Live-Bed Scour at Bridge Piers in a Lightweight Polystyrene Bed

Bernd Ettmer[1]; Franciska Orth[2]; and Oscar Link[3]

Abstract: Experiments on scour at bridge piers were carried out in a sediment recirculating flume with a bed of polystyrene particles. The focus of the research reported in this paper was given to live-bed experiments. All experiments were run until equilibrium conditions with flow velocities u ranging from 0.8–8.5 times the critical velocity for the incipient motion of sediment particles u_c. Maximum scour depth was continuously measured with an endoscopic camera from inside the pier, which was constructed by a plexiglass cylinder. Bed load transport with dunes was identified as the main transport mode for $1 < u/u_c < 4$. For ratios of $u/u_c \geq 4$ entrainment into suspension without development of bedforms dominated. Results show that scour rapidly reach equilibrium in the bed of polystyrene pellets. In the clear-water experiments equilibrium scour depth remained constant in time. In the bed load region the fluctuation of scour depth corresponded to the dune migration through the scour hole, while in the suspended load region the fluctuation of scour depth was negligible and was superposed by general erosion. For both clear-water and live-bed conditions maximum equilibrium scour depth continuously increased with flow intensity u/u_c. Maximum scour depth was in accordance with a logarithmic curve and reached values up to 3.3 times the pier diameter for $u/u_c = 8.5$. Extrapolation of the obtained results for an estimation of equilibrium scour depth in a lifelike worst-case scenario is discussed. **DOI: 10.1061/(ASCE)HY.1943-7900.0001025.**

Author keywords: Bridges; Piers; Scour; Erosion; Sediment hydraulics.

Introduction

The majority of bridge failures worldwide occur during flood events under live-bed conditions caused by high flow intensities u/u_c, where u is the section-averaged flow velocity; and u_c is the critical velocity for the incipient motion of sediment particles. Even in flat land rivers the flow velocity usually exceeds magnitudes of 5 m/s under extreme flood conditions. Thus, the boundary conditions for fine bed material, i.e., sand with u_c near 0.25 m/s would achieve flow intensities of $u/u_c = 20$ or more. Fig. 1 shows photographs of collapsed bridges during the 1998 El Niño flood event at the Piura River, Peru. During the flood, flow velocities reached values of 5–6 m/s, and the river bed evidenced high mobilization with bed load layer of several meters overlapped with local scouring effects (Alvarado and Ettmer 2008). Boundary conditions for bridge pier failures in nature are significantly different to those at the majority of the known laboratory scour experiments, where flow intensity was limited to ratios of u/u_c typically between 0.5 and 2, and frequently the focus was given to clear-water conditions. Chreties et al. (2008) noted that equilibrium scour depth was rarely reached in sand flume experiments. Experimental difficulties in achieving higher flow intensities are often attributed to the limited pump capacities at the laboratories and to the lack of the necessary scaling laws in sediment transport for working with lightweight materials (Heller 2011).

Among others, Laursen and Toch (1956), Larras (1963), Breusers (1965), Shen et al. (1969), Coleman (1971), Hancu (1971), Neill (1973), Breusers et al. (1977), Jain (1981), Chitale (1988), Melville and Sutherland (1988), Breusers and Raudkivi (1991), Johnson (1992), Ansari and Qadar (1994), Melville (1997), and Oliveto and Hager (2002) focused on clear-water scour. For $0.5 < u/u_c < 1.0$ maximum scour depth y/D was reported in a wide range from 0.75 to 2.5, where y is the maximum scour depth; and D is the pier diameter. In most cases, a scour depth peak was observed at $u/u_c = 1$. Investigations on scour under live-bed conditions were carried out by Jain and Fischer (1980), Zanke (1982), Melville (1984), Raudkivi (1986), Kothyari et al. (1992), Jones and Sheppard (2000), Melville and Coleman (2000), Link (2006), and Sheppard and Miller (2006). Some of the results show live-bed scour exceeding the clear-water scour, and others show the reverse as also noted by Melville and Sutherland (1988). Bedforms are periodically transported into the scour hole causing a corresponding periodic fluctuation of maximum scour depth, e.g., Sheppard and Miller (2006). Jain and Fischer (1980) carried out tests using fine, medium, and coarse sand with flow intensities $u/u_c =$ 1.5–4.1, 1–3, and 0.8–2.1, respectively. A maximum scour depth $y/D = 3.1$ was observed for $u/u_c = 4.1$. Zanke (1982) conducted experiments using sand and a synthetic pellet called Hostyren achieving values of up to $u/u_c = 9$. Results showed a maximum scour depth of $y/D = 2.5$. Sheppard and Miller (2006) carried out tests with uniform medium sand and u/u_c up to 6. The maximum scour depth was measured near $y/D = 2.2$, which is small compared with other researchers and is attributed to limited test duration. Fig. 2 presents selected scour depths y/D over flow intensity u/u_c at cylindrical piers from literature review. On a superior envelope a clear-water peak is identified near $u/u_c = 1$ with a local maximum of $y/D = 2.5$ based on single experiments from Melville and Chiew (1999). Under clear water conditions with ratios of $0.5 < u/u_c < 1$ maximum scour depth range from y/D near

[1]Professor, Dept. of Water and Waste Management, Univ. of Applied Sciences Magdeburg, Breitscheidstraße 2, 39104 Magdeburg, Germany. E-mail: bernd.ettmer@hs-magdeburg.de

[2]Research Fellow, Dept. of Water and Waste Management, Univ. of Applied Sciences Magdeburg, Breitscheidstraße 2, 39104 Magdeburg, Germany (corresponding author). E-mail: franciska.orth@hs-magdeburg.de

[3]Associate Professor, Dept. of Civil Engineering, Univ. of Concepción, Edmundo Larenas 270, Concepción, Chile. E-mail: olink@udec.cl

Note. This manuscript was submitted on April 11, 2014; approved on February 23, 2015; published online on May 4, 2015. Discussion period open until October 4, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydraulic Engineering***, © ASCE, ISSN 0733-9429/04015017(10)/$25.00.

Fig. 1. Collapsed bridges during the 1998 El Niño flood event at Piura River, Peru (images courtesy of Cesar Alvarado Ancieta)

