Seismic Screening of Large Water Pipelines for TWC's Seismic Improvement Program

Gee-Yu Liu, Chin-Hsun Yeh, and Lee-Hui Huang

ABSTRACT

Mitigation of water supply systems against earthquake hazard is always a crucial task in Taiwan. In order to mitigate the seismic risk of water pipes more effectively, a screening of the large pipelines is essential. A study was therefore conducted to utilize existing or develop new seismic hazard maps of ground shaking, soil liquefaction, active faults, and landslide relating to the cause of damages in buried pipes. The inventory of pipelines of Taiwan Water Corporation (TWC) with a diameter of 800mm or greater was collected and calibrated. It consists of 2,229 km of pipes of various sizes and pipe types (joints). The seismic risk of each pipe as a combination of hazard severity and pipe vulnerability was quantified and ranked. The importance of each pipe has also been classified according to the volume of water it conveys and the existence of any redundancy. Finally, pipes of high importance and at high seismic risk have been screened out. They were grouped into three priorities ready for TWC to implement seismic improvement program in the near future.

BACKGROUND

Taiwan is located on the circum-Pacific seismic belt, one of the most earthquake-prone areas in the world. In the 1999 Chi-Chi earthquake (Mw 7.6), the most devastating event in decades, a widespread damage in water supply systems occurred. As many as 4,411 damages to water pipes were recorded, among which 28 occurred in pipes of ϕ500mm or larger. The worst single damage occurred near Fengyuan, Taichung. It is a ϕ2000mm steel pipe, the only common outlet of Fengyuan First and Second Water Treatment Plants, which met 70% of the water demand from Taichung metropolitan area before the event. It was bent 90 degree and buckled by the offset of Chelungpu fault rupture (TWC, 2000). The 2016 Meinong earthquake (Mw 6.6) caused substantial damage to water pipelines in Tainan, especially in its southern area metropolitan area. The ϕ2000mm pipeline conveying water from Nanhua Water Treatment Plant to downtown Tainan was damaged at three sites. These damages caused widespread water outage lasting for quite some time (Liu et al., 2016).

Evidences indicate that many of the large water pipes of TWC do not have enough strength to withstand medium to large seismic actions. In order to mitigate the risk more effectively, a seismic screening of the large pipelines is desired.

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GOAL AND METHODOLOGY

This study focused on the water pipelines of TWC with a diameter of 800mm or greater (up to 3,200mm). Its goal is to: (1) make a sorting of the target pipelines according to their importance to the water supply systems, (2) make a ranking of the target pipelines according to the seismic risk they are exposed to, and (3) screen out pipelines of high importance and at high risk for the seismic improvement program of TWC.

The seismic risk of pipelines is very difficult to define or quantify. For the sake of simplicity, the "hazard" and "vulnerability" of a pipeline are assumed independent on each other. Efforts were done to collect existing or develop new seismic hazard maps of Taiwan. Hazards of ground shaking, soil liquefaction, active faults and landslide, which are inevitably the causes of pipe damages, have all been considered. Each type of hazard to a pipeline was quantified. A normalized "summation of hazards" and a normalized "pipeline vulnerability" were defined and finally "combined" to get the "risk" of a pipeline.

According to the value of risk, all target pipelines could be ranked from high to low, and evenly divided into an array of "risk groups." By spreading out the array with respect to the importance of pipelines, a seismic risk matrix could be generated, from which the pipes of high importance and at high seismic risk could be easily identified.

PIPELINE INVERTORY AND IMPORTANCE

The inventory of the target pipelines was first collected and calibrated. The total length of the pipelines is 2,229 km. The digitized GIS data consist of more than 6,500 polylines, some of which being very short and some other very long. They were re-organized into 1,687 units of similar length so as to be of roughly equal representation. This was achieved by either grouping of neighboring pipes or division of long pipes. These units were termed "pipe evaluation units," and were employed as the base units for analysis and further seismic risk mitigation.

The importance of large water pipes consists of two different elements. One is about the pipes' role. TWC operates several large water supply systems in urban areas. Some pipelines convey a very large volume of raw or clear water daily, and are therefore very important to the people's lives and socio-economic activities. The other is about their criticality, namely the existence of any redundant pipe as backup when they fail.

