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DESIGN OF A FLOW MEASUREMENT FACILITY BY HYDRAULIC MODELLING

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ABSTRACT

Abitibi-Price faced a problem measuring effluent flow in an existing partially filled pipe with supercritical flow. Hydraulic scale modelling was employed to develop and evaluate the accuracy of an effective layout for a flow measurement facility consisting of an impact stilling basin and Parshall flume.

RÉSUMÉ

La société Abitibi-Price a connu certains problèmes relativement à la mesure du débit sortant d'un tuyau partiellement obstrué dans lequel le fluide s'écoulait suivant un écoulement supercritique. Une modélisation hydraulique à l'échelle a été réalisée pour mettre au point et évaluer le schéma de montage d'une installation permettant de mesurer le débit et comportant un bassin permettant d'amortir l'impact environnemental et un canal Parshall.

MANAGEMENT PERSPECTIVE

Abitibi-Price, Inc. has been requested by regulatory authorities to develop a water pollution control plan for their pulp and paper plant at Grand Falls, Newfoundland. The first step in this process was to establish the capability to monitor the plant effluent discharge under adverse conditions precluding conventional solutions. Recognizing the expertise available at the National Water Research Institute, Abitibi-Price commissioned the Institute to develop a conceptual design of the effluent monitoring facility by means of hydraulic modelling. Details of this conceptual design are presented in the report that follows. Preliminary field verifications indicate that the recently built facility meets all design objectives and should provide the data required in the future design of water pollution control.

PERSPECTIVE-GESTION

Les autorités gouvernementales responsables de l'application des règlements relatifs à la protection de l'environnement ont demandé à la société Abitibi-Price, Inc. de mettre au point un plan de contrôle de la pollution de l'eau pour son usine de pâte et papier à Grand Falls, dans la province de Terre-Neuve. La première étape de ce projet consistait à déterminer s'il était possible de contrôler la décharge des eaux de l'usine dans des conditions difficiles qui écartaient le recours à des solutions classiques. La société Abitibi-Price, étant avertie de la compétence de l'Institut national de recherche sur les eaux, a demandé à cet institut de créer un modèle hydraulique de l'installation de contrôle de la décharge des eaux de l'usine. Les détails de ce modèle sont présentés dans le rapport qui suit. Les essais préliminaires sur le terrain montrent que l'installation, qui a été récemment construite, satisfait à tous les objectifs établis lors de l'élaboration du modèle et devrait permettre d'obtenir les données nécessaires à l'élaboration des systèmes de contrôle de la pollution de l'eau dans le futur.

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ABSTRACT

Abitibi-Price faced a problem measuring effluent flow in an existing partially filled pipe with supercritical flow. Hydraulic scale modelling was employed to develop, and evaluate the accuracy of, an effective layout for a flow measurement facility consisting of an impact stilling basin and Parshall flume.

KEYWORDS: FLOW MEASUREMENT, HYDRAULIC MODELLING

INTRODUCTION

At the Grand Falls Division of Abitibi-Price Inc., estimation of effluent discharges from a major outfall based on measurements of tributary streams had proven inadequate. Regulatory agencies requested measurement of the total combined flow, presenting technical problems which could not be solved by a standard measurement installation. The existing 1.07 m (42") diameter main sewer was some 4.3 m below grade when it emerged from the mill structure, flowed partially full at supercritical velocity, and occasionally carried wooden logs. The measurement facility had to be constructed without interrupting plant operations if possible.

Recognizing the difficulties in designing a nonstandard flow measurement facility, Abitibi-Price retained the National Water Research Institute in Burlington, Ontario to produce a conceptual design in the form of a hydraulic model. The model would reproduce hydraulic behaviour of the proposed flow measurement structure and could thus be used to evaluate the layout and develop a rating curve for the system. In part, the Institute was chosen on the basis of their past experience with similar contracts.

Hydraulic modelling is also useful in evaluating accuracy and redesigning existing flow measurement structures. A recent survey by Canviro [1] of 55 effluent flow measurement devices used by the pulp and paper industry in Ontario concluded that only 30% were completely acceptable in terms of accuracy. The remaining 70% required verification of accuracy or modification, often because of turbulence or other adverse flow conditions in approach channels of flow measurement devices. Many of the deficient installations could be effectively evaluated or improved through hydraulic modelling.

