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Estimación de la profundidad de socavación local bajo condiciones hidráulicas impermanentes

(Effective flow work for estimation of pier scour under flood waves)

Tesis para optar al grado de Magister en Ciencias de la Ingeniería con mención en Ingeniería Civil

ALONSO VICENTE PIZARRO VALDEBENITO
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Profesor Guía: Oscar Link Lazo
Dpto. de Ingeniería Civil, Facultad de Ingeniería
Universidad de Concepción

ABSTRACT

Bridges are important for society, especially for the mobility, economy and development of humanity. The main objectives for the design of bridges are linked to life expectancy, stability, and safety during natural extreme events such as earthquakes and floods. The global climate change increases the magnitude and frequency of extreme precipitations and floods events confirming the necessity for a better bridge-pier design ad-hoc to unsteady hydraulic conditions. Generally during a flood event, the maximum scour depth at peak-flow may be smaller than the equilibrium scour depth, which is commonly estimated using peak-flow conditions for design of bridge piers. If the local scour depth is sub-estimated the hydraulic structure can fail and on the other hand, if this scour depth is overestimated, that construction has no economic justification.

The objective of this work was to study the impact of the shape, duration and peak discharge of flood hydrograph on the maximum scour depth under clear-water scour conditions and over natural uniform sediment. Scour experiments were conducted at the Laboratory of Hydraulic Engineering, University of Concepción, with constant discharges until equilibrium and with hydrographs having different duration, shapes and peak discharge.

Finally, the pier scour caused by flood waves is analyzed introducing the idea of an effective work by the flow on the sediment bed around the pier. Following dimensional considerations, the author shows different possible formulations for the dimensionless flow work W^* and the corresponding dimensionless parameters that govern scouring. In each case, the dimensionless flow work is shown to be a generalization of the flow intensity concept u/u_c, commonly used in existent scour formulas. A novel experimental installation able to reproduce any hydrograph with high precision in the laboratory flume is described and four series of experiments are presented. The first series consists of experiments with constant discharge until advanced stages of scour. The second and third series, of scour experiments with flood waves of different shapes and durations, respectively. The fourth series consists of scour experiments caused by hydrographs with multiple peaks. Results confirm that the dimensionless flow work W^* represent a reliable concept for the prediction of scour caused by any hydrograph.

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CHAPTER 1 INTRODUCTION

1.1 Motivation

Recent advances in bridge scour monitoring and development of scour countermeasures motivate research on the pier scour caused by single hydrologic events like flood waves, and in general by real hydrographs. In deep knowledge on the flood wave scour might provide an alternative to sounding approaches in hydraulic design of bridge piers, which consider an extreme peak discharge, typically a 100-years flood, acting on the sediment bed over a theoretically infinite duration, i.e. at least the flood duration must equal the equilibrium time needed to achieve equilibrium or final scour. This approach is followed in several design guidelines worldwide, e.g. Federal Highway Administration (FHWA), German Association for Water, Wastewater and Waste (DWA), New Zealand, and Chilean Ministry of Public Works. With the exception of large rivers however, floods are typically much shorter than equilibrium time. The latter is typically in the order of weeks for alluvial sediments, i.e. sand and gravels. Consequently, after a single hydrological event scour might be smaller than equilibrium scour for a number of cases. Also, several floods with peak discharges smaller than the 100-years discharge might produce comparable scour, depending on the lasting time. Motivated by this fact, the author investigated the bridge pier scour caused by flood waves. The aim was to determine sets of controlling parameters for prediction of maximum scour depth around a bridge pier after the passage of flood waves and to explore the functional relationship between scour depth and the effective flow work.

River floods are single, long, gravitational waves that produce scour in a different mode than coastal, periodic waves such as wind and tidal waves, which are well represented in terms of the Keulegan-Carpenter number. Flood waves exhibit a hydrograph characterized by its peak discharge, base time or duration, and shape. Additionally, base flow as well as time to peak can be indicative of interesting hydrological aspects of the flood, like rainfall intensity and runoff, land uses and basin lag time. Moreover, hysteretic effects might even change relations between flow velocity, flow depth, discharge, and bed shear stress during rising and recession limbs.

Unsteady scour around bridge piers was previously studied for rather idealized hydrographs, such as the step hydrograph, the triangular hydrograph, and the exponential hydrograph. Lai *et al.* (2009) assumed that recession is not important for scouring. However, when flood duration is significantly smaller than equilibrium time, as in a number of real cases, recession is expected to play an important role in final scour depth. Thought the flow acceleration during flood waves is small, it is completely neglected when using step hydrographs. The lack of more realistic hydrograph shapes in previous investigations is attributed to the experimental difficulties associated with precise discharge control in laboratory flumes. Scour rate is highly dependent on antecedent scour depth, thus application of existent formulas for estimation of scour depth caused by a flood wave is not straightforward, especially in case of complex hydrograph shapes.

1.2 Hypothesis

The research hypothesis was that the scour depth depends of sediment properties, but not to the flow conditions.

1.3 Objectives

1.3.1 General objective

The research objective of this study was to study the impact of the shape, duration and peak discharge of flood hydrograph on the scour evolution process under clear-water scour conditions and over natural and uniform sediment.

1.3.2 Specific objectives

To achieve the research objective the following tasks are defined:

a) Identify the main variables in the local scour phenomenon.

b) Make dimensional analysis.

c) Make experiments in laboratory.

d) Process experimental data to find the influence of different hydraulic flow parameters and time on the local scour parameters.

e) Find experimentally the mathematical relation between the effective flow work W^* over the dimensionless scour depth Z^* under steady and unsteady flow conditions.

