ON THE TIME-DEPENDENT SCOUR-HOLE VOLUME EVOLUTION AT A CIRCULAR PIER IN UNIFORM COARSE SAND

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An experimental study of the time-dependent scour hole volume evolution at a circular pier in uniform coarse sand (0.6 - 2.0 mm) is presented. The results are of practical relevance, because they show a mathematical correlation between the scour volume and the maximum scour depth for water depth on pier diameter ratios between 1 and 2. Laboratory tests were conducted in a 40 m long, 2 m wide and 1 m deep flume under clear water and live bed conditions. The scour geometry was measured with a laser distance sensor placed in a 20cm diameter plexiglass pier. Data were aquired over eight vertical profiles during about 20 hours. The obtained results allow to extend information from scour monitoring that usually consists of a continuous record of the scour depth in front of the pier. In bridge pier design, empirical formulas for maximum scour depth estimation present discrepances in the order of a factor five, which result in very conservative security factors that significantly increase the bridge costs since to achieve stability longer piers must be also wider. The design process can be optimized if one assumes smaller design scour depths, but considering some management of the foundation soil, i.e.: periodically refillment of the scoured volume. The important questions that arise are when to refill a scour hole and what amount of material is needed. The results are also usefull for numerical model calibration and validation, since the provided information is fully three-dimensional in time.

1 Introduction

Scouring of foundation sourrounding sediment is the most common cause of bridge failure. Traditional scour countermeasurements like rip-rap, collars, deflectors or matresses are usually implemented at the beginning of the structure life and also produce additional local scour problems. Since scour formulas are still very unaccurate and produce discrepant results, to avoid structural failures some large security factors must be considered in the determination of design scour depths with the problem that larger piers notably increase the bridge costs. Zanke (1994) proposed the use of empty piers which are filled with rip-rap material. As scour progresses, the rip-rap automatically fills the scoured hole, difficulting local scouring around a pier that is highly dependent on the initial or actual conditions imposed by the scour hole geometry (Link and Zanke, 2002). Following this idea, it is important to somehow estimate the scour volume in time. Figure 1 shows laboratory tests of a hollow pier filled with rip-rap material. Since usually the scour depth monitoring consist in a record of the maximum scour depth at the nose of the pier, laboratory experiments were conducted to obtain an empirical relation between scour volume and maximum scour depth. In the literature, there are few authors who based a sediment mass balance at the scour hole scale to derive a scour-predictor equation. Some of them assumed the scour hole geometry as the one of a frustum of an inverted cone, e.g. Yanmaz and Altinbilek (1991) and Mia and Nago (2003). Others, like Dey (1999) assumed the volume as a third order polynomial function of the maximum scour depth, $O(z_{max}^3)$. Zanke (1982) assumed it as a parabolic function.

Figure 1. Laboratory test of a hollow pier filled with rip-rap (source: Zanke, 1994).

In field cases, prediction of scour around bridge piers is affected by pier and channel geometry and by non stationary discharges, among others. These effects are difficult to take into account by using empirical scour-predictor formulas and a better estimation can be achieved through numerical modelling. For hydrodynamic simulation of flow around piers, usually scour scenarios are assumed to provide the bed geometry. Kamil and Karim (1998) predicted the flow field around a cylinder for rigid beds and for scour holes of different sizes resulting from different time-durations. Richardson and Panchang (1998) calculated the flow field around a cylinder in an inverted frustum of a cone. Recently, Salahedin, Imran and Chaudhry (2004) performed computations of the flow field around a cylinder in a flat bed and in a scour hole with different turbulence models and compared the obtained results. The numerical modelling of scouring must include the bed evolution as part of the model. Some complete models has been proposed by Olsen and Melaaen (1993) and Yen, Lai and Chang (2001). Anyway, there is a clear lack of experimental information concerning the 3D flow field and scour geometry to calibrate and validate numerical models. In this article, experimental results on scour geometry evolution are presented.

2 Experimental Setup

The experiments were carried out in a flume 26 m long, 2.0 m wide, and 1.0 m deep, using a 20 cm-diameter cylindrical pier. In the experiments, the grain size corresponded to a uniform mixture of coarse sand ranging between 0.6 and 2.0 mm with a d_{50} of 0.97 mm. The geometric standard deviation of the grain size was 1.4. The depth and velocity of the approach flow were systematically varied. The flow rate in the flume was adjusted using an electronic valve and the flow depth was measured with a point gauge. The average flow velocities were determined from the continuity condition.