PROPOSED FLOW MEASUREMENT FACILITY

The new facility at Grand Falls is expected to measure flows ranging from 0.58 m^3/s to 2.43 m^3/s (50,000 to 210,000 m^3/day) carried by the existing 1.07 m

(42") diameter stainless steel outfall pipe. The facility must interface with the effluent pipe without causing extensive backwater which would lead to plant flooding, withstand occasional passage of wooden logs, and must be suitable for construction and commissioning without disrupting plant operations.

A number of short term flow measurements using fluorescent dye tracer techniques were available to define the expected flow range. The extraordinarily high discharge rates largely represent high reject flows from the mill fresh water intake screens, which are periodically subject to frazil ice formation in winter.

The first design consideration was the existing flow regime. At the upper range of expected flow rates, the Froude number was determined to be 3.05, implying that the flow is supercritical with high velocity, aeration of flow and major water surface disturbances. Considering these conditions and the earlier stated design objectives and constraints, a Venturi-type flume was chosen as the primary element of flow measurement. Among such devices, the Parshall flume is particularly popular and used in some 42% of effluent measurement installations in the Ontario pulp and paper industry [1].

Venturi flumes must be installed in subcritical flow regime. They function by creating critical flow for which the relationship between the depth and discharge is defined. In the proposed installation, the supercritical flow in the effluent pipe had to first be converted to subcritical flow, by dissipating the excessive flow energy.

Efficient energy dissipation can be achieved in an "impact stilling basin", as developed by the U.S. Bureau of Reclamations [2] for pipe outlets. Thus, the flow measurement facility (Figure 1) should consist of a stilling basin coupled to a Parshall flume, with transition structures both upstream and downstream to connect to the existing pipe.

Uncertainty in the design relating to constraints such as prevention of backwater flooding, and the necessity of insuring adequate dissipation of kinetic energy, indicated the need for careful hydraulic analysis of the proposed facility through hydraulic modelling. Such modelling could quickly and economically evaluate design alternatives and produce a reliable final design. Consequently, a model was constructed in the Hydraulics Laboratory of the National Water Research Institute for detailed testing.

Hydraulic Model of the Proposed Facility

Hydraulic models are widely accepted as one of the tools of hydraulic design, particularly when addressing hydraulic phenomena which are too complex to be rigorously described by mathematical techniques. It is generally recognized [3] that even in relatively simple design cases, such models provide for fast and inexpensive design. In this case modelling was used to evaluate the effectiveness of the impact stilling basin in dissipating flow energy, to assess flow conditions at the entrance to the Parshall flume and the risk of flooding upstream of the facility, and to design the transition between the flume outlet and the existing pipe with minimum head loss.

