A LABORATORY STUDY OF BED MATERIAL WITHDRAWAL IN FARM TURNOUTS

by

Ata Mohammad Nazar

Prepared under support of

United States Agency for International Development
Contract No. AID/csd-2162

"Water Management Research
in Arid and Sub-Humid Lands of the
Less Developed Countries"

and

Grant No. AID/csd-2460

"Optimum Utilization of Water Resources
with Emphasis on Water Delivery and Removal Systems"

Colorado State University

Fort Collins, Colorado

May 1973

CET72-73AN28

THESIS

A LABORATORY STUDY OF BED MATERIAL WITHDRAWAL IN FARM TURNOUTS

Submitted by

Ata Mohammad Nazar

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

May, 1973

COLORADO STATE UNIVERSITY

MAY 1973

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION

BY [illegible]

ENTITLED A LABORATORY STUDY OF [illegible] MATERIAL WITHDRAWAL IN EARTH TURGORITS

BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Committee on Graduate Work

Co-Adviser

Co-Adviser

Head of Department

ABSTRACT

The phenomenon of bed material withdrawal through a farm turnout was studied in an indoor laboratory flume. Depth of flow in the flume, discharge in the flume, turnout elevation from the concrete bed of the flume, and the discharge through the turnout were the variables whose effect on the variation of sediment discharge through the turnout was to be determined.

The statistical analysis of the data (Eq. 5-1) indicates that the sediment discharge through the turnout is almost directly proportional to the sediment concentration in the flume. Data taken at two different turnout elevations confirmed (Fig. 5-3) that most of the sediment load was transported close to the bed of the channel and the variation in sediment concentration at higher elevations from the bed of the channel was not significant.

Based on a series of special runs plus visual observation, it was found that the amount of sediment discharge through the turnout was significantly affected by the bed form movement in the flume. A collapse of sharp peak or unstable bed formation which was irregular in time and space in the vicinity of the turnout would increase the sediment discharge through the turnout considerably. The analysis of data shows that the scour pit formation near the turnout remains geometrically similar under different conditions of flow in the flume and the turnout. It was also found that the depth of scour pit increases with an increase in the discharge ratio.

ACKNOWLEDGMENTS

The writer, with profound and sincere gratitude acknowledges the support and guidance received from Dr. M. L. Albertson, Centennial Professor of Civil Engineering, advisor and the chairman of the author's graduate committee. The writer is particularly grateful to Dr. A. G. Mercer, Professor of Civil Engineering and co-chairman of the author's graduate committee for his comments and suggestions in the preparation of this thesis.

Special appreciation is expressed to Dr. K. Mahmood, Professor of Civil Engineering and member of the writer's graduate committee for his generous assistance and patience during the entire course of this study. Indebtedness is expressed to Dr. S. A. Schumm, Professor of Geology, and Professor G. L. Smith of Civil Engineering for their comments and suggestions

The writer is thankful to the people in the machine shop and electronics shop for their prompt help whenever needed. Thanks are due to Rashid Makhdoom, a graduate student in civil engineering for his help in collecting the data, and Azizullah Sharify, Dastagir Ghiacy, and Jafer Kazemi, graduate students in civil engineering for their suggestions and encouragement. The writer is indeed grateful to Mrs. Arlene Nelson and Mrs. Eunice Felton for their cooperation and help in typing this material.

Funds for the study were provided by two U. S. Agency for International Development projects entitled Water Management Research in Arid and Sub-humid Lands of the Less Developed Countries (Contract AID/csd-2162), and Optimum Utilization of Water Resources with Emphasis on Water Delivery and Removal System (Grant AID/csd-2460).

TABLE OF CONTENTS

Chapter		Page
	ABSTRACT	iii
	ACKNOWLEDGMENTS	iv
	LIST OF TABLES	vii
	LIST OF FIGURES	viii
	LIST OF SYMBOLS	x
I	INTRODUCTION	1
	Sediment Problem in Irrigation System	2
II	LITERATURE REVIEW	6
	Sediment Transport in Alluvial Channels	7
	Sediment Transport Related to Channel Bifurcation	9
	Vertical Distribution of Suspended Materials	10
	Farm Turnouts	12
	Previous Work on Farm Turnouts	15
III	THEORETICAL AND DIMENSIONAL ANALYSIS	20
	Modes of Transport	20
	Einstein's Analysis of Suspended Sediment Transport	22
	Variables Affecting Bed Material Discharge	23
	Scour Pit near Turnout	27
IV	EXPERIMENTAL PROCEDURE AND EQUIPMENT	32
	Flume	32
	Turnout	34
	Measuring Devices	34

TABLE OF CONTENTS (continued)

Chapter		Page
	Sediment Samplers	36
	Sonic Depth Sounder	36
	Data Taking Procedure	38
	Probable Sources of Error in Data	40
V	ANALYSIS OF DATA AND DISCUSSION OF RESULTS	42
	Analysis of Flume and Turnout Data	43
	Discussion of Results	47
	Effect of Bed Form Movement	50
	Scour Pit Formation	56
	From Model to Prototype	59
VI	SUMMARY AND CONCLUSIONS	65
VII	RECOMMENDATIONS FOR FUTURE STUDY ON THIS PROJECT .	67
VIII	REFERENCES	68
IX	APPENDIX A	75
X	APPENDIX B (Sonic Depth Sounder)	82

LIST OF TABLES

Table		Page
5-1	Summary of the data for the special runs	50
I	Flume data	76
II	Scour pit data	78

LIST OF FIGURES

Figure		Page
2-1a	Typical design of open flume turnout as used in West Pakistan	16
2-1b	Standard design of orifice semi-module as used in West Pakistan	16
3-1	Relative location and Dimensions of turnout in the flume	24
3-2	Top view of the experimental section in the flume . .	29
3-3	Hypothetical sand bed form in the experimental section of the flume. Bed form actually observed in lab is included in the Appendix	29
4-1	Schematic diagram of the flume	33
4-2	General layout of turnouts	35
4-3	Sediment sampler in the delivery pipe of flume pump	37
4-4	Sediment sampler in the delivery pipe of turnout pump	37
5-1	Plot of concentration ratio versus discharge ratio with the depth ratio Y_t as a third variable	44
5-2	Plot of sediment concentration through the turnout (measured versus computed)	48
5-3	Variation of bed material concentration throughout the depth of flow in the laboratory flume used for this study	49
5-4	Hypothetical sand-bed profiles, indicating the longitudinal areas referred to in the text	52
5-5a	The effect of bed form movement in the flume on the variation of sediment concentration through the turnout	53
5-5b	The effect of bed form movement in the flume on the variation of sediment concentration through the turnout. The relative magnitues of the longitudinal areas are about the same as for Figure 5-5a	54

LIST OF FIGURES (continued)

Figure		Page
5-5c	The effect of bed form movement on the variation of sediment concentration through the turnout. The relative magnitude of the longitudinal areas are about the same as for Figure 5-5a	55
5-6a	Depth and the size relation of the scour-pit	57
5-6b	Depth and size relation of the scour-pit	58
5-7a	Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} - 0.25 mm)	60
5-7b	Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.35 mm)	61
5-7c	Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.45 mm)	62
5-7d	Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.55 mm)	63
A-1	Sand-bed profile actually observed in the lab	81

