STUDIES OF INCLINED THIN-PLATE RECTANGULAR FULL-WIDTH WEIRS

BY

IBRAHIM BABBAJI

B.Eng. (Civil), A.B.U.

A thesis submitted to the Postgraduate School, Ahmadu Bello University, In partial fulfillment of the requirements for the degree of:-

Master of Engineering (Water Resources and Environmental Engineering).

Faculty of Engineering,

Ahmadu Bello University, Zaria.

March, 1985.

All rights reserved.

No part of this thesis may be reproduced by any means, nor translated into a machine language without the written permission of the author.

DECLARATION

I hereby declare that this thesis has been composed by myself and that it is a record of my own research work. It has not been accepted in any previous application for a higher degree. All sources of information are specifically acknowledged by means of references.

I. Babbaji.

CERTIFICATION

This project thesis entitled "Studies of Inclined Thin-plate Rectangular Full-width Weirs", by Ibrahim Babbaji, meets the regulations governing the award of the degree of Master of Engineering (M.Eng) of Ahmadu Bello University, and is approved for its contribution to scientific and literary presentation.

Dr. S. Mustafa
Chairman, Supervisory Committee
Date: 26/3/85

Dr. L.I. Odigie
Member, Supervisory Committee
Date: 26/3/85

Dr. A. Kuzniar
Member, Supervisory Committee
Date: 26/3/85

Prof. J.A. Ogunrombi.
Head of Department
Date: 26/3/85

Prof. G.E. Osuide.
Dean, Post-Graduate School
Date: 26/3/85

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to the following:-

1. Dr. S. Mustapha, B. Eng, M.Sc., Ph.D, MIWES, MNSE, Department of Water Resources and Environmental Engineering, for his proper guidance in carrying out this work.
2. Dr. L. I. Odigie, B. Eng, M. Eng, Ph.D, of the same department for critically going through the thesis as Internal Examiner.
3. Professor M. A. Gill (formerly of the same Department) for suggesting the study.
4. The General Manager, Chad Basin Development Authority (CBDA), Engr. B.S. Musa, and the entire management committee of CBDA for granting sponsorship to undertake the postgraduate study; and
5. The entire technical staff of the Hydraulics Laboratory, Department of water Resources and Environmental Engineering, for their untiring help throughout the laboratory work.

ABSTRACT

The need to conserve available water resources cannot be overemphasized. One method is to make accurate measurement and regulation of discharges. A thin-plate full-width rectangular weir can be employed for the purpose. In this study, an attempt has been made to study the effects of inclination on the characteristics of such weirs. The characteristics are the ability of the weir to develop head, measure or pass discharges, and its sensitivity within the range of head used. The study showed that an inclined weir develops less head than a normal weir, for same flow rate, and the more inclined the weir, the lesser the head developed. The sensitivity of the weir was also shown to decrease with increasing inclination for same weir height. This property of the thin-plate weir can be used to advantage in irrigation water supply and in research laboratories where water level needs to be controlled.

TABLE OF CONTENTS

Chapter		Page
	Title Page	i
	Declaration	ii
	Certification	iii
	Acknowledgements	iv
	Abstract	v
	Table of Contents	vi
	List of Tables	vii
	List of Figures	ix
	List of Appendices	xi
	Abbreviations and Symbols	xii
1.	INTRODUCTION	1
1.1:	Nature and Importance of Hydraulic Structures	1
1.2:	Types of Hydraulic Structures	2
1.3:	Objectives and Scope of Study	3
2.	LITERATURE REVIEW	5
2.1:	Definition	5
2.2:	Weir Classification	6
2.2.1:	Thin-plate weirs	6
2.2.2:	Broad-crested weirs	10
2.3:	Factors affecting flow over the Thin-plate weirs	11
2.3.1:	Aeration	11
2.3.2:	Approach Channel Conditions	11
2.4:	Some Theories of Thin-plate weirs	14
2.5:	Hydraulic of Thin-plate Rectangular weirs	20
2.5.1:	The Simplified Weir Flow Equation	20
2.5.2:	Thin-plate Weir Sensitivity	25
		27

3.	EXPERIMENTAL SET UP	27
3.1:	Experimental Facility	27
3.2:	Experimental Procedure	30
4.	RESULTS	31
4.1:	Analysis of Results	31
4.2:	Calibration of Weir Plates	39
4.3:	Weir Sensitivity Analysis	42
4.4:	Experimental Relationship between h/p and θ	44
4.4.1:	Experimental Relationship between h_y/h_{sk} and Q	47
4.5:	Discussion of Results	50
5.	SUMMARY AND CONCLUSIONS	54
5.1:	Summary	54
5.2:	Conclusions	55
List of References		57
	Appendices	59

LIST OF TABLES

			PAGE
Table	4.1:	Data for p = 10.16cm; θ = 0; b = b_s = 15.24cm; L_h = 20cm.	33
Table	4.2:	Data for p = 10.16cm; θ = 15^0; b = 15.24cm; b_s = 15.80cm; L_h = 20cm.	34
Table	4.3:	Data for p = 10.16cm; θ = 30°; b = 15.24cm; b_s = 17.60cm; L_h = 20cm.	35
Table	4.4:	Data for p = 10.16cm; θ = 45°; b = 15.24cm; b_s = 21.60cm; L_h = 20cm.	36
Table	4.5:	Data for p = 10.16cm; θ = 60°; b = 15.24cm; b_s = 30.48cm; L_h = 20cm.	37
Table	4.6:	Data for p = 10.16cm; θ = 75°; b = 15.24cm; b_s = 58.90cm; L_h = 20cm.	38
Table	4.7:	Table showing the calculated values of h/p used in plotting Figure 4.6.	45
Table	4.8:	Table showing the calculated values of h_o/h_{sk} used in plotting Figure 4.7.	48

LIST OF FIGURES

		PAGE
Figure 2.1:	Definition sketch for a rectangular thin-plate weir	5
Figure 2.2:	Rectangular full-width weir	8
Figure 2.3:	Contracted weir	8
Figure 2.4:	V-notch weir	8
Figure 2.5:	Trapezoidal weir	8
Figure 2.6:	Parabolic weir	9
Figure 2.7:	Circular weir	9
Figure 2.8:	Compound weir	9
Figure 2.9:	Oblique weir	9
Figure 2.10:	Broad-crested weir	10
Figure 2.11:	Definition sketch of oblique weir	16
Figure 2.12:	Silting behind a weir (due to Isrealson and Hansen, 1962)	18
Figure 2.13:	Oblique weir of finite crest width	18
Figure 2.14:	Simplified weir flow	22
Figure 2.15:	Actual weir flow	22
Figure 2.16:	Inclined weir definition (Author's)	24
Figure 3.1:	Sketch of weir models	28
Figure 3.2:	Experimental set-up	29
Figure 4.1:	Plot of discharge Q versus head h for weir height p = 10.16cm for various weir inclinations	40
Figure 4.2:	Plot of Log Q versus Log h at weir height p = 10.16cm for various weir inclinations	41
Figure 4.3:	Plot of sensitivity σ versus discharge Q for weir height p = 10.16cm at various angles of inclinations	43

Figure 4.4: Plot of the ratio h/p versus weir inclination θ at a discharge of 1 x 10^{-3} m^3/s 46

Figure 4.5: Plot of the ratio h_y/h_{sk} versus discharge Q for weir height p = 10.15cm at various angles of inclination. 49

Figure 4.6: Plot of the ratio h_o/h_{sk} versus weir inclination θ at various weir heights for a discharge of 2 x 10^{-3} m^3/s 53

LIST OF APPENDICES

	PAGE
Appendix A	59
Appendix B	62
Appendix C	78

ABBREVIATION AND SYMBOLS

B = Approach channel width, m

BS = British Standards

b = Weir crest length, m

b_e = effective weir length, m

C = a coefficient

C_d = discharge coefficient for normal weir

C_{sk} = discharge coefficient for oblique weir

d = diameter of circular weir, m

dh = elementary increase in head, m

dQ = elementary increase in flow rate, m^3/s

$\frac{dh}{dt}$ = rate of change of water level with time

f( ) = function of what is contained in the brackets

g = acceleration due to gravity, m/s^2

H = total head over weir crest corrected for approach velocity, m

h = head over weir crest, m

h_e = effective head on weir, m

h_o = head over normal weir, m

h_{sk} = head over inclined weir, m

h_v = approach velocity head, m

ILRI = International Institute for Land Reclamation and Improvement.

K = a constant

k_b = constant to take care of effects of viscosity and surface tension on the width of the weir

k_h = constant to take care of effect of viscosity and surface tension on head.

L = length of weir crest in flow direction, m

L_h = location upstream of weir plate where head is measured, m

n = Number of end contractions

p = weir height above approach channel bottom, m

Q = weir discharge, m^3/s

Q_h = flow rate in horizontal channel, m^3/s

Q_m = actual discharge in unsteady state, m^3/s

Q_s = steady state discharge, m^3/s

Q_s = flow rate in corresponding sloping channel, m^3/s

q = weir discharge per metre width of crest, m^2/s

R = Reynold's Number

S = surface tension, N/m

S_e = energy slope

S_{eh} = energy slope in horizontal channel

S_{es} = energy slope in sloping channel

USBR = United States Bureau of Reclamation

V_1 = approach velocity, m/s

V_2 = flow velocity in vena contract of nappe, m/s

V_a = approach velocity above weir crest, m/s

V_b = approach velocity below weir crest, m/s

V_w = wave velocity, m/s

W = Weber Number

x,y = rectangular cartesian coordinates

α = angle of side slope for trapezoidal weir

ϕ = weir inclination with respect to centre line of flow(due to Michel), degrees.

β = a dimensionless empirical function of ϕ

θ = weir inclination with respect to the axis perpendicular to the flow direction, degrees

ρ = density of water, Kg/m^3

μ = viscosity of liquid, Ns/m^2

σ = weir sensitivity, $ /m^2$

CHAPTER 1

INTRODUCTION

1.1 Nature and Importance of Hydraulic Structures

World population is ever on the increase and with it water demand continues to grow. As new sources of water become more and more difficult to find, efficient management of available water resources is becoming more and more important. One way of conserving the available water resources is to reduce the amount of water loss, through efficient management techniques such as by accurate measurement and regulation of discharges. In other words, discharge measurement and regulation form an important aspect of water resources development during the exploitation of both surface and ground waters. It is important, for example, to estimate how much water will be available at a particular reach of a river before constructing a dam in that location. Streamflow and flood measurements thus become significant. The reservoir constructed may serve varied purposes such as municipal water supply, irrigation water supply, water supply to industries, hydroelectric power generation, and a couple of others. Irrigation water to farms can be conveyed through canals or pipes and how much water to apply must be known and monitored depending on crop needs. Flow measurements and regulation at various sections of canals and at various diversion points from the canals to the fields, therefore, become important.

For purposes of research and development of design parameters for various hydraulic structures, laboratory measurements using models are important. After a hydraulic structure has been designed and constructed, field measurements may be taken to correlate the performance of the structure with the design specifications. The importance of hydraulic measurements both in the field and in the laboratory therefore becomes obvious.

1.2 Types of Hydraulic Structures

There are various devices in use for flow measurements, among which are weirs, Parshal flume, Venturi meter, etc. "Weirs are one of the oldest, simplest, and most reliable structures that can be used to measure the flow of water in canals and ditches" (USBR, 1967). They are also used in raising and regulating water level in canals for purposes of diverting the water into farms. "Weirs generally employed in irrigation works are rectangular, trapezoidal and V - notch weirs" (USBR, 1967). Weirs are broadly classified into thin-plate (sharp-crested) and broad - crested weirs. A thin-plate weir is a weir whose crest thickness in the flow direction is thin enough for the lower surface of the sheet of water passing over it to spring clear of the lower edge of the crest on the downstream face of the weir. A broad - crested weir is a weir whose crest thickness in the flow direction is long enough for the lower surface of the sheet of water flowing over it to adhere to the downstream edge of the weir crest. The thin-plate weirs in particular, (subject of this study) also find wide application in laboratory research work where they are used to measure the flow or raise the water level. They are also used in water supply systems to gauge small compensation water flows, and, in commerce, to gauge effluents of clean water or water containing only dissolved pollutants. Their attraction is their cheapness, and the ease with which they may be made with simple workshop facilities from readily available sheet material (White, 1978).

Quite a number of works have been carried out on weirs generally, and on the thin-plate weirs in particular. The International Institute for Land Reclamation and Improvement, ILRI (1976), for example, reported the work carried out on oblique weirs by Alchel in 1953. Alchel investigated the effect of inclination on discharge of the normal weir,

and developed a relationship for the unit discharge of the oblique weir. He conducted his experiments in a canal. Another interesting work reported was the research carried out by Muralidhar in 1965. Lakshmana Rao (1975) reported that Muralidhar investigated effects of inclination on the discharge co-efficient of weirs of finite crest width, and concluded that the discharge co-efficient decreased with increasing inclination of the weir.

1.3 Objective and Scope of Study

The objective of this study is to investigate the effects of inclination on the characteristics of a rectangular thin-plate weir. The characteristics investigated are the ability of the weir to develop head, measure or pass discharges under varying heads, and how sensitive the weir is within the range of head used. Inclination refers to the angle at which the weir is placed with respect to the axis perpendicular to the flow direction.

In carrying out this study, experiments were conducted in the laboratory. An open channel 15.24cm wide by 30.48 cm deep and 6m long was used to run the experiments. Weir models (3mm thick) of height 10.16cm and of inclination in 15^{o} increments from 0 to 75^{o} were used to run the first set of experiments. The experiments were then repeated for two weir heights of 15.24cm and 20.32cm. Eighteen weir models were used for the experiments. During the tests, head over the weir crest, and the discharge passing over the weir were measured. The head was measured using a point gauge (BS: 3680: part 7), and the discharge was measured using the weighing method. Water for the experiments was recirculated by means of an electrically operated centrifugal type pump which raised the water from a sump below the channel to about 2m into the channel.

To assess the head development characteristic of the weir, three sets of graphs were drawn, viz:- (1) Graphs of discharge (Q) against head (h) for each weir height, p, (2) graphs of the ratio $\frac{h}{p}$ against θ for fixed discharges (for three different heights), where θ = weir inclination, and (3) graphs of the head ratio h_o/h_{sk} against Q, where h_o = head on normal weir, and h_{sk} = head on inclined weir.

Graphs of the ratio h_o/h_{sk} against θ for fixed discharge were also drawn to illustrate the use of this ratio in choosing the angle at which a weir can be placed in a canal or channel in order to satisfy a given head ratio.

Sensitivity of the weirs were computed and plotted against discharge in order to see the trend of sensitivity with varying discharges.

CHAPTER 2

Literature Review

2.1. Definition

A weir may be defined simply as any partial obstruction in an open channel on top of which the liquid flows with a free surface. The weir crest is the edge or top surface of the weir. The sheet of water flowing over the weir crest is called the nappe. The vertical distance of the crest from the bottom of the channel is the weir height, p. The upstream section of the channel leading to the weir is termed the approach channel. The depth of water above the weir crest is termed the head over the weir, h. Figure 2.1 shows a definition sketch for a rectangular thin - plate weir.

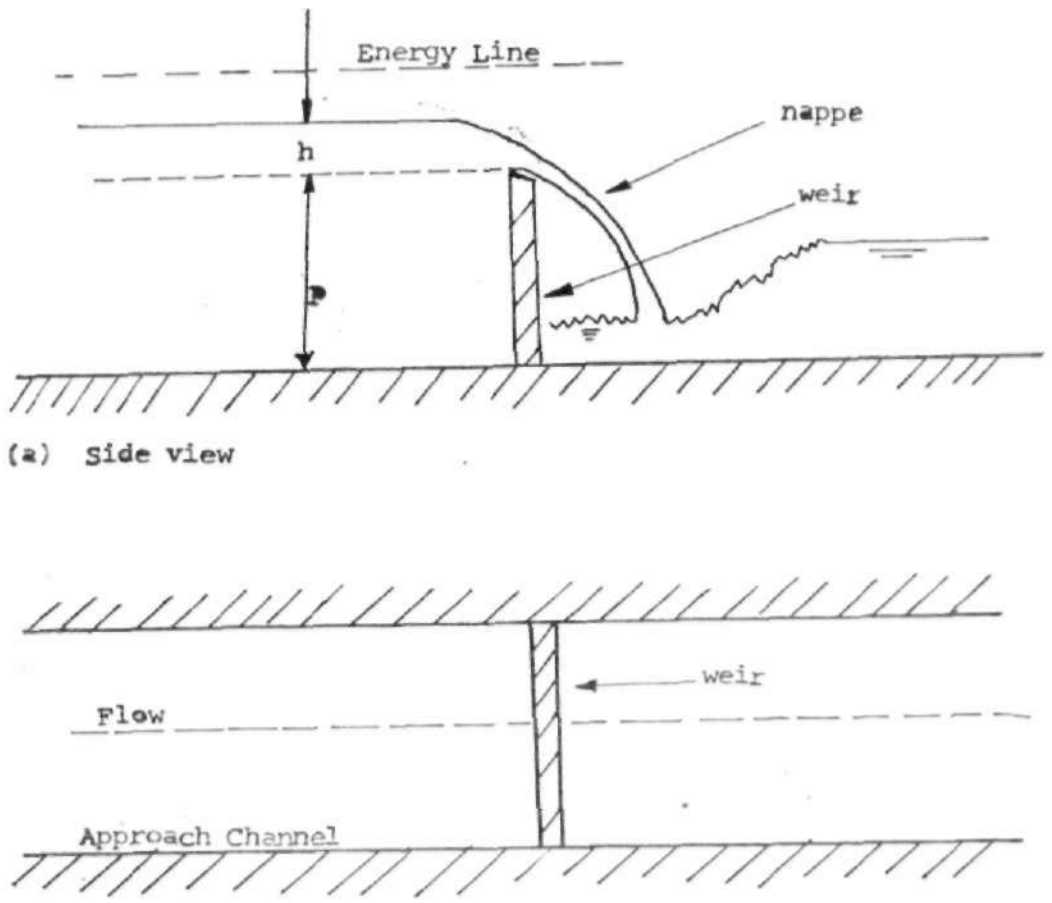


Figure 2.1: Definition Sketch for a rectangular thin-plate weir

2.2. Weir Classification

Weirs can be classified into various types depending on their geometry and nature of the crest. The geometry, to a large extent, determines the flow characteristics of a particular type of weir. They are broadly classified into thin - plate and broad-crested weirs, the most important of which are briefly discussed below:-

2.2.1 Thin-plate weirs

A thin-plate weir is a weir whose crest thickness in the flow direction is thin enough for the lower nappe surface to spring clear of the lower edge of the crest on the downstream face of the weir (Figure 2.1). The thin-plate weirs are the most frequently used in laboratories. Their main attraction is their cheapness as they can be made with materials readily available in the field. Steel plates and perspex, for example, have been commonly used. Moreover, laboratory conditions can be quite accurately reproduced in the field when using the thin - plate weirs. Their disadvantage, however, is that the crest can be easily damaged by suspended materials especially when the weir is put to use for a long period. They, therefore, require considerable maintenance, and are best suited for use in sediment-free water.

The thin-plate weirs are also referred to as "sharp-crested weirs" and are further subdivided as follows:-

(i) Rectangular full-width weirs are thin-plate weirs of rectangular cross-section and occupying the full width of the channel in which they are placed (Figure 2.2). The term "suppressed weir" is also applied to the full-width weir.

(ii) Weirs with end contractions (contracted weirs) are those weirs that do not occupy the full-width of the channel in which they are placed (Figure 2.3).

(iii) V - notch weirs are those with triangular cross-section, with the apex of the triangle downwards. The included angle in the "V" varies, but the most common in use is 90^{o} (White, 1978), Figure 2.4. The V-notch weirs have advantages over the rectangular weirs in that they can be used to measure much lower flows accurately than the rectangular weirs, and they are also more sensitive. The discharge of V-notch weirs increases more rapidly with the head than that of rectangular weirs.

(iv) Trapezoidal weirs are weirs of trapezoidal cross-section (Figure 2.5). A typical case of this weir is the Cipolletti weir, which has a side slope of 4:1 (USBR,)..

(v) Parabolic weir.

This has parabolic cross-section as shown in Figure 2.6, and the section is defined by

$$X^2 = Ky$$

(vi) Circular weir, which is a weir with circular cross-section shown in Figure 2.7.

(vii) Compound weirs.

These are weirs of cross-section combining a rectangle and a triangle. It is in effect a special combination of rectangular and V-notch weirs. The advantage of this is that the same weir can be used to measure accurately very low flows using the V-section and at high flows the rectangular section is also used. The compound weir section is shown in Figure 2.8.

(viii) Oblique weirs.

An oblique weir is a weir which makes an angle with the axis perpendicular to the flow direction (Figure 2.9). It is the type under investigation in this study. Much more would be

discussed about this later in the text.

