Local Scour Around Structures in Tidal Flows

By

Richard W P May[1] and Manuela Escarameia[2]

ABSTRACT

An experimental study was carried out to investigate the development of local scour around structures in tidally-reversing flows. Tests were made in a laboratory flume with square, circular and rectangular structures (aspect ratio = 2) for a range of water depths and with two sizes of bed sediment. Two types of tidal profile were studied: a square-wave profile with a constant velocity in each direction and a profile in which the velocity was varied sinusoidally so as to be representative of conditions in astronomical tides. Tests were made with a range of different tidal durations and peak velocities. After a sufficient number of cycles, the scour depths at either end of a structure reached an equilibrium value. In most of the tests with clear-water scour, the equilibrium depth was significantly less than the maximum depth that would have been produced by a unidirectional current of the same magnitude. However, in the case of live-bed scour, the equilibrium scour depth was found to be similar to the corresponding unidirectional value. Based on an analysis of the results, a method of predicting the equilibrium scour depth was developed using existing data on unidirectional scour and the ratio between the half-cycle duration of the tide and a characteristic time of the scouring process.

1. INTRODUCTION

Structures located in channels or rivers produce local changes in flow velocity and turbulence that can give rise to scouring of the bed or nearby banks. Although there has been considerable research on local scour around structures in unidirectional flows, much less is known about how the depth of erosion is influenced by tidal conditions that produce periodic reversals of flow direction. The development of tidal scour around a structure can be envisaged as passing through the following stages, assuming for convenience that scouring starts from an initially flat bed condition.

- In the first half-cycle of the tide, a scour hole will develop around the upstream face of the structure, but due to the limited tidal period the scour depth will normally be much less than the maximum value associated with an equivalent unidirectional current of long duration.

[1] Technical Director, Water & Industry Group, HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, United Kingdom.
[2] Principal Engineer, Water & Industry Group, HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, United Kingdom.

- When the flow reverses in the second half-cycle, scour will start to occur at the opposite end of the structure and some of the eroded sediment will be carried downstream into the first scour hole and thereby begin to fill it up again.

- In the next half-cycle, the process is reversed again with the newly-deposited sediment in the first scour hole being eroded and with, possibly, some additional scour taking place in the time remaining before the tide reverses.

- This process will continue until a state of quasi-equilibrium is reached in which the amount of sediment eroded from a scour hole in one-half cycle is, on average, equal to the amount of sediment deposited in the hole in the following cycle. In most cases, the resulting equilibrium depth of scour will be less than the equivalent value that would occur with an equivalent unidirectional flow. This can be appreciated by considering two limiting cases: if the half-cycle duration of the tide is extremely short, no significant amount of erosion will be able to occur before the flow direction reverses; at the other extreme, if the duration is very long, the scour depth will almost reach the maximum value for unidirectional flow.

Another point of difference for tidal flows is the profile of the bed upstream of the structure. Even if the peak tidal velocity does not exceed the critical threshold velocity needed to erode sediment from an initially flat bed, the areas of erosion and deposition around the structure will locally disturb the flow conditions near the bed and cause dunes to propagate outwards from the structure. The final shape of the sediment bed is therefore likely to be highly complex and very different from the flat bed case that often applies in laboratory studies of unidirectional scour.

2. BASIC APPROACH TO STUDY

Previous research on local scour at structures in unidirectional flow (see for example Breusers & Raudkivi, 1991 and Melville & Coleman, 2000) has shown that the ultimate depth of scour, S_∞ , at a structure (occurring after a time $t \rightarrow \infty$) depends on the following factors:

$$\frac{S_\infty}{B} = \text{function}_1\,(\text{shape of structure}) \times \text{function}_2\,(Y/B) \times \text{function}_3\,(U/U_c) \times \text{function}_4\,(\text{angle of incidence of flow}) \qquad (1)$$

where:

S_∞ = ultimate depth of scour below mean upstream bed level
Y = depth of water above mean upstream bed level
B = width of structure transverse to the flow
U = depth-averaged flow velocity upstream of structure
U_c = critical value of U at threshold of movement of sediment in bed.

For non-cohesive bed sediments, the mean size, d_{50}, of the material does not normally need to be considered directly because studies have shown that its effect can be satisfactorily allowed for by the value of its critical flow velocity, U_c.

In the case of tidal flows, the equilibrium scour depth, S_{eq}, that is reached after a sufficient number of tidal cycles can be expected to be related to S_∞ for unidirectional flow by the following additional factors:

$$\frac{S_{eq}}{S_\infty} = \text{function}_5\,(R/Y_m) \times \text{function}_6\,(D_T/T_C) \times \text{function}_7\,(\text{shape of tide curve, e.g. } U_p/U_{av}) \qquad (2)$$

where:

- R = tidal range (i.e. difference between high and low water levels during tide)
- Y_m = value of Y at mean tide level
- D_T = duration of tidal half-cycle (e.g. ≅ 6.2 hours for astronomical tides)
- T_C = characteristic scouring time of sediment
- U_p = peak velocity during tide
- U_{av} = average velocity during half-cycle.

The characteristic scouring time, T_C, is related to the rate at which the scouring process occurs and needs to be defined in a way that enables it to be reliably assessed from experimental data.