1.4 Methodology

In this work, an experimental installation able to reproduce any hydrograph shape at the laboratory scale was used and the flow intensity concept to the unsteady case was generalized, in order to estimate maximum scour depth produced by different hydrographs. Experiments on scour were conducted with constant discharges until equilibrium and with hydrographs having different duration, shapes and peak discharge. All the experiments were conducted under clear-water scour condition and over natural and uniform sediment.

1.5 Structure of the thesis

In the next section, a dimensional analysis, showing sets of controlling parameters of the flood wave scour, including different possibilities for the definition of the dimensionless flow work is presented. In the third section, the experimental setting adopted in the present work is described. Thereafter, the obtained results on scour under flood waves are analyzed and commented. The last section of the conclusion contains the final remarks on the obtained results.

CHAPTER 2 DIMENSIONAL ANALYSIS

2.1 Important variables influencing the bridge pier scour

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

$$f(\mu, \rho, u, h, g, d_s, \rho_s, \sigma, D, t, z) = 0, \tag{2.1}$$

where z is the time-dependent scour depth; μ is the fluid dynamic viscosity; ρ is the fluid density; u is the section averaged flow velocity; h is the flow depth; g is the gravitational acceleration; d_s is the representative sediment particle diameter; ρ_s is the density of a sediment particle; σ is the standard deviation of the sediment particle sizes; D is the pier diameter; and t is the time. Equation 2.1 constitutes the base of all scour formulas.

Ettema *et al.* (1998) analyzed the scale effects in pier scour experiments. In their analysis sediment density and standard deviation of grain sizes were omitted in Equation 2.1, but instead the section averaged critical velocity for initiation of motion of sediment particles u_c was introduced. Taking ρ, u, and D as repeating variables, after proper combination they obtained:

$$f\left(\mathrm{Re}_{pier}, \mathrm{Fr}_{pier}, \frac{u}{u_c}, \frac{h}{D}, \frac{d_s}{D}, \frac{z}{D}\right) = 0, \tag{2.2}$$

where $\mathrm{Re}_{pier} = \rho u D/\mu$ is the pier Reynolds number; $\mathrm{Fr}_{pier} = u^2/(gD)$ is the pier Froude number; u/u_c is the flow intensity; h/D is the relative pier size; d_s/D is the relative roughness; and z/D is the relative scour depth. Further, Ettema *et al.* (2006) analyzed the effects of pier Reynolds and Froude numbers on scour, linking them to the large scale turbulence.

Other sets of dimensionless parameters explaining scour can be obtained if different repeating variables are considered. Taking ρ, u, and d_s, Equation 2.1 leads to:

$$f\left(\frac{\rho u d_s}{\mu}, \frac{u^2}{g d_s}, \frac{\rho_s}{\rho}, \sigma, \frac{h}{d_s}, \frac{D}{d_s}, \frac{ut}{d_s}, \frac{z}{d_s}\right) = 0, \tag{2.3}$$

Proper combination of the first three parameters leads to the dimensionless particle diameter $D^* = \left((\rho' g)/\nu^2\right)^{1/3} d_s$, where ρ' is the relative particle density, and ν the kinematic viscosity. Rearranging Equation 2.3:

$$f\left(D^*, \rho', \sigma, \frac{u^2}{\rho' g d_s}, \frac{h}{d_s}, \frac{D}{d_s}, \frac{ut}{d_s}, \frac{z}{d_s}\right) = 0, \tag{2.4}$$

The group of dimensionless parameters presented in Equation 2.4 is rewritten to consider an unsteady condition. Following Bagnold (1966), the rate of work done on a unit bed area by the flow to transport sediment is $w \sim \tau_0 u$ and as the shear stress is $\tau_0 \sim \rho u^2$ the rate of work is proportional to the velocity cubed: $w \sim u^3$. Lai *et al* (2009) adopted the concept by Bagnold (1966) for the particular case of scour caused by a rising hydrograph, proposing:

$$w = \int_0^{t_p} \left(\frac{u(t)}{u_c} - 0.5\right)^3 dt, \tag{2.5}$$

where t_p is the time to peak and 0.5 is a threshold for incipient scouring around a cylindrical pier.

2.2 Dimensionless flow work W^*

Considering the rising and recession limbs in dimensionless form the author proposes:

$$W^* = \int_0^{t_{end}} \frac{1}{t_R} \left(\frac{u - 0.5u_c}{u_R} \right)^3 \delta \, dt \, , \tag{2.6}$$

where W^* is the dimensionless flood work, t_{end} is the hydrograph duration, t_R and u_R are a reference time and velocity, respectively. Implicitly, W^* includes effects of hydrograph shape, duration and peak discharge on scour, during the rising and recession limbs. For practical purposes, it is assumed that scour occurs when $u \geq 0.5u_c$, thus:

$$\delta = \begin{cases} 0 & u/u_c < 0.5 \\ 1 & u/u_c \geq 0.5 \end{cases} \, , \tag{2.7}$$

The dimensionless flow work is a generalization of the flow intensity concept to the unsteady case. Equation 2.4 can be written as:

$$Z^* = f\left(D^*, \rho', \sigma, \frac{h}{d_s}, \frac{D}{d_s}, W^* \right). \tag{2.8}$$

