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Bridge Improvement and Foundation Protection Method for Wu-Xi Bridge

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Abstract: The Wu-Xi Bridge, located on Provincial Highway No. 63 and spanning the Wu-Xi between Taichung City and Nantou County, has experienced significant structural challenges due to severe scouring and floodplain migration following typhoon-induced flooding after 2002. In particular, the caisson foundations of Piers P42 to P47 have become critically exposed, with depths reaching up to 8 meters—posing substantial risks to the bridge's structural integrity. To address these issues, the Directorate General of Highways initiated a comprehensive improvement project that includes geological investigation, structural assessment, and pier reconstruction. The project involves replacing the vulnerable caisson foundations with full-casing pile foundations to enhance flood resilience and seismic performance. Empirical scour analysis, hydrological assessments, and structural evaluations under both normal and seismic conditions confirm that the new design significantly improves safety margins, with all key safety factors exceeding required thresholds. This project ensures the long-term durability and safety of the Wu-Xi Bridge as a critical transportation corridor and sets a precedent for future infrastructure adaptation in riverine environments.

1 Commentary

1-1 Origin of the plan

Provincial Highway No. 63 begins at the intersection of Zhongming South Road and Provincial Highway No. 3 in the South District of Taichung City, and extends southward to Provincial Highway No. 14B in Caotun Township, Nantou County, with a total length of 18.980 kilometers. Since its completion and opening to traffic in January 1998, it has served as a major transportation corridor connecting Taichung City and Nantou County. The location of the project bridge Wu-Xi Bridge is shown in Figure 1.1-1.

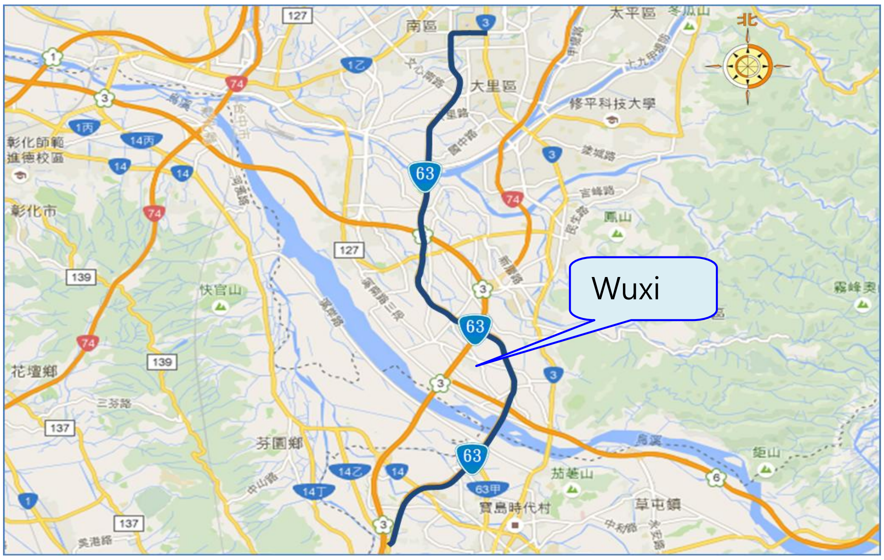

Figure 1-1-1 Project location

Prior to 2002, the river channel of the Wu-Xi at the project bridge site was approximately divided by Pier P41, with the northern side consisting of a deep river channel and the southern side comprising high floodplains. After 2002, due to extreme typhoon-induced flooding and subsequent scouring, the floodplain gradually retreated southward to the vicinity of Pier P47. This resulted in severe exposure of the caisson foundations of the bridge piers originally located in the floodplain area (P42–P46), as illustrated in Figure 1-1-3. The maximum exposure depth reached approximately 8 meters, accounting for half the total caisson depth.

Beginning in 2013, foundation protection works for the Wu-Xi Bridge were successively carried out. To fundamentally enhance the bridge’s resilience against flood-induced scouring and ensure that the foundations can independently resist fluvial erosion—thereby safeguarding both the structure and its users—the bridge was classified as a Level-1 Priority Monitoring Bridge by the competent authority in 2015. In response, the “Bridge Improvement Project for Wu-Xi Bridge (P41–P47) on Provincial Highway No. 63” was initiated.

To comprehensively enhance the bridge’s flood resistance and foundation stability, the Second Maintenance and Construction Office of the Directorate General of Highways, MOTC (hereinafter referred to as "the Office") publicly invited qualified consulting firms to undertake the “Survey, Design, Geological Investigation, and Environmental Compliance Services for the Bridge Improvement Project of Wu-Xi Bridge (P41–P47) on Provincial Highway No. 63.”

The scope of services includes design, geological investigation, and preparation of the environmental content change comparison table. Through the implementation of these services, the Office aims to ensure that the project is completed on schedule, with the required quality, and within the designated budget and scope.