It is apparent from Equation (2) that tidal conditions introduce a significant number of extra variables to the scouring process and make it difficult to obtain general results from a limited number of laboratory experiments. Apart from the effects caused by reversals in flow direction, it is apparent that the rate of scouring will vary continuously with time due to the variations in flow velocity and water depth. At some points in the cycle, the velocity may be well above the critical velocity of the bed and therefore produce high rates of bedload transport, while at other times during the cycle the velocity may be too low to produce any erosion at all.

For these reasons, it was decided to make some simplifications to the way in which the tides were represented in the experiments described in Section 4. Since for astronomical tides the maximum velocity in either direction normally occurs around mean tide level, it can be argued that the equilibrium scour depth, S_{eq}, is likely to be best characterised by the flow velocities and water depth occurring at this level. The experiments were therefore carried out at different constant water depths but with the flow speed and direction varied with time to simulate two different types of tidal cycle:

(a) Square-wave cycle – i.e. constant velocity U in one direction for one half-cycle time D_T, then velocity U in opposite direction for an equal time, and so on.

(b) Sinusoidal cycle – with instantaneous velocity at time t given by :

$$u = U_p \sin(\pi t / D_T) \qquad (3)$$

Although case (a) is not realistic in comparison with astronomical tides, it was considered that it was important to understand this simpler case before attempting to analyse data for sinusoidal tides in case (b).

When seeking to derive general methods that can be applicable to both model results and possible prototype situations, it is important to ensure that time factors, such as the ratio D_T/T_C specified in Equation (2), are correctly evaluated. Since T_C depends on the rate of sediment erosion from the scour hole, simple Froudian scaling of D_T between the astronomical tide and the model tide (based on the square root of the length scale) cannot be assumed. For this reason, the experiments were made with a wide range of D_T values to enable time-dependent effects to be evaluated from the data.

A final factor that influenced the design of the experimental programme was the wish to produce a prediction method for tidal conditions that was consistent with other generally accepted results for local scour at structures. Therefore, in the limiting case of a tide with an extremely long duration, the method should predict a scour depth similar to that given by previous studies on scour in unidirectional flows.

3. TEMPORAL DEVELOPMENT OF SCOUR

The first step in the study was to develop a suitable definition of the characteristic scouring time, T_C. For this purpose, data from a previous study by May & Willoughby (1990) on the rate of increase of scour depth with time were analysed.

This study was principally concerned with determining the ultimate scour depth occurring in steady unidirectional flows for structures such as cofferdams that are large in relation to the water depth. The tests were made with square and circular piers with transverse widths of B = 0.10 m, 0.20 m and 0.40 m, and with relative water depths between Y/B = 4.0 and 0.125. The bed sediment was sand with a mean size of d_{50} = 0.145 mm, and the tests were carried out in a 2.4 m wide flume at flow velocities up to and including the critical threshold velocity, U_c, for the sediment bed upstream of the pier. The following best-fit equations for the ultimate scour depth occurring in unidirectional flows were obtained from the experimental data:

- For circular piers of diameter B:

$$\frac{S_\infty}{B} = 2.4\left[0.44\left(\frac{Y}{B}\right)^{0.67}\right]\left[1 - 3.66\left(1 - \frac{U}{U_c}\right)^{1.76}\right] \qquad (4)$$

for $Y/B \leq 3.4$ and $0.522 \leq U/U_c \leq 1.0$.

When $Y/B > 3.4$, the first square bracket is replaced by a constant value of 1.0. Similarly, when $U > U_c$, the second square bracket is assumed to have a maximum value of 1.0; when $U < 0.522\, U_c$, no scouring occurs and $S_\infty = 0$.

- For square piers of transverse width B (at zero angle of incidence to the flow):

$$\frac{S_\infty}{B} = 3.2\left[0.44\left(\frac{Y}{B}\right)^{0.67}\right]\left[0.6\left(\frac{2.67\,U}{U_c} - 1\right)\right] \tag{5}$$

for $Y/B \leq 3.4$ and $0.375 \leq U/U_c \leq 1.0$.

As with Equation (4), the first square bracket is replaced by a constant value of 1.0 when $Y/B > 3.4$. When $U > U_c$, the second square bracket has a maximum value of 1.0; when $U < 0.375\,U_c$, no scouring occurs and $S_\infty = 0$.

As part of this study, measurements were also made of the change in scour depth with time up to the point at which the ultimate value was effectively reached. Initial attempts were made to fit the data to an equation of the form:

$$\frac{S}{S_\infty} = 1 - \exp\left[-\left(\frac{t}{T_c}\right)^p\right] \tag{6}$$

where S is the scour depth at time t. However, problems were encountered in obtaining stable estimates of S_∞ , the factor p and the characteristic time, T_c. A simpler approach was therefore adopted using the equation:

$$\frac{S}{S_\infty} = \left(\frac{t}{T_E}\right)^\alpha \quad , \text{ for } 0 \leq t \leq T_E \tag{7}$$

where S_∞ is the ultimate scour depth obtained by May & Willoughby (1990) and T_E is the time at which the value was reached in the experiments. Nine tests on circular piers gave values of α between 0.21 and 0.41, with an average of $\alpha = 0.327$. The twelve tests on square piers gave values between 0.10 and 0.18, with an average of $\alpha = 0.165$. The difference in the values of α for the two types of structure reflects the fact that the initial rate of scour development at the square piers was proportionately greater than at the circular piers, possibly because the flow separation at the sharp corners created stronger flow separation and more turbulence.

