

# Measurements and prediction of typhoon-induced short-term general scours in intermittent rivers

Chih-Chiang Su · Jau-Yau Lu

Received: 19 March 2012 / Accepted: 20 November 2012 / Published online: 6 December 2012  
© Springer Science+Business Media Dordrecht 2012

**Abstract** Most rivers in Taiwan are intermittent rivers. A short-term general scour usually occurs in the river during the rising limb of a flood due to the transitory sediment imbalance and the steep slope gradient. In this study, a severe maximum general scour depth of 4.5 m was measured near the Highway Bridge hydrological station in a gravel-bed reach of the lower Dajia River, which was caused by a flood induced by Typhoon Sinlaku in 2008. This type of short-term general scour is usually very significant and cannot be neglected as it has caused many casualties in Taiwan such as bridge and embankment failures, for example, the Houfeng Bridge failure in the lower Dajia River (Hong et al. in *J Hydraul Eng ASCE* 138(2):186–199, 2012) and the Shuangyuan Bridge failure in the lower Gaoping River. Based on the collected field data, a general scour formula was developed and gave reasonable predictions. In conjunction with the real-time ultrasonic water level measurements, the formula can be used as a potential tool for the emergency evacuation or bridge closure purposes.

**Keywords** Short-term general scour · Scoured flow depth · Scour and fill · Gravel bed · Sand bed · Intermittent river · Embankment failure · Bridge failure · Typhoon-induced flood

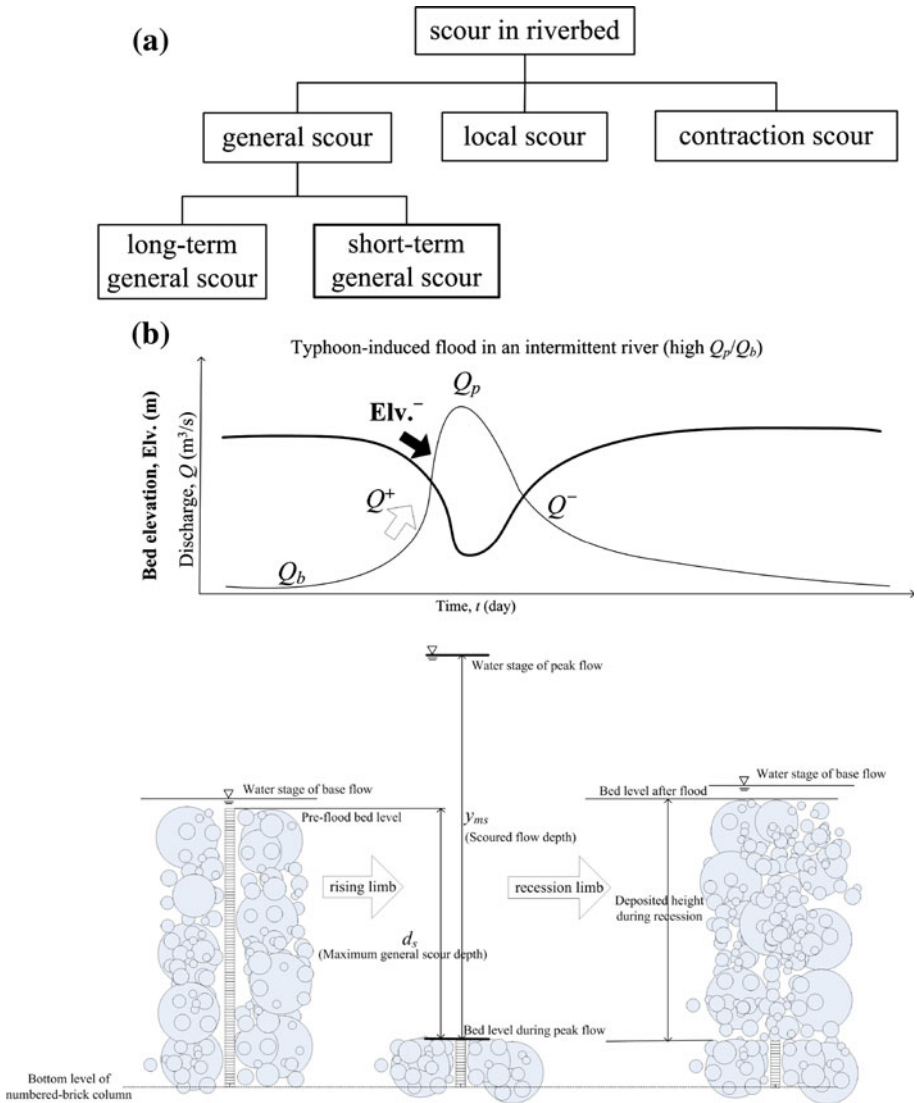
## 1 Introduction

The characteristics of scour and fill in the riverbed during a flood event have significant relation to the riverbed stability (Galay 1983). For hydraulic engineering, as shown in

---

C.-C. Su · J.-Y. Lu (✉)  
Department of Civil Engineering, National Chung Hsing University,  
250 Kuo-Kuang Rd., Taichung 402, Taiwan, ROC  
e-mail: jyly@mail.nchu.edu.tw

J.-Y. Lu  
Taiwan Typhoon and Flood Research Institute, National Applied Research Laboratories,  
Taichung, Taiwan, ROC



**Fig. 1** Schematic diagrams: **a** scour types in a riverbed; **b** evolution of short-term general scour during a typhoon-induced flood in an intermittent river ( $Q_p$  = peak flow,  $Q_b$  = base flow)

Fig. 1a, scour in a riverbed can be divided into general scour, local scour, and contraction scour (Melville and Coleman 2000). Local scour and contraction scour occur within a short distance in a river course. Local scour refers to riverbed scour caused by the local restriction or interference of water flow, attributable to the human-imposed structures in the river course, such as bridge pier, cross-dyke, dam, or ground sill. Contraction scour usually occurs when the waterway is restricted by the bridge embankment, foundation, and/or piers in the local river course, especially for the bridge built in a natural narrow reach. General scour is the long-distance longitudinal riverbed changes. Based on the timescale, it can be further divided into long-term and short-term general scours.

Long-term general scour usually occurs over relatively long reaches and long time, e.g., several years. The causes of long-term general scour are rather complex. It occurs most obviously in the river reach where man-made structures, such as dam, weir, or ground sill are set, and also in the watershed where the base level lowering of the riverbed occurred due to the landslide or fault rupture induced by an earthquake. A river reach with long-term general scour usually has a relatively low recovery ratio. To study the long-term trend and evolution of a particular river reach, research is usually conducted through numerical simulation or measurement of average riverbed elevation changes. Short-term general scour is the change of riverbed caused by one or several floods. The process is usually reversible, that is, the difference in riverbed elevations before and after the flood is insignificant.