LIST OF SYMBOLS

Symbol	Definition	Dimension
A_1	Area upstream from the center line of the turnout in the experimental section of the turnout	L^2
A_2	Area downstream from the center line of the turnout in the experimental section of the flume	L^2
A_d	Longitudinal section area of the sand-bed profile downstream from the center line of the turnout	L^2
A_u	Longitudinal area of the sand-bed profile upstream from the center line of the turnout	L^2
b	The width of turnout	L
C_f	Concentration in the flume	ppm
C_r	Concentration ratio $(\frac{C_t}{C_f})$	none
C_t	Concentration in the turnout	ppm
d	Depth of flow	L
d_c	Elevation of the turnout crest from the average sand-bed level	L
d_f	Depth of flow in the flume	L
d_t	Depth of sand plus depth of water in the flume $(d_f + D_{ms})$	L
D	Sand particle diameter	mm
D_{ms}	Mean depth of sand-bed in the experimental section of the flume	L
D_{as}	The average depth of scour in the experimental section of the flume	L
D_d	Average depth of scour downstream from the center line of the turnout	L
D_{T1}	The average depth of scour near the turnout	L
D_{50_f}	Average diameter of sand in the flume	mm

LIST OF SYMBOLS (continued)

Symbol	Definition	Dimension
D_{50_t}	Average diameter of sand in the turnout	mm
D_r	Depth ratio $\left(\frac{E_t - D_{ms}}{d_t - D_{ms}}\right)$	none
D_u	Average depth of scour upstream from the center line of the turnout	L
E_t	Turnout elevation from the concrete bed of the flume	L
Fn	Froude number	none
f_s	Seepage losses through the bed of the stream	none
g	Gravitational acceleration	L/T^2
h	Height of turnout	L
K	Von Karman constant	none
Q_f	Discharge in the flume	L^3/T
Q_t	Discharge in the turnout	L^3/T
Q_r	Discharge ratio $\left(\frac{Q_t}{Q_f}\right)$	none
R	Hydraulic radius	L
R_e	Reynolds number	none
S	Water surface slope	none
S_c	Shape factor of the cross section of a channel	none
S_f	Shape factor of the turnout	none
S_p	Shape factor of the particle	none
S_r	Shape factor of the reach of the stream	none
S_s	The specific gravity of sand	none
T	Temperature	C^o
U_*	Shear velocity	L/T

LIST OF FYMBOLS (continued)

Symbol	Definition	Dimension
V	Flow velocity	L/T
V_f	Flow velocity in the flume	L/T
V_t	Flow velocity through the t urnout	L/T
V_d	Volume of scour downstream from the center line of the turnout	L^3
V_u	Volume of scour upstream from the center line of the turnout	L^3
W	Fall velocity of sand particle	L/T
Y_t	Depth ratio $\left(\frac{d_t - E_t}{d_t - D_{ms}}\right)$	none
Z	Rouse number	none
ν	Kinematic viscosity	L^2/T
σ	Particle size distribution (gradation)	none
σ_f	Particle size distribution (gradation) in the flume	none
σ_t	Particle size distribution (gradation) in the turnout	none

Chapter I

INTRODUCTION

The tremendous increase in world population, both actual and predicted, has created a great demand for improved methods of food production and distribution. It is true that many of the more developed countries now produce food in excess of the need of their present population. Political and economic realities indicate that only a small amount of this excess production has been channeled for use by the less developed countries where the food shortage is most acute: It is therefore necessary that the less developed countries seek ways of increasing internal food production in order to be assured of sufficient food to meet their needs. This is, of course, a very complicated problem. A multitude of factors must be considered. Not only the obvious ones of topography, climate, soil conditions but cultural, political and economic factors within the area play a definite role in any program for improved food production.

It would be beyond the scope of this or any study to undertake an analysis of all these factors. Each requires a separate and detailed analysis for any real understanding to accrue. However, all of these factors must be considered if thorough comprehension and solution of the food problem is to be attained.

An important question in any agricultural project is the provision of an adequate quantity and quality of water. In certain areas and with certain crops, rainfall provides all the water which is necessary for successful agricultural production. In many instances, however, this is not the case, and an additional supply of water must be brought

to the area. One of the popular ways of doing this, of course, is the diversion of water from a natural stream through canals to an irrigation distributary network.

Within the area of irrigation, much information must be gathered for optimal use of the irrigation system to be attained. Moreover, the construction of a modern and expensive irrigation system does not guarantee its successfulness; proper maintenance is an important factor in the continuing functioning of an irrigation structure. More importantly, the system must be designed with consideration of local conditions. A successful irrigation blueprint cannot be applied in every area without detailed study of all its implications.

Sediment Problem in Irrigation System

An important factor in the design of an irrigation system is the sediment problem. Numerous instances may be cited showing irrigation projects which have been rendered virtually ineffective because of inadequately managed problems of sedimentation. In fact, the sediment problem in irrigation systems motivated the evolution of extensive sediment exclusion practices, particularly in the Indo-Pakistan Subcontinent (Mahmood, 1973).

Regardless of the method of sediment exclusion used, it is practically impossible to completely eliminate the entry of sediment into the irrigation system. The amount of sediment going into the system depends, to an extent, on the design of the head structure. It usually is small for high head diversion structures and is large for low head structures. In the case of low head structures on sand-bed rivers, the sediment content of the irrigation supply is usually large

and generally causes major operational problems. Generally, irrigation water diverted from alluvial rivers carries sufficient sediment load to create serious problems if not properly allocated in the system.

In designing an irrigation system, it is necessary to have means for disposing of sediment entering the system. Also in the design of the system, consideration should be given to the type of land, the quantity and quality of sediment, the mineral constitution of land and sediment, means of removing sediment and the cost of alternatives. Sometimes, it may be necessary for certain areas in the system to accept more sediment than others (Mahmood, 1973).

On the basis of transport phenomena, sediment load entering an irrigation system may be divided into fine material load and bed material load. Fine material load is almost uniformly distributed in the depth of flow. In general, it is difficult and economically infeasible to eliminate the entry of fine materials into an irrigation system. Within the system, its distribution is little affected by the distribution structures and is easily transported to the farm units. The concentration of bed material load, on the other hand, increases toward the bed of a channel. Its entry into the irrigation system and its distribution within the system can be controlled, to an extent, at the control structures.

The objective of this thesis is to study the phenomena of sediment withdrawal in farm turnouts and explore the possibilities of using the turnout as a control device for sediment distribution within the irrigation system. For the preceding reasons, the fine material load is not considered as a part of the sediment load that can be controlled or manipulated in an irrigation system.

Turnouts are called by different names in different parts of the world. In some parts of India, it is called a 'sluice', in Pakistan, it is called an 'outlet', and in America it is termed a 'turnout' (Mahbub and Gulhati, 1951). A turnout is defined as a device through which the field channel is connected to the distributing channel.

