Scour at cofferdam structures on river walls

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ABSTRACT

Construction activities in rivers and estuaries require cofferdams to be installed to provide a dry working area. Predictions of scour at these temporary structures are made using methods proposed for river abutments in industry guidance with engineering judgement made on the selection of coefficients. The area of the cofferdam and protrusion in the waterway is often larger than the permanent works they are facilitating and they are long, in some instances several hundred metres along the flow direction. Clear-water scour experiments in the General Purpose Flume at HR Wallingford explore the influence of wall mounted cofferdam shape and length, water depth and flow speed on scour. The results provide information of use to engineers working with cofferdams and comments are made on the application of predictive methods.

INTRODUCTION

Construction activities in rivers or estuaries require cofferdams to be installed to exclude water and sediment and provide a dry working area (Figure 1). Sheet-piled cofferdams that are square or rectangular in shape are easy to construct but often are the worst shape for scour (Kirby *et al.*, 2015). The cofferdams protrude into the waterway from the river wall or embankment and the associated change in flow pattern and increased turbulence around the structure causes scouring of the bed. In estuaries, even when the structure is located outside the main flow channel upon the intertidal area, they may be subject to localised scouring. Predictions of scour at these temporary structures are required to ensure the foundation toe depth is selected correctly.

The nature of cofferdams is somewhat different compared to the permanent works they are facilitating in that they are not usually designed for long-term performance, although the scour allowances may be comparable to those at a permanent structure. Scour estimates are often made with methods proposed for river abutments in the Hydraulic Engineering Circular (HEC) or the Construction Industry Research and Information Association (CIRIA) guidance, with engineering judgement made on the selection of coefficients (Arneson *et al.*, 2012; Kirby *et al.*, 2015).

An abutment whether related to a bridge or another type of structure that projects into the main river channel will cause the flow to be accelerated creating local scour. There has been a considerable amount of physical modelling and analysis of local scour at abutments reported on in the technical literature (Melville and Coleman, 2000; Barkdoll *et al.*, 2007). Sometimes, issues arise due to limited flume widths for experiments making it difficult to separate local scour from contraction effects. Therefore, there is uncertainty associated with about how those results are applied in practise for prediction of local scour.

Figure 1: Temporary cofferdam works within an estuary. (*Source: J. Harris*)

Flume experiments with a sand bed have been used to investigate some of the controlling processes, including the effect of sediment mobility, and quantified the patterns and depths of scour that can be expected. The results from a range of structure plan-shapes including rectangular and triangular are summarised and compared, and the beneficial effect on scour of streamlining the corner of a rectangular structure is explored. The experimental results and comments on the application of predictive methods are of use to engineers working with cofferdams.

METHOD

Physical model experiments in the General Purpose Flume (25 m long, 2.4 m wide and 0.9 m deep) at HR Wallingford explored the influence of cofferdam shape and length, water depth and flow speed on the scour development in the clear-water regime. The test structures were founded in a 0.5 m deep bed of medium grained sand with appropriate upstream and downstream boundary conditions to obtain reliable results in the test section. The upstream boundary condition for the bed was a solid bed with roughness to minimise scour at the transition to the mobile bed and a polystyrene sheet floating on the water surface to reduce surface disturbances from the inlet weir. The downstream boundary condition was a fixed bed and an adjustable weir to set the water level. The flow discharge, flow velocity, water levels and bed levels were recorded. Tests were run until the scour hole depth appeared to have stabilised, which was after 50 to 75 hours and tests were left to continue running overnight so as not to disturb the results by stopping and re-starting the flow.

The scoured bed level was monitored visually against marked elevations on the structures (Figure 2a). On start and completion of each test a full 3-dimensional bed elevation model was surveyed from a frame over the flume with a terrestrial laser scanner. The data enabled both the depth and the horizontal extent of scour (and deposition) to be determined (Figure 2b). Negative values indicate scour below the initial bed level and positive values equate to sediment build up.

