Seismic Enhancement Framework and Screening of Critical Water Mains – A Proposal

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ABSTRACT

Water supply systems may lose serviceability after disastrous earthquakes. One of the major causes is the damage in water mains due to severe seismic hazards including ground shaking, fault rupture, liquefaction, slope failure, etc. As a result, the systems may fail in raw water conveyance and treated water transmission. In this study, a framework is proposed to accommodate the procedure for performing seismic upgrading of water mains as well as the essential information, data and factors. In this procedure, there are two stages of seismic screening. The preliminary screening is to identify the exposure of water mains to high seismic hazards. The secondary screening is to narrow down the exposure to limited ones being most critical and vulnerable. The result can be employed to develop a seismic mitigation program of water pipelines which may be more effective and finically feasible. The seismic hazards and inventory of water mains in Taiwan are overviewed. A pilot project using slip-out resistant ductile iron water pipes in a liquefaction susceptible site in New Taipei City is introduced.

Keywords: water pipes, seismic enhancement, seismic screening

INTRODUCTION

Taiwan is located on the circum-Pacific seismic belt. It is one of the most earthquake-prone countries in the world. In the 1999 Chi-Chi earthquake, the largest event in recent decades in Taiwan, a widespread damage in water supply systems was observed (Chen and Wang, 2003). According to Taiwan Water Corporation's report, as many as 3,826 damages in utility-owned pipeline were recorded, among which 351 occurred in pipes with diameters between 300 and 2,600mm (TWC, 2000). The most significant single damage occurred near the Feng-Yuan First Water Filtration Plant, as depicted in Figure 1. It is a ϕ2,000mm steel pipe served solely as a common outlet of Feng-Yuan First and Second Water Filtration Plants, which provide 70% of water demand from 740 thousand customers in the Taichung metropolitan area before event. It was bent 90 degree and buckled by the offset of Chelungpu fault rupture. It is now kept at the Water Park in Taipei for permanent exhibition.

As upgrading of water pipes against earthquake hazards is an urgent need in Taiwan, a procedure for performing seismic upgrading of water mains is conceptually proposed in this study. The process of seismic screening of water mains is discussed. The seismic hazards and inventory of water mains in Taiwan are overviewed.

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Figure 1 A ϕ2,000mm steel pipe bent and damaged at Chelungpu fault crossing near the Feng-Yuan First Water Filtration Plant in Chi-Chi earthquake (courtesy Taiwan Water Corp.)

SEISMIC UPGRADING OF WATER MAINS THROUGH SCREENING

The water supply systems may be damaged when a major earthquake occurs. Buried water pipes may be damaged due to various factors. According to “Seismic Fragility Formulations for Water Systems” (ASCE, 2001), these factors consist of ground shaking, landslides, liquefaction, settlement, and fault crossings. In addition, pipe properties also contribute to the fragility. For example, each of continuous pipeline, segmented pipeline, appurtenances and branches, and age and corrosion of pipes has its own characteristics of fragility.

A solution that can help enhance the seismic safety of water pipeline infrastructures should be both effective and finically feasible. It can be achieved by seismic screening, as it can narrow down all water mains into a manageable scope of pipes being most critical and vulnerable. A framework is proposed to accommodate the procedure for performing seismic upgrading of water mains as well as the essential information, data and factors, as depicted in Figure 2. The procedure consists of four steps: (1) preliminary screening, (2) secondary screening, (3) prioritization, and (4) implementation of seismic enhancement.

There are two stages of seismic screening. The preliminary screening requires both the knowledge of known seismic hazards and the database of water pipes. The former, termed as seismic hazard maps, includes the information of active fault traces, liquefiable areas, unstable slopes, and so forth. The later, termed as inventory of pipes, includes basic properties and service capacity of the pipes. They can be over layered to identify the exposure of water mains to high seismic hazards.