Bettess (2002) indicated that the factors affecting general scour include (1) change in cross-sectional area of flow, (2) change in discharge, (3) sediment grading, (4) upstream sediment supply, and (5) duration of flow. For a short-duration flood event, the scour may not achieve an equilibrium condition. Lauchlan and May (2002) summarized several general scour prediction equations and made comparisons of the predicted general scours for 100- and 200-year floods on three case studies. Nevertheless, no field data were included in their study. One of the most famous general scour formula is the Blench’s (1969) formula based on the regime theory and can be expressed as follows

$$y_{ms} = 1.20 \left[ \frac{q^{2/3}}{D_{50}^{1/6}} \right] \quad \text{for sand-bed with } 0.06 < D_{50} \leq 2 \text{ mm} \quad (1)$$

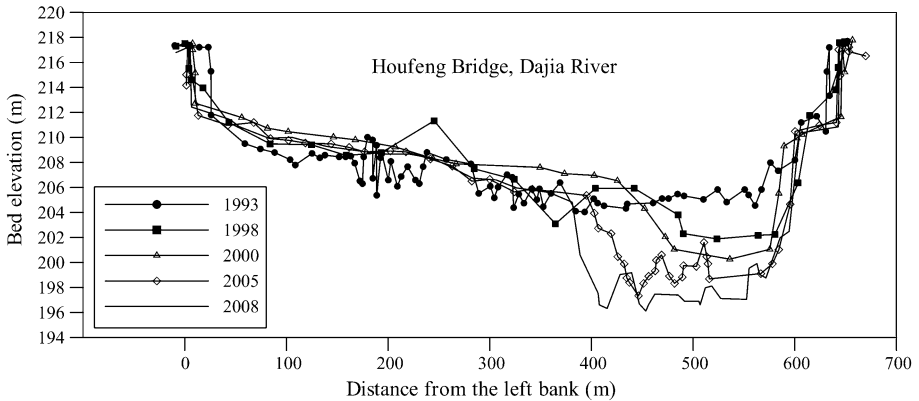
$$y_{ms} = 1.23 \left[ \frac{q^{2/3}}{D_{50}^{1/12}} \right] \quad \text{for gravel-bed with } D_{50} > 2 \text{ mm} \quad (2)$$

in which  $q$  ( $\text{m}^3/\text{s}/\text{m}$ ) is the unit flow discharge of the main channel,  $D_{50}$  (mm) is the median size of the bed material, and  $y_{ms}$  is the mean scoured flow depth below the free surface. Empirical formulas usually have certain limitations on their application due to the scale effect for the flow and sediment parameters.

Foley (1975), Hassan (1990), and Powell et al. (2005) collected scour and fill data in the ephemeral sand-bed and gravel-bed streams during flash floods. In addition, Nawa and Frissell (1993) and May et al. (2009) measured the general scours for monitoring stream habitat in the gravel-bed streams.

Taiwan is characterized by towering mountains, frail geology, and frequent earthquakes. About 30 % of the island is covered with mountains over the elevation of 1,000 m, of which the geology is mainly composed of sedimentary and metamorphic rocks. Most rivers in Taiwan are short, and the corresponding average slopes are rather high. Located in the subtropical area, Taiwan has ample rain, and its average annual rainfall is around 2,500 mm. However, the rainfall distribution is very uneven in a year, concentrating in the typhoon-induced torrential rains in summer and autumn. Due to the effects of geography and typhoons, most of the rivers in Taiwan are intermittent rivers with a great disparity in discharge and high sediment transport rates. A short-term general scour, as indicated in Fig. 1b, is usually caused by the non-equilibrium sediment transport during the typhoon-induced rapidly varied flood. The feature of severe scour and fill of the riverbed in a steep slope intermittent river is quite different from that in a mild slope perennial river. However, during the recession of the flood, the entrained sediment particles tend to deposit on the riverbed to nearly the initial mean bed level if it is in quasi-equilibrium over the long term.

Figure 2 shows the incision of the main channel near Houfeng Bridge in the lower Dajia River due to the long-term general scour caused by the sand mining, the degradation below



**Fig. 2** Typical riverbed incision of the main channel near Houfeng Bridge due to long-term general scour in the lower Dajia River

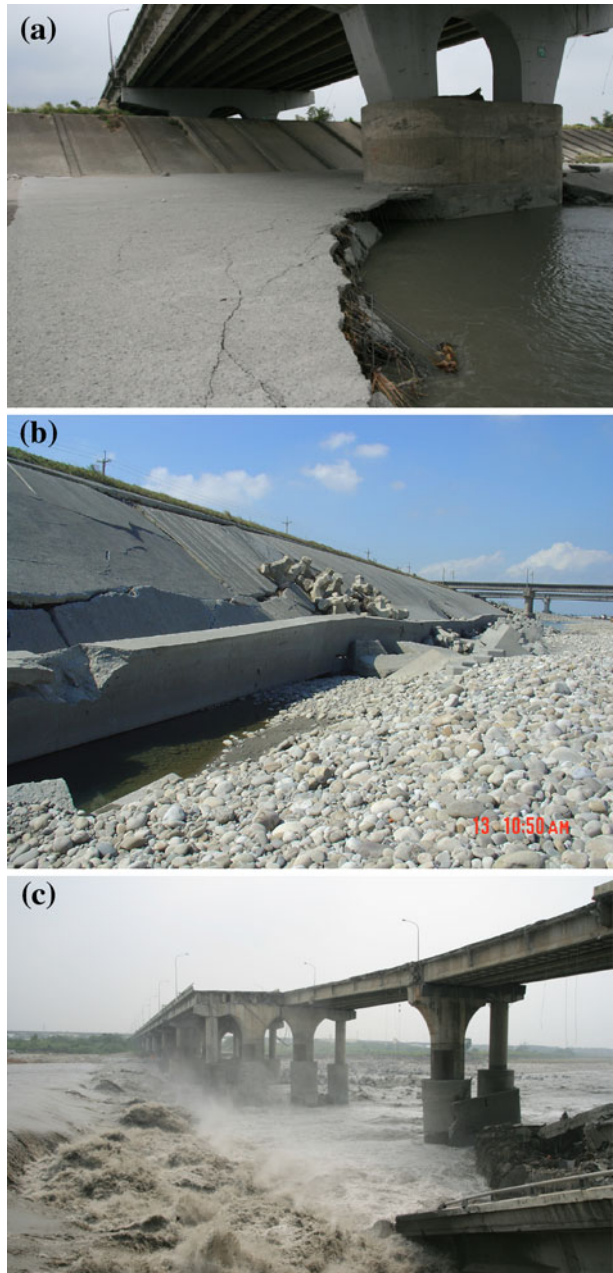
the Shihkang Dam, and the 921 Chi–Chi Earthquake (1999, magnitude of 7.3 in Richter scale, Lin et al. 2011). Furthermore, more typhoon-induced concentrating rainfalls (maximum rainfall intensity  $I_{\max} > 150$  mm/h) have occurred due to the global warming effect (Esteban et al. 2009), causing severe soil erosion and debris disasters in the upper watershed and extreme short-term general scour in the lower river reaches, particularly for the gravel-bed reaches with high sediment gradations. The short-term general scour for the gravel-bed intermittent rivers is usually very significant as it is one of the most important factors causing the embankments or bridge failures (Lu et al. 2007), and other river-crossing structure failures. Figure 3 shows three photographs taken after Typhoon Sinlaku in 2008 (flood-peak  $Q_p = 4,225$  m<sup>3</sup>/s  $\approx Q_5 = 3,800$  m<sup>3</sup>/s) for the bridge and hydraulic structure hazards owing to the short-term general scours, including the damage of the protection work of Piers 28 and 29 under Highway Bridge, the damage of Kechuang Embankment, and the Houfeng Bridge failure near the peak flow (Hong et al. 2012) in the lower Dajia River. Coleman and Melville (2001) also investigated three case studies of scour damage for New Zealand bridges and indicated that it is important to strengthen the general scour estimates during floods.