The scour hole geometry was measured with a laser distance sensor. The sensor was installed inside the pier and the scour hole radius was measured. To take vertical profiles, the sensor was mounted on a step motor. The step motor was mounted on a rotary plate, so that profiles in all directions around the pier could been recorded. Data were aquired with a frequency of 70 Hz. 30 measurements on each point were recorded. Figure 2 shows a typicall measurement of the scour hole geometry. 8 vertical profiles has been taken on four different direction around the pier at 0°, 45°, 90° and 135° with respect to the symmetry plane. The scour hole volume for each measurement was computed from the eight vertical profiles through convolution.

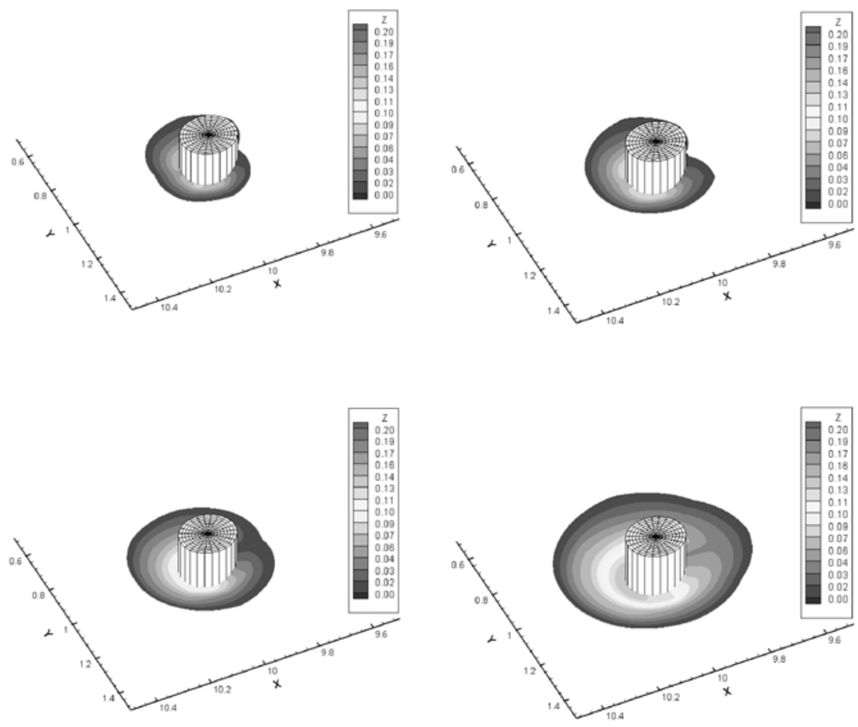

Figure 2. Measured scour hole geometry after 0.44, 0.93, 3.41 and 13.07 hours.

Clear-water experiments were conducted during about 20 hours until a quasi-equilibrium stage was reached, i.e. scour progressed at about d_{50} mm per hour. Live-bed experiments were conducted during about 6 hours, after six or seven dunes passed through the scour hole. Since for the live bed experiments, the time required for the development of the most active scour-stage was in the same order of magnitude as the time required for the development of natural dunes, manually prepared sand-dunes were implemented as reported by Talmon, van Mierlo and Struiksama (1995). The dimensions of the dunes were based on previous experimental results for the same material and hydraulic conditions.

Three sets of experiments with different approach flow velocity, u_∞ have been carried out. Each set consisted of experiments with different approach flow depth, H. In the first set the flow velocity was set to 0.5 times the critical velocity, u_{cr} . In the second set the velocity was adjusted slightly under the critical velocity. In the third set the velocity was adjusted to 2 times the critical velocity. In each set, the approaching flow depth was varied between one and two pier diameters, b. The relevant parameters of the experimental conditions are summarised in table 1.

Table 1. Summary of tests conditions.

Set	Run	u_∞ / u_{cr}	H/ b
1	1	0.5	1.00
1	2	0.5	1.50
1	3	0.5	2.00
2	1	1.0	1.00
2	2	1.0	1.25
2	3	1.0	1.50
2	4	1.0	1.75
2	5	1.0	2.00
3	1	2.0	1.00
3	2	2.0	1.50
3	3	2.0	2.00

3 Experimental Results

Scour started at the sides of the cylinder, about 55° from the symmetry plane. From the sides, scour progressed to the front of the pier and after a very short time (about 5-10% of the defined equilibrium stage) the maximum scour depth was found at the nose of the pier. Figure 3 show the scoured volume on time for different hydraulic conditions. For each serie the average velocity was kept constant and the water depth was varied. Three velocities were tested, corresponding to the minimal condition necessary for scour initiation, the critical velocity for the initiation of sediment motion and a live-bed condition.

