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Effect of Post-Earthquake Bed Degradation on Bridge Stability

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ABSTRACT

Earthquake and Typhoon are two major nature hazards in Taiwan. The Chi-Chi Earthquake with a magnitude of 7.3 on Richter scale occurred in central Taiwan on September 21, 1999. On September 14, 2008, nine years after the Chi-Chi Earthquake, Houfeng Bridge, located 4.5 km downstream of the Chelungpu Fault on Da-Chia River, collapsed due to the flood event induced by Typhoon Sinlaku. Three vehicles fell into Da-Chia River and six people died because of the collapse of the bridge. The main objective of this paper is to investigate the relative importance of different scour components in this event. The proposed methodology provides reasonable estimates for various scour components, and indicates that the bed degradation caused by the earthquake and all preceding Typhoon-induced floods contributed 27% to the total scour depth. It implies that the long-term general scour cannot be neglected in the bridge stability analysis.

INTRODUCTION

Taiwan is one of the archipelagos of islands in East Asia that frequently are exposed to two different major natural hazards: typhoon and earthquake. Bridges in Taiwan often are subjected to threats imposed by the rivers with steep slope gradient and rapid flows during floods associated with typhoons, which are common from June – October. This often leads to bridge failures. Typhoon Sinlaku pelted Taiwan in September 2008, the Houfeng Bridge, which crosses the Da-Chia River in central Taiwan, collapsed at 6:50 pm on September 14, 2008. Figure 1 shows the bridge one day after the actual collapse; it reveals that the direct cause of failure is the damage to a pier (P2) close to the right bank of the river. Figure 2(a) shows the flow condition upstream of the Houfeng Bridge after recession of the flood on September 24, 2008. The photograph clearly reveals the presence of an encased pipeline located at about 20 m upstream of the bridge, which causes the formation of an impinging jet flow towards the bridge. Figure 2(b), which is a photograph taken when the flood discharge was still high, clearly shows how the jet impinges directly onto the piers. Figure 2(a) also shows how the overall bed degradation associated with long-term general scour of the river bed had exposed the caisson, which forms the foundation of the bridge.

Figure 1. Damage of Houfeng Bridge on Sept. 14, 2008, looking downstream, with flow from right to left

Figure 2(a). Flow field around Houfeng Bridge showing the presence of an upstream encased pipeline (Sept. 24, 2008)

Figure 2(b). Impinging jet downstream of encased pipeline at Houfeng Bridge (Sept. 15, 2008)

The cause of the failure of the Houfeng Bridge is complex. Although the direct cause of failure may be attributed to local pier-scour, it is naïve to suggest that it is the only factor. Based on visual evidences and all available data prior to and during the flood, we are attempting to put together an explanation on all contributing factors that lead to the eventual failure of the bridge. It is hoped that this thorough review and examination of events, either natural or man-made, will allow engineers to better tackle bridge safety worldwide in general, and in Taiwan in particular in the future. Moreover, an attempt is also made to evaluate the various scour depths, both general and local, associated with Pier 2 using published scour formulas. This will allow us to have a clearer understanding on how each of these components contributes to the eventual undermining of the caisson. If such formulas are found to be accurate in determining the extent of scour, they may be used for future design of pier foundation in Taiwan with a higher degree of confidence.

SITE DESCRIPTIONS AND FLOW INFORMATION

The Houfeng Bridge, which was opened to traffic in 1990, is a four-lane, two-way, provincial highway 13 bridge that spans the Da-Chia River in central Taiwan. It connects the Houli township in the north and the Fengyuan City in the south. The length of the bridge is 640 m with 16 spans. The superstructure consists of steel plate girders with a reinforced-concrete slab deck. Each pier consists of four 2-m-diameter reinforced-concrete cylinders tied with a reinforced-concrete capping

beam. These circular piers were founded on cylindrical concrete caissons with diameter of 4 m and length of 14 m (see Figure 2a). All the caissons were originally designed to be completely embedded within the river bed.

