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國家實驗研究院

Seismic Scenario Simulation of Water Supply Systems

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National Center for Research on Earthquake Engineering

承諾・熱情・創新

Outline

- Objectives and probable applications
- Seismic disaster simulation technology
- PGD and the associated encounter rupture probability
- Post-quake serviceability of a water treatment plant and a water pipeline
- Concluding remarks

Objectives of this Study

- Evaluate post-quake performance of water systems in system level and component level
- Estimate amount of water shortage and number of households without potable water after devastating earthquakes
- Propose a systematic, scenario-based approach and analytic models to obtains these estimates

Probable Applications and Benefits

- Seismic disaster simulations may help in proposing feasible and effective disaster reduction plans
- May be applied in early seismic loss estimation to provide useful and reliable data soon after earthquakes for emergency responses
- May be applied in seismic risk management through a probabilistic approach
- May cooperate with experts to interpret the results correctly and to assist in detail analysis

Seismic Disaster Simulation (SDS)

Given a set of seismic source parameters (a *scenario earthquake*), SDS may assess *probable consequences* due to the seismic event

- Database collection
- Specification of a scenario earthquake
- Seismic hazard analysis
  - Ground shaking → Intensity and frequency content
  - Ground failure
    - Fault rupture
    - Soil liquefaction

    } ●Severity of ground deformation
    ●Occurrence (encounter) probability
- Damage and socio-economic impact assessment
  - Buildings
  - Facilities/Bridges
  - Pipeline systems

  } ●Damage-state-probabilities and/or repair rates
  ●Human casualties
  ●Post-quake fires, debris, etc.
  ●Resource needs for rescue, medical-care, shelter, etc.
  ●Restoration cost and time, interruption losses, etc.

Esti. of Water Available to Customers

(through scenario-based approach)

Water available to customers after a severe earthquake

Post-quake remaining capacity of water treatment plants

$$D' = \theta \cdot (1-L) \cdot \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right]$$

$$\sum_{j=1}^{M_k} \lambda_j \equiv 1$$

Post-quake serviceability of transmission and distribution pipelines in the service area

Post-quake serviceability of main transmission pipelines

The area is served by N water treatment plants $\bar{D} = \sum_{k=1}^{N} \bar{D}_k$

In normal times

$\theta = 1$ $L = 0$

$O_k = 1$ $\Omega_j = 1$

θ (post-quake) *serviceability* of transmission pipelines

L (post-quake) *water loss ratio* of distribution pipelines

O_k (post-quake) *remaining capacity ratio* of k-th water treatment plant

Ω_j (post-quake) *serviceability* of j-th main transmission pipeline from k-th plant

