

## **SIMILITUDE OF COHERENT TURBULENCE STRUCTURES IN FLUME STUDIES OF BRIDGE SCOUR**

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The relaxation of similitude parameters associated with laboratory modeling of local-scour development causes scale effects, some of which get factored into scour equations used for predicting scour depth at bridge piers and abutments. However, two parameters generally have been overlooked or inadequately taken into account. They relate to the scaling of coherent turbulence structures – wake eddies, shear eddies, horseshoe vortex — and have an important effect on equilibrium scour depth. This paper reports the findings of a series of experiments on the similitude of coherent turbulence structures, especially wake eddies, and thereby on the equilibrium scour depth at circular cylinders placed in a bed of uniform sand. The experiments show that the parameters play an important role in scour development and on maximum scour depth.

### **1 INTRODUCTION**

Scour around the foundation of a bridge pier or an abutment involves a complex flow field featuring coherent turbulence structures –horseshoe vortex, wake eddies, and other structures generated by the flow through the scouring channel around a pier or abutment. To date, scour has been studied by means of laboratory flume experiments entailing the use of dimensionless parameters relating maximum scour depth to the flow field and the sediment bed in which the pier or abutment is founded. There are numerous flume studies providing semi-empirical equations for the maximum scour depth. A concern, though, is that the available scour equations over predict the scour depth compared to field-observed scour depths. Such overestimation may be due to several reasons, but one substantial similitude effect seems to have been repeatedly overlooked in prior studies. That effect concerns simulation of the coherent turbulence structures formed by flow around a pier or an abutment.

Formal similitude analysis of the variables involved in the scour process shows that the influences of two parameters have been inadequately understood and taken into account in prior studies. The influences concern the scaling of coherent turbulence structures. The paper presents insights showing that the two parameters, and thereby the similitude of coherent turbulence structures, has an important effect on the equilibrium scour depth. The two parameters describe the strength and frequency of eddies shed from a pier or abutment.

The writers conducted a series of flume experiments to determine whether the frequency of vortex shedding and vorticity in the wake of the cylinders would influence the scour development and equilibrium scour depth. The experiments involved a set of circular cylinders of differing diameter placed in the same approach flow. Kirkil (2004) documents the experiments.

## 2 MISSING PARAMETERS

For steady flows over a planar bed consisting of uniform sediment (effects of particle shape, uniformity of particle size, and cohesion neglected), pertinent variables are

$$\rho, \mu, u_{*0}, y_0, g, d, u_{*c}, D, \beta, B$$

in which  $\rho$  and  $\mu$  are fluid density and viscosity, respectively;  $u_{*0}$  is shear velocity,  $y_0$  is undisturbed approach flow depth,  $g$  is gravitational acceleration,  $d$  is representative grain size,  $u_{*c}$  is critical shear velocity for bed sediment entrainment,  $D$  is pier diameter,  $\beta$  is angle of flow and  $B$  is channel width. The variables can be arranged as a set of independent parameters that relate equilibrium scour depth,  $d_{se}$ , to the flow, sediment and the cylinder characteristics. Using  $y_0$ ,  $u_{*0}$  and  $\rho$  as normalizing variables, the variables expressed as in Eqn. (1). Here, use is made of  $U_0 = u_{*0} \sqrt{8/f}$  where the Darcy-Weisbach resistance coefficient  $f = F(d/y_0)$  in fully turbulent flow; and  $U_0$  is the mean velocity. The functional relationship for scour depth can be expressed as

$$\frac{d_{se}}{D} = f_1 \left( \frac{U_0}{U_c}, \frac{U_0^2 f}{gD}, \frac{\rho U_0 D \sqrt{f}}{\mu}, \frac{D}{d}, \frac{D}{y_0}, \beta, \frac{D}{B} \right) \quad (1)$$

Comparison of standard scour prediction equations with Eqn. (1) reveals that prior studies have not considered two parameters;  $\rho U_0 D \sqrt{f} / \mu$  (a Reynolds number) and  $U_0^2 f / gD$ . Prior studies generally state that Reynolds number can be ignored for the range of scales commonly used in scour experiments. Furthermore,  $U_0^2 f / gD$  is usually configured as Froude number ( $y_0$  instead of  $D$ ), and considered not directly relevant to scour depth (unless the flow becomes super-critical). Evaluation of available scour prediction equations suggests that resolution of scale-issue concerns requires consideration of the influences of the parameters  $\rho U_0 D \sqrt{f} / \mu$  and  $U_0^2 f / gD$  on scour depth. The two parameters, though, express similitude in the frequency and strength of eddies shed from a pier;  $\rho U_0 D \sqrt{f} / \mu$  links to Strouhal number,  $St = nD/U_0$ , in which  $n$  = shedding frequency; and,  $U_0^2 f / gD$  is a normalized expression of wake-eddy vorticity.