The field channels are managed by a farmer, or a group of farmers, and the distributing channel is either managed by government or a public organization. The fact that the turnout connects two parts of an irrigation system which belong to two different parties, makes it necessary that the device should be designed such that the overall operation of the irrigation system is to the best satisfaction of both sides. The success of an irrigation system, to a large degree, depends on the successful operation of the turnouts. In the design of an irrigation system, there is probably no other single item which has a greater effect on the distribution of water than the type and design of a turnout (Mahbub and Gulhati, 1951).

This study was conducted in a 102 feet long, 8 feet wide, and 3.33 feet deep concrete flume. There were two locations for turnouts in the walls of the flume structure. The turnout was located 12.83 feet upstream from the tail box. The independent variables of the study were: depth of flow in the flume, discharge in the flume, discharge in the turnout, and the elevation of the turnout. The range of variation of unit discharge in the flume was from 1.20 cubic feet per second to 2.4 cubic feet per second, and the depth of flow in the flume

was varied from 0.89 feet to 1.89 feet. The range of variation of discharge in the turnout was from 0.23 cubic feet per second to 1.70 cubic feet per second. The data were obtained at two different elevations of the turnout from the bed of the flume, that is at 0.740 feet and 1.073 feet respectively.

Bed material used in this study had an average diameter of 0.19 mm and a standard deviation (gradation) of 1.30. Sediment concentration in the flume and turnout were the dependent variables of the study. The range of variation of sediment concentration in the flume was from 1 to 1050 parts per million and that in the turnout varied from 3 to 3860 parts per million. The fine material load was not measured in this study.

The result of this study which expresses sediment concentration in the turnout in terms of concentration and hydraulic variables of the flume, is presented as a predictive equation. This is obtained from the statistical analysis of data for 126 runs collected under steady state flow conditions in the flume and the turnout. The scour pit formation in the vicinity of the turnout is also analyzed. The relationship of the size and geometry of the scour pit versus the flow parameters in the flume and turnout is investigated.

Chapter II

LITERATURE REVIEW

Sediment problems are associated with almost any irrigation system. The sediment may come either from the source of irrigation water supply or from the erosion of the banks and beds of the channels in the irrigation system. The usual source of sediment is from the diversion of irrigation water supply from an alluvial river.

Water intake structures are designed with the consideration of whether to remove the sediment, or pass it down the canal or the river. When water with a large sediment load is diverted into the irrigation system, problems are developed immediately. Sediment deposition will take place, particularly at areas where the flow velocity is slow. This causes reduction in the canal capacity to properly handle the necessary amount of water-sediment mixture. Cleaning silted canals is expensive and it is usually uneconomical to clean miles of canals, especially in developing nations where the available facilities are generally inadequate. Economic disposal of sediment requires a comprehensive knowledge of sediment control devices and the cost of their operation and maintenance.

In the design of an irrigation system, special consideration is due in the design of the turnouts. Farm turnouts are not only responsible to pass an adequate amount of water from the distributing channel to the field channel which take the water to the crops, but they are also required to carry their share of sediment. The design of the turnout and its elevation from the bed of the distributing channel, beside other factors (cost, simplicity, etc.), depends on the

amount of water it should pass, and the vertical distribution of the sediment load in the distributing channel.

The following Review of Literature has been divided into the categories:

1. Sediment transport in alluvial channels,
2. Sediment transport related to channel bifurcation,
3. Vertical distribution of suspended material,
4. Farm turnouts, and
5. Previous work on farm turnouts.

The forementioned divisions of the Review of Literature are based on the facts that for sediment to pass through the turnout, sediment has to be transported in the parent channel. Sediment transport is also related to channel bifurcation and farm turnout can be considered as an extreme case of the bifurcated channels. Since the vertical distribution of suspended material in the parent channel affects the relative location of the turnout from the bed of the parent channel, the amount of sediment passed through the turnout is controlled by this distribution.

Under farm turnouts, the common types of turnouts and their role in the irrigation system has been discussed. The findings of other people in regard to sediment conduction through the farm turnouts are included in the last part of this chapter.

Sediment Transport in Alluvial Channels

Lacey, a pioneer in the study of alluvial channels, did his work in India and Pakistan. He states that the branch of hydraulics which is concerned with the transport of sediment in alluvial channels is the most complex and inexact of all. The complexity is mainly due to the number of

independent variables which determine the geometry of the channel at a given discharge. The more important of these variables are the density and size of the sediment particles, the settling velocity of the particle, and the sediment concentration.

Lacey (1966) is of the opinion that, with the present knowledge of sedimentation, only provisional conclusions can be drawn. He emphasizes the importance of small scale model study in the design of canal systems and feels that in some instances the existing canals could be used as scale models. Lacey notes that, in the design of irrigation systems, consideration should be given to the headworks on the parent river, because the nature and quantity of sediment entering the system largely depends on the headworks and flow conditions in the main river. According to him the entry of coarse sediment into the system is undesirable and it should be excluded, while fine sediment load is sometimes advantageous. The deposition of fine material load on the bed and banks of the channel reduces seepage losses and it could also be used as soil conditioner on the farm. Lacey has stressed the importance of slope and width of a channel and believes that in field data, velocity, depth, and slope should be expressed as functions of the discharge per unit width.

Simons and Miller (Sixth Congress on Irrigation and Drainage, New Delhi, 1966) believe that the success and failure of a canal system depends on many factors, mainly on the ability of the canal to transport the required amount of water and sediment with minimum scour and deposition. To design such a canal, consideration should be given to the mechanics of flow of water and sediment in alluvial channels, fluvial morphology, and the specific design concept.

They have explained the forms and importance of bed roughness as developed in alluvial channels. The order of occurrence of these forms with increasing stream power (stream power equals shear stress times the flow velocity) are: ripples, ripples superposed on the backs of dunes, dunes, a transition range of stream power within which the form roughness changes from dunes to plane or flat bed, plane bed, standing waves, and antidunes. The bed roughness and its effect on flow is a very complex phenomenon and varies with variation in depth of flow, channel slope and velocity.

Sediment Transport Related to Channel Bifurcation

The location of a water intake structure on a river reach is very important. It has a tremendous effect on the flow of sediment into the system. Therefore, the location should be based on hydraulic principles with due consideration to the sediment characteristics. The dynamic hydraulic and sediment characteristics are different in a river that follows a curved path from the one that flows along a relatively straight course. The flow patterns in a bend are characterized by a secondary circulation within the flow. The faster moving surface water plunges to the bottom of the outside bend and rises on the inside bend. This causes a spiral current through the bends which tends to concentrate sediment along the inside bank. Degradation and scour occurs on the outside bank of the bend and a pool is usually formed.

A series of model studies conducted by Habermass and summarized by Mosonyi (Chapter 22, River Mechanics, editor H. W. Shen, Colorado

A series of model studies conducted by Habermass and summarized by Mosonyi (Chapter 22, River Mechanics, editor H. W. Shen, Colorado State University, 1971), show the effect of different intake structure arrangements on the amount of sediment entry to the canal system. Models used for this study were rigid bed models and in each case 50 percent of the flow was diverted. As a result of these tests, it was recommended that intake structures be built toward the downstream end of the curve for the structure to operate satisfactorily.

