Hydraulic Performance Analysis of Water Systems under Major Earthquakes

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Acknowledgment

- National Science Council, Taiwan – funding through Grant No. NSC-96-625-Z-492-007 (2007)
- Taipei Water department – hydraulic analysis data of its water system

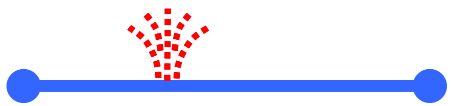
Backgrounds

- 1906 SF earthquake, 1923 Kanto earthquake,…
- 1994 Northridge, 1995 Kobe, 1999 Izmit, Turkey and Chi-Chi, Taiwan earthquakes,…

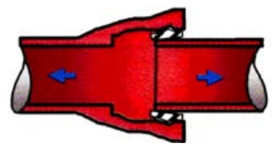
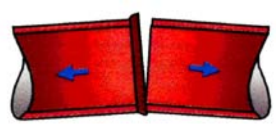
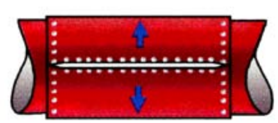
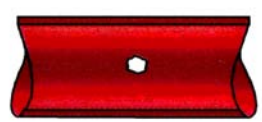
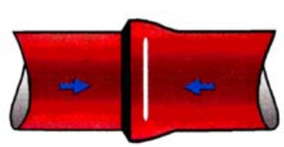
- ~ late 80': connectivity analysis
- 90'~: hydraulic network analysis

- **EPANET** software (US Environmental Protection Agency, 2000)
- **GIRAFFE** software (Graphical Iterative Response Analysis of Flow Following Earthquakes; developed at Cornell University by O'Rourke et al., 2006)

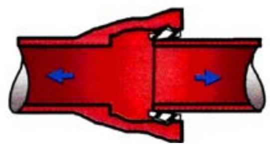
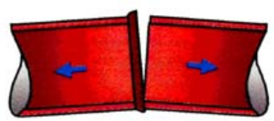
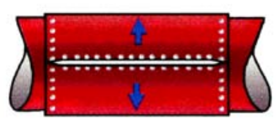
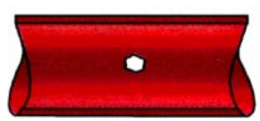
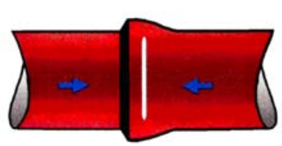
Probabilities of occurrence of pipe break or leak for various pipe materials (GIRAFFE model, 1/3)

Damage type		Cast iron	Ductile iron	Riveted steel	Welded steel	Jointed concrete
Leak		0.8	0.8	0.8	0.2	0.8
Break		0.2	0.2	0.2	0.0	0.2

Probabilities of occurrence of different pipe leak models for various pipe materials (GIRAFFE model, 2/3)

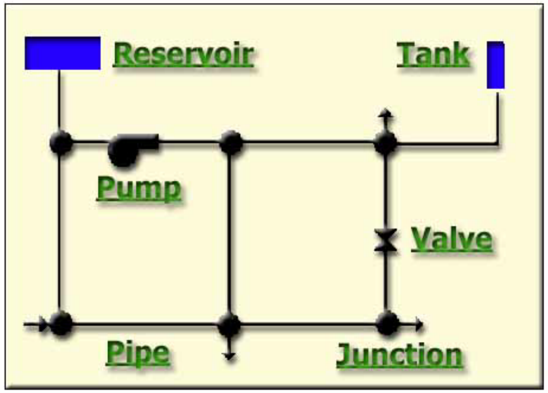
Pipe leak model		Cast iron	Ductile iron	Riveted steel	Welded steel	Jointed concrete
Annular disengagement		0.3	0.8	0.6	-	1.0
Round crack		0.5	-	-	-	-
Longitudinal Crack		0.1	0.1	0.3	-	-
Local loss of pipe wall		0.1	0.1	0.1	-	-
Local tear of pipe wall at welded slip joint		-	-	-	1.0	-

Parameters of various types of leak (GIRAFFE model, 3/3)

Pipe leak model		Diameter of the fictitious pipe	Values of parameters
Annular disengagement		$2\sqrt{tkD}$	$k = 0.3 \quad t = 10\text{mm}$
Round crack		$\sqrt{2\theta D}$	$\theta = 0.5^{\circ} = 0.00873$
Longitudinal Crack		$2\sqrt{LD\theta / \pi}$	$\theta = 0.1^{\circ} = 0.00175$
Local loss of pipe wall		$2\sqrt{k_1 k_2 D}$	$k_1 = k_2 = 0.05$
Local tear of pipe wall at welded slip joint		$2\sqrt{kWD}$	$k = 0.3 \quad W = 12\text{mm}$

Hydraulic analysis of pressurized pipe flows by EPANET

- **Unknowns**
  - Nodal heads: h_i (no. = N)
  - Pipe flows: q_{ij} (no. = N_P)

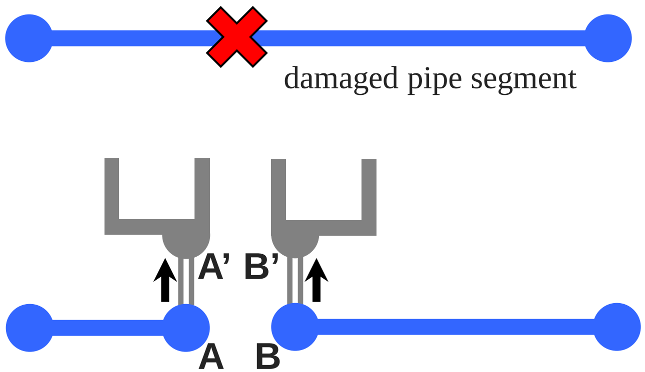


N nodes + N_P pipes

- **Governing equations**
  - Continuity (no. = N, linear in q_{ij})
  - Flow headloss relation: the change in the heads of two end nodes of a pipe (no. = N_P, nonlinear in q_{ij})