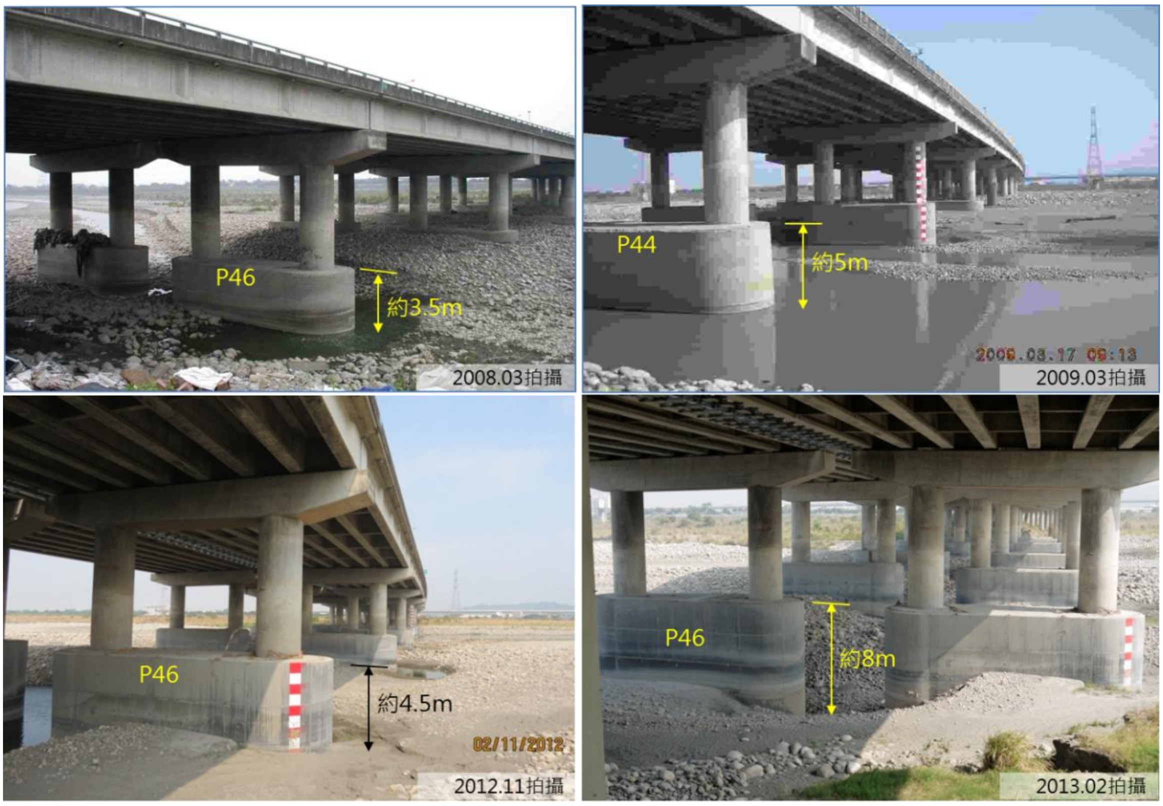

Figure 1-1-3 P42~P46 Bridge pier exposed

1-2 Location and scope of the plan

The project bridge is located along Provincial Highway No. 63, between KM 13K+806M and 14K+879M, spanning the Wu-Xi and connecting Wufeng District, Taichung City and Caotun Township, Nantou County. This bridge not only serves as a critical inter-county crossing over the Wu-Xi, but also provides a direct connection from Provincial Highway No. 63 to National Freeway No. 3. The project location is shown in Figure 1-2-1.

Figure 1-2-1 Schematic diagram of the scope of the project

2 The Current Situation of the Corridor

2-1 Geographical Location and Topographical Conditions

This bridge is part of the Zhongtou Highway – Wuquan South Road Extension Project in Taichung City, Contract Section CT010, originally commissioned by the former Housing and Urban Development Bureau of the Taiwan Provincial Government, and was completed in January 1998. It now functions as the Wu-Xi Bridge on Provincial Highway No. 63. The total bridge length is 1,073 meters, of which 997 meters (Piers P31 to P56) are located within the Wu-Xi channel.

The bridge is a pre stressed I-girder bridge. The pier foundations within the river channel adopt caisson foundations, while the foundations within the levee area use spread footing design. The caisson depth is 18 meters for Piers P31 to P50, and 16 meters for Piers P51 to P56. The bridge deck consists of two separate structures, each accommodating northbound and southbound traffic, with a total width of 20 meters per structure, configured with three traffic lanes and one motorcycle lane, as illustrated in Figure 2-1-1.

Figure 2-1-2 shows the current exposure condition of the pier foundations following the completion of protection works this year. Specifically, Piers P42 to P45 have caisson foundations currently exposed by 4 meters, Piers P46 to P47 by 2 meters, and Pier P31 by 1 meter. All other pier foundations remain covered. A review of the as-built drawings indicates that the foundation depths of piers within the river channel vary, and the elevation at which the caissons were installed also differs depending on local topography. A summary of the foundation exposure conditions for river channel piers is presented in Table 2-1-1.