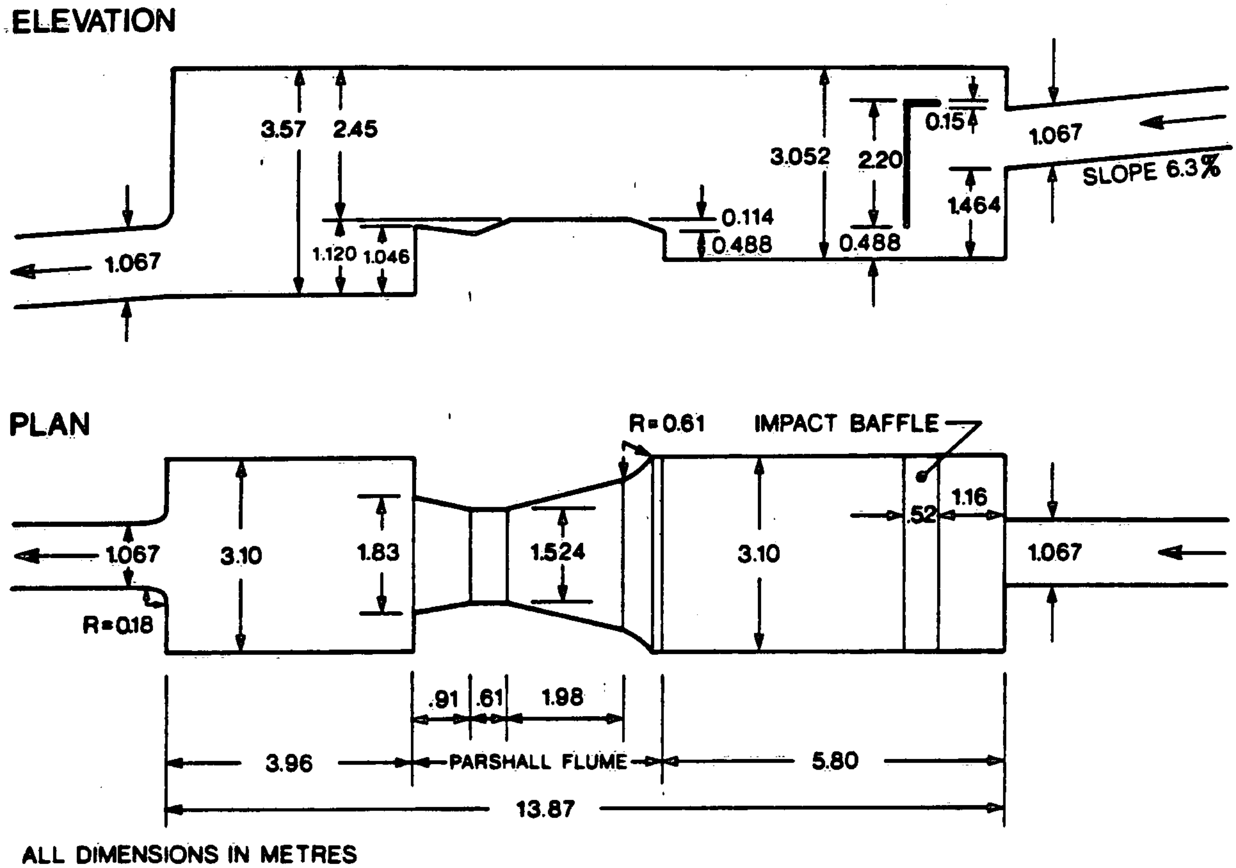

Figure 1 - Recommended layout for flow measurement facility

In a hydraulic model, dynamic similarity of predominant forces must be achieved. For flow through a Parshall flume the predominant force is that of gravity and dynamic similarity is achieved by matching Froude numbers in the model and prototype. The hydraulic model is built as a scale model of the prototype, with a geometric scale S_L and the corresponding discharge scale $S_Q = (S_L)^{2.5}$ [3].

The choice of a suitable model scale generally depends on the available space, water supply and ease of construction. The model must also be large enough that secondary forces such as those due to surface tension are negligible. The scale chosen in this case was 1:7, which resulted in throat width of 218 mm, and the ability to model the existing 1.07 m (42") diameter pipe using an available 0.15 m (6") diameter acrylic pipe.

The scale model of the proposed facility included a section of the rectangular channel beneath the plant buildings, the existing transition of this channel into the 1.07 m (42") diameter pipe, the impact stilling basin, Parshall flume and downstream transition section, and a length of the existing pipe downstream of the transition.

In model tests, discharges through the model flume and the corresponding heads were measured. Discharges less than 15 L/s were measured by weighing the total flow collected over a timed interval. Higher discharges were measured in a volumetric tank in which model discharge was collected over a measured time and the volume of collected water was determined from the observed depth of water and tank dimensions. The accuracy of both measuring techniques was 1%. Flume head was measured by a point gauge inside a stilling well. Although the point gauge was read to within 0.1 mm, some surging in the stilling well and a concomitant loss of precision were noticed [4].

The model investigations were done in several phases, namely (i) design of the facility layout, (ii) calibration of the Parshall flume and evaluation of its accuracy, and (iii) a qualitative evaluation of passage of logs through the facility. Important phases of the model investigations were recorded on a video tape.