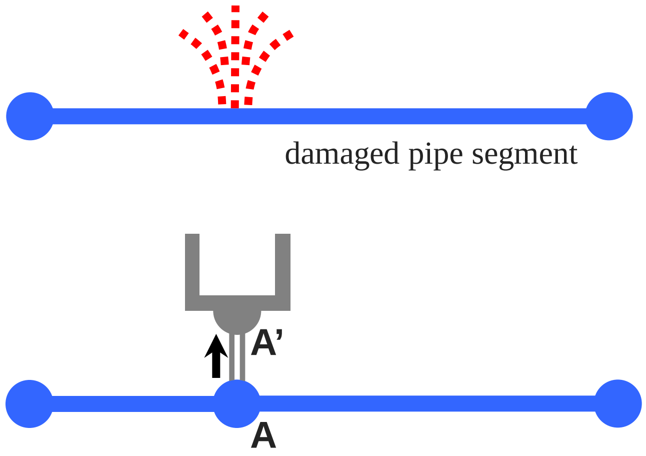
The steps to model a pipe break hydraulically in the EPANET input file

1. Decide the location and elevation of pipe break point
2. Remove the original link (pipe segment)
3. Add two new nodes A and B at the location of pipe break point
4. Add two new links connecting the original pipe segment ends to A and B, respectively
5. Add two new nodes A’ and B’ with the elevation of pipe break point and designate them as reservoirs
6. Add two new links connecting A-A’ and B-B’ and specify them with one-way check valves, respectively



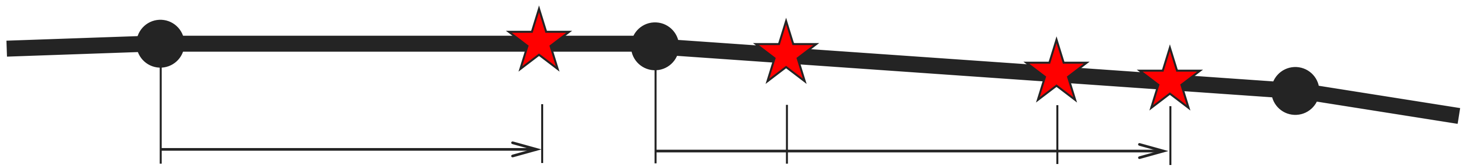
The steps to model a pipe leak hydraulically in the EPANET input file

1. Decide the location and elevation of pipe leak point
2. Remove the original link (pipe segment)
3. Add a new node A at the location of pipe leak point
4. Add two new links connecting the original pipe segment ends to A
5. Add a new node A' with the elevation of pipe leak point and designate it as a reservoir
6. Add a new link connecting A and A' and specify it (1) as a **fictitious pipe with a diameter** of corresponding pipe leak model, and (2) with a one-way check valve



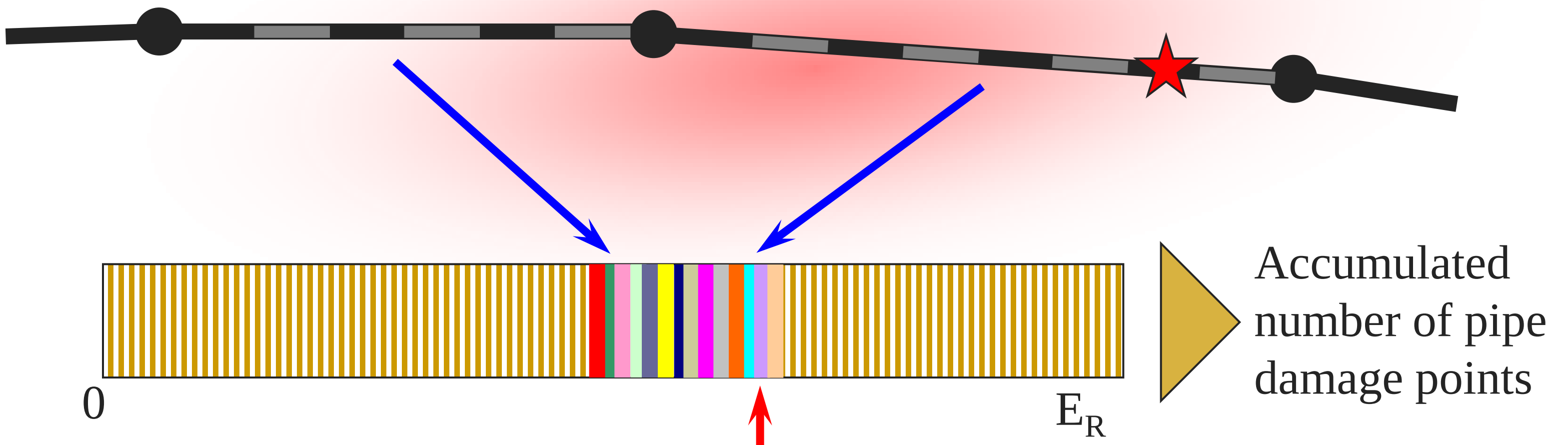
Generation of locations of pipe damage points

