THE INFLUENCE OF A DIP PLATE ON THE DISCHARGE OF WATER OVER A SHARP CRESTED RECTANGULAR WEIR

by

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'I will treat of such a subject. But first of all I shall make a few experiments and then demonstrate why bodies are forced to act in this manner.

This is the method that one has to pursue in the investigation of phenomena of nature. It is true that nature begins by reasoning and ends by experience; but, nevertheless we must take the opposite route: as I have said, we must begin with experiment and try through it to discover the reason.'

Leonardo da Vinci
Dip plates (sometimes referred to as scum plates) are used with increased frequency upstream of weirs in drainage systems in order to separate sewage from clean, rain (storm) water and in streams and canals to protect the weir structure from floating debris. However, there is a marked lack of information on the effect that introduction of these structures has on the discharge over a weir. The present investigation was initiated in an attempt to rectify that situation.

The problem was tackled both experimentally and analytically.

Apparatus used for the experimental part of the investigation consisted of a suitably modified laboratory test channel 24 inches (609.6 mm) wide, in which additional measuring stations were introduced.

Modifications of channel geometry consisted of designing and building a weir dip plate assembly which enabled the distance between the two plates to be varied. False side plates were also introduced and suitable adjustable fittings designed so that the ratio of channel/weir width could be pre-set as required. Tests were carried out at three values of that ratio; these were 1/1, 1.6/1 and 2.4/1.

Water surface level was measured at various points both upstream and downstream of the dip plate. Measurements of flow velocities were also carried out. In positions where the velocities were small and the use of pitot tubes resulted in inadmissibly low readings of manometers, a specially designed velocity meter based on the principle of drag on a sphere was used.

Altogether 107 calibrations of the weir with the upstream head ranging from zero to 7 inches were carried out.

The distance between weir and dip plates was varied from ½ inch to 5 inches. The depth of immersion of the dip plate varied from the bottom edge of the plate level with the sill of the weir to 4 inches below it. The width of the weir was 10 inches (254 mm).
In addition to depth and velocity measurements, the pattern of flow both on the surface and within the body of the fluid was observed. Visualisation of surface currents was done by sprinkling coloured perspex filings on to the water surface. Deep currents could be seen by observing the motion of small polystyrene beads dropped into the flow.

Further indication of the flow pattern was obtained from tracings and photographs of motion of the beads in a narrow glass sided flow visualisation flume.

As a first approach to the analytical solution of the problem of discharge over a weir provided with a dip plate, a unidimensional approximation was applied.

The flow through dip plate - weir configuration was considered to be equivalent to a flow which first passes through a drowned orifice and then over a weir. The head downstream of the orifice (formed by the dip plate) acts at the same time as the upstream head of the weir. Bearing in mind that the rate of flow is the same through both devices, a relationship determining the value of the head downstream of the dip plate in terms of the upstream head and the channel - dip plate - weir configuration is established (equation 3.12). Substitution of this expression into the conventional equation for a rectangular weir gives a prediction of a rate of flow over the weir (equation 3.13).

The flows calculated using the analytically deduced equation and based on the assumption of the coefficient of discharge for the weir, equal to unity, are compared with the experimentally obtained results. The correlation between the two sets of results is such that it only requires an introduction of a constant value coefficient of discharge (independent of the variation of upstream head) in order for the calculated values to fall within the band of uncertainty of experimental results. The values of the coefficient, dependent on the dip plate - weir plate configuration,
are all found to fall numerically in the range accepted (BS 3680) for the coefficients of discharge for sharp crested rectangular weirs. The variation in the value of coefficient is observed and discussed.

The investigation thus resulted in providing a method of prediction of the rate of flow over a rectangular sharp crested weir fitted with a dip plate. It has also indicated a method of approach to any similar problem.

In addition, the change in a flow pattern resulting from the introduction of a dip plate was studied and discussed.
ACKNOWLEDGEMENTS

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Thanks are due to Mr. J. Lorek for his willing, meticulous and precise manufacture of modifications to the experimental apparatus; to Mr. E.H. Wilson in recognition of fruitful discussions and helpful, friendly criticism of the manuscript.

To all friends and colleagues, too numerous to mention by name, who by their assumptions have kept the work going, a very sincere thank you.

And last but not least thanks are due to Miss C.M. Hunter for typing and checking the manuscript.
LIST OF SYMBOLS

A    a coefficient (defined in equation (3.8))
A_s  projected frontal area of sphere
B    width of approach channel
b    width of weir
b_e  effective width of weir
C    a coefficient
C_D  coefficient of drag of a sphere
C_p  coefficient of drag of a sphere
C_o  discharge coefficient of orifice
C_w  discharge coefficient of weir
D    height of sill of weir above channel bottom
D_s  drag of sphere
d    depth of immersion of dip plate
d_s  diameter of sphere
f    a function
g    gravitational acceleration
H    head upstream of dip plate
H_e  effective head
h    head downstream of dip plate
h_v  dynamic head
K    a coefficient
n    number of end contractions
p    pressure
Q    volumetric rate of flow (discharge)
R_s  resultant force on sphere
R_e  Reynolds number
U    velocity of flow
v    velocity component
W_e  effective weight of sphere
LIST OF SYMBOLS (continued)

$x_s$ horizontal displacement of sphere

$\rho$ density of water

$\mu$ dynamic viscosity coefficient

$\nu$ kinematic viscosity coefficient
1.0  

INTRODUCTION

Dip plates, sometimes referred to as scum plates, are placed upstream of a weir with the primary object of protecting the weir from debris floating downstream. This protection is of dual nature. On the one hand a large and thus heavy object moving at high velocity might, when striking the weir, damage its structure; on the other, light objects floating on the surface might get wedged in the weir passage and form obstructions to the free discharge of water.

Dip plates are most commonly used in sewer structures where the additional service they can perform is the separation of the heavy sewage, moving at the bottom of the channel from the light refuse floating on or near the surface of the flow. Heavy sewage will be directed into passages constructed at the base of the weir plate. Light debris is usually allowed to discharge over a side weir situated upstream of the dip plate and almost clean water will flow over the weir plate (61). In other configurations, which utilise the formation of secondary currents at the bends of the channels, side weirs, provided with dip plates and orifices, placed below the side weirs, are used for the purpose of separating relatively clean storm water from common sewage (20, 49).

However, dip plates are also used, positioned upstream of flow measuring weirs, in small streams and non-navigable channels constructed for conveying water.

Flow measuring procedures and formulae used with rectangular sharp crested weirs are well documented and do not present any difficulty. However, the situation changes radically if a dip plate is introduced upstream of the weir. The effect of its presence on the rate of flow over the weir was either not considered at all, or the assumptions used were completely hypothetical and unconfirmed by experimental evidence (1).
This absence of reliable information was first noticed by the author when working on the problem of utilisation of secondary currents generated in bends of a channel to the separation of storm water from conventional everyday sewage. It was with an idea of at least partially filling this deficiency of data that the present work was started.

It is unfortunate that at only a slightly later time the author was introduced to and became involved in an extremely absorbing and interesting field of fluid mechanics in the form of haemodynamics, 'for after all blood is a liquid'. As a result of the introduction of this sideline, which soon developed into a mainstream of interest, the present investigation was relegated into the background and thus its completion took considerably longer than originally intended.

It was decided from the start to approach the problem both experimentally and analytically.

No special grant was applied for to carry out the investigation; consequently most of the experimental work was done using the standard laboratory equipment with only the minimum of modifications. Similarly, standard instruments with only some adaptations were used for measurement. A noteworthy exception in the last category consisted of the 'drag on a sphere' velocity measurement system. These instruments did not form a part of laboratory instrumentation but were conceived and constructed in an attempt to measure low velocity values in the approach channel.

The basis of the apparatus was the weir calibration channel, provided with a specially constructed weir dip plate assembly and additional channel sides. This last addition was made in order to be able to perform experiments at various ratios of approach channel to weir width.

Ideally the analytical and experimental work should be developed simultaneously so that the results of one are supported by findings of the other. The present investigation was limited in this respect by the
necessity to finish all the experimental work before a fixed deadline. This was due to the moving of the laboratory. In addition, only some of the laboratory apparatus was to be transferred. Some equipment, including the experimental flume, used for the present investigation, was to be dismantled and not moved to the new site.

The experimental programme had thus to be given priority over all other considerations. Theoretical analysis of the phenomenon had to be postponed and experiments had to be planned almost before the results of the previous findings could be thoroughly analysed. This resulted in a slight imbalance in the experiments. Some of the findings and trends of results may seem to be overemphasised while others have to be looked for. The expected, predictable variation could be planned for without much trouble. However, at all times the changes in configuration had to be arranged in such a way that, if an unexpected finding arose, close analysis at a later date could confirm its validity. The easiest way out of the dilemma would have been to test all the possible configurations; unfortunately this would have resulted in over five hundred calibration runs, each taking a working day. With the time limitation of slightly over one hundred and twenty days this was an impossible and unnecessary task.

The final experimental programme consisted of 107 calibration runs covering three values of the ratio of the width of weir to the width of approach channel.

A full range of the distances between the weir and dip plate, together with a variation of the depth of immersion of the latter, were investigated. The whole range of values was covered in both cases; however individual values were chosen in such a way that possible non-dimensional relationships could be easily established.

The dip plate was positioned both with the chamfered edge facing upstream and downstream. Again only some of the configurations originally
tested with the chamfered edge of the dip plate facing downstream (side A) were subsequently tested with the dip plate in the reversed position (side B).

A variable, the effect of which was not considered, was the size of the passage between the lowest edge of the dip plate and the bottom of the channel. This passage, when its size is smaller than that of the cross-sectional area between the dip and the weir plate, would constitute one of the controlling sections of the flow. It was expected that the effect of the two sections (below the dip plate and between dip and weir plate) would be identical, both acting as an equivalent drowned orifice. The controlling action would be taken over by which ever of the two is the smaller. It would have been interesting to have this assumption proven experimentally. This, however, is of completely academic interest and has no practical value whatsoever.

Whether in a front or a side weir configuration, the action of a dip plate is confined to the upper portion of the channel or stream and thus the depth of immersion of the plate will be relatively small. The passage below the plate will therefore be of a larger cross-section than the one between the dip and weir plate. It will be an extremely rare instance in which the distance between the two plates will exceed that below the dip plate. In this rare case the distance between the two plates will be sufficiently large for the effect of the dip plate to be so small, that the weir could be considered to be flowing free. Thus the head just downstream of the dip plate would be practically equal to that in the approach channel.

Considered analytically, the flow in the dip plate - weir configuration was assumed to be equivalent to that through a drowned orifice followed by discharge over a weir. This assumption was not dependent on whether the passage between the two plates, or that below the dip plate, formed the drowned orifice.
Although of only an approximate nature, the analysis by unidimensional flow approach produced a good estimate of discharge. Various factors dependent on configuration could be and were included in the formulae which were deduced analytically. The calculated results were compared with the values obtained experimentally. The correlation between the two sets was of a good order.

Although the primary object of the investigation was the calibration of the weir under various dip plate configurations, qualitative analysis of the phenomenon was also carried out. This considered the effects which could not be included in the development of the head and discharge relationships. These unaccounted for factors included the effect of the depth of immersion of the dip plate, side flows in the case of a weir with unsuppressed end contractions and the effect on flow resulting from the reversal of the chamfered edge at the bottom of the dip plate.

Most of the factors mentioned above affect primarily the intensity and extent of one or more of the three regions of the separated flow, generated by the dip plate - weir plate configuration. Two of these regions occur at the water surface on either side of the dip plate, the third at the bottom of the channel immediately upstream of the weir plate. Any attempt at an analytical treatment of the separated flows is subject to numerous, extensive assumptions. At this stage its inclusion was not considered helpful in an analytical solution for the estimation of the rate of flow through a weir provided with a dip plate. Nevertheless a qualitative analysis of the phenomenon was carried out.

When manufactured, the apparatus and the modifications were dimensioned in the foot, pound, second system of units. The measuring instruments, surface point depth gauges and weighing machine were calibrated and inscribed in the same units. The only exceptions were the scale of the manometer used in conjunction with the pitot tube and the scale of the
travelling telescope used to observe the displacement of the sphere in the drag-on-sphere velocity meter. These were calibrated in centimetres.

As a consequence of the above facts it was more convenient to work and display the results in foot (inch), pound units. However, in a number of instances 'rounded off' values are given in S.I. Units.

The symbols used in the analytically deduced formulae are the same throughout the work.
2.0 REVIEW OF PREVIOUS WORK

2.1 Rectangular Sharp-edged Weirs

The sharp crested weir is the oldest form of the flow measuring device for an open channel, antedating the broad crested weir by over a hundred years and a venturi flume by almost two hundred years.

Like so many inventions and constructions the first recorded trace of a sharp crested weir appears in the sketches of Leonardo da Vinci (1503) (Fig. 2.1 a and b). It seems, however, that Leonardo intended that the device would be used not as a flow measuring apparatus but as a separator of immiscible fluids. This assumption is based on, if not confirmed by, the words 'olio' and 'aqua' written on the two regions of flow in Fig. 2.1a.

The first analytical treatment of the flow over a sharp crested rectangular weir is due to Giovanni Poleni, who in his 'De moto aque mixto' published in 1717 indicates a solution of the problem. Poleni has divided the area of the weir into a number of horizontal strips and assumed that the velocity of flow through each strip is proportional to the square root of its distance from the free surface of the flowing fluid. The rate of discharge is then represented by the area of the parabolic velocity curve drawn between the sill of the weir and the free surface of the fluid. Thus:

\[ Q = \left(\frac{2}{3}\right) h b \sqrt{f} \]  

(2.1)

where \( f \), assumed proportional to \( h \), is referred to as 'velocity function'.

Jean C. Borda in his 'Memoire sur l'ecoulement des fluides par les orifices des vases' published in 1766 was the first to use the proportionality factor of '2g' in flow relationship. This finding was used by Pierre Du Buat who amplified Poleni's analysis in his work 'Principes d'hydraulique' published in 1786. He used the expression for the velocity of flow in the form \( u = \sqrt{2gh} \), thus modifying the 'strip integration' formula to the now accepted form of:

\[ Q = \left(\frac{2}{3}\right) b h \sqrt{2gh} \]  

(2.2)
Sketch by Leonardo of flow over a contracted weir.

Fig. 2.1 a

Surface profile at a free overfall.

Fig. 2.1 b
He further noticed that due to the vertical component of velocity at the bottom of the weir, the totally horizontal flow occurred at a contracted section some distance away from the plane of the weir. Consequently he assumed that the integration should extend from the top of the free water level to the bottom of the nappe at the contracted section. According to du Buat's observations the thickness of the nappe was equal to about half the head of liquid in the plane of the weir. Thus when integrated within these limits the resulting equation for the rate of flow over the weir became:

\[ Q = 0.65 \left( \frac{2}{3} \right) b \left( \frac{h}{2g} \right) \]  

(2.3)

This last modification is equivalent to the introduction of a coefficient of discharge of a value \( Cd = 0.65 \) into the modern form of the equation written as:

\[ Q = Cd \left( \frac{2}{3} \right) b \sqrt{2gh} \]  

(2.4)

Apart from introducing in a justifiable way a numerical value of a coefficient of discharge due to contraction of the nappe, du Buat was first to propose that the flow over a submerged weir be treated as a combined sum of flow over a free weir in its upper region and through a submerged orifice in the lower strata. This proposal seems to have been a direct result of du Buat's interest and his solution of the flow from under a sluice gate.

Giorgio Bidone, professor of hydraulics at the University of Turin, was the first to investigate the profile of the free water surface and to attempt to describe its shape in mathematical terms.

In his work on discharge over broad crested weirs J.B. Belanger introduced in 1849 the concept of minimum energy for a given rate of flow. Although not interested in the problem of flow over sharp edged weirs himself, his concept of maximum discharge for the given upstream conditions was applied to sharp edged weirs by a number of later workers.
The first attempt to introduce the effect of velocity of flow of water in the approach channel into the expression for the discharge over a sharp crested weir is due to Julius Weisbach.

The equation:

\[ Q = \left( \frac{2}{3} \right) C_d \sqrt{2g} b \left[ (h + \frac{u^2}{2g})^{\frac{3}{2}} - (\frac{u^2}{2g})^{\frac{3}{2}} \right] \quad (2.5) \]

which he deduced in 1841 was obtained by changing the limits of integration of the modified Poleni equation to include the kinetic head due to the velocity of flow in the approach channel.

Unfortunately, as the velocity of the approach \( u \) is a direct function of the unknown value of the rate of discharge \( Q \), equation (2.5) has to be solved using successive approximation techniques. Without the use of a computer this method of flow prediction is extremely involved and time consuming. In order to avoid this complicated method of calculation, Weisbach finally adopted an equation deduced empirically:

\[ Q = \left( \frac{2}{3} \right) C_d \left[ 1.04 + 0.37 \left( \frac{h}{h+D} \right)^2 \right] \sqrt{2g} b \left( \frac{h}{h+D} \right)^{\frac{3}{2}} \quad (2.6) \]

where \( D \) is the height of the sill above the bottom of the approach channel.

This empirical expression can be considered to be the first of a long family of experimentally deduced equations in which the numerous effects influencing the rate of flow are taken into account by introduction of various geometrical ratios.

A very complete and thorough investigation of flow over sharp crested weirs was undertaken by Henri Emile Bazin, some of whose results, published in 1888, are still used as design criteria when constructing flow measuring weirs. Bazin investigated the shape of the nappe by determining the coordinates of the top and bottom surfaces, measured the pressure and velocity distribution within the free falling nappe. He also established an empirical discharge equation in the form first suggested by Weisbach:
Bazin limited his experimental investigations to the weirs in which the width of the approach channel was equal to that of the sill of the weir (suppressed weirs). He carried out experiments both with the nappe discharging freely over the sill of the weir and with the downstream water level above the level of the sill (drowned weir conditions).

In contrast to Bazin, whose contribution to fluid mechanics is primarily empirical, his contemporary Joseph Boussinesq, professor at the Sorbonne from 1885, concerned himself almost exclusively with the analytical approach to the subject. His contribution to the problem of flow over sharp crested rectangular weirs was centred on an attempt to deduce an expression for the rate of flow.

Boussinesq approached the problem by considering the nappe discharging over the sill of the weir. He assumed that at the plane of contraction (the vena contracta) where the direction of velocity is horizontal throughout the nappe, the streamlines may be considered to form a series of concentric circles with a velocity distribution equivalent to that of a free vortex. The velocity at the lowest point he assumed to be that corresponding to the stagnation value of the hydrostatic pressure. After integration of the resulting expression, an equation for the rate of discharge is obtained, which includes the geometrical co-ordinates of the nappe.

With the introduction of Belanger's concept of maximum rate of flow through a section and Bazin's geometrical findings, Boussinesq obtained the following expression for the rate of discharge:

\[ Q = (0.405 + \frac{0.003}{h}) \left[ 1.0 + 0.55\left(\frac{h}{h+D}\right)^2 \right] \sqrt{2gh} \frac{h^{3/2}}{b} \]  

Equation (2.7)

The value of the numerical factor in equation (2.8) is equivalent to the introduction of a coefficient of discharge whose value is constant at all heads and equal to \( C_d = 0.6345 \).
Theodor Rehbock, during the tenure of his appointment as Professor of Hydraulics at the Polytechnic Institute at Karlsruhe, initiated building of a modern laboratory including the installation of a glass-sided flume which was used both for teaching and demonstration experiments as well as research investigations.

During the period between 1911 and 1929 an exhaustive series of experiments relating to the sharp crested rectangular weirs were carried out. Rehbock introduced numerous refinements to the empirical expressions used for prediction of rate of flow through the weir. This was made possible by the accuracy and care taken during performance of experiments. He paid particular attention to the turbulence and eddy currents caused by the separation of flow due to the introduction of the weir. The effect of both the bottom and the side contraction was studied, although both his formulae, one deduced in 1913 and the other published in 1924, relate to the full channel width weir.

The problem of the effect of side, sometimes referred to as end, contractions was very thoroughly investigated by J.B. Francis, who during the period 1848 to 1852 took an active interest in establishing a valid discharge formula for this type of weir. Besides carrying out a number of experiments himself, Francis included in his analysis results obtained by Poncelet and Lesbros in 1828 and 1834. At first he assumed the validity of the equation in the form:

\[ Q = K b h^n \]  

(2.9)

with both \( K \) and \( n \) constant. In the first series of investigations he found that \( n \) could be assumed to be a constant \( (n = 1.47) \). The value of \( K \) however was found to be dependent on the approach channel - weir configuration and in addition was also dependent on the value of head over the sill. Not satisfied with these findings Francis continued with his experiments and finally established the equation which has become commonly
associated with his name, i.e:

\[ Q = 3.33 \left( b - \frac{n}{10} h \right) h^{\frac{3}{2}} \]  

(2.10)

where \( n \) is the number of end contractions. The numerical value of the coefficient, viz: 3.33, makes the equation applicable to the foot-pound-second system of units only. In a more general way Francis' formula can be re-written as:

\[ Q = 0.622 x \left( b - \frac{n}{10} h \right)^{2/3} \sqrt{\frac{2g}{h}} h^{\frac{3}{2}} \]  

(2.11)

which can be used in any system of units.

Francis carried out his experiments in a channel almost 14 ft wide, provided with weirs with the length of sill of 4 ft and 10 ft. Heads were varied between 0.62 ft and 1.55 ft. The results were published in 'Lowell Hydraulic Experiments', the first edition of which appeared in 1855 and which also included the work on the turbine which has since become known by his name. The weir was used to measure the discharge through the turbine, the method used as a standard for a number of years.

The structure of the equation for the flow rate through a weir with the end constrictions originated by Francis was used by Fteley and Stearns (28). During the period 1877 to 1879 they experimented with two sharp crested weirs, varying the head over the sill from 0 to 1.6 ft. In the equation deduced they take into account both the effect of end contractions and the velocity of flow in the approach channel:

\[ Q = 3.31 b_e H_e^{1.5} + 0.007 b \]  

(2.12)

In their equation Fteley and Stearns introduced two new concepts. These are the effective width of the weir \( b_e = (b - 0.1nh) \), the same value as previously used by Francis, and effective head \( H_e = h + 1.5h_v \) where velocity head \( h_v \) is the dynamic head due to the velocity of flow in the approach channel.

Further modification of the Francis equation is due to Hamilton Smith Jnr who published the results of his investigations in 1886. The
main difference between the Francis and Hamilton Smith formulae is the magnitude of the 'side effect' correction which in the latter is almost halved. The Hamilton Smith formula for the weir with two end contractions is:

\[ Q = 3.29 (b - 0.1 H_e) H_e^{1.5} \]  

(2.13)

The value of the 'effective head' is also changed when compared with Fteley and Stearns, for in (2.13) \( H_e = h + 1.4 h_v \).

The Hamilton Smith formula with further additions and refinements in the calculation of the numerical values of coefficients forms a basis for the British Standards rectangular weir formula.

It may be noticed that at about this time the attempts at new analytical solutions for the rate of flow through rectangular shaped weirs became rarer; the investigators concentrating on the improvement of the accuracy of the coefficients of the original Poleni equation, which becomes expressed in the generalised form of:

\[ Q = C_d b_e \left( \frac{2}{3} \right) \sqrt{2g H_e} H_e^{3/2} \]  

(2.14)

The effort of improving the accuracy of the rate of flow prediction has proceeded along two distinct paths. Some of the investigators concentrating on the simplicity of the expression will use a single numerical coefficient and will fix rigid limits, in terms of head to width ratios, head values, etc., within which those values may be applied. In some cases the variation in value of the coefficient is shown in the form of a series of graphs, in others tabular method of presentation is preferred.

In contrast, a number of workers have followed the approach initiated by Weisbach, and have attempted, with a varying degree of success, to deduce equations which with a good degree of accuracy would be applicable to a large range of heads and geometrical approach channel - weir plate configurations.
The effect of configuration is usually taken into account in the form of a function of ratio of dimensions in which the variation of head is also included. But even with the inclusion of these effects and consequent complicated form of the equation, the range of both the heads and weir widths over which the flow can be predicted accurately is strictly limited. Use of such equations outside the specified range may result in large errors. In some extreme cases the predicted flow may even be negative, a physical impossibility.

This second method of representation was very popular for some years and a number of involved equations were deduced and used (Table 2.1).

It is not unusual to find that the investigators have based their formulae not only on the results of their own experiments but have also included the findings of the previous workers. Thus Schoder and Turner (59) in addition to 1275 separate measurements of their own have included the results from 1162 experiments carried out by other investigators.

The various National Standards formulae were also deduced by compilation of the results of a number of investigators, and are usually based on one of the previously established formulae suitably augmented in accuracy. The formula of the Swiss Society of Engineers and Architects, used as a standard in many European countries is similar in type to the expression of Weisbach. Its coefficient of discharge incorporates a number of geometrical ratios of channel-weir widths and heights of the sill above the channel bottom, thus taking into account the effect of velocity of approach and of end contractions.