## 3 EXPERIMENTS

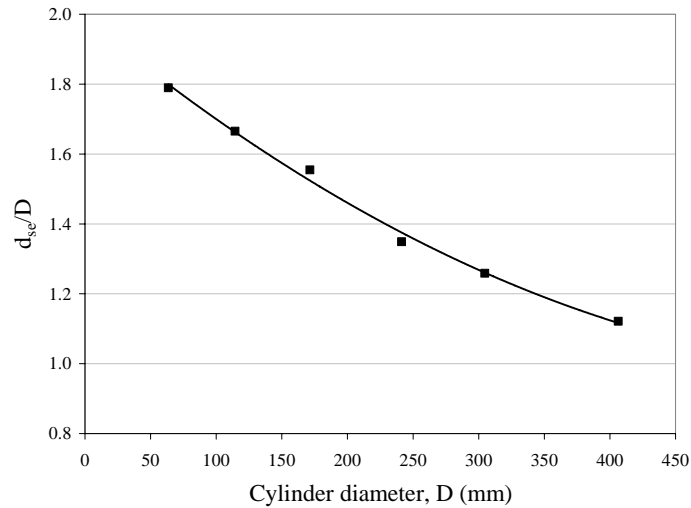
The reported experiments involve measurements of the maximum scour depth for a series of different-sized circular cylinders in the same approach flow. Frequency, spectral power, and vorticity of eddies shed from the cylinders were measured. The measurements were interpreted to explain the variation of  $d_{se}/D$  with cylinder diameter in terms of the frequency and vorticity of eddies shed from each cylinder.

### 3.1 Maximum scour depth

Experiment conditions are summarized in Table 1. Reynolds number based on diameter of the cylinders indicate subcritical flow regime in terms of vortex shedding ( $St = 0.2$ ). Figure 1 plots  $d_{se}/D$  versus  $D$ , and it shows that  $d_{se}/D$  indeed was larger for the smaller cylinders. The experiments also showed that  $d_{se}/D$  varied inversely with  $D$  (i.e.  $U^2 f / gD = k/D$ , for same approach flow; here  $k$  is constant).

Table 1. Experimental conditions for scour experiments

Flow Depth	Average Velocity U	$u_w/u_{wc}$	Pier Diameter D	Reynolds Number
mm	m/s		mm	Re(D)
1000	0.46	0.80	406	1.86E+05
1000	0.46	0.80	305	1.39E+05
1000	0.46	0.80	241	1.10E+05
1000	0.46	0.80	172	7.84E+04
1000	0.46	0.80	114	5.22E+04
1000	0.46	0.80	64	2.90E+04

Figure 1. Data on  $d_{sc}/D$  variation with D

### 3.2 Vortex-shedding frequency and intensity

To determine the shedding frequency and intensity of the wake eddies formed by the cylinders, the wake flow formed downstream by each cylinder was observed and, to a limited extent, measured. Experimental conditions were same with previous experiments on scour depth. In these experiments, point velocity measurements were performed in the wake of each cylinder using ADV. Measurements were located at  $(2.5D, 1.5D)$  downstream of the centre of each cylinder. Here, the first coordinate is in streamwise, second one is in transverse direction. A single measurement point is chosen in spanwise direction; 0.75m above the bed elevation. Power-spectrum analyses of the streamwise velocities are shown in Figure 2 for the tested cylinders.

