Seismic Scenario Simulation of Water Supply Systems

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ABSTRACT

Lack of water for a long time after disastrous earthquakes may cause severe inconvenience to the daily lives of people in the affected areas, not to mention fire-fighting, medical-care, sanitation, and so on. To reduce losses and disruption time, water companies and authorities may develop a seismic scenario simulation technology to assess various kinds of probable outcomes due to large earthquakes, such as the distribution of ground motion intensity, the extent of ground failures, the damage-state of facilities, the number of repairs in pipelines, the amount of water shortages, the number of households without potable water, the expected restoration time and losses due to damage of facilities and pipelines, etc. Countermeasures could be proposed and executed accordingly before earthquakes to enhance the preparedness or emergency response in an appropriate and timely manner. In this paper, a seismic scenario simulation technology developed by NCREE (the National Center for Research on Earthquake Engineering, Taiwan) was introduced. The ground motion intensity and the ground failure extent due to fault rupture or soil liquefaction were considered in the seismic hazard analysis model. The damage and loss assessment models of water facilities and pipelines have been proposed and used in the scenario simulation. The water outage in terms of reduction in daily supply and the number of households without potable water soon after the scenario earthquake were also output base on damage and loss-of-function assessment of facilities and pipelines. The coefficients of analysis models used in the scenario simulation technology were calibrated by the observations from the 1999 Chi-Chi earthquake; and they have been also verified by the 2016 Meinong earthquake.

OVERVIEW OF SEISMIC SCENARIO SIMULATIONS

Generally speaking, seismic scenario simulation technology is to estimate probable consequences given a set of seismic source parameters including earthquake magnitude, epicenter location, focal depth, rupture fault length, width, dip angle, and so on. Depending on the details of the seismic source characteristics, the energy release mechanism of an earthquake may be modeled as a point-source, a line-source or a plane-source. For large earthquakes with magnitude greater than 7.0, the geometry of rupture fault plane should be specified more carefully. The potential earth science hazards induced by a scenario earthquake can be estimated through empirical attenuation laws, site-modification factors, soil liquefaction assessment, and so on. Depending on the site-specific geologic conditions, hazard estimates and the structural seismic capacities, the damage-state probabilities of various kinds of civil infra-structures, such as buildings, bridges, water facilities and pipeline systems, can also be estimated [1].

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Starting from 1999, a GIS-based Windows application, named "Taiwan Earthquake Loss Estimation System (TELES)", was developed by the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. It was later customized to estimate the damage and loss of potable water facilities and pipeline systems, such as water treatment plants, storage tanks, transmission and distribution pipelines, etc., during earthquakes. The customized software was called Twater. Integrating with Taiwan Rapid Earthquake Information Release System which is developed and maintained by the Central Weather Bureau, early seismic loss estimation (ESLE) technology was also developed to provide brief but reliable disaster estimates, such as identification of facilities which may exposed in hotspots, probable number of repairs in pipeline systems, etc, soon after earthquakes to assist in starting up emergency responses. This paper mainly explains several unique features of hazard analysis and damage assessment used in Twater.

ESTIMATION OF PERMANENT GROUND DEFORMATION

Permanent ground deformation induced by soil liquefaction and/or fault rupture is one of the major hazards caused by earthquakes. As shown in Figure 1, 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 peak ground acceleration (PGA) or any other ground shaking parameter is used to estimate the failure probability of facilities and pipeline systems, it often overestimates the damage-state-probability of facilities or the expected number of pipe repairs. To improve the accuracy, both ground shaking parameter (such as PGA and 1-second spectral acceleration) and permanent ground deformation should be taken into consideration in hazard, damage and loss estimations.

The permanent ground deformation due to soil liquefaction and the liquefaction probability may be estimated by empirical formulas proposed by Yeh, et al. [2]. The permanent ground deformation (PGD) due to fault rupture may be estimated by the following model,

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

where D is the mean slip (or dislocation) of the rupture fault, which can be estimated by the well-known empirical formulas proposed by Wells and Coppersmith (1994) [3] considering earthquake magnitude and different style of faulting; d_{sr} is the depth of seismogenic rupture top; d is the estimated minimum distance between the facility/pipeline and the rupture fault plane; f_H and f_F are coefficients reflecting different attenuation rates on the hanging wall and footwall side, respectively. The f_H and f_F are assumed to be functions of dip angle (α) of the rupture plane, i.e., $f_F = \text{abs}(\alpha)/180$ and $f_H = 1 - f_F$.