The forementioned statements about bifurcated channels in regard to sediment transport, can also be applied to a farm turnout. When the turnout is opened, it allows part of the water flowing in the distributing channel to pass through it to the field channel. The turnout may pass only a small percentage of the total flow in the distributing channel, but the flow is still considered as a divided flow at this point when the turnout is operating.

Vertical Distribution of Suspended Materials

The characteristic definition of a suspended solid particle is that its weight is supported by the surrounding fluid during its entire motion. The concentration of suspended particles is greatly affected by the channel bed roughness. Changes in bed forms bring variation in local depth and are associated with large scale eddies that cause appreciable fluctuations in the concentration of sediment in suspension. Instantaneous fluctuations in the concentration of suspended sediment is related to the scale and intensity of stream turbulence and particle size present in the bed of the channel. While being moved by the fluid, the solid particle, which is heavier than the fluid, tends to settle in

the surrounding fluid. If the fluid flow has only horizontal velocities, it is not possible to explain how any sediment particle can be permanently suspended. Only if the irregular motion of the fluid particles, called turbulence, is introduced can one show that sediment particles may be permanently suspended (Einstein, 1950).

The concentration of suspended sediment varies from a minimum at the water surface to a maximum at the bed of the channel. The concentration of a given grain size at a distance Y from the bed of channel, can be calculated by using the suspended load equation discussed in Chapter III.

Sand bed channels usually have the greatest variation in sediment concentration. Fine material load that is silt and clay, on the contrary, is usually distributed uniformly in the depth of flow. Deviation from the mean value of concentration is maximum in streams where the suspended load consists largely of bed materials, and it is minimum for streams where silt and clay constitutes a large portion of sediment load in suspension. Thus the amount of the momentary fluctuation in concentration of the suspended sediment at any depth varies with the ratio of the concentration of the sand fraction to the total concentration (ASCE, 1969, p 1480).

The distribution and concentration of sediment particles in the depth of flow are also affected by the water temperature. The viscosity of water varies inversely with the water temperature, that is the water is more viscous when it is cold than hot. The fall velocity of sediment particles is affected by changes in water viscosity.

Rubey in 1933 has provided an equation for determining the fall velocity of sand particles (Mahmood, February 1971).

$$W = \frac{(\frac{2}{3} g(S_s-1)D^3 + 36\nu^2)^{\frac{1}{2}} - 6\nu}{D}$$

g = gravitational acceleration

S_s = the specific gravity of sand

ν = the kinematic viscosity, and

D = the particle diameter

In Rubey's equation, when the specific gravity of sand S_s and the sand particle diameter D are kept constant, the fall velocity W varies inversely with the water viscosity and directly with the water temperature. Lane (ASCE, 1969, p 1482) in a study of sediment transport in the Lower Colorado River, found that the suspended load discharge increased approximately 2½ times from summer to winter for equivalent water discharge for sediment particles smaller than 0.3 mm. Brice (ASCE, 1969, p 1482) in a review of data from the Middle Loup River at Dunning, Nebraska, found that as the water temperature decreases, the suspended sediment concentration increases.

Farm Turnouts

Sediment deposition in the irrigation distributary system is undesirable. Every effort is made to stop the entry of sediment from a natural stream to the canal system at the headworks. Yet there is not a single economically feasible method available to completely eliminate all the sediment. There is always some sediment flow present in most irrigation systems.

For economic reasons as well as the potential damage to the crops, the flow of sediment in the irrigation network should be treated in such a way that the overall efficiency of the system remains at optimal level. The design of a farm turnout is primarily responsible for the fair share distribution of sediment in the system. In the design of a farm turnout, it is important to consider local irrigation practices, local conditions, water supply, demand on supply, and operation and maintenance of the structures and the system.

Kennedy in 1906, in Punjab Irrigation Paper No. 12 (Mahbub and Gulhati, 1951), has considered the following as essential conditions for all farm turnouts:

1. A farm turnout should be strong and should not have moving parts liable to derangement or requiring periodic attention.

2. Interference by the cultivator must be difficult and, if made, should be readily detectable.

3. The turnout should draw its fair share of the sediment carried by the parent channel, but should not be liable to derangement by sediment or weeds.

4. It should be possible for the farm turnout to work efficiently with a small working head. The larger the working head the higher the water level required in the parent or distributing channel and the higher the cost of the distributing system.

5. The cost of the turnout should not be high.

Mahbub and Gulhati (1951) believe that the optimum capacity of a farm turnout is the discharge which the farmer can handle efficiently and should be such that the absorption losses in the water course or

field channel and in the field are minimum. The longer the time taken to irrigate a field, the greater is the amount of absorption in the part of the field already irrigated, while applying the minimum irrigation required for the remainder. It has been found that a turnout capable of passing water at the rate of two cubic feet per second is generally the best when the farmer irrigates flat fields of about ½ acre in area. Malhotra (Mahbub and Gulhati, 1951), has worked out theoretically a relation between the size of the field and the optimum turnout discharge. According to the results of Malhotra's findings for optimum conditions, the discharge of a turnout in cubic feet per second should be about five times the area in acres of the field it irrigates.

Farm turnout may be divided into three classes (Mahbub and Gulhati, 1951):

1. Non-modular turnouts are the type of turnouts whose discharge is a function of the difference between the water level in the distributing channel and the field channel. Variations in either one affect the turnout discharge.

2. Semi-modular turnouts, or semi-modules, are those turnouts whose discharge is only affected by the water level in the distributing channel and is independent at the water level in the field channel, provided the minimum working head required for the operations of the device is available.

3. Modular turnouts are those turnouts whose discharge is independent of the water levels in both the distributing channel and the field channel, within reasonable working limits. There are two general types of modular turnouts; modular turnouts with moving parts and modular turnouts without moving parts.

From the economic point of view, as well as the simplicity and stability of the structure, semi-modular turnouts were generally adapted in the Indo-Pakistan Subcontinent. Among the many versions of the semi-module, the open flume type semi-modular turnout gained more popularity (Rakha, 1971).

The open flume turnout is simply a smooth weir (see Figs. 2.1a and 2.1b) with a sufficiently constricted throat to ensure a velocity above the critical and long enough to ensure that the controlling section remains within the parallel throat at all discharges up to the maximum (Mahbub and Gulhati, 1951). A gradually expanding flume is provided at the outfall, to obtain the maximum recovery of head. The entire work is built in brick masonry, but the controlling section is generally provided with cast iron or steel bed and check plates. There are various forms of open flume turnouts which differ from each other only in detail.