In summary, there was a lack of the field measurements in the intermittent rivers with steep slopes in the literature. For engineering practices, it is very important to develop a suitable short-term general scour formula for the water resources management, flood mitigation planning, and the bridge closure or emergency evacuation purposes. The main objectives of this study are: (1) to measure the scoured flow depth and the maximum scour depth during the peak flow of a flood for both sand-bed and gravel-bed river reaches, and (2) to derive an empirical formula to predict the short-term general scour in the high-gradient intermittent river.

## 2 Site description

The main test sites in this study include the Dajia River and the Choshui River basins in central Taiwan. Both rivers originate from the Central Mountains and flows into the Taiwan Strait, as shown in Fig. 4.

**Fig. 3** Hazards in the lower Dajia River basin caused by Typhoon Sinlaku in 2008: **a** Damaged protection work of piers under Highway Bridge; **b** Damaged Kechuang embankment; **c** Houfeng Bridge failure (photographs by author)



The Dajia River is the third longest river in Taiwan with a total length of 124 km, average riverbed slope  $S_0$  of  $1/60$ , and a drainage area of  $1,236 \text{ km}^2$ . It is a gravel-bed stream with Shihkang Dam located 23.4 km upstream from the river mouth. The average riverbed slope for the river reach downstream of Shihkang Dam is approximately  $1/90$ . Field experiments were conducted at Highway Bridge hydrological station (about 5.4 km upstream of the river mouth;  $S_0 \cong 1/90$ , median size of bed material  $D_{50} = 96 \text{ mm}$ ,



**Fig. 4** Location map of the Dajia River and the Choshui River basins

geometric standard deviation of the sediment  $\sigma_g = \sqrt{D_{84}/D_{16}} = 19.96$ , and cross-section No. 27 (0.9 km downstream of Houfeng Bridge, and about 17.7 km upstream of the river mouth;  $S_0 \cong 1/90$ ,  $D_{50} = 136$  mm,  $\sigma_g = 5.35$ ).

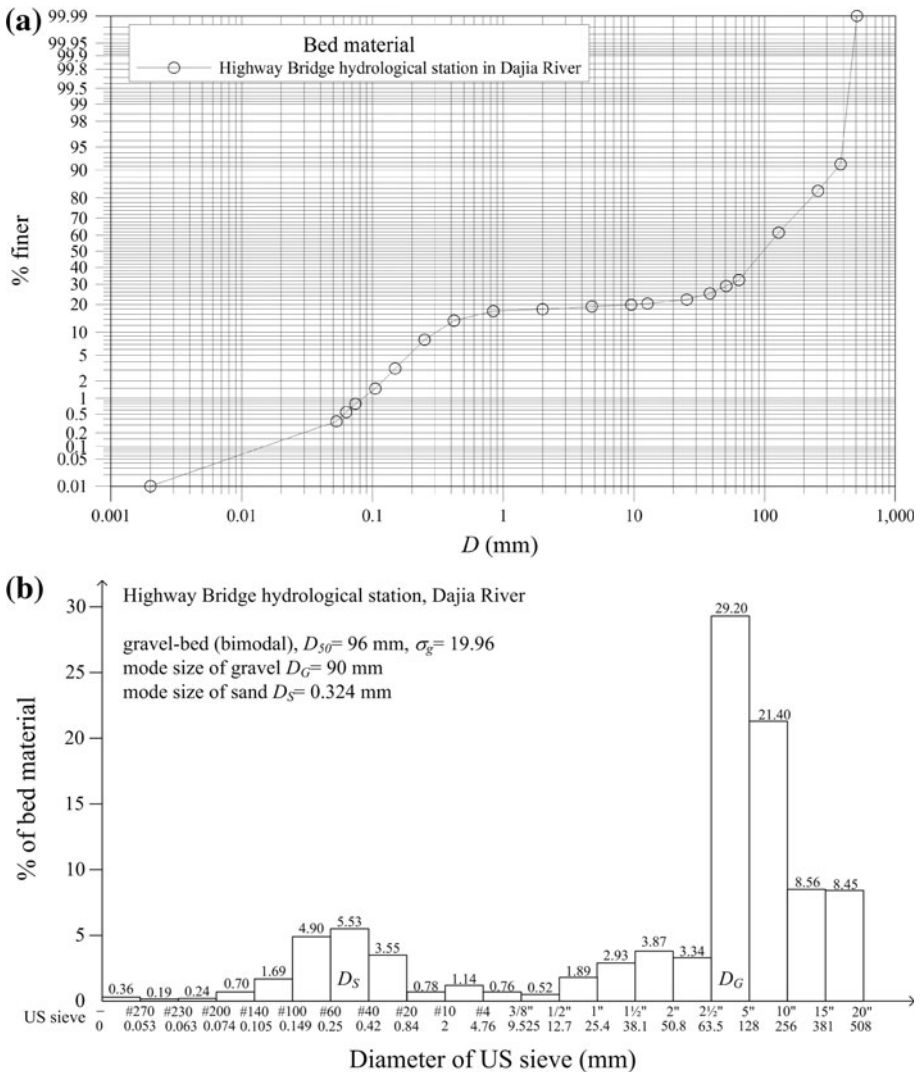
The Choshui River is the longest river in Taiwan with a total length of 186.4 km, average riverbed slope of 1/190, and a drainage area of 3,157 km<sup>2</sup>. The upper Choshui River belongs to gravel-bed reach, the midstream belongs to gravel-bed or braided reach, and the lower Choshui River is a sand-bed reach. Our study was performed in the sand-bed reach near the Silo Bridge (23.6 km upstream of the river mouth;  $S_0 \cong 1/1,000$ ,  $D_{50} = 2$  mm,  $\sigma_g = 9.86$ ), and the gravel-bed reach at Mingchu Bridge (50.3 km upstream of the river mouth;  $S_0 \cong 1/100$ ,  $D_{50} = 35$  mm,  $\sigma_g = 10.49$ ).