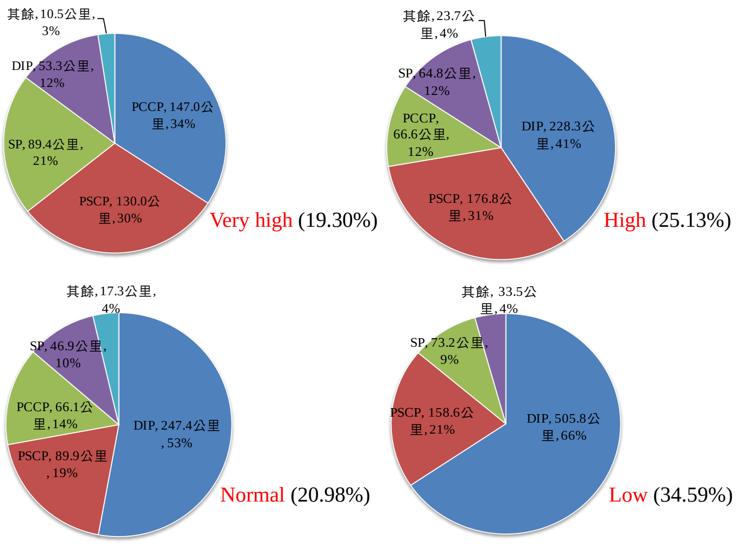

Figure 1. Percentages of pipes of various classes of importance, and percentages of various types of member pipes they consist of.

Taking the two elements into account, each pipe evaluation units was classified as one of the four classes of importance: very high, high, normal, and low importance. Figure 1 summarizes the percentages of pipes of various classes of importance, and the percentages of various types of member pipes they consist of. It is worth noticing that, for pipes of very high importance (19.30% of total pipelines), the majorities are PCCP (pre-stressed concrete cylinder pipes, 34%) and PSCP (pre-stressed concrete pipes, 30%). Such pipes are brittle and seismically very vulnerable.

SEISMIC HAZARD TO PIPELINES

Ground Shaking

Ground shaking is inevitably the most common cause of pipe damage. Theoretically, peak ground velocity (PGV) is proportional to the ground strain, the seismic action exerting upon a pipe and may cause its damage during ground shaking. It is employed to measure the rate of pipe damage (number of repairs per unit pipe length) conventionally.

Therefore, the value of PGV at a return period of 10% in 50 years (design earthquake) is used to specify the hazard of ground shaking in this study. A formula for estimating the value of PGV (unit: cm/s) of a site is employed. It is expressed as

$$PGV = 0.885 \cdot \frac{9.81 \cdot S_{D1}}{2\pi} \tag{1}$$

where S_{D1} is the code-specified value of spectral acceleration at period T = 1.0s at a return period of 10% in 50 years (design earthquake), with the amplification by both site and near-fault effects (Taiwan Building Seismic Design Code, Version 2011) considered. This formula is actually a simplified formula to the one suggested by AASHTO (2010). As a result, a hazard map of PGV of Taiwan can be prepared.

According to a study in Japan (Miyajima, 2013), the rate of pipe damage is proportional to $(PGV-15)^{1.14}$, where 15 cm/s stands for the threshold of damage occurrence. If the size of the interested pipes is large (e.g. with a diameter of 800mm or greater), then a base value with respect to, say, 30 cm/s should be specified and removed to count for the damaging effect of ground shaking. As a result, the hazard of ground shaking H_{GS} to a pipeline evaluation unit may be defined as

$$H_{GS} = (\overline{PGV}-15)^{1.14} - (30-15)^{1.14} = (\overline{PGV}-15)^{1.14} - 21.915 \tag{2}$$

where $\overline{PGV}$ is the weighted PGV of the pipeline evaluation unit, or

$$\overline{PGV} = \sum_j \frac{A_j}{A} \cdot PGV_j \tag{3}$$

where A_j and PGV_j are the jth area and its PGV value, respectively, of a 10m radius buffer of the pipeline evaluation unit.

Soil Liquefaction

Soil liquefaction is one of the major causes of pipe damage, too. Conventionally, the liquefaction potential index (P_L) proposed by Iwasaki, et al. (1982) is used to indicate how susceptible a site is for liquefaction to occur.

