6) 7.2(0.2)	1810	2495	1898
21	Chenyulanchi	N-S	50E	Thrust	36	0	15	20	2.0	705	0.4(0.2) 0.8(0.6) 1.2(0.2)	6.8(0.2) 7.0(0.6) 7.3(0.2)	1207	2023	1533
22	Chiuchiungkeng	NNE	35E	Thrust	24	0	15	26	1.8	628	4(0.2) 10(0.6) 15(0.2)	6.8(0.2) 7.0(0.6) 7.2(0.2)	109	150	114
23	Kukeng	NW	90	Sinistral	10	0	15	15	0.5	161	1.5(0.2) 3.0(0.6) 4.5(0.2)	6.1(0.2) 6.3(0.6) 6.6(0.2)	136	204	162
24	Meishan	N75E	90	Dextrtal	14	0	15	15	0.7	216	3.0(0.2) 6.0(0.6) 9.0(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	94	124	98
24BT	Chaiyi blind thrust	N10E	30E	Thrust	36	2	15	26	2.5	936	6(0.2) 12(0.6) 18(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	122	163	122
25	Chukou	NE	40E	Thrust	70	0	15	25	4.5	1745	5(0.2) 10(0.6) 15(0.2)	7.3(0.2) 7.5(0.6) 7.7(0.2)	221	298	219
26+27	Muchiliao+Liuchia	NNE	35SE	Thrust	30	0	15	26	2.2	785	4.0(0.2) 8.0(0.6) 12.0(0.2)	6.9(0.2) 7.1(0.6) 7.3(0.2)	155	217	164
28	Tsochen	NW	90	Sinistral	12	0	15	15	0.6	180	1.3(0.2) 2.5(0.6) 3.8(0.2)	6.2(0.2) 6.4(0.6) 6.6(0.2)	192	263	209
29	Hsinhua	N70E	90	Dextrtal	12	0	15	15	0.6	180	2.5(0.2) 5.0(0.6) 7.5(0.2)	6.2(0.2) 6.4(0.6) 6.6(0.2)	96	132	104
30	Houchiali	NNE	60W	Thrust	12	0	15	17	0.7	208	2.5(0.2) 5.0(0.6) 7.5(0.2)	6.2(0.2) 6.4(0.6) 6.7(0.2)	83	145	114
30BT	Tainan blind thrust	N10E	30E	Thrust	36	2	15	26	2.5	936	5(0.2) 10(0.6) 15(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	146	195	146
31	Hsiaokangshan	NNE	50SE	Reverse	12	0	15	20	0.7	235	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.3(0.2) 6.5(0.6) 6.7(0.2)	347	523	411
32	Chishan	NE	45E	Thrust	60	0	15	21	3.3	1273	1.5(0.2) 3.0(0.6) 4.5(0.2)	7.1(0.2) 7.3(0.6) 7.5(0.2)	507	796	592
50	Yueikangshan	N70E	80S	Reverse & Sinistral	12	0	10	12	0.5	139	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.0(0.2) 6.2(0.6) 6.5(0.2)	312	554	443
33	Yuchang	NE	50E	Reverse	12	0	12	16	0.6	195	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.2(0.2) 6.4(0.6) 6.6(0.2)	437	694	548
34+35	Yenwu+Fenshan	NW	50E	Reverse	21	0	12	16	1.0	329	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.5(0.2) 6.7(0.6) 6.9(0.2)	487	653	507
36	Liukuei	NE	50E	Reverse	20	0	15	20	1.2	392	0.2(0.2) 0.5(0.6) 0.8(0.2)	6.5(0.2) 6.7(0.6) 7.0(0.2)	1229	2196	1697
37a	Chaochou(north)	N-S	50E	Reverse	55	0	20	26	3.7	1436	2.0(0.2) 4.0(0.6) 6.0(0.2)	7.2(0.2) 7.4(0.6) 7.6(0.2)	471	647	479
37b	Chaochou(south)	N-S	50E	Reverse	40	0	20	26	2.8	1044	1.5(0.2) 3.0(0.6) 4.5(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	433	699	523
38	Hengchun	NNW	50E	Reverse	40	0	20	26	2.8	1044	1.0(0.2) 2.0(0.6) 3.0(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	650	1048	784
39	Ilan	NE	60SE	Normal	30	0	15	17	1.5	520	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	623	882	675
40	Chiaochi	NE	60SE	Normal	25	0	15	17	1.3	433	1.0(0.2) 2.0(0.6) 3.0(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	397	587	452
41a	Lishan(a)	NNE	60E	Normal	30	0	15	17	1.5	520	0.8(0.2) 1.5(0.6) 2.3(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	623	882	675
41b	Lishan(b)	NNE	60E	Normal	25	0	15	17	1.3	433	0.6(0.2) 1.2(0.6) 1.8(0.2)	6.6(0.2) 6.8(0.6) 7.0(0.2)	666	978	753
41c	Lishan(c)	NNE	60E	Normal	30	0	15	17	1.5	520	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1323	1013
41d	Lishan(d)	NNE	60E	Normal	30	0	15	17	1.5	520	0.5(0.2) 1.0(0.6) 1.5(0.2)	6.7(0.2) 6.9(0.6) 7.1(0.2)	940	1323	1013
42	Meilun	N30E	50E	Reverse & Sinistral	30	0	30	39	3.1	1175	10(0.2) 20(0.6) 30(0.2)	7.1(0.2) 7.3(0.6) 7.5(0.2)	83	113	84
43	Ueimei	N30E	50E	Reverse & Sinistral	45	0	30	39	4.5	1762	10(0.2) 20(0.6) 30(0.2)	7.3(0.2) 7.5(0.6) 7.7(0.2)	111	148	109
49	Chimei	N40E	50E	Reverse & Sinistral	25	0	30	39	2.6	979	2.0(0.2) 4.0(0.6) 6.0(0.2)	7.0(0.2) 7.2(0.6) 7.4(0.2)	354	502	377
44	Yuli	N30E	50E	Reverse & Sinistral	48	0	30	39	4.7	1880	8(0.2) 16(0.6) 24(0.2)	7.3(0.2) 7.5(0.6) 7.7(0.2)	130	193	142
45	Chihshang	N25E	50E	Reverse & Sinistral	30	0	30	39	3.1	1175	10(0.2) 20(0.6) 30(0.2)	7.1(0.2) 7.3(0.6) 7.5(0.2)	83	113	84
46	Yuli west	NNE	50W	Reverse & Sinistral	40	0	25	33	3.4	1305	5(0.2) 10(0.6) 15(0.2)	7.1(0.2) 7.3(0.6) 7.5(0.2)	150	243	180
47	Luyeh	N-S	50E	Reverse	18	0	25	33	1.7	587	4.0(0.2) 8.0(0.6) 12.0(0.2)	6.7(0.2) 6.9(0.6) 7.2(0.2)	105	179	137
48	Lichi	N-S	50E	Reverse & Sinistral	24	0	25	33	2.2	783	8(0.2) 16(0.6) 24(0.2)	6.9(0.2) 7.1(0.6) 7.3(0.2)	78	108	82