2.3 Alternatives for the reference values

Three alternatives are analyzed for the reference values:

a) Reference time and velocity correspond to equilibrium time and critical velocity. Thus:

$$W^* = \int_0^{t_{end}} \frac{1}{t_{eq}} \left(\frac{u}{u_c} - 0.5 \right)^3 \delta \, dt \, , \tag{2.9}$$

and for the steady case:

$$Z^* = f\left(D^*, \rho', \sigma, \frac{h}{d_s}, \frac{D}{d_s}, \frac{u}{u_c}, \frac{t}{t_{eq}}\right), \qquad (2.10)$$

Assuming the absence of viscous effects and constant relative density of sediment, a possible expression for the scour depth at a cylindrical pier in uniform sediment is:

$$Z^* = f\left(\frac{h}{D}, \frac{d_s}{D}, \frac{u}{u_c}, \frac{t}{t_{eq}}\right), \qquad (2.11)$$

where $Z^* = z/D$. Equation 2.11 is the basis of the scour formula by Melville and Chiew (1999).

b) Reference time and velocity correspond to definitions by Oliveto and Hager (2002):

$$z_R = \left(D^2 h\right)^{1/3}, \qquad (2.12)$$

$$u_R = \sqrt{\rho g d_s}, \qquad (2.13)$$

$$t_R = \frac{z_R}{u_R} = \frac{\left(D^2 h\right)^{1/3}}{\sqrt{\rho g d_s}}, \qquad (2.14)$$

For the steady case:

$$Z^* = f\left(D^*, \rho', \sigma, \frac{u}{u_R}, \frac{z_R}{d_s}, \frac{D}{d_s}, \frac{t}{t_R}\right), \qquad (2.15)$$

Assuming the absence of viscous effects, constant the relative density of sediment and neglecting influences of flow depth, a possible expression for the scour depth at a cylindrical pier in uniform sediment is:

$$Z^* = f\left(\frac{u}{u_R}, \frac{D}{d_s}, \frac{t}{t_R}\right), \qquad (2.16)$$

where $Z^* = z/z_R$. Equation 2.16 is the basis of the scour formula by Oliveto and Hager (2002).

c) Following Guo (2014), the characteristic time for the pier local scour phenomenon based on the mass conservation law is:

$$t_c = \frac{D^2}{d_s\left(2u - u_c\right)} \ , \tag{2.17}$$

taking the reference velocity by Oliveto and Hager (2002), it can be shown that:

$$t_c = \frac{D^2}{d_s\left(2u - u_c\right)} = \frac{D^2}{2d_s u_R \left(\frac{u - 0.5u_c}{u_R}\right)} = \frac{z_R}{u_R \left(\frac{u - 0.5u_c}{u_R}\right)} = \frac{t_R}{\left(\frac{u - 0.5u_c}{u_R}\right)} \ , \tag{2.18}$$

$$t_R = \left(\frac{u - 0.5u_c}{u_R}\right) t_c \ , \tag{2.19}$$

with $z_R = D^2/2d_s$ .Thus the dimensionless work parameter is:

$$W^* = \int_0^{t_{end}} \frac{1}{t_c}\left(\frac{u - 0.5u_c}{u_R}\right)^3 \delta\, dt = \int_0^{t_{end}} \frac{1}{t_R}\left(\frac{u - 0.5u_c}{u_R}\right)^4 \delta\, dt \ , \tag{2.20}$$

Herein, Equation 2.15 applies for the steady case, but taking the definitions for the reference variables of alternative c).

In the following, the predictive ability of W^* on Z^* is investigated experimentally using several different hydrographs.

CHAPTER 3 EXPERIMENTAL SETUP

Scour experiments were conducted at the Laboratory of Hydraulic Engineering, University of Concepción, Chile. Tests were conducted within an in-floor rectangular flume of 26 m long, 1.5 m wide and 0.74 m deep. A Plexiglas cylindrical pier with a diameter D = 0.15 m was mounted in the middle of a sediment-recess located 20 m downstream of the flume entrance. The sediment-recess had a length of 2 m, a width of 1.5 m and a depth of 0.3 m. Details are given in Link *et al.* (2013).

3.1 Measuring techniques

Discharge was controlled with a closed loop control system, taking the measured discharge and flow depth as output. Corrections to account for differences between specified and measured discharges were made on the frequency of the pump motor, based on a fuzzy logic feedback through a programmable logic controller (PLC) and a variable-frequency drive (VFD). The discharge was measured with an orifice plate device installed in the recirculation system with a precision of ±1%. Flow depth was controlled by adjusting the tail gate at the end of the flume, and was measured with ultrasonic distance sensors (UDS) placed along the flume. The closed loop control system allowed the generation of practically any given discharge time series, and thus the simulation of flood waves and hydrographs with different duration, peaks and shape.

The scour-hole radius was measured with an accuracy of ±0.4 mm using a laser distance sensor (LDS) located inside the Plexiglas pier and aligned in horizontal and radial direction, so that no refraction on the cylinder wall was observed. The sensor was driven in the vertical direction by a step-motor with a precision of ±1/50 mm. In the azimuthal direction, the vertical positioning system was driven by a second step-motor with an accuracy of ±1/100°. That allowed the turnaround view of the distance sensor in the scour-hole, taking various vertical profiles in different azimuthal half- planes, determining the azimuthal half-plane where maximum scour depth occurred. The measured radius R, vertical coordinate z and the azimuthal coordinate of the sensor position were registered with a frequency of 70 Hz.

Figure 3.1 shows a schematic view of the experimental installation in the flume, the LDS device for measuring scour installed inside the plexiglass cylindrical pier, and the flow controlling system.