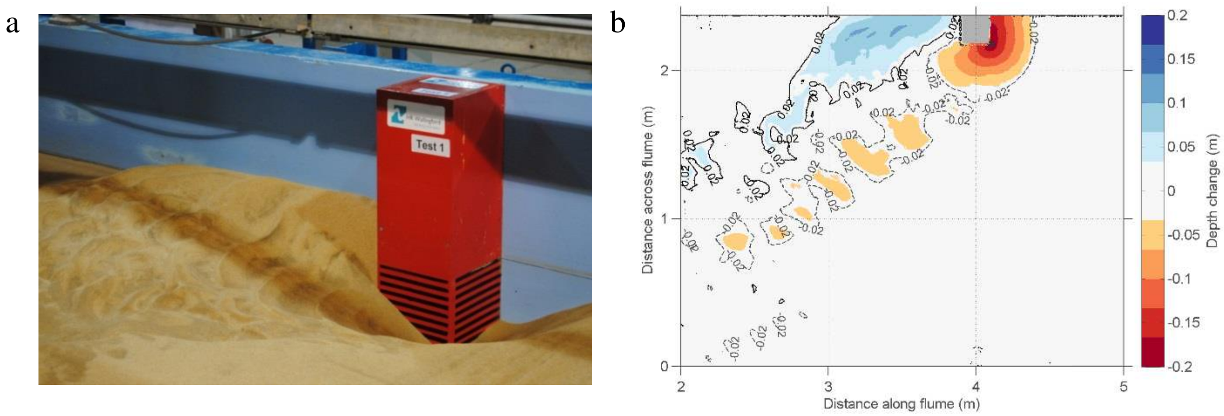

Figure 2: Test 1 result (flow from right to left); a. photograph of the post-test result (black and red graduations at 10 mm spacing) and b. difference in bed elevation between start and end of test.

Six different shaped structures were tested in a total of 10 tests. The structure shapes are shown in Figure 3, where the current direction is downwards from the top of the page. The tests were designed to ensure no contraction scour would result from placing structures in the flume section. The maximum structure blockage in the cross-section did not exceed the 1/6th ~17% consideration for model design (Whitehouse, 1998). In some cases two structures were tested simultaneously on either side of the flume, yielding interesting results because two different structures could be compared with identical testing conditions. A total of 14 different structure - flow condition combinations were tested, all providing independent results for local scour.

The purpose of the different shapes was to illustrate the following effects:

- Structure A compared to Structure C to examine the increase in length (parallel to flow).
- Structure C compared to Structure B to examine the increase in structure width (across flow).
- Structures D and E are variations on the rectangular plan shape of Structure C.
- Structure F is a complex shape version of B with the same width.
- Structure G provides comparison for a pier of the same size as Structure A on the wall.

The grain size parameters for the quartz sand used in the tests were d_{10} = 0.326 mm, d_{50} = 0.525 mm and d_{90} = 0.673 mm characterizing a well-sorted sand with coefficient of uniformity (d_{60}/d_{10}) of 1.8. Fresh water was used and the temperature varied from 9 to 15 °C during all the tests. Using the method of Soulsby (1997) the threshold current U_{cr} for water depths of 0.2 and 0.1 m were estimated to be 0.27 m/s and 0.24 m/s, respectively. Observations of the initial mobilisation of sediment during calibration confirmed these results.

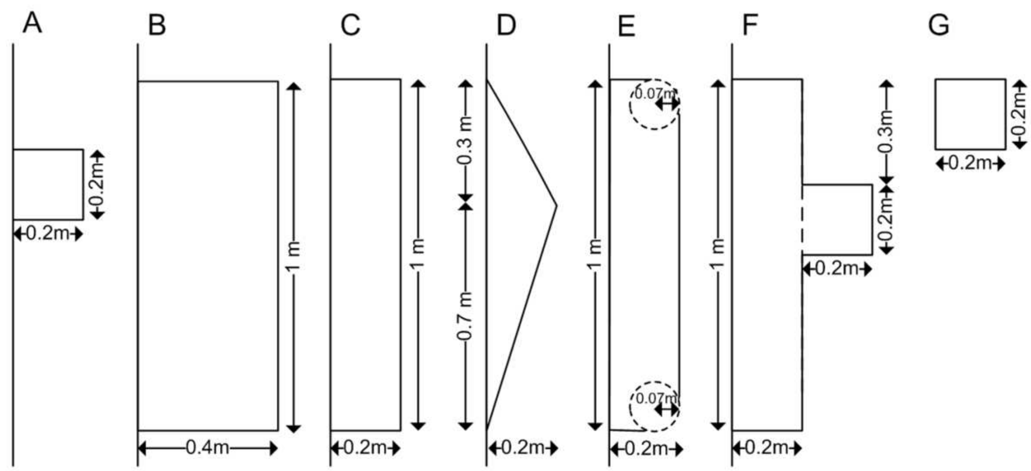

Figure 3: Cofferdam shapes used in the model experiments. The wall is on the left hand side of Structures A to F. The length of the structure is the distance along the wall and the width the distance the structure protrudes from the wall.