In the British Standards formula the validity of the Hamilton Smith expression is assumed for the case of flow through weirs with end contractions and of the Rehbock equation for a suppressed (full width) weir. In addition, the range of head to width of weir ratio over which the formulae are applicable is strictly defined. For the calculations involving work
outside these limits an alternative expression based on the Kindsvater and Carter equation, with tabulated values of coefficients, has to be used.

The Kindsvater and Carter equation, with only minor modifications, also forms the basis of the United States Bureau of Reclamation (USBR) formula, which is a 'de facto' American Standard.

The work by Kindsvater and Carter (39, 40) is probably the most comprehensive analysis to date of the investigations of sharp crested rectangular weirs. After analysing both the experimental data and the empirically deduced expressions of previous investigators, the authors start with the generalised Polen equation (2.14). They attempt to establish expressions for the effective length (width) of the crest, effective head and the discharge coefficient. The expressions were established by a semi-empirical method, the flow being first analysed by means of a dimensional analysis and the relevant factors included in the equations.

More recent work is no longer concerned with the establishment of rate of flow expressions. The experiments are directed towards studies of the nappe with two aims in view, one a possibly more rigid and elegant analytical treatment of flow - on the lines of approach taken by Boussinesq; the other directed towards the shaping of the crest of the overflow to the contours of the discharging nappe. This last approach may result in a 'narrow-crested-curved-topped' weir, the discharge characteristics of which could finally, within a narrow range of heads, be superior to both the broad and sharp crested types (32, 35, 45, 58).
### TABLE 2.1

**Some Expressions for Coefficient of Discharge**

<table>
<thead>
<tr>
<th>Expression</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Du Buat</td>
<td>0.65</td>
</tr>
<tr>
<td>Weisbach</td>
<td>( C_d \left[ 1.04 + 0.37 \left( \frac{h}{h+D} \right)^2 \right] )</td>
</tr>
<tr>
<td>Fteley &amp; Stearns</td>
<td>( 0.623 (1 + 1.5 \frac{h}{H})^{\frac{3}{2}} + \frac{0.007}{H^{\frac{3}{2}}} )</td>
</tr>
<tr>
<td>Bazin</td>
<td>( (0.6075 + \frac{0.0045}{h}) \left[ 1.0 + 0.55 \left( \frac{h}{h+D} \right)^2 \right] )</td>
</tr>
<tr>
<td>Frese</td>
<td>( (0.5755 + \frac{0.017}{h+0.18} - \frac{0.075}{b+1.2}) \left{ 1.0 + \left[ 0.25 \left( \frac{b}{B} \right)^2 + 0.025 \frac{0.0375}{(h+w) + 0.02} \right] \left( \frac{h}{h+w} \right)^{\frac{3}{2}} \right} )</td>
</tr>
<tr>
<td>Hansen</td>
<td>( 0.616 / \left[ 1 - 0.358 \sqrt{h^3} \right] )</td>
</tr>
<tr>
<td>Rehbock</td>
<td>( (0.6035 + 0.08 \frac{h}{D} + \frac{0.00099}{D}) (1 + \frac{0.0011}{h})^{\frac{3}{2}} )</td>
</tr>
<tr>
<td>Von Mises</td>
<td>( \frac{\pi}{h+2} = 0.611 )</td>
</tr>
<tr>
<td>Tieplow</td>
<td>( (0.607 + \frac{3.0}{520h+20}) \left[ 1 + 0.55 / (1 + \frac{D}{h})^2 \right] )</td>
</tr>
<tr>
<td>Hamilton Smith</td>
<td>0.615 (1 - 0.1 \frac{h}{B})</td>
</tr>
<tr>
<td>King</td>
<td>( 0.624 \left( \frac{1.0}{H+0.5} \right) \left[ 1 + 0.56 \frac{H^2}{(w+h)^2} \right] )</td>
</tr>
<tr>
<td>Soc. Swiss Eng. Arch.</td>
<td>0.615 ( \left[ 1 + 0.5 \left( \frac{h}{h+0.5} \right)^2 \right] )</td>
</tr>
<tr>
<td>or</td>
<td>( \left[ 0.578 + 0.037 \left( \frac{b}{B} \right)^2 + \frac{3.615 - 3\left( \frac{b}{B} \right)^2}{1000h - 1.6} \right] \left[ 1 + 0.5 \left( \frac{b}{B} \right)^4 \left( \frac{h}{h+D} \right)^2 \right] )</td>
</tr>
</tbody>
</table>
2.2 Narrow Rectangular Notches

An almost separate field of study is formed by the narrow notches, i.e., weirs in which the width of the crest is not only much smaller than the width of the approach channel, but also where the head/width ratio exceeds unity. This type of weir is normally used to gauge small rates of flow, quite often of liquids other than water, and thus is of only limited interest. It therefore falls outside the range usually covered by national or international standards. In this field of study the investigation by Burnell (11) led to the establishment of a formula which in its structure is similar to that established by Francis for the wide weirs.

Burnell, after analysing the experimental results of a number of investigators, proposed two expressions; one which would cover the conventional range of weirs with a width/head ratio greater than 2.0, the other for the non-standard weirs in which the above ratio is smaller than 0.5. For this latter range Burnell proposed the equation:

\[ Q = 3.29 \beta (h - 0.1 \beta) h^{1/2} + 0.01 h \]  

(2.15)

The numerical coefficient 3.29 of the above equation requires the use of foot-pound-second system of units. In order to make the equation applicable to any system of units, it has to be re-written in the form:

\[ Q = 0.615(2/3)^{1/2} \sqrt{2g} \beta (1-0.1 \frac{\beta}{h}) h^{1.5} + 0.0093 h \]  

(2.15a)

The author of the present investigation (72) has carried out a series of tests on a number of narrow weirs with a head to width ratio of \(0.2 < \frac{H}{b} < 8.5\) and has found that a much better correlation of the Burnell formula with the experimental results would be obtained had the correction for the effective width of the weir (0.1 \(\frac{b}{h}\)) been halved. His own proposal is of a simplified formula of the form:

\[ Q = 0.616(2/3)^{1/2} \sqrt{2g} \beta H^{1.5} \]  

(2.16)
2.3 Sharp Crested Rectangular Weirs with a Dip Plate

A study of the effect of the dip (scum) plate on the flow is also a relatively recent development. Dip plates may be introduced into the stream for a number of reasons. In some cases the object of their introduction is the division of the stratified flow (10, 30, 31). In others, when the plate is installed in sewage stilling basins, the reason for its introduction is the rejection of the suspended particles of sewage from the otherwise clean rain water (1, 20, 49). Finally, in a number of cases a sturdy dip plate will be placed upstream of a delicate weir plate so as to protect it from the heavy particles and debris carried by the current.

Whatever the reason for placing the dip plate upstream of the weir, its presence will affect both the rate and the configuration of the flow over the weir.

A limited number of publications which have appeared on the subject of dip plates have not analysed their effects on flow, but have considered the efficiency of flow separation.

Sharpe & Kirkbride (61) have investigated the efficiency of sewage separation in a stilling pond. Their plywood model was provided with a weir over which the 'clean water' could flow and below which the 'dirty sewage' pipe (throttle pipe) was placed. The inflow to the open topped pond was by means of a pipe (sometimes not running full). Both the dip plate and the weir plate extended over the whole width of the pond. A diagrammatic sketch of the apparatus is shown in Fig. 2.2. The stilling pond can be considered to be equivalent to a very short approach channel.

The tests were carried out using water into which simulated sewage was introduced. The variation of density of sewage was obtained by use of wooden beads with various size holes filled with lead or paraffin wax. In this way a relative density range of 0.9 to 1.2 was covered.
Fig. 2.2

Fig. 2.3
The authors distinguish six types of flow (see Fig. 2.3), one of which is produced by the introduction of a second dip plate. The effectiveness of the configuration was correlated to the degree to which the flow was divided into the heavy sewage swept into the throttle pipe, clean water allowed to flow over the weir and the light sewage retained on the surface of the stilling pond.

In his theoretical work on the discharge through the side weirs Ackers (1) introduces the effect of the dip plate, but considers only the case where the distance between the dip and weir plates is very small compared with the head of liquid over the sill of the weir (h).

Ackers assumes that under these conditions the discharge will not be proportional to the head raised to the power of 1.5 (ie: $h^{3/2}$) but will be equivalent to the flow through an orifice. It is thus proportional to the area of the passage multiplied by the square root of the head (ie: $A h^{1/2}$).

Prus-Chacinski and Wielogorski (49) have introduced a dip plate in their design of the storm water overflow system, but no analytical solution was attempted. The dip plate in this design of an S-shaped channel (Fig. 2.4) provided with a side weir over its length was utilised as a flow separator and a device to stop the floating debris and sewage from discharging over the weir. The principle of operation was that the secondary currents initiated at the bend of the channel caused the overflow of clean storm water over the weir while the sewage was discharged along the channel.

Bradley and Peterka in their very exhaustive study on stilling basins mention the use of dip plates not only as a flow separator but also as an energy dissipation structure (10).

The use of dip plates in stilling basins and overflows is mentioned in other publications (13, 61, 66). In all analytical approaches, the assumption of rate of flow proportional to the square root of head is taken.
Fig. 2.4 a

Fig. 2.4 b

α₂ Angle of direction of flow near lea
α₁ Angle of direction of flow near surface
O Outer wall
I Inner wall
vₗ Radius component of velocity
A dip plate or a skimmer wall situated far away from the weir was also utilised (30, 31, 71) to separate stratified fluids of varying density. This density variation might be due to the different salinity (50) of water or to the variation in temperature, as in the discharge channels from power stations.

No analytical solutions were attempted and the empirical findings are of a qualitative rather than quantitative nature. They are all limited to dimensional and similitude analyses (60), all too often based on experimental evidence applicable to only a limited range of conditions.
3.0 **ANALYTICAL CONSIDERATIONS**

3.1 **Introduction**

All the investigations into the effect of introduction of a dip plate into the flow, upstream of a weir, were so far limited to purely experimental findings (20, 49, 60, 61, 71). In addition no comparisons were made with the flow configuration without a dip plate. The only attempt at a prediction of the rate of flow is by Ackers (1) who states intuitively that if a dip plate is situated at a very small distance from the weir of sill length $b$, and is working under an upstream head $h$, the rate of flow which originally could be expressed by:

$$Q_w = C b h^{3/2}$$

where $C$ is a numerical coefficient, will have to be modified to:

$$Q_w = C_d l b h^{1/2}$$

where $C_d$ is a new value of a coefficient and $l$ the distance between the dip and weir plate.

In effect Ackers, by proposing the above formula, considers that the introduction of the dip plate will change the performance of a weir into that of an orifice.

Even with Ackers' assumption of a very small distance between dip and weir plates, the final form of the equation seems to be suspect, as the orifice would operate under drowned conditions.

There is therefore a need for a completely new analysis, which would take into account as many factors influencing the flow as is practicable. In a similar way to the studies of freely flowing weirs, two ways of approaching the problem are possible. One is to develop a complete all-embracing equation; the other, more conventional, is to first deduce an expression based on the unidimensional approximation and then introduce correction coefficients, based on the dimensional analysis and experimental findings.
As the present work forms the first attempt at formulating a rational expression for the rate of flow, the second method of approach to the problem - that of first establishing an approximate unidimensional expression - has been chosen.

3.2 Unidimensional Flow Analysis

The steady turbulent flow over a rectangular sharp edged weir, provided with a dip plate, may be schematically represented in Fig. 3.1.

![Fig. 3.1](image)

The depth of water flowing in the approach channel measured above the sill of the weir is \( H \). After passing under the dip plate the depth decreases of \( h \) and this is the effective head of water flowing over the weir.

The distance between the weir and dip plate is \( l \) and the latter is immersed to the depth \( d \) below the level of the sill, which is situated at height \( D \) above the bottom of the channel.

The flow may be considered to pass through a number of devices situated in series, each of which may be able to govern the rate of flow, thus in effect becoming a 'control section'.

Moving in the direction of flow these possible control sections will be:

(a) The section below the dip plate; the cross-sectional area of the section \( [(D - d) \times B] \), where \( B \) is the width of the approach channel and \( D \) and \( d \) as shown in Fig. 3.1. This section will behave as a 'drowned orifice' acting under the effective differential head \( (H - h) \).
(b) The passage between the dip and weir plate; the cross-sectional area of the passage is \( 1B \) (in the same notation as above) and the section will behave as a drowned orifice under the action of differential head \( (H - h) \).

(c) The passage over the weir; here there are two possible alternatives, the existence of which depends on whether the width of the channel is the same or larger than the width of the weir passage.

In the first case, ie: if \( B = b \), the action of the weir will be that of the suppressed (full width) type, the effective head being equal to \( h \). If the width of the channel is larger \( (B > b) \), the weir will be of a fully contracted type. The difference in the flow rate formula for the two cases is accounted for in the value of discharge coefficient.

The relative importance of the individual control section will be dependent upon the channel - weir geometry and the magnitude of the head upstream of the dip plate.

In the only analytical solution published to date, Ackers (1) assumes the pre-eminence of case (b) mentioned above. He does not, however, treat it as a drowned orifice, operating under the differential head of \( (H - h) \), but as a free orifice through which water discharges under the full head \( H \) prevailing in the approach channel.

The true flow situation, even if a unidimensional simplification is accepted, is considerably more complicated.

First of all a choice has to be made between the effects of sections (a) and (b). The relative importance of these two sections would depend solely on the geometry of the approach channel, namely the depth of immersion of the dip plate and its distance from the weir plate. Thus when \( (D - d) < 1 \), ie: the area of the passage below the dip plate is smaller than that between the dip and weir plate, the effect of the first [section (a)] will predominate. For small depths of immersion of the dip plate \( (D - d) > 1 \), the
situation is reversed and the effect of constriction at section (b) becomes more important and then it is that passage which has to be treated as one of the 'control sections'.

Whatever other passages are considered the flow through the plane of the weir [section (c)] has always to be treated as a controlling factor. It is also beyond any doubt that for steady flow the rate of flow through all the controls considered must be the same at all times.

If the case of a small depth of immersion of the dip plate is considered, the control section of case (b) has to be used. The action of the passage between the dip plate and weir plate is that of a drowned orifice operating under the differential head \((H - h)\) and the rate of flow may be expressed by:

\[
Q_0 = C_0 B \frac{1}{2} \sqrt{2g} (H - h)^{1/2}
\]  

where \(C_0\) is the discharge coefficient, the value of which will, as a rule, depend upon the geometrical properties of the passage and the magnitude of the differential head.

Equation (3.1) above may, for convenience, be re-written in the form:

\[
Q_0 = K_0 (H - h)^{1/2}
\]  

where \(K_0 = C_0 B \frac{1}{2} \sqrt{2g}\)

The rate of flow through the rectangular thin plate (sharp edged) weir is given (B.S. 3680 pt 4A; 1965) by the general equation:

\[
Q_w = C_w \frac{2}{3} \sqrt{2g} b h^{3/2}
\]  

In the above equation \(C_w\) denotes the coefficient of discharge which under various conditions may be expressed as:

\[
C_w = 0.602 + 0.083 h/D
\]  

for the suppressed or full width weir. (\(D\) in the expression above denotes the height of the weir sill above the channel bottom). Or:

\[
C_w = 0.616 \left[1 - 0.1 \frac{h}{b}\right]
\]  

for the unsuppressed weir with a fully developed end contraction. Some
other forms of expression for the discharge coefficient are shown in
Table 2.1, Chapter 2.

Whatever the configuration, i.e.: suppressed or fully developed, and
whatever expression is used to describe the dependence of \( C_w \) on other
variables, the equation (3.2) may be conveniently re-written as:

\[
Q_W = K_w \frac{h^{3/2}}{\sqrt{2g}}
\]

where \( K_w = C_w^{2/3} \sqrt{2g} b \)

As it has been mentioned before, the rate of flow through all the
control sections must be the same, thus:

\[
Q_0 = Q_W
\]

or

\[
K_o (H - h)^{1/2} = K_w^{3/2}
\]

If the equation (3.5a) be squared, it then becomes:

\[
K_o^2 (H - h) = K_w^2 h^3
\]

or, after some simple re-arrangement:

\[
h^3 + \left( \frac{K_o}{K_w} \right)^2 h - \left( \frac{K_o}{K_w} \right) H = 0
\]

and after denoting \( \left( \frac{K_o}{K_w} \right)^2 = A \)

\[
h^3 + Ah - AH = 0
\]

The coefficient \( A \) in equation (3.7) is a dimensional quantity \([\text{its}
\] dimensions are: \((\text{length})^2\)] and its value is a function of the channel -
weir - dip plate geometry and the values of the coefficient of discharge,
for both the 'drowned orifice' and the rectangular sharp edged weir:

\[
A = \left( \frac{C_o B 1 \sqrt{2g}}{2/3 \ b \sqrt{2g} C_w} \right)^2 = \left( \frac{3 \ C_o B 1}{2 \ C_w b} \right)^2
\]

In the case of the fully suppressed weir when \( B = b \), the expression
for \( A \) is simplified still further.

Under certain circumstances the value of \( A \) may be assumed to remain
constant for a given geometrical configuration. The conditions which have
to be satisfied for this assumption to be valid are that either:

(a) both \( C_0 \) and \( C_w \) do not change with the variation of \( H \) and \( h \) at least within the limits considered, or

(b) the change in the values of the two coefficients with the change in head is such that the ratio \( (C_0/C_w) \) remains constant within the range of heads under consideration.

When the value of the coefficient \( A \) is assumed to remain constant, equation (3.7) may be solved by the method outlined below (69):

If \( h \) is expressed as:

\[
h = z + v
\]

then when raised to the third power:

\[
h^3 = (z + v)^3 = z^3 + v^3 + 3zv(z + v)
\]

or

\[
h^3 = z^3 + v^3 + 3zvh
\]

which when re-written gives:

\[
h^3 - 3zv(h) - (z^3 + v^3) = 0 \quad (3.9)
\]

When equations (3.7) and (3.9) are compared, it is noticed that:

\[
3zv = -A \quad \text{or} \quad z^3v^3 = -A^3/27
\]

and

\[
z^3 + v^3 = AH
\]

Consequently a quadratic equation can be set up such that the roots of equation are \( z^3 \) and \( v^3 \), the product of the roots being equal to \((-A^3/27)\) and their sum to \((AH)\). This equation will be:

\[
x^2 - AHx - A^3/27 = 0 \quad (3.10)
\]

The solution of equation (3.10) is:

\[
x = \frac{AH}{2} \pm \sqrt{\left(\frac{AH}{2}\right)^2 + \frac{A^3}{27}}
\]

It can be said that:

\[
x_1 = \frac{AH}{2} + \sqrt{\left(\frac{AH}{2}\right)^2 + \frac{A^3}{27}} = z^3
\]

and

\[
x_2 = \frac{AH}{2} - \sqrt{\left(\frac{AH}{2}\right)^2 + \frac{A^3}{27}} = v^3
\]
from which:
\[
h = z + \frac{v}{\sqrt[3]{\left(\frac{AH}{2} + \frac{(AH)^2}{4} + \frac{A^3}{27}\right)}} + \frac{AH}{2} - \frac{(AH)^2}{4} + \frac{A^3}{27}\right)^{1/3} (3.11)
\]
now
\[
\frac{AH}{2} + \frac{(AH)^2}{4} + \frac{A^3}{27} = \frac{AH}{2} \left[1 + \sqrt{1 + \frac{4A}{27H^2}}\right]
\]
and similarly:
\[
\frac{AH}{2} - \frac{(AH)^2}{4} + \frac{A^3}{27} = \frac{AH}{2} \left[1 - \sqrt{1 + \frac{4A}{27H^2}}\right]
\]
Consequently equation (3.11) may be re-written as:
\[
h = \left(\frac{AH}{2}\right)^{1/3} \left[1 + \sqrt{1 + \frac{4A}{27H^2}}\right]^{1/3} + \left[1 - \sqrt{1 + \frac{4A}{27H^2}}\right]^{1/3} (3.12)
\]
Equation (3.12) describes the head h upstream of the weir but downstream of the dip plate, in terms of H, the head in the approach channel upstream of the dip plate and the geometry of the apparatus expressed in terms of the value of coefficient A.

If the depth of immersion of the dip plate is large and at the same time there is a large gap between the dip plate and the weir, so that the cross-sectional area of the passage below the dip plate is small compared with that between the dip and weir plates, the flow controlling effect moves to section (a). The approach to the problem is, however, identical to the one outlined above, the only difference being in the expression for the coefficient A.

The expression for A is obtained in this case by first modifying the equation for the volumetric flow rate through the drowned orifice formed by the passage below the dip plate to:
\[
Q_0 = C_0 B (D - d) \sqrt{2g} (H - h)^{1/2} (3.1b)
\]
This results, after the transformations similar to ones outlined previously, in the expression:
\[
A = \left(\frac{3 C_0 B (D - d)}{2 C_w b}\right)^2 (3.8a)
\]
After that the procedure is the same as before, resulting in the same form of equation (3.12).

Equation (3.12) can be solved numerically for a predetermined value of A. The flow diagram of the solution is shown in Fig. 3.2 and the tabular representation of the solution in Table 3.1.

The solution of equation (3.12) will establish the value of h, the head, just upstream of the weir for a given known value of \( H \), the head upstream of the dip plate, and a given channel - weir plate - dip plate configuration. It will not by itself furnish any information about the rate of flow. This will be obtained when the appropriate values are substituted into either the orifice equation (3.1), or equation (3.2) expressing the rate of flow through the rectangular sharp edged weir.

As the object of the present work is the investigation of the effect of the dip plate on the discharge over a rectangular sharp crested weir, the substitution of the calculated value of h into the weir equation is the more logical of the two possible solutions.

Substituting equation (3.12) which in general can be expressed as

\[
h = f(H)
\]

Equation (3.2) can be re-written as:

\[
Q = C_w \left( \frac{2}{3} \right) \sqrt{2g} \, b \, [f(H)]^{3/2}
\]

or in more detailed manner:

\[
Q = C_w \left( \frac{2}{3} \right) \sqrt{2g} \, b \, \left[ \left( \frac{AH}{2} \right)^{1/2} \right] \left[ \frac{1}{\sqrt{2}} \left[ \sqrt{1 + \left( \frac{4A}{27H^2} \right)^{1/3}} - 1 \right] + 1 - \sqrt{1 + \left( \frac{4A}{27H^2} \right)^{1/3}} \right]^3
\]

(3.13)

The above equation expresses the rate of flow over the weir in terms of the upstream head \( H \), channel - weir width ratio \( \frac{B}{b} \) parameter, and \( l \) the distance between the weir and dip plate.
Fig. 3.2 - Flowdiagram
Calculations - Equation (3.12)
A tabular representation of the intermediate results of calculations
of equation (3.12), i.e:

\[ h = \left( \frac{AH}{2} \right)^{\frac{1}{3}} \times \left\{ 1 + \frac{1}{1 + \frac{4A}{27H^2}} \right\} \]\n
The value of A is kept constant predetermined from equation (3.8)

<table>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>h</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.1**

Column 13 gives the value of h corresponding to an assumed value of H
3.3 Dimensional Analysis

It will be realised, even by a casual observer, that the flow pattern, in particular in the neighbourhood of the dip plate, diverges considerably from the one given by the unidimensional flow assumption. The reason for the use of that assumption is that it affords a solution in terms of easily measured quantities. This argument touches on the age old question, well known to every engineer involved in the problem of rate of flow measurement. This is: whether to keep the basic equations simple and easily remembered and put all the real fluid and configuration effects into the coefficient of discharge; or to include, if possible, all these effects of viscosity, compressibility and other properties of fluid and the device into the basic equation. This latter course of action removes the necessity of introducing an empirical coefficient which will then be disdainfully called 'a coefficient of ignorance'.

The assumption of unidimensional motion will be particularly non-representative of the true pattern of flow in the case in which the width of the approach channel is larger than that of the weir sill. This will be particularly true in the region between the dip and weir plates where, with the above configuration, the flow velocity vectors will have transverse components directed towards the plane of symmetry of the channel, vertical components directed downwards, besides the longitudinal components directed towards the exit of the channel.

A more complete insight into the problem than the one given by the unidimensional flow assumption may be gained by analysing the phenomenon dimensionally.

The rate of flow ($Q$) through the weir will be governed by the viscosity ($\mu$) and density ($\rho$) of the fluid flowing. Also the gravitational acceleration ($g$), the dimensions of the weir, primarily its width ($b$), and the hydrostatic pressure of the water in the channel ($p$). But in addition the
pattern of flow will also be a function of the width of the approach channel (B), depth of immersion of the dip plate (d), its distance from the weir plate (l), and finally the hydrostatic pressure (p_w) immediately upstream of the plane of the weir plate.