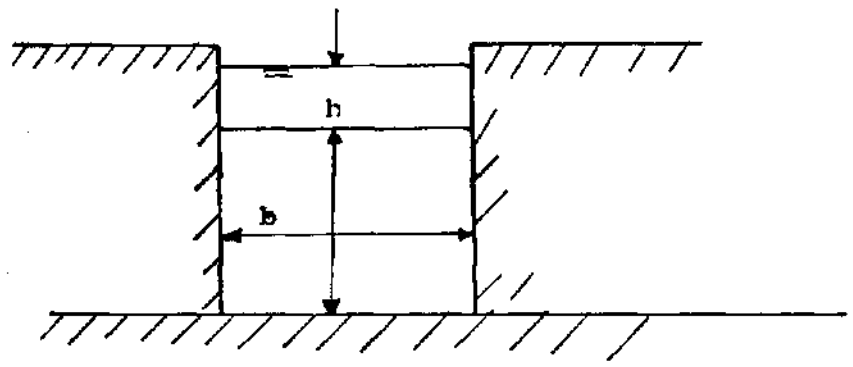


Figure 2.2: Rectangular full-width weir

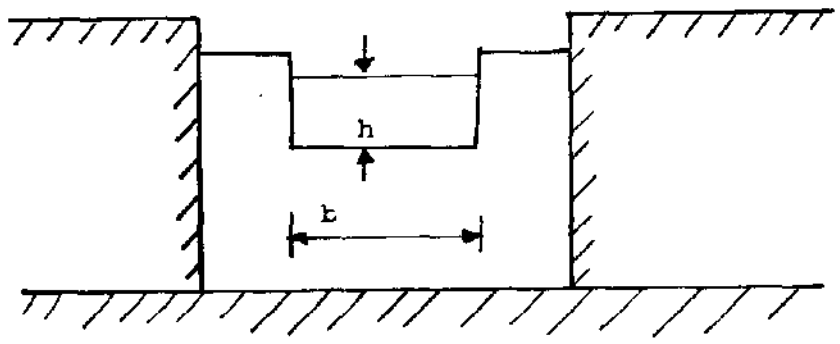


Figure 2.3: Contracted weir

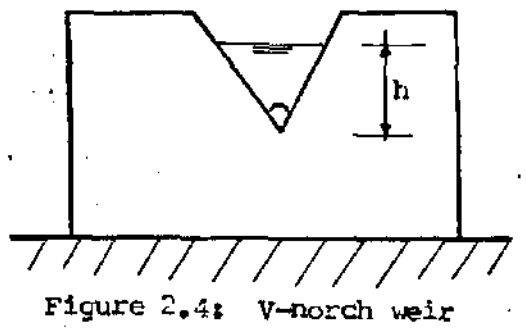


Figure 2.4: V-norch weir

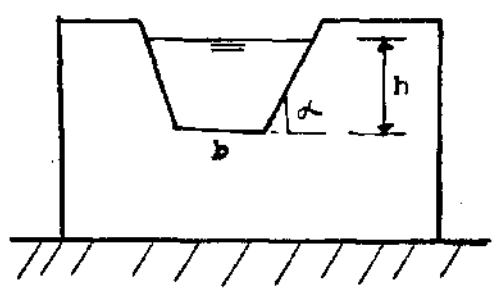


Figure 2.5: Trapezoidal weir

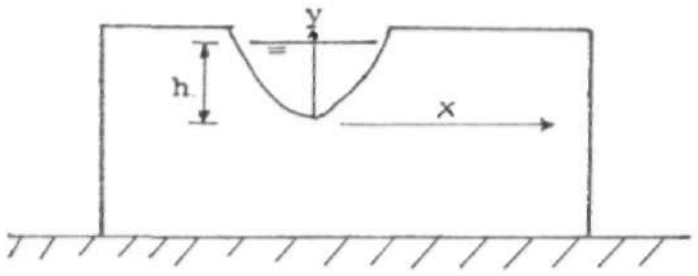


Figure 2.6: Parabolic weir

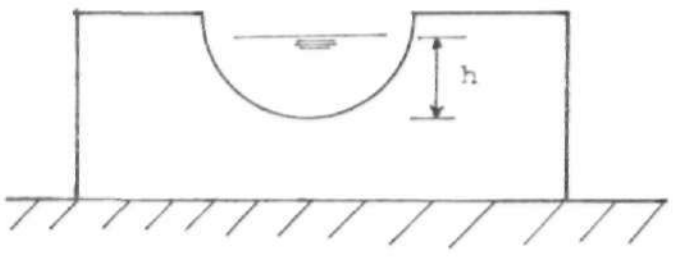


Figure 2.7: Circular weir

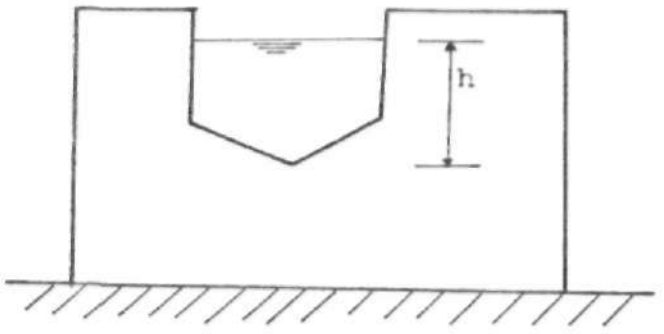


Figure 2.8: Compound weir

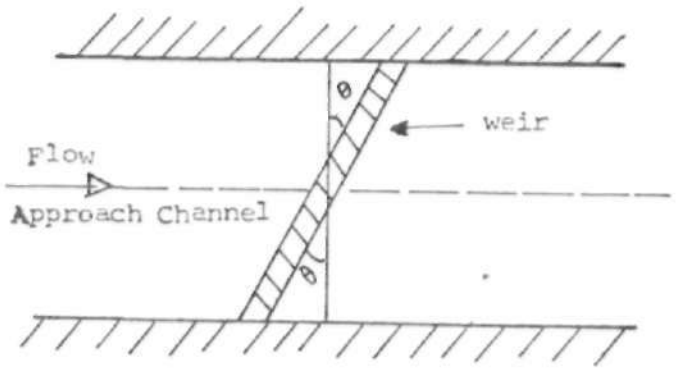


Figure 2.9: Oblique weir

2.2.2 Broad-crested Weirs

These are weirs with finite crest thickness, as a result of which they are also referred to as "weirs of finite crest width". Unlike in the thin-plate type, the lower surface of the nappe adheres to the downstream edge of the weir crest (Figure 2.10). As with the thin-plate weirs, they can be of any cross-section such as rectangular, triangular, trapezoidal, parabolic, circular or compound, and their discharge relationships likewise depend on the type of cross-section.

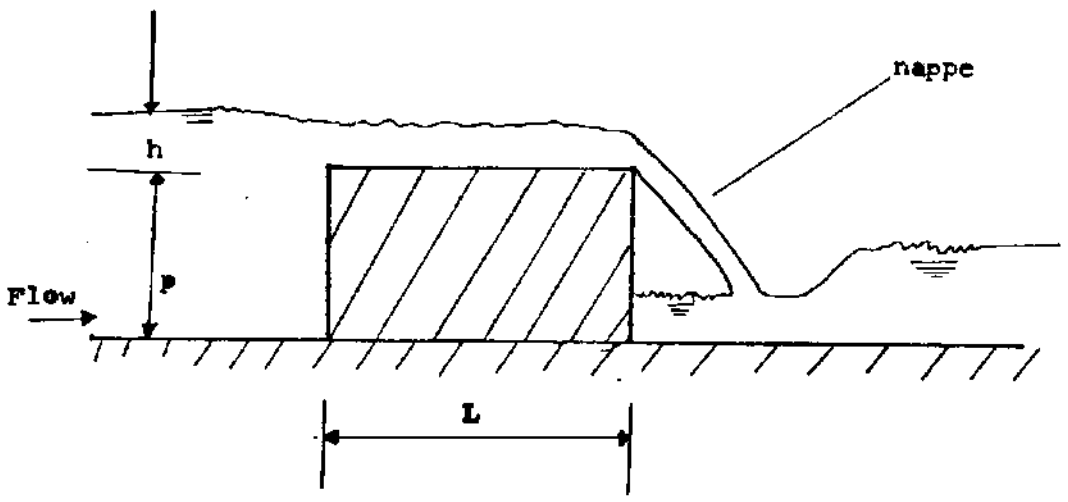


Figure 2.10: Broad - Crested weir

2.3. Factors Affecting Flow over the thin-plate Weirs

Quite a number of factors affect the performance of weirs generally. Some of these are:-

2.3.1. Aeration

A thin-plate weir must be properly aerated for reliable and stable performance. In this weir type the nappe springs clear of the lower edge of the crest on the downstream face of the weir. As a result of this, pockets of air form beneath the nappe, and from this air pocket, a quantity of air is continuously being removed by the overfalling jet (ILRI, 1976). This consequently lowers the pressure beneath the nappe, thus increasing the pressure difference between the upper and lower surface of the nappe thereby increasing its curvature and consequently increasing the discharge coefficient. "An underpressure beneath the nappe will deflect the nappe downwards and thus gives a smaller radius to the streamlines, which results in a higher discharge coefficient" (ILRI, 1976). It also results in unreliable and unstable performance of the weir. To guide against these effects, the nappe must be properly ventilated. To do this, a continuous supply of air is often passed to the underside of the nappe. In a situation, however, where the weir is to be operated under submerged flow conditions the need for aeration does not arise as the weir itself is completely drowned in the flowing water, and both upstream and downstream head measurements are needed to compute the discharge over the weir.

2.3.2. Approach Channel Conditions

The approach channel is the upstream section of the channel leading to the weir. It may be of regular or irregular cross-section. Velocity distribution in the approach channel affects the flow over the thin-plate weirs. The approach velocity is obtained by dividing the measured discharge by the cross-sectional area of the water depth in the approach channel, assuming that the distribution is uniform. The velocity distribution,

however, is not always uniform but varies with the channel geometry. If the approach channel is straight and reasonably regular for a distance of at least five times its surface width, the velocity distribution is practically uniform, and there will be no significant water level variation across the channel width (White, 1978).

Skewness of the weir can also affect the flow over the weir. In an oblique weir, the discharge is observed to be concentrated towards the side further downstream. If the weir is the contracted type then its positioning whether symmetrical or asymmetrical to the flow direction may further affect the flow.

Weir height also affects the flow by affecting the approach velocity distribution. When a weir is installed across a river or channel, the water level rises upstream of the weir, resulting in lower velocities. If, in addition, the channel bed is erodible, it will result in sediments depositing on the upstream side. If the deposition becomes significant immediately upstream of the weir, it will reduce the effective weir height, and consequently increase the discharge coefficient (Lakshmana Rao, 1975). The effective height of such a weir constructed across a river or channel with erodible beds can be maintained by removing the deposited sediments using silt extracting devices.

Studies on weirs have been based on steady state conditions in the approach flow. Unsteady flow has effect on the flow over the weir. It is not possible under unsteady state flow conditions to measure satisfactorily the head over the weir. It seems, however, that no systematic investigation has been carried out on the effect of this type of flow (Lakshmana Rao, 1975).

Liquid properties such as surface tension and viscosity are also found to affect the flow characteristies of the weir (Lakshmana Rao, 1975). The effect of surface tension has been found to be more pronounced at low heads and large crest thickness. Viscosity effects also follow the same trend. However, the effects can be neglected at high heads.

The location where head over the weir is measured is also significant. This is because the water surface profile upstream of the weir is not horizontal (White, 1970). Immediately upstream of the weir, there is the drawdown region, and further upstream frictional losses produce a water surface slope towards the weir plate. To avoid these areas the common practice is to take the head measurements at a distance of at least four times the maximum head over the weir (BS: 3680: part 4A), but not further upstream as to be strongly influenced by frictional losses. This location has at best remained approximate because it has not been possible to come up with a fixed location. Fixing the maximum head in a laboratory model is relatively easier as the dimensions of both the channel and those of the weir can be fixed. Usually when a weir is to be constructed across a river or stream, flow duration studies would be necessary to determine the maximum head to be used.

2.4. Some Theories of Thin-plate Weirs.

Several investigations have been carried out on weirs generally, and on the thin-plate weirs in particular in the past two and a half centuries. (Lakshmana Rao, 1975).

Fteley and Stearns (1883), for example, ran tests with two thin-plate full width weirs, 1.50m and 5.00m long, and deduced the following formula for the discharge of water over the weir,

$$Q = 1.83bH^{3/2} + 0.002b \qquad (2.1)$$

They suggested the range of applicability of the formula as heads of 2cm to 50cm.

Francis performed experiments with the thin-plate weir in 1884 and developed following relationship for full - width weirs (Brater and King, 1976),

$$Q = 1.85bh^{3/2} \qquad (2.2)$$

He conducted his experiments within the following range:-

(a) head over the weir of 10 to 50cm;

(b) weir crest lengths of 2.40 to 3.00 m;

(c) weir heights of 0.60 and 1.50 m; and

(d) Approach velocities of 0.060 to 0.30 m/s.

Troskolanski (1960) reported that Hansen ran experiments with the thin-plate full width weirs in 1892. The weirs had crest length of 1.0 m and height of 0.514m. Head over the weir was measured at a distance of 1.10 m upstream of the weir. The range of head over the weir was 10 to 40 cm. Hansen presented the relationship between the head over the weir and the discharge passing over the weir in tabular form.

Schoder and Turner (1929) conducted very many experiments for the discharge over the thin-plate full width weir. Based on the data obtained,

Schoder suggested the following formula for the discharge over the weir,

$$Q = 1.84b\left[\left(h + \frac{V_a^2}{2g}\right)^{3/2} + \left(0.54h\ \frac{V_b^2}{2g}\right)\right] \qquad (2.3)$$

Schoder's work suggested that in situations where the approach velocity distribution is not uniform, the effect of velocity above and below the weir crest should be considered.

Rehbock (1929) also carried out intensive studies into the characteristics of the full-width thin-plate weirs, and developed the following expression for the discharge over the weir, and which he presented in his discussion of Schoder's work.

$$Q = 2/3\sqrt{2g}\ b\ (0.602 + 0.0832\ \frac{h}{p})\ (h + .00125)^{3/2} \qquad (2.4)$$

The formula, he suggested, applied in general to any full-width thin-plate vertical weir with a perfectly free and fully aerated nappe, and with practically uniform approach velocity, within the following limitations:-

(a) $0.003 < h < 0.75m$;

(b) $b > 0.30$ m;

(c) $p > 0.30$ m; and

(d) $\frac{h}{p} < 1.0$.

The International Institute for Land Reclamation and Improvement, ILRI (1976), reported that Alchel performed experiments with oblique weirs placed in a rectangular canal with upstream weir face vertical, and with the crest length L (in flow direction) small compared to the crest width, b, as shown in Figure 2.11. He suggested that the discharge per unit width of crest, q_{sk} over the weir can be determined from the following relationship,

$$q_{sk} = (1 - \frac{h}{p}\beta)q \qquad (2.5)$$

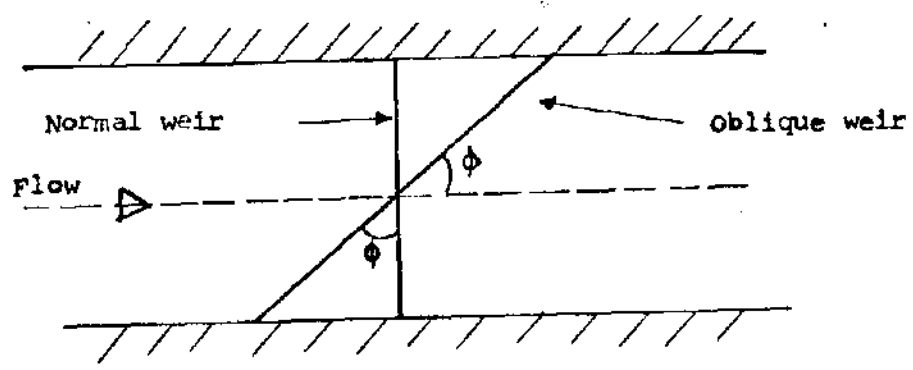


Figure 2.11: Definition Sketch of Oblique weir

Kinsvater and Carter (1959) introduced the concept of effective head and width into the thin-plate weir discharge equation, to account for the effects of viscosity and surface tension. They argued that the influence of both viscosity and surface tension was to increase the head, and to increase or decrease the width of the weir. The influence decreased as both the head on the weir and the weir width increased. They suggested a discharge coefficient independent of the viscosity and surface tension effects, but dependent only on the ratios b/B and h/p. They experimented with a thin-plate rectangular weir whose b/B ratio varied from less than one to one, and proposed the following equation as applicable for all rectangular thin-plate weirs,

$$Q = C_e b_e h_e^{3/2} \qquad (2.6)$$

where $b_e = b + k_b$

$h_e = h + k_h$

The effects of surface tension were further studied by Sarginson in 1972 (Lakshmana Rao, 1975). He came up with the following expression for the discharge over the weir,

$$Q = \left(1.81 + \frac{4.22}{W} + 0.22\,\frac{h}{p}\right) bh^{3/2} \qquad (2.7)$$

Sarginson observed that the formula is valid for heads of 1 cm and above, and only for a weir with well - aerated nappe.

The effects of variable channel slope on discharge was studied by Hiranandani and Chitale in 1960 (Lakshmana Rao, 1975). They suggested that the following expression would take care of such effects.

$$\frac{Q_h}{Q_s} = \left(\frac{S_{eh}}{S_{es}}\right)^{1/2} \qquad (2.8)$$

Hiranandani and Chitale also studied the effect of unsteady flows on the discharge, and recommended the use of Wiggin's flood formula to compute unsteady discharge over the weir. Wiggin's formula is given by

$$\frac{Q_o}{Q_m} = \left[1 - \left(\frac{1}{V_w\ S_e}\right)\frac{dh}{dt}\right]^{1/2} \qquad (2.9)$$

Israelson and Hansen (1962) described the effects of deposition of sediments upstream of the weir, on weir discharge. According to them, deposition of sediments upstream of the weir changed the approach flow geometry, and caused the discharge to increase to a value more than that determined from the measured head over the weir. Figure 2.12 shows the definition sketch used by them.

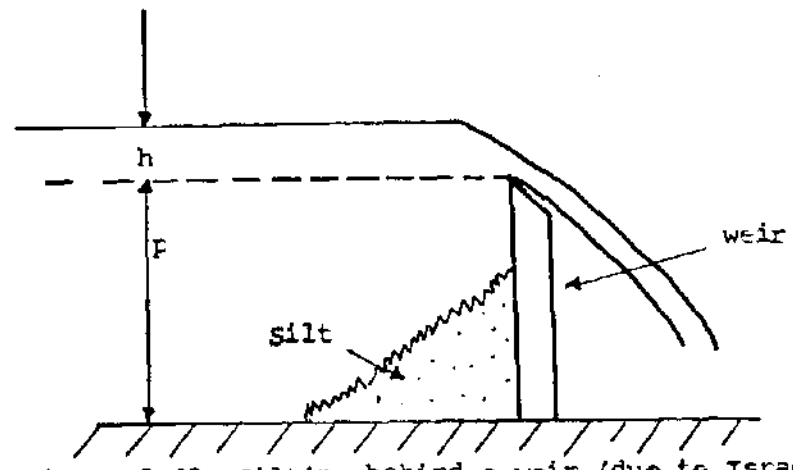


Figure 2.12: Silting behind a weir (due to Israelson and Hanson, 1962)

Muralidhar carried out studies on oblique weir of finite crest width in 1965 (Lakshmana Rao, 1975). He observed discharge concentration towards one side of the weir, and that the discharge coefficient decreased with increasing angle of alignment. The coefficient was also found to be affected by the ratio B/b_s (Figure 2.13). He suggested that the discharge coefficient can be expressed by

$$C_{sk} = f(h, V_1, B, b_s, L) \qquad (2.10)$$

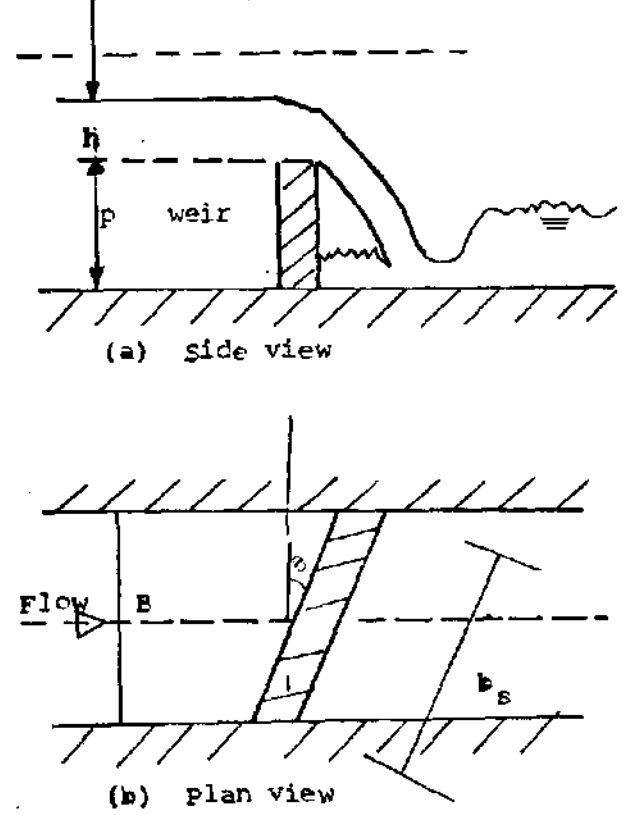


Figure 2.13: Oblique weir of finite crest width

White of the Hydraulics Research Station, Wallingford, England, investigated the effect of the location for head measurement, on the discharge (Ackers et al, 1980). Based on a fixed location of $\frac{L_h}{p} = 2.67$, he developed the following relationship for the discharge,

$$Q = 0.562b \sqrt{g} \left(1 + 0.153 \frac{h}{p}\right) (h + 0.001)^{3/2} \qquad (2.11)$$

It can be seen from the literature cited that a number of investigators came up with different equations and formulae for the weir. This probably is due to the different experimental conditions and limitations under which the experimenters worked. The complexity and interaction of the factors affecting the weir characteristics also probably add to this. The best practical method of using a particular weir as a device is therefore to calibrate the weir in the field especially to determine its coefficient and discharge characteristics, and these have to be reviewed from time to time to make sure the characteristics have not changed with time due to possible changes in the behavious of the channel or stream or the geometry of the weir. This is particularly so for the thin-plate weir whose crest can easily be damaged by obstructions or debris in the channel in which it is constructed.