Site and Attenuation Model





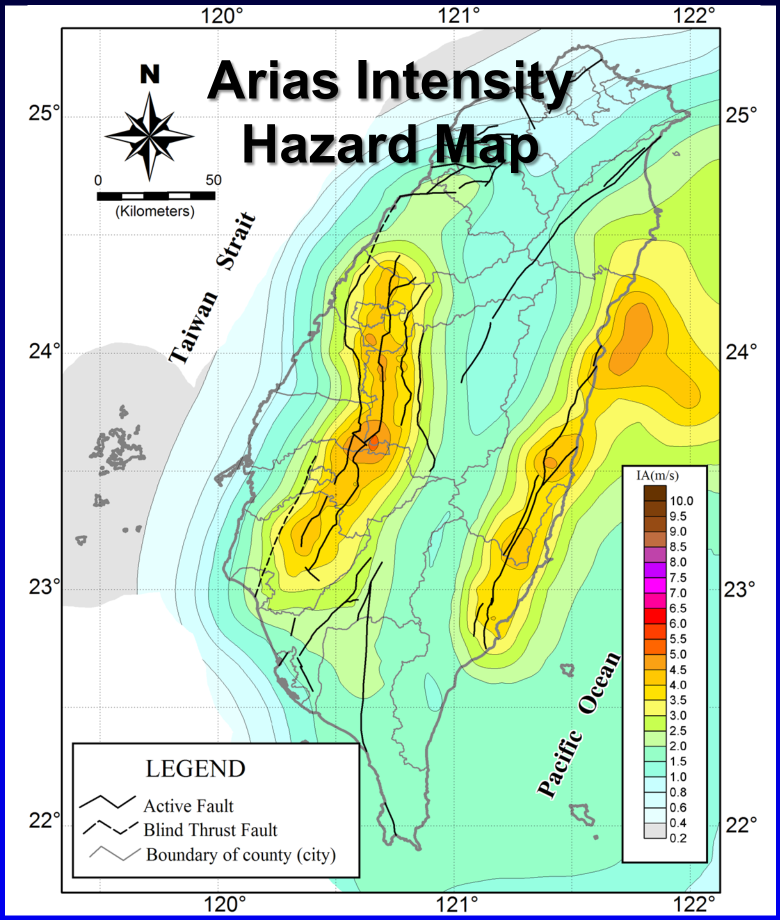
Crustal attenuation curves with different Vs30

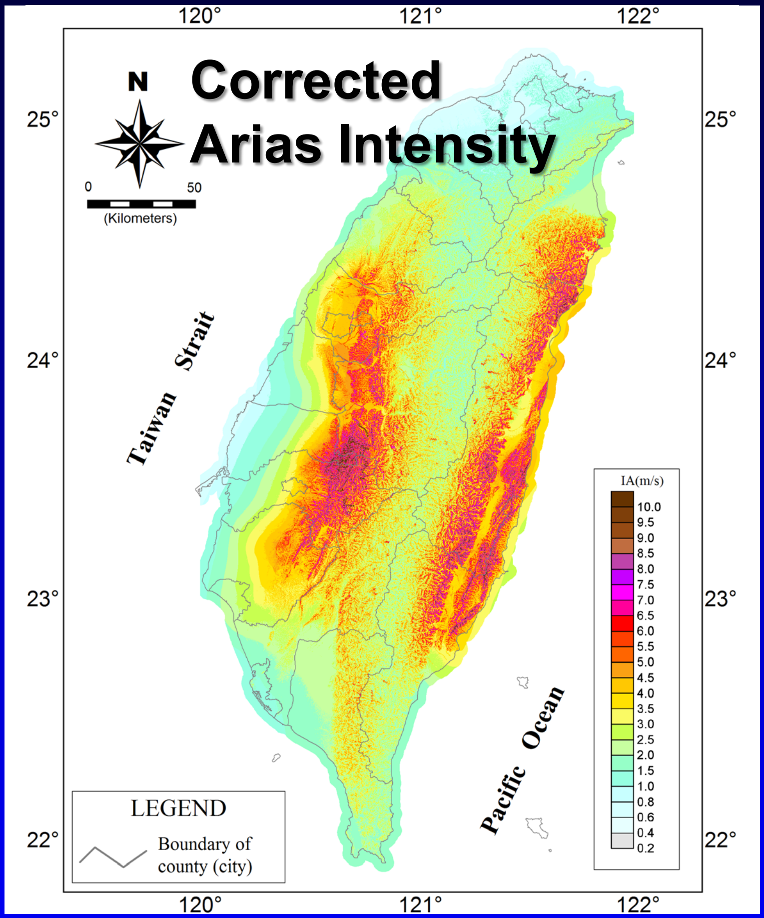
$$\ln I_a = 3.757 - 1.043(M-6) + 18.077\ln(M/6) - 2.251\ln\left(\sqrt{R^2+9.56^2}\right) - 1.042\ln(V_{s30}/1130) - 0.214F_N + 0.22F_R \qquad \sigma = 0.994$$