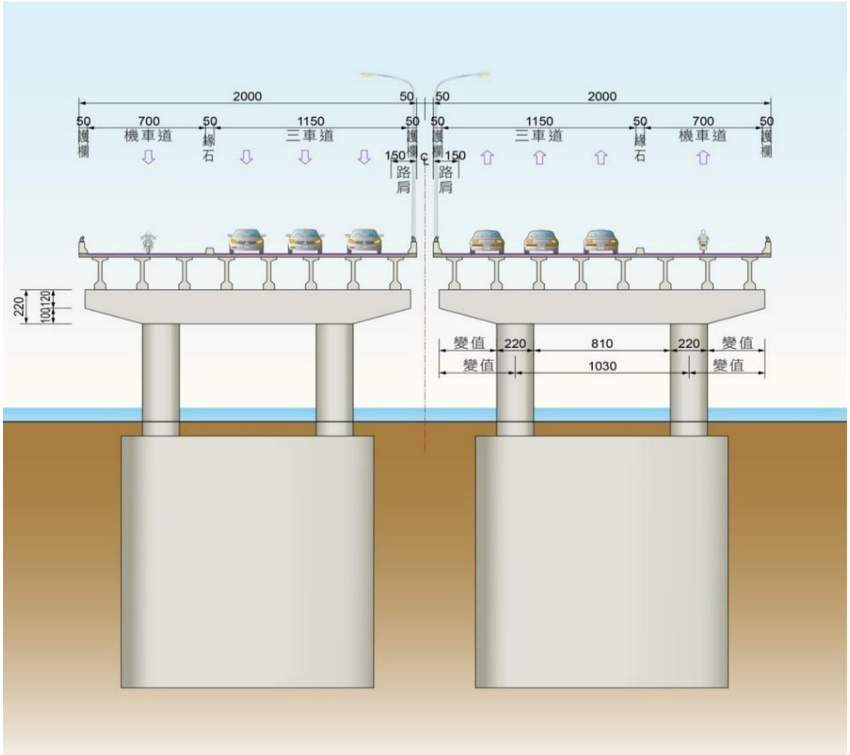

Figure 2-1-1 Elevation of the bridge

Table 2-1-1 Relationship between bridge pier foundation and existing riverbed

Bridge pier number	P31~ P32	P33~ P38	P39~ P41	P42~ P45	P46~ P47	P48~ P50	P51~ P56
CAISSON DEPTH L(M)	18	18	18	16	16	16	16
Caisson top elevation(E.L.)	78	78	76	80	80	80	80
Current River Bed Elevation (E.L.)	77	80	76.0	76.0	78.0	83.0	83.0
Existing pier foundation depth (M)	17	18	18	12	14	16	16
Exposed length of pier foundation (M)	1	0	0	4	2	0	0

2-2 Regional environment

2-2-1 River data

The project bridge is located in the midstream section of the Wu-Xi, approximately at cross section No. 53 of the river. Relevant planning documents are summarized in Table 2-2-1. The bridge was completed in 1998 and was affected by the 921 Chi-Chi Earthquake in 1999. According to the “Post-Disaster Review of the Rehabilitation Plan for the Wu-Xi System Following the 921 Earthquake” (November 2000), the bridge site at cross section 53 was inspected and found to be within acceptable accuracy limits.

Based on the “Wu-Xi System Master Plan” (including the main stream and tributaries Fazih River and Mei River), published by the former Taiwan Provincial Water Resources Bureau in March 1991, the design discharge at the bridge location is specified as Q_{100} = 11,000 CMS (100-year return period), as shown in Figure 2-2-1. The design riverbed elevation is E.L. 78.68, the design flood level is E.L. 84.07, and the design levee crest elevation is E.L. 85.57.

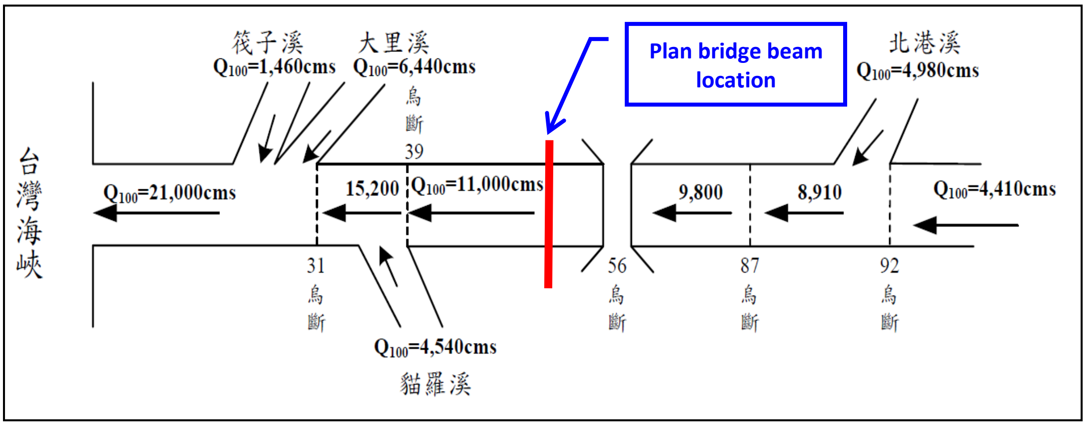

Figure 2-2-1 Flow distribution of the Wuxi Project

According to the survey results from the “2013 Survey Report on Major Cross Sections of the Wu-Xi, Mei River, Nangang River, and Beigang River” published by the Water Resources Agency, the current girder soffit elevation at the project bridge site is E.L. 89.45, which is higher than the design levee crest elevation of E.L. 85.57 for the Wu-Xi.