of Households w/o Potable Water

$$S \equiv \frac{\bar{D} - D'}{\bar{D}}$$ post-quake water shortage ratio

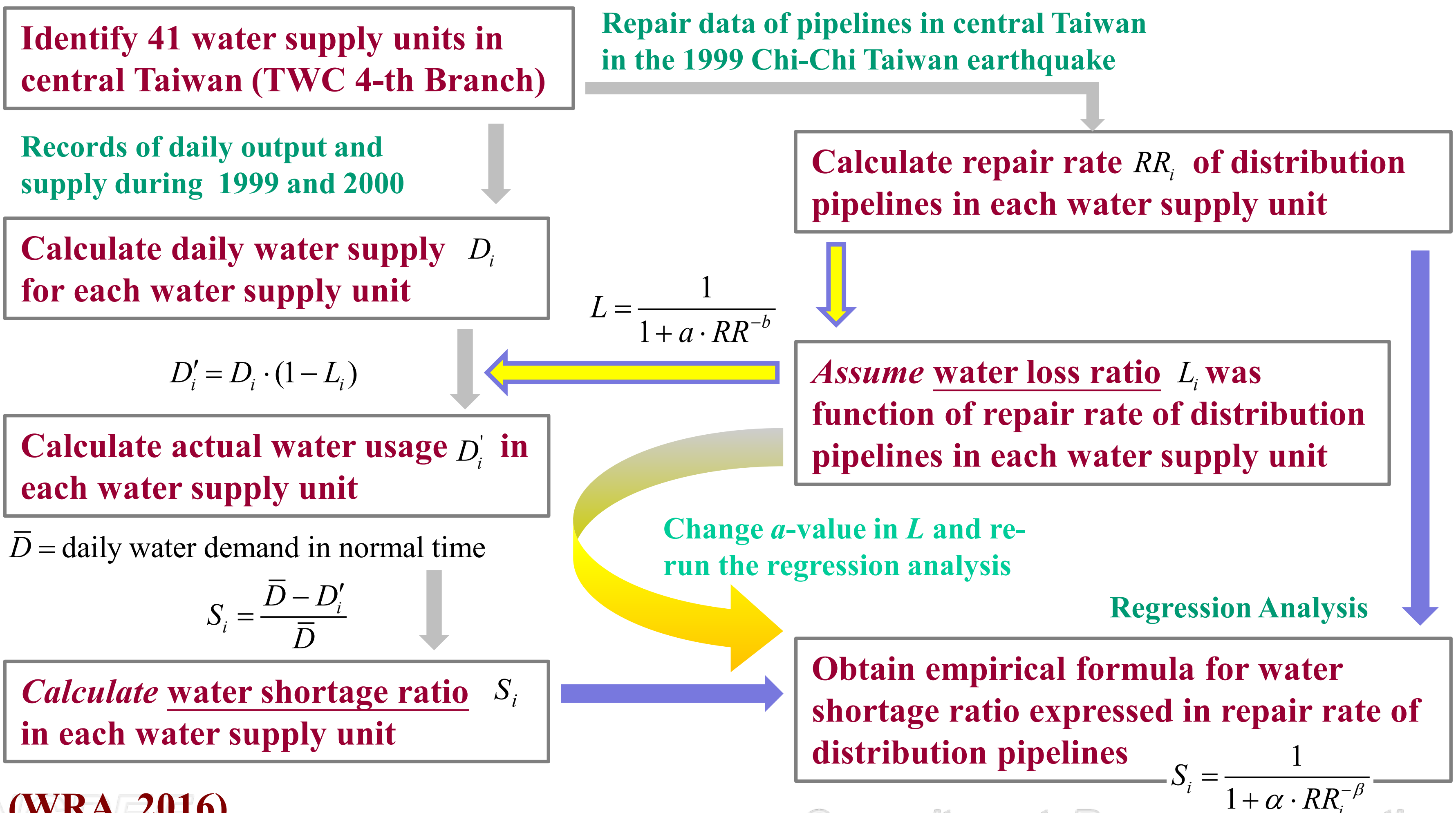
+

$\bar{d} = \bar{D} / H$	daily usage per household
$\gamma \cdot \bar{d}$	post-quake daily usage per household
H	total number of households in the service area

$$H' = \frac{D'}{\gamma \cdot \bar{d}} = \frac{\bar{D} \cdot (1 - S)}{\gamma \cdot \bar{d}} = \frac{1 - S}{\gamma} \cdot H$$ # of households having potable water

