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EFFECTS OF RELATIVE BED COARSENESS AND BLOCKAGE RATIO ON LOCAL SCOUR AROUND BRIDGE ABUTMENTS

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Abstract: Based on a series of experiments conducted at the Sedimentation and Scour Study Laboratory at the University of Windsor, the effect of relative bed coarseness and blockage ratio on local scour around bridge abutments are presented. Scour around semi-circular bridge abutments with different diameters are compared under identical flow conditions for several blockage ratios. The objective is to provide a clearer understanding on the impacts of relative bed coarseness and blockage ratio on the local scour profile and maximum scour depth. Results of this study indicate that both equilibrium scour depth and scour profile are affected by blockage ratio. Clear differences can be noted in the scour geometry even for small changes in blockage ratio. With the increase of relative bed coarseness, the scour width and scour depth decrease correspondingly. Additionally, the approach flow depth shows a strong influence on the scour geometry. The study provides additional support for considering relative bed coarseness and blockage ratio in local scour prediction around bridge foundations.

1 INTRODUCTION

The local scour has been one of the major concerns in hydraulic engineering. Excessive scour around bridge foundations may potentially result in structural failure, which may pose a significant threat to public safety (Sturm et. al. 2011). Six of ten bridge failures that occurred in New Zealand during cyclone Bola were related to abutment scour (Kandasamy and Melville, 1998). Over 500 State or locally owned bridges were damaged in the flooding from storm Alberto in 1994, and nearly one third of failures were identified due to scour damage (FHWA-HIF, 2012). One of the challenging problems in hydraulic engineering is to predict the maximum scour depth around abutments and piers to avoid possible damage to the foundations. Various studies have been conducted in the past to derive empirical relationships using laboratory flumes.

Some milestone work includes that of Froehlich (1989), Melville (1992, 1997), Lim (1997), Ettema and Muste, (2004), Sturm (2006), and Ettema et al. (2010). Barbhuiya and Dey (2004) provide a good review of several of the empirical equations on the local scour at bridge abutments. It was noticed that equations suggested by Richardson et al. (2001) and Oliveto & Hager (2002) provide a conservative estimate of scour depth. Ghazvinei et al. (2012) conducted a detailed comparison of scour equations using statistical analysis. They found that the equations provided by Laursen (1963) and Melville (1992) can provide acceptable prediction of local scour around abutments. Due to the different settings in experimental setup, the prediction formulae provide different results on the scour depth and scour geometry. No standardised equation can be presently found in the literature.

Five parameter groups have been found to influence scour around abutments (Sturm et al., 2011). These include: flow and sediment variables; relative abutment and sediment scales; abutment and flow geometry variables; flow distribution ratios and abutment stability parameters. The scour estimation methods presently available for flow past abutments do not adequately take all parameters into account. Some have noticed the dimensionless groups such as V/Vc (Vc is the critical velocity for sediment movement), H/R and R/d50 are useful to describe the physics of the local scour process around bridge piers (Meilville 1997; Sheppard and Miller, 2006; Lee and Sturm, 2009). Sheppard et al. (2014) reviewed laboratory and field data and presented one comprehensive equation (hence forth referred to as Sheppard/Melville equation) for the estimation of scour depth around bridge piers, which included the impact of R/d50. However, for bridge abutments, the role of R/d50 (R = abutment radius) has not been fully considered in the estimation formula. Additionally, blockage ratio was not discussed in the equation.

To address the specific issue of relative bed coarseness, an experimental research is conducted to investigate the effect of (R/d50) and blockage ratios (R/B) on the scour depth. Here, B is the width of the flume. Considering that one type of abutment (semi-circular) and one type of sediment is used in the study, a simplified dimensional analysis leads to the following set of parameters:

[1] ds/R = f (R/B, R/d50, H/R)

Here, ds is the equilibrium maximum scour depth; V and Vc are the approaching flow velocity and critical velocity, respectively; d50 is the median grain size, R is the abutment radius, H is the depth of approaching flow and B is the width of the channel.