Consequently a relationship between ten variables will be required:

\[ Q; \rho; \mu; g; b; p; B; d; l; p_w \]

Using the Buckingham \( \Pi \) method of analysis seven non-dimensional groups will be obtained. Following the advice of Wielogorski (73), the choice of 'standard' variables is: density from the group of variables describing the fluid; width of the weir plate sill from the group describing the device and upstream pressure from the group of variables describing the motion. The non-dimensional groups will thus be made up as follows:

\[
\begin{align*}
\Pi_1 &= b^{x_1} \rho^{y_1} p^{z_1} Q \\
\Pi_2 &= b^{x_2} \rho^{y_2} p^{z_2} \mu \\
\Pi_3 &= b^{x_3} \rho^{y_3} p^{z_3} g \\
\Pi_4 &= b^{x_4} \rho^{y_4} p^{z_4} B \\
\Pi_5 &= b^{x_5} \rho^{y_5} p^{z_5} d \\
\Pi_6 &= b^{x_6} \rho^{y_6} p^{z_6} l \\
\Pi_7 &= b^{x_7} \rho^{y_7} p^{z_7} p_w \\
\end{align*}
\]

When the analysis of the dimensions of the \( \Pi \) groups is carried out, these result in the following:

\[
\begin{align*}
\Pi_1 &= Q \sqrt[\rho^2/b^2 p} \\
\Pi_2 &= \mu \sqrt[\rho^2 p^2 b} \\
\Pi_3 &= g \rho b/p \\
\Pi_4 &= B/b \\
\Pi_5 &= d/b \\
\Pi_6 &= l/b \\
\Pi_7 &= p_w/p \\
\end{align*}
\]
From the hydrostatic pressure equation:
\[ p = \gamma g H \quad \text{and} \quad p_w = \gamma g h \]
\[ \pi_1 = Q/\gamma g H b^2 \]
\[ \pi_2 = \mu/\gamma g H \gamma b \]
\[ \pi_3 = b/H \]
\[ \pi_4 = B/b \]
\[ \pi_5 = d/b \]
\[ \pi_6 = 1/b \]
\[ \pi_7 = h/H \]

Thus the functional form relationship:
\[ \pi_1 = f(\pi_2; \pi_3; \pi_4; \pi_5; \pi_6; \pi_7) \]

can be formulated as follows:
\[
\frac{Q}{\gamma g H b^2} = f\left(\frac{\mu}{\gamma b H}; \frac{B}{b}; \frac{d}{b}; \frac{1}{b}; \frac{h}{H}\right) \tag{3.21}
\]
or in a more conventional form:
\[
Q = b \sqrt{g H} \frac{3/2}{(\gamma b H)} f\left(\frac{\mu}{\gamma b H}; \frac{B}{b}; \frac{d}{b}; \frac{1}{b}; \frac{h}{H}; \frac{b}{H}\right) \tag{3.22}
\]

Equation (3.22) has the form of the standard weir equation, the function \( f \) denoting the coefficient of discharge and enumerating the factors on which it is dependent.

The factor \( \frac{\mu}{\gamma b H} \) represents Reynolds number and is primarily dependent on the viscosity of the fluid. It is expected that its effect, although similar to that occurring in the unobstructed weir flow, will be considerably smaller.

The influence on the discharge of the width/head ratio \( (b/H) \) is expected to be similar to that occurring in the free, unobstructed weir. The effect of the end contractions, occurring when the width of the approach channel \( (B) \) is greater than that of the weir, will also be of the same order.
The effect of the ratio of head downstream of the dip plate to the upstream head (h/H) has already been taken into account, at least partially, by carrying out the calculations indicated by the unidimensional flow approximation. The influence of the distance between the weir and dip plate is accounted for in the same way. The ratio (l/b) is included in the expression for coefficient A:

\[ A = \left( \frac{3}{2} \frac{C_o}{C_w} \frac{1}{b} B \right)^2 \]

which is used in equation (3.13).

A completely new and so far unaccounted for effect is that of the depth of immersion of the dip plate (d/b). It is not included in the head ratio relationship, neither, for obvious reasons, does it appear in the coefficient of discharge of a free weir.

The effect of the depth of immersion of the dip plate has to be investigated experimentally when the results, calculated by means of a unidimensional relationship, are compared with the experimental results obtained at various depths of immersion.

It has to be remembered that if the unidimensional flow approximation is to be applied, the flow coefficient is of a dual nature. On one hand it will, for a given value of H (the head upstream of the dip plate), affect the value of h (the head immediately upstream of the weir plate). But on the other hand it will also influence the rate of discharge through the weir.

The magnitude of the coefficient and the relative importance of the two effects will primarily be dependent on the extent and intensity of the various regions of separated flow, caused by both the weir plate and the additional introduction of a dip plate.
3.4 Regions of Separated Flow

The separation of the mainstream of fluid from the solid boundaries of the devices in which the flow took place was observed quite early in the studies of hydraulics. The regions of flow separation referred to in various ways as regions of "eddying flow," or regions of "pronounced turbulence," have been observed and studied in diffusers and abrupt changes in cross-sectional area of flow for quite a long time. Various partial explanations for their formation and existence have been put forward. Among these, the over-acceleration, the inability of fluid to follow the shape of the solid boundary, the jetting of the flow. The investigations resulted in purely empirical guidelines for the design of particular types of devices. An example of this is an arbitrarily fixed limiting divergence angle of 70° quoted quite often for design of the diffusers (12, 29).

The more rigorous and exact approach to the problem dates from the studies of Ludwig Prandtl who in the early twenties was involved in investigating the problem of pressure recovery in diffusers.

Prandtl introduced the concept of the boundary layer and has also observed that the separated flow regions were created by the separation of the boundary layer from the solid boundary surrounding the fluid flow. Further, this boundary layer flow separation will occur only if the pressure gradient is positive in the direction of flow, i.e., pressure increases in that direction. In this way Prandtl has stipulated two requirements which must occur simultaneously if a region of separated flow is to be formed. One is that the viscous boundary layer must exist and the other is that there must exist an adverse pressure gradient in the direction of flow. Although the boundary layer may be laminar or turbulent, and the fluid either compressible or of invariable density, the separation will eventually occur for any combination if the adverse pressure gradient exists.
The mechanics of boundary layer flow separation may be visualised by analysing the variation of longitudinal velocity $u$ with the direction normal to the flow $y$. If the assumption of 'no slip at the boundary' be taken to be valid, then $(u)_{y=0} = 0$. However, the velocity gradient $\frac{\partial u}{\partial y}_{y=0} > 0$, as the velocity will increase gradually so as to reach the undisturbed flow velocity at the edge of the boundary layer. With the pressure decreasing along the direction of flow or even with a constant pressure, this situation may continue without change. If, however, an adverse pressure gradient exists, i.e. pressure increases along the direction of flow, the momentum and consequently the velocity of flow must decrease. Eventually this decrease will cause the velocity gradient at the boundary to become $\frac{\partial u}{\partial y}_{y=0} = 0$. Then, the point at which the velocity gradient is positive will move from the solid boundary and thus a separation of the mainstream or the boundary layer flow from the solid boundary will occur.

Fig. 3.3 The velocity change near the point of separation

The velocity distribution downstream of the separation point will at first have a point of inflection, and eventually a region of reverse flow will be formed next to the solid boundary.

This can be analysed by considering the steady state momentum equation for the two-dimensional boundary layer flow of an invariable density fluid:
\[ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} \]

At the material boundary both \( u \) and \( v \) are equal to zero and consequently:

\[ -\frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \frac{\partial^2 u}{\partial y^2} = 0 \]

or

\[ \frac{1}{\rho} \frac{\partial p}{\partial x} = \nu \frac{\partial^2 u}{\partial y^2} \]

As the pressure rises along the flow:

\[ \frac{\partial p}{\partial x} > 0 \]

and consequently:

\[ \frac{\partial^2 u}{\partial y^2} < 0 \]

At the point of separation \( \left| \frac{\partial u}{\partial y} \right| = 0 \) and downstream from that point it becomes negative, thus \( \frac{\partial^2 u}{\partial y^2} \) becomes negative, hence at a certain finite distance from the material boundary \( \frac{\partial^2 u}{\partial y^2} \) must be equal to zero and the velocity profile has got a point of inflexion.

The position of the point of separation may be obtained if the pressure gradient and the velocity distribution are known or assumed.

In steady flow the region of the reversed flow downstream of the separation point, often referred to as the separation bubble, may be of

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![Fig. 3.4 Open type of separation bubble](image-url)
an open or closed type. The open type of bubble shown in Fig. 3.4 is
typical of separation occurring at a stalling angle over an aerofoil or
in a two-dimensional diffuser (12). It forms a starting region of a wake.
In both of these two flow configurations the existence of a region of
separated flow leads to increased pressure losses and loss of efficiency.
Considerable efforts were thus directed towards establishing the point at
which separation occurs and control and delay of that phenomenon (9, 12, 29).

One of the two methods by means of which this is usually achieved is
the suction of the boundary layer. The effects of this method are twofold;
it changes the pressure gradient at the material boundary and keeps the
boundary layer in its laminar form, and as the velocity gradient of the
laminar boundary layer is of a steeper form than that of a turbulent one
the point of inflexion and consequently the point of separation is moved
further downstream.

The other method of decreasing the value of the adverse pressure
gradient is by decreasing the divergence angle of the solid boundary.
The adverse effect of this method is the longitudinal extension of the
boundary and a consequent increase of viscous wall friction. This effect
is not as detrimental as it appears at first glance. It has been found
(9, 12, 29) that friction factor (defined by $f = \frac{T}{(\mu u^2/2)}$), the value of
which for a smooth wall is of the order of 0.005, increases to the value
of between 0.037 and 0.094 for the jets and wakes. Thus the friction
losses in a jet flowing over a separation bubble will far outweigh the
increase due to the lengthened wall. Unfortunately these values cannot
be predicted analytically but must be measured by experiment.

The closed type of the separation bubble, shown diagramatically in
Fig. 3.5, occurs typically in flows with abrupt area changes.

The discontinuity of area may be facing either downstream or upstream.
In the first case, of the enlargement of area, the separation bubble will
be positioned downstream of the discontinuity. If the area contracts abruptly the bubble will be positioned ahead of the discontinuity with, possibly, an additional separation area just downstream of it (12, 46).

It is these types of separation bubble which occur in channels in the immediate neighbourhood of the flow measuring devices of the weir type (9, 12, 46), both broad crested and sharp edged. The interest in these types of separation was considerably smaller than in the open type, as its effect was predictably confined to the influence on the value of the coefficient of discharge of the weir. The value of this coefficient was usually finally determined by experiment.

The separation bubble situated upstream of the discontinuity may in certain cases become unstable (9, 12). The point of reattachment normally situated at the edge of the discontinuity may be temporarily swept downstream and the bubble will extend beyond the edge of discontinuity (Fig. 3.6).

This region is, however, subject to accelerated flow with decreasing pressure and as a result reattachment will occur. Usually this cycle will then be repeated at an irregular frequency.
Fig. 3.6 Unstable separation bubble

The study of the separated flow is divided into three areas. The most frequently investigated is the effect of the separation bubble on the remainder of the free flow. The main difficulty here is the analytical prediction of the size of the separation region. This difficulty arises from two factors.

One occurs in the prediction of the position of the separation point in the originally undisturbed flow. In the case of the laminar boundary layer this position can be estimated with the aid of relatively uncomplicated analysis, particularly if the flow takes place around a body, eg: the determination of onset of stall on an aerofoil (9, 12). However, if the boundary flow is of the turbulent type, where the relationship between the fluctuating and time average values of the parameters is unknown, the estimation of the position of the separation point must be done by empirical modelling methods.

The other difficulty arises from the fact that once established, the separated flow changes the previously determined pressure gradient and the whole pattern of flow is modified. Consequently an iterative method of estimation has to be employed and again the simplest answer lies in the empirical approach.
The second area in which the study of separated flow is carried out is the estimation of losses due to formation and existence of the separation bubble. This again is primarily done by the use of experimental techniques.

Finally the third area of investigation, which has received the least attention, is concerned with the prediction of momentum and mass transfer between the separation bubble and the remainder of the free flow.

Most of the studies of the separation bubble, be it of the open or a closed type, assume that the pressure within the bubble is constant. This assumption is borne out by experimental evidence (9, 12, 29).
4.0 THE EXPERIMENTAL APPARATUS

4.1 Experimental Channel Modifications

The investigation was not supported by any outside grant and thus a limitation of the capital outlay on building of experimental apparatus was applied.

Consequently the experimental part of the investigation was carried out in a flume originally built for undergraduate experiments in the calibration of sharp crested weirs. The modifications required did not alter the basic layout of the channel.

The flume was of rectangular section 24 in (0.61 m) wide and 22 in (0.56 m) high with the overall length of 13 ft (3.96 m). Both the bottom and sides of the flume were made of mild steel plate which was subsequently painted.

Water was drawn from the main laboratory sump by means of a low head centrifugal pump, Type Tangye AR2, and supplied to the flume by means of an overhead pipe, provided with a flow regulating valve. The outlet of the pipe was fitted with a perforated shroud in order to reduce the jet effect. The rate of flow of water was measured by timing the collection of a predetermined quantity of water in a tank placed on a weighing machine. The capacity of the tank was limited to 4 cwt (203.2 kg).

The tank was placed under a chute providing an alternative path for water discharging from the downstream end of the flume. During the flow rate measurement the chute was lifted, thus allowing the water to flow into the collecting tank (Fig. 4.1). At any other time, lowering the chute diverted the flow of water into the sump (Fig. 4.2).

The basic apparatus together with some modifications, carried out before the test programme was started, is shown in Fig. 4.3 and Fig. 4.4.

A rectangular weir plate of sufficient stiffness not to be deflected under the action of water pressure was manufactured out of $\frac{3}{16}$ inch (4.8 mm)
Fig. 4.1 Flow of water into the collecting tank; with the moveable part of the water chute raised, the nappe discharging over the weir plate is directed into the weighing (collecting) tank.
Fig. 4.2 Flow of water into the sump; when the moveable part of the chute is lowered, water discharged over the weir is directed into the laboratory sump (normal position of chute).
Fig. 4.3 Sketch of the experimental apparatus

a - experimental flume
b - dip plate
c - weir plate
d₁ )
   ) depth gauges
d₂ )
e - water chute
e' - moveable portion of the chute
f - collecting tank on weighing machine
g - laboratory sump
h - circulating pump
j - flow regulating valve
k - perforated shroud
l - perforated screens
m - false walls of flume
Fig. 4.4 Overall view of the channel; the chute with its moveable portion is visible in the foreground; looking upstream the weir plate with dip plate fixing rod nuts, depth gauges (with side pointers), dip plate and upstream depth gauges are also visible.
steel plate. The weir, situated symmetrically about the longitudinal
centre plane of the flume, had its sill at $9\frac{3}{8}$ inch (238 mm) above the
bottom of the flume and was 10 inches (254 mm) wide. The sharp edge was
formed by a $45^0$ angle cut made on the sill and sides of the weir on the
downstream side of the plate.

Four nuts were brazed to the same (downstream) side of the plate.
These were spaced in pairs, symmetrically about the centre line (Fig. 4.5).
The lower pair was situated at 12 inches (305 mm) and the higher at 17 inches
(432 mm) above the bottom of the flume. The plate was drilled and the
holes carefully tapped so as to form a continuation of the nut threads.
Four rods were screwed from the upstream side and held firmly in position
by locknuts.

The protruding rods formed a supporting structure for the dip plates.
These were made of a $3/8$ inch (9.5 mm) thick Tufnol plate with the bottom
edge cut at an angle of $45^0$. Slip-fit clearance holes were drilled in the
dip plates to pass the supporting rods (Fig. 4.5).

Two identical plates, except for the position of the holes, were made.
One had holes drilled in such a way that when placed in its uppermost
position, i.e. with the lower pair of supporting rods passing through the
bottom pair of holes, the lowest (sharp) edge of the plate was level with
the sill of the weir plate. Other holes were positioned so that the plate
could be moved down by steps of 1 inch (25.4 mm) until the bottom edge of
the dip plate was 5 inches (127 mm) below the level of the sill. The
other plate, when placed in its uppermost position, had the bottom edge
0.5 inch below the level of the sill. This plate could also be moved down
by 1 inch (25.4 mm) intervals to its lowest position, with its bottom edge
4.5 inches (114.3 mm) below the sill of the weir.

The distance between the notch and dip plate could be varied by
inserting on to the dip plate supporting rods distance pieces cut from a
Fig. 4.5 Weir plate-dip plate assembly

This sketch shows the method of connection of dip plate to the weir plate, indicating schematically the position of the four interconnecting rods; distance pieces were slipped over these rods.
Tufnol tube. These tubes were cut and carefully faced to be of exactly the lengths required, varying in steps of 0.5 inch (12.7 mm) from the smallest of 0.5 inch (12.7 mm) to the longest of 5 inches (127 mm).

For the study of the effect of the end contractions of the weir two possible approaches to the design of the apparatus were considered. One, possibly simpler at first glance, was to construct a number of weir plates of various widths. This solution was rejected because, when studying the unconstricted weir its width would extend over the whole 24 inches width of the approach channel. The rates of discharge over the weir would become very large and with the capacity of the collecting tank limited to 7.2 ft$^3$ (0.2 m$^3$) the time of collection would become very short (less than 5 sec), resulting in an excessively inaccurate measurement of rate of flow. Due to the siting of the flume, an increase in size of the collecting tank was impossible. As a result, another solution had to be considered, and was accepted.

This solution consisted of constructing additional (inner) sides to the flume. These were made of $\frac{3}{16}$ inch (4.76 mm) thick steel plates placed vertically on the channel bottom at predetermined distances. The inner, false walls of the flume had to extend both upstream and downstream of the dip plate. The downstream parts were cut to exactly the same lengths as the dip plate distance pieces. In order to eliminate the leakage, all joints were sealed on the outside with Bostik filling compound. The false sides were kept in position by fixing them to two plates placed transversely over the top of the channel. A stiff junction was obtained by means of a $1\frac{1}{2} \times 1\frac{1}{2}$ inch angle, bolted both to the false (inner) side and a fixing plate. The holes in both plates were made oblong so that minor ($\pm 0.125$ in) adjustments both in a transverse and vertical direction could be made when finally positioning the plates.
At the bottom the inner (false) wall was provided with 1\frac{1}{2} x 1\frac{1}{2} inch angle bolted to the plate, the holes in the plate also allowed for the final adjustment in situ. Bostik sealing strip was firmly fixed to the angle to prevent leakage.

At first, distance pieces were placed at the bottom to prevent any movement of the inner walls; however, it was soon found that this precaution was not necessary as the weight of the structure (about 100 lb) was sufficient to keep it in place once the fixing plates were firmly fitted to the top of the channel.

The section through the flume with the false sides in position is shown in Fig. 4.6. The width of the channel with false sides was either 10 inches (full width weir conditions) or 16 inches. Thus a weir with no side contractions and two configurations of side contraction were investigated.

At the upstream end the flume was provided with five perforated screens. These served to break up the random currents created by the discharge from the supply pipe and generate a reasonably uniform velocity and turbulence distribution over the cross-sectional area at the entrance to the approach channel.
Fig. 4.6 False sides of the channel

Sketch shows diagramatically the method of fixing false sides used to vary the width of the approach channel.
4.2 Instrumentation

4.2.1 Rate of Flow Measurement

The primary object of the investigation was to establish the way in which the introduction of a dip plate upstream of a rectangular sharp crested weir would affect the discharge through it. In the simplest, conventional way, this would require the calibration of the weir first, without any upstream obstruction, and then with the dip plate mounted in various positions.

The original apparatus was designed for calibration of weirs and consequently the instrumentation in this respect was adequate. The rate of flow was measured by means of timing of a direct collection. This method has no equal in accuracy, provided that the time of collection is sufficiently long. In this last respect the apparatus used suffered, as mentioned before, from an unfortunate limitation in the size of the collecting tank which at high heads reduced the time of collection to between 10 and 15 seconds, with a consequent reduction of accuracy of measurement to about 4%.

4.2.2 Measurement of Head

The measurement of head above the sill of the weir also formed a part of the original design of apparatus and consequently the flume was provided with rails on which a carriage supporting the point surface gauge could be moved along the length of the approach channel. The carriage was fitted with two transverse rails made out of an angle section and provided with a calibrated scale. This made possible the adjustment of the position of the gauge in the direction normal to the axis of the channel whenever that was necessary.

In the present investigation the head of water downstream of the dip plate but upstream of the plane of the crest of the weir had to be measured as well. The distance between the two plates was not
sufficient to introduce the gauge carriage into this space and thus a special support had to be made. This consisted of a length of a well finished 0.5 in by 1.5 in rectangular section steel rod which could be firmly attached to the side of the channel. The point surface gauges were fixed to the rod by means of G-clamps. No provision was made for the transverse movement of the gauges which were fixed in predetermined positions along the beam. Not less than three gauges were used (the number depended on the distance between the inner walls of the channel), one of which was always placed on the centre line of the weir (Fig. 4.7 and Fig. 4.8).

When the weir and dip plate were very close together, making it difficult to operate the depth gauges, the gauges were placed in the clear weir space. Wire extensions, bent sideways, were used to make the contact with the surface of the water (Fig. 4.8).

4.2.3 Flow Visualisation

As the sides and bottom of the experimental flume were made of steel plate, observation of the flow pattern was not possible. The only exception was the motion of water at and near the free surface. This was studied by observing the motion of Perspex filings sprinkled on to the water surface.

The use of coloured (blue) polystyrene beads of about 1.5 mm diameter and average relative density of approximately 1.07 helped with observations of 'below the surface' currents.

The beads, if deposited gently on the surface of water, floated for some time supported by surface tension forces and in this way indicated the surface flow pattern. When the beads became wetted they sunk slowly, at the same time moving with the water currents, and thus indicated their direction and intensity. If the sinkage occurred close to the upstream face of the dip plate, an idea of the
This photograph shows the method of mounting the depth gauges placed between the dip and weir plate; the method of fixing the side pointers is clearly visible.
Fig. 4.8 Downstream depth gauges

This photograph shows the method of mounting the depth gauges placed between the dip and weir plate; the method of fixing the side pointers is clearly visible.
Fig. 4.9 Flow visualisation channel
path of water under the dip plate could be obtained by observing the motion of the beads. The observation of individual beads in order to trace particular path lines was, however, extremely difficult.

In order to investigate more fully the flow patterns consequent to the introduction of the dip plate, in particular the formation and extent of the regions of the separated flows, use was made of a small model channel. Because of its dimensions, the observations made in this flume could not be applied directly, but served only as a qualitative picture of the flow pattern.

The glass-sided channel is very narrow, being \( \frac{1}{4} \) inch (20 mm) wide, 6 inches (152 mm) deep and 25 inches (635 mm) long, as shown in Fig. 4.9. Tufnol weir and dip plates were made to fit tightly between the glass sides.

Various materials were tried as flow visualisation media. As previously mentioned, coloured polystyrene beads were found to be most suitable for the 'naked eye' observations. Perspex filings were most suited for the photographic studies. Both materials were introduced into the circuit; the water together with the suspended polystyrene beads and Perspex filings was continuously circulated by the pump.

4.2.4 Velocity Measurements

Drag-on Sphere Velocity Meter

An attempt was made to measure the velocity, its distribution and changes in different positions along the approach channel and also in the space between the dip plate and the weir. At first measurements by means of pitot tubes were tried. A mini pitot tube, 2 mm diameter Furness Controls Type 600, was fitted in a depth gauge holder and consequently could be positioned very accurately. Unfortunately, the method suffered from two drawbacks. One of these was that, except in the space between the dip and weir plates, the flow velocity was so
Fig. 4.10 Pitot tube manometer; a water manometer mounted on the side of the tank used in conjunction with a Furness 2 mm pitot-static tube.
small that no accurate estimation of velocity distributions was possible. The other was the inertial delay in the connections between the pitot tube and the manometer (Fig. 4.10). Consequently the pitot tube was used for the velocity of flow estimation only in certain regions of flow and another device had to be adopted for a more general application.

In view of the relatively small velocities involved, an attempt was made to develop a measuring device utilising the drag force exerted on a sphere submerged in a flowing fluid.

The principle of operation and the balance of forces acting on the sphere is illustrated in Fig. 4.11 below:

\[ \text{In the force diagram} \]

\[ W_e \] - is the effective weight of the sphere

\[ \text{ie: } W_e = \text{weight of sphere} - \text{force due to buoyancy} \]

\[ D_s \] - is the hydrodynamic drag exerted on the sphere by the flowing water

\[ R_s \] - is the result of the two forces pulling the sphere so that the direction of its action will be the same as the direction of the link \( L_s \) connecting the sphere to the fixed point of attachment \( P \). The angle \( \theta \) at which the link is inclined to the
vertical is given by:
\[ \theta = \tan^{-1} \frac{D_s}{W_e} \quad (4.1) \]

The value of the angle may also be obtained by the geometry of the configuration from the known and constant value of the length of the link \( L_s \) and the horizontal displacement \( x_s \) of the sphere from the point of attachment.
\[ \theta = \sin^{-1} \frac{x_s}{L_s} \quad (4.2) \]

The distance \( x_s \) may be measured with a reasonable degree of accuracy due to the fact that the position of the sphere may be observed in the direction normal to the water surface and therefore any parallax effects will be minimal.