Conventional approach:



Assume that pipe damage follows a Poisson process

Proposed approach:

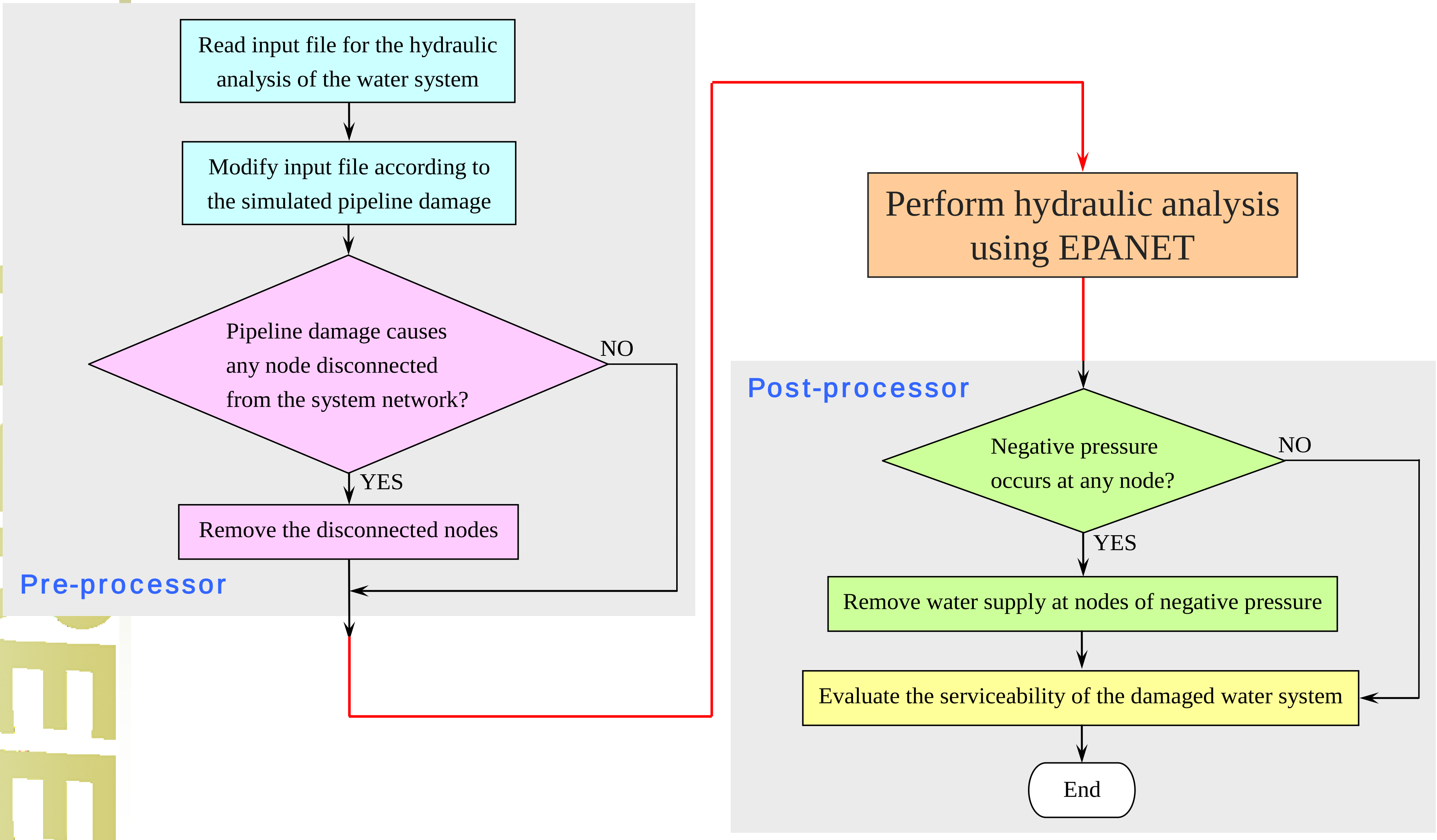


Generate a random number within [0, E_R], designate the location, and repeat E_R times

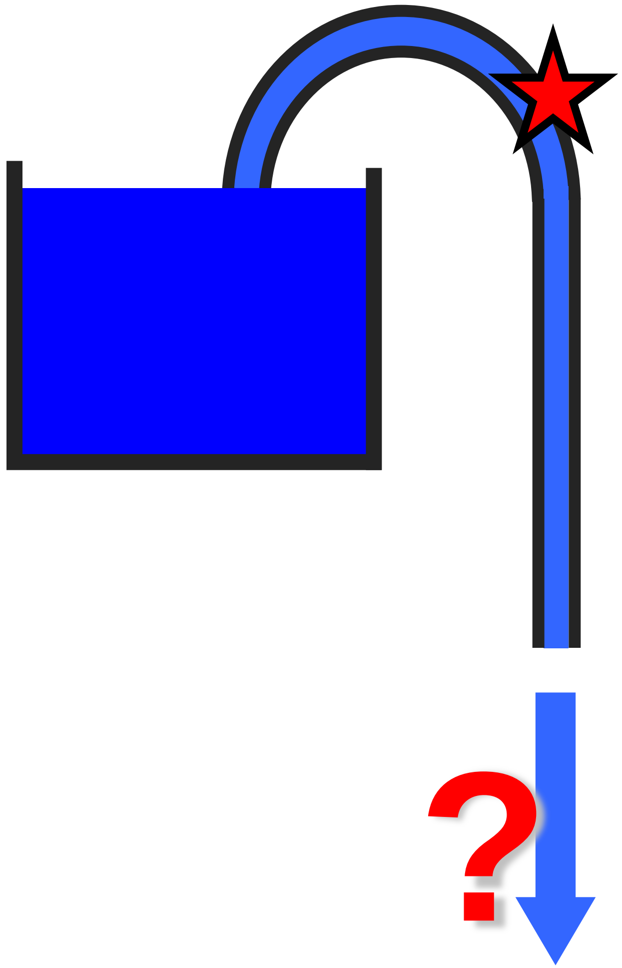
Merits of the proposed approach to generate damage points