On the basis of these results, it is convenient to define a new characteristic time, T_{50}, which is defined as the time taken for the scour depth to reach 50% of the final equilibrium scour value. From Equation (7) it follows that:

$$\frac{S}{S_\infty} = \frac{1}{2}\left(\frac{t}{T_{50}}\right)^\alpha \tag{8}$$

where it can be assumed that $\alpha = 0.165$ for square structures and $\alpha = 0.327$ for circular structures.

T_{50} can be considered as having some similarities to the "half-life" used for describing the decay rate of radioactive materials. The major advantage of using T_{50} as the characteristic time factor for the erosion process is that it can be found quite precisely from data on the rate of scour development, whereas the time T_E to final equilibrium can be much more difficult to determine with certainty. Also, T_{50} is more relevant to practical problems of tidal scour because the half-cycle duration of the tide will usually be much closer to T_{50} than to T_E.

The characteristic time, T_{50} , can be expected to become shorter as the flow velocity increases and to be greater for larger structures than for small ones. Various non-dimensional groupings of the variables were investigated using the data from the 21 unidirectional flow tests, and it was found that the best correlation was obtained using the quantity:

$$X = \frac{(\beta U - U_c) T_{50}}{B} \tag{9}$$

The coefficient β is the local velocity intensification factor due to the presence of the structure. Thus βU is the effective flow velocity occurring at the structure when the upstream flow velocity is U. Values of β can be determined by assuming that local scouring of the bed will start to occur if $\beta U = U_c$. For circular structures, it follows from Equation (4) that $\beta = 1/0.522 = 1.92$; for square (and rectangular) structures in line with the flow, it can be seen from Equation (5) that $\beta = 2.67$.

Analysis of the data from the unidirectional flow tests showed that the value of X was reasonably constant (given the scatter inherent in sediment erosion studies) and that it did not have any dependence on the relative flow depth, Y/B. The mean value was found to be X = 5500 with a standard deviation equivalent to 36% of the mean (see Escarameia & May, 1999, for more details). A reasonable estimate of the characteristic time, T_{50}, can therefore be obtained from Equation (9) in the form:

$$T_{50} = \frac{5500\,B}{(\beta U - U_c)} \tag{10}$$

where consistent units must be used (e.g. B in m, U and U_c in m/s, and T_{50} in s). It should be noted that this result was obtained from tests in which the flow velocity U did not exceed the critical threshold velocity U_c. Additional data from tests with higher flow velocities are needed to extend the range of application of this approach.

4. EXPERIMENTS WITH TIDAL FLOWS

Full details of the scour measurements with tidal flows are given in Escarameia (1998) and Escarameia & May (1999) and are summarised in Table 1. The tests were made in a 24 m long reversing flume having a width of 0.605 m, depth of 0.440 m and pump capacity of 60 l/s. The main experiments were carried out with two different sands as bed material (with mean sizes of d_{50} = 0.75 mm and 0.44 mm) and with three shapes of structure:

- Circular pier of 75 mm diameter
- Square pier measuring 75 mm × 75 mm in plan

- Rectangular pier with transverse width of 75 mm and length of 150 mm.

Each tidal test was continued until the maximum depths of scour occurring at either end of the structure were effectively the same at the end of each tidal cycle; the average value of this equilibrium scour depth is given as S_{eq} in Table 1. However, during the development of the scour holes, greater depths of erosion sometimes occurred in individual cycles; the maximum depth of scour recorded in each test is given as S_{max} in Table 1. Separate tests were also made to investigate requirements for the extent of bed protection necessary to prevent local scour; full details are given in the above two references.

Before starting the tidal experiments, two tests were made with unidirectional flows (see Tests A.1 and J.1 in Table 1) to ensure that the facility gave consistent results relative to the earlier study by May & Willoughby (1990), which was carried out in a larger flume and with a different size of sediment.

In order to investigate the relative effects of the square-wave and sinusoidal tidal cycles on the equilibrium depth of scour, results were compared on the basis of the volume of tidal flow, Δ_T , per unit width occurring in each half-cycle. For the square-wave profile with a constant velocity U and half-cycle duration, D_T :

$$\Delta_T = Y\,U\,D_T \qquad (11)$$

For the sinusoidal profile with a peak velocity, U_p , and half-cycle duration, D, the equivalent result is:

$$\Delta_T = Y\int_0^D U_p \sin(\pi t / D)\,dt = \frac{2}{\pi} Y\,U_p\,D \qquad (12)$$

If the unit tidal volume is made equal for the two types of profile, it follows that:

$$U\,D_T = \frac{2}{\pi} U_p\,D \qquad (13)$$

Two alternatives were studied in the tests:

Option I – U_p in sinusoidal profile = U in square-wave profile
– Duration (D) of sinusoidal half-cycle = $\pi/2 \times$ duration (D_T) of square-wave half-cycle.

Option II – U_p in sinusoidal profile = $\pi/2 \times$ U in square-wave profile
– Duration (D) of sinusoidal half-cycle = duration (D_T) of square-wave half-cycle.

Thus, as an example, Tests B.1, C.1 and D.1 in Table 1 can be compared as having the same unit tidal volume but different profiles of tidal cycle.

Most of the tests were carried out with the velocity, U, upstream of the piers just equal to the threshold velocity, U_c , of the sediment so that there was no general bed-load movement. The conditions were therefore equivalent to the limit between what is termed "clear-water" scour (with no bed-load transport) and live-bed" scour (with bed-load transport). In unidirectional flows with uniformly graded sediment, this limiting condition usually produces the maximum possible scour depth (see, for example, Breusers & Raudkivi, 1991). However, a limited number of tests were also carried out in this study with $U > U_c$ to study the live-bed condition.