The Da-Chia River Basin upstream of the Houfeng Bridge has a drainage area of 1,204 km². As the third longest river in Taiwan, Da-Chia River, which has a total length of 124 km, flows westward for another 25 km from the Houfeng Bridge before reaching the Taiwan Strait. The tidal effect from the river mouth does not influence flows at the bridge. The Shihkang Dam, which was constructed in 1977 to supply water for domestic use in the central part of Taiwan, is located about 5 km upstream of the Houfeng Bridge. The aerial photograph in Figure 3 shows the braided character of Da-Chia River in the reach between the Houfeng Bridge and National Expressway No. 1 Bridge. According to surveys conducted by the Third River Management Office in Taiwan from 1999 to 2004, the thalweg of Da-Chia River in the reach near the Houfeng Bridge is generally located on the northern side of the river (right bank). The river approaches the bridge at an angle of 15° to the longitudinal axis of the bridge.

Figure 3. Aerial photograph around Houfeng Bridge in 2007. Flow is from right to left. (courtesy of the Shihkang Dam Water Resources Management)

Bed samples obtained in the vicinity of the Houfeng Bridge has a median size (D_{50}) of about 80 mm and a geometric standard deviation (σ_g) of about 6.32. This shows that the bed sediments are small cobbles and the sediment particles are poorly sorted.

AUXILIARY MAN-MADE ENGINEERING STRUCTURES

A search through the records in engineering works carried out around the Houfeng Bridge reveals that three important auxiliary man-made structures were constructed before the demise of the bridge in September 2008. They are (1) an encased pipeline; (2) a tetrahedron type grade-control structure; and (3) a steel-fence type grade-control structure. The first one was located upstream while the others were located downstream of the bridge (see Figure 4). It is envisaged that items (1) and (3) have important influence in contributing to the eventual collapse of the bridge. Table 1 summarizes all pertinent information on the bridge geometry, channel geometry, and the bed material relevant to the Houfeng Bridge.

Figure 4. Schematic site plan of the Houfeng Bridge near-field at failure

Table 1. Site description of Houfeng Bridge

Bridge Geometry	Cylindrical pier, caisson
Bridge length (m)	640
Number of piers	14
Bridge span (m)	40
Cylindrical pier	2
Caisson width	4
Drainage area (km ²)	1,204
Channel geometry	Braided channel, curved reach
Centre-line bend radius (km)	2.78
Channel slope	1/90
Bed material	Gravel, cobble
D_{50} (mm)	80
D_{90} (mm)	230
Standard deviation of particles, σ_g	6.32

MAJOR EVENTS AND CAUSES OF THE COLLAPSE

An extremely important factor that has significantly contributed to the collapse of Houfeng Bridge is the considerable bed degradation due to general scouring of the Da-Chia River. It is interesting to note that the Chi-Chi Earthquake, which took place on September 21, 1999, had a direct influence on long-term riverbed degradation, which in turn may have significantly contributed to the collapse of the bridge. The destructive Chi-Chi Earthquake with a magnitude of 7.3 on the Richter scale occurred in the center of Taiwan. The death toll in this catastrophe reached more than 2,000. Figure 5 shows variations of the longitudinal riverbed profiles of the Da-Chia River from 1993 to 2008.

The bed level has reached a quasi-equilibrium condition over the period from 1993 to 1998. In 1999, nine years after the opening of the Houfeng Bridge, the Chi-Chi Earthquake occurred, resulting in the lifting of the surrounding ground levels along a fault line just upstream of the Shihkang Dam to create an average 10-m drop in the Da-Chia River. Over the subsequent years from 1999 to 2008, the Da-Chia River

responded to this abrupt lifting through significant bed degradation in the river reach downstream of the dam. Coupled with this scour potential, the flood flows associated with typhoons have contributed to extensive general scour of the river. The combined effect of both these occurrences leads to an average lowering rate of the river bed at the Houfeng Bridge of about 0.5 m/year or a total of 4.51 m over the past 9 years. In the next section, quantitative evaluation of scour depths relating to different scour processes will be given to confirm our hypotheses.