$$\ln I_a = 4.358 + 3.056(M-6) - 2.325\ln(M/6) - 2.38\ln R - 0.677\ln(V_{s30}/1130) - 0.199F_N + 0.24F_R + 1.447Z_t$$

F_N: mormal faulting mechanism,
F_R: reversel faulting mechanism.

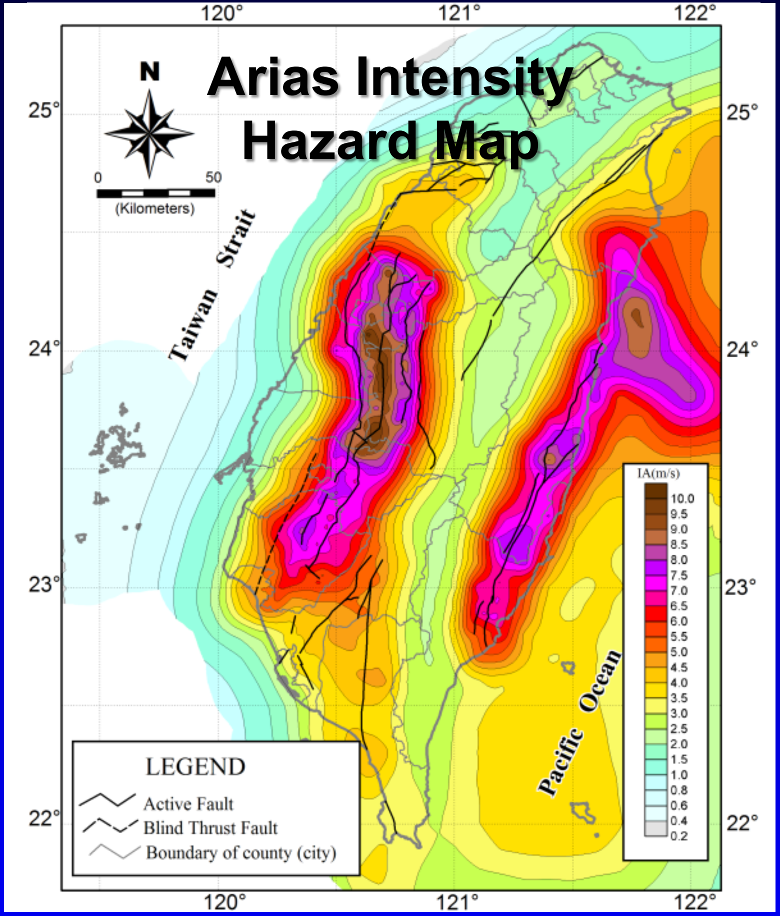
475-year Arias Intensity Map

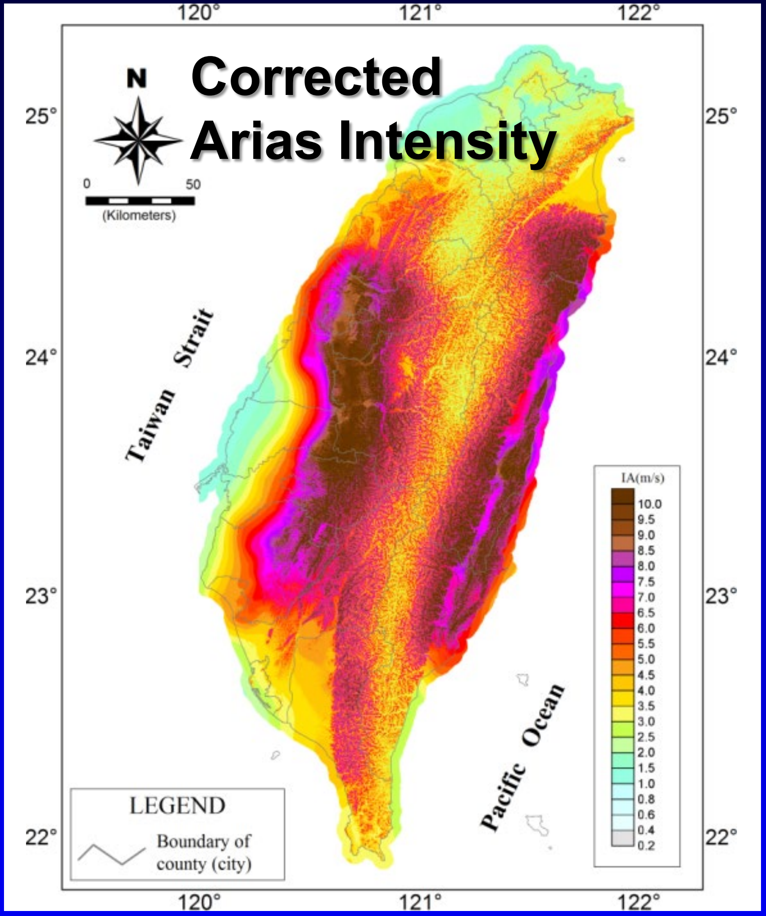




We used our seismic hazard model (Cheng et al., 2007) and a new Arial intensity attenuation relationship (Lee et al., 2012) to perform a PSHA and got a 475-year Arial intensity map for Taiwan (left). Then the Arial intensity was topographically corrected by an empirical formula proposed by Lee et al. (2008). The corrected Arial intensity (right) is then applied to the Chi-Chi seismic landslide hazard model, and then a 475-year seismic landslide hazard map for whole Taiwan is constructed .