5. RESULTS FROM EXPERIMENTS

The key results from the experiments were as follows.

(a) In the case of the square-wave tidal cycles carried out with the flow velocity equal to the critical threshold velocity (i.e. $U = U_c$), the final equilibrium scour depth, S_{eq} , was always intermediate between the ultimate scour depth, S_∞ , occurring with unidirectional flow and the scour depth, S_D , achieved at the end of the first half-cycle (i.e. at time $t = D_T$). These findings are illustrated by Figure 1, which shows how the scour depth varied with time at the square pier for the case of unidirectional flow and for a square-wave tide having a half-cycle duration of $D_T = 2.0$ hours. The data for the tidal test are shown as two sets of points, with those for the "flood" condition corresponding to the scour depths measured at the end of the pier that was facing the flow in the first half-cycle of the test. Similarly, the data for the "ebb" condition correspond to the depths at the opposite end of the pier that was facing the flow in the second half-cycle.

(b) For a given set of conditions, increasing the duration of the tidal cycle increased the value of the equilibrium scour depth. This applied both for square-wave and sinusoidal tidal cycles, as illustrated by Figure 2 for the case of the square pier with a relative water depth of $Y/B = 1$.

(c) For unidirectional flows, previous studies have shown that scour depths at circular structures are typically about 75% of those at square piers for the same transverse width and flow conditions (cf Equations (4) and (5)). However, in the present tests, there was very little difference between the equilibrium scour depths for the circular and square piers under similar tidal conditions. Corresponding scour depths around the rectangular pier (aspect ratio = 2) were about 90% of those for the square and circular piers. This may have been because the greater length of the rectangular structure reduced the degree of interaction between the scour holes at either end.

(d) The equilibrium scour depths produced by the sinusoidal tidal cycles were about 88% of those produced by the square-wave cycles when compared on the basis of Option I in Section 4 (i.e. with $U_p = U_c$ and a longer tidal duration). However, Option II (with $U_p = 1.57\ U_c$ and the same duration) gave scour depths that were on average 1.73 times those occurring with the square-wave cycles. With Option II, live-bed scour occurred around the peak of each cycle and this caused the erosion to develop much more rapidly, with the values of the equilibrium scour depth, S_{eq} , being close to the value of S_∞ that was obtained in the unidirectional flow test with $U = U_c$ (see Figure 2).

6. ANALYSIS OF DATA

As explained in item (a) of Section 5, the value of the equilibrium depth of scour, S_{eq}, in tidal conditions will normally lie between the scour depth, S_D, achieved after the first half-cycle of the tide (starting from a flat bed condition) and the ultimate depth, S_∞, produced by an equivalent unidirectional current. If the half-tidal duration, D_T or D, is small in relation to the characteristic time, T_{50}, of the scouring process, then S_{eq} is likely to be closer to S_D than to S_∞, and vice versa.

Experimental data on values of S_∞ are now available for many types of hydraulic structure, and the type of approach suggested in Section 3 provides a method of estimating the first half-cycle scour depth, S_D. This enables the value of equilibrium scour depth to be assessed taking into account the relative magnitudes of D_T and T_{50}.

The suitability of the proposed method for estimating S_D was checked using the data from the experiments with square-wave tidal profiles and $U = U_c$ (i.e. the limiting case of clear-water scour). The characteristic scouring time, T_{50}, for each test was calculated from Equation (10) and then substituted in Equation (8) to give:

$$S_D = \frac{S_\infty}{2}\left(\frac{D_T}{T_{50}}\right)^{\alpha} \qquad (14)$$

where $\alpha = 0.327$ for circular piers and $\alpha = 0.165$ for square piers. Estimates of S_∞ for the two shapes of structure were determined from Equation (4) for circular piers or Equation (5) for square piers. The predicted values of S_D are compared in Figure 3 with the values of S_D that were actually measured in the experiments after the first half-cycle of each tidal test. The overall agreement is satisfactory and shows no major discrepancies for the range of tidal durations studied or for the two structure shapes and two sediment sizes. It should be noted that the prediction method was developed independently using only data from the earlier study on unidirectional scour by May & Willoughby (1990). As mentioned above, the pier sizes, water depths and sediment size in that study were significantly different from those in the present tidal tests.

The effect of the time ratio D_T/T_{50} on the scour ratio S_{eq}/S_D is shown in Figure 4 for the case of square-wave tidal cycles. In the case of the results for the square piers with $U = U_c$ (which cover three different water depths and two sediment sizes), the values of S_{eq}/S_D vary between about 0.9 and 1.2 with an average of about 1.1, but with no clear dependence on the value of D_T/T_{50}. For conservative estimates, it is recommended to assume:

$$S_{eq} = 1.2 S_D \quad , \quad \text{for } D_T / T_{50} \le 8 \qquad (15)$$

In the case of the circular piers, the expected dependency of S_{eq}/S_D on D_T/T_{50} is more apparent, and it is recommended to use the following estimation formulae:

$$S_{eq} = \left[2.0 - 0.267\left(\frac{D_T}{T_{50}}\right)\right] S_D \quad , \quad \text{for } D_T / T_{50} \le 3 \qquad (16)$$