Thus with the known and constant values of \( W_e \) and \( L_s \), both previously established, and a measured value of \( x_s \) the magnitude of the drag force exerted on the sphere can be calculated. By solving equations (4.1 and 4.2) for \( D_s \):
\[ D_s = \frac{W_e \cdot x_s}{\sqrt{L_s^2 - x_s^2}} \quad (4.3) \]

The hydrodynamic drag is given, by definition, by:
\[ D_s = \frac{1}{2} C_D A_s \rho U^2 \quad (4.4) \]

Thus when equations (4.3) and (4.4) are solved in terms of \( U \), the velocity of flow is obtained:
\[ U = \left[ \frac{2W_e}{C_D A_s \rho} \sqrt{\frac{x_s}{L_s^2 - x_s^2}} \right]^{\frac{1}{2}} \quad (4.5) \]

In the above expression \( \rho \) is the density of fluid, \( A_s \) the projected frontal area of the sphere \( (A_s = \pi d^2 / 4) \) and \( C_D \) the drag coefficient.

It has to be borne in mind that \( C_D \) is not a constant, but a function of Reynolds Number and thus dependent on the velocity of
Fig. 4.12
Coefficient of drag of a sphere as a function of Reynolds number
flow. The calculations would have to be done in stages, first with an estimated value of $C_D$ as obtained from the $C_D \rightarrow R_e$ graph (Fig. 4.12). Depending on the rapidity of variation one or more corrections may be necessary.

To test the feasibility of this method of velocity measurement a number of small spheres were prepared. Small nylon 'poppet beads' of nominal diameters of 1.2 cm, 0.9 cm and 0.8 cm were used as the material for the spheres. The beads were of three types, some had two protrusions on a diametral line, some had a protrusion on one side and a hole on the other, while the remainder had holes on both sides. The protrusions were carefully shaved off, the holes were weighted with small lead shot and stopped with paraffin wax or nylon solution. Nylon thread was used as the means of anchoring the beads.

It was found that the beads with holes on both sides or with a shaved off protrusion and a hole were the most convenient to use. The nylon thread which formed the link between the sphere and the fixed point of attachment was embedded in the material filling the hole in the bead and thus it was fixed firmly to the sphere. At the point of attachment to the tube the thread was allowed to pass through a small bore (ca 1.0 mm) tube and was fixed to the upper part of the tube (Fig. 4.13). This method of attaching the thread ensured that there was no pretensioning at the fixed point. The tube to which the thread was attached was inserted into a tube of a larger diameter which was then firmly fixed to the depth gauge holder and thus the position of the bottom of the tube (the fixed point in the geometry of the measuring device) could be placed exactly in any position relative to the channel.

The performance of this method of velocity measurement did not justify the effort expended on the production of the spheres. On
Fig. 4.13

Drag-on-sphere velocity meter

Sketch shows the assembly of the bead on the nylon thread and the two tubes. Small diameter steel tube to produce minimum flow disturbance and a larger diameter brass tube which fits into a depth gauge holder.
testing it was noticed that the thread did not stretch in a straight line, but formed a curve from the tip of the tube to the point of attachment at the bead. As a result the angle $\theta$ could not be calculated easily from the values of length of the free thread and the horizontal displacement of the bead from its point of attachment (Fig. 4.14). This effect is due to the drag exerted by the water on the connecting thread.

An attempt to eliminate the curvature effect of the thread was made by impaling the bead on to a darning needle, passing the thread through the eye of the needle, adjusting its length so that it just protruded from the small bore (holder) tube and fixing the thread to the tube (Fig. 4.15 and Fig. 4.16).

Although with this configuration the connecting link is straight, no absolute reliance could be made on the value of the angle, i.e. the horizontal displacement of the bead, as a link had a finite weight and the fluid exerted a finite drag on it. Both these forces were comparatively small and thus it was assumed that they did not warrant a separate correction. Nevertheless the measurements could not be relied upon absolutely and the readings of this velocity meter were considered in a qualitative, comparative way.

It has also to be remembered that the point at which the velocity is measured is situated at the centre of the bead, and not directly below the tip of the holder tube. Therefore at each measurement a correction has to be made for the position of the bead and as a result the measurements of velocity are made along a curved line. This modifies the conventional meaning of the expression 'velocity distribution' (Fig. 5.1).

Equation (4.5) gives an expression for $U$, the velocity of flow, in terms of characteristic dimensions of the assembly and drag
Fig. 4.14 Drag-on-sphere velocity meter
This sketch shows a thread-bead configuration when placed in water current.
Fig. 4.15 Drag-on-sphere velocity meter
Sketch showing final configuration with the rigid link (darning needle) between the bead and steel tube.
Fig. 4.16 Drag-on-sphere velocity meters
coefficient of a sphere which in itself is a function of velocity. Consequently the direct solution of the equation requires the use of successive approximations. A more convenient approach to solve the equation expressing the displacement of the sphere in terms of velocity of flow:

Equation (4.5) may be re-written as:

\[ U^2 = \frac{2We}{C_D A_s} \tan \theta \]

and when solved for \( \tan \theta \)

\[ \tan \theta = \frac{C_D \frac{U^2 A_s}{2We}} {\tan \theta} \quad (4.6) \]

bearing in mind that:

\[ \tan \theta = \frac{x_s}{\sqrt{L_s^2 - x_s^2}} \]

A numerical solution for \( x_s \) in terms of predetermined values of \( U \) is both easy and straightforward and does not require corrections for assumed values of \( C_D \).

The flow diagram of the calculations of \( x_s \) in terms of \( U \) and particulars of a given sphere is shown in Table 4.I.

Data of the spheres used are shown in a tabular form in Table 4.II. The numerical values of the horizontal displacement calculated for various spheres are tabulated in Table 4.III and the relationships between the velocity of flow and the consequent displacement of the sphere are shown in graphical form in Fig. 4.17 to 4.23.
Table 4.1
Calculations flow diagram

1. $u$

2. $Re$

3. $C_D$

4. $u^2$

5. $D$

6. $\tan \alpha$

7. $\alpha$

8. $\sin \alpha$

9. $\chi$

10. $\psi$

11. $\frac{A e}{2g}$

12. $Re$

13. $Cd$

14. $D$

15. $\tan \alpha$

16. $\sin \alpha$

17. $\chi$

18. $\psi$
Table 4.11
Dragon Spheres
Sphere data

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<th>No.</th>
<th>Dia</th>
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<th>We</th>
<th>cW</th>
<th>k</th>
<th>L</th>
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<td>cm</td>
<td>cm³</td>
<td>cm²</td>
<td>gm</td>
<td>gm</td>
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Table 4.31

DragonSphere

Horizontal displacement

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Fig. 4.18 - Drag on Sphere
B2 - Calibration
Fig. 4.19 - Drag on Sphere

B3 - Calibration
Fig. 4.20: Drag on Sphere
B4 - Calibration
Fig. 4.21 - Dragon Sphere

B 5 - Calibration
Fig. 4.22 - Drag on Sphere
R1 - Calibration
Fig. 4.23 - Drag on Sphere
R2 - Calibration
5.0 EXPERIMENTATION

The investigation started as an attempt to determine to what extent, and in what way the presence of a dip plate would affect the rate of flow through a rectangular sharp crested weir. Although this primary aim was always kept in mind, it soon became apparent that an investigation embracing more than just the calibration of the weir in the form of \( Q = f(H) \), where \( H \) is the head of water upstream of the dip plate, would have to be carried out.

One important factor which had to be borne in mind at all times while the experiments were carried out was that, as the apparatus was due for dismantling, the experiments could not be repeated at a later time, and consequently confirmatory tests could not be carried out after a certain date.

Therefore extreme care, attention to detail and precision had to be exercised at all times. A number of measurements had to be carried out in anticipation of their being necessary at a later date. Due to time limits only a cursory analysis of the results could be carried out and planning of further experiments had to be based partly on experience and partly on intuition, not the best guide for experimental procedure.

In all 107 calibration runs were carried out. All of them involved measurement of a series of rates of flow and corresponding heads, taken at a number of stations both upstream and downstream of the dip plate. Visualisation of currents both on the surface of the water and within the body of the flow was also carried out in a proportion of the tests. The former were observed by sprinkling multi-coloured perspex filings on to the surface of the water and tracing their movement. The path of the deep currents was studied by immersing blue polystyrene beads and observing their motion.
Estimations of distribution of velocity were done, in the first instance, using a 2 mm diameter pitot-static tube. When placed in the approach channel the indications of the manometer were so small that the use of this method was limited to the area of flow between the dip and the weir plates.

In order to get an indication of the velocity distribution in the channel upstream of the dip plate, a number of 'drag-on-sphere' instruments were constructed (Chapter 4.2.4). The two dip plates constructed had their edges chamfered at 45°. The original intention was to carry out the tests with the chamfer directed towards the weir plate. Eventually, however, quite a number (about a quarter of the total) of runs were repeated with the dip plate turned so that the chamfer was facing upstream. A summary of the tests is shown in Table 5.1.

5.1 Procedure

The procedure followed for each of the runs varied slightly, depending on the configuration. (E.g: false sides of the approach channel were not fitted when full channel width was used.) Estimation of the velocity distribution and the visualisation of currents was carried out only during a limited number of tests.

5.1.1 Assembly of Apparatus

The first choice to be made was that of distance 1 between the dip and weir plate, immediately followed by the selection of width B of the approach channel.

With the weir plate and the dip plate fixing rods firmly in position, the required distance pieces were slipped on to the rods and corresponding lengths of the false sides erected on the channel bottom. The dip plate was then pushed on to the fixing rods in its highest position and held tightly with four nuts (one on each rod). With previous exact machining of distance pieces and short lengths
### Table 5.1
**Summary of tests**

#### Series 1 - \( B = 24 \) in

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#### Series 3 - \( B = 16 \) in

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</table>
of the false sides no additional fixing of the assembly was necessary.

Next, the long (upstream) side plates were assembled. This was done by first placing the fixing plates on the side walls of the flume and adjusting the angle brackets to the required width. The false sides were placed in position resting on the channel floor and then at the top and bottom were bolted to the angle brackets, as shown in Fig. 4.6.

The whole structure was then pushed against the dip plate and the two small fixing plates were firmly secured, by means of G-clamps, to the sides of the channel.

Extra holes in the dip plate (not covered by the fixing rods) and the gap below the dip plate between the two parts of the false sides were filled with Bostik sealing compound. Bostik compound, in strip form, was used to cover all the joints between plates in order to seal any possible gaps.

When fixing the plates used to locate the false sides of the channel, care had to be exercised not to interfere with the movement of the rails supporting the point depth gauges.

Two such pairs of rails were placed upstream of the dip plate, one at a distance of about 5 ft (1.5 m), the other within 1 ft (0.3 m) of the plate. With the false side fixing plates situated at about 6 ft (1.8 m) and 2 ft (0.6 m) upstream, the head of water over the crest of the weir could be measured over a very wide area of the approach channel.

In the region between the weir and dip plate the method of measurement of the head was dependent (as mentioned in Chapter 4.2.2) on both the distance between the two plates and the width of the channel.
If the distance between the plates was 4 in (100 mm) or more, the conventional pair of rails was used as the depth gauge support; for smaller distances a specially manufactured narrow plate fixed to the side of the channel by means of a G-clamp was used to support the depth gauges.

5.1.2 Measurement of Head and Rate of Flow

With the apparatus ready for the start of the run, the low head centrifugal pump was started and the valve in the supply pipe opened to allow water to flow into the channel until the level of the sill of the weir was reached. The valve was then closed and zero readings of all the depth gauges taken and noted.

The valve in the supply pipe was then opened slightly and conditions allowed to settle. Readings of depth gauges were taken both upstream and downstream of the dip plate.

It soon became evident that upstream of the dip plate readings had to be taken only on the centre line and even there the difference in the readings taken just upstream and at the distance of about 5 ft from the dip plate was negligible. However, these two readings were taken at all times.

The situation was considerably different at the downstream side of the dip plate. Here it was found very soon that the water level varied both in the transverse and longitudinal directions. Consequently depth gauge readings were taken as a matter of course

(i) on the centre line
(ii) 2 inches (50.8 mm) away from the centre line
(iii) 5 inches (127 mm) from the centre line (at the edge of the weir)
(iv) 8 inches (203.2 mm) away from the centre line (only for the channel width of 16 in and 24 in)
(v) any other position of special interest (eg: minimum or maximum level)
In some cases, as mentioned in Chapter 4.2.2 and shown in Fig. 4.7 and Fig. 4.8, special attachments were fitted to the tip of the gauge in order to reach into the space between dip and weir plates. This was necessary when this gap was small, and the width of the channel exceeded that of the weir.

The rate of flow over the weir was measured by timing the collection of a predetermined weight of water in the tank placed on the weighing machine at the outlet of the channel (Fig. 4.1 and Fig. 4.3).

The outlet valve of the collecting tank was closed, the moveable part of the chute, normally directing the discharged water into the laboratory sump, was lifted, thus allowing the discharge to flow into the tank. When the original weight bias and the water collected were in equilibrium, the timing was started, a required weight pre-set and when the equilibrium was restored the timing was stopped. The moveable part of the chute was replaced and the collected water released from the tank by opening the tank outlet valve. The mass of water collected and the time of collection were noted. The rate of flow is obtained by dividing the quantity collected by the time of collection. Timing of collection was done at least twice. If the difference between the two readings was not more than 0.3 seconds, the average figure was taken; if more, a third measurement was carried out.

If done during a given test, the visualisation of flow currents and estimations of velocity distributions would be carried out after completion of rate of flow measurement. However, as these observations were done on a limited number of tests, the description of the procedure is left until later.

The rate of flow over the weir was increased by opening the valve in the supply pipe by a further small amount, and when the conditions
settled the measurements were carried out again as described above. This procedure was repeated between twenty to thirty times for a given dip plate position, until the point at which the time to fill the collecting tank dropped to so small a figure that the accuracy of further measurements became unacceptably low.

The run having been completed, the vertical position of the dip plate was changed (lowered). The change in the vertical position of the dip plate requires least rearrangement of the apparatus, the only exception being the reversal of the side of the dip plate in the same vertical position.

With the dip plate in the new position, a new test run was carried out, following the procedure outlined above.

When all the required vertical positions of a given dip plate have been tested, the other dip plate, with holes displaced by half an inch in relation to the sill of the weir was mounted, and test runs carried out in the same way. If deemed necessary, runs were performed with dip plate chamfered edge facing both upstream and downstream (Table 5.1).

One of the dip plates was tested first with its lowest edge position level with the sill of the weir plate and then at one inch steps until four inches below. The starting point of the other plate was half an inch below the sill and then, in two one inch steps, down to 2½ inches below the level of the weir sill.

With the exhaustion of all the required changes in the vertical position of the dip plate, test runs with the new distance (1) between the weir and dip plate were carried out.

The smallest of the distance pieces being half an inch, the ratio of the distances were two, three, four, then six and eventually ten to one.
As can be seen from Table 5.1, not all the configurations were tested and it is here in their choice that intuitive estimation had to be exercised.

When the whole series of calibrations for one of the chosen widths of the approach channel was finished, the approach channel configuration was changed and a new series carried out. The order in which the tests were done was the first series with the full width (no false sides) channel, then a suppressed (no end contraction) weir with the false sides at 10 inches (254 mm) apart and finally with a width of the approach channel of 16 inches (406.4 mm).

At the end of each series a free weir (ie: with the dip plate removed) was calibrated.

5.1.3 Visualisation of Flow

As mentioned before, the observations of the surface currents were not carried out in every calibration run, but were used as a confirmatory method of observation when unaided visualisation was deemed to be insufficient. As a rule, water in the channel carried sufficient dust and dirt particles for a careful observer to be able to establish roughly the direction of flow. It was when the surface currents were observed to move in an upstream direction, over part of the surface of the approach channel, that coloured perspex filings were sprinkled over the surface of the water. Their motion confirmed the suspected movement.

Blue coloured polystyrene beads were used in order to study the path of the currents within the body of the flow and, in particular, the region of separation just downstream of the dip plate. Two distinct types of flow and, consequently, two values of head downstream of the dip plate, were observed relatively early in the investigation. One, characterised by a pronounced eddying and lower
head immediately next to the plate, the other, further away, formed a clearly defined jet, the top of which was almost level with the upstream head. Polystyrene beads dropped into the water a few at a time were used to observe the formation and the extent of the separate regions. Beads, whose density was slightly greater than that of water, when dropped, sunk slowly but at the same time were swept downstream, thus indicating by the speed of their movement the intensity and approximate direction of the current.

Beads dropped at a relatively large distance from the dip plate indicated the path of the main current and usually were swept away directly over the weir, although some eventually entered the separation region upstream of the dip plate.

When dropped near the upstream face of the dip plate, beads travelled through the separated region upstream of the dip plate; some of them entered the downstream separated flow region and some found their way into the mainstream.

Beads, and a very small quantity of perspex filings, were dropped into the low head region just downstream of the dip plate. Observation of their behaviour indicated the extent of the separated flow region downstream of the dip plate.

5.1.4 Estimation of Velocity Distribution

Similarly to the flow visualisation, the estimation of the distribution of velocity formed a qualitative rather than a quantitative form of the investigation.

Two methods of velocity estimation were used. First a 2 mm diameter pitot-static tube was used for measurements both upstream of the dip plate and in the region of flow between dip and weir plate. Very soon, however, it was found that the indications of the manometer used in conjunction with the pitot tube were so small, when
the latter was placed upstream of the dip plate, that its use had to be limited to the area downstream of the plate. These measurements were made with the channel widths of 16 inches and 24 inches as a crude attempt at estimating the ratio of the flow rate moving directly downstream to that coming down the two sides.

The pitot tube used was mounted in a depth gauge holder and was zeroed to the level of the sill of the weir. With the careful adjustment of the micrometer screw, the head of the tube was moved through steps of half an inch, readings on a water manometer being taken at each step. Velocity was estimated using the pitot head equation and introducing a calibration coefficient of unity as specified by the manufacturers.

Resulting velocity indications, it must be realised, were not those of total velocity of flow, but only of its component in the horizontal direction. Although the nappe of the sideways flow was confined by the dip and weir plates and thus its width was constant, it did vary in the vertical plane, and thus without the ability to vary the inclination of the pitot tube holder the effect of the vertical component of velocity could not be taken into account.

This made the readings of velocity of only a limited application, useful as comparative values applied to the distribution of velocity, but of a doubtful value as means of calculation of the rate of discharge.

In the region upstream of the dip plate, ie: in the approach channel, velocity was estimated using the 'drag-on-sphere' method of measurement.

One of the instruments shown in Fig. 4.13, 4.15 and 4.16 was fitted into a depth gauge holder, this in turn being placed on the rails supported on the walls of the channels. This arrangement
provided a very accurate positioning of the 'point of attachment' of the thread or a needle on which the ball was fixed. Unfortunately this did not apply to the 'point of measurement' situated theoretically at the centre of the sphere. This was displaced from its still water position horizontally in the downstream direction by \( L \sin \theta \), and vertically by \( L \left( 1 - \cos \theta \right) \). The estimations of velocity were thus not carried out along a single vertical line, but at a number of points determined by the vertical adjustment of the depth gauge holder micrometer screw and the displacement of the sphere from the still water position. This variation, together with the corresponding velocity distribution, is shown in Fig. 5.1 for one of the measurements carried out with sphere B2.

As in the case of the pitot tube, the vertical movement of the holder of the drag-on-sphere apparatus was in half inch steps. But, as can be seen in Fig. 5.1, the real vertical movement of the sphere is dependent on its horizontal displacement.

The procedure of measurement was as follows: Having decided on the point of measurement in the horizontal plane, the starting point was usually with the tip of the steel tube just touching the surface of the water. In this highest position of the holder the sphere was about 2 inches (50 mm) below the surface of the water. This distance is equal to the length of the link connecting the sphere to the holder. The horizontal displacement of the sphere was estimated by the movement of an eyepiece mounted on a graduated scale on the side wall of the channel. This accuracy of measurement was only partially justified, as in some of the positions tested the sphere tended to oscillate due to the turbulence of the current and inaccuracies in construction of the spheres.
Fig. 5.1
Positions of Sphere and velocity distribution
Drag on Sphere
1. sphere position
2. end of tube
3. still water
1" actual sphere elevation
5 sphere position
16. water surface
U cms
16 12 8 4
Vertical position of the tip of the steel tube relative to the water surface and the lateral displacement of the centre of the sphere were recorded. Using the appropriate calibration chart (Fig. 4.17 to 4.23) velocity corresponding to a recorded value of displacement was obtained. The true position of the sphere was estimated by adding the length of the connecting link to the recorded position of the tip of the steel tube, and then applying a vertical correction, as indicated by the relationship between horizontal displacement and vertical elevation for the sphere used. This was obtained from one of the graphs Fig. 5.2 a to g. Thus the value of velocity and corresponding point in the fluid was found (see Fig. 5.1).

The flow in the approach channel upstream of the dip plate is predominantly horizontal, thus the fact that the measurement was not done on a vertical line but along a curve did not materially influence the results. Much more important were other factors, some of which were mentioned in Chapter 4.1. These were the curvature of the nylon thread connecting link which effectively changed the distance between the tip of the steel tube and the sphere. When nylon thread was replaced by darning needles (spheres B2 and B5), the weight of the needle changed the effective weight of the sphere.

In addition, the shape of the spheres was not perfect. This might have caused changes in the assumed value of drag coefficient. Although the diameter of each sphere was measured on at least three different axes, discrepancies in shape might have been present, resulting in errors of estimation of both volume and frontal area.

As a result, the values of velocity were not utilised in any calculations, but were used in a qualitative way only, as an illustration of the way in which the presence of the dip plate affects the velocity distribution in the approach channel.
Fig. 5.2 a Sphere B1

Drag on Sphere
Relationship between horizontal displacement and vertical elevation of spheres
Fig. 5.2 c  Sphere B3

Drag on Sphere

Relationship between horizontal displacement and vertical elevation of spheres
Fig. 5.2 e  Sphere B5

Fig. 5.2 f  Sphere R1

Drag on Sphere

Relationship between horizontal displacement and vertical elevation of spheres
Fig. 5.2 g  Sphere R2
Drag on Sphere
Relationship between horizontal displacement and vertical elevation of spheres
6.0 SUMMARY AND DISCUSSION OF EXPERIMENTAL RESULTS

6.1 Suppressed (Full width) Weir

It is usual to divide the flow over rectangular sharp edged weirs into two types. When the width of the weir is smaller than that of the approach channel and the nappe does not extend over the whole width of the weir, the flow is said to be contracted. These contractions are caused by transverse components of velocity at the sides of the weir plate. However, when the weir plate extends over the whole width of the channel, the components of velocity in transverse direction are absent and the end contractions are said to be suppressed.

This conventional approach seems to be even more important in the case of a weir provided with a dip plate. In this configuration the flow just upstream of the weir plate is considerably more complicated than in the case of a free weir without a dip plate, and the degree of complication is dependent on whether the width of the channel is the same or larger than that of the weir.

It is thus proposed to discuss the less complicated situation first. This occurs when the end contractions are suppressed in the case of a full width weir.

The shape of the water surface and the pattern of flow is shown qualitatively in Fig. 6.1.

Upstream of the dip plate the water level was found to be horizontal in virtually all cases tested. In some instances a slight elevation of the level not exceeding 0.02 inch (about 0.5 mm) was observed just upstream of the dip plate. This increase in the water level occurs due to the formation of a roller of separated flow upstream of the dip plate. This separation of flow is caused by the deceleration of the top layers of water due to the presence of the dip plate.
The existence of the roller and the consequent reversed flow at the top of the channel was confirmed on a number of occasions, when it was observed that perspex filings sprinkled on the surface of the water just upstream of the dip plate moved in the upstream direction, away from the dip plate. However, if perspex filings were sprinkled on the surface of the water at a distance greater than 1.5 m upstream of the dip plate, the direction of movement of these filings was downstream towards the dip plate.

The result of this counter flow is the meeting of the two surface currents at a distance of between 0.75 m to 1.0 m upstream of the dip plate.

The line of encounter of the two currents formed a slight ripple on the surface of the water which could be observed even without the use of perspex filings. The line was usually normal to the axis of the channel, the deviation from that direction, if present at all, never exceeding ten degrees.

The phenomenon just described was observed on a number of occasions, even when the level of water in the approach channel was seen to be constant both in the axial and transverse directions.

As can be observed in Fig. 6.1, the shape of the water surface downstream of the dip plate is considerably more complicated than that upstream.

The shape of the water surface and the pattern of flow is also illustrated in Fig. 6.2 to 6.8. These photographs have been taken in the narrow (20 mm wide) flow visualisation channel.

It will be noticed that in all cases, irrespective of the depth of immersion of the dip plate and its distance from the weir plate, the flow can be divided into two regions. One, immediately downstream of the dip plate, is characterised by a relatively low level of head; also, if perspex filings are sprinkled on the surface, these move upstream towards the dip plate, thus indicating the presence of a roller of separated flow. The other region of flow is situated immediately upstream of the weir plate.
Here the water level is higher than in the first region, usually reaching its greatest height directly over, or in the immediate neighbourhood of the weir plate. Perspex filings deposited on the surface of the water in this region were immediately swept downstream, indicating high velocity of flow.

