Lecture at Graduate Institutes of Geophysics and Applied Geology, National Central University

Earthquakes and Water

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National Cheng Kung University, Taiwan

Personal Background

- **Education**

Ph.D., 2009, Resources Engineering, National Cheng Kung University (Engineering Hydrogeology)

M.Eng., 2002, Resources Engineering, National Cheng Kung University (Civil Engineering)

B.Eng., 2000, Resources Engineering, National Cheng Kung University (Engineering Geology)

- **Work Experience**

2017.08- Assistant Professor, Graduate Institute of Applied Geology, National Central University

2015.12-2017.07 Associate Researcher & Southern Branch Representative, Southern Branch Office, Sinotech Engineering Consultants, Inc.

2013.01-2015.12 Assistant Researcher, Georesources Research Center, National Cheng Kung University

2012.01-2012.12 Postdoctoral Researcher, Department of Resources Engineering, National Cheng Kung University

2010.07-2011.12 Project Researcher, Georesources Research Center, National Cheng Kung University

- **Specialty and current interest**

Coupled solid-fluid interactive theory and numerical analysis,

Earthquake hydrogeology investigation,

Subsidence hazard analysis, and

Groundwater resources assessment.

Main publications

- **Stochastic poroelastic theory**

The Application of the First-Order Second-Moment Method to Analyze Poroelastic Problems in Heterogeneous Porous Media, *Journal of Hydrology*.

Dynamics of Deformation and Water Flow in Heterogeneous Porous Media and its Impact on Soil Properties, *Hydrological Processes*.

Estimating Poromechanical Properties Using a Nonlinear Poroelastic Model, *Journal of Geotechnical and Geoenvironmental Engineering*.

Dynamic Interactions of Groundwater Flow and Soil Deformation in Randomly Heterogeneous Porous Media, *Journal of Hydrology*.

Stochastic Analysis of Coupled Thermal-Hydraulic-Mechanical Modeling for Nuclear Waste Repositories. (preparing for *Journal of Hydrology*)

- **Earthquake hydrogeology investigation**

Estimating the extent of stress influence by using earthquake triggering groundwater level variations in Taiwan, *Journal of Asian Earth Sciences*

Evaluation of Hydraulic Properties of Aquitards Using Earthquake-Triggered Groundwater Variation, *Groundwater*.

The Mechanism of the Pre-seismic Groundwater Level Variation in Hualien Well, Eastern Taiwan. (preparing for *GRL*)

- **Subsidence hazard analysis**

A Technique for Quantifying Groundwater Pumping and Land Subsidence Using a Nonlinear Stochastic Poroelastic Model, *Environmental Earth Sciences*.

Combining Gray System and Poroelastic Models to Investigate Subsidence Problem in Tainan, Taiwan, *Environmental Earth Sciences*.

Dimensional Upgrade Approach for Spatial-Temporal Fusion of Trend Series in Subsidence Evaluation, *Entropy*.

- **Groundwater resources assessment**

Groundwater Resources Management for Public Water Supply in Changhua County, Taiwan – 1. Model Analysis. (writing)

Groundwater Resources Management for Public Water Supply in Changhua County, Taiwan – 2. The Influence of Climate Change. (writing)

Participated Projects

- **NCU => Stochastic poroelasticity, Water resources**

序率孔彈性理論之發展與地層下陷研究之應用(科技部)

東港溪流域水文與水質監測計畫(南水局)

- **Sinotech Inc. => Water resources, Mountain hydrogeology, Groundwater quality, Site safety**

大潮州人工湖補注對於東港溪流域水文及水質影響探討 (南水局)

地下水防災緊急備援井網規劃－桃園地區之水質及水文地質評估; 嘉義高雄地區地下水污染傳輸之模擬與分析研究

台灣山區地下水資源調查研究整體計畫 (105-106); 曾文水庫大壩安全監測分析及檢查(105-106)

核能電廠因地震、豪雨誘發之順向坡滑移、山崩及廠區因發生強震致重要道路液化等之調查暨評估

- **NCKU Center => Water resources, Subsidence hazard, Disposal site, Groundwater contaminant transport**

台灣中段山區地下水資源調查與評估(1~4)；臺灣南段山區地下水資源調查與評估(1)

103-104年旗山溪流域山區水文地質與伏流水資源調查；台灣地區伏流水開發對地下水環境影響之調查評估

氣候變遷對水旱災災害防救衝擊評估研究計畫(1~2)；氣候變遷對中部地區水旱災災害防救衝擊評估及調適策略擬定(1~2)

雲林地區公共給水抽取地下水與高鐵沿線等地層下陷成因研究分析; 處置場熱水化作用不確定性分析

鳥嘴潭人工湖設置對彰化地區地層下陷防治之研究(1~2); 氣候變遷下臺灣九大地下水資源區地下水潛能變化之研究(1~2)

地下水污染傳輸之模擬與分析研究

- **Ph.D. degree => Earthquake hydrogeology, Coupled solid-fluid interactive mechanism**

地震發生前後地下水水位異常之研究(II-V)；地震與地下水文異常變化分析研究(1/4)

孔彈性理論之序率分析—應用在地層下陷之研究；地層下陷區地下水流與土壤沉陷交互作用之研究

低含水量水庫淤泥開採可能性示範之研究(II); 因應氣候變遷治水與國土規劃之創新策略…

- **Master degree => Earthquake induced slope stability problem**

旗山斷層及雞冠山斷層之工程特性實驗及其應用; 由集集地震造成之雲嘉地區潛在山崩位置及其危害性

地震衍生之邊坡破壞行為及防治對策研究(III)-以位移法分析自然邊坡破壞行為之研究

Office and Lab. information

- Laboratory：土水力學研究室 (Geohydraulics Research Group)
- Courses：(106-1) 地震水文學 (Earthquakes and Water)

  (106-2) 土水力學與應用 (Geohydraulics and Applications)
- Office： 335R (3rd floor), Science Building 1
- Tel：(03) 422-7151 #65870
- Email：sjwang@ncu.edu.tw; sjwang1230@gmail.com

~ Welcome to my office ~

Outline

- Introduction to Earthquake Hydrology
- Topic 1. Extent of stress influence (co-seismic)
- Topic 2. Parameter inversion (post-seismic)
- Topic 3. Pre-seismic mechanism (pre-seismic)
- Conclusions

News and Knowledge

- **炎亞綸Event – Rainfall might trigger earthquake.**
  - What is your opinion when you hear his statement?
  - Do you try to find out if it is truth?
  - Kafri, U. and A. Shapira, 1990, A correlation between earthquake occurrence, rainfall and water level in Lake Kinnereth, Israel, *Physics of the Earth and Planetary Interiors* 62(3-4), 277-283.
- **Fluid-driven cracks => Earthquakes?**
  - Ma, K.-F., Y.-Y. Lin, S.-J. Lee, J. Mori, E. E. Brodsky, 2012, Isotropic Events Observed with a Borehole Array in the Chelungpu Fault Zone, Taiwan, *Science* 337, 459.

Possible?

- Heavy Rainfall Can Cause Huge Earthquakes - National Geographic
  - The devastating magnitude 7.0 earthquake that hit Haiti in early 2010 came only 18 months after Haiti had been deluged by several hurricanes and tropical storms.
  - A magnitude 6.4 temblor that rocked Taiwan in 2009, occurred only seven months after the area had been hit by Typhoon Morakot, which dropped 9.5 feet (2.9 meters) of rain in five days.
- “the Earth’s crust can be so close to failure that even tiny pressure variations associated with precipitation can trigger earthquakes” (Geophysical Research Letters, DOI: 10.1029/2006GL027642)

Introduction to Earthquake Hydrology

- For thousands of years, a variety of hydrology changes has been documented following earthquakes.
- Examples include the liquefaction of sediments, increased stream discharge, changes in groundwater level, changes in the temperature and chemical composition of groundwater, formation of new springs, disappearance of previous active springs, and change in the activities of mud volcanos and geysers.
- It is not unexpected that earthquakes can cause hydrologic changes because the stresses created by earthquakes can be large.

From: Wang, Chi-yuen and Michael Manga, 2010, *Earthquakes and Water*, Springer-Verlag Berlin Heidelberg.

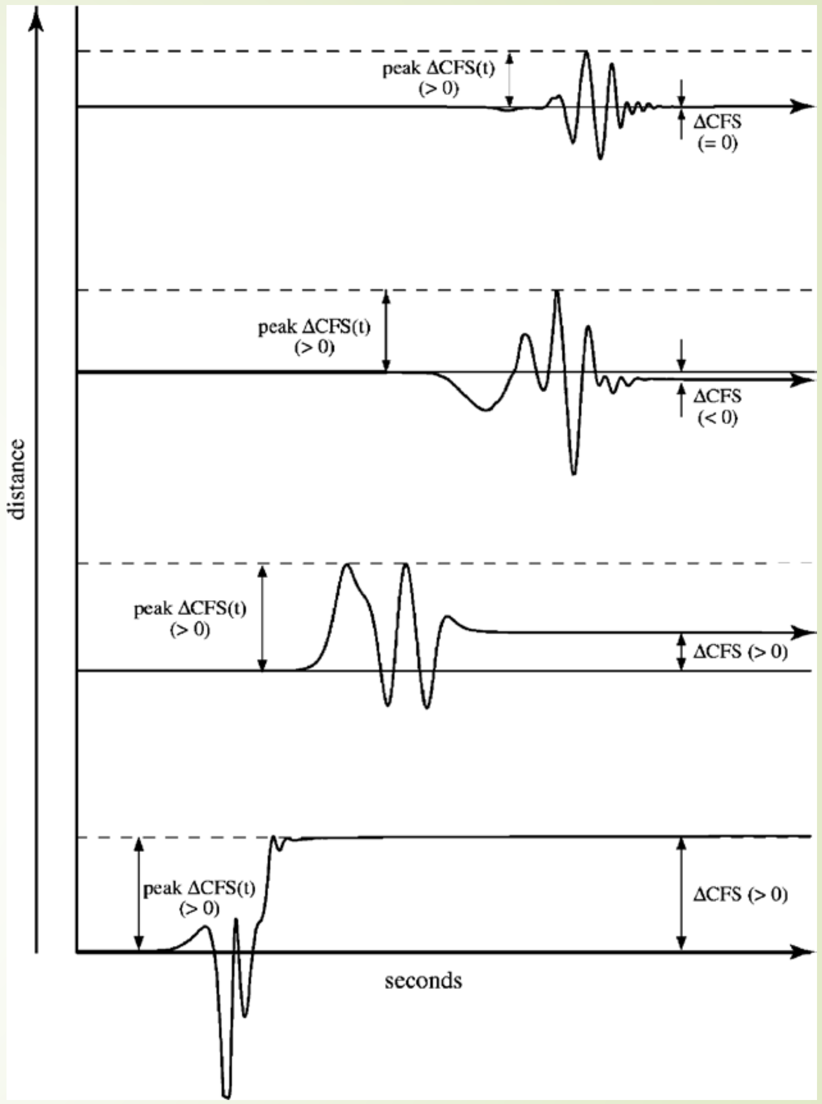
Mechanism

- Following the 2004 M9.2 Sumatra earthquake, groundwater erupted in southern China, 3200 km away from the epicenter, and the water fountain reached a height of 50-60 m above the ground surface.
- Earthquake and water interact with each other through changes in both stress and physical properties of rock.
- Understanding the origin of hydrological responses can provide unique insight into hydrogeologic and tectonic processes at spatial and temporal scales that otherwise could not be studied.

Well in China responding to the December 26, 2004, M 9.2 Sumatra earthquake 3200 km away. The picture was taken by Hou Banghua, Earthquake Office of Meizhou County, Guangdong, 2 days after the Sumatra earthquake. The fountain was 50 – 60 m high when it was first sighted 1 day after the earthquake

Stress change

- Earthquakes cause both static and dynamic changes of the stresses in the crust.
  - Static: time independent
  - Dynamic: time dependent
- Both types of stress change decrease with increasing distance from the earthquake, but at different rates.
- The static stress change diminishes much more rapidly with distance than the transient, dynamic change.



Cartoon illustrating the peak dynamic Coulomb stress change (peak CFS(t)) and static Coulomb stress change (CFS), and their variation with distance from the ruptured fault. CFS(t) $\equiv \tau(t) - \mu[\sigma_n(t) - P(t)]$, where τ is shear stress on the fault, σ_n is the stress normal to the fault, P is the pore pressure, and μ is the coefficient of friction. In the far field, peak dynamic stresses, CFS(t), are far greater than the static change, CFS, but in the near field, both are comparable in magnitude (Modified from Kilb et al., 2002)

Field scales

- At close distances the ratio (peak dynamic / static stress) is approximately proportional to the source-receiver distance, r, and at larger distances proportional to r^2 (Aki and Richards, 1980).
- At distances up to ~ 1 ruptured fault length, the static and the peak dynamic changes are comparable in magnitude, while at distances greater than several ruptured fault length, the peak dynamic change is much greater than the static change.
  - Near field => distances within about one ruptured fault length
  - Far field => distances many times greater than the fault length
  - Intermediate field => between near and far fields

Important implications

- The study of earthquake-induced hydrologic changes also has important implications for water resources, hydrocarbon exploration and engineering enterprise.
- Groundwater level changes following earthquakes can affect water supplies (Chen and Wang, 2009) and it is sometimes necessary to evaluate the causative role of an earthquake in insurance claims for loss of water supply (Roeloffs, 1998)
- Earthquake-induced increase in crustal permeability has important implications on hydrocarbon migration and recovery on the one hand, and contaminant transport on the other.

