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# Unsteady bridge scour monitoring in Taiwan

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## Abstract

Fully understanding of bridge pier scour process during floods is very helpful for ensuring public safety and minimizing the repairing cost of vulnerable bridges. Many research papers have been published on the local scour of non-cohesive sediment around a pier based on the laboratory experiments with steady uniform flows. However, reliable field data for bridge scours during unsteady flows are still limited.

In this study, a field bridge scour experiment was conducted at Si-Lo bridge in the lower Cho-Shui River, the longest river in Taiwan. Total scour depths were successfully measured near a pier in the main channel using a sliding magnetic collar (SMC). In addition, a column of “numbered bricks” was installed about 100 m upstream of the bridge pier to measure the general scour. During Typhoon Mindulle (2004), the time variation of total scour was monitored continuously for about 24 hours. Emphasis was placed on the separation of general and local scours.

Many existing local scour formulas were selected to compare with the measured data. The local scour at a pier is time dependent. It was found that most of the existing local scour formulas tended to overestimate the pier scour. The “numbered bricks” and SMC were proved to be powerful tools for measuring the general and total scours near the bridge pier.

*Keywords : Local scour, general scour, sliding magnetic collar, unsteady flow*

## I. INTRODUCTION

Bridge scour has an increasing worldwide awareness over the past decade. Scour is the erosion of the soil surrounding bridge piers and abutments by water. Scour around bridge foundation is the leading cause of bridge failure. In the US, Reference [1] reported that scour has been associated with 95% of all seriously damaged and failed highway bridges over waterways. Aggressive river scour has been blamed for the collapse of a river pier on a major bridge on the A12 motorway linking Munich and Verona near Kufstein in Austria in 1990 [2]. In Taiwan, several important bridges, including the Tou-Chien-Shi bridge, Chu-Tung highway bridge, Li-Kang bridge, and Kao-Ping bridge, collapsed seriously during Typhoon Herb in 1996. To avoid these failures, it is necessary to fully understand the causes and processes of bridge scour, especially during floods.

Most of the research on bridge scour has been conducted in the laboratory with equilibrium conditions, and with limited field data validation, e.g. [3, 4, 5]. As the floods in the natural rivers are unsteady flows, one may overestimate the scour depth if it is estimated based on the peak flow discharge. Many researchers also investigated the time variations of the scour depth under steady flows, e.g. [6, 7, 8].

Reference [9] measured the three-dimensional velocities, flow depths and streambed near bridge piers during floods on the Mississippi River, Brazos River and Sacramento River during 1993~1995 using a remote-control boat with ADCPs. The remote-control boat was proved to be an efficient and viable tool for data collection on small streams. However, this system may not applicable to rivers with highly turbulent or rapid flows. Instead of measuring the bridge scour for a particular flood event, Reference [10] installed sliding collar and sonar upstream of bridge piers in New York between August 1994 and February 1995 for a long term bridge scour observation. The transducer sometimes gave inaccurate data when exposed to air or because of the debris problem. Reference [11] observed the bridge scour using a ring with magnet sensor and found that the maximum scour occurred near the flood peak. It has to be pointed out that these three field studies only focused on total scour (local scour plus general scour) around the bridge piers. The separation of local scour from total scour was not considered.

Recently, pier scour subject to flood waves was investigated in the laboratory for clear-water scour conditions in reference [12]. A computational procedure for pier scour evolution under unsteady flow was proposed.

So far field measurements during the entire flood events for the live-bed scour conditions are still limited. During the floods, high sediment concentration and the debris problem are important characteristics for the ephemeral rivers in Taiwan. After careful consideration of the safety, reliability and the cost of instruments, a sliding magnetic collar probe (SMC) and the “numbered bricks” were used for measuring the total and general scours, respectively in this study. With proper separation of the general scour from the total scour, one can then calculate the local scour indirectly. This paper describes the scour monitoring system for collecting the scour data during floods. Results calculated from different existing local scour formulas were also compared and discussed based on the collected field data.