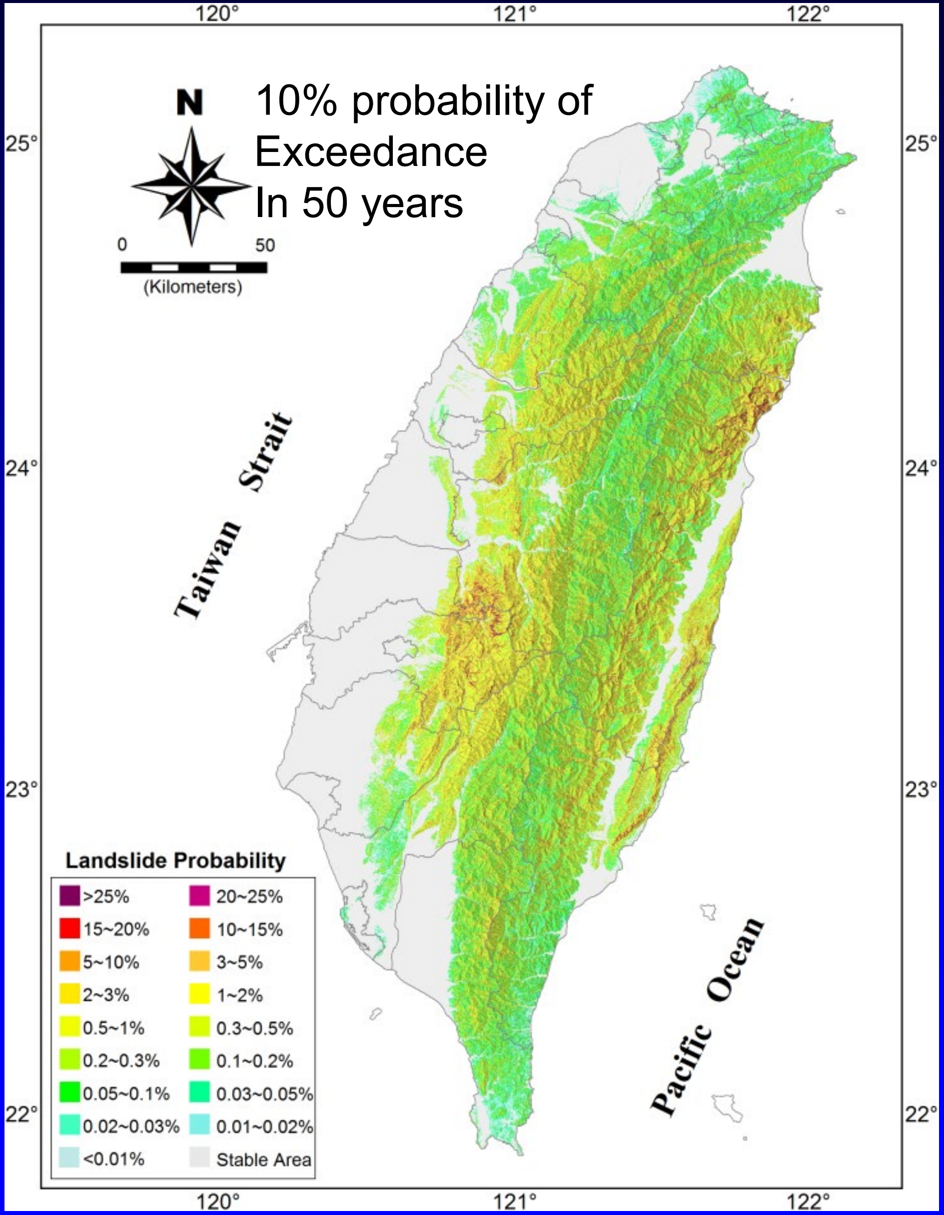
2475-year Arias Intensity Map



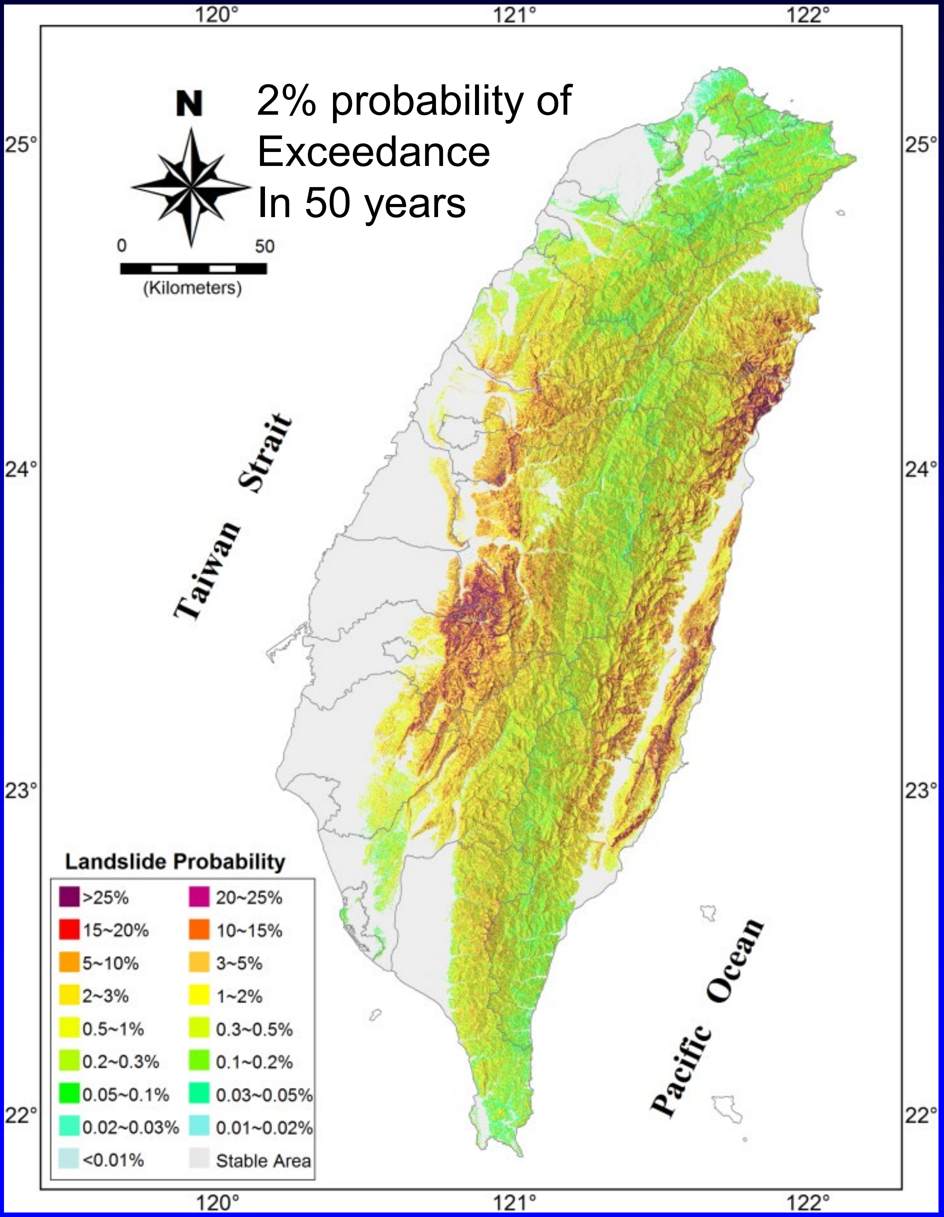


We used our seismic hazard model (Cheng et al., 2007) and a new Arial intensity attenuation relationship (Lee et al., 2012) to perform a PSHA and got a 2475-year Arial intensity map for Taiwan (left). Then the Arial intensity was topographically corrected by an empirical formula proposed by Lee et al. (2008). The corrected Arial intensity (right) is then applied