- The probability of being damaged of any pipe segment is **rigorously consistent with** its expected value (number of damages)
- It allows a **varying repair rate** along a pipe (of considerable length or crossing sites of different soil conditions…)
- It generates pipe damages with **a total number exactly the same** as the expected value

Flowchart for performance analysis of a damaged water system

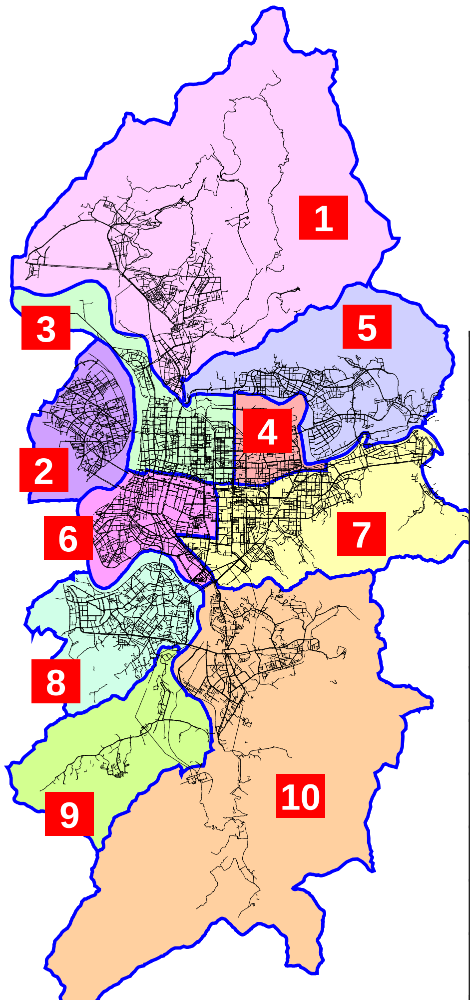


Negative pressure



- Low pressure: causing extra problems in fire-fighting, sanitation
- Negative pressure: theoretically impossible in pipes not air-tight (eg. broken pipes)
- Past approaches:
  - *Ballantyne* (1990)
  - *Shinozuka* (1992)
  - *Markov* (1994)
  - *O'Rourke et al.* (2006)
  - …

The water system of the Taipei Water Department (TWD)



- Service region: 434 square kilometer, including the whole Taipei City plus 4 most populated cities of the Taipei County, divided into 10 service areas
- Serving 1.51 million customers or 3.85 million people
- Daily water supply: 2.5 million tons
- Total pipe length: 7,153 Km (including customer pipes)

	Nodes	Pipes	Pumps	Tanks	Reservoirs	Pipe Length (m)
01	3,254	3,376	40	10	0	171,359
02	2,289	2,366	18	3	0	102,684
03	4,288	4,421	27	2	0	143,565
04	1,769	1,822	18	2	0	68,446
05	2,591	2,673	10	2	0	116,349
06	3,691	3,796	17	2	0	142,553
07	4,985	5,127	32	3	1	193,524
08	2,338	2,394	5	1	0	98,039
09	587	601	12	2	0	28,829
10	2,716	2,799	20	3	0	130,933
Total	28,508	29,375	199	30	1	1,196,281

