Seismic Evaluation and Retrofit of Existing Water Pipe Bridges in Taipei

Wei-Hsiang Lee, Kuan-Hua Lien , Po-Ming Cheng and Chii-Jang Yeh

ABSTRACT

Taipei is the capital city of Taiwan and its population is more than 2.7 millions, so water supply system is especially important. Moreover, the four existing water pipe bridges managed by Taipei Water Department play a pivotal role in the water supply system. The four existing water pipe bridges were designed according to the old version of the seismic code. If the existing water pipe bridges are damaged during the earthquake and unable to supply the water. It will bring people's livelihood problem; enlarge secondary disasters and delay post-earthquake reconstruction. Therefore, this paper presents the seismic assessment of Yuanshan, Yongfu, Hsintien arch water pipe bridges and Jiantan cable-stayed water pipe bridge. The seismic performance criteria follow Draft of the Taiwan Bridge Performance-Based Seismic Design and Water Facilities Seismic Design Guide and Commentary to examine the seismic capacity of existing water pipe bridges and check whether the corresponding retrofits are necessary or not. The static nonlinear pushover analysis is carried out using SAP2000 to capture the overall seismic capacity of existing water pipe bridges, respectively. The nonlinear time history analysis is also carried out using SAP2000 to obtain the member force and displacement of superstructures for the existing water pipe bridges. According to the analysis results, Yuanshan, Hsintien and Jiantan water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria but the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility. The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme. The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme.

Keyword: Existing Water Pipe Bridge, Seismic Evaluation, Seismic Retrofit, Static nonlinear pushover analysis, nonlinear time history analysis

Wei-Hsiang Lee, Structural Engineer, Structural Engineering Department, Sinotech Engineering Consultants, 11th Fl. 171, Nanking East Road, Section 5, Taipei 10570,Taiwan.
Kuan-Hua Lien, Structural Engineer, Structural Engineering Department, Sinotech Engineering Consultants, 11th Fl. 171, Nanking East Road, Section 5, Taipei 10570,Taiwan.
Po-Ming Cheng, Structural P.E., Technical Manager, Structural Engineering Department, Sinotech Engineering Consultants, 11th Fl. 171, Nanking East Road, Section 5, Taipei 10570,Taiwan.
Chii-Jang Yeh, Project Manager, Structural Engineering Department, Sinotech Engineering Consultants, 11th Fl. 171, Nanking East Road, Section 5, Taipei 10570,Taiwan.

INTRODUCTION

Chichi Earthquake on September 21, 1999, caused severe property losses and casualties to central Taiwan. Since earthquakes are unpredictable, they often cause more severe disasters if they are not treated carefully. Taipei is the capital city of Taiwan and its population is more than 2.7 millions, so water supply system is especially important. Moreover, the four existing water pipe bridges managed by Taipei Water Department play a pivotal role in the water supply system. The four existing water pipe bridges were designed according to the old version of the seismic code. If the existing water pipe bridges are damaged during the earthquake and unable to supply the water. It will bring people's livelihood problem; enlarge secondary disasters and delay post-earthquake reconstruction. Therefore, Taipei Water department took preventive measures to review and evaluate the four existing water pipe bridges. In this paper, Yuanshan, Yongfu, Hsintien arch water pipe bridges and Jiantan cable-stayed water pipe bridge are used as an example to illustrate the seismic assessment and retrofit of existing water pipe bridge.

STRUCTURE DESCRIPTION OF EXISTING WATER PIPE BRIDGES

The four existing water pipe bridges are shown in Figure 1. Yuanshan water pipe bridge is single-span simply supported arch steel bridge having the total length of 100.6 m. It is supported and transversely connected on abutments. The abutments are supported on pile foundations, respectively. The pipe diameter is 2000mm. Yongfu water pipe bridge is multi-span simply supported arch steel bridge having the total length of 360 m with 3 equal spans of 80 m length. It is support on four-column bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2400mm. Hsintien water pipe bridge is multi-span simply supported arch steel bridge having the total length of 290 m with 3 equal spans of 80 m length. It is support on single pier type bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2400mm. Jiantan water pipe bridge is multi-span simply supported cable-stayed steel bridge having the total length of 140 m with main span of 72 m length. It is support on single pier type bents, which are transversely connected by the bent cap. The bridge piers and abutments are supported on pile foundations. The pipe diameter is 2000mm.