Damage

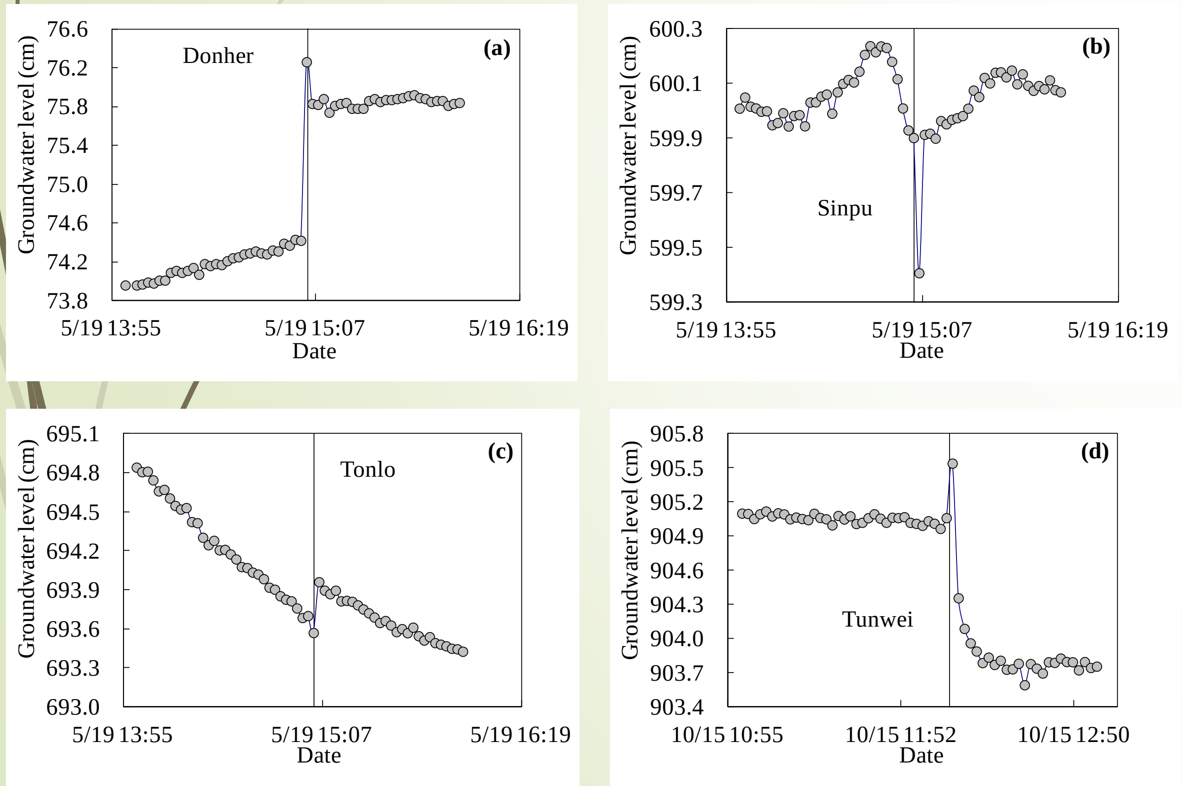
- A mud volcano eruption in the Indonesian city of Sidoarjo, in the eastern Java, that led to massive destruction of property and evacuation of people (Manga, 2007).
- Groundwater level changes following earthquake may put some underground waste repositories at risk (Roeloffs, 1998).
- Earthquake-induced fluid pressure changes can induce liquefaction of the ground that causes great damage to engineered structures (Seed and Lee, 1966), affect oil well production (Beresnev and Johnson, 1994), and trigger seismicity (Hill and Prejean, 2007).

Precursor

- Measured changes of the pore pressure in rock and/or the chemical composition of groundwater are sometimes taken as signatures of the crustal response to tectonic deformation (Davis et al., 2006) or even as earthquake precursors (Silver and Wakita, 1996)

Classification of anomalous groundwater variations triggered by earthquake

- Examples of categories for groundwater level anomalies triggered by earthquakes.
  - (a), (b), and (c) are for M6.5 May 19, 2004, earthquake, and (d) is for M7.0 October 15, 2004, earthquake.

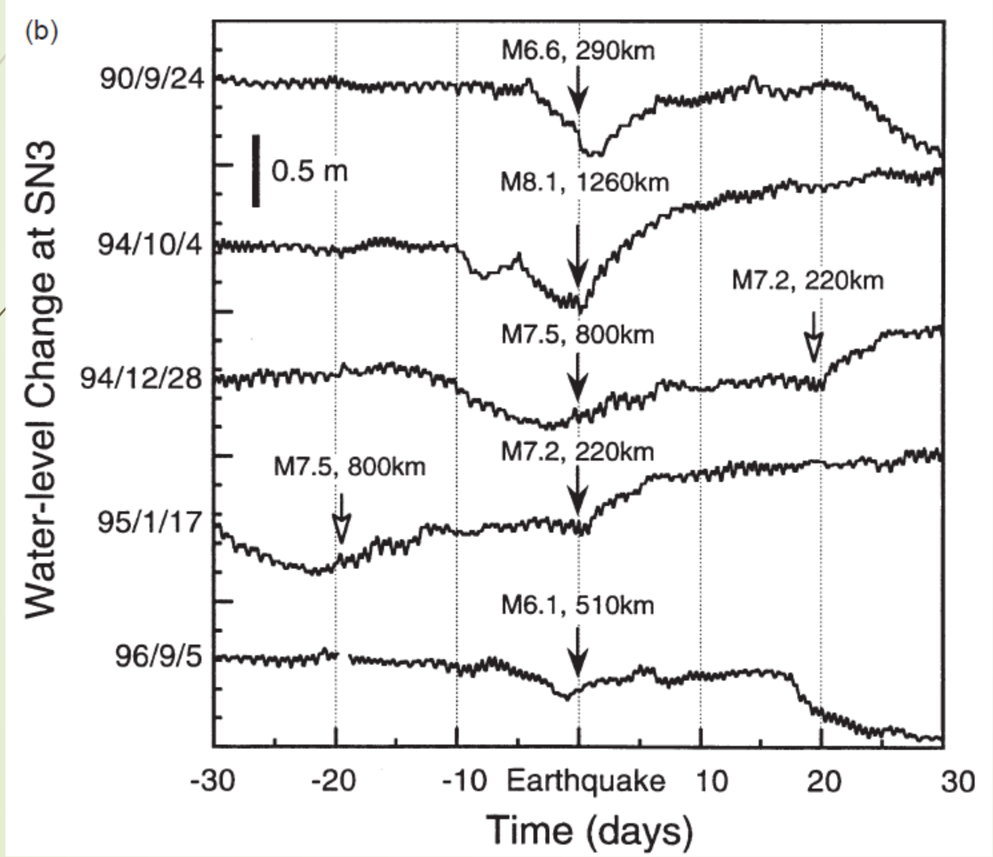


Sampling frequency: 2 minutes

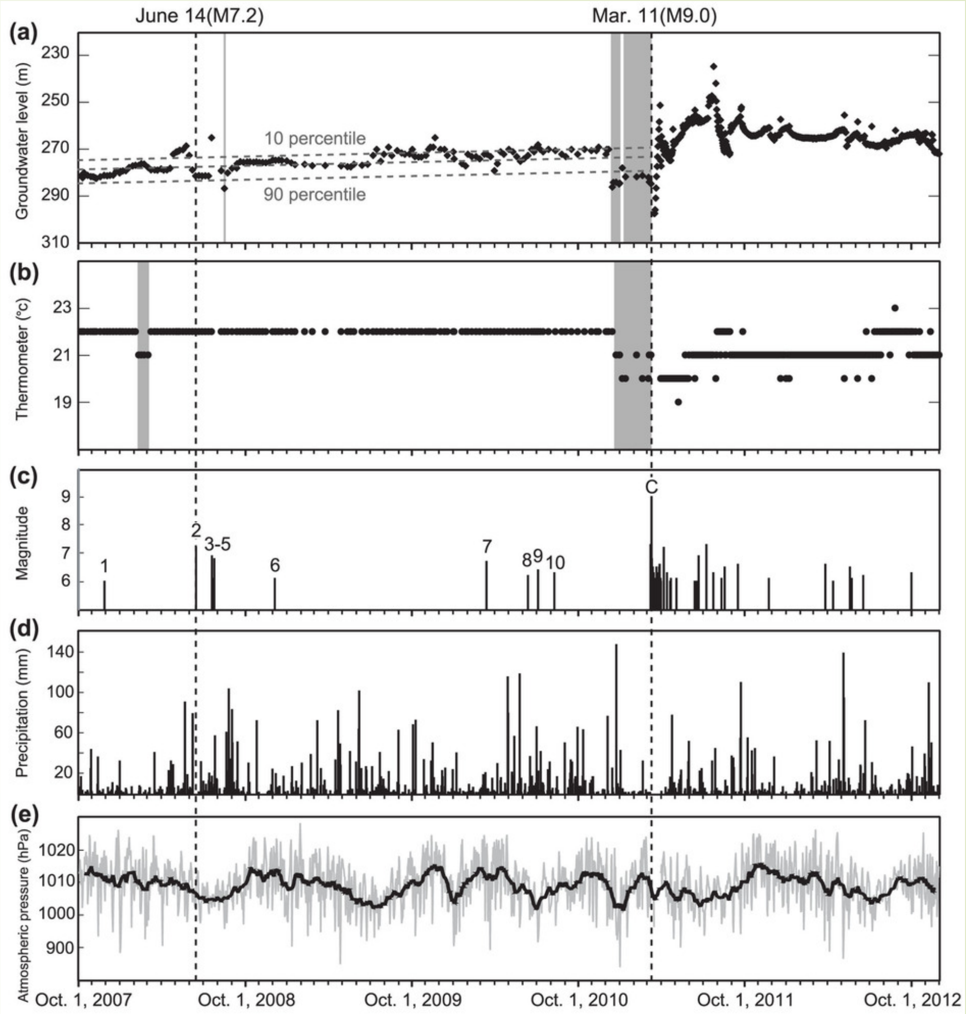
Earthquake number	Observation station	Time difference (T)	Oscillation (O)	Step (S)	Recovery (R)	Position (P)
17	Donher	co	u	u	o	u
17	Sinpu	co	d	o	o	o
17	Tonlo	co	o	u	o	u
19	Tunwei	co	u	d	d	d

Motivation

- Groundwater level anomaly is a potential signal for pre-seismic phenomena



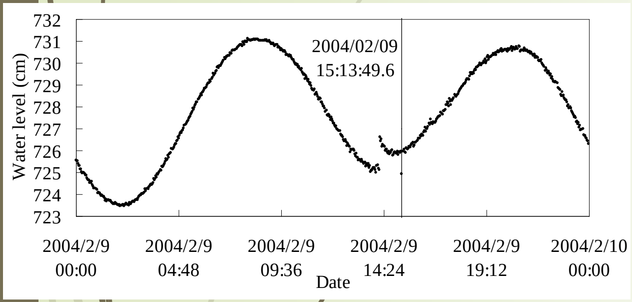
King et al. (2000) In search of earthquake precursors in the water-level data of 16 closely clustered wells at Tono, Japan, *Geophysical Journal International*.

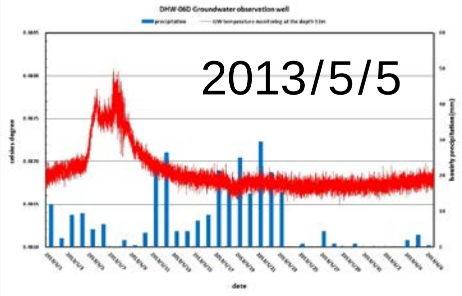


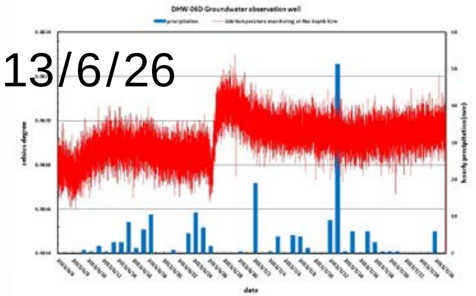
Orihara et al. (2014) Preseismic Changes of the Level and Temperature of Confined Groundwater related to the 2011 Tohoku Earthquake, *Nature*.

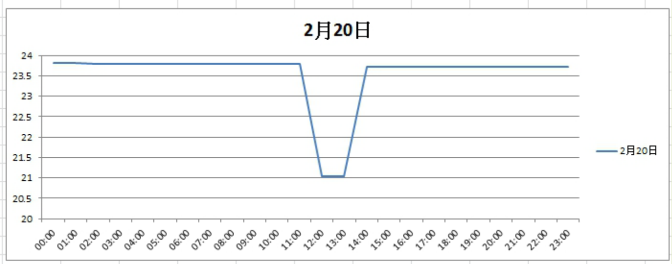
Taiwan cases

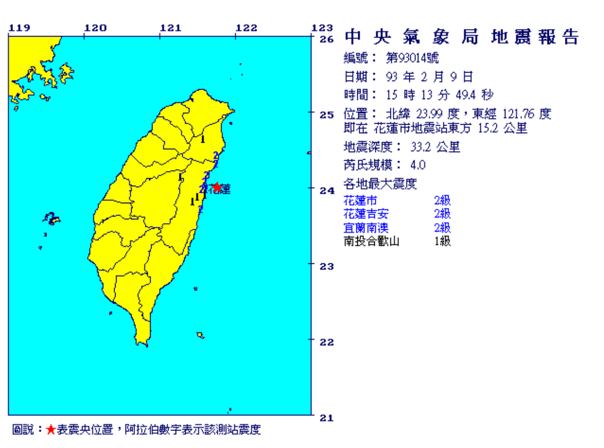
- Suspected pre-seismic groundwater level change on February 9, 2004, in the Hualien station.
- Suspected pre-seismic groundwater temperature variation on May and June, 2013, in Wuling station.
- Suspected pre-seismic groundwater level change on February 20, 2017, in MH-10 station.