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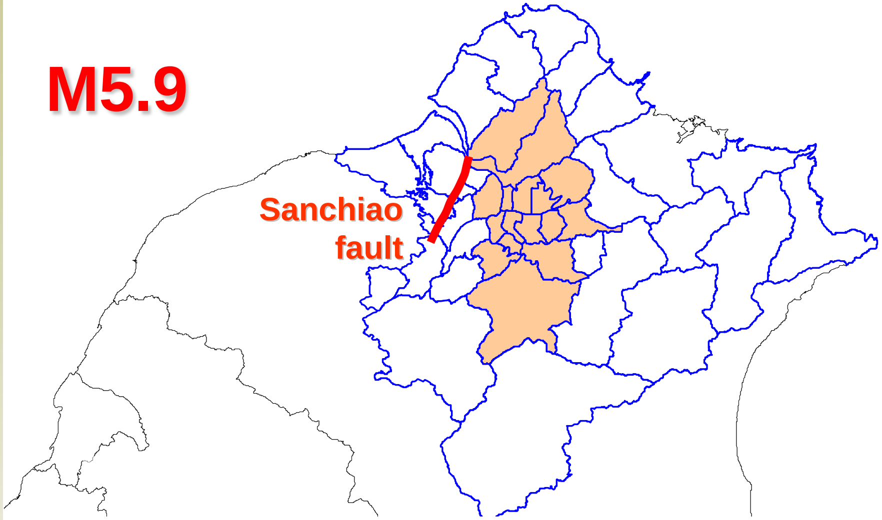
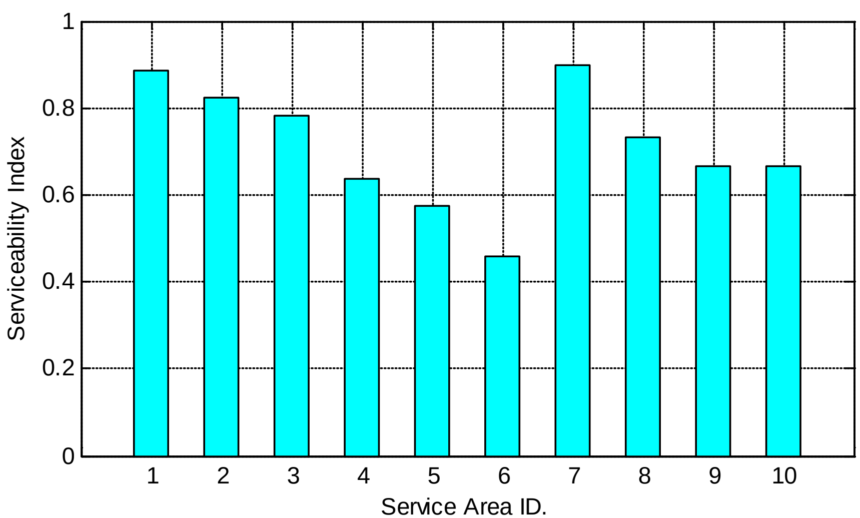
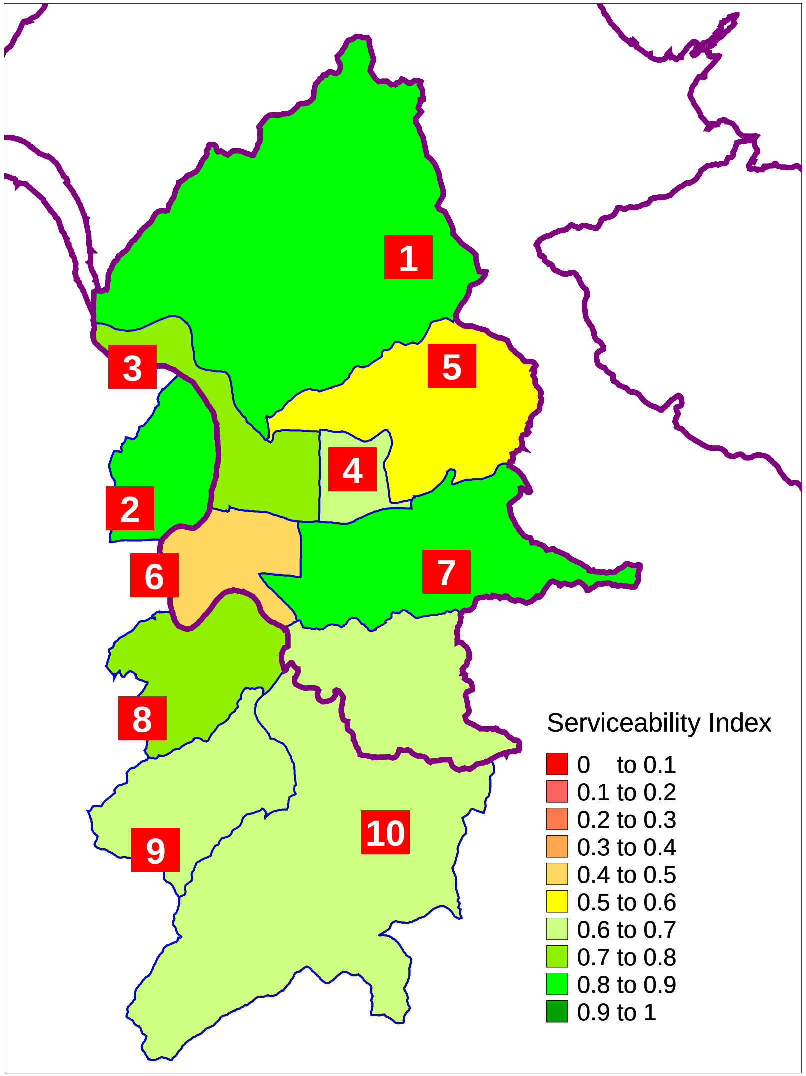
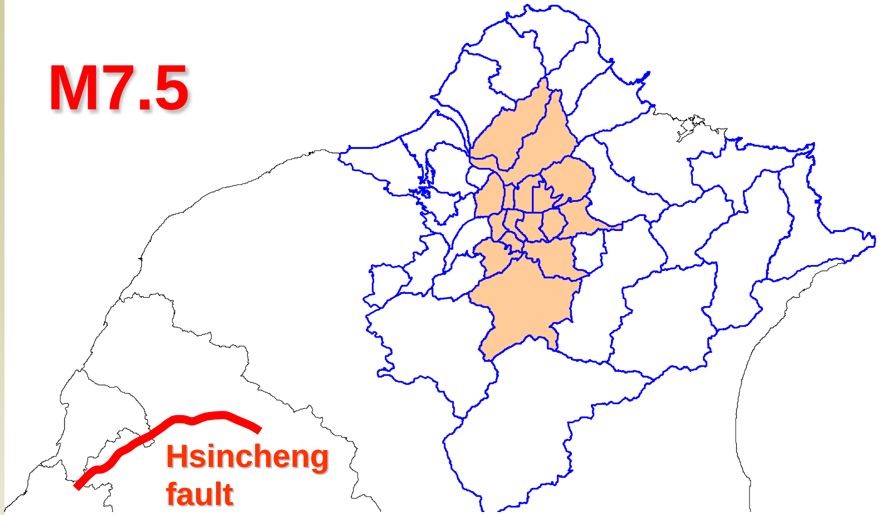
M5.9 Sanchiao fault earthquake – simulation of TWD system performance