Levee systems currently exist on both banks of the bridge site, namely the Wufeng Levee on the left bank and the Fenyuan Levee on the right bank. Based on overlay mapping of levee boundaries and river cadastral data (Figure 2-2-2), the design river width at the bridge location is 980 meters, while the total length of the existing bridge is 1,073 meters, indicating that the structure meets or exceeds the required design parameters.

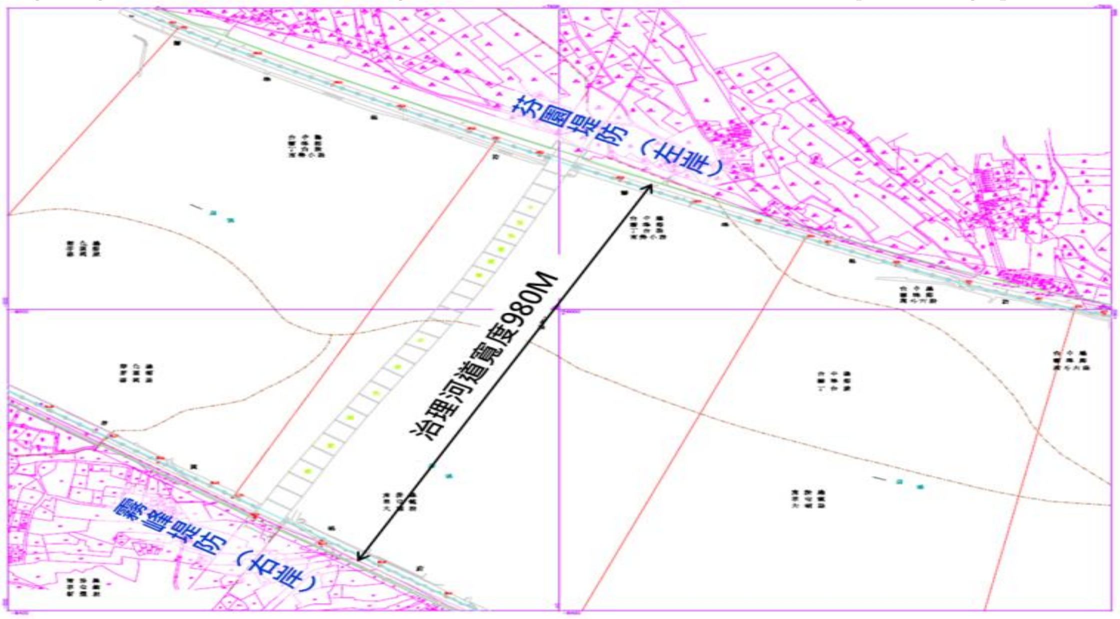

Figure 2-2-2 Flow distribution of Wuxi plan

Table 2-2-1 Summary of Relevant River Data for the Project Bridge

Relevant river information		Does it include a review of the project bridge
1991年3月	"Basic Plan for the Treatment of the Water System of Wuxi River (Main River and its tributaries Raft Creek and Meixi)"	not
2000年11月	"Review of the Post-Disaster Management Plan of the Wuxi River System after the 921 Earthquake"	not
February 2003	Integrated Management and Comprehensive Remediation Plan for the Wu-Xi Basin	not

December 2005	Research Findings on Riverbed Stability and Management Strategies for the Mainstream of the Wu-Xi	be
In 2013	2013 Survey Report on Major Cross Sections of the Wu-Xi, Mei River, Nangang River, and Beigang River	是

2-2-2 Hydrological data

The bridge site is located in the midstream section of the Wu-Xi. Investigation shows that the upstream catchment area includes the Beigang River, Nangang River, and Mei River. The main rainfall stations within the watershed are Liufenliao, Caotun, Qingliu, Cuiluan, and Beishan, as shown in Figure 2-2-3.

Based on recent rainfall records from these stations, the average annual precipitation across the entire watershed is approximately 2,000 mm. Among the stations, Cuiluan, Qingliu, and Beishan record relatively higher rainfall amounts. Therefore, it is recommended that rainfall monitoring during future construction activities focus primarily on these three stations (Figure 2-2-4) in order to effectively assess runoff and flow conditions within the watershed.