The secondary screening required further knowledge of the known seismic hazards and detailed data of water pipes. The former, termed as seismic hazard models, includes methods and information for quantifying the seismic hazards. The later, termed as the pipe vulnerability models, takes into account pipe properties that affect a pipe’s seismic vulnerability. They can be compiled to achieve a group of water mains which need being enhanced most.

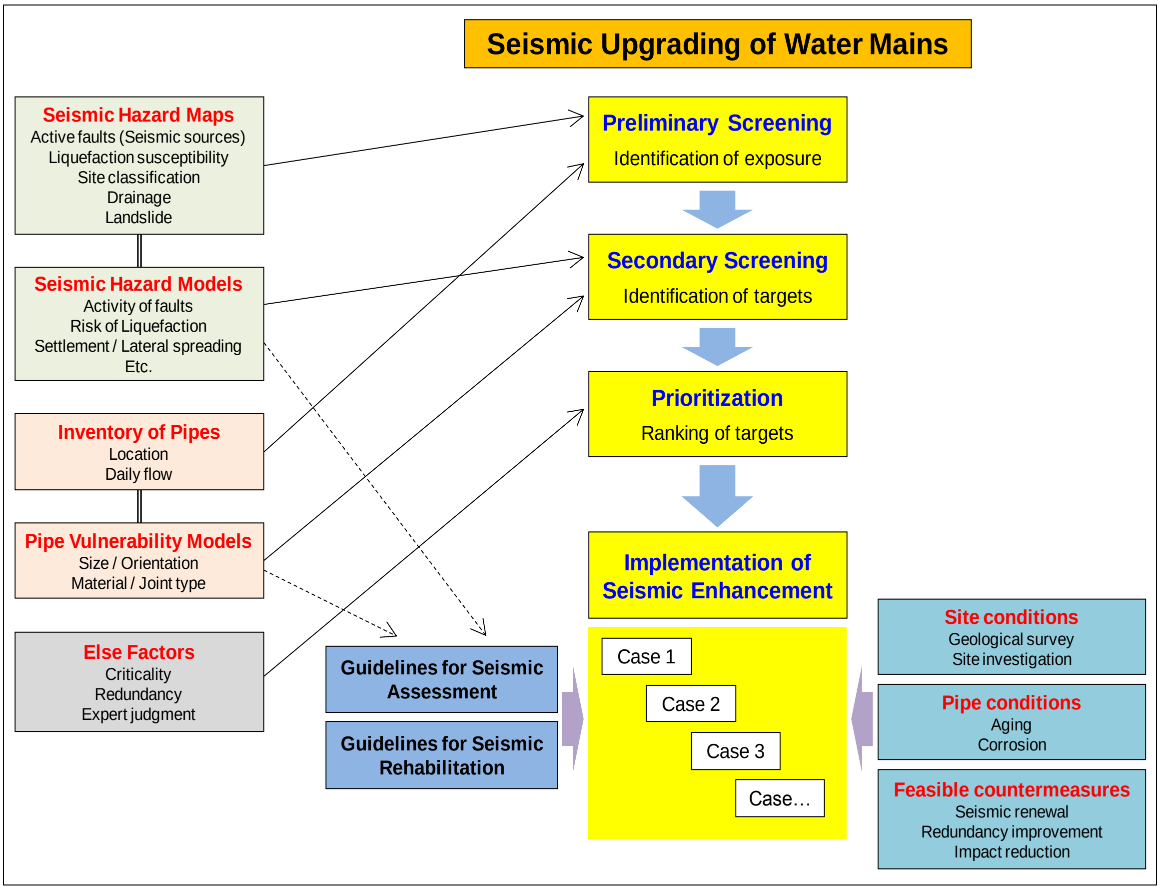

Figure 2 The proposed framework for performing seismic upgrading of water mains and the required models and data of hazards and pipe inventory

