Chapter 4

Experimental Work and Analysis

4.1 Introduction

This chapter will describe the design, construction and test methodology of the experiments that were conducted to study the global flow characteristics of trapezoidal profile weirs. The general objectives and the scope of the experiment will be explained briefly in subsequent sections. Although the models represent the case of flow over short- and broad-crested weirs, this experimental program excludes the investigation of flow over a long broad-crested weir. The criterion to analyse scale effects on experimental results will also be described. Analyses of the experimental data and a brief discussion of the results will be presented in Section 4.7.

4.2 Objectives

In this work, experimental investigation of flow over trapezoidal profile weirs was carried out to understand the nature of the global characteristics of the flow over these weirs under free and submerged flow conditions for modelling purposes. One of the aims of the experimental study was to validate the predictions of the proposed model for head-discharge relationships, bed pressure and flow surface profiles of flow over short- and broad-crested types of these weirs. Besides establishing empirical relations for the submerged flow rate of these weirs, the experimental program was also designed to assess the effects of boundary roughness and streamline curvature on the solutions of the numerical model.

The experimental data required to accomplish these objectives were those to define the criteria for free flow discharge as well as the global flow characteristics under free and submerged flow conditions.
4.3 Experimental equipment

4.3.1 General arrangement

A number of model trapezoidal profile weirs were placed in an existing plexiglass recirculating flume. The water was supplied to the head tank of the flume from the laboratory sump through a main supply line. This main line was equipped with a valve for controlling the inflow to the head tank. Water flowed from the head tank into the flume through the upstream sluice gate. A tailgate was installed at the downstream end of the flume to regulate the level of the tailwater. The maximum discharge used in the tests was about 26 L/s. Figures 4.1 and 4.2 show the general arrangement of the experimental set-up. Elements to improve the large-scale turbulent nature of the approach flow were provided upstream of the trapezoidal profile weir model. Flow stabilisers such as honeycomb plate were used to minimise any wave disturbance at the inlet section. This made the approach flow to the weir model free of surface waves and flow concentrations. The joints between the walls of the flume and the weir models were made watertight by using a special type of glue or adhesive.

4.3.2 Flume

The experiments were performed in a flume 300 mm wide, 380 mm deep, and 7100 mm long. The average inside width at the position of the trapezoidal profile weir was 303 mm. The flume was completely made of plexiglass and had an adjustable bed slope and a tailgate to control the downstream flow depth. A hole of diameter 30 mm as shown in Figure 4.1 was drilled at the centreline of the flume bed at a distance of 4100 mm from the face of the upstream gate. This hole facilitated the direct connection of the pressure taps and piezometer using long plastic tubes. Water entered the flume from a 115 mm pipe, which discharged horizontally into the head tank that was situated at the upstream end of the flume. A screen was provided in the head tank near the entrance of this pipe to dampen the turbulence generated by the incoming flow into the tank. Flows under smooth and rough bed conditions were tested using this flume. For the latter, a typical wire screen, of which details will be presented in Section 4.4, was placed on the bed to simulate the roughness condition of the approach channel and the surface of the weir.
Figure 4.1: Experimental set-up for the embankment shaped weir model (not to scale)

Figure 4.2: View of the model in the test flume
4.3.3 Weir models

Trapezoidal profile weirs, which are a family of broad-crested weirs having constant upstream and downstream slopes, were used to conduct the experiments. The weirs were symmetrical about the crest, with slopes $1V : 2H$, both for the upstream and downstream weir faces. From geotechnical considerations such as bank stability and seepage control, the slopes of most embankment shaped weirs are close to this value. To examine the influence of the streamline curvature on the flow behaviour, trapezoidal profile weirs of different crest lengths but constant height were used for the tests. Accordingly, three trapezoidal profile weirs which were made of plexiglass and were all of similar construction; were all 150 mm high and, respectively, 700 mm, 750 mm and 1000 mm long. Internal ribs were used to stiffen the 150 mm and 400 mm crest lengths weir models so that the models could resist the dynamic impact of the water. The edges of the crest of all models had sharp corners. When in use, the models were sealed in position in the flume with their crest horizontal. For the case of the 150 mm crest length model, a wire screen was used to roughen the surface of the model. For this particular weir model, the experiments were performed both on smooth and artificial roughened surfaces. For the rest of the models, the experiments were conducted only on smooth surfaces without introducing any artificial surface roughening. Figure 4.3 shows the section of the model, and the cross-sectional dimensions of the three trapezoidal profile weir models are tabulated in Table 4.1.

<table>
<thead>
<tr>
<th>Profile number</th>
<th>Crest length, $L_w$ (mm)</th>
<th>Length of the weir, $L_b$ (mm)</th>
<th>Weir height, $H_w$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pn10</td>
<td>100</td>
<td>700</td>
<td>150</td>
</tr>
<tr>
<td>Pn15</td>
<td>150</td>
<td>750</td>
<td>150</td>
</tr>
<tr>
<td>Pn40</td>
<td>400</td>
<td>1000</td>
<td>150</td>
</tr>
</tbody>
</table>

Holes of diameter 3 mm were also drilled along the centreline of the weir models. The drilled holes satisfied the recommended specifications (Streeter, 1966, p400) for accurate recording of the bed pressures. Accordingly, the length of each drilled hole was greater than two times its diameter and its axis was perpendicular to the surface of the bed profile. In order to avoid the formation of any eddies at the openings which are capable of distorting measurements, the holes were drilled as much as possible free of burrs at their edges.
4.3.4 Discharge measurement

