TWC's Thoughts on Implementing Seismic Improvement to Large Water Pipelines

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ABSTRACT

Many of the pipelines and facilities of Taiwan Water Corporation (TWC) were built in early years without any seismic consideration. They are very vulnerable to earthquake hazards. One of the most important tasks in front of TWC is to improve its large water pipelines seismically. In order to help all branches and headquarter of TWC to implement in a more uniformly manner, some shared criteria and procedures should be specifies first. To be precise, TWC needs to (1) specify the seismic objectives for pipelines of different importance, (2) specify the procedure that TWC should follow to develop pipeline seismic assessment reports and implement seismic countermeasures. In this paper, some of TWC's thoughts on these topics have been summarized.

INTRODUCTION

Taiwan Water Corporation (TWC) is the largest water utility in Taiwan. It consists of 12 branches all over the island, which operates 144 systems with a total capacity of 11.42 million CMD. It provides water supply to 6.87 million customers or 17.98 million people (2016). It was established in 1974. Since then, it has made a significant contribution to the welfare of the people, and played as a pivotal role to the rapid economic development of the country.

However, many of TWC's pipelines and facilities were built in early years without any seismic consideration. They are very vulnerable to earthquake hazards. Especially, the majority of large water pipelines are concrete pipes installed in early years. This is due to the fact that concrete pipes cost less and are easy to install. Many of them are PCCP (pre-stressed concrete cylinder pipes) and PSCP (pre-stressed concrete pipes), which are brittle and very vulnerable to medium to large seismic actions. Aging and material deterioration have made the situation even more worsen. As a result, one of the most important tasks in front of TWC now is to improve the large water pipelines seismically.

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Recently, a prioritized seismic retrofit scheme has been proposed to TWC (Liu et al., 2017) regarding all water pipes with a diameter of 800mm or greater (up to 3,200mm). A total of 232 pipes called "pipeline evaluation units" have been suggested for seismic enhancement. The suggestion was made according to two factors. The first is the importance of the pipes. All pipes were classified into four classes of importance: very high, high, normal, and low. This was done according to the volume of water a pipe conveys daily, as well as the existence of any redundant pipe as backup. The second is the seismic risk of the pipes. It is a combination of seismic hazard level a pipe is exposed to, and the seismic vulnerability of the pipe itself.

Therefore, TWC is about to implement the proposed scheme to enhance the target large water pipelines of (very) high importance and at high seismic risk in the near future. In order to help all branches and headquarter of TWC to implement in a more uniformly manner, some shared criteria and procedures should be specifies first. To be precise, TWC needs to

- Specify the seismic objectives for pipelines of different importance,
- Specify the procedure that TWC should follow to develop pipeline seismic assessment reports and implement seismic countermeasures,
- Specify the analysis/design methods for pipeline seismic enhancement.

This paper aims at providing an overview of TWC's thoughts on the first two topics.

SEISMIC DEMANDS

The seismic design (enhancement) of water pipelines and their appurtenances should be based on the intended operational performance level the system must achieve in a post-earthquake disaster situation. This requires seismic performance objectives to be selected for the system (ALA, 2005). A performance objective consists of two elements: seismic demand (hazard level) and performance level.

Seismic demand refers to the site-specific hazard at prescribed level. It is employed to the assessment/design/analysis of a pipeline, which will qualify the performance objective if the associated performance level can be satisfied. In the following sub-sections, the proposed seismic demands of ground shaking, soil liquefaction, fault offset, and landslide will be introduced. In the next section, the proposed seismic performance level will be introduced.

Ground Shaking

Conventionally, peak ground velocity (PGV) is employed in the design of buries pipelines against earthquake ground shaking. This is because ground strain, the seismic action that exerts upon a pipe and causing damage, is theoretically proportional to PGV.