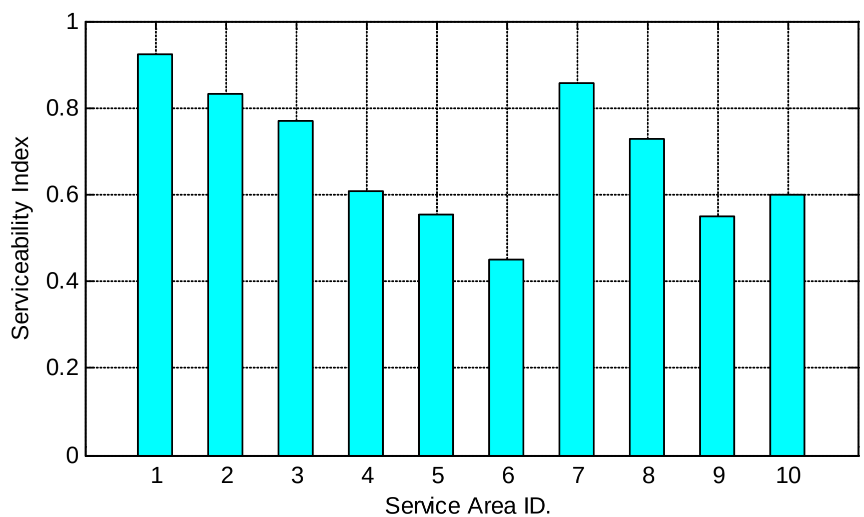


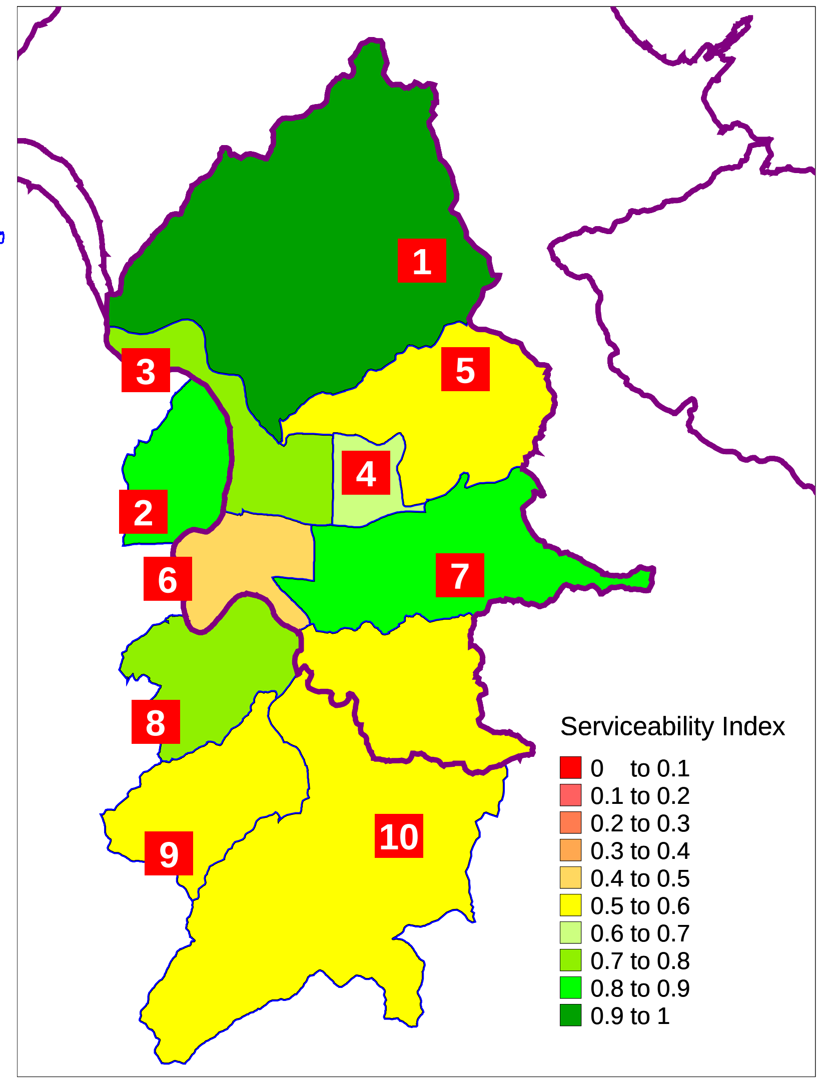




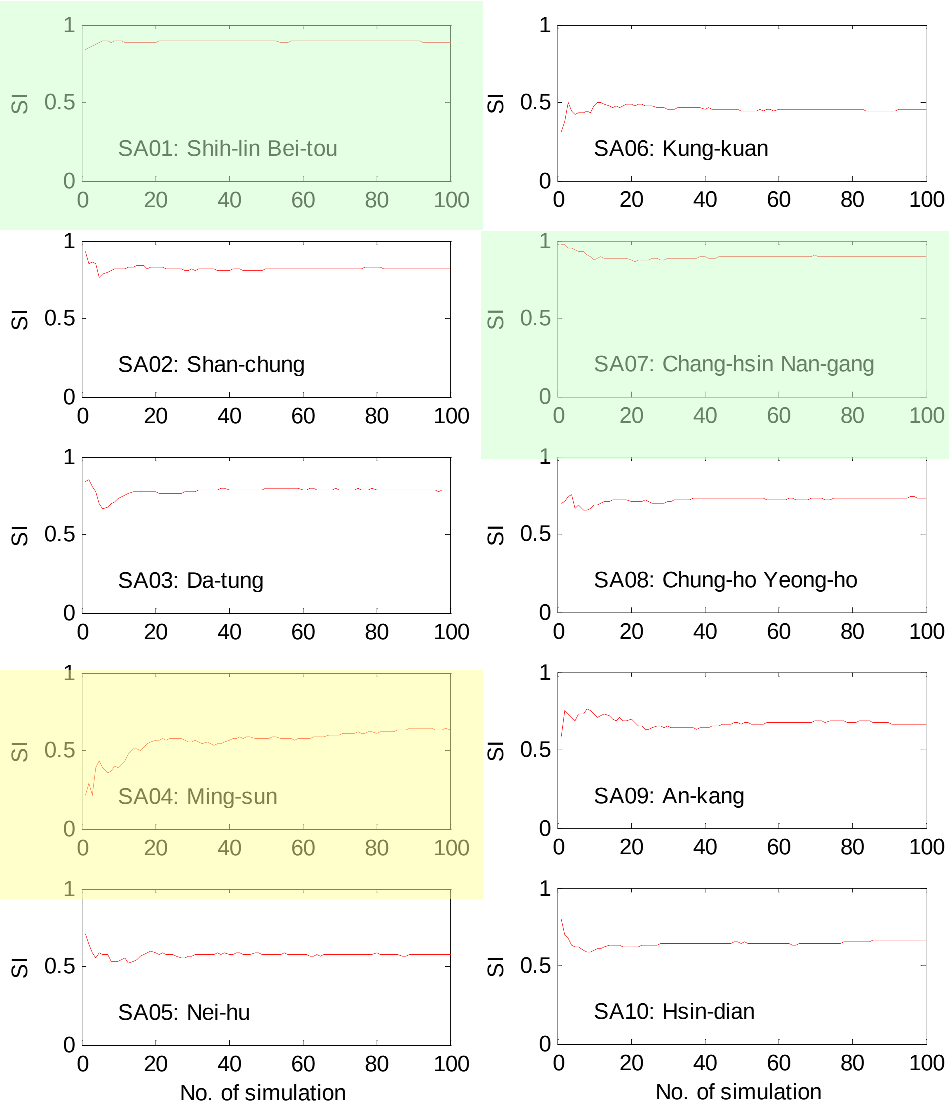
M7.5 Hsincheng fault earthquake – simulation of TWD system performance