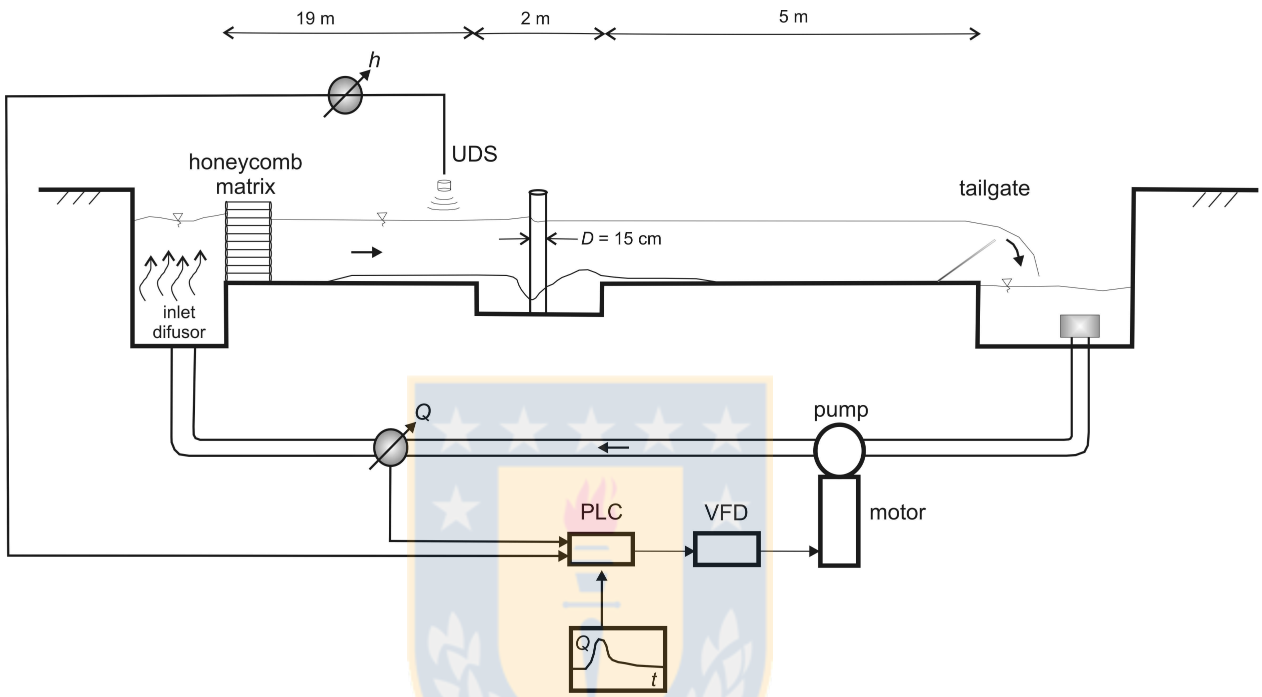

Figure 3.1 Schematic view of the experimental installation with scheme of the flow controlling system

3.2 Bed material

In the experiments, fine sand was used as bed material. Particle density and characteristic grain diameters were determined following standard soil mechanics procedures. The critical velocity for the incipient motion of the sediment particles u_c was experimentally determined in preliminary runs with the same hydraulic conditions as in the scour experiments. Table 3.1 summarizes the properties of the bed material.

Table 3.1 Properties of the bed material

Property	**Quantity**
Density ρ_s (kg/m³)	2650
Characteristic grain diameter d_{84} (mm)	0.59
Characteristic grain diameter d_{50} (mm)	0.36
Characteristic grain diameter d_{16} (mm)	0.28
Geometric standard deviation of sediment size distribution σ	1.45
Critical velocity u_c (m/s)	0.32

3.3 Hydraulic conditions and experimental series

Experiments on scour were conducted with constant discharges until equilibrium and with hydrographs having different duration, and shapes. Maximum discharge during an experiment corresponded to 95% of Shields critical condition for the initiation of motion of the sand particles at the undisturbed plane bed. Thus, the runs corresponded to clear water conditions. A base flow of 35 l/s and a section averaged flow depth of h = 0.21 m, corresponding to a flow intensity of 0.37, were imposed as initial condition. A total of four experimental series is analyzed: Series A included two scour experiments with constant discharge having different flow intensities, with the aim of exploring the relationship between W* and Z* until advanced stages of scour. Series B and C included hydrographs with different shapes and duration, but the same W^* in order to test the validity of the parameter for representing scour caused by any given hydrograph. Finally, Series D included hydrographs with multiple peaks and shapes closer to reality for testing the effects of flow acceleration. Figure 3.2 shows the hydrographs corresponding to each experiment.