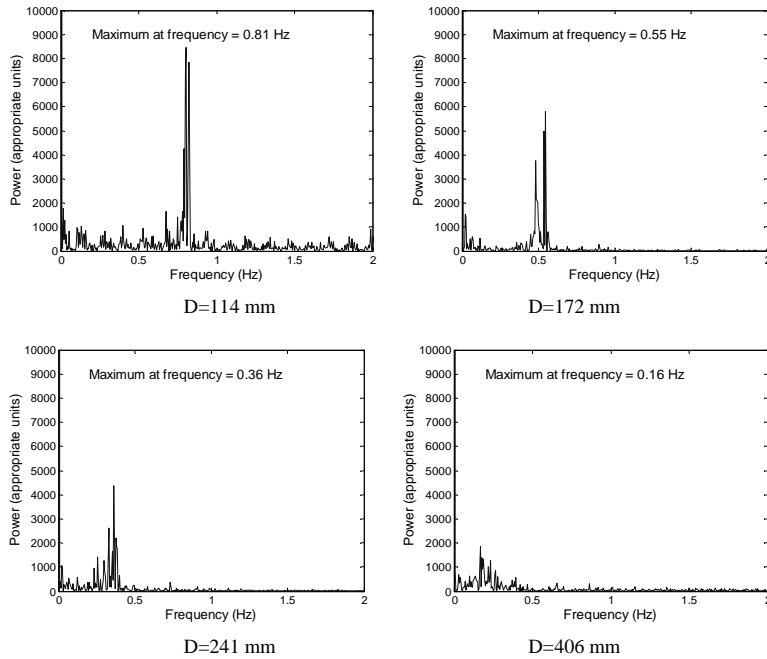


Figure 2. Power spectrum plots of the velocity measurements for 4 cylinders

Distinct frequency peaks in the power spectrum plots indicate the frequencies of coherent eddies that are shed from the cylinder boundary layer. They also coincide with the frequencies estimated from the relationship between cylinder Reynolds number and Strouhal number. The peak frequencies are plotted versus cylinder diameter in Figure 3, which shows that the frequency of vortex shedding decreases with the increasing diameter of the cylinders.

The peak in the power spectrum is associated with the strength of vorticity in the wake of the cylinder. In turn, the strength of vorticity infers the capacity of the flow to erode bed sediment from the cylinder rear. The power peak of the velocity time series is plotted versus cylinder diameter in Figure 4. The figure shows that as diameter increases, the power associated with the peak frequency decreases; i.e. the vorticity of wake-eddies decrease.