An indication of the length of the region of reversed flow at the foot of the weir was obtained from observation of the polystyrene beads which came to rest on the bottom of the channel upstream of the weir plate. Most of these beads were originally introduced into the water some distance upstream of the dip plate.

A better picture of the extent of this region is obtained from the photographs of the flow visualisation study carried out in the small, narrow glass sided channel (Fig. 6.2 to 6.8).

It has to be remembered that, due to its small width, the studies in the flow visualisation channel can serve only as a qualitative measure. Further, the picture thus obtained can only be used as a guide to the behaviour of water in the weir with suppressed end contractions, as no transverse currents are possible.

No components of flow in the direction normal to the plane of symmetry of the channel were observed in the experimental flume during any of the runs when the width of the approach channel was equal to that of the weir. Some occasional ripples were seen on the surface of the water downstream of the dip plate; these appeared only during some of the runs, usually when the distance between the dip and weir plate was small, and were of a transient character.

As a result of the above observations the flow can be broadly divided into two types: mainstream and areas of separated flow. The mainstream starts in the approach channel, where it extends over the whole depth and width of the passage. As it approaches the dip plate the flow undergoes
a contraction and the first area of separated flow is formed upstream of the plate and near the surface of the water (Fig. 6.1). The velocity of the mainstream is thus gradually increased (see Fig. 6.36). (p.162)

After passing underneath the dip plate, the mainstream is turned in an upward direction to pass between the dip and weir plate, and after another change of direction discharges over the sill of the weir.

Two areas of separated flow are formed in the region between the dip and weir plates. The action of these is to constrict the cross-sectional area of the mainstream still further.

One of the separated flow rollers is situated at the surface of the water just downstream of the dip plate, the other at the foot of the weir plate.

The separated flow area at the foot of the weir has been observed by a number of experimenters working on the problem of flow over rectangular weirs, both sharp edged and broad crested (8, 14, 32, 36, 39, 46, 52).

This type of roller is caused by the presence of a stagnation point situated directly at the foot of the weir plate and therefore it will be formed independently of whether the dip plate has been introduced into the approach channel. The presence of the dip plate will only affect the extent of the area of flow separation. A study of Fig. 6.2 to 6.8 shows that an increase of the depth of immersion of the dip plate has the tendency to decrease the affected area but, at the same time, the intensity of rotating motion is increased. Fig. 6.9 shows the comparative intensity and extent of the roller at the foot of the weir plate when the dip plate is removed.

The two areas of separated flow, situated just upstream and downstream of the dip plate at the free surface of the water, are formed as a direct result of the introduction of the dip plate into the flow. The roller upstream of the plate is formed due to deceleration and finally stagnation
of the upper layers of flow approaching the plate, with a simultaneous acceleration of that part of flow which makes up the mainstream and passes underneath the dip plate. The separated flow on the downstream side of the dip plate is of a 'closed bubble' type. It may be considered to be a form of wake caused by a high velocity mainstream issuing from underneath the dip plate.

The relationship between the head downstream of the dip plate \( h \) and the magnitude of the upstream head \( H \) is shown in graphical form in Fig. 6.10 to 6.15.

Each figure refers to a given constant value of distance between the dip and weir plate. The individual curves, formed by the experimental points, describe the relationship at a predetermined depth of immersion of the dip plate.

The choice of co-ordinates was dictated by the wish to compare the experimental results with the values of the downstream head predicted analytically using equation (3.12) deduced previously in Chapter 3.1.

Calculated values, when superimposed on the experimental results, form a single curve for a given value of \( 1 \) (distance between dip and weir plate). The influence of depth of immersion of the dip plate was not included in the analytical considerations and has to be deduced from the experimental results.

Analysing experimental curves drawn in Fig. 6.10 to 6.15, it will be observed that in all of them, irrespective of the distance between the dip plate and the weir, the curve corresponding to a larger depth of immersion lies above that drawn for a smaller depth. Thus, at any given value of upstream head \( H \) and distance between the dip and weir plate \( 1 \), the experimental value of the downstream head \( h \) is larger for a larger depth of immersion of the dip plate. However, that effect of dip plate immersion decreases as the distance between the dip and weir plate is increased.
Thus analysing the changes in value of the downstream head when the head upstream of the dip plate $H = 0.5$ ft, it is observed that when the distance between the plates is 0.5 in (Fig. 6.10), $h$ increases from 0.13 ft at $d = 0.0$ in, to 0.248 ft when $d = 4.0$ in, a nett change of almost 0.12 ft, or approximately 30%, based on the higher of the two figures. However, when the distance between the dip and weir plate is 3.0 in (Fig. 6.14), the corresponding values of $h$ are 0.28 ft for $d = 0.0$ in and 0.33 ft for $d = 4.0$ in, the increase of 0.05 ft or about 15% based on the figure for $d = 4.0$ in. The difference is even smaller as $l$ is increased to 5.0 inches.

It will also be observed that both in the calculated and experimental results the values of the head downstream of the dip plate are larger when the distance between the dip and weir plate is increased. In the calculated results this trend was expected as a consequence of the form of equation (3.12); it was satisfying to observe that it was also followed by experimental values.

When the relative position of the calculated and experimental results are compared, it will be noticed that for relatively small distances between the dip and weir plate the calculated results fall within the lower range of the experimental values. However, as the distance between the plates is increased, the calculated values move towards the higher range of experimental results. This phenomenon is a direct result of the formation of a roller of separated flow downstream of the dip plate, and the effect its strength and extent has on the magnitude of head in that region.

The effect of the separated flow downstream of the dip plate can also be deduced by the study of graphs drawn in Fig. 6.16 to 6.19. These figures show the effect of reversal of the dip plate, the two positions of the dip plate being referred to as 'Side A' and 'Side B'.
As mentioned in Chapter 4.1, the dip plate was made of \( \frac{3}{8} \) inch (9.5 mm) thick 'Tufnol' plate chamfered at the bottom edge at 45°.

Side A refers to the dip plate fixed in such a way that the chamfered side faces downstream, the upstream face vertical down to the bottom edge (Fig. 6.1). Side B indicates that the position of the dip plate is reversed, the chamfered side facing upstream and the lowest edge of the plate being \( \frac{3}{8} \) inch nearer to the weir plate. Photographs of a flow visualisation channel showing an example of the effect of the dip plate reversal on flow pattern can be seen in Fig. 6.20 a and b. A diagrammatic representation of the flow pattern in the two cases is shown in Fig. 6.21.

With the flat face facing upstream (Side A), the separation streamline starts upstream of the dip plate at the water surface, moves downwards and downstream touching the tip of the dip plate. On the downstream side of the dip plate the downward movement continues and the lowest point of its trajectory is reached both below and downstream of the dip plate.

When Side B faces upstream, the separation streamline was observed to follow a similar path, but the lowest point of its trajectory was seen to coincide with the tip of the dip plate. Thus it is situated higher and is further away from the weir plate than in the case of Side A, leaving a larger free passage for the mainstream flow. Consequently the separated flow is smaller in extent and the head, just downstream of the dip plate, lower.

The pattern of flow and the value of head just downstream of the dip plate is of considerable importance when solving the problem of separating 'clean water' from sewage, in the case of storm water overflows (1, 20, 49, 60, 61, 71). However, the ability to predict the rate of flow over the weir is of the utmost importance in every kind of use to which the weir may be put.
As outlined in Chapter 3.2, the estimate of the rate of flow over the weir is obtained using equation (3.13). In the first instance the prediction of the values is made with the assumption of a coefficient of discharge equal to unity. The values thus calculated, together with the rates of flow obtained experimentally, are plotted as a function of $H$ (head upstream of the dip plate) in Fig. 6.22 to Fig. 6.27.

Each graph refers to a predetermined distance between the weir and dip plate, each curve on the graph shows the relationship for a given value of the depth of immersion of the dip plate. These experimental curves are so close together that an 'experimental average' could easily be drawn for each distance between the dip and weir plate. It was also noticed that the trend of spacing of the individual curves was not continuous. As the depth of immersion is increased (the dip plate lowered from its original position of the lowest edge level with the sill of the weir) the discharge, for a given upstream head, decreases until a minimum value is reached. This occurs in every case at a point at which the depth of immersion is equal to the distance between the dip and weir plates. When the depth of immersion is increased further, the discharge over the weir increases.

Analysing Fig. 6.28 to Fig. 6.31 which show the effect of dip plate reversal on discharge, it is noted that in all cases the discharge is smaller when Side B is facing upstream. This phenomenon is in agreement with the findings of Fig. 6.16 to Fig. 6.19, where it was found that, with the same depth of immersion and distance between the dip and weir plate, the head downstream of the dip plate was always larger when Side A was facing upstream.

It will also be noticed that the difference in the value of discharge for the two positions of dip plate decreases as the distance between the dip plate and weir is increased. This is easily explained as the magnitude
of the mainstream makes the effect of changes in separated flow less important.

In all cases the shape of the curves formed by the results calculated, using equation (3.13) and the value of the coefficient of discharge equal to unity, conforms perfectly to the experimental results. However, the calculated values of discharge over the weir are, at all configurations, much higher than the rates of flow measured experimentally. This indicates that a more realistic, i.e. $C_w < 1.0$ value of the coefficient of discharge has to be used.

Graphs on Fig. 6.33 to Fig. 6.35 were drawn in order to observe the effect of the distance of the dip plate from the weir when the depth of immersion of the former is kept constant. The measured rate of flow over the weir is plotted as a function of the upstream head.

It is immediately noticeable that on each of the three graphs, as the distance of the dip plate from the weir increases the curves, which for the small distances were concave downwards, gradually decrease in curvature and eventually become concave upwards. Thus with the increase of the distance between the two plates the relationship tends to the free weir case. It must, however, be noted that the change in relationship is not of a simple form:

$$Q = K H^n$$

where $n$ is a constant whose value would be dependent on the distance between the two plates.

Observing closely the shape of the curves, a point of inflection will be noticed in virtually all of them. This change in curvature is also suggested by the form of equation (3.13), which when expanded would form an infinite binomial series in terms of powers of $H$. 

6.1a Velocity Distribution Measurements

Some of the limitations and problems encountered when attempting to measure velocity and its distribution in the approach channel have already been mentioned in Chapters 4 and 5. The range of the pitot tube manometer readings was so small that no reliance could be placed on them and as a result a new system of velocity measurement had to be devised. The system designed utilised the force of drag on a small sphere immersed in water. The limitation on accuracy and reliability of the device was due to the undeterminable extra force exerted on the attachment. If the sphere was attached by nylon thread, drag was exerted on it, whereas if a steel needle was used as the means of attachment both the drag force on it and its weight affected the results. Consequently, the measured displacements of the sphere were used as comparative indications of the velocity distribution rather than the measure of true velocity of flow.

In this however, the results, even if numerically inaccurate, are of importance as they indicate the way in which the pattern of flow is affected by the introduction of the dip plate into the channel.

The original intention was to establish the variation of velocity both in the vertical and the horizontal (transversely to the axis of the approach channel) direction. However, when it was realised that no real practical information would be gained due to the unreliability of the method, a gradually decreasing number of measurements was taken. The purpose of taking them at all in the later stages of experimentation was to check whether a change in the dip plate position might in some circumstances result in a basic change in the flow pattern.

The measurement was consequently reduced from four vertical traverses on the centre line of the channel with two horizontal, to a single traverse (vertical) taken at a distance of 4.5 ft upstream of the dip plate.
The overall shape of the velocity distribution followed the expected pattern, thus only one example is shown in Fig. 6.36 a to d. This refers to the distance between the dip and weir plate of 3.0 inches and the depth of immersion of the dip plate of 2.5 inches below the sill of the weir. The rate of flow over the weir is 0.368 ft³/s (0.00104 m³/s) and the head upstream of the weir 4.7 inches (120 mm). The velocity traverses were done on the centre line of the channel at distances of 7 ft, 5 ft, 3 ft and 1 ft upstream of the dip plate. The sphere used was attached to the tube by means of a steel needle and thread (see Fig. 4.15), i.e.: Sphere B2.

It will be noticed that the measurements illustrated in Fig. 6.36 start some distance below the free surface of the water. The highest point at which measurement was made is such that the tip of the supporting tube was just under the surface of the water. In this way it was ensured that the needle holding the sphere was always completely immersed in water and consequently the conditions under which the measurements were made were as constant as possible.

The inspection of velocity distribution indicates that the effect of the dip plate becomes gradually more pronounced the nearer to it the velocity traverse is carried out. However, it is also seen that even at the first set of measurements carried out 7 ft upstream of the plate, its presence affects the velocity distribution. The maximum value of velocity is well below mid depth. This is in marked contrast to Fig. 6.37 on which the velocity distribution in a channel without dip plate is plotted. In this case the maximum velocity is situated considerably above the mid depth point.

The difference in the elevation of the maximum velocity position in the two cases is due to the introduction of an obstruction into the flow. The dip plate lowers the velocity of the top layers of flow, while in the case of the free weir the lower portion of the channel is obstructed by the weir plate.
Observing changes in velocity distribution along the channel, it is seen that at first (Fig. 6.36a) the velocity increases gradually with the increase of depth, reaching a maximum velocity at a point below the mid depth of the channel. As the position at which the velocity traverse is taken gets closer to the dip plate (Fig. 6.36b and 6.36c) the velocity distribution changes in character. The top layers are slowed down while the increase of velocity with depth becomes curvilinear in character. The position of the maximum velocity gradually gets nearer to the mid height of the passage below the dip plate. In the close neighbourhood of the dip plate (Fig. 6.36d) the flow divides itself into two regions. The velocity in the upper region is considerably reduced, the high velocity lower region will change into the mainstream passing under the dip plate and eventually flow over the weir.

6.1b Pattern of Flow Downstream of the Dip Plate

Most of the information about the flow in the region between the dip and weir plate is obtained from the flow visualisation channel. It has to be borne in mind, however, that the information is of purely qualitative nature. This refers in particular to some atypical results when, due to an involved pattern of flow, the movement of polystyrene beads and perspex dust did not show on any of the photographs taken.

These phenomena - that of a double, and in one instance a treble roller downstream of the dip plate - are shown in Fig. 6.38a and 6.38b, and occur at a large dip plate - weir plate distance. In fact, the treble roller was not observed in the large channel and was seen in the flow visualisation channel only by chance. The diagrams are copies of scaled sketches taken during visual observations of the pattern of flow. A double roller seems to be an alternative configuration to the one shown in Fig. 6.1. Although its start was never observed, it is assumed that it develops when the downwash of the single roller takes place before the dip plate is reached.
Once developed, it is a persistent phenomenon (a change from a two roller to a single roller configuration has never been observed).

A treble roller is an unstable phenomenon, the third downstream roller appearing only periodically. It is probable that its initiation and disappearance is caused by the instability of the region of separated flow at the foot of the weir plate.

It is also probable that it is that instability, mentioned previously when discussing flow separation in Chapter 3.4, which caused occasional oscillations of the nappe issuing from the weir in the main channel. This phenomenon was noticed in some configurations during discharge calibration tests. Usually at large flows, with large depths of immersion of the dip plate and small distances between the dip and weir plate, the nappe leaving the weir started oscillating.

At first it was thought that the reason lay in an occasional decrease of upward momentum by the mainstream as it approached the crest of the weir. However, on reflection it was concluded that the reason must lie in the bubble of separated flow at the foot of the weir plate being drawn over the sill of the weir. This action momentarily increases the effective height of the weir, thus changing the position and angle of the nappe. Although once started the phenomenon continued for some time, it was extremely difficult to replicate.
6.2 Weir with Unsuppressed End Contractions

6.2.1 Approach Channel 16 inches wide ($B/b = 1.6$)

The flow through an unsuppressed rectangular weir provided with a dip plate can be divided, in a way similar to the full width weir flow, into two distinct regions.

The first of the two regions covers the approach channel upstream of the dip plate. The pattern of flow here is virtually identical with the one observed in the suppressed weir. The head of water is found to be virtually constant both in the longitudinal and transverse direction. The surface currents observed by sprinkling perspex filings on to the surface of the water indicate the existence of a region of reversed flow (a roller) upstream of the dip plate. This region extends for up to half a metre (1.7 ft), and in a way similar to the full width weir its edge does not deviate by more than $10^\circ$ from the line normal to the axis of the channel.

The pattern of the velocity distribution along the centre line of the approach channel is similar to the one described in the case of a full width weir. However, the variation of velocity along the line normal to the axis of the channel is more pronounced. The velocities on the centre line are higher than those measured at 6 inches (in the case of the 16 inch wide channel) and 6 inches and 9 inches (in the case of the full width channel) away from the centre line. The difference becomes more pronounced as the point of measurement approaches the dip plate. The measurements are not sufficiently accurate to establish a functional relationship between their value and distance. The changes are, however, sufficiently pronounced to be noted.

The most pronounced difference between the pattern of flow in the suppressed and unsuppressed weir case occurs in the region
situated between the weir and dip plates. In the case of a weir with suppressed end contractions, the head of water downstream of the dip plate is virtually constant along the width of it.

If the width of the approach channel is larger than that of the weir, the head downstream of the dip plate varies considerably with the transverse distance from the channel centre line.

Two types of variation have been noticed; both can be seen in Fig. 6.39. The figure shows the variation of head when the dip plate was placed 2 inches away from the weir, with its tip 2 inches below the sill level.

For the sake of clarity of figure, the distribution of the head for a number of flow rates (in particular for small discharges) have been omitted. For the same reason the vertical scale used is twice that of the horizontal; this makes for a clearer, although slightly distorted picture. The levels of the upstream head are also indicated on the diagram.

At large heads, the level of water, highest at the edge of the channel, decreases slowly at first until the side edge of the weir is reached. The rate of change of head is then considerably increased, but further towards the centre of the channel the change becomes more gradual until the lowest level is reached on the centre line of the weir.

A much more common type of transverse variation of head is the one in which the water level, highest at the edge of the channel, follows the previous pattern of change in the transverse direction but just before a centre line of the weir a ridge of higher levels is formed. This ridge is the result of the meeting of two flows directed towards the centre of the channel.
It can be seen in Fig. 6.40 that the ridge extends all the way towards the dip plate and spreads along its downstream side. Thus it is this height which has to be considered equal to the downstream head.

The relationship between the head on the downstream and upstream side of the dip plate for the channel width of 16 inches is shown in Fig. 6.41 to 6.45. Consistent with the case of the full width weir, the dip plate was placed with Side A directed upstream, as the basic configuration.

The curves are similar in shape to those obtained in the case of the suppressed, full width weir. Increase of the depth of immersion of the dip plate, when the distance between the dip and weir plate is kept constant, results in the increase of downstream pressure. This effect is much smaller than in the full width weir and consequently the use of 'mean experimental' curve for the comparison purposes would be quite justified.

The difference between the 'mean experimental' and calculated results diminishes with the increase of the distance between the dip and weir plate, and when that reaches a value of 3 inches the calculated curve passes through the middle of the experimental range (Fig. 6.45).

It will be noticed however, that whereas in the case of the full width weir the calculated results were on the whole higher than the experimental, in the case of the weir with unsuppressed end contractions the reverse is true. This result is easily explained. The experimental values of the head downstream of the dip plate were in most cases measured at the top of the ridge formed by the two converging transverse currents and were thus overestimates of the assumed values. Of the two types of surface profiles shown in Fig. 6.39, the smooth profile with the lowest head extending over a large fraction
of the weir width is the nearest to the idealised case, assumed in the unidimensional calculations.

The effect of the dip plate reversal is shown in Fig. 6.46 and Fig. 6.47. Here again an effect similar to that observed in the full width weir is seen. For a given value of the upstream head the head downstream of the dip plate is greater when Side A of the dip plate is facing upstream.

Not unexpectedly the transverse flow in the region between the dip and weir plate is found to be symmetrical with respect to the centre plane of the channel. This symmetry is observed both in the distribution of head (Fig. 6.39) and in the measurements of velocity distribution shown in Fig. 6.48. The velocity readings were taken on the mid line of the gap between the dip and weir plate by means of a pitot tube connected to the U-tube manometer. The vertical stem of the pitot tube was aligned with the edge of the weir plate. Although, as mentioned in Chapter 5.4, the accuracy of the readings cannot be assumed to exceed ± 5%, it is immediately apparent that the velocity distribution and the resulting transverse flow on the two sides of the weir are virtually identical.

The rate of flow over the weir expressed as a function of the upstream head is shown, for various dip plate - weir plate distances, in Fig. 6.49 to 6.53. Each figure shows a number of experimental results for various depths of immersion of the dip plate as well as the calculated values (using equation (3.13)) with the weir coefficient of discharge assumed equal to unity. The spread of experimental points is such that one can, without undue inaccuracy, refer to a 'mean experimental' curve for a given distance between the dip plate and weir. Although in each case individual curves for each of the depths of immersion could be drawn, there would exist an overlap of the bands
of uncertainty. As in the case of the full width weir, the points get closer together when the distance between the weir and dip plate is increased.

It is, however, noticed that the rate of flow at any pre-set upstream head is larger in the case of the weir with unsuppressed end contractions than that in the full width weir. This is easily explained if it is remembered that in the former case, in addition to the purely longitudinal flow, there are two transverse currents contributing to the total discharge over the weir. This situation does not occur in the case of the weir not fitted with the dip plate (B.S. 3680 pt. 4).

The similarity in shape between the 'mean experimental' and calculated curves indicates that the deviation from the unidimensional flow assumed in deducing equation (3.13) can still be taken into account by introduction of a coefficient of discharge.

The effect of reversal of the dip plate is shown in Fig. 6.54. Only two depths of immersion at one dip plate - weir plate distance are illustrated. The reversal of the dip plate from Side A facing upstream to Side B results in the decrease of flow at a given value of upstream head. This finding is in agreement with the results shown in Fig. 6.46, indicating a decrease in the head downstream of the dip plate when its position is reversed.

Fig. 6.55 and Fig. 6.56 show the relationship between the discharge and upstream head for various distances between the dip and weir plate, the depth of immersion of the dip plate being held constant.

The general shape of the curves is identical in both figures and also virtually indistinguishable from those shown in Fig. 6.33, 6.34 and 6.35 which refer to the full width weir. A detailed comparison can be made between Fig. 6.33 and Fig. 6.55. Both diagrams refer to
the same depth of immersion of the dip plate, namely \( d = 0.0 \) (the bottom edge of the dip plate level with the sill of the weir). It is noticeable that for any given distance between the weir and dip plate the rate of flow is higher in the case of the contracted weir than in the full width one. This is due to the existence of the 'side flow' originating in the corner areas between the weir and dip plate where the head downstream of the dip plate is almost equal to that upstream of it.

The comparison of Fig. 6.55 and Fig. 6.56 brings out yet another factor. In both figures the configuration of channel - weir width ratio, depth of immersion of the dip plate is the same, the difference lies in the dip plate Side A facing upstream in Fig. 6.55 and Side B in Fig. 6.56.

The fact that the discharge in the case of Side A is larger in all cases has been mentioned before. However, if attention is directed to the difference in the values of discharge for each individual configuration, it will be noticed that the difference becomes smaller when the distance between the weir and dip plate is increased. This observation confirms the proposed explanation of the reason for the difference between the flow under the two configurations. The larger the dimension of the passage, the smaller will be the effect of contraction caused by the reversal of the dip plate.

### 6.2.2 Approach Channel 24 inches wide (\( B/b = 2.4 \))

Experimental results obtained from tests on a full width channel, not provided with the additional side plates, are similar to the ones obtained in the case of the channel - weir width ratio of 1.6 (additional 'false sides' placed at 8 inches distance from the centre line of the channel).
The head downstream of the dip plate varies in a way similar to that observed with channel - weir width ratio of 1.6. At high upstream heads, water level downstream of the dip plate, highest at the edge of the channel, decreases towards the centre plane of the weir; lowest level extends to slightly less than 2 inches on either side of the centre line of the weir. An alternative to the central plateau is the formation of a central elevated ridge. In this configuration the level of the water decreases towards the centre, reaches a minimum and then forms an elevated ridge extending over approximately 2 inches of the central part of the weir. No reason for the preferential formation of one or the other type of surface could be observed. However, studying Fig. 6.57 to Fig. 6.62, which show experimental relationship between the head downstream of the dip plate and the upstream head, it will be noticed that some of the curves exhibit abrupt changes. These occur at the points where one type of surface (with a central ridge) changes into the other (with a central plateau). The changes can be observed in Fig. 6.57 for depth of immersion of the dip plate \( d = 0.0 \) inches, Fig. 6.59 for \( d = 2.5 \) inches and Fig. 6.61 for the curve describing the relationship at \( d = 2.5 \) inches.

It is noticed that experimental points corresponding to the lower (plateau) type of the downstream head configuration conform much better to the calculated values. This observation was expected, as the central ridge is the result of the meeting of two side currents whereas the plateau configuration represents a more realistic head variation.

When the distance between the weir and dip plate is relatively small, the values of downstream head predicted by the unidimensional analytical equation (equation (3.12)) fall below experimentally obtained ones. The prediction improves as the distance is increased.
The distance above which the correlation between calculated and experimental values becomes near perfect, for both the channel - weir width ratio of 1.6 and 2.4, is 1.5 inches.

