Disaster Prevention Research Center,
National Cheng Kung University, Taiwan

Tectono-Hydrology Research Group

AIST The National Institute of Advanced Industrial Science and Technology
Geological Survey of Japan

The study of the mechanisms of earthquake-induced groundwater variation in Taiwan, 2003~2009

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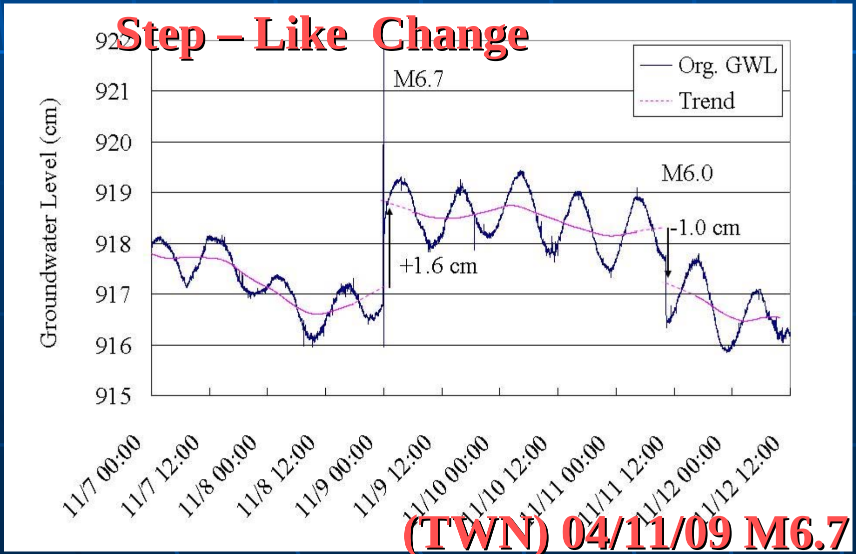
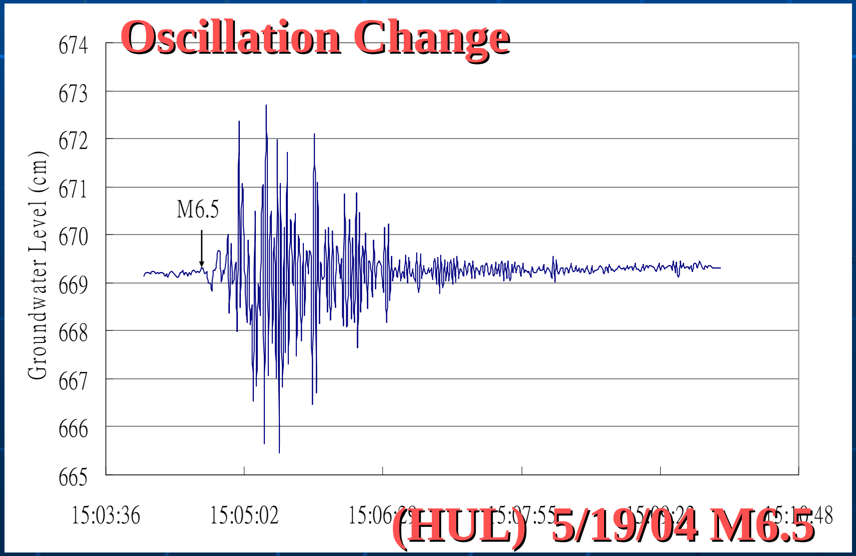
I. Observation (03'~09')

- Total 196 Observation, step changes (S) 36 events, oscillation (O) 129 events, O+S 31 events

Catalog	Events	HUL	TWN	LUJ	NAB	HRD	DHR	TLO	SIP
2003/4/3 Tainan, M=4.9	2			S	S				
2003/6/10 Taitung, M=6.5	4			S	O		O+S		O
2003/6/17 Taitung , M=5.9	2				O				O
2003/12/10 Taitung , M=6.6	7	O+S	O+S	S		S	O+S	O+S	O
2003/12/11 Taitung, M=5.7	1				S				
2003/12/18 Taitung, M=5.8	1	O							



(TWN) 04/11/09 M6.7



(HUL) 5/19/04 M6.5

II. Problem statement

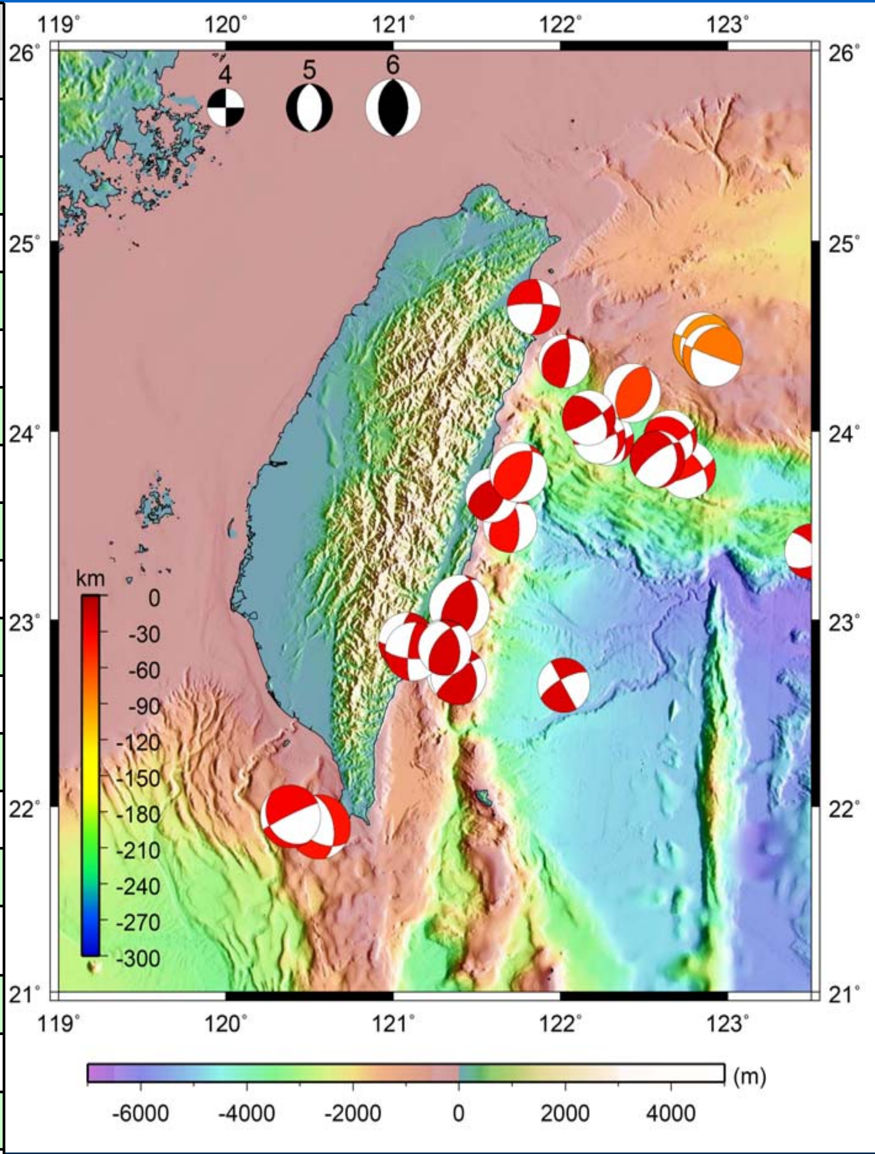
- Observed coseismic patterns can fit to strain model , but the amplitudes are amplify tens~hundreds times compare to the static strain sensitivity estimated from tidal response.

- Some wells seems always coseismic roses or coseismic lowering, them were not expected by the fault-dislocation volumetric strain .

- The mechanism of the coseismic groundwater level changes remains unknown.

Observed coseismic events (03'~09')

No.	Time	Lat.	Long.	Depth (km)	M_L
1	2003/6/10 8:40	23.50	121.70	27.59	6.54
2	2003/12/10 4:38	23.07	121.40	10.00	6.60
3	2004/2/4 3:24	23.38	122.15	4.07	6.03
4	2004/5/16 6:04	23.05	121.98	12.52	6.00
5	2004/5/19 7:04	22.71	121.37	8.68	6.49
6	2004/10/15 4:08	24.46	122.85	58.84	7.03
7	2004/11/8 15:54	23.79	122.76	10.00	6.60
8	2004/11/11 2:16	24.31	122.16	27.3	6.04
9	2005/9/6 9:16	23.96	122.28	16.8	6.12
10	2006/4/1 18:02	22.88	121.08	7.2	6.35
11	2006/4/16 6:40	22.86	121.3	17.9	6.20
12	2006/7/28 15:40	23.97	122.66	28.00	6.06
13	2006/8/28 1:11	24.80	123.07	135.3	6.10
14	2006/10/9 18:01	20.70	119.83	28.00	6.10
15	2006/10/9 19:08	20.77	119.93	8.00	6.10
16	2006/10/11 14:43	20.89	119.9	10.00	6.00
18	2006/12/26 20:34	21.95	120.39	47.03	6.40
19	2007/1/25 18:59	22.65	122.02	20.00	6.20
20	2007/7/23 21:40	23.67	121.72	29.50	6.00



Static Volumetric Strain Sensitivity

	TLO	DHR	LUJ	NBA	TWN	HUL
	Amplitude (10^{-8}) [Phase Shift (degree)]					
Vol. strain by M_2 earth tide, t_e	**1.35 [0]**	**1.37 [0]**	**1.38 [0]**	**1.38 [0]**	**1.35 [0]**	**1.37 [0]**
Vol. strain by M_2 oceanic tidal loading, t_o	**2.08 [-321]**	**0.18 [-276]**	**0.11 [-290]**	**0.11 [-301]**	**0.60 [-227]**	**6.10 [-184]**
Vol. strain by earth + oceanic tide, $t_t = t_e + t_o$	**3.25 [-336]**	**1.40 [-352]**	**1.42 [-356]**	**1.45 [-356]**	**1.04 [-335]**	**4.73 [-185]**
M_2 amplitude(water level, t_w)	**3.72±0.67 [-282±49]**	**6.17±0.60 [-339±23]**	**2.54±0.59 [-350±34]**	**4.24±0.29 [-349±15]**	**3.93±0.27 [-272±21]**	**23.77±0.50 [-21±6]**
Strain sens. by **Water Level** M_2 tide, $Ws = t_w/t_t$ (mm/10^{-8})	**1.14**	**4.39**	**1.78**	**2.92**	**3.78**	**5.02**
Strain sens. by **Coseismic Responses** (mm/10^{-8})	**18.42**	**42.22**	**76.15**	**56.93**	**43.85**	**25.82**

