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EVALUATION OF CHANNEL BLOCKAGE AS A GOVERNING INFLUENCE IN LOCAL SCOUR

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Abstract: Previous evaluation of dimensionless parameters used in governing pier scour depth prediction methods has indicated that channel blockage influences local scour geometry. The majority of predictive methods are functions of previously-defined scour-governing parameters (Williams et al. 2017), and do not include parameters related to so-called blockage effects. The effect of blockage ratio, defined as the ratio between pier diameter (D) and channel width (b), has been erroneously defined in literature as negligible when blockage ratio is less than 10 percent (Chiew 1984). Recent investigations have determined that small changes in values of blockage ratio influence scour geometry (Hodi 2009, D'Alessandro 2013), even when blockage ratio is less than the stated threshold of 10 percent. Sidewall influence on the flow characteristics around a bluff body can be reduced using U_s, the magnitude of streamwise velocity along the separating streamline (Ramamurthy and Lee 1973). Using a similar procedure, the present study investigates the influence of blockage ratio on bridge pier scour. Scour experiments for cylindrical cylinders were carried out at low values of blockage ratio with all other scour-governing parameters held constant in order to isolate the effect of sidewall influence. Experimental results indicated that scour depth increases with increasing blockage ratio. Experimental results from the current investigation were analysed together with results from literature in order to develop a new scour depth prediction method. The present study also includes a discussion on influence of blockage ratio on scour geometry around triangular-nosed cylinders, through analysis of literature results.

1 INTRODUCTION

Scour and erosion have been established as the leading causes of bridge failure in North America, with as many as 60 percent of investigated failures attributed to scour or scour-related complications (Shirhole and Holt 1991, Wardhana and Hadipriono 2003, Miroff 2007). Bridge pier foundation design with respect to scour is therefore an area of particular interest to practicing engineers. This design is usually based on one of several code-specified approved methods, which are typically empirical equations used to calculate foundation head (the depth below which pier foundations should be placed to avoid a loss of lateral support caused by scour). Such empirical equations were developed largely by curve-fitting to experimental data.

For tests in fully turbulent subcritical flow around cylindrical piers in acceptably-graded sediment, dimensional analysis indicates the three dimensionless parameters which can be used to calculate relative scour depth d_{se}/D, where d_{se} is the maximum scour depth in the vicinity of the pier at equilibrium conditions and D is the pier diameter. The aforementioned parameters are relative coarseness D/d_{50} (where d_{50} is the median diameter of sediment), flow shallowness h/D (where h is flow depth) and flow intensity U/U_c (where U is free-stream velocity and U_c is the critical velocity of sediment required for incipient motion). The relationship between each dimensionless parameter and d_{se}/D have been discussed at length and well-established in literature (Melville and Coleman 2000, Lee and Sturm 2009). Analysis of the accuracy of these predictive methods has shown that many equations frequently used in practice generate unnecessarily high estimates of foundation head (Williams et al. 2013). This tendency can be at least partially attributed to scale effects between model and prototype conditions, particularly in relation to sediment size. However, since different equations often yield significantly different estimates of d_{se}/D even under the same testing conditions, it can be inferred that scour geometry is influenced by other parameters which have not yet been employed in predictive methods.

One such parameter is blockage ratio, which in itself is a scale effect as channel banks do not often influence scour around piers under typical field conditions, but sidewall proximity is a concern in laboratory flumes. Blockage ratio, defined as the relationship between D and channel width b, has been previously neglected in scour research. A value of $D/b = 10$ percent has been an incorrectly defined threshold value under which blockage effects have been taken as negligible (Chiew 1984). However, recent investigations have provided new insight into the effect of blockage ratio on local scour. In general, as blockage ratio increases, its influence on scour depth and geometry also increases. It has been determined that small changes in blockage ratio values of less than ten percent result in changes in scour geometry (Hodi 2009). Similarly, changes in blockage ratio values have been shown to influence scour for small values of D/d_{50} (D'Alessandro 2013). Interestingly, the influence of blockage ratio on scour is more significant for tests with D/d_{50} values greater than 100 than for tests with D/d_{50} values less than 100 (Tejada 2014).

Sidewall influence on the flow characteristics around a bluff body can be reduced using U_s, the magnitude of streamwise velocity along the separating streamline (Ramamurthy and Lee 1973). The current investigation compares the scour profiles of three experiments conducted under identical testing parameters, with the exception of blockage ratio, in order to isolate its influence. Analysis of the results of Ramamurthy and Lee (1973) as well as scour results from literature indicates that parameter, k_c, the ratio of U_s to critical velocity U_c, influences scour. A predictive method used to calculate scour depth based on flow shallowness and k_c for tests in a specific range of flow intensity is investigated for both circular and triangular-nosed cylinders.