It is worth mentioning that the particle size distribution of the gravel bed is often bimodal. Figure 5 shows the cumulative particle size distribution and the bimodal particle size distribution of the bed material at the Highway Bridge hydrological station in the lower Dajia River. As shown in the figure, the percentages of sand ( $D < 2$  mm) and gravel ( $D > 2$  mm) are about 15 and 85 %, respectively. However, the particle size distribution of the sand-bed reach near the Silo Bridge (not shown in the figure) is unimodal.

### 3 Method

The scour and fill in the riverbed are very difficult to monitor for the typhoon-induced flood. Lu et al. (2008) and Deng and Cai (2010) made comparisons of the monitoring techniques for total scour near the bridge in the natural river. It was found that the scour chain, sliding-bead monitor (Nawa and Frissell 1993), and the numbered-brick column (Lu et al. 2008) are more suitable to measure the short-term general scour in the riverbed. The main purpose of this study is to investigate the short-term general scour in the intermittent rivers. Therefore, the measuring position has to be at least about 150 m upstream or downstream of a bridge. Our study employed the “numbered-brick column” technique to



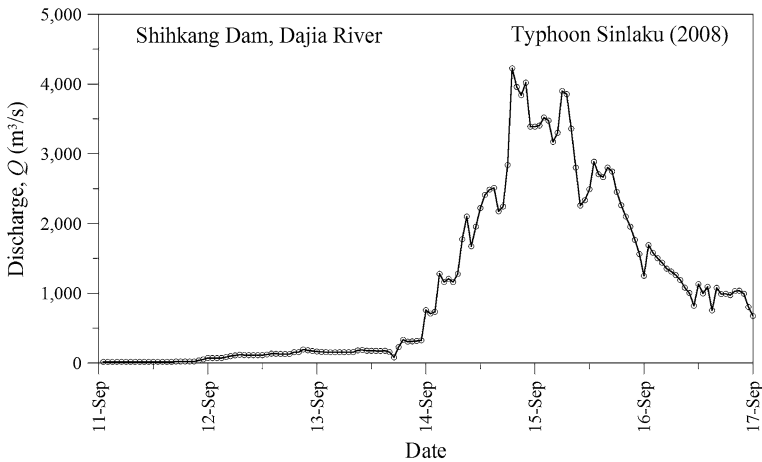


**Fig. 5** **a** Cumulative particle size distribution; **b** bimodal particle size distribution of bed material for the gravel-bed reach at Highway Bridge hydrological station in the lower Dajia River

measure the general scour depth, which is a direct observation method. A high-efficient scour brick column laying technology was developed, which uses a 5-m-long supplementary hollow steel rod with openings at both ends and two excavators. The excavators can simultaneously place about 90 pieces of numbered bricks (length 200 mm × width 100 mm × height 60 mm each) at a time, as shown in Fig. 6. The laying work was performed near one side of the main channel during the low flow period. A transit was used to locate the position of the brick column. Also, a flood stage gauge was installed on the embankment or floodplain to observe the corresponding peak flood level. After a flood, the riverbed was excavated to measure the short-term maximum general scour depth ( $d_s$ ) in the river reach and the corresponding mean peak scoured flow depth ( $y_{ms}$ ).



**Fig. 6** High-efficient brick column laying method (Highway Bridge hydrological station in the lower Dajia River)



**Fig. 7** Typical flow hydrographs in the intermittent Dajia River during Typhoon Sinlaku (2008)

## 4 Results

### 4.1 Typical flow hydrographs in intermittent river

The number of occurrences of typhoon-induced floods with short-term general scours is limited each year for the intermittent rivers in Taiwan. Also, the data collection for these rivers is a very challenging task during the rapidly varied floods. Figure 7 depicts a typical flow hydrograph collected during Typhoon Sinlaku in 2008 for the lower Dajia River. One

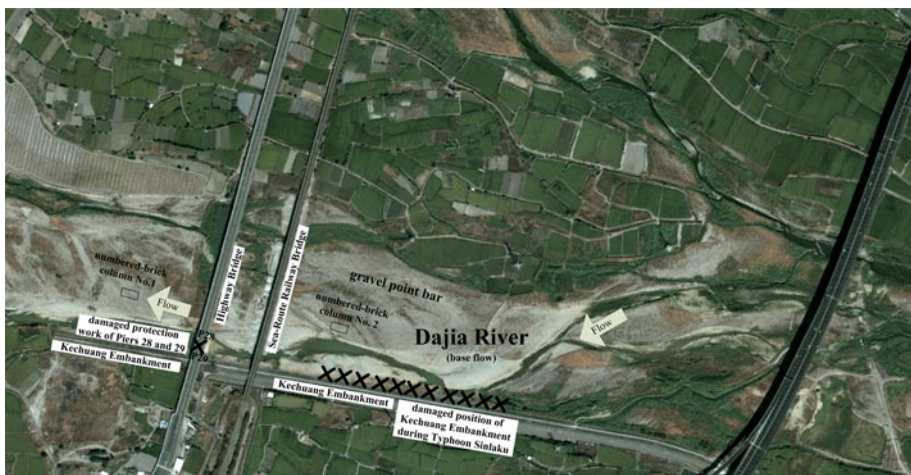


can see the rapid variation of the flow in this intermittent river. A short-term general scour usually occurs during the rising limb, and a deposition occurs during the recession limb of the flood (Lu et al. 2008). For example, both the Houfeng Bridge failure in Dajia River (Typhoon Sinlaku, peak flow  $Q_p = 4,225 \text{ m}^3/\text{s}$ , which was close to the 5-year flood,  $Q_5 = 3,800 \text{ m}^3/\text{s}$ ; Hong et al. 2012) and the Shuangyuan Bridge failure in lower Gaoping River (Typhoon Morakot,  $Q_p = 27,360 \text{ m}^3/\text{s} \approx Q_{200}$ ) occurred near the flood-peaks in 2008 and 2009, respectively.