Therefore, the value of PGV of a site at a return period of 10% in 50 years (design earthquake) is proposed as the seismic demand due to ground shaking. It can be employed in the analysis and design of segmented and continuous pipes following various seismic design guidelines. A formula for estimating the value of PGV (unit: cm/s) of a site is expressed as

$$PGV = 0.885 \cdot \frac{9.81 \cdot S_{D1}}{2\pi} \quad (1)$$

$$S_{D1} = F_v^{\ D} \cdot N_v^{\ D} \cdot S_1^{\ D} \quad (2)$$

where $S_1^{\ D}$ is the code-specified spectral acceleration at a structural period of 1.0s at a return period of 10% in 50 years (design earthquake), and the multiplier F_v^D and N_v^D stand for the site amplification and near fault effects specified. Equation (1) is actually a simplified formula to the one by AASHTO (2010).

Soil Liquefaction

Soil liquefaction may result in settlement and lateral spreading of the ground. The resulted permanent ground displacement (PGD) is one of the major causes of pipe damage. Similar to the concept of soil liquefaction susceptibility categories in HAZUS (RMS, 1997), a method to decide the soil liquefaction susceptibility categories of a site in Taiwan has been proposed by Yeh et al. (2015). In addition, a set of empirical formulas have been proposed for assessing the mean ground settlement. Therefore, with the code-specified PGA and M at a return period of 10% in 50 years (design earthquake), the site-specific settlement PGD can be estimated according to the susceptibility category determined by borehole data.

While for the lateral spreading PGD, there is no prediction model ready for use in Taiwan. Site-specific geoscience investigation to decide the mean value and pattern, either longitudinal or transverse to the pipe orientation, see Figure 1, is preferred.

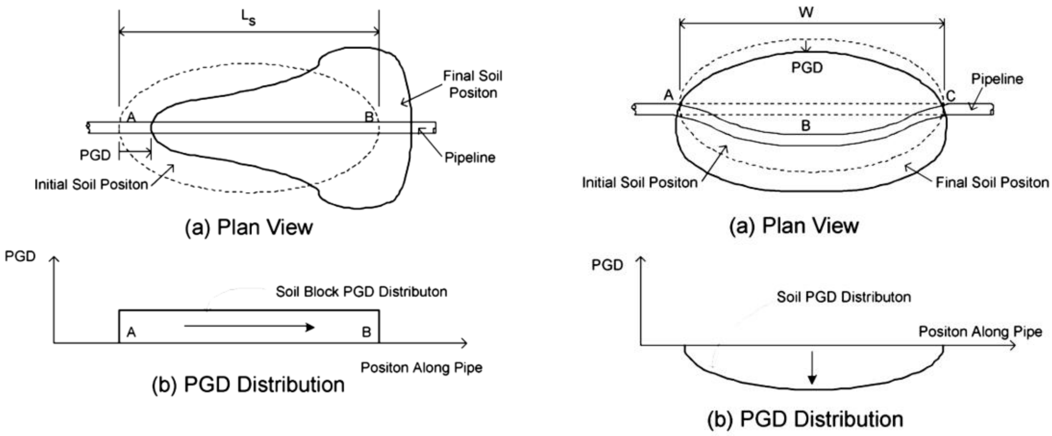

Figure 1. Pipe response to longitudinal (left) and transverse (right) PGD (ALA, 2005).

Once the mean liquefaction PGD is estimated, the design movement specified in Table 1 should be adopted to the analysis and design of pipes through the liquefaction zone. These values follow the suggestion by ALA (2005).

Table 1. The design movement of a liquefied site for pipe analysis and design.

Class of pipeline importance	Design movement
Normal and low	PGD
High	1.35 × PGD
Very high	1.50 × PGD

Fault Offset

Fault offset is the most severe hazard to buried water pipes. A pipeline should be designed to account for fault offset whenever there is a fault crossing. The amount of offset occurred in a fault rupture event can be estimated by using the model of Wells and Coppersmith (1994), which reads

$$\log \overline{D} = \begin{cases} 1.04 \cdot \log L - 1.7 & \text{strike-slip faults} \\ 0.31 \cdot \log L - 0.6 & \text{reverse faults} \\ 1.24 \cdot \log L - 1.99 & \text{normal faults} \\ 0.88 \cdot \log L - 1.43 & \text{all faults} \end{cases} \tag{3}$$

where $\overline{D}$ is the average offset (unit: m) and L is the length of the fault, respectively. As denoted by Wells and Coppersmith (1994), to estimate the offset of a reverse fault, the expression for all faults should be employed instead.