## II. SITE DESCRIPTION

The abvoe-mentioned technique was applied to Si-Lo bridge, located downstream of Cho-Shui river, the longest river in Taiwan. Fig. 1 presents the location of the Si-Lo bridge as well as the Cho-Shui river basin. There is a groundsill about 100 m downstream of the Si-Lo bridge, where no riprap or gabion countermeasure was used to protect the piers. The drainage area upstream of the bridge is 2988 km$^2$. There is a stream-gauging station named Hsi-Chou bridge located about 1 km upstream of the Si-Lo bridge. As there is no tributary between the Si-Lo bridge and the Hsi-Chou bridge, the flow discharge measured at the Hsi-Chou bridge is fairly close to that for the Si-Lo bridge. The channel slope at the site is about 0.001. Bed material samples indicate a median size $d_{50}$ of 2 mm, with a geometric standard deviation $\sigma_g$ of about 7.8. The 1.94 km long Si-Lo bridge, built in 1952, consists of 31 elliptical reinforced-concrete piers, with 62.5 m spans. The pier width and length are 3.5 m and 11 m, respectively.

## III. DATA COLLECTION TECHNIQUE

It is very difficult and dangerous to collect hydraulic and sediment data in sufficient detail for bridge scour study during floods. Unfortunately, the scour occurs mainly during high flow conditions. A scour monitoring system consisting of numbered bricks and a sliding magnetic collar was applied to measure the time variations of the general scour and total scour, respectively in this study. With proper separation of the general scour from the total scour, one can then calculate the local scour indirectly. The detailed procedures are discussed in the following sections.

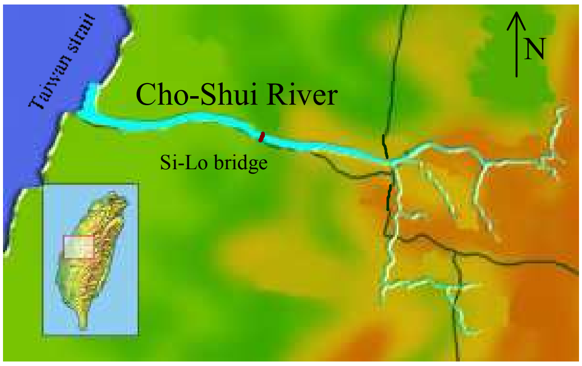

Figure 1. Location map of Cho-Shui River basin

### A. *Total scour measuring equipment - sliding magnetic collar*

The sliding magnetic collar (SMC) measuring system was developed by the ETI Inc. for measuring the maximum total scour depth at piers. Both manual and automated-readout devices are available. An automated-readout device eliminates the need for a manual probe. However, it is not suitable for the high flow conditions during the floods since the junction of the wiring and the sliding collar pipe is vulnerable to damage from debris in the rapid flows. The manual-readout system consists of a stainless-steel support pipe, sliding collar and measurement probe. The steel pipe was placed vertically into the riverbed with the sliding collar that drops as the bridge pier scour progresses.

As shown in Figure 2, the sliding magnetic collar has cylindrical shape (165 mm in diameter, 178 mm high), with three round-bar magnets (22 mm in diameter, 76 mm long) fully enclosed in three stainless-steel housing to prevent corrosion. Also, a stainless-steel plate was added outside the SMC to minimize the possible damages due to debris impact. This modification is especially important for steep rivers with rapid flows such as those in Taiwan.

To determine the position of collar, a measurement probe consisting of a magnetic switch attached to a battery and buzzer on a long graduated cable was fabricated. In operation, the cable and probe was lowered through the center of the support pipe until the sensor was adjacent to the magnetic collar and activate a buzzer. The sliding magnetic collar position was located by using the cable to determine the distance from an established datum near the top of the support pipe to the magnetic collar. The graduation was added for a length of 10 m near the annunciator housing. The stainless-steel support pipe was manufactured in Taiwan. The upper end of the pipe was terminated with a locking cap near the handrail of the bridge sidewalk. The installation was completed by inserting the stainless-steel pipe into a predrilled hole. A staff gauge was set up on pier P15 for the observation of water level from the river bank or the bridge deck. Figure 3 shows a completed installation of a manual-readout sliding magnetic collar scour monitor at P16.

Figure 2. Sliding collar

Figure 3. Completed installation of the manual-readout SMC scour monitor

### B. *General scour measuring equipment - numbered bricks*

A column of numbered bricks was placed at about 100 m upstream of pier P16 to measure the general scour. The bricks used in this study were the commercially available red bricks, 22 cm long, 9 cm wide and 5.5 cm thick. The top surface of each brick was continuously numbered with white paint. The top surface of the brick column was flushed with the initial riverbed. The location of the center of the brick column was accurately measured with a total-station transit. After the flood, again the center of the brick column was identified with accurate survey using the total-station transit. The deposited material above the brick column was carefully removed with an excavator. The number on the first brick of the brick column was read and recorded. Therefore, the number of the bricks which was washed out with the flood and the general scour depth can be calculated. Figure 4 is a sketch showing the general and total scour measuring system at Si-Lo bridge.