Yuanshan arch water pipe bridge

Yongfu arch water pipe bridge

Hsintien arch water pipe bridge

Jiantan cable-stayed water pipe bridge

Figure 1. Four existing water pipe bridges

SEISMIC RETROFT PERFORMANCE CRITERIA OF WATER PIPE BRIDGE

As the seismic retrofit standard of the existing water pipe bridge should be another 50-year service life, and based on Seismic Retrofitting Manual for Highway Bridges[1], Draft of the Taiwan Bridge Performance-Based Seismic Design [2] and Water Facilities Seismic Design Guide and Commentary [3], the seismic performance criteria for water pipe bridge worked out are shown in TABLE I.

TABLE I. SEISMIC RETROFT PERFORMANCE CRITERIA OF WATER PIPE BRIDGE

Earthquake level	Horizontal acceleration coefficient		Seismic restraint concept	Service performance	Damage grade
Moderate earthquake	Divided by administrative region		Structure keeps elastic	Normal water supply after earthquake	Slight
	1/3.25 of earthquake of 475-year return period				
Design earthquake (I=1.2) Return period:975years 50-year exceeding probability:5%	Divided by administrative region		Component has plastic hinge, exerting admissible toughness capacity	Limited water supply after earthquake	Repairable
	S_S^D	0.72			
	S_1^D	1.60、1.30、1.05			

The seismic performance requirements for water pipe bridges in terms of performance PL3 and PL1(2), respectively, according to bridge safety, bridge serviceability and bridge reparability were described in TABLE II. The performance object is shown TABLE III. The allowable displacements as a fraction of the displacement capacity are provided in TABLE IV, so that to identify and distinguish the acceptance point 3 and 1 as shown in Figure 2. Therefore, the structural capacity is predetermined by using static nonlinear pushover analysis, and the goal is to verify the water pipe bridge behavior at multiple performance points.

TABLE II. SEISMIC PERFORMANCE OF WATER PIPE BRIDGE

Performance level	Safety		Serviceability	Reparability	
	structure	foundation		Short period	Long period
PL3	Structure remains elastic and no unseating	elastic	As same as prior to the earthquake	none	
PL1(2)	limited damages and no unseating	elastic	Normal water supply	Partially repair or replace damaged member	

TABLE III. SEISMIC PERFORMANCE MATRIX

Seismic hazard	Performance level
Moderate earthquake	PL3
Design earthquake (I=1.2)	PL1(2)

TABLE IV. ALLOWABLE DISPLACEMENT OF THE DISPLACEMENT CAPACITY

Performance state	Taipei Basin
PL3	0
PL1(2)	1/2(1/4)