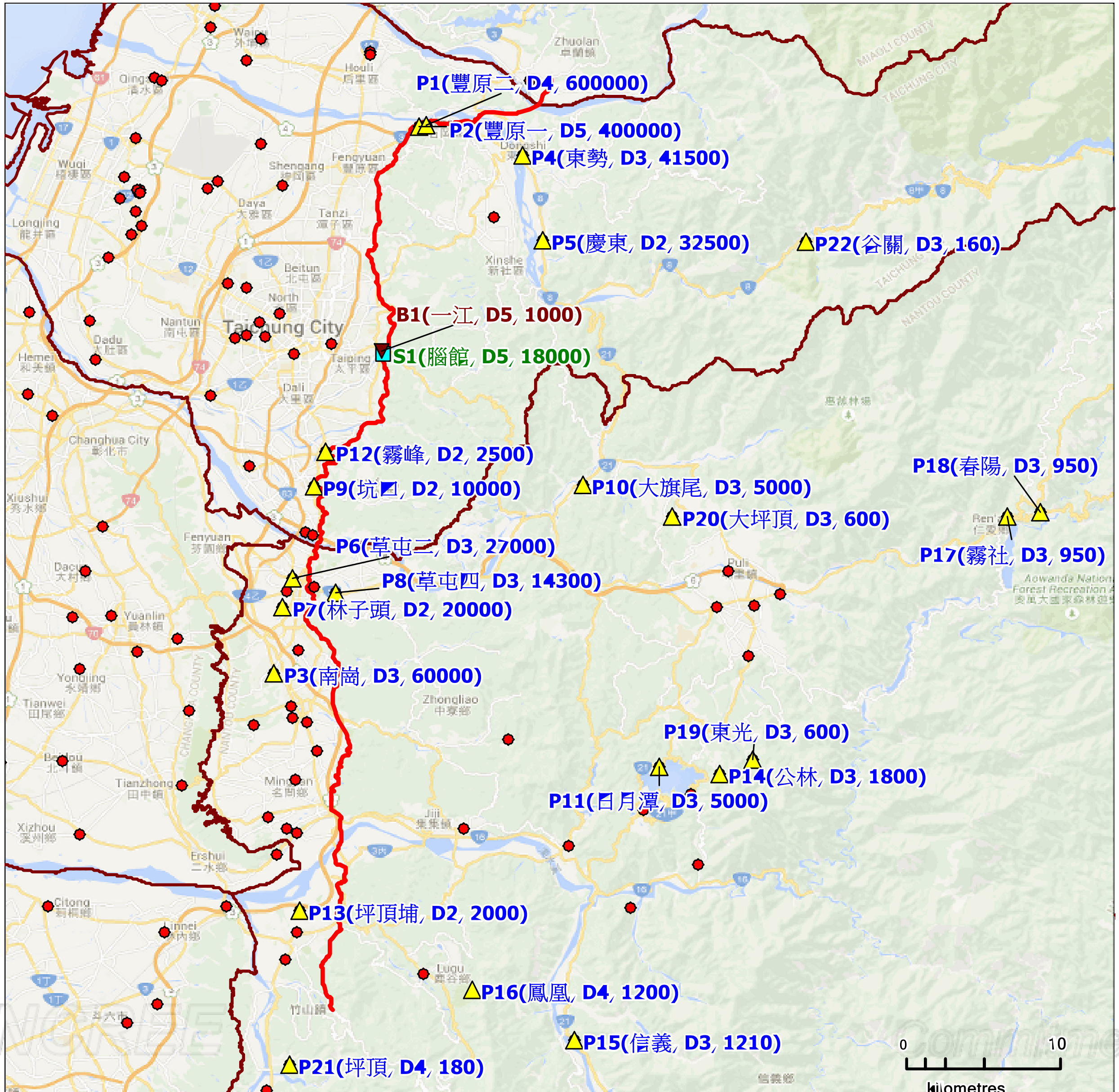
$$V = H - H' = H \cdot [1 - \frac{1 - S}{\gamma}]$$ # of households without potable water

Development of Empirical Formula for Water Shortage Ratio in any Service Area



(WRA, 2016)

Observed Distr. of Damaged Water Facilities



Red line: Chelongpu fault

First char. of symbol indicates
P: water treatment plant
S: storage tank
B: pipe bridge

(name, damage-state, capacity)
where capacity indicates
P: daily output (CMD)
S: storage capacity (m^3)
B: pipe diameter (mm)

- Most of the damaged water facilities during Chi-Chi Taiwan earthquake in 1999 were located near the ruptured Chelongpu fault and on the hanging-wall side
- If only PGA is used, it often overestimates the damage-state-probability of facilities or the expected number of pipe repairs

Ground Deformation due to Fault Rupture

$$\mathrm{PGD}=\begin{cases} D & \text{within 10 m} \\ (1/d_{sr})\cdot f_H\cdot D\cdot \exp[-d/(d_{sr}\cdot f_H)] & \text{hanging wall (outside 10 m)} \\ (1/d_{sr})\cdot f_F\cdot D\cdot \exp[-d/(d_{sr}\cdot f_F)] & \text{footwall (outside 10 m)} \end{cases}$$

d : closest distance to rupture plane (km)

α : dip angle (degree)