Figure 5. Variations of longitudinal riverbed profiles for Da-Chia River

ANALYSIS OF DIFFERENT SCOUR COMPONENTS

Field evidences and thorough analysis of available data associated with the Houfeng Bridge reveal that failure of the bridge likely is due to undermining of the caisson connected to Pier 2 (P2). Hence, it is reasonable to surmise that the total depth of scour at this location may have approached the embedment depth of the caisson, which is at 191.27 m MSL (the caisson top level = 205.27 m MSL; the depth of caisson = 14 m). Examinations of all the events before and during the flood associated with Typhoon Sinlaku show that the total scour depth is a combination of the following scour depths: (1) general scour, both long-term and short-term; (2) contraction scour depth; (3) bend scour depth; (4) pier scour depth; and (5) impinging jet scour depth. The overall effect of each of these inter-related scour processes is a very complex phenomenon. So far, interactions of the processes of general scour, contraction scour, bend scour, local scour and impinging jet scour are unknown. Federal Highway Administration guidelines (Richardson and Davis, 1995) and bridge scour texts such as Melville and Coleman (2000) recommended that all the components of scour depths can be assumed to be independent. Based on this assumption, the total depth of scour at the bridge is then simply the sum of all the scour components to provide a conservative estimate. In this section of the paper, an attempt is made to compute the total depth of scour at the pier by independently evaluating

each of these scour depths using published formulas.

General scour

General scour, which occurs irrespective of the presence of a hydraulic structure, such as a pier, is defined as the continuous lowering of the river bed with time. It may be in the form of long-term (bed degradation) or short-term general scour. The former occurs over a considerably length of time, normally in the order of several years or longer, while the latter occurs during floods (Melville and Coleman, 2000). Measured field data show that the Houfeng Bridge experienced both these types of scour.

Long-term general scour (bed degradation)

Table 2 shows the extent of bed degradation downstream of the Shihkang Dam before and after the Chi-Chi Earthquake. Figure 6 shows how this severe bed degradation has caused the caisson at Pier 2 to be protruded above the mean river bed level, which was at 199.45 m MSL in 2008. The field data in Table 2 also show how the bed degradation rate of Da-Chia River is significantly affected by the Chi-Chi Earthquake. For example, the respective rates of degradation are 0.93 versus 0.11 m/year at the new Railway Bridge and 0.50 versus 0.05 m/year at the Houfeng Bridge, i.e. the post-earthquake bed degradation rate being close to one order of magnitude larger than its pre-earthquake counterpart.

The extent of bed degradation regarded as long-term general scour depth of 4.51 m at the Houfeng Bridge from 1999 to 2008 is not directly related to Typhoon Sinlaku. It is a response of the river to the cumulative effect of the Chi-Chi Earthquake and all preceding Typhoon-induced floods. Notwithstanding the severity of this effect, it still is unable to undermine the caisson attached to Pier 2 of the Houfeng Bridge. Its final demise must therefore be related to the Typhoon Sinlaku-induced flood on September 14, 2008. In the next section, each of the scour components is computed using the available information and actual flood data.

Table 2. Bed degradation downstream of the Shihkang Dam in Da-Chia River after the Chi-Chi Earthquake from 1999 to 2008

Site	Distance to Shihkang Dam (km)	Degradation between 1993 to 1999 (m)	Degradation between 1999 to 2008 (m)	Average degradation Rate between 1993 to 1999 (m/yr)	Average degradation Rate between 1999 to 2008 (m/yr)
Befeng Bridge	0.84	1.55 (245.75-244.2)	3.31 (242.15-239.38)	0.26	0.37
Railway Bridge (old)	2.41	1.45 (231.1-229.65)	1.28 (228.52-228.47)	0.24	0.14
Railway Bridge (new)	3.58	0.64 (221.21-220.57)	8.35 (221.97-214.32)	0.11	0.93
Houfeng Bridge	4.78	0.31 (206.72-206.41)	4.51 (203.96-200.24)	0.05	0.50
National Expressway No.1 Bridge	7.70	0.86 (173.78-172.92)	1.31 (172.78-172.13)	0.14	0.15

Note: The above data were reported by the Water Resources Planning Institute (2005).