Previous Work on Farm Turnouts

The only previous studies done on sediment discharge through farm turnout is by Minhaj-ud-din and Sharma (Rakha, 1971) and by Rakha (1971). These two investigators have concluded that the maximum sediment concentration in a turnout, when fixed near the bed of channel is 1.2 times the sediment concentration in the channel. Rakha (1971) studied the sediment conduction phenomenon through a farm turnout at Colorado State University Engineering Research Center in Fort Collins. The results of his study show that the sediment concentration in the turnout is about 4 to 5 times the sediment concentration in the flume. Rakha in his master's thesis has also stated that in his study the

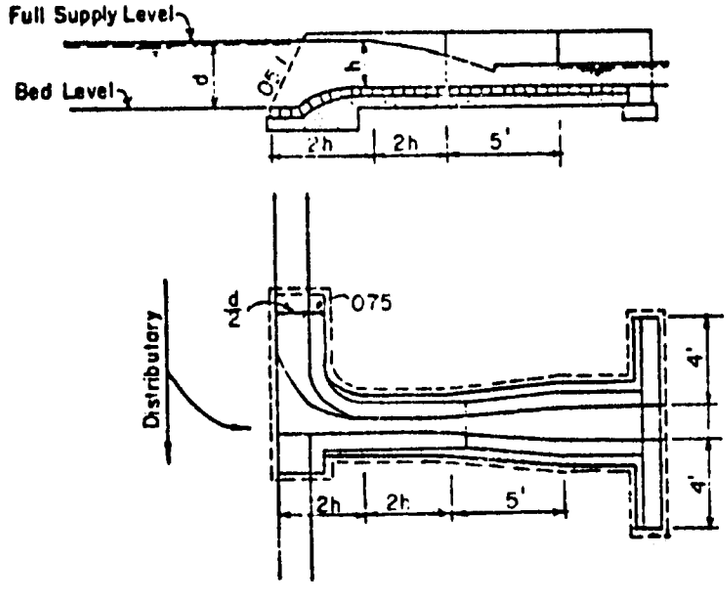


Figure 2-1a. Typical design of Open Flume Turnout as used in West Pakistan (after Mahbub and Gulhati).

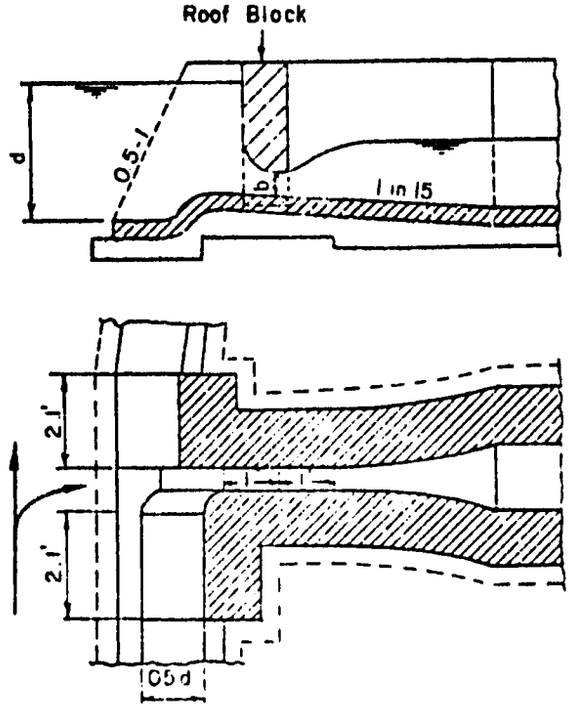


Figure 2-1b. Standard Design of Orifice Semi-module as used in West Pakistan (after Mahbub and Gulhati).

turnout was fixed near the bed of the flume and the sediment concentration was higher in the lower layers of flow. Therefore, the sediment concentration was much higher in the turnout than in the flume. He has also explained that the sediment concentration in the turnout depends, among other parameters, on the vertical distribution of sediment in the channel. If most of the sediment load is moving in suspension and is uniformly distributed in the vertical, the ratio of the sediment concentration in the turnout to the sediment concentration in the channel will be around unity.

Rakha has plotted sediment concentration in the turnout against the sediment concentration in the flume. The functional relationship between these two parameters indicates that the sediment concentration in the turnout is directly proportional to the availability of the sediment load in the parent channel. In other words, more sediment will pass through the turnout when there is more available in the flume or the parent channel.

Rakha has also plotted the sediment concentration in the turnout against the sediment concentration in the flume for different ratios of the depth of flow d to the median diameter D of the bed material. Since the same sand was used for the entire study, the median diameter D of the bed material, therefore, remained unchanged. The change in the ratio of the depth of flow to the median diameter of the bed material, therefore, was only due to the change in the depth of flow. From these plots, Rakha concluded that for the same sediment concentration in the flume the sediment concentration in the turnout was greater when the depth of flow was small and vice versa.

In reference to the scour formation at the vicinity of turnout, Rakha believes that with the other variables kept constant, the scour is a direct function of the turnout discharge. An increase in turnout discharge, causes an increase in the velocity of flow in the channel upstream of the turnout. This increase in velocity increases the shear stress acting on the channel bed upstream of the turnout. An increase in shear stress, will scour the area upstream of the turnout which will in turn increase the sediment discharge through the turnout. The water passed through the turnout has a higher sediment concentration than the water passing by the turnout. Therefore, the water passing by the turnout, makes up for the deficiency of its sediment level by scouring the region downstream of the turnout. Hence, the larger the discharge through the turnout, the lower the sediment concentration in the water passing by the turnout, and the lower the sediment concentration in the water passing by the turnout, the greater its tendency to scour the region downstream of the turnout.

In regard to sediment size, Rakha claims that the median size of the sediment passing through the turnout was greater than that of the sediment moving in the channel. He attributes this finding to the fact that the coarser materials move near the bed and the fine material goes into suspension in the upper layers of flow. The turnout being fixed near the bed of the channel, the major part of the sediment flowing into the turnout consisted of coarser particles moving in the lower layers of the flow.

The results of Rakha's analysis are based on a small number of experiments. In his study, the data were obtained only at one elevation

of the turnout from the bed of the channel. Therefore, it was decided that more data were needed to supplement Rakha's work and the study was also extended to a different elevation of the turnout from the bed of the channel. This additional data were obtained under this study at the same place, and the same facilities were used.[1] The sand used as bed material was also the same in both studies.

---

[1] The data for this study are available at the Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, and can be made available to others also.

Chapter III

THEORETICAL AND DIMENSIONAL ANALYSIS

Sediment transport in alluvial channels may be in the form of bed load, or as a combination of bed load and suspended load. The mode of transport depends on the flow conditions in the channel and the nature (size, shape, specific weight) of the sediment load transported. If the channel carries fine materials, that is, silt and clay, the load will be uniformly distributed throughout the depth of flow. For coarser materials, on the other hand, the sediment concentration in the channel varies from a maximum at the channel bottom to a minimum at the water surface. The sediment transport through the turnout is a function of the total transport in the channel. It also depends on the vertical distribution of sediment load in the parent channel.

Sediment discharge through a turnout is a function of several variables pertinent to the turnout and the parent channel flow. A functional relationship which has been derived from the viewpoint of dimensional analysis is included in this chapter. Also included is a discussion regarding the formation of a scour-pit in the neighborhood of a turnout.

Modes of Transport

In alluvial channels, sediment particles are transported in the following modes:

1. Bed Load: this consists of particles rolling or sliding over the bed of the channel so that their weight is partially supported by contact with other particles on the bed.

2. Saltation Load: this consists of particles that are leaping into the flow, staying in suspension for short periods of time and then returning to the bed. The weight of these particles is partly supported by the bed and partly by the surrounding fluid. Saltation is not as important in transport by water as it is for transport by wind.
3. Suspended Load: this consists of particles that are entirely supported by the surrounding fluid during their motion. Those particles near the bed are in a continuous exchange with similar particles on the bed.