The dominant factors causing the Houfeng Bridge failure were local scour, long-term general scour, and jet scour (Hong et al. 2012). Although the short-term general scour contributed only 6 % to the total scour, the bridge failure occurred when the short-term general scour depth was maximum near the peak of the flood induced by Typhoon Sinlaku. In addition, in terms of the scouring rate, it was 0.98 m/day for the short-term general scour during Typhoon Sinlaku, which was about 3 orders of magnitude larger than that for the long-term general scour (0.0014 m/day). Therefore, the maximum general scour depth ( $d_s$ ) was usually measured near the flood-peak in this study. Of course, the bridge failure may also occur during the recession of a flood. For example, the Kaoping Bridge failure (Aug. 27, 2000) occurred during the recession when the flow discharge was about  $1,500 \text{ m}^3/\text{s}$  (less than 2-year flow,  $Q_2 \cong 8,000 \text{ m}^3/\text{s}$ ), which was caused by the short-term general scour since the upstream sediment supply was very much limited due to the constructions of the hydraulic structures.

#### 4.2 Extreme short-term general scour during peak flow of Typhoon Sinlaku

As shown in Fig. 8, two numbered-brick columns of about 5 m long were placed 155 m downstream and 245 m upstream of the Highway Bridge at the main channel in the Dajia River before Typhoon Sinlaku (2008) for measuring the short-term general scours. From Table 1, the measured maximum general scour depth  $d_s$  was 4.5 m ( $75 \times 0.06 \text{ m}$ ) at the downstream measuring position (No. 1) in the straight river reach, which was a very high value and essentially occurred near the flood-peak. As shown in Fig. 3a, the damage of the



**Fig. 8** Layout of the numbered-brick columns for measuring short-term general scours at Highway Bridge hydrological station in the lower Dajia River

**Table 1** Short-term general scours measured by the numbered-brick columns during Typhoon Simlaku ( $Q_p = 4,225 \text{ m}^3/\text{s}$ ) near Highway Bridge hydrological station in the lower Dajia River in 2008

Distance from highway bridge	(1) Pre-flood bed level (top level of numbered-brick column) (m)	(2) Bed level after flood (m)	(3) = (2)–(1) Difference of bed level before and after flood (m)	(4) Maximum general scour depth $d_s$ (m)	(5) = (1)–(4) Bed level during peak flow (m)	(6) = (2)–(5) Deposited height during recession (m)	(7) Water stage of peak flow (m)	(8) = (7)–(5) Scoured flow depth $y_{ms}$ (m)
155 m downstream (No. 1)	52.09	53.75	1.66	4.5 ( $75 \times 0.06 \text{ m}$ )	47.59	6.16	55.32	7.73
245 m upstream (No. 2)	54.72	55.02	0.30	2.28 ( $38 \times 0.06 \text{ m}$ )	52.44	2.58	61.60	9.16

protection work of Piers 28 and 29 under Highway Bridge was mainly due to the insufficient design foundation depth (about 3 m). Also, the recovery ratio of the river reach after the flood-peak was rather high. In fact, the bed level after the flood was 1.66 m higher than that before the flood. The result indicates that the riverbed variation is very severe near the flood-peak (which was close to  $Q_5$  in this case) for the midstream and downstream of the gravel-bed reach in the intermittent river in Taiwan. The measured scour record was much greater than that in the perennial river with mild slopes (Maza Alvarez and Echavarria Alfaro 1973; Galat et al. 1997) or the ephemeral river (Foley 1975; Hassan 1990; Powell et al. 2005) in the literature.

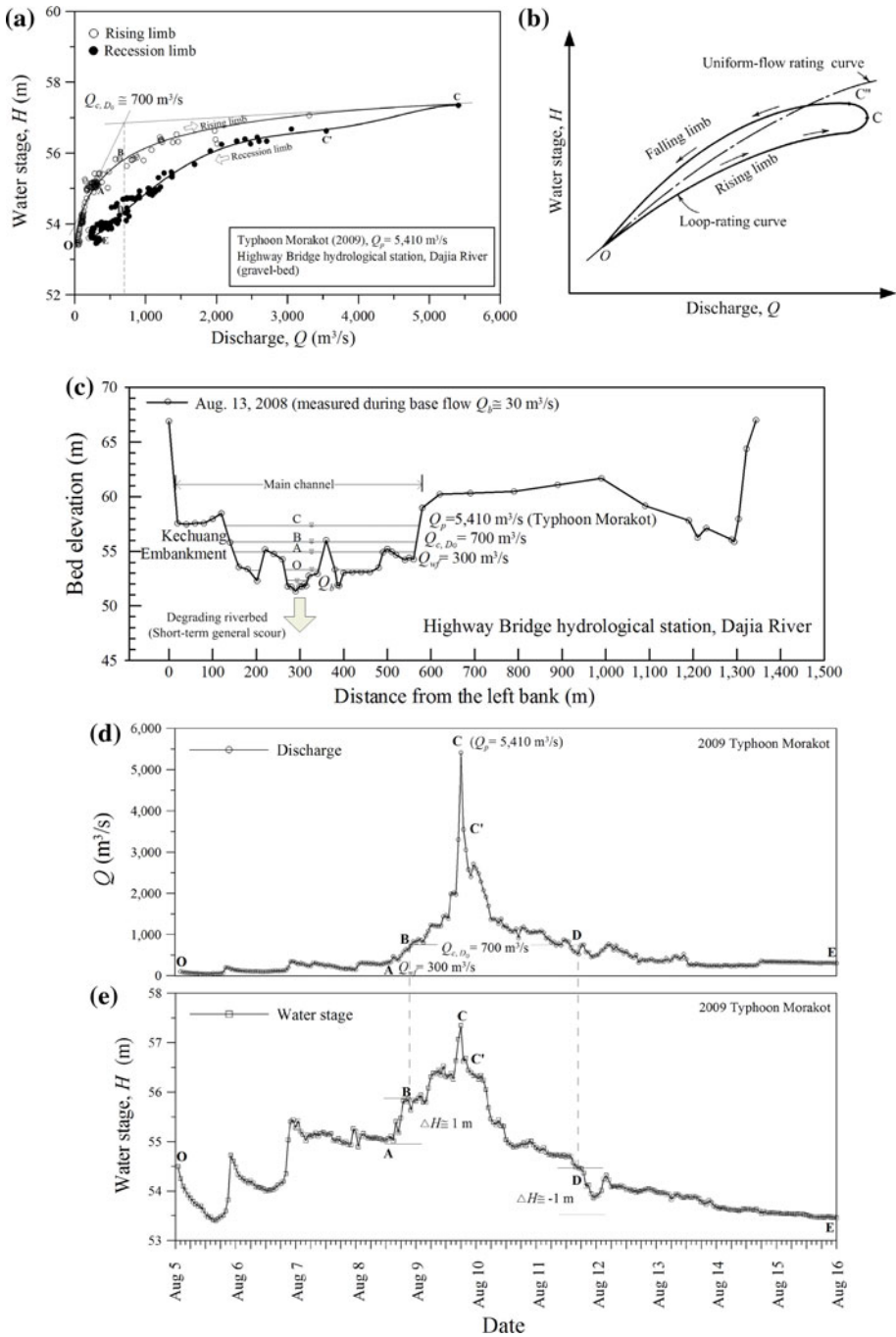
The water stage near peak flow at downstream measuring position measured by the flood stage gauge was about 55.32 m. Accordingly, the scoured flow depth during the peak flow was approximately 7.73 m. Under the effect of high flood-peak, the maximum short-term general scour depth  $d_s$  was more than half of the scoured flow depth ( $d_s > 0.5 y_{ms}$ ). It could cause serious impact on the safety of bridges or other river-crossing structures. For example, the failure of Houfeng Bridge led to a casualty of 6 death and the crash of 3 vehicles in the Dajia River caused by the flood induced by Typhoon Sinlaku in 2008 (Hong et al. 2012). The Typhoon Morakot ( $Q_p = 27,360 \text{ m}^3/\text{s}$ ) (Hsu et al. 2011) also caused the failure of Shuangyuan Bridge in Gaoping River in southern Taiwan in 2009. Even though Shuangyuan Bridge was adjacent to the river mouth, it was collapsed due to the severe short-term general scour during the flood-peak, causing the falling of 12 people and 8 vehicles into the river. Therefore, acquiring the maximum general scour depths and the scoured flow depths is of great importance to the engineering application and disaster prevention.