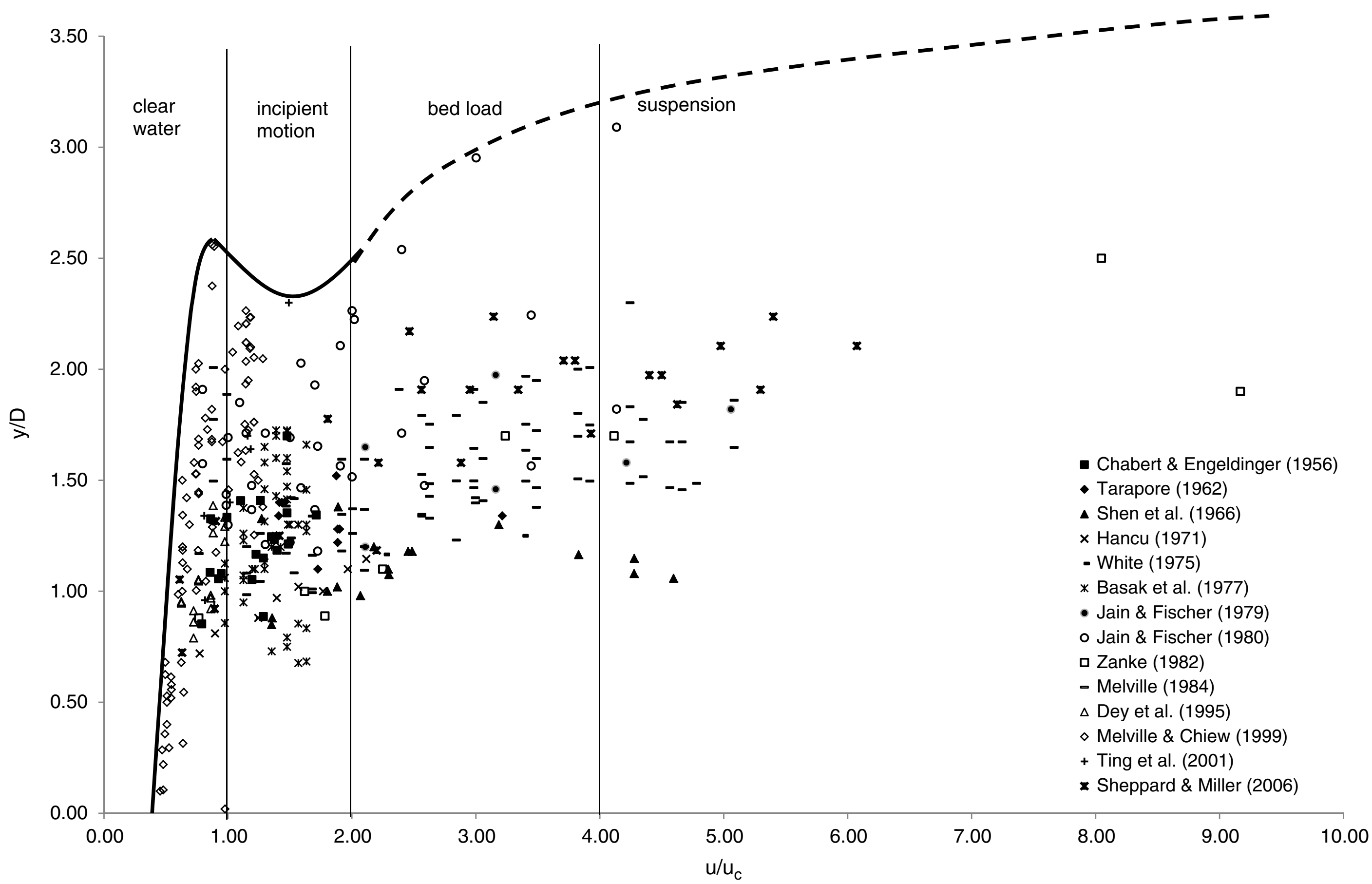


Fig. 2. Selected scour depths y/D over flow intensity u/u_c at cylindrical piers from literature review and enveloping curve

0–2.5. For flow intensities $1 < u/u_c < 2$ the incipient transport is achieved and a superior envelope curve of the available data decreases from $y/D = 2.5$ to 2.3–2.0, whereas most data are in the range of $y/D = 0.75$–1.75. For $2 < u/u_c < 4$ bed load is the dominating transport mode. In this range scour depth shows different tendencies in the different data sets. For instance, the data set by Jain and Fischer (1980) presents an increase up to $y/D = 3.1$ at $u/u_c = 4$, while the data by Sheppard and Miller (2006) present values of y/D between 1.6 and 2.2, fluctuating around 2.0. Discrepancies are detected for $u/u_c > 4$. Results by Zanke (1982) show that y/D increase from 2.0 to 2.5 with u/u_c, whereas the results by Sheppard and Miller (2006) show that y/D fluctuates around 2.0, and the results by Shen et al. (1966) show a decreasing tendency of y/D from 2.0 to 1.2 with u/u_c. A large scatter in the dataset is observed. Mainly, it is attributed to the fact that points with equal flow intensity in Fig. 2, differ considerably in other

Table 1. Relevant Parameters and Equilibrium Information for Datasets of Fig. 2

Author	Equilibrium	Time (min)	h (m)	D (m)	d_{50} (mm)	ρ_s (kg/m^3)
Chabert and Engeldinger (1956)	Yes	—	0.10–0.35	0.10–0.15	0.52–3,00	2,650
Tarapore (1962)	Yes	—	0.037	0.05	0.15–0.50	2,650
Shen et al. (1966)	Yes	—	0.1137–0.2131	0.1500–0.1524	0.24	2,650
Hancu (1971)	Yes	—	0.05	0.13	0.50	2,650
White (1975)	Yes	—	0.10	0.08	0.90	2,650
Basak et al. (1977)	Yes	—	0.0326–0.1430	0.040–0.395	0.70	2,650
Jain and Fischer (1979)	Yes	—	0.1016	0.0508–0.1016	0.25	2,650
Jain and Fischer (1980)	Yes	—	0.120–0.247	0.0508–0.1016	0.25–2.50	2,650
Zanke (1982)	No	0.5–12,000	0.42–0.55	0.09	0.24–2.40	1,035–2,650
Melville (1984)	Yes	—	0.10	0.0508–0.1016	0.38–1.40	2,650
Dey et al. (1995)	Quasi	720	0.035–0.05	0.057–0.076	0.26–0.58	2,650
Melville and Chiew (1999)	Yes	200–6,280	0.05–0.20	0.016–0.200	0.8–5.35	2,650
Ting et al. (2001)	No	292–554	0.17–0.40	0.025–0.075	0.14–0.60	2,650
Sheppard and Miller (2006)	No	20–19,920	0.2–0.49	0.152	0.27–0.84	2,650

important parameters, e.g., grain size, flow depth, and pier diameter. Also, different sets were obtained with very different measuring techniques, from graded tapes to laser distance sensors. Moreover, the deepest point of the scour-hole bottom is located at a small distance from the pier corresponding to the ratio of the first ring around the pier which is caused by the vortex closest to the pier. Sometimes, the maximum scour depth was assumed equal to the one measured directly at the pier wall, other times it was interpolated from the measured data, or it was measured directly, e.g., with a point gauge manually. Duration is also an issue in experiments with live bed and dunes, as there is no definite criteria for the termination of scour hole experiments. Among others Ting et al. (2001) did not reach equilibrium scour depths. Zanke (1982) presented experiments on the scour evolution in time with sand and synthetic pellets for the validation of a time-dependent scour formula. Experiments duration ranged from 2.7 h in case of synthetic pellets to 10 days in case of sand as bed material. In all cases scour depth variation in time was negligible small at the end of the experiments, but a maximum scour depth was not achieved. Previous researchers adopted different criteria in order to reasonably assume that the measured scour was close enough to the equilibrium scour (Chreties et al. 2008; Simarro et al. 2011). In live-bed cases, for an adequate determination of the temporal average, a number of bedforms are needed to pass the equilibrium scour hole. Table 1 shows the range of the relevant parameters and equilibrium information for each dataset plotted in Fig. 2.

Although live-bed scour experiments with high flow intensities ($u/u_c > 1$) are limited, they show that live-bed scour can be significantly higher than clear-water scour. This opens an important question as approaches to scour prediction, particularly maximum scour depth, are typically based on clear water experiments. A systematic study, on the isolated effect of flow intensity on scour is needed. The aim of the present paper is to present clear-water and live-bed equilibrium scour experiments covering a wide range of u/u_c from 0.8 to 8.5, in order to analyze the effect of flow intensities and corresponding transport modes on scour.