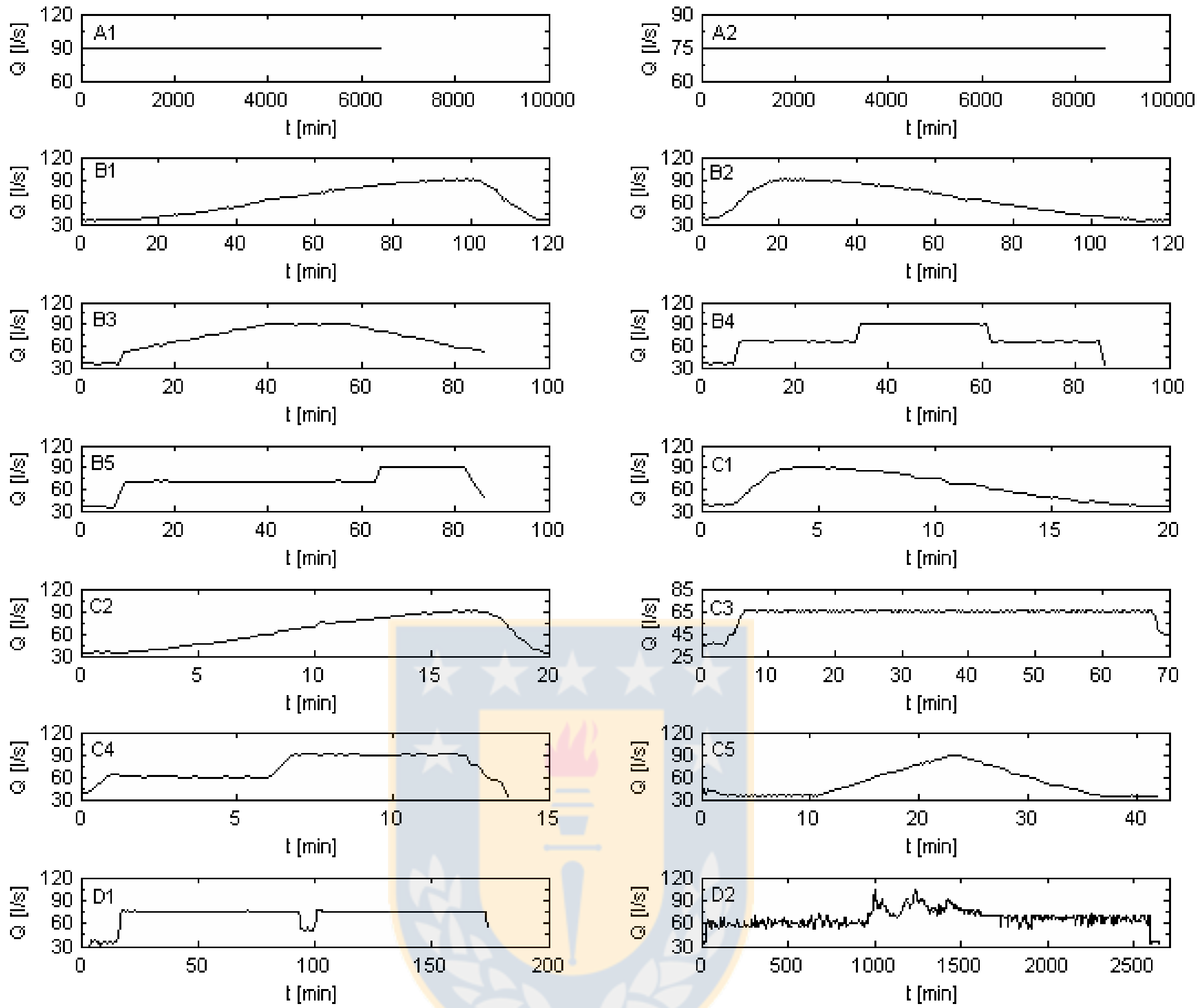

Figure 3.2 Hydrographs in the different experimental runs

Remarkably, the experimental installation was able to generate constant, sinusoidal, step, triangular, and multiple peaks hydrographs. Table 4.1 summarizes the hydraulic conditions in the experimental series.

CHAPTER 4 RESULTS

Results corresponding to a total of fourteen scour experiments are analyzed. In all experiments dimensionless particle diameter $\left(D^* = 9\right)$, relative density $\left(\rho' = 1.65\right)$, standard deviation of sediment particle sizes $\left(\sigma = 1.45\right)$, relative depth $\left(h/d_s > 600\right)$, and relative roughness $\left(D/d_s = 416.67\right)$. Table 4.1 summarizes the experimental runs, covering peak discharges from 65 to 104.5 l/s, and durations from 13 to 8600 minutes. The resulting scour depth varied from 16 to 80% of the equilibrium scour depth.

Table 4.1 Summary of the experimental results obtained for each of the hydrograph considered

(1) No.	(2) Q_B (l/s)	(3) Q_P (l/s)	(4) u_B (m/s)	(5) u_P (m/s)	(6) h_B (m)	(7) h_P (m)	(8) t_P (min)	(9) u_P/u_c (-)	(10) $h_P/z_R \times 10^{-3}$ (-)	(11) W^* (-)	(12) $Z^* \times 10^{-3}$ (-)
A1	90	90	N/A	0.29	N/A	0.22	N/A	0.91	7.0	9498	7.14
A2	75	75	N/A	0.24	N/A	0.23	N/A	0.76	7.4	1112	5.66
B1	35	90	0.12	0.29	0.21	0.22	100	0.91	7.0	42.1	2.30
B2	35	90	0.12	0.29	0.21	0.22	20	0.91	7.0	40.1	2.24
B3	35	90	0.12	0.29	0.21	0.22	40	0.91	7.0	38.1	2.24
B4	35	90	0.12	0.29	0.21	0.22	34	0.91	7.0	42.9	2.27
B5	35	90	0.12	0.29	0.21	0.22	64	0.91	7.0	41.6	2.24
C1	35	90	0.12	0.28	0.21	0.23	3.8	0.87	7.4	4.4	1.18
C2	35	90	0.12	0.28	0.21	0.23	16.6	0.87	7.4	4.5	1.25
C3	35	65	0.12	0.21	0.21	0.22	6.2	0.66	7.0	4.0	1.12
C4	35	90	0.12	0.28	0.21	0.23	6.2	0.87	7.4	4.8	1.22
C5	35	90	0.12	0.28	0.21	0.23	23	0.87	7.4	4.0	1.25
D1	35	75	0.12	0.25	0.21	0.215	16-100	0.78	6.9	44.3	2.30
D2	35	104.5	0.12	0.31	0.21	0.24	1236	0.97	7.7	396	4.86

where Q, u, h and t are discharge, average velocity, flow depth and time, respectively, and subindices "B" and "P" refer to base and peak flow, respectively.

