Hydraulics Research
Wallingford

HYDRAULIC STRUCTURES AND ALLUVIAL PROCESSES

Summary Report

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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.

(b) improve techniques for the prediction of:

sediment loads entering reservoirs; the aggradation, 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 work was carried out under Contact PECD 7/7/29-204/83, funded by the Department of the 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 partly supported under Contract PECD7/7/29-204/83, funded by the Department of the Environment. This was 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;

(b) improve techniques for prediction of:

sediment loads entering reservoirs; the aggradation, degradation and local scour associated with dams and other structures; sediment exclusion at intakes; and the long term stability of flood relief channels or other man-made waterways.

The terms of reference for the study were:

(a) Vortex inhibitors

Vortices at reservoir or pump intakes may severely limit the operation and efficiency of such installations. An existing large experimental facility will be used to study the formation of vortices; and a systematic study of the comparative performance of various designs of vortex inhibitors will be carried out. The results will be related to earlier work at HR Limited and elsewhere on vortex formation and suppression.

(b) Energy dissipators

Certain types of design of dam spillway and other reservoir outlets result in free-falling, high energy jets of water impacting onto a solid surface. A laboratory installation will be constructed and experiments performed to measure pressures for various flow conditions and tailwater levels. Scaling laws will be developed to improve prediction of prototype conditions from physical model studies.

(c) Other structures

An analysis will be carried out of the needs of designers in consulting firms, water authorities and other bodies for further research in hydraulic structures. A suitable research programme will be proposed.

(d) Reservoir sedimentation

Loss of storage caused by sedimentation is a major factor in determining the useful life of a reservoir. Using information from earlier experimental work and analysis, an existing numerical model will be further developed to study reservoir sedimentation and sediment flushing. Efforts will be made to predict the shape of re-eroded channels using regime theory, see (e), or other techniques.

(e) Regime theory

Using recent developments in theories describing sediment transport and alluvial friction, HR has developed a regime theory to predict the size and shape of a stable channel flowing through an alluvium; this theory is more rationally based than earlier versions which were dependent on empirical data collected from canals. A desk study will be carried out to assess the problems of applying regime theory to practical situations, especially in rivers.

(f) Physical processes

Existing information on the physics of sediment-related phenomena is deficient in several respects. It will be enhanced in the following ways:

(i) Frictional resistance. Laboratory experiments in an existing installation will be undertaken to investigate the effect of armouring or fine material on the frictional resistance of alluvial channels.

(ii) Local scour. A desk study and laboratory experiments in an existing installation will be carried out to investigate rates of local scour of alluvial materials and soft rock.

(iii) Scaling laws for mobile-bed physical models. Information will be exchanged with other researchers as part of an IAHR task force.

The work was funded principally by the Department of the Environment. Work on the contract was also undertaken by two foreign visitors to Hydraulic Research who, while they were at Hydraulic Research were supported by their respective governments. Thus the DOE contribution to the work was approximately 75% while that obtained from other sources was approximately 25%.

This report provides a brief introduction to the topics covered under the research contract and provides a broad outline of the work done. Comprehensive reports and papers 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 VORTEX INHIBITORS

In the civil engineering field most problems with vortices occur either at pumping stations or at intakes in reservoirs, rivers or the sea. Vortices are normally undesirable because they can cause vibrations in intake structures and reduce the efficiency of pumps and turbines; the entrainment of air magnifies these problems and can produce surging in pipelines downstream of an intake. One of the major problems associated with the design of an intake is that of predicting whether vortices will occur under the planned operating conditions and, if they do, how best to prevent them. The most satisfactory ways of solving the problem are either to build a physical model or to use the results of previous investigations, which in most cases will have also been carried out in the laboratory. A satisfactory understanding of the scaling laws which apply to vortices is therefore needed if reliable predictions are to be obtained from model studies. Much research has been done on this topic, but so far it has not led to any widely-accepted method of scaling.

A study has been carried out on a variety of different types of vortex inhibitor in order to compare their performance under a series of standard test conditions. Some tests have been carried out at two scales, each of the test installations being a scaled version of the other.

The study has led to the identification of several inhibitor designs that are comparatively successful in delaying the onset of vortex activity. Mounting the intake with its entrance flush with a large headwall was found to be very successful. If the intake projects into the reservoir, then a number of local modifications at the intake itself were found to be successful.

If vortices are found to occur unexpectedly at a site, two types of floating inhibitors were found to be effective. Further work needs to be done on some of these devices in order to determine the optimum geometry.