Dimensional Considerations

Scour depth at a cylindrical bridge pier depends on variables characterizing the fluid, flow, bed sediment, and pier. In functional form

$$y = f(\nu, \rho, u, h, g, d, \rho_s, u_c, D) \tag{1}$$

where f = function; y = scour depth; ν = kinematic viscosity; ρ = fluid density; u = section averaged flow velocity; h = flow depth; g = gravitational acceleration; d = sediment particle diameter; ρ_s = density of a sediment particle; u_c = critical velocity for the incipient motion of sediment particles; and D = pier diameter. According to the π-Buckingham theorem, the set of nine independent variables could be reduced to six nondimensional parameters as given in Eq. (2)

$$y/D = f(\mathsf{R}', \mathsf{F}', \rho', u/u_c, h/D, D/d) \tag{2}$$

where $\mathsf{R}' = ud/\nu$ is the particle Reynolds number; $\mathsf{F}' = u^2/(gd)$ is the particle Froude number; $\rho' = (\rho_s - \rho)/\rho$ = relative density; u/u_c = flow intensity; h/D = relative flow depth; and D/d = relative sediment roughness. Assuming that sediment mobility under the action of a turbulent flow is described by the dimensionless grain diameter $D^* = (\mathsf{R}'^2/\mathsf{F}'/\rho') = [(\rho' g)/\nu^2]^{1/3} d$ as presented, i.e., by Bonneville (1963), Dietz (1969), van Rijn (1984), and Ettmer et al. (2009), the dimensionless parameters R', F', and ρ' are substituted by D^* and the functional relationship describing scour depth normalized with pier diameter is given by Eq. (3)

$$y/D = f(D^*, u/u_c, h/D, D/d) \tag{3}$$

As the dimensionless grain diameter D^*, the relative flow depth h/D and the relative sediment roughness D/d were kept constant in all experiments in the research reported in this paper, the focus is on the effect of high ratios of u/u_c on y/D

$$y/D = f(u/u_c) \tag{4}$$

This functional relationship will be investigated through laboratory experiments in the subsequent sections. The scalability of results needs to take the possible effects on scour of all involved dimensionless parameters in Eq. (3). In case of lightweight sediments, especial attention must be given to D^*. Related aspects will be discussed in a subsequent section.

Experimentation

Experiments were carried out at the Laboratory for Hydraulic Engineering of the Magdeburg University of Applied Sciences, Germany.

Experimental Setup and Measuring Techniques

Tests have been conducted in a rectangular flume with glass sidewalls, 17.5-m long, 0.6-m wide, and 0.8-m deep, coupled with a sediment recirculating system. A plexiglass cylinder with 7-cm

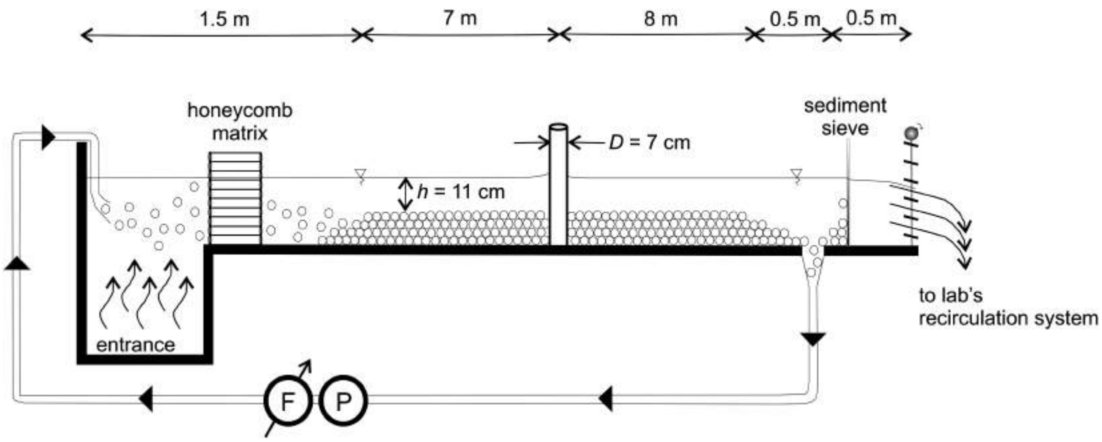
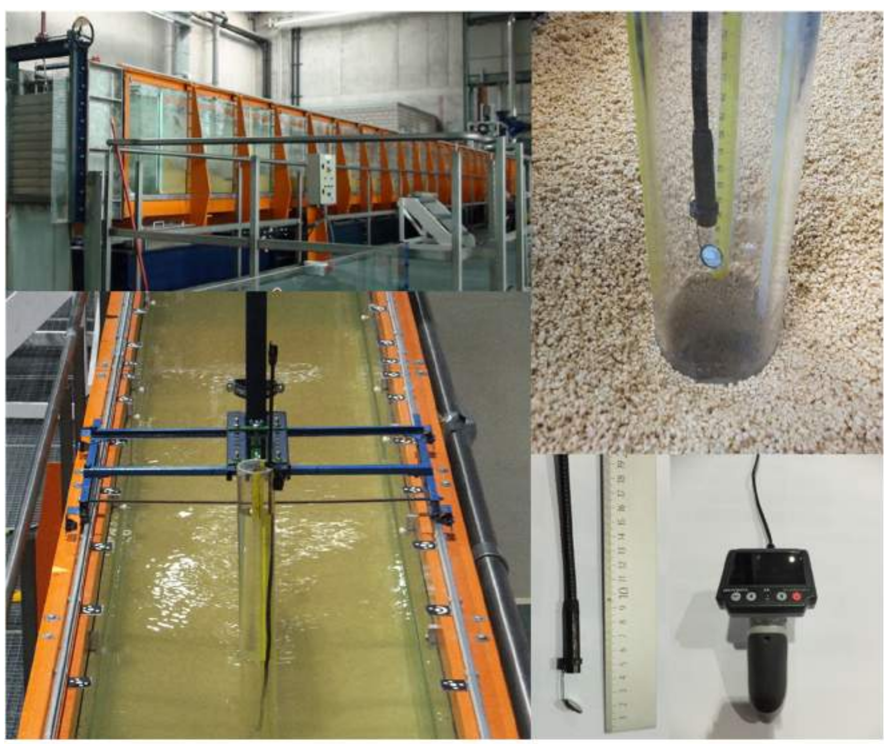


Fig. 3. Experimental installation, schematically

diameter was placed in the central section of the flume at a distance of about 7 m from the intake and 8 m to the outlet. Fig. 3 shows the experimental installation, schematically. Discharges ranged from 0 to 84 L/s, and were measured with an electromagnetic flow meter having an accuracy of ±0.1 L/s. Flow depth was adjusted with a tailgate and measured at the undisturbed flow, 3 m upstream the pier, with a point gauge having an accuracy of ±0.1 mm.

The sediment recirculating system consisted of a closed pipeline, a pump, and an inductive flow meter, that could be used independent of the water supply system of the flume. At the end of the flume, the sediment was pumped out with discharges varying between 1 and 13 L/s. The pump caused a sediment sink in a length of up to 1 m. The sediment concentration in the recirculating system was very low with rates equal to the sediment discharge caused by the flow in the flume. The sediment was supplied into the flume inlet.

The scour process was monitored with an endoscope camera which was placed inside the plexiglass cylinder. The camera was adjusted with a movable arm in vertical and radial directions. The scour hole in front of the pier was filmed continuously and visualized at an external monitor. Fig. 4 shows photographs of the recirculating flume and an endoscope camera in the plexiglass cylinder. The maximum scour depth was measured on a scale placed inside the cylinder. The accuracy of the measurement was ±1 mm. In the live-bed experiments, bed degradation was observed due to entrainment into suspension from the flat bed. Bed degradation was measured at scales along the flume with an accuracy of ±1 mm.



(a) (b)

Fig. 4. (a) Recirculating flume; (b) endoscope camera in the plexiglass cylinder

Bed Material

Polystyrene pellets were used as bed material. Particles density was $\rho_s = 1{,}058\ \mathrm{kg/m^3}$ and the characteristic grain diameter was $d_{50} = 2.0$ mm, where d_{50} is sediment size for which 50% by weight is finer. The SD of the sediment size distribution was $\sigma_g = d_{60}/d_{10} = 1.19$ with $d_{60} = 2.059$ mm and $d_{10} = 1.726$ mm, where d_{10} is sediment size for which 10% by weight is finer; and d_{60} is sediment size for which 60% by weight is finer. The shape of the polystyrene pellets was cylindrical with a shape factor (SF) = 0.7. The corresponding dimensionless sediment diameter was $D^* = 16.6$. The critical velocity for the incipient motion of the sediment particles u_c was experimentally determined in preliminary runs to $u_c = 0.090$ m/s with the same conditions as in the scour experiments, i.e., $h = 11$ cm. The settling velocity w was determined in a settling tube with 1.5-m length and 0.2-m diameter. It was $w = 0.031$ m/s yielding a ratio of $u_c/w = 2.9$. Mainly, the polystyrene pellets were used due to their small critical velocity u_c, which allows high ratios u/u_c under laboratory conditions. The flume was filled up with a 0.31-m layer of polystyrene pellets.