The rate of flow over the weir expressed as a function of head upstream of the dip plate is shown in Fig. 6.63 to Fig. 6.68. The shape of the 'mean experimental' curve for any configuration again conforms to the calculated results. The numerical difference between the two values is the result of using in the calculations the coefficient of discharge equal to unity.

For any given distance between the weir and dip plate the experimental points denoting different depths of immersion of the dip plate lie so closely together that there is a complete overlap of the bands of uncertainty. This closeness of the curves increases with the increase of the distance between the weir and dip plate. Both the above effects, although occurring to a slightly lesser degree, were observed in the results of tests for a channel - weir width ratio of 1.6. The reference to the 'mean experimental' curve is thus more justified the larger that ratio becomes.

It was also noticed that for any given configuration, ie: distance between the weir and dip plate and depth of immersion of the latter, the measured rate of flow over the weir is larger than for either the full width weir or the channel - weir width ratio of 1.6. This observation was confirmed by the calculated discharge curve for any given value of the distance between the weir and dip plate being higher the larger the width of the approach channel.

The effect of the reversal of the dip plate is illustrated in Fig. 6.69 to Fig. 6.71. For the sake of clarity only two depths of immersion of the dip plate are shown on any figure (this principle was also applied in cases of uncontracted weir and channel - weir
width ratio of 1.6). The pattern of results is found to be compatible with the previous findings in that the flow with Side B facing upstream is smaller in all configurations. The difference in flow resulting from the reversal of the dip plate decreases with the increasing distance between the weir and dip plate. This phenomenon has previously been noticed in the case of the full width weir and the channel - weir width ratio of 1.6; and it indicates a decreasing effect of jetting of the mainstream flow when the size of passage becomes larger.

A similar decrease of the effect of the dip plate position reversal with the increase of passage area is noticed when the channel - weir width ratio is changed.

The effect of changing the distance between the weir and dip plate when the depth of immersion of the latter is kept constant is shown in Fig. 6.72.

The pattern of results in the channel - weir width ratio of 2.4 is the same as in the previous two cases. Curves formed by the experimental points exhibit a change of shape as the distance between the weir and dip plate is changed. At small distances the curves are predominantly concave downwards, but as the distance is increased this tendency gradually diminishes and a concave upwards curve becomes predominant. However, the discharge - upstream head relationship is not, as can be deduced from equation (3.13), of a simple single power index form.

When the values of discharge at the same configurations (ie: same l and d) are compared for the three widths of the approach channel tested (Fig. 6.33 for the full width weir, Fig. 6.55 for the channel - weir width ratio of 1.6, and Fig. 6.72 corresponding to the value of that ratio of 2.4), it is noticed that these become larger for the greater values of channel - weir width ratio. This observation again
confirms the validity of equation (3.13). The value of coefficient A in that equation is proportional to the square of the value of the channel - weir width ratio. As the head downstream of the dip plate is a function of A, the rate of flow over the weir at any given upstream head must increase when the channel - weir width ratio becomes higher.
Fig. 6.1 - Diagrammatic representation of flow pattern
Fig. 6.2 Photograph of pattern of flow in a flow visualisation channel showing the three areas of separated (vortex) flow.

The configuration A 10/2, i.e.: side A, of the dip plate is facing upstream; the distance between the dip and weir plate is 10 units; the depth of immersion of the dip plate is 2 units (tip of the dip plate is 2 units below the sill of the weir).
Photographs of flow pattern in a flow visualisation channel
Fig. 6.5 Configuration B 4/2

Photographs of flow pattern in a flow visualisation channel

Fig. 6.6 Configuration A 3/1
Fig. 6.7 Configuration B 2/1

Fig. 6.8 Configuration A 2/1

Photographs of flow pattern in a flow visualisation channel
Fig. 6.9 This photograph in the flow visualisation channel shows the formation of a separated flow area at the foot of the weir plate.
Full width weir

Fig. 6.10 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

B = 10.0 in  \ l = 0.5 in

Dip plate side "A"

+ d = 0.0 in
\times d = 0.5 in
\downarrow d = 4.0 in

—_ calculated c = 1.0

band of uncertainty
Full width weir

Fig. 6.11 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

B = 10.0 in  l = 1.0 in
Dip plate side "A"

+ d = 0.0 in
x d = 0.5 in
o d = 1.0 in
φ d = 1.5 in
• d = 2.5 in
d = 4.0 in
--- calculated c ± 0.1
I band of uncertainty
Fig. 6.12 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\[ B = 10.0 \text{ in} \quad \ell = 1.5 \text{ in} \]

Dip plate side "A"

\[ \begin{align*}
+ & \quad d = 0.0 \text{ in} \\
\times & \quad d = 0.5 \text{ in} \\
\Phi & \quad d = 1.5 \text{ in} \\
\bullet & \quad d = 2.5 \text{ in} \\
\Phi & \quad d = 4.0 \text{ in} \\
\end{align*} \]

--- calculated \( c = 10 \)

\[ \text{band of uncertainty} \]
Fig. 6.13 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\[ B = 10.0 \text{ in} \quad l = 2.0 \text{ in} \]

Dip plate side "A"

<table>
<thead>
<tr>
<th>Band of uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ d = 0.0 in</td>
</tr>
<tr>
<td>× d = 0.5 in</td>
</tr>
<tr>
<td>○ d = 1.0 in</td>
</tr>
<tr>
<td>♦ d = 2.0 in</td>
</tr>
<tr>
<td>◦ d = 2.5 in</td>
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<tr>
<td>♠ d = 3.0 in</td>
</tr>
<tr>
<td>♤ d = 4.0 in</td>
</tr>
</tbody>
</table>

- Calculated \( c = 1.0 \)
Fig. 6.14 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

B = 10.0 in, \( l = 3.0 \) in

Dip plate side "A"

\[ \text{band of uncertainty} \]
Fig. 6.15 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

B = 100 in  l = 5.0 in

Dip plate side A

+ d = 0.0 in
• d = 2.5 in
♦ d = 4.0 in

--- calculated ± 10

I band of uncertainty
Full width weir

Fig. 6.16 - Head downstream of dip plate as a function of upstream head - effect of plate reversal

$B = 10.0 \text{ in} \quad l = 1.0$

Dip plate
side "A" \quad $d = 0.0 \text{ in} \quad + d = 4.0 \text{ in}$
side "B" \quad $d = 0.0 \text{ in} \quad \times d = 4.0 \text{ in}$

$\pm$ calculated $c = 1.0$

Band of uncertainty
Fig. 6.17 - Head downstream of dip plate as a function of upstream head - effect of plate reversal

B = 10.0 in  \ l = 1.5 in

Dip plate
side \"A\"  • d = 0.5 in  + d = 2.5 in
side \"B\"  • d = 0.5 in  × d = 2.5 in

-+- calculated c = 1.0

I band of uncertainty
Fig. 6.18 - Head downstream of dip plate as a function of upstream head - effect of plate reversal

\[ B = 10.0 \text{ in} \quad l = 2.0 \text{ in} \]

Dip plate
side \(A\) \quad \(\cdot d=0.5 \text{ in}\) \quad \(\cdot d=2.5 \text{ in}\)
side \(B\) \quad \(\cdot d=0.5 \text{ in}\) \quad \(\times d=2.5 \text{ in}\)

- Calculated \(c=1.0\)

Band of uncertainty
Full width weir

Fig. 6.19 - Head downstream of dip plate as a function of upstream head - effect of plate reversal

B = 10.0 in   \( \ell = 3.0 \) in

Dip plate
side \( A \), \( d = 0.0 \) in   \( + d = 1.0 \) in
side \( B \), \( d = 0.0 \) in   \( \times d = 1.0 \) in

--- calculated \( c \times 10 \)

| band of uncertainty
Fig. 6.20a  Dip plate Side A facing upstream  
Configuration A 3/1

Fig. 6.20b  Dip plate Side B facing upstream  
Configuration B 3/1

Photographs of flow pattern in a flow visualisation channel
Fig. 6.21 - Effect of plate reversal on flow pattern
Fig. 6.22 - Discharge over the weir as a function of upstream head - effect of depth of immersion

$B = 10.0 \text{ in}$  \hspace{1cm} $l = 0.5 \text{ in}$

Dip plate side "A"

- $d = 0.0 \text{ in}$
- $d = 0.5 \text{ in}$
- $d = 4.0 \text{ in}$

--- calculated $c = 10$

\[\text{band of uncertainty}\]
Fig. 6.23 - Discharge over the weir as a function of upstream head - effect of depth of immersion.

B = 10.0 in      l = 1.0 in
Dip plate side "A"     

+ d = 0.0 in
x d = 0.5 in
o d = 1.0 in
α d = 1.5 in
* d = 2.5 in
+ d = 4.0 in
--+-calculated c = 1.0
        I band of uncertainty
**Fig. 6.24** - Discharge over the weir as a function of upstream head - effect of depth of immersion

\[ B = 10.0 \text{ in} \quad l = 1.5 \text{ in} \]

Dip plate side "A":
- + \( d = 0.0 \) in
- × \( d = 0.5 \) in
- • \( d = 1.5 \) in
- • \( d = 2.5 \) in
- • \( d = 4.0 \) in

---

<table>
<thead>
<tr>
<th>+</th>
<th>•</th>
<th>×</th>
<th>--- calculated c = 1.0</th>
</tr>
</thead>
<tbody>
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<td>( d = 0.0 ) in</td>
<td>( d = 0.5 ) in</td>
<td>( d = 1.5 ) in</td>
<td>--- calculated c = 1.0</td>
</tr>
<tr>
<td>( d = 2.5 ) in</td>
<td>( d = 4.0 ) in</td>
<td>( d = 2.5 ) in</td>
<td>--- calculated c = 1.0</td>
</tr>
</tbody>
</table>

Band of uncertainty:

---
Fig. 6.25 Discharge over the weir as a function of upstream head - effect of depth of immersion

**B = 10.0 in  \( l = 2.0 \text{ in} \)**

Dip plate side "A"

\[ h \]

\[ H \]

\[ l \]

\[ d \]

\[ \pm \text{ band of uncertainty} \]

- + \( d = 0.0 \text{ in} \)
- x \( d = 0.5 \text{ in} \)
- o \( d = 1.0 \text{ in} \)
- \( d = 2.0 \text{ in} \)
- \( d = 2.5 \text{ in} \)
- \( d = 3.0 \text{ in} \)
- \( d = 4.0 \text{ in} \)

- - calculated \( c = 1.0 \)
Fig. 6.26 Discharge over the weir as a function of upstream head - effect of depth of immersion

B = 10·0 in  l = 3·0 in  

Dip plate side "A"

+ d = 0·0 in  o d = 1·0 in  
• d = 2·5 in  + d = 3·0 in  
• d = 4·0 in  --- calculated c = 1·0  
--- band of uncertainty
Fig. 6.27 - Discharge over the weir as a function of upstream head - effect of depth of immersion

B = 10.0 in  l = 5.0 in
Dip plate side A

+ d = 0.0 in
● d = 2.5 in
● d = 4.0 in
--- calculated c = 10

I band of uncertainty
Fig. 6.28 - Discharge over the weir as a function of upstream head - effect of plate reversal

\[ B = 10.0 \text{ in} \quad l = 1.0 \text{ in} \]

Dip plate
- side \( A \) : \( \cdot d = 0.0 \text{ in} \quad + d = 4.0 \text{ in} \)
- side \( B \) : \( \cdot d = 0.0 \text{ in} \quad \times d = 4.0 \text{ in} \)

\( \text{I band of uncertainty} \)
Discharge over the weir as a function of upstream head - effect of plate reversal

Fig. 6-29

B = 10.0 in  \( l = 1.5 \text{ in} \)

Dip plate
- side "A"  \( d=0.5 \text{ in} \)
- side "B"  \( d=0.5 \text{ in} \)
-  \( d=2.5 \text{ in} \)

I band of uncertainty
Fig. 6.30 - Discharge over the weir as a function of upstream head - effect of plate reversal

\[ B = 10.0 \text{ in} \quad l = 2.0 \text{ in} \]

Dip plate

- Side "A" • \( d = 0.5 \text{ in} \)
- Side "B" • \( d = 0.5 \text{ in} \)
- • \( d = 2.5 \text{ in} \)
- \( \times \) band of uncertainty
Full width weir

Fig. 6.31 - Discharge over the weir as a function of upstream head - effect of plate reversal

*B* = 10.0 in,  *l* = 3.0 in

Dip plate

- Side "A",  *d* = 0.0 in,  *d* = 1.0 in
- Side "B",  *d* = 0.0 in,  *d* = 1.0 in

I band of uncertainty
Fig. 6.32 - Discharge over the weir as a function of upstream head - effect of depth of immersion

$B = 10.0 \text{ in}$ \quad $l = 1.0 \text{ in}$

Dip plate side $B$

$+$ $d = 0.0 \text{ in}$

$*$ $d = 1.0 \text{ in}$

$*$ $d = 2.5 \text{ in}$

$*$ $d = 4.0 \text{ in}$

--- calculated $c = 1.0$

Band of uncertainty
Fig. 6.33 - Discharge over the weir as a function of upstream head - effect of dip plate distance

B = 10.0 in   d = 0.0 in
Dip plate side, A

- l = 0.5 in
- l = 1.0 in
- l = 1.5 in
- l = 2.0 in
+ l = 3.0 in
x l = 5.0 in
@ Free weir

| band of uncertainty
Full width weir

Fig. 6.34 - Discharge over the weir as a function of upstream head-effect of dip plate distance

\[ B = 10.0 \text{ in} \quad d = 2.5 \text{ in} \]

Dip plate side \( A \)

\[ \begin{align*}
\bullet & \quad l = 1.0 \text{ in} \\
\circ & \quad l = 1.5 \text{ in} \\
\ast & \quad l = 2.0 \text{ in} \\
+ & \quad l = 3.0 \text{ in} \\
\times & \quad l = 5.0 \text{ in} \\
\circ & \quad \text{Free weir}
\end{align*} \]

\[ \text{Band of uncertainty} \]
Fig. 6.35  Discharge over the weir as a function of upstream head - effect of dip plate distance

B = 10.0 in    d = 4.0 in
Dip plate side "A"

\[ Q = \frac{2 \times 10^{-3} \times B \times H^2}{d} \]

- \( l = 0.5 \) in
- \( l = 1.0 \) in
- \( l = 1.5 \) in
- \( l = 2.0 \) in
- \( l = 3.0 \) in
- \( l = 5.0 \) in
- Free weir

\[ \text{band of uncertainty} \]
Fig. 6.36 - Velocity distribution in the approach channel.
Fig. 6-36 - Velocity distribution in the approach channel
Fig. 6.37 - Velocity distribution in the approach channel - no dip plate fitted.
a) Double roller

b) Treble roller

Fig. 6.38 - Flow downstream of dip plate
Fig. 6.39 - Transverse variation of head downstream of dip plate

$B = 16 \text{ in} \quad l = 2.0 \text{ in} \quad d = 2.0 \text{ in}$
Fig. 6.40 Photograph of the nappe showing the central ridge of the water resulting from the meeting of the two transverse currents
Unsuppressed weir \( (B/b) = 1.6 \)

\[ h_{ft} \]

**Fig. 6.41** - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\( B = 16.0 \text{ in} \quad l = 0.5 \text{ in} \)

Dip plate side \( A \),

\( + d = 0.0 \text{ in} \)
\( \times d = 0.5 \text{ in} \)
\( o d = 1.0 \text{ in} \)
\( \phi d = 2.0 \text{ in} \)
\( \text{o} d = 3.0 \text{ in} \)

--- calculated \( c = 1.0 \)

Band of uncertainty
Unsuppressed weir (B/b) = 1.6

Fig. 6.42 - Head downstream of a dip plate as a function of upstream head - effect of depth of immersion

B = 16.0 in  l = 1.0 in
Dip plate side 'A'

--- calculated c=1.0
I band of uncertainty
Unsuppressed weir \((B/b)=1.6\)

**Fig. 6.43** - Head downstream of a dip plate as a function of upstream head - effect of depth of immersion.

- \(B=16.0\) in, \(l=1.5\) in
- Dip plate side „A“

- \(+ d=0.0\) in
- \(\oplus d=1.5\) in
- \(\ast d=2.5\) in
- \(\ast d=4.0\) in
- --- calculated \(c=1.0\)

| Band of uncertainty |
Unsuppressed weir \((B/b)=1.6\)

Fig. 6.44 - Head downstream of a dip plate as a function of upstream head - effect of depth of immersion

\[ B = 16.0 \text{ in} \quad l = 2.0 \text{ in} \]

Dip plate side, A

- \(d = 0.0 \text{ in}\)
- \(d = 1.0 \text{ in}\)
- \(d = 2.0 \text{ in}\)
- \(d = 4.0 \text{ in}\)

---

-+- calculated \(c=1.0\)

\[ \text{band of uncertainty} \]
Unsuppressed weir \((B/b)=1.6\)

Fig. 6.45 - Head downstream of a dip plate as a function of upstream head - effect of depth of immersion

\(B = 16.0\) in \quad \(l = 3.0\) in

Dip plate side "A"

\(d = 0.0\) in
\(d = 1.0\) in
\(d = 1.5\) in
\(d = 3.0\) in

--- calculated \(c = 1.0\)

I band of uncertainty
Unsuppressed weir \((B/b) = 1.6\)

**Fig. 6.46** - Head downstream of a dip plate as a function of upstream head - effect of plate reversal

-**B = 160 in** \(l = 0.5\) in
- Dip plate
  - Side "A" \(d = 0.0\) in + \(d = 3.0\) in
  - Side "B" \(d = 0.0\) in \(\times d = 3.0\) in
- Band of uncertainty
Unsuppressed weir \((B/b)=1.6\)

Fig. 6.47 - Head downstream of a dip plate as a function of upstream head - effect of plate reversal

- \(B = 16.0\) in
- \(d = 0.0\)
- Dip plate
  - Side "A": \(l = 0.5\) in, \(l = 3.0\) in
  - Side "B": \(l = 0.5\) in, \(l = 3.0\) in
- Band of uncertainty
Fig. 6.48 - Transverse flow between dip and weir plates

$B = 16$ in, $l = 2.0$ in, $d = 2.0$ in

--- left side    --- right side.
Unsuppressed weir \((B/b) = 1.6\)

Fig. 6.49 - Discharge over the weir as a function of upstream head - effect of depth of immersion

- \(B = 16.0\) in
- \(l = 0.5\) in
- Dip plate side "A"

- \(d = 0.0\) in
- \(d = 0.5\) in
- \(d = 1.0\) in
- \(d = 2.0\) in
- \(d = 3.0\) in

--- calculated \(c = 10\)

\(-\) band of uncertainty
Unsuppressed weir \((B/b)=1.6\)

**Fig. 6.50** - Discharge over the weir as a function of upstream head - effect of depth of immersion

- **B** = 16.0 in
- **l** = 1.0 in
- Dip plate side "A"
- \(d=0.0\) in
- \(d=1.0\) in
- \(d=2.0\) in
- \(d=4.0\) in
- - - calculated c=1.0
- I band of uncertainty
Unsuppressed weir \((B/b) = 1.6\)

**Fig. 6.51** - Discharge over the weir as a function of upstream head-effect of depth of immersion

\[\begin{align*}
B &= 16.0 \text{ in} \\
l &= 1.5 \text{ in} \\
\text{Dip plate side "A"} \\
+ d &= 0.0 \text{ in} \\
\approx d &= 1.5 \text{ in} \\
* d &= 2.5 \text{ in} \\
\cdot d &= 4.0 \text{ in} \\
+ \text{calculated } c = 1.0 \\
\text{I band of uncertainty}
\end{align*}\]
Unsuppressed weir \((B/b) = 1.6\)

**Fig. 6.52** - Discharge over the weir as a function of upstream head - effect of depth of immersion

- **B** = 16.0 in
- **l** = 2.0 in
- Dip plate side "A"

- \(d = 0.0\) in
- \(d = 1.0\) in
- \(d = 2.0\) in
- \(d = 4.0\) in
- Calculated \(c = 1.0\)
- Band of uncertainty
Unsuppressed weir $(B/b) = 1.6$

Fig. 6.53 - Discharge over the weir as a function of upstream head - effect of depth of immersion

$B = 16.0$ in \hspace{1cm} $l = 3.0$ in

Dip plate side "A"

- $d = 0.0$ in
- $d = 1.0$ in
- $d = 1.5$ in
- $d = 3.0$ in

---

Calculated $c=1.0$

\hspace{1cm} Band of uncertainty
Unsuppressed weir \((B/b)=1.6\)

**Fig. 6.54** - Discharge over the weir as a function of upstream head - effect of plate reversal

- \(B = 16.0\) in \(l = 0.5\) in
- Dip plate, side "A" - \(d = 0.0\) in \(d = 3.0\) in
- Dip plate, side "B" - \(d = 0.0\) in \(d = 3.0\) in
- Band of uncertainty
Unsuppressed weir (B/b)=1.6

Fig. 6.55 - Discharge over the weir as a function of upstream head - effect of dip plate distance

B = 16.0 in  \( d = 0.0 \) in

Dip plate side "A".

\[ Q_{\text{ft}^3} \]

\[ H_{\text{ft}} \]

- \( + \): \( l = 0.5 \) in
- \( \times \): \( l = 1.0 \) in
- \( \circ \): \( l = 1.5 \) in
- \( \ast \): \( l = 2.0 \) in
- \( \circ \): Free weir

\( \pm \) band of uncertainty
Fig. 6.56 - Discharge over the weir as a function of upstream head - effect of dip plate distance

Unsuppressed weir \((B/b)=1.6\)

- \(B=16.0\) in
- \(d=0.0\) in
- Dip plate side "B"
Unsuppressed weir $(B/b) = 2.4$

Fig. 6.57 - Head downstream of clip plate as a function of upstream head - effect of depth of immersion

B = 24.0 in  \hspace{1cm} l = 0.5 in

Dip plate side "A"

- + d = 0.0 in
- × d = 0.5 in
- - d = 1.0 in
- o d = 2.5 in
- α d = 3.0 in
- - d = 4.0 in
- --- calculated c = 1.0
- I band of uncertainty
Unsuppressed weir \((B/b)=2.4\)

Fig. 6.58 - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\[B = 24.0\text{ in} \quad l = 1.0\text{ in}\]

Dip plate side "A"

\[\begin{align*}
\text{d} & = 0.0\text{ in} \\
\circ \text{d} & = 1.0\text{ in} \\
\dag \text{d} & = 2.0\text{ in} \\
\circ \text{d} & = 2.5\text{ in} \\
\dag \text{d} & = 4.0\text{ in} \\
\text{--- calculated c \cdot 1.0}
\end{align*}\]

Band of uncertainty
Unsuppressed weir \( B/b = 2.4 \)

**Fig. 6.59** - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\[ B = 24.0 \text{ in} \quad l = 1.5 \text{ in} \]

Dip plate side "A"

- \( d = 0.0 \text{ in} \)
- \( d = 1.5 \text{ in} \)
- \( d = 2.5 \text{ in} \)
- \( d = 3.0 \text{ in} \)
- \( d = 4.0 \text{ in} \)

--- calculated c. 10

\( \text{--- band of uncertainty} \)
Unsuppressed weir \((B/b)=2.4\)

Fig. 6.60  Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\(B = 24.0\) in  \(l = 2.0\) in

Dip plate side "A"

\(d = 0.0\) in
\(d = 1.0\) in
\(d = 2.0\) in
\(d = 2.5\) in
\(d = 3.0\) in

-- calculated \(c=10\)

\(\) band of uncertainty
Unsuppressed weir \((B/b) = 2.4\)

**Fig. 6.61** - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\(B = 24.0\) in \(\quad l = 3.0\) in

Dip plate side \(A\)

- \(d = 0.0\) in
- \(d = 1.0\) in
- \(d = 2.5\) in
- \(d = 3.0\) in
- \(d = 4.0\) in

--- calculated \(c = 10\)

\(\underline{\text{Band of uncertainty}}\)
Unsuppressed weir \( (B/b) = 2.4 \)

**Fig. 6-62** - Head downstream of dip plate as a function of upstream head - effect of depth of immersion

\[ B = 24.0 \text{ in} \quad l = 5.0 \text{ in} \]

Dip plate side "A".

- \( d = 0.0 \)
- \( d = 1.0 \)
- \( d = 2.5 \)
- \( d = 4.0 \)

--- calculated \( c = 1.0 \)

\( \text{I band of uncertainty} \)
Unsuppressed weir \((B/b) = 2.4\)

Fig. 6.63 - Discharge over the weir as a function of upstream head - effect of depth of immersion

\(B = 24.0\) in \(\;\) \(l = 0.5\) in

Dip plate side 'A'

\[+ d = 0.0\) in\]
\[\times d = 0.5\) in\]
\[\circ d = 1.0\) in\]
\[\ast d = 2.5\) in\]
\[\# d = 3.0\) in\]
\[\dagger d = 4.0\) in\]

-- calculated \(c = 10\)

\[\text{I band of uncertainty}\]
Unsuppressed weir \((B/b) = 2.4\)

Fig. 6.64 - Discharge over the weir as a function of upstream head - effect of depth of immersion.