to the Chi-Chi seismic landslide hazard model, and then a 2475-year seismic landslide hazard map for whole Taiwan is constructed .

Seismic Landslide Harzard Map of Taiwan



Landslide Probabilithy Map for 475-year EQ



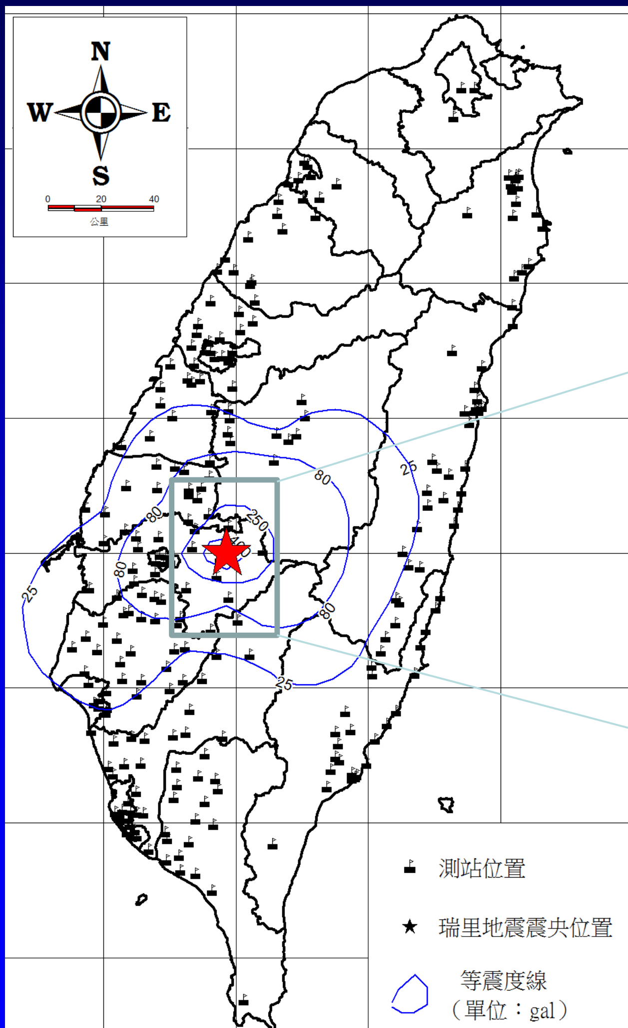
Landslide Probabilithy Map for 2475-year EQ

Early Estimate of triggered Landslides

- The **Arias intensity map** could be estimated from a **scenario earthquake** or from a probabilistic seismic hazard analysis (PSHA).