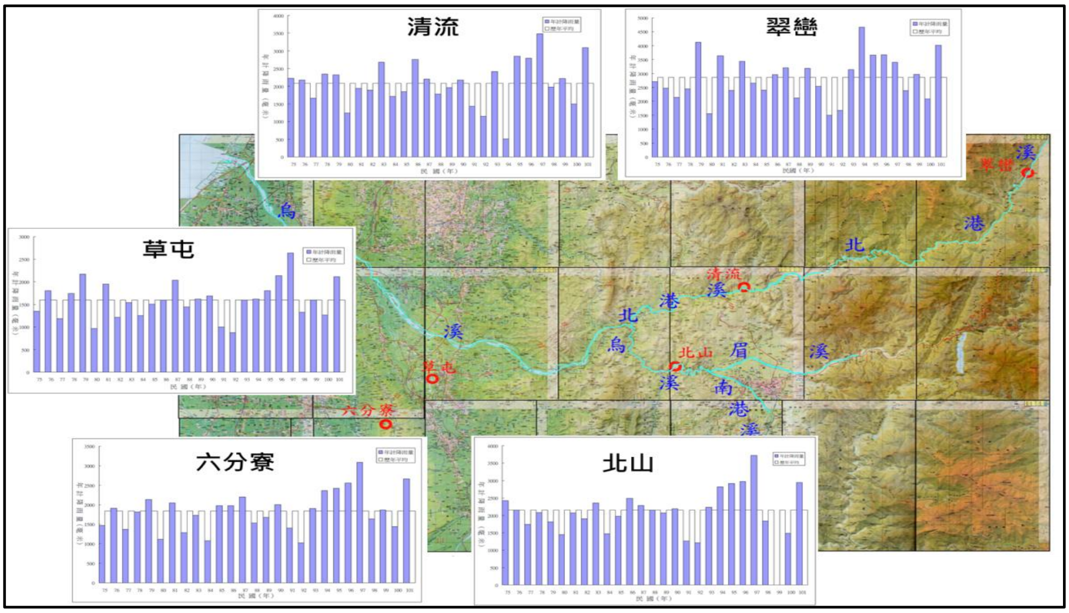

Figure 2-2-3 Locations of major rainfall gauge stations in Wuxi catchment area

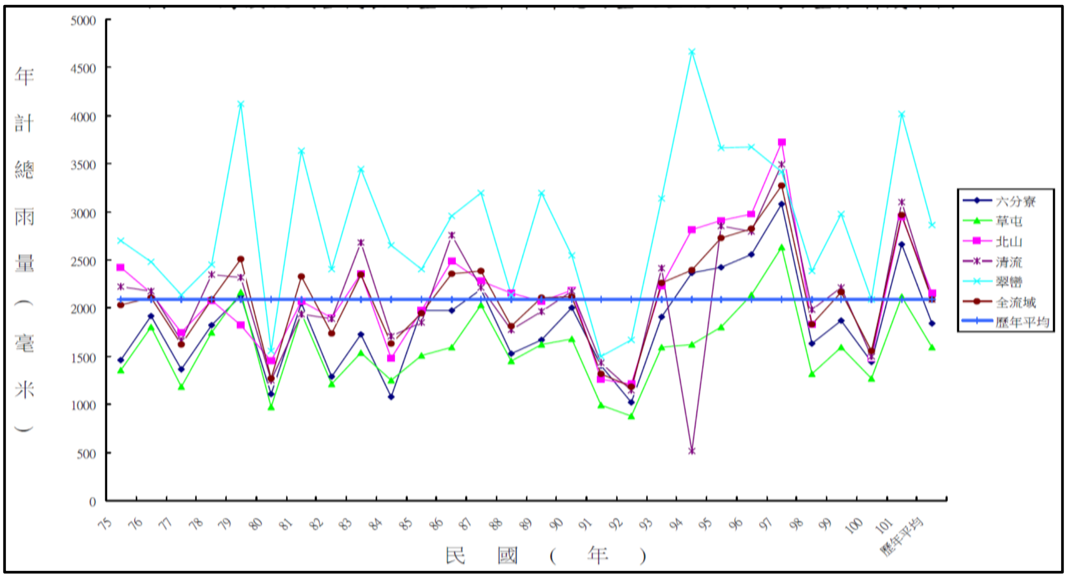

Figure 2-2-4 Statistics of rainfall at Wuxi rainfall gauge station in recent years

2-3 Overview of Geological Structures, Drilling Data of Adjacent Strata

2-3-1 Drilling data for adjacent strata

Field investigations indicate that the current riverbed surface and floodplain areas at the site primarily consist of gravel mixed with silty sand. According to data from the Central Geological Survey, Ministry of Economic Affairs, the geological formation at the bridge site is classified as alluvial deposits, and the site is located approximately 1.7 kilometers from the Chelungpu Fault. Additionally, based on the as-built drawings of the ZhongtouWu-Xi Bridge, the deepest borehole at the bridge site reaches a depth of 35 meters, with the entire profile composed of sandy gravel or gravel. Further reference to borehole data from the Wu-Xi Bridge on Provincial Highway No. 3 (upstream) reveals that the subsurface composition consists of cobble gravel interbedded with silty sand down to about 7 meters, followed by sandy shale or shale at greater depths.

A total of six boreholes were installed within the project site, each with a depth of 40 meters, resulting in a combined drilling depth of 240 meters. During the drilling process, the Standard Penetration Test (SPT) was performed at 1.5-meter intervals or whenever a change in lithology was observed. The resulting N-values were recorded to provide reference data for future engineering design.

According to the results of the geological drilling, the subsurface strata at the project site primarily consist of cobble gravel layers interbedded with brown-yellow and brown-gray silty fine to coarse sands. The cobble gravel layer contains gravels of varying diameters, approximately 5 to 30 cm, with densely packed and tightly contacting particles. The voids between gravels are filled with brown-yellow and brown-gray silty fine sand, resulting in a dense and hard composition. Standard Penetration Tests (SPT) conducted on-site during drilling revealed N-values greater than 100, indicating very dense ground conditions.