2.5 Hydraulics Of Thin-plate Rectangular Weirs

2.5.1 The Simplified Weir Flow Equation

The flow over the thin-plate weir is essentially two-dimensional (Vennard and Street, 1976), and is a complex problem that often leads to complicated mathematical analysis. This is because although most of the factors affecting the flow can be identified, their individual influences are either inter-related or can at best be verified only experimentally. It is clear, therefore, that to derive a simple flow formular for the weir analytically, requires simplification of the problem by certain assumptions, and the result is therefore, approximate. With appropriate experimentally determined coefficient applied to the simple relationship, however, a better insight into the weir problem is obtained.

The simple weir equation is derived analytically by referring to Figure 2.14 and 2.15 and making use of the following assumptions (Vennard and Street, 1976):-

(1) That the approach velocity distribution is uniform,

(2) That particles of fluid move horizontally as they pass over the weir crest

(3) That the nappe is adequately aerated so that the pressure inside it is zero,

(4) That the effects of viscosity, surface tension, turbulence and secondary flows are negligible.

Applying Bernoulli's equation between any point on section (A) - (A) and point B(the centre of gravity of the vena contracta in the nappe) with velocity V_2 we obtain,

$$h + \frac{V_1^2}{2g} = (h-y) + \frac{V_2^2}{2g} \qquad (2.12)$$

$$V_2 = \sqrt{2g\left(Y + \frac{V_1^2}{2g}\right)} \qquad (2.13)$$

If dq = the flow per unit crest length through the element of height dy, then

$$dq = V_2 \, dy$$

$$dq = \sqrt{2g\left(y + \frac{V_1^2}{2g}\right)} \, dy \qquad (2.14)$$

Integrating equation (2.14) between y = 0 and y = h we obtain,

$$q = \frac{2}{3}\sqrt{2g}\left[\left(h+\frac{V_1^2}{2g}\right)^{3/2} - \left(\frac{V_1^2}{2g}\right)^{3/2}\right] \qquad (2.15)$$

For a weir of crest length, b, the total flow Q is then given by

$$Q = \frac{2}{3}\sqrt{2g}\, b\left[\left(h+\frac{V_1^2}{2g}\right)^{3/2} - \left(\frac{V_1^2}{2g}\right)^{3/2}\right] \qquad (2.16)$$

To transform equation (2.16) into actual flow equation, the effects of the factors disregarded in the basic assumptions as well as other factors that may be affecting the flow must be taken care of. To do this, a coefficient, C, is introduced to give

$$Q = \frac{2}{3}\sqrt{2g}\, cb\left[\left(h+\frac{V_1^2}{2g}\right)^{3/2} - \left(\frac{V_1^2}{2g}\right)^{3/2}\right] \qquad (2.17)$$

and yet another coefficient, C_d, defined by $C_d = \frac{2}{3}\sqrt{2g}\, C$ is introduced to give $Q = C_d \, b\left[\left(h+\frac{V_1^2}{2g}\right)^{3/2} - \left(\frac{V_1^2}{2g}\right)^{3/2}\right]$ (2.18)

where C_d = discharge coefficient of the weir.

As in most weir problems, the approach velocity is small, the term $\frac{V_1^2}{2g}$ is often neglected to give the simplified weir flow equation in the form, $Q = C_d \, bh^{3/2}$ (2.19).

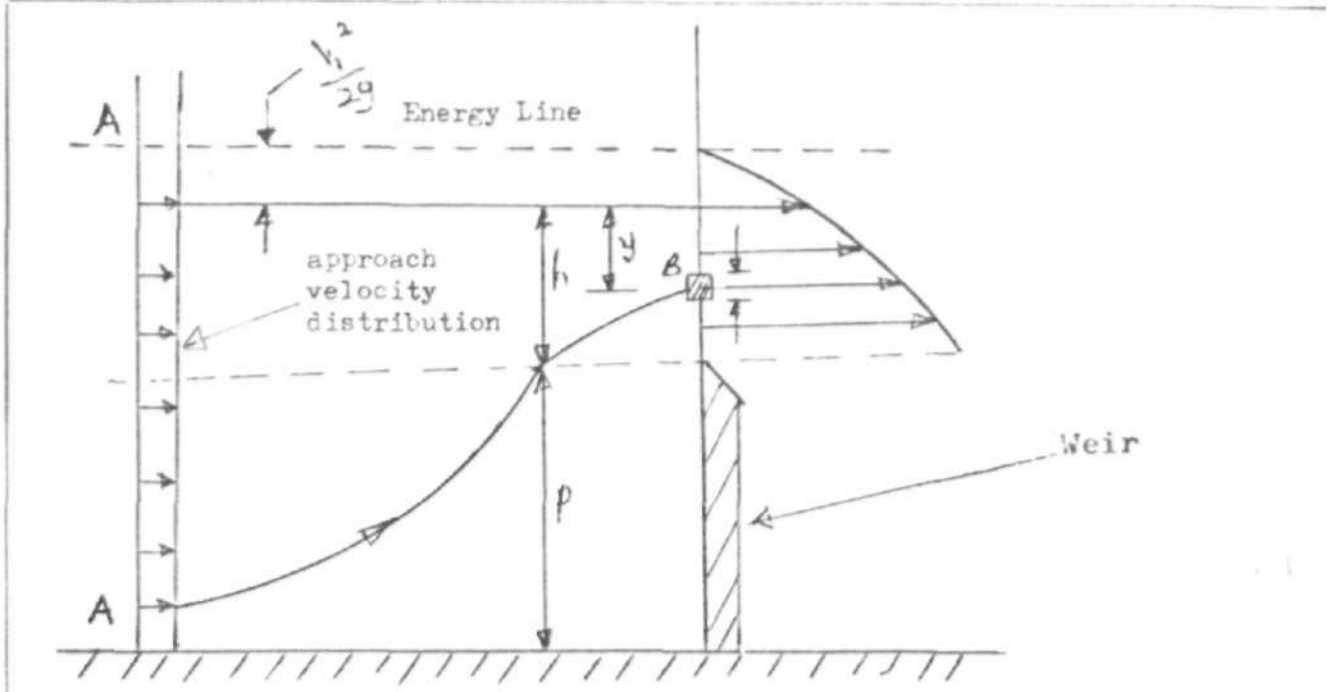


Figure 2.14: Simplified Weir Flow

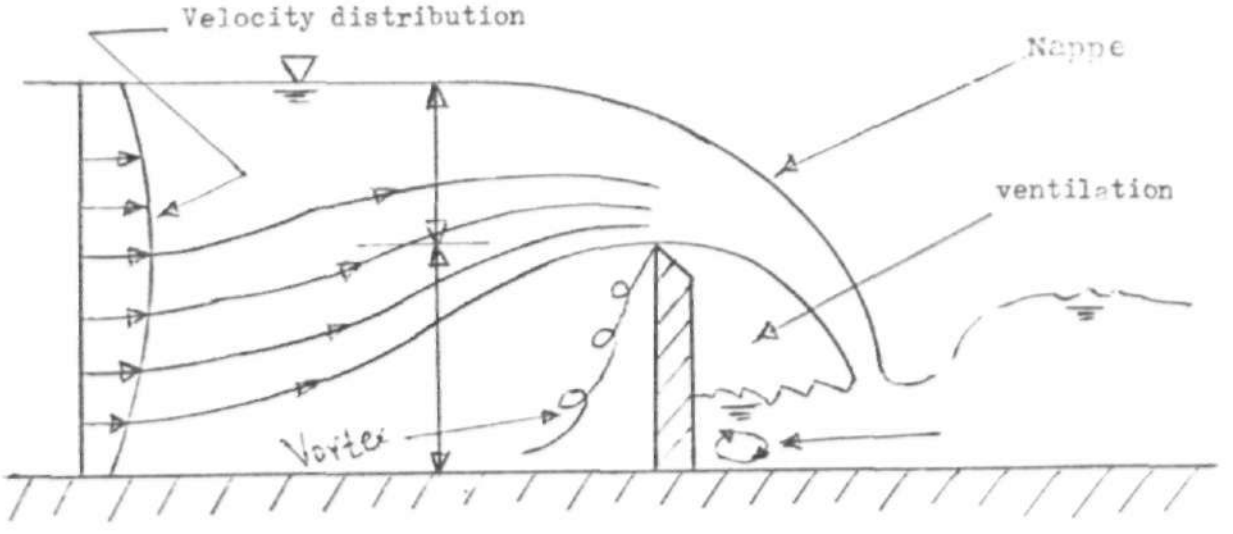


Figure 2.15: Actual Weir Flow

It is to be noted that the coefficient of discharge C_d, as already mentioned, takes care of the effects of the phenomena disregarded in developing the simplified equation and transforms it into actual flow equation. It is in effect, a coefficient which expresses the extent of contraction of the true nappe. It is also to be noted that C_d must be determined experimentally for a given set of conditions. Rehbock (Vennard and Street, 1976), for example, investigated this coefficient, and came up with the following empirical relationship,

$$C_d = 0.605 + 0.08\frac{h}{p} + \frac{1}{1000h} \qquad (2.20)$$

The weir equation can also be derived by the method of dimensional analysis. The geometry of the flow pattern over the weir can be described by the head over the weir crest, h, the weir height, p, the fluid viscosity, μ, surface tension, s, fluid density, ρ, and acceleration due to gravity, g, all forming independent variables. The dependent flow characteristic can either be the discharge per unit width of the weir crest, q, or the head over the weir, h. As the head is already taken as an independent variable, the dependent flow characteristic is then the flow, which can be expressed as

$$q = f(h,p,\mu,s,\rho,g) \qquad (2.21)$$

When dimensional analysis is performed on equation (2.21) the following relationship (see Appendix A) is obtained,

$$q/h^{3/2}\sqrt{g} = f_1\left(\frac{h}{p},R,W\right) \qquad (2.22)$$

The left hand side of equation (2.22) is actually equal to $C_d/\sqrt{g}$ (based on equation 2.19). Equation (2.22), therefore, becomes

$$\frac{C_d}{\sqrt{g}} = f_1\left(\frac{h}{p}, R, W\right) \qquad (2.23)$$

From equation (2.23) the discharge, q, is given by

$$q = C_d h^{3/2} \qquad (2.24)$$

For a weir of width b, the total discharge Q is given by

$$Q = C_d b h^{3/2} \qquad (2.25)$$

Equation (2.25) is the same as equation (2.19), and equation (2.22) shows the effect of the ratio $\frac{h}{p}$ the Reynold's Number, and the Weber's Number, on the weir flow. The ratio $\frac{h}{p}$ takes care of the weir geometry, and the Reynold's and Weber's Numbers take care of the influence of viscosity and surface tension respectively.

For an oblique weir, an additional veriable, b_s, which is the length of the oblique weir crest, is expected to affect the flow. The flow, q_{sk}, can be expressed as

$$q_{sk} = f_3 (h, p, \mu, S, \rho, g, b_s) \qquad (2.26)$$

Dimensional analysis (Appendix A) of equation (2.26) gives the weir coefficient as

$$C_{sk} = f_3 \left(\frac{h}{p}, R, W, \frac{b}{b_s} \right) \qquad (2.27)$$

The weir crest length b_s can be expressed as

$$b_s = \frac{b}{\cos\theta} \qquad (2.28)$$

(Equation (2.28) follows from Figure (2.16)

The flow relationship for the oblique weir can then be written as

$$Q_{sk} = C_{sk} b_s h_{sk}^{3/2} \qquad (2.29)$$

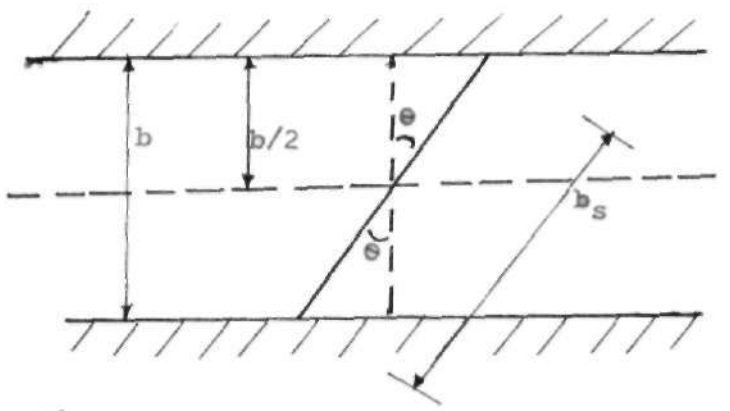


Figure 2.16: Inclined weir definition (Author's)

2.5.2 Thin-plate Weir Sensitivity

A weir develops a certain head upstream of it as a result of certain discharge passing over it. As the discharge is increased the head over the weir crest increases resulting in variations in head. How much head varistions a weir develops under changing discharges indicates its sensitivity as a hydraulic device. A very sensitive weir is expected to produce measurable head v variations for very small changes in discharge. When two weirs are compared, for example, the more sensitive of them is the one in which greater increase in head is produced for same increase in flow, both weirs starting with same initial flow (Troskolanski, 1960; Lakshmana Rao, 1975). There is no doubt, therefore, that the concept of sensitivity is another way of assessing the performance and reliability of a weir as a hydraulic device.

The sensitivity of a weir is defined as the ratio of the elementary increase in head to the elementary increase in flow rate (Troskolanski, 1960). It can be expressed mathematically as

$$\sigma = \frac{dh}{dQ} \qquad (2.30)$$

It can be clearly seen from equation (2.30) that the sensitivity depends on the flow characteristics of the weir. For a thin-plate weir, for example, the sensitivity depends to a large degree on the crest geometry in terms of how well it has been formed and how carefully it is being maintained.

Considering the normal thin-plate weir in particular, the typical discharge equation is

$$Q = C_d\, bh^{3/2} \qquad \text{(equation 2.19)}$$

Differentiating,

$$\frac{dQ}{dh} = \frac{3}{2}\, C_d\, bh^{\frac{1}{2}} \qquad (2.31)$$

From equation (2.19),

$$h = \left(\frac{Q}{C_d b}\right)^{2/3} \tag{2.32}$$

Combining equation (2.31) and (2.32),

$$\sigma = \frac{2}{3}\left(\frac{1}{C_d b}\right)^{2/3} \frac{1}{Q^{1/3}} \tag{2.33}$$

Equation (2.33) shows that for a constant C_d value, the sensitivity is expected to decrease with increased flow. When equation (2.33) is applied to an oblique weir, becomes,

$$\sigma = \frac{2}{3}\left(\frac{1}{C_{sk} b_s}\right)^{2/3} \frac{1}{Q_{sk}^{1/3}} \tag{2.34}$$

$$\sigma = \frac{2}{3}\left(\frac{\cos\theta}{C_{sk} b}\right)^{2/3} \frac{1}{Q_{sk}^{1/3}} \tag{2.35}$$

The concept of sensitivity, as already mentioned, is another way of assessing the performance of weirs. It has been used in this study to indicate the reliability and performance of the various weir models used in the experiments.

CHAPTER 3

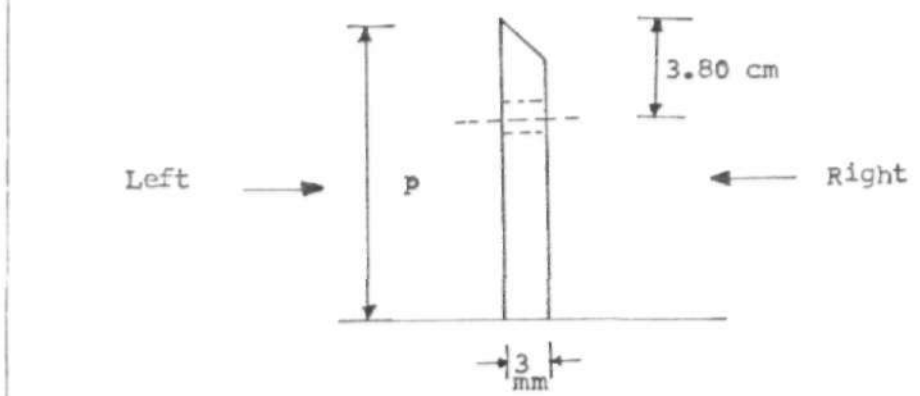
EXPERIMENTAL SET-UP AND RESULTS

3.1 Experimental Facility

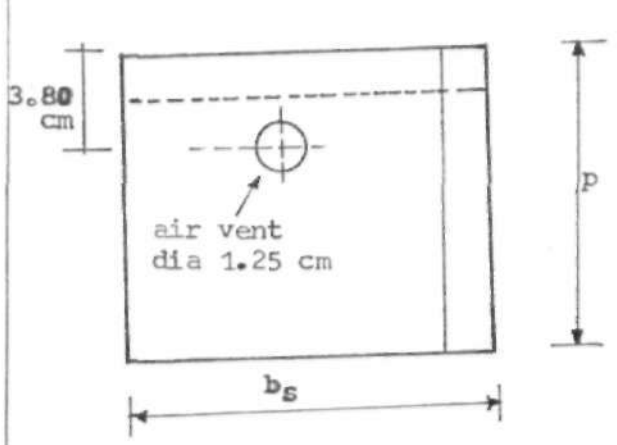
The study sought to investigate the effects of inclination on the characteristics of oblique thin-plate rectangular full-width weirs. It essentially involved measuring head over the weir crest upstream of the weir and the discharge passing over it.

A 15.24 cm wide by 30.48 cm deep, and 6m long glass walled channel was used for running the experiments. Water for the tests was recirculated by means of a small centrifugal type pump drawing the water from a sump beneath the channel to a height of about 2m into the channel.

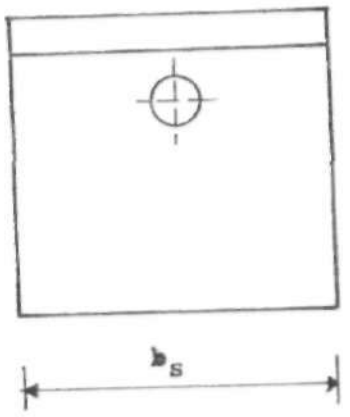
Steel thin-plate of 3mm thickness was used for constructing the weir models. The height of the weirs was 10.16cm, aligned in the channel in 15° increments from 0 to 75°. These were used in running the first set of experiments. The experiments were then repeated with weirs of heights 15.24cm and 20.32cm. Eighteen models were used. The downstream edge of each model was chamfered to about 45°. Air vent of 1.25cm diameter was drilled at mid-length of the crest with its centre 3.80cm below crest level. Figure 3.1. shows a typical sketch of the weir models, while Figure 3.2 shows the laboratory experimental set-up.



(a) Longitudinal view



(b) Weir seen from left



(c) Weir seen from right

Figure 3.1: Sketch of weir models

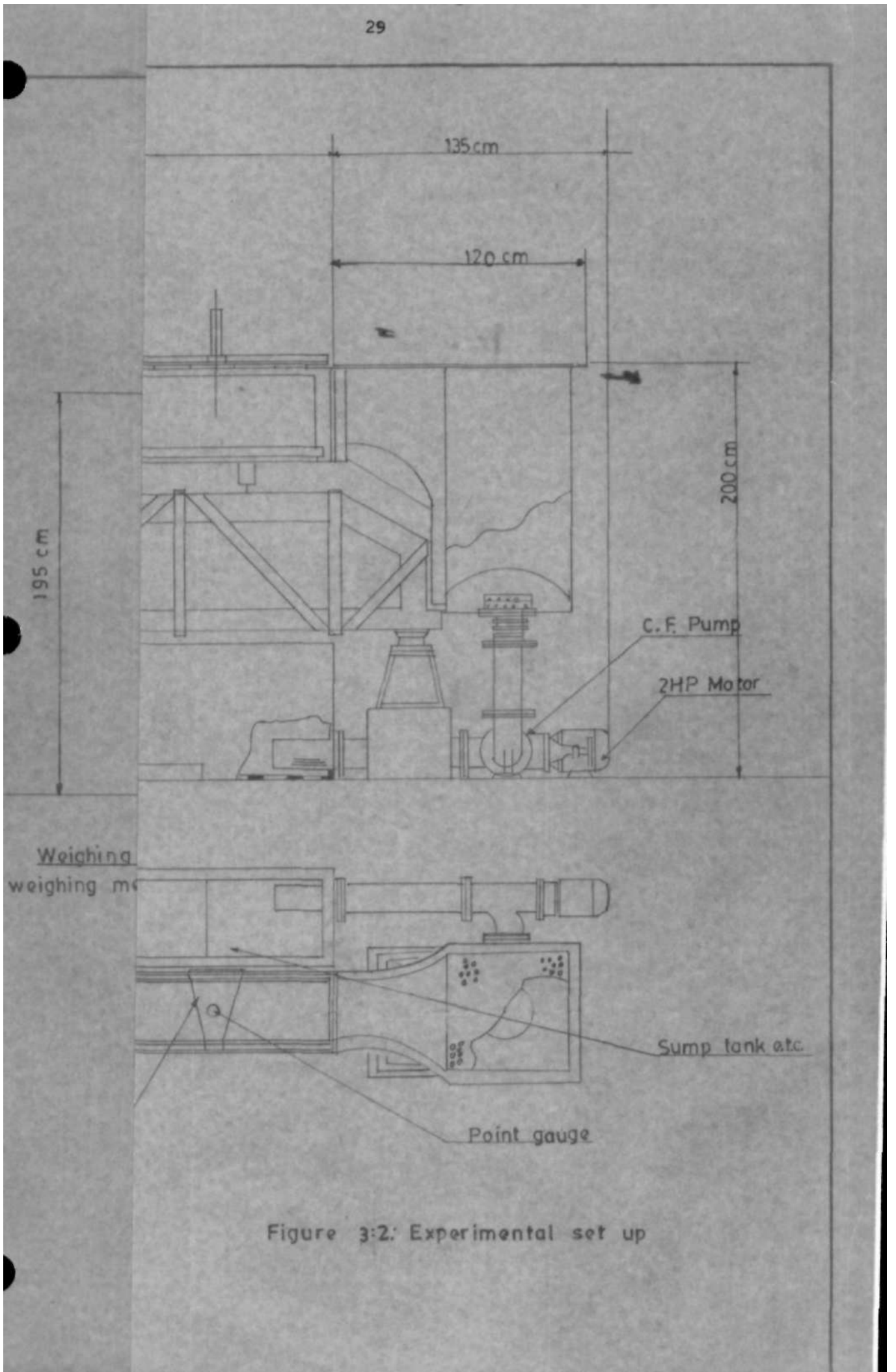


Figure 3:2: Experimental set up

3.2. Experimental Procedure

The weir plate was installed in position. A copper tube 50cm long with a 135° bend was tightly fitted into the air vent in the plate, and to the other end of the copper tube was fitted a 100cm long plastic tube. The free end of the plastic tube extended outside the channel, resting on the channel side wall so that air freely entered it. This formed the ventilation conduit with which the lower surface of the nappe was aerated. Putty was used to prevent water leakage.