\(B = 24.0 \text{ in} \quad l = 1.0 \text{ in}\)

Dip plate side A

\(d = 0.0 \text{ in}\)
\(d = 1.0 \text{ in}\)
\(d = 2.0 \text{ in}\)
\(d = 2.5 \text{ in}\)
\(d = 4.0 \text{ in}\)

+ calculated \(c = 10\)

\[\text{band of uncertainty}\]
Unsuppressed weir \((B/b) = 2.4\)

![Graph showing discharge over the weir as a function of upstream head - effect of depth of immersion.](image)

**Fig. 6.65** - Discharge over the weir as a function of upstream head - effect of depth of immersion

\(B = 24.0\) in \hspace{1cm} \(l = 1.5\) in

Dip plate side "A"

- \(d = 0.0\) in
- \(d = 1.5\) in
- \(d = 2.5\) in
- \(d = 3.0\) in
- \(d = 4.0\) in
- Calculated \(c = 10\)

\[\text{Band of uncertainty}\]
Unsuppressed weir \((B/b) = 2.4\)

Fig. 6.66 - Discharge over the weir as a function of upstream head - effect of depth of immersion

\(B = 24.0\) in \(\quad l = 2.0\) in

Dip plate side "A"

\[ + d = 0.0\] in
\[ o d = 1.0\] in
\[ * d = 2.0\] in
\[ * d = 2.5\] in
\[ \# d = 3.0\] in
\[ + \text{ calculated } c = 10\]

\[ \text{band of uncertainty} \]
Unsuppressed weir \((B/b) = 2.4\)

**Fig. 6.67** Discharge over the weir as a function of upstream head - effect of depth of immersion

- \(B = 24.0\) in
- \(l = 3.0\) in

Dip plate side "A"

- \(d = 0.0\) in
- \(d = 1.0\) in
- \(d = 2.5\) in
- \(d = 3.0\) in
- \(d = 4.0\) in
- Calculated \(c = 1.0\)
- Band of uncertainty
Unsuppressed weir \((B/b)=2.4\)

**Fig. 6.68** - Discharge over the weir as a function of upstream head-effect of depth of immersion

- **B** = 24.0 in
- **l** = 5.0 in
- Dip plate side "A"

- \(d=0.0\) in
- \(d=1.0\) in
- \(d=2.5\) in
- \(d=4.0\) in
- Calculated \(c=1.0\)
- Band of uncertainty
Unsuppressed weir \((B/b)=2.4\)

**Fig. 6.69** - Discharge over the weir as a function of upstream head - effect of plate reversal

\[ \begin{align*}
Q \text{ ft}^3/\text{s} & = 0.6 \\
0.5 & \leq Q \geq 0.1 \\
H \text{ ft} & = 0.6 \\
0.4 & \leq H \geq 0.1 \\
0.3 & \leq H \geq 0.1 \\
0.2 & \leq H \geq 0.1 \\
0.1 & \leq H \geq 0.1 \\
\end{align*} \]

**B = 24.0 in \hspace{1cm} \ell = 1.0 in**

Dip plate

side "A" \hspace{1cm} \circ d = 0.0 in \hspace{1cm} + d = 4.0 in

side "B" \hspace{1cm} \ast d = 0.0 in \hspace{1cm} \times d = 4.0 in

\[ \text{Band of uncertainty} \]
Unsuppressed weir \((B/b) = 2.4\)

Fig. 6.70 - Discharge over the weir as a function of upstream head - effect of plate reversal

\(B = 24.0 \text{ in} \quad l = 2.0 \text{ in}\)

Dip plate
side "A"  \(\circ d = 0.0 \text{ in} \quad \times d = 3.0 \text{ in}\)
side "B"  \(\bullet d = 0.0 \text{ in} \quad \times d = 3.0 \text{ in}\)

\| band of uncertainty
Unsuppressed weir \((B/b)=2.4\)

![Graph](image)

**Fig. 6.71** - Discharge over the weir as a function of upstream head - effect of plate reversal

\(B=24.0\) in \(l=3.0\) in

Dip plate
- Side "A": \(d=0.0\) in \(d=3.0\) in
- Side "B": \(d=0.0\) in \(d=3.0\) in

I band of uncertainty
Unsuppressed weir \((B/b) = 2.4\)

**Fig. 6.72** - Discharge over the weir as a function of upstream head - effect of dip plate distance

- \(B = 24.0\) in
- \(d = 0.0\) in

\(\text{Dip plate side, } A,\) band of uncertainty

- \(\ell = 0.5\) in
- \(\ell = 1.0\) in
- \(\ell = 1.5\) in
- \(\ell = 2.0\) in
- \(\ell = 3.0\) in
- \(\ell = 5.0\) in
- Free weir

\(Q \text{ ft}^3/\text{s}\)

\(H \text{ ft}\)
7.0 ANALYSIS OF RESULTS

7.1 Weir Discharge Coefficient

All calculated results, based on the analytically deduced equations, are subject to a number of assumptions. The most important of these is that of the flow being unidimensional. This assumption, which neglects the effect of components of velocity in directions normal to that of the main flow, requires the introduction of at least one coefficient.

Equation (3.13), describing the relationship between the rate of flow over the weir and upstream head, contains two coefficients of discharge. One of these refers to the drowned orifice \( C_0 \), formed by the passage between the weir and dip plate, the other is the discharge coefficient of the weir \( C_w \). The coefficients are used in the form of a ratio \( C_0/C_w \) when the head downstream of the dip plate is calculated as a function of the upstream head. The weir discharge coefficient is also used on its own to estimate the rate of flow over the weir.

As a first approximation to simplify the calculations it was assumed that the ratio of the two coefficients was constant throughout and equal to unity \( C_0/C_w = 1.0 \). This assumption can be satisfied in a number of ways. The simplest of these is that both coefficients are equal to unity and constant throughout the range tested. Such a situation is very unlikely and will not be considered further.

A much more realistic situation is the one in which the coefficients, although numerically equal, are dependent on the configuration and, possibly, the value of the upstream head.

It has already been noticed (Chapter 6) that in all configurations tested the curves calculated using equation (3.12) and (3.13) are very similar in shape to the relationships obtained experimentally. This similarity implies the existence of a coefficient of proportionality, constant in value for each set of experimental results. All experimental
curves are plotted as a function of the upstream head. Thus the fact that the value of an individual coefficient may be assumed to be constant indicates that it is, within the experimental range, independent of upstream head.

An exact prediction of the rate of flow over the weir, provided with a dip plate, can be obtained using equation (3.13) into which the appropriate value of weir discharge coefficient is introduced.

The calculations were carried out for all three channel - weir width ratios investigated, and in each of these for all positions of the dip plate at which tests were performed. For any test run, carried out at a given setting of a dip plate, a single value of the weir discharge coefficient was used for the whole range of the upstream heads tested.

The values of the coefficient used were 'rounded off' at the second decimal place. It was considered that the figures were still sufficiently accurate. The band of uncertainty thus introduced is no larger than ± 0.005. This, when expressed as a percentage of the value of the coefficient, lies between ± 0.9% and ± 0.5%. The accuracy compares well with the band of uncertainty of the experimental results which may, at the high values of discharge, reach a value of ± 3%.

When the calculated curves are plotted together with the experimental results for the corresponding configuration, the correlation between the two is of a very high degree. In all cases the calculated points fall within the range of the experimental error band; in some they coincide with the mean experimental curve.

Although the calculations and plots have been carried out for all experimental configurations, only a few curves are shown in Fig. 7.1. These are an illustration of the accuracy of the calculations.

The value of the weir discharge coefficient varies both with respect to the depth of immersion of the dip plate and its distance from the weir plate.
In the case of the full width weir with suppressed end contractions, the variation of discharge coefficient with respect to the depth of immersion of the dip plate is shown in Fig. 7.2. Each curve represents the variation of the coefficient for a constant value of the distance between the weir and dip plates.

It is observed that the curves are similar in shape. The value of the discharge coefficient at first decreases with the increase of the depth of immersion of the dip plate. This trend continues until the depth of immersion becomes equal to the distance between the weir and dip plate. When this distance is exceeded the value of the weir discharge coefficient increases. The rate of increase is gradually smaller and seems to indicate that the coefficient will tend asymptotically to a constant value.

This last observation has to be treated with caution, because as the depth of immersion of the dip plate is increased the area of the passage between the lower edge of the dip plate and the bottom of the channel gets smaller. Eventually the size of this passage must take over as the controlling factor.

Two curves do not exhibit a minimum in the value of the coefficient. Nevertheless, both curves conform to the overall pattern. In one case the curve for \( l = 5.0 \) inches, the minimum point has not been reached. In the case of \( l = 0.5 \) inch only the second, weir discharge coefficient increasing in value with increasing depth of immersion, part of the curve is apparent.

The same type of dependence of the discharge coefficient on the depth of immersion of the dip plate is observed in weirs with unsuppressed end contractions. Fig. 7.3 shows the variation of the coefficient for the approach channel 16 inches wide (channel - weir width ratio 1.6). The relationship between weir discharge coefficient and depth of immersion of the dip plate for the channel - weir width ratio of 2.4 is shown in Fig. 7.4.
On both figures the existence of a minimum value of a coefficient of discharge can be observed. In each curve, drawn for a constant value of a distance between the weir and dip plates, the minimum value of the coefficient occurs when the depth of immersion of the dip plate is equal to the distance between the plates.

It is noticeable that on each of the three diagrams (Fig. 7.2, 7.3 and 7.4) the variation in the value of the weir discharge coefficient becomes smaller when the distance between the weir and dip plate is increased. Comparing the three diagrams further, it is observed that the individual curves are much closer together when the width of the approach channel is larger than that of the weir. The gradually closer grouping of the values of the weir discharge coefficient with the increase of the B/b (channel - weir width ratio) can also be observed in Fig. 7.5.

This diagram shows the variation of the weir discharge coefficient as a function of distance between the weir and dip plate for a constant depth of immersion of the latter. Comparing the three curves, relating to the three ratios B/b tested, it is noticed that the shape of all of them is similar. The highest value of the coefficient occurs when the dip plate is closest to the weir. As the distance between the two plates is increased the value of the weir coefficient decreases. The rate of change of its value with respect to distance gets smaller and each of the curves appears to tend asymptotically to a constant value. This asymptotic value decreases with the enlargement of the width of the approach channel.

This observation is in agreement with the calibrations of the free weir, i.e.: the weir with the dip plate removed. When the calibration readings are plotted in $Q - H^{3/2}$ co-ordinates, (Fig. 7.6 a, b, c) all three form straight lines passing through the origin of the system. This indicates a relationship of the type:

$$Q = K H^{1.5}$$
The value of $K$, constant in each case, was found to be $K = 2.90$ for the full width (suppressed end contractions) weir, $K = 2.76$ for the weir with the approach channel 16 inches wide and $K = 2.65$ when the approach channel width is 24 inches. With the ideal unidimensional relationship given by $Q = 4.458 H^{15}$ the corresponding values of the coefficient of discharge are: 0.65, 0.62 and 0.59.

When discussing (Chapter 6) the graphs describing the relationship between the rate of flow over the weir and the head upstream of the dip plate, mention was made of the close grouping of the experimental curves. The curves, for various depths of immersion, but a constant value of distance between the weir and dip plate, were in a number of cases so close together that the bands of experimental uncertainty overlapped. It was consequently felt that the use of 'mean experimental' curves was justified. A single curve was drawn through the experimental points, one for each channel - weir width ratio, and a given distance between the weir and dip plate. It was observed that a constant value of weir discharge coefficient, independent of the upstream head, could be found to fit a given curve. The values thus obtained are plotted, as a function of distance between the weir and dip plate, in Fig. 7.7. The three curves, one for each of the channel - weir width ratios, exhibit a distinct similarity to the curves of Fig. 7.5. The relative position of the three curves is the same, the value of the weir discharge coefficient becoming smaller for the larger channel - weir width ratio. The value of the coefficient decreases when the distance between the weir and dip plate becomes larger. The rate of decrease of the coefficient becomes progressively smaller. The values of the coefficient at large distances between the weir and dip plate are, within the limits of the experimental uncertainty, equal to the values obtained from the free weir calibrations. It may thus be concluded that, as a very first approximation, a single mean experimental curve for a given distance between the weir and dip plate would be sufficiently accurate.
7.2 Weir Coefficient with Dip Plate Reversed

The reversal of position of the dip plate, so that the chamfered side of it faces upstream (Side B), results in a decrease in the rate of observed flow. As mentioned already in Chapter 6, no change in the shape of the curves describing the flow - head relationship was observed when compared with those for Side A.

On comparison of calculated curves with the experimental results, it was found that the assumption of constant values of the discharge coefficient, independent of the upstream head, gave the same accuracy of flow prediction as for Side A.

The comparison of calculated and experimental relationship between the discharge over the weir and the head upstream of the dip plate is shown in Fig. 7.8. Only two depths of immersion of the dip plate, for one width of the approach channel, and a single value of distance between the weir and dip plate are shown. In a way similar to Fig. 7.1, the depths of immersion shown are the ones requiring the highest and lowest values of weir discharge coefficient. The remaining values, not drawn for the sake of clarity of diagram, are tabulated in Table 7.I for the case of the dip plate position in Side A, and Table 7.II for the reversed position of the dip plate (Side B).

The reversal of the dip plate influences only the magnitude of the coefficient. In both cases the minimum values occur at the configuration in which the depth of immersion of the dip plate is equal to its distance from the weir plate. In all configurations tested it was found that, when all other geometrical factors were the same, the value of the discharge coefficient was lower when the dip plate was placed with the chamfered edge facing upstream (Side B).

It was also observed that the change of values of the weir coefficient, when the distance between the weir and dip plates was varied, followed a
TABLE 7.1
WEIR DISCHARGE COEFFICIENTS - DIP PLATE SIDE 'A'

(a) Approach channel width 10 inches

<table>
<thead>
<tr>
<th>d</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>4.0</th>
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<tr>
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<td>1.00</td>
<td>1.05</td>
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<td>0.62</td>
<td>0.63</td>
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</tr>
<tr>
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<td></td>
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(b) Approach channel width 16 inches

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<th>1.5</th>
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<th>2.5</th>
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<td>0.66</td>
</tr>
<tr>
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<td>0.62</td>
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<tr>
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<td>0.61</td>
<td>0.59</td>
<td>0.59</td>
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<tr>
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</table>

(c) Approach channel width 24 inches

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<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
<th>4.0</th>
</tr>
</thead>
<tbody>
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<td>0.64</td>
<td>0.69</td>
<td>0.68</td>
</tr>
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<td></td>
<td>0.63</td>
</tr>
<tr>
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<td></td>
<td>0.55</td>
<td></td>
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<td>0.57</td>
<td>0.58</td>
</tr>
<tr>
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<td>0.56</td>
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<td>0.56</td>
<td>0.57</td>
<td>0.56</td>
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</tr>
<tr>
<td>3.0</td>
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<td></td>
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<td></td>
<td>0.58</td>
<td>0.54</td>
<td>0.54</td>
</tr>
<tr>
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<td>0.56</td>
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<td>0.55</td>
</tr>
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</table>
TABLE 7.II
WEIR DISCHARGE COEFFICIENTS - DIP PLATE SIDE 'B'

(a) Approach channel width 10 inches

<table>
<thead>
<tr>
<th>d in</th>
<th>0.0</th>
<th>0.5</th>
<th>1.0</th>
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(b) Approach channel width 16 inches

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(c) Approach channel width 24 inches

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pattern similar to that obtained when the dip plate was placed with the flat face facing upstream (Side A).

7.3 Head Downstream of the Dip Plate

So far the analysis of the results has been concerned with the application of equation (3.13). This equation gives a direct relationship between the rate of flow over the weir and the head of water upstream of the dip plate. After the introduction of the appropriate value of weir discharge coefficient, the predictions of flow fall well within the band of experimental uncertainty.

Although that degree of accuracy was deemed sufficient, it was decided that for comparison purposes calculations based on the experimentally obtained values of head downstream of the dip plate should be carried out. Equation (3.2), i.e.: $Q = C_w \left(2\sqrt{gh/3}\right) b h^{1.5}$, was used to estimate the rate of flow over the weir.

The results of calculations using an assumed value of $C_w = 1.0$ are plotted, together with the experimental results in Fig. 7.9 a to Fig. 7.9 f. As the results were not encouraging, only some of the configurations for which the calculations were done are shown. These illustrate two extremes of distance between the weir and dip plate for the three widths of the approach channel.

It was noticed that when the distance between the weir and dip plate is small (Fig. 7.9 a, c and e), the values calculated with the aid of equation (3.13) give a much better approximation to the experimental results. In order to conform to the experimental values, the calculations on the basis of the head downstream of the dip plate require the introduction of unrealistic values of $C_w$. The weir discharge coefficient would have to decrease with the increasing value of head from about 0.8 to a value of the order of 0.35 when the upstream head is equal to about 0.5 ft.
It is only at large distances between the weir and dip plate that the results of calculations based on the measured value of downstream head are comparable to those obtained using equation (3.13). Even in this case the weir discharge coefficient has to be introduced, but its value is in the range of about 0.6. Thus it offers no advantage over the use of equation (3.13).

The cause of inaccuracy of discharge prediction, based on values of head downstream of the dip plate, is the uncertainty in measurement of those values. Water, contained between the weir and dip plate, did not form a level surface. In fact the water surface varies in elevation, sometimes very abruptly. This is particularly noticeable at small distances between the weir and dip plate.

It was mentioned in Chapter 6 that the flow may be considered to be divided into the mainstream, moving towards and over the weir plate, and a separated roller, clinging to the downstream side of the dip plate. With the width of approach channel equal to the width of the weir (B/b = 1.0) the maximum level reached by the mainstream was relatively steady with respect to time. This level could not, however, be considered to be equivalent to the head downstream of the dip plate. The reason was that it contained components of both the static and dynamic head of the mainstream. The area of relatively level water just downstream of the dip plate was finally chosen as equivalent to the 'head downstream of the dip plate'.

This area forms the top of a region of separated flow and although the time-average level is of a steady appearance, two types of instantaneous random variations are present. One of these is of the irregular oscillatory nature and is present all the time. The other is in the form of ripples travelling across the area at a much longer interval. These unsteady vibrations and ripples cause the band of uncertainty of the measurement to be much larger than in the case of the upstream head.
The turbulent, randomly time dependent character of water surface in the region of flow between the weir and dip plate shows up to even higher degree in the case of the weir with developed end contractions. In this case, when the width of the channel is greater than that of the weir, the time-averaged water surface varies in elevation both in the longitudinal and transverse direction. As in a previous case, the flow forms the mainstream near the weir plate and a roller next to the dip plate. Superimposed on these there exists a symmetrical flow directed towards the centre plane of the channel, which originates from two regions of virtual stagnation at the edges of the channel. This combination of flows results in an even greater random change in the position of water surface, making the measurement of head still more difficult and uncertain than in the case of the weir with suppressed end contractions.

The inescapable conclusion of the above observations is that, except at very large distances between the dip and weir plates, the estimation of the head downstream of the dip plate is so inaccurate that its measured value should not be used in any further calculations aimed at predicting the flow or any other variable.

7.4 Ratio of Coefficients \( C_0/C_w \)

When equation (3.12) was deduced a method of deducing the ratio \( C_0/C_w \) in terms of the depth of immersion of the dip plate was devised. The reliability of the method is dependent on the accurate measurement of the head downstream of the dip plate. It is proposed to outline the method so that it can be applied in future investigations in which a greater reliance may be laid on the measurement of downstream head.

When illustrating the relationship between the head downstream of the dip plate and the upstream head, only a single calculated curve was drawn for a given constant distance between the weir and dip plate. During the calculations it was assumed that the numerical value of the coefficient for the orifice \( C_0 \) was at all times equal to that for the weir \( C_w \).
The variation in value of \( \frac{C_0}{C_w} \) may be determined without undue difficulty using equation (3.7). This equation, giving the interrelation between upstream head \( H \), head downstream of the dip plate \( h \) and a coefficient \( A \), can be easily transformed to:

\[
A = \frac{h^3}{(H - h)}
\]  

(7.1)

The coefficient \( A \) is given by:

\[
A = \left[ \frac{C_0}{C_w} \left( \frac{3}{2} \frac{B_l}{B} \right) \right]^2
\]

thus it is seen that for the constant value of \( \frac{B_l}{b} \) there will exist an interdependence between the values of \( \frac{C_0}{C_w} \) and \( \frac{h}{H} \).

If a convenient reference value of \( H \) is chosen and substituted into equation (7.1), a relationship between the value of \( A \) and the head downstream of the dip plate is obtained. The solution of that relationship for a value of \( H = 0.5 \) ft is represented graphically in Fig. 7.10 as an example.

Graphs such as that shown in Fig. 7.10 form a basis of the procedure.

When an experimental value of \( h \) (head downstream of the dip plate) resulting from the reference value of \( H \) (upstream head) is applied to the graph, a unique corresponding value of \( A \) (say \( A = A_n \)) is obtained. This value refers to a given value of width of the approach channel, distance between the weir and dip plate and the depth of immersion of the latter.

A value of \( A \) which corresponds to the same width of the channel and distance between the weir and dip plate at the same reference value of \( H \) is calculated. This value of \( A \), denoted by \( A = A_{\text{ref}} \), corresponds to the assumption of \( \frac{C_0}{C_w} = 1.0 \). The ratio \( \frac{A_n}{A_{\text{ref}}} = A_r \) is equal to the square of ratio \( \frac{C_0}{C_w} \), i.e:

\[
\sqrt{A_r} = \frac{C_0}{C_w}
\]

In this way a definite and unique value of the \( \frac{C_0}{C_w} \) ratio may be assigned to each of the experimental configurations.

The values of the depth of immersion of the dip plate \( d \) and distance between the weir and dip plates are known for each of the configurations.
Thus a nondimensional value of the immersion/distance ratio \((d/l)\) may be established. The relationship between \((C_0/C_w)\) and \((d/l)\) may thus be easily obtained. With the values of \(C_w\) deduced separately, the extent of the deviation of flow from the unidimensional approximation can be determined.

There exists a considerable temptation to express the relationships exclusively in terms of nondimensional numbers. Although this method has a number of advantages, it has to be remembered that in the case of a weir, provided with a dip plate, not only the ratios of the dimensions but their absolute values will be of importance. It has already been observed that for any distance between the weir and dip plate the minimum value of weir coefficient \(C_w\) occurs when the depth of immersion is equal to that distance. But at the same time the variation in the value of \(C_w\) decreases as the distance between the dip and weir plates becomes larger. This confirms the simultaneous but unequal effect of the two variables. There exists a range in which the ratio of the variables plays a predominant role, but outside that range the absolute value of one of the variables takes over.

This effect is well known in modelling and if not appreciated may lead to considerable errors.

7.5 Regions of Separated Flow

The existence of flow coefficients other than unity in the configurations investigated is caused primarily by the development of regions of separated flow. The extent and number of these regions which in all cases develop into rollers, depends on the geometrical configuration of the test.

The simplest configuration occurs when the width of the approach channel is equal to that of the weir. The flow is basically two dimensional and the three rollers, one at the surface of the flow just upstream of the dip plate, the second downstream of it and the third at the foot of the weir plate, are situated as shown in Fig. 6.1.
The situation becomes more complicated when the width of the channel exceeds that of the weir. The first roller, upstream of the dip plate, remains unchanged. It extends the whole width of the channel and its axis is normal to the direction of flow. The change occurs in the remaining two rollers, situated in the space between the weir and dip plate. This change is due to the formation of two regions of stagnation at the extreme edges of the weir plate. With the largest channel/weir width ratio it was noticed that the water level downstream of the dip plate was, at the edge of the channel, equal to that upstream of the dip plate. The roller formed at the bottom of the weir plate is changed a little over most of the width of the weir. Near the edges of the weir the effect of the stagnation areas begins to be felt. In the corner regions the flow passing under the dip plate encounters the weir plate, but is unable to continue over it. This results in a change of the shape of the roller which, not being bound by the mainstream, extends upwards to the level of the upstream head. The direction of further movement of water depends on the distance from the centre plane of the channel. At the very edge of the channel the surface filaments move towards the dip plate and there is a merger of the roller developed at the bottom of the weir plate with that originated at the surface just downstream of the dip plate. Towards the centre of the channel the effect of flow over the weir increases and the head becomes smaller. This results in a development of flow directed towards the centre plane of the channel. The flow merges with the mainstream forming a complicated three dimensional pattern. The transverse variation of the head is of the type shown in Fig. 6.39. The surface can be observed in Fig. 6.40 and Fig. 7.11. It will be seen on both of these photographs that the water surface is far from smooth. The ripples, visible in both cases, move over the surface which in itself is subject to irregular oscillations due to the unsteady character of side flows. This causes difficulties in
measurement of the height of the central ridge and results in a large band of uncertainty in estimation of the head downstream of the dip plate.