The upstream measuring position (No. 2 in Fig. 8) was located in the meandering reach near the Kechuang Embankment, and the maximum short-term general scour depth  $d_s$  was 2.28 m ( $38 \times 0.06 \text{ m}$ ), which was much lower than 4.5 m measured at No. 1, since the flow had an attack angle of about  $45^\circ$  nearby the gravel point bar. The Kechuang Embankment hazard was caused by the short-term general scour due to the direct impact of the flood-peak against the footing of the embankment (about 3 m deep). However, it can be deduced that the total scour depth near the Kechuang Embankment was about 4.5 m (same as the value measured downstream), which was estimated according to the elevation difference in the concrete-block elevation near the embankment before and after the attack of Typhoon Sinlaku.

#### 4.3 Unusual rating curve of gravel-bed intermittent river

Figure 9a shows the loop stage-discharge rating curve measured at Highway Bridge hydrological station for the flood induced by Typhoon Morakot in the lower Dajia River in 2009. For the dynamic flood wave in a perennial river in regime (i.e., no severe river-bed change), the loop stage-discharge rating curve (with discharge as abscissa) is usually counterclockwise in the textbook as shown in Fig. 9b (Henderson 1966). The unusual, clockwise loop-rating curve is mainly due to the severe scouring of riverbed during the rising stage near the flood-peak for the steep gradient gravel-bed river reach of the intermittent river.

It is worth mentioning that a small flood event with a clockwise loop-rating curve induced by a monsoon with a peak discharge of about  $700 \text{ m}^3/\text{s}$  also occurred in 2010. However, it was found that only the top brick of the brick column moved downstream for about 1 m. As the size of brick (equivalent diameter of about 100 mm) is very close to the



**Fig. 9** a Measured loop stage-discharge rating curve; b Traditional loop-rating curve in a perennial river (Henderson 1966); c Cross-sectional; d Flow discharge hydrograph; and e Water stage hydrograph for the flood induced by Typhoon Morakot in 2009 at Highway Bridge hydrological station in the lower Dajia River

mode size of the gravels  $D_G$  (see Fig. 5b), it is reasonable to assume that the critical discharge of  $D_G$  (or incipient riverbed scour) is close to  $700 \text{ m}^3/\text{s}$ .

The process of sediment transport in the gravel-bed reach of the intermittent river in Taiwan is rather complex. As mentioned previously, the river reach is characterized by (1) a significant change on flow discharge during the flood (high  $Q_p/Q_b$  value), and (2) a bimodal and wide gradation of riverbed material (as indicated in Fig. 5). Most sediment particles of the bed material (about 85 %) in such reach essentially move irregularly as bed load. The critical (threshold) velocities or discharges for individual gravels are quite different (Linares and Belleudy 2007). In order to further explain the physical phenomenon, Fig. 9c–e shows the cross-section measured during the base flow at the Highway Bridge hydrological station, flow discharge hydrograph, and water stage ( $H$ ) hydrograph, respectively, for the flood induced by Typhoon Morakot.

Initially, when the discharge rises from the base flow ( $Q_b$ ) in this gravel-bed reach, only sand and fine gravel particles are movable. Thus, the riverbed does not change significantly and the water level rises rapidly for the segment OA of the rising limb in Fig. 9a. Note that the flow always remained in the main channel during this flood event (see Fig. 9c). For the segment AB, when the flow increased from  $300 \text{ m}^3/\text{s}$  (width-full flow,  $Q_{wf}$ , see Fig. 9c) to  $700 \text{ m}^3/\text{s}$  ( $Q_{c, D_G}$ ), the water stage increased for about 1 m (Fig. 9e). After the discharge exceeds  $Q_{c, D_G}$ , most gravels start moving vastly, the riverbed scour (short-term general scour) starts, and the rising rate of water level begins to slow down (segment BC in Fig. 9a). When the flow was close to the flood-peak, even the cobbles may start moving in a short time. The sediment transport was in a highly non-equilibrium condition and the riverbed lowered down quickly. As shown in Fig. 9c–e, without significant change in flow width, the water stage ( $H$ ) only increased for about 1.5 m between Point B ( $700 \text{ m}^3/\text{s}$ ) and Point C ( $5,410 \text{ m}^3/\text{s}$ ), indicating severe short-term general scour occurred for the segment BC, especially near the flood-peak (Point C) since the slope of the rating curve (Fig. 9a) is very flat. Due to the severe scouring of the riverbed (steep bed slope of about 1.1 %) before the flood-peak, the water stage decreased ( $\partial H/\partial t < 0$ ) for the falling limb near the flood-peak (e.g.,  $CC'$ ), causing a clockwise loop-rating curve. This is different from the counterclockwise loop stage-discharge rating curve for the perennial river with milder bed slope, where a rising of the water stage occurs after the flood-peak ( $\partial H/\partial t > 0$  for segment  $CC''$ ), as shown in Fig. 9b. Nevertheless, due to the gradual deposition of the cobble and gravel particles on the riverbed during the recession, the riverbed gradually approached the bed level before the flood. Finally, the water stage fell quickly for the falling limb from D to E ( $\Delta H \cong -1 \text{ m}$ ) when the flow discharge was less than  $Q_{c, D_G}$  since the riverbed change was very minor, which was similar to the segment AB of the rising limb ( $\Delta H \cong 1 \text{ m}$ ).