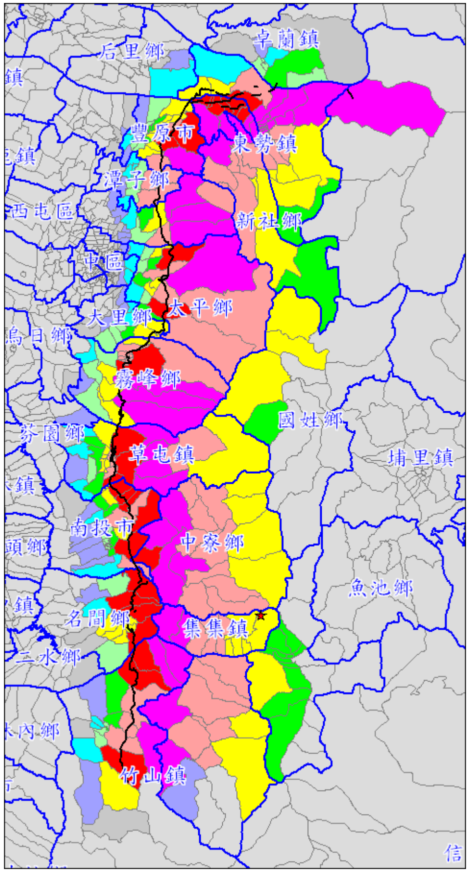
d_{sr} = **depth of seismogenic top (km)**

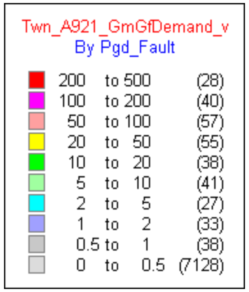
$$f_F=\mathrm{abs}(\alpha)/180$$

$$f_H=1-f_F$$

$$\log D=\begin{cases} 1.03M_w-7.03 & \text{strike-slip fault} \\ 0.29M_w-1.84 & \text{reverse fault} \\ 0.89M_w-5.90 & \text{normal fault} \\ 0.82M_w-5.46 & \text{general fault} \end{cases}$$