The centrifugal type pump was started which raised the water from the sump to the channel passing over the weir crest. When steady state condition was established, the head over the weir was measured using a point gauge. Corresponding to this head, the discharge was measured using a weighing arrangement at the discharge end of the channel shown in Figure 3.2. For each experiment three discharge readings were taken and the mean discharge corresponding to the measured head taken.

The discharge, and so the head, over the weir were varied by manually regulating the valve located at the discharge end of the pump. Measurements were stopped as soon as water drops from the tail-water started getting into the ventilation conduit thereby reducing the ventilation of the nappe. This in fact limited the maximum head that could be reliably measured.

CHAPTER 4

RESULTS

4.1 Analysis of Results

Three sets of weirs of heights 10.16, 15.24 and 20.32cm were used for running the laboratory experiments. For every height, inclinations of $0, 15^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}$ and 75° were used. The parameters measured during the tests were the head over the weir, h, and the discharge passing over the weir, Q. From the measured values of Q and h, various other parameters were computed. The resulting data obtained are presented in tabular form. Graphs were also drawn using the data.

Tables 4.1 to 4.6 give data for 10.16cm weirs at various inclinations. Columns (2) and (3) show the values of h and Q as measured in the laboratory. Columns (4), (5), (6) and (7) show, respectively, the values of Log(h), Log(Q), weir coefficient, C_{sk}, and weir sensitivity, σ, as computed from the measured values of Q and h. In addition, corresponding data for the 15.24 and 20.32cm weirs are given in Appendix B (Tables B1 to B6, and B7 to B12, respectively).

The ratios head to weir height, h/p, against inclination θ, were also computed from the measured values of Q and h for all weir heights. Table 4.7 gives the values for a fixed discharge of 1×10^{-3} m^3/s, while Tables B13 and B14 of Appendix B give corresponding values for discharges of 2×10^{-3} and 3×10^{-3} m^3/s, respectively. The reason for using three different discharge values was to see whether there was any significant variation in the ratios h/p against θ under different discharges.

The values of the ratios head on normal weir to head on inclined

weir h_o/h_{sk}, against θ for the 10.16cm weir at various discharges, are given in Table 4.8. Tables B15 and B16 (Appendix B) show similar values for the 15.24 and 20.32cm weirs, respectively.

Various graphs were plotted using the data obtained and these will be discussed in the following sections:-

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $(\times 10^{-2}$ m)	Q $(\times 10^{-3}$ $m^3/s)$	log(h)	log(Q)	C_{sk}	σ
1.	1.52	0.57	-1.82	-3.24	2.00	17.76
2.	1.70	0.68	-1.77	-3.17	2.01	16.67
3.	1.90	0.80	-1.72	-3.10	2.00	15.87
4.	2.05	0.90	-1.69	-3.05	2.01	15.18
5.	2.20	1.05	-1.66	-2.98	2.11	13.98
6.	2.65	1.30	-1.58	-2.89	1.98	13.60
7.	2.79	1.49	-1.55	-2.83	2.10	12.48
8.	3.40	1.89	-1.47	-2.72	1.98	11.97
9.	3.50	2.00	-1.46	-2.70	2.00	11.69
10.	3.85	2.30	-1.41	-2.64	2.00	11.17
11.	4.50	2.84	-1.35	-2.55	1.95	10.58
12.	4.75	3.12	-1.32	-2.51	1.98	10.15
13.	5.26	3.67	-1.28	-2.44	2.00	9.55
14.	5.64	4.15	-1.25	-2.38	2.03	9.07

Table 4.1. Data for P = 10.16cm; θ = 0; b = b_s = 15.24cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	Log(Q)	C_{sk}	σ
1.	1.40	0.60	-1.85	-3.22	2.29	15.57
2.	1.65	0.75	-1.78	-3.12	2.24	14.67
3.	2.03	1.00	-1.69	-3.00	2.27	13.21
4.	2.34	1.25	-1.63	-2.90	2.21	12.49
5.	2.56	1.40	-1.59	-2.85	2.16	12.21
6.	2.85	1.65	-1.55	-2.80	2.06	12.10
7.	3.05	1.80	-1.52	-2.74	2.14	11.30
8.	3.20	1.90	-1.49	-2.72	2.10	11.23
9.	3.35	2.07	-1.47	-2.68	2.13	10.82
10.	3.70	2.40	-1.43	-2.62	2.13	10.28
11.	4.15	2.88	-1.38	-2.54	2.15	10.44
12.	4.70	3.42	-1.33	-2.47	2.12	9.17
13.	5.00	3.75	-1.30	-2.43	2.12	8.90
14.	5.40	4.22	-1.27	-2.37	2.13	8.53

Table 4.2: Data for P = 10.16 cm; $\theta = 15^{\circ}$; b = 15.24 cm;
b_s = 15.80 cm; L_b = 20 cm

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	$\frac{h}{x10^{-2}}$ m	$\frac{Q}{x10^{-3}}$ m³/s	log(h)	log(Q)	C_{sk}	σ
1.	1.63	0.77	-1.79	-3.10	2.10	14.13
2.	1.70	0.80	-1.77	-3.10	2.06	14.13
3.	1.91	0.98	-1.72	-3.01	2.11	13.00
4.	2.13	1.14	-1.67	-2.94	3.08	12.48
5.	2.40	1.32	-1.54	-2.88	2.02	12.12
6.	2.63	1.55	-1.58	-2.81	2.07	11.30
7.	2.88	1.74	-1.62	-2.76	2.02	11.05
8.	3.09	1.90	-1.51	-2.72	1.99	10.89
9.	3.23	2.02	-1.49	-2.69	1.99	10.60
10.	3.47	2.34	-1.46	-2.63	2.06	9.88
11.	3.89	2.68	-1.41	-2.57	1.99	9.66
12.	4.07	2.92	-1.39	-2.53	2.02	9.30
13.	4.39	3.18	-1.36	-2.50	1.96	9.22
14.	4.72	3.65	-1.33	-2.44	2.02	8.63
15.	5.10	4.10	-1.29	-2.39	2.02	8.30

Tables 4.3. Data for p = 10.16cm; θ = 30° ; b = 15.24 cm;

bs = 17.80cm; Lh = 20cm

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.60	0.90	-1.80	-3.05	2.06	11.85
2.	1.70	0.97	-1.77	-3.01	2.02	11.71
3.	1.91	1.12	-1.72	-2.95	1.97	11.35
4.	2.19	1.32	-1.66	-2.88	1.88	11.09
5.	2.29	1.45	-1.64	-2.84	1.94	10.52
6.	2.54	1.65	-1.60	-2.78	1.88	10.29
7.	2.69	1.82	-1.57	-2.74	1.91	9.86
8.	2.82	2.00	-1.55	-2.70	1.95	99.42
9.	3.02	2.19	-1.52	-2.66	1.94	9.17
10.	3.35	2.40	-1.47	-2.60	1.88	8.97
11.	3.63	2.77	-1.44	-2.56	1.85	8.75
12.	3.72	2.92	-1.43	-2.53	1.88	8.51
13.	3.90	3.10	-1.41	-2.51	1.86	8.39

Table 4.4. Data for p = 10.16cm; $\theta = 45^{\circ}$; b = 15.24 cm;
bs = 21.60cm; Lh = 20cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	$\underline{h}_2$ x10 m	$\underline{Q}_3$ x10m3/s	log (h)	log (Q)	C_{sk}	σ
1.	0.83	0.50	-2.08	-3.30	2.16	11.10
2.	0.99	0.64	-2.00	-3.19	2.14	10.29
3.	1.05	0.70	-1.98	-3.15	2.14	9.99
4.	1.20	0.78	-1.92	-3.11	1.94	10.29
5.	1.27	1.04	-1.90	-2.98	2.38	8.15
6.	1.58	1.15	-1.80	-2.94	1.90	9.16
7.	1.70	1.57	-1.77	-2.80	2.32	7.23
8.	2.09	1.78	-1.68	-2.78	1.94	7.81
9.	2.18	2.11	-1.66	-2.68	2.16	7.87
10.	2.46	2.36	-1.61	-2.63	2.00	6.97
11.	2.55	2.50	-1.59	-2.60	2.02	6.79
12.	2.77	2.84	-1.56	-255	2.02	6.39
13.	2.90	3.00	-1.53	-2.52	2.00	6.43
14.	3.07	3.13	-1.51	-2.50	1.90	6.56
15	3.45	3.61	-1.46	-2.44	1.84	6.39
16	3.75	4.15	-1.43	-2.38	1.85	5.76
17	3.85	4.50	-1.41	-2.35	1.96	5.70
18	4.30	4.84	-1.37	-2.32	1.78	5.95
19	4.51	5.05	-1.35	-2.30	1.72	5.98

Table 4.5. Data for p = 10.16cm; $\theta = 60^{\circ}$; b = 15.24cm,

b_s = 30.48cm; L_h = 20cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	$\underline{h}_2$ x10 m	q_3 x10 m^2/s	log(h)	log(Q)		
1.	1.00	1.38	-2.00	-2.86	2.34	4.84
2.	1.02	1.50	-1.99	-2.82	2.47	4.54
3.	1.09	1.60	-1.96	-2.80	2.40	4.53
4.	1.16	1.80	-1.94	-2.74	2.43	4.32
5.	1.20	1.82	-1.92	-2.74	2.34	4.41
6.	1.30	2.10	-1.89	-2.68	2.43	4.09
7.	1.37	2.31	-1.86	-2.64	2.43	3.79
8.	1.47	2.47	-1.83	-2.61	2.34	3.98
9.	1.52	2.67	-1.82	-2.57	2.43	3.79
10.	1.67	3.00	-1.78	-2.52	2.34	3.73
11.	1.82	3.47	-1.74	-2.46	2.40	3.50
12.	1.82	3.47	-1.74	-2.40	2.20	3.80
13.	1.85	3.50	-1.73	-2.46	2.34	3.55

Table 4.6. Data for p = 10.16cm; θ = 75°; b = 15.24cm;

bs = 58.90cm; Lh = 20cm.

4.2 Calibration Of Weir Plates

Figure 4.1 shown overleaf was plotted from Tables 4.1 to 4.6 and shows graphs of discharge passing over the weir, Q, against head, h, for the 10.16cm weir at inclinations of 0, 15°, 30°, 45°, 60° and 75°. The graphs were plotted as smooth curves. Similar graphs for the 15.24 and 20.32cm weirs are shown in Appendix C (Figures C1 and C2 respectively). The curves show that for a given discharge, the effective head on the weir decreases with increasing inclination. For example, for the 10.16cm weir, the graph shows that under a discharge of 2×10^{-3} m^3/s, the normal weir would develop about 3.5cm, whereas the weirs inclined at 15°, 30°, 45°, 60°and 75°, would develop about 3.2,3.1,2.8,2.1 and 1.25cm respectively. Other values of discharge would show similar trend, indicating that in terms of development of head, the more inclined the weir, the less effective it is. The inclined weir would thus develop less head than the normal weir operating under the same flow rate.

Figure 4.2 which was plotted from Tables 4.1 to 4.6 shows graphs of Log(h) against Log(Q) for the 10.16cm weir. Corresponding graphs for the 15.24 and 20.32cm weirs are in Appendix C (Figures C3 and C4). All the graphs plotted gave straight lines parallel to each other for different inclinations. The lines in general have a slope of 1.50, and, consequently, Equation (2.29) was fitted for application to all the weirs.

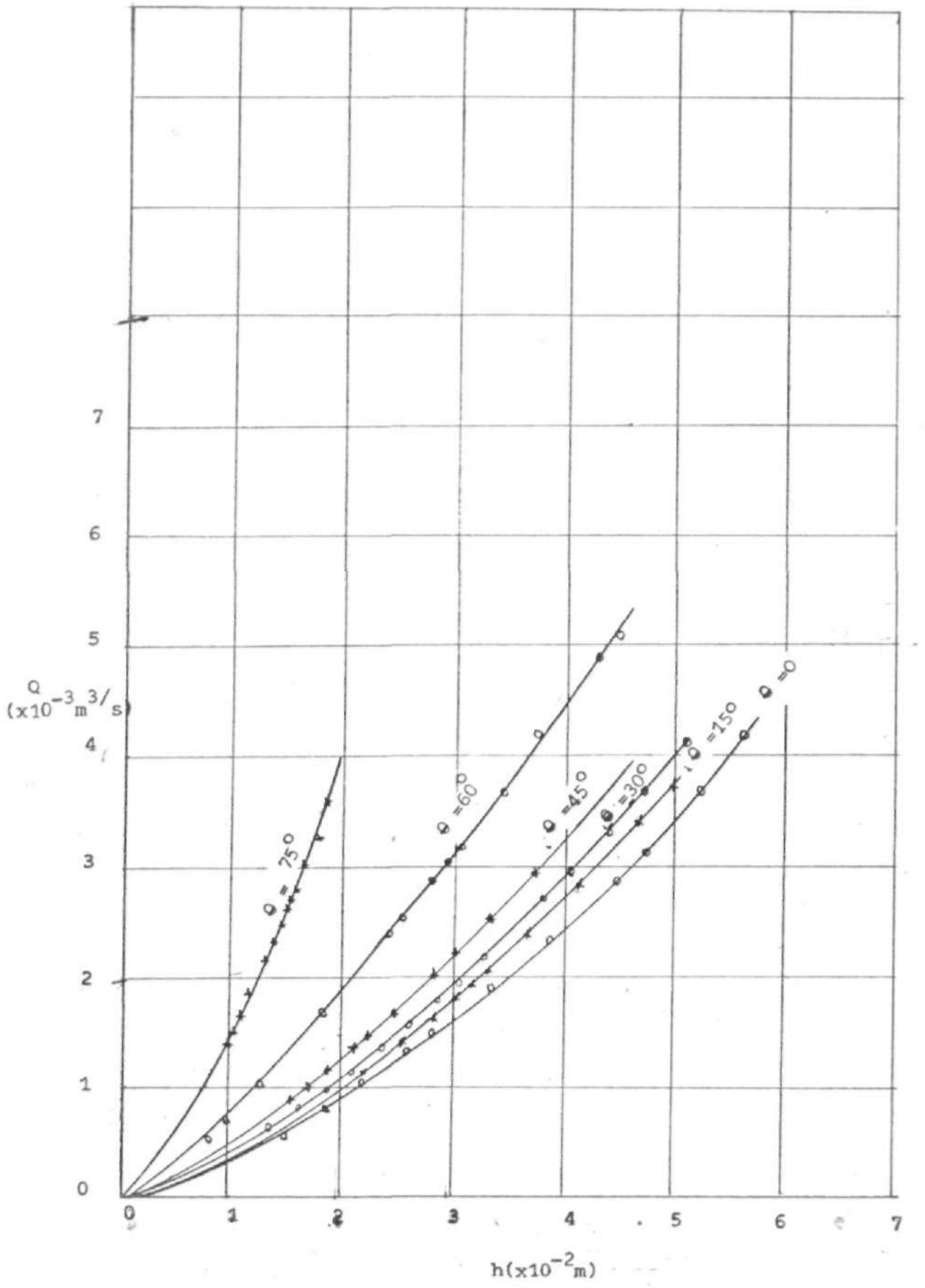


Figure 4.1: Plot of discharge Q versus head h for weir height p = 10.16cm for various weir inclinations.

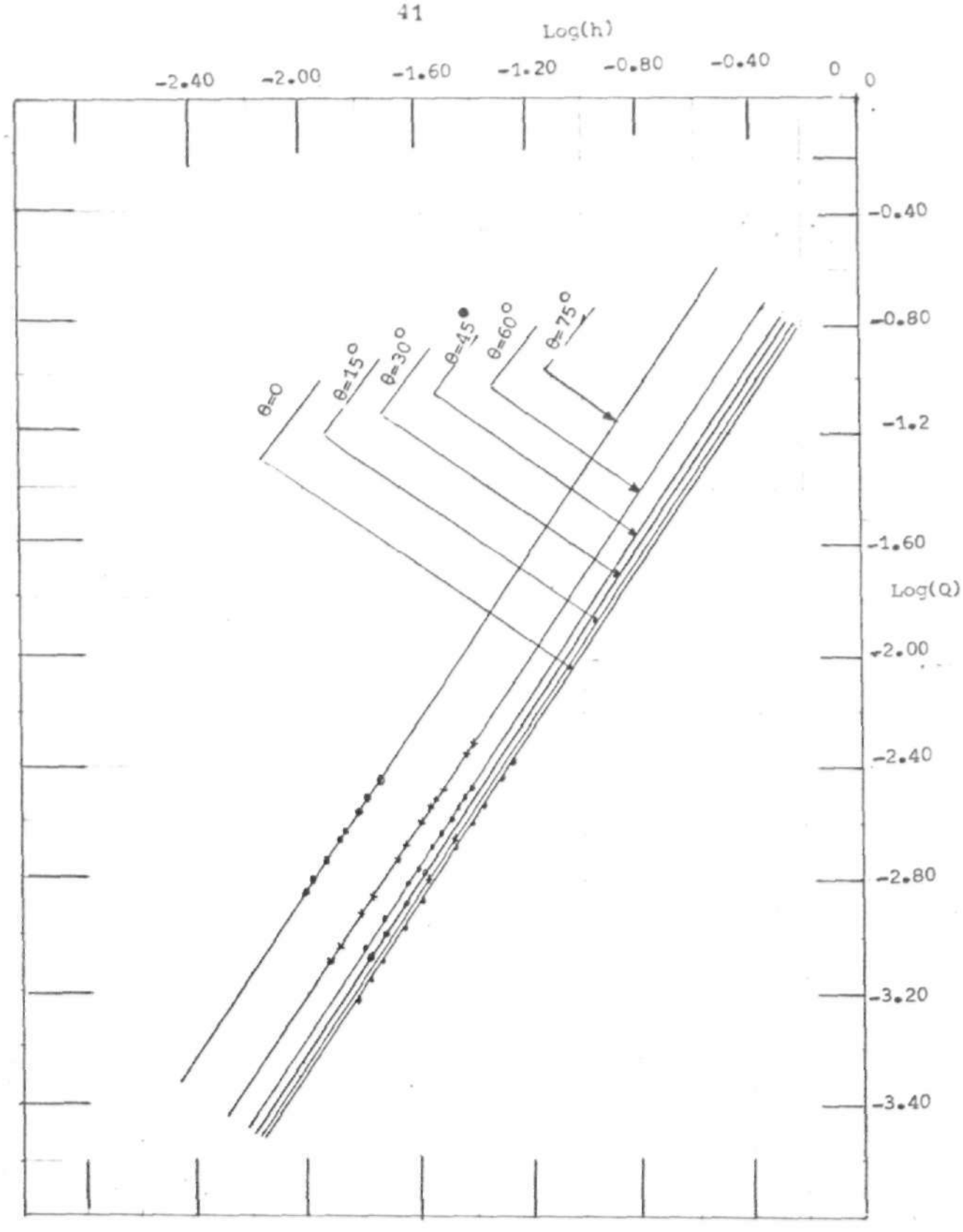


Figure 4.2: Plot of Log Q versus Log h at weir height p = 10.16cm for various weir inclinations.

4.3 Weir Sensitivity Analysis

Figure 4.3 plotted from Tables 4.1 to 4.6 shows sensitivity curves for the 10.16cm weir inclined at $0, 15^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}$, and 75°. Corresponding graphs for 15.24 and 20.32cm weirs are shown in Appendix C (Figure C5 and C6 respectively). The graphs indicate that for any given thin-plate weir, the sensitivity decreases with increased discharge as well as with more inclination. The graphs for the 20.32cm weir, however, show an intersection between the curves for 0 and 15° inclinations at about 5.5×10^{-3} m^3/s discharge. Such a trend is not observed in the other curves. This interaction may, therefore, possibly be due to experimental error. The sensitivity of the thin-plate weir is dependent on factors like the sharpness of the crest and the chamfer of the downstream edge of the crest. It would also depend on the extent of contraction of the nappe, i.e. the amount of ventilation provided beneath the lower surface of the nappe. Although the ventilation provided could be assumed satisfactorily constant, it is not possible due to construction tolerances to have the weir crest exactly of the same sharpness and chamfer. Inclining the weir increases the length and so more frictional resistance on the crest surface develops. This, in itself, would affect the sensitivity of the weir; increased frictional resistance causing decrease in sensitivity.