4.1 Steady flows

The functional relationship between dimensionless scour depth Z^*, and dimensionless flow work W^* is explored through Series A, with experiments having a constant discharge. Following Chreties *et al.* (2008) it is hypothesized that the relation is unique under different hydraulic conditions, i.e. a given value of work produce only one single value of scour depth. Figure 4.1 shows the evolution of dimensionless scour depth on dimensionless flow work for the two experiments of Series A, according to the three alternative formulations of the reference values.

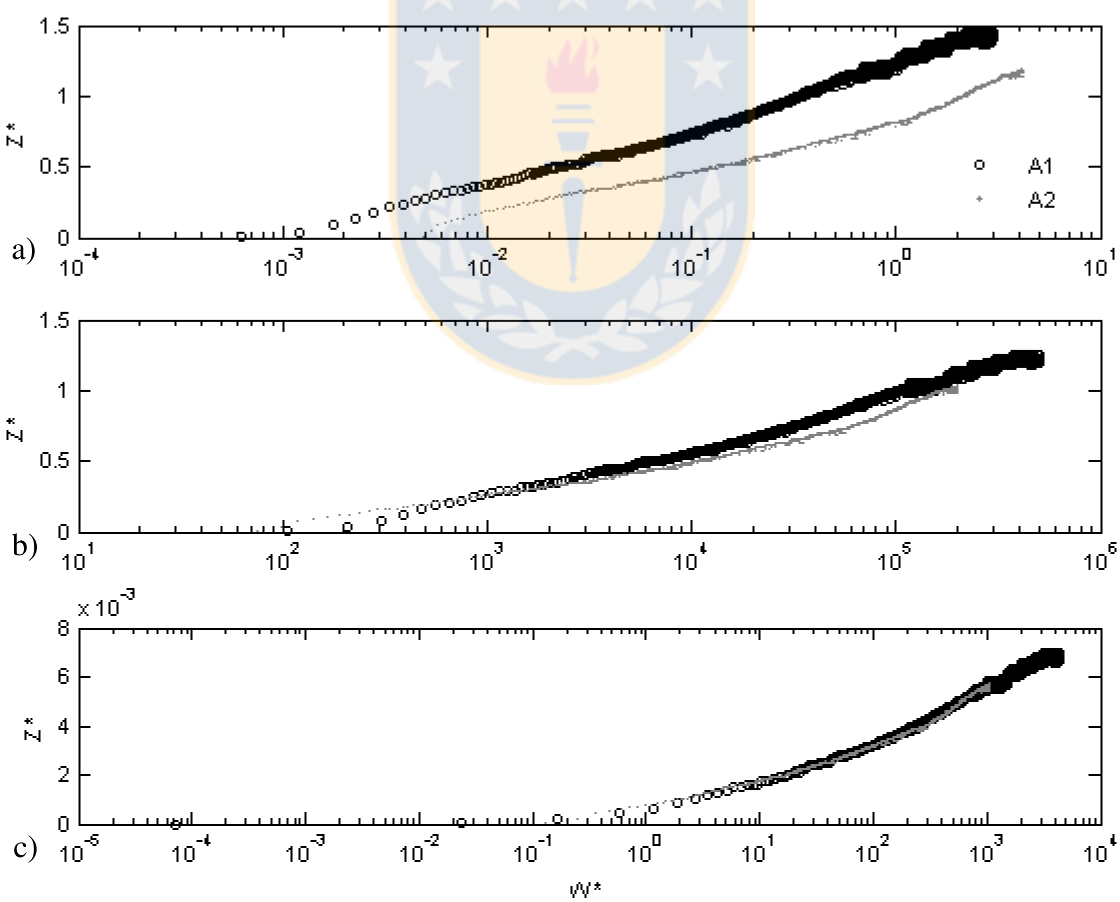

Figure 4.1 Dimensionless scour depth Z^* on dimensionless flow work W^* in the two experiments of Series A according to reference values

All formulations of the reference values proposed in alternatives a), b) and c) show the same tendency, increasing Z^* with W^*. For the alternative c) measured values clearly collapse into one single curve, showing that the relation between Z^* and W^* is unique. Thus reference variables are adopted as defined in this alternative. Similarly to Simarro-Grande and Martín-Vide (2004) and Lança *et al.* (2013) the author adopts the mathematical model suggested by Franzetti *et al.* (1982), in order to describe the relation between the dimensionless scour depth and work in alternative c):

$$Z^* = c_1\left(1 - e^{-c_2\left(W^*\right)^{c_3}}\right), \tag{4.1}$$

where c_1, c_2 and c_3 are coefficients that were determined by the Matlab nonlinear curve-fit function, obtaining $c_1 = 0.00748336$, $c_2 = 0.09694$ and $c_3 = 0.3804$ with a determination coefficient $r^2 = 0.996$. Remarkably, Equation 4.1 allows a straightforward prediction of scour depth caused by any given hydrograph.