(Wells and Coppersmith (1994); unit: m





Simulated coseismic ground surface deformation after Chi-Chi EQ

Most of damaged structures in Chi-Chi EQ were mainly due to fault rupture

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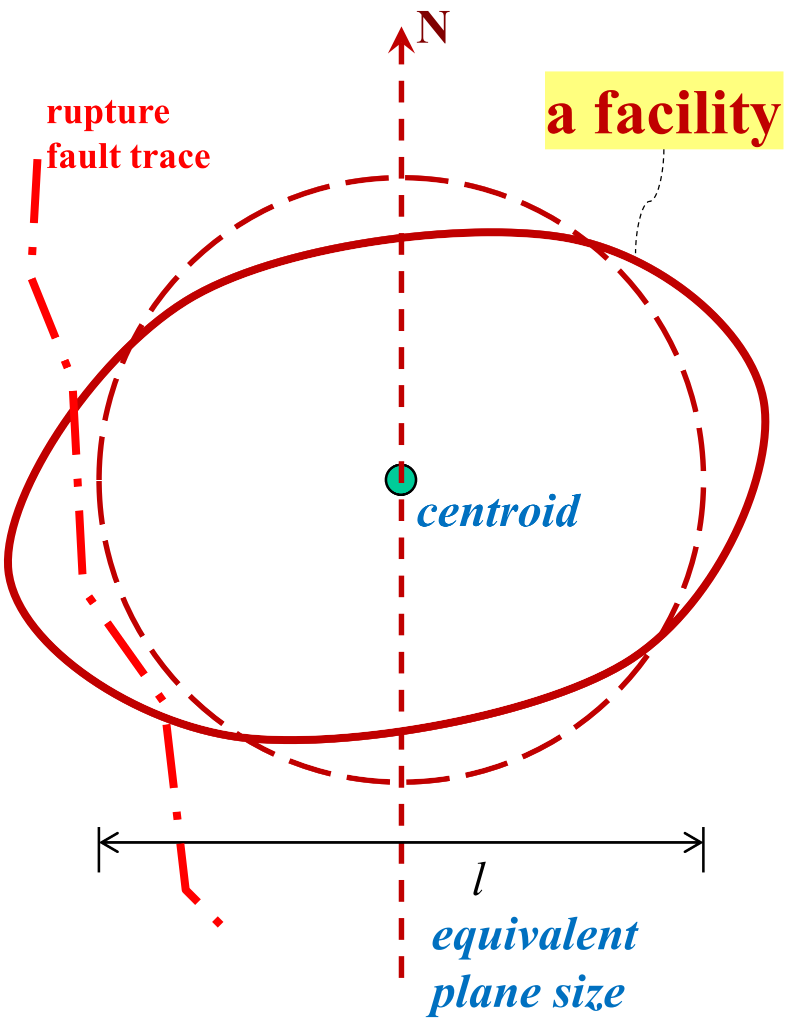
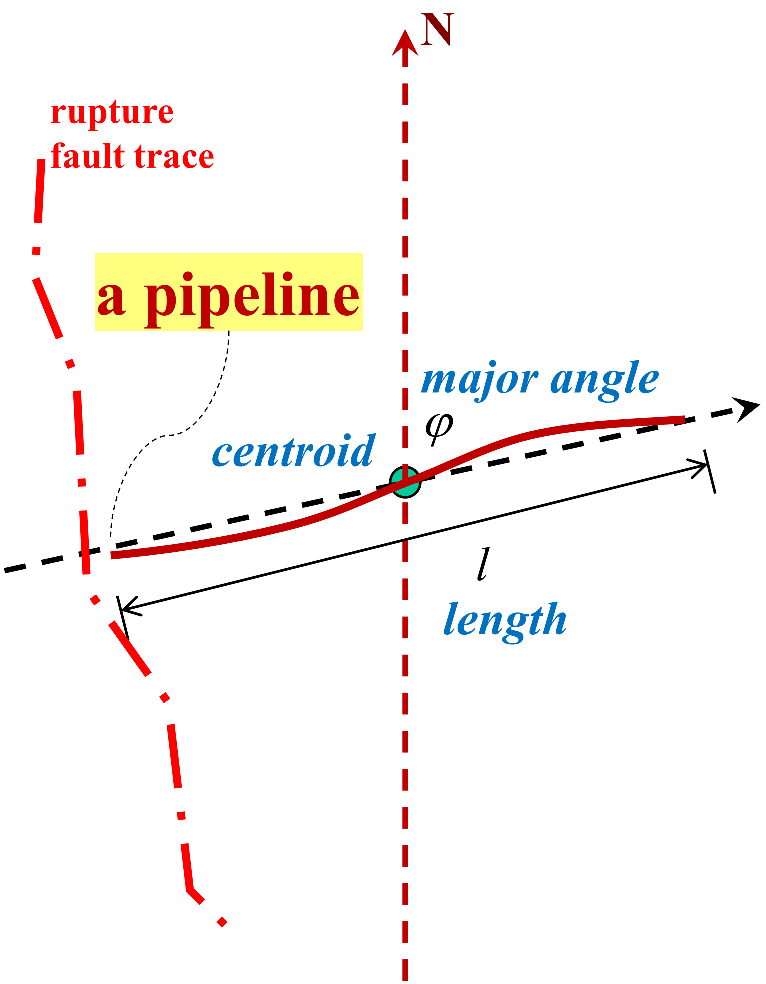
Centroid / Size / Angle of a Facility/Pipeline