Observed coseismic events (03'~06')

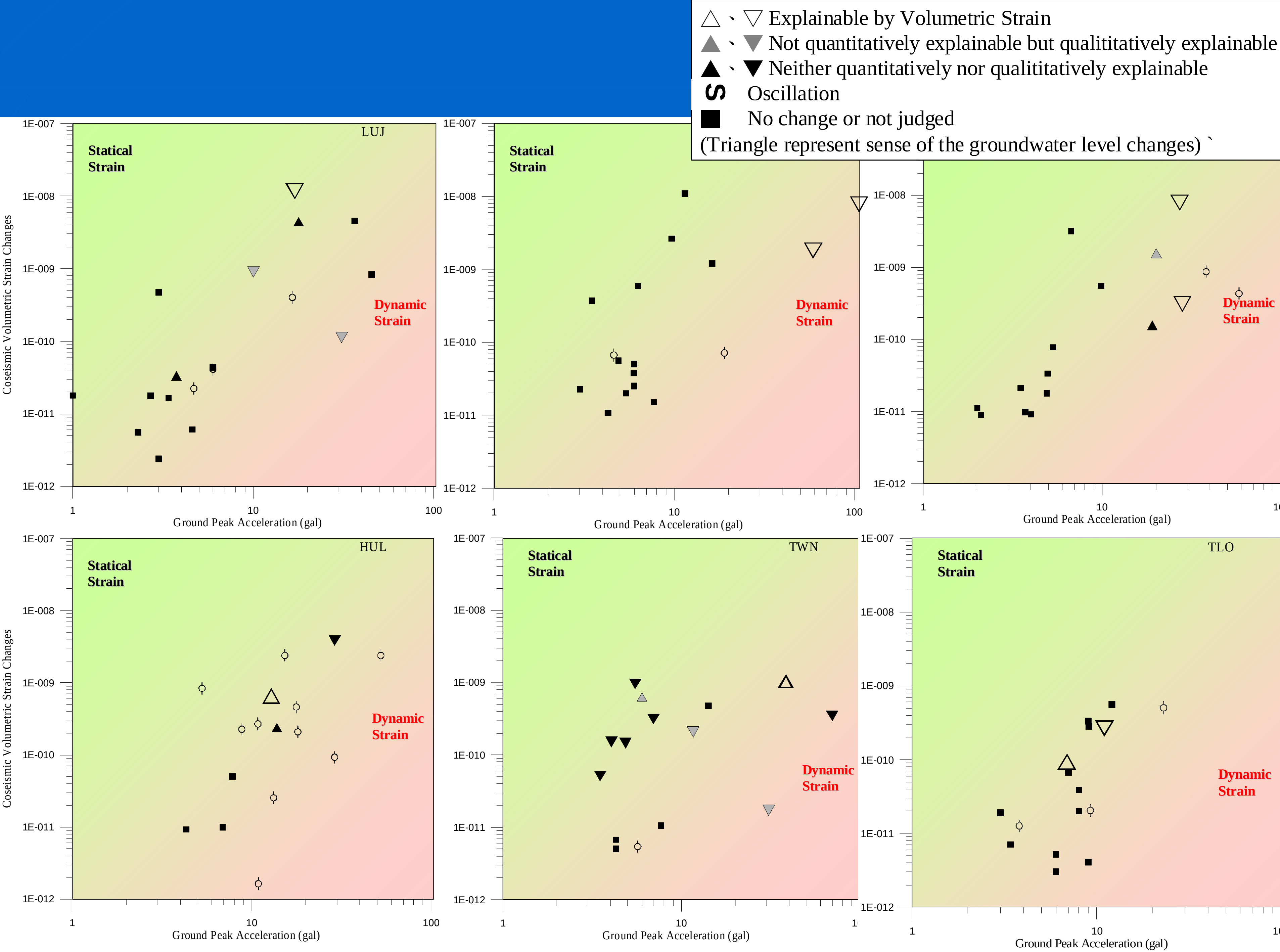
No.	LUJ					NBA					DHR				
	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	-16.70	S	1.13E-10	-0.64	31	±3.51	O	7.15E-11	-0.24	20	-1.69	O+S	3.09E-10	-0.70	28
2	-275.66	S	1.16E-08	-65.32	17		N	1.09E-08	-37.32	11	-23.51	O+S	7.91E-09	-18.02	27
3		N	1.77E-11	-0.10	3		N	1.52E-11	-0.05	8		N	-2.77E-15	0.00	2
4	0.93	S	3.16E-11	-0.18	4		N	2.51E-11	-0.09	6		N	-1.02E-14	0.00	2
5	-0.51	S	9.01E-10	-5.06	10		N	1.20E-09	-4.11	16	18.23	S	1.50E-10	-0.34	19
6		O	-4.01E-10	2.25	17		N	-3.71E-10	1.27	4	0.28	S	-1.50E-09	3.42	20
7	±1.20	O	2.23E-11	-0.13	5	±1.50	O	6.68E-11	-0.23	5		N	5.54E-10	-1.26	10
8	±2.40	O	-4.11E-11	0.02	6		N	3.77E-11	-0.13	6		N	-3.36E-11	0.08	5
9		N	6.11E-12	-0.03	5		N	1.08E-11	-0.04	4		N	-1.78E-11	0.04	5
10	7.76	S+O	4.19E-09	-23.54	18		N	2.63E-09	-9.00	10		N	3.20E-09	-7.28	5
11		N	4.71E-10	-2.65	3		N	5.91E-10	-2.02	6		N	7.79E-11	-0.18	7
12		N	-2.40E-12	0.01	3		N	-7.51E-13	0.00	2		N	-9.82E-12	0.02	5
13		N	5.54E-12	-0.03	2		N	5.56E-11	-0.20	5		N	-9.12E-12	0.02	4
14		N	4.38E-11	-0.25	6		N	5.04E-11	-0.17	7		N	2.12E-11	-0.05	4
15		N	-1.66E-11	0.09	3		N	-2.00E-11	0.07	5		N	-8.93E-12	0.02	2
16		N	-1.79E-11	0.10	2		N	-2.27E-11	0.08	4		N	-1.12E-11	0.03	2
17		N	8.25E-10	-4.64	45	-12.23	O+S	1.81E-09	-6.21	59	±27.13	O	-8.75E-10	1.99	38
18		N	4.55E-09	-25.56	37	-25.75	O+S	7.74E-09	-26.52	106	±15.29	O	4.33E-10	-0.99	58

Observed coseismic events (07'~09')

No.	Time	MW	HUL					TWN					JUS					WUJ				
			Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	2007/1/25 18:59	6.2	0.65	O	-3.58E-10	-0.18	12			-1.71E-10	-0.06	6			-1.51E-10	-0.27	4			-1.86E-10	-0.06	3
2	2007/7/23 21:40	6			-5.14E-09	-2.58	59			-2.99E-10	-0.11	5			-2.26E-10	-0.40	5			-3.12E-09	-0.93	6
3	2007/9/7 1:51	6.6			-2.70E-09	-1.35	61			-2.61E-09	-0.99	105			-1.91E-09	-3.40	48			-3.62E-10	-0.11	72
4	2008/6/1 9:57	6.8			-3.73E-11	-0.02	2			-2.03E-11	-0.01	2			-1.93E-11	-0.03	2			-2.11E-11	-0.01	2
5	2008/6/2 0:59	6			-3.98E-10	-0.20	4			1.36E-09	0.51	62			2.49E-09	4.43	35	4.80	O	6.70E-10	0.20	14
6	2009/7/14 2:05	6.3			-1.36E-09	-0.68	14	-1.48	S	-3.86E-10	-0.15	42										
7	2009/8/17 8:05	6.8			3.18E-09	1.60	18	-0.85	S	1.28E-09	0.48	11										
8	2009/10/4 1:36	6.1	±0.13	O	9.23E-10	0.46	81	-1.60	S	9.14E-11	0.03	21										
9	2009/11/5 17:32	6	±0.08	O	1.95E-10	0.10	49	-2.41	S	-7.85E-12	0.00	11										