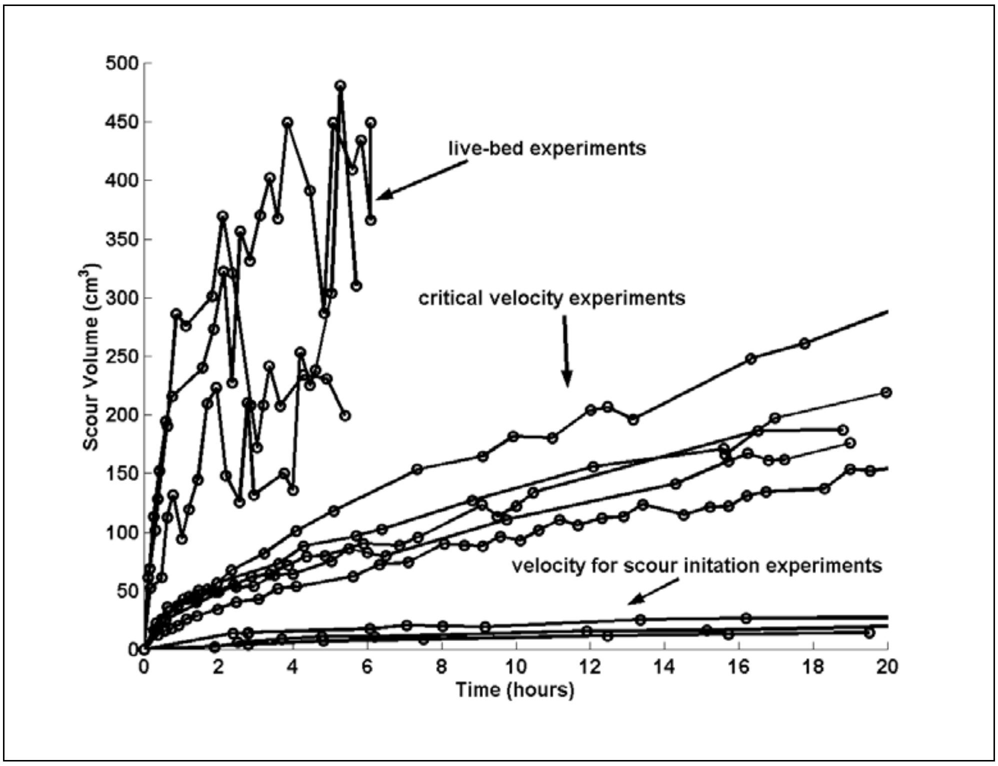

Figure 3. Scour hole volume on time.

The form of the scour hole remained constant during its development, i.e. the relation between volume and maximum scour depth remained the same independently from hydraulic conditions and time point at which it was achieved. Figure 4 show the maximum scour depth on maximum scour radius.