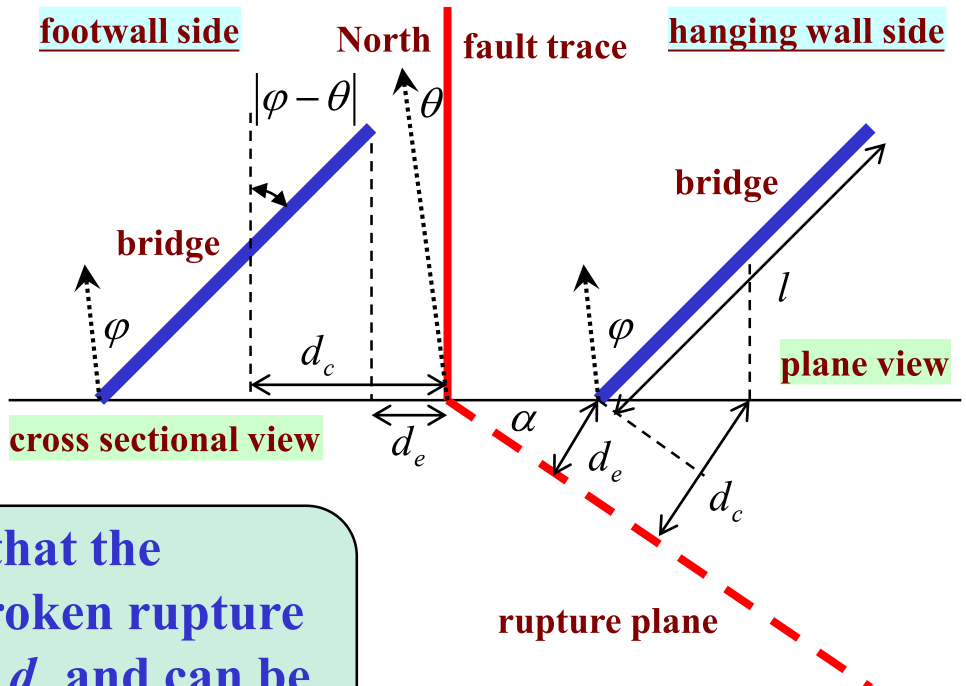


Closest Fault Distance and Encounter Probability

Closest Distance between a Facility/Pipeline and Rupture Fault

$$d_e = \begin{cases} \max(0, \quad d_c - 0.5 \cdot l \cdot \sin|\varphi - \theta| \cdot \sin\alpha) & \text{hanging wall side} \\ \max(0, \quad d_c - 0.5 \cdot l \cdot \sin|\varphi - \theta|) & \text{footwall side} \end{cases}$$

d_c	the closest distance from centroid to rupture plane
l	plane size or pipeline length
$\lvert\varphi-\theta\rvert$	angle between pipeline and fault trace
α	dip angle of fault plane
d_e=0	means the facility/pipeline may cross the major rupture plane



Encounter probability: probability that the facility/pipeline actually crosses a broken rupture plane. It is assumed to be related to d_e and can be expressed as follows: $p = 0.7 \cdot \exp(-d_e / 2)$

Post-quake Capacity of a Water Treatment Plant

Due to

- Damage of facilities in a water treatment plant
- Serviceability of raw water supply systems

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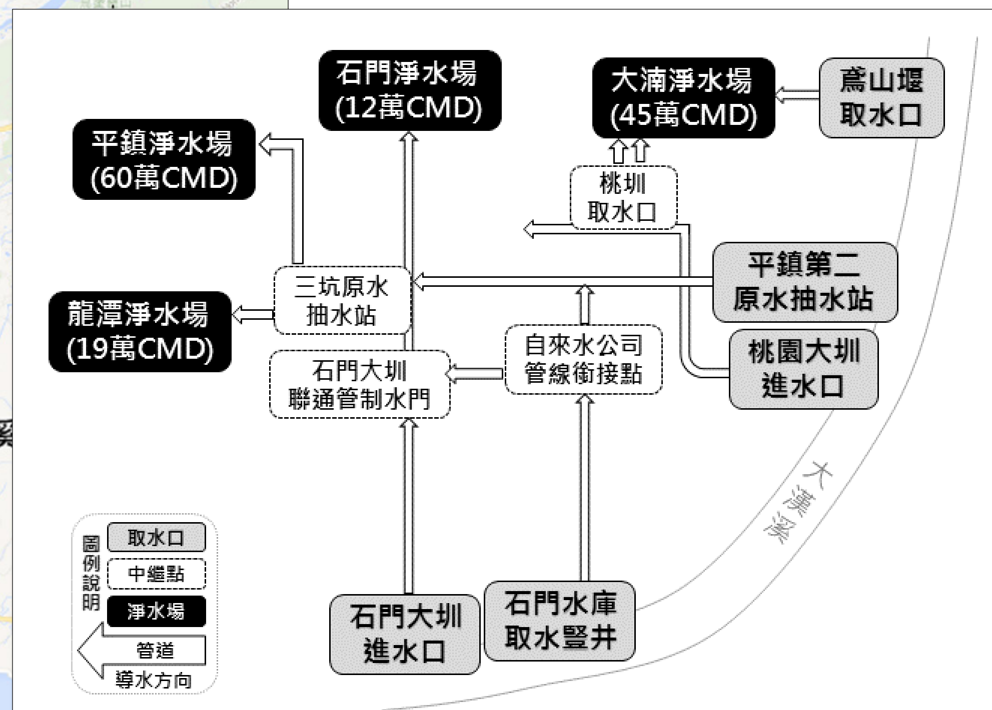
Raw Water Aqueducts in 2-nd Branch of TWC