It should be noted that the ground deformation induced by fault rupture is neither uniform nor continuous. Therefore, like liquefaction probability, the encounter rupture probability at fault distance d is assumed to be $p_{fault} = 0.7 \cdot \exp(-d/2)$, where d is expressed in km. In addition, for a large-size facility and/or a long transmission pipeline, if the size of facility/pipeline and the major orientation of it are known, the nearest fault distance (d_e) between the facility/pipeline and the rupture plane may be updated using the following model.

$$d_e = \begin{cases} \max\left(0, \quad d_c - 0.5 \cdot l \cdot \sin\left|\varphi - \theta\right| \cdot \sin\alpha\right) & \text{(hanging wall)} \\ \max\left(0, \quad d_c - 0.5 \cdot l \cdot \sin\left|\varphi - \theta\right|\right) & \text{(footwall)} \end{cases} \tag{2}$$

where d_c is the minimum fault distance between the centroid of facility/pipeline and the rupture plane; α is the dip angle of rupture plane; l represents the size of facility/pipe; φ and θ are the major orientations of the facility/pipeline and the rupture fault trace, respectively, as shown in Figure 2. The updated minimum fault distance (d_e) is then used in Eq. (1) to calculate PGD that may be occurred at the facility or pipeline. Use of Eq. (2), some large-size facilities, such as Fengyuan water treatment plant with daily total output 1,000,000 CMD, as shown in Figure 1, were identified to be very close to the Chelongpu fault and would suffer severe damage due to fault rupture in 1999 Chi-Chi earthquake.