RESULTS

Table 3 summarizes the tests. When the test number has an 'a' and 'b' two structures were tested simultaneously on opposite walls of the flume. For the majority of tests the flow speed was 0.17 m/s, water depth 0.2 m and unobstructed flume cross-sectional area of 0.480 m^2. Some tests also considered the influence of reduced water depth (0.1 m with cross-sectional area of 0.24 m^2) and different flow speeds. The width, W, is defined as the distance the structure projects across the flow and the length, L, is the along flow distance.

The scour depths are represented by two values in Table 3; one for the scour depth at the cofferdam wall S_{str} and a second for the maximum scour depth S_{max} from the laser scanner which was not always at the wall. The bed elevation changes from the laser scanner are plotted in Figure 4. Tests 6b and 8b were run for the same conditions to check repeatability with Structure C under the same flow conditions and difference in test duration of less than one hour. The scour depths S_{str} at the corner of the structure differed by 8 mm between these two tests which is less than 10% of the measured values. The maximum scour depths only differed by 1 mm (1%).

To provide a comparison with the wall mounted structure (Test 2, Figure 4b) an open water pier of the same dimensions was tested in Test 10 (Figure 4j). The scour pattern in Test 10 was typical of a square pier with scour developing at the corners and along the upstream face whilst depositing sediment downstream. The scour depth in Test 10 was compared to the square pier data of May and Willoughby (1990) and found to be in general agreement when plotted in terms of the sediment mobility (Figure 5). Mounting the cube on the wall reduced the scour depth by approximately 29%.

The results in Figure 4 where two structures were installed showed that there was no contraction scour between the structures as expected. In Tests 7a and b with the high bed mobility (Figure 4g) the bed instability caused by the scour propagated downstream and interacted beyond the end point of the structures on the wall, so the impact on the local scour at the structures themselves was minimal.