Once the average fault offset is estimated, the design offset specified in Table 2 should be employed to the analysis and design of pipes at fault crossing. These values follow the suggestion by ALA (2005), too.

Table 2. The design offset of a fault for pipe analysis and design.

Class of pipeline importance	Design offset
Normal and low	$\overline{D}$
High	$1.5 \cdot \overline{D}$
Very high	$2.3 \cdot \overline{D}$

Whenever a design offset is decided, its components should be determined according the specific pattern of fault offset at the fault crossing. As depicted in Figure 2, the vector of the design offset consists of two components: dip slip (Sd) and strike slip (Ss). The vector of dip slip consists of two components: vertical displacement (Sv) and thrust displacement (Sh).

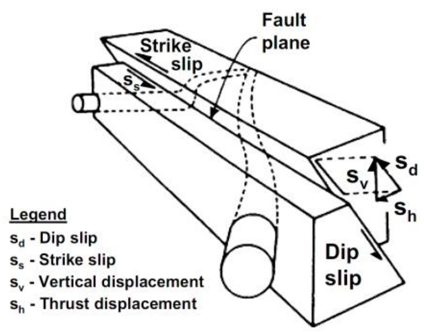

Figure 2. The schematic diagram for the various components of a design offset (ALA, 2005).

Finally, in order to take into account the uncertainty of ground rupturing along a fault trace, various scenarios of offset should be considered. For the sake of simplicity, the offset is suggested at three locations for a strike-slip fault: (1) the fault trace, (2) 150m to one side of the fault trace, and (3) 150m to the other side of the fault trace. While for a normal or reverse fault, the three locations are: (1) the fault trace, (2) in the hanging wall 200m away from the fault trace, and (3) in the footwall 100m away from the fault trace.

Landslide

The hazard of earthquake-induced landslide won't be considered at this stage. This decision is made according to evidences from past earthquake experiences in Taiwan.

SEISMIC PERFORMANCE LEVELS

There are generally two issues involved in specifying the seismic performance levels of large water pipes. The first is about the pipes' behavior and structural characteristics, for example the chance to survive a prescribed seismic hazard (e.g. ground shaking or failure), the ability to be bypassed, and the pipes' reparability. The second is about their criticality to the water systems, for example the existence of any redundancy.

TWC operates several large water supply systems in urban areas in Taiwan. Some of the large pipelines convey a very large volume of raw or treated water daily, and is therefore very important to the people and socio-economic activities there. Under such circumstance, it is reasonable to assume that half of the volume is the minimum required amount of water supply to keep the lives and activities go without much inconvenience or disruption. Therefore, it is proposed that pipes of very high importance in TWC should meet one of the following seismic performance levels:

- The pipes are functional under the specified seismic demand; or
- The pipes have redundant pipes, or the associated area is connected with supporting pipes from elsewhere, such that while becoming not functional, the redundant and supporting pipes are able to provide 50% routine water need or more; or
- Following above, the redundant and supporting pipes are able to provide 25%, while temporary pipes could be installed within 24 hours and able to provide additional 25%; or
- The pipes could be repaired and functional again within 3 days, and sufficient water storage exists for the first 3 days' urgent need.

The likely numerous damages in transmission, distribution, and customer pipelines at the same time should be considered in the scenarios. In the meanwhile, the surge of urgent water need for firefighting, medical caring, shelters, and mobile water delivery to the affected people should be well considered, too.

Similarly, pipes of high importance should meet one of the following levels:

- The pipes are functional under the specified seismic demand; or
- The pipes have redundant pipes, or the associated area is connected with supporting pipes from elsewhere, such that while becoming not functional, the redundant and supporting pipes are able to provide 30% routine water need or more; or
- Following above, the redundant and supporting pipes are able to provide 15%, while temporary pipes could be installed within 24 hours and able to provide additional 15%; or
- The pipes could be repaired and functional again within 7 days, and sufficient water storage exists for the first 7 days' urgent need.