The total sediment load in an alluvial channel is equal to the sum of bed load and suspended load. It is also the sum of bed material load and wash load. Because of its smaller size fraction, wash load is not related to the local flow or bed material and cannot be predicted from local conditions. In 1950, Einstein suggested that the division line between wash load and bed material load can be arbitrarily drawn from the mechanical analysis of sediment deposit in the bed of the channel. He considered the upper limit for the grain diamter in wash load that particle size of which 10 percent of the bed mixture is finer. This approach, although arbitrary in nature, has practical application. He defined bed material load as that part of the sediment load which consists of grain sizes found in significant quantity in the bed of the channel and wash load as that part of the sediment load which consists of grain sizes finer than those found in the bed of the channel.

Suspended load in many sand-bed channels is a major part of the total sediment load. The vertical distribution of sediment

concentration in suspended load basically depends on the size of sediment particles in suspension. For fine materials, the distribution of sediment concentration throughout the depth of flow is nearly uniform and the variation in sediment withdrawal through the turnout at different elevations from the bed of the channel is insignificant. If the channel carries considerable amount of coarse material in suspension, then the concentration varies greatly over the depth of flow and the elevation of the turnout from the bed of the channel might become a factor in the amount of sediment withdrawal from the channel.

Analysis of Suspended Sediment Transport

For particles of a grain size fraction carried in suspension, the concentration C_y at any elevation y from the bed of channel can be determined from the suspended load equation (Einstein, 1950) provided the concentration of the same particles at some reference level a in the flow in known. In equation form this is:

$$\frac{C_y}{C_a} = \left(\frac{d - y}{y} \quad \frac{a}{d - a}\right)^Z \tag{1}$$

in which

Z = Rouse number defined as $\frac{W}{ku^*}$

W = fall velocity of the particles

k = von Karman's universal constant

u^* = shear velocity = $\sqrt{gR\,S}$

R = hydraulic radius

S = energy gradient

g = acceleration due to gravity

d = depth of flow in the channel

Equation (1) allows calculation of the flow rate of sediment particles at elevation y per unit area and time: $C_y \overline{V}_y$, in which

$\overline{V}_y$ = the average point velocity at distance y from the bed of channel.

Variables Affecting Bed Material Discharge

The bed material discharge in an alluvial channel is a function of the channel geometry, flow properties, fluid properties and sediment properties. The variables involved in this phenomenon as pointed out by Simons and Richardson (1966) are:

V = velocity in the channel

d = depth of flow in the channel

S = slope of the energy grade line

ρ = mass density of water sediment mixture

ν = apparent kinematic viscosity of the water sediment mixture

g = gravitational constant

σ = measure of the size distribution of the bed material

W = fall velocity of sand particles

ρ_s = density of sediment

S_p = shape factor of the particles

S_c = shape factor of the cross section of the stream

S_r = shape factor of the reach of the stream

f_s = seepage forces in the bed of the stream

Hence

$$C_f = f\ [V, d, \nu, g, \rho, \rho_s, W, f_s, S_p, S_c, S_r, S, \sigma\ ] \qquad (2)$$

in which

C_f = the concentration of bed material discharge in the flume

Concentration of bed material discharge through a turnout is not only a function of the variables in Eq. (2), its value is also affected by the additional parameters introduced by the turnout itself. These parameters are based on the geometry and hydraulics of the turnout. For an orifice type turnout, these variables are defined as follows:

b = width of turnout

h = height of turnout

d_c = elevation of turnout crest from the average sand bed elevation

S_f = shape factor of turnout

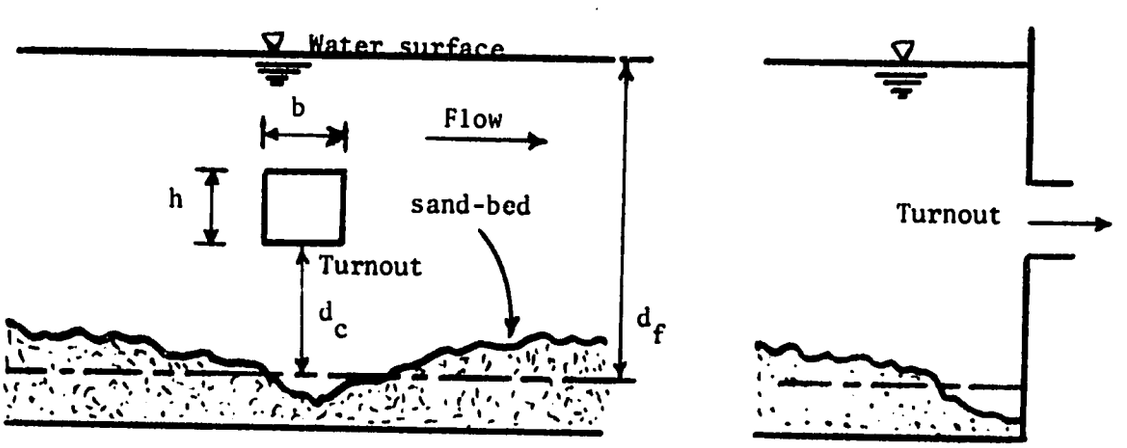


Figure 3-1. Relative Location and Dimensions of Turnout in the Flume

The hydraulic parameter of the turnout is discharge of water sediment through the turnout, Q_t . Therefore, sediment concentration through the turnout, expressed in terms of both flume or channel parameters and turnout parameters is:

$$C_t = f[V,d,\rho,\rho_s,\nu,g,W,h,b,d_c,C_f,f_s,\sigma,S_p,S_c,S_r,S,S_f] \qquad (3)$$

If velocity V , depth d of the flow in the channel and mass density ρ of the fluid in Eq. (4) are to be considered as repeated variables, then in terms of dimensionless parameters, the value of C_t is expressed as:

$$C_t = f[C_f, \frac{d}{d_c}, \frac{V}{W}, \frac{h}{d}, \frac{\rho_s}{\rho}, Re, Fn, \frac{f_s}{V^2 d^2 \rho}, S, S_p, S_r, S_c, S_f, \sigma] \qquad (4)$$

in which

Re = Reynolds number

Fn = Froude number and

the other parameters are as defined previously.

The dimensionless numbers on the right side of Eq.(4) include nearly all the parameters that may affect the sediment concentration through the turnout. Not all of these necessarily have considerable or measurable effect in every channel or laboratory flume. Some of these parameters may either be kept constant or their effect on sediment discharge could be ignored for all practical purposes.

In this study which was conducted in an indoor laboratory flume of concrete bed, the following parameters were either kept constant or their contribution to the variation of sediment concentration was considered to be negligible.

$\frac{fs}{V^2 d^2 \rho}$: since the study was done in a flume made of concrete, the effect of the seepage force was absent.

Sc, Sr : as a first approximation, these are omitted from consideration

S_p : bed material consisted of uniform sand with average particle diameter equal to 0.19 mm and particle size distribution equal to 1.30. The same sand was used during the entire study.