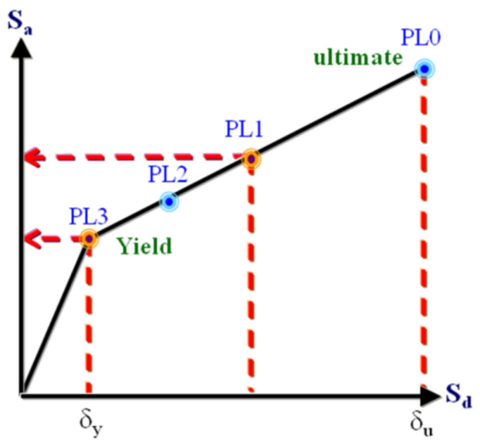


Figure 2. Seismic object and verification at Taipei Basin

EVALUATION OF THE SEISMIC CAPACITY

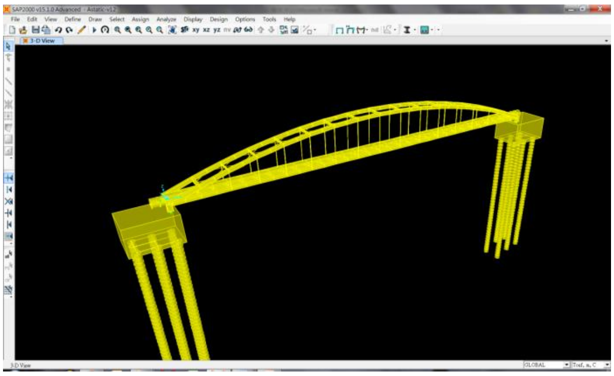
There are two detailed evaluation methods for bridge seismic capacity: (1) static nonlinear pushover analysis, (2) nonlinear time history analysis.

The pushover analysis analyzes the force-deformation behavior when the whole bridge collapses under increasing lateral force, so it lays emphasis on capacity of pier and foundation for the existing water pipe bridges. The time history analysis lays emphasis on capacity of superstructure. The method can master the key points in component reinforcement clearly, the member force and displacement of superstructures for the existing water pipe bridges can be evaluated b using this method.

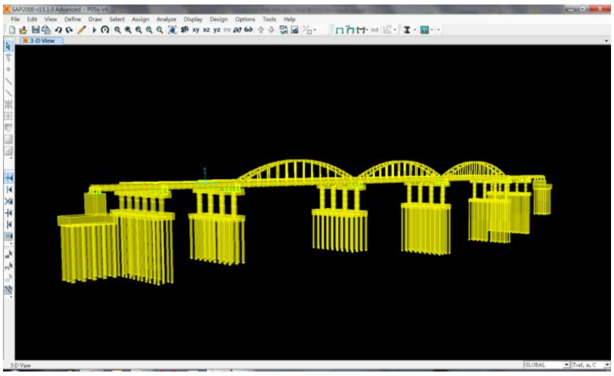
Numerical Modeling

The four three dimensional finite element model of existing water pipe bridges were created using Structural Analysis and Program software SAP2000 as shown in Figure 3, respectively. The structural model includes the complete foundation which considers the nonlinear force-displacement characteristics of foundations as well as the soil stiffness. The pier cap and the piers were modeled as beam-column elements and the hinge properties were assigned to each end of the column.

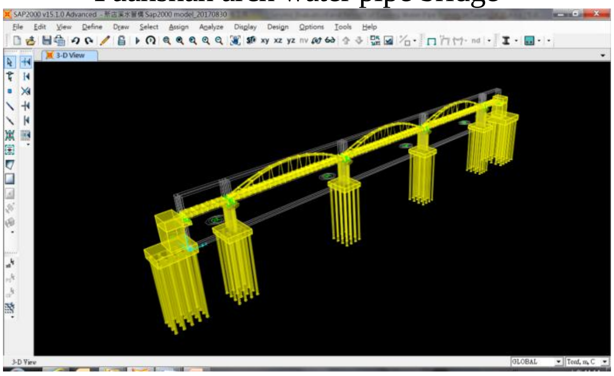
The eigenvalue analysis was carried out as the first step to obtain the mode shapes and frequencies of the bridges as shown in Figure4, respectively. In the next step, static nonlinear pushover analysis and nonlinear time history analysis were performed to capture the seismic capacity of the existing water pipe bridges.