Finally, for pipes of normal or low importance, TWC won't specify any seismic performance levels. They will be upgraded by routine pipeline replacement.

DEVELOPING AND IMPLEMENTING PIPELINE SEISMIC IMPROVEMENT

The procedure for developing and implementing seismic enhancement of large water pipelines is depicted in Figure 3. Typically, a pipeline network consists of many links and nodes. Each link may consist of several pipes. Any link survives only if all its member pipes survive. Therefore, from the viewpoint of a pipeline network, if some of the pipeline evaluation units belong to the same link, they should be grouped together and be enhanced seismically at the same time. In addition, the rest pipe (s) of the same link should be grouped together, too. The rest pipe(s), although at lower risk, may be damaged and fail the link if without any enforcement and unable to withstand the seismic load in future earthquakes. Such "node-to-node" link in the pipeline network, as shown in Figure 4, is termed a "pipeline conveyance unit." Therefore, the first thing that should be done is to identify all the pipeline conveyance units. Afterward, each unit should be associated with a seismic assessment project.

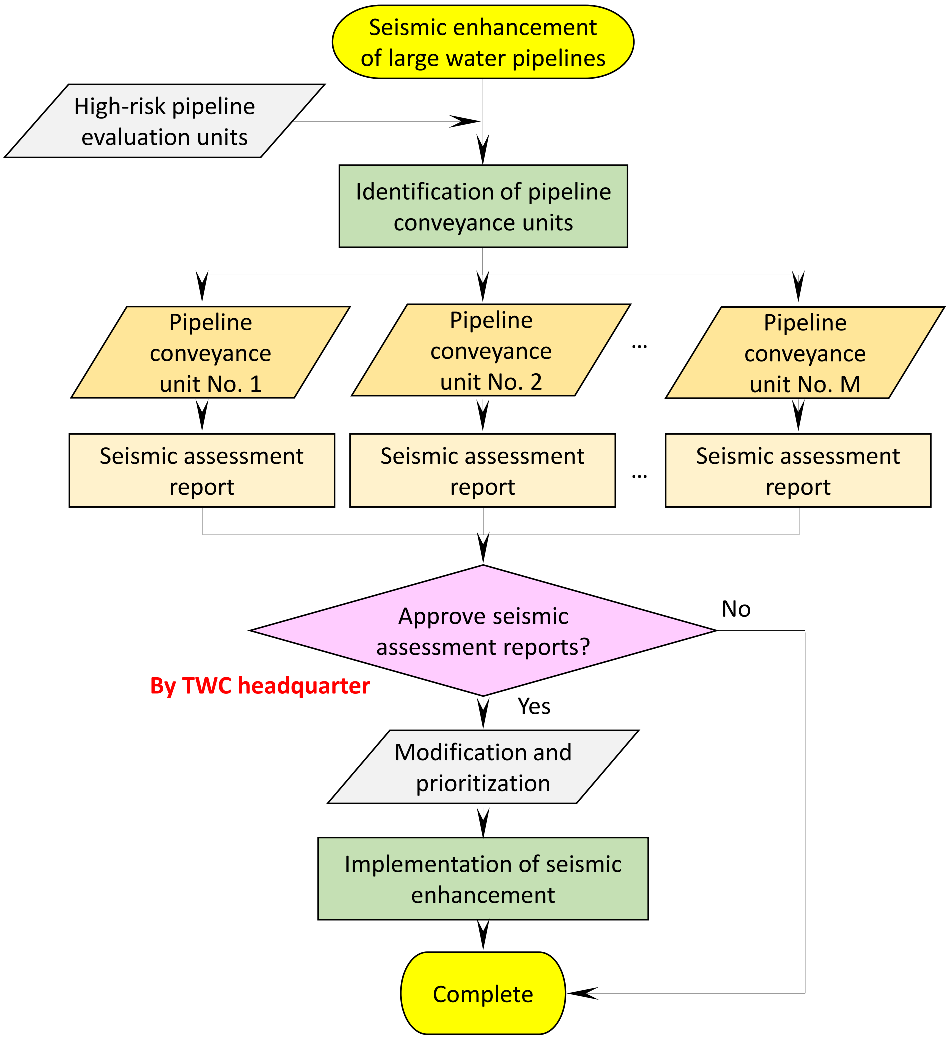

Figure 3. The procedure for developing and implementing large pipeline seismic enhancement.