The following slides introduce how to develop an Arias intensity may for a scenario earthquake and then used in developing a return-period landslide probability map.

Arias Intensity Map of the 1998 M6.2 Jueli Earthquake



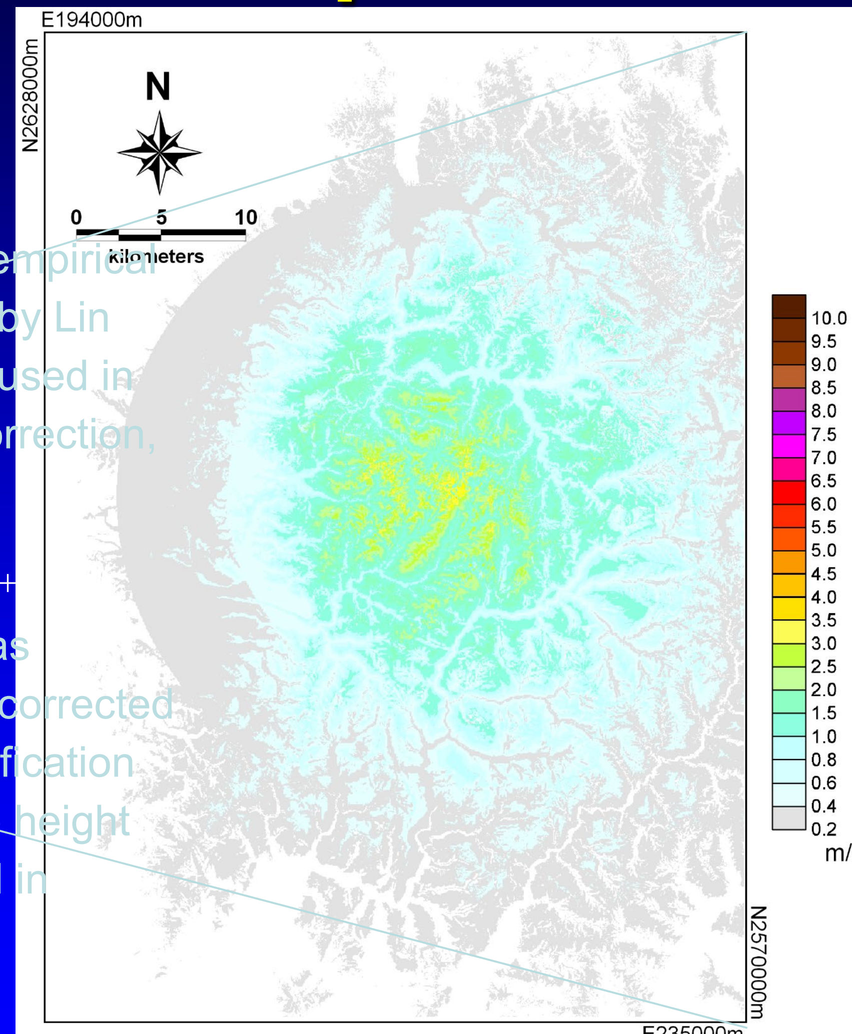
Location map

The following the empirical formula proposed by Lin and Lee (2003) is used in the topographic correction,