Similar to the concept of soil liquefaction susceptibility categories in HAZUS (RMS, 1997), a map of soil liquefaction susceptibility categories of Taiwan has been proposed by Dr. C. H. Yeh of NCREE. It is based on the borehole database from Central Geological Survey, MOEA, together with the map of geology, digital terrain model, and map of drainage. A site will be classified as one of the nine categories, i.e. Cat. 1 to 9, depending on how easily liquefaction will occur given the same excitation. A site of Cat. 0 suggests that liquefaction will never occur there. In addition, a set of empirical formulas for have been proposed by Yeh et al. (2015) to assess the P_L value of each soil liquefaction susceptibility category. The peak ground acceleration (PGA), earthquake magnitude (M) and ground-water depth (D) are the three parameters required in the formulas. With the code-specified PGA and M at a return period of 10% in 50 years (design earthquake), a hazard map of liquefaction potential index P_L can be prepared again. An illustration of this procedure is given in Figure 2.

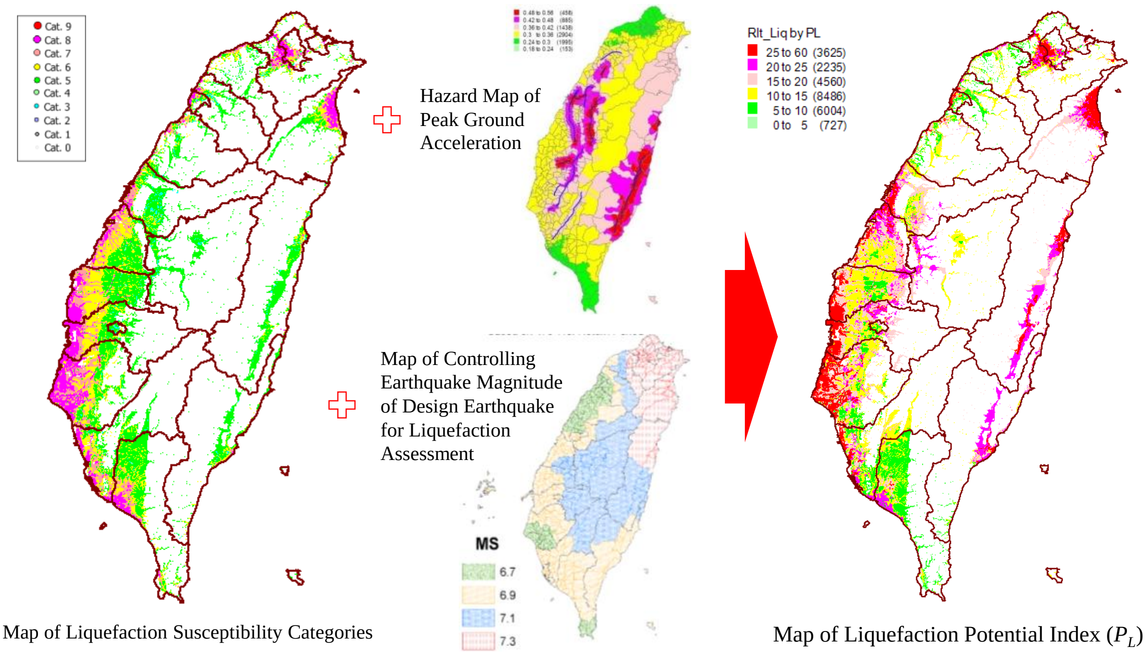

Figure 2. The procedure for creating the hazard map of liquefaction (potential index).

As a result, the hazard of soil liquefaction H_{LQF} to a pipeline evaluation unit is defined as

$$H_{LQF} = \overline{PL} \cdot \log_{10} L \tag{4}$$

$$\overline{PL} = \begin{cases} 0 & P_L < 10 \\ P_L - 10 & 10 \le P_L < 30 \\ 20 & P_L \ge 30 \end{cases} \tag{5}$$

where P_L is the weighted soil liquefaction potential index of a pipeline, which can be computed similarly to Equation (3), except that a 100m radius buffer is employed instead. The factor $\log_{10} L$ is for reflecting that fact that, given the same liquefaction potential, the affected range of the member pipes and its severity of a pipeline evaluation unit are positively correlated to the total length L.