In contrast, for the sand-bed river reach with a mild slope in the intermittent river, the moving velocities of the finer particles usually are very fast and the sediment load is dominated by the near-saturated suspended load during a flood. As a result, the riverbed scour depth is expected to be less than the gravel-bed reach in the same river, and the loop-rating curve would be similar to the traditional loop (counterclockwise) in a perennial river.

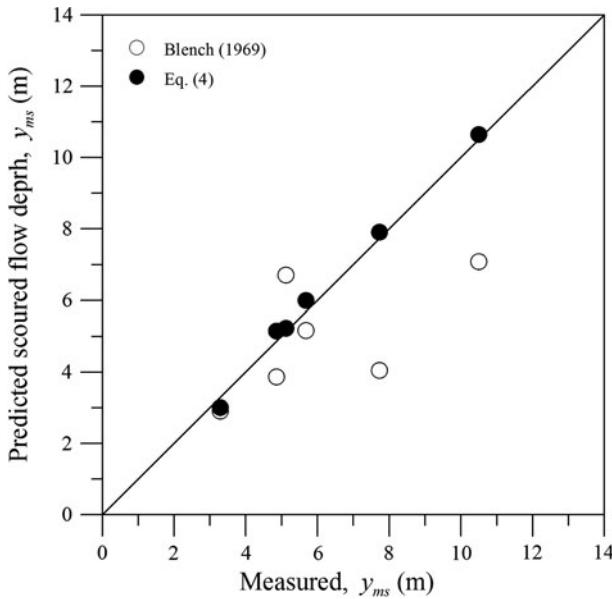
It has to be mentioned that if one only measures the cross-sectional changes before and after the flood, the information of the scour and fill process cannot be fully grasped. At present, under the circumstances of global warming and climate change, the probability of the occurrences of highly intensified concentrating rainfalls increases. Reasonable estimation of the flood-peak-related information in an intermittent river [e.g., scoured flow depth ( $y_{ms}$ ) and/or maximum general scour depth ( $d_s$ )] is very much helpful to the disaster prevention and the bridge safety management.

**Table 2** Short-term general scour field data collected in the current study

River basin	Field experimental site	$Q_p$ (m <sup>3</sup> /s)	$B$ (m)	$q$ ( $=Q_p/B$ ) (m <sup>3</sup> /s/m)	$S_0$ (%)	Bed material		$d_s$ (m)	$y_{ms}$ (m)	$y_{ms}$ (m) by Blench (1969)
						$D_{50}$ (mm)	$\sigma_g$			
	Flood event									
Choshui river	Silo Bridge, 2003 Typhoon Dujuan	2,268	506	4.46	0.1	2	9.86	1.2	3.29	2.91
	Silo Bridge, 2004 Typhoon Mindulle	8,050	758	10.62	0.1	2	9.86	1.65	5.68	5.12
	Mingshu Bridge, 2003 Typhoon Dujuan	2,146	247	8.69	1	35	10.49	2.1	4.86	–
Dajia river	Mingshu Bridge, 2004 Typhoon Mindulle	7,250	275	21.54	1	35	10.49	6	10.5	–
	Highway Bridge, 2008 Typhoon Sinlaku	4,225	400	10.56	1.11	96	19.96	4.5	7.73	–
	Houfeng Bridge, 2009 Typhoon Morakot	5,410	230	23.52	1.11	136	5.35	1.56	5.12	–

$Q_p$  = peak discharge of a flood event;  $B$  = flow width;  $q$  = unit peak discharge for the main channel;  $S_0$  = bed slope;  $D_{50}$  = median size of bed material;  $\sigma_g$  = geometric standard deviation of the sediment;  $d_s$  = maximum short-term general scour depth; and  $y_{ms}$  = scoured flow depth





**Fig. 10** Comparison of the predicted and measured scoured flow depths ( $y_{ms}$ )

#### 4.4 Scoured flow depth prediction formula

Maximum short-term general scour usually occurs near the flood-peak during the rising of a flood for either sand-bed or gravel-bed river reach due to the non-equilibrium sediment transport in a natural river. Table 2 presents the field data for the short-term general scours and the basic parameters collected during the typhoon-induced floods in the intermittent rivers at the field experimental sites of both the Choshui River and the Dajia River.

The sediment load during a flood in a sand-bed river reach is usually suspended load dominant due to the high flow intensity (also high shear velocity) for the finer particles of bed material. As shown in Table 2, the maximum short-term general scour depth ( $d_s$ ) for the sand-bed reach (unimodal) at Silo Bridge during Typhoon Mindulle in the Choshui River was 1.65 m, which is much smaller than that for the gravel-bed reach (bimodal) at Mingchu Bridge (6 m). This is mainly caused by the difference in the degree of non-equilibrium of sediment transport. In this event, the scour potential for the gravel-bed reach is much larger than that for the sand-bed reach. With regard to the scoured flow depth ( $y_{ms}$ ), Eq. (1) of Blench’s (1969) formula, which was developed based on the limited field channel data (Indian canals in regime), is reasonably applicable. In contrast, for the gravel-bed river reach of the Choshui River, Eq. (2) of Blench’s (1969) formula, which was developed based on Gilbert’s (1914) equilibrium and steady flow flume data, underestimates the  $y_{ms}$  values.

In this section, a scoured flow depth prediction formula is to be developed for the highly unsteady flows such as the typhoon-induced floods in the intermittent rivers. Based on the preliminarily physical investigation of our field data, it was found that besides the unit flow discharge of the main channel ( $q$ ) and the median sediment size of the bed material ( $D_{50}$ ), the short-term general scoured flow depth also should be related to the bed slope ( $S_0$ ) and the geometric standard deviation of the bed material ( $\sigma_g$ ), i.e.,

$$y_{ms} = fn(q, S_0, D_{50}, \sigma_g) \quad (3)$$

Processing the field data as shown in Table 2 with regression analysis, the following relationship is obtained:

$$y_{ms} = 1.26 \left[ \frac{q^{0.80} \times S_0^{0.27} \times \sigma_g^{0.74}}{D_{50}^{0.23}} \right] \quad (4)$$

in which  $y_{ms}$ ,  $q$ , and  $D_{50}$  are in m,  $\text{m}^3/\text{s}/\text{m}$ , and mm, respectively, and the coefficient of determination  $r^2 = 0.99$ . The comparison of values estimated by Eq. (4) and Blench's (1969) formula is presented in Fig 10, indicating Eq. (4) gives reasonably good predictions. Equation (4) can be applied for the flow and bed material data ranges shown in Table 2.