2 METHODOLOGY

Experiments were carried out at the University of Windsor in Windsor, Ontario. A horizontal recirculating flume of 10 m in length, 1.22 m in width and 0.84 m in height was used to carry out bridge pier scour tests. The flume was fitted with two flow straighteners in order to maintain flow quality and ensure that flow approaching the test section was two-dimensional. A ramp on an incline of 7°lead to a sediment recess of 3.68 m in length and 0.23 m in depth. A gravel boundary layer trip preceded the test section in order to ensure fully developed flow. The flume was serviced by a 60-HP pump, for which a performance curve was generated using standard V-notch weir methods. The sediment recess was filled with erodible sand, for which an ASTM sieve analysis indicated a median sediment diameter value (d_{50}) of 0.77 mm and standard deviation of sediment size (σ_g) of 1.34. The critical velocity of the sediment was visually established and calculated using appropriate methods. Prior to testing, the required pump frequency corresponding to a depth-averaged flow intensity of 0.85 was determined using the pump curve and a velocity profile taken using a Nortek Acoustic Doppler Velocimeter.

A schematic of the experimental setup can be seen in Figure 1. Two adjustable walls were installed in the flume in order to control the channel width. Prior to each test, the movable sidewalls were spaced in the sediment recess such that the desired channel width was achieved. Once the test pier was centred and levelled between the sidewalls, the bed sediment was levelled using a trowel and the flume was filled slowly in order to avoid disturbance of the bed material. Once the water depth was at the desired level, the pump was started and its frequency was increased to the previously-established required level. A gate at the downstream end of the flume was adjusted to maintain desired flow depth and the test was left to run for a time period of 48 hours. A time series was previously carried out under similar flow conditions and it was established that d_{se} experienced negligible changes after 48 hours. Comparison of scour profiles for tests conducted for 48 hours and 72 hours showed a change of less than 5 percent in both scour hole depth and width. Therefore, 48 hours was deemed an acceptable period of time for equilibrium conditions to be reached under the described experimental conditions. Once the testing period had elapsed, the pump frequency was gradually decreased and turned off. The flume was drained slowly in order to avoid disturbance of the bed formations. For each test, a streamwise profile along the geometric centre of the pier and a contour of the scour hole and downstream bed formation were taken using a Leica laser distance meter.

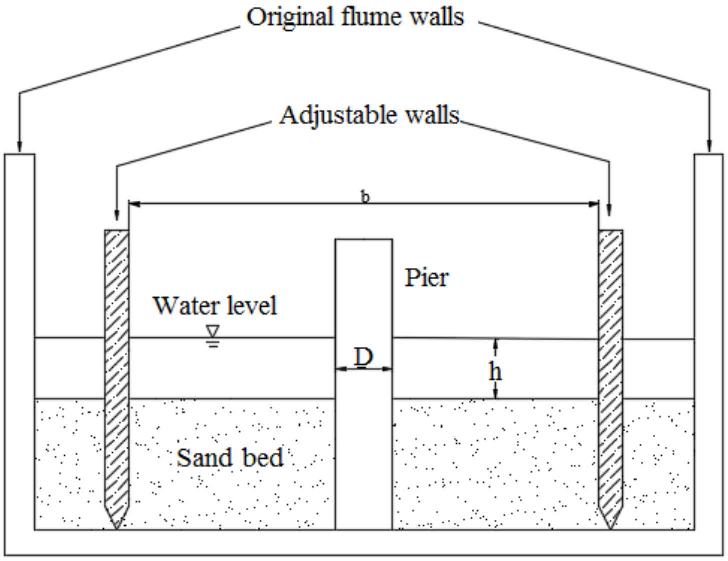

Figure 1: Schematic of experimental set-up

Three tests of varying blockage ratios (5%, 10 % and 15%) were carried out under otherwise identical testing conditions. Flow intensity was maintained at 0.85 in order to ensure scour in the clear-water regime. Flow shallowness was held to a value of 1.4 in order to avoid the effects of flow depth as per Melville and Coleman's (2000) conclusions. Pier diameter D was constant at 0.06025 m for each test, relative coarseness also remained unchanged. The test conditions were thus controlled in order to isolate the influence of sidewall proximity for the current investigation.

