HR Wallingford

Hydraulic Structures and Alluvial Processes (1987-90)

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Address: **Hydraulics Research Ltd,** Wallingford, Oxfordshire OX10 8BA, United Kingdom.
Telephone: 0491 35381 International + 44 491 35381 Telex: 848552 HRSWAL G.
Facsimile: 0491 32233 International + 44 491 32233 Registered in England No. 1622174

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HR nominated Project Officer : Dr W R White.

The DoE nominated officer is Mr P Woodhead. This report is published with the permission of the Department of the Environment, but any opinions expressed are not necessarily those of the Department.

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ABSTRACT

This report summarises the results of a programme of work designed to:

(a) predict the hydraulic performance of certain engineering structures in rivers and their consequences to the environment; to optimise the design of the structures in terms of safety and economy. This involved the study of vortex inhibitors, the pressures associated with falling-jet energy dissipation and scour at large obstructions.

(b) Improve techniques for the prediction of: non-cohesive sediment transport and general scour in river channels.

The work was carried out under Contract PECD 7/6/113, funded by the Department of Environment.

A detailed account of the work carried out under each part of the programme has been provided in separate reports. These are listed in the appendix of this report.

CONTENTS

1. INTRODUCTION

This report describes work supported under Contract PECD 7/6/113. funded by the Department of the Environment.

The broad objectives of the programme are:

(a) To predict the hydraulic performance of certain engineering structures in rivers and their consequences to the environment; to optimise the design of the structures in terms of safety and economy.

(b) To improve techniques for predictions of : sediment transport in rivers; degradation and local scour associated with dams and other structures; and the long-term stability of flood relief channels or other man-made waterways.

The terms of reference for the study were:

(i) Energy dissipation

Measurements of the mean and fluctuating pressures produced by plunging jets on the apron floor, are made for a range of conditions. Factors varied include: tailwater level, flow velocity, turbulence level and amount of entrained air. This was a continuation from an earlier study.

(ii) Vortex inhibitors

Submerged screens, floating rafts and vertical cords have been shown to inhibit vortex formation. Tests will be carried out to optimise the geometry of these devices and to provide design information. This is a continuation of an earlier study.

Tests will be carried out on some additional types of inhibitor and measurements will be made of the pressure distribution and head losses in the intakes. The mechanism of vortex formation at intakes will also be studied.

(iii) Scour at large obstructions

Although there has been much research on local scour around obstructions, the conditions encountered in practice are often outside the range of conditions for which the original research was done. For instance, the cofferdams used during the construction of a bridge are frequently very much wider, relative to the depth of flow in the river, than the obstructions that have been studied in previous research. Scour equations based on this research predict extremely large scour depths for such wide structures, but there is some evidence that these predictions may be too conservative. Framed structures are often constructed in rivers, and there is a dearth of information about the local scour that they will produce.

The aim of the proposed research is to extend the range of experimental conditions to cover the types of construction that are often encountered i.e. wider and of a more complex geometry.

Experiments will be carried out in a flume. Local scour will be measured for a range of hydraulic conditions and a number of different geometries.

(iv) Temporal, local variations in river bed levels

When considering local scour association with engineering works it is normally assumed that the surrounding bed level remains constant. In certain circumstances however, part of the channel may be subject to general accretion or erosion. There is a requirement for a method of modelling general bed movement which can be incorporated with predictions of local scour. The study will aim to produce such a model.

(v) Sediment transport predictions

In 1973 Ackers and White published a sediment transport theory developed by fitting appropriate equations to a wide range of data. The theory was developed using most of the laboratory and field data available at that time. Since then there has been a large increase in the amount of published data, particularly on the movement of fine and coarse sediment. In the light of our increase in knowledge since 1973 we will produce an up-dated version of the Ackers and White theory that will provide more accurate predictions, particularly for fine and coarse sediments.

In the study as much new sediment transport data as possible (ie. from literature since 1973) would be collected and used to extend the original data set. Retaining the original functional form developed by Ackers and White, values of the empirical constants will be re-evaluated using the extended data set to determine new values for the constants involved. This report provides a brief introductions to the topics covered under the research contract and provides a broad outline of the work done.