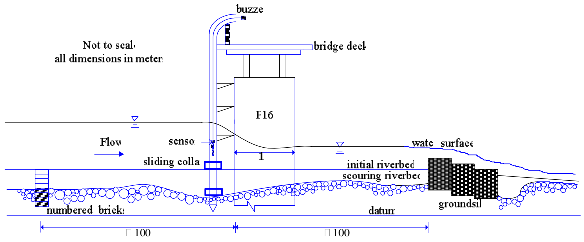

Figure 4. Schematic diagram of general and total scour measuring system at Si-Lo bridge

## IV. FIELD MEASUREMENT DURING FLOODS

A stream-gauging station, namely, Hsi-Chou bridge was located at about 1 km upstream of the field measurement site, Si-Lo bridge. The flow discharge was about the same at these two stations as there is no tributary in between. During the period of observation (2003~2004), two flood events (Typhoons Dujuan and Mindulle) were investigated. For Typhoon Dujuan (Sept. 2 2003), it only rained in the upper Cho-Shui river basin, and no rainfall occurred near the field measurement site (Si-Lo bridge). Therefore, the maximum total scour depth at pier P16 and the maximum general scour at about 100 m upstream of Si-Lo bridge were only measured after the flood. On the other hand, the total scour depth was monitored continuously for about 24-hr using a SMC during Typhoon Mindulle (July 2~6, 2004). Fig. 5 shows the stage hydrographs at Hsi-Chou bridge for Typhoons Dujuan (Sept. 2, 2003) and Mindulle (July 2~6, 2004).

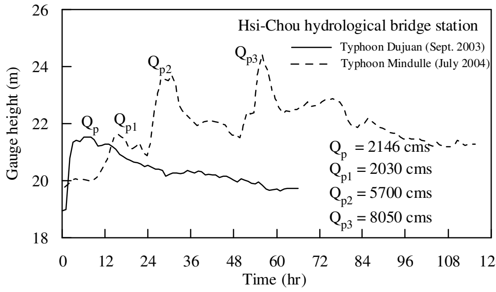

Figure 5. Stage hydrographs at Hsi-Chou bridge during Typhoons Dujuan and Mindulle

Typhoon Dujuan had a single peak flow discharge of 2146 cms, whereas Typhoon Mindulle had multiple peak flow discharges (2030, 5700 and 8050 cms). The duration of the peak flow for Typhoon Dujuan was longer than each of the three peak flows for Typhoon Mindulle. The slope of the rising limb for Dujuan was greater than that for the first peak discharge $Q_{p1}$ of Mindulle, though they had very close flow discharge values. Also, the duration of the recession limb increased with the increase of the peak flow discharge for Mindulle.

Fig. 6(a) shows the temporal variations of flow stage at Hsi-Chou bridge and Si-Lo bridge for Typhoon Mindulle. Both stage hydrographs are fairly consistent as there is no tributary between these two bridges. Fig. 6(b) shows the temporal variations of total scour depth measured by the SMC at the pier P16.

Since the SMC was damaged at the largest peak flow ( 8050 cms ), Fig. 6 only shows the results related to the first two peak flows ( 2030 and 5700 cms ). The effect of the third peak flow (8050 cms) on the scour depth will be further discussed later.

As regards the relationship between the water stage and the scour depth measured by SMC, initially the scour depth increased rapidly ( from 0.7 m to 2.7 m ) during the first rising limb. After the first peak flow ( $Q_{p1} = 2030$ cms ), the scour rate decreased significantly during the first recession limb ( $d_{TS} \cong 2.94$ m ~ 3.2 m ). For the first flood peak, as shown in Fig. 6, the maximum scour depth occurred about 1 hr after the peak of the flow. The scour depth increased slightly during the second rising limb ( $d_{TS} \cong 3.2$ m ~ 3.35 m ), while it remained almost unchanged during the second recession limb.