3 RESULTS AND DISCUSSION

3.1 Influence of blockage ratio on scour geometry

Figures 2 and 3 show the centreline and contour profiles for three tests with blockage ratios of 5%, 10% and 15%. Figure 2 shows that the scour profiles upstream of the pier are very similar for all three values of blockage ratio; as is expected for tests completed in bed sediment of the same angle of repose, the slope of the scour hole in the upstream region is similar for each profile. The main differences lie in the maximum scour depth very close to the lee side of the cylinder, d_{se}, which is smaller for D/b = 5% than D/b = 10% and 15%. However, d_{se} and the profiles in general are very similar for D/b = 10% and D/b = 15%, indicating that perhaps as blockage ratio increases beyond some threshold value, its influence on scour geometry may reach constancy. However, further experimentation of a similar nature is required before significant conclusions in this vein can be drawn.

As is characteristic of most scour tests comparing blockage ratios, the main differences in the scour profiles lie in the downstream formation. While the downstream slope of the scour hole in the vicinity of the pier is similar for all tests, there is a more significant deviation between the profiles for D/b = 5 percent and D/b = 10 and 15% than in the profiles upstream of the pier. The length of the primary deposit (not shown for D/b = 10% and 15%) is also less for D/b = 5% (as an example, this length is approximately 6D for D/b = 5% and 8D for D/b = 15%). As previously described, the velocity along the separating streamline extending from the side of the pier and around the wake in plan has been shown to be indicative of sidewall influences on scour geometry. This provides an explanation for the deviation in scour profile differences between the upstream and downstream regions of the profiles; separation velocity occurs near the sides of the pier and in the wake, and therefore its magnitude, related to blockage ratio, has a stronger influence on scour formations downstream of the pier. Since flow is subcritical and the control of the flow is downstream, it is logical that the upstream scour depths would also be influenced by changes in the separation velocity, albeit to a lesser extent as indicated by the profiles.

The contour profiles in Figure 3 also show that the extent of scour for D/b = 5% is less than the extents for D/b = 10% and D/b = 15%. Furthermore, the scour profile for D/b = 5% does not reach the sidewalls, unlike the profile for D/b = 15%. The contours are also very similar for the tests with D/b = 10% and D/b = 15%. In fact, the contour for D/b = 10% is slightly larger than the contour for D/b = 15%. In general, it can be stated that scour depth and extent is lesser for D/b = 5% than for D/b = 10% and 15%, and that minimal differences are noted between profiles for tests completed under the two larger blockage ratios.