S_f : there were no changes made in the geometry of the turnout during the course of study.

In the case of $\frac{h}{d}$ and $\frac{h}{D}$, h and D are constants and the effect of d has been taken care of in other terms. The ratio ρ_s/ρ is also constant for this study. The effect of slope S and the fall velocity W could be represented by the Rouse number Z . After these manipulations, the final expression for C_t has the form:

$$C_t = f[\, C_f \,,\, \frac{d}{d_c} \,,\, Re,\, Fn,\, Z] \tag{5}$$

Rakha in his thesis (Rakha, 1971), in terms of dimensional analysis concluded that:

$$C_t = f[\, C_f m \;\; \frac{d}{D},\; \frac{h}{d} \,] \tag{6}$$

The dimensionless parameters which are not present in the expression derived by Rakha compared to what is obtained in this study are Re, Fn, and Z .

The effect of these parameters on the variation of sediment concentration was found to be measurable but not very significant. The

most important parameter which is present in both expressions is the sediment concentration in the flume C_f .

Scour Pit near Turnout

Diversion of water through the turnout disturbs the local equilibrium of stream bed and presents possibilities of local erosion. The local velocity due to diversion is increased and the sediment carrying capacity of stream beyond the turnout becomes in excess of the bed load carried by the stream. In order to make up for this difference, the stream scours its bed immediately downstream from the point of diversion.

The concept of regime could also be applied to the problems of local scour. The scour develops as time goes on and the local velocity drops to the point at which the local capacity to carry out material becomes equal to the supply rate of the incoming material. The amount of time required for local scour to reach equilibrium depends on the rate of bed load transported by the stream. Experiments have shown that the magnitude of scour increases with increase in velocity and decreases with increase in sediment size, whereas the time required to reach a limit decreases with either increase in velocity or sediment size (Tarapore, 1966).

The number of turnout structures in an average size irrigation network are by hundreds. If preventive measures against the formation of scour pit are not taken, the average depth of flow in the parent channel will drop and the system may not function efficiently. Also scour pit formation may endanger the foundation of turnout structures

which might end with complete failure or undesirable functioning of the system.

The experimental section of the flume where the sand-bed profiles were observed and recorded during the course of this study is shown in Figure 3-2. The width of the flume (5 ft) was divided into ten sections along which the sand-bed profiles were observed. The average depth of the sand-bed for the bed profiles, obtained at 2 feet, 3 feet, and 4 feet from the turnout side of the flume, was considered as the mean depth of sand for the entire experimental section (10 ft by 5 ft). The average depth of scour upstream and downstream from the center line of the turnout was determined from the longitudinal area of each profile (see Fig. 3-3). In each case the depth of scour was measured in reference to the mean depth of sand in the experimental section. For the purpose of symmetry in the analysis of bed profiles, only a 4½ foot length of the surface area upstream from the turnout was considered.

The following notations were adopted for the quantities derived from this analysis:

D_{ms} = The average depth of sand-bed obtained from the bed profiles taken at distances of 2 feet, 3 feet, and 4 feet from the turnout side of the flume. This depth was considered to be the mean depth of sand in the entire experimental section. (ft)

A_{ui} = The longitudinal sectional area of the sand-bed profile over a distance of 4½ feet upstream from the center line of the turnout (i - T_1, T_2,...T_7, and L_2, L_3, and L_4). (ft^2)

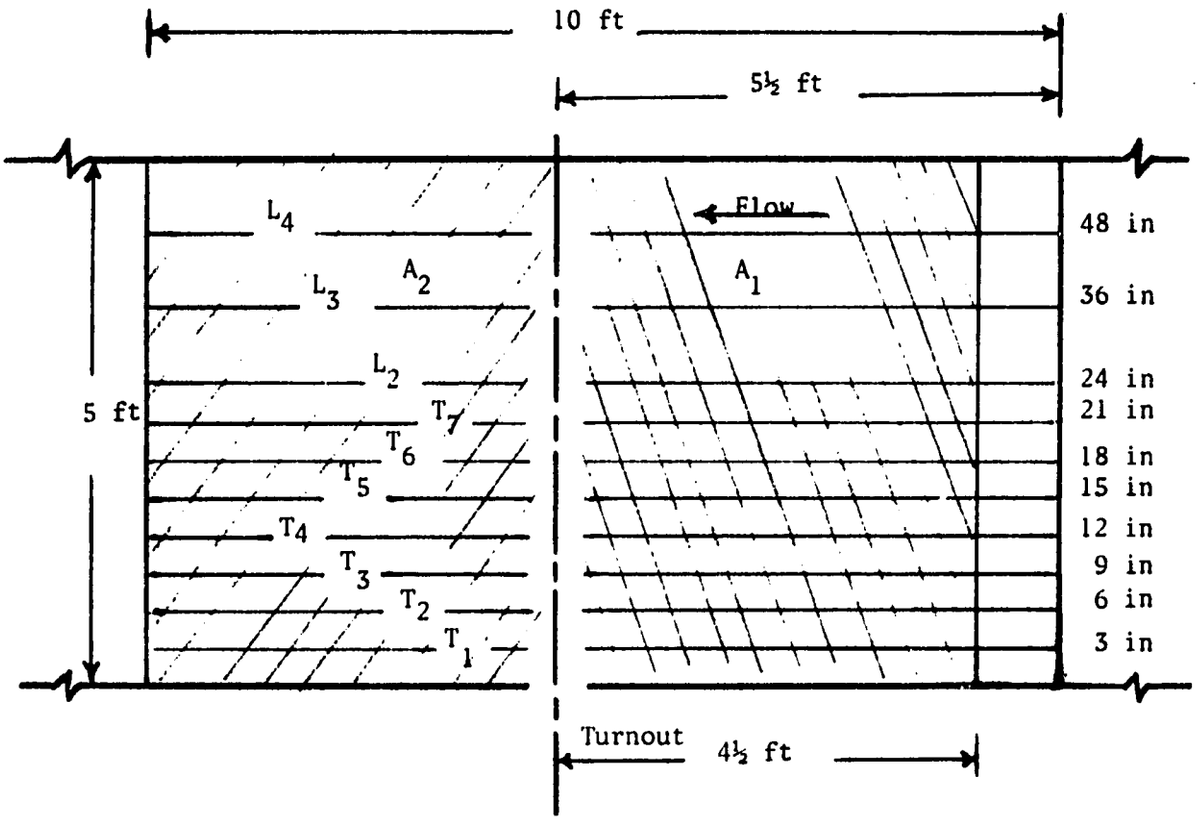


Figure 3-2. Top view of the experimental section in the flume.