$$I_a' = f I_a ,$$

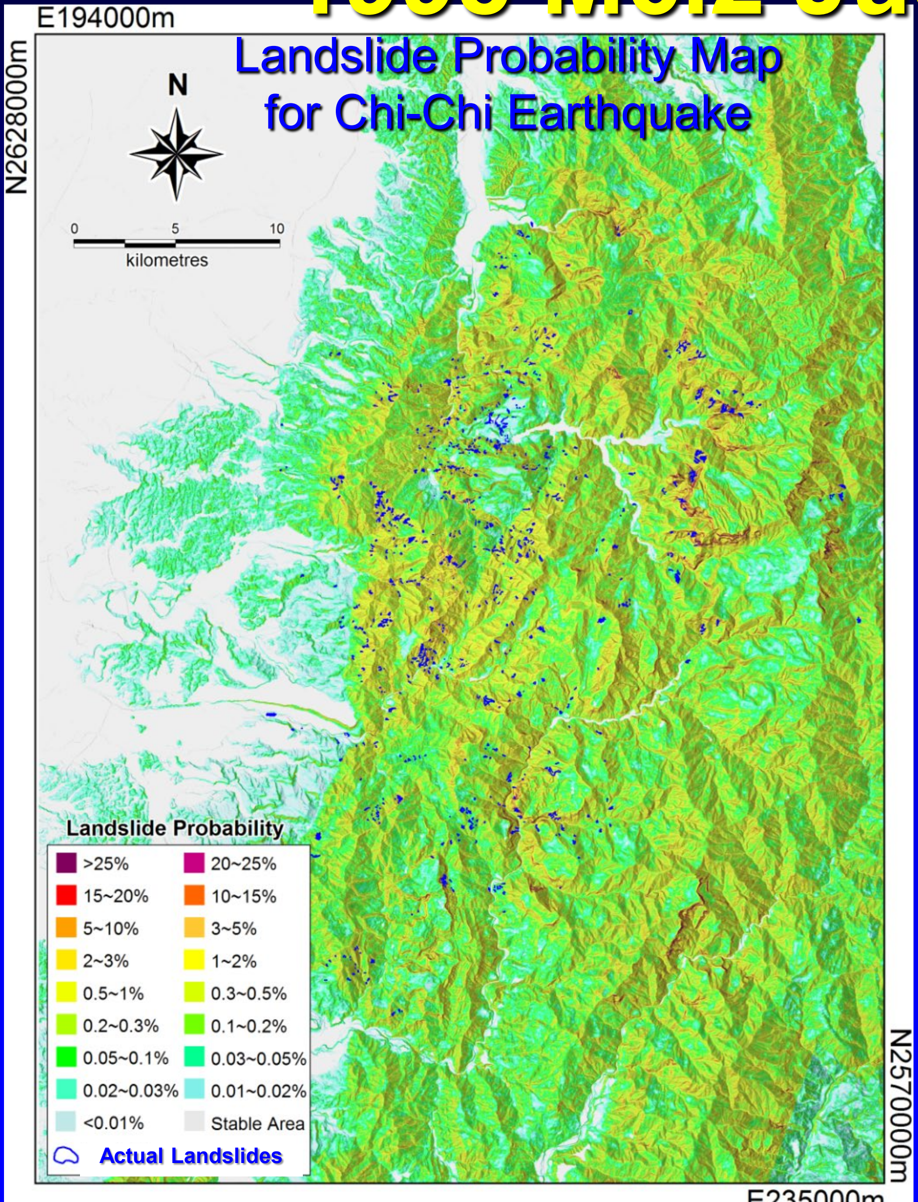
$$f = \sqrt{h / 93.8 + 0.287 +$$

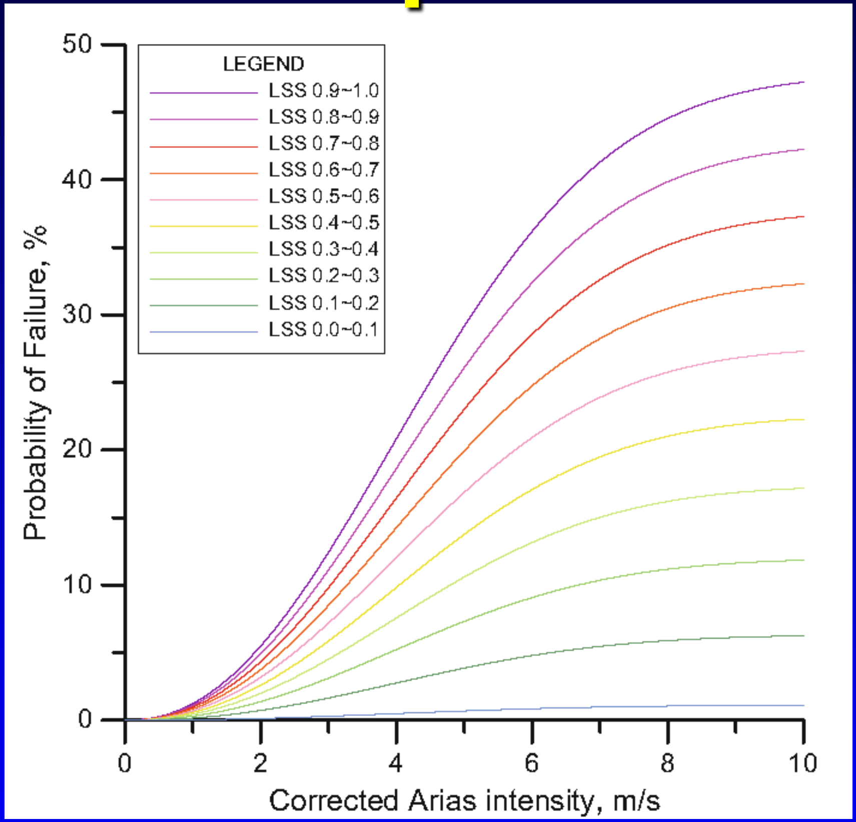
where I_a is the Arias intensity; I_a' is the corrected one; f is the amplification factor; and h is the height relative to riverbed in meters.



Corrected Arias Intensity

Landslide Prediction for the 1998 M6.2 Jueli Earthquake





$$y = 43.928\lambda(1 - e^{-11.956\lambda^{0.994}})(1 - e^{-0.020x^{2.669}})$$

x: corrected Arias intensity,

y: probability of failure,

λ: event-independent susceptibility.

SUMMARY and RECOMMENDATIONS (1/4)

- An earthquake-induced **Landslide Prediction Model** for predicting shallow landslides has been developed. It has been trained by using EQ-induced landslide data, landslide susceptibility values, and topographically corrected Arias intensity of EQ.

- The model can directly applied to map probability of landslide failure of a region under certain return-period EQ-intensity.

- The model can directly applied to **Early Estimate of triggered Landslides** after a major earthquake by inputting EQ intensity data, which are estimated from a GMPE for Arial intensity, providing earthquake location and magnitude are known. It would be better if fault rupture information is also known.