node-link representation for raw water aqueducts

Repair Rate (RR) of a Pipeline or a Channel

$$RR = \max\left(RR_{PGA},\quad p_{fault}\cdot RR_{PGD(fault)},\quad p_{lqf}\cdot RR_{PGD(lqf)}\right)$$

$$RR_{PGA} = 4.5\cdot C_{S_i-PGA}\cdot C_{T_i}\cdot(\mathrm{PGA}-0.1)^{1.97}$$ repair rate due to ground shaking

$$RR_{PGD} = 0.04511\cdot C_{S_i-PGD}\cdot C_{T_i}\cdot \mathrm{PGD}^{0.728}$$ repair rate due to ground deformation

C_{S_i-PGA} correction of pipe size due to ground shaking

C_{S_i-PGD} correction of pipe size due to ground deformation

C_{T_i} correction of pipe material/joint type

$$BR_{PGA} = \begin{cases} B_{S_iT_j-PGA}\cdot 2\cdot(\mathrm{PGA}-0.1) & 0.1g<\mathrm{PGA}<0.6g \\ B_{S_iT_j-PGA} & \mathrm{PGA}\geq 0.6g \end{cases}$$

$$BR_{PGD} = \begin{cases} B_{S_iT_j-PGD}\cdot 0.01\cdot\mathrm{PGD} & \mathrm{PGD}<100\ \mathrm{cm} \\ B_{S_iT_j-PGD} & \mathrm{PGD}\geq 100\ \mathrm{cm} \end{cases}$$

the break ratio of repairs depends on pipe size, material/joint type, PGA and PGD

(WRA, 2017)

Serviceability of a Pipeline or a Channel

Formula (1)

$$\Omega = \exp[-(0.5 n_l + n_b)]$$
$$= \exp[-0.5(n_r + n_b)]$$

n_l number of leaks

n_b number of breaks

n_r number of repairs

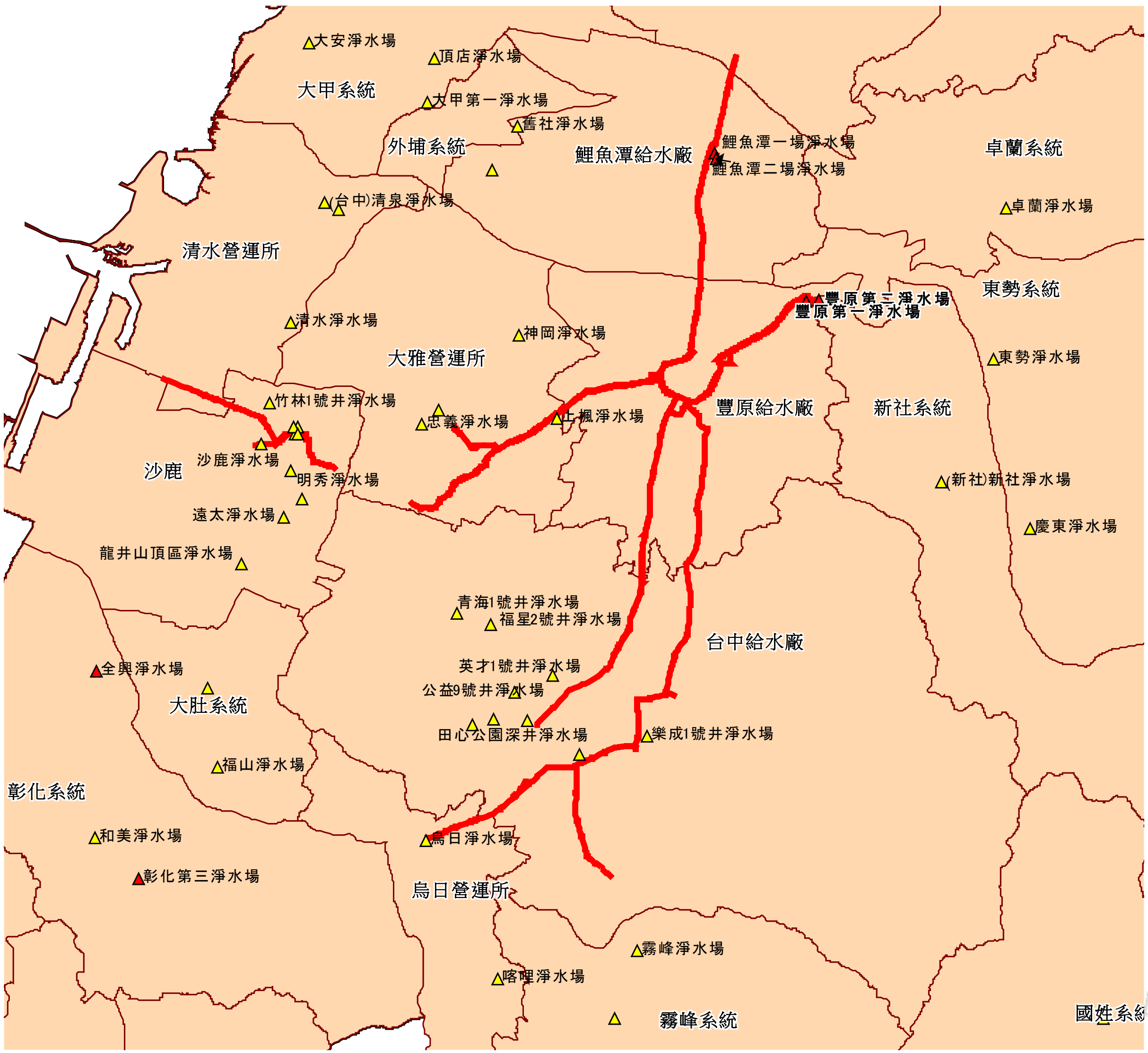
Formula (2)