SEISMIC HAZARDS IN TAIWAN AND THEIR EFFECTS ON BURIED WATER PIPES

The tectonic setting and interaction of the Eurasian and Philippine Sea Plates are the major triggering mechanism of seismic activities in vicinity of Taiwan. Recently, Central Geological Survey (CGS), MOEA released an active fault map of Taiwan, as depicted in the left of Figure 3. There are 33 active faults on the island, 20 of which belonging to the Category I and the rest Category II. The former refers to faults that activate within past 10,000 years and are considered more active, while the later activate within past 100,000 years and less active (CGS website). Currently, only the active faults of Category I are considered in “Taiwan Building Seismic Design Code (2011)” to account for the effects of fault crossing and near-fault ground shaking. Based on CGS research reports, Wen et al. have summarized some of the properties of major active faults, listed in Table 1, for engineering applications (2005). There exist other active fault maps of Taiwan based on various studies. The right of Figure 3 depicts the map by Institute of Applied Geology, NCU, Taiwan, which lists a total of 50 active faults.

According to “Seismic Fragility Formulations for Water Systems” (ASCE, 2001), fault offset movement will heavily damage segmented pipes. Continuous butt-welded steel pipes are less prone to damage if they are oriented such that tensile strains result. Pipelines in compression may buckle as a beam or it may deform by local warping and wrinkling of its wall.