2 METHODOLOGY

The experimental study was conducted in a re-circulating flume at the University of Windsor. The flume is 12 m in length, with 1.22 m in width and 0.91 m in depth. A sand box of 3.65 m long was placed inside the flume to simulate sediment movement around abutments. The headwater can be adjusted by using the tailgate at the end of the flume. The flume has been well calibrated in previous studies and the quality of the flow has been well established.

As shown in Figure 1, a clear plastic half-pipe is attached to the side wall to simulate the semi-circular abutment.

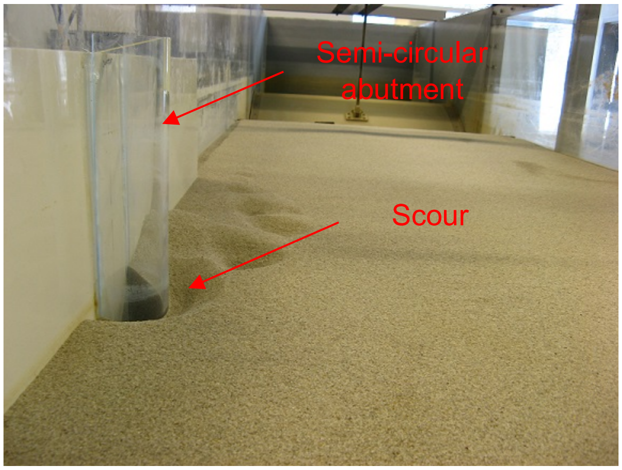

Figure 1: Experimental setup and scour around the abutment

The principal objectives were to investigate the effect of the relative coarseness and blockage ratio on scour. Therefore, a constant approaching velocity (15% below the critical velocity) was selected to avoid general scour and live bed scour. The blockage ratios is limited to 10%, which is commonly used as the maximum blockage ratio in bridge engineering experiments. One uniform sediment size (d_{50} = 0.77 mm) is used in all the experiments.

Three semi-circular abutments with radii, R = 21.1, 36.5 and 60.0 mm, are attached to one moveable smooth wall as shown in Figure 1 to simulate the scour around abutment with solid foundation in the riverbed. The relative bed coarseness (R/d_{50}) ranges from 27 to 78.

By adjusting the distance between two movable walls, different blockage ratios can be generated, namely 5%, 7.5% and 10%. Additionally, two water depths (H = 120 mm and 150 mm) are used in the experiments. The average flow velocity is maintained constant at V = 0.26 m/s which corresponds to 85% of the critical velocity (V_c). The densimetric Froude number is held constant at 2.33. In total, 18 experiments were conducted as shown in Table 1. By comparing the scour depth at 48 hours and 90 hours, it was noted that the scour profile are very similar. Therefore, most tests were conducted at 48 hours and the scour profiles can be identified as equilibrium scour depth. At the end of each test, the flume was drained completely and the scour geometry was measured using a digital laser point gauge (Leica DISTO E7400x).

Table 1: Experimental conditions

Group	R (mm)	B (mm)	H (mm)	R/B (%)	H/R	R/d_{50}
A	60.0	1200	120	5	2.0	78
	60.0	800	120	7.5	2.0	78
	60.0	600	120	10	2.0	78
	60.0	1200	150	5	2.5	78
	60.0	800	150	7.5	2.5	78
	60.0	600	150	10	2.5	78
B	36.5	760	120	5	3.3	47
	36.5	487	120	7.5	3.3	47
	36.5	365	120	10	3.3	47
	36.5	760	150	5	4.1	47
	36.5	487	150	7.5	4.1	47
	36.5	365	150	10	4.1	47
C	21.1	440	120	5	5.7	27
	21.1	281	120	7.5	5.7	27
	21.1	211	120	10	5.7	27
	21.1	440	150	5	7.1	27
	21.1	281	150	7.5	7.1	27
	21.1	211	150	10	7.1	27

3 RESULTS AND ANALYSIS

3.1 Relative bed coarseness

The impact of relative bed coarseness on scour depth around abutments are shown in Figures 2 to 4 at different blockage ratios. Figure 2 shows the scour profile in the flow direction at 5% blockage under two flow depth, H = 120 mm and 150 mm. Figure 3 and Figure 4 have the same arrangement as in Figure 2, but at different blockage ratios of 7.5% and 10%, respectively.