Comprehensive reports have been produced on each topic and these should be referred to for further details. A full list of the reports and papers produced under the contract is given in the Appendix.

2 ENERGY DISSIPATION

Dams with overfall crests or high-level sluices produce near-vertical water jets whose energy can be dissipated in concrete-lined plunge basins. In order to design such basins it is necessary to have information on the mean and fluctuating pressures acting on the floor slabs. This experimental study investigated how the impact pressures produced by a vertical rectangular jet varies with velocity, water depth and amount of air within the jet.

The first stage of the study comprised a literature review and testing of a small-scale rig (see interim report by Perkins (1987)). Results from this stage assisted in the development of a larger test rig which was used for the experiments described in this report. The rig was capable of producing a rectangular jet measuring 200 mm x 67 mm with an impact velocity of 8.5 m/s. The water depth in the basin was varied from zero to 0.8m, and the jet could be arranged to discharge vertically above the basin (as a plunging jet) or below the water surface (as a submerged jet). The amount of entrained air in the jet was varied up to a maximum concentration of 20%. Impact pressures on the floor of the basin were measured using five transducers. The results were recorded and analysed to determine the characteristics of the mean and fluctuating components of the impact pressures. A total of 35 different conditions were studied.

The turbulent pressure fluctuations were found to be fairly uniform within and immediately around the jet, and were little affected by changes in air concentrations. The turbulence at the floor of the basin was strongest when the water depth was between 10 and 12 times the thickness of the jet. Correlations were established for estimating the root-mean-square and extreme values of the pressure fluctuations. The probability distributions of the turbulence were found, on average, to be more sharply peaked than a Gaussian distribution and were positively skewed, ie. the positive fluctuations tended to be larger than the negative ones. Spectral analysis showed that the turbulence energy was most concentrated at frequencies of 0-2Hz and generally decreased to low levels beyond about 25Hz. The results of the study confirmed the validity of using Froudian scaling in model tests of plunge basins.

3 VORTEX INHIBITORS

In the field of civil engineering hydraulics, vortices are most commonly encountered at intakes which draw water from tanks, reservoirs, rivers and the sea. Vortex formation is usually undesirable and may cause the following problems:

- additional head losses in the intake
- draw down of floating debris
- structural vibrations
- uneven running and reduced efficiency of hydraulic machinery due to swirl and entrained air
- slug flows in downstream conduit due to entrained air

- increased risk of cavitation

Much research has been carried out on vortices at intakes, and the principal aspects which have been studied are:

- mathematical descriptions of vortex motion
- experimental measurements of fluid motion near the vortex core
- determination of critical conditions for vortex formation using physical models
- scale effects in physical models

In the case of pumping stations, experience accumulated from model studies and prototype installations has helped to identify design features which will prevent or inhibit the formation of vortices. References such as Prosser (1977) therefore provide guidance on the necessary approach conditions, the geometry of the sump, the position of the suction pipe and the minimum depth of submergence.

In the case of reservoirs, less progress has been made. The mechanism by which vortices are generated is not properly understood, and mathematical solutions of the theoretical Navier-Stokes equations cannot at present be obtained for the complex geometries which exist in natural reservoirs. Experimental research has provided data on the critical conditions for vortex formation, but each study tends to be specific to the particular type of intake and reservoir geometry tested. Various criteria for scaling vortex motion between model and prototype have been proposed, but none is yet widely accepted, due partly to the difficulty of obtaining field data.

The experimental study carried out at Hydraulics Research (HR) compared the performance of different types of vortex inhibitor and provides guidance on suitable designs for reservoir intakes. The emphasis in this study on comparative performance therefore enabled the problem of scale effects to be partially side-stepped.

The first stage of work was completed in 1987 and was described in HR Report SR 122. Fourteen types of intake design were studied in a specially constructed tank measuring 6m by 6m in plan and 3.6m in depth. Further tests were then made using a smaller tank which reproduced the geometry of the first one at a scale of approximately 1:3.2. Eighteen types of intake were studied in the second tank, some of these being equivalent to designs tested previously in the larger tank.