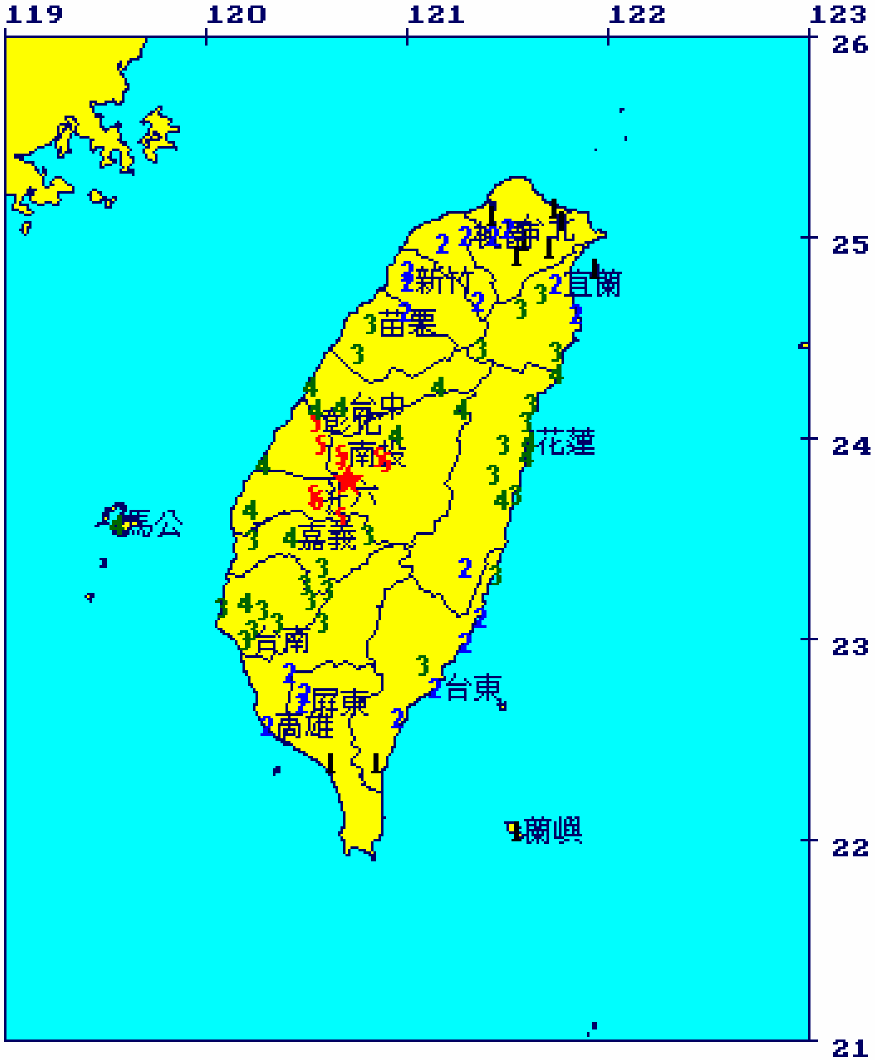
No.	Time	MW	CHK					HRK					TLO					HTN				
			Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)	Gw_{obs}	Type	Vol. Strn.	GW_{exp}	PGA(gal)
1	2007/1/25 18:59	6.2			-3.48E-11	-0.0114	1.51	0.37	O	7.41E-12	0.00169	3.61			1.874E-11	0.00214	8.03			1.562E-10	0.05	9.3
2	2007/7/23 21:40	6			-9.72E-11	-0.03	6	-0.50	O	-1.15E-10	-0.03	5			-1.15E-10	-0.01	6			-1.50E-10	-0.04	17
3	2007/9/7 1:51	6.6			5.69E-11	0.02	12	2.04	O+S	7.08E-11	0.02	13	0.44	O	7.22E-11	0.01	10			1.51E-11	0.00	22
4	2008/6/1 9:57	6.8			-2.07E-11	-0.01	1			-2.38E-11	-0.01	1			-2.45E-11	0.00	2			-3.28E-11	-0.01	2
5	2008/6/2 0:59	6			1.66E-10	0.05	5			-2.06E-10	-0.05	3			-2.22E-10	-0.03	3			-1.39E-10	-0.04	7
6	2009/7/14 2:05	6.3	0.66	S	-2.05E-09	-0.67	15			-2.00E-09	-0.46	7						0.23	O	-8.42E-10	-0.25	10
7	2009/8/17 8:05	6.8			8.56E-10	0.28	6			9.31E-10	0.21	7								9.39E-10	0.28	16
8	2009/10/4 1:36	6.1			5.63E-10	0.18	13			7.68E-10	0.18	6								6.97E-10	0.20	30
9	2009/11/5 17:32	6			-2.30E-10	-0.08	7			-5.91E-10	-0.13	27						3.27	O	-3.11E-09	-0.91	207.35

DHR SBT TUS LUJ



△、▽ Explainable by Volumetric Strain
▲、▼ Not quantitatively explainable but qualititatively explainable
▲、▼ Neither quantitatively nor qualititatively explainable
Oscillation
■ No change or not judged
(Triangle represent sense of the groundwater level changes)
LUJ
HUL
TWN
TLO
Statical Strain
Dynamic Strain
Coseismic Volumetric Strain Changes
Ground Peak Acceleration (gal)
1E-007
1E-008
1E-009
1E-010
1E-011
1E-012
1
10
100

III. Case Study:
98/11/5 17:32 Nantou Eq. M6.0



圖說：★表震央位置，阿拉伯數字表示該測站震度

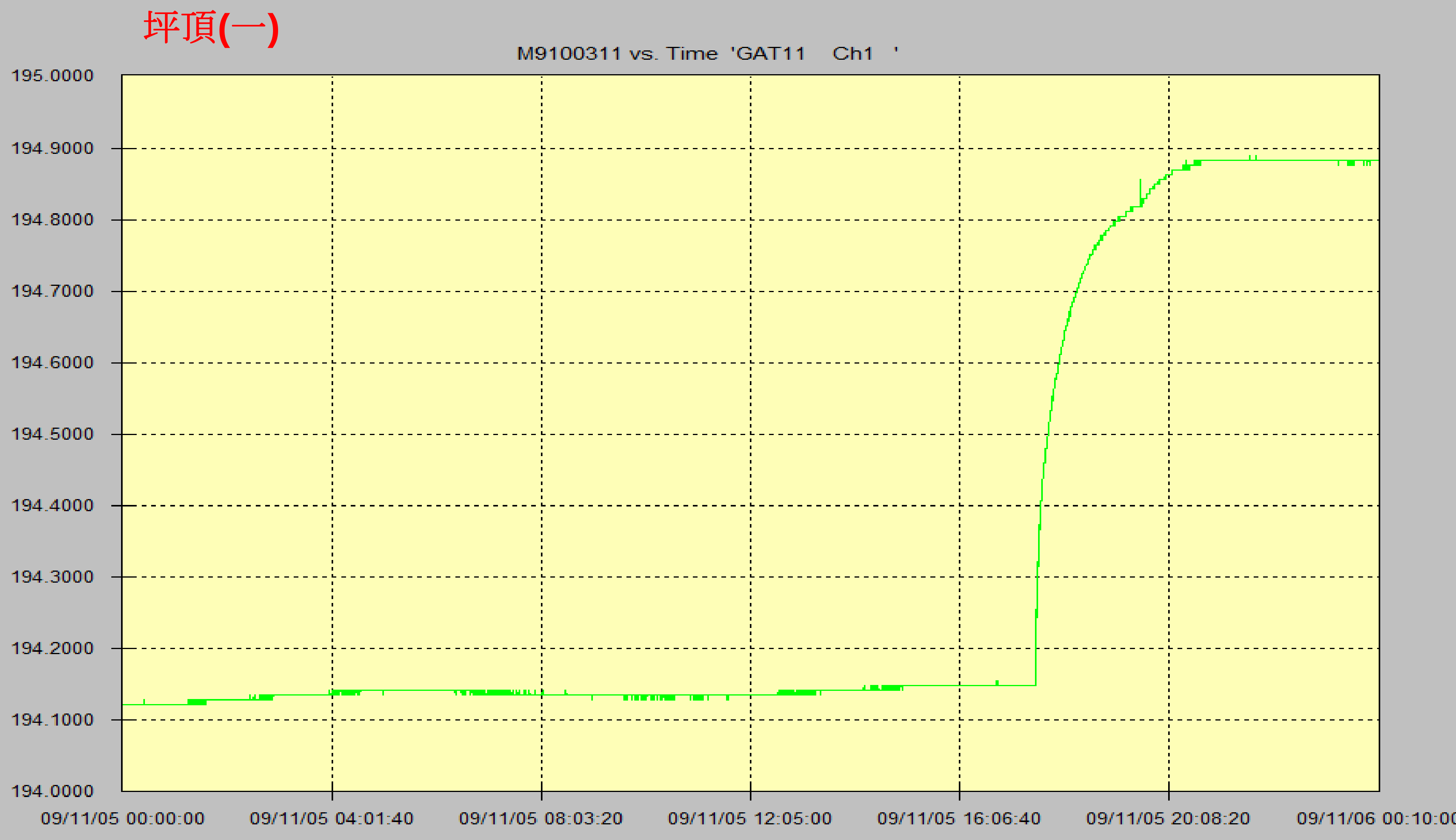
中 央 氣 象 局 地 震 報 告

編號： 第98125號
日期： 98 年 11 月 5 日
時間： 17 時 32 分 56.5 秒
位置： 北緯 23.79 度，東經 120.72 度
即在 南投名間地震站南偏東方 10.3 公里
地震深度： 19.3 公里
芮氏規模： 6.0
各地最大震度