Facility Component Design

The facility design evolved through several stages of model investigations, structural design, and consultations with plant personnel. The first phase dealt with the original proposal to locate the facility immediately outside the plant building, where the kinetic energy was least. Model testing found that this location imposed severe restrictions on the facility capacity and operation. Sufficient head to measure high flows while avoiding plant flooding could only be gained by excessively lengthening the facility which would increase construction costs considerably. Consequently, a more advantageous site was selected further downstream, where there was no risk of plant flooding and the head required to pass peak flows through the facility could be gained by reconstructing a relatively short section of pipe downstream of the facility. The remainder of this paper concentrates on the final layout at this downstream site.

Impact Stilling Basin

The impact stilling basin developed by the U.S. Bureau of Reclamations (USBR) is an efficient stilling device for conditions with deficient tailwater, relatively small discharges, and incoming flow velocities below 10 m/s. Energy dissipation is accomplished by the impact of the incoming jet on a vertical hanging baffle, and by eddies which are formed from the changed jet direction after striking this baffle [2].

The width of the impact stilling basin was determined from the USBR design chart [2] and then increased slightly to match the 3.1 m entrance width of the 1.524 m (60") Parshall flume required to measure the given flow range. The vertical impact baffle was placed 1.7 m downstream of the pipe inlet as specified in the design charts. The need to introduce the inlet pipe to the facility at a relatively high elevation resulted in an upwards extension of the baffle, with its bottom edge remaining at the same elevation as the entrance lip of the Parshall flume. Early tests with the model led to an extension of the stilling basin from the standard 4.1 m to a length of 5.8 m, to provide more quiescent flow at the flume entrance.

Smooth flow conditions observed at the exit from the impact stilling basin indicated that the basin was effective in dissipating the incoming flow energy, particularly for low-to-intermediate discharges. For discharges close to the upper design limit, an upwelling at the downstream end of the basin was noted, resulting in surface disturbances at the entrance to the Parshall flume. These disturbances appear to be responsible for the somewhat reduced accuracy of the flume, as discussed below.

Parshall Flume

The Parshall flume is a popular choice in industrial flow measurements. Well installed flumes are highly accurate, reliable, cause only small head losses, and require little maintenance. In this case, the location of the flume immediately downstream of the impact stilling basin was expected to be a non-standard installation in terms of approach velocity distribution. The effects on the flume rating curve and/or measurement accuracy were checked in a hydraulic model.

Upon consideration of expected flow range in this case, a Parshall flume with a 1.524 m (60 inch) throat width was selected. According to the flume specifications [5], the entrance wing walls may be built either as straight vertical walls at an angle of 45^o, or as round walls. The latter arrangement was chosen after observing in the model that the straight walls caused the formation of standing waves in the flume entrance section, close to the point where head is measured. Although the entrance flow was subcritical, the relatively fast inflow caused noticeable surface turbulence in the flume. To prevent significant loss of accuracy, it was recommended that direct head measurements of the water surface should be avoided. Instead, the head should be measured in a stilling well connected to the flume by an intake tube which will require periodic inspection and cleaning. To dampen out head fluctuations and to ensure an adequate response of the stilling well to head changes in the flume, the cross-sectional area of the intake should be at least one percent of the cross-sectional area of the stilling well [6].

The scale model of the Parshall flume was calibrated by taking 33 measurements of flume heads and discharges. The experimental results are plotted in Fig.2. As stated earlier, some surging of the flume head was observed, contributing to experimental scatter.

The observed flume data were approximated by an empirical equation which on average differed by only 1.4 % from the standard Parshall flume equation. To avoid confusion, it was decided to ignore this minor difference and to adopt, as the rating curve of the Abitibi-Price flume, the standard equation of the form:

$$Q = 3.732\ h^{1.587} \qquad (1)$$

where Q is the flume discharge in m^3/s and h is the flume head in metres, measured at a specified location [5].

The goodness of fit of the above equation to the experimental data was described by the expression $(Q_{obs} - Q_{calc})/Q_{obs}$. The mean value of this expression for 33 observations was -1.4% and the standard deviation was 6.1%. This scatter is somewhat high for a laboratory installation and seems to be caused by flow disturbances originating in the impact stilling basin.