$$\Omega = \exp[-1.582 \cdot (1 - e^{-(0.5 n_l + n_b)})]$$
$$= \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})]$$

- **Assume two leaks in a pipeline are equivalent to one break in the pipeline**
- **May assume that if there is one break in a pipeline, the pipeline will totally lose its function**

Post-quake Serviceability of Main Transmission Pipelines

Taichung Area (TWC 4-th Branch)



Main transmission pipelines (≧ 800 mm) are used to deliver huge amount of water between two places at a distance

Post-quake serviceability may be estimated by

$$\Omega = \exp[-1.582 \cdot (1 - e^{-(0.5 n_l + n_b)})]$$
$$= \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})]$$

n_l number of leaks

n_b number of breaks

n_r number of repairs

The function form is solely due to stability consideration. If one break is expected, the post-quake serviceability may expect reduced to 0.368

Post-quake Serviceability of Transmission Pipelines in a Service Area

$$\theta = \begin{cases} \exp[-1.582 \cdot (1 - e^{-0.1(n_r + n_b)})], & \bar{D} \geq 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.2(n_r + n_b)})], & 10{,}000 \leq \bar{D} < 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})], & \bar{D} < 10{,}000 \text{ CMD} \end{cases}$$

n_l number of leaks

n_b number of breaks

n_r number of repairs

- **Transmission pipelines (≧ 500 mm) are used to deliver treated water inside a system or between two nearby systems.**
- **It may form a network-type, a tree-type or a simple line-type depending on the daily water usage of the service area.**

Post-quake Water Loss Ratio of Distribution Pipelines

$$L = \begin{cases} 1/(1+0.667 \cdot RR^{-1.113}), & \bar{D} \geq 10{,}000 \text{ CMD} \\ 1/(1+1.5 \cdot RR^{-1.113}), & \bar{D} < 10{,}000 \text{ CMD} \end{cases}$$

RR average repair rate in the service area

- **Distribution pipelines (≧ 100 mm, but ≦450 mm) are used to distribute treated water inside a system.**
- **The complexity of distribution network often depends on the daily water usage of the service area.**

Concluding Remarks

- Both ground shaking intensity and permanent ground deformation due to fault rupture/soil liquefaction have been considered in seismic disaster simulations
- The amount of water shortage and the number of households without potable water soon after earthquake may be estimated through a scenario-based approach
- The analysis models have been calibrated by the observations from the 1999 Chi-Chi earthquake; and they have been also verified by the 2016 Meinong earthquake