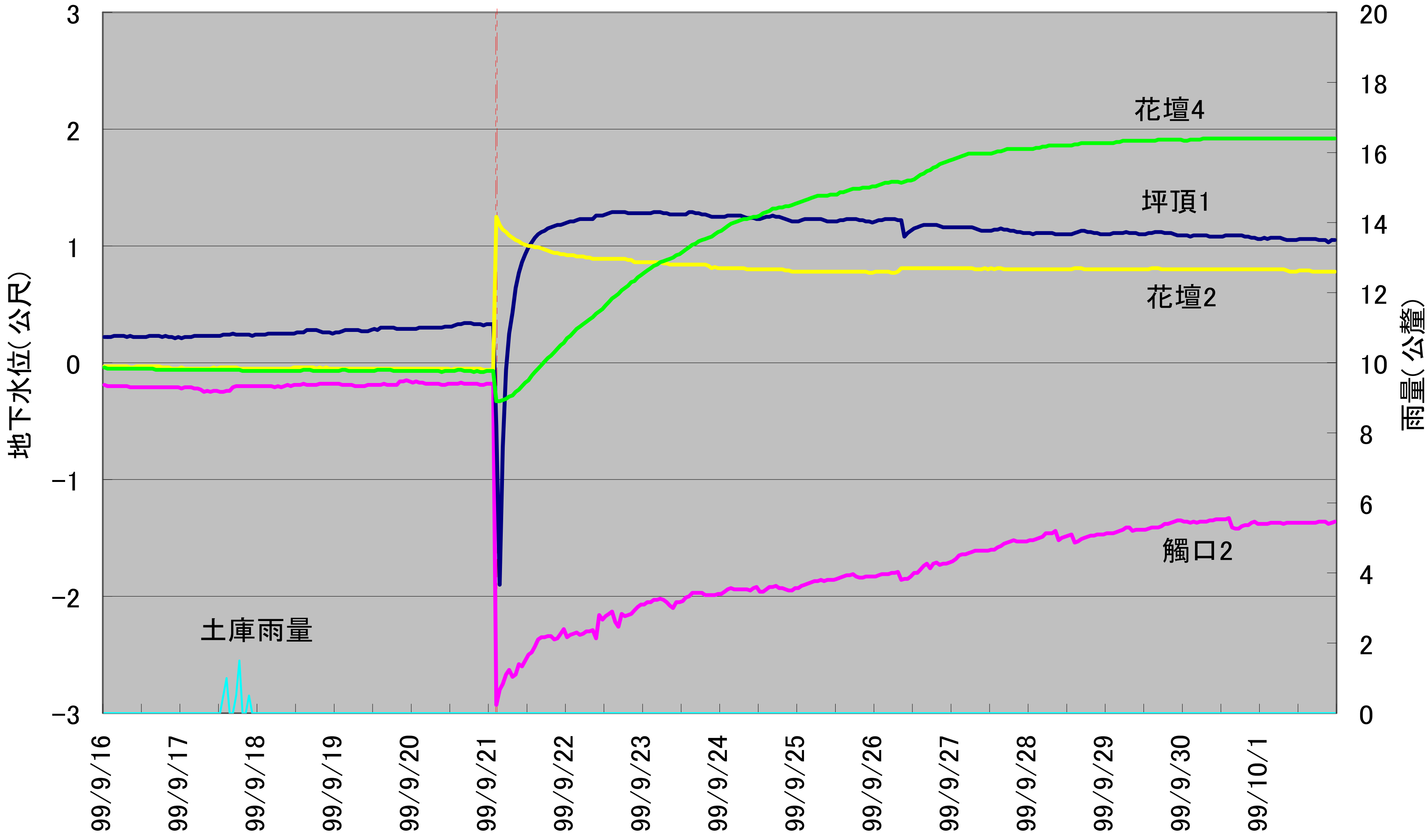
南投名間	7級	苗栗市	3級
雲林古坑	6級	台東長濱	3級
南投市	5級	宜蘭南山	3級
斗六市	5級	台南市	3級
彰化員林	5級	新竹市	2級
彰化市	5級	桃園三光	2級
台中市	4級	新竹竹北	2級
嘉義市	4級	屏東九如	2級
台中港	4級	台東市	2級
花蓮光復	4級	高雄市	2級
台南佳里	4級	桃園市	2級
花蓮市	4級	宜蘭市	2級
澎湖馬公	4級	台北板橋	2級
嘉義草山	3級	屏東市	2級
苗栗三義	3級	台北市	2級
高雄甲仙	3級		

本報告係中央氣象局地震觀測網即時地震資料地震速報之結果。

III. Case Study:
98/11/5 17:32 Nantou Eq. M6.0

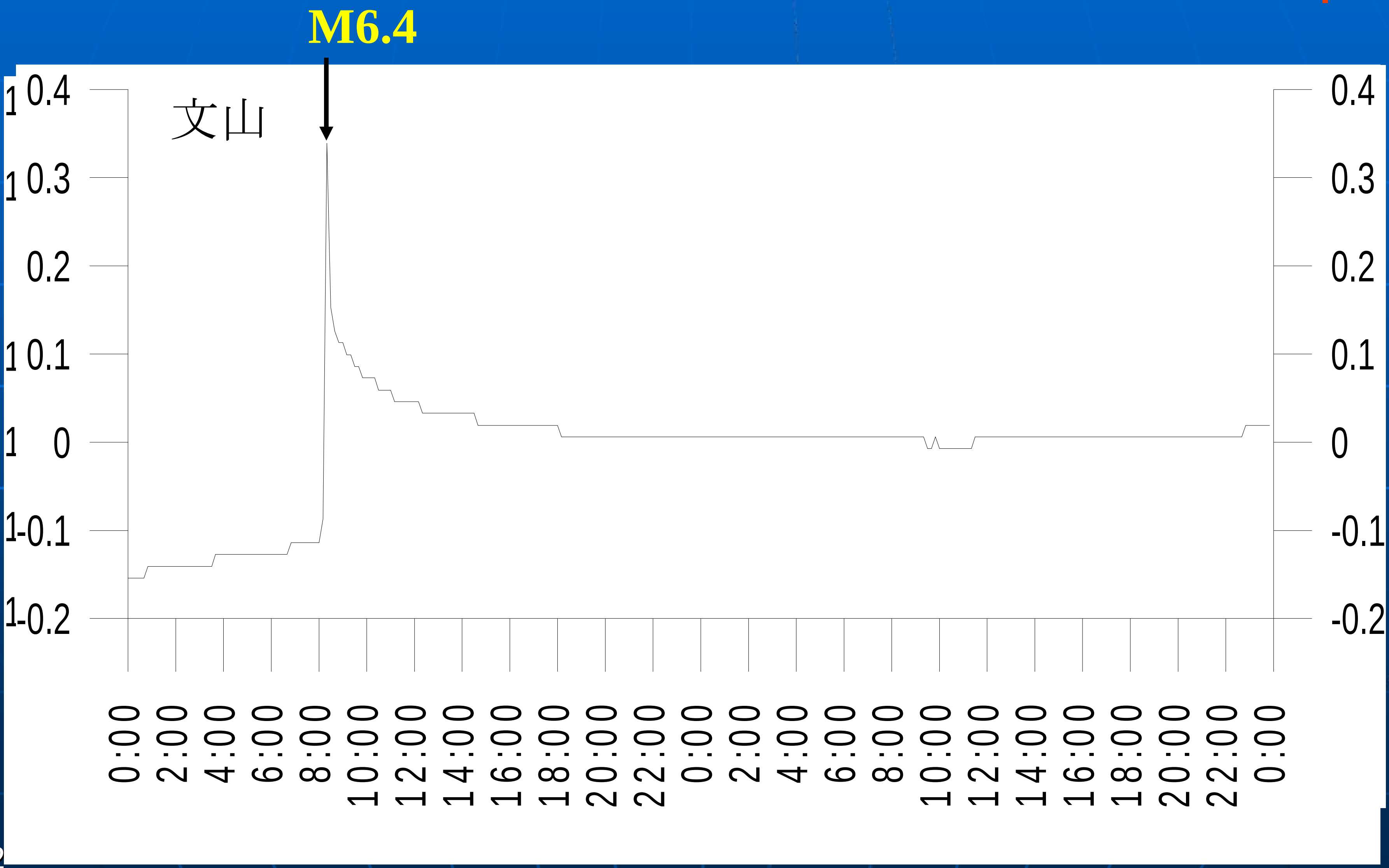


1999/9/21 Chi-Chi Earthquake



III. Case Study:
2010/3/4 Chiashian Eq. M_L 6.4

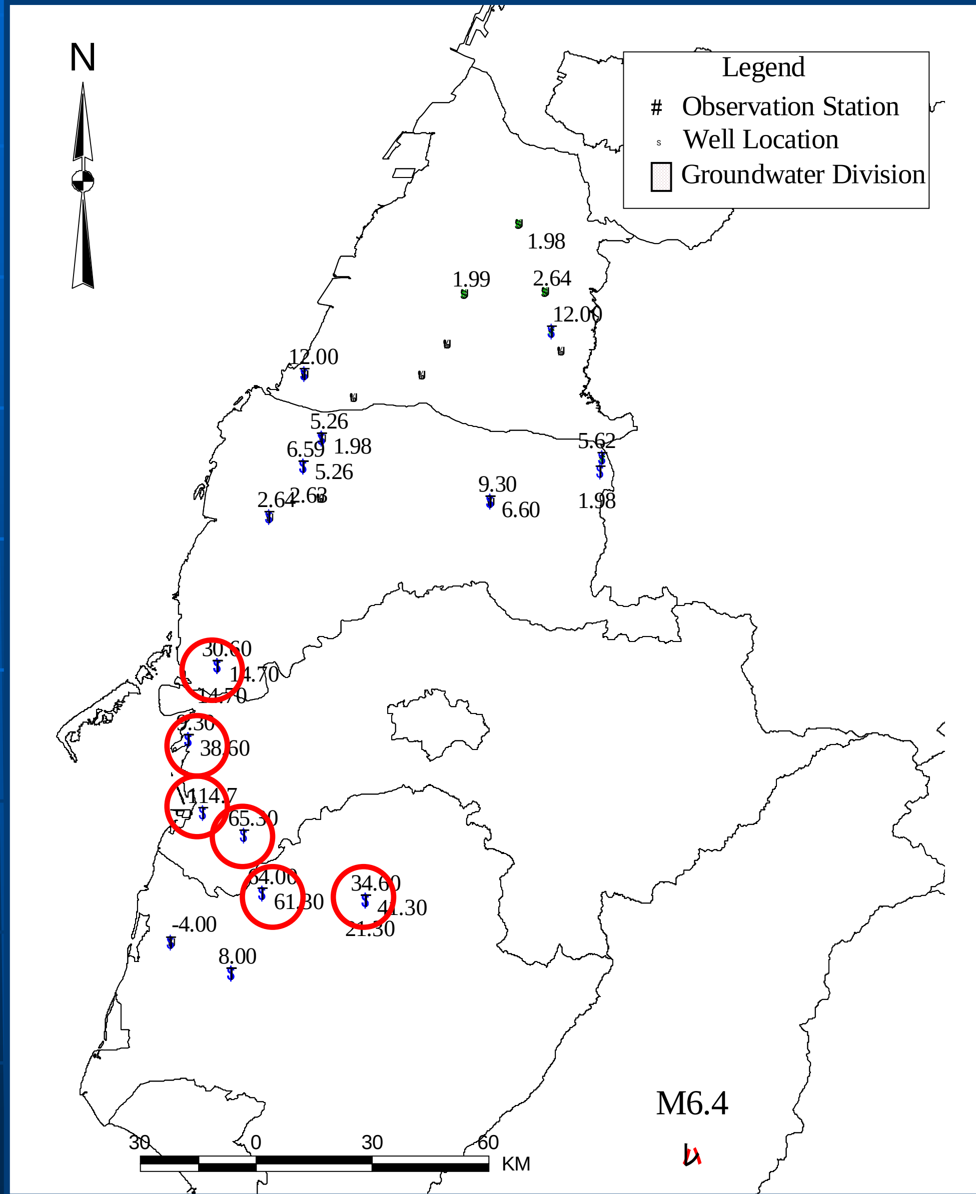
DP RC



Well	PGA (gal)	Vol. Strain	Oscillation (cm)	Step-offset (cm)	G_{exp}(cm)
花壇(2)	52	-1.13E-09	±1.98	—	0.49
員林(1)	37	-1.41E-09	±2.64	—	0.62
文山(1)	50	-1.75E-09	—	12.00	0.77
文山(2)	50	-1.75E-09	±4.00	—	0.77
溪湖(1)	65	-2.09E-09	±1.99	—	0.92
西港(1)	60	-2.83E-09	—	12.00	1.24
虎溪(1)	119	-6.16E-09	—	9.30	2.70
虎溪(2)	119	-6.16E-09	—	6.60	2.70
觸口(1)	115	-2.86E-09	—	5.62	1.26
觸口(2)	115	-2.86E-09	±85.80	—	1.26
坪頂(1)	118	-3.24E-09	—	1.98	1.42
豐榮(2)	75	-3.60E-09	—	5.26	0.64
豐榮(3)	75	-3.60E-09	—	1.98	0.64
興化(1)	85	-3.67E-09	—	6.59	0.65
興化(2)	85	-3.67E-09	—	5.26	0.65
興化(3)	85	-3.67E-09	—	2.63	0.65
安南(2)	88	-3.60E-09	—	2.64	0.64