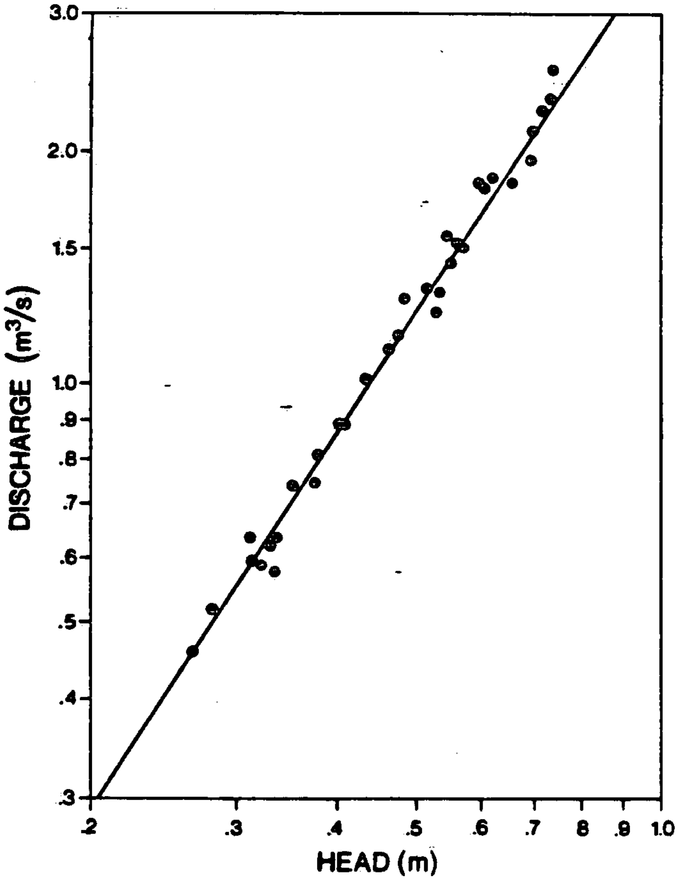

Figure 2 - Rating Curve of the Parshall Flume

Downstream Transition

The last special structure to be designed was the downstream transition which directs the outflow of the Parshall flume into the existing 1.07 m diameter pipe. The capacity of this structure must be sufficient to prevent submergence of the flume exit.

Hydraulic considerations of flow entry into the existing pipe below the Parshall flume require that the available head compensates for the pipe entrance head loss. As this entrance loss is dependent on both entrance geometry and flow velocity, it can be reduced by a proper hydraulic design in the form of a bell-mouth transition, as shown in Fig.1 [4]. For this design, a minimum head of 0.5 m (about 1.3 times the velocity head of the pipe flow) was required, indicating that the invert of the existing pipe inlet must be at least 0.5 m below the exit section of the Parshall flume. This requirement could be met by either extending the length of the downstream transition with a level floor, or by relaying a section of the downstream pipe at a lower elevation and slightly reduced slope. The latter, less expensive alternative was selected.

MEASUREMENT ACCURACY OF THE ABITIBI-PRICE FACILITY

The expected accuracy of the designed flow measurement facility was evaluated, recognizing that the measured discharge values are only estimates of the true flows. Measurement errors are generally classified into three categories; random errors caused by experimental or reading errors, systematic errors which may be either constant or variable, and spurious errors caused by human mistakes or instrument malfunctions. Spurious errors invalidate measurements and cannot be included in the statistical analysis of errors. Such errors must be detected and the data discarded, if no corrections are possible.

Random errors are those which affect the reproducibility of measurements. The mean random error of integrated discharge will decrease as the number of discharge determinations within the integration period increases. In the case of time dependent random errors, the mean error should approach zero over a sufficiently long period of measurement. Systematic errors cannot be reduced by the number of measurements so long as the experimental installation and conditions remain unchanged. The effects of random and systematic errors in this study are summarized below.