Figure 6. Schematic diagram for the quantitative analysis of scour depth

Evaluation of scour depth induced by typhoon sinlaku

Melville and Coleman (2000) proposed a methodology to calculate scour depths quantitatively. In this paper, their method is adopted and modified as shown in Figure 7 to evaluate the scour depth. Table 3 summarizes all relevant data needed for the scour calculation.

Figure 7. Methodology for quantitative prediction of scour depth (modification of method proposed by Melville and Coleman, 2000)

Short-term general scour

The short-term general scour depth is assumed to be directly related to the peak flood associated with Typhoon Sinlaku on Sept. 14, 2008. Based on the peak flow condition, the average scoured flow depth of 5.63 m is calculated using the relationships proposed by Lacey (1930), Blench (1969) and Maza Alvarez and Echavarria Alfaro (1973). The value based on Lacey's (1930) method was

disregarded because the y_{ms} -value is less than the upstream unscoured flow depth y_u , and the size of the sediment particles of the Da-Chia River is markedly higher than that recommended by this approach.

Table 3. Basic data for the scour analysis of Houfeng Bridge

Category	Basic data	Typhoon Sinlaku (Sept. 14, 2008)
Channel	Channel centre-line radius of curvature r_c (m)	2870
	Channel slope S_b	0.011
	Channel width W (m)	230
Flow	Flow discharge Q (m ³ /s)	4230
	Average upstream un-scoured flow depth y_u (m)	4.657
	flood peak duration t (days)	0.0625
Bed material	Median size d_{50} (mm)	80
	Geometric standard deviation σ_g	6.32
	Specific gravity G_s	2.65
Pier	Pier width b (m)	2
	Caisson width b^* (m)	4
	Caisson depth L_c (m)	14
	Angle of attack θ (degree)	15
Protection work of pipeline	Downstream slope of protection work S_m (V:H)	0.31
Grade-control structure	Length of grade-control structure L_g (m)	81
Elevation	Water stage as pier failed EL_{wrf} (m)	204.107
	Caisson top level (in main channel) EL_c (m)	205.27
	Caisson toe level EL_{ct} (m)	191.27
	Top level of pipeline protection work EL_p (m)	200.70
	Flood-level warning 1 EL_{fwt} (m)	204.27

Contraction scour

Recently, Dey and Raikar (2005) investigated the long contraction scour depth and the bed variation in the streamwise direction under the clear-water scour conditions. Based on Laursen's (1962) equation and Dey and Raikar's (2005) experimental results, the long contraction scour depth and the ratio of the contraction scour depth at Pier 2 to equilibrium contraction scour depth $d_{sc}/d_{sc,e}$ are estimated to be 2.08 m and 0.25, respectively. Based on this calculation, the contraction scour depth at Pier 2 is found to be 0.52 m.

Bend scour

Computation of bend scour was conducted using three different approaches: Chatley (1931); Thorne (1988); and a simple graphical solution proposed by Lacey (1930). The results from the calculation conducted using the methods of Thorne (1988), Lacey (1930), and Chatley (1931) are 7.56 m, 7.66 m and 5.35 m, respectively; they yield an average maximum bend scour depth of 6.86 m (y_{BS}) or 197.25 m MSL.

Local pier and jet scour

The scour relationship proposed by Melville and Coleman (2000) was used to calculate the local pier scour depth, while the jet scour formula proposed by Bormann and Julien (1991) was used to compute the jet scour depth induced by the upstream

encased pipeline. Table 4 summarizes all the computed scour depths in the study. First of all, the results show that the total depth of scour (without long-term general scour) is 12.06 m. With the addition of the long-term general scour depth of 4.51 m over the past 9 years since the Chi-Chi Earthquake, the total scour depth at Pier 2 of the Houfeng Bridge (P2) is a whopping 16.57 m! This value confirms the hypothesis that undermining of the caisson at Pier 2 is completely plausible since it is 3.88 m below the bottom of the caisson level. This undermining is, to a large extent, confirmed by field evidences at the bridge site after the flood.