The groundwater table at the site, based on field drilling data, was observed at depths ranging from GL -12.8 meters to GL -14.8 meters within the borehole depth range. Due to variations in location and seasonal influences (e.g., rainy seasons or extreme rainfall events), the groundwater level is expected to fluctuate significantly (typically rising). Therefore, it is recommended that the groundwater level be remeasured prior to construction. During construction, continuous monitoring is advised to prevent potential risks associated with groundwater seepage or inflow.

3 Project Planning

3-1 Road works

This project involves pier replacement construction, wherein the superstructure will retain its existing alignment, longitudinal gradient, and cross-sectional profile, ensuring that current traffic operations remain unaffected. Only the substructure components, specifically the bridge piers, will be reconstructed.

3-2 Bridge girder works

3.2.1 Design Codes and Reference Documents

1. Highway Bridge Design Specifications, Ministry of Transportation and Communications (MOTC), April 2015 (Taiwan Year 104)
2. Seismic Design Specifications for Highway Bridges, MOTC, June 2009 (Taiwan Year 98)
3. Seismic Design Specifications for Highway Bridges, MOTC, June 2009 (Taiwan Year 98) (duplicate entry; consider revision)
4. Traffic Engineering Specifications, MOTC, December 2015 (Taiwan Year 104)
5. Highway Drainage Design Specifications, MOTC, December 2009 (Taiwan Year 98)
6. Regulations for the Installation of Road Traffic Signs, Markings, and Signals, jointly issued by MOTC and Ministry of the Interior, May 2015 (Taiwan Year 104)
7. AWS D1.1:2015 Structural Welding Code – Steel, American Welding Society (AWS), 2015
8. Specifications for Highway Bridges, Japan Road Association, 2002 (Heisei 14)
9. ACI 318-05: Building Code Requirements for Structural Concrete, American Concrete Institute (ACI), 2005

3-2-2 Heavy

1. Reinforced concrete2400kgf/M3
2. Steel7850kgf/M3
3. Asphaltconcretesurfacecourse2300kgf/M3
4. Backfill 1900kgf/M3
5. Railings, attached pipelines Calculated by actual weig

3-2-3 Design live load

The design live load shall be handled according to HS20-44 plus 30%. No reduction for more than three lanes.

3-2-4 Design seismic forces

According to the "Seismic Design Specifications for Highway Bridges" revised and promulgated by the Ministry of Transportation and Communications (MOTC) in 2009, the design spectral acceleration coefficients at short period (Ss) and one-second period (S1) for firm ground in the seismic zone, as well as the maximum considered earthquake (MCE) spectral acceleration coefficients at short period (SMS) and one-second period (SM1), and the fault characteristics, are summarized in the table below

3-2-5 Other loads

Wind power: The general bridge design wind speed is 200km/hr according to Section 3.15 of the Highway Bridge Design Code of the Ministry of Communications in 98.

3-3 In-depth analysis of bridge beam brush (moving bed).

According to the "Manual of Safety Inspection and Response Measures for Flood-Induced Scour at River-Crossing Bridge Foundations"—a guideline referenced by the Directorate General of Highways during the implementation of bridge closure level assessments—when caisson foundations are exposed to one-half of their total depth during a flood event, a warning state should be declared. If the exposure reaches two-thirds of the caisson depth, traffic control measures or full bridge closure should be initiated.

Based on an evaluation of all piers (P31–P56) of the Zhongtou Wu-Xi Bridge located within the river channel, using current riverbed elevations as a reference, it was determined that under a Q100 flood event, the exposed foundation lengths of Piers P42 to P47 would reach 12 to 14 meters. This exceeds the critical threshold of 12 meters, which corresponds to two-thirds of the caisson depth, thereby justifying that Piers P42 to P47 be prioritized for replacement under the current pier reconstruction project.

Status: The caisson is exposed on the piers

- The current exposed caisson foundations of the bridge piers have a width of 5.0 meters on the upstream face, with a long axis of 15 meters oriented along the direction of flow. Preliminary calculations indicate that, under a 100-year return period flood event, in addition to general local scour, the presence of a skew angle between the flow and the caisson geometry necessitates the consideration of angle-of-attack-induced scour.
- Taking into account the effect of flow attack angle (with $L/Dp = 15/5 = 3$, and an approximate flow attack angle of 8 degrees), the scour amplification factor due to flow angle (m_3) is determined to be 1.1. Incorporating both the angle-of-attack effect and local scour, the estimated total scour depth at the bridge foundation is approximately 9.97 meters (Table 3-4-1).
- For the existing bridge piers P42 to P47, the caisson foundations are currently exposed by approximately 4 meters. Each pier is equipped with caissons of 16 meters in total depth. Under a 100-year flood event, with a scour depth estimated at 10 meters, only about 4 meters of the caisson foundation would remain embedded, which poses a significant structural risk.

It is recommended that the reconstructed bridge piers adopt a circular cross-section to mitigate the effects of scour caused by oblique flow (angle of attack). Based on preliminary estimates for a cylindrical pier with a diameter of 3 meters, under a 100-year return period flood event, the scour depth around the pier body is estimated to be approximately 6.86 meters (Figure 3-4-1; Table 3-4-1).