The ratio of R/d50 has been used in the past to represent relative bed coarseness. In the present study, the impact of relative bed coarseness on scour depth is analyzed. It is clear that with the increase in R/d50, the dimensionless scour depth decreases. Similar changes can be noted at both flow depths. However, for a given R/d50, the scour depth is significantly larger at a larger flow depth (H = 150 mm) compared with that at H = 120 mm. For all abutments, the average increase is around 40% with change in flow depth at R/B = 5%. In Figures 3 and 4, the average increase is 30% with increase in flow depth at a given R/d50 for blockage ratios of 7.5% and 10%.

It should also be noted that the scouring area decreases with the increase in R/d50 from 27 to 78. The scour depth at R/d50 = 27 is the largest among all the three blockage ratios. With a lower value of R/d50 (= 27), the dimensionless scour depth is about 30% larger compared to that at R/d50 = 47. Furthermore, when R/d50 = 47, the dimensionless scour depth is 30% larger compared to that at R/d50 = 78. From Figures 2 to 4, it is clear that relative bed coarseness has a significant impact on scour depth around abutments.

As seen in Figures 2 to 4, a significant difference in scour depth can be noticed between the two flow depths, which indicates the strong role of flow depth on local scour. In Figure 2, with the increase in flow depth from 120 mm to 150 mm, the average increase of scour depth is around 70%, which may due to the stronger down flow in the case of larger flow depth. In the case of 7.5% and 10% blockage, the increase in scour depth is smaller when the flow depth was changed from 120 mm to 150 mm. The impact of flow depth on scour depth is obvious when one compares Figure 2 to Figure 4.

As expected, with a small value of R/d50, the scour depth has the largest value in the present study. It is also clear that the approaching flow water depth has a strong influence on the depth of scour. It is necessary to consider the impact of relative bed coarseness on the scour prediction equations.

3.2 Blockage ratio

To further examine the effect of blockage ratio on scour depth, the maximum scour depth is used for comparison as shown in Figure 5. The maximum scour depth is presented at two flow depths.

At H = 120 mm, with the increase of blockage ratio from 5% to 10%, the dimensionless scour depth also increases from 0.82 to 1.50 at R/d50 = 27. With the increase in R/d50, the difference in the dimensionless maximum scour depth among the blockage ratios becomes smaller. This is clear at H = 150 mm. When the R/d50 is held constant at 78, the scour depth only slightly increased from 1.2 to 1.3 with the increase in blockage ratio. It seems like the average increase of maximum scour depth at a larger flow depth is smaller compared to that at shallow waters. In other words, the blockage ratio plays a more significant role at smaller water depth. In deep water, due the dominant role of flow depth in affecting the scour depth, the impact of blockage ratios becomes less.

To further investigate the effect of blockage ratio and relative coarseness, Figure 6 is introduced. It summarizes the impact of relative bed coarseness on maximum scour depth. The open symbols represent the results at the smaller water depth while the closed symbols show the maximum depth of scour at H = 150 mm. We can see from the figure that the largest dimensionless scour depth occurs at a 10% blockage ratio under both flow depths. It is a clear from the figure that blockage ratio coupled with other factors influence the extent of scour around the abutment.