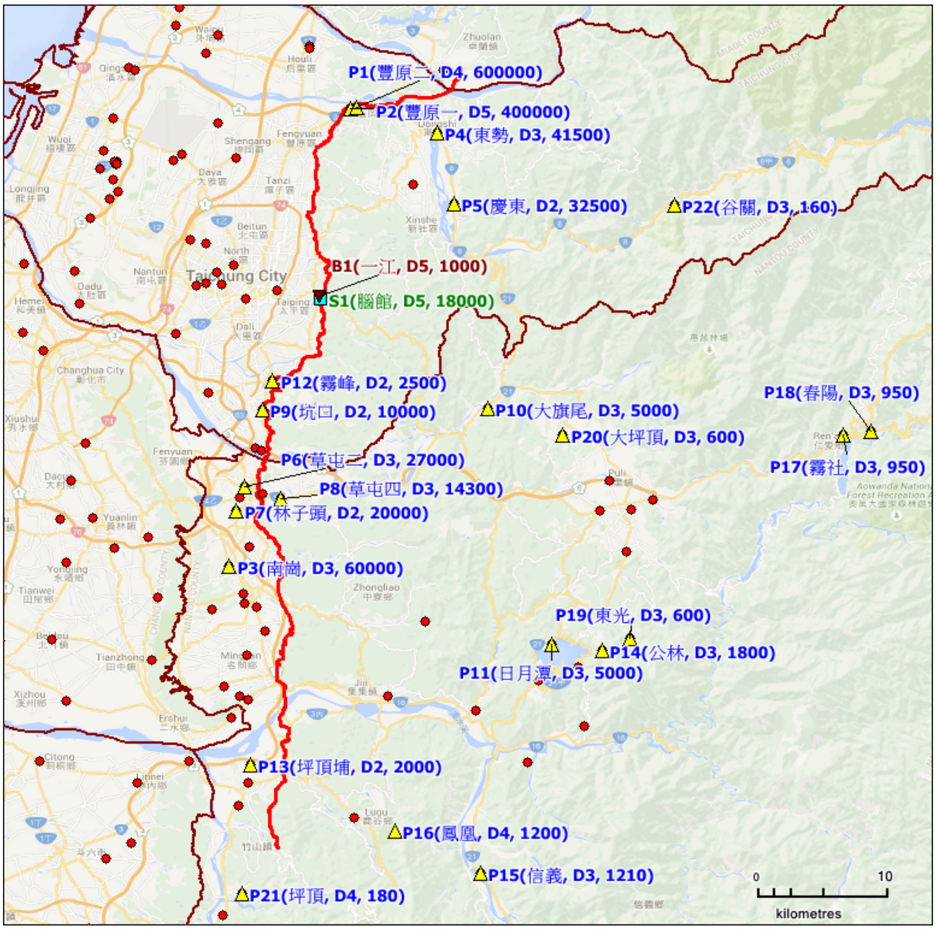

Figure 1 Observed distribution of damaged water facilities in 1999 Chi-Chi Taiwan earthquake. The thick red line is the ground surface trace of Chelongpu fault, which was ruptured in the Chi-Chi earthquake. The prefix of each ID: P stands for treatment plant, S stands for storage tank, and B stands for pipe bridge. Inside parentheses, the first item is the name of facility (in Chinese), the second item is the damage-state observed, and the third item indicates the capacity of facility. The small red dots show the locations of all treatment plants with or without damage.

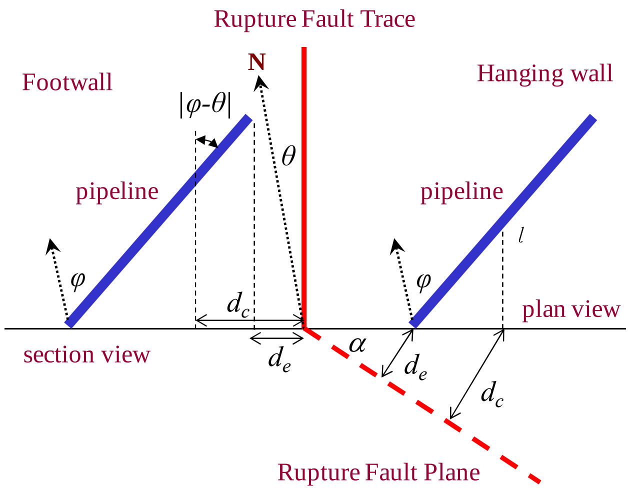

Figure 2 A schematic diagram explaining how to calculate minimum distance (d_e) between a long pipe with length l and the rupture plane, when d_c is known.

ESTIMATION OF POST-QUAKE SERVICEABILITY OF PIPELINES

Unlike damage assessment of facilities, the estimations of loss-of-function, repair cost and restoration time of pipelines are often expressed as functions of repair rate and/or repair number. The repair rate is defined as the number of repairs per unit length of pipeline. The three hazard estimates mentioned before, i.e., ground shaking intensity in terms of PGA, permanent ground deformation due to soil liquefaction and fault rupture, are all considered in the calculation of probable repair rate for any specific pipeline. The probable repair rate is expressed as

$$RR = \max\left(RR_{PGA},\quad p_{fault}\cdot RR_{PGD(fault)},\quad p_{lqf}\cdot RR_{PGD(lqf)}\right) \tag{3}$$

where RR_{PGA}, $RR_{PGD(fault)}$ and $RR_{PGD(lqf)}$ are the estimated repair rates using empirical formulas based on peak ground acceleration (PGA), and permanent ground deformation (PGD) due to fault rupture and soil liquefaction, respectively; p_{fault} and p_{lqf} are the encounter rupture probability and soil liquefaction probability, respectively. The RR_{PGA} and RR_{PGD} can be expressed as

$$RR_{PGA} = 4.501\cdot C_{S_i-PGA}\cdot C_{T_j}\cdot(\mathrm{PGA}-0.1)^{1.97} \tag{4}$$

$$RR_{PGD} = 0.04511\cdot C_{S_i-PGD}\cdot C_{T_j}\cdot \mathrm{PGD}^{0.728} \tag{5}$$

where C_{S_i-PGA}, C_{S_i-PGD} and C_{T_j} are correction coefficients for different pipe sizes (S_i) and material/joint types (T_j), as given in reference [4]. It is noted that C_{S_i-PGA} and C_{S_i-PGD} for any specific pipe size have been assigned different values to reflect different seismic capacity with respect to ground shaking and ground deformation.