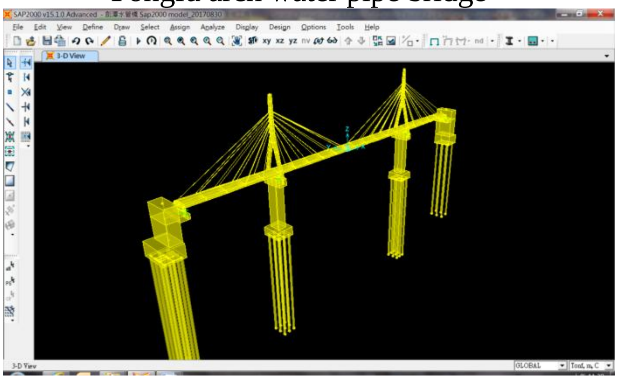
Yuanshan arch water pipe bridge



Yongfu arch water pipe bridge

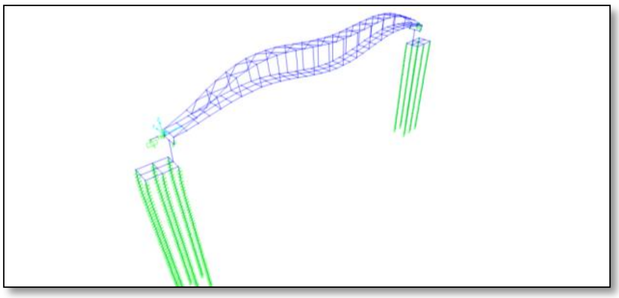


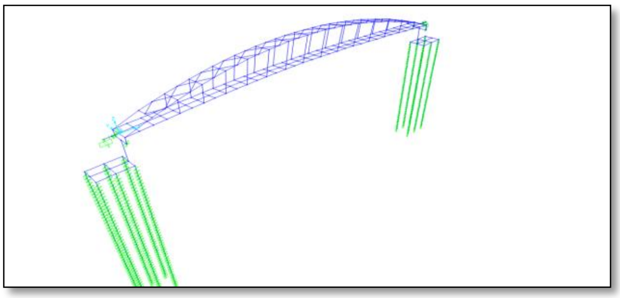
Hsintien arch water pipe bridge



Jiantan cable-stayed water pipe bridge

Figure 3. 3D analysis Model of existing water pipe bridges in SAP2000

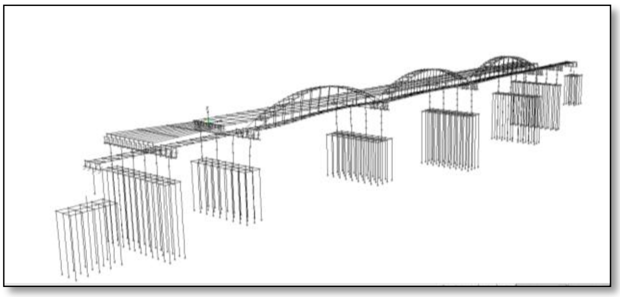


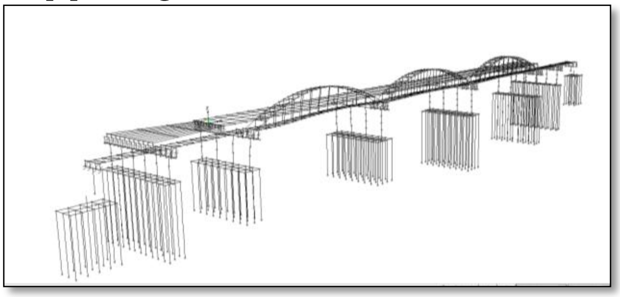


First mode in longtitudinal direction,
Period=0.27 sec

Mode 1 in transverse directon,
Period=2.07 sec

Yuanshan arch water pipe bridge

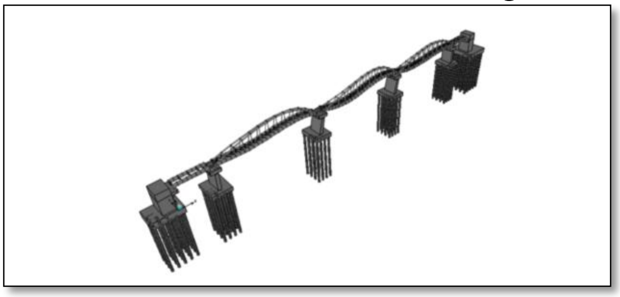


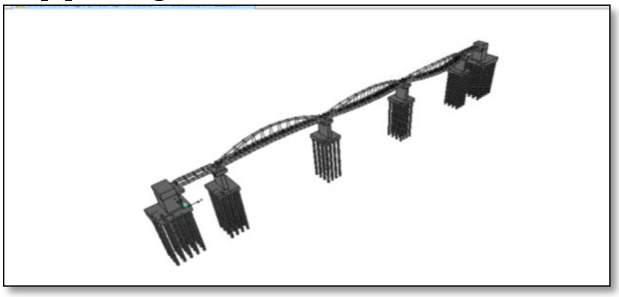