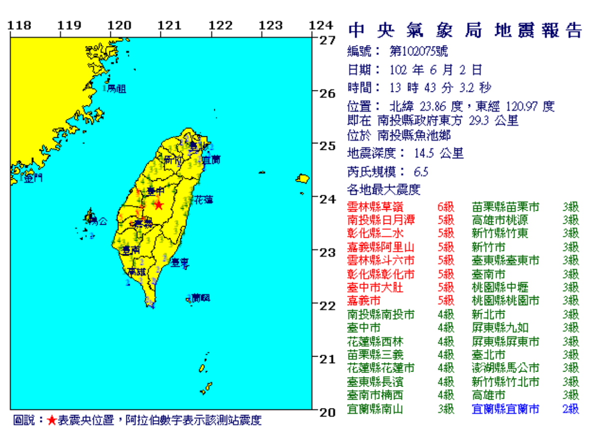




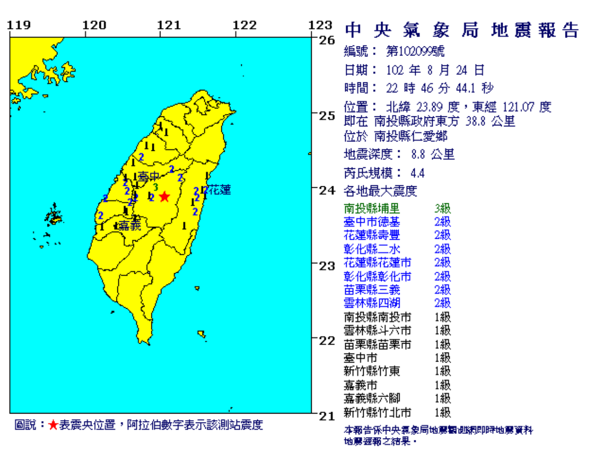




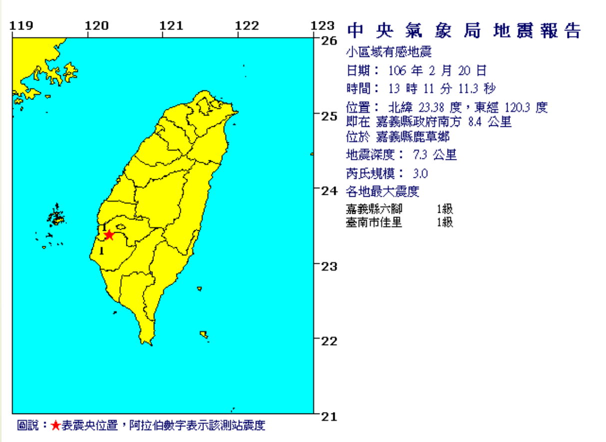
Pre: 50 minutes



Pre: 5/5~6/2 = 28 days



Pre: 6/26~8/24 = 59 days



Pre: 2 hours

Topic 1. Extent of stress influence

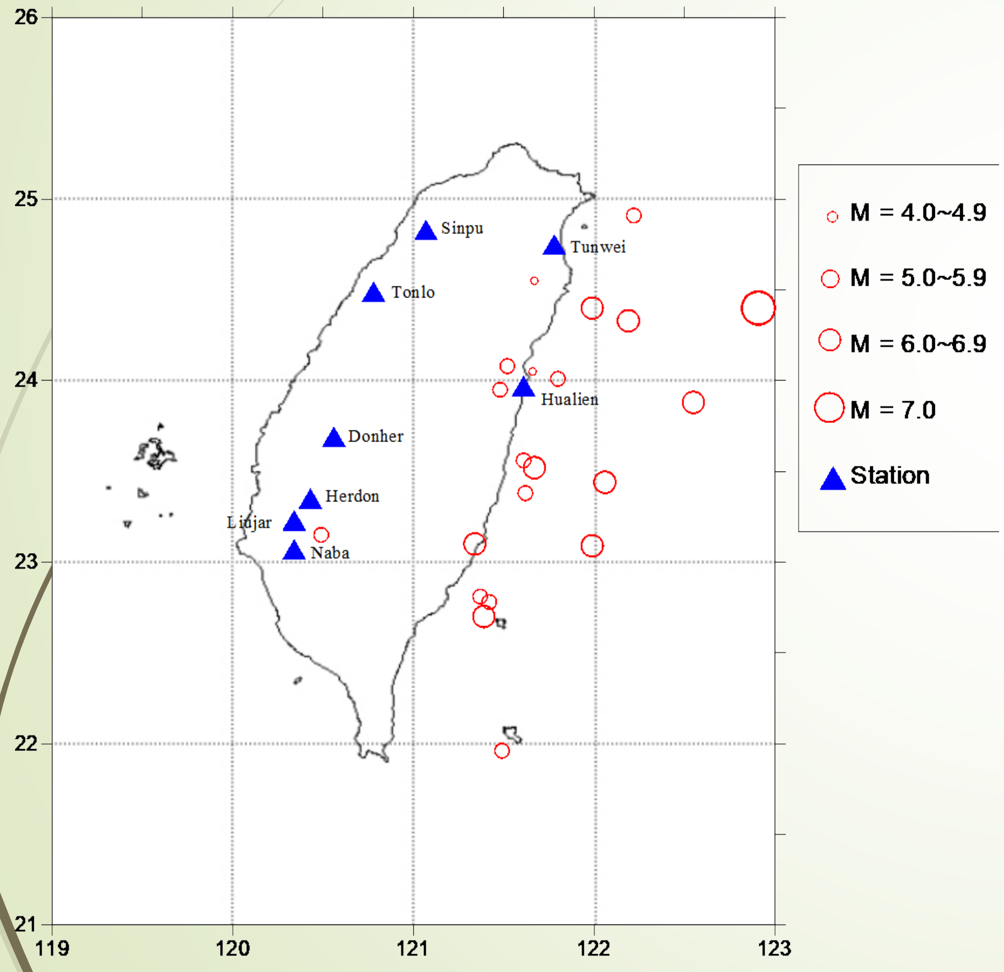
Estimating the extent of stress influence by using earthquake triggering groundwater level variations in Taiwan, *Journal of Asian Earth Sciences*

Introduction

- The earthquake focal area is usually in an area with anomalous stress (Stein, 1999; Parsons et al., 2008).
  - Dobrovosky et al. (1979) proposed an empirical relationship between the earthquake magnitude and the maximum influence distance for a given strain.
  - Niu (2000) used the sudden changes of crust deformation at various stations to predict the location of the epicenter of an earthquake in China.
  - Chen et al., (2015a, 2015b) using momentary high-conductivity materials to estimate the hypocenter for earthquakes in Taiwan.
- The stress (or strain) caused by earthquakes should be related to the earthquake magnitude and epicentral distance. The signal of the stress (or strain) can be detected by groundwater variations.
- A multivariable equation from an analytical solution based on poroelastic theory is used to construct the model for evaluating the extent of stress influence by using earthquake magnitude, epicentral distance, and magnitude of groundwater level variation.
- The extent of stress influence is defined as the distance over which an earthquake can induce a step change of the groundwater level.

Study background

- Locations of the eight observation wells and 21 earthquake events used in this study.



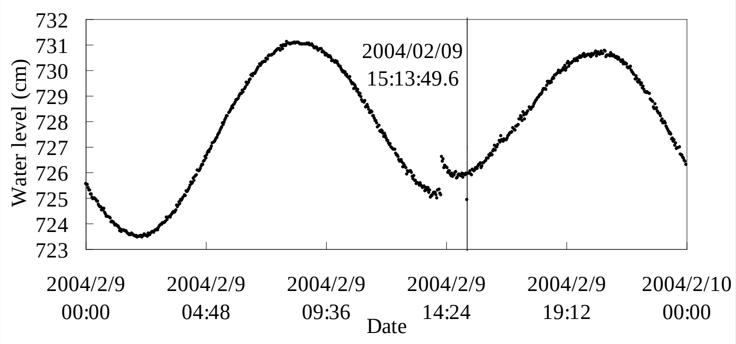
Earthquake number	Local time*	Local magnitude	Hypocentral depth (km)	Position	
				Longitude	Latitude
1	2003/04/03 14:59:33.7	5.0	14.5	120.5	23.2
2	2003/06/09 09:52:52.6	6.3	21.3	122.0	24.4
3	2003/06/10 16:40:32.7	6.5	27.6	121.7	23.5
4	2003/06/17 02:33:39.9	5.9	18.8	121.6	23.6
5	2003/12/10 12:38:15.2	6.6	10.0	121.3	23.1
6	2003/12/11 08:01:49.8	5.7	12.6	121.4	22.8
7	2004/01/01 11:15:18.5	5.9	17.8	121.6	23.4
8	2004/01/06 08:55:33.5	4.6	54.9	121.7	24.6
9	2004/01/13 17:29:00.8	5.0	19.8	121.8	24.0
10	2004/02/04 11:24:00.5	6.0	4.1	122.1	23.4
11	2004/02/09 15:13:49.6	4.3	37.8	121.7	24.1
12	2004/04/20 01:51:24.7	5.1	43.4	121.4	22.8
13	2004/04/24 23:20:31.2	5.3	20.7	121.5	24.0
14	2004/05/01 15:56:13.3	5.8	17.8	121.5	24.1
15	2004/05/08 16:02:48.4	5.7	6.2	121.5	22.0
16	2004/05/16 14:04:08.3	6.0	12.5	122.0	23.1
17	2004/05/19 15:04:12.0	6.5	8.7	121.4	22.7
18	2004/07/06 15:32:03.3	5.8	9.8	122.2	24.9
19	2004/10/15 12:08:50.2	7.0	58.8	122.9	24.4
20	2004/11/08 23:54:58.8	6.7	10.0	122.6	23.9
21	2004/11/11 10:16:44.4	6.0	13.9	122.2	24.3

Observations

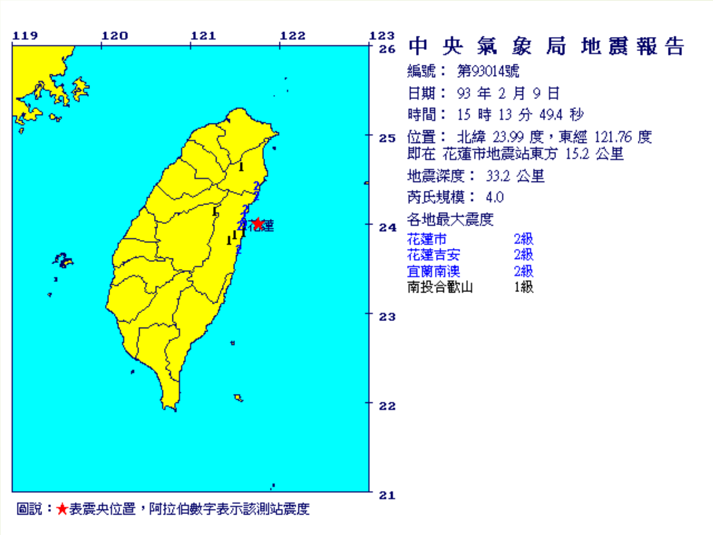
- Among the eight observation wells, Tunwei and Hualien were the most sensitive to earthquakes.
- Not all wells close to the epicenter responded to the earthquakes.

Frequency of oscillatory and step changes of groundwater level

Observation well	Oscillation	Step	Total
Tunwei	7	6	13
Liujar	4	3	7
Donher	4	3	7
Hualien	10	2	12
Naba	6	2	8
Tonlo	6	1	7
Herdon	5	1	6
Sinpu	5	1	6
Total	47	19	66



Suspected pre-seismic groundwater level change on February 9, 2004, in the Hualien station before an M_L 4.0 earthquake.



Methodology

- **Poroelastic solution**
  - The analytical solution of the groundwater level change in response to the force in three dimensions is (Lu, 1991):

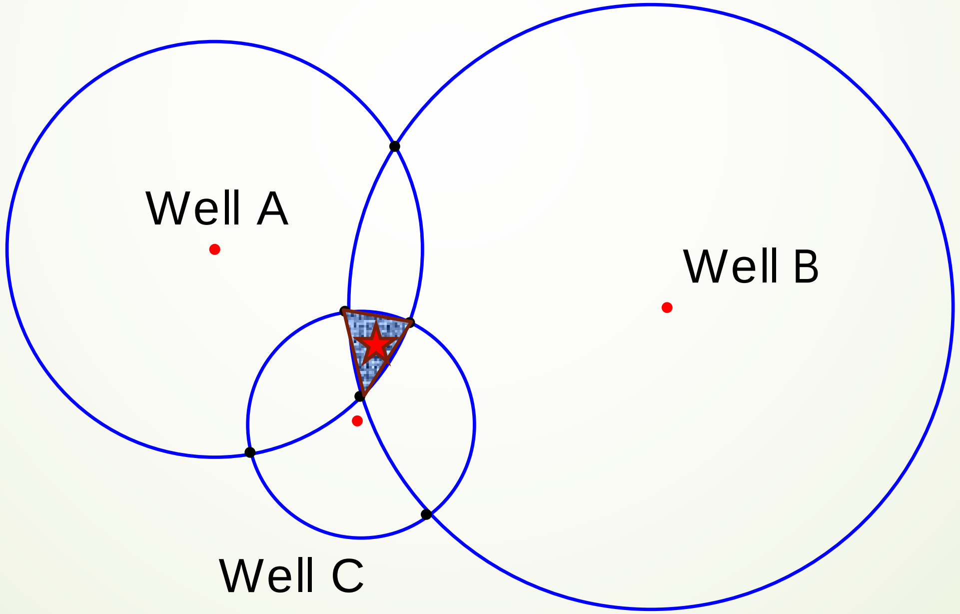
$$\Delta h = \frac{P}{\gamma_w} = \frac{C_0 F(r+z)}{R^3}\left[erf\left(D'^{\frac{1}{2}} \right) - \left(\frac{4D'}{\pi} \right)^{\frac{1}{2}} exp(-D') \right] \Rightarrow \Delta h = \frac{C_0 F(r+z)}{R^3}$$

  - The two-dimensional solution can be simplified as:

$$\Delta h = \frac{C_0 F}{r^2}\left[erf\left(\bar{D}^{\frac{1}{2}} \right) - \left(\frac{4\bar{D}}{\pi} \right)^{\frac{1}{2}} exp(-\bar{D}) \right] \Rightarrow \Delta h = \frac{C_0 F}{r^2}$$

Conceptual model for estimating area of anomalous stress

- Using intersection method, three wells can form an intersection area
- Factors: groundwater level step, distance, force magnitude



Results and discussion

Detection limit of groundwater variations

- From the collected data in Taiwan for step changes variation, the maximum detectable distance to the epicenter or hypocenter is about 250 km and that the minimum detectable earthquake magnitude is M_L 5.0.
- For earthquakes that caused oscillatory changes in the groundwater level, the maximum detectable distance is less than 300 km and the minimum earthquake magnitude is M_L 4.3.
- However, some data show that oscillatory- and step-type groundwater level variation can be observed in the installed monitoring wells as responses to distant earthquake such as the Sumatra and Wen-Chuan earthquakes, whose epicentral distances were farther than 3,000 and 1,900 km from Taiwan, respectively.

- The relationship between the maximum detectable epicentral distances (or hypocentral distances) and the earthquake magnitude

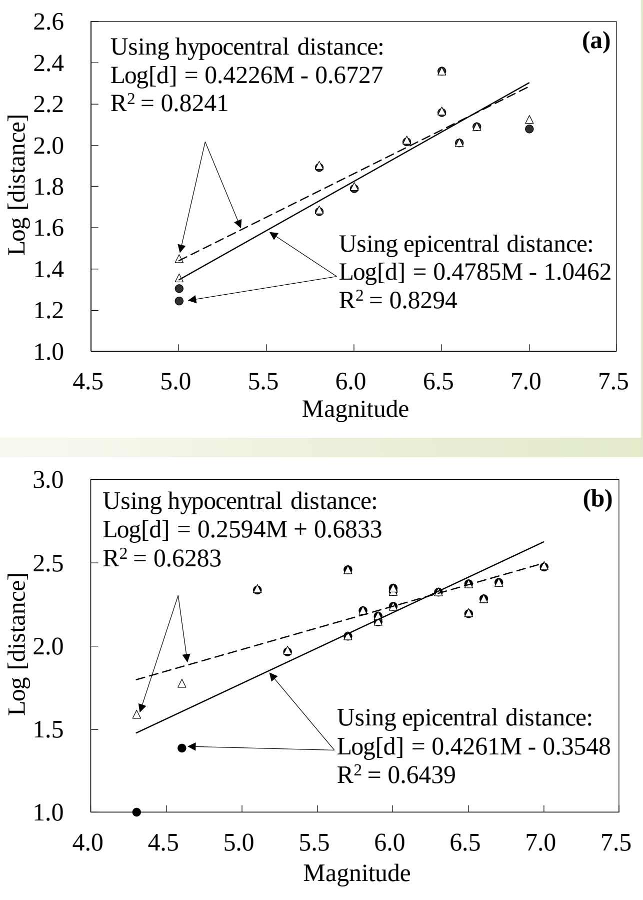
$$d = 0.090 \times 10^{0.4785M}$$

$$D = 0.212 \times 10^{0.4226M}$$

where d and D are the maximum detectable epicentral and hypocentral distances, respectively.

- Dobrovosky et al. (1979) suggested an empirical relationship between the earthquake magnitude and the maximum distance that leads to a strain of 10^{-8} caused by earthquakes. The equation is:

$$d = 10^{0.43M}$$



Relationship between maximum epicentral (or hypocentral) distances and earthquake magnitude for groundwater variation with (a) step and (b) oscillatory changes observed in Taiwan.