A number of different methods for predicting critical threshold conditions were examined, in the light of data obtained from these experiments. This raised a number of questions on the relationship between discharge and circulation, and the effect that intake geometry and submergence have on them. The need for further measurements is identified.

3 ENERGY DISSIPATION

On a number of dams, water from the spillways is discharged into the atmosphere, falling freely and landing close to the foot of the dam. In many cases concrete lined plunge pools are provided to absorb some of the energy of the falling jet: in other cases the jet falls on the native bed rock. Whatever the system adopted, however, there is need for information on the impact pressures generated. There are numerous cases, reported in the literature, of the severe damage that can be produced by high energy, falling jets.

The first part of the research was a review of the literature to determine the amount of available information on impact pressures. It was clear from this that very little was known in detail about the magnitudes of the pressure fluctuations and the effect on them of jet break-up (such as commonly is the case in nature) and of tailwater depth.

A research programme to look at some of these aspects in more detail has been drawn up, and an experimental rig has been constructed. Basically this consists of a vertical rectangular pipe whose length is adjustable, but which at its maximum is roughly 3.5m long. The jet is 200 x 67mm in section and velocities of up to 5m/s can at present be generated. The jet is discharged into a pool, in the floor of which are mounted pressure transducers. Simultaneous measurements of pressure can be made at fifteen different locations.

The aim of the experiments is to determine how the pressures beneath the jet vary with velocity, turbulence intensity, air concentration, plunge pool depth, and height of free fall.

The experimental programme is now under way, but so far only a small amount of data has been collected.

4 HYDRAULIC STRUCTURES: RESEARCH NEEDS

In order to ensure that the research being carried out at Hydraulics Research is directed to the needs of the civil engineering industry, the views of practising engineers are continually being sought. As part of this exercise, a questionnaire has been circulated recently to a variety of firms, representing consultants, water and local authorities. Seventy five different organisations were approached and replies were received from fifty one.

The prime aim of the survey was to determine the types of structures in which the various bodies were interested and what research they considered to be necessary. On the basis of the replies, a number of proposals for further research have been put forward.

Six topics for research were identified, and the research proposals, in outline, are as follows:

1. To produce a manual on non-standard flow measuring structures, based partly on reviewing existing literature, and partly on experimental research.

2. To produce an illustrated guide to the roughness of British rivers.

3. To produce a manual on the design of small energy dissipators, and carry out research on protection measures downstream from such structures.

4. Research on the hydraulic characteristics of circular tide flaps.

5. Research on drowned, venturi-type sluices.

6. Research on a number of aspects of sediment removal devices.

5 RESERVOIR SEDIMENTATION

It is of the nature of the reservoirs that they lead to a reduction of both the velocity of flow in a river and the water surface slope. This reduces the capacity of the river to transport sediment and encourages the deposition of sediment in the reservoir. The accumulation of sediment reduces the amount of water storage available and hence the utility of the reservoir. In extreme cases effectively all the useful storage may be lost due to sedimentation. The rate at which sediment accumulates has a major impact on the useful life of a reservoir and so is significant in assessing the economics of a proposed reservoir. There is, therefore, the need to be able to assess sedimentation when a reservoir is being planned.

In considering the impact of sedimentation on a storage scheme it is important to know the loss of available storage after a given time period as this directly affects the yield of the reservoir. The distribution of the sediment deposits affects the stage/storage curve and so may have an impact on the operating rules of the reservoir. For the designer, therefore, there is a need to be able to predict both the amount and distribution of sedimentation.

The adverse effects caused by reservoir sedimentation may include:

(a) a reduction in the storage available and hence a reduction in the yield provided by the reservoir,

(b) degradation downstream of the dam. This may threaten structures associated with the dam and lead to problems at structures further downstream such as bridges or intakes,

(c) deposition at the head of the reservoir leading to an increase in flood levels in the contributing streams upstream,

(d) increased evaporation losses for a given storage volume.

Present methods of estimating reservoir sedimentation are unreliable as they do not take into account sediment size, the details of the flow through the reservoir, the distribution in time and the flows into the reservoir and the way that the reservoir is operated. Two examples of the consequences are:

(a) A storage reservoir at Osborne on the Salmon river, Kansas filled with sediment in one year.

(b) Yasuoka reservoir on Teryu river in Japan lost 85% of its storage volume in 13 years.

These simple methods cannot predict the consequences on the river upstream which may be dramatic:

(a) Significant sediment deposits were found 55 miles upstream of the Imperial dam on the Colorado River 10 years after construction.

