UNIVERSITY OF TECHNOLOGY, SYDNEY

# Bridge Pier Flow Interaction and Its Effect on the Process of Scouring

By

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of the requirement for the degree of
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# CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Chij Kumar Shrestha

Sydney, September 2015

# ABSTRACT

Previous investigations indicate that scour around bridge piers is a contributor in the failure of waterway bridges. Hence, it is essential to determine the accurate scour depth around the bridge piers. For this purpose, deep understanding of flow structures around bridge piers is very important. A number of studies on flow structures and local scour around bridge piers have been conducted in the past. Most of the studies, carried out to develop a design criterion, were based on a single column. However, in practice, bridge piers can comprise multiple columns that together support the bridge superstructure. Typically, the columns are aligned in the flow direction. The design criteria developed for a single column ignore the most important group effects for multiple columns cases such as sheltering, reinforcement and interference effects. These group effects can significantly be influenced by the variation of spacing between two columns. This is evident by the fact that insufficient investigations and development have been reported for the flow structure and maximum scour depth around bridge piers comprising multiple columns. It is therefore necessary to investigate the effects of multiple columns and spacing between them on the flow structure and local scour around bridge piers and develop a practical method to predict the maximum scour depth.

The main objectives of this research work are to analyse the effect of spacing between two in-line circular columns on the flow structure and to develop a reliable method for prediction of the maximum local scour depth around bridge piers. To meet the objectives this research, detailed experimental studies on three dimensional flow structures and local scour around two-column bridge piers were carried out. A series of laboratory experiments were conducted for no column, a single column and two in-line columns cases with different spacing. Two in-line columns were installed at the centre of the flume along the longitudinal axis. Three dimensional flow velocities in three different horizontal planes were measured at different grid points within the flow using a micro acoustic doppler velocimeter (ADV). The velocity was captured at a frequency of 50Hz. Additionally, in vertical planes, particle image velocimetry (PIV) technique was employed to measure the two dimensional instantaneous velocity components. All experiments on flow structures were conducted under no scouring and clear water flow

conditions. Similarly, an array of experimental tests were conducted under different flow conditions for studying the temporal development of scour depth and the maximum local scour depth around a single column and two-column bridge piers.

The measured instantaneous three dimensional velocity components were analysed and the results for flow field and turbulence characteristics were presented in graphical forms using vector plots, streamline plots, contour plots and profile plots. The results indicated that the flow structures around two- columns bridge piers is more complex than that of a single column case. Furthermore, the spacing between two columns significantly affects the flow structures, particularly in the wake of the columns. It was observed that for the spacing-column diameter ratio ($L/D$) < 3, the vortex shedding occurred only behind the downstream column. Hence, the flow pattern was more or less similar to that of the single column case. However, the turbulence characteristics such as turbulence intensity, turbulent kinetic energy and Reynolds shear stresses were notably different from those of a single column case. When the spacing was in the range of $2 \leq L/D \leq 3$, stronger turbulence structures were noticed behind the upstream column. Further increase in the spacing between two columns resulted in a decrease in the strength of turbulence characteristics.

The experimental results on temporal development of local scour depth reveal that approximately 90% of the maximum scour depth around the upstream column was achieved within the first 10 hours of the experiments. However, for the downstream column, 90% of the scour depth was achieved within 20 hours. Similarly, the results from the experiments on local scour indicated that the maximum scour depth occurred at the upstream column, when the spacing between two columns was $2.5D$. The maximum value of local scour depth for the two-column case was observed about 18% higher than the value obtained for the single column case. The reasons for maximum scour depth at the spacing of $2.5D$ were identified as the reinforcing effect of downstream column, the strong horseshoe vortex at upstream column, strong turbulence characteristics at the wake of upstream column, and the highest probability of occurrence of sweep events at upstream side of upstream column. Furthermore, a semi empirical equation was developed to predict the maximum scour depth as a function of the spacing between two

columns. The findings of this study can be used to facilitate the position of columns when scouring is a design concern.

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# LIST OF NOTATIONS

$a$ = Edge of the bed layer at z=a

$C'$ = Chezy coefficient related to sediment grain

$C1$ = Column at upstream side (Column 1)

$C2$ = Column at downstream side (Column 2)

$C_c$ = Coefficient of curvature

$C_d$ = Drag coefficient

$C_u$ = Coefficient of uniformity

$c$ = Sediment concentration

$D$ = Diameter of a pier

$D_p$ = Projected width of a pier

$d$ = Size of the sediment particle

$d_*$ = Dimensionless particle parameter

$d_1$ = Equilibrium depth for single column bridge pier

$d_{50}$ = Mean grain size of the sediment

$d_s$ = Depth of scour at any time

$d_{se1}$ = Equilibrium depth of scour at Column 1

$d_{se2}$ = Equilibrium depth of scour at Column 2

$F$ = Dimensionless shape factor of sediment

$F_c$ = Coulomb force of resistance

$F_d$ = Drag force

$F_g$ = Submerged weight of a particle

$Fr$ = Froude number

$f$ = Frequency of vortex shedding

$G$ = Parameter describing the effects of lateral distribution of flow in the approach channel and the cross sectional shape of the approach channel