The second stage of the HR study was more limited in scope, and covered three recommendations for further work which were made after completion of the first stage. The tests were carried out in the smallest tank and investigated:

- the performance of some additional inhibitors
- the effects of vortex formation on pressures and head losses in selected intakes
- the effect of intake type on vortex strength

The relationship between vortex strength and discharge was studied in detail for two intake configurations: the plain horizontal pipe representing an "inefficient" design, and the pipe with an extended longitudinal fin representing an "efficient" one. It was found that the two intakes had different strength/

discharge relationships even though the approach conditions of the flow were the same. The conclusion, therefore, is that the strength of vortex which develops at an intake is partly determined by its geometry and not solely by the approach conditions (as is sometimes supposed). Based on these findings, a general description of vortex action at intakes is presented in the report.

The report of the study (HR Report SR 231) gives general advice about the configuration of the intake and the headwall to minimise vortex development. It also recommends various forms of vortex inhibitors. This should aid the designer in producing proposals to minimise vortex development and the results will also be of interest in designing vortex suppression devices for existing installations where there are vortex-generated problems.

4. SCOUR AT LARGE OBSTRUCTIONS

A structure located in flowing water produces a complex three-dimensional flow pattern that may cause localised scouring of a sand or gravel bed. The foundations of bridges which cross alluvial channels can therefore be undermined by local scour, and failures have occurred fairly regularly in the UK and around the world. As a result, much experimental research has been carried out on local scour in order to identify the mechanisms involved and develop methods of prediction. The subject has proved to be very complex, but there are now methods which can be used to estimate scour depths for simple shape of pier that are relatively slender in relation into the depth of flow (see for example Melville and Sutherland (1988)). It has been found from many small-scale studies that maximum depths of scour are typically between 1.5 times and 3.0 times the width of the structure, and these results are supported reasonably well by field measurements of scour at bridge piers. However, as pointed out by Carstens & Sharme (1975), simple geometric scaling seems unreasonable when applied to large structures which can have diameters from 10s to 100s of metres. For such structures the standard scour equations would calculate scour depths of up to 300m. It is likely in such cases that other turbulent flows intervene to prevent the occurrence of very large scour depths.

A particular example of this problem occurs with cofferdams and caissons used during the construction of river and estuary crossings. These structures are usually much larger than the final bridge piers, and can therefore represent a more critical design conditions.

Limited research has indicated that scour depths are reduced when a structure is large in relation to the depth of flow. However, results from some model studies of bridge crossings carried out by Hydraulics Research indicated that existing formulae tended to overestimate scour depths at large obstructions such as cofferdams. In this situation the designer has problem of designing the scour protection. If standard scour equations are used then the depth of scour will be overestimated and significant extra cost will be incurred. If the designer arbitrarily reduces the depth of scour protection then he risks the failure of the structure due to scour. The present study was therefore designed to investigate systematically the effect of structure size in relatively shallow flows using a large flume available at Hydraulics Research.

Scour tests were carried out for a range of flow conditions and pier shape and the results summarised as a sequence of equations described in HR Report SR 240. The equations take account of pier size and shape, flow depth and flow velocity, giving estimates of scour in uniform sediments that are conservative relative to all the tests carried out in the present study. The new equations are considered to be more accurate (and economical) than existing design formulae when applied to large obstructions such as cofferdams in relatively shallow water. These equations enable the prediction of scour depths for small relative depths, that is, large obstructions in shallow flows; they show that previous equations by Breusers et la (1977) and Torsethaughen (1975) tend to over predict scour depths for small relative depths.

The results of this research have already been applied by HR to the design of the replacement railway bridge at Inverness.

5. TEMPORAL, LOCAL VARIATION IN RIVER BED LEVELS

In natural channels in which the bed of a river can be moved by the flow, the bed level may fluctuate vertically as the flow varies. Any reduction in bed level is generally referred to as scour, or erosion. Scour is an important factor in the safety or stability of any structure associated with the river, if the bed level of the river around a bridge is lowered then the loss of foundation strength or, in the extreme case, the undermining of the foundations, may lead to the failure of the structure. Regrettably, failure due to scour is not uncommon. In a study of bridge failures, Smith showed that over 59% of failures of bridges over 2 years old were due to bridge hydraulics.

To design a new structure or to assess the safety of an existing one, it is important to be able to predict how much scour can take place. This report described experiments which examine the ability of a numerical model to predict scour due to the construction of a river channel.