The discharge for all the tests was determined from measurements made with the laboratory’s measuring tank system. Flow from the downstream end of the flume was normally conveyed by a small concrete canal to the sump of the laboratory for recirculation purpose. During the tests this flow was diverted directly into the measuring tank which was located below the floor level of the test room for the purpose of measuring the volume rate of the flow. A centrifugal pump was used to empty this tank after each test run. The discharge measuring system consists of a tank with plan dimensions of 2000 mm by 1500 mm and depth of 4500 mm, and a manometer inclined at angle of 56.62° (to the horizontal) to measure the depth of water in the tank. During the tests, a tank filling time longer than one minute was used to minimise errors associated with the starting and stopping of the stopwatch. Figure 4.4 shows the measuring tank apparatus of the experiment. For each test, two to three readings were taken for each parameter related to the discharge measurement and the average of the resulting discharge values was used in the analysis. In the course of the experiment, the discharge measurements were checked against predictions that were made based on the integration of the velocity profiles taken at two sections (2800 mm and 3300 mm from the upstream gate) upstream of the weir model. The result indicated that the maximum error in the determination of the flow rate was 4% (see Table 4.2). It is important to note that this error includes the uncertainty related to the velocity measurements, which will be described in Section 4.3.6. The repeatability of the discharge measurements using the measuring tank system would be better than the velocity profile integration method. However,
running of tests for many times to collect sufficient data for the purpose of uncertainty analysis would be uneconomical and time consuming.

Table 4.2: Summary of discharge uncertainty

<table>
<thead>
<tr>
<th>Q^0 (L/s)</th>
<th>Q^0 (L/s)</th>
<th>Average (L/s)</th>
<th>Measured (L/s)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.844</td>
<td>22.015</td>
<td>21.929</td>
<td>20.96</td>
<td>-4.42</td>
</tr>
</tbody>
</table>

Notes: 

a) Velocity measurement section, 2800 mm from the upstream gate.

b) Velocity measurement section, 3300 mm from the upstream gate.

For the small volumetric tank which was used in these experiments, the volume calibration equation reads as

\[ V_v = 2.3938(H_f - H_i) + (\Delta V_f - \Delta V_i), \]  

(4.1)

where:

- \( H_i \) and \( H_f \) = the initial and final manometer readings for the water level in the tank respectively in m,
- \( \Delta V_i \) and \( \Delta V_f \) = the volume adjustments corresponding to the initial and final manometer readings respectively in m³,
- \( V_v \) = the total volume of water diverted into the tank in m³.

The volume adjustment for each manometer reading was taken from the tank calibration curve. The volume adjustment introduced in equation (4.1) accounts for space occupied by auxiliary equipments in the tank such as a ladder as well as internal dimension errors due to imperfection of the tank walls. For the recorded tank filling time \( t \), the steady flow discharge can be determined from the following equation:

\[ Q = \frac{V_v}{t}. \]  

(4.2)

Equations (4.1) and (4.2) were employed in this research project to estimate the discharge that corresponds to each test.

4.3.5 Flow profile and bed pressure measurements

As mentioned before, the experimental program was designed to run tests at different flow rates. The maximum discharge value corresponding to free flow conditions varied for different weir model sizes. In general, the experiments were conducted for flow rates between 5 L/s – 26 L/s. The longitudinal flow surface profile for each run was observed.
with a manual point gauge of reading accuracy 0.10 mm. However, the accuracy of the point gauge measurements depends on the degree of the instability of the flow surface. It is believed that the flow profile measurements were accurate within 0.20 mm using this instrument for the transcritical flow profiles of the weir. This point gauge was used to measure the bed and water surface levels at every 50 mm and 100 mm horizontal intervals (depending on the curvature of the flow surface) along the centreline of the flume and the weir model. Water depths were calculated from the difference in these two readings at each measuring point in the flow domain. The tailwater gauging station was located 1100 mm upstream of the tailgate for recording the tailwater level. The depth at this station was observed using a similar point gauge. The accuracy of the measurements of submerged flow profiles particularly at low submergence ratios and tailwater depths corresponding to different downstream flow conditions was up to ±4 mm, due to surface undulations and turbulence. The longitudinal position for the point-gauge measurements was obtained from a steel tape placed on the top edge of the flume.

For recording the bed pressure, steel pressure taps of external diameter 3 mm were fixed along the centreline of the weir model at the drilled holes (see Figure 4.7). The maximum horizontal distance between the pressure taps was 80 mm, but the spacing was much closer at the upstream and downstream edges of the weir crest where the
effects of the curvature of the streamlines are very significant. These pressure taps were connected by long plastic tubes to vertical water piezometers (internal diameter of 8 mm) of reading accuracy to 1 mm. The effect of surface tension (capillary rise) on the bed pressure reading for this size of piezometer tube was insignificant. For each experiment, the base reading for the pressure taps was obtained immediately after the flow was shut off. Figures 4.5 and 4.6 illustrate the positions of the different tapping points for the symmetrical half part of the trapezoidal profile weirs. The horizontal spacings of these tapping points are given in Table 4.3.