Eqs. (3), (4) and (5), together with the encounter rupture probability and the soil liquefaction probability, may be used to estimate the probable number of repairs in the pipeline systems when a scenario earthquake occurs. In order to evaluate more accurately the post-quake serviceability in system level, it is desirable to differentiate the level of severity at the pipe repair. For simplicity, only two levels of severity are considered, i.e. leak and break. Since it is unlikely to have a pipe break when the pipeline is subjected to small shaking and/or ground deformation, the expected break ratio (BR_{PGA} and BR_{PGD}) of pipe repair rate is linearly adjusted within ranges of small ground shaking ($\mathrm{PGA} < 0.6g$) and ground deformation ($\mathrm{PGD} < 100$ cm), and can be modeled as follows

$$BR_{PGA} = \begin{cases} B_{S_iT_j-PGA} \cdot 2 \cdot (\mathrm{PGA} - 0.1) & 0.1g < \mathrm{PGA} < 0.6g \\ B_{S_iT_j-PGA} & \mathrm{PGA} \geq 0.6g \end{cases} \tag{6}$$

$$BR_{PGD} = \begin{cases} B_{S_iT_j-PGD} \cdot 0.01 \cdot \mathrm{PGD} & \mathrm{PGD} < 100 \text{ cm} \\ B_{S_iT_j-PGD} & \mathrm{PGD} \geq 100 \text{ cm} \end{cases} \tag{7}$$

where $B_{S_iT_j-PGA}$ and $B_{S_iT_j-PGD}$ are the upper limits of expected break ratio due to ground shaking and ground deformation, respectively. These upper limits should depend on the pipe sizes (S_i) and material/joint types (T_j), as indicated in the subscripts.

The pipes in a water supply system may be classified into transmission pipelines, distribution pipelines and service laterals. If there is no information about the role of each pipeline in the water supply system, it may be roughly classified by pipe size only. In this study, the main transmission pipelines refer to those with diameter greater than or equal to 800 mm. They play the most important role in water supply systems and often used to deliver huge amount of water (either treated or untreated) between two places separated by a long distance. Considering the level of severity and the uncertainty in repair-rate assessment, assuming the impact of two leaks in pipeline are equivalent to that of one break in pipeline, the post-quake serviceability (Ω) of transmission pipelines may be estimated by the following model

$$\begin{aligned} \Omega &= \exp[-1.582 \cdot (1 - e^{-(0.5n_l + n_b)})] \\ &= \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})] \end{aligned} \tag{8}$$

where n_r, n_l and n_b are the expected number of repairs, leaks and breaks on the transmission pipeline, respectively, due to a scenario earthquake. The function form used in Eq. (8) is solely due to stability consideration. For example, if one break is expected (but in reality the break may not happen at all), the post-quake serviceability may expect to reduce to 0.368 comparing to normal times when $\Omega = 1$.

Pipelines with diameter greater than or equal to 500 mm but less than 800 mm are referred to as sub-transmission pipelines in this study. Since the sub-transmission pipelines may form a network-type, a tree-type or a simple line-type depending on the service area and the daily water usage ($\bar{D}$) of a system, the post-quake serviceability (θ) of sub-transmission pipelines inside a water supply system may be estimated by the following model

$$\theta = \begin{cases} \exp[-1.582 \cdot (1 - e^{-0.1(n_r + n_b)})], & \bar{D} \geq 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.2(n_r + n_b)})], & 10{,}000 \text{ CMD} \leq \bar{D} < 100{,}000 \text{ CMD} \\ \exp[-1.582 \cdot (1 - e^{-0.5(n_r + n_b)})], & \bar{D} < 10{,}000 \text{ CMD} \end{cases} \tag{9}$$

where n_r and n_b are the expected number of repairs and breaks on sub-transmission pipelines inside the water supply system, respectively, subjected to a scenario earthquake.

Pipelines with diameter greater than or equal to 100 mm and less than 500 mm are referred to as distribution pipelines in this study. The water loss ratio (L) due to damage of distribution pipelines after a scenario earthquake may be estimated by the following model

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

where RR is the average repair rate of distribution pipelines inside the water supply system after the earthquake.