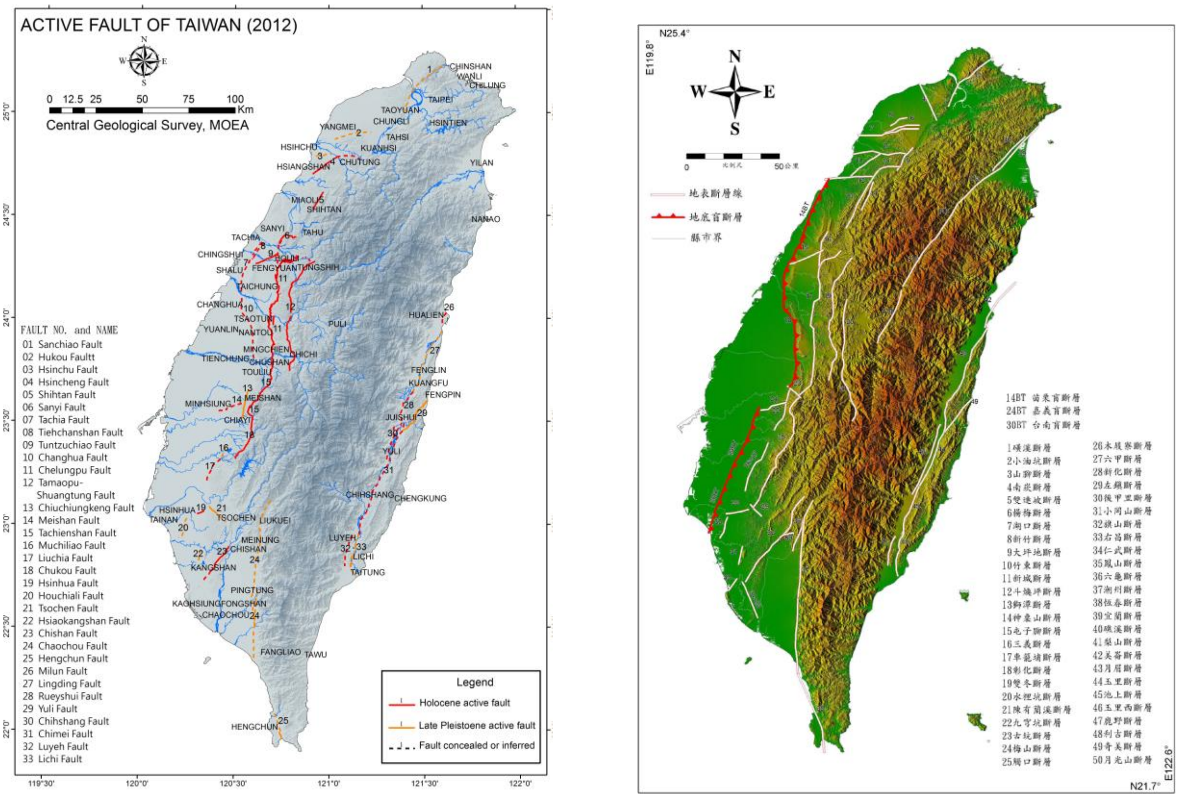

Figure 3 Maps of active faults in Taiwan by Central Geological Survey, MOEA (left, Ver. 2012) and Institute of Applied Geology, NCU, Taiwan (right, courtesy Prof. Lee, Chyi-Tyi)

Table 1 Properties of major active faults in Taiwan (Wen et al., 2005)

Name	Length (km)	Type	Max. Offset (m)		Return Period (yr.)	Upper Bound of Magnitude (M_L)	Last Event (yr.)
			Hor.	Ver.			
Shintan	12	reverse	-	3	-	6.8	1935
Shenchoshan	5	reverse	-	0.6	-	6.8	1935
Tuntzuchiao	14	reverse	1.5	-	-	6.8	1935
Meishan	13	oblique reverse	2.4	1.8	114	7.1	1906
Hsinhua	6~12	oblique reverse	2	0.76	210	6.1	1946
Milun	7~25	oblique reverse	2	1.2	600~700	7.0	1951
Chimei	18	reverse	-	1~2	-	7.3	1951
Yuli	43	oblique reverse	-	1.63	< 250	7.3	1951
Chihshang	47	oblique reverse	-	< 0.5	-	7.3	1951
Hsincheng	15~28	reverse	-	1.3~1.85	2000	> 7.0	-
Chelungpu	-	reverse	-	-	400~1000	7.3	1999
Tachienshan	25	reverse	3.94	-	-	-	-
Chukou	40	reverse	-	-	-	-	-

The factors affecting soil liquefaction occurrence include the seismic intensity and duration of ground motions, and the ground water depth. Usually, the peak ground acceleration (PGA) is used for the seismic intensity, while the earthquake magnitude is employed to stand for the duration of ground motions. Following the methodology of HAZUS (RMS, 1997), the soil liquefaction susceptibility is classified into six categories, that is, “very high”, “high”, “moderate”, “low”, “very low” and “none”. Yeh et al. (2002) has analyzed more than 11,000 sets of borehole data in Taiwan, and then proposed a classification scheme to identify the liquefaction susceptibility category of each borehole. Based on the specified liquefaction susceptibility of each borehole as well as geological maps, the liquefaction susceptibility map of Taiwan has been developed. As an example, Figure 4 shows the boreholes and soil liquefaction susceptibility map in Taipei city.

Liquefaction may result in local ground settlement as well as lateral spreading. According to “Seismic Fragility Formulations for Water Systems” (ASCE, 2001), pipe breaks occur due to vertical settlement at transition zones, and in areas of young alluvial soils prone to localized liquefaction. Heavy concentrations of pipe breaks will occur in areas of lateral spreading.