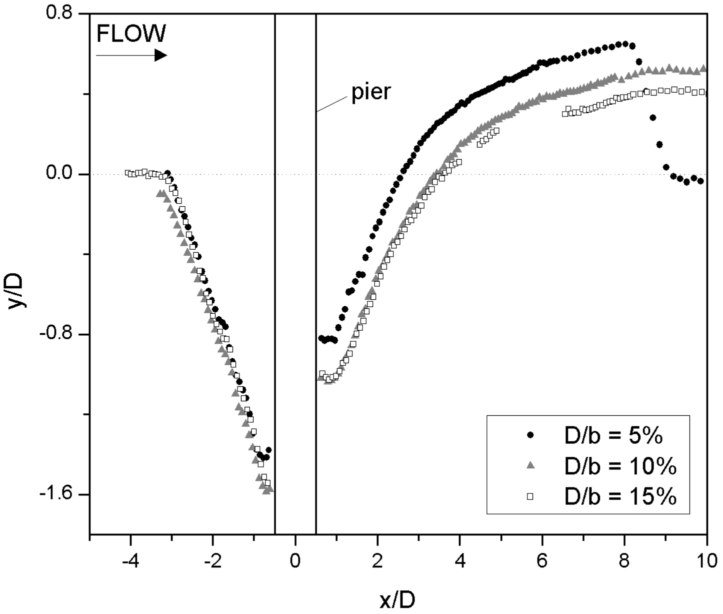

Figure 2: Centreline profiles for tests with D/b = 5%, D/b = 10% and D/b = 15%

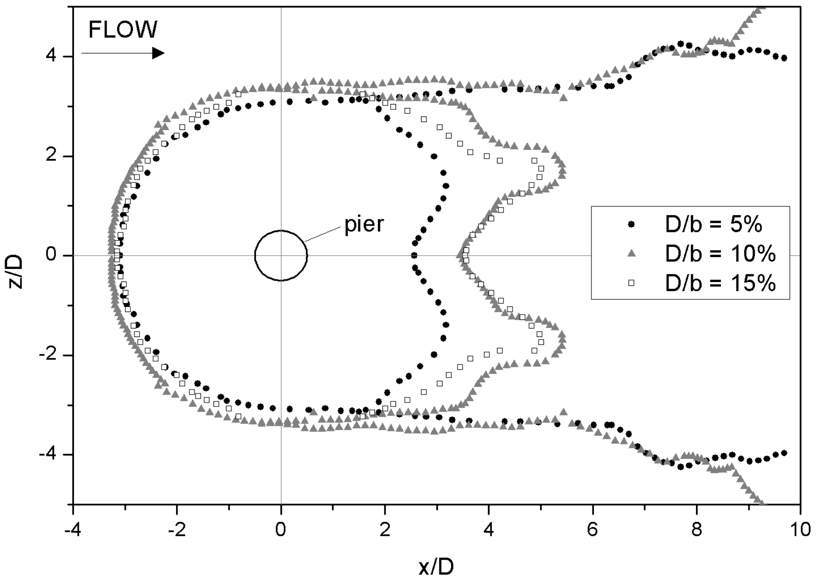

Figure 3: Contour profiles for tests with D/b = 5%, D/b = 10% and D/b = 15%

3.2 Influence of blockage ratio on separation velocity

Figure 4 shows the relationship between blockage ratio and k (= the ratio between U_s and U) for various body shapes based on the analysis of Ramamurthy and Lee (1973). The authors in this investigation compiled results from literature and synthesized with their own experimental data in order to derive a single curve relating D/b to k. Figure 4 shows separate curves based on these results for circular cylinders as well as triangular prisms in two different orientations, where θ = 0° for a prism base on the lee side, and θ = 60° for a prism base on the wake side. Using the curves in the figure for each figure type, k was determined for tests from the current investigation as well as tests from the literature with values of flow intensity between 0.75 and 0.90, as is typical for a clear-water investigation. A new parameter k_c was then determined by combining k and flow intensity, such that $k_c = U_s/U_c$. Since U_s is related to blockage ratio and U_c is specific to sediment type, parameter k_c incorporates both sidewall effects and sediment characteristics, and when implemented as a scour-governing parameter, eliminates the need to include either D/b or D/d_{50} for calculation of d_{se}/D. The inset in Figure 4 shows the relevant parameters used in analysis.

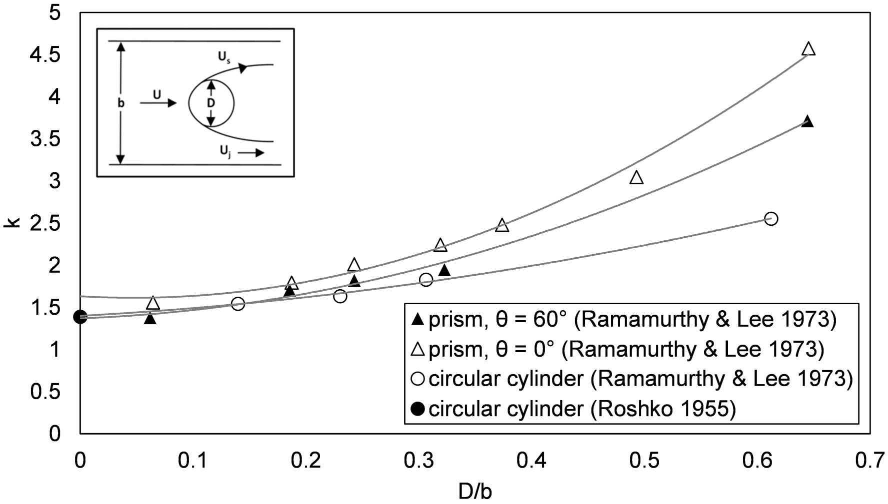

Figure 4: Relationship between k and D/b for various cylinder shapes and orientations

3.3 Relationship between k_c and relative scour depth

A scour-predicting equation was then established by linear regression, incorporating both k_c and flow shallowness, h/D, for circular cylinders, as shown in Equation 1:

$$[1]\ \frac{d_{se}}{D} = 0.76{k_c}^{1.69}\left(\frac{h}{D}\right)^{0.32}$$

Figure 5 shows the relationship between k_c and d_{se}/D for experimental results from the current investigation as well as results from the literature. The dashed lines in the figure show the values of d_{se}/D using Equation 1 for h/D = 1.0 to 4.0. The data points in black are experiments for scour around circular cylinders, the results of which were used to develop Equation 1. The data points in red are experiments for scour around triangular-nosed cylinders. The distribution of the results for the triangular-nosed cylinders show a similar relationship between k_c and d_{se}/D as that of circular cylinders. However, the inset in Figure 5 shows the relationship between experimentally derived scour depth, $(d_{se}/D)_m$ and relative scour depth calculated using Equation 1, $(d_{se}/D)_p$. Predicted and measured results for circular cylinders (in black) show a strong agreement (this is to be expected, since these results were used to develop the relationship). However, the figure indicates that results for the triangular-nosed cylinders are over-predicted. While Figure 5 exhibits a clear relationship between k_c and relative scour depth for triangular-nosed cylinders, such that k_c can be used to predict d_{se}/D, the inset shows that further experimentation on scour around triangular-nosed piers is required in order to obtain a larger sample of data for regression analysis similar to that used in order to develop Equation 1 for circular cylinders.

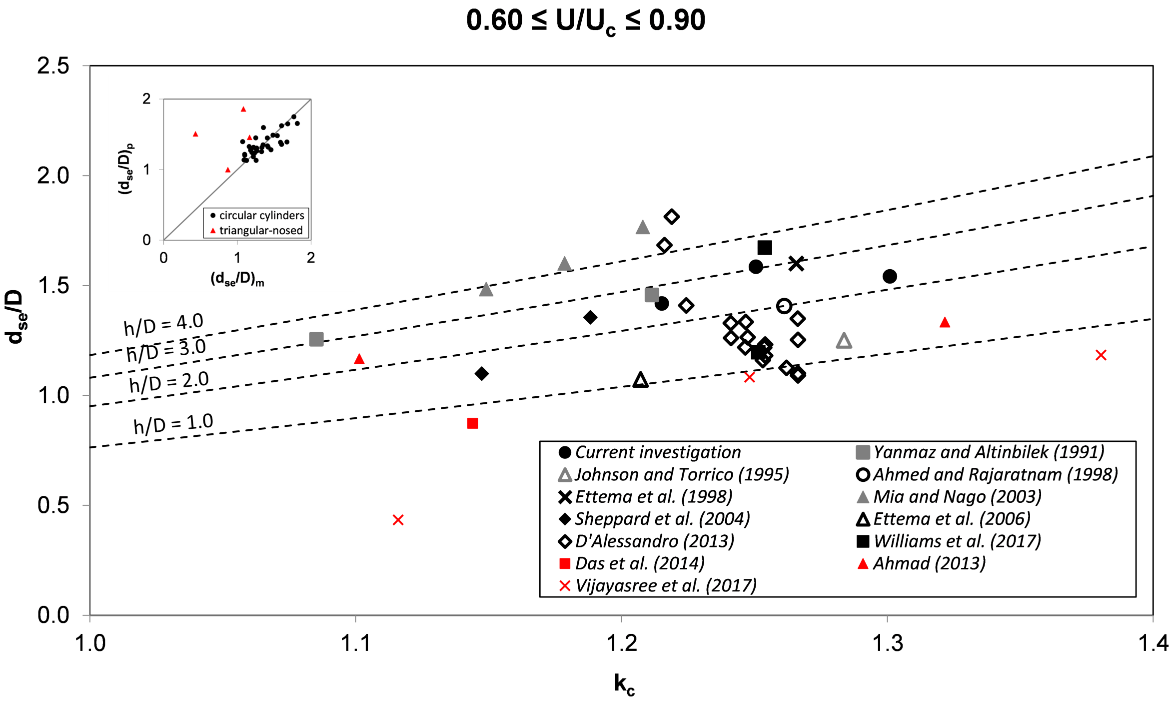

Figure 5: Relative scour depth vs. k_c (U_s/U_c) for experimental results from current investigation and literature

4 CONCLUSIONS AND RECOMMENDATIONS

The influence of channel blockage on bridge pier scour was investigated experimentally and analytically. Test results indicate that sidewall proximity influences the depth and extent of scour profiles; however, further investigation is required in the literature-defined threshold region of D/b = 10%. Use of the velocity along the separating streamline, known as separation velocity U_s, is confirmed as the proper quantity for scaling based on experimental results as well as analysis of literature results. A scour-predicting equation based on test results from the current investigation and results from literature for circular cylinders is presented, indicating a strong relationship between parameter k_s (the ratio between U_s and critical velocity of sediment U_c) and relative scour depth. A similar relationship can be shown for triangular-nosed cylinders; however, the presented equation over-predicts d_{se}/D for triangular-nosed cylinders. Further experimentation is required in order to acquire an appreciably large sample of data in order to develop a similar relationship for scour prediction for triangular-nosed piers.

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