First mode in longtitudinal direction,
Period=0.76 sec

Mode 1 in transverse directon,
Period=0.74 sec

Yongfu arch water pipe bridge

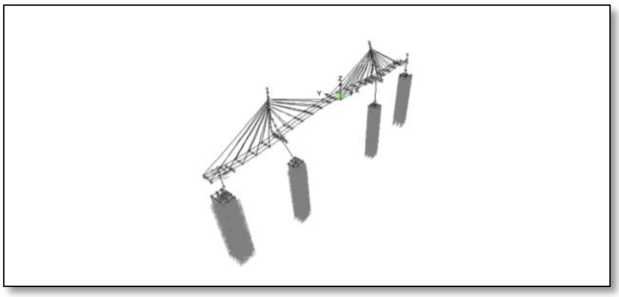


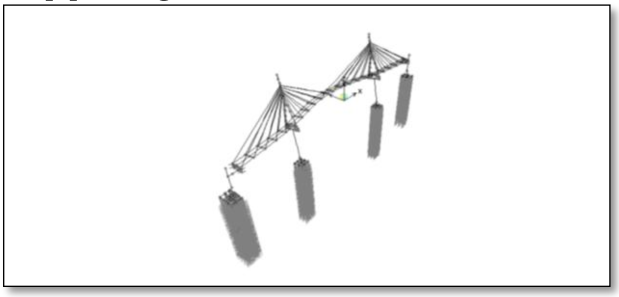


First mode in longtitudinal direction,
Period=0.804 sec

Mode 1 in transverse directon,
Period=0.843 sec

Hsintien arch water pipe bridge





First mode in longtitudinal direction,
Period=1.365 sec

Mode 1 in transverse directon,
Period=1.115 sec

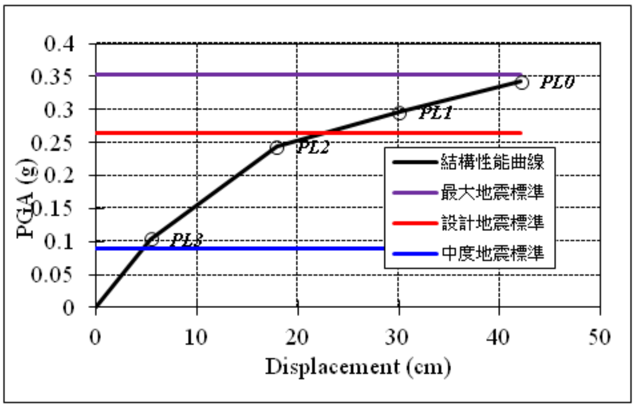
Jiantan cable-stayed water pipe bridge

Figure 4. Mode shapes and frequencies of existing water pipe bridges in the longitudinal direction