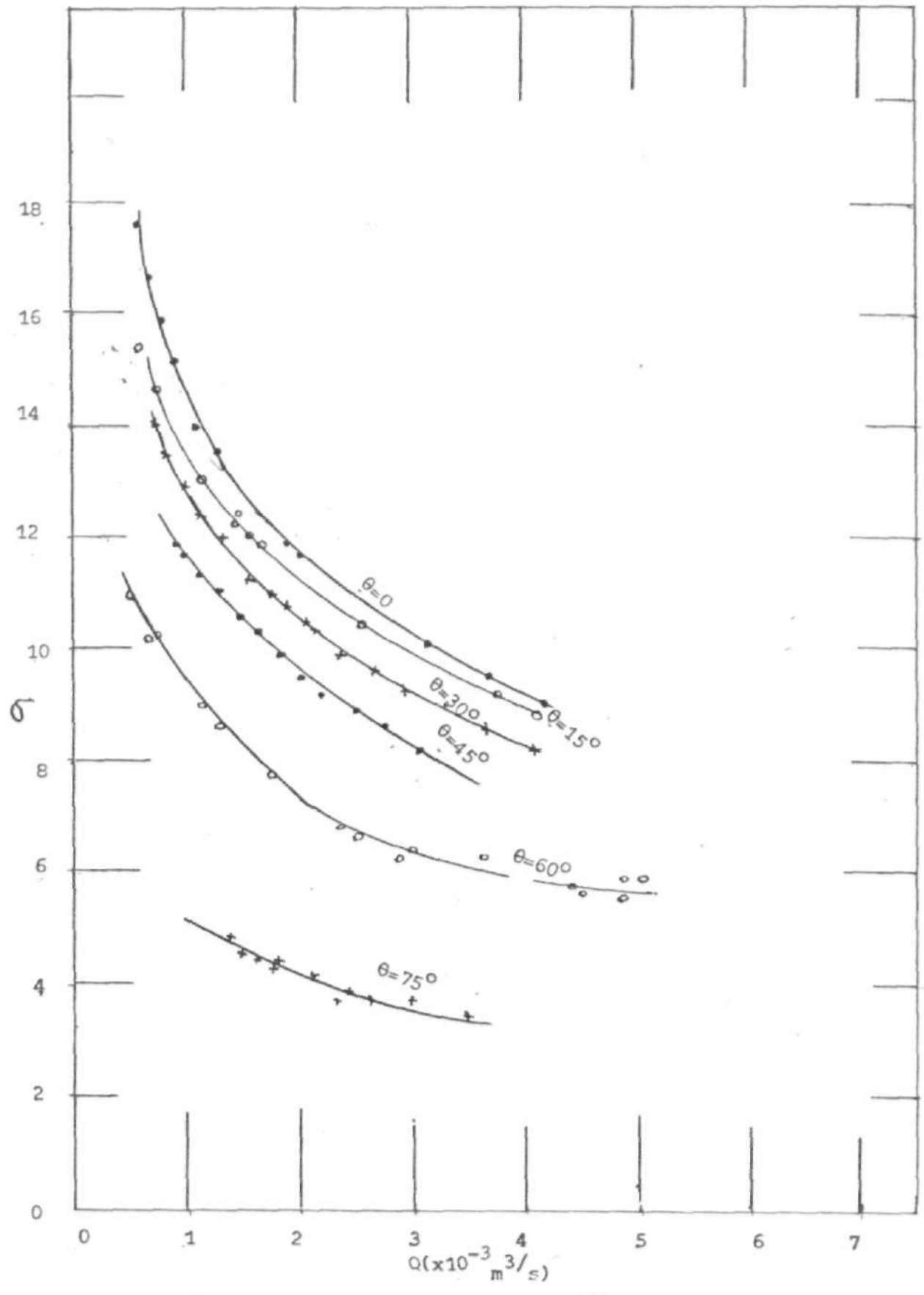


Figure 4.3: Plot of sensitivity σ versus discharge Q for weir height p = 10.16cm at various angles of inclinations.

4.4 Experimental Relationship Between h/p and θ

Figure 4.4 was plotted from Table 4.7 and shows plots of h/p against θ for all weir heights at a fixed discharge of $1x10^{-3}$ m^3/s.. Similar graphs for discharges of $2x10^{-3}$ and $3x10^{-3}$ m^3/s are shown in Appendix C (Figure C7 and C8 respectively). The plots show smooth curves which are linear initially and become more curved with increased θ. They indicate that the ratio h/p decreases with increasing inclination. As the weir height, p, is constant, the plots show that the effective head decreases with increased weir inclination. This is in line with the observation made in section 4.2 emphasising that an inclined weir would develop less head than a normal weir operating under same flow.

Q = 1 x 10^{-3} m^3/s								
P = 10.16cm			P = 15.24cm			P = 20.32cm		
S/NO.	θ	h/p	S/NO.	θ	h/p	S/NO.	θ	h/p
1.	0	0.219	1.	0	0.148	1.	0	0.110
2.	15°	0.219	2.	15°	0.138	2.	15°	0.105
3.	30°	0.196	3.	30°	0.126	3.	30°	0.096
4.	45°	0.179	4.	45°	0.111	4.	45°	0.084
5.	60°	0.139	5.	60°	0.10	5.	60°	0.070
6.	75°	0.081	6.	75°	0.056	6.	75°	0.038

Table 4.7: Table showing the calculated values of h/p used in plotting Figure 4.4

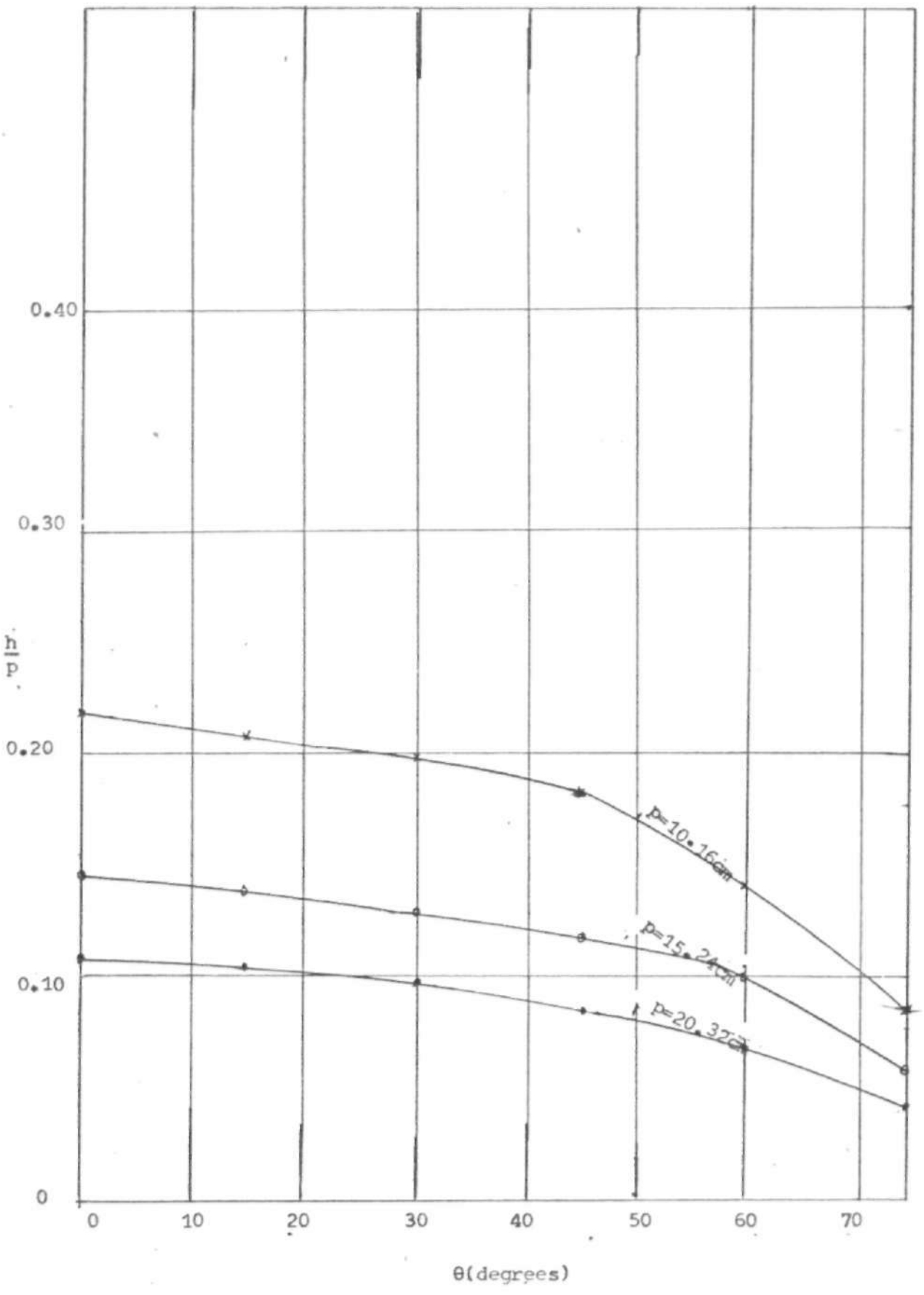


Figure 4.4: Plot of the ratio h/p versus weir inclination θ at a discharge of 1×10^{-3} m^3/s

4.4.1 Experimental Relationship Between h_o/h_{sk} and Q

Figure 4.5 was plotted from Table 4.8 and shows graphs of h_o/h_{sk} against Q for 10.16cm weir inclined at 0, 15°, 30°, 45°, 60° and 75°. The ratio h_o/h_{sk} is termed the head ratio. Similar plots for 15.24 and 20.32cm weirs are in Appendix C (Figure C9 and C10 respectively). All these figures show that the ratio h_o/h_{sk} decreases with increasing discharge. The same figures show that the ratio increases with increasing inclination. This results in a decrease in head with increasing inclination for same weir height, which is the same as the inferences obtained in Sections 4.2 and 4.3.

			Weir height p = 10.16cm				
Q	0.5	1.0	1.5	2.00	2.5	3.0	3.5
θ (degrees)	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	1.21	1.06	1.09	1.06	1.08	1.07	1.07
30	1.36	1.13	1.13	1.11	1.13	1.13	1.11
45	1.42	1.23	1.23	1.23	1.23	1.22	1.17
60	1.73	1.72	1.70	1.63	1.62	1.59	1.55
75	3.37	2.69	2.83	2.80	2.83	2.80	2.75

Table 4.8: Table showing the calculated values of h_o/h_{sk} used in plotting Figure 4.5.

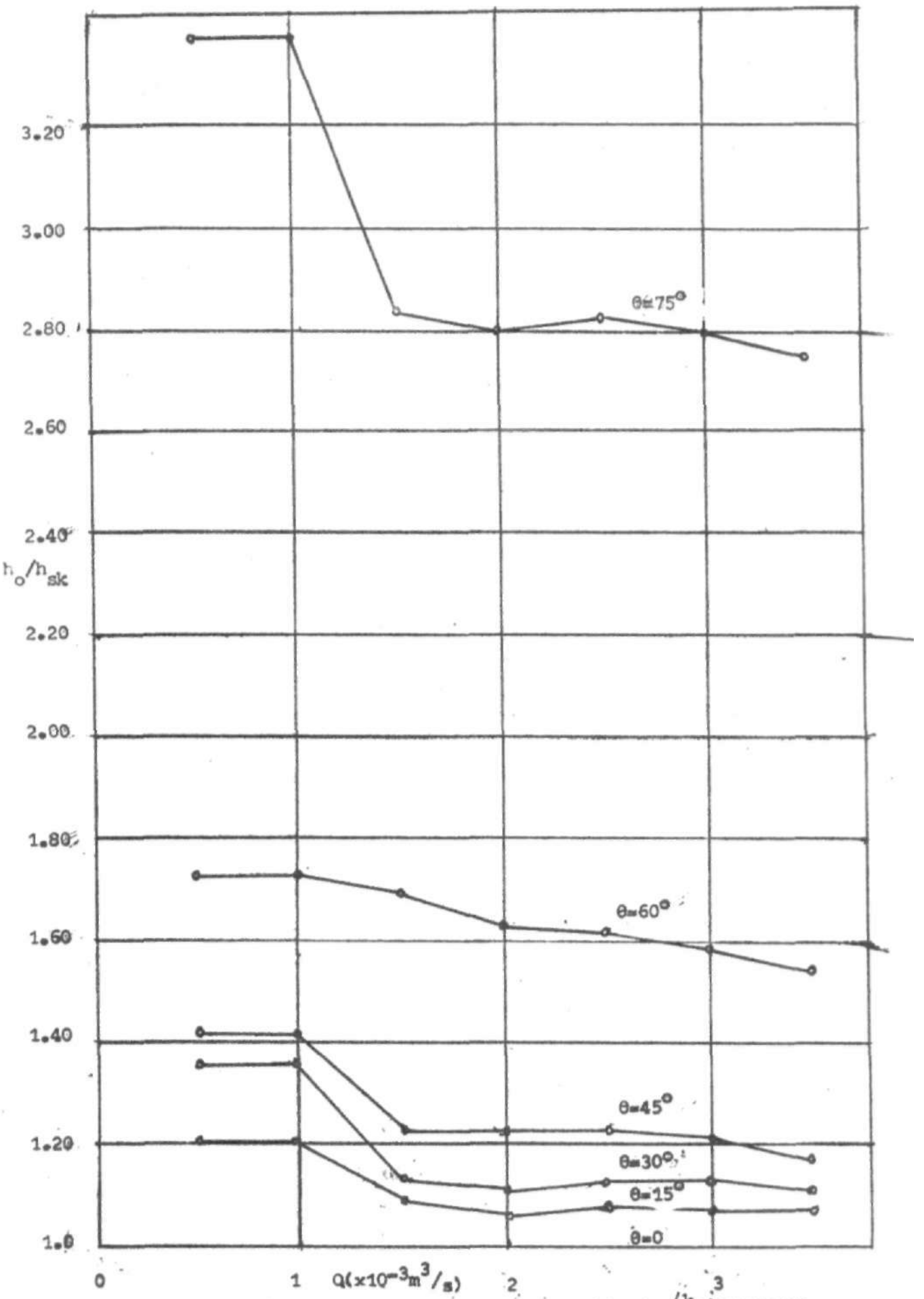


Figure 4.5: Plot of the ratio h_o/h_{sk} versus discharge Q for weir height p = 10.16cm at various angles of inclination.

4.5. Discussion Of Results

It is seen from the foregoing analysis that an inclined thin-plate weir develops less head than a normal weir for the same discharge, and the more inclined the weir, the lesser the head developed. This can be explained as follows:-

Inclining the weir increases the weir crest length and so more hydraulic friction between the flowing water and the weir surface exists. Part of the energy in the flowing water upstream is used to overcome this friction. This extra energy use is reflected in reduction of the head over the weir crest. The more the weir is inclined, the longer is the weir crest and so more friction on the weir surface and consequently more energy is dissipated in overcoming this friction. The result is a decreasing head on the weir as the weir inclination is increased.

The reduction in the head can also be explained by the application of the continuity equation to the flow in the channel. The flow passing over the weir obeys equation 2.9 ($Q_{sk} = C_{sk}\, b_s\, h_{sk}^{3/2}$) and is the same for the normal and the inclined weirs of the same height. The weir crest length b_s is increased by inclining the weir. The coefficient C_{sk} does not vary significantly from one discharge to another as can be seen from Tables 4.1 to 4.6. An average value can thus practically be assumed for a particular weir type and height to cover both the normal and inclined weirs. With the value of C_{sk} fixed and the discharge passing the same, it is obvious that the head on the inclined weir will decrease.

It can be deduced from the foregoing discussion that a key factor is the weir crest length and as this is increased, the head

over the weir must decrease since the flow passing does not change.

The sensitivity of the weir was also shown to decrease with increased discharge as well as with more inclination. This can be seen from the definition of the parameter, equation 2.34. In this expression, the sensitivity is shown to vary inversely with the cube root of the discharge and directly with the factor $\frac{2}{3}\left(\frac{1}{C_{sk}\, b_s}\right)^{2/3}$. The coefficient C_{sk} is practically constant while b_s increases with the weir inclination. The overall effect is that the sensitivity decreases with more weir inclination and as the discharge increases.

A relationship, equation 2.9 is fitted for application to the inclined weir. This means that with an experimentally determined coefficient C_{sk}, the inclined weir can be used to measure discharges. This is because as the weir crest length b_s is fixed for any given weir, what is required is to measure the head over the weir crest, and the discharge is calculated using the relationship. The inclined weir can thus be used to measure flow as accurately as the normal weir.

The applicability of above results can be found in following circumstances:-

In order to protect farmland from being flooded by canal waters, an inclined weir can be used to pass same discharge. As the inclined weir develops less head, it would provide an increased safety for the canal against overtopping. Normally a canal is designed for a given free board. A normal weir can be used to measure flow in the canal to a maximum permissible value of flow. If more flow is required to be passed through the canal due to increased demand,

an inclined weir of same height as the normal one can be used without causing the water to flow onto the canal banks and without the need to deepen the canal. The weir inclination to be used would depend on the ratio h_o/h_{sk} which in turn would depend on the permissible free board. Secondly laboratory flumes used for research work are of fixed dimensions. A thin-plate weir can be used to measure flow into the flume or raise the water level. If more flow is required to be passed without the water spilling over the channel sides an inclined weir can be used instead of a normal one.

The issue is then to determine what inclination is to be used. Figure 4.6 shows graphs of the ratio h_o/h_{sk} versus θ for a fixed discharge of 2×10^{-3} m^3/s. For a given h_o/h_{sk} ratio and weir height, the inclination required can be read from the graphs. As an example, if for a given weir height of 20.32cm, a head ratio of $h_o/h_{sk} = 1.20$ is required, the required weir inclination is 33^o. Different discharges can be used to plot graphs of h_o/h_{sk} versus θ and the graphs used to determine weir inclinations.

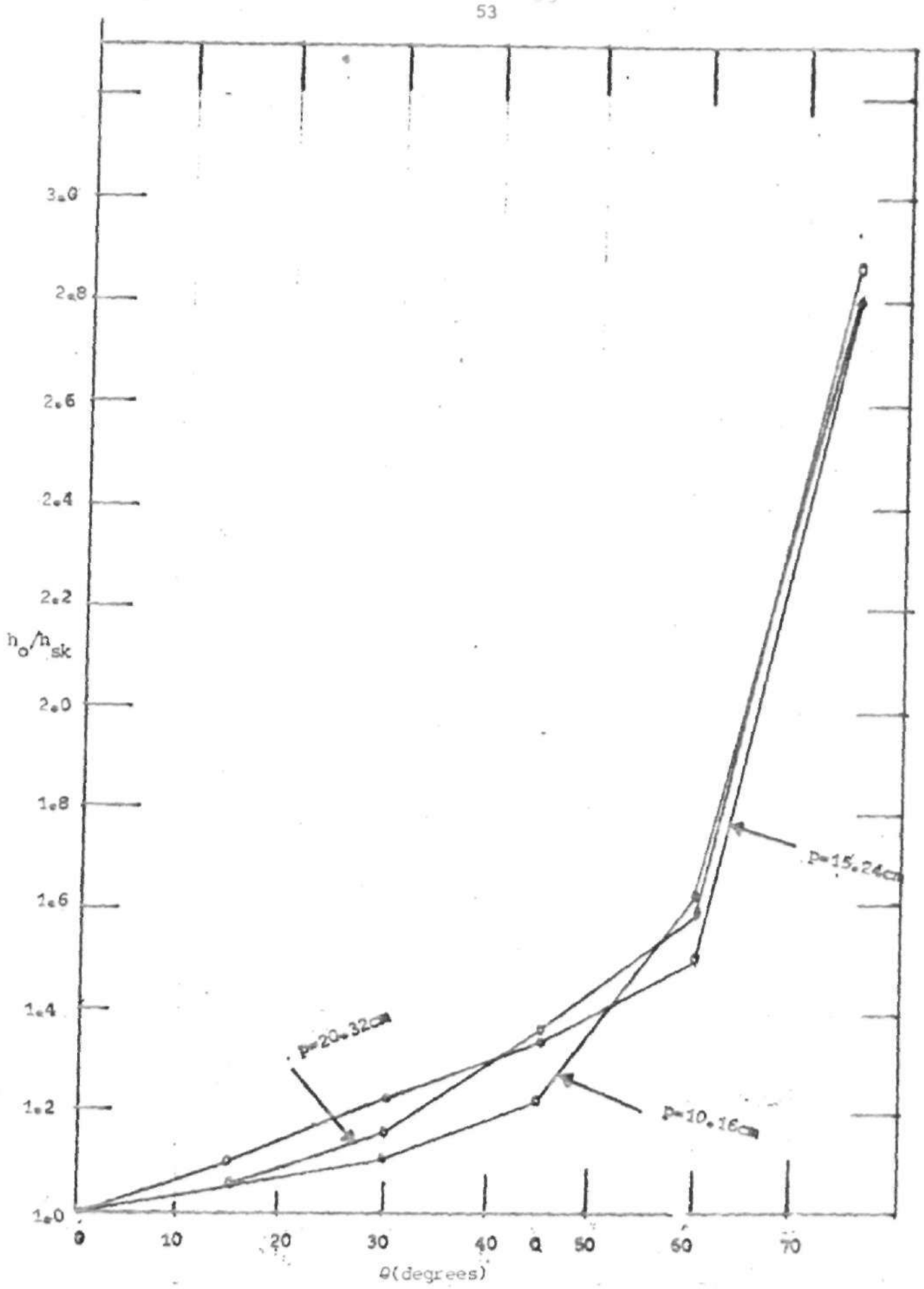


Figure 4.6: Plot of the ratio h_o/h_{sk} versus weir inclination θ at various weir height for a discharge of 2×10^{-3} m^3/s.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 Summary

The objective of this study is to investigate the effects of inclination on (a) the ability of a thin-plate weir to develop head, measure or pass discharges and (b) the sensitivity of the weir within the range of head used.

Experiments were conducted in the laboratory using a 15.24cm wide by 30.48cm deep and 6m long glass walled open channel. Water for the test was recirculated by means of a centrifugal type pump which raised the water from a sump below the channel to about 2m up into the channel. Eighteen experiments using eighteen weir models, were carried out. The weirs were of three sets of different heights 10.16cm, 15.24, and 20.32cm. For each of these heights inclinations in 15° increments from 0 to 75° were used. During the experiments the head over the weir crest and the discharge passing over the weir were measured. The head was measured using a point gauge and the discharge was measured using the weighing method.