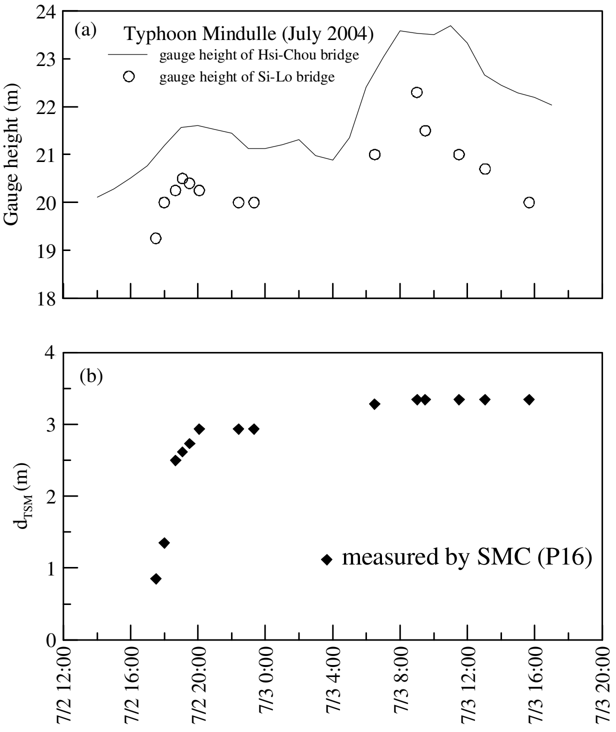

Figure 6. Relationship between measured scour depth and gauge height at Cho-Shui river near Si-Lo and Hsi-Chou bridge during Typhoon Mindulle

As mentioned before, SMC can only be used to measure the cumulative scour depth. It cannot detect the deposition of sediment since it dosen't move upward. The variation of total scour depth $d_{TS}$ during the first recession limb can be further explained. For the first hour after the peak flow ( $Q_{p1} = 2030$ cms ), the approach flow decreased, but the intensity of the horseshoe vortex inside the scour hole was still high enough to move the sediment near the bottom of the scour hole. For the next 3.7 hrs [as shown in Fig. 6(b)], the approach flow further decreased, and the intensity of the horseshoe vortex inside the scour hole was too weak to move the sediment near the bottom of the scour hole. The deposition might have occurred in the scour hole.

The first rising limb lasted about 2 hrs, and the first recession limb lasted about 4.7 hrs. A total scour depth of 2.94 m was associated with the first peak discharge. The scour action of the downflow associated with the second peak discharge ($Q_{p2}$ = 5700 cms) was significantly damped out due to the "cushion effect" (increase of the flow depth).

## V. COMPARISON OF MONITORING RESULTS WITH EMPIRICAL FORMULAS

After the floods induced by Typhoons Mindulle and Dujuan, general scour depths of 1.65 m and 1.10 m were measured at about 100 m upstream of P16 by excavating the pre-installed scour-brick column, respectively. Table I gives a summary of the measured and calculated data. There was a groundsill about 100 m downstream of Si-Lo bridge as shown in Fig. 4. It is reasonable to assume that the general scour depth was negligibly small near the groundsill. Therefore, the general scour depth at Si-Lo bridge can be obtained by linear interpolation. The net local scour depth caused by the pier can then be obtained.

TABLE I. SUMMARY OF MEASURED AND CALCULATED DATA

| Si-Lo bridge | Typhoon Dujuan ( 2003 ) | Typhoon Mindulle ( 2004 ) |
|---|---|---|
| Peak discharge | $Q_P$ = 2146 | $Q_{P3}$ = 8050 |
| V | 1.25 | 1.85 |
| y | 3.10 | 5.70 |
| y/b | 0.89 | 1.63 |
| $d_{TS}$ | 2.92 | 3.35* |
| $d_{GSU}$ | 1.10 | 1.65 |
| $d_{GS}$(at P16) | 0.55 | 0.83 |
| $d_{CS}$ | 0.125 | 0.230 |
| $d_{LS}$ | 2.220 | 2.290 |
| $d_{GS}/ d_{TS}$ | 0.188 | 0.248 |
| $d_{CS}/ d_{TS}$ | 0.042 | 0.069 |
| $d_{LS}/ d_{TS}$ | 0.770 | 0.683 |

$Q_P$, $Q_{P1}$, $Q_{P2}$ = peak flow discharges (cms)

V = main channel approach flow velocity (m/s)

y = main channel approach flow depth (m)

* assume reached equilibrium condition.