In order to predict the total depth of scour at a bridge, it is necessary firstly to identify the different types of scour, which are caused by distinct processes.

Four types of scour can be identified:

(i) local scour
(ii) general scour
(iii) natural scour
(iv) progressive degradation

Local scour is a lowering of the bed level adjacent to structures such as piers and abutments, and is caused by complex three-dimensional flows around obstructions. General scour results from the increase in flow velocities at a constriction. The constriction may for example be due to a narrowing of the river between bridge abutments. General scour can occur across the whole width of the river, whereas local scour is confined to the region adjacent to the obstruction. both types are confined to the reach of river in the neighbourhood of the bridge. Natural scour and progressive degradation are not confined to the neighbourhood of structures, but can occur over long reaches of river. This type of bed level change is associated with natural or man made changes to the river regime, and may be independent of the structures which are affected.

Methods for predicting general scour are at present based on regime or empirical methods. These are limited by the variables which are considered, and by the range of conditions on which they are based. The aim of this study was to investigate the feasibility of applying a numerical sediment transport model to prediction of general scour.

The study initially considered steady discharge conditions. In the absence of any field or laboratory data with which to compare the results of the numerical model it was not possible to quantitatively judge the predictions of general scour. The numerical model however successfully represented the process of general scour in a qualitative sense. Further testing and comparison with laboratory results are necessary to confirm that the model is capable of making accurate quantitative predictions. The numerical model results were compared with calculations using a number of recognised scour prediction formulae which are recommended for design and analysis. The model predicted greater depths of scour than were calculated using these formulae.

Further tests were carried out to examine whether the model can accurately represent the effect of unsteady flows on general scour. It has been shown that the duration of a flood can affect maximum scour depths, and that scour due to floods will in general be less than scour due to steady discharges with the same value as the peak flood discharge.

This work provides, for the first time, a reliable method for predicting general scour at a structure. This should enable safer and more effective design of structures.

6. SEDIMENT TRANSPORT PREDICTIONS

In 1973 Ackers and White published a theory to predict the transport of non-cohesive sediments. These equations are widely used to calculate sediment transport, morphological changes in channels, the size of stable alluvial channels and the design physical models. While in general providing reliable predictions, application of the equations to fine and coarse sediments has raised uncertainties about the confidence that can be placed on predictions in these ranges. When deriving the empirical parameters little data has been available in these ranges, A feature of the theory was that it assumed different modes of transport for coarse and fine sediments. It was assumed that coarse sediments are moved predominantly on or adjacent to the bed and the transport rate depends upon the shear stress exerted on the bed. Fine sediment was assumed to be distributed throughout the flow and the transported rate to be a function of the total energy loss in the channel. Transition sizes between fine and coarse were assumed to be transported by a combination of the two processes. The theory is thus capable of dealing with a wide range of sediment sizes and has been successfully applied in a large number of situations (White, Milli, Crabbe 1973) In common with all presently used sediment transport theories the Ackers and White theory contains a number of parameters which must be determined empirically. A notable feature of the original development of the theory was the use of an extensive set of laboratory data on which to determine the empirical parameters. This undoubtedly contributed to the wide applicability of the theory.

In their original derivation Ackers and White used an optimisation procedure to select values of the parameters which minimised the difference between the observed and predicted sediment transport rates. As the parameters are assumed to be functions of the sediment size the optimisation procedure is used to determine values of the parameters for different sediment sizes. A function then has be to fitted to these values. The form and precise nature of these functions depends upon the observed data on which the optimisation is carried out.

Since the original derivation of the theory in 1973 more sediment transport data has become available. The opportunity has, therefore, developed to use this extra data to improve the values of the parameters determined originally. There was particular interest in the values of the parameters for the fine and coarse sediments as originally they had been derived from limited data.

The results of the work were revised equations for the parameters m and C. The impact of the modifications for a given flow condition is to alter the predicted sediment transport routes for fine and coarse sediments. For intermediate sediment sizes there is little overall change.

The work will enable more accurate predictions of sediment transport by engineers and will improve the accuracy of numerical models which are based on the Ackers and White sediment transport theory.