Hydraulic Conditions

Clear-water and live-bed experiments were conducted for 6 and 1 h after equilibrium was achieved, respectively. Flow velocities varied from $u = 0.072$–0.77 m/s and corresponding flow intensities u/u_c from 0.8 to 8.5. The flow depth was set to $h = 0.11$ m. Flow Froude and Reynolds number ranged from 0.07 to 0.74 and from 7,920 to 84,150, respectively. Under the clear-water condition equilibrium scour was assumed when measured scour depth reached constant values over 1 h, which for motion of lightweight sediments like polystyrene is a very long time. Under the live-bed condition equilibrium was assumed when measured scour depth fluctuated around an average value over 1 h. To describe the fluctuation of scour depth under live-bed conditions the SD σ of the equilibrium scour depth was used as given in Eq. (5)

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(z_i - \bar{z})^2} \tag{5}$$

where n = total number of observations during a given experiment; z_i = equilibrium scour depth; and $\bar{z}$ = average equilibrium scour depth.

Results

Results corresponding to a total number of 20 experiments are analyzed. Table 2 summarizes the experimental runs.

Observations

Local scour depths as well as general erosion reached equilibrium very fast in the lightweight sediment bed. For ratios $u/u_c \leq 1$ clear-water conditions were observed. For $u/u_c > 1.0$ generalized sediment transport affects the local scour process. In the range $1.0 < u/u_c < 4.0$ dunes developed but the main bed level was constant, i.e., neither aggradation nor degradation took place. Maximum dune height was observed at $u/u_c = 2.0$. For $u/u_c > 4.0$ bed degradation was observed and overlapped with the local scour at the bridge pier. As an example, Fig. 5 shows side views of the sediment transport during experiments with $u/u_c = 1.5$ and 5.0. In case of $u/u_c = 1.5$ a dune passing through the equilibrium scour hole is observed. Bed load was the dominating sediment transport mode. The dune velocity was one dune length per about 5 min. No bed degradation is observed. In case of $u/u_c = 5$ entrainment into suspension dominated and a thick sediment layer was mobilized, but no bedforms developed. Bursting events were frequently observed. Fig. 6 presents the measured bed level and scour depth over time for $u/u_c = 2.0$, 4.0, and 8.5. On the basis of the previous observations, bed degradation was distinguished from local scour. Both processes increased with u/u_c and bed degradation depths being significantly smaller than local scour depths. In the subsequent text scour depth is considered as the total scour including bed degradation and local

Table 2. Experimental Runs

1	2	3	4	5	6	7	8	9
Number	t (min)	u (m/s)	F (dimensionless)	u/u_c (dimensionless)	$y_{\max}/D$ (dimensionless)	$y_{\min}/D$ (dimensionless)	y_{average}/D (dimensionless)	$\sigma(y/D)$ (dimensionless)
S1	360	0.072	0.069	0.80	0.81	0.81	0.81	0
S2	360	0.077	0.074	0.85	1.10	1.10	1.10	0
S3	360	0.081	0.078	0.90	1.23	1.23	1.23	0
S4	360	0.086	0.082	0.95	1.34	1.34	1.34	0
S5	360	0.090	0.087	1.00	1.51	1.51	1.51	0
S6	60	0.135	0.130	1.50	1.67	1.31	1.54	0.07
S7	60	0.180	0.173	2.00	1.77	1.09	1.48	0.13
S8	60	0.225	0.217	2.50	1.96	1.53	1.79	0.10
S9	60	0.270	0.260	3.00	2.26	1.79	2.07	0.12
S10	60	0.315	0.303	3.50	2.37	1.97	2.22	0.10
S11	60	0.360	0.347	4.00	2.51	2.13	2.40	0.07
S12	60	0.405	0.390	4.50	2.64	2.44	2.57	0.04
S13	60	0.450	0.433	5.00	2.84	2.59	2.73	0.05
S14	60	0.495	0.477	5.50	3.01	2.73	2.88	0.05
S15	60	0.540	0.520	6.00	3.09	2.84	2.99	0.04
S16	60	0.585	0.563	6.50	3.21	2.99	3.10	0.05
S17	60	0.630	0.606	7.00	3.23	2.99	3.15	0.05
S18	60	0.675	0.650	7.50	3.29	2.94	3.18	0.05
S19	60	0.720	0.693	8.00	3.29	3.00	3.21	0.04
S20	60	0.765	0.736	8.50	3.33	2.99	3.22	0.06

Note: Flow depth was $h = 0.11$ m during all runs.

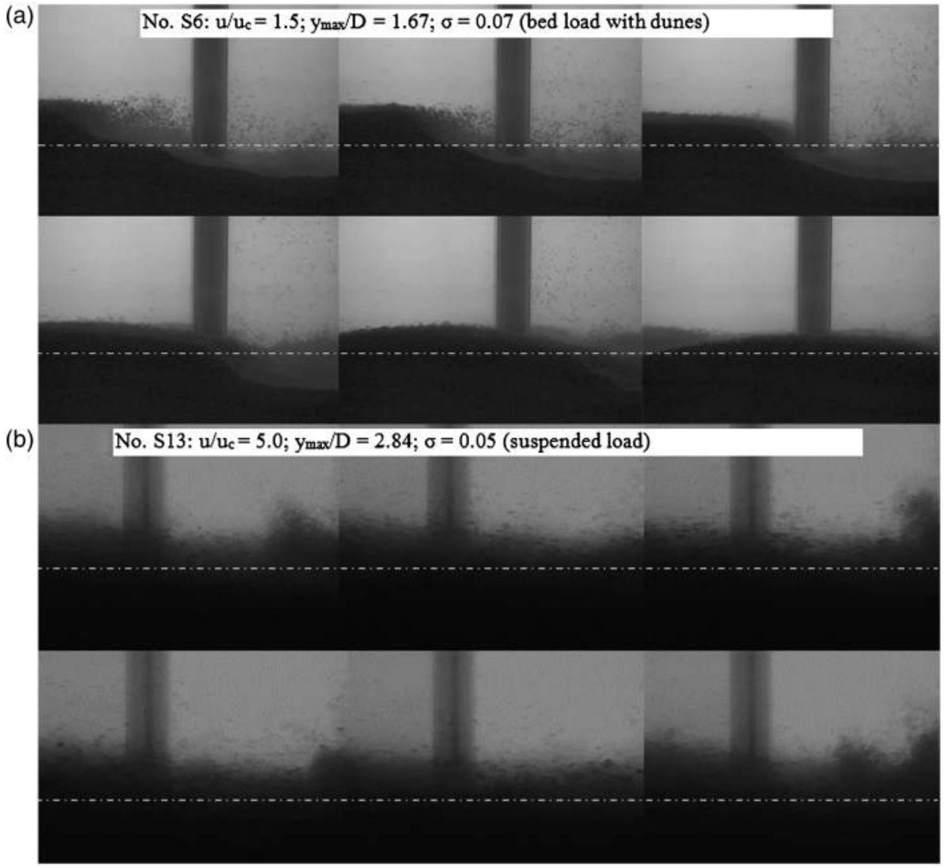


Fig. 5. Sediment transport during experiments (white line shows original bed): (a) $u/u_c = 1.5$; (b) $u/u_c = 5.0$