Fault Rupture

According to the active fault map of Taiwan by Central Geological Survey (CGS), MOEA, 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).

In order to account for the damaging effect of fault rupture on pipelines once it occurs, two buffers have been created for each fault trace, as depicted in Figure 3. The first is a 15m radius buffer denoted as "fault crossing area," while the second is a 150m radius buffer denoted as "fault vicinity area." For the case of a normal or reverse fault, the buffers will be shifted to the hang-wall side by 5m and 50m, respectively, to account for the hang-wall effect.

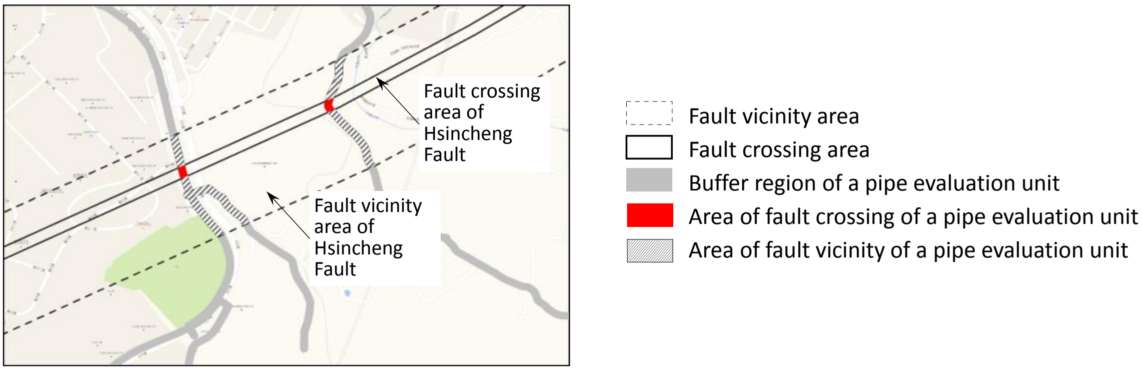

Figure 3. Example fault crossing area and fault vicinity area of an active fault trace.

In addition, the 10m radius buffer of a pipeline buffers is overlaid upon these two buffers to decide the sizes of area within, denoted as A_c and A_v. Accordingly, the effective length of fault-crossing and length of fault-vicinity of the pipeline can be defined as $L_c = A_c / 20$ and $L_v = A_v / 20$, respectively. As a result, the hazard of fault rupture H_F to a pipeline evaluation unit is defined as

$$H_F = \min(10L_c + L_v, 600) \cdot \bar{D} \cdot \bar{f} \tag{6}$$

$$\bar{D} = \begin{cases} D & D < 1.0 \\ 1.0 & D \geq 1.0 \end{cases} \tag{7}$$

$$\bar{f} = \begin{cases} 1 & R \geq 500 \\ 2 - \dfrac{R-200}{300} & 200 < R < 500 \\ 2 & R \leq 200 \end{cases} \tag{8}$$

where D and R are the average fault offset (unit: m) predicted by using the model of Wells and Coppersmith (1994), and the return period (unit: year) of the fault.

Landslide

The map of landslide potential in Taiwan has been released by Central Geological Survey, MOEA. It classifies the landslide potential into four categories: none, low, medium, and high. It is supposed that the occurrence of landslides induced by earthquake in Taiwan is closed correlated to the potential specified on this map. A landslide score of 3, 1, 0, and 0 is specified to these categories, respectively. As a result, the hazard of landslide H_{LS} to a pipeline evaluation unit is defined as

$$H_{LS} = \sum_{j=1}^{4} \frac{A_j}{A} \cdot LS_j \tag{9}$$

where A_j and LS_j are the jth area and its landslide score, respectively, of a 100m radius buffer of the interested pipeline evaluation unit.