7 CONCLUSIONS

The work carried out on hydraulic structures under the contract has improved the ability to predict the hydraulic performance of vortex inhibitors and the pressures associated with the falling-jet energy dissipations. The work has enabled improved predictions of scour at large obstructions. Overall the work will result in improvements in the design of structures in terms of safety and economy.

As a result of the work carried out on alluvial processes an improvement has been made in our ability to predict sediment transport rates for non-cohesive sediments and a method has been developed for the predictions of general scour.

8. RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Energy dissapators

Further work is recommended to investigate, over a larger range, how the fall height of the jet in air and its initial level of turbulence influence the impact pressures on the floor of the basin.

8.2 Performance of vortex inhibitors for reservoir intakes

A semi-theoretical equation for vortex formation at intakes was proposed in SR 231 and tested using the data obtained during the study. A potential advantage of the equation is that it enables allowance to be made for scale effects associated with tests in small models. The initial comparisons were promising, but the equation needs to be evaluated for a wider range of conditions. Further experimental work is not necessary at this stage. Instead it is recommended that experimental data from other studies should be collected and collated, and a desk study carried out to evaluate the proposed new method.

8.3 Local scour around large obstructions

Further experimental work on three aspects of local scour would be of benefit to bridge designers.

(1) The study described in SR240 investigated scour around caissons and cofferdams in uni-directional flows. However, many such structures are used in tidal estuaries and so are subject to reversing flows. Research is therefore needed to investigate the long-term equilibrium depths of scour which develop around caissons and cofferdams under tidal conditions.

(2) The second subject concerns local scour at bridge abutments in uni-directional flows. Little information is available on the three-dimensional flow patterns and scour depths which occur at abutments; factors that need to be studied are the size and shape of the contraction produced by an abutment, the effect of flow depth and the relationship with the associated general scour in the contraction.

(3) The third area for research relates to scour at bridge piers of complicated design involving groups of vertical and raking piles tied together by capping beams at or above the river bed. These designs are commonly used but no formulae are available for predicting depths of local scour. Experiments are necessary to investigate the effects of pile spacing and of the size, shape and height of the capping beam.

It is important to be able to predict the scour that can take place at such pile groups so that the designer can ensure that the pile will withstand the structural loads placed upon them when the bed has been scoured away. Otherwise scour can reduce the load-bearing capacity of the piles and lead to failure of the structure.

8.4 Temporal, local variations in bed levels

Field monitoring and desk studies suggest that under many circumstances the ultimate scour depth is rarely achieved. It is important, therefore, that further work should be carried out on the effect of unsteady flows.

In the present study attention was confined to uniform sediments. Many naturally occurring river sediments, however, contain a wide range of sizes and the work should be extended to graded sediments. The model could then be used to predict the effect of armouring, whereby scour has the effect of increasing the proportion of coarse sediment on the surface of the bed. To improved confidence in the modelling approach a more detailed comparison with laboratory and field measurements should be made.

The overall aim should be the production of guidelines to enable more national and accurate estimates of local scour to be made

8.5 Sediment transport predictions

The present work concentrated on the prediction of sediment transport of uniform sediments. Many naturally occurring river sediments contain a wide range of sizes and there is a need to extend the work to widely graded sediments. This would enable improved predictions of sediment transport to be made. The benefit would be more accurate predictions of the impact engineering works on rivers and hence a reduction in adverse effects and the need for remedial measures.

APPENDIX

Reports produced under the contact:

Hydraulics Research, 1987, Impact pressures in falling-jet energy dissipators, Hydraulics Research Report SR 124

Hydraulics Research, 1990, Performance of vortex inhibitors for reservoir intakes, Hydraulics Research Report SR 231

Hydraulics Research, 1990, Local scour around large obstructions, Hydraulics Research Report SR 240

Hydraulics Research, 1990, Sediment transport. The Ackers and White theory revised, Hydraulics Research Report SR 237

Hydraulics Research 1990, Impact pressure in plunge basins due to vertical falling jets, Hydraulics Research Report SR 242

Hydraulics Research 1990, Temporal, local variations in river bed levels. Hydraulics Report SR 248

Hydraulics Research, 1990, Hydraulics Structures and Alluvial Processes: Summary Report, Hydraulics Research Report SR 256.