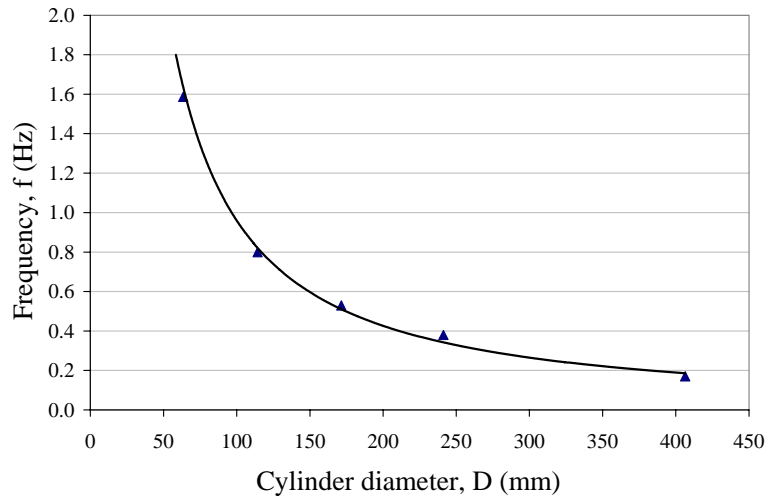


Figure 3. Experimental vortex shedding frequencies in the wake of the cylinders

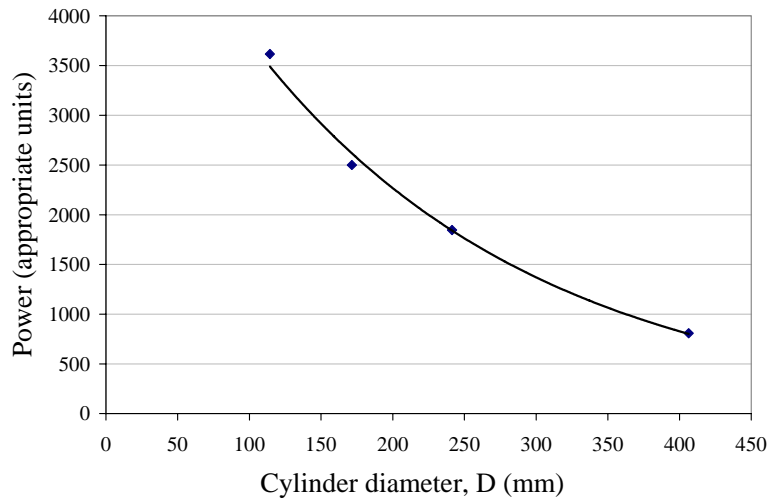


Figure 4. Power peak in the velocity spectrum vs. cylinder diameter

### 3.3 Vorticity measurements

A useful way to illustrate the strength or intensity of the wake eddies in the flow behind the cylinders is to determine the vorticity contours of the wake flow field. Note that the aim here was to visualize the large-scale coherent eddies in the flow field. The time average structure of the wake vortices was revealed from the instantaneous vorticity plots obtained from Large-scale Particle Image Velocimetry (Figures 5 and 6).

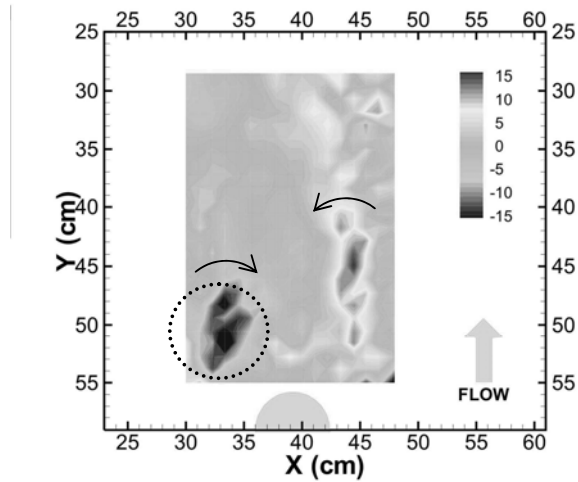


Figure 5. Instantaneous  $z$ -vorticity contour in the wake of the cylinder ( $D = 64$  mm)

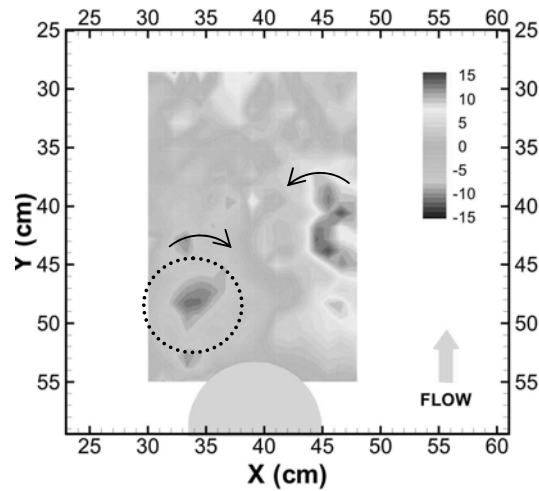


Figure 6. Instantaneous  $z$ -vorticity contour in the wake of the cylinder ( $D = 114$  mm)

The approximate position of the vortex core illustrated is the point of maximum vorticity (figures 5 and 6). The vorticity plots show that the vortices remain as coherent structures in the wake of each cylinder, and confirm that the smaller cylinder indeed produced wake vortices of stronger vorticity. The two vorticity plots are drawn for the same contour range and at the same scale. Two dominant shedding vortices are observable in the wake: the clockwise vortex and counterclockwise vortex. Comparison of the color density of the clockwise vortices at the lower left corners of the frames indicates that the vortex corresponding to the small cylinder ( $D = 64$  mm) has higher vorticity compared to one corresponding to the large cylinder ( $D = 114$  mm) and thus it is

stronger. The maximum out of plane vorticity magnitudes ( $w_z$ ) were measured for these clockwise vortices for each cylinder. The maximum z-vorticity in the wake of the small cylinder ( $-24.52 \text{ s}^{-1}$ ) was higher than the large cylinder ( $-11.71 \text{ s}^{-1}$ ), a finding that supports the idea that scaling of coherent turbulence structures is an important similitude consideration in scour experiments.

### 3.4 Flow visualization

Flow visualization was performed to observe how the wake vortices formed from the cylinders affected the sediment erosion from the bed near a cylinder. A digital video camera was used for recording flow and sediment movement. Streamlines of the flow field were visualized by use of a viscous, non-dissipative dye. The video camera recorded the development of scour (one cylinder is used for this purpose:  $D = 172 \text{ mm}$ ) and the entrainment of sediment.