Table 4.3: Spacing of the pressure taps for the weir model profiles

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Spacing (mm)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_1</td>
<td>40</td>
<td>horizontally</td>
</tr>
<tr>
<td>S_2</td>
<td>80</td>
<td>horizontally</td>
</tr>
<tr>
<td>S_3</td>
<td>50</td>
<td>along the horizontal crest</td>
</tr>
<tr>
<td>S_4</td>
<td>35</td>
<td>along the horizontal crest</td>
</tr>
</tbody>
</table>

4.3.6 Velocity measurement

The velocity measurements were conducted using the field type Acoustic Doppler Velocimeter (ADV; SonTek) with random noise approximately 1% of the velocity range at 25 Hz. The ADV system, which operates at 10 MHz acoustic frequency, applies acoustic sensing techniques to measure flow velocity in a remote sampling volume ($\leq 0.25 \text{ cm}^3$) that is located to the right of the tip of the side-looking probe. The acoustic sensor consists of transmitting and receiving transducers. The former produces a periodic short acoustic pulse. As the acoustic pulse is sent out into the flow, it intercepts ambient matter like a microbubble or suspended particle as a target. The target scatters the incident pulse in all directions; some are directed towards the receiver. As far as the receiving transducer concerned, the target has generated (by reflection) an acoustic signal that propagates from the target in a sample volume. Assuming that the target travels with the same velocity as the flow, the Doppler shift corresponding to the relative motion of the target enables the evaluation of the velocity of the flow. The velocity measurements are influenced by the concentration of the scattered particles in the flow, which can be explained from the dependent relationship of the Doppler noise and signal strength. For flow with weaker signal strength, the Doppler noise becomes high. Such situation results in poor quality of velocity measurements by this instrument. It is rec-
Chapter 4. Experimental Work and Analysis

Figure 4.5: Plan view of a broad-crested weir model with tapping points

Figure 4.6: Plan view of a short-crested weir model with tapping points
ommended that the velocity range of the ADV be set to the minimum value that covers the range of velocities expected in the flow.

The two-dimensional side-looking probe (see Figure 4.8) which was used in this experimental work has the advantage of measuring the velocity very close to the bed. For this version of the instrument, the sampling volume is located $50 \text{ mm}$ (horizontally) away from the tip of the probe. This enables measurements to be taken without interfering with the flow.

The main objectives of the velocity profile measurement were to collect sufficient data for determining the Boussinesq and Coriolis coefficients at different sections for flow over trapezoidal profile weirs and also estimating the equivalent sand roughness height of the artificially roughened bed. For these purposes, velocity observations were taken upstream of the critical section of the flow in the converging zone as well as in the approach channel along the centreline of the flume. As much as possible, the velocity profile reading was done at sufficiently closely spaced sections so that they could accurately describe the actual flow conditions. The duration of the measurement for every position of the instrument was set between $55$ to $65 \text{ s}$. In the course of the measurement, the vertical position of the probe was measured using a point gauge attached to the ADV holder to obtain the height of the sampling volume from the bed. Since the velocity of the flow was measured indirectly from the scatter, seeding materials were added in each experiment to improve the quality of the observed data by decreasing the Doppler noise.
In order to obtain reliable results, WinADV32 software was used to filter poor quality data from the data file based on the criteria of signal-to-noise ratio (SNR) and the correlation (COR) parameters. SNR value of 20 (Kraus et al., 1994) and manufacturer’s recommendation of COR not less than 70 were used to filter the data between the recorded flags (event markers) 1 and 2 (see Figure 4.10). The time average local velocities at different levels were also calculated using this software. Figures 4.9 and 4.10 show the time series velocity and the associated average values of the COR and SNR parameters for typical velocity measurement at height of 133.0 mm above the bed of the flume. In Figures 4.10 and 4.12 the lower and upper curves are for the variation of the average values of the SNR and COR parameters respectively.

Uncertainty analysis for velocity measurement

The results of the uncertainty analysis in any experiment can be used to describe the inaccuracies related to the measurement of different parameters. Kline (1985) states that uncertainty describes the dispersion usually in terms of a measure associated with a stated probability level such as the standard deviation. The uncertainty assigned to a given variable represents an estimate of the scatter which would be observed if that variable were measured many times under prescribed conditions and depends on what
Figure 4.9: Velocity time series measurement in subcritical flow region, $z = 133$ mm

Figure 4.10: Average SNR and COR values and recorded flags for measurement at $z = 133$ mm

Figure 4.11: Velocity time series measurement in supercritical flow region, $z = 12$ mm
factors of the experiment are allowed to vary during those repeated trials. In this study only measurement errors are considered in the analysis of uncertainty assuming that the instrument does not have any calibration errors (no biases). The first-order uncertainty analysis method (Moffat, 1985) is applied here to estimate this error. This method predicts the scatter which would result from repeated trials using the same apparatus and instruments.

Prior to commencing the experimental work, a series of experiments were conducted in the upstream subcritical flow region as well as in the supercritical flow region over the crest of the weir to confirm the accuracy of the velocity measurements using the ADV instrument. Velocity measurements were taken at the centreline of the flume at sections, 2200 mm and 3960 mm from the upstream gate of the flume for these two flow regions. During the test, the flow was artificially seeded so that in each reading the SNR and COR values were kept greater than 20 and 80 respectively (see Figures 4.10 and 4.12). This was necessary in order to acquire higher quality data for assessing the repeatability of a particular set of readings. Three representative points within the operating range of the instrument were selected for uncertainty analysis to achieve the objective of this part of the experiment. Thirty measurements were taken at two points located in the subcritical flow region that were in the same vertical section but at different heights from the bed of the flume. Similarly, additional observations were taken at a selected point in the supercritical flow region to represent the maximum flow velocity. The depth of the flow for the test was 265.6 mm and 81.7 mm for the sections in the subcritical and supercritical flow regions respectively. The discharge of the flow was set to be \( 0.0673 \text{ m}^3/\text{s} \) per metre width of the flume.