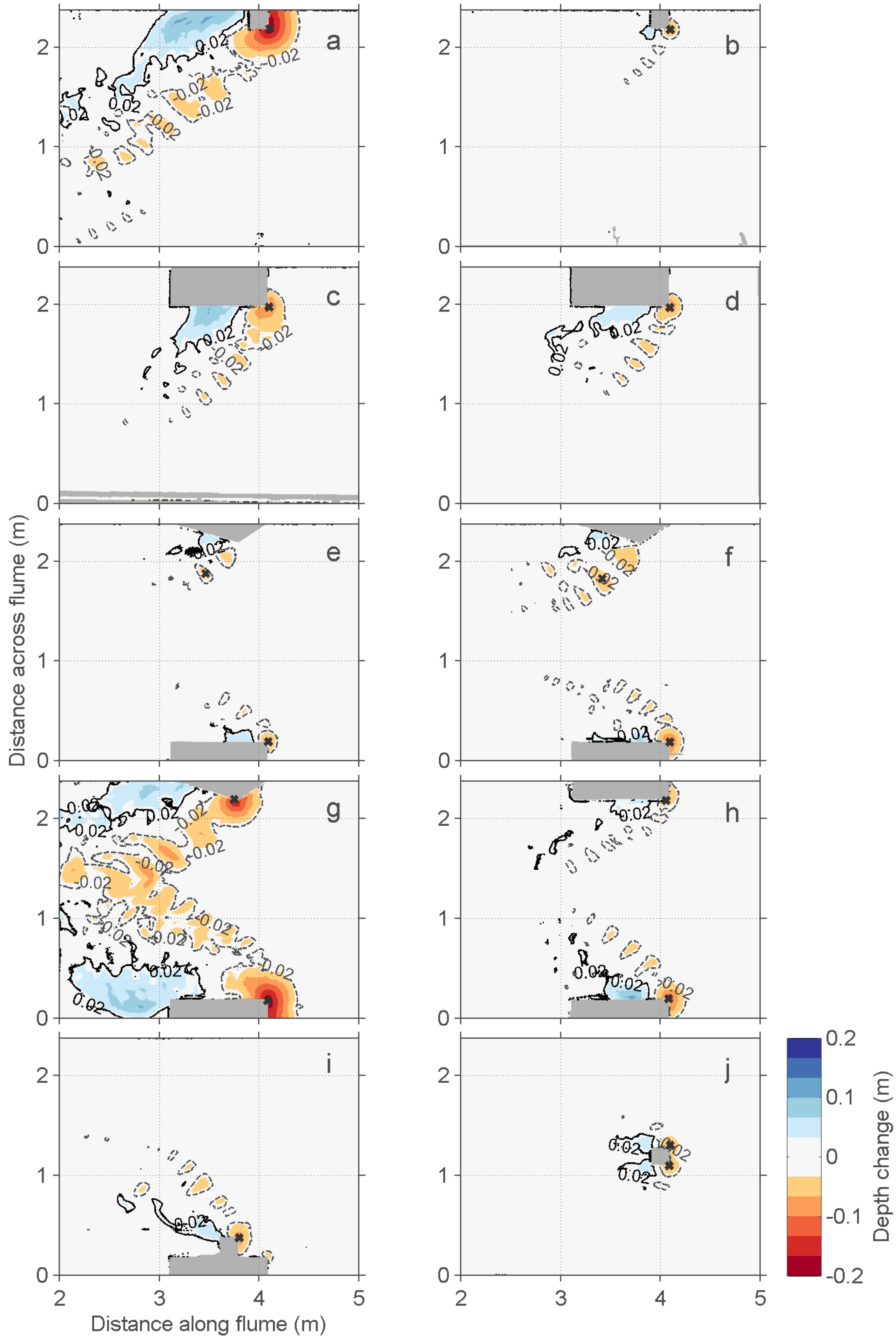

Figure 4: Change in bed elevation: a. Test 1; b. Test 2; c. Test 3; d. Test 4; e. Test 5a & 5b; f. Test 6a & 6b; g. Test 7a & 7b; h. Test 8a & 8b; i. Test 9; j. Test 10.

Table 3: Test conditions and results (For Shape see Figure 3). † **Corner 1, *Corner 2.**

Test	Shape	Width W	Length L	Water Depth h	Flow speed U	Test Length	$\frac{U}{U_{cr}}$	S_{str}	S_{max}
-	-	m	m	m	m/s	hours	-	m	m
1	A	0.2	0.2	0.2	0.244	72.88	0.90	0.180	0.188
2	A	0.2	0.2	0.2	0.173	57.32	0.64	0.070	0.074
3	B	0.4	1.0	0.2	0.173	49.30	0.64	0.100	0.107
4	B	0.4	1.0	0.1	0.150	74.38	0.63	0.100	0.102
5a	D	0.2	1.0	0.1	0.150	74.75	0.63	0.002	0.047
5b	C	0.2	1.0	0.1	0.150	74.75	0.63	0.074	0.081
6a	D	0.2	1.0	0.2	0.173	74.75	0.64	0.003	0.062
6b	C	0.2	1.0	0.2	0.173	74.75	0.64	0.100	0.120
7a	D	0.2	1.0	0.2	0.244	31.30	0.90	0.140	0.155
7b	C	0.2	1.0	0.2	0.244	31.30	0.90	0.170	0.197
8a	E	0.2	1.0	0.2	0.173	75.42	0.64	0.058	0.070
8b	C	0.2	1.0	0.2	0.173	75.42	0.64	0.108	0.119
9	F	0.4	1.0	0.2	0.173	74.83	0.64	0.047† 0.091*	0.048† 0.089*
10	G	0.2	0.2	0.2	0.173	76.25	0.64	0.095	0.101