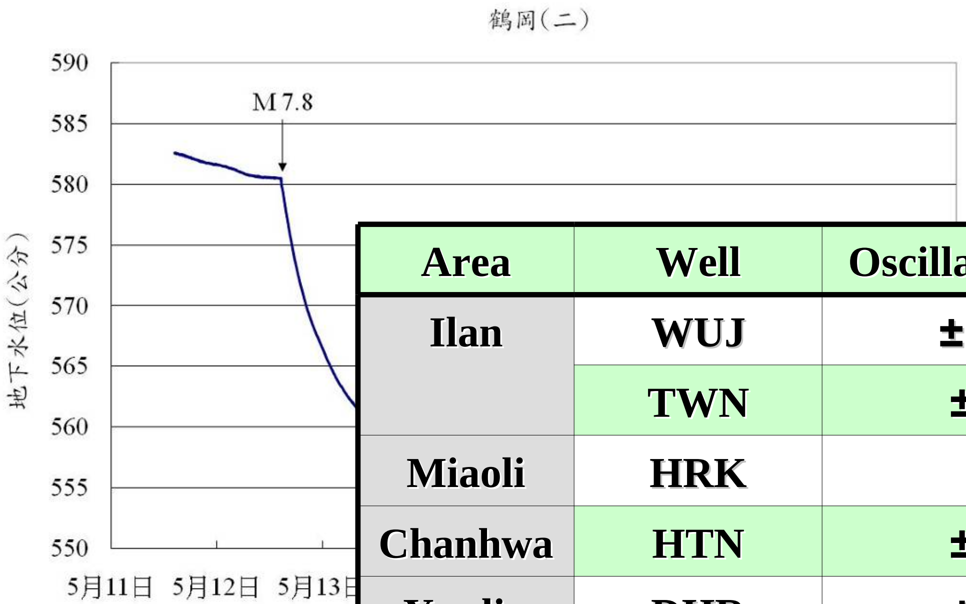
III. Case Study:
2010/3/4 Chiashian Eq. M_L 6.4

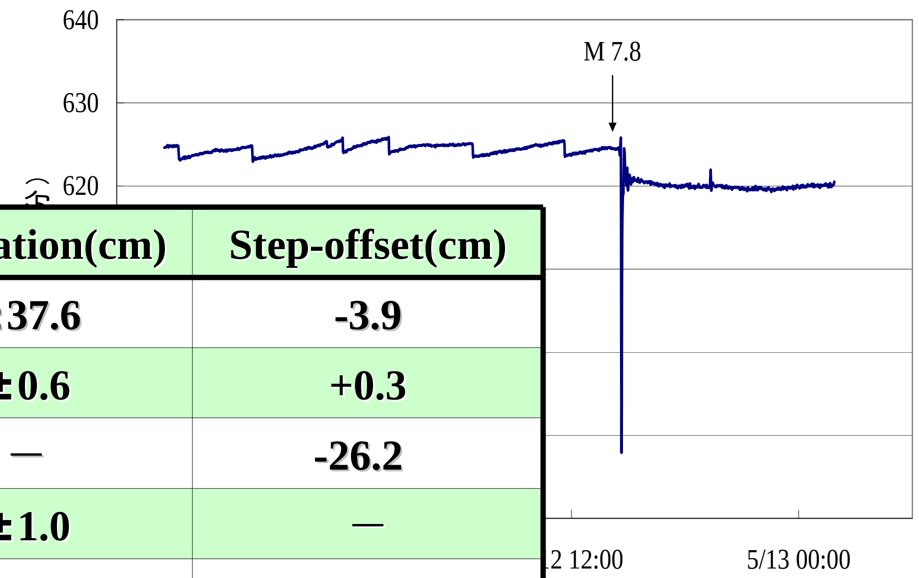
- Large step-roses
- Amplfication in the coastal area
- Shallow well >> Deeper well in the same sites.
- Oscillation mainly in the hill, slope area.
- Amplitudes of the step proportion to PGA



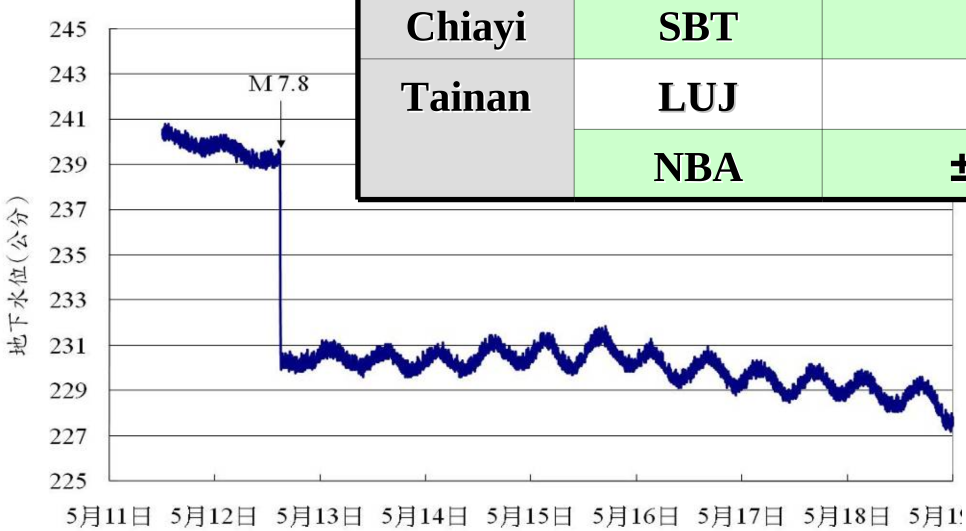
III. Case Study:

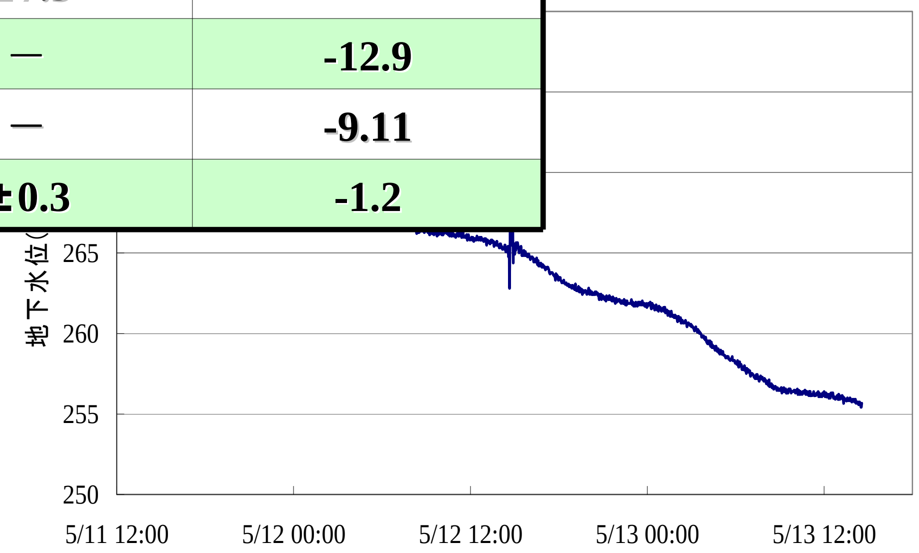
2008/5/12 Wenchuan, China Eq. (M_L 8.0)





Area	Well	Oscillation(cm)	Step-offset(cm)
Ilan	WUJ	±37.6	-3.9
	TWN	±0.6	+0.3
Miaoli	HRK	—	-26.2
Chanhwa	HTN	±1.0	—
Yunlin	DHR	±7.3	—
Chiayi	SBT	—	-12.9
Tainan	LUJ	—	-9.11
	NBA	±0.3	-1.2