$$S_{eq} = 1.2 S_D \quad , \quad \text{for } 3 < D_T / T_{50} \le 8 \tag{17}$$

For a sinusoidal profile with $U_p = U_c$ and a duration equal to 1.57 × the duration of an equivalent square-wave tide (Option I in Section 4), the equilibrium scour depth could be expected to be about 90% of that predicted from the above equations. For the case of a sinusoidal profile with $U_p = 1.57\ U_c$ and duration equal to that of the square-wave tide (Option II), insufficient data are available from these tests to define an equivalent prediction method. However, the results suggest that if a significant degree of live-bed scour occurs (e.g. U or $U_p > 1.5\ U_c$) both square-wave and sinusoidal tides will tend to produce equilibrium scour depths, S_{eq}, that are close to the ultimate value, S_∞, that would be produced by a unidirectional current of $U = U_c$. This conclusion is in accordance with results of Sumer et al (1992, 1993) who studied wave-induced scour at structures. In the present tests, equivalent values of the Keulegan-Carpenter number (defined here as $KC \equiv 2\,U\,D_T / B$) range from about 6000 to 52 000. In their wave tests, Sumer et al found that when the value of KC reached about 5000 the equilibrium scour depth was similar to that produced by an equivalent unidirectional current

7. SUGGESTED DESIGN PROCEDURE

Based on the results of this initial study, the following procedure is tentatively proposed for estimating the equilibrium depth, S_{eq}, at a structure in tidal conditions.

(1) Determine the variation in tidal velocity with time at the site being considered and calculate the average tidal volume, Δ_T, in one half-cycle of the tide. Calculate the half-cycle duration, D_T, of an equivalent square-wave tide with a flow velocity U equal to the peak velocity, U_p, in the actual tide, i.e. $D_T = \Delta_T/(U_P\,Y)$, where Y is the water depth at mean tide level.

(2) For the values of U and Y, estimate the ultimate depth of scour, S_∞, that would be produced by a unidirectional current, e.g. using Equations (4) or (5) or other formulae suitable for the type of structure and flow conditions being considered.

(3) If $U > 1.5\ U_c$, where U_c is the critical threshold velocity for the bed sediment, it is likely that the equilibrium scour depth, S_{eq}, under tidal conditions will not be significantly less than S_∞.

(4) If $U \le 1.0$, estimate the characteristic scouring time, T_{50}, from Equation (10).

(5) Determine the scour depth, S_D, that would occur after one half-cycle of the equivalent square-wave tide using Equation (14).

(6) Calculate the equilibrium scour depth, S_{eq}, produced after successive tidal cycles from Equations (15), (16) or (17) depending on the shape of the structure (i.e. sharp-edged or rounded) and the value of D_T/T_{50}.

(7) An astronomical tide will produce somewhat less scour than the equivalent square-wave tide defined in step (1). Therefore, the actual equilibrium scour depth at the structure should be estimated as equal to 90 % of the value of S_{eq} obtained from step (6).

(8) For rectangular structures having an aspect ratio (length / transverse width) ≥ 2, the equilibrium scour depth is likely to be about 90 % of the value for a square pier of the same transverse width (assuming that in both cases they are in-line with the flow).

(9) No data are yet available for the intermediate case in which $1.0 < U/U_c < 1.5$. An approximate value of the equilibrium scour depth may be calculated on a pro-rata basis using the value of S_{eq} from step (3) for $U = 1.5\ U_c$ and the value from step (7) or (8) for $U = U_c$.

8. CONCLUSIONS

The study has shown that, in the case of clear-water scour (with $U \leq U_c$), the equilibrium scour depths at hydraulic structures in tidal flows can be significantly less than can occur with equivalent unidirectional currents. However, in the live-bed scour case, the equilibrium depths are likely to be close to the unidirectional flow values due to the faster development of the scour holes in each tidal cycle and due to the formation around the structure of a duned bed of complex shape.

The analysis of the data for the clear-water case suggests that a non-dimensional formulation based on the ratio between the tidal duration and a characteristic scouring time is useful in predicting the value of the equilibrium scour depth in tidal conditions. Further experimental study is needed to extend the analysis to the case of live-bed scour.

9. ACKNOWLEDGEMENTS

This study was partially funded by the Construction Directorate of the UK Department of Trade and Industry under its Partners in Innovation programme. The authors are grateful for the assistance of Ms Ruth Cano who carried out many of the experimental measurements.

10. REFERENCES

Breusers H N C & Raudkivi A J (1991). "Scouring". International Association for Hydraulic Research. A.A. Balkema/Rotterdam/Brookfield, The Netherlands. ISBN 90 6191 983 5.

Escarameia M (1998). Laboratory investigation of scour around large structures in tidal waters. 3rd International Conference on Advances in Hydro-Science and – Engineering, Cottbus, Germany, Vol III.

Escarameia M & May R W P (1999). Scour around structures in tidal flows. Report SR 521, HR Wallingford, England.

May R W P & Willoughby I R (1990). Local scour around large obstructions. Report SR 240, HR Wallingford, England.

Melville B W & Coleman S E (2000). “Bridge scour”. Water Resources Publications, LLC (Colorado).

Sumer B M, Fredsoe J & Christiansen N (1992). Scour around a vertical pile in waves. Journal of Waterway, Port, Coastal and Ocean Engineeering, ASCE, Vol 118, No 1, pp 15-31.

