Local Scour at Bridge Piers

by

Y.M. CHIEW

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Supervised by
Professor A.J. Raudkivi and Dr B.W. Melville

Department of Civil Engineerinng
Auckland University
Private Bag
Auckland
New Zealand

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to my wife

Abstract

Local scour at cylindrical bridge piers in both uniform and non-uniform cohesionless sediments was investigated experimentally. The aim of the study was to improve understanding of local scour around bridge piers with sediment transport. Three empirical functions which relate the equilibrium depth of scour with approach velocity, flow depth and sediment size were obtained for uniform sediments. The effects of armouring and sediment sizes were also investigated for non-uniform sediments.

The experimental results for the variation of equilibrium scour depth (normalised with the pier diameter) with approach velocity show that the equilibrium scour depth reaches a maximum at the threshold condition of the bed sediment. Above the threshold velocity, the scour depth first decreases and then increases again with increasing velocity to a maximum at the transition flat bed condition. At still higher velocities, the equilibrium scour depth decreases due to the formation of antidunes. Lesser scour depths are recorded with ripple forming sediment at threshold conditions because the bed associated with a ripple forming sediment is unable to remain planar. In live-bed conditions, the effect of rippling diminishes for increasing velocity and becomes negligible for $U_o/U_{oc} > 2$.

The experimental results for the variation of equilibrium scour depth with flow depth show that the trend for live-bed scour of increasing scour depth with increasing Y_o/D until a maximum influence of Y_o/D is reached, is similar to that for clear water scour as shown by Ettema (1980). A flow depth adjustment factor, $K(Y_o/D)$, which is related to Y_o/D with D/d_{50} as the third parameter is presented which

indicates to a designer the sequence of estimation of the effect of flow depth on the equilibrium depth of scour.

The effect of sediment size on the equilibrium scour depth is presented in terms of the relative size of pier to sediment, D/d_{50}. A family of curves, at various values of U_o/U_{oc}, which relate d_{av}/D and D/d_{50} for live-bed scour was obtained. The curves show that the equilibrium scour depth increases almost linearly for increasing values of D/d_{50} until it reaches the value of $D/d_{50} = 50$ after which the scour depth becomes independent of D/d_{50}. A similar trend was obtained by Ettema (1980) for clear water scour. For design purposes, the data for large values of Y_o/D are presented in terms of a sediment adjustment factor, $K(D/d)$, which is shown to be independent of the flow velocity. Both flow depth and sediment size functions include results by Shen et al (1966), Ettema (1980), Chee (1982), and the present study.

Armouring and sediment size play an important role in reducing the equilibrium scour depth for non-uniform sediments. The latter is particularly significant in laboratory experiments where the size of the pier is generally small relative to the size of the coarse particles in non-uniform sediments. Experiments were conducted under dynamic equilibrium conditions where there is continuous sediment input from upstream of the scour hole such that at equilibrium, the amount of sediment entering the bridge site is equal to that leaving. Both the effects of armouring and sediment size diminish for increasing velocity. At high velocity where all the sediment particles are mobile, the non-uniform sediment behaves like a uniform sediment. Hence, armouring does not occur and the equivalent size used for sediment adjustment is based on the d_{50} size of the sediment bed. At low velocity, armouring at the base of the scour hole is prominent and adjustment of D/d is based on the d_{90} size of the original mixture.

An alternative condition can exist in natural rivers in contrast to the dynamic equilibrium conditions simulated in this study. This is where the upstream river is armoured such that there is little or no sediment input to the scour hole. It is postulated that, in this case, the equilibrium scour depth can approach the maximum equilibrium scour depth for clear water conditions (i.e. $d_{av}/D \to 2.3$) when the approach velocity is equal to the critical velocity of the non-uniform sediment.

Finally, a design flow chart is presented for estimation of the equilibrium depth of local scour for design purposes. In live-bed scour where bed features are present, the results show that half the height of the bed features can be added to the estimated equilibrium scour depth.

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Symbols

a	Constant
b	Constant
B	Width of the flume
c	Cohesiveness
C	Total sediment concentration, % by weight
C_s	Sediment concentration in the sediment line, % by weight
C_w	Sediment concentration in the water line, % by weight
d, d_{50}	Mean particle size
D	Pier diameter
d_s	Local scour depth
d_{av}, d_{se}, d_{sea}	Equilibrium scour depth
$d_{\{max\}}$, d_{sem}	Maximum scour depth
$d_{\{min\}}$, d_{ses}	Minimum scour depth
Fr	Froude Number
F_c	Froude Number at critical velocity of the bed sediment
g	Gravitational acceleration
h_o	Height of bed feature
H_1, H_2	Pump head
H_b	Local scour due to bed forms
H_p	Local scour due to the pier
k, k'	Size of entrainment zone
$K(D/d)$	Sediment size adjustment factor
K_s	Pier shape factor
$K(Y_o/D)$	Flow depth adjustment factor

K_α	Flow alignment factor
N_1, N_2	Speed in RPM
N_s	Sediment number, $U_o/\sqrt{(ss-1)gd}$
P	Protrusion of a particle into the flow
q	Flow rate per metre width
q_s	The rate of local scouring in volume per unit time
q_{s1}	The rate of sediment transported into the scour hole in volume per unit time
q_{s2}	The rate of sediment transported out of the scour hole in volume per unit time
Q_s	Flow rate in the sediment line
Q_w	Flow rate in the water line
Q_{tot}	Total flow rate
r	Correlation factor
Re	Reynolds Number
S_o	Energy slope
S_s	Specific gravity of sediment
t	Time
T	Temperature
U, U_o	Mean velocity
u_*	Shear velocity, $\sqrt{g\ Y_o S_o}$
u_{*c}	Critical shear velocity for particle entrainment
U_{oc}	Critical mean velocity for particle entrainment
U_{ob}	Mean velocity which corresponds to the (first) maximum local equilibrium scour depth with non-uniform sediment
$U_{\{bed\}}$	Mean velocity above which armouring of a bed does not occur
V_{max}	Pier downflow velocity
w	Fall velocity
y_o, Y_o	Flow depth
z	Normal distance from channel wall
α	Static angle of repose
γ	Specific weight of water
γ_s	Specific weight of sediment
$\Delta\ d_s$	Fluctuation of the scour depth, $d_{s\{max\}} - d_{s\{min\}}$

Γ	Circulation
θ	Dimensionless shear stress, $u_*^2/(S_s - 1)gd$
θ_c	Critical value of θ for particle entrainment, $u_{*c}^2/(S_s - 1)gd$
λ	Wavelength
ν	Kinematic viscosity
ρ	Density of fluid
σ_g	Standard deviation
τ_o	Temporal mean bed shear stress
τ_{oc}, τ_c	Critical shear stress for particle entrainment
τ'_o	Shear stress corresponding to the grain particles, or surface drag
τ''_o	Shear stress corresponding to the bed feature, or form drag
$\tau_o U_o$	Stream power
ψ	Shape factor

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