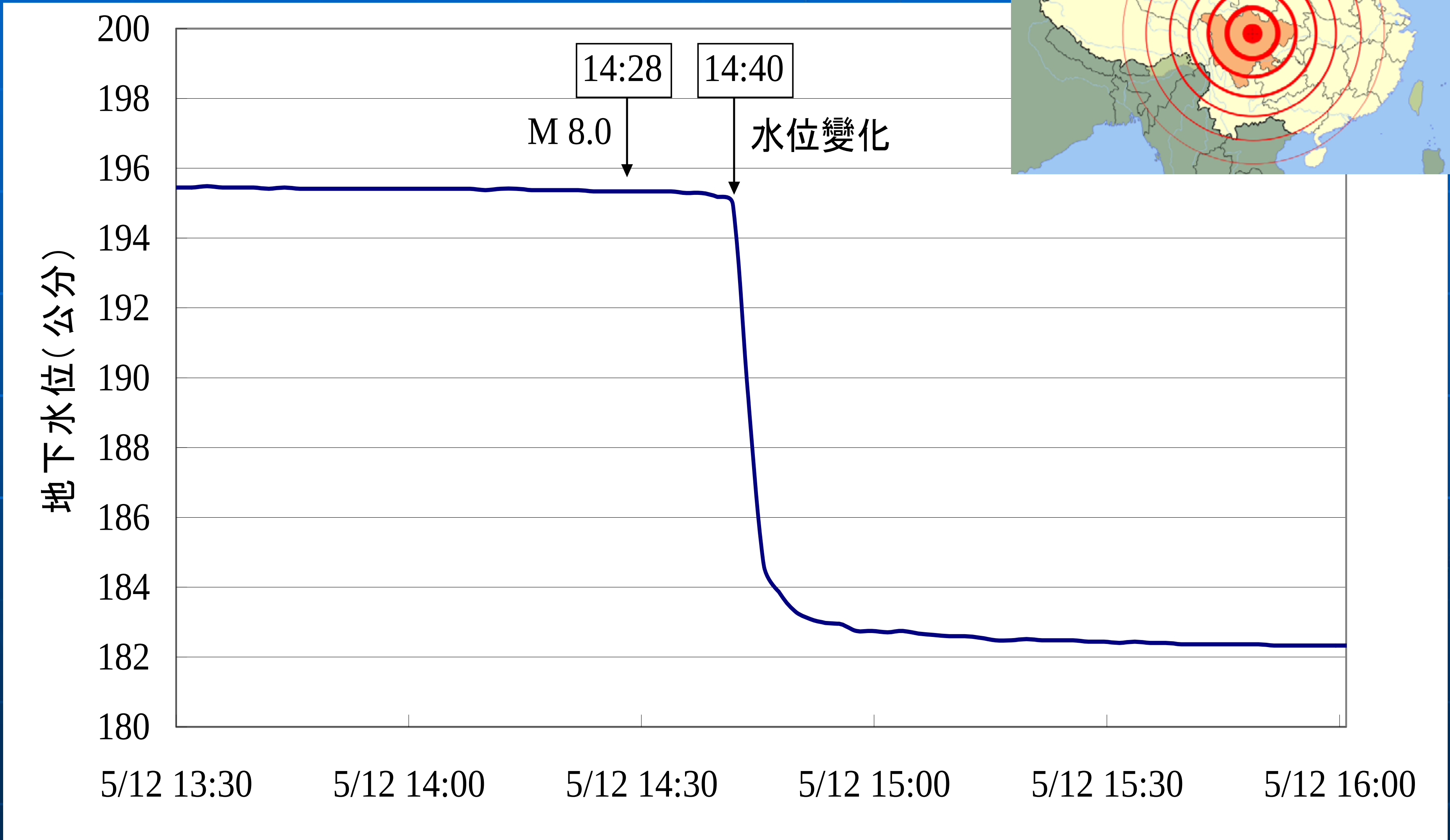


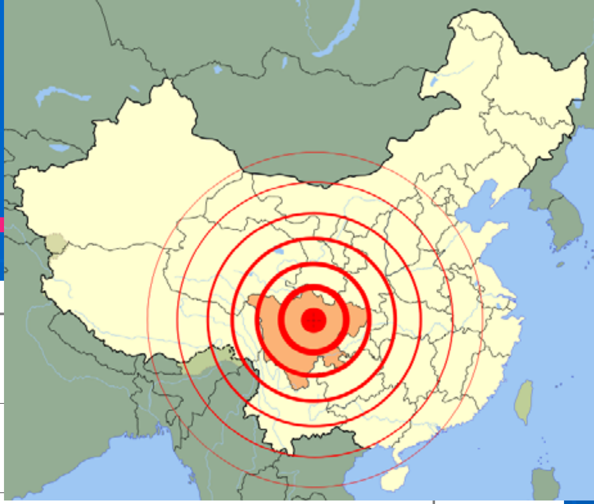
III. Case Study:

2008/5/12 Wenchuan Earthquake (M_L 8.0)

Area	Well	Strain Sensitivity ($mm/10^{-8}$)	Vol. strain (10^{-10})	Δh_{exp} (cm)	Δh_{obs} (cm)
Ilan	WUJ	2.28	2.05	-0.05	-3.9
	TWN	3.78	2.06	-0.08	+0.3
Miaoli	HRK	1.14	2.32	-0.03	-26.2
Chang-hwa	HUT	1.84	2.31	-0.04	—
Yunlin	DHR	4.39	2.17	-0.10	—
Chayi	SBT	5.02	2.24	-0.11	-12.9
Tainan	LUJ	1.78	2.19	-0.04	-9.11
	NBA	2.92	2.15	-0.06	-1.2

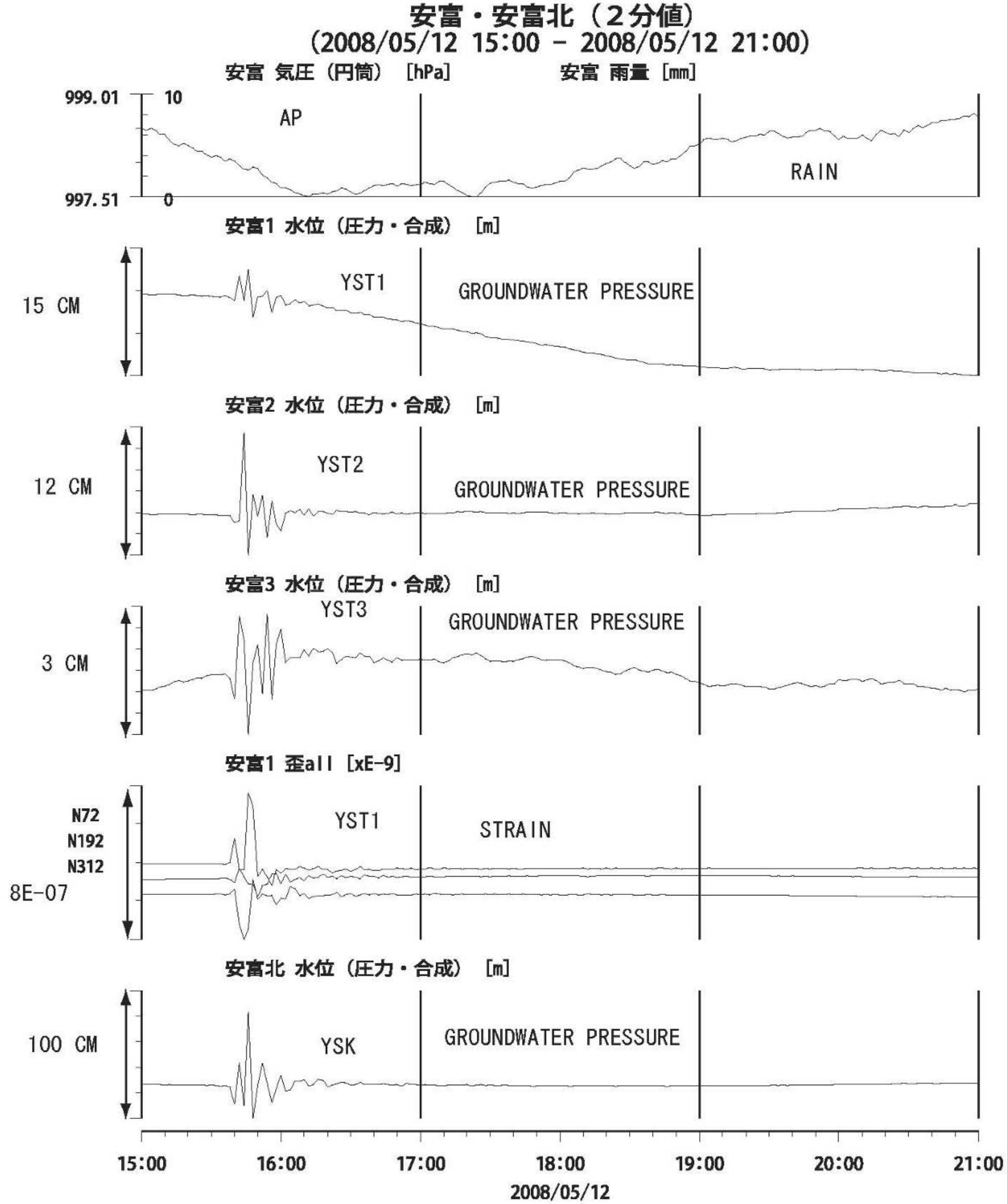
III. Case Study: 2008/5/12 Wenchuan Eq. (M_L 8.0)