Sumer B M, Christiansen N & Fredsoe J (1993). Cross section influence on wave scour around piles. Journal of Waterway, Port, Coastal and Ocean Engineeering, ASCE, Vol 119, No 5, pp 477-495.

Table 1 Summary of test data

Test No	Structure type	Sediment size d_{50} (mm)	Water depth Y (m)	Critical velocity U_c (m/s)	Characteristics of tidal cycle				Predicted characteristic scour time T_{50} (h)	Equilibrium scour depth S_{eq} (m)	Maximum scour depth S_{max} (m)
					Peak velocity in cycle U (m/s)			Duration of half-cycle D or D_T (h)			
					Unidirectional	Square-wave	Sinusoidal				
A.1	Square	0.75	0.075	0.274	$U = U_c$			–	0.250	0.116	–
B.1	Square	0.75	0.075	0.274		$U = U_c$		0.250	0.250	0.057	0.057
B.2	Square	0.75	0.075	0.274		$U = U_c$		0.500	0.250	0.064	0.067
B.3	Square	0.75	0.075	0.274		$U = U_c$		1.000	0.250	0.066	0.070
B.4	Square	0.75	0.075	0.274		$U = U_c$		2.000	0.250	0.079	0.088
C.1	Square	0.75	0.075	0.274			$U_{max} = \pi U_c/2$	0.250	0.131	0.100	0.102
C.2	Square	0.75	0.075	0.274			$U_{max} = \pi U_c/2$	0.500	0.131	0.105	0.109
C.3	Square	0.75	0.075	0.274			$U_{max} = \pi U_c/2$	1.000	0.131	0.118	0.120
D.1	Square	0.75	0.075	0.274			$U = U_c$	0.390	0.250	0.049	0.052
D.2	Square	0.75	0.075	0.274			$U = U_c$	0.785	0.250	0.057	0.057
D.3	Square	0.75	0.075	0.274			$U = U_c$	1.570	0.250	0.059	0.059
D.4	Square	0.75	0.075	0.274			$U = U_c$	3.140	0.250	0.068	0.070
E.1	Square	0.75	0.075	0.274		$U = \pi U_c/2$		0.250	0.131	0.110	0.111
E.2	Square	0.75	0.075	0.274		$U = \pi U_c/2$		0.500	0.131	0.120	0.122
F.1	Square	0.75	0.056	0.259		$U = U_c$		0.250	0.265	0.049	0.049
F.2	Square	0.75	0.056	0.259		$U = U_c$		0.500	0.265	0.050	0.053
F.3	Square	0.75	0.056	0.259		$U = U_c$		2.000	0.265	0.068	0.071
G.1	Square	0.75	0.0375	0.239		$U = U_c$		0.250	0.287	0.032	0.041
G.2	Square	0.75	0.0375	0.239		$U = U_c$		0.500	0.287	0.035	0.039
G.3	Square	0.75	0.0375	0.239		$U = U_c$		2.000	0.287	0.042	0. 044
H.1	Circular	0.75	0.075	0.274		$U = U_c$		0.250	0.455	0.057	0.060
H.2	Circular	0.75	0.075	0.274		$U = U_c$		0.500	0.455	0.064	0.065
H.3	Circular	0.75	0.075	0.274		$U = U_c$		1.000	0.455	0.068	0.070
H.4	Circular	0.75	0.075	0.274		$U = U_c$		2.000	0.455	0.072	0.073
I.1	Rectangular	0.75	0.075	0.274		$U = U_c$		0.250	0.250	0.050	0.056
I.2	Rectangular	0.75	0.075	0.274		$U = U_c$		1.000	0.250	0.060	0.070
I.3	Rectangular	0.75	0.075	0.274		$U = U_c$		2.000	0.250	0.070	0.075
J.1	Square	0.44	0.075	0.253	$U = U_c$			–	0.271	0.112	–
J.2	Square	0.44	0.075	0.253		$U = U_c$		0.250	0.271	0.051	0.056
J.3	Square	0.44	0.075	0.253		$U = U_c$		1.000	0.271	0.072	0.075
J.4	Square	0.44	0.075	0.253		$U = U_c$		2.000	0.271	0.081	0.087