The overall error in the measured flow Q results from various contributory errors. The propagation of errors is generally described by coefficients of variation (C_v) of measured values. For a single measurement, the relative error of the flow rate, X_q, can be expressed at a 95% confidence level as:

$$X_q = 2\ [(C_{vqr})^2 + (C_{vqs})^2]^{0.5} \qquad (2)$$

where C_{vqr} is the coefficient of variation of random errors, and C_{vqs} is the coefficient of variation of systematic errors [7]. For a well constructed flume without submergence, the random component error will depend on errors in recorded heads and the systematic error will be caused by the combined error in the coefficients of discharge and approach velocity. After substitutions, the final expression is obtained in the form:

$$X_q = 2\ [\ u^2(C_{vhr})^2 + (C_{vC})^2]^{0.5} \qquad (3)$$

where u is the rating curve exponent, C_{vhr} is the coefficient of variation describing the random error in the flume head h, and C_{vC} is the coefficient of variation of the combined coefficient C. The error in C can be conservatively estimated to have a value of 3% [7] and the error in hr depends on the accuracy of head measurements. Considering the difficulties with head measurements in the model, it is expected that in the prototype the accuracy of such measurements will be only +10 mm. The range of errors according to equation (3) is therefore calculated to vary between ±7.3% at high flows and ±12% at low flows. It should be reiterated that these errors correspond to a single measurement and a 95% confidence level. Flow measurement errors are frequently described, with reduced confidence, by the coefficient of variation alone. By this definition, the errors are equal to one half of those calculated from equations (2) and (3).

VERIFICATIONS IN THE PROTOTYPE

The construction of the Grand Falls flow measurement facility was completed in December, 1988. It is now possible to verify the modelling results in the prototype. To date, the highest flows observed at the facility almost reached the maximum design flow. Within the range of observed flows, the facility performed satisfactorily and holds promise to function well for the full range of flows. At this time, only qualitative observations of flow conditions in the prototype have been made. These observations indicate that the model predicted well the flow conditions in the prototype in terms of water surface agitation in the stilling basin and Parshall flume. More detailed observations are planned, including in situ calibration.

CONCLUSIONS

Redesign of existing flow measurement structures or the fitting of structures into existing facilities often necessitates departures from standard design conditions for common flow measurement devices. These can be effectively accomplished by means of hydraulic modelling. An example of such an approach was given for the flow measurement facility at the Abitibi-Price newsprint mill in Grand Falls, Newfoundland. In this case, a hydraulic model was found to be highly effective in:

- examining the feasibility of various sites along the existing effluent pipe,
- developing a conceptual design of an impact stilling basin to convert supercritical flow to subcritical flow,
- evaluating the effects of this basin on the operation of a Parshall flume,
- determining the minimum head required to transport the peak flow from the flume into the existing effluent pipe.

The construction of the Abitibi-Price flow measurement facility was recently completed. Observations of the operation of this facility confirmed the modelling results and advantages of the design approach based on hydraulic modelling.

REFERENCES

1. CANVIRO CONSULTANTS. Flow Measurement and Sampling Study for the Pulp and Paper Sector in Ontario. Ministry of the Environment, Toronto, Ontario (1988).

2. U.S. DEPARTMENT OF THE INTERIOR. BUREAU OF RECLAMATIONS. Design of Small Dams. U.S. Department of Interior, Washington, D.C., (1960).

3. SHARP, J.J. Hydraulic Modelling. Butterworths & Co., London,(1981).

4. MARSALEK, J. and F. DUNNETT. Flow Measurement Facility for Abitibi-Price Inc., Grand Falls, Nfld. Client report, National Water Research Institute, Burlington, Ontario, 19 pp., (1988).

5. CHOW, V.T. Open-Channel Flow Hydraulics. McGraw-Hill Book Company, New York, (1959).

6. Brakensiek, D.L., Osborn, H.B., and W.J. Rawls. Field Manual for Research in Agricultural Hydrology. Agricultural Handbook No.224, U.S.

Department of Agriculture, Washington, D.C., (1979).

7. BOS, M.G. (Editor). <u>Discharge Measurement Structures.</u> International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, Publication No.161, (1976).