$g$ = Acceleration due to gravity

$H$ = Hole size (threshold level for bursting process)

$h$ = Depth of flow

$I_e$ = Sorting function for ejection event

$I_s$ = Sorting function for sweep event

$K_{Gmn}$ = Correction factor proposed by Ataie-Ashtiani and Beheshti (2006)

$K_I$ = Flow intensity parameter

$K_{s1}$ = Column-spacing factor for Column 1

$K_{s2}$ = Column-spacing factor for Column 2

$K_{sh}$ = Shape parameter of a pier

$K_t$ = Time factor for equilibrium scour depth

$K_w$ = Adjustment factor for wide pier

$K_\alpha$ = Angle of flow attack parameter of a pier

$k_s$ = roughness height

$L$ = Centre to centre distance between two columns

$L'$ = Length of the pier / Distance between two-column measured outer to outer face of the columns.

$m$ = Number of piles in line with flow as in Ataie-Ashtiani and Beheshti (2006)

$n$ = Number of piles normal to the flow as in Ataie-Ashtiani and Beheshti (2006)

$n_e$, $n_k$ = Dimensionless number to find the roughness height

$P_i$ = Probability of occurrence of the events, where $i = 1, 2, 3$ and 4

$Q_i$ = Quadrant zones, where, $i = 1, 2, 3$ and 4

$q$ = The rate of local scour in volume per unit time

$q_1$ = The rate at which sediment is transported out from the scour hole in volume per unit time

$q_2$ = The rate at which sediment is supplied to the scour hole in volume per unit time

$q_b$ = Rate of bed load transport

$q_b^*$ = Dimensionless Einstein number to quantify bed load transport

$q_s$ = Rate of suspended load transport

$R$ = Radius of the vortex

$Re$ = Reynolds number

$Rel$ = Reynolds number with respect to length of boundary layer

$S$ = Bed slope

$S_i$ = Stress fraction, where $i = 1, 2, 3$ and 4

$St$ = Strouhal number

$s$ = Specific gravity of the water

$s'$ = Submerged specific gravity of sediment particle

$s_s$ = Specific gravity of the sediment

$T$ = Dimensionless transport stage parameter

$TI_u$ = Turbulence intensity component in stream-wise direction (x-direction)

$TI_v$ = Turbulence intensity component in transverse direction (y-direction)

$TI_w$ = Turbulence intensity component in vertical direction (z-direction)

$TKE$ = Turbulence kinetic energy

$t_e$ = Time to develop equilibrium scour depth

$u$ = Velocity component in stream-wise direction (x-direction)

$u_*$ = Bed shear velocity

$u_c$ = Critical shear velocity

$u'$ = Fluctuating component of velocity in stream-wise direction (x-direction)

$V$ = Mean approach flow velocity

$\bar{V}$ = Depth averaged velocity of fluid

$V_a$ = Critical mean flow velocity for armour peak

$V_c$ = Critical mean flow velocity for sediment entrainment

$V_{lp}$ = Live bed peak velocity of flow

$V_\theta$ = Tangential vortex velocity = $\omega_0 R$

$v$ = Velocity component in transverse direction (y-direction)

$v'$ = Fluctuating component of velocity in transverse direction (y-direction)

$W$ = Width of the flume

$w$ = Velocity component in vertical direction (z-direction)

$w'$ = Fluctuating component of velocity in vertical direction (z-direction)

$w_s$ = Top width of the scour hole

$x$ = Distance measured in stream-wise direction

$y$ = Distance measured in transverse direction

$Z, Z'$ = Sediment number

$z$ = Distance measured in vertical direction

$\Gamma$ = Vortex strength

$\delta$ = Thickness of boundary layer

$\mu_c$ = Coulomb friction coefficient

$v$ = Kinematic viscosity of fluid

$\rho$ = Density of fluid

$\rho_s$ = Density of sediment material

$\sigma_g$ = Geometric standard deviation of the sediment

$\tau$ = Bed shear stress

$\tau_*$ = Dimensionless critical shear stress parameter (Shields parameter)

$\tau_c$ = Critical shear stress

$\tau_{uv}$ = Reynolds shear stress component in *uv* direction

$\tau_{uw}$ = Reynolds shear stress component in *uw* direction

$\tau_{vw}$ = Reynolds shear stress component in *vv* direction

$\psi$ = Correction factor for stratification

$\omega_0$ = Angular velocity of revolution