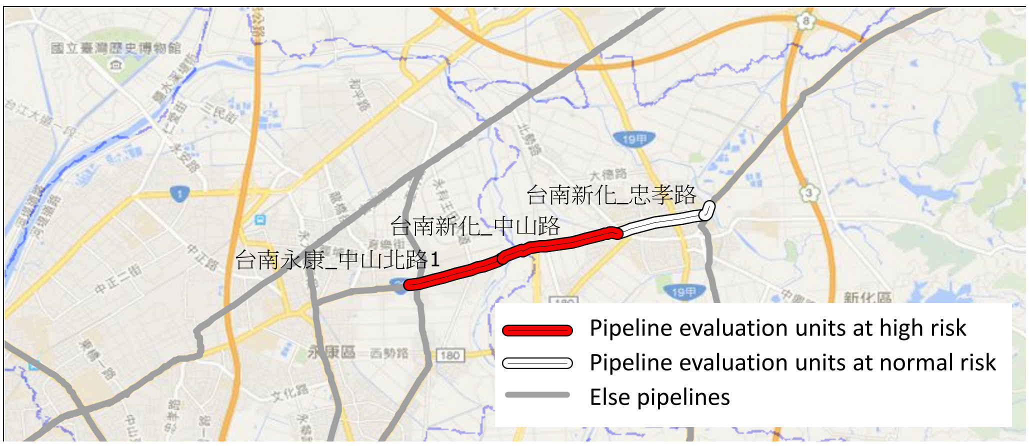

Figure 4. Example of a pipeline conveyance unit, a node-to-node link in a pipeline network.

When a seismic assessment project of a target pipeline conveyance unit is launched, the procedure depicted in Figure 5 should be follow. Surveys of the involved pipelines and the site condition of where they locate should be done first. The site survey is for identifying the soil properties and site condition, fault zone (if any) and pattern of offset, ground water level and liquefaction-induced ground movement (if likely), etc. Site survey involves not only technical reviews of various geological maps, but also drillings at carefully selected sites along the pipelines and its neighborhood for additional geological evidences needed for seismic assessment of the target unit. The pipeline survey is for confirming the location and properties of the pipelines, and the current condition of deterioration. The role of the pipeline conveyance unit in the water supply system should be clarified, too. The impact to the system performance due to the failure of this unit should be investigated. The redundancy (if any) to and the likely redundant pipes of the target unit should be identified.

Within a TWC branch, a technical working group (TWG) should be organized. The TWG should include system operator, pipeline engineer, geotechnical scientist and engineer, pipe flow analyzer, and third-party consultants as its members. The TWG should decide whether or not a target pipeline conveyance unit meets any of the performance levels given the specified seismic demands. If not, they should develop several countermeasures to the target unit such that, once it is implemented, the performance levels can be satisfied. Additional feasibility and cost-and-benefit analysis to each countermeasure should also be considered in detail. The likely impact to water supply, traffic and environment should be minimal. Finally, the TWG should prepare the seismic assessment report. It should be submitted to TWC headquarter for approval.