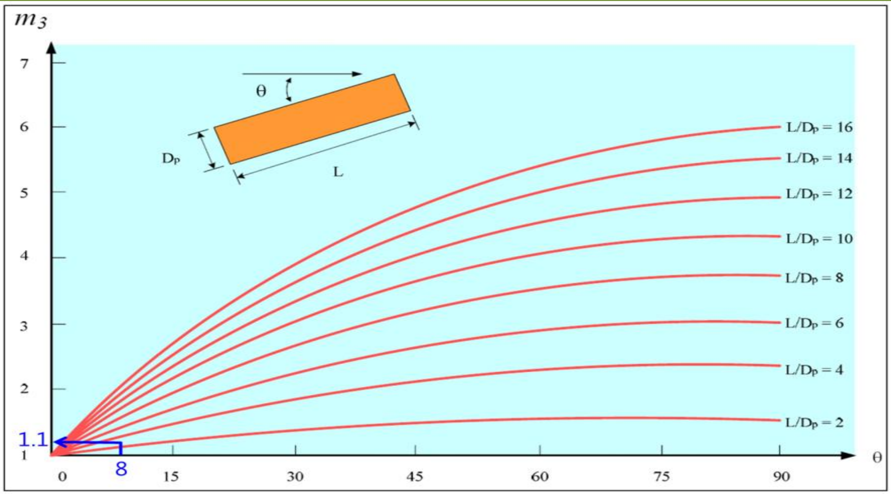

Figure 3-4-1 Curve of Flow Angle Coefficient for Bridge Piers [Breusers et al., 1977]
Table 3-4-1 Pier foundation of Wuxi Bridge 耐沖刷分析表

Scour Analysis for Reconstructed Bridge Piers

The river reach at the project site exhibits the characteristics of a braided river, with the location of deep channels varying over time due to sediment deposition. These deep channel zones represent areas of higher scour potential for the bridge pier foundations.

In the context of scour analysis, the commonly observed failure mechanisms include general (or long-term) scour, contraction (or constriction) scour, and local scour around piers. These are described as follows:

1. General and Contraction Scour:

For general scour, reference is made to the “2013 Survey Report on Major Cross Sections of the Wu-Xi, Mei River, Nangang River, and Beigang River” published by the Water Resources Agency. The survey data indicate that, between 2007 and 2013 (Taiwan Year 96 to 102), the average riverbed elevation and thalweg at the upstream and downstream reaches of the project site have not undergone significant changes. There has been no observable trend of riverbed degradation at the bridge location in recent years.

As for contraction scour, it is considered that no special hydraulic structures exist at the bridge site that would obstruct the flow and induce secondary currents resulting in significant contraction scour. The only contraction condition arises from the variation in flow-blocking cross-section due to the presence of piers.

The increase in flow velocity caused by flow constriction around the piers has already been accounted for in the velocity factor used in the hydraulic analysis. The impact of this increased velocity on scour is thus reflected within the local scour calculations, rather than being treated as a separate contraction scour component.

Based on the above assessment, the following is only for the analysis and description of the local scouring depth of the bridge pier after reconstruction:

2. Local Scouring:

The results of the hydraulic analysis of the upstream end section of the P42~P47 bridge pier across the Wuxi Bridge of Taiwan Line 63 are summarized as follows for the reference of the local scouring calculation.

item	value	item	value
Flow Rate (cms)	11,000	Average flow velocity (m/s)	3.29
Minimum riverbed height (m)	EL 74.5	Water flow area (m2)	3,371.08
Flood level (m)	EL 83.86	Water Surface Width (m)	740

In this project, Piers P42 to P47 are to be reconstructed using column-type piers with pre stressed concrete (PC) pile foundations, with a pier face width of 3 meters on the upstream side. Based on the conditions of the reconstructed piers, the average local scour depth under a 100-year return period flood is estimated to be 5.76 meters, as shown in Table 3-4-3.

After completion, the elevation difference between the backfill line and the top of the foundation cap for Piers P42 to P47 will be 8.5 meters (Figure 3-4-2). Therefore, under the design condition of a 100-year flood event, foundation exposure is not expected to occur.

Table 3-4-3 Estimated Local Scour Depths for a 100-Year Design Flood

formula		V_2 In front of the pier velocity of flow (m/s)	D_p Pier Width Facing Flow (m)	H_2 In front of the pier depth (m)	F_r Froude Number Upstream of Pier	D_{50} Median particle size (m)	H_s Partial brushing depth (m)
1	Laursen	3.29	3.0	9.36	0.46	0.09	5.82
2	Shen et al.(1)	3.29	3.0	9.36	0.46	0.09	5.80
3	Shen et al.(2)	3.29	3.0	9.36	0.46	0.09	4.76
4	Jain and Fischer	3.29	3.0	9.36	0.46	0.09	5.92
5	Ettema et al.	3.29	3.0	9.36	0.46	0.09	6.49
						average	5.76