The three regions of separated flow which follow each other along the mainstream are all of the closed type. All three are caused by the change of the direction of flow. The first region, upstream of the dip plate, may be compared with the situation which occurs in the case of flow under a sluice. This similarity extends also to the mainstream flow. When the velocity distributions on the centre plane upstream of the dip plate, obtained in the present investigation (Fig. 6.36a, b, c, d, and Fig. 6.37), are compared with results published by Rajaratnam and Subramanya (51), a striking similarity in the trend of results is observed. This occurs in spite of the differences in the basic configurations of the two investigations. The flow downstream of the sluice in the investigation is unobstructed and allowed to develop freely. In the present investigation the mainstream is caused to bend around the dip plate by the presence of the weir plate and the associated roller of separated flow.

This separation is again caused by an obstruction placed in the path of the stream. A stagnation point is formed at the foot of the weir plate and its action extends for some distance upstream. In some cases, when the dip plate is close to the weir, the areas of the two separated flow regions overlap. The separation point of the bottom roller is then situated upstream of the dip plate.

In the majority of tests the roller upstream of the weir plate was of the steady closed type, the point of reattachment being situated on the weir plate just under the edge of the sill. It has been noticed, however, that with the dip plate close to the weir plate and large rates of flow the nappe fell into intermittent oscillations with an amplitude of between 5 cm and 10 cm. The only explanation of this phenomenon is that due to the high velocity of flow the point of reattachment of the roller
moves downstream, thus losing contact with the weir. This causes a change in the shape of the nappe, contact is re-established and the cycle repeated. The separation bubble is changed into the oscillating type.

No confirmation of this assumption could be obtained as no observation was possible in the steel sided experimental channel and the phenomenon could not be replicated in the glass sided observation channel.

The extent of the separation bubble (roller) situated just downstream of the dip plate was estimated using coloured perspex filings sprinkled on the surface of the water. It was observed that the length of the bubble extended to between one quarter and one half of the distance between the dip and weir plate. The absolute length of the roller increased when the distance between the weir and dip plate was increased. However, when expressed as a fraction of that distance, the length of the bubble got smaller. No effect of the change in depth of immersion of the dip plate was observed. This was due primarily to the inaccurate method of observation.

No tests relating to the effect of the size of passage underneath the dip plate were made. These could be considered to be confirmatory to the validity of the assumptions made when deducing equation (3.13). If, with the distance between the weir and dip plate exceeding that between the lower edge of the dip plate and the bottom of the channel, the latter were shown to be of primary importance, this fact would have been an additional confirmation of the validity of the assumptions.

There were, however, two reasons for not doing another series of tests. One was the limit on the time available for the end of the experimental programme. The other, and at the time more important one, as the experimental work was finished with time to spare, was that these tests would have no practical application at all. The case in which the dip plate would be immersed to a sufficient depth to make the size of that passage of primary importance could not be envisaged as a practical proposition.
In the region in which the position of the dip plate would have a practical significance, the flow predictions were shown to give a very good correlation with the experimental results. In virtually every case the calculated results fall well within the range of experimental uncertainties.

It is therefore judged that, as a result of the present investigation, a method of analytical solution of the problem of prediction of discharge over the weir, provided with a dip plate, has been devised. The previous absence of data on which a designer could base his calculations has been rectified.
Fig. 7.1a - Discharge over the weir as a function of upstream head - coefficient of discharge

$B = 10\, \text{in} \quad l = 1.0\, \text{in}$

Dip plate side "A".

Experimental: $\circ d = 1.0\, \text{in}$
$\bullet d = 4.0\, \text{in}$

Calculated $\div c_w = 1.0$
$\times c_w = 0.91$
$\Rightarrow c_w = 0.74$

I band of uncertainty
Unsuppressed weir \((B/b)=1.6\)

Fig. 7.1b - Discharge over the weir as a function of upstream head - coefficient of discharge

\(B = 16\) in \(l = 1.0\) in

Dip plate side "A"

Experimental:
- \(d = 1.0\) in
- \(d = 4.0\) in

Calculated:
- \(c_w = 1.0\)
- \(c_w = 0.78\)
- \(c_w = 0.67\)

\(\) band of uncertainty
Unsuppressed weir \((B/b)=2.4\)

Fig. 7.1c - Discharge over the weir as a function of upstream head - coefficient of discharge

\[ B = 24 \text{ in} \quad l = 1.0 \text{ in} \quad \text{Dip plate side 'A'} \]

Experimental:

- \(d = 1.0 \text{ in}\)
- \(d = 4.0 \text{ in}\)

Calculated:

- \(c_w = 1.0\)
- \(c_w = 0.63\)
- \(c_w = 0.58\)

Band of uncertainty
Full width weir

Fig. 7.2 - Weir coefficient as a function of depth of immersion of dip plate

B = 10.0 in

- \( l = 0.5 \) in
- \( l = 1.0 \) in
- \( l = 1.5 \) in
- \( l = 2.0 \) in
- \( l = 3.0 \) in
- \( l = 5.0 \) in

Band of uncertainty

\( d = l \)
Unsuppressed weir \((B/b) = 1.6\)

**Fig. 7.3** - Weir coefficient as a function of depth of immersion of dip plate

- **B = 16.0 in**
  - \(l = 0.5\) in
  - \(l = 1.0\) in
  - \(l = 1.5\) in
  - \(l = 2.0\) in
  - \(l = 3.0\) in
  - Band of uncertainty
  - Locus \(d = l\)
Unsuppressed weir \((B/b) = 2.4\)

**Fig. 7-4** - Weir coefficient as a function of depth of immersion of dip plate

\(B = 24.0\) in

- \(\times\) \(l = 0.5\) in
- \(\times\) \(l = 1.0\) in
- \(\times\) \(l = 1.5\) in
- \(\times\) \(l = 2.0\) in
- \(\times\) \(l = 3.0\) in
- \(\times\) \(l = 5.0\) in

Band of uncertainty
Fig. 7.5 - Weir coefficient as a function of distance between weir and dip plate

- $d = 0.0$ in

- $B = 10.0$ in \( \frac{B}{b} = 1.0 \)
- $B = 16.0$ in \( \frac{B}{b} = 1.6 \)
- $B = 24.0$ in \( \frac{B}{b} = 2.4 \)
- Band of uncertainty
Full width weir

Fig. 7.6a - Weir calibration

No dip plate  B = 10 in

* experimental points
I band of uncertainty
Unsuppressed weir \((B/b) = 1.6\)

Fig. 7.6b – Weir calibration

No dip plate  \(B = 16\) in

x experimental points
I band of uncertainty
Unsuppressed weir \((B/b) = 2.4\)

Fig. 7.6c - Weir calibration

No dip plate \(B = 24\) in

* experimental points

I band of uncertainty
Fig. 7.7 - Weir coefficient ($C_w$) as a function of distance between weir and dip plate. "Mean experimental" values

- $B = 10.0$ in $(B/b) = 1.0$
- $B = 16.0$ in $(B/b) = 1.6$
- $B = 24.0$ in $(B/b) = 2.4$
- Band of uncertainty
Full width weir

![Graph showing discharge over the weir as a function of upstream head - coefficient of discharge]

**Fig. 7.8** - Discharge over the weir as a function of upstream head - coefficient of discharge

\[ B = 10 \text{ in} \quad l = 1.0 \text{ in} \]

Dip plate side "B"

Experimantal:  \( \circ d = 1.0 \text{ in} \)
\( \odot d = 4.0 \text{ in} \)

Calculated:  \( \div c_w = 1.0 \)
\( \times c_w = 0.78 \)
\( \gamma c_w = 0.63 \)

\[ \text{Band of uncertainty} \]
Fig. 7.9a - Discharge as a function of upstream head

$B=10\text{ in}$  $l=0.5\text{ in}$  $d=0.5\text{ in}$

- experimental points
- calculations based on experimental values of $h$ and $c_w=1.0$
+ calculations based on Eq. 3.13 with $c_w=1.0$
| band of uncertainty
Fig. 7.9b - Discharge as a function of upstream head

$B = 10$ in, $l = 5.0$ in, $d = 4.0$ in

- experimental points
- calculations based on experimental values of $h$ and $c_\text{w} = 1.0$
+ calculations based on Eq. 3.13 with $c_\text{w} = 1.0$
- band of uncertainty

$Q \text{ ft}^3/\text{s}$

$H \text{ ft}$
Unsuppressed weir \( (B/b)=1.6 \)

Fig. 7.9a - Discharge as a function of upstream head

\[ B=16.0 \text{ in} \quad l=0.5 \text{ in} \quad d=0.0 \text{ in} \]

- experimental points
- \( \times \) calculations based on experimental values of \( h \) and \( c_w=1.0 \)
- \( + \) calculations based on Eq. 3.13 with \( c_w=1.0 \)
- \( \text{I} \) band of uncertainty
Fig. 7.9d - Discharge as a function of upstream head

B = 16.0 in  l = 3.0 in  d = 0.0 in

- experimental points
× calculations based on experimental values of h and cw = 1.0
+ calculations based on Eq. 3.13 with cw = 1.0
I band of uncertainty
Fig. 7.9e - Discharge as a function of upstream head

\( B = 24.0 \text{ in} \quad l = 0.5 \text{ in} \quad d = 0.0 \text{ in} \)

- experimental points
- \( \times \) calculations based on experimental values of \( h \) and \( c_w = 1.0 \)
- \( \dagger \) calculations based on Eq. 3.13 with \( c_w = 1.0 \)
- \( \| \) band of uncertainty
Fig. 7.9f - Discharge as a function of upstream head

$B = 24.0\,\text{in} \quad l = 5.0\,\text{in} \quad d = 0.0\,\text{in}$

- experimental points
- $\times$ calculations based on experimental values of $h$ and $c_w = 1.0$
- $+$ calculations based on Eq. 3.13 with $c_w = 1.0$
- band of uncertainty
Fig. 7.10 - Coefficient $A$ as a function of downstream head $h$. 
Fig. 7.10 - Upstream head $H = 0.5$ ft.
Fig. 7.11 Photograph showing variation of head downstream of the dip plate
The present investigation deals with both the analytical and experimental approach to the problem of flow over a rectangular weir fitted with a dip plate. It has validated the assumption, made by the author, that the solution of the problem can be obtained by comparing the flow with that through a drowned orifice followed by a free weir.

It has also been shown that a unidimensional flow approach gives results the accuracy of which is comparable to that obtained in the well established weir formulae.

The expression for the discharge over the weir, deduced by the author, is:

\[
Q = C_w \frac{2}{3} b \sqrt{2g} \left( \frac{AH}{2} \right)^{\frac{1}{2}} \left\{ 1 + \left[ 1 + \frac{4A}{27H^2} \right]^{\frac{1}{3}} + \left[ 1 - \left[ 1 + \frac{4A}{27H^2} \right]^{\frac{1}{3}} \right]^{\frac{3}{2}} \right\}
\]

is shown to fit the experimental results within ± 5% both in the case of full width weir and when the width of the approach channel is greater than that of the weir.

The effect of the channel/weir width ratio (B/b) is accounted for in the value of coefficient A given by:

\[
A = \left( \frac{\frac{3}{2} C_o B}{C_w b} \frac{1}{1} \right)^2
\]

The coefficient incorporates also the distance (l) at which the dip plate is placed upstream of the weir. However, the effect of change in depth of immersion of the dip plate has to be taken into account by the variation of the value of the weir coefficient (Cw). This variation is shown in Table 7.I and Table 7.II, and in graphical form in Fig. 7.2, Fig. 7.3 and Fig. 7.4.

Although the calculations have been carried out in the foot-pound-second system of units, the equations can be used without change for any consistent system of units. The investigation has thus established a
generally applicable equation which can be used for prediction of rate of flow over a rectangular sharp edged weir provided with a dip plate. Further, by indicating the method of approach, it has paved the way for solving other similar configurations.

It has also been shown that the experimentally obtained value of head downstream of the dip plate should not be used for calculating the flow over the weir. The width of the resulting band of uncertainty is of such a magnitude that any results obtained using these values are most unreliable. The only exception occurs when the distance between the weir and the dip plate is very large and the effect of the roller formed downstream of the latter becomes negligible.

The prediction of flow over the weir, when a dip plate is fitted upstream of it, should be carried out using equation 3.13 and on the basis of a head of water measured upstream of the dip plate.

The investigation has thus provided a method of predicting the rate of flow over a rectangular weir but, in a way which often occurs, it has also indicated a number of problems which need further investigation.

It has been mentioned that the main reason for the necessity of introduction of the coefficients of discharge both for the drowned orifice and the weir is the existence of the regions of separated flow. These regions should be further investigated both with respect to the size and intensity of the vortex flow in the roller.

An insight into the behaviour of fluid inside the rollers would be obtained from observation in a glass-sided channel. This can be done in
the form of a visual and photographic observation in a flow visualisation channel. Some such experiments, using perspex and polyethelene particles suspended in water, have already been carried out and are reported in Chapter 6, sample photographs being shown in Fig. 6.2 to Fig. 6.10.

In order to carry out a more indicative investigation a full size, glass-sided channel should be assembled. This should be provided with a facility for high light intensity velocity measurement. Beam traverse or laser Doppler method of velocity estimation could then be used both for the separated flow regions and the mainstream part of the flow. The velocity distributions could then be obtained without interference with the flow pattern. The measurements thus obtained could be used to correlate the values of the discharge coefficients with the extent and intensity of separated flow areas.

The accuracy of estimation of head downstream of the dip plate would be considerably improved by the use of water level recorders. The use of these would make it possible to analyse the oscillations in the water level and to estimate a more accurate and precise time-average value of the downstream head. It is, however, doubtful whether even with this improvement the head downstream of the dip plate would be used for the purpose of flow estimation.

A suspicion has been voiced before (Chapter 7) that with large depths of immersion the passage between the lower edge of the dip plate and the bottom of the channel might form the control section. Although the practical application of this finding cannot be envisaged, the confirmatory experiments might be performed with an advantage to the overall understanding of the problem.

A given value of coefficient $A$ in equation 3.13 is not unique to a single configuration of channel/weir width ratio ($B/b$) and the distance between the weir and dip plate ($l$). It can, due to its form $A = K \left( \frac{Bl}{b} \right)^2$,
where \( K \) is a constant, be applied to a number of configurations as long as the product \( (Bl) \) remains constant in value.

In the present investigation two such pairs of values have been encountered. In one of these the channel width of 24 inches and distance between weir and dip plate of 2 inches corresponded to channel width of 16 inches and weir - dip plate distance of 3 inches, both gave \( Bl = 48 \). The other paired configuration gave \( Bl = 24 \), i.e. with the same channel widths the distances between the weir and dip plate were equal to half of those of the first pair.

The relationships between discharge and the upstream head are shown in Fig. 6.51 and Fig. 6.64 for \( Bl = 24 \), and Fig. 6.53 and Fig. 6.66 for the case of \( Bl = 48 \). The calculated results are, as expected, identical for each pair. The main significance lies in the closeness of the experimental results. In the case of \( Bl = 48 \) these overlap and a single curve could be drawn. There is a difference between the experimental points obtained in the two channels when the value of \( Bl \) was equal to 24. It would be of some interest to observe that effect in a larger number of cases.

The experimental work in the present investigation has been carried out on a weir of a single dimension (10 inches wide). The correlation between the results calculated by means of the equation proposed by the author (equation 3.13) and the experimental results is such that the calculated curves fall within the band of experimental uncertainty. It is felt, however, that before this equation (3.13) be accepted as a standard to be universally used, tests on weirs of other dimensions could be done with advantage.

The developments and further tests proposed in this chapter are directed primarily towards a deeper and more detailed understanding of the problem of flow patterns caused by the introduction of a dip plate.
upstream of a weir. The practical engineering problem is concerned with the effect of this action on the rate of flow over the weir. It is proposed that the author's equation, coupled with the experimental investigation, forms a sufficiently accurate basis for any further development of the problem.
APPENDIX I

ERRORS AND INACCURACIES OF MEASUREMENT

An experimental reading or a variable deduced from a number of such readings is usually assigned a single, definite value. However, in reality, the value thus obtained is subject to a number of inaccuracies. These are divided into two categories. One is due to the inaccuracies in manufacture of apparatus and calibration of instruments, the other is caused by errors made by the observer taking the reading.

AI.1 Human Observer's Errors

The human error most commonly made is due to interpolation. It is exceptional for a reading to fall exactly on to the marking of an instrument. The estimate of the reading in an intermediate position is unlikely to be exact. Its accuracy depends on the type of scale used, conditions under which the reading is made and the experience of the observer.

Further, in a number of instances, particularly in flow situations, the magnitude of variables is not constant with respect to time. The value consists of a large steady component constant in time on which a small, time dependent, variation is superimposed. Unless a permanent record of variations is first obtained, it is extremely difficult to establish the mean value of the variable being measured. The accuracy of the estimate which is dependent on the amplitude, type and frequency of the variable component will also, according to some investigators (25, 26), largely depend on the observer making the measurement.

Another type of operator error occurs during timing of an experimental phenomenon. If this is done by means of a device actuated by the observer, there will exist a 'human reaction' time lag.

Human reaction time has been found to vary between 0.2 and 0.5 second. This time depends on the individual and the type of stimulus to which that individual is reacting.
The overall effect of this error is usually decreased by the fact that the lag will occur both at the start and the end of the experiment. However, on a number of occasions the author has observed an anticipatory reaction before the stimulus has been applied. When this occurs the errors are additive.

When tested, the author's reaction time lag was found to lie between 0.25 and 0.35 second.

AI.2 Combination of Errors

Very often the value of a variable is obtained as a result of more than a single measurement, each of these being subject to an error. The combined error in the value of the deduced variable may be estimated with relative ease. If the power relationship between the independent (measured) and dependent (deduced) variables is assumed, this can be written as:

\[ w = \frac{x^n y}{z^m} \]  

(5.1)

where \( x, y, z \) are the measured variables, \( n \) and \( m \) constants and \( w \) the deduced variable.

Equation (5.1) can be expressed as:

\[ \ln w = n \ln x + \ln y - m \ln z \]

or

\[ \frac{dw}{w} = n \frac{dx}{x} + \frac{dy}{y} - m \frac{dz}{z} \]  

(5.2)

Equation (5.2) expresses in a mathematical form the statement: the proportional error of a derived variable is equal to the sum of the proportional errors of the component variables multiplied by the respective powers to which the variables are raised.

AI.3 Estimation of the Band of Uncertainty of Readings and Results

The head of water over the sill of the weir was measured both upstream and downstream of the dip plate. Although the method used in estimation of the value of the head in the two regions was the same, the conditions under which the measurements were made differed and consequently influenced the accuracy of the result.
The value of the head is a result of two readings of water level done by means of a point gauge. The first (zero) reading is carried out under static conditions and its accuracy may be assumed to be of the order of ± 0.005 in. The second reading of the water level, done under dynamic conditions, is dependent on the type of flow at the point of measurement.

Upstream of the dip plate the water surface is smooth and, as a result, the level can be measured with an accuracy of the order of ± 0.02 in. (about ± 0.0017 ft).

The resultant band of uncertainty for the measurement of head upstream of the dip plate is ± 0.002 ft. This is equivalent to a relative error of about ± 0.23% at a large head of 0.7 ft, increasing to about 8% at the smallest heads of about 0.025 ft.

The measurement of head downstream of the dip plate is considerably less accurate. The accuracy further depends on whether the width of the channel is equal or larger than that of the weir.

In the former case oscillating ripples are formed on the water surface, making the estimation of the time-average position of water level very difficult. The accuracy of the reading is no better than ± 0.05 in (approx. 0.004 ft) at low heads (up to about 0.1 ft), decreasing to an estimated ± 0.15 in (approx 0.012 ft) at large heads, and small distances between dip and weir plate.

When the width of the channel exceeds that of the weir transverse currents are formed in the space downstream of the dip plate. The water level varies both in the transverse and longitudinal direction.

The transverse currents, directed towards the centre plane of the channel, cause a ridge of water to be formed there. Both currents are unstable and consequently the band of uncertainty in the estimation of the level of the top of the central ridge is of the order of ± 0.2 in (0.017 ft) at downstream heads of 0.5 ft. This corresponds to the percentage error of about 3.5%.
AI.4 Estimate of the Rate of Flow

The main composite variable in the present investigation is the rate of flow \( Q \). This is measured by timing the collection of 4 cwt of water in a tank placed on a weighing machine. The machine was calibrated shortly before the start of the investigation and was guaranteed accurate to 0.25 lb. Thus with 4 cwt collected the percentage error was \( \pm 0.06\% \). The main cause for the uncertainties in the value of discharge over the weir is the inaccuracy in timing. With the author's reaction time lag of 0.3 second, the percentage error in timing is within limits given by \( \pm \frac{30}{t} \% \), where \( t \) is the time of collection in seconds, and the band of uncertainty of discharge is given by \( \pm \left( \frac{0.3}{t} Q \right) \).

The relationship between \( \delta Q \) and \( Q \) is shown in tabular form in Table AI.1.

Discharge over the weir may also be estimated on the basis of head either upstream of the dip plate or upstream of the weir plate.

In both cases the relative error in discharge will be equal, in accordance with equation (5.2), to the error in estimate of head multiplied by 1.5 (the power to which head is raised).

The resultant uncertainties will thus become about 0.5% when calculations are based on the head upstream of the dip plate and over 0.5% if the head downstream of the dip plate is used in calculations.
TABLE AI.I

(all values in ft$^3$/s)

<table>
<thead>
<tr>
<th>Q</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta Q$</td>
<td>0.0004</td>
<td>0.0017</td>
<td>0.0038</td>
<td>0.0067</td>
<td>0.0104</td>
<td>0.0150</td>
<td>0.0204</td>
</tr>
</tbody>
</table>
COMPUTER PROGRAMME

All the calculations in the investigation were carried out using a hand-held electronic calculator. It was considered, at that time, that the relatively straightforward calculations involved in the solution of equations (3.12) and (3.13) did not warrant the additional time and complications of the use of the University’s central computer services.

The relative simplicity of the calculations can be judged by inspecting the calculation flow charts shown in Fig. 3.2 for equations (3.12) and (3.13) and in Table 4.1 for equation (4.6).

The first of these gives the downstream head and rate of flow over the weir in terms of the head upstream of the dip plate. The second, Table 4.1, gives the interdependence between the velocity of flow and horizontal deflection of the drag-on-sphere velocity meter.

In both cases the chart forms a single chain of calculations without loops and only a very limited number of 'remembered values' is required. A pocket calculator with four memory compartments was quite sufficient to carry out all calculations.

The situation has changed somewhat with the introduction of desk-top computers. This resulted in an increased access to the computer both from the point of view of availability of time and the ease of 'conversation'. Consequently it was decided to set up a programme using 'Basic' to be used on a Commodore 'Pet' computer freely available in the Department.

The calculation flow chart outlined in Fig. 3.2 can serve as the Basic flow chart for the programme for the solution of equation (3.12).

The programme itself is given overleaf.
5 REM "DIP PLATE DOWNSTREAM HEAD"
10 INPUT "WIDTH RATIO";B
20 INPUT "DIP DISTANCE";C
25 REM "CONFIGURATION CONSTANT",A
30 A=((3/2)*B*C/12)^2
35 PRINT "CONFIGURATION CONSTANT",A
40 INPUT "UPSTREAM HEAD";H
50 D=H*A/2
60 E=D^0.3333
70 F=4*A/(H^2*27)+1
80 G=F^0.5+1
90 J=F^0.5-1
100 K=G^0.3333
110 L=J^0.3333
120 M=K-L
125 REM "DOWNSTREAM HEAD",N
130 N=M*E
140 PRINT "DOWNSTREAM HEAD",N
150 IF N>0.7 GO TO 900
300 GO TO 40
900 END

In order to change the programme to solve equation (3.13), its title would have to be changed, ie:

5 REM "DIP PLATE DISCHARGE"

and lines:

160 REM "DIP PLATE DISCHARGE"
170 Q=4.4573*N^1.5
180 PRINT "IDEAL DISCHARGE",Q

would have to be introduced between lines 150 and 300.
With the programme recorded on magnetic tape or disc, calculations, following any further experiments on the effect on the dip plate, would be speeded up enormously.
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**Fig. 7.5** Weir coefficient as a function of distance between weir and dip plate - \( d=0.0 \)

**Fig. 7.6** Weir calibration - no dip plate
   - a \( B=10 \)
   - b \( B=16 \)
   - c \( B=24 \)

**Fig. 7.7** Weir coefficient as a function of distance between weir and dip plate - 'mean experimental'

**Fig. 7.8** Discharge as a function of upstream head
   Side B; \( B=10; \ l=1.0 \)
   - a \( B=10; \ l=0.5; \ d=0.5 \)
   - b \( B=10; \ l=5.0; \ d=4.0 \)
   - c \( B=16; \ l=0.5; \ d=0.0 \)
   - d \( B=16; \ l=3.0; \ d=0.0 \)
   - e \( B=24; \ l=0.5; \ d=0.0 \)
   - f \( B=24; \ l=5.0; \ d=0.0 \)

**Fig. 7.10** Coefficient A as a function of downstream head - upstream head \( H=0.5 \)

**Fig. 7.11** Variation of head downstream of dip plate
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