Figure 1 Development of scour in unidirectional and tidal flows

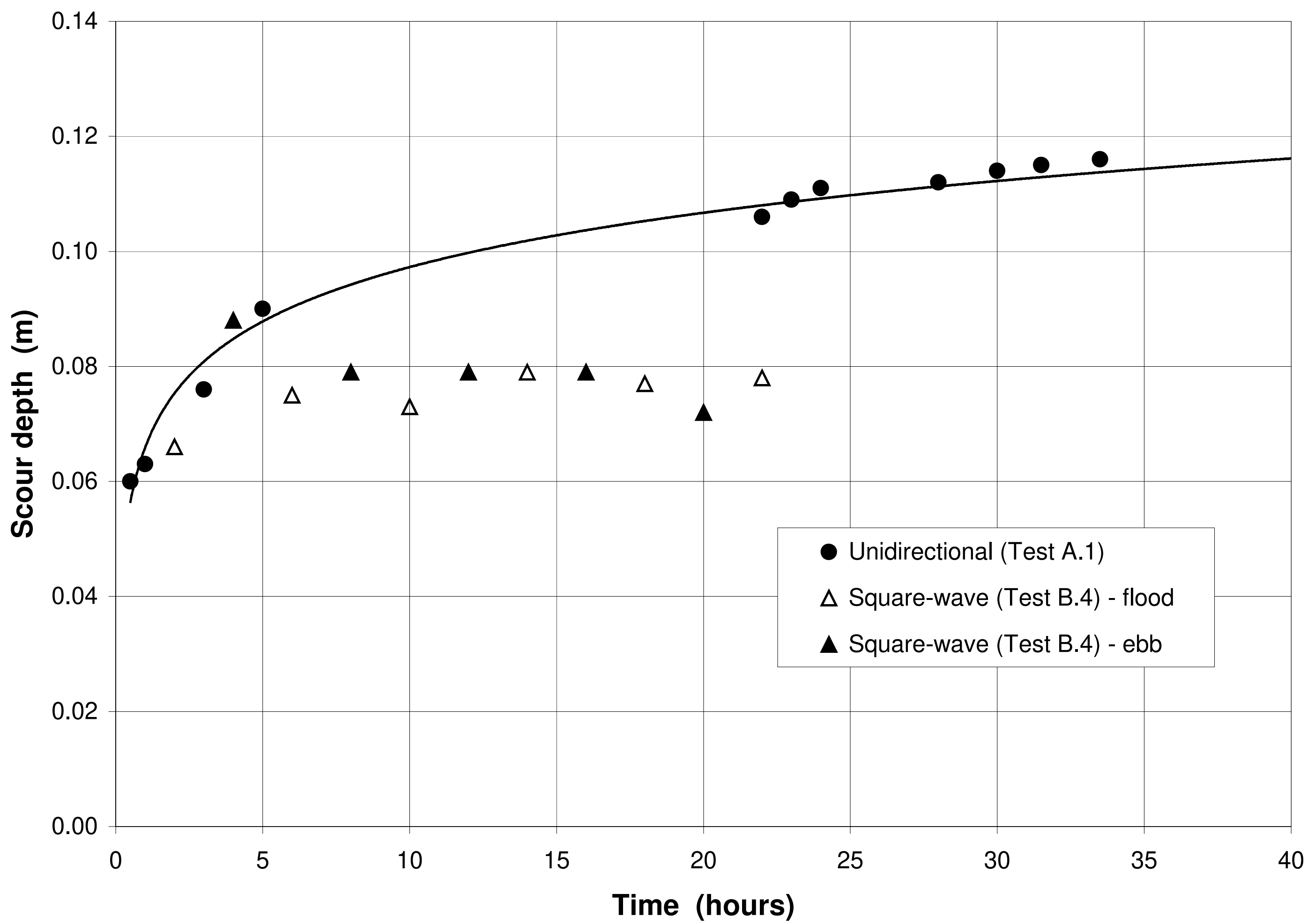

Figure 2 Variation of equilibrium scour depth with half-cycle duration

Square pier - water depth Y = 0.075 m

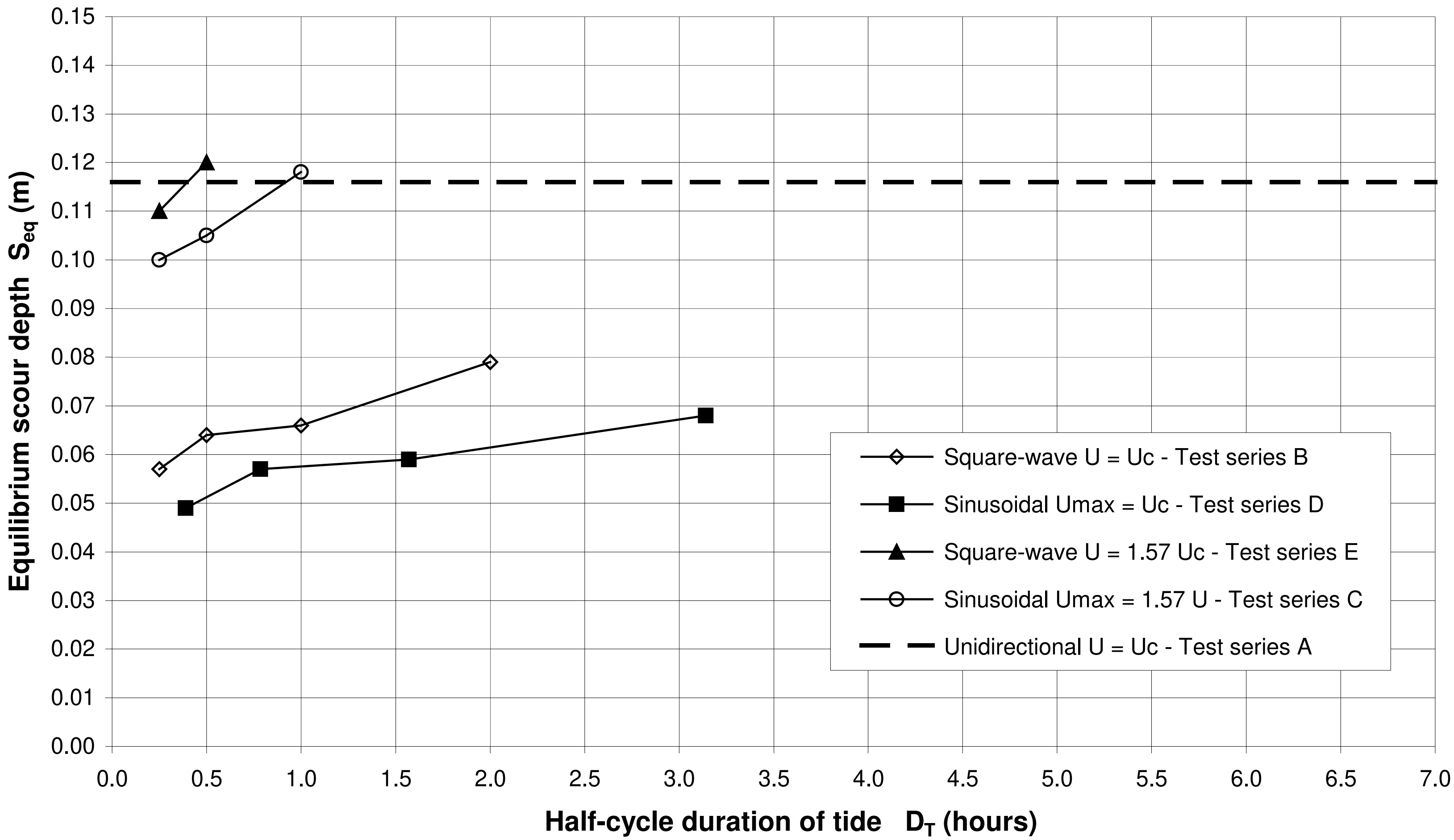