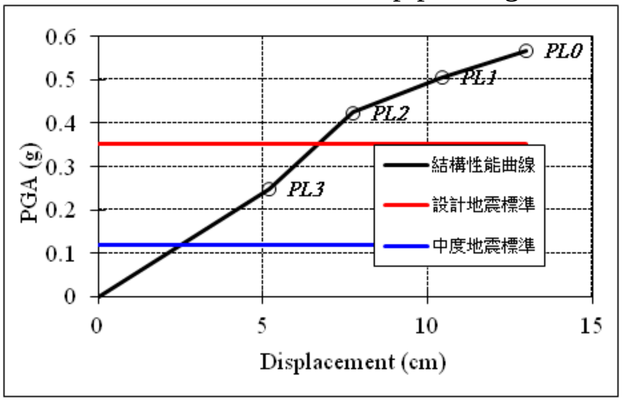
Pushover Analysis Results

The static nonlinear pushover analysis was conducted for existing water pipe bridges, respectively. According to the pushover curve, the ground acceleration corresponding to existing water pipe bridges in different seismic points (see Figure 2) are obtained. The design ground acceleration corresponding to the existing water pipe bridges within the expected service life are obtained in concept of damage evaluation. Based on the seismic capacity of existing water pipe bridges are evaluated and listed in TABLE V. The performance curve of existing water pipe bridges in the longitudinal direction are shown in Figure 5, respectively. According to the analysis results (TABLE V), Jiantan, Yongfu(retrofitted by steel jacket) Hsintien water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria, respectively.

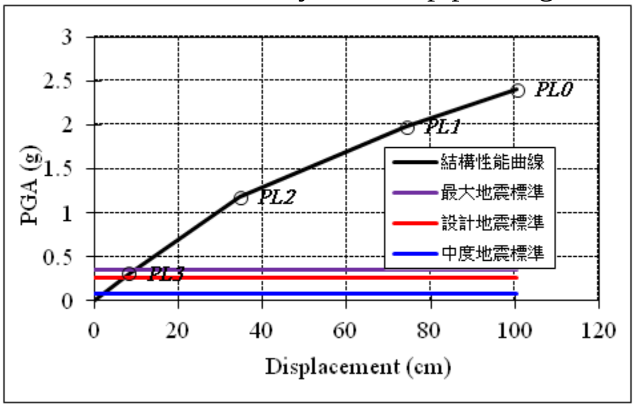
Yuanshan arch water pipe bridge



Jiantan cable-stayed water pipe bridge



Yongfu arch water pipe bridge



Hsintien arch water pipe bridge

Figure 5. Mode shapes and frequencies of existing water pipe bridges in the longitudinal direction

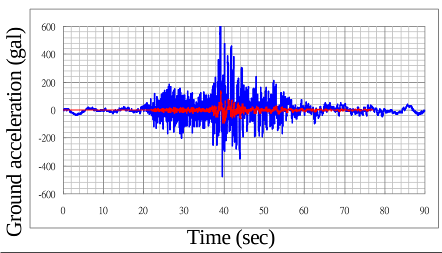
TABLE V. SEISMIC CAPACTITY OF EXISTING WATER PIPE BRIDGES (LONGITUDINAL DIRECTION)

Bridge	Performance objective		Performance capacity	
	Earthquake level	Ground acceleration (g)	Performance level	Ground acceleration (g)
Yuanshan (single-span)	Moderate earthquake	-	-	-
	Design earthquake	-	-	-
Jiantan	Moderate earthquake	0.07	PL3	0.104
	Design earthquake	0.24	PL1	0.296
Yongfu(retrofitted by steel jacket)	Moderate earthquake	0.07	PL3	0.25
	Design earthquake	0.24	PL1	0.50
Hsintien	Moderate earthquake	0.07	PL3	0.31
	Design earthquake	0.24	PL2	1.18

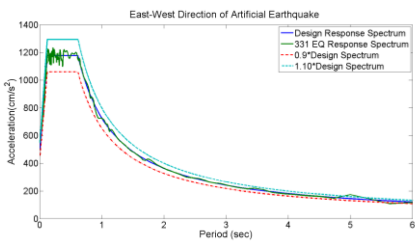
Time History Analysis Results

The four earthquakes are selected based on two parameters; the closest distance to site and the moment magnitude. Based on the four earthquakes, most of the artificial time histories are generated from the design response spectra, respectively, as shown in Figure 6 (left). The response spectra of the original and artificial acceleration in comparison with the design spectrum are shown in Figure 6 (right).