The parameters weir sensitivity, the ratio head to weir height (h/p) and the ratio head on normal weir, to head on inclined weir, (h_o/h_{sk}) were computed from the experimental data obtained. Graphs were plotted to analyse the data.

The study indicates that (i) a rectangular inclined thin-plate weir develops less head than a normal weir under the same operating flow conditions and the more inclined the weir the lesser the head developed; (ii) the ratio head to weir height decreases with increased inclination of the weir, (iii) the sensitivity of the

the thin-plate rectangular weir decreases with increased discharge as well as with increased inclination, (iv) the ratio head on normal weir to head on inclined weir, h_o/h_{sk} decreases with increased discharge and increases with more inclination of the weir, and (v) a graph of the ratio h_o/h_{sk} against θ can be used to determine at which angle a thin-plate rectangular weir is to be inclined in order to achieve a given head reduction.

5.2 Conclusions

From the study it can be concluded that:-

1. An inclined rectangular thin-plate weir develops less head than a normal weir for same discharge and the more inclined the weir the lesser the head developed.
2. An inclined rectangular thin-plate weir canbe used to measure discharges as accurately as a normal weir.
3. The sensitivity of the thin-plate rectangular weir decreases with increased discharge as well as with more inclination.

4(a) The development of less head by an inclined weir can be used to advantage in:-

(i) Surface Irrigation systems, where water conveyance is by canals. When an increased discharge is to pass through an existing canal in which the flow is measured with a normal weir, an inclined weir of same height as the normal weir can be used to pass and measure the increased discharge without overtopping the canal banks.

(ii) Research laboratories, where flumes are normally of fixed dimensions. A normal weir can be used to measure flow and regulate the head. An increased flow can be passed by an inclined weir of same height without the danger of the

water spilling over the channel side.

(b) The inclination required for a particular head reduction can be determined from plot of the ratio head on normal weir h_o, to head on inclined weir, h_{sk} (h_o/h_{sk}) against inclination, θ, for various discharge ranges.

List of References

1. Ackers, P., White, W.R; Perkins, J.A; and Harrison, A.J.M(1980), Weirs and Flumes for Flow Measurement, Willey Interscience Publication, pp. 44-83.
2. Brater, E.F; and King; H.W. (1976), Handbook of Hydraulics Mcgraw-Hill Book, Sixth Edition, pp. 5-2 to 5-45.
3. British Standard Institution (1965), Measurement of Liquid Flow in Open Channels: Thin-plate weirs and Venturi flumes, BS 3680 Part 4A.
4. British Standard Institution (1971a) Measurement of Liquid Flow in Open Channels: the measurement of liquid level (stage). Bs 3680: Part 7.
5. Fteley, A; and Stearns, F.P.(1883), Flow of water over weirs, Transactions, American Society of Civil Engineers, Volume 12, pp. 1-118.
6. International Institute for Land Reclamation and Improvement, ILRI (1976), Discharge Measurement Structures, Publication 20, pp. 155-181 and pp. 426-429.
7. Israelson, O.W; and Hansen, V.E. (1962), Irrigation, Principles and Practices, Third Edition, John Willey and sons, New York, pp. 105-123.
8. Kinsvater, C.E; and Carter, R.W.(1959), Discharge Characteristics of Rectangular Thin-Plate Weirs, Transactions, American Society of Civil Engineers, Volume 124, pp. 772- 822.
9. Lakshmana Rao, N.S.(1975), Theory of weirs in Advances in Hydroscience, volume 10, Academic Press, New York, pp.309-398.
10. Rehbock, T. (1929), Discussion of reference 11, Transactions, American Society of Civil Engineers, volume 93, Number 1711, pp. 1143.1162.

11. Schoder, E.W; and Turner, K.B. (1929), Precise Weir Measurements, Transactions, American Society of Civil Engineers, volume 93, Number 1711, pp.999 - 1190.

12. Troskolanski, A.T. (1960), Hydrometry, Theory and Practice of Hydraulic Measurement, Pergamon Press, pp. 281 - 311.

13. United States Department of the Interior Bureau of Reclamation, USBR (1967), Water Measurement Manual, a Water Resources Technical Publication, pp. 741.

14. Vennard, J.K; and Street, R.L. (1976), Elementary Fluid Mechanics Fifth Edition, John Willey and Sons, pp. 556 - 574.

15. White, W.R. (1978), Flow Measuring Structures, in Hydrometry (Edited by Herschy, R.W.), A Willey Interscience Publication, pp. 83-107.

APPENDICES

APPENDIX A

(i) Dimensional analysis applied to the thin-plate full-width weir flow (Vennard, J.K; and Street, R.L. (1976)).

(a) Normal weir:-

$$q = f(h, \rho, \mu, s, \rho, g) \quad (1)$$

$$q = kh^a p^b \mu^c s^d \rho^e g^f \quad (2)$$

Where a, b, c, d, e, f, k are constants.

Putting in dimensions of all variables in equation (2) we get

$$\frac{L^2}{T} = L^a L^b \left(\frac{M}{LT}\right)^c \left(\frac{M}{T^2}\right)^d \left(\frac{M}{L^3}\right)^e \left(\frac{L}{T^2}\right)^f \quad (3)$$

Equating the powers of M, L, T, in eqn(3)

$$0 = c + d + e \quad (4)$$

$$2 = a + b - c - 3e + f \quad (5)$$

$$1 = c + 2d + 2f \quad (6)$$

From eqn (4), $e = -c - d$ (7)

From eqn (6), $f = \frac{1}{2} - \frac{1}{2}c - d$ (8)

Substituting (7) and (8) in (5) gives

$$a = 3/2 - b - 3/2c - 2d \quad (9)$$

Substituting for a, e, and f in eqn (2)

and manipulating, gives

$$q = k\sqrt{g}\, h^{3/2} \left(\frac{p}{h}\right)^b \left(\frac{\mu}{h^{3/2}\sqrt{g}}\right)^c \left(\frac{s}{h^2 \rho g}\right)^d \quad (10)$$

$$\frac{q}{h^{3/2}\sqrt{g}} = f_1\left(\frac{h}{p}, \frac{\mu}{\rho\sqrt{g}\, h^{3/2}}, \frac{s}{\rho g h^2}\right) \quad (11)$$

Velocities near the weir crest are proportional to $\sqrt{gh}$, which may therefore be substituted for velocity. Reynold's Number then becomes

$$R = \frac{\rho v l}{\mu} = \frac{\rho \sqrt{gh}\, l}{\mu} \qquad (12)$$

where l = the most significant length. For large full-width weirs, the most significant length is the head, and for small narrow weirs, both the head and the width are independently significant. Hence the Reynold's Number may be given by

$$R = \frac{\rho \sqrt{gh}\, h}{\mu} = \frac{\rho \sqrt{g}\, h^{3/2}}{\mu} \qquad (13)$$

$$\text{or} \quad R = \frac{\rho \sqrt{gh}\, h}{\mu} \qquad (14)$$

Similarly the Weber Number, W, given by

$$W = \frac{v \sqrt{l}}{\sqrt{s/\rho}} \quad \text{may be expressed}$$

$$\text{as} \quad W = \frac{\sqrt{gh}\; h}{\sqrt{s/\rho}}$$

$$\text{or} \quad W^2 = \frac{gh^2}{s/\rho} \qquad (15)$$

Hence eqn (11) becomes

$$\frac{q}{h^{3/2}\sqrt{g}} = f_1\left(\frac{h}{p}, R, W\right) \qquad (16)$$

$$\text{or} \quad \frac{C_d}{\sqrt{g}} = \frac{q}{\sqrt{g}\, h^{3/2}} = f_1\left(\frac{h}{p}, R, W\right)$$

$$\text{or} \quad C_d = f_1\left(\frac{h}{p}, R, W\right) \qquad (17)$$

(ii) The same procedure can be applied to the oblique weir flow, thus:-

$$q_{sk} = f_2\left(h, p, \mu, s, \rho, g, b_s\right) \tag{18}$$

$$\text{or } q_{sk} = k h^a p^b \mu^c s^d \rho^e g^f (b_s)^i \tag{19}$$

where a,b,c,d,e,f,i,k are constants

$$\text{or } \frac{L^2}{T} = L^a L^b \left(\frac{M}{LT}\right)^c \left(\frac{M}{T^2}\right)^d \left(\frac{M}{L^3}\right)^e \left(\frac{L}{T^2}\right)^f L^i \tag{20}$$

Equating the powers of M, L, T in eqn (20)

$$0 = c + d + e \tag{21}$$

$$2 = a + b - c - 3e + f + i \tag{22}$$

$$1 = c + 2d + 2f \tag{23}$$

$$e = -c - d$$

$$f = \tfrac{1}{2} - \tfrac{1}{2} c - d \tag{24}$$

$$a = 3/2 - b - 3/2\, c - 2d - i$$

$$\text{and } \frac{q_{sk}}{\sqrt{g}\ h^{3/2}} = k\left(\frac{p}{h}\right)^b \left(\frac{\mu}{h^{3/2}\sqrt{g}}\right)^c \left(\frac{s}{h^2 \rho\ g}\right)^d \left(\frac{b_s}{h}\right)^i \tag{25}$$

$$\text{or } \frac{q_{sk}}{\sqrt{g}\ h^{3/2}} = f_3\left(\frac{h}{p}, R, W, \frac{h}{b_s}\right) \tag{26}$$

If for the oblique weir, the discharge per unit width is given by

$$q_{sk} = C_{sk} h^{3/2} \tag{27}$$

$$\text{then } C_{sk} = f_3\left(\frac{h}{p}, R, W, \frac{h}{b_s}\right) \tag{28}$$

where C_{sk} = discharge coefficient for the oblique weir

(iii) Computations

1. Weir sensitivity is computed from $\frac{2}{3}\left(\frac{\cos\theta}{C_{sk}^b}\right)^{2/3} \left(\frac{1}{Q_{sk}}\right)^{1/3}$ ...

2. C_{sk} is computed from $Q_{sk} = C_{sk} b_s h_{sk}^{3/2}$

APPENDIX B

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.91	0.82	-1.72	-3.09	2.04	15.54
2.	2.19	1.00	-1.66	-3.00	2.02	14.60
3.	2.72	1.33	-1.57	-2.88	1.95	13.64
4.	3.00	1.60	-1.52	-2.80	2.02	12.51
5.	3.61	1.96	-1.44	-2.71	1.88	12.73
6.	4.39	2.63	-1.36	-2.58	1.88	11.13
7.	4.95	3.20	-1.31	-2.49	1.91	10.32
8.	5.59	3.83	-1.25	-2.42	1.90	9.74
9.	6.00	4.32	-1.22	-2.37	1.93	9.26
10.	6.46	3.98	-1.19	-2.40	1.59	10.82
11.	7.24	5.50	-1.14	-2.26	1.85	8.79
12.	8.51	6.61	-1.07	-2.18	1.77	8.59

Table B1: Data for p = 15.24cm; θ = 0; b = b_s = 15.24cm;

L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	2.08	1.17	-1.68	-2.92	1.12	13.32
2.	2.51	1.45	-1.60	-2.84	2.31	11.54
3.	3.61	2.25	-1.44	-2.65	2.08	10.69
4.	3.76	2.30	-1.42	-2.62	2.07	10.51
5.	4.62	3.07	-1.34	-2.51	1.96	10.03
6.	5.13	3.75	-1.29	-2.43	2.04	9.13
7.	5.46	4.02	-1.26	-2.40	2.00	9.04
8.	6.22	4.85	-1.21	-2.31	1.98	8.55
9.	6.48	5.35	-1.19	-2.27	2.05	8.06
10.	6.96	6.00	-1.16	-2.22	2.07	7.78
11.	7.98	7.05	-1.10	-2.15	1.98	7.55
12.	8.13	7.20	-1.09	-2.14	1.98	7.52
13.	8.64	8.15	-1.06	-2.09	2.03	7.07
14.	9.14	9.14	-0.99	-1.04	2.04	6.71

Table B2. Data for p = 15.24cm; $\theta = 15^{\circ}$; b = 15.24cm;
b_s = 15.80 cm; L_h = 30cm

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.51	0.79	-1.82	-2.10	2.41	12.78
2.	1.62	0.87	-1.79	-3.06	2.40	12.41
3.	2.19	1.32	-1.66	-2.88	2.31	11.08
4.	2.95	2.00	-1.53	-2.70	2.24	9.85
5.	3.09	2.09	-1.51	-2.68	2.18	9.88
6.	3.24	2.24	-1.49	-2.65	2.18	9.65
7.	3.55	2.51	-1.45	-2.60	2.14	9.41
8.	4.17	3.10	-1.38	-2.50	2.12	8.92
9.	4.68	3.72	-1.33	-2.43	2.09	8.39
10.	5.09	4.15	-1.29	-2.38	2.06	8.16
11.	5.90	1.23	-2.31	-1.94	1.94	8.04
12.	6.60	5.90	-1.18	-2.20	1.97	7.48
13.	6.92	6.31	-1.16	-2.20	1.97	7.31
14.	7.41	6.92	-1.13	-2.16	1.95	7.14
15.	7.59	7.24	-1.12	-2.14	1.96	7.01
16.	9.33	9.55	-1.05	-2.02	1.89	6.55

Table B3. Data for p = 15.24cm; $\theta = 30^0$; b = 15.24cm;

b_s = 17.16cm; L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $x10^{-2}$ m	Q $x10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	0.89	0.41	-2.05	-3.39	2.26	14.48
2.	1.52	0.88	-1.82	-3.07	2.09	11.97
3.	1.63	0.98	-1.79	-3.01	2.18	11.09
4.	2.09	1.32	-1.68	-2.88	2.02	10.57
5.	2.63	1.91	-1.58	-2.72	2.08	9.16
6.	3.24	2.56	-1.49	-2.59	2.04	8.42
7.	3.45	2.95	-1.46	-2.52	2.14	7.80
8.	3.60	3.13	-1.44	-2.50	2.12	7.68
9.	4.01	3.72	-1.40	-2.43	2.08	7.34
10.	4.57	4.30	-1.34	-2.37	2.04	7.08
11.	4.90	4.79	-1.31	-2.32	2.05	6.81
12.	5.28	5.34	-1.28	-2.27	2.04	6.59
13.	5.45	5.62	-1.26	-2.23	2.05	6.46
14.	5.68	6.03	-1.25	-2.19	2.06	6.29
15.	6.31	7.24	-1.20	-2.15	2.12	5.80

Table B4. Data for p = 15.24cm; $\theta = 45^{\circ}$;

b = 15.24cm; b_s = 21.60cm; L_h = 30cm

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	2.09	1.58	-1.68	-2.80	1.72	8.81
2.	2.29	1.82	-1.64	-2.74	1.72	8.40
3.	2.41	1.98	-1.62	-2.70	1.74	8.11
4.	2.69	2.34	-1.57	-2.63	1.74	7.67
5.	2.87	2.62	-1.54	-2.58	1.76	7.33
6.	2.95	2.66	-1.53	-2.58	1.76	7.29
7.	3.30	3.10	-1.48	-2.51	1.70	7.09
8.	3.56	3.35	-1.45	-2.47	1.64	7.08
9.	4.32	4.42	-1.36	-2.35	1.62	6.51
10.	4.37	4.50	-1.36	-2.35	1.62	6.47
11.	4.45	4.68	-1.35	-2.33	1.62	6.38
12.	5.08	5.49	-1.29	-2.26	1.58	6.15
13.	5.13	6.03	-1.29	-2.22	1.70	5.68
14.	5.82	6.87	-1.24	-2.17	1.60	5.67
15.	6.07	7.28	-1.22	-2.14	1.60	5.55

Table B5. Data for $\dot{p}$ = 15.24cm; $\theta = 60^{\circ}$;

b = 15.24cm; b_s = 30.48cm, L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $x10^{-2}$ m	Q $x10^{-3}$ m^3/s	log(h)	log(Q)	Csk	σ
1.	1.00	1.38	-2.00	-2.86	2.36	0.61
2.	1.15	1.66	-1.94	-2.78	2.28	0.59
3.	1.29	1.91	-1.89	-2.72	2.20	0.57
4.	1.38	2.09	-1.86	-2.68	2.20	0.57
5.	1.45	2.29	-1.84	-2.64	2.24	0.58
6.	1.58	2.51	-1.80	-2.60	2.16	0.56
7.	1.66	2.75	-1.78	-2.56	2.20	0.57
8.	1.82	2.88	-1.74	-2.54	2.01	0.52
9.	1.91	3.16	-1.72	-2.50	2.05	0.53
10.	2.04	3.47	-1.69	-2.46	2.01	0.52
11.	2.19	3.80	-1.66	-2.42	2.01	0.52
12.	2.24	4.27	-1.65	-2.37	2.16	0.56
13.	2.34	4.68	-1.63	-2.33	2.20	0.57

Table B6. Data for p = 15.24cm; $\theta = 75^{\circ}$;

b = 15.24cm; b_s = 58.90cm; L_h = 30 cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.95	0.83	-1.71	-3.08	2.00	15.67
2.	2.19	0.95	-1.66	-3.02	1.92	15.39
3.	2.57	1.17	-1.60	-2.93	1.95	14.31
4.	2.95	1.57	-1.53	-2.82	1.96	13.01
5.	3.59	2.00	-1.45	-2.70	1.93	11.97
6.	4.68	2.63	-1.33	-2.58	1.70	11.89
7.	5.13	3.31	-1.29	-2.48	1.87	10.33
8.	5.75	3.98	-1.24	-2.40	1.89	9.65
9.	6.31	4.79	-1.20	-2.32	1.98	8.80
10.	7.41	6.31	-1.13	-2.20	2.05	7.84
11.	8.51	6.76	-1.07	-2.17	1.79	8.39

Table B7. Data for p = 20.32cm; θ = 0

b = b_s = 15.24cm; L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/No.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m³/s	log(h)	log(Q)	C_{sk}	σ
1.	1.24	0.37	-1.91	-3.43	1.70	22.30
2.	1.86	0.83	-1.73	-3.08	2.07	14.95
3.	2.54	1.14	-1.60	-2.94	1.78	14.87
4.	2.85	1.53	-1.55	-2.82	2.01	12.44
5.	3.30	1.88	-1.48	-2.73	1.99	11.69
6.	3.40	2.00	-1.42	-2.70	2.02	11.34
7.	3.53	2.07	-1.45	-2.68	1.98	11.36
8.	3.94	2.32	-1.40	-2.63	1.87	11.36
9.	4.67	3.14	-1.33	-2.50	1.97	9.92
10.	5.28	3.14	-1.29	-2.46	1.90	9.86
11.	5.28	3.69	-1.28	-2.43	1.93	9.53
12.	5.69	4.01	-1.24	-2.40	1.87	9.46
13.	6.25	4.76	-1.20	-2.32	1.93	8.75
14.	6.48	5.07	-1.19	-2.29	1.95	8.51
15.	7.52	6.23	-1.12	-2.21	1.98	8.03
16.	8.13	6.87	-1.09	-2.16	1.87	7.91

Table B8. Data for p = 20.32cm; θ = 15°;
b = 15.24cm; b_s = 15.60cm; L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $\times 10^{-2}$ m	Q $\times 10^{-3}$ m^3/s	log(h)	log(Q)	CC_{Sk}	σ
1.	0.81	0.38	-2.09	-3.42	2.96	14.22
2.	1.40	0.75	-1.85	-3.12	2.57	12.46
3.	1.60	0.90	-1.80	-3.05	2.52	11.88
4.	1.90	1.08	-1.72	-2.97	2.34	11.74
5.	2.29	1.31	-1.64	-2.88	2.15	11.65
6.	2.75	1.67	-1.56	-2.78	2.08	10.99
7.	3.12	1.97	-1.51	-2.71	2.02	10.60
8.	3.47	2.29	-1.46	-2.64	2.01	10.53
9.	4.01	2.86	-1.40	-2.54	2.02	9.36
10.	4.62	3.36	-1.34	-2.47	1.92	9.18
11.	1.93	3.75	-1.31	-2.43	1.95	0.76
12.	5.50	4.45	-1.26	-2.35	1.96	8.24
13.	6.48	5.44	-1.19	-2.26	1.87	7.96
14.	6.65	5.68	-1.18	-2.25	1.88	7.81
15.	7.34	6.53	-1.13	-2.19	1.87	7.49

Table B9. Data for p = 20.32cm; $\theta = 30^{\circ}$;

b = 15.24cm; b_s = 17.60cm; L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $x10^{-2}$ m	Q $x10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.02	0.53	-1.99	-3.28	2.38	12.84
2.	1.40	0.83	-1.85	-3.08	2.32	11.25
3.	2.49	1.79	-1.60	-2.75	2.11	9.28
4.	2.88	2.34	-1.54	-2.68	2.22	8.20
5.	3.30	2.59	-1.48	-2.59	1.99	8.53
6.	3.81	3.19	-1.42	-2.50	1.98	7.98
7.	4.06	3.46	-1.39	-2.46	1.95	7.85
8.	4.07	3.47	-1.96	-2.46	1.95	7.84
9.	5.08	4.83	-1.24	-2.00	1.95	7.02
10.	5.70	5.96	-1.24	-2.22	2.02	6.39
11.	6.55	7.08	-1.18	-2.15	1.95	6.18
12.	7.08	7.95	-1.15	-2.10	1.95	5.95

Table B10. Data for p = 20.32cm; $\theta = 45^{o}$;
$b = 15.24cm$; $b_s = 21.60cm$; $L_h = 30cm$.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $x10^{-2}m$	Q $x10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.83	1.65	-1.68	-2.78	2.06	7.70
2.	2.51	2.19	-1.60	-2.66	1.80	7.66
3.	3.00	2.81	-1.52	-2.55	1.78	7.11
4.	3.48	3.48	-1.46	-2.46	1.76	6.67
5.	3.86	4.03	-1.41	-2.39	1.74	6.40
6.	4.50	4.77	-1.35	-2.32	1.64	6.29
7.	5.44	6.19	-1.26	-2.21	1.60	5.86
8.	6.48	7.43	-1.19	-2.13	1.48	5.81
9.	6.70	8.10	-1.17	-2.09	1.54	5.50
10.	7.32	8.80	-1.14	-2.05	1.48	5.47

Table B11. Data for p = 20.32cm; $\theta = 60^{o}$;

b = 15.24cm; b_s = 30.48cm; L_h = 30cm.