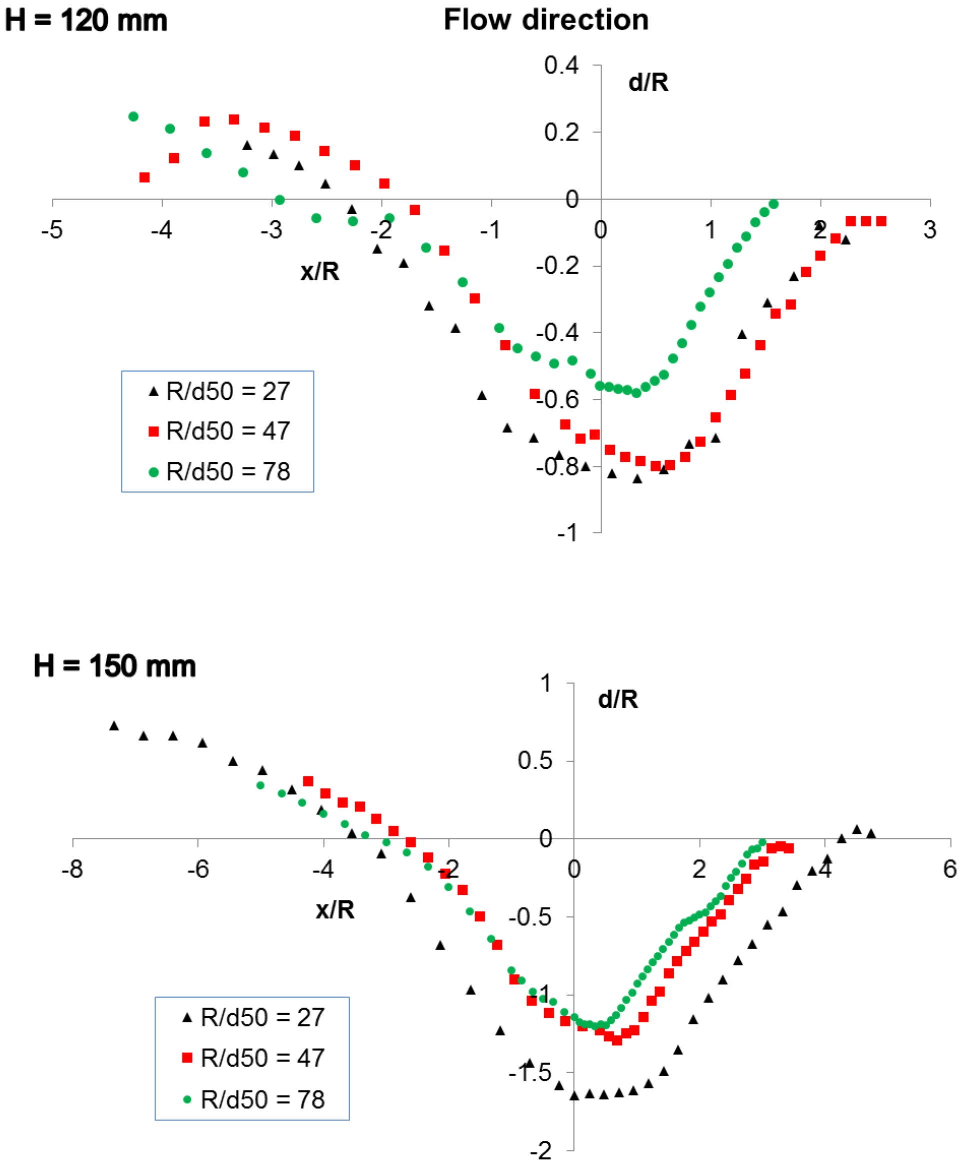

Figure 2: The impact of R/d50 on the dimensionless scour profile in the flow direction at 5% blockage