(b) Construction of the Elephant Butte dam on the Rio Grande River caused bed levels to rise upstream so that the town at San Marcial was threatened with flooding and flood levees had to be constructed.

By contrast a numerical model takes account of sediment size, the nature of flow in the reservoir, the distribution in time of inflows into the reservoir and the way that the reservoir is operated. The models can predict:

- volume of sediment deposited over a specified period
- location of sediment deposits
- annual stage/storage curves
- longitudinal profile of the reservoir at specified times

Present study

In the present study work has been carried out to improve the predictive capability of numerical models by more realistically simulating the physical processes involved. The topics considered where:

(a) the prediction of changes in the shape of the cross-sections describing the geometry of the reservoir. As sediment is deposited or re-eroded the shape of a cross-section may change,

(b) the compaction of deposited sediments. Deposited sediment gradually becomes progressively more dense through time, particularly if more sediment is deposited on top of it.

(c) the modelling of fine silts. In reality a continuous range of sediment sizes are present and since sediment transport depends upon sediment diameter a complete range of sediment behaviour is present. In any numerical model the behaviour of the sediment must be described by at most a few representative sediment diameters. The problem is how to describe this continuous range of behaviour with a small number of discrete sediment sizes.

The study has identified how these effects can be included in a numerical model. This has lead to an improvement in the predictive capability of such models.

6 REGIME THEORY

The aim of regime theory is to predict the "natural" or equilibrium dimensions of a channel and its slope. Study of regime theory first began in the late nineteenth century when British engineers were required to design large irrigation canals in the Indian sub-continent. The difficulty was to know what was the appropriate width and depth of channel and the appropriate velocity to carry a given flow. If the channel were over-sized sediment deposition would take place and channel capacity reduced. If the channels were too small erosion would take place threatening the banks of the canal.

The theories developed at that time were purely empirical and relied on data collected from canals that appeared to be stable or in "regime". More recently as our understanding of the fundamental processes of sediment mechanics has improved it has become possible to base a regime theory on the equations describing the dominant individual processes such as sediment transport, flow resistance and bank stability. Hydraulics Research developed a regime theory of this form in 1981. Such a theory has been called a rational regime theory to distinguish it from the earlier empirical approach. So far such a rational approach has been based upon the selection of appropriate equations describing sediment transport and alluvial friction together with an extremal hypothesis. These extremal hypotheses are normally of the form that the width adjust to maximise or minimise a quantity such as slope, sediment concentration, stream power or unit stream power.

A number of empirical regime theories were developed in the past. These were valid over different ranges and where those ranges overlapped were not necessarily in agreement. To all but a few very familiar with the field there was a bewildering array of different, apparently irreconcilable theories. This had an effect on the acceptability and use of such theories. The development of rational regime theory held out the prospect for a regime theory that was both accurate and could be applied confidently over a wide range of conditions. As, however, a number of different sediment relations or extremum principles could be used in the same framework we foresaw that there was a danger of another confusing multiplicity of theories arising.

The work undertaken under the present contract was aimed at establishing the accuracy and reliability of the theory in predicting regime conditions and to provide unequivocal recommendations as to which sediment relationship and extremal hypothesis provided the best predictions in order to demonstrate that the method could be used with confidence by all. A number of external hypotheses and sediment relationships were selected and the resulting regime predictions were compared with observations of the size, shape and slope of stable channels in regime. The combination of external hypothesis and sediment relations which gave the best agreement with the observations was identified.

The development of rational regime theory has emphasised the importance of both sediment size and sediment concentration in determining regime conditions. In previous empirical regime theories there has only been rudimentary allowance for sediment size and sediment concentration. Our results have shown, however, that changes in sediment concentration can lead to changes of up to 60% in the dimensions of the appropriate stable channel.

Regime theory was first developed for canals which are characterised by near constant discharges. Under the present contract we have also studied the difficulty caused by the large flow variability of applying regime theory to natural rivers. It has been suggested that the effect of the range of flow can be represented by one "dominant" discharge. A number of previously suggested definitions of dominant discharge have been compared and a recommendation made as to which provides the best agreement with observations.

A rational regime theory based upon a well-established understanding of sediment transport processes has the advantage that it should have a wide range of applicability. Empirical regime theories are limited to the range of the data on which they were developed.