The coefficients in Eq. (10) had been calibrated in the previous study on deriving empirical formula, using the 1999 Chi-Chi earthquake data [5, 6, 7], to estimate water shortage ratio by repair rate of distribution pipelines in water supply systems, as shown in the schematic diagram (see Figure 3). Let the daily water demand by customers in normal times be denoted by $\bar{D}$ and the actual water supply in the i-th day after earthquake be denoted by $D_i^{'}$, then water shortage ratio (S_i) in the i-th day can be defined as

$$S_i = (\bar{D} - D_i^{'}) / \bar{D} \qquad (11)$$

The average daily water usage ($\bar{D}$) in normal times could be calculated for each water supply system before and after the Chi-Chi earthquake; however, the actual amount of water delivered to customers during restoration period after the Chi-Chi earthquake were missing. It was not possible to obtain reliable value of $D_i^{'}$ in Eq. (11). Therefore, different sets of coefficients a and b, used in estimating the water loss ratio L, as shown in Figure 3, had been tested in regression analysis. In that study, the coefficients used in Eq. (10) seem reasonable; and the empirical formula for water shortage ratio immediately after earthquake (S_1) was expressed in terms of repair rate of distribution pipelines as follows

$$S_1 = 1/(1 + 1.008 \cdot RR_1^{-0.7085}) \qquad (12)$$

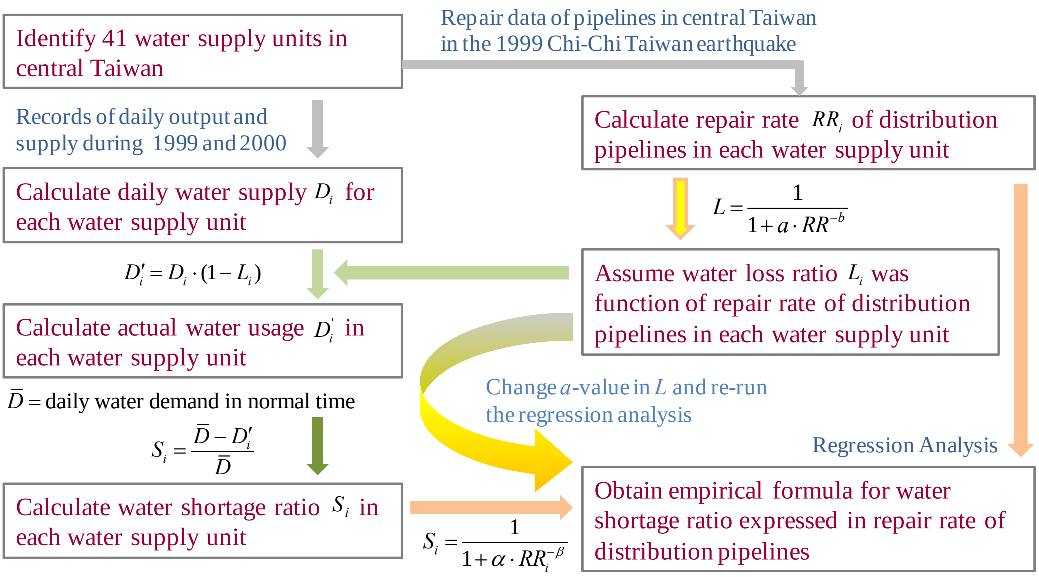

Figure 3 Schematic diagram of regression analysis using pipe repair data and water supply data before and after the 1999 Chi-Chi earthquake to obtain the empirical formula, which may estimate water shortage ratio by repair rate of distribution pipelines after earthquakes

ESTIMATION OF REMAINING CAPACITY OF WATER TREATMENT PLANTS

As observed in the 1999 Chi-Chi earthquake (Figure 1), the damage-state of water treatment plants due to earthquakes are highly correlated to both ground shaking and ground deformation. The parameters of shaking-related and deformation-related fragility curves may be properly calibrated using historical investigation data. The damage-state-probability of any specific water treatment plant may then be calculated as long as the ground shaking and the ground deformation estimates have been reasonably obtained in hazard analysis.

However, the predicted damage-state often represents the most severe part of the plant. In other words, the damage-state of individual facility inside the plant, such as pipelines, channels, storage tanks and pumping equipments, may not be the same. Depending on the amount of daily water demand, the plane size of water treatment plant may vary from several meters to several hundred meters. The plane size of water treatment plant should be taken into consideration in scenario simulations in order to improve the accuracy of estimation results.

For large water treatment plants, there may be more than one set of water treatment unit which may operate independently. These independent water treatment units are not likely to complete damage at the same time; and in most cases, only a small portion of a large water treatment plant may be completely damaged, the rest can be restored in short time. Therefore, the number of independent water treatment units in a large plant should be taken into consideration in estimating capacity after earthquakes.