Based on the work of Coleman and Steele (1995), the repeatability of the velocity measurement was determined. A two-tailed \( t \)-value of 2.0456 was obtained for the thirty
velocity measurements using a linear interpolation technique from the tabulated values 
(Coleman and Steele, 1995) for the twenty nine degrees of freedom at a 95\% level of 
confidence. This value was then multiplied by the standard deviation of the observa-
tions for each of the elevation to determine the uncertainty in the repeatability of the 
velocity measurements. Table 4.4 summarises the results for the mean velocity, \( \bar{U} \), 
measurements (statistical mean velocity) at three different points. The analysis results 
at \( z = 8.3 \) mm and 133.0 mm for the subcritical flow region represent the uncertainty 
of the instrument readings for velocity observations with and without the influence of 
the bottom solid boundary.

<table>
<thead>
<tr>
<th>Distance, ( z ) (mm)</th>
<th>( U ) (cm/s)</th>
<th>Standard deviation (cm/s)</th>
<th>Uncertainty in ( U ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.3 (( Fr &lt; 1 ))</td>
<td>9.61</td>
<td>0.0719</td>
<td>±1.531</td>
</tr>
<tr>
<td>133.0 (( Fr &lt; 1 ))</td>
<td>26.99</td>
<td>0.1264</td>
<td>±0.958</td>
</tr>
<tr>
<td>12.0 (( Fr &gt; 1 ))</td>
<td>84.50</td>
<td>0.2513</td>
<td>±0.608</td>
</tr>
</tbody>
</table>

The results indicate a relatively higher uncertainty value for the velocity observations 
near the bed. The uncertainty value decreases with increasing of distance from the 
bed of the flume as well as flow velocity. The overall accuracy of the equipment for 
measuring flow velocity is acceptable for this work.

## 4.4 Scope of the weir profile design variation

The scope of the weir design variations involved in the tests is given in Table 4.5. All 
the embankment shaped models described in that table were made of the same type of 
materials. The design of the profiles was based on the size and capacity of the existing 
flume which is found in the Michell Laboratory of the University of Melbourne, but 
they were regarded as adequate for the determination of information for the purpose of 
flow model validations.

In the design of the models, only the length of the crest of the weir was varied. Two 
of the profiles (Pn10 and Pn40) were designed to simulate separately the actual flow 
behaviours of short- and broad-crested trapezoidal profile weirs. The purpose of these 
models was to assess the influence of the ratio of the crest-referenced head, \( H_1 \), to the 
length of the weir crest, \( L_w \), on the numerical solutions of the weir flow problems. 
For the given rate of water flowing over these weirs, this parameter determines the
degree of the curvature of the streamlines. This allows us to examine the effect of the curvature of the streamlines on the solutions of the models as well as on head-discharge relationships of these weirs. The third profile was intentionally designed to reproduce the flow characteristics of both the short- and broad-crested weirs depending on the value of $H_1/L_w$. This profile was also used to study the influence of surface roughness on the flow characteristics of the weirs. The surfaces of the model and the bed of the flume were artificially roughened to replicate the practical conditions of flow over such type of weir. However, roughness investigation for free surface flows are complicated by the fact that the depth of flow varies with discharge. Furthermore, the nature of prototype roughness is extremely variable and very difficult to simulate in the laboratory using small-scale model.

Table 4.5: Summary of design variations for the tested models

<table>
<thead>
<tr>
<th>Model</th>
<th>Crest length (mm)</th>
<th>Surface conditions</th>
<th>Range of $H_1/L_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pn10</td>
<td>100</td>
<td>Smooth</td>
<td>[0.46, 1.16]</td>
</tr>
<tr>
<td>Pn15</td>
<td>150</td>
<td>Smooth</td>
<td>[0.34, 0.89]</td>
</tr>
<tr>
<td>Pn15</td>
<td>150</td>
<td>Wire screen (all surfaces)</td>
<td>[0.29, 0.91]</td>
</tr>
<tr>
<td>Pn40</td>
<td>400</td>
<td>Smooth</td>
<td>[0.14, 0.32]</td>
</tr>
</tbody>
</table>