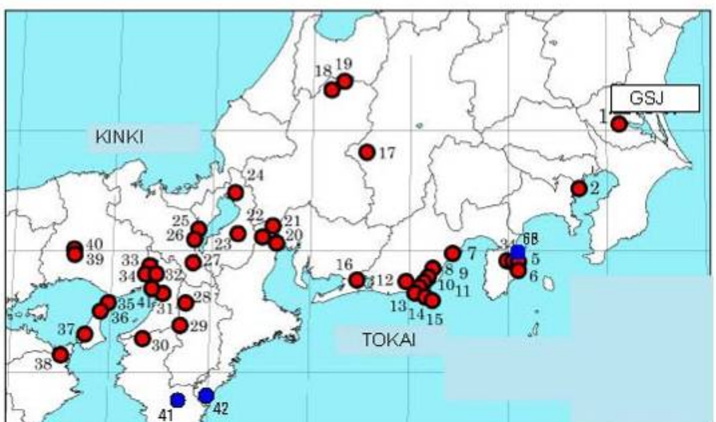




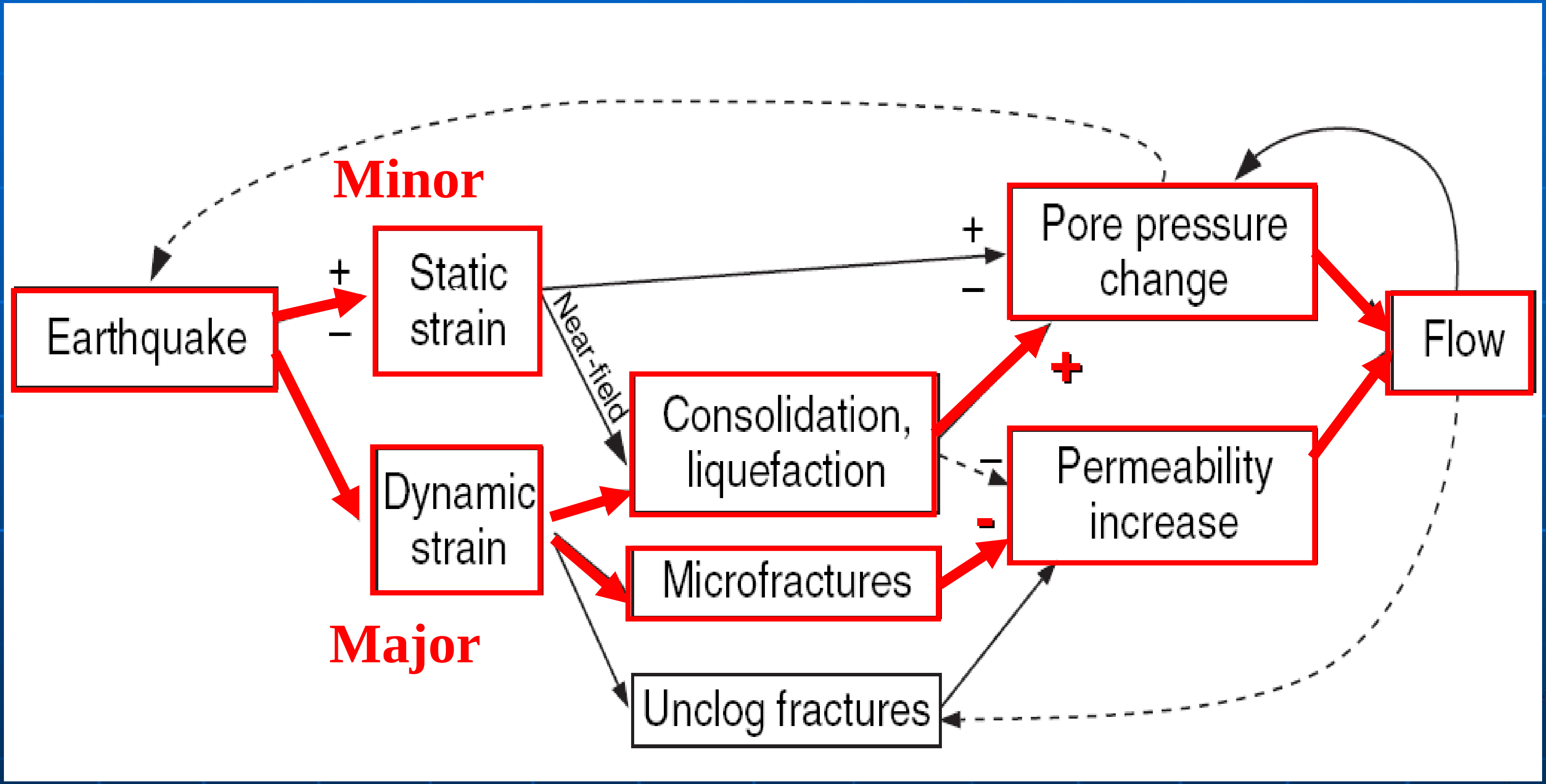
Coseismic Changes in GSJ’s observation well

(GSJ’s data)





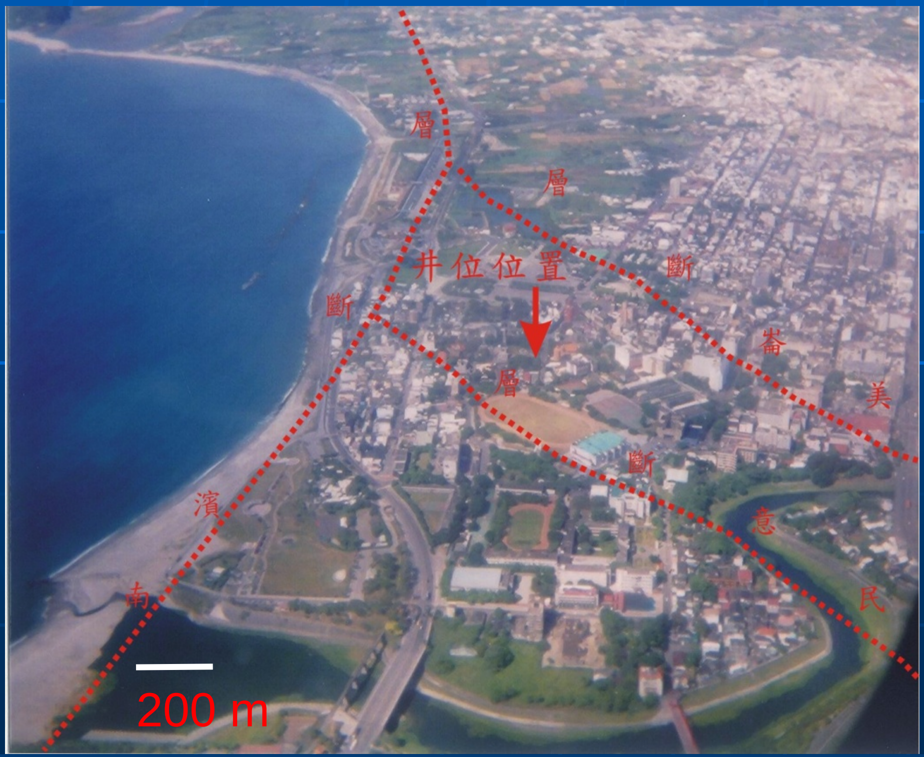
Mechanism of coseismic groundwater level changes