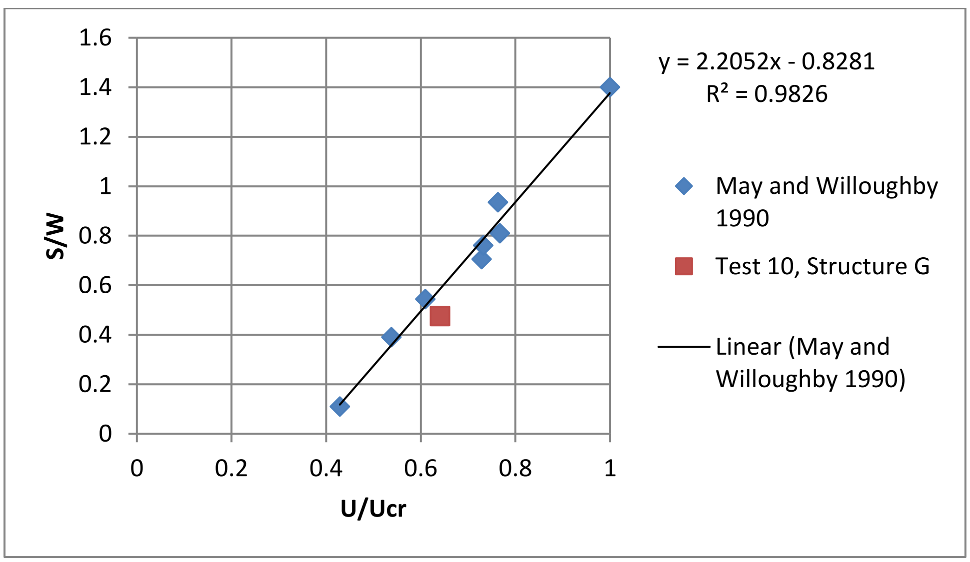

Figure 5: Comparison of square pier result with May and Willoughby (1990).

DISCUSSION

The increase in length of the structure parallel to the flow direction was explored in Tests 6b and 8b with Structure C and Test 2 with Structure A. In Test 2 (Figure 4b) the downflow on the leading face and flow acceleration around the structure caused scour to develop on the leading corner. Deposition occurred in the lee side as the flow expanded behind the short structure. The scour at the leading corner in the case of Structure C (Figure 4f and 4h) expanded across the front towards the flume wall and along the outside face downstream. Because of the increased length, sediment was deposited within the first one-third to one-half of the length of the structure. The duration of Tests 6b and 8b were longer than Test 2 (Table 3) and hence the scour after 57.32 hours (end of Test 2) was extracted for Tests 6b and 8b. The scour depths were 0.095 m and 0.102 m compared with 0.070 m for Test 2 demonstrating an increase of 40% due to the increased length of the structure.

Structure F is a complex shape (Test 9), combining Structures A and C with the same projected width into the flow as Structure B, with scour forming at two corners (Figure 4i and Figure 6). Scour developed more slowly at Corner 1, both due to the pattern of flow around the structure and from the blockage effect preventing the scour hole at Corner 1 extending downstream. The scour depth at Corner 1 was about 50% of that which formed at Corner 2.

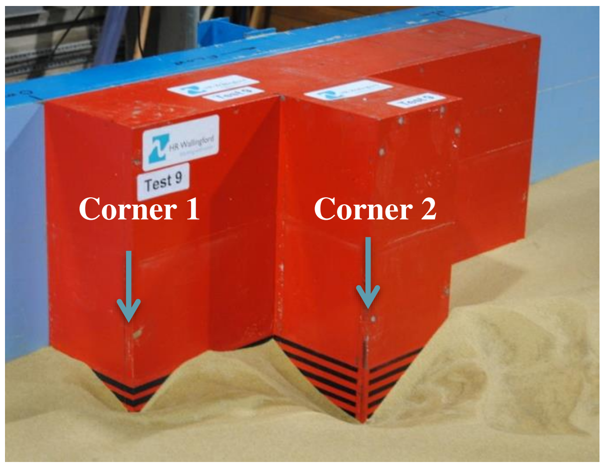

Figure 6: Structure F (Test 9) result.

A shallower water depth was used in Tests 4 and 5 (Figure 4d and 4e) with flow speed also reduced to maintain the value of U/U_{cr}. If we compare Test 5a with 6a and 5b with 6b we observed that with the shallower depth the spatial extents of scour and erosion were reduced. The maximum scour depth was 24% less in Test 5a than 6a, and 33% less in Test 5b than 6b.