Once a reliable rational regime theory has been developed it can be applied not only to the design of canals but to a whole range of problems. Problems studied at HR using regime theory have included:

1. predicting the size and shape of natural rivers
2. prediction of plan form of rivers
3. assessing morphological change in rivers as a result of river engineering works
4. design of mobile-bed physical models

7 PHYSICAL PROCESSES

To enable predictions to be made of sediment-related phenomena it is important to understand the physics of the dominant processes involved. This part of the contract was aimed at improving the understanding of some of these processes.

7.1 Frictional resistance

To calculate flow or sediment transport in an alluvial channel an engineer is faced with the problem of determining the frictional losses on the boundary of the channel.

For artificial, regular channels which are fixed in shape and carry little sediment there is data readily available which can be used as a basis for the estimation of appropriate friction factors. When natural channels are considered the problems of estimating the friction losses grow. In this case, not only must the frictional losses due to the composition of the banks and bed of the channel be estimated but also due allowance must be given for the effects of channel irregularities and other factors. If one considers channels with movable beds the problems are compounded. The frictional losses are dependent on the bed features present, but these are influenced by the transport of the sediment. The sediment transport, however, depends on the fluid motion and is hence inseparable from the determination of the frictional losses.

The work undertaken for this contract started with some experiment on the frictional resistance of sand-silt mixtures. This experimental work was predominantly carried out by A Bassi, a visitor to HR. The analysis of the results of these experiments lead to doubts about the previously derived relationships which described alluvial friction for uniform sands. A further series of experiments were, therefore, instituted to look further at the alluvial friction of uniform sands. Some of these experiments were carried out at higher Froude numbers than had previously been considered. The results lead to an extension of the existing theory for alluvial friction to include these higher Froude number flows. This latter series of experiments and subsequent analysis was predominantly carried out by Mr Wang Shiqiang, a visitor to HR. The work carried out has greatly extended the range of conditions for which reliable predictions of frictional resistance can be made.

7.2 Local scour

Flowing water exerts a shear stress on the bed of a channel. Due to the geometry and nature of the flow this shear stress may be increased in a local area, for example, when a bridge pier is placed in a river. This increase in shear stress affects the sediment movement in the area and may lead to the removal of sediment from the area of increased shear stress. This is known as local scour. Despite having been studied for many years structures still are frequently endangered or fail due to local scour; bridges collapse due to piers being undermined and there are numerous cases of serious scour problems associated with dams. Frequently when dealing with local scour problems only the final depth of scour is important but there are cases when it is important to know the time evolution of this scour. For example, during the closing of part of an estuary scour would not have time to develop to its ultimate depth. In cases of scour associated with permanent structures then, because of the unsteady nature of the flow, it may be important to be able to predict the dependence of scour on time.

A literature review was carried out to describe the work that has been done on the development of local scour with time. Additionally a series of experiments were performed to investigate the rate of local scour under a vertical jet. The work has improved our knowledge of local scour and has elucidated the problem of predicting the rate of scour in a prototype from a knowledge of the rate of scour measured in a model study.

7.3 Scaling laws for mobile-bed physical models

It was intended that this part of the contract would support an HR input to an IAHR (International Association for Hydraulic Research) Task Force on the design of mobile-bed physical models. Unfortunately, despite pressure from HR there have been no developments on this since April 1984, the start of the present contract.

8 CONCLUSIONS

The work carried out on hydraulic structures under the contract has lead to an increased ability to predict the hydraulic performance of vortex inhibitors and the pressures associated with falling-jet energy dissipation. This will result in improvements in the design of structures in terms of safety and economy. A survey has also been carried out to enable HR research to be directed towards the needs of the of the Civil Engineering industry.

As a result of the work carried out on alluvial processes the predictive ability of reservoir sedimentation models has been improved, our ability to predict the long-term stability of man made channels has increased and our knowledge of the physical processes underlying sediment transport phenomena has improved, particularly in the prediction of alluvial friction.

9 RECOMMENDATIONS FOR FURTHER RESEARCH

9.1 Vortex inhibitors

There are a number of promising avenues for further research; they are, in outline, as follows:

(a) Further measurements to investigate whether the relationship between discharge and circulation is a function of intake geometry and submergence depth. Also to investigate whether the Kolf number can be assumed to be constant for the threshold conditions for a particular intake.

(b) To investigate the effect of vortex formation on the pressure distribution within an intake and on its coefficient of discharge.

(c) To study alternative geometries for the submerged screen type of inhibitor.

(d) To study the feasibility of the vertical cord type of inhibitor, and to develop a more effective method of mooring for the floating raft inhibitor.