## 5 Conclusions

One of the main natural hazards in the intermittent river basins in Taiwan is the short-term general scour due to the steep terrain, weak geological formation, and the frequent occurrences of typhoons. Using a high-efficient numbered-brick column laying method, valuable short-term general scour data were successfully collected during the typhoon-induced floods for both gravel-bed and sand-bed reaches in the steep intermittent rivers in Taiwan. The flow usually varies rapidly leading to a severe scour and fill near the peak flow of a typhoon-induced flood, particularly for a bimodal gravel-bed reach in which the maximum general scour depth can be as high as half of the scoured flow depth. Furthermore, it was uniquely found that the stage-discharge rating curve (with discharge as abscissa) is a clockwise loop for the bimodal gravel-bed reach in the steep intermittent Dajia River due to the severe short-term general scour during the typhoon-induced flood. Thus, it is very much dangerous to predict the bridge failure simply based on the water surface level in such river reaches. From the experimental results, it can be concluded that the scour potential is rather high in the steep, wide gradation gravel-bed river reach during the typhoon-induced flood because the sediment particles essentially move irregularly as bed load, and the peak flow discharge is high. In contrast, for the sand-bed river reach with a mild slope, the scour potential is low because the sediment load is dominated by the near-saturated suspended load due to the abundant sediment supply from the riverbed. In general, the scoured flow depth formula developed in the current study gave reasonable predictions. Due to the global warming, more extreme typhoon-induced floods may occur. With a slight modification when more data are available, the proposed equation can be used as a powerful tool for the design of the cross-river hydraulic structures and the bridge closure.

**Acknowledgments** This research was supported by the Water Resource Agency, Ministry of Economic Affairs of R.O.C. The writers would like to acknowledge Dr. Jian-Hao Hong and Dr. Zhong-Zhi Shi for their assistances during the field experiments.

## References

- Bettess R (2002) A review of predictive methods for general scour. In: Chen H-C, Briaud J-L (eds) Proceedings of first international conference on scour of foundations, Nov 17–20, Texas, USA, pp 162–174
- Blench T (1969) Mobile-bed fluviology. University of Alberta Press, Edmonton

- Coleman SE, Melville BW (2001) Case study: New Zealand Bridge scour experiences. *J Hydraul Eng*, ASCE 127(7): 535–546. doi:[10.1061/\(ASCE\)0733-9429\(2001\)127:7\(535\)](https://doi.org/10.1061/(ASCE)0733-9429(2001)127:7(535))
- Deng L, Cai CS (2010) Bridge scour: prediction, modeling, monitoring, and countermeasures—review. *Practice Periodical Struct Design Construction ASCE* 15(2):125–134. doi:[10.1061/\(ASCE\)SC.1943-5576.0000041](https://doi.org/10.1061/(ASCE)SC.1943-5576.0000041)
- Esteban M, Webersik C, Shibayama T (2009) Effect of a global warming-induced increase in typhoon intensity on urban productivity in Taiwan. *Sustain Sci* 4(2):151–163
- Foley MG (1975) Scour and fill in ephemeral streams. Rep. KH-R-33, W.M. Keck Lab., Calif. Inst. of Technol., Pasadena, Calif
- Galat DL, Kubisiak JK, Hooker JB, Sowa LM (1997) Geomorphology, distribution and connectivity of lower Missouri River floodplain waterbodies scoured by the flood 1993. *Verh Internat Verein Limnol* 26:869–878
- Galay VJ (1983) Causes of river bed degradation. *Water Resour Res* 19(5):1057–1090
- Hassan MA (1990) Scour, fill, and burial depth of coarse material in gravel bed streams. *Earth Surf Proc Land* 15:341–356
- Henderson FM (1966) *Open channel flow*. Macmillan, New York
- Hong JH, Chiew YM, Lu JY, Lai JS, Lin YB (2012) Case study: Houfeng Bridge failure in Taiwan. *J Hydraul Eng ASCE* 138(2): 186–199
- Hsu WK, Huang PC, Chang CC, Chen CW, Hung DM, Chiang WL (2011) An integrated flood risk assessment model for property insurance industry in Taiwan. *Nat Hazards* 58:1295–1309. doi:[10.1007/s11069-011-9732-9](https://doi.org/10.1007/s11069-011-9732-9)
- Lauchlan C, May R (2002) Comparison of general scour prediction equations for river crossings. In: Chen H-C, Briaud J-L (eds) *Proceedings of first international conference on scour of foundations*, Nov. 17–20, Texas, USA, pp 189–197
- Lin YJ, Chang YH, Tan YC, Lee HY, Chiu YJ (2011) National policy of watershed management and flood mitigation after the 921 Chi-Chi earthquake in Taiwan. *Nat Hazards* 56:709–731. doi:[10.1007/s11069-010-9584-8](https://doi.org/10.1007/s11069-010-9584-8)
- Linares MD, Belleudy P (2007) Critical shear stress of bimodal sediment in sand-gravel rivers. *J Hydraul Engrg ASCE* 133(5): 555–559
- Lu JY, Hong JH, Su CC, Wu IY (2007) Field measurements of bridge scour in a steep gravel river reach, In: *River sediment in the environment*. Session 5, *Proceedings of 10th international symposium on river sedimentation*, Aug 1–4, Moscow, Russia, vol 5, pp 209–216
- Lu JY, Hong JH, Su CC, Wang CY, Lai JS (2008) Field measurements and simulation of bridge scour-depth variations during floods. *J Hydraul Engrg ASCE* 134(6):810–821
- May CL, Pryor B, Lisle TE, Lang M (2009) Coupling hydrodynamic modeling and empirical measures of bed mobility to predict the risk of scour and fill of salmon redds in a large regulated river. *Water Resour Res* 45:W05402. doi:[10.1029/2007WR006498](https://doi.org/10.1029/2007WR006498)
- Maza Alvarez JA, Echavarria Alfaro FJ (1973) Contribution to the study of general scour. *Proceedings of International Symposium on River Mech.*, IAHR, Bangkok, Thailand, pp 795–803
- Melville BW, Coleman SE (2000) *Bridge scour*. Water Resources Publications, Highlands Ranch
- Nawa RK, Frissell CA (1993) Measuring scour and fill of gravel streambeds with scour chains and sliding-bead monitors. *North Am J Fish Manag* 13:634–639
- Powell DM, Brazier R, Wainwright J, Parsons A, Kaduk J (2005) Streambed scour and fill in low-order dryland channels. *Water Resour Res* 41:W05019. doi:[10.1029/2004WR003662](https://doi.org/10.1029/2004WR003662)