Models for evaluating extent of stress influence

- Semi-empirical model (model I)

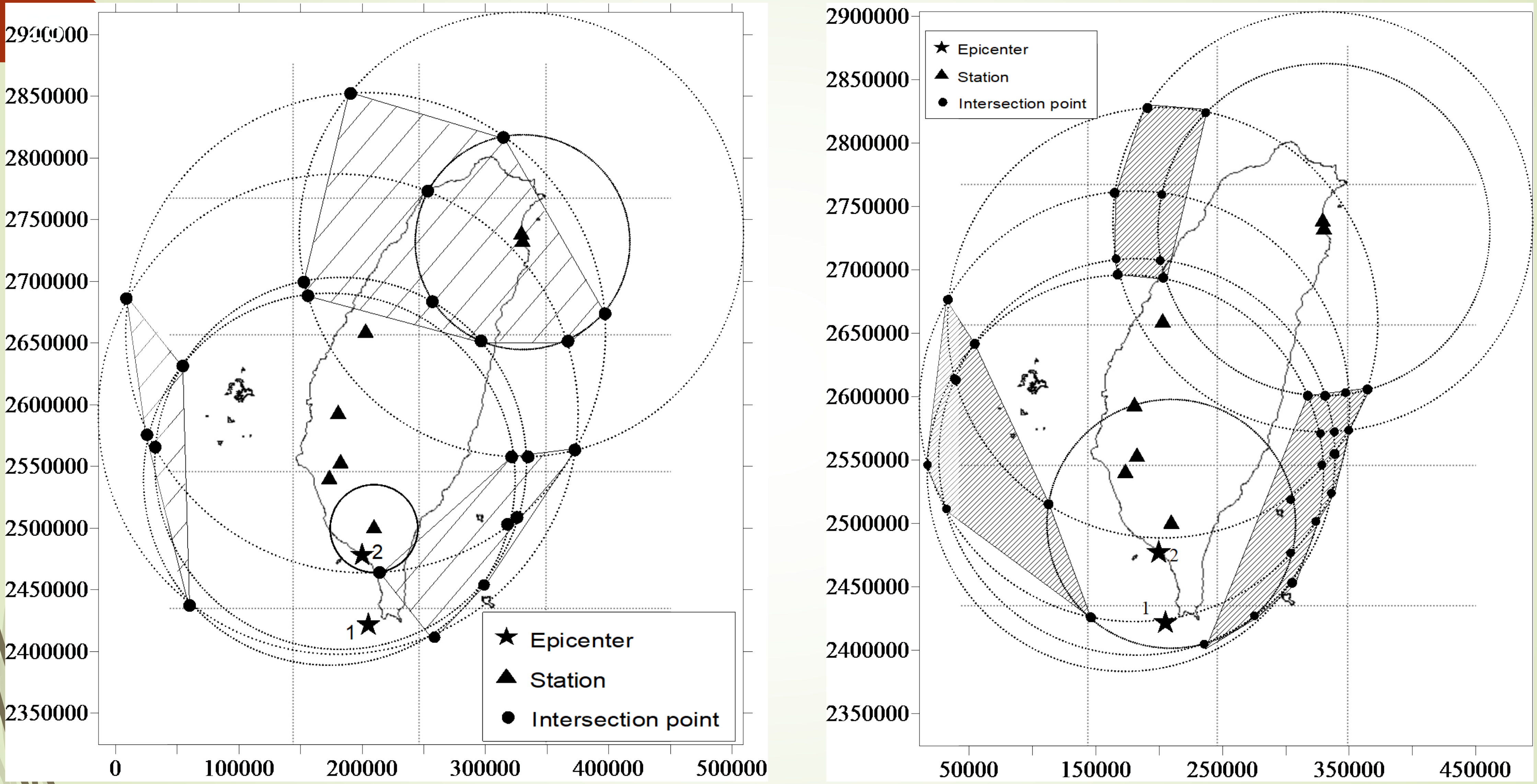
$$\log(d) = -0.5\log(\Delta h) + 0.62385M + 0.001503$$

- Fully-empirical model (Model II)

$$\log(d) = -0.1613\log(\Delta h) + 0.5934M + 0.8960$$

where the units of d and Δh are both meters and M is the local earthquake magnitude

Estimation of anomalous stress area



Anomalous stress area estimated using Model I and Model II with seven wells for an earthquake sequence that happened within 8 minutes on December 26, 2006, with M_L 6.7 and 6.4, respectively.

Summary

- Quantitative empirical models were proposed to estimate the extent of stress influence by using groundwater level variations triggered by earthquakes.
- The maximum extent of stress influence of a step-type anomaly from groundwater observation is about 250 km and the minimum detectable earthquake magnitude is 5.0 in the Taiwan area.
- The results show that the cross areas of these two models, though, do not cover epicenter, the areas close to it.

Topic 2. Parameter inversion

Evaluation of Hydraulic Properties of Aquitards Using Earthquake-Triggered Groundwater Variation, *Groundwater*

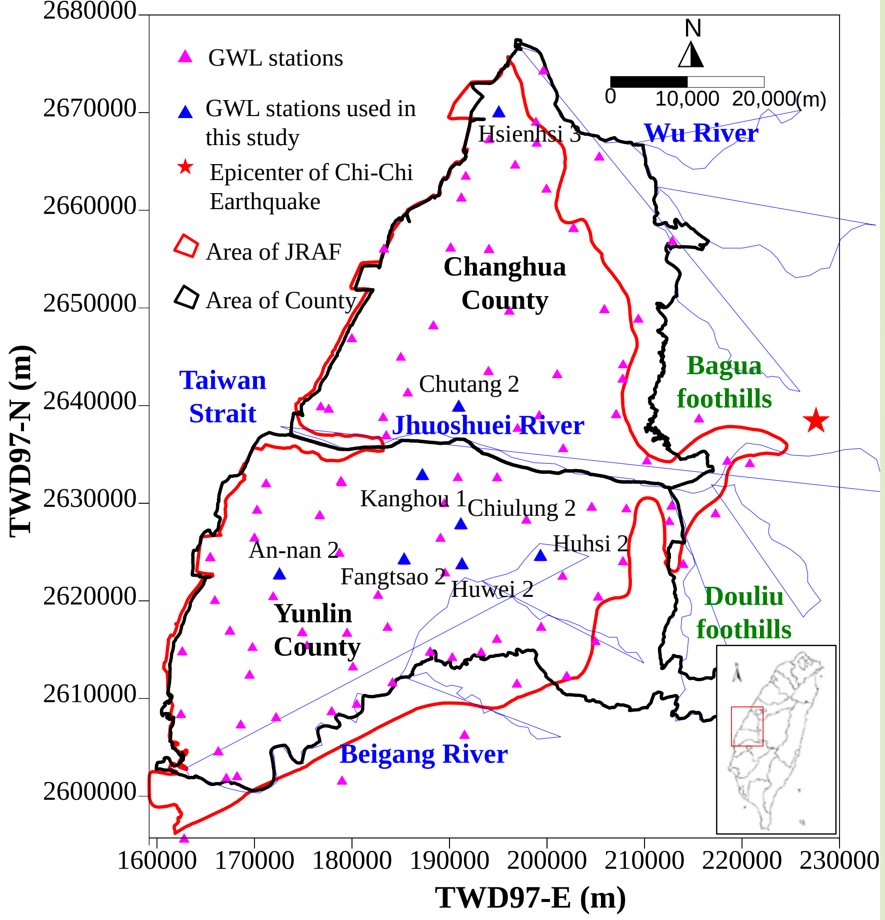
Introduction

- The hydraulic property of aquitard plays the main role for groundwater flow and groundwater resource in an aquifer system. For example,
  - leakage of aquitard induces the contaminant solutes to transport from aquifer to aquifer and influences the estimated area of contaminant (Schwartz and Zhang, 2003);
  - an aquitard window will induce an overestimation for groundwater exploitation (Timms, 2001);
  - the difference of the hydraulic property of aquitard could induce an increase or decrease of pore water pressure under groundwater extraction; (Hsieh, 1996);
  - clayey interbed aquitard is the main compaction area for land subsidence (Galloway and Burbey, 2011)
- The hydraulic property of aquitard is, however, not easily obtained from the groundwater monitoring system.
- A method that can estimate the hydraulic properties of aquitard will be usable and valuable.

- Earthquake induced crust stress (strain) is a natural huge driving force, which triggering groundwater level variations in a short period in a large area.
- A recovery behavior often occurs after a step change of groundwater level (post-seismic), which is induced by the dissipation of excess pore water pressure passing through the porous media.
- The recovery groundwater level implies the hydraulic characteristic of the porous media, that information can be used to estimate the hydraulic property of the aquifer system (Roeloffs, 1996).
- This study proposes a method which uses the recovery phenomena to estimate the hydraulic property of an aquifer system and then calculated the hydraulic conductivity of aquitard.

Study background

- The Chi-Chi earthquake with Richter magnitude 7.3 took place in 1999 in the eastern area of Jhoushuei River Alluvial Fan, Taiwan, which causes groundwater level variations for a large number of groundwater monitoring wells.
- To eliminate the influence of aftershock, only the groundwater level data in the period of main shock is adopted for the estimation of hydraulic property of aquitard. The total period is 5.2 days.
- The recovery phenomenon of groundwater level triggered by Chi-Chi Earthquake is used in this study to estimate the hydraulic property of aquitard by using the recovery theory proposed by Roeloffs (1996).



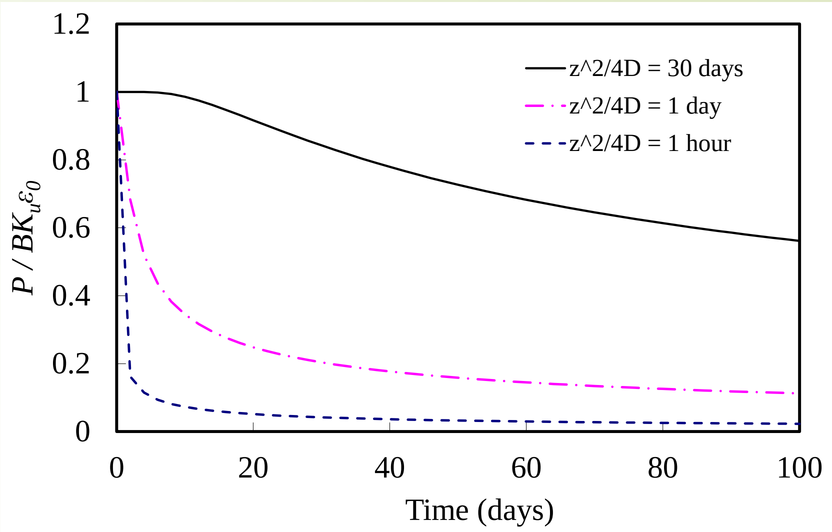
Basic information for the adopted groundwater monitoring wells

Well names	X-coordinate	Y-coordinate	Aquifer layers	Screen depth (m)	Groundwater level depth (m)
Chiulung 2	191168	2627781	2-2	97-115	6.99
Chutang 2	190948	2639823	2-2	77-125	10.16
Fangtsao 2	185350	2624184	2-1, 2-2	76-124	9.79
Huwei 2	191285	2623689	2-1, 2-2	72-102	11.91
Huhsi 2	199331	2624542	2-1, 2-2	96-123	3.98
Hsienhsi 3	195062	2669966	2-2	105-117	8.49
An-nan 2	172567	2622644	3	159-195	15.43
Kanghou 1	187220	2632820	2-1	52-64	8.56

Methodology

- Groundwater recovery theory (follow Roeloffs, 1996):

$$-\frac{P(z,t)}{BK_u\varepsilon_0} = erf\left\{\left[(z-z_w)^2/4Dt\right]^{1/2}\right\}$$

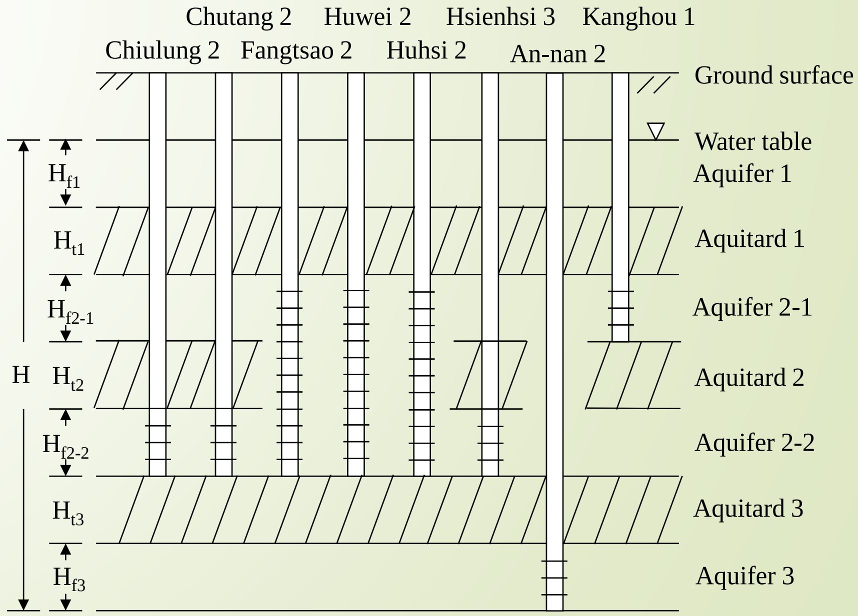


- The mean hydraulic conductivity for the formations can be calculated by:

$$K_H = D \times S_s$$

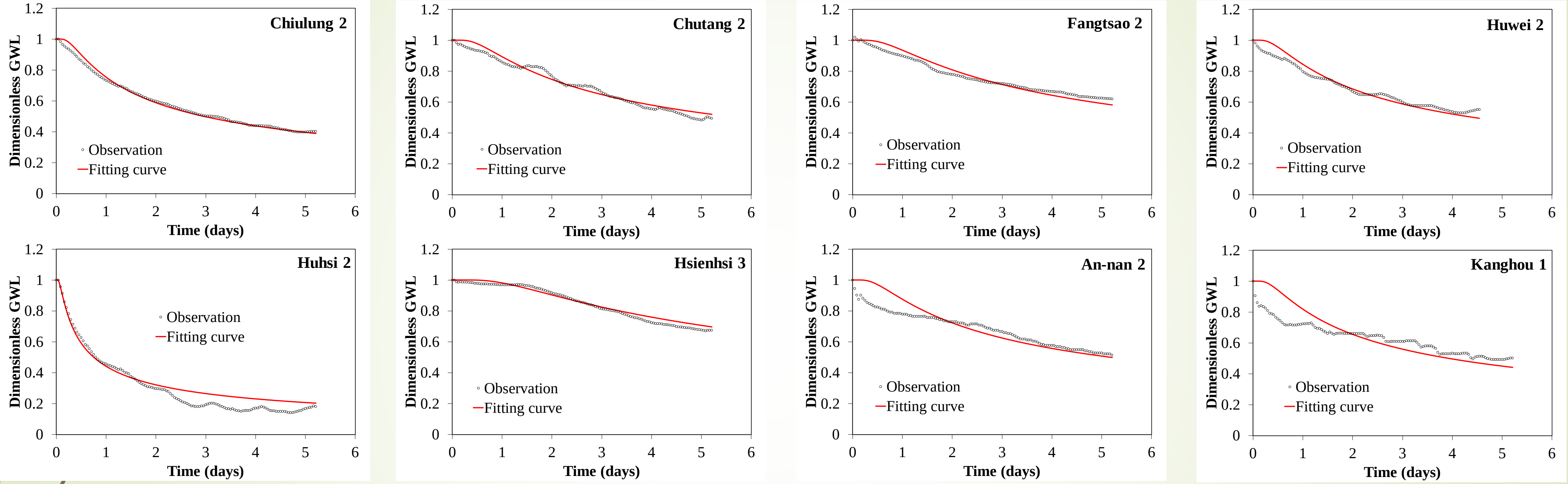
- The equivalent vertical hydraulic conductivity for the aquifer system can be written as (Schwartz and Zhang, 2003):

$$\frac{H}{K_H} = \frac{H_{f1}}{K_{f1}} + \frac{H_{t1}}{K_{t1}} + \frac{H_{f2-1}}{K_{f2-1}} + \frac{H_{t2}}{K_{t2}} + \frac{H_{f2-2}}{K_{f2-2}} + \frac{H_{t3}}{K_{t3}} + \frac{H_{f3}}{K_{f3}}$$