$d_{TS}$ = total scour depth at pier nose (measured by SMC at P16)

$d_{GSU}$ = general scour depth measured at about 100 m upstream of P16 by brick column

$d_{GS}$ = general scour at P16 by linear interpolation (assume no general scour at groundsill)

$d_{CS}$ = contraction scour depth near pier (Laursen [13])

$d_{LS}$ = local scour depth at pier nose [= $d_{TS}$-$d_{GS}$-$d_{CS}$]

As shown in Table I, the general scour depths 100 m upstream of Si-Lo bridge are 1.1 m and 1.65 m for Typhoon Dujuan and Mindulle, respectively. Although the maximum peak discharge of Typhoon Mindulle was about 4 times that for Typhoon Dujuan, the difference of general scour depth was only 0.55 m. This was mainly caused by the groundsill downstream of the Si-Lo bridge. The groundsill could restrict the lowering of the river bed for flows below a critical value. It can be noted that since the ratio of pier width to the pier centerline separation is very small (0.056), the calculated contraction scour depths were also very small in our study.

For Typhoon Mindille, the gauge height of the third peak was higher than the second peak for about 1 m when the flow discharge increased for about 2350 cms (see Fig. 5) because of the overflow of the floodplain. As shown in Table 1, the ratio of water depth to pier diameter (y/b) at the third peak flow during Typhoon Mindulle was about 1.63. Fig. 7 is a relationship between the dimensionless local scour depth $d_{LSE}/b$ and the dimensionless flow depth y/b based on the experimental data collected by Melville and Coleman [14]. As shown in the figure, the increase of the the local scour rate significantly reduces when y/b exceeds about 1.5. A fitted curve is also added by the writers to more clearly demonstrate the trend. In the natural river, the live-bed scour occurs frequently, where the sediment particles fill into the scour hole and reduce the net local scour depth. Therefore, the local scour increasing rate reduces even faster with an increase of y/b for the live-bed scour condition. Even though the scour monitoring equipment was damaged after the second flood peak during Typhoon Mindulle, the difference between the total scour depths at the third and the second flood peaks was probably fairly limited.

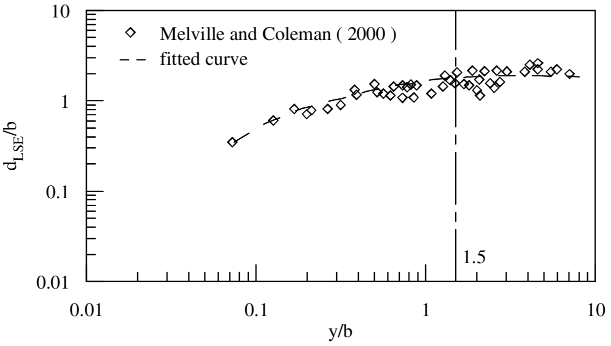

Figure 7. The influence of flow shallowness on local scour depth

With the assumptions of linear change of general scour and zero scour at groundsill, the general scour at P16 can be estimated. The net local scour depth can then be obtained by the proper separation. Table 1 indicates that the ratio of the local scour to total scour decreases with an increase of the flow.

The interaction between channel environment and bridge is so complex that even with considerable laboratory and prototype studies, estimation of scour depth and its geometry in a generalized and accurate form are still very difficult. Based on the peak flow discharges (as was assumed by most of the local scour estimations), the differences between the observed and computed local scour depths for the selected formulas are listed in Table II. None of the formulas consistently computed a scour depth that closely matched the observed scour depth for the measured conditions. In general, most formulas overestimated the local scour. Shen et al. [4], Jain and Fischer [15] and HEC-18 [1] gave better predictions (value of $d_{LSE}/d_{LSM}$ closer to 1). However, it has to be point out that the comparison was based on the peak flows, which may also somehow overestimate the local scour depth.

References [14, 16] indicated that many laboratory experiments have been undertaken using sands to model sand bed rivers. In general, water depth/pier diameter ratio y/b, dimensionless flow intensity $V/V_c$, sediment characteristic variables ($b/d_{50}$ and geometric standard deviation $\sigma_g$ ) are the most important parameters in local scour. Both parameters y/b and $V/V_c$ are relatively easier to model in the laboratory. For comparison, data ranges of the parameters for different studies are summarized in Table III. As shown in Table III, the $\sigma_g$ value in our field experiment ($\sigma_g = 7.8$) was higher than those for all of the laboratory studies listed in Table III. When the gradation of the bed material is large for a natural river, the bed armoring (or sheltering effect) may occur during a flood. Among the local scour formulas compared in this study, HEC-18 [1] was the only one considering the bed armoring effect. As a result, it was also one of the most accurate formulas for predicting the local scour depth based on our field data. Furthermore, the overestimations were also affected by the flood durations since the flows were not under equilibrium conditions for peak discharges.