(1)	(2)	(3)	(4)	(5)	(6)	(7)
S/NO.	h $x10^{-2}$ m	Q $x10^{-3}$ m^3/s	log(h)	log(Q)	C_{sk}	σ
1.	1.05	1.51	-1.98	-2.82	2.40	4.62
2.	1.15	1.70	-1.94	-2.77	2.36	4.49
3.	1.29	1.95	-1.89	-2.71	2.24	4.44
4.	1.38	2.19	-1.86	-2.66	2.28	4.22
5.	1.51	2.51	-1.82	-2.60	2.28	4.03
6.	1.62	2.82	-1.79	-2.55	2.32	3.83
7.	1.82	3.24	-1.74	-2.49	2.24	3.75
8.	1.91	3.47	-1.72	-2.46	2.24	3.66
9.	2.09	3.80	-1.68	-2.42	2.13	3.67
10.	2.29	4.37	-1.64	-2.36	2.13	3.51
11.	2.40	4.68	-1.62	-2.33	2.13	3.43

Table B12. Data for p = 20.32cm; $\theta = 75^{\circ}$;

b = 15.24cm; b_s = 58.90cm;

L_n = 30cm.

Q = 3 x 10^{-3} m^3/s								
P = 10.16cm			P = 15.24cm			P = 20.32cm		
S/NO.	θ	h/p	S/NO.	θ	h/p	S/NO.	θ	h/p
1.	0	0.345	1.	0	0.234	1.	0	0.176
2.	15°	0.326	2.	15°	0.217	2.	15°	0.169
3.	30°	0.311	3.	30°	0.200	3.	30°	0.156
4.	45°	0.284	4.	45°	0.177	4.	45°	0.136
5.	60°	0.220	5.	60°	0.160	5.	60°	0.116
6.	75°	0.125	6.	75°	0.088	6.	75°	0.063

Table B13: Table showing the calculated values of h/p used in plotting Figure C7

Q = 3 x 10^{-3} m^3/s								
P = 10.16cm			P = 15.24cm			P = 20.32cm		
S/NO.	θ	/h/p	S/NO.	θ	h/p	S/NO.	θ	h/p
1.	0	0.450	1.	0	0.307	1.	0	0.232
2.	15°	0.427	2.	15°	0.286	2.	15°	0.225
3.	30°	0.404	3.	30°	0.262	3.	30°	0.206
4.	45°	0.366	4.	45°	0.233	4.	45°	0.181
5.	60°	0.290	5.	60°	0.209	5.	60°	0.156
6.	75°	0.163	6.	75°	0.115	6.	75°	0.086

Table B14: Table showing the calculated values of h/p used in plotting Figure C8

Table D15 Table showing the calculated values of h_o/h_{sk} used in plotting Figure C9

		Weir height p = 15.24cm.						
Q_3 m^3/s x10	0.5	1.0	1.5	2.0	2.5	3.0	4.0	5.0
θ(degrees)	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	1.30	1.18	1.12	1.11	1.10	1.07	1.07	1.08
30	1.30	1.25	1.23	1.23	1.21	1.18	1.16	1.15
45	1.36	1.32	1.31	1.35	1.35	1.34	1.36	1.33
60	1.94	1.61	1.52	1.51	1.51	1.48	1.44	1.43
75	3.02	2.74	2.81	2.79	2.68	2.58	2.61	2.65

			Weir height p = 20.32cm							
$\frac{Q}{B}$ x10^{-3} m^3/s	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
θ (degrees)	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}	h_o/h_{sk}
0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
15	1.25	1.08	1.05	1.06	1.06	1.06	1.04	1.03	1.03	1.02
30	1.37	1.26	1.19	1.16	1.17	1.15	1.13	1.12	1.12	1.07
45	1.46	1.37	1.34	1.37	1.37	1.33	1.29	1.28	1.28	1.27
60	2.28	1.84	1.69	1.60	1.56	1.52	1.51	1.47	1.45	1.41
75	3.26	2.81	2.86	2.87	2.85	2.82	2.75	2.71	2.67	2.62

Table B16: Table showing the calculated values of h_o/h_{sk} used in plotting Figure C10.

APPENDIX C

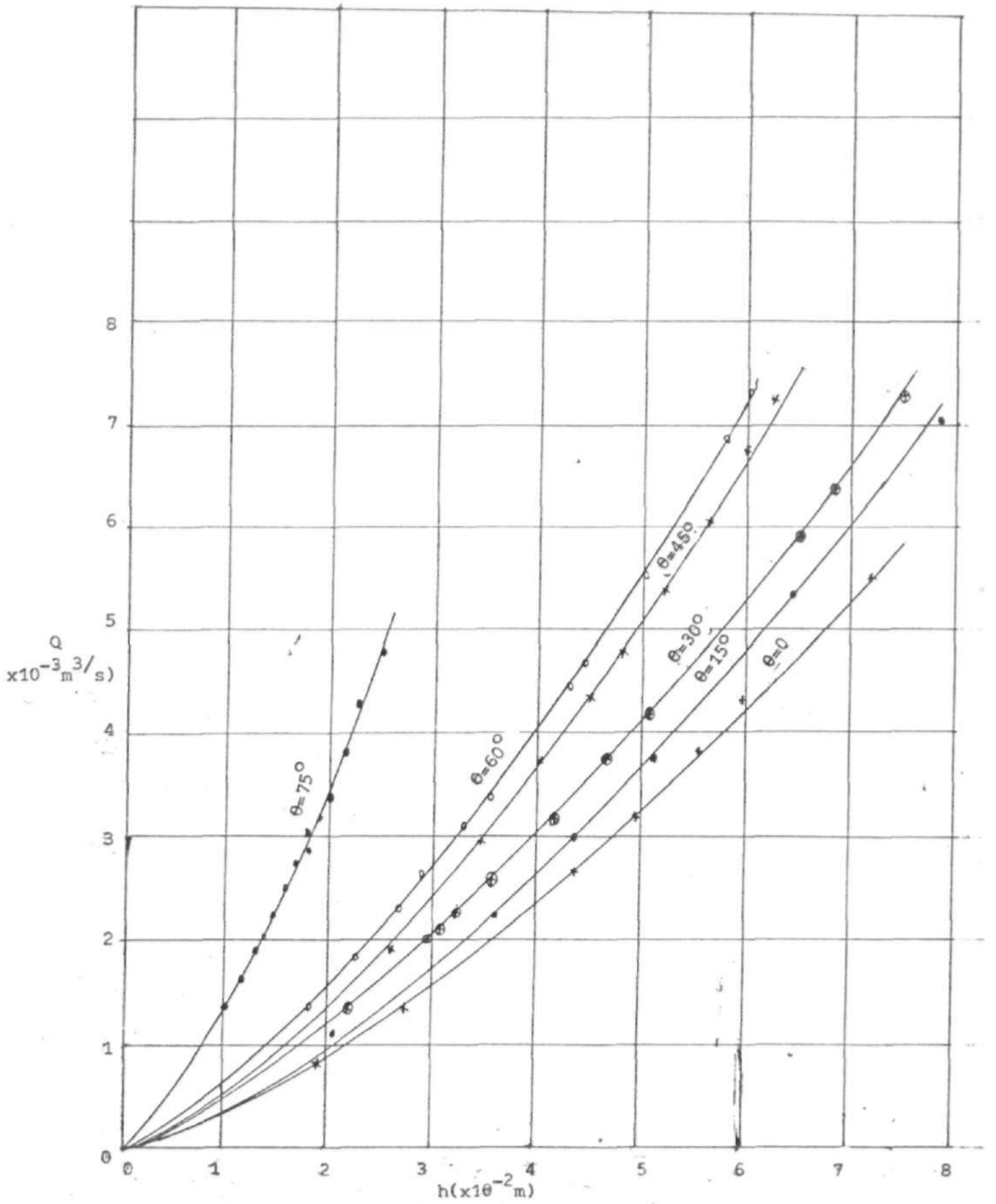


Figure C1: Plot of discharge Q versus head h for weir height p = 15.24cm for various weir inclinations.

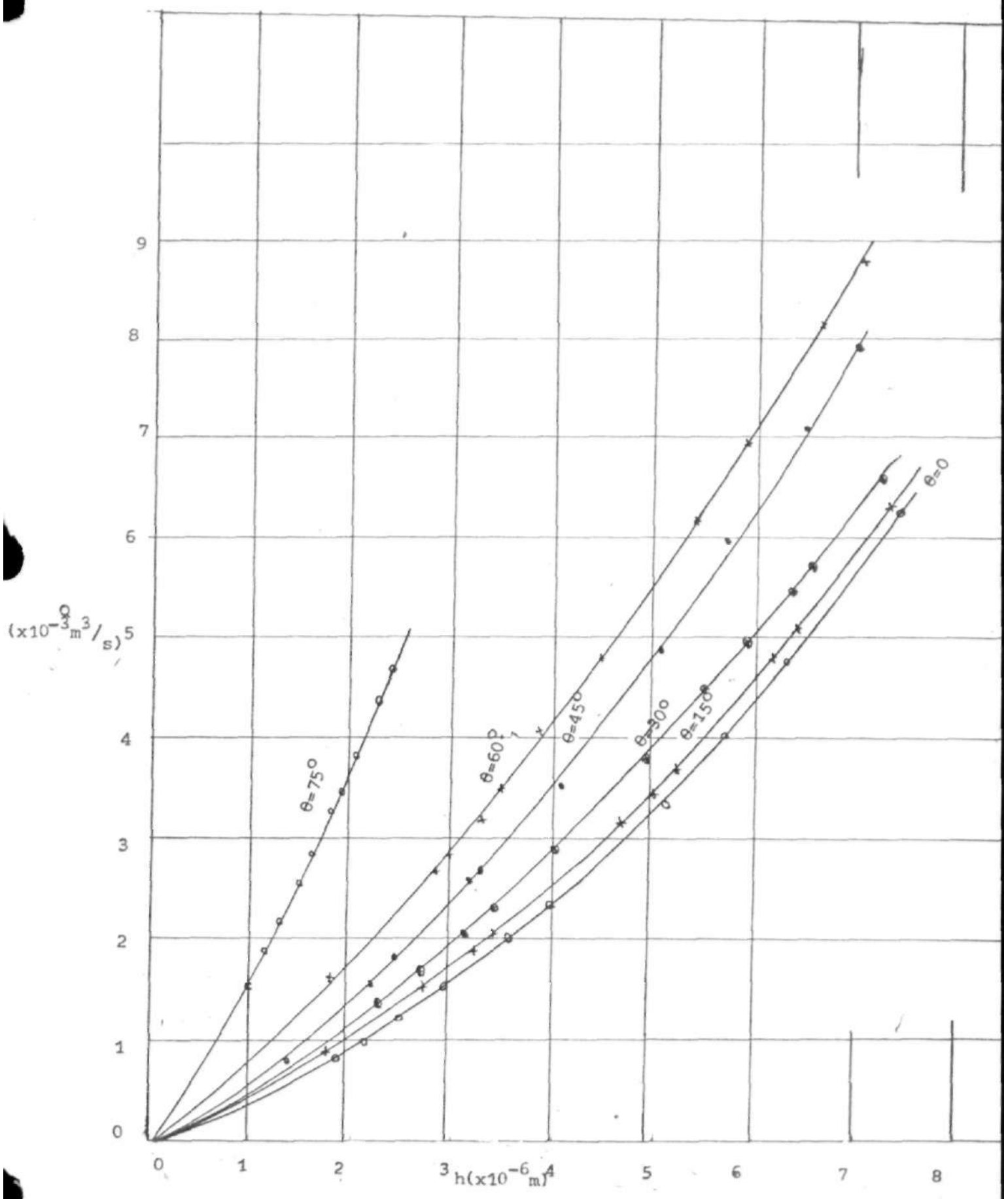


Figure C2: Plot of discharge Q versus head h for weir height p = 20.32cm for various weir inclinations.

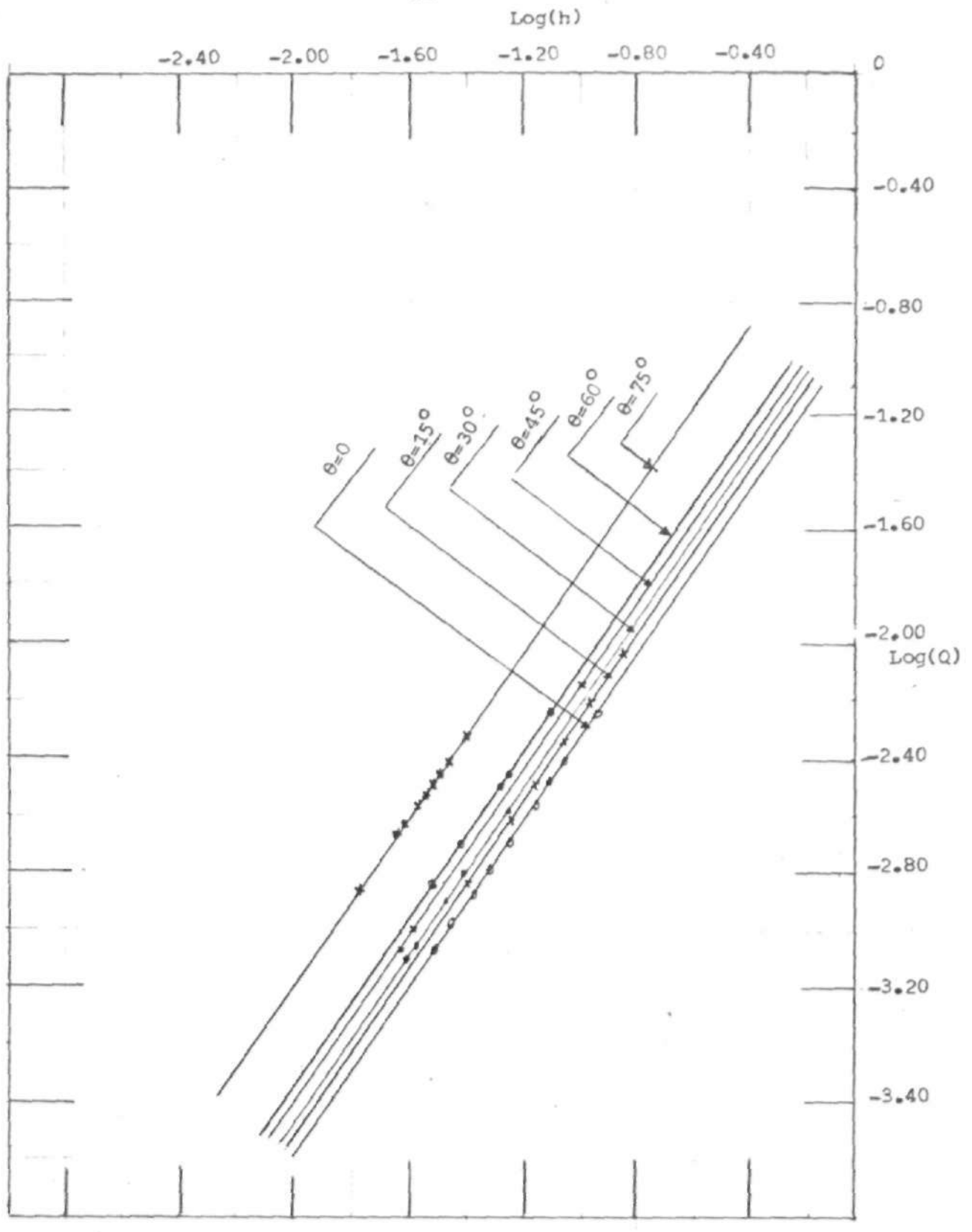


Figure C3: Plot of Log Q versus Log h at weir height p = 15.24cm for various weir inclinations.

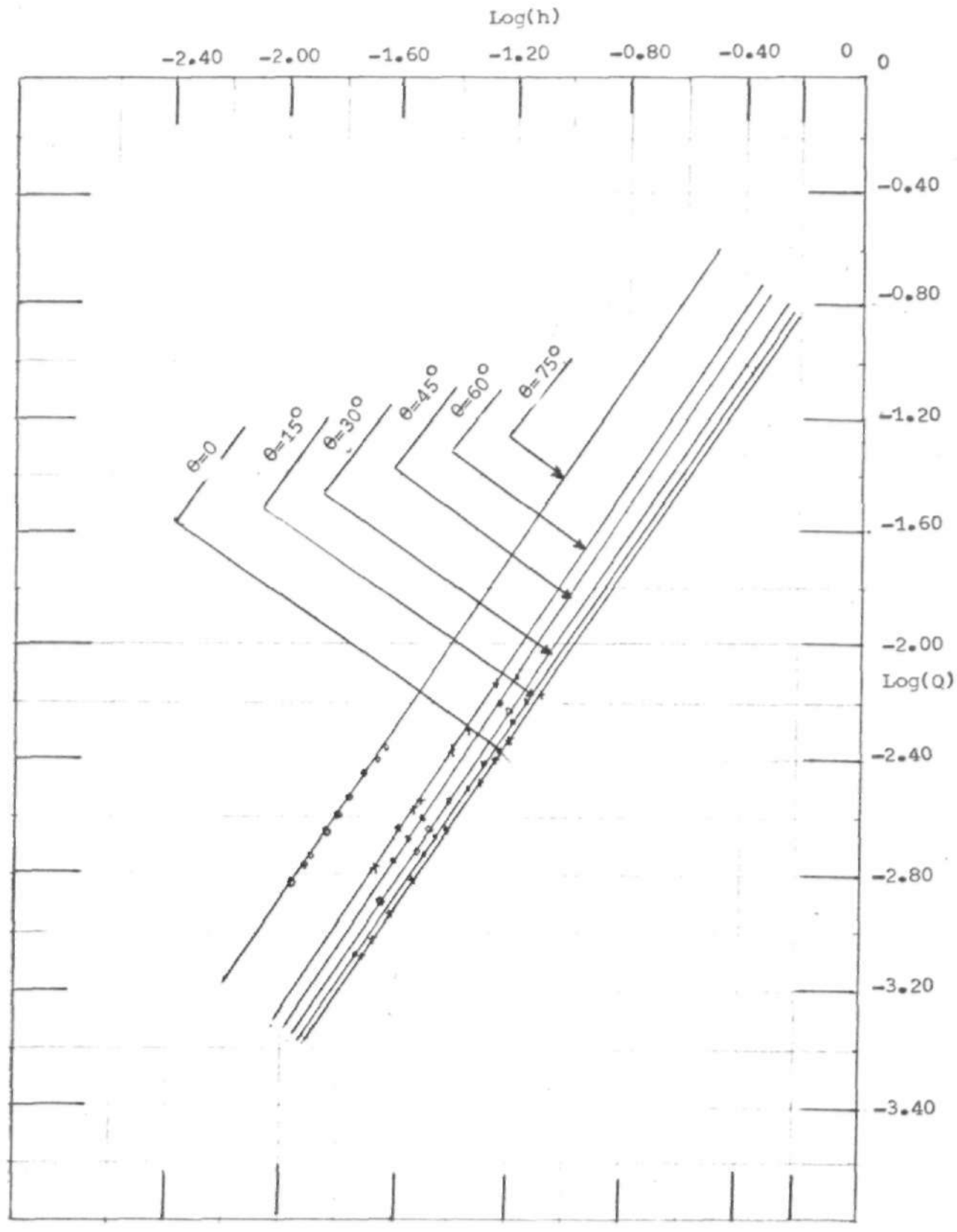


Figure C4: Plot of Log Q versus Log h at weir height p = 20.32cm for various weir inclinations.