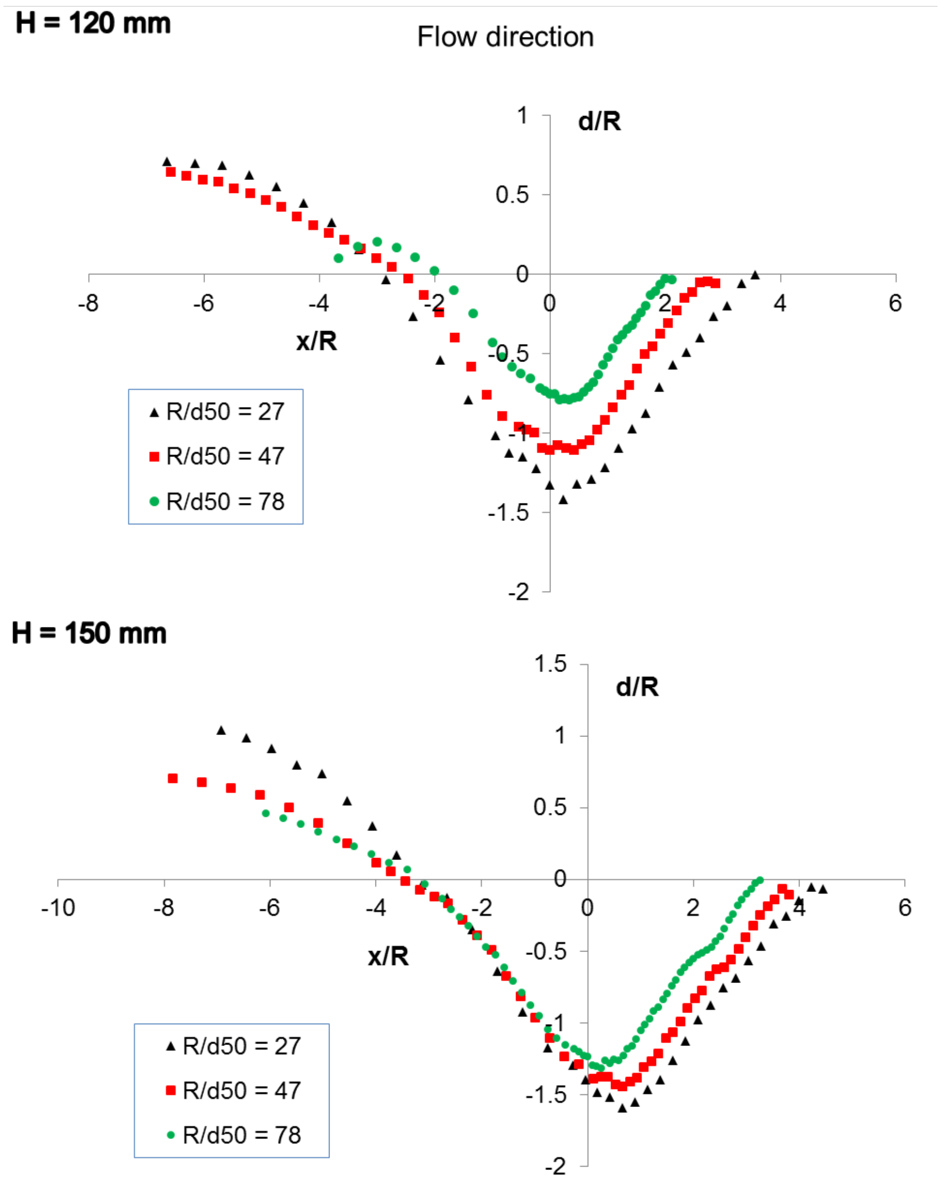

Figure 3: The impact of R/d50 on the dimensionless scour profile in the flow direction at 7.5% blockage