Only one method of surface roughening, a wire screen, was used in the experimental study. This method was chosen because the wire screen was uniform in size and spacing, easily reproducible, convenient to apply and remove from the surface of small-scale models, and relatively low in cost. Such method of roughening has been used in the past for simulating bed roughness in free surface flow (see e.g., Bauer, 1954; Kindsvater, 1964; Rajaratnam et al., 1976). It is recommended to use a piece of wire screen completely free of folds, bulges, and kinks; only a perfect piece of the screen can lie flat on the plexiglass bed without the use of an adhesive. In this study, a piece of new mild steel wire screen with mesh size 6.5 mm square was stretched taut over the entire surface of the model and dots of superglue was used to fix the screen flat on the bed (see Figure 4.13). The diameter of the wire from which the screen was made was 0.56 mm. This wire screen was also used to roughen the bed of the flume. In order to reduce the length of the full development of turbulent boundary layer, a trip wire of diameter 3 mm was placed at the entrance of the flume (see e.g., Chow, 1959, p194; Balachandar et al., 2002).
It is evident that the discharge capacity of a weir under free flow conditions is primarily a function of the overflow head, roughness of the surface, and overflow head to crest length ratio. Similarly, the discharge for submerged flow conditions is mainly a function of the submergence ratio and roughness of the structure. Therefore, the scope of the profile design variation was limited to investigate only the effects of the variation of the length of the crest of the weir and roughness of the surfaces on the numerical simulation of the global flow characteristics of these weirs. The influences of the variation of the height and slope of the upstream and downstream faces of the weir on the characteristics of the flow were not considered in this experimental work.

4.5 Scope of the experiment

As described before, one of the purposes of conducting the experiments at different discharges on different sizes of weir models was to assess the effect of the curvature of the streamline on the numerical solution of the models as well as on head-discharge relationships. Four series of experiments were performed with the three weir models. In each series with a weir of constant height and crest length, several experiments were performed with different discharges. For each of the smooth bed profiles, nine to ten experiments were conducted. Also, ten experiments were performed on the rough bed weir model (Pn15). The increment of discharge between each experiment was in the range of 2 L/s to 4 L/s depending on the size of the weir model. This gradual increment
of discharge in each experiment enabled us to observe the change in the curvature of the streamline of the flow over the crest of the weir. When the experiments were performed, colouring dye was injected at different points in the flow region to trace this flow pattern clearly. The impact of the tailwater depth on the flow behaviour was also investigated by changing the tailwater level for a constant discharge. The scope of the discharge variations involved in the tests is given in Table 4.6. In this experimental study the discharge, the overflow head, the weir crest length and the roughness of the surface were chosen as the primary parameters to achieve the objectives of the research project.

Table 4.6: Details of the experimental tests

<table>
<thead>
<tr>
<th>Profile number</th>
<th>Number of experiments</th>
<th>Discharge (L/s)</th>
<th>Discharge increment (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pn10</td>
<td>9</td>
<td>5.0 – 24.0</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Pn15 (smooth bed)</td>
<td>10</td>
<td>5.0 – 26.5</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Pn15 (rough bed)</td>
<td>10</td>
<td>4.56 – 27.0</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Pn40</td>
<td>9</td>
<td>6.0 – 23.0</td>
<td>2 – 4</td>
</tr>
</tbody>
</table>

4.6 Scale effects and flow separation assessments

4.6.1 Effects of viscosity and surface tension

When the discharge over a control structure such as a weir becomes small, surface tension and viscosity effects significantly affect the flow behaviour. In this experimental study, the scale effects due to surface tension and viscosity on the experimental results were assessed based on the criterion developed by Ranga Raju et al. (1990) for flow over trapezoidal profile weirs. The characteristic parameter to establish the criterion is

\[ \varpi = R_e W_b^3, \]  

(4.3)

where:

- \( R_e = \sqrt{gh_1^2/\nu} \) is the Reynolds number,
- \( W_b = (\rho gh_1^2/\sigma_s)^{1/2} \) is the Weber number,
- \( h_1 \) = crest-referenced overflow depth,
- \( \sigma_s \) = surface tension.

According to this criterion, for \( \varpi \) greater than \( 10^3 \) the flow behaviour over the trapezoidal profile weir is free of surface tension and viscosity effects. However, this criterion was established without considering the influence of the geometry of the trapezoidal profile weirs. The minimum overflow head to avoid any scale effects from equation (4.3)
can be written as

\[ h_1 > \left( \frac{\nu \sigma^3 \rho}{g} \right)^{2/9}. \] (4.4)

In the course of the experimental work, the temperature of the water was measured. The record showed a variation of temperature between 18 °C to 20 °C. After inserting the values of the viscosity and surface tension corresponding to an average temperature of 19 °C in this equation, a minimum overflow depth of 4 mm is found. Practically this corresponds to a discharge of less than one litre per second. This implies that the scale effects are dominant for small flow depths over the crest of the structure which correspond to very low flow rate.

Further analysis is also made using the experimental data of this study. The variations of the non-dimensional discharge, \( q_t = q / \sqrt{2gH_1^3} \) with both the Reynolds and Weber numbers are presented in Figures 4.14 and 4.15 for flow over short- and broad-crested trapezoidal profile weirs with smooth beds. The trends of the variations are approximated by straight lines (almost horizontal), as shown in the figures. It can be seen from these figures that the observed discharges are almost independent of the magnitudes of viscosity and surface tension. Accordingly, the effects of viscosity and surface tension on the experimental results are negligible.

4.6.2 Effect of flow separation on bed pressure

The effect of flow separation on the bed pressure reading was assessed by injecting a colouring dye at selected sections of the flow. The colouring dye helped us to examine the flow pattern near the upstream and downstream corners of the crest of the trapezoidal profile weirs. However, no flow separation phenomenon was observed near these corner points. As noted by Rao (1975), providing a gentle slope (not steeper than \( 1V : 2H \)) for the upstream and downstream faces of the weir minimises the occurrence of flow separation in such types of flow control structure. This showed that the pressure taps close to the crest corners did not record the pressure head in the separation bubble, but they measured the bed pressure over the surface of the weir model for each test.

