Physical Model Testing and Validation of Large Long-Throated Flumes

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ABSTRACT

Long-throated Flumes (LTFs) are widely-used structures for monitoring flow rates in open channels. They may be built in a variety of different shapes and are generally very accurate when operated under unsubmerged flow conditions. This paper deals with the application of LTFs to monitor the flow distribution within a complex open channel system in a sewage treatment system. Augmentation of the capacity of the system required the construction of new channels and associated Long-throated flumes to control and to monitor the various flow distributions. The preliminary design of the LTFs was carried out using the HEC-RAS backwater program coupled with the WINFLUME program for the flumes themselves. The preliminary design was tested within a large physical model, operated under the Froudian similarity law. It is shown that the accuracy of the flow distribution predicted by the HEC-RAS program requires a very precise determination of the energy losses, and that this determination is not possible with standard analytical models. On the other hand, a high degree of correlation is shown between theory, physical model, and prototype measurements of the designed LTFs.

INTRODUCTION

Long-throated Flumes (LTFs) are widely-used structures for monitoring flow rates in open channels. They may be built in a variety of different shapes and are generally very accurate when operated under unsubmerged flow conditions. When operated in this mode, LTFs may be used to control the distribution of flow through an upstream bifurcation in addition to monitoring the flow within each channel.

In this paper, a case study is presented in which LTFs are used to control and monitor the flow distribution within a complex open channel system in a sewage treatment system. Augmentation of the capacity of the system required the construction of new channels and associated LTFs to control and to monitor the various flow distributions.

The particular application presented is of the design of a new bifurcation within an existing channel. An LTF is present on the existing channel and has been subjected to extensive in-situ field calibration. The new channel from the bifurcation is also to have an LTF built on it. Despite the channels having different hydraulic characteristics, a principal design requirement was that the two LTFs should provide control such that the flow is distributed as evenly as possible throughout the design flow range.

The preliminary design of the new LTF was carried out using the HEC-RAS backwater program, US Army Corps of Engineers (2008), coupled with the WINFLUME program, Clemmens et al (2001), for the flumes themselves. This preliminary design was tested within a large physical model, operated under the Froudian similarity law. The fact that extensive field calibration data are available for the LTF on the existing flume provided an opportunity to test the WINFLUME program for LTF design, the physical model tests, and the prototype calibration against each other.

In this paper, the theoretical analysis of the LTF is first briefly reviewed. The design of the new LTF, utilizing HEC-RAS and WINFLUME, is then described. The physical model is described and the results presented.

Comparative results of analysis, physical modeling, and field measurements of the existing LTF are then presented and discussed. Conclusions complete the paper.

ANALYSIS OF LONG-THROATED FLUME

The analysis of the LTF has been presented previously in Bos (1976). It is included herein for completeness.

The major property of an LTF is that it is designed to create a constriction in the flow area sufficient to produce critical flow over the full range of expected flow rates. In addition, the head loss across the structure should not be excessive and afflux should be kept to a minimum.

The general profile of flow through an LTF is shown schematically in Figure 1, which also shows the notation for the theoretical analysis of the flume. In particular, it is noted that the energy level, H, and the stage height, h, are referenced to the invert level in the throat.

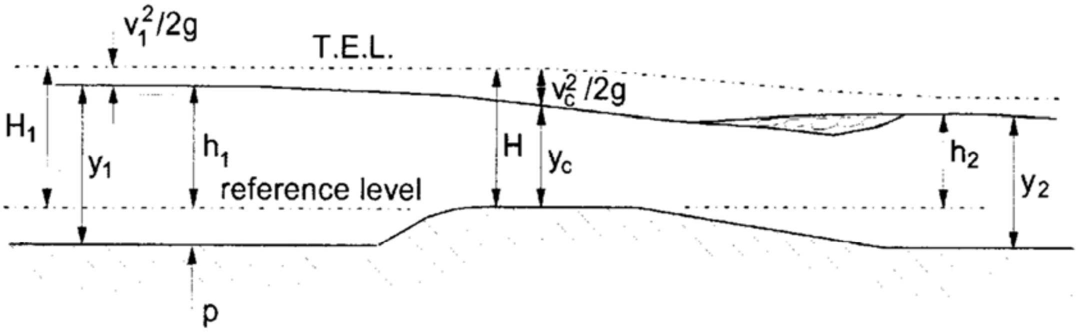

Figure 1: Flow profile through a long-throated flume

The control section is the approximate location of critical flow within the throat of the flume. It is not necessary to know precisely where this occurs because the developed head-flow rate relationship is expressed in terms of the head upstream.