TABLE II. COMPARISON WITH LOCAL SCOUR FORMULAS

| Investigators | Typhoon Dujuan<br>$d_{LSM}$ = 2.22 m<br>$Q_p$ = 2146 cms | | Typhoon Mindulle<br>$d_{LSM}$ = 2.29 m<br>$Q_{p3}$ = 8050 cms | |
|---|---|---|---|---|
| | $d_{LSE}$ | $\frac{d_{LSE}}{d_{LSM}}$ | $d_{LSE}$ | $\frac{d_{LSE}}{d_{LSM}}$ |
| Neill [3] | 5.15 | 2.32 | 6.08 | 2.66 |
| Shen et al. [4] | 2.94 | 1.32 | 3.67 | 1.60 |
| Breusers et al. [5] | 4.63 | 2.09 | 5.83 | 2.55 |
| Jain and Fischer [15] | 3.01 | 1.36 | 4.75 | 2.07 |
| Froehlich [16] | 4.55 | 2.05 | 6.51 | 2.84 |
| HEC-18 [1] | 3.30 | 1.49 | 4.62 | 2.02 |
| Melville and Coleman [14] | 6.79 | 3.06 | 8.40 | 3.67 |
| Note: $d_{LSM} = d_{TS}$-$d_{GS}$-$d_{CS}$, $d_{LSE}$ = calculated by formulas | | | | |

TABLE III. SUMMERY OF DATA RANGES FOR DIFFERENT STUDIES

| Data source | y/b | V/Vc | $b/d_{50}$ | $\sigma_g$ | Note |
|---|---|---|---|---|---|
| Shen et al.[4])<br>& HEC-18[1] | 0.67~ 2.33 | 0.54~ 5.14 | 331~ 1988 | 1.37~ 2.18 | Lab |
| Jain and Fischer [15] | 2.01~ 4.86 | 0.79~ 3.00 | 20~ 406 | 1.25~ 1.34 | Lab |
| Melville and Coleman [14] | 0.67~ 11.81 | 0.50~ 4.56 | 4~ 1000 | 1.30~ 5.50 | Lab |
| Sheppard et al. [17] | 0.19~ 11.14 | 0.75~ 1.21 | 143~ 4155 | 1.21~ 1.51 | Lab |
| Landers and Mueller [18] - data only | 0.12~ 23.0 | 0.70~ 49.6 | 9~ 17929 | 1.30~ 12.1 | Field |
| Typhoon Dujuan (2003) $Q_p$ | 0.89 | 0.87 | 1750 | 7.8 | Field |
| Typhoon Mindulle (2004) $Q_{p3}$ | 1.63 | 0.92 | 1750 | 7.8 | Field |

## VI. CONCLUSIONS

Based on this case study, the following conclusions can be drawn:

1. The sliding magnetic collar (SMC), and the numbered brick column are useful tools to measure the total bridge pier scour and the general scour in ephemeral rivers. With proper separation of the general scour and contraction scour from the total scour, the true local scour at the pier nose can be obtained. The above bridge scour monitoring system had been successfully applied to continuously measure the bridge scour depth for about 24 hrs in the lower Cho-Shui River, the longest river in Taiwan, during Typhoon Mindulle.
2. In this study, the general scour depth at about 100 m for upstream of the bridge pier was measured and used to estimate the general scour at the bridge pier by linear interpolation. The local scour depth at the pier was then calculated by subtracting this estimated general scour depth and the contraction scour depth from the total scour depth. This strict procedure is a more reasonable estimation of the "pure local scour depth." The ratio of the local scour to the total scour decrease with an increase of the flow discharge.
3. Based on the peak flow discharge, Shen et al. [4], HEC-18[1], Jain and Fischer[15] gave reasonably good predictions ($1 < d_{LSE} / d_{LSM} < 2$) for our field data. Calculations based on the peak flow discharges tended to overestimate the scour depths. For practical applications, one may select the proper formulas based on his safety requirement.
4. When the gradation of the bed material is large for a natural river, the bed armoring (or sheltering effect) may occur during a flood. Among the local scour formulas compared in this study, HEC-18 [1] was the only one considering the bed armoring effect. As a result, it was also one of the most accurate formulas for predicting the local scour depth based on our field data.

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