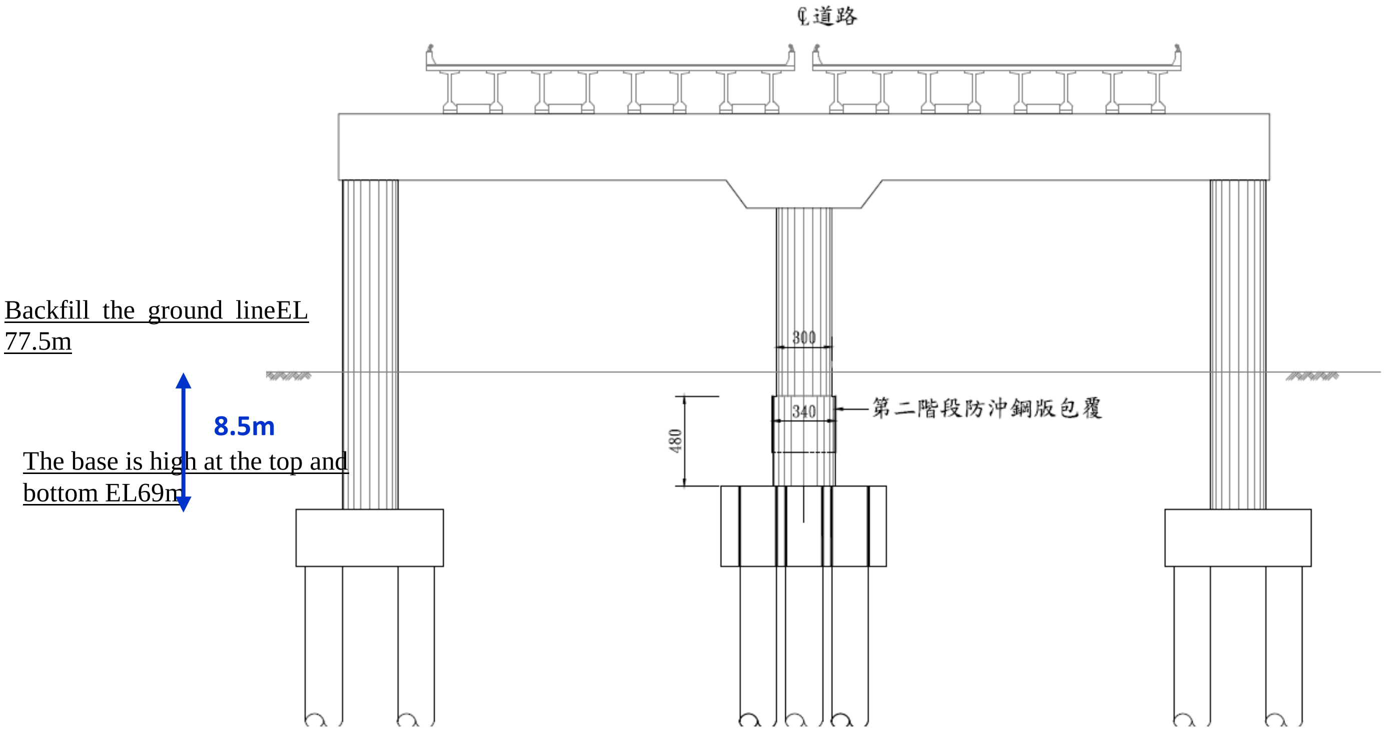

Figure 3-4-2 Cross-sectional view of the reconstruction of the abutment of the 63-line cross-Wuxi Bridge

Based on the foregoing analysis, it is recommended that the design scour reference elevation for the bridge piers be established not only by considering the planned riverbed elevation at the bridge site (E.L. 78.68), but more conservatively, by adopting the current riverbed elevation of E.L. 76 as the scour reference level for the reconstructed piers.

4 Conclusion

1. In both normal and seismic condition analyses, the original caisson foundations exhibited safety factors lower than the required thresholds for the warning water level (FS < 1.5) and the bridge closure level (FS < 1.2). This indicates potential safety concerns regarding the bridge's flood resilience under normal conditions and seismic resistance during earthquake events.
2. After the substructure was replaced with pile foundations, the evaluated safety factors were found to fully comply with both flood and seismic performance requirements. A summary table of the safety factors is provided below.

4-1 Table: Caisson Foundation Before Pier Replacement

	Vertical Bearing Capacity FS1	Lateral Displacement FS2	Angular Rotation FS3
Normal Conditions	1.12(<1.2 NG)	1.72(>1.5 OK)	2.8(>1.5 OK)
During Seismic Events	1.85(>1.5 OK)	1.97	1.28(<1.5 NG)

4-2 Pile Foundations on Both Sides of the Pier after Reconstruction

	Vertical Bearing Capacity FS	Lateral Bearing Capacity FS
Normal Conditions	3.3(>1.5 OK)	10.9(>1.5 OK)
During Seismic Events	1.93(>1.5 OK)	2.7(>1.5 OK)

4-3 Central Pile Foundation beneath the Pier after Reconstruction

	Vertical Bearing Capacity FS	Lateral Bearing Capacity FS
Normal Conditions	1.97(>1.5 OK)	2.96(>1.5 OK)
During Seismic Events	2.3(>1.5 OK)	3.05(>1.5 OK)

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