With reference to Figure 1, application of the energy equation yields:

$$H_1 = y_c + \frac{v_c^2}{2g} \tag{1}$$

where subscript, *c*, refers to critical conditions.

To proceed further, the shape of the control section must be known. For a rectangular cross-section, the properties of critical flow are such that:

$$y_c + \frac{v_c^2}{2g} = \frac{3}{2} y_c = \frac{3}{2} \sqrt[3]{\frac{q^2}{g}} \tag{2}$$

where *q* is the flow rate per unit width within the control section and *g* is acceleration due to gravity.

Substitution of Equation (2) into (1) and expanding yields:

$$H_1^3 = \left(\frac{3}{2}\right)^3 \frac{q^2}{g} \tag{3}$$

from which:

$$q = \frac{2}{3} \sqrt{\left(\frac{2}{3} g\right)} H_1^{3/2} \tag{4}$$

In terms of the width of the control section, b_c, Equation (4) is written as:

$$Q = \frac{2}{3} \sqrt{\left(\frac{2}{3} g\right)} b_c H_1^{3/2} \tag{5}$$

where Q is the total flow rate.

The development of Equation (5) has assumed ideal flow conditions – in particular, that there is no energy loss between the location of the upstream head, H_1, and the critical control. Secondly, Q is expressed as a function of H, the total energy level, whereas it is much more useful to express Q as a function of the measured upstream head, h.

These are taken into account by introducing a discharge coefficient, C_d, and a velocity coefficient, C_v such that

$$Q = C_d C_v \frac{2}{3}\sqrt{\left(\frac{2}{3}g\right)} b_c h_1^{3/2} \tag{6}$$

It can be shown, Bos (1976), that C_d and C_v are given by:

$$C_d = \left(1 - \frac{0.006L}{b_c}\right)\left(1 - \frac{0.003L}{h}\right)^{3/2} \tag{7}$$

and

$$C_v = \left(1 + \frac{Q^2}{2gh_1A_1^2}\right)^{3/2} \tag{8}$$

Equations (5) to (8) can be generalized for non-rectangular cross-sections once the relationship between the critical depth, y_c, and the upstream energy level, H_1 is known. These equations, or their equivalent for non-rectangular cross-sections, represent the computational heart of the WINFLUME program.

DESIGN OF NEW LONG-THROATED FLUME

The basic layout of the upstream bifurcation is shown in Figure 2.

The existing LTF is shown on the lower channel and the new LTF on the upper channel. These two flumes provide the downstream control on the flow distribution at the bifurcation.

A HEC-RAS model of the bifurcation down to and including the LTFs was established. The design of the new LTF was then carried out iteratively by running the HEC-RAS model with progressively different geometries for the new LTF until the desired flow distribution was achieved. This flow distribution is shown in Figure 3.