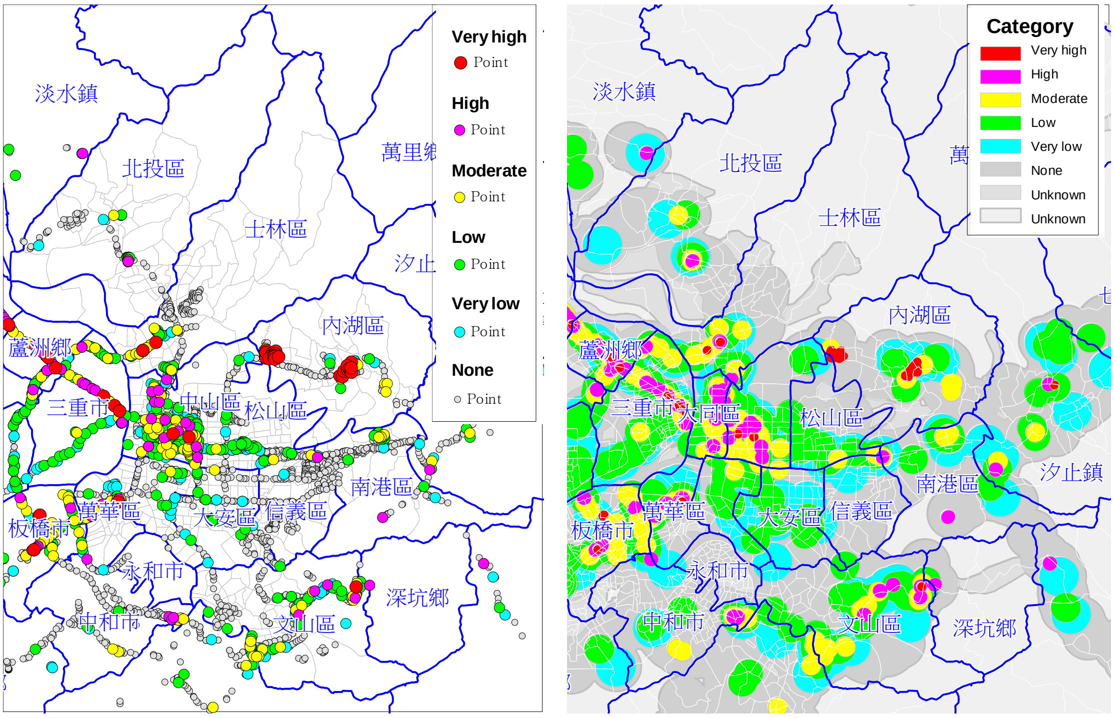

Figure 4 Maps of boreholes and their liquefaction susceptibility category (left) and soil liquefaction susceptibility (right) of Taipei city (Yeh et al., 2002)

INVENTORY OF WATER MAINS IN TAIWAN AND THEIR VULNERABILITY

Figure 5 depicts two percentage charts of pipe materials of Taiwan Water Corporation’s water mains (WRA, 2014). The left one is for pipes with diameters between 800 and 1,500mm, and the right one is for pipes greater than 1,500mm. It indicates that, for very large water mains (greater than 1,500mm), the majority are PCCPs (pre-stressed concrete cylinder pipes, 30%), PSCPs (pre-stressed concrete pipes, 23%) or SPs (welded steel pipes, 23%). While for smaller water mains (between 800 and 1,500mm), the majority are DIP_Ks (ductile cast iron pipes of K-type joint, 30%), PSCPs (28%) or DIP_As (ductile cast iron pipes of A-type joint, 19%). All of these, except SPs, are segmented pipelines.

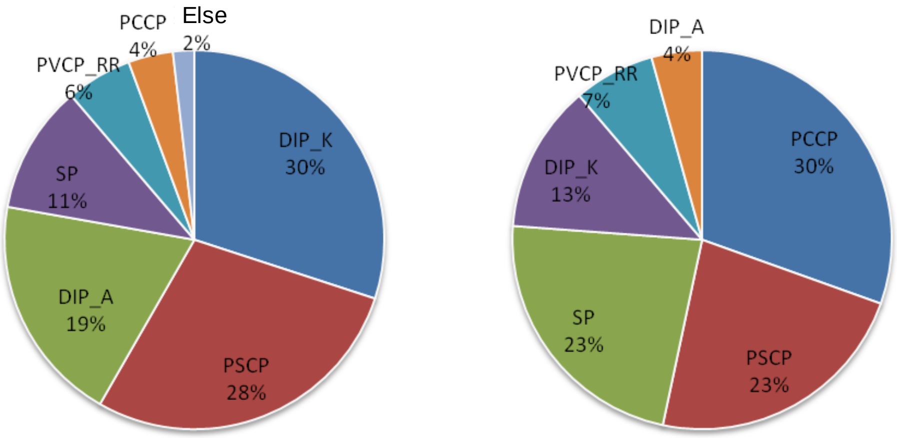

Figure 5 Percentages of pipe materials of TWC's water mains with diameters between 800 and 1,500mm (left), and above 1,500mm (right) based on preliminary statistics (WRA, 2014)