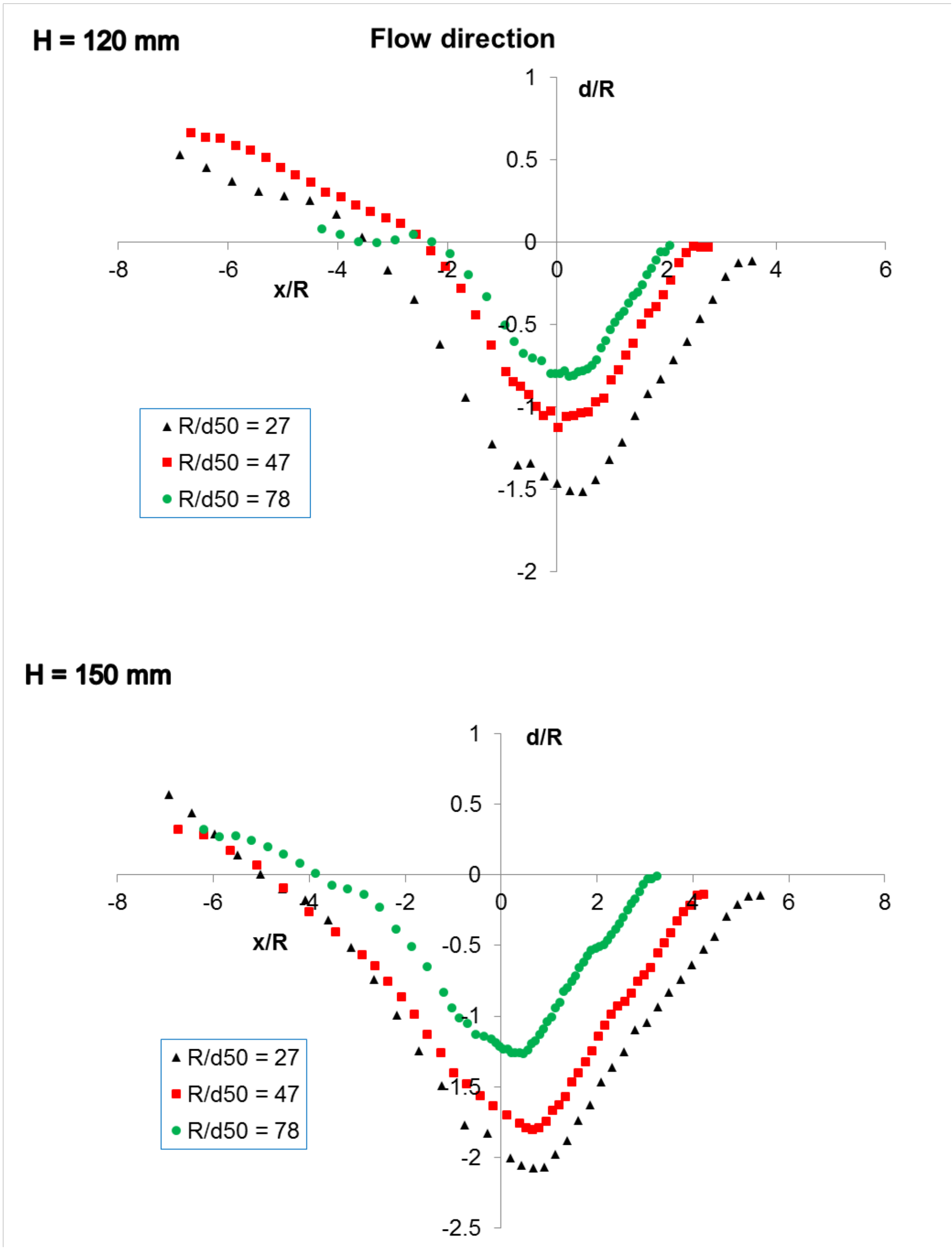

Figure 4: The impact of R/d50 on the dimensionless scour profile in the flow direction at 10% blockage