Tests 1, 7a and 7b were run at a higher flow speed. In Test 1 the area of scouring remained focused on the leading corner. However, the area of deposition, which for the lower speed test (Test 2) was attached to the downstream corner, shifted downstream and became attached to the flume wall. Similarly in Test 7, compared with Test 6, the areas of scouring remained focused on the leading corner, whilst the deposition area shifted further downstream. Increasing the flow speed, with all other variables fixed, will have increased the sediment mobility and the Froude number, resulting in deeper scour depths.

Structure E investigated the impact of rounding off the corners. This shape was used in Test 8a and was comparable with Shape C used in the same test on the opposite wall (Test 8b). The patterns of scour and deposition observed around both structures were very similar, but a reduction in scour depth of 46% at the wall and 41% for the maximum local scour depth was achieved.

The triangular shaped structure, Structure D, (Tests 5a, 6a, 7a – Figures 4e, 5f, 5g) also yielded smaller scour depths than a rectangular structure of the same width and length (Tests 5b, 6b, 7b). The angled leading face (33°) offers up less of an obstacle to flow. At low mobility the maximum scour depth was well detached from the cofferdam wall and reduced on average by 45% when compared with a rectangle of the same width. During Test 7 with higher mobility the scour pattern was similar to a rectangular structure and the maximum scour was reduced by 21%.

For most tests the width of the abutment was kept fixed (at 0.2 m). However, Shape B used in Tests 3 and 4 had a width double this (0.4 m). Test 3 is comparable with Test 6b, however, the duration differed between these two tests. To make them comparable the scour depth for Test 6b was extracted at 49 hours, giving a scour depth at the wall of 0.094 m. The result of doubling the width of the abutment was to increase the scour depth at the cofferdam wall by 6%. Comparing Test 4 with Test 5b in shallower water showed additional width increases the scour by 26%.

COMPARISON WITH PREDICTIONS

The maximum local scour depth that can occur at a cofferdam for a uniformly graded sediment is at the limit of clear-water scour when the sediment mobility parameter U/Ucr = 1 (Kirby *et al.*, 2015). As a result, whilst our tests with U/Ucr < 1 will not give the maximum scour depths for these structures, they provide valid data for comparison with previous empirical models. Having said this, in areas with coarse, and often heterogeneous, sediments the mobility is characterised by values of $U/U_{cr} < 1$, clear-water scour predominates, and the comparative experimental results will be informative.

The results were compared to predictions from existing design formulae (Richardson and Davis, 2001 and Sheppard *et al.*, 2011 – used in Arneson *et al.*, 2012; Kirby *et al.*, 2015; Breusers *et al.*, 1977). The Breusers, Richardson and Davis, and Sheppard methods apply to bridge piers and have been compared to the result from Structure G. The methods in Kirby *et al.* applies to bridge piers and to abutments. All the formulae have been applied to estimate scour at the cofferdams (Figure 7).

As part of the analysis the simplified cofferdam structures were also assessed as being equivalent to a half-pier to allow the methods of Breusers *et al.*, Richardson and Davis and Sheppard *et al.* to be applied in addition to the abutment method given in Kirby *et al.* (2015). Most approaches tended to over-predict the scour, although Richardson and Davis tended to give over-predictions that were offset from the 1:1 line of agreement and from a design point of view would appear to be acceptable. The approaches of Sheppard *et al.* and Kirby *et al.* led to significant over-prediction whilst the approach of Breusers *et al.* may or may not be conservative partly depending on what multiplier was used in the equation.

Ultimately, the results suggest that the prediction method specifically designed to predict scour development at abutment structures (i.e. Kirby *et al.*, 2015) may be overly conservative. This highlights that careful choices need to be made on appropriate methods and scour allowances based on an evaluation of the location of the cofferdam, flow and sediment conditions and detailed consideration of plan shape.

The methods are good at dealing with the impact of flow intensity and depth variation. None of the predictive equations used have a parameter to define the impact of length of structure along the flow, although the information in Barkdoll *et al.* (2007) on parallel-wall countermeasures and Kirby *et al.* (2015) on guide banks and revetments may be relevant (not analysed in the current paper). The equations do not capture well the decrease in scour depth due to the rounding of the corner, and do not include an approach for complex (multi-faced) structures. Finally, the half-pier assumption for predicting abutment scour could benefit from being tested further.