PCCP and PSCP are, while being designed to take optimum advantage of the tensile strength of steel and corrosion inhibiting properties of concrete, considered a brittle pipe material and very vulnerable to ground deformations. DIP_A is an old version of ductile cast iron pipe. With insufficient length of socket, it is also very vulnerable to ground deformations, too. DIP_K, a modification from DIP_A, has a longer socket and improved rubber gasket. It is arguably of good seismic capacity against ground shaking, especially in area of stiff site condition.

Therefore, the majority of water mains do not have enough seismic capacity to withstand devastating seismic actions. There is an urgent need to carry out an earthquake hazard mitigation plan to water pipeline infrastructures in Taiwan to confront major earthquakes in the future.

PRIORTIZATION AND IMPLEMENTATION OF PIPE ENHANCEMENT

After the secondary screening, a group of most critical and vulnerable water mains can be marked. A prioritized scheme should be developed and applied to this group of water mains. In addition to the severity of seismic hazards and the seismic vulnerability of the pipes themselves, else factors should be included to decide the ranking of the pipes, as depicted in Figure 2. Factors affecting the ranking of a pipe may be: (1) its criticality to the serviceability of the entire water system, (2) the numbers of customers related, (3) the importance of the area served, (4) its redundancy, (5) emergency facilities (i.e. large hospitals, shelters) served, and finally (6) others by expert judgment.

As suggested in Figure 2, when it comes to action to enhance any of the leading pipes, the kind of hazard and pipe failure mode should be identified, and the actual sites conditions and pipe conditions should be investigated. Engineering or non-engineering solution (improved emergency response, for example) should be developed according to the situation. It is highly desired to have prescribed guidelines for pipe seismic assessment and rehabilitation. They may be derived from the seismic hazard models and pipe vulnerability models presented in Figure 2. They will guarantee that the implementation of pipe seismic enhancement will be conducted in a more practical and uniform way.

In 2014, Taipei Water Department (TWD) carried out a first ever project using slip-out resistant pipes in Taiwan (Wu, 2014). As depicted in Figure 6, the site locates in the Erchong Floodway Redevelopment Zone, Sanchong, New Taipei city. It is of alluvial soil, topographically flat and liquefaction susceptible. The employed ϕ150mm and ϕ200mm pipes, K-bar DIPs, add bar-like mechanisms to the joints of DIP_Ks for slip-out resistance. They were manufactured locally. Before installation, specimens were tested at National Center for Research on Earthquake Engineering. They were verified capable of providing a slip-out resistance of Class B specified in ISO 16134 (ISO, 2006).

Figure 6 A pilot project using K-bar slip-out resistant ductile iron water pipes in Erchong Floodway Redevelopment Zone, Sanchong, New Taipei city (Wu 2014; courtesy TWD)

CONCLUDING REMARKS

In this study, a framework prescribing how to perform seismic upgrading of water mains has been proposed. There are four steps involved: (1) preliminary screening, (2) secondary screening, (3) prioritization, and (4) implementation of seismic enhancement. A two-stage seismic screening is adopted in the framework for achieving a group of water mains which need being enhanced most. The seismic hazards and inventory of water mains in Taiwan have been overviewed. It is shown that there is an urgent need to carry out earthquake hazard mitigation plans to water pipeline infrastructures to confront future big earthquakes. A TWD pilot project using slip-out resistant ductile iron water pipes in a liquefaction susceptible site is introduced. Hopefully, this pilot project could shed light on the development and employment of water pipes of better seismic performance in Taiwan in the future.

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