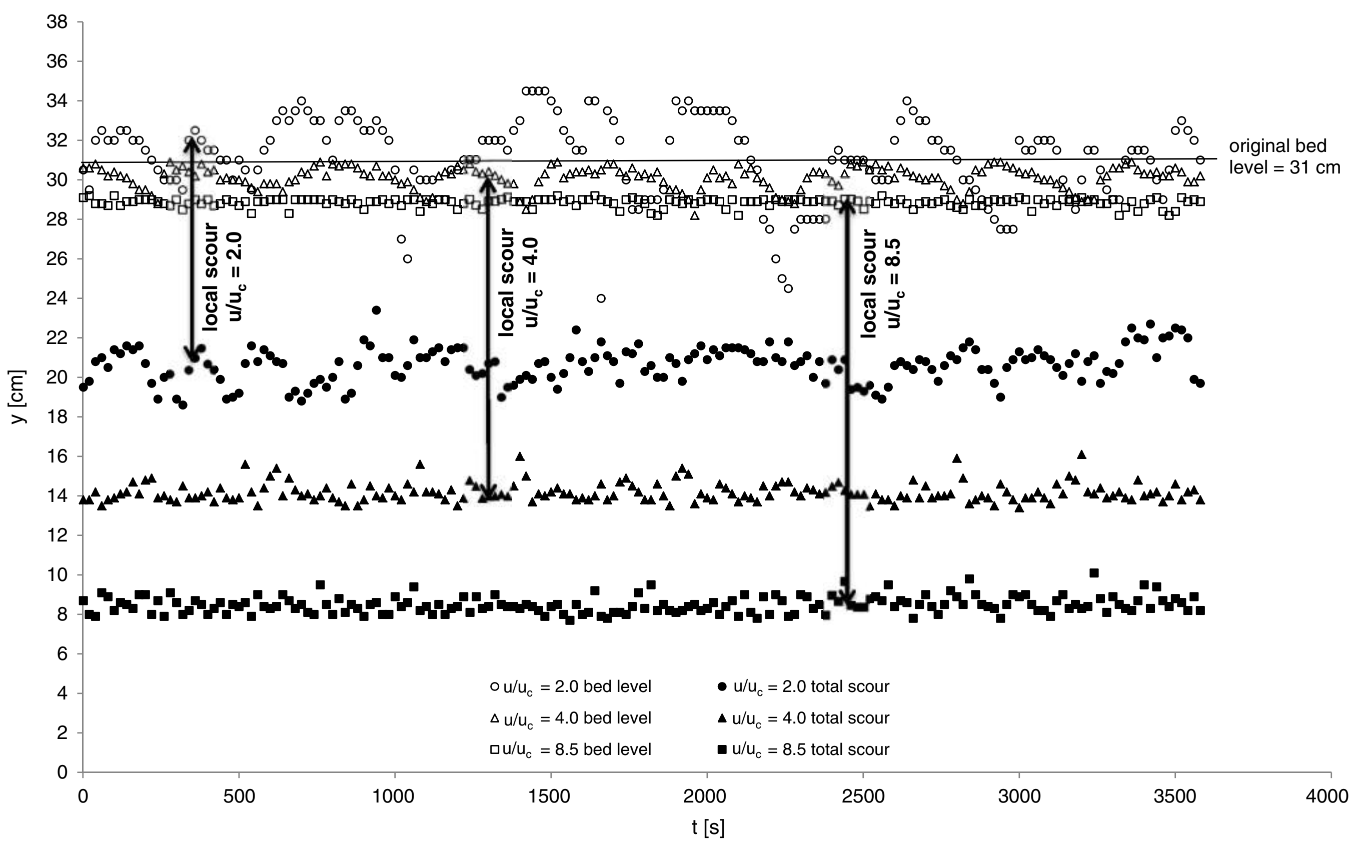


Fig. 6. Bed level and scour depth over time for $u/u_c = 2.0$, 4.0, and 8.5

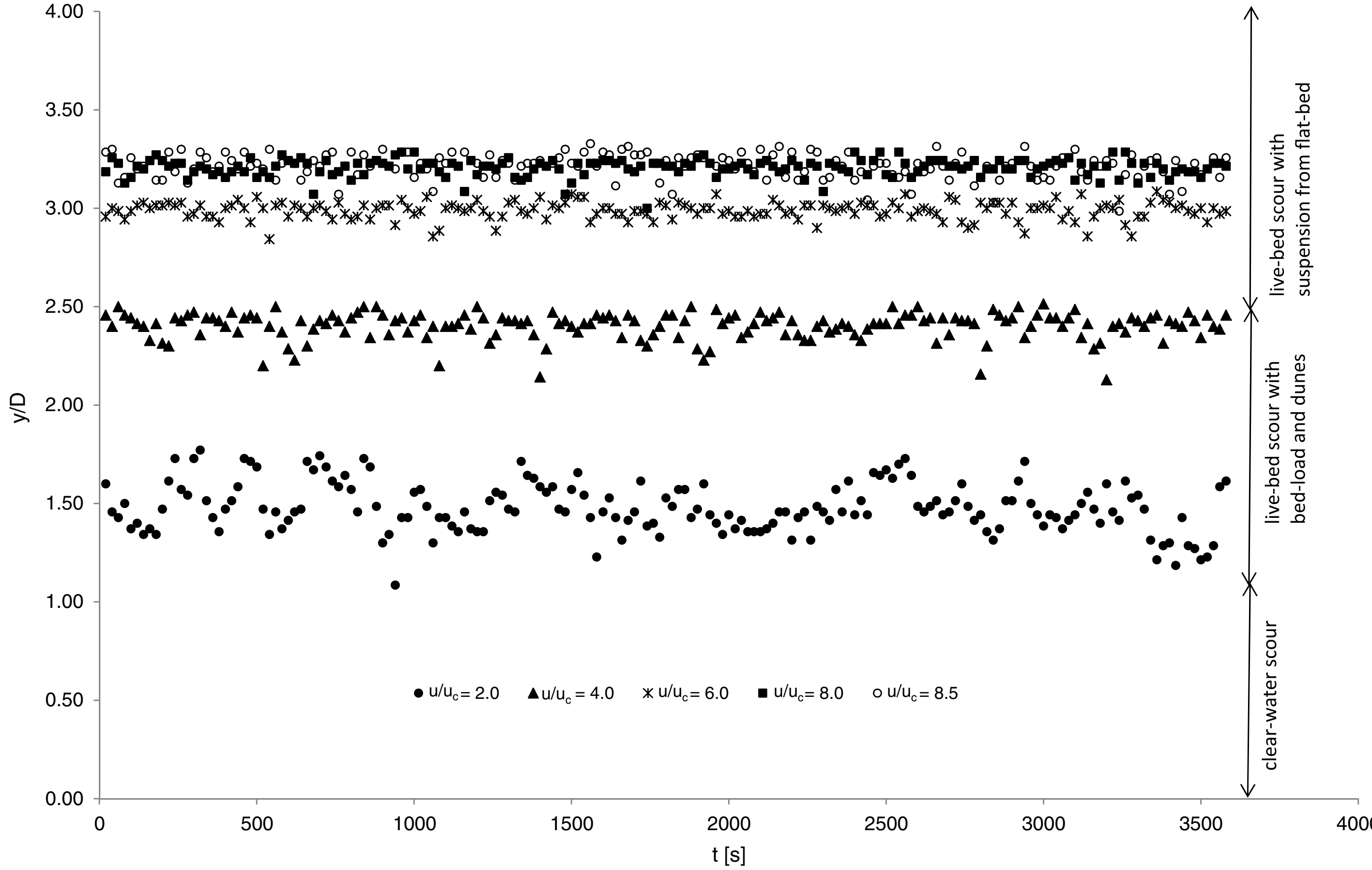


Fig. 7. Scour depth y/D over time for $u/u_c = 2.0$, 4.0, 6.0, 8.0, and 8.5

scour, to be on the safe side for engineering design. Bed degradation is different to zero only for $u/u_c > 4.0$.