The above fact implies that numerical procedure for bed separation profile due to cavity flow is not required to exclude the region of a separation bubble from the solution domain. Hence, the model pressure equation can be solved numerically to predict the bed pressure profile throughout the whole computational domain for this flow problem.
Chapter 4. Experimental Work and Analysis

Figure 4.14: Effect of viscosity

Figure 4.15: Effect of surface tension
Chapter 4. Experimental Work and Analysis

4.7 Analysis of experimental data

4.7.1 Experimental data

Several tests were conducted for each series of the experiments to collect the following data:

1. free flow, submerged flow and bed pressure profiles at different discharges;
2. overflow head and discharge for discharge rating curves;
3. velocity profiles at different sections for each model;
4. tailwater depth and the corresponding crest-referenced upstream depth for the development of an empirical relation for submerged flow discharge;
5. tailwater level limits to define the transition range for the downstream submerged flow as well as the modular limit.

A summary of the experimental data for the characteristics of flow over trapezoidal profile weirs under free and submerged flow conditions is given in Appendix B.

The first two sets of data in the list were used to validate the solutions of the numerical model of the current study. The remaining data were analysed using the appropriate methods, which were described in Chapter 3, to obtain the required results according to the objectives of the study. Some of the main results of the analysis will be discussed in the following subsections.

4.7.2 Variation of horizontal velocity in the flow field

Figures 4.17 and 4.18 show the distributions of the horizontal velocities of the flow at different sections for \( H_t/L_w = 1.10 \) \((q = 691.6 \text{ cm}^2/\text{s})\). Logarithmic and linear curves are fitted to the experimental data and are also shown in the figures. In these figures the time-mean local point velocities at any section are shown versus the non-dimensional height above the bed, \( h_s/H \) \((h_s = \text{velocity measurement depth above the bed}, \ H = \text{flow depth at the section})\). Velocity observations were taken for sections near the gauging station and control sections besides other intermediate stations, which are shown in Figure 4.16. It is seen from Figures 4.17 and 4.18 that at stations 1, 2 and 3 there is a boundary layer occupying about 15% of the depth with an essential uniform velocity distribution in the upper 85% of the flow depth. For the intermediate stations between sections 3 and 7, the boundary layer depth is approximately 20% of
the depth of flow. In these stations above the boundary layer, the velocity distribution slightly deviates from uniform distribution due to the weak curvature of the streamlines as well as the gradual change of flow cross-sectional areas. Over the crest of the weir, the considerable curvature of the streamline modifies the velocity distributions, so that the velocities are relatively higher in the lower regions. This feature is clearly seen in Figure 4.18 for the observed stations.

![Figure 4.16: Velocity observation sections for flow with $H_1/L_w = 1.10$](image)

4.7.3 Velocity distribution coefficients

The velocity observation sections for flow over a broad-crested trapezoidal profile weir ($L_w = 400$ mm) are shown in Figure 4.19. Figure 4.20 illustrates the numerical results of the momentum and energy correction coefficients for this weir model for flow with $q = 625.7$ cm$^2$/s. It can be seen from Figure 4.20 that the energy and momentum correction coefficients attain a maximum value of 1.15 and 1.08 respectively at section 3 ($x = -0.025$ m). Further upstream of this section, the magnitudes of these coefficients are gradually decreasing and approaching the known theoretical value of unity ($\alpha \to 1.0$ and $\beta \to 1.0$). In this flow region, the streamline of the upstream approach flow has insignificant curvature and as a result the flow becomes nearly horizontal. The
Figure 4.17: Velocity distribution upstream of the weir crest for flow over a short-crested weir ($L_w = 100$ mm)

Figure 4.18: Velocity distribution around the crest of a short-crested weir ($L_w = 100$ mm)
result also shows that downstream of section 3 the values of the velocity distribution coefficients decrease to relatively minimum values at section 6 ($x = 0.145$ m) and then increase to local maximum values of 1.14 and 1.05 for the energy and momentum correction coefficients respectively. For the considered case of flow over hydraulically smooth flow boundary where the roughness of the bed does not play any role to influence the flow behaviour, the maximum values of the coefficients are observed at sections associated with rapid change of flow cross-section besides the pronounced curvature of the streamline of the flow. On the crest of the weir ($x = 0.545$ m), the values of these coefficients are slightly deviating from unity. This confirms that flow over the crest of such type of weir satisfies the quasi-uniform flow condition for $H_1/L_w < 0.50$.

Similar features as for the case of flow over a broad-crested weir for the variation of the momentum and energy coefficients upstream of the crest section can be seen in Figure 4.21 for flow over a short-crested trapezoidal profile weir ($L_w = 100$ mm, $H_1/L_w = 1.10$). On the crest of this weir model ($0.30$ m $\leq x \leq 0.40$ m), however the values of these coefficients are exceeding unity. This numerical investigation indicates that between the upstream and crest sections the magnitudes of the distribution coefficients vary from section to section along the length of the flow domain considered. This implies that the values of the distribution coefficients are not uniform throughout the flow field for flow with substantial curvature of streamline i.e., $\partial \beta / \partial x \neq 0$ and $\partial \alpha / \partial x \neq 0$.