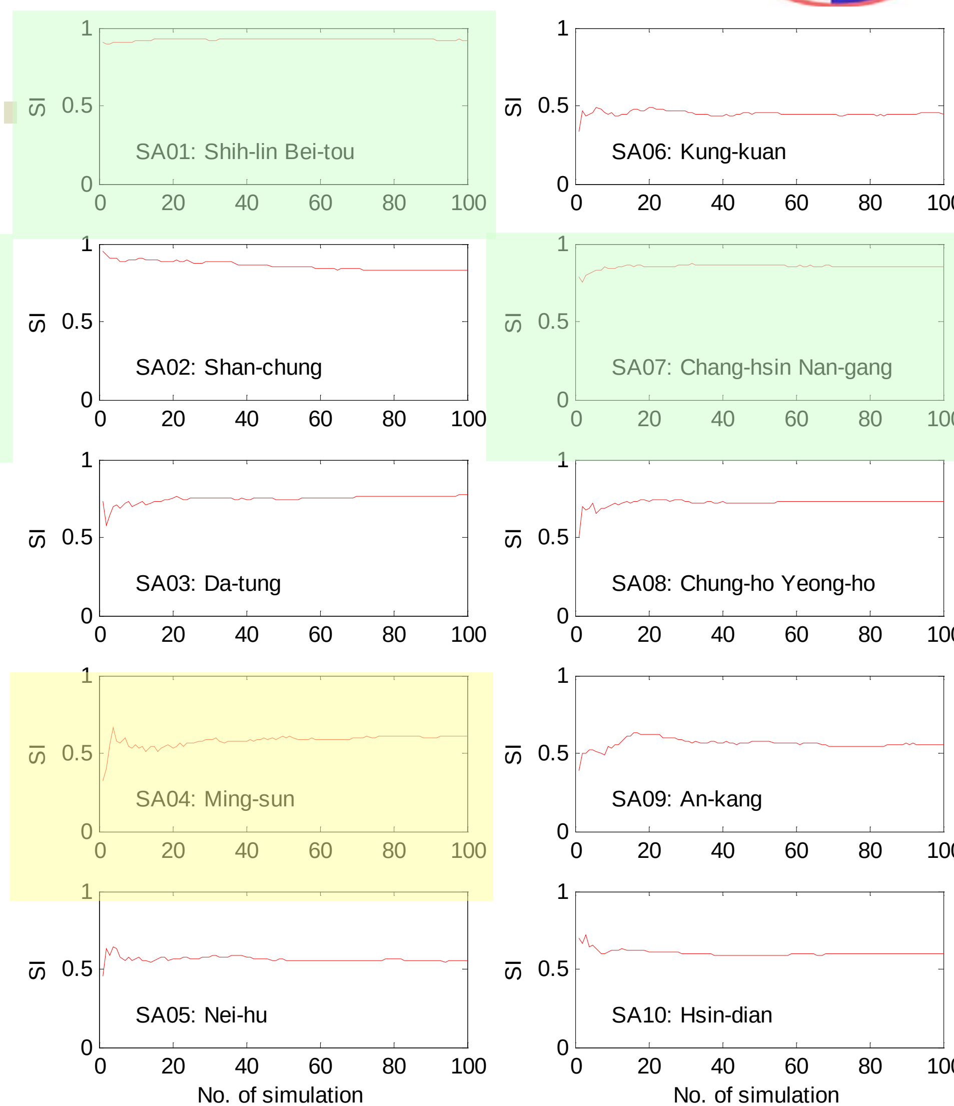




Convergence curves of MCS

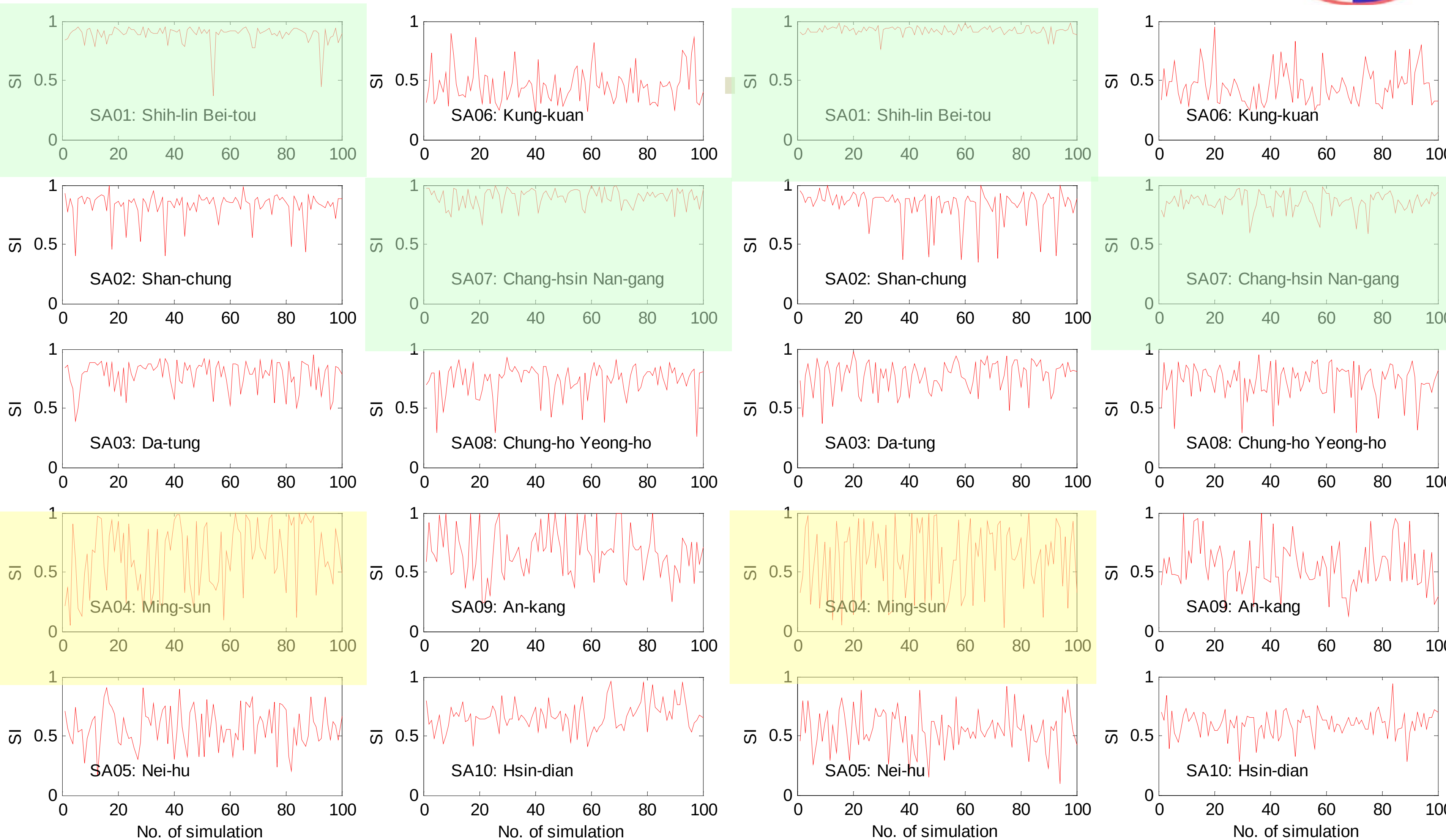


M5.9 Sanchiao fault EQ



M7.5 Hsincheng fault EQ

SI Values for each case in MCS



M5.9 Sanchiao fault EQ

M7.5 Hsincheng fault EQ

Concluding remarks

- The technology of hydraulic performance analysis of water systems after major earthquakes has been developed.
- Observations from simulation in case study:
  - Characteristics of convergence seems to be predominated by the networking of a system, and have to be identified before performing Monte Carlo simulation
  - In post-quake situation, a mere probabilistic scenario simulation is not enough to assess the system performance; critical damages in the system should be deterministically treated

Thanks for your attention!