Results

Post-seismic groundwater level fitting



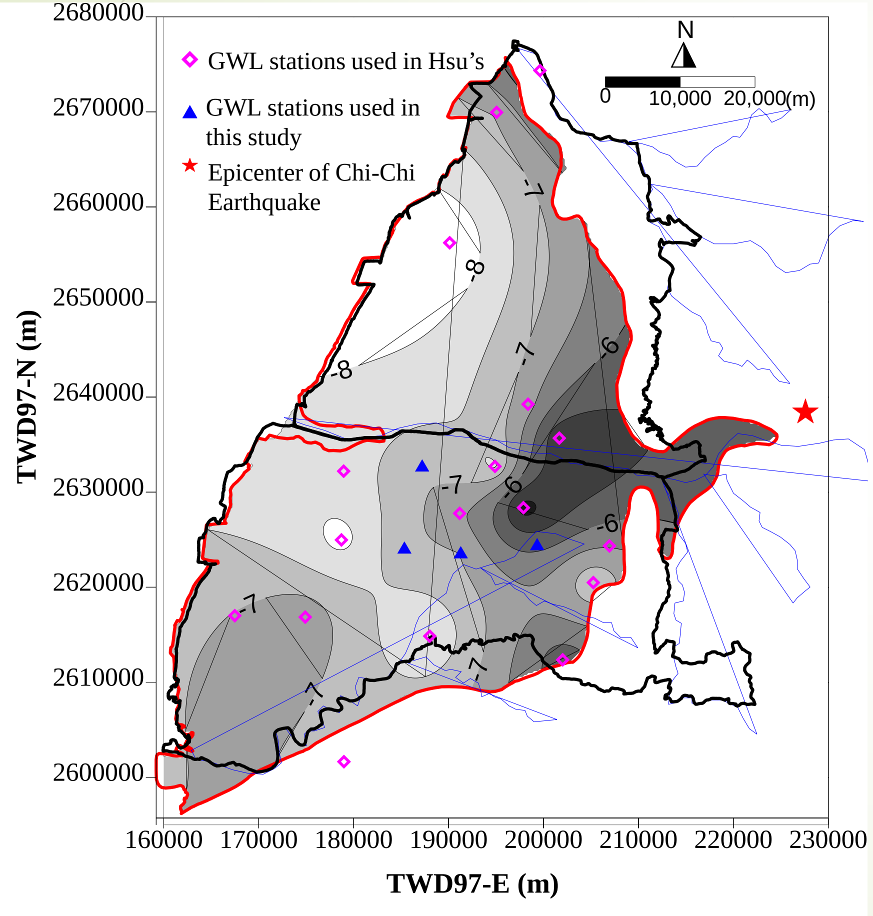
Well names	Mean hydraulic diffusivity (m^2/s)	Specific storage (m^{-1})	Mean hydraulic conductivity (m/s)	Coefficient of variation	R-square
Chiulung 2	4.21×10^{-2}	2.50×10^{-5}	1.05×10^{-6}	0.029	0.989
Chutang 2	1.83×10^{-2}	2.50×10^{-5}	4.59×10^{-7}	0.037	0.970
Fangtsao 2	1.38×10^{-2}	2.50×10^{-5}	3.46×10^{-7}	0.036	0.941
Huwei 2	1.62×10^{-2}	2.50×10^{-5}	4.05×10^{-7}	0.048	0.935
Huhsi 2	1.88×10^{-1}	2.50×10^{-5}	4.69×10^{-6}	0.159	0.934
Hsienhsi 3	3.42×10^{-2}	2.50×10^{-5}	8.55×10^{-7}	0.022	0.972
An-nan 2	6.39×10^{-2}	2.50×10^{-5}	1.60×10^{-6}	0.090	0.657
Kanghou 1	7.91×10^{-3}	2.50×10^{-5}	1.98×10^{-7}	0.127	0.292

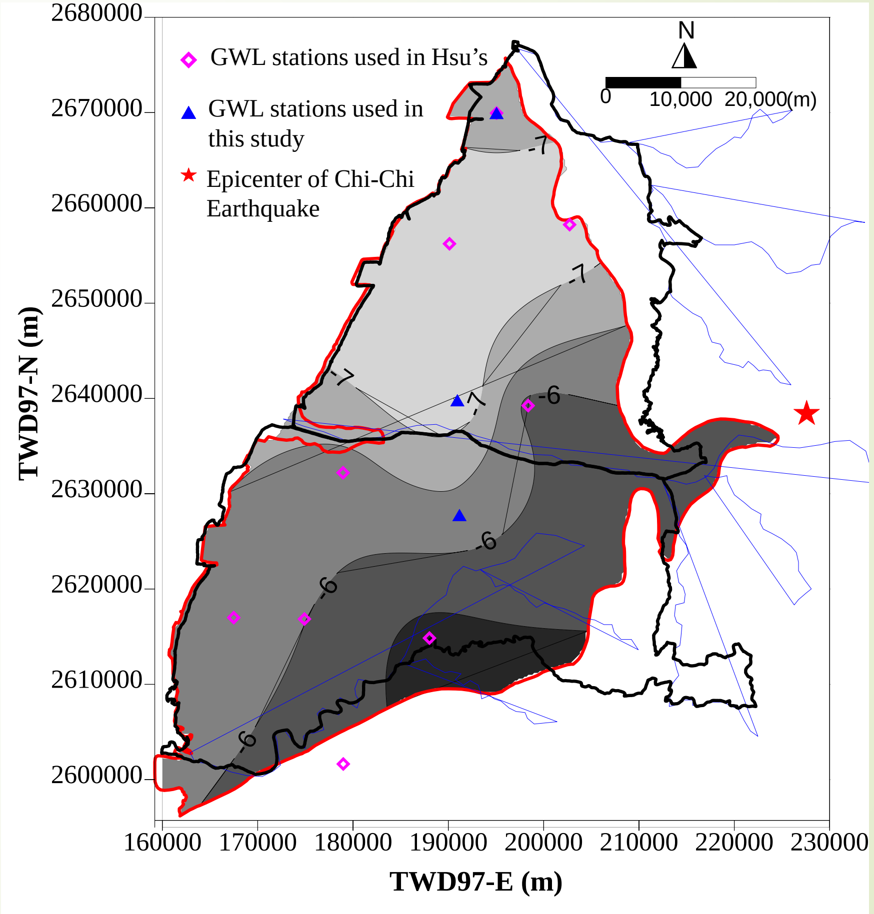
Estimated hydraulic conductivity of aquitard

	Chiulung 2	Chutang 2	Fangtsao 2	Huwei 2	Huhsi 2	Hsienhsi 3	An-nan 2	Kanghou 1	Mean
Mean	1.05×10^{-6}	4.59×10^{-7}	3.46×10^{-7}	4.05×10^{-7}	4.69×10^{-6}	8.55×10^{-7}	1.60×10^{-6}	1.98×10^{-7}	1.20×10^{-6}
Aquifer 1	8.98×10^{-4}	1.79×10^{-3}	1.46×10^{-4}	1.13×10^{-3}	7.01×10^{-4}	1.70×10^{-4}		1.51×10^{-3}	9.06×10^{-4}
Aquifer 2-1	9.33×10^{-4}	5.20×10^{-4}				8.49×10^{-4}	6.10×10^{-4}	8.27×10^{-4}	7.48×10^{-4}
Aquifer 2-2	9.33×10^{-4}	5.20×10^{-4}	5.37×10^{-4}	6.03×10^{-4}	6.73×10^{-4}	8.49×10^{-4}	6.10×10^{-4}		6.75×10^{-4}
Aquifer 3							1.62×10^{-4}		1.62×10^{-4}
Aquitard 1	*	*	7.65×10^{-8}	1.04×10^{-7}	1.49×10^{-6}	*	*	8.39×10^{-8}	4.38×10^{-7}
Aquitard 2	4.31×10^{-7}	3.03×10^{-8}				1.79×10^{-7}	*		2.14×10^{-7}
Aquitard 3							2.06×10^{-6}		2.06×10^{-6}

* indicates a lack value of hydraulic conductivity of that aquitard, the mean value (last column) calculated from other wells is adopted in the calculation.

Distribution of hydraulic conductivity of aquitards





The distribution of hydraulic conductivity of aquitards one and two by combining the results of this study and reference.

Summary

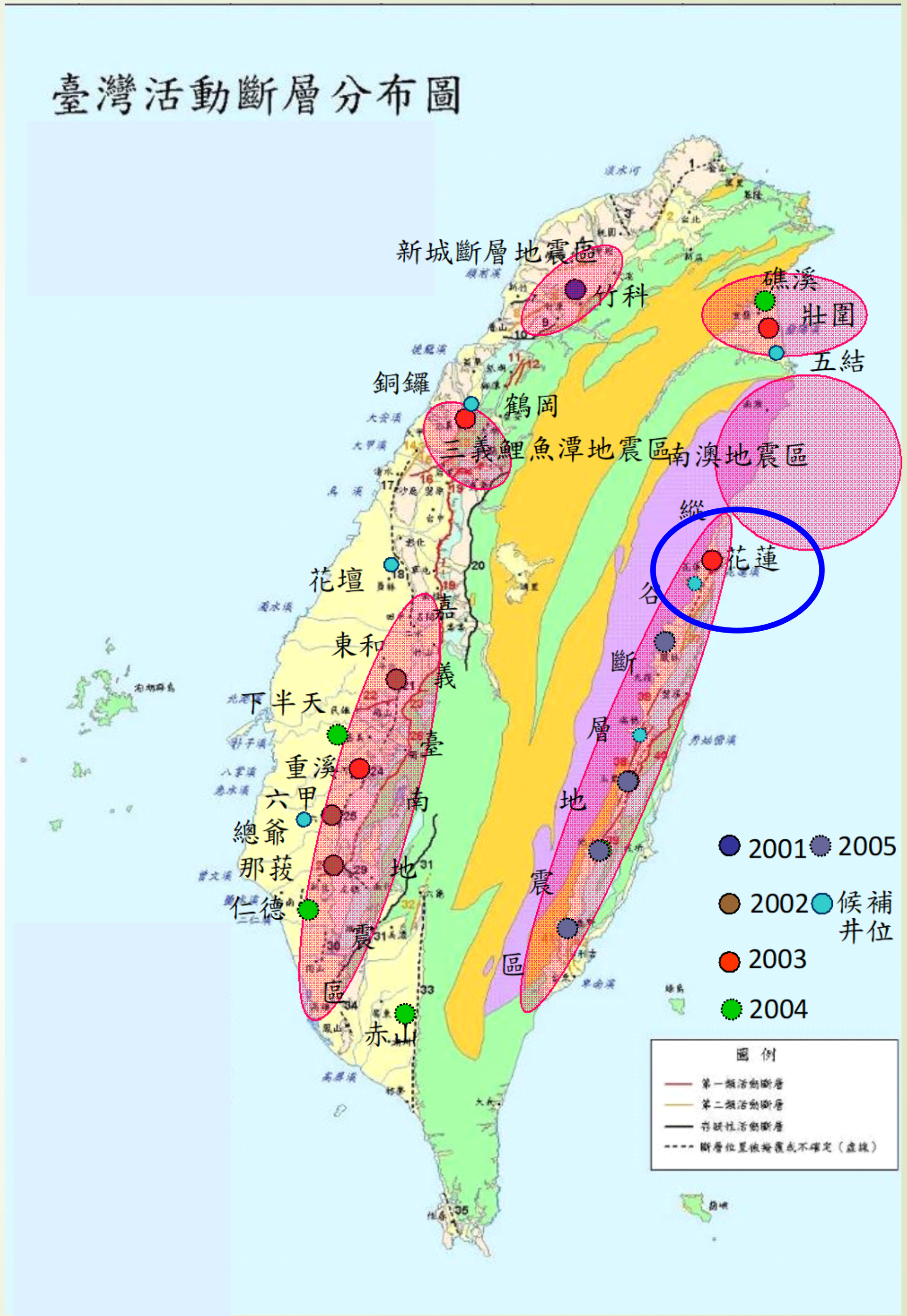
- Groundwater level recovery phenomena induced by the main shock of Chi-Chi Earthquake were used to fitting a post-seismic recovery theory to inverse the hydraulic properties of aquitard in Jhoushuei River Alluvial Fan, Taiwan.
- The fitting results showed that the mean hydraulic diffusivities of aquifer system are 7.91×10^{-3} ~ 1.88×10^{-1} m^2/s and the hydraulic conductivities of aquitard are 3.03×10^{-8} ~ 2.06×10^{-6}.
- The dissipation path for the excess pore water pressure induced by the earthquake at depths of 70-130 m is mainly upward.
- The adopted one-dimensional recovery theory for post-seismic phenomena is under the assumption of drainage in one dimension vertically, which might induce a discrepancy in the estimation.