In addition, most of the raw water required by large water treatment plants in Taiwan comes from distant reservoir through large-size raw water aqueducts and tunnels. If any one section of aqueduct or tunnel is severely damaged, the water treatment plant will lose its function, too.

ESTIMATION OF POST-QUAKE SERVICEABILITY IN SYSTEM LEVEL

Integrating all the estimation results on the serviceability of various kinds of pipelines and the remaining capacity of water treatment plants, the water shortage ratio in Eq. (11) may be calculated in another way. Let the daily water demand in a specific water supply system is supplied by N water treatment plants. The k-th water treatment plant contributes $\bar{D}_k$ daily before earthquake. Since some of water treatment plants locate far away from the system or population dense areas, the treated water must be delivered through main transmission pipelines. Assume there are M_k main transmission pipelines available to deliver treated water from k-th water treatment plant to the system. The j-th main transmission pipeline shares λ_j of $\bar{D}_k$. Before entering the trunks and distribution pipelines, the remaining amount of water (D) that the system may obtain from N water treatment plants after earthquake can be expressed as

$$D = \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \tag{13}$$

where O_k is the remaining capacity ratio of the k-th water treatment plant; Ω_j is the post-quake serviceability of j-th main transmission pipeline, which may be estimated by Eq. (8)

In most cases, the trunks and distribution pipelines may also suffer damages after severe earthquakes. The actual amount of water available to customers (D') can be expressed as

$$\begin{aligned} D' &= \theta \cdot (1-L) \cdot D \\ &= \theta \cdot (1-L) \cdot \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \end{aligned} \tag{14}$$

where θ is the post-quake serviceability of the trunks, as calculated by Eq. (9); L is the water loss ratio, as calculated by Eq. (10). The O_k, Ω_j, θ and L are functions of time. Complete restoration time depends on all of these four factors.

In summary, the water shortage ratio (S) can be expressed as

$$S = \frac{\bar{D} - D'}{\bar{D}}$$
$$= 1 - \frac{\theta \cdot (1-L)}{\bar{D}} \cdot \sum_{k=1}^{N} \left[\bar{D}_k \cdot O_k \cdot \sum_{j=1}^{M_k} (\lambda_j \cdot \Omega_j) \right] \tag{15}$$

where $\bar{D}$ is the daily water demand by customers in normal times; D' is the actual amount of water available to customers; O_k, Ω_j, θ and L are defined as before. The number of households without potable water (V) may be then estimated by the following model

$$V = H \cdot \left[1 - \frac{1-S}{\gamma} \right] \tag{16}$$

where H is the total number of households in the water supply system; γ is the reduced ratio of daily water demand after earthquakes.

CONCLUSION

A seismic scenario simulation technology developed by NCREE was introduced. Both ground shaking intensity and permanent ground deformation due to fault rupture and/or soil liquefaction is considered in seismic damage and loss assessment. The damage and loss assessment models of water facilities and pipelines have been proposed and used in seismic scenario simulations. The water outage in terms of reduction in daily supply and the number of households without potable water soon after earthquake may also be estimated base on damage and loss-of-function assessment of water treatment plants, transmission and distribution pipelines. The coefficients used in 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.

REFERENCES

[1] Yeh, C. H., C. H. Loh and K. C. Tsai, 2006. "Overview of Taiwan Earthquake Loss Estimation System", Natural Hazards, 37, pp. 23-37.

[2] Yeh, C. H., G. Y. Liu and L. H. Huang, 2015. "New Study on Soil Liquefaction Susceptibility Categories", 9th WRF/JWWA/CTWWA Water System Seismic Conference, Sendai, Japan.

[3] Wells, D. L. and K. J. Coppersmith, 1994. "New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, and Surface Displacement," Bull. Seism. Soc. Am., Vol. 84, pp.974-1002.

[4] Water Resources Agency, Ministry of Economic Affairs, 2016, Research Report of "A Study on the Seismic Scenario Simulation Technology for Public Water Supply Systems", Program No. MOEA-WRA- 1050316 Taipei

[5] Taiwan Water Corporation, 2000, "九二一集集大震自來水搶修(復舊)紀實"

[6] Taiwan Water Corporation, 2000, "台灣省自來水公司八十八年底各區管理處供水系統設計供水人口數及出水量統計表"

[7] Taiwan Water Corporation, 2001, "台灣省自來水公司八十九年底各區管理處供水系統設計供水人口數及出水量統計表"