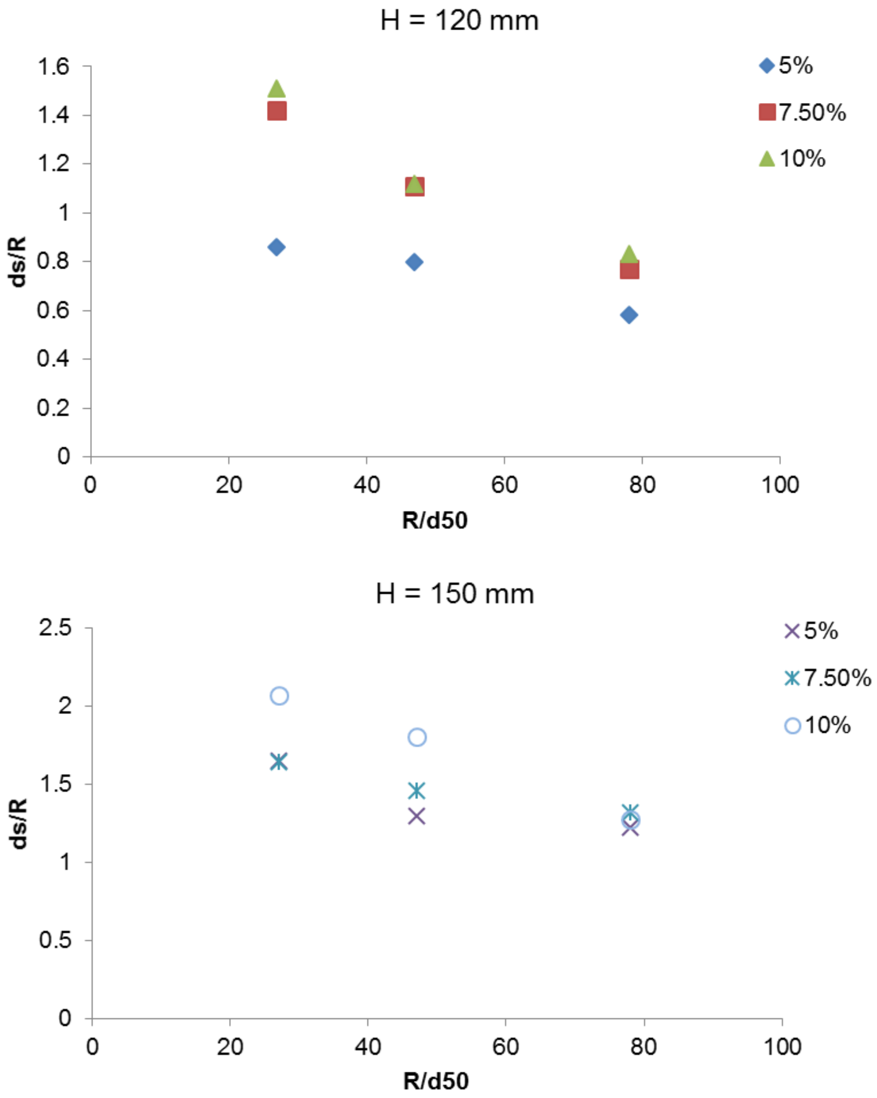

Figure 5: The dimensionless maximum scour depth at different blockage ratios

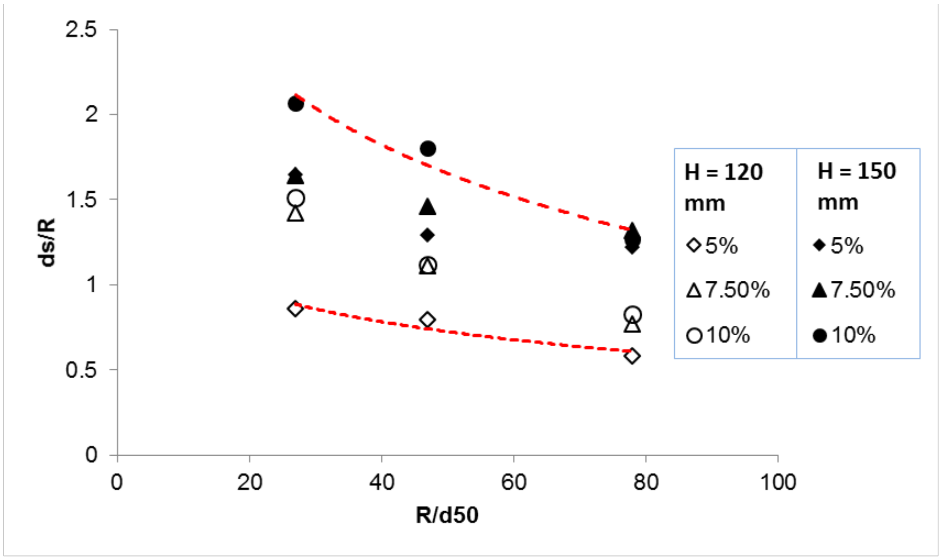

Figure 6: The comparison of maximum scour depth at different blockages and relative bed coarseness

4 CONCLUSION

The present study presents the effect of relative bed coarseness and blockage ratios on the scour profile and maximum scour depth around bridge abutments. With the increase in R/d50, the scour depth decreases correspondingly. Larger blockage ratios result in larger scour depth. The present experimental research shows extra support for including relative bed coarseness and blockage ratio in abutment scour estimation formulae.

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