Topic 3. Pre-seismic mechanism

The Mechanism of the Pre-seismic Groundwater Level Variations in Hualien Well, Eastern Taiwan, *Studying*

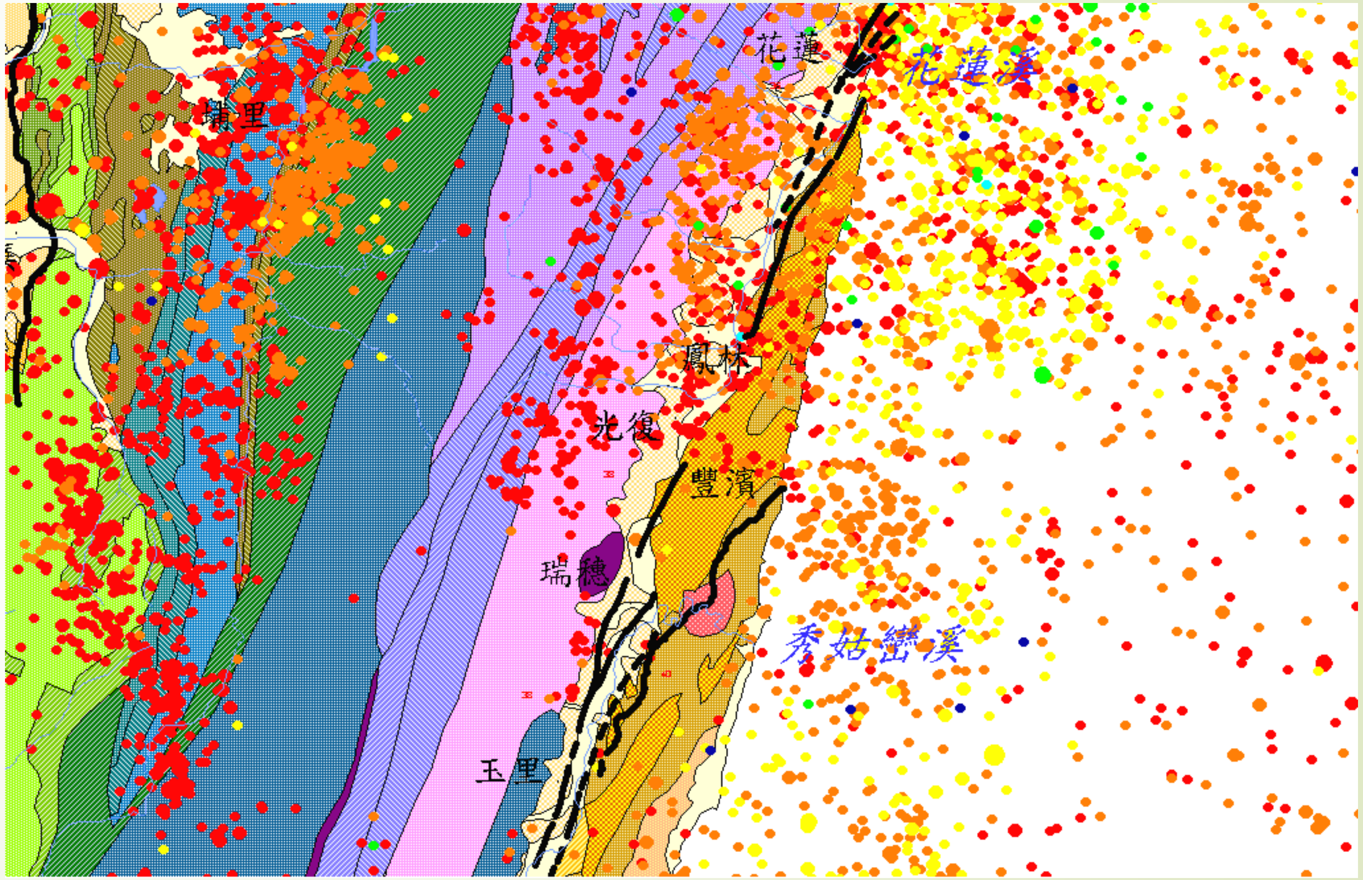
Introduction

- Central Weather Bureau and Water Resources Agency have setup groundwater level stations for earthquake observation
- Hualien observation well is sensitive to earthquake signal
- A conceptual model with a poroelastic theory is proposed to explain the mechanism of pre-seismic phenomena



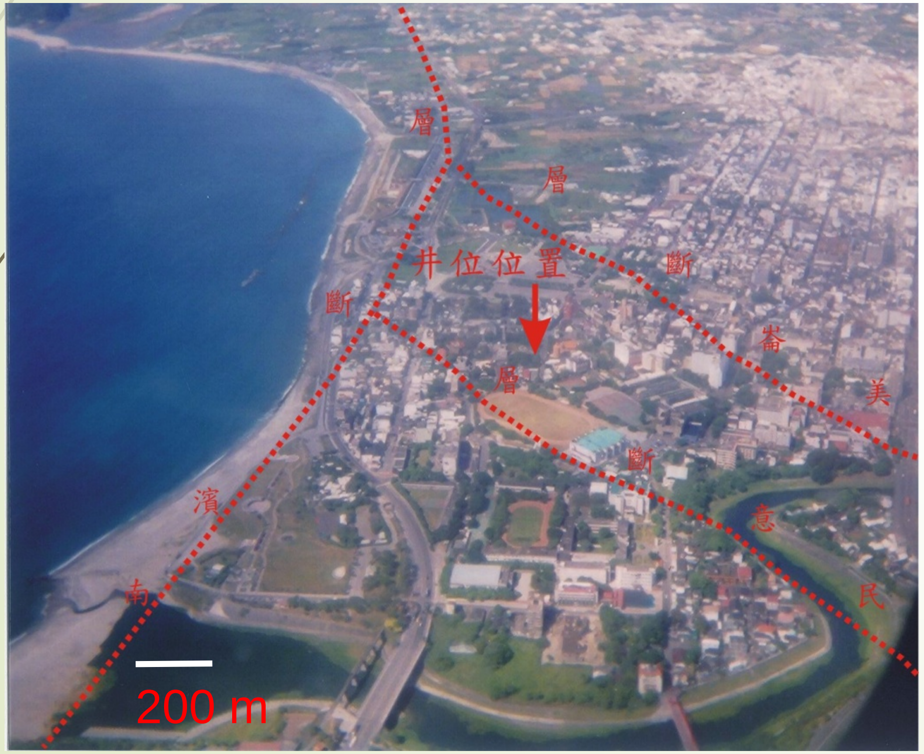
Study background

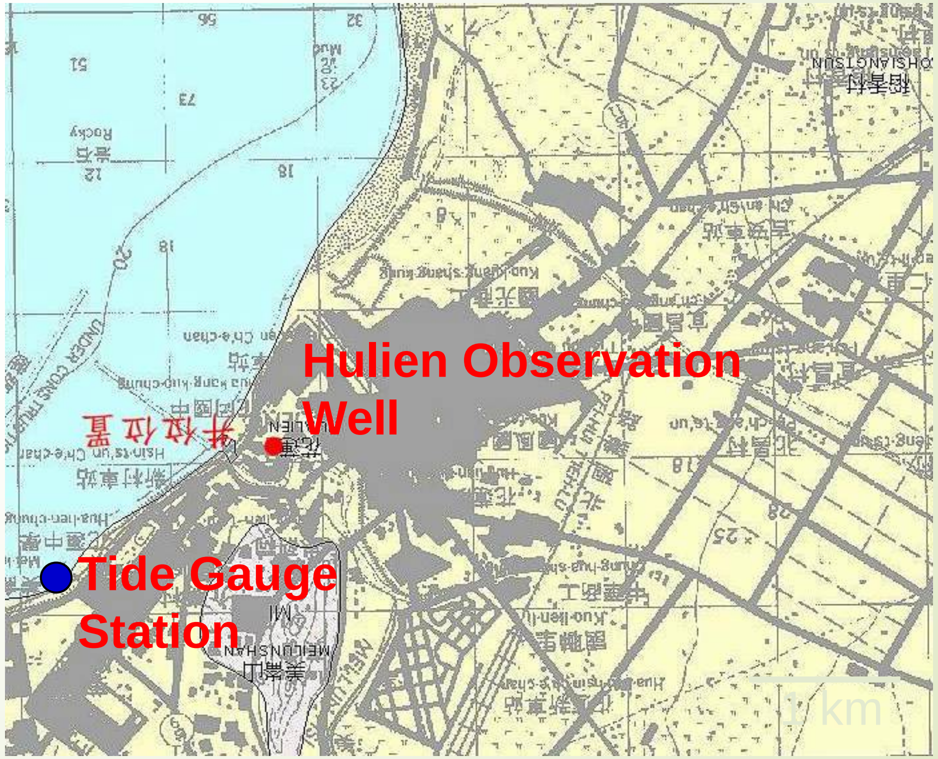
- Earthquake events are plenty in Hualien County
- The fault system is well developed, though complex
- The aquifer system is good for observation condition



Observation well

- GWL in Hualien well affected by ocean tide
- Located on Pleistocene ~ Quaternary conglomerate, situated inside the fault zones.