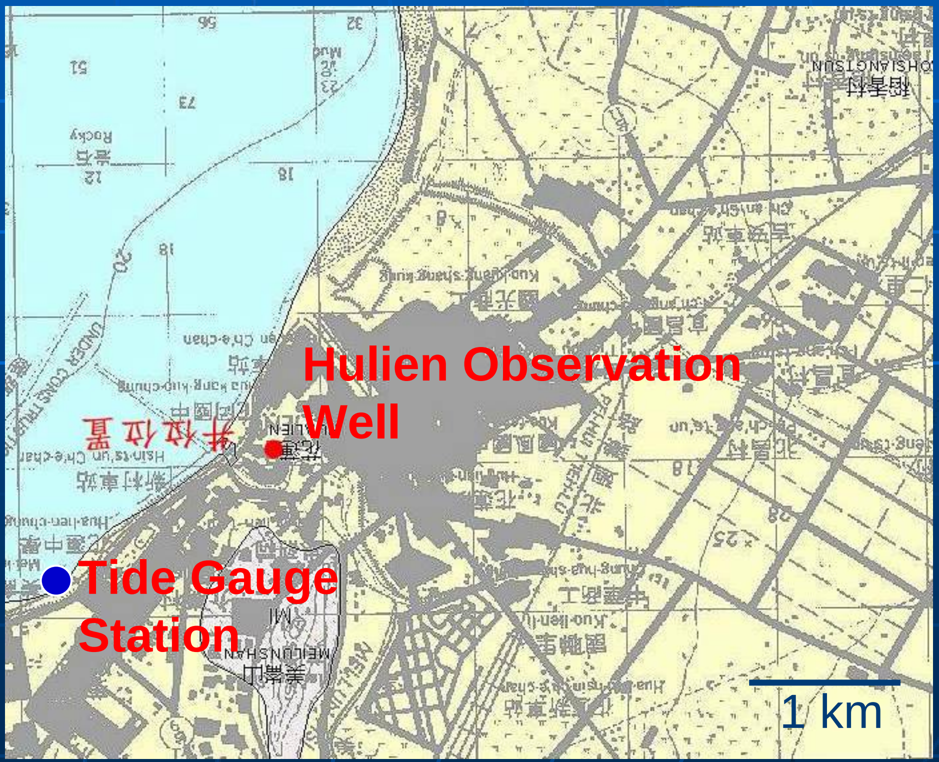


M. Manga and C.-Y. Wang (2007)

IV. *Possible Mechanism of Preseismic Changes in Hulien Observation Well*

- Effected by ocean tide
- Located on complex fault zone

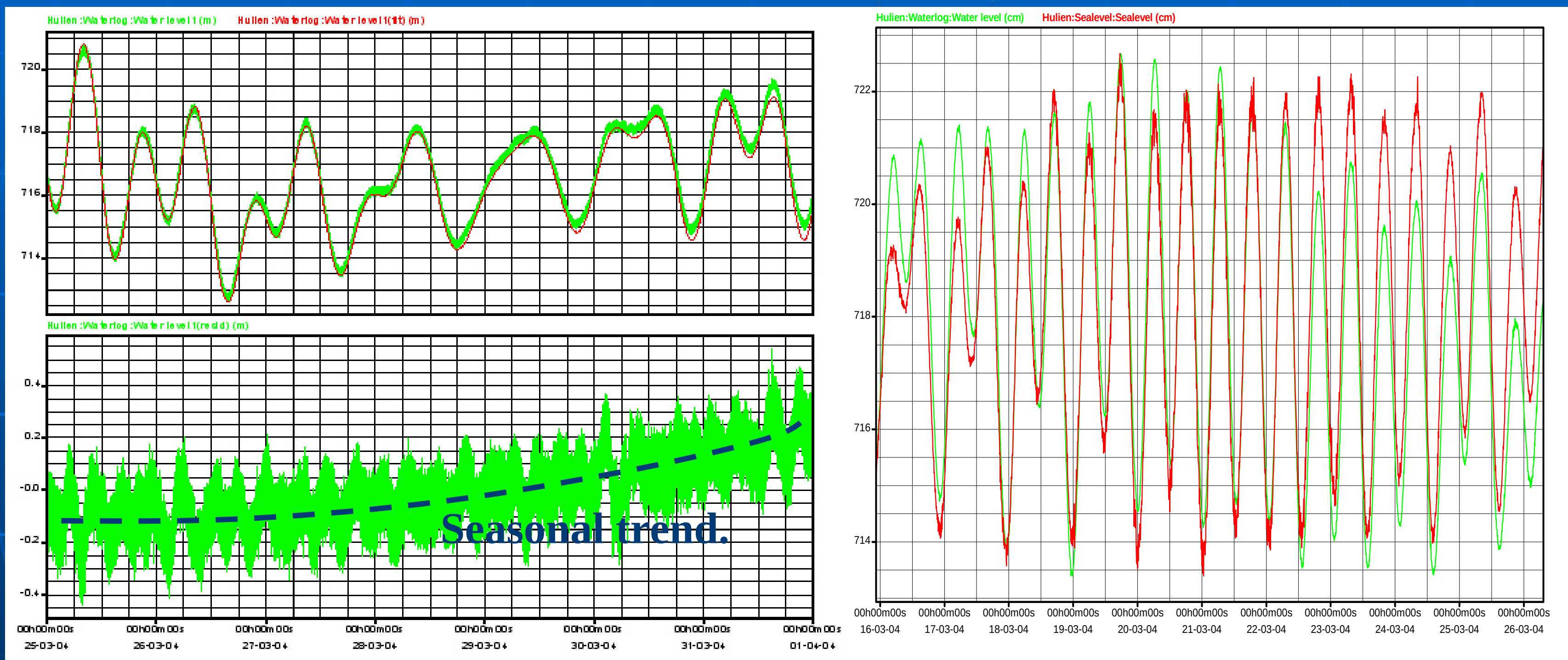




Location of Hulien observation well and tidal gauge station

Comparison of Sea Level and Groundwater Level Observation

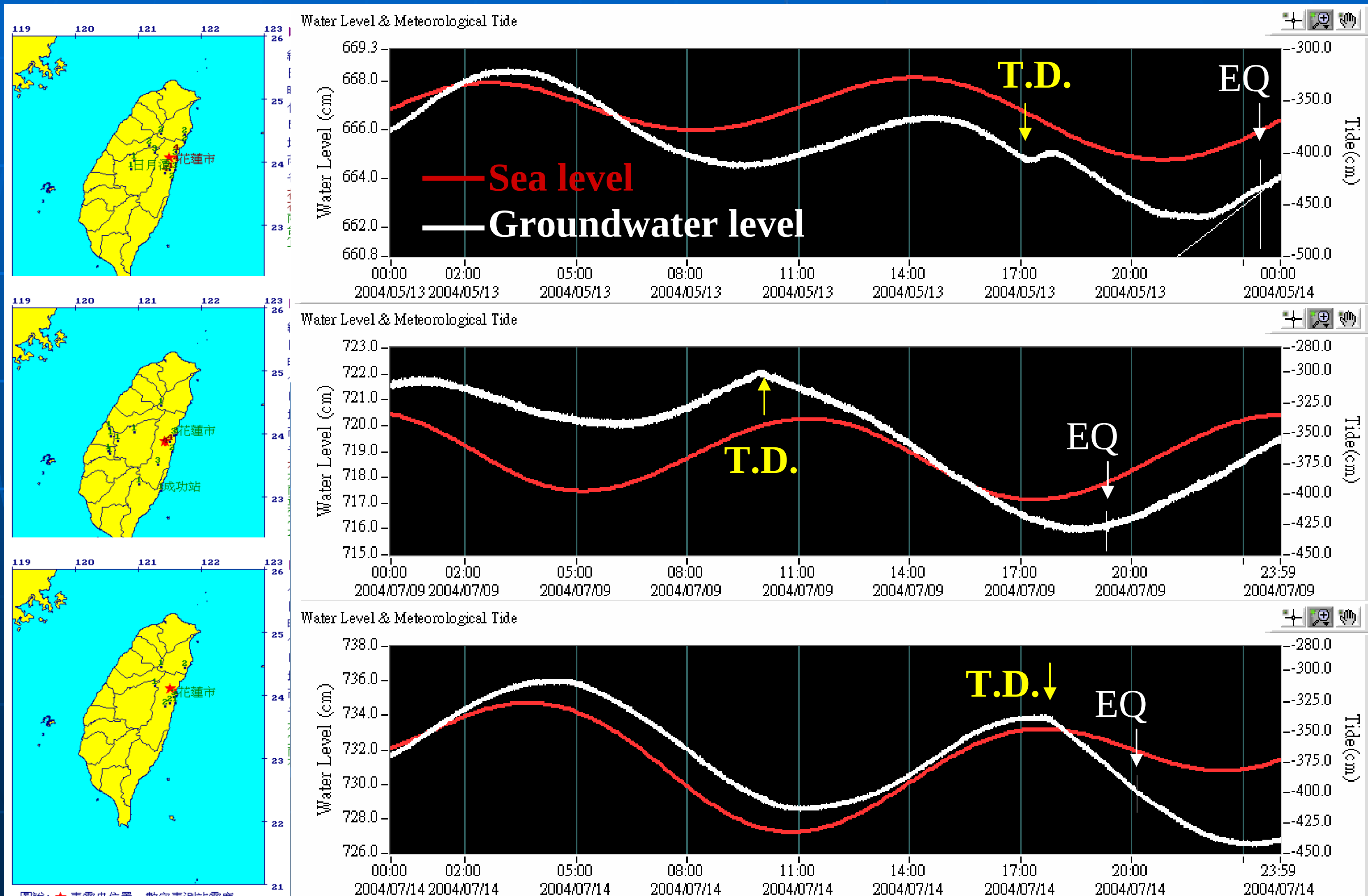
DPRC



Red: sea level observation in Huilen Harbor (6 min)

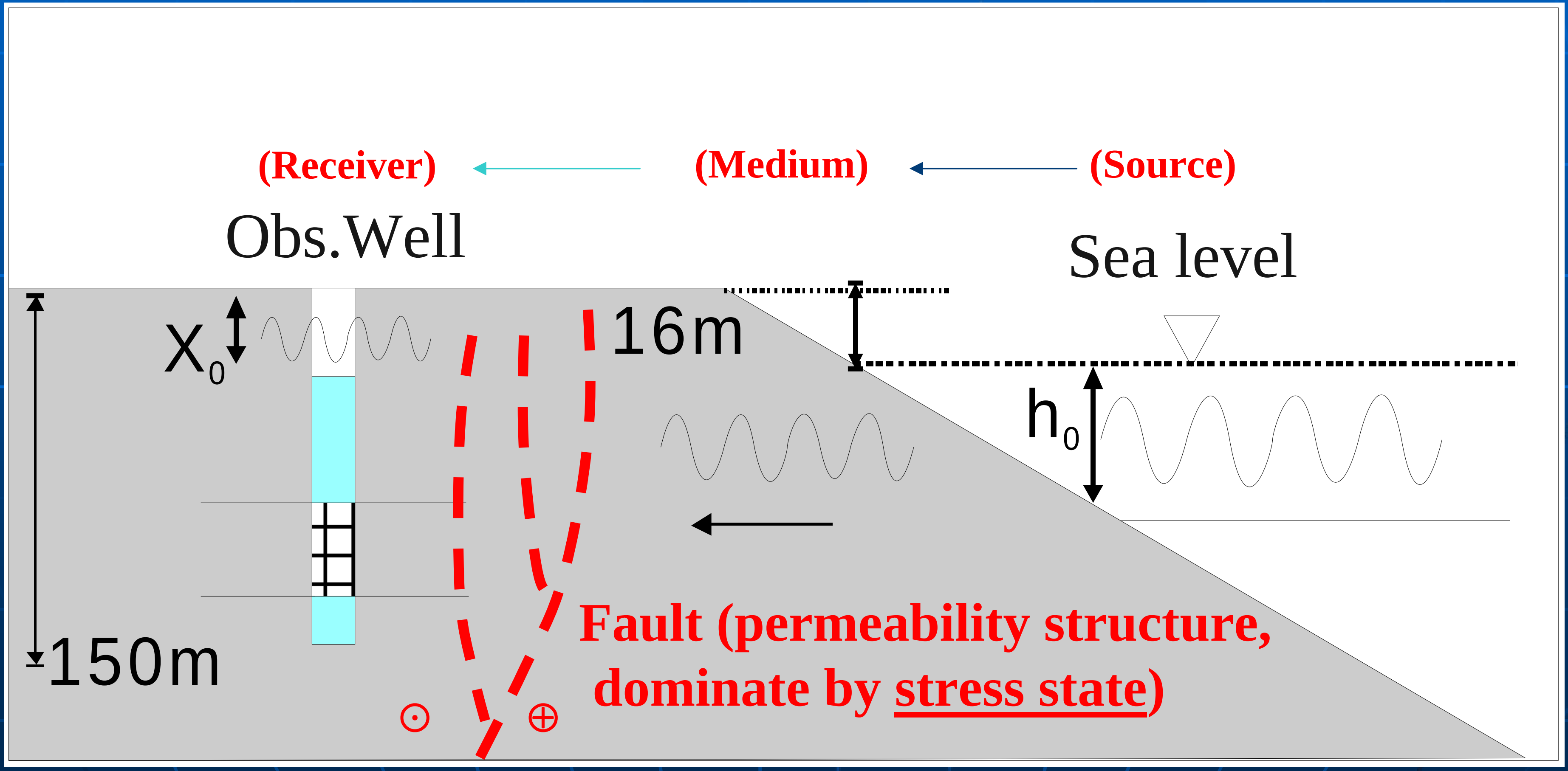
Green: Groundwater level observation in Huilen Observation(2 min)

No.	Occ. Time	M_L	Lon.	Lat.	Depth (km)	Distance (km)	Obs. Sta.	Intens.
93053	2004/05/13 23:28:47	4.6	121.51	24.05	18.9	13.3	HUL	4
93069	2004/07/09 19:19:29	4.8	121.43	23.86	19.5	23.3	HUL	3
-	2004/07/14 20:04:30	4.1	121.52	24.09	21.1	15.7	HUL	1



Possible Mechanism of Observation in Hulien Observation Well

- Wave Propagation Model (fault permeability structure)



V. Summary

- The results show that the dynamic strains induced by ground shaking could be another possible factor for the coseismic groundwater level changes.
- It seems to appear especially in shallow aquifers with high hydraulic conductivity in lose-cemented and permeable sedimentary deposits.
- The similar effects can also be recognized in the coseismic groundwater level changes related to the 1999 Chi-Chi earthquake, 2004 Wenchuan earthquake ,and 2010 Chiashian earthquake .

V. Summary

- The same patterns of coseimic changes in same wells between 1999 Chi-Chi earthquake with 2009 Nantou earthquake recognize the elastic mechanism.
- Curiously pre-seismic groundwater level changes in the pattern of tidal deviation occurred repeatedly in several local seismic events nearby the HUL.
- The wave propagation model were issued from HUL observation results.

Thank you !