Equilibrium Scour Depth

Fig. 7 presents measured scour depths over time under the live-bed condition with $u/u_c = 2.0$, 4.0, 6.0, 8.0, and 8.5. For the previously given u/u_c the time-averaged equilibrium scour depth was $y_{\text{average}}/D = 1.48$, 2.4, 2.99, 3.21, and 3.22, fluctuating between 1.09 and 1.77, 2.13 and 2.51, 2.84 and 3.09, 3.0 and 3.29, and 2.99 and 3.33, respectively. Fluctuation of y/D decreases with increasing u/u_c. The SD of equilibrium scour depth over u/u_c is shown in Fig. 8. In the bed-load region the SD ranges between $\sigma(y/D) = 0.07$ and 0.13 with a maximum at $u/u_c = 2.0$. The significant fluctuating SD in the range $1 < u/u_c < 4$ is attributed to dune migration passing through the scour hole. The maximum value of $\sigma(y/D)$ was observed at $u/u_c = 2.0$, where the maximum dune height was detected. In the suspended load region the SD was significantly smaller than in the bed load region with a nearly constant value of $\sigma(y/D) = 0.05$, evidencing the transition to a flat bed.

Variation of Equilibrium Scour Depth with Flow Intensity

Fig. 9 shows equilibrium scour depth y/D over flow intensity u/u_c. The fluctuation of scour depth for $u/u_c > 1$ is additionally plotted as minimum and maximum value. For $u/u_c < 1$ minimum, averaged and maximum scour depths coincided and increased with flow intensity up to a peak by $u/u_c = 1$. For $1 < u/u_c < 2$ average scour depth decreased with flow intensity until a local minimum and increased continuously for $u/u_c > 2$. The same tendency is observed in the context of the minimum scour depth. In contrast, maximum scour depths increased continuously with flow intensity for $u/u_c > 1$ reaching its highest value of 3.33 at $u/u_c = 8.5$. These value is significantly higher than the clear-water scour depth equal 1.51 observed at $u/u_c = 1.0$. Minimum and average scour depths exhibit a local minima at $u/u_c = 2.0$ and an envelope curve of those minimum and average equilibrium depths coincides well with results of previous investigations, i.e., Melville and Coleman