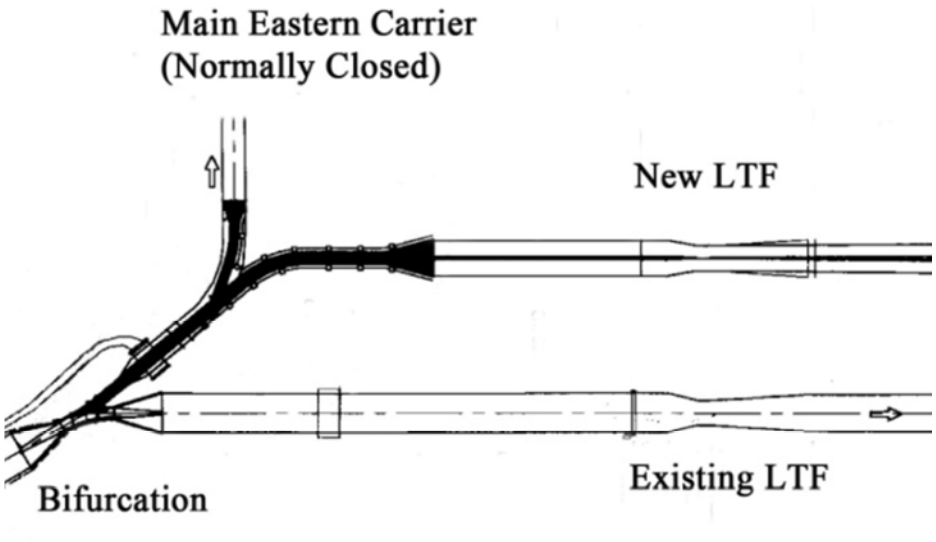

Figure 2: Basic layout of upstream bifurcation

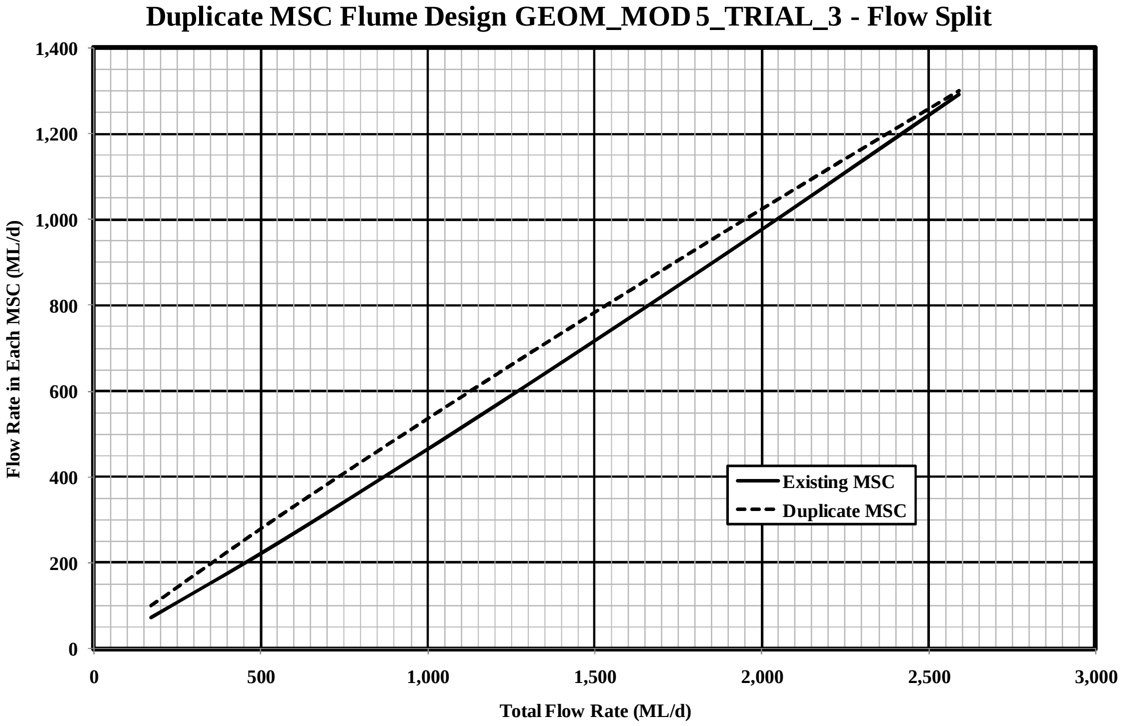

Figure 3: Designed flow distribution at bifurcation

The results of the analysis and design leading to Figure 3 were then tested in the physical model, as described in the following section.

PHYSICAL MODEL STUDY AND RESULTS

The physical model was designed according to Froudian principles, requiring equality of the Froude number at homologous points in both model and prototype. A scale ratio of 1:20 was chosen as being the largest possible, consistent with available space and water supply.

The preliminary design for the new flume, developed theoretically as outlined in the previous section, was reproduced in the physical model, together with the existing flume shown in the lower channel in Figure 2. The flow split at the bifurcation was determined over the full flow range and the results are presented in Figure 4, together with the flow split established during the design phase.