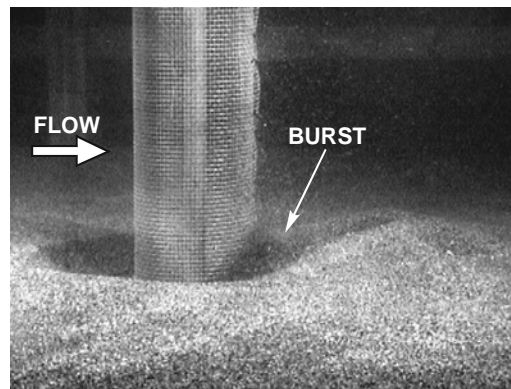


Figure 7. Snapshot from a video recording

Initially, horseshoe vortex was very active in scouring. Strong bursts were observed on the bed immediately downstream of the cylinder (Figure 7), and resulted from the wake eddies (as well as eddies shed the horseshoe vortex) impinging on the bed. The role of the wake vortices (and all shed vortices) in the early stage of scour was in transporting the sediment already entrained by the flow. Typically, the path of particle transportation was not parallel to the bed. Due to the wake eddies, particles followed a spiral path, which often was strong enough that single sediment particle could be lifted up to 80% of the flow depth above the bed. As the coherent eddies formed from the side of the cylinder weakened with distance downstream, they became less able to convey sediment, and sediment particles consequently returned to the bed. This influence is partially responsible for the formation of a sediment mound a short distance downstream of the cylinder. Also, in the latter stage of scour, the eddies significantly contributed to erosion of sediment from the rear of the cylinder.

It can be conjectured that, if there were no wake vortices to move sediment particles further downstream, the sediment particles moved by horseshoe vortex and downflow

could settle on the bed a rather short distance behind the cylinder, and scour hole could not deepen too much; in this regard, it is useful to envision the scour development by a vertical jet in stationary water. The observations suggest that wake vortices play a substantial role in clearing sediment from a scour hole, and thereby enabling the scour hole to deepen.

#### 4 CONCLUSIONS

The findings from the experiments support the postulate stated at the outset of this paper. They show that vortex shedding from a cylinder directly affects the dimensionless scour depth,  $d_{se}/D$ . The value of  $d_{se}/D$  decreases as cylinder diameter  $D$  increases for a series of cylinders placed in the same approach flow. The experiments also show that lack of attention to scaling of vorticity in prior studies has led to significant scale effects in flume experiments on local scour.

The data from the present study can be plotted so as to give the value of an adjustment factor for use in accounting for the mis-scaling of the coherent turbulent structures. Figure 8 shows the resulting plot.

#### 5 ACKNOWLEDGEMENT

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#### 6 REFERENCE

Kirkil, G. (2004). "Similitude of Coherent Eddies in Flume Experiments on Bridge Scour." *MS Thesis, Department of Civil and Environmental Engineering, The University of Iowa.*

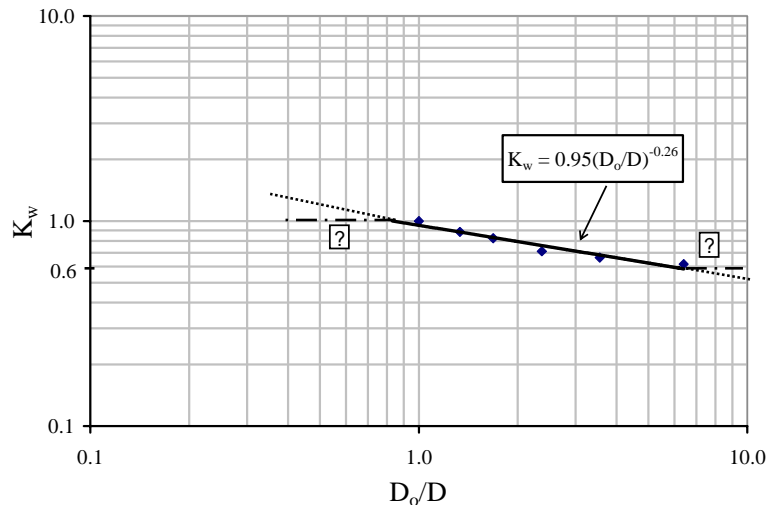


Figure 8. Adjustment factor,  $K_w$ , to account for inadequate similitude of coherence turbulence structures