Nonlinear time history analyses with artificial time histories were performed using SAP2000 to capture the overall dynamic response of the existing water pipe bridges, respectively. The relative displacements between superstructure and the abutment are smaller than the flexible capacity of pipe expansion joint for the four water pipe bridges, respectively , as shown in TABLE VI. The bearings of existing water pipe bridges fail to meet the seismic performance criteria.



(a) Original vs. Artificial ground motion



(b) Artificial response spectrum

Figure 6. Artificial ground acceleration time history

TABLE VI. DISPLACEMENT CAPACTITY OF EXISTING WATER PIPE BRIDGES

Bridge	Earthquake station/record	Axial displacement (Demand/Capacity)	Bridge	Earthquake station/record	Axial displacement (Demand/Capacity)
Yuanshan	TAP007/0206	1.45/± 20 cm	Hsintien	TAP033/0331	3.5 /± 8.8 cm
	TAP008/0331	2.03/± 20 cm		TAP053/0401	5.8 /± 8.8 cm
	TAP013/0921	2.11/± 20 cm		TAP034/0921	4.6 /± 8.8 cm
Yongfu	TAP029/0206	22.0/± 24.3 cm	Jiantan	TAP007/0206	11.8/± 24.8 cm
	TAP028/0331	23.8/± 24.3 cm		TAP008/0331	23.4/± 24.8 cm
	TAP028/0921	21.2/± 24.3 cm		TAP006/0921	15.8/± 24.8 cm

SEISMIC RETROFIT STRTEGY

According to the seismic evaluation results of the existing water pipe bridges, the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility, as shown in Figure 7.

Figure 7. The piers of Yongfu water pipe bridge with steel jacket

The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme as shown in Figure 8.

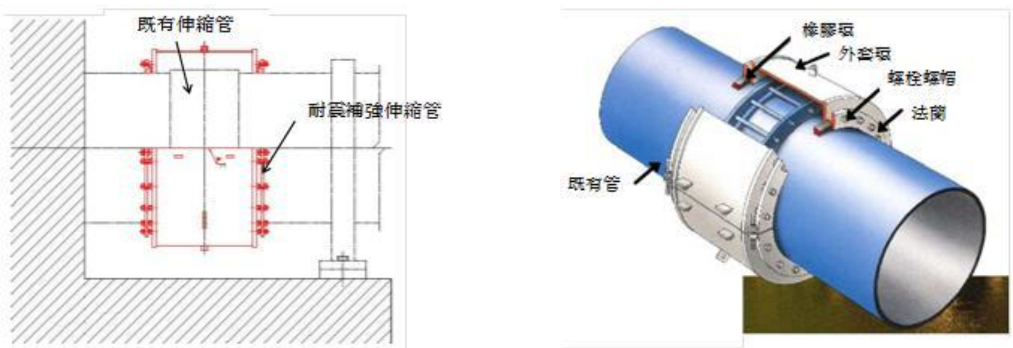


Figure 8. Outer flexible expansion joint

The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme as shown in Figure 9.