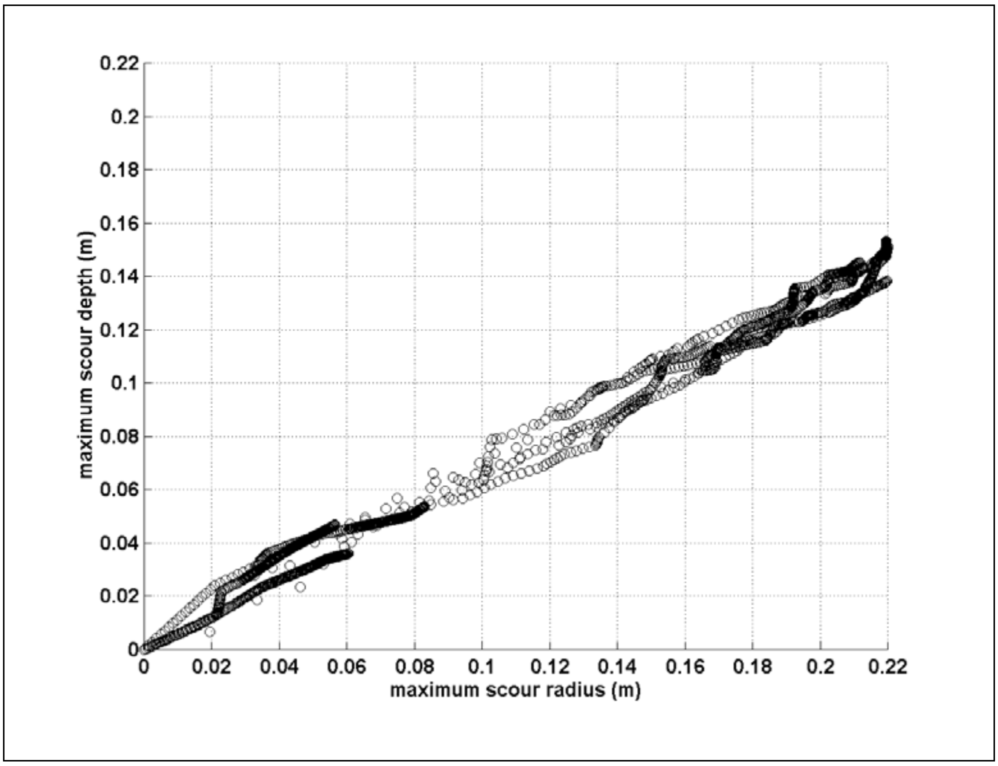

Figure 4. Maximum scour depth on maximum radius.

If one plots the scoured volume on the maximum scour depth, it is found that with some scatter of about ±35%, all the experiment collapse on one single curve following:

$$V = (7z^2 + 5z)10^{-5} \quad (m^3) \tag{1}$$

Equation (1) can be used for the estimation of the scour volume, with the maximum scour depth as independent variable.

Figure 5 shows the scour hole volume on maximum scour depth for all the conducted experiments. The volume of a frustum of an inverted cone on the maximum scour depth is also plotted in figure 4. Provided that the hole side angle of inclination is given, this approximation gives also acceptable results for small scour holes but tends to overestimate the scoured volume by live-bed experiments, when scour holes result larger. For the presented experiments, the side angle of inclination was 34°, about 15% higher than the natural angle of repose.

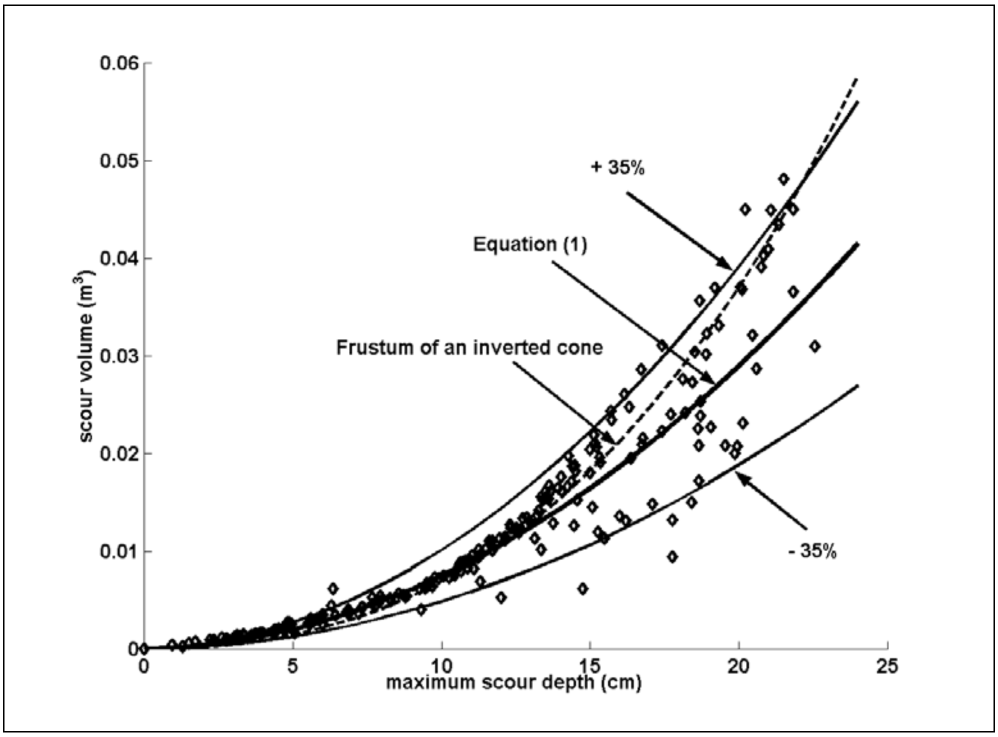

Figure 5. Scour hole volume on maximum scour depth for clear-water and live-bed experiments.

4 Conclusions

Laboratory experimental results on time-dependent scour hole evolution were presented. It was shown that the scour volume can be assumed as a parabolic function of the maximum scour depth, accordingly to equation (1). This is of practical relevance in the use field scour monitoring data, because usually only information about the maximum scour depth is registered and the amount of refilling-material is desired for a good management of the foundation sourrounding bed.

The presented data can be used for the calibration and validation of numerical models of scour around bridge piers. Complementary, velocity fields measurements were taken during the experiments.

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