4.2 Unsteady flows

Series B and C included single peak hydrographs with different shape and duration, and Series D included hydrographs with multiple peaks and shapes closer to real cases, with the aim to explore effects of flow acceleration. Figure 4.2 shows W^* over Z^* for each experiment as well as Equation 4.1.

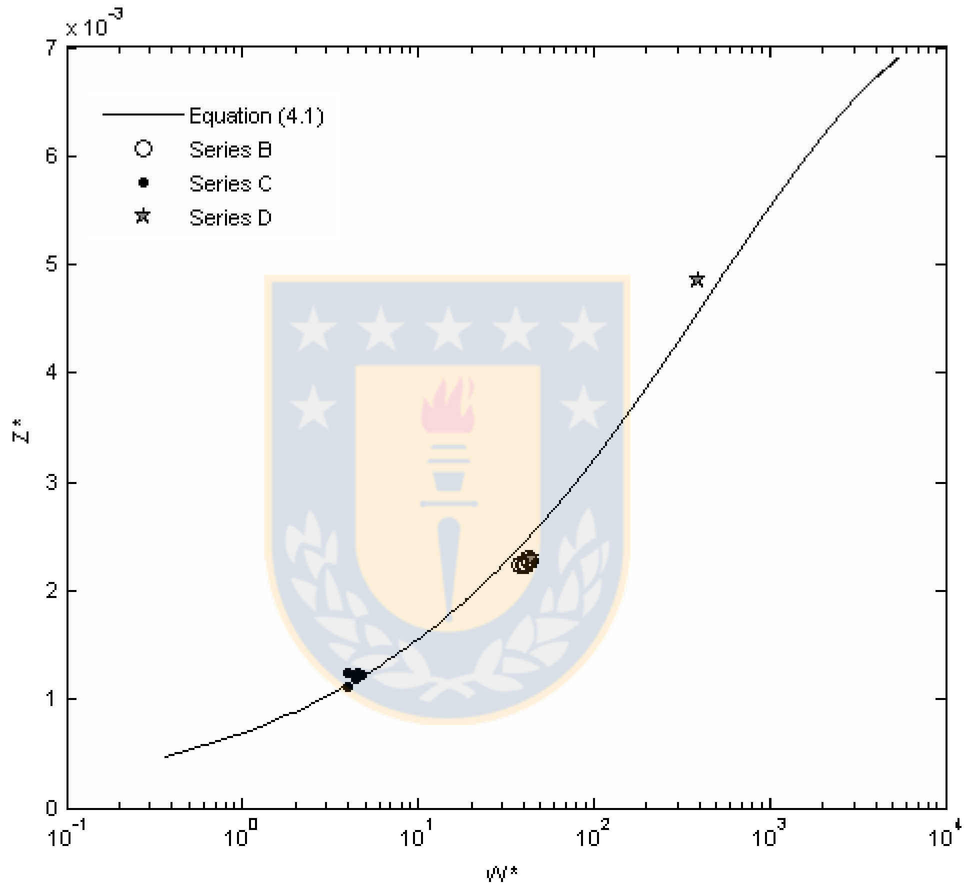

Figure 4.2 Measured and predicted Z^* over W^* in all experimental series

Practically the same value of W^* and Z^* was achieved at the end of each experiment in each of the series B and C. Also in multiple peaks experiments Z^* achieved similar values as in constant discharge experiments, for a certain W^*, confirming the validity of the dimensionless work as a parameter able to predict scour under flood waves. The root mean square error for all experimental runs is 0.00017. Moreover, the good agreement between measured and computed values, especially in Series D, confirms our hypothesis that for practical purposes scour occurs for flow intensities $u \geq 0.5u_c$. This implies that flow acceleration plays a minor role in scouring.

4.3 Comparison with literature data

Only scarce data have been published in the literature to test the model proposed in Equation 4.1 for prediction of scour under flood waves. The author recovers experimental results by López *et al.* (2014) resumed in Table 4.2.

Table 4.2 Experimental runs for validation of predicted Z^*

(1) Original run	(2) Q_B (l/s)	(3) Q_P (l/s)	(4) u_B (m/s)	(5) u_P (m/s)	(6) h_B (m)	(7) h_P (m)	(8) t_P (h)	(9) u_P/u_c (-)	(10) W^* (-)	(11) z (cm)	(12) z cal. (cm)	(13) Error (%)
U1a	40.6	69.2	0.30	0.45	18.3	20.4	4.500	0.82	403.64	12.51	14.94	19%
U1b	40.3	70.1	0.30	0.47	18.0	20.1	4.250	0.85	466.32	12.34	15.43	25%
U1c	38.4	68.8	0.29	0.46	17.8	20.0	4.125	0.84	371.15	12.08	14.66	21%
U2a	42.6	69.7	0.32	0.46	17.9	20.0	2.250	0.85	276.73	11.31	13.66	21%
U2b	40.4	69.8	0.30	0.46	17.9	20.1	2.125	0.85	236.30	11.16	13.14	18%
U3	38.8	69.4	0.29	0.47	17.7	19.8	8.500	0.85	888.55	13.19	17.61	33%
U4	39.2	70.2	0.29	0.47	18.0	20.1	1.125	0.85	141.40	10.74	11.48	7%
U5	24.9	54.3	0.29	0.40	11.5	18.3	1.125	0.73	31.33	7.73	7.35	5%
U6	24.9	54.0	0.29	0.40	11.3	18.2	0.750	0.73	20.27	7.41	6.40	14%
U7	25.1	54.6	0.29	0.40	11.4	18.1	4.500	0.74	140.06	11.30	11.45	1%