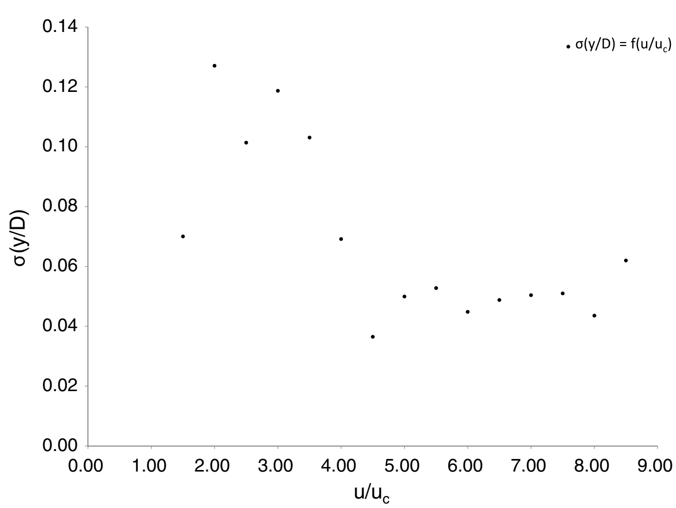


Fig. 8. SD σ of equilibrium scour depth y/D over u/u_c

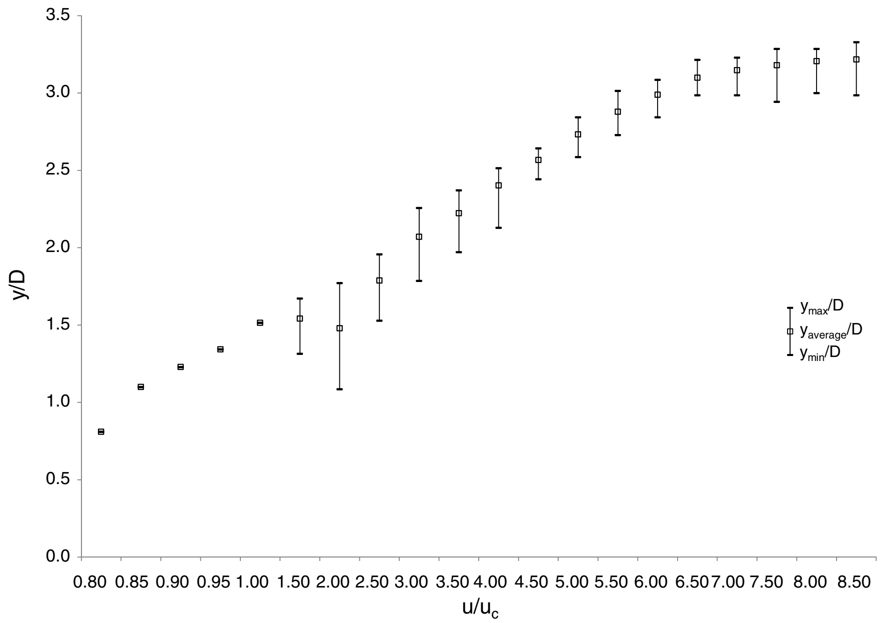


Fig. 9. Measured equilibrium scour depth y/D over flow intensity u/u_c

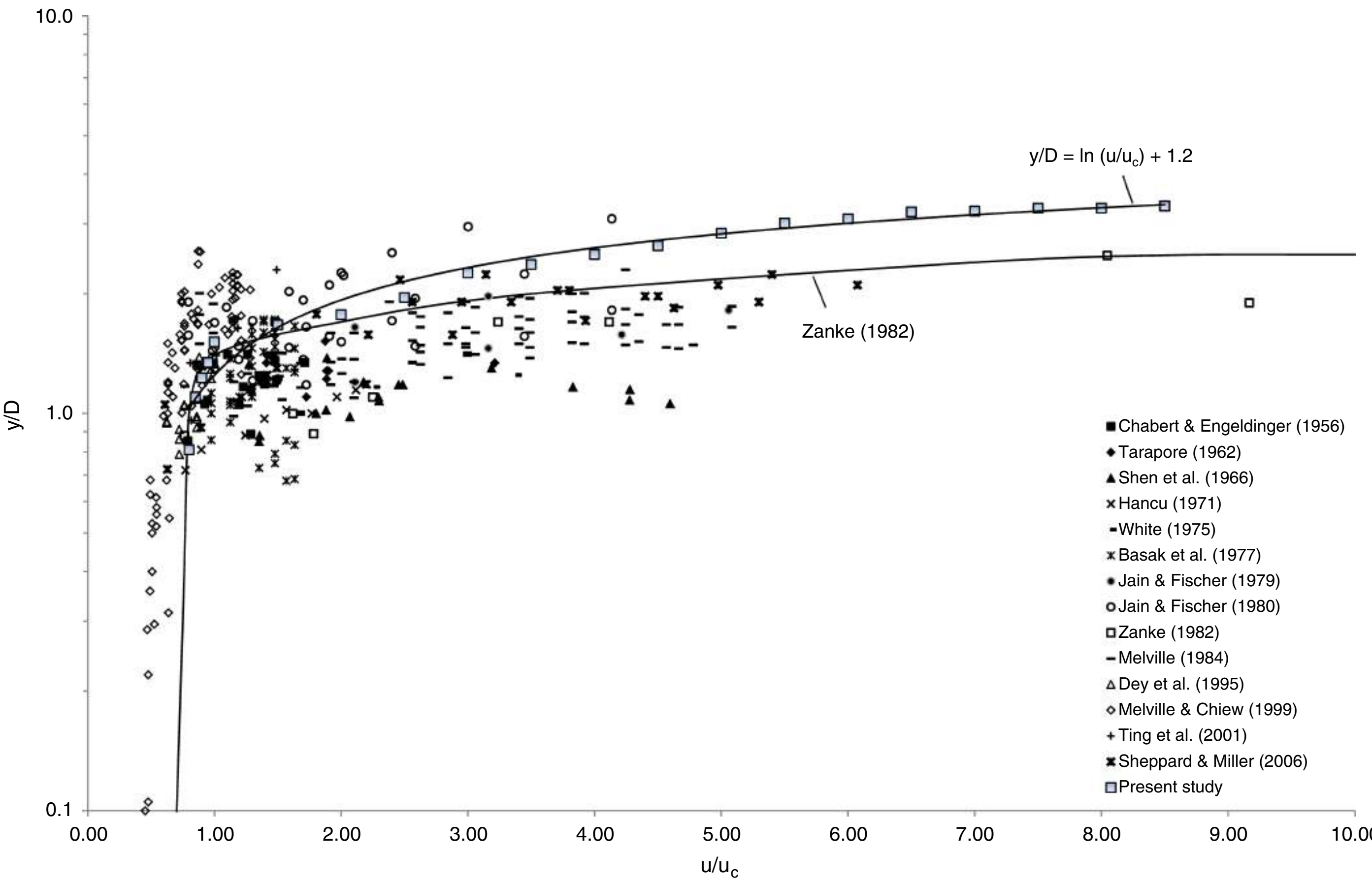


Fig. 10. Literature data and relative scour depth computed with Eq. (6) and additionally the maximum scour curve proposed from Zanke (1982)

(2000). Furthermore, it was detected that under bed-load conditions with $1 < u/u_c < 4$ the maximum scour depth was approximately 10–20% deeper than the average, while for $u/u_c \geq 4$ maximum scour depth was approximately 5% deeper than the average. That results accords well with results by Richardson and Davis (2001) who remark that maximum scour depth under sediment transport conditions can be significantly deeper than under clear-water conditions.

Influence of Boundary Conditions to Experimental Results

As shown in Eq. (3) further effects on scour depth in addition to those caused by low flow depth might be taken into account. In the presented experiments the relative flow depth was $h/D = 1.6$. That low ratio h/D was chosen to favor high flow intensities. Since ratios of $h/D > 1.5$ are required for an undisturbed scour process at bridge piers it is expected that higher ratios do not affect the reported behavior of scour. However, in reality, smaller relative flow depths might produce, if any, only slightly different scour (Melville and Coleman 2000). Additionally a generally agreed minimum ratio of flume width B to pier diameter D at which contraction effects on the flow and pier scour appear is $B/D > 8$ (Istiarto 2001). In the presented experiments $B/D = 60/7 = 8.6 > 8.0$. Consequently, contraction scour was negligible. In real-world cases, contraction scour might be present and should be added to the scour depth predicted by Eq. (6). The influence of the relative sediment roughness D/d to the scour process was investigated by Ettema (1980), Breusers and Raudkivi (1991), Melville and Chiew (1999), and Melville and Coleman (2000). According to Melville and Sutherland (1988) the influence of D/d to the scour hole process is negligible if $D/d > 25$. As the presented experiments were carried out with $D/d = 70/2 = 35$ it is expected that no further effects due to relative roughness influenced the presented results.

Estimation of Equilibrium Scour Depth onto a Lifelike Worst-Case Scenario

For practical purposes the prognosis of maximum scour depth for extreme flood situations is of interest. The maximum scour depth is needed for planning of bridge pier foundation and for the approximation of riprap protection around the pile. On the basis of the obtained results with u/u_c from 0.8 to 8.5 an approximation to the data with a logarithmic function is proposed according to

$$y_{\max}/D = \ln(u/u_c) + c \tag{6}$$

where c is a constant that takes the value of 1.2 for best data fit. Fig. 10 shows the literature data and relative scour depth computed with Eq. (6) for u/u_c up to 8.5 and additionally the maximum scour curve proposed from Zanke (1982). With respect to a worst-case scenario under lifelike conditions a conservative estimation is proposed by extrapolating Eq. (6) to a possible lifelike maximum of $u/u_c = 20$. Therefore, a maximum scour depth of $y/D = 4.2$ can be expected, which is significantly higher than scour depths under clear-water conditions.

Conclusions

A literature review showed an important scatter of the measured scour depth with the flow intensity in previous datasets, which is mainly attributed to differences in other controlling parameters like grain size, flow depth, and pier width. Even when tendencies observed in the single datasets were consistent for clear-water cases, they opened questions regarding magnitudes of expected scour under live-bed conditions. Thus, a systematic study on the isolated effect of flow intensity on scour was needed. Experiments on scour at a plexiglass cylinder embedded in a bed of polystyrene particles under clear-water and live-bed conditions have been presented. Experiments were conducted until equilibrium covering a wide range of flow intensities u/u_c, from 0.8 to 8.5. During the running experiments, scour depth was continuously measured with an endoscopic camera from inside the pier. Equilibrium scour was rapidly reached in the bed of polystyrene pellets. For flow intensities $1 < u/u_c < 4$ the main transport mode was bed load with dunes, and for $u/u_c \geq 4$ entrainment into suspension without development of bedforms dominated. In the clear-water experiments equilibrium scour depth remained constant whereas in the live-bed experiments equilibrium scour depth exhibited fluctuation in time, which in the bed load region was attributed to the migration of dunes passing the scour hole, and in the suspended load region was negligibly small, evidencing the transition to a flat bed. Minimum and average equilibrium scour depths varied with flow intensity exhibiting a local minima at $u/u_c = 2.0$ in good agreement with previous investigations. Maximum equilibrium depth was measured to $y_{\max}/D = 1.51$ and 3.3 for $u/u_c = 1$ and 8.5, respectively. Scour under live-bed conditions was significantly higher than under clear-water conditions, increasing with flow intensity. A logarithmic function was proposed for the extrapolation of the obtained results for estimation of scour depth in a lifelike worst-case scenario. The extrapolation showed that for ratios of $u/u_c = 20$ a scour depth of $y_{\max}/D = 4.2$ can be expected.

Acknowledgments

The financial support of the German academic exchange service Deutscher Akademischer Austauschdienst (DAAD) and the Chilean research council (CONICYT) through Grant PCCI 12027 is greatly acknowledged. The third author was also funded by Grant VRID 214.091.047-1.0. The polystyrene material was provided by Mr. Bernd Hentschel from the Federal Waterway Engineering and Research Institute Karlsruhe, Germany. Thanks go to the students Robert Koch and Franziska Richter and the research fellow Stefan Orlik, M.Eng., from the Department for Water and Waste Management of the University of Applied Sciences Magdeburg for their practical work and collaboration during the experimental runs.

Notation

The following symbols are used in this paper:

B = flume width;
D = pier diameter;
d = grain diameter, mostly d_{50};
D^* = dimensionless grain diameter;
d_{10} = sediment size for which 10% by weight is finer;
d_{50} = sediment size for which 50% by weight is finer;
d_{60} = sediment size for which 60% by weight is finer;
F = Froude number;
f = arbitrary function;
F' = particle Froude number;
g = gravitational acceleration;
h = section-averaged flow depth;
n = number of observations;
R' = particle Reynolds number;
t = time;
u = section-averaged velocity at the undisturbed bed;
u_c = critical velocity for the incipient motion of sediment particles;
ν = kinematic viscosity;
w = settling velocity of the sediment particles;
y = scour depth;
λ = geometric scale;
ρ = water density;
ρ_s = sediment density;
ρ' = relative density = $(\rho_s - \rho)/\rho$;
σ = standard deviation; and
σ_g = standard deviation of sediment particle sizes.