SUMMARY and RECOMMENDATIONS (2/4)

- The present proposed hazard model is good for

  prediction of landslide spatial probability during an earthquake event,

  mapping of the seismic landslide hazard probability for a certain return-period earthquake,

  decision making for regional planning, site selection, hazard mitigation, and

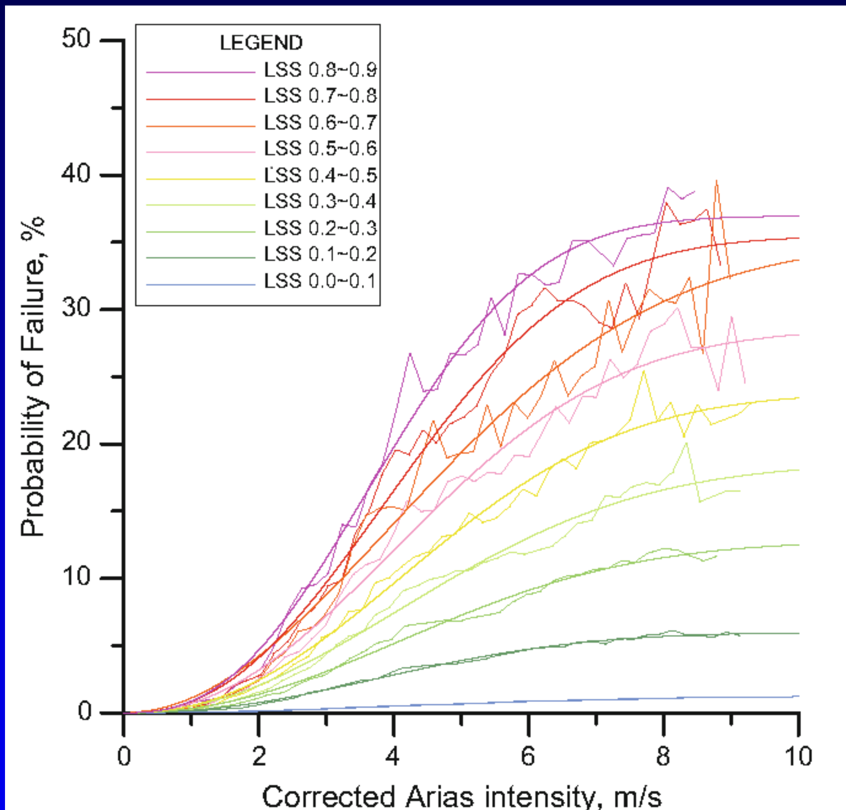
  estimation of sediment products for a drainage basin after an earthquake event.

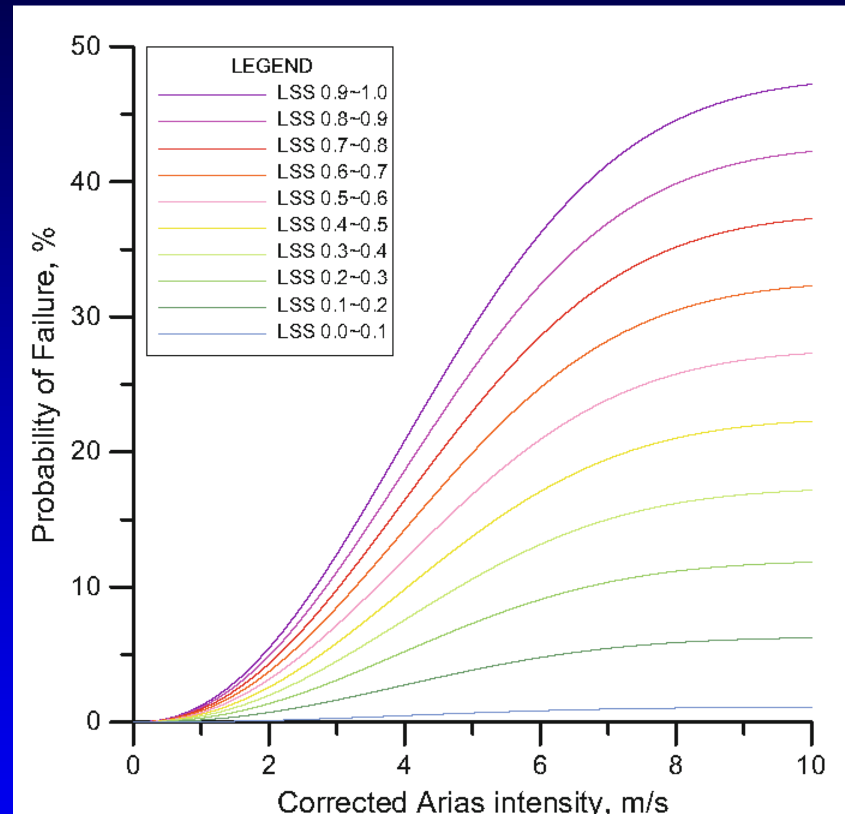
- However, there is still lacking of output in regards to the **landslide magnitude** which is very important in risk assessment. This problem needs further study.

Thanks for your attention!

謝謝

Probability of Failure as a function of Corrected Arias Intensity and λ





A probability of failure curve is fitted with corrected Arias intensity at each susceptibility bin at the first step. Then, a probability of failure as a function of x and λ is developed.

$$y = 43.928\lambda(1 - e^{-11.956\lambda^{0.994}})(1 - e^{-0.020x^{2.669}})$$

x: corrected Arias intensity,

y: probability of failure,

λ: event-independent susceptibility.