4.7.4 Bed pressure analysis

Crest bed pressure variation

The bed pressure variations over the crest of the short- and broad-crested trapezoidal profile weirs are shown in Figures 4.22 and 4.23. In these figures the non-dimensional bed pressures along the centreline of the crest of the trapezoidal profile weirs, $p_c/p_0$ ($p_c =$ the crest bed pressure, $p_0 = \gamma H$) are shown versus the normalised distance from the axis of symmetry, $X = \tilde{x}/H$. As can be seen from Figure 4.22, the normalised crest bed pressure, $p_c/p_0$ decreases with increasing of the overflow head to crest length ratio. For a constant length of weir crest, $p_0$ increases at a faster rate compared to $p_c$ with increasing of flow over the crest of the weir. This is true for the case of a convex shape flow surface profile such as flow over short-crested weirs where the vertical component of the centrifugal acceleration of the flow has a negative impact on the bed pressure.
Figure 4.19: Velocity observation sections for flow with \( H_1/L_w = 0.28 \)

Figure 4.20: Momentum and energy correction coefficients \((L_w = 400 \text{ mm})\)
distribution. Consequently, the bed pressure to the hydrostatic pressure ratio, \( \frac{p_c}{p_0} \), is decreasing rapidly and attains value less than unity at any section on the crest of the weir (see Figure 4.22). The analysed experimental data presented in this figure are for flow with \( H_1/L_w > 0.48 \) and as expected, the curvature of the streamlines significantly influences the distribution of the bed pressure.

It is clearly seen from Figure 4.22 that the bed pressure variation along the crest of the weir is nonlinear and can be described approximately by the following general equation:

\[
\frac{p_c}{p_0} = C_2 X^2 + C_1 X + C_0,
\]

where \( C_0, C_1 \) and \( C_2 \) are constants and their values depend on the overflow head to crest length ratio. As the radius of curvature of the streamline at the surface \( R \approx (d^2 \eta/dx^2)^{-1} \rightarrow \infty \) especially for the case of flow with weak streamline curvature, \( C_2 \rightarrow 0, C_1 \rightarrow 0 \) and \( C_0 \approx 1.0 \). Under this flow condition, equation (4.5) degenerates to the equation of a hydrostatic bed pressure variation which is similar to the equation of the corresponding flow profile with a constant water surface slope.

For the case of flow over a broad-crested weir with \( H_1/L_w \leq 0.27 \), the crest bed pressure distributions show two distinct characteristics with delineating boundaries at
Figure 4.22: Bed pressure variation over the crest of a short-crested weir

$X \approx -0.80$ and $2.0$ (see Figure 4.23). In the flow region where $-0.80 \leq X \leq 2.0$, the normalised crest bed pressure value at any section is very close to unity regardless of the magnitude of $H_1/L_w$ and its nature is very similar to the nature of a hydrostatic bed pressure distribution. In fact the flow in this region does not possess any substantial flow surface curvature and the slope of the water surface is nearly constant throughout this region at different flow discharges. This implies the validity of the assumption of a hydrostatic pressure distribution at a control section (situated in this flow region) provided that $H_1/L_w < 0.32$. Unlike flow over a short-crested weir, the crest bed pressure (normalised) variation along the crest length is constant ($C_1 = C_2 \approx 0$).

For $X < -0.80$ and $X > 2.0$, the character of the crest bed pressure distribution resembles that of a short-crested weir. This is due to the fact that very close to the upstream and downstream edges of the crest of the weir the flow surface is curved (convex shape) so that the streamlines possess considerable curvatures. The crest bed pressure profile in this range has very steep slope near the edges of the crest of the weir. It is seen from this figure that for $H_1/L_w = 0.32$, the crest bed pressure distribution demonstrates the influence of the curvature of the streamlines. Even though it is difficult to determine the limiting value precisely based on experimental investigation, this value is very close
to the reported upper limit range of the character of the flow over a broad-crested weir (see e.g., French, 1978, #8.3). In both cases of flows (short- and broad-crested weir flows) the crest bed pressure is above the atmospheric pressure for the considered range of discharges.

**Minimum bed pressure**

Figures 4.24 and 4.25 show the variation of the bed pressure, the difference between the local pressure head and weir bottom elevation, along the horizontal length of the trapezoidal profile weirs. As discussed before, all bed pressure measurements were taken along the centreline of the weir profiles assuming that the variation of the bed pressure in the transverse direction is negligible. In both cases of flow over short- and broad-crested types of these weirs only one absolute minimum value of bottom pressure occurs at a tapping point near the downstream edge of the crest of the weir (see Figures 4.24 and 4.25). This is because of the supercritical flow which possesses higher value of centrifugal acceleration due to the effect of the negative curvature of the flow surface in the vicinity of the downstream edge of the crest of the weir. From these figures, the
influence of the overflow head to crest length ratio on the minimum bed pressure value is clearly seen.