SEISMIC VULNERABILITY OF PIPELINES

Following the formula of pipe damage rate by Miyajima (2013), of which the rate is proportional to $C_p \cdot C_d \cdot C_g \cdot (PGV - 15)^{1.14}$, where C_p, C_d, C_g are the correction factors of pipe type (joint), pipe diameter, and micro-topography, respectively. Generally speaking, the stronger the pipe (type-joint), the lower the C_p value and pipe damage rate; the larger the pipe diameter, the lower the C_d value and pipe damage rate.

The proposed values of C_p of various water pipe (joint) types were summarized in Table 1. They are either following the values by Miyajima or simply specified by the authors according to judgment.

Table 1. Correction factors of pipe type (joint) for pipe damage rate estimation.

Type of pipe (joint)	Correction factor C_p
DIP(K) – Ductile cast iron pipes of K-type joint	0.5
DIP(U) – Ductile cast iron pipes of U-type joint	
SP – Welded steel pipes	
WSP – Segmented steel pipes (installed by pipe jacking method)	
SP(F) – Segmented steel pipes with flange joint	1.0
CIP – Cast iron pipes	2.5
PSCP – Pre-stressed concrete pipes	
PCCP – Pre-stressed concrete cylinder pipes	
ACP – Asbestos pipes	7.5
RCP – Reinforced concrete pipes	

Therefore, given a pipe of specific type (joint) and diameter, its vulnerability V is quantified in this study as

$$V = \log_{10}\left(10 \cdot C_p\right) \cdot \left(\frac{800}{\phi}\right)^{0.125} \tag{10}$$

where ϕ is the pipe diameter (unit: mm). This functional form of V is very carefully specified such that, given the wide ranges of C_p and ϕ, the range of V is small but enough to distinguish the fragile pipes from the others. Whenever a pipeline evaluation unit consists of more than of pipes, its V value should be the summation of vulnerability of all member pipes weighted by their length ratio, or

$$V = \sum_k \frac{L_k}{L} \cdot V_k \tag{11}$$

where L and L_k are the total length of the pipeline evaluation unit and the length of the *k*th member pipe, respectively. Finally, the normalized vulnerability $\overline{V}$ of every pipeline evaluation unit is computes as

$$\overline{V} = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \tag{12}$$

which has a numeric range of $[0,1]$.

SEISMIC RISK AND ENHANCEMENT PRIORITIES OF PIPILINES

The hazards to a pipeline evaluation unit defined in Equations (2), (4), (6), and (9) have completely different physical meanings and numeric ranges. They have to be transformed into numbers which are normalized and addible. As the goal here is merely making a comparison among the "hazard," the sum of four quantified hazards, to each and every pipeline evaluation units, the numbers can be anything that provides information of high or low hazard potential. For that reason, the "order point" is employed in this study. For example, if the H_{GS} value of a specific pipeline evaluation unit is 67.3 cm/s, which is ranked the jth among all 1,687 units sorted from low to high, then the order point of its ground shaking hazard is $\overline{H}_{GS} = r(j/1687)$, where $r(\cdot)$ is the round-off operator. The other three values of quantified hazards can be transformed into the corresponding order points in the same way.

Finally, the "hazard" of a pipeline evaluation unit in terms of hazard order points is defined as

$$\overline{H} = 0.45 \cdot \overline{H}_{GS} + 0.45 \cdot \overline{H}_{LQF} + 0.08 \cdot \overline{H}_F + 0.02 \cdot \overline{H}_{LS} \tag{13}$$

which has a numeric range of $[0,1]$, too. The weighting numbers 0.45, 0.45, 0.08, and 0.02 are carefully chosen so as to keep balance of the contribution from different hazards.

Eventually, the risk of a pipeline evaluation unit is defined as

$$R = \left(1 + \overline{H}\right) \cdot \left(1 + \overline{V}\right) \tag{14}$$

which has a numeric range of $[1,4]$. The higher the risk of a pipeline evaluation unit is, the higher the seismic hazard potential it is exposed to, or the more vulnerable it is seismically.

According to the value of risk, all pipeline evaluation units could be ranked from high to low, and evenly divided into ten "risk groups" from R1 to R10. Combining with the pipelines' importance classified earlier, a risk-importance matrix can be achieved as summarized in Table 2. It can help decide that, among all, which pipeline evaluation units should be enhanced first.