The Department of the Environment has agreed to provide further funding for research on vortex inhibitors and this will enable work to be done on some of the aspects listed above.

9.2 Energy dissipators

It is recommended that further measurements are taken of impact pressures over a wide range of conditions. The main parameters that should be varied are:

(a) the velocity of the jet
(b) the depth of water in the plunge pool
(c) the height of the free fall to the plunge pool surface

Initially naturally aerated jets should be studied. Subsequently jets whose air content has been artificially enhanced could be considered.

9.3 Hydraulic structures

Six topics for research were identified, and the research proposals, in outline are as follows:

1. To produce a manual on non-standard flow measuring structures, based partly on reviewing existing literature, and partly on experimental research.

2. To produce an illustrated guide to the roughness of British rivers.

3. To produce a manual on the design of small energy dissipators, and carry out research on protection measures downstream from such structures.

4. Research on the hydraulic characteristics of circular tide flaps.

5. Research on drowned, venturi-type sluices.

6. Research on a number of aspects of sediment removal devices.

9.4 Reservoir sedimentation

The development of numerical reservoir models is that they now incorporate our present knowledge of the relevant sediment mechanics. Present shortcomings of such models such as:

(a) prediction of movement of fine silts and clays

(b) inclusion of unsteady effects

(c) inclusion of spatial variation, particularly the distribution of deposited sediment across a section,

arise from our inadequate knowledge of the relevant physical processes.

Though numerical reservoir sedimentation models produce more accurate and detailed predictions than were previously available there is still a need for a quick, reliable method to estimate reservoir sedimentation while a number of possible proposals are being considered at the design stage. What is required is a method as simple as the earlier trapping efficiency approach but more reliable. With the aid of the present numerical models it is possible to develop just such a quick, reliable method of assessing reservoir sedimentation.

9.5 Regime theory

In the rational regime theory discussed above an extremal hypothesis is introduced effectively to determine the width of the channel and, therefore, implicit in it is an assumption about the distribution of shear stress across the bed and the banks of the river. At the present what this assumption is, is unknown. If one were able to make this assumption about the distribution of shear explicit then one would be able to take account of the varying composition of bed and bank material and the effect, if any, of vegetation.

9.6 Physical processes

Experiments need to be carried out to look at the transition between lower and upper regime flows, to determine when such a transition takes place and whether the system exhibits hysteresis. For upper regime flows more experiments are required to determine the frictional relationship for different sediment sizes, particularly coarse sediments.

More careful consideration is required of the scaling laws for local scour experiments to determine the way that local scour results from a model study can be scaled to give prototype values.

APPENDIX.

APPENDIX

List of publications produced under the contract

White, W R and Bettess, R, 1984. The feasibility of flushing sediments through reservoirs. Proc of Symposium "Challenges in African Hydrology and Water Resources", Harare, July 1984, IAHR Publ No 144, pp 577-587.

Bettess, R and White, W R, 1985. Extremal hypotheses applied to river regime, International workshop on gravel-bed rivers, Colorado, USA.

Bassi, A, 1985. Experiments on alluvial friction of sand-silt mixtures, Hydraulics Research Report SR 55.

Wang Shiqiang, Bettess, R and White, W R, 1986. A rational approach to river regime. paper presented at Third International Conference on River Sedimentation, Jackson, Mississippi, USA.

Hydraulics Research, 1986. Reservoir sedimentation: Interim Report, Hydraulics Research Report SR 62.

Wang Shiqiang, White, W R and Bettess, 1986. Experiments on alluvial friction, Hydraulics Research Report SR 83.

Hydraulics Research, 1986. A study on river regime, Hydraulics Research Report SR 89.

Hydraulics Research, 1987. Hydraulic Structures: Research needs, Hydraulics Research Report SR 120.

Hydraulics Research, 1987. Vortex inhibitors, Hydraulics Research Report SR 122.

Hydraulics Research, 1987. Physical processes, Hydraulics Research Report SR 123.

Hydraulics Research, 1987. Impact pressures in falling-jet energy dissipators: Literature review and preliminary experiments. Hydraulics Research Report SR 124.

Hydraulics Research, 1987. Reservoir sedimentation, Hydraulics Research Report SR 126.

White, W R, Bettess, R and Wang Shiqiang. The frictional characteristics of flow in upper and lower regime. Proc ICE, to appear.

Hydraulics Research, 1987. Hydraulic Structures and Alluvial Processes: Summary Report, Hydraulics Research Report SR 131.