![Graph showing bed pressure variation along the surface of a broad-crested weir](image)

**Figure 4.24: Bed pressure variation along the surface of a broad-crested weir**

The bed pressure variations for weir flow over smooth and rough beds are shown in Figures 4.26 and 4.27. Comparison of these figures reveals that the bed pressure distribution for rough bed flow shows a very steep pressure gradient near the flow region around the minimum bed pressure compared to the bed pressure distribution for flow over smooth boundary. For overflow head to weir crest length ratio greater than 0.29, the minimum bed pressure reading for rough bed flow is nearly constant (about 0.80 cm), independent of the increment of discharge (see Figure 4.27). In the case of flow over a smooth boundary, the minimum bed pressure value is between 2 to 2.4 cm depending on the value of $H_1/L_w$ ratio for flow with $H_1/L_w > 0.34$. The experimental result indicates that the effect of the roughness of the surface on the absolute minimum bed pressure is to reduce its magnitude. On the other hand, the variation of the bed pressure on the upstream and downstream faces of the weir models is similar in both cases of flow over smooth and rough boundaries.
Chapter 4. Experimental Work and Analysis

Figure 4.25: Bed pressure variation along the surface of a short-crested weir

Figure 4.26: Bed pressure variation for flow over smooth surface boundary
Figure 4.27: Bed pressure variation for flow over rough surface boundary

The non-dimensional minimum bed pressure, \( Y = \frac{p_{\text{min}}}{p_0} \) versus the overflow head to weir crest length ratio, \( X_c = \frac{H_1}{L_w} \) is shown in Figure 4.28. This figure also compares the minimum bed pressure for flow over trapezoidal profile weirs of different crest lengths. In all cases, the variation of the minimum bed pressure is approximated by a linear relationship. For the case of a long broad-crested weir, \( L_w \to \infty \) and therefore \( X_c \to 0 \). The extrapolated minimum bed pressure ratio for this condition approaches an average value of 0.40 for the three cases of weir flow situations. The result also shows the influence of the curvature of the streamline on the magnitude of the minimum bed pressure. For the considered range of flow, all the minimum bed pressure values are above the atmospheric pressure (see Figure 4.28).
Effect of roughness on bed pressure distribution

The variation of the bed pressure with discharge for flow over trapezoidal profile weirs with smooth and rough boundaries is shown in Figure 4.29. The average curves fitted to the experimental data and the position of the tapping point from the heel of the trapezoidal profile weir are also shown in the figure. The experimental bed pressure results for smooth and rough beds flow for the tapping points at $x = 4.03$ cm, $19.95$ cm and $42.99$ cm are almost identical, and the effect of the bed roughness is not clearly seen for the bed pressure readings at these tapping points. The bed pressure results of the other two tapping points show the influence of the roughness of the bed. At these tapping points, the bed pressure for flow over smooth bed is greater than for rough bed flow. These two tapping points are located very close to the upstream and downstream edges of the crest of the weir.

4.7.5 Flow surface profile analysis

The normalised flow surface profile for free flow over a short-crested trapezoidal profile weir with $H_1/L_w > 0.50$ is shown in Figure 4.30. In this figure, the normalised depth $Z(X) = H^*(X)/h_1$ is plotted versus the non-dimensional distance $X = x/h_1$, where
Figure 4.29: Bed pressure variation with discharge for free flows over trapezoidal profile weirs

$H^*(X)$ is the vertically measured flow depth above the crest for $x < 30$ cm, and above the bottom flow boundary for $x \geq 30$ cm ($x = 0$ cm is at the heel of the trapezoidal profile weir). The data can be described by a smooth average curve which starts at $Z(X \to -\infty) = 1$ and approaches asymptotically to a value of $Z(X) \approx 0.30$ for $X \to \infty$. The curve is almost symmetric about an average value $Z(X) \approx 0.65$ at location $X \approx 3.70$. For the flow condition considered here, this curve is defined by

$$Z(X) = 0.65 - 0.34 \tanh \left( \frac{X - 3.70}{1.81} \right).$$  (4.6)

It can be seen from Figure 4.30 that the approximate limit where the curvature of the upstream flow surface profile becomes negligible is at a location $X \approx -1$ or $h_1$ from the heel of the trapezoidal profile weir. Upstream of this section, the effect of the non-hydrostatic pressure distribution on the behaviour of the flow is insignificant. This indicates that this is the nearest section for the correct measurement of the overflow head of this type of wear under free flow conditions. For the considered range of $H_1/L_w$, all the experimental flow profile data are collapsed close to the average curve.
Chapter 4. Experimental Work and Analysis

4.8 Summary and conclusions

In this chapter, a brief description of the objectives, scope, test methodology and results of the experimental work of the thesis was presented. The precision uncertainties for the velocity measurements were determined using repeatability tests. Furthermore, the effects of surface tension and viscosity on the experimental results were analysed. For the considered range of test discharges, the analysis result confirmed that the scale effects on measurement results were negligible. Results of the analysis also demonstrated the impact of the curvature of the streamline on the distribution of the crest bed pressure as well as on the magnitudes of the velocity distribution coefficients.

An attempt was made to generalise the non-dimensional flow surface profiles for flow over trapezoidal profile weirs. For flow over such weirs with $H_1/L_w > 0.50$, the non-dimensional flow surface profiles with normalised coordinate $X$ are approximately described by the equation of the average curve, equation (4.6). The result also suggested that the nearest station for the correct measurement of the overflow head under free flow conditions is at a distance $h_1$ from the heel of the trapezoidal profile weirs.
The next chapter, Chapter 5, will discuss the discretisation of the flow equations using the finite difference discretisation method for the purpose of simulating flow situations with predominant non-hydrostatic pressure distribution effects. The solution procedure of the numerical model for solving such type of flow problem will also be described.
Author/s:
Zerihun, Yebegaeshet Tsegaye

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