Figure 3 Comparison of predicted and measured scour depths after first half-cycle of square wave tides (with $U = U_c$)

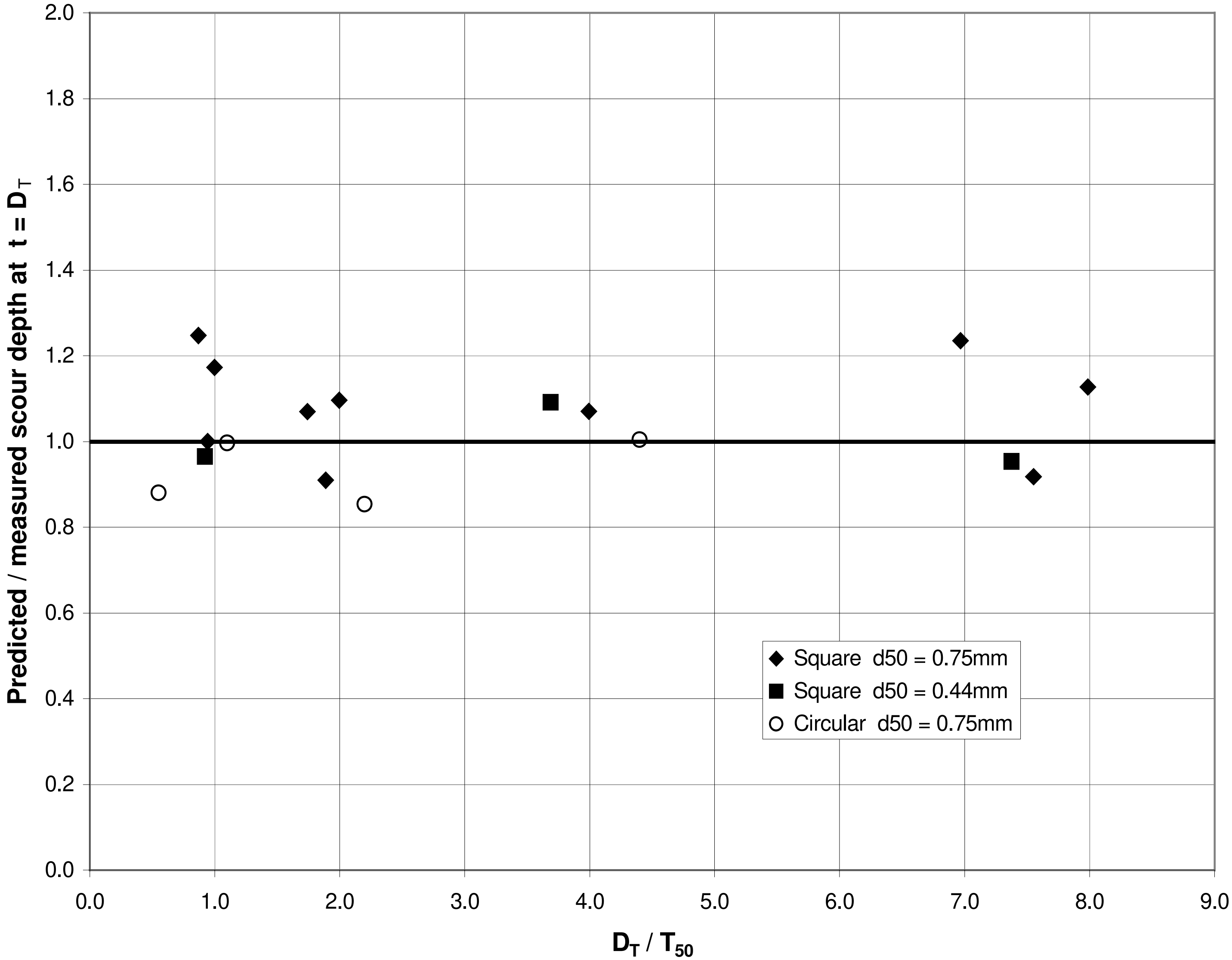

Figure 4 Relationship between equilibrium scour depth and predicted scour depth after first half cycle of square-wave tides