In order to assure an effective and financially feasible seismic enhancement of large water pipes, a prioritized implementation is preferred. From the risk-importance matrix, three priorities could be suggested, as specified in Table 3. Each priority consists of two elements from the matrix. For example, the first priority consists of 82 units, of which 29 are from the combination of (Very high, R1), while the other 53 are from (Very high, R2). A total of 232 pipeline evaluation units are suggested to TWC for seismic enhancement in the future.

Table 2. The numbers of pipeline evaluation units distributed in the risk-importance matrix.

Risk group	Very high	High	Normal	Low	Sum
R1	29	51	38	51	169
R2	53	33	40	43	169
R3	46	38	34	51	169
R4	20	56	28	65	169
R5	34	55	30	50	169
R6	18	45	47	59	169
R7	22	35	57	55	169
R8	24	34	44	67	169
R9	41	27	31	70	169
R10	6	48	26	86	166
Total	293	422	375	597	1687

Table 3. The number and priority of pipeline evaluation units suggested for seismic enhancement.

Priority	Order	Combination of (Importance, Risk group)	No. of evaluation units
First	1	(Very high, R1)	29
	2	(Very high, R2)	53
Second	3	(High, R1)	51
	4	(Very high, R3)	46
Third	5	(High, R2)	33
	6	(Very high, R4)	20

In reality, the suggested 232 pipeline evaluation units are not evenly distributed. The units located in Taichung (74) and Kaohsiung (65 in total), as illustrated in Figures 4 and 5, respectively, outnumber those in other areas in Taiwan. Both are vast and densely populated areas relying on water supply from limited water treatment plants. Particularly, Taichung area is of high potential in ground shaking and fault rupture hazards due to the existence of many active faults in the neighborhood.

CONCLUDING REMARKS

Water pipelines of high importance and at high seismic risk have been screened out. They were grouped into three priorities ready for TWC to implement seismic improvement program in the near future. Major assumptions behind the analysis include: (1) the hazard and vulnerability of a pipeline are independent on each other, and (2) the existing or developed seismic hazard maps of ground shaking, soil liquefaction, active faults and landslide are reliable and with enough resolution. At the present stage of preliminary screening, they seem fine. Nevertheless, TWC should adopt field-investigated hazard and more rigorous hazard-vulnerability analysis in the next stage of pipeline seismic assessment and enhancement.