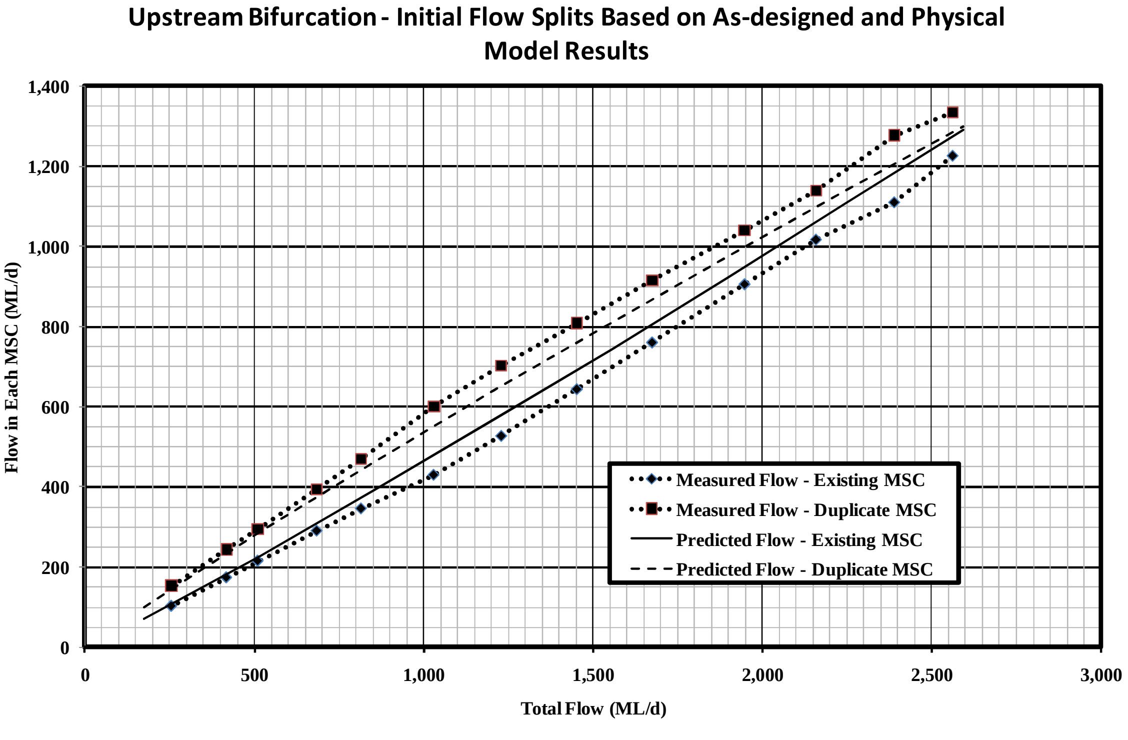

Figure 4: Theoretical and experimental flow distribution at bifurcation

The physical model results in Figure 4 show a significantly greater bias towards the new LTF in the upper channel than the predicted results, obtained from the use of the HEC-RAS and WINFLUME models. These results were considered to be sufficiently different to prompt a full review of the methodology of the predictions and of the physical modelling. This review highlighted some significant difficulties, unique to this site.

In particular, it was noted that a hydraulic jump formed right at the bifurcation and that its precise location depended on the magnitude of the total flow rate.

Two issues arise here. Firstly, the HEC-RAS computer modelling of the bifurcation has to accurately model the energy losses across the hydraulic jump, in addition to accurately model the bifurcation losses themselves, in order to predict an accurate flow split at the bifurcation. Secondly, the location of the hydraulic jump is not necessarily accurately predicted by the physical model. Even very small changes in flow depth can result in a significant shift in location of the hydraulic jump.

On balance, it is considered that the physical modelling issues impose a lesser effect than the theoretical issues. Accurate theoretical modelling requires more than the ability to predict the rating curve – the HEC-RAS component of the model must allow correctly for the head losses at the bifurcation, and across the transitions in both channels upstream of the LTFs.

From the discussion above, it is concluded that the flow split results from the physical model are to be trusted ahead of the theoretical HEC-RAS model, but that even the physical model results should be treated with some caution.

One important issue is to examine the correlation between physical model results, theoretical analysis, and prototype measurements. These are all available for the existing LTF and the correlation is examined in the following section.

STUDY OF EXISTING LONG-THROATED FLUME

The existing LTF in the lower channel of Figure 2 has a known rating curve which has been developed from field gauging. This rating curve has been used by the system operators to monitor the flows in the channel for operational purposes. Figure 5 shows a photograph of this flume.

Because the present study requires the application of this rating curve as one of the boundary conditions of the HEC-RAS modelling, the opportunity was taken to check the field-determined rating curve against that predicted from the WINFLUME computer program and that determined from the physical model study. The results of this comparison are presented in Figure 6.