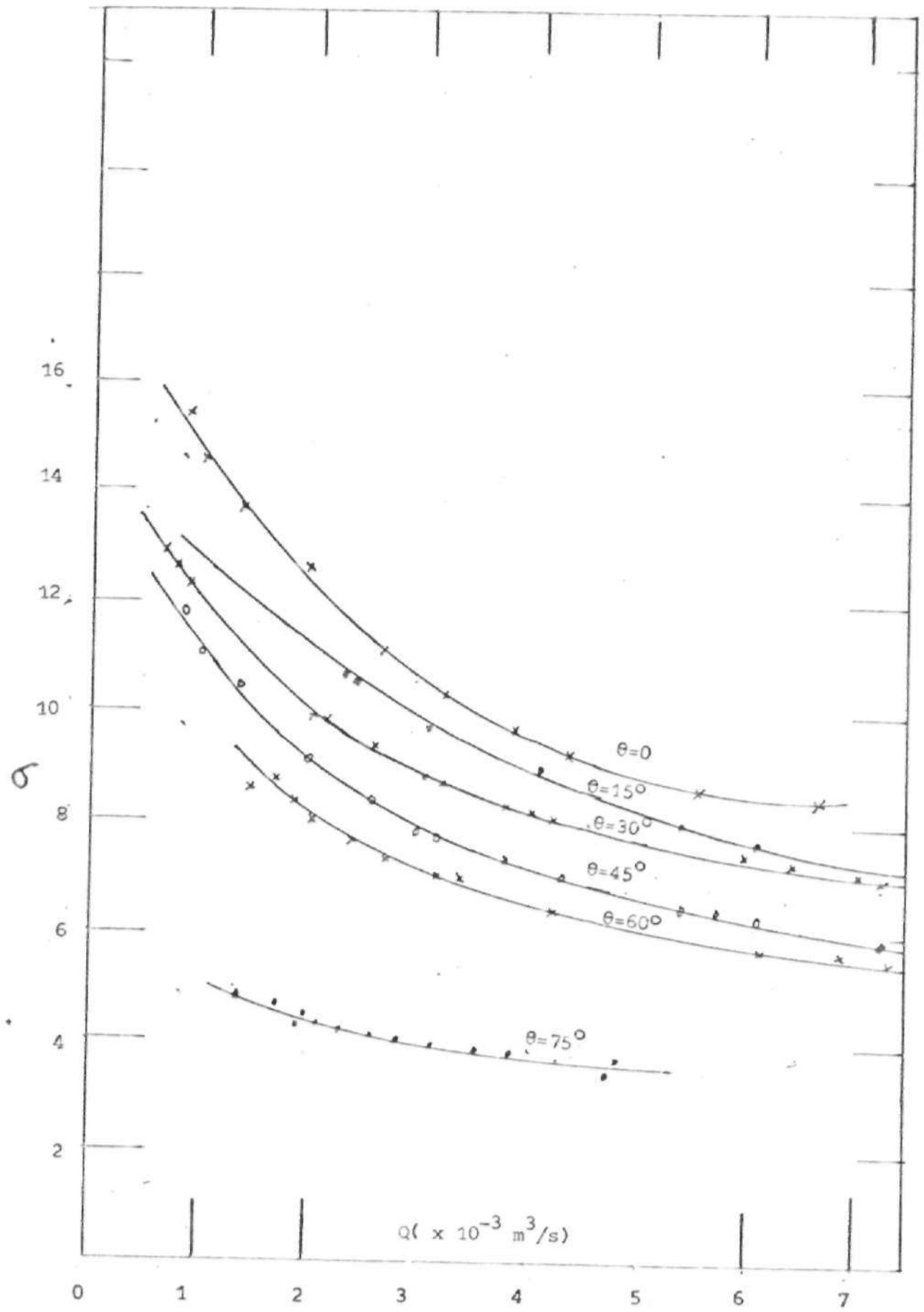


Figure C5: Plot of sensitivity versus discharge Q for weir height p = 15.24cm at various angles of inclinations.

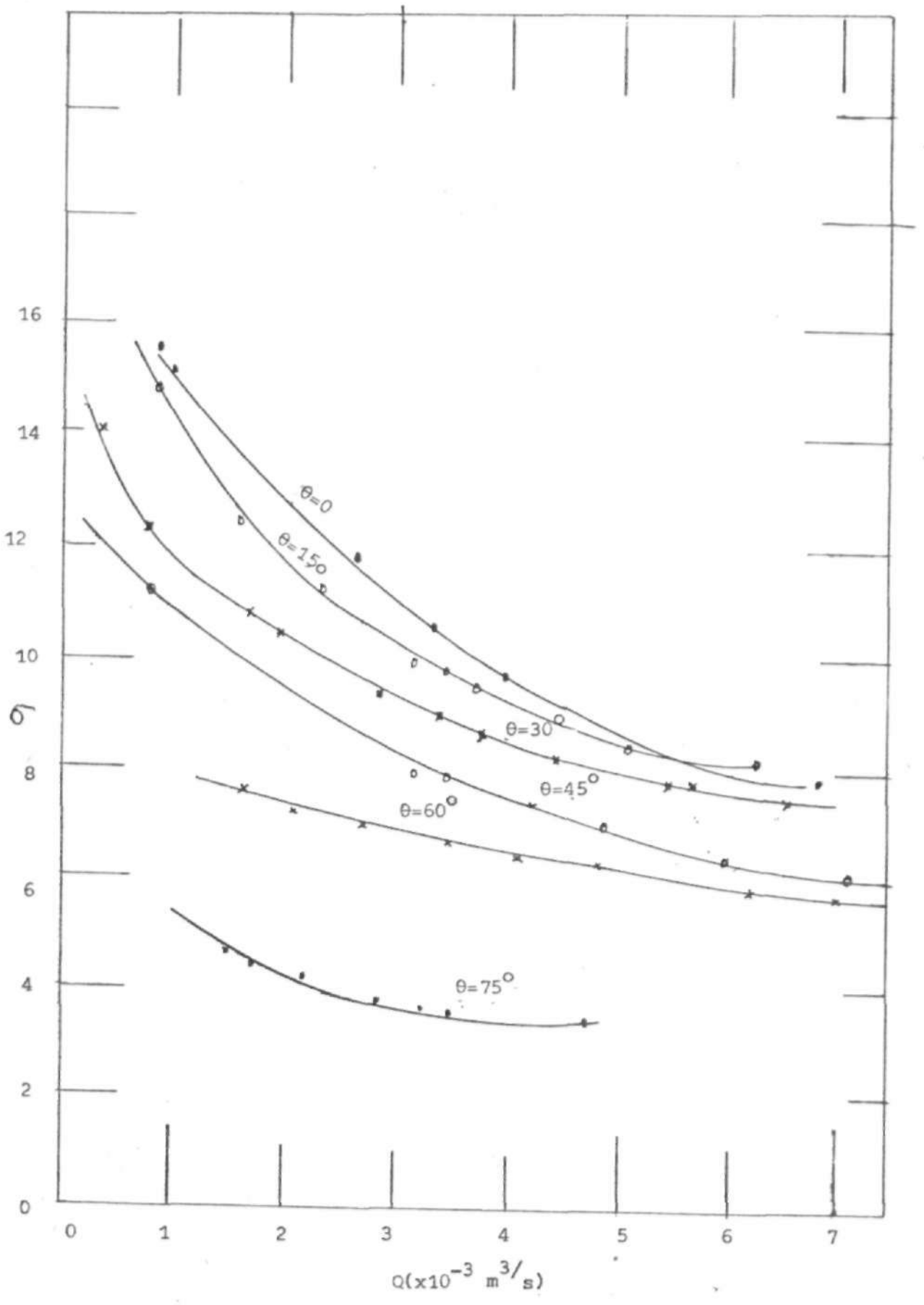


Figure C6: Plot of sensitivity σ versus discharge Q for weir height p = 20.32cm at various angles of inclinations.

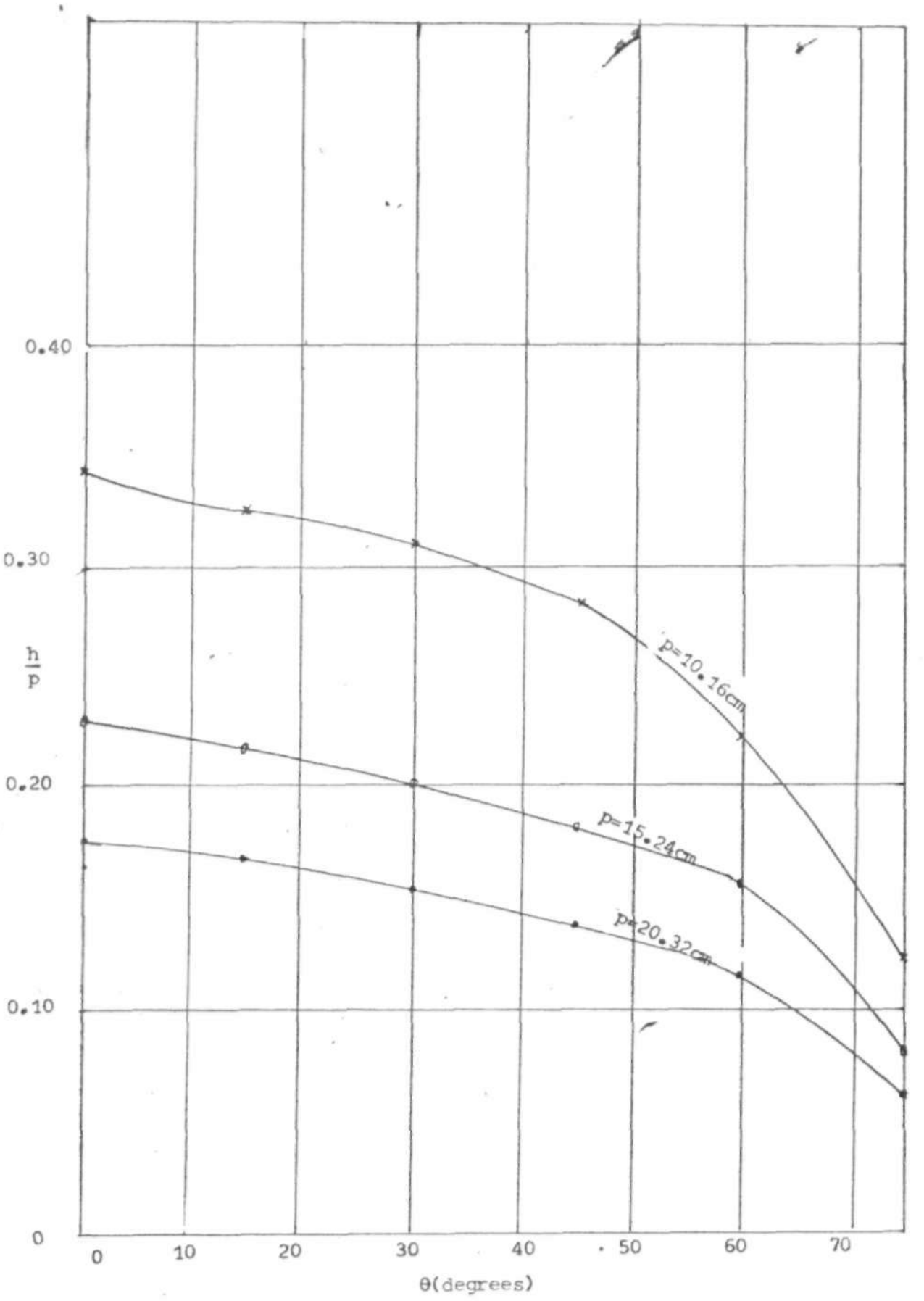


Figure C7: Plot of the ratio h/p versus weir inclination θ at a discharge of 2×10^{-3} m^3/s

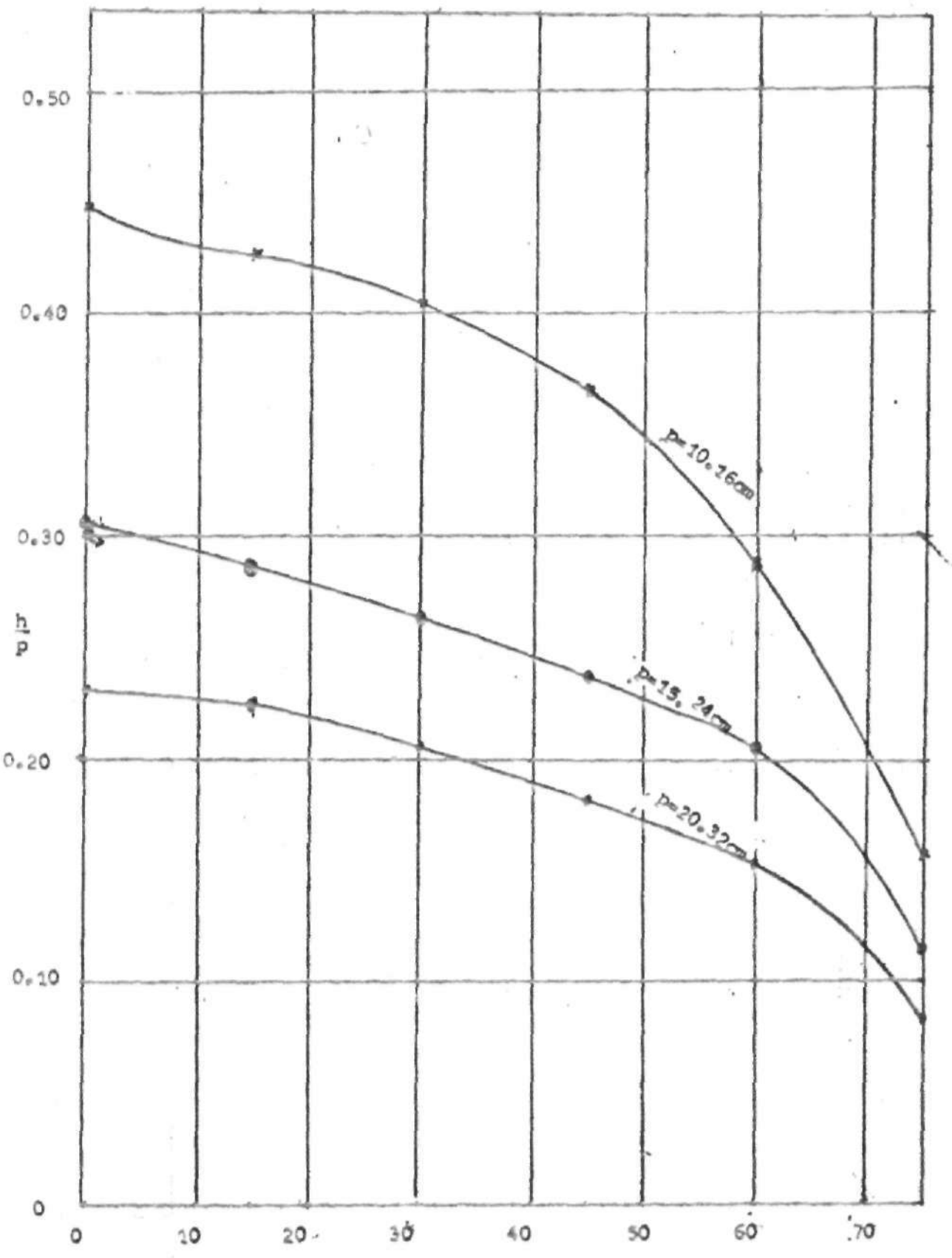


Figure C8: Plot of the ratio h/p versus weir inclination θ at a discharge of 3×10^{-3} m^3/s.

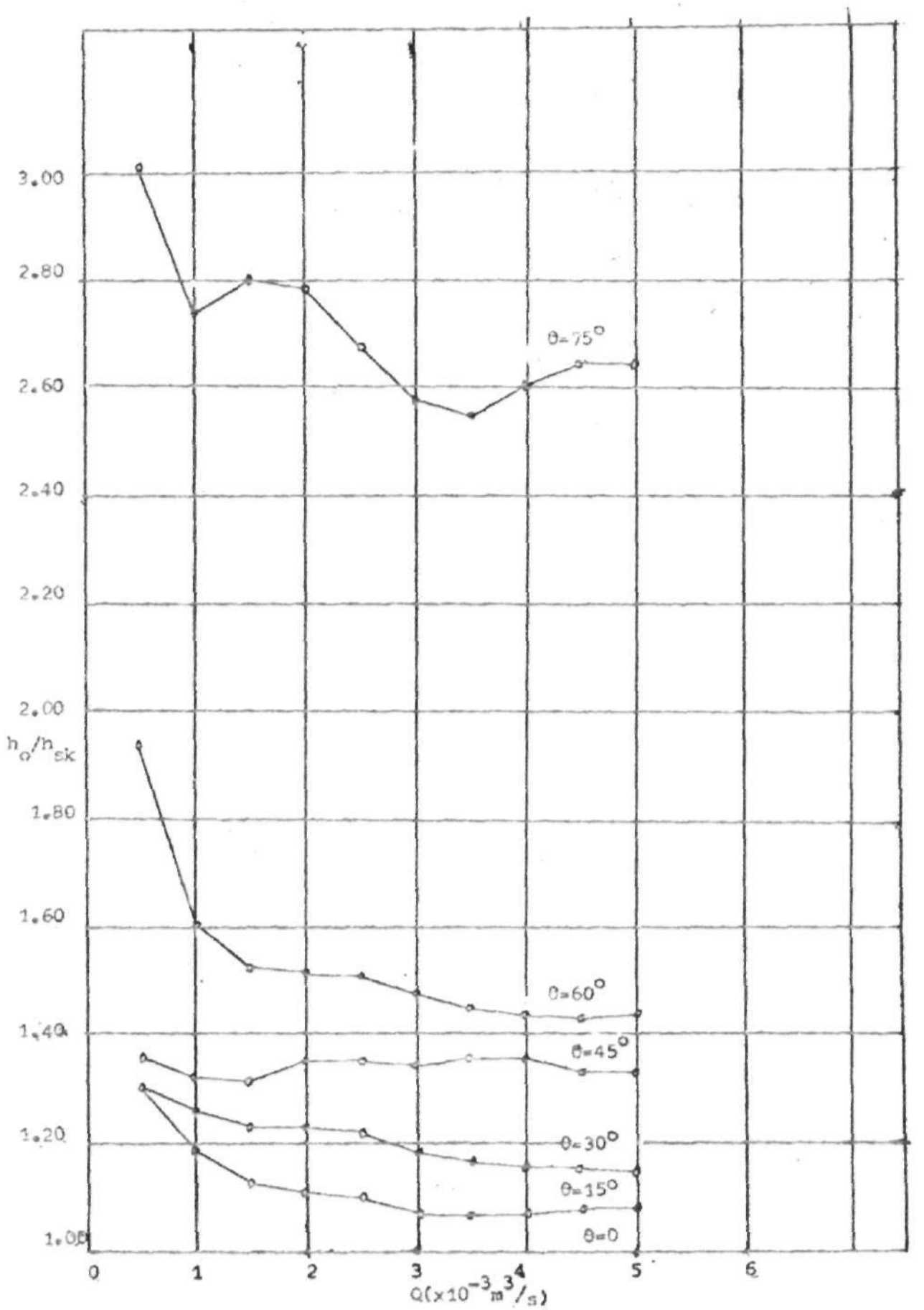


Figure C9: Plot of the ratio h_o/h_{sk} versus discharge Q for weir height p = 15.24cm at various angles of inclination.

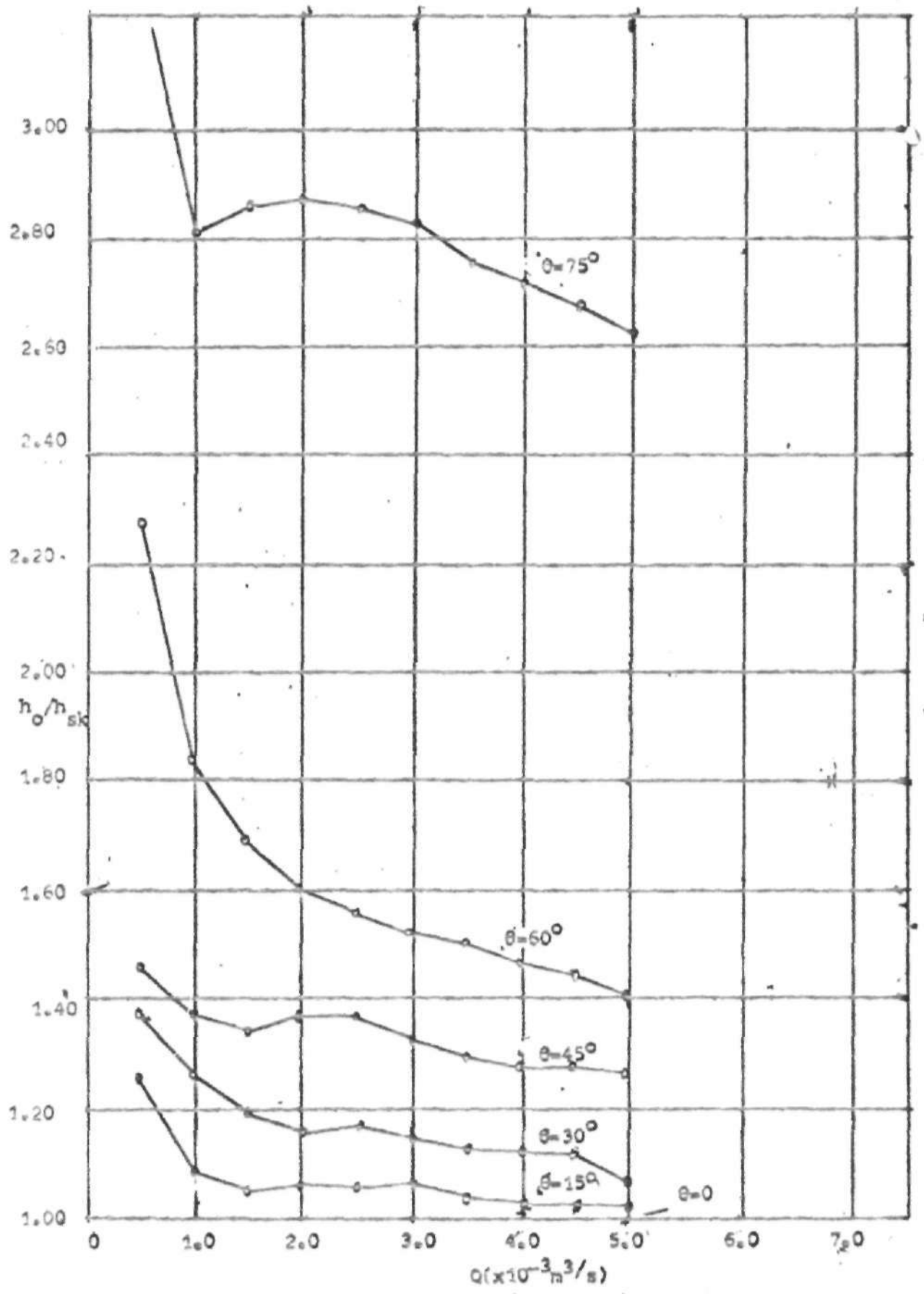


Figure C10: plot of the ratio h_o/h_{sk} versus discharge Q for weir height p = 20.32cm at various angles of inclination.