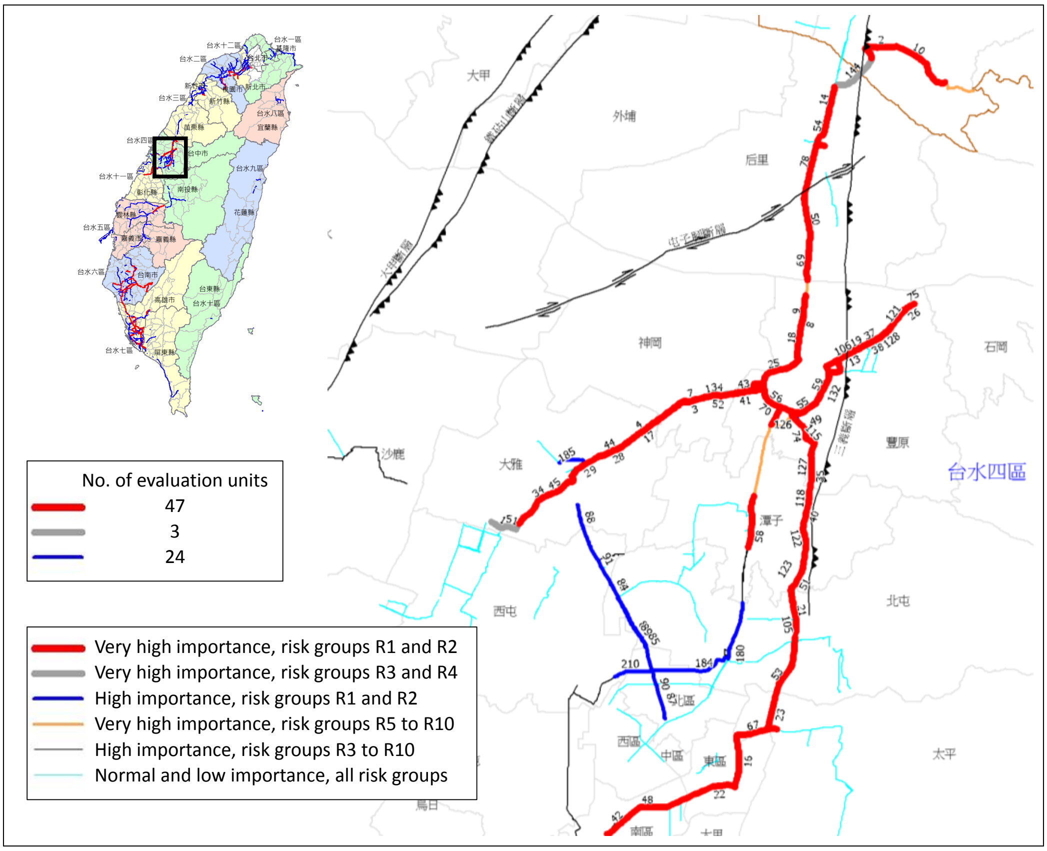

Figure 4. The suggested pipeline evaluation units in Taichung for seismic enhancement.

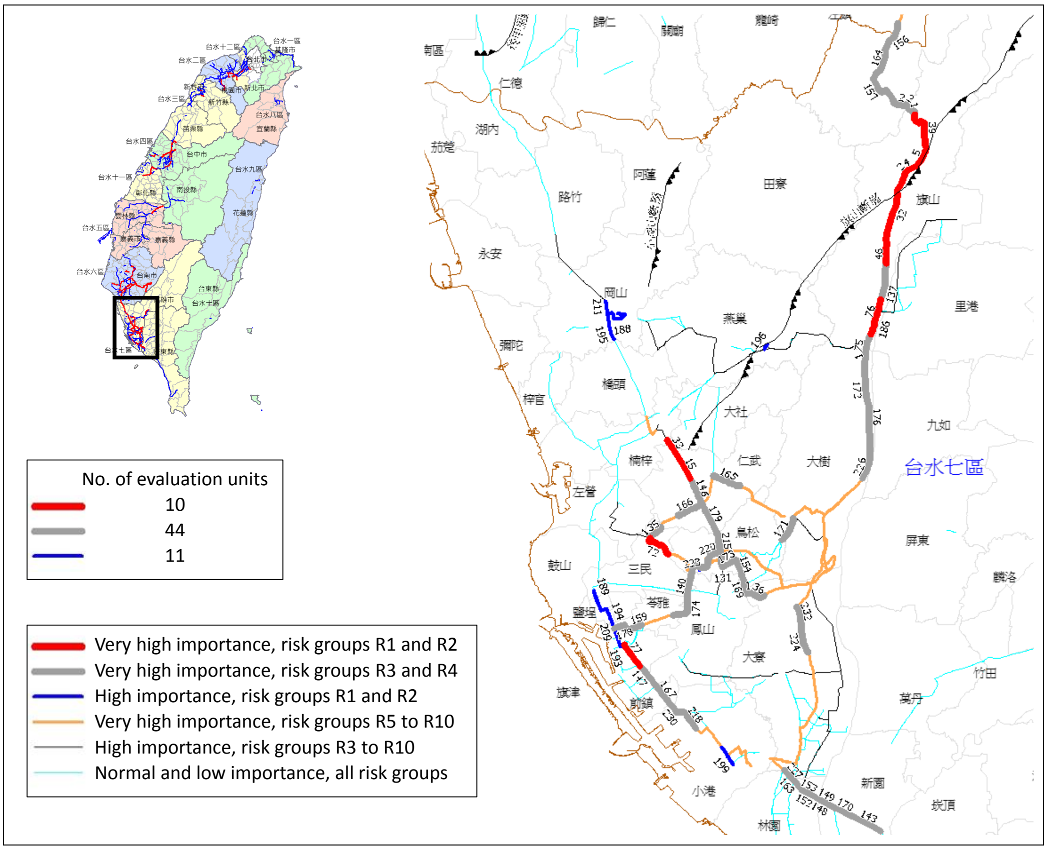

Figure 5. The suggested pipeline evaluation units in Kaohsiung for seismic enhancement.

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