Figure 6 shows an almost exact comparison between the WINFLUME theoretical rating and the field-determined rating curve. The physical model rating is slightly above the other two. Compared with the theoretical rating, the field-rating under-predicts the flow rate by about 3% at low flow rates and 0.7% at high flow rates. Because of scale effects, the physical model under-predicts the flow rate by about 8% at low flow rates and about 3% at high flow rates.

Notwithstanding these comments, the obvious closeness of the ratings lends confidence to the use of the WINFLUME program in the present flume design study and also to the modelling procedures in the associated physical model study.

Figure 5: Photograph of existing long-throated flume

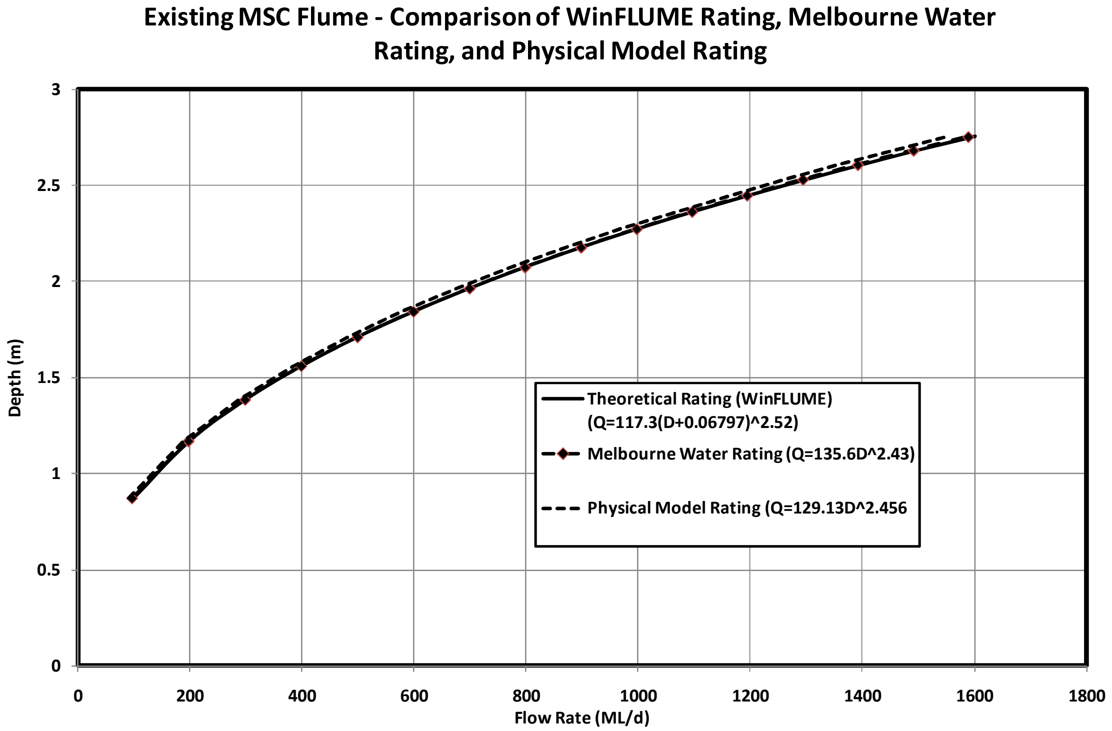

Figure 6: Comparisons of correlations for existing long-throated flume

CONCLUSIONS

The preliminary design for the new flume in the upper channel of Figure 2 was undertaken using HEC-RAS and WINFLUME modelling and was based on the requirement of a flow distribution throughout the flow range that was as even as possible.

The physical modelling was shown to bias the flow distribution towards the upper channel. In assessing the reason for the discrepancy between the theoretical and physical modelling it is concluded that the HEC-RAS model was unable to adequately reproduce all of the channel and structure head losses in conjunction with a mixed flow junction analysis. A further complicating factor was the occurrence of significant turbulence and an associated hydraulic jump at the bifurcation.

Through comparisons with physical modelling results and field rating of an existing flume the WINFLUME modelling and the physical modelling were shown to be very accurate.

ACKNOWLEDGEMENT

The physical modeling was undertaken in the Hydraulics Laboratory at the Department of Civil Engineering, Monash University. Grateful thanks are expressed to Frank Winston and Eduardo Daly for assistance with the experimental work.

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