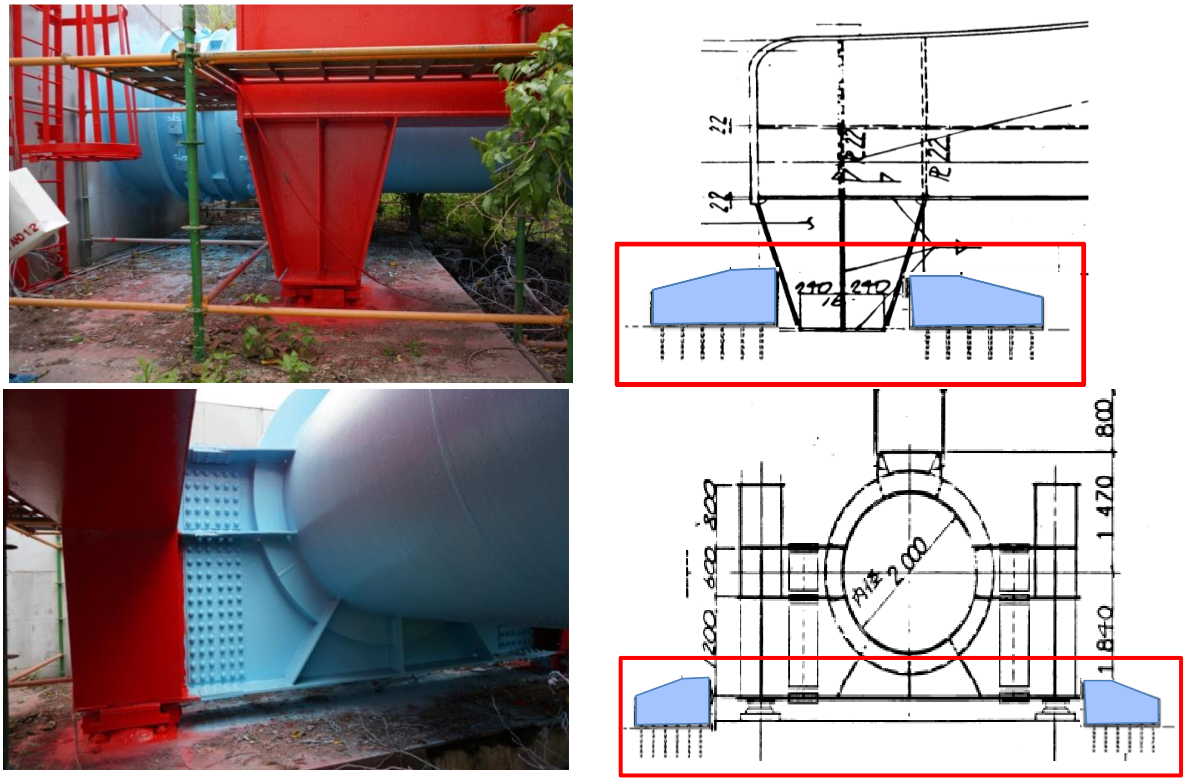


Figure 9. The bearings of existing water pipe bridge with steel anti-shock devices

CONCLUSON

Following conclusion are drawn from the present general review of seismic evaluation for the four existing water pipe bridges managed by Taipei Water Department using static nonlinear pushover analysis and nonlinear time history analysis.

- **Pushover Analysis Results:** Yuanshan, Hsintien and Jiantan water pipe bridges have enough seismic capacity to satisfy the seismic performance criteria but the seismic capacity of Yongfu water pipe bridge in longitudinal direction fails to meet the seismic performance criteria. The piers of Yongfu water pipe bridge had been retrofitted by steel jacket for insufficiency of ductility.
- **Time History Analysis Results:** The relative displacements between superstructure and the abutment are larger than the flexible capacity of pipe expansion joint for the Yongfu and Jiantan water pipe bridges, respectively. There are two retrofit options are considered. One is the replacement pipe expansion joint scheme, the other is the additional Outer flexible expansion joint scheme. The bearings of existing water pipe bridges fail to meet the seismic performance criteria, therefore there are two retrofit options are considered. One is the replacement bearings scheme, the other is the additional RC or steel anti-shock devices scheme.

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REFERENCES

[1] Chang, K. C., Tsai, I. C., Chang, D. W., Sung, Y. C., Liao, J. F., Chai, J. F., Liu, K. Y., Hung, H. H., Wu, H. M., Qi, S. R., and Chen, Y. H., 2009. *Seismic Assessment and Retrofit Manual for Highway Bridges.* Rport No. NCREE-09-028, NCREE, Taipei. (In Chinese)

[2] Taiwan Area National Expressway Engineering Bureau, MOTC., 2012. *Draft of the Taiwan Bridge Performance-Based Seismic Design.* Rport No. 173, Taiwan Area National Expressway Engineering Bureau, MOTC., Taipei. (In Chinese)

[3] Chinese Taiwan Water Works Association, 2013. *Water Facilities Seismic Design Guide and Commentary.* Rport, Chinese Taiwan Water Works Association, Taipei. (In Chinese)