References

Alvarado, C., and Ettmer, B. (2008). "Agradation-degradation process of the Piura river during an El Niño event and corresponding realignement of the main cannel at Piura, Perú." *Hydraul. Eng. México*, 23(3), 5–28 (in Spanish).

Ansari, S. A., and Qadar, A. (1994). "Ultimate depth of scour around bridge piers." *Proc., ASCE National Hydraulics Conf.*, Vol. 1, Reston, VA, 51–55.

Basak, V., Baslamisli, Y. and Ergun, O. (1977). "Local scour depths around circular pier groups aligned with the flow." *Rep. No. 641*, State Hydraulic Works, Ankara, Turkey (in Turkish).

Bonneville, R. (1963). "Essais de synthese des lois de debut d'entrainement des sedimentes sous l'action d' un courant en regime uniforme." *Bulletin du Centre de Recherche et d'Education en Communication (CREC), No. 5*, Chatou, France (in French).

Breusers, H. N. C. (1965). "Conformity and time scale in two dimensional local scour." *Rep. Prepared for the Delft Hydraulics Laboratory*, Delft, Netherlands.

Breusers, H. N. C., Nicollet, G., and Shen, H. W. (1977). "Local scour around cylindrical piers." *J. Hydraul. Res.*, 15(3), 211–252.

Breusers, H. N. C., and Raudkivi, A. J. (1991). *Scouring*, Balkema, Rotterdam, Netherlands.

Chabert, J., and Engeldinger, P. (1956). "Study on scour around bridge piers." *Rep. Prepared for the Laboratoire National d'Hydraulique*, Chatou, France (in French).

Chitale, S. V. (1988). "Estimation of scour at bridge piers." *Water Energy Int.*, 45(1), 57–68.

Chreties, C., Simarro, G., and Teixeira, L. (2008). "New experimental method to find equilibrium scour at bridge piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2008)134:10(1491), 1491–1495.

Coleman, N. L. (1971). "Analyzing laboratory measurements of scour at cylindrical piers in sand beds." *Proc., 14th Congress of the Int. Association of Hydraulic Research (IAHR)*, Vol. 3, 307–313.

Dey, S., Bose, S. K., and Sastry, G. L. N. (1995). "Clear water scour at circular piers: a model." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1995)121:12(869), 869–876.

Dietz, J. W. (1969). "Scouring in fine or lightweight bed materials by subcritical flow." *Mitteilungen der Versuchsanstalt für Wasserbau und Kulturtechnik*, Theodor-Rehbock-Flußbaulaboratorium, Universität Karlsruhe, Heft, Germany, 1–120 (in German).

Ettema, R. (1980). "Scour at bridge piers." *Rep. No. 216*, School of Engineering, Univ. of Auckland, New Zealand.

Ettmer, B., Alvarado, C., and Ramírez-Bernini, P. (2009). "Local erosiona round waterworks: Scaling laws and predictability in physical models with fine sediments." *Hydraul. Eng. México*, 24(4), 23–36 (in Spanish).

Hancu, S. (1971). "Computation of local scour in the vicinity of bridge piers." *Proc., 14th Int. Association of Hydraulic Research (IAHR) Congress*, 299–305 (in French).

Heller, V. (2011). "Scale effects in physical hydraulic engineering models." *J. Hydraul. Res.*, 49(3), 293–306.

Istiarto, I. (2001). "FLOW around a cylinder in a scoured channel bed." Ph.D. thesis, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Jain, S. C. (1981). "Maximum clear-water scour around circular piers." *J. Hydraul. Div.*, 107(HY5), 611–626.

Jain, S. C., and Fischer, E. E. (1979). "Scour around bridge piers at high Froude numbers." *Rep. No. Federal Highway Administration (FHWA) 220*, Washington, DC, 79–104.

Jain, S. C., and Fischer, E. E. (1980). "Scour around bridge piers at high flow velocities." *J. Hydraul. Div.*, 106(HY11), 1827–1842.

Johnson, P. A. (1992). "Reliability-based pier scour engineering." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1992)118:10(1344), 1344–1358.

Jones, J. S., and Sheppard, D. (2000). "Scour at wide bridge piers." *Building Partnerships*, ASCE, Reston, VA, 1–10.

Kothyari, U. C., Garde, R. C. J., and Ranga Raju, K. (1992). "Temporal variation of scour around circular bridge piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1992)118:8(1091), 1091–1106.

Larras, J. (1963). "Maximum scour depths around bridge piers in rivers." *Annales des Ponts et Chaussées*, 133(4), 411–424 (in French).

Laursen, E. M., and Toch, A. (1956). *Scour around bridge piers and abutments*, Iowa Highway Research Board, Iowa State Univ., Ames, IA.

Link, O. (2006). *An investigation on scouring around a single cylindrical pier in sand*, Vol. 136, Mitteilungen des Institutes für Wasserbau und Wasserwirtschaft der Technischen Universität Darmstadt, Heft, Germany (in German).

Melville, B. W. (1984). "Live-bed scour at bridge sites." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1984)110:9(1234), 1234–1247.

Melville, B. W. (1997). "Pier and abutment scour: Integrated approach." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1997)123:2(125), 125–136.

Melville, B. W., and Chiew, Y.-M. (1999). "Time scale for local scour at bridge piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1999)125:1(59), 59–65.

Melville, B. W., and Coleman, S. E. (2000). *Bridge scour*, Water Resources, Littleton, CO.

Melville, B. W., and Sutherland, A. J. (1988). "Design method for local scour at bridge piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1988)114:10(1210), 1210–1226.

Neill, C. R. (1973). *Guide to bridge hydraulics*, Roads and Transportation Association of Canada, University of Toronto Press, Toronto.

Oliveto, G., and Hager, W. H. (2002). "Temporal evolution of clear-water pier and abutment scour." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2002)128:9(811), 811–820.

Raudkivi, A. J. (1986). "Functional trends of scour at bridge piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1986)112:1(1), 1–13.

Richardson, E. V., and Davis, S. R. (2001). *Evaluating scour at bridges*, 4th Ed., Federal Highway Administration, Washington, DC.

Shen, H. W., Schneider, V. R., and Karaki, S. (1969). "Local scour around bridge piers." *J. Hydraul. Div.*, 95(HY6), 1919–1940.

Shen, H. W., Schneider, V. R., and Karaki, S. S. (1966). *Mechanics of local scour*, National Bureau of Standards, Washington, DC.

Sheppard, D. M., and Miller, W., Jr. (2006). "Live-bed local pier scour experiments." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2006)132:7(635), 635–642.

Simarro, G., Fael, C. M. S., and Cardoso, A. H. (2011). "Estimating equilibrium scour depth at cylindrical piers in experimental studies." *J. Hydraul. Eng.*, 10.1061/(ASCE)HY.1943-7900.0000410, 1089–1093.

Tarapore, Z. S. (1962). "A theoretical and experimental determination of the erosion patterns caused by obstructions in an alluvial channel with particular reference to a vertical cylindrical pier." Ph.D. thesis, Univ. of Minnesota, Minneapolis.

Ting, F. C. K., Briaud, J.-L., Chen, H. C., Gudavalli, R., Perugu, S., and Wei, G. (2001). "Flume tests for scour in clay at circular piers." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(2001)127:11(969), 969–978.

van Rijn, L. C. (1984). "Sediment transport. Part I: Bed load transport." *J. Hydraul. Eng.*, 10.1061/(ASCE)0733-9429(1984)110:10(1431), 1431–1456.

White, W. R. (1975). "Scour around bridge piers in steep streams." *Proc., 16th IAHR Congress*, Vol. 2, 279–284.

Zanke, U. (1982). "Scour at piles in steady unidirectional flow and under the action of waves." *Rep. Prepared for the Mitteilungen des Franzius-Instituts*, Universität Hannover, Heft, Germany (in German).