Location of Hualien observation well and tidal gauge station

Typical Hydrograph of observation

GWL

Barometric pressure

Barometric component

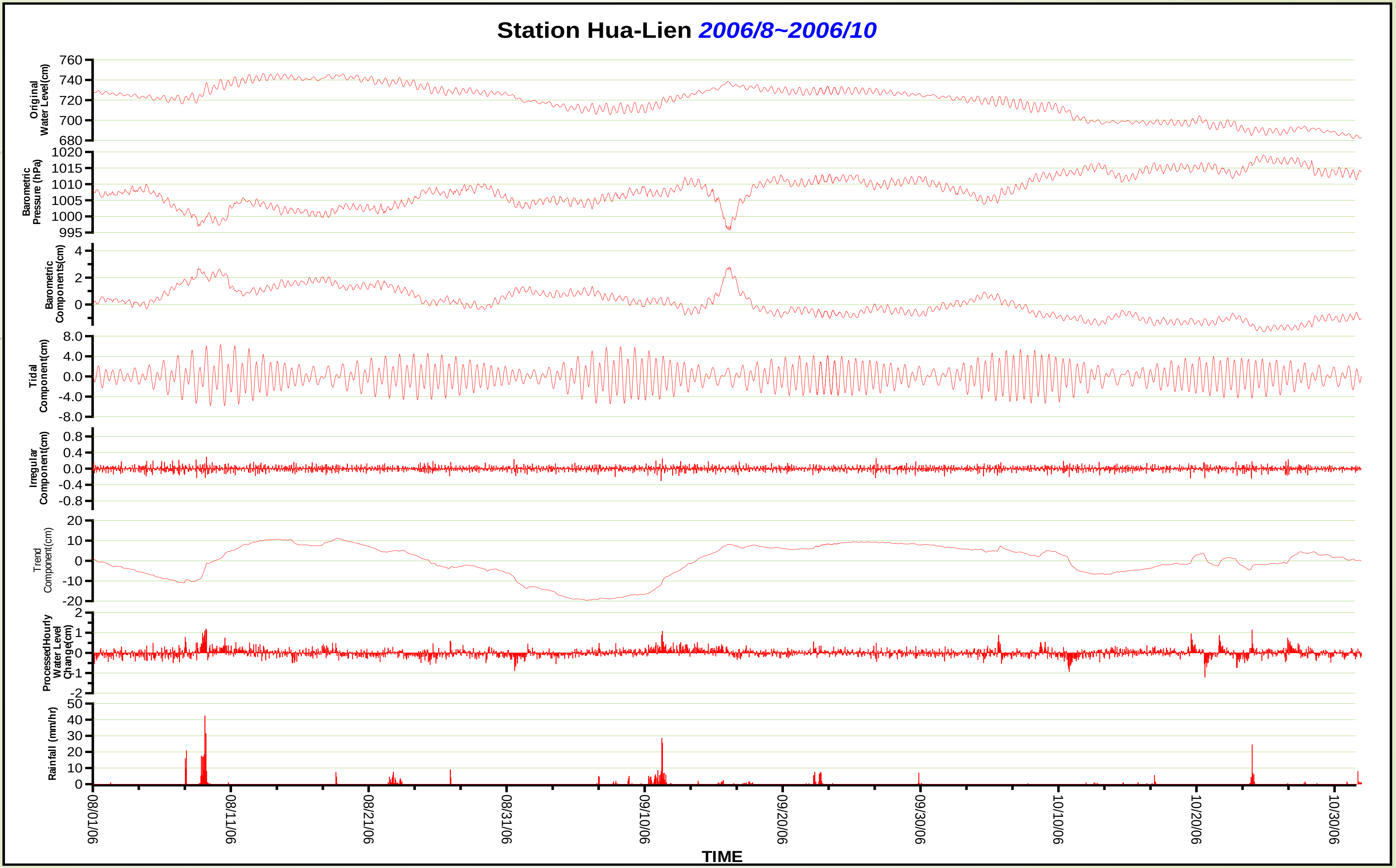
Tide component

Irregular component

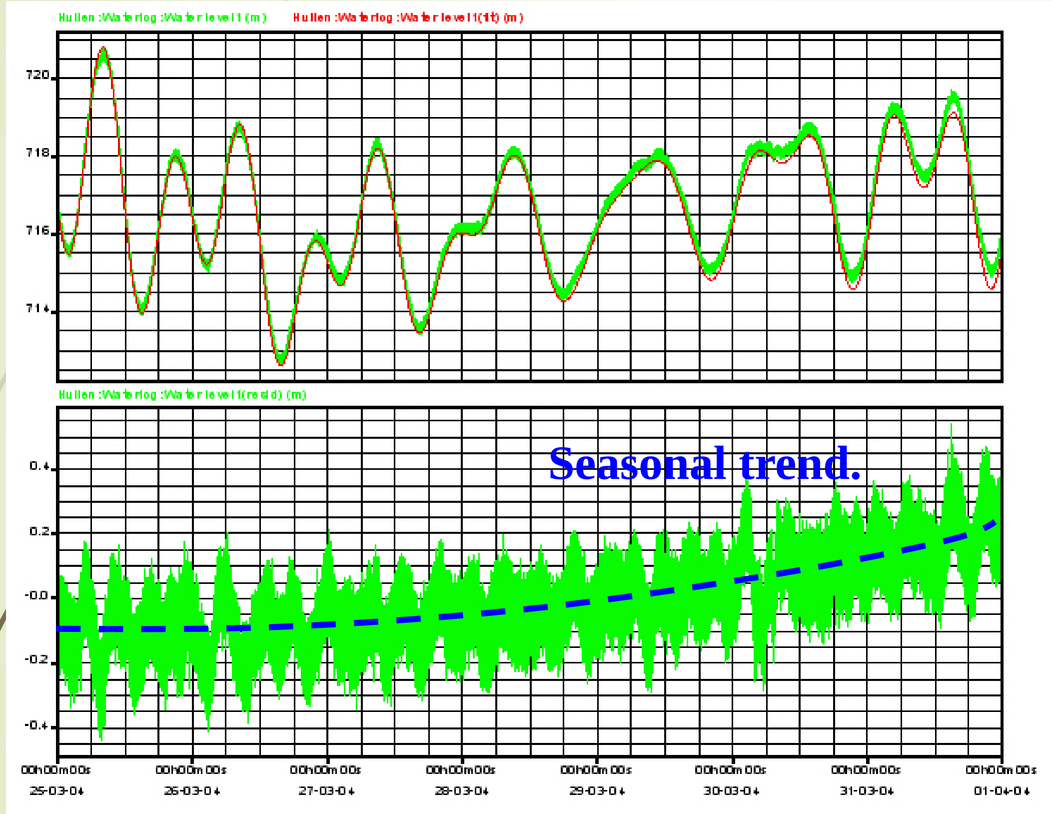
Trend component

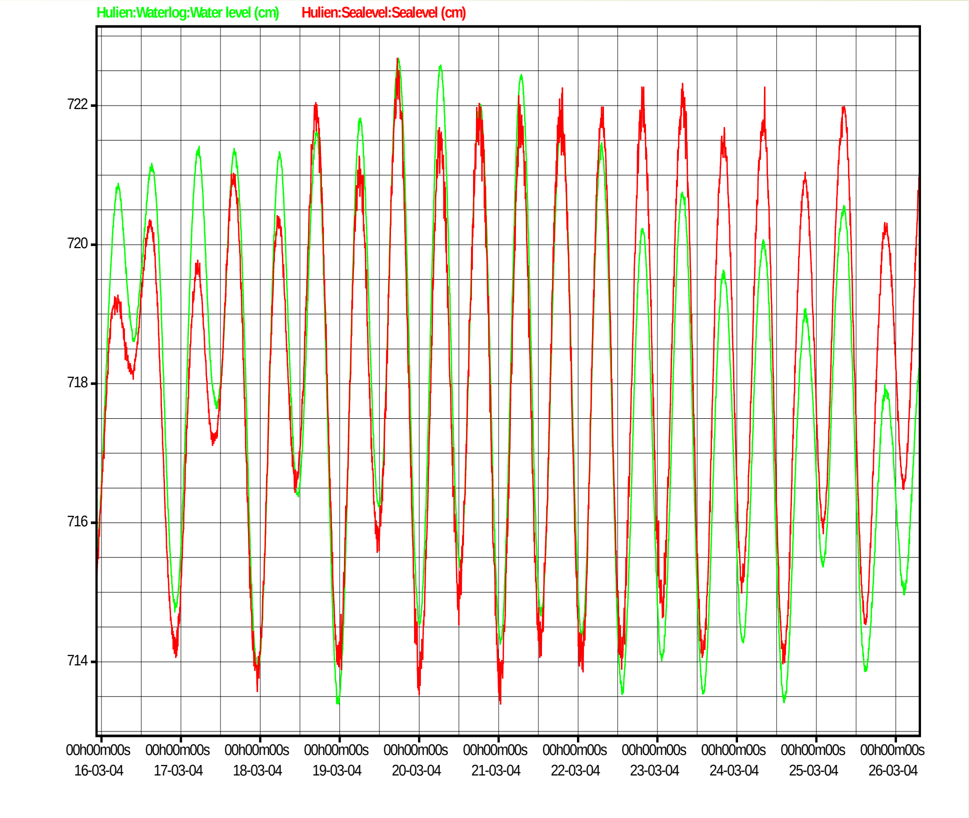
Proceed Hourly GWL

Precipitation



Comparison of SL and GWL Observation



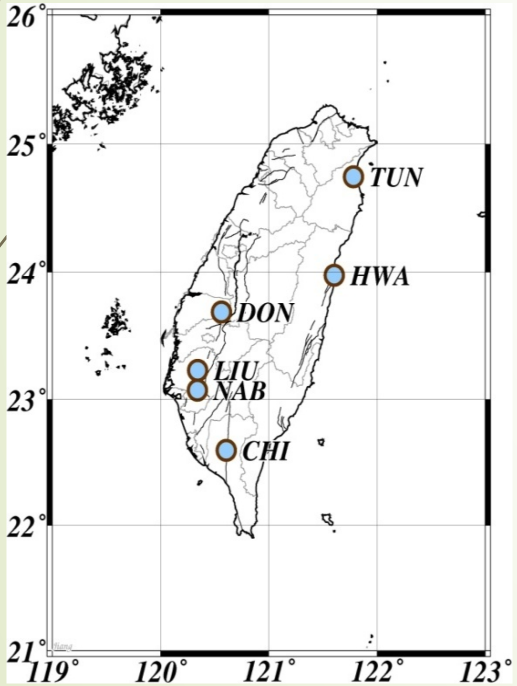


Red: Sea level observation in Hualien Harbor (6 min)

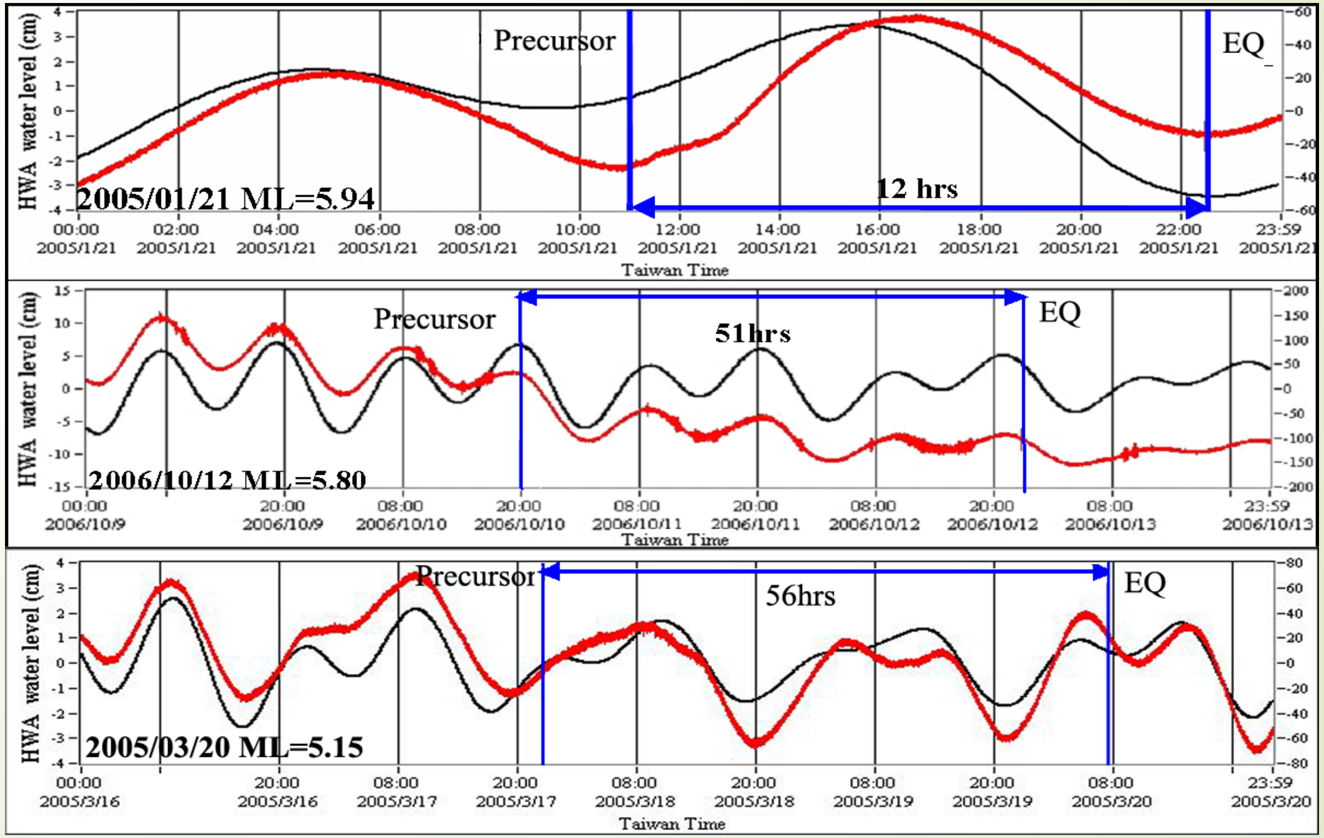
Green: Groundwater level observation in Hualien Observation (2 min)

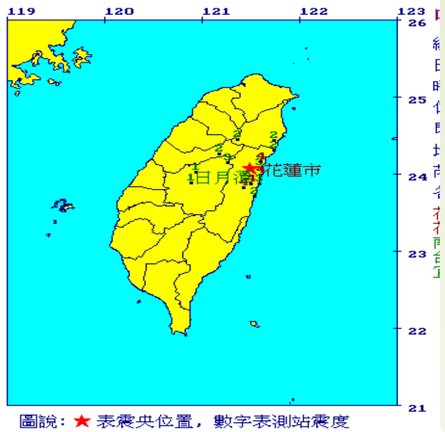
Anomalies (Tidal Deviation)

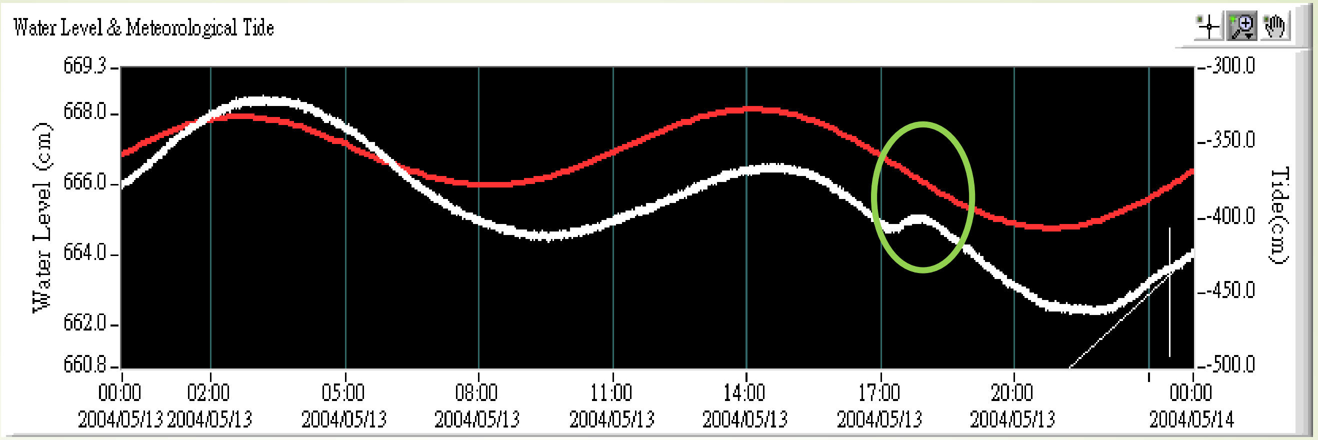
- The anomalies detecting criteria had been defined by the amplitude ratio and phase angle of the cross-correlation