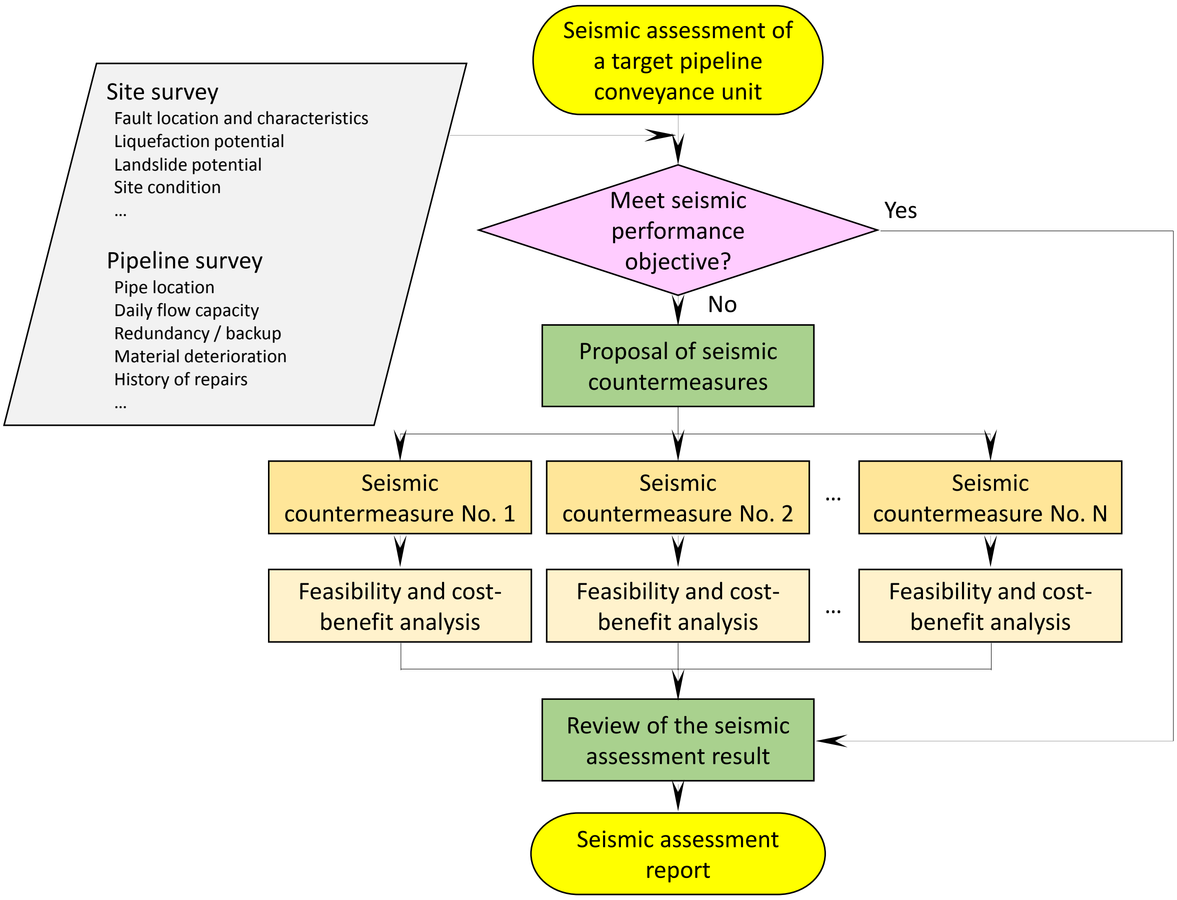

Figure 5. The procedure for seismic assessment of a target pipeline conveyance unit.

A special committee should be established in the TWC headquarter. The members of the committee should include chief engineer, department managers, finance officer, accounting officer, representatives from TWC branches, etc. After all TWGs submit their pipeline seismic assessment reports to the committee, the reports should be carefully reviewed. As each report has already been settled with the best seismic countermeasure according to feasibility and cost-benefit analysis, the mission of the committee is very simple. It should decide whether or not each project should be granted, and, for the granted projects, what should be prioritized for implementation. The decision should be made by taking into consideration the following issues:

- The optimal seismic improvement outcome to TWC as a whole,
- The capital and resources available within the frame of time,
- The expectation and supports from the authorities and communities,
- Else managerial and financial concerns.

CONCLUDING REMARKS

As TWC is about to enhance large water pipelines of high importance and at high seismic risk, some shared criteria and procedures have seen specified by TWC to help future implementation in a more uniformly manner. The seismic demands and performance levels for the assessment/ design/analysis of a pipeline of a specific class of importance have been proposed. A procedure for developing pipeline seismic assessment reports and implementing seismic countermeasures has been proposed, too. Issues that TWC should take into consideration to review and approve a pipeline seismic assessment report issued by TWC branches have been identified.

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