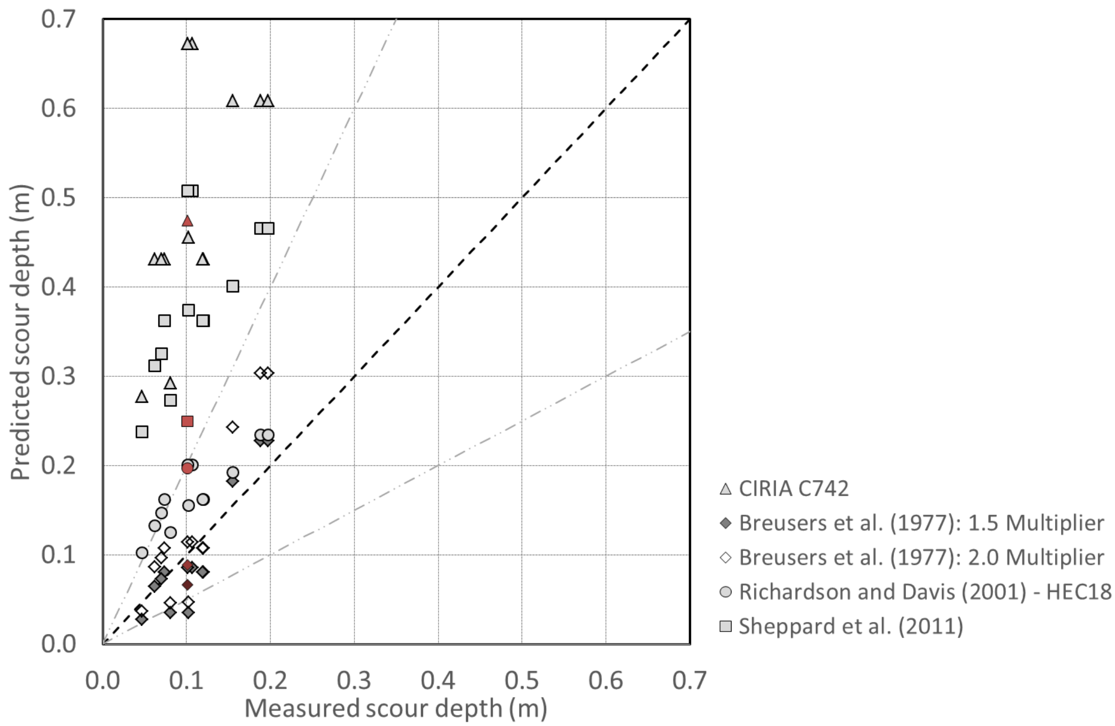

Figure 7: Comparison of predicted scour depths with measurements S_{max}. Red filled symbols refer to Test 10 square pier. Dashed line is 1:1 and chain lines are factor of 2.

CONCLUSIONS

The scour development around cofferdams on river walls was assessed using mobile bed physical modelling. The experiments, in unidirectional flow with a bedload dominated clear-water scour condition, explored the effects of cofferdam size and shape, water depth and flow speed on the scour depth and extent. The patterns of scour and deposition were quantified and it was evident that the maximum scour depth did not always occur at the cofferdam wall.

For a given flow speed and water depth the largest scour was associated with square or rectangular cofferdams. Reduced scour depths were produced with rounded cofferdam corners and a triangular shaped outline.

The scour extent in the flow direction was contained within the structure length for all tests except with a short square cofferdam with high sediment mobility. The deposition footprint of scoured material extended beyond the structure for the small square cofferdam and a long cofferdam with high sediment mobility. In all other cases it was contained within the length.

Application of predictive methods to the measurements showed reasonable comparison with Breusers *et al.* (1977) formula, dependent on the leading coefficient used, and Richardson and Davis (2001). The methods of Sheppard *et al.* (2011) and Kirby *et al.* (2015) produced large over-predictions. The results of the experiments and comparison with predictive methods provides insights into predicting scour at cofferdams.

Selection of cofferdam shape influences constructability, but the effects of scour should be included when making design choices about the plan shape and pile toe depth of the cofferdam, and whether there is any lowering of the bed expected at the river wall. In addition, allowances for contraction scour and general bed level lowering should be factored into the design. The impacts arising from deposition of scoured sediment and siltation in newly coffered locations should also be considered.

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