In all experiments by López et al. (2014) $D^* = 41.5$, relative density $\rho' = 1.65$, $\sigma = 1.32$, relative depth $h/d_s > 68$, and relative roughness $D/d_s = 54.55$. Note that relative density in López *et al.*'s (2014) experiments is the same as in this study. The standard deviation of sediment particle sizes are in both cases $\sigma < 1.5$ thus sediments are considered homogeneous and no influence of σ on scour is expected. Relative depth reach high values in a range where no effects on Z^* are expected. In consequence, differences between López *et al.*'s (2014) measured scour depth and that predicted by Equation 4.1 are attributable to D^* and relative roughness D/d_s. In order take scale effects due to differences in relative roughness into account, the author corrected the predictions of Equation 4.1 following Lee and Sturm (2009):

$$\frac{z}{D}=\begin{cases} 5.0\log\left(\frac{D}{d_s}\right)-4.0, & 6\le\frac{D}{d_s}\le 25 \\ \frac{1.8}{\left(0.02\frac{D}{d_s}-0.2\right)^2+1}+1.3, & 25\le\frac{D}{d_s}\le 1\times10^4 \end{cases}, \quad (4.2)$$

Figure 4.3 shows the agreement between measured and with Equation 4.1 computed scour depth.

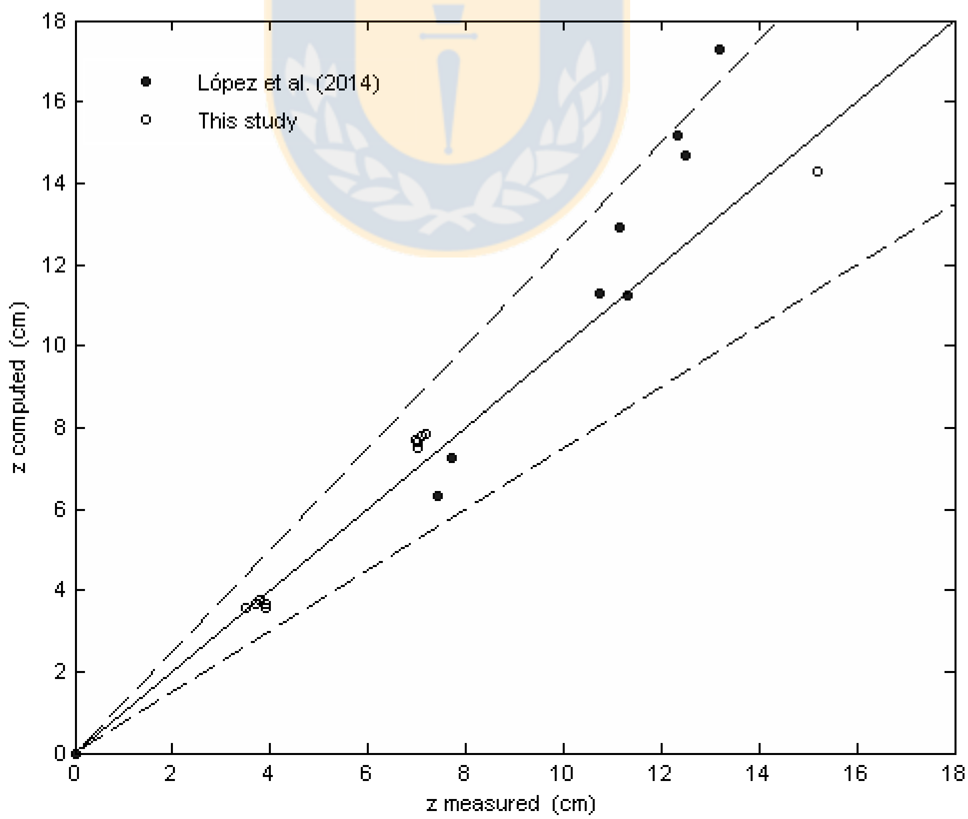

Figure 4.3 Computed over measured final scour depth. Dashed lines indicate 25% error

Except run U3, all experiments by López *et al.* (2014) are predicted by Equation 4.1 with errors less than 25%, confirming the good performance of the proposed model. While in the present study $D^* = 9.0$ in López *et al.*'s (2014) experiments $D^* = 41.5$. Oliveto and Hager (2006) showed that the flow transition zone between smooth and rough occurred when $9 \leq D^* \leq 55$. Accordingly, observed differences between calculated and by López *et al.* (2014) measured z are attributable to viscous effects.

CHAPTER 5 CONCLUSIONS

The pier scour caused by several different flood hydrographs was analyzed introducing the idea of an effective work by the flow on the sediment bed around the pier. Different possible formulations for the dimensionless flow work and the corresponding dimensionless parameters that govern scouring were tested with laboratory experiments conducted in a novel installation able to reproduce any hydrograph with high precision in a flume.

Results highlighted that the effective dimensionless work W^* has a high predictive capacity of scour caused by any hydrograph, as the relation between W^* and Z^* is univoque. In particular, the proposed model in Equation 4.1 provides good performances allowing a straightforward prediction of maximum scour depth caused by any given hydrograph. Moreover, the results showed that flow acceleration is negligible for practical purposes, with scouring occurring when flow intensity exceeds a threshold of 0.5.

The presented experiments represent a first step in the study of the interaction of more complex flood hydrographs with fluvial structures. In the next future, the author plans to explore the role of sediment properties on scour, as well as the scour behavior under flood waves with significantly higher flow velocities to deepen our understanding regarding the reliability of the proposed formulation.

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