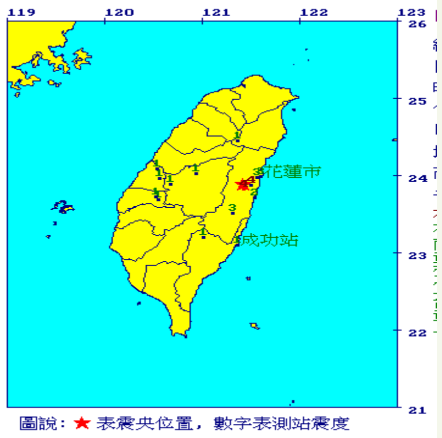
CWB Observation

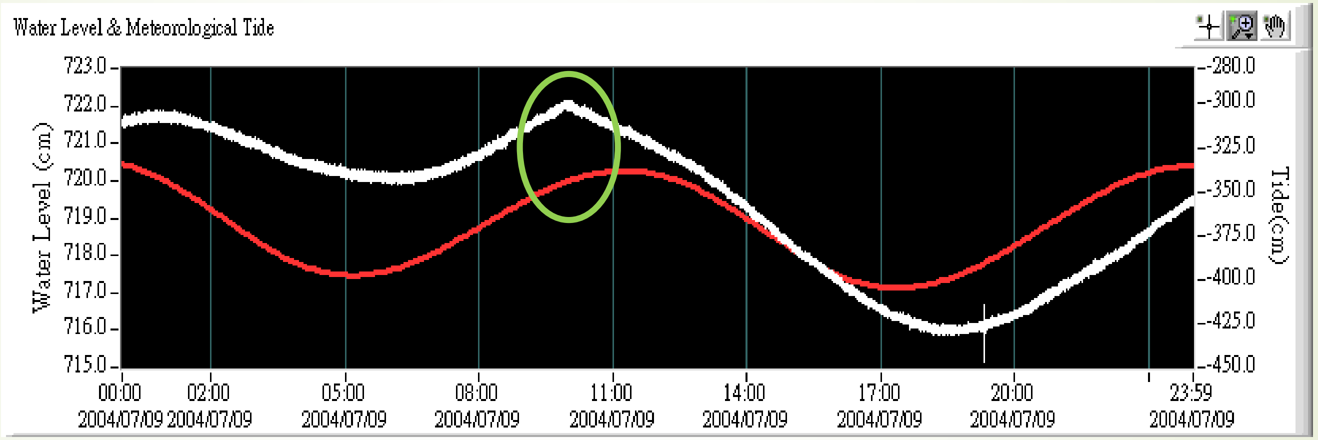




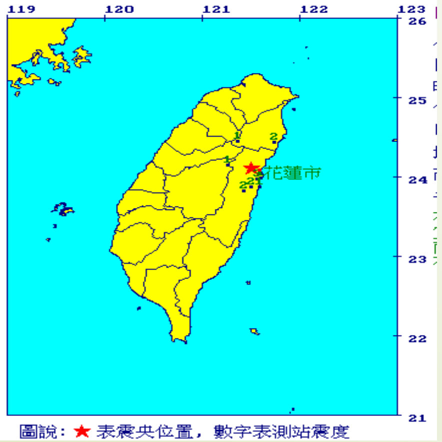


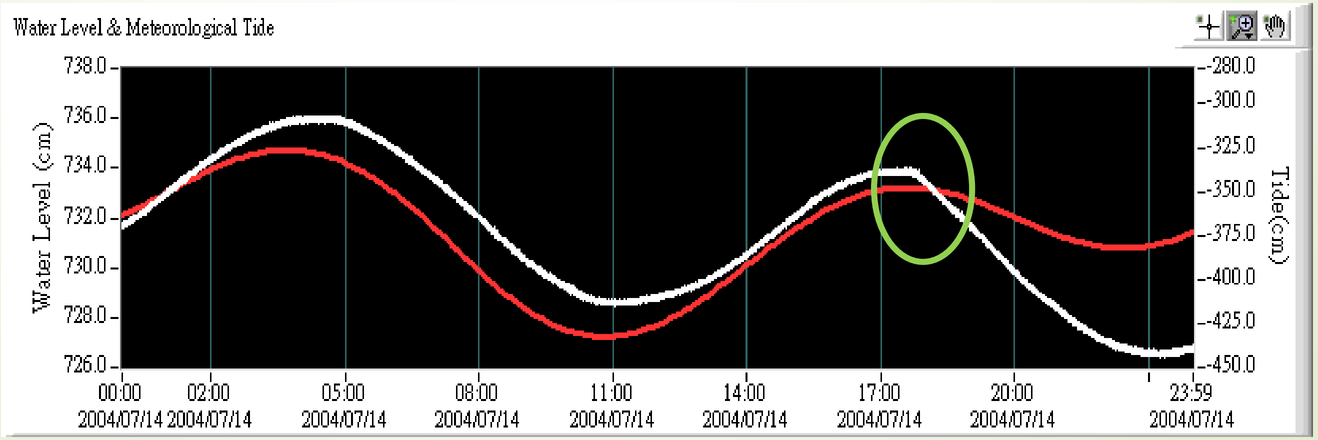
ML = 4.2
Depth = 20 km





ML = 4.5
Depth = 19.6 km



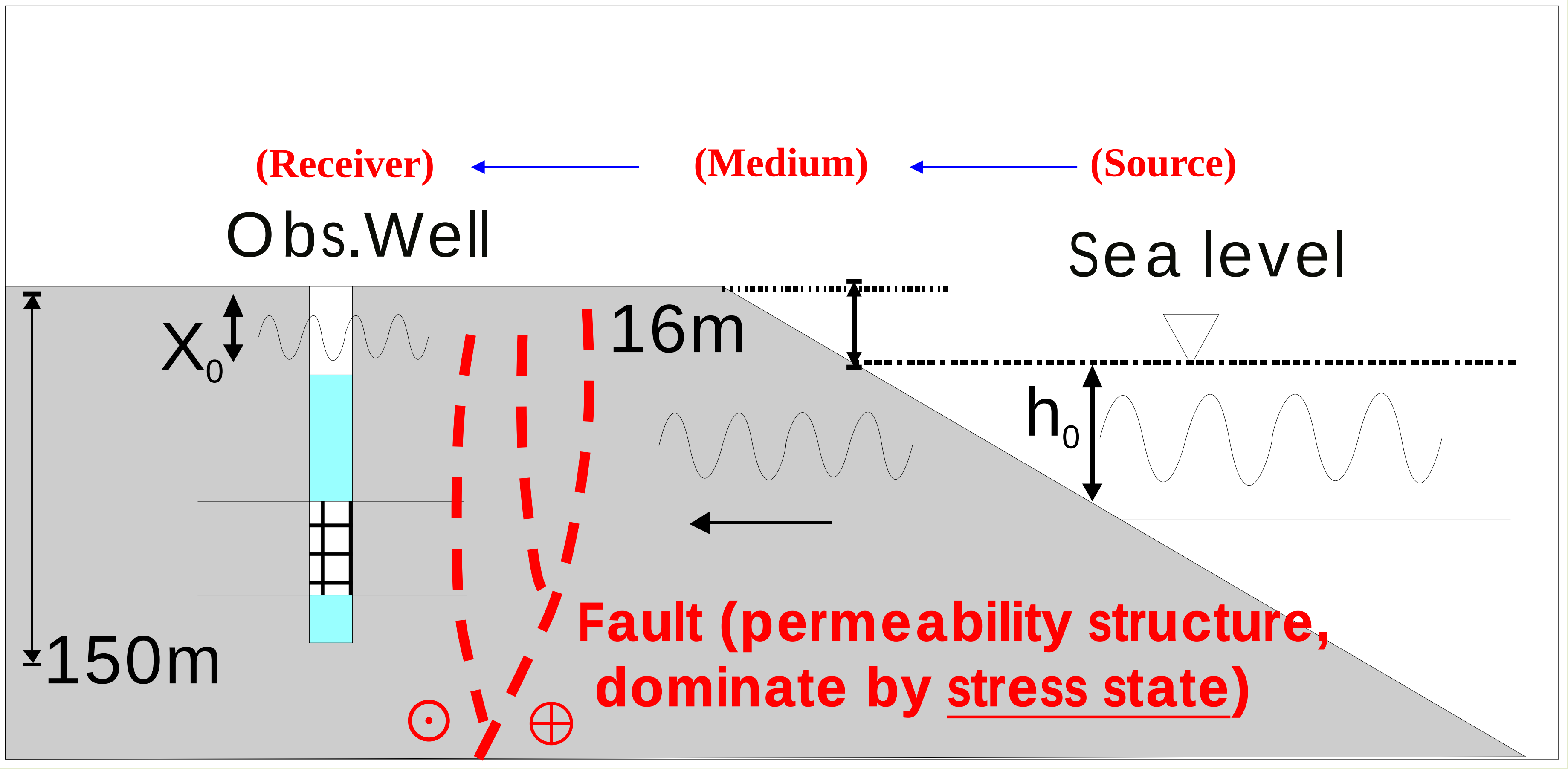


ML = 4.6
Depth = 22 km

Pre-seismic events for GWL (蔡俊雄，2004)

Possible mechanism

- Wave Propagation Model (fault permeability structure)

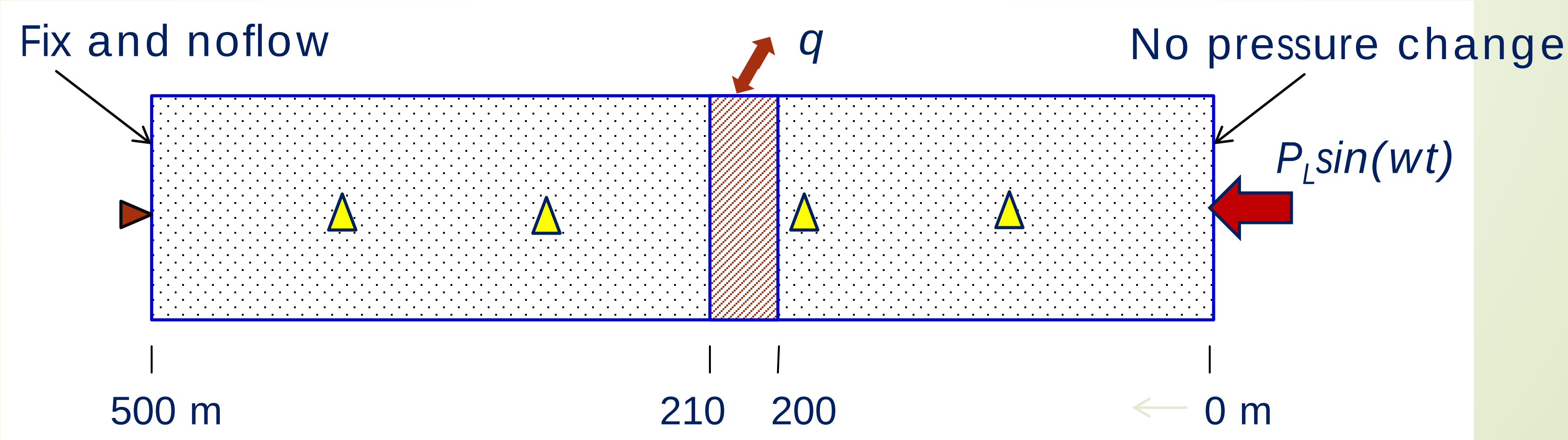


Poroelastic model

- Governing equations

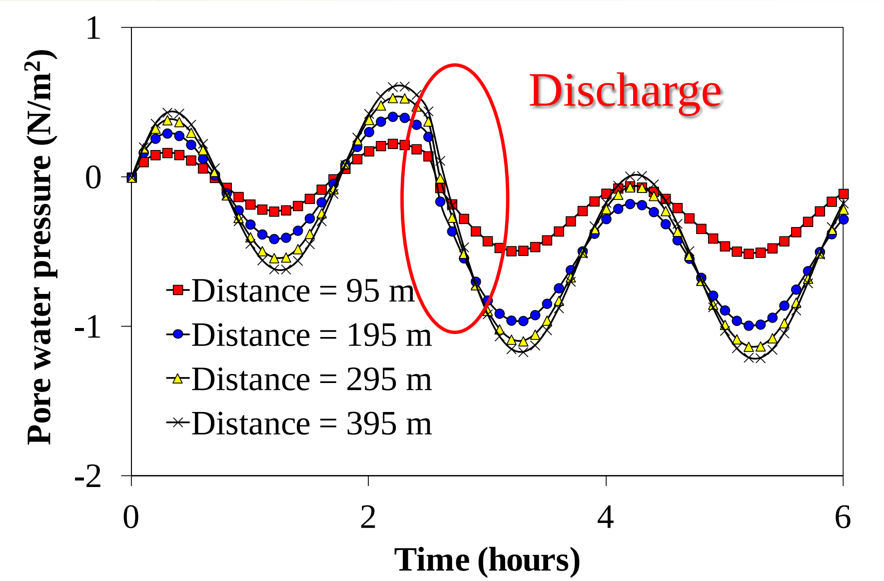
$$\frac{\partial}{\partial z}\left[a^{-1}\frac{\partial w}{\partial z}-\alpha P\right]=0$$

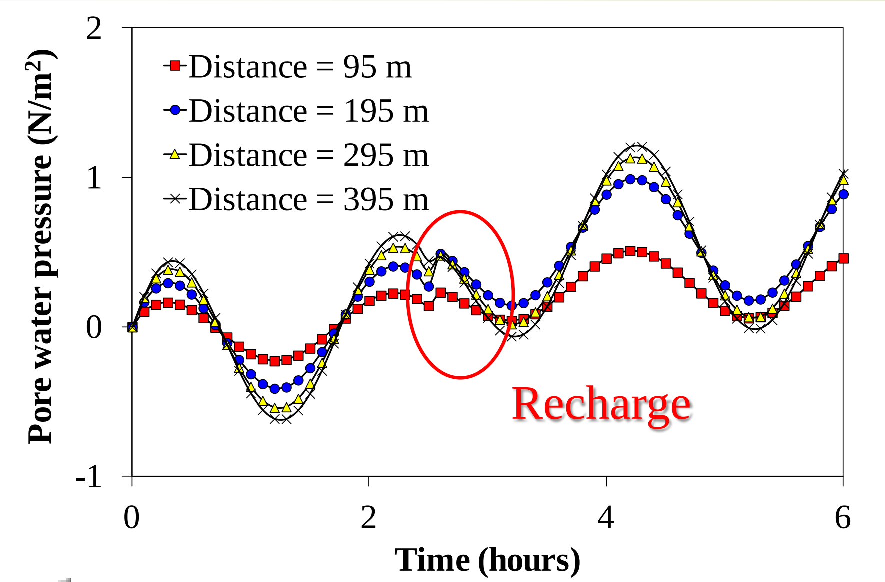
$$\frac{\partial}{\partial t}\left[\alpha\frac{\partial w}{\partial z}+Q^{-1}P\right]-\frac{\partial}{\partial z}\left[\kappa\frac{\partial P}{\partial z}\right]-q=0$$

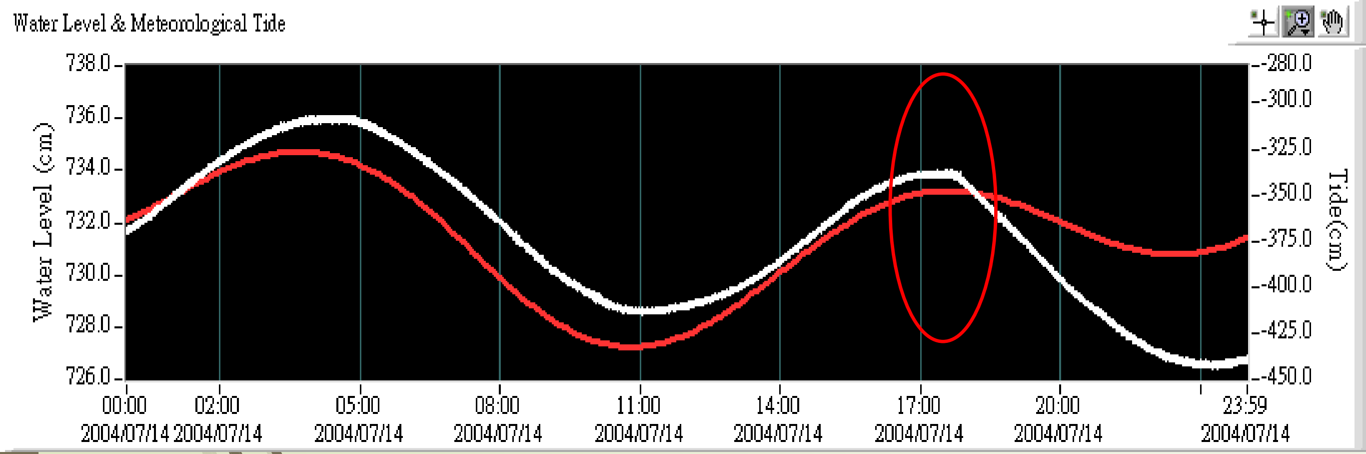


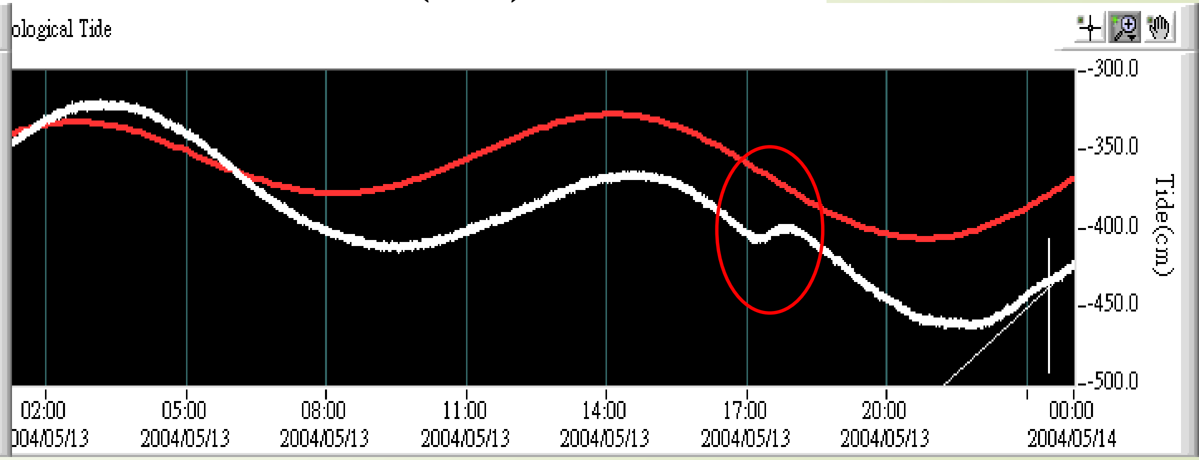
Results and discussion

- Loading quantity (P_L) = 1 N/m^2
- Loading period (T) = 2 hr
- Discharge or recharge (q) at t = 2.5 hr









Summary

- A recharge or discharge at a fault zone maybe the mechanism for groundwater pre-seismic change in Hualien monitoring well.
- Large elastic and hydraulic properties can induce small responses of pore water pressure. But elastic and hydraulic properties causes different behavior in the coupled system.
- The proposed model provides a possible pre-seismic mechanism in Hualien monitoring well but required further investigations.

Conclusions

- Earthquake can induce different types of groundwater anomalies which can be used in hydrogeology investigations.
- Groundwater can detect pre-seismic signal which has the potential for earthquake prediction.
- Earthquake hydrogeology includes great challenges and plenty unknown phenomena which is worth to involve.

Conan: Only one truth prevails

Q&A