Considering only the total scour depth without contribution from long-term general scouring, the results reveal that local pier-scour contributes 53% of the overall scouring at the pier-caisson, while the short-term general scour (8%), contraction scour (4%), bend scour (6%) and impinging jet scour (29%) combine to contribute the remaining 47%. The data also show that the impinging jet generated by the encased pipeline had contributed significantly to the overall scour at the pier. This issue must be addressed if the Houfeng Bridge were to be re-built at its present location.

Table 4. Comparison of scour components calculated by the proposed methodology

Scour components			Ratio of scour components to total scour			
			without bed degradation		including bed degradation	
Long-term general scour depth	$d_{L-GS}(m)$	4.51	—	—	$d_{L-GS} / d_{TS,2}$	0.27
Short-term general scour depth	$d_{S-GS}(m)$	0.98	$d_{S-GS} / d_{TS,1}$	0.08	$d_{S-GS} / d_{TS,2}$	0.06
Contraction scour depth	$d_{CS}(m)$	0.52	$d_{CS} / d_{TS,1}$	0.04	$d_{CS} / d_{TS,2}$	0.03
Bend scour depth	$d_{BS}(m)$	0.70	$d_{BS} / d_{TS,1}$	0.06	$d_{BS} / d_{TS,2}$	0.04
Local scour depth	$d_{LS}(m)$	6.34	$d_{LS} / d_{TS,1}$	0.53	$d_{LS} / d_{TS,2}$	0.38
Jet scour depth	$d_{JS}(m)$	3.52	$d_{JS} / d_{TS,1}$	0.29	$d_{JS} / d_{TS,2}$	0.21
Total scour depth without long-term general scour depth	$d_{TS,1}(m)$	12.06	$d_{TS,1} / d_{TS,1}$	1.00	$d_{TS,1} / d_{TS,2}$	1.0

Note: Bed degradation from 1999 to 2008 in the vicinity of Houfeng Bridge, d_{L-GS} = 4.51 m

$$d_{TS,1} = d_{S-GS} + d_{CS} + d_{BS} + d_{LS} + d_{JS} \quad (\text{without long-term general scour})$$

$$d_{TS,2} = d_{L-GS} + d_{S-GS} + d_{CS} + d_{BS} + d_{LS} + d_{JS} \quad (\text{including the long-term general scour})$$

Additionally, if long-term general scour (bed degradation = 4.51 m) from 1999 to 2008 are included in the consideration, the total scour depth ($d_{TS,2}$) at Pier 2 is 16.56 m. About 27% of the total scour depth is attributed to long-term general scour of the Da-Chia River around the Houfeng Bridge, while the short-term general scour (6%), contraction scour (3%), bend scour (4%), local pier-scour (38%), and the impinging jet scour (21%), combine to contribute the remaining 73%.

CONCLUSIONS AND SUGGESTIONS

Based on the case study of the Houfeng Bridge failure, the following conclusions and suggestions can be drawn:

1. The destructive Chi-Chi Earthquake (7.3 on the Richter scale) has a significant long-term effect on bed degradation downstream of the Shihkang Dam.

According to the analysis with the consideration of long-term general scour caused by the Chi-Chi Earthquake in the present study, the calculated results reveal that about 27% of the total scour depth is attributed to long-term general scour of the Da-Chia River around the Houfeng Bridge. Both long-term general scour and the impinging jet generated by the encased pipeline have contributed significantly to the overall scour at the pier.

2. Proper precautions need to be taken if damage to or failure of the downstream bridges is identified. The failure of the Houfeng Bridge also highlights the potential risk associated with human interventions, e.g., construction of the encased pipeline or grade-control structures to overall bridge stability.
3. With proper modifications, quantitative analysis of the Houfeng Bridge using Melville and Coleman's (2000) method provides reasonable estimates for various scour components in such a complex inter-related scour phenomenon. It implies that before the construction of a new bridge or the rebuilding of an old bridge, one can use appropriate methodology and formulas to evaluate the scour potential and improve bridge design.

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