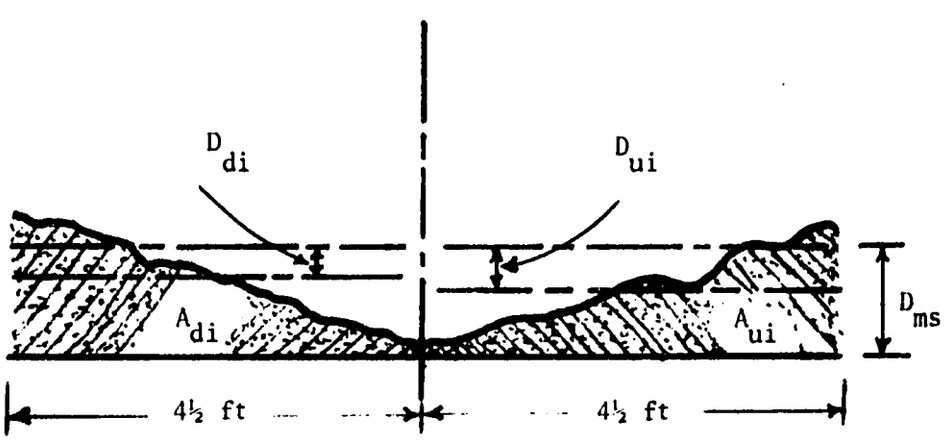


Figure 3-3. Hypothetical sand bed form in the experimental section of the flume. Bed form actually observed in lab is included in the Appendix.

A_{di} = The longitudinal area of the sand-bed profile over a distance of 4½ feet downstream from the center line of the turnout ($i = T_1, T_2, \ldots T_7$, and L_2, L_3, and L_4). (ft^2)

$\bar{D}_{ui} = \frac{A_{ui}}{4\frac{1}{2}}$ = The average depth of scour upstream from the center line of the turnout along bed profile i (i is as defined previously). (ft)

$\bar{D}_{di} = \frac{A_{di}}{4\frac{1}{2}}$ = The average depth of scour downstream from the center line of the turnout along bed profile i (i is as defined previously). (ft)

The forementioned quantities were used to calculate some of the following parameters;

V_u = Volume of scour below the mean bed level occurring upstream of the turnout center line. (ft^3)

A_1 = Surface area extended 4½ feet upstream of the turnout and the full width of the flume (5 ft) (ft^2)

$\bar{D}_u = \frac{V_u}{A_1}$ = The average depth of scour in the upstream section of the turnout. (ft)

V_d = Volume of scour below the mean bed level occurring downstream of the turnout center line. (ft^3)

A_2 = Surface area extended 4½ feet downstream of the turnout and the full width of the flume. (ft^2)

$\bar{D}_d = \frac{V_d}{A_2}$ = The average depth of the scour in the downstream section of the turnout. (ft)

$D_{as} = \frac{1}{2}(\bar{D}_u + \bar{D}_d)$ = The average depth of scour in the entire experimental section. (ft)

$D_{u_{T1}}$ = The average depth of scour in the upstream section of the turnout for the bed profile taken along T_1 (the closest profile to the turnout side of the flume). (ft)

$D_{d_{T1}}$ = The average depth of scour in the downstream section of the turnout for the bed profile taken along T_1 (the closest profile to the turnout side of the flume). (ft)

$\overline{D}_{T1}$ $\frac{1}{2}(D_{u_{T1}} + D_{d_{T1}})$ = The average depth of scour along T_1 (ft)

An effort was made to find a relationship between the depth of scour as determined from the analysis of bed profiles and the flow parameters in the flume and the turnout. By applying correlation techniques to the data at hand, this relationship was obtained. The equation so obtained is presented in Chapter V.

Chapter IV

EXPERIMENTAL EQUIPMENT AND PROCEDURE

This study was conducted in a 102-foot by 8-foot by 3.3-foot recirculating concrete flume. The main components of the experimental setup consisted of; flume, turnout, measuring devices, sediment samplers, and sonic depth sounder. Each one of these components are discussed and schematic diagrams are presented in the following. cation in the pages that follow.

Flume

In this recirculating flume of length = 102 feet, width = 8 feet, and depth = 3.3 feet, water was put into circulation by an 18-inch diameter and 50 hp centrifugal pump (see Fig. 4-1). This pump located at the upstream end of the flume was provided with 16-inch butterfly valve and had a pumping capacity of 16 cubic foot per second. It received water through a 16-inch by 16-inch return tunnel constructed at the bottom of the flume. The pump discharged this water back at the upstream end of the flume through a T-shaped diffuser. A wave suppressor was provided after the diffuser for reducing disturbance in the flume. For the completion of circulation cycle, water made its way back to the return pipe through a tail box. This 16-inch long, 62-inch deep, and 8-inch wide addition to the flume, received water from the flume through a series of wooden baffles.

The width of flume as constructed was 8 feet. But due to incapabilities of some components of the setup to provide adequate flow conditions, the width was reduced to 5 feet by building a wooden partition along the full length of the flume.

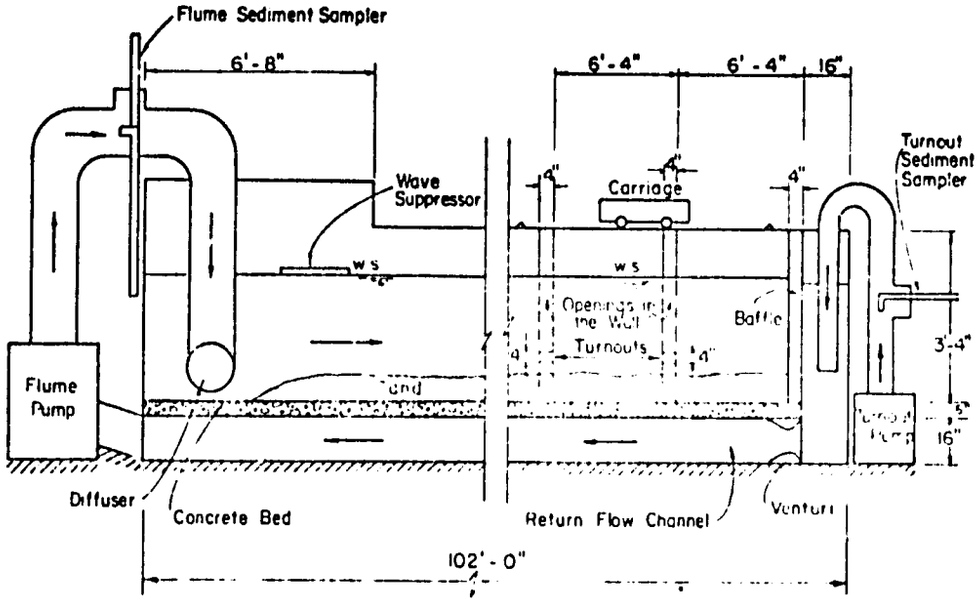


Figure 4-1. Schematic diagram of the flume (after Rakha).

Turnout

The flume structure had two locations for turnouts, one 6½ feet from the tail box and the other one 12.83 feet from the tail box. In this study only the turnout located at 12.83 feet upstream from the tail box was used. This turnout had a 4½-inch by 4½-inch bell-mouth shaped entrance and was connected to a flexible hose through a plexiglass packing plate. Water diverted at the turnout made its way through the flexible hose to the second pump (see Fig. 4-2). This 5-inch and 15 hp centrifugal pump which was provided with a gated valve, had a pumping capacity of 3 cfs. It pumped the water it received from the turnout through an elbow pipe back to the tail box. The end of the elbow pipe in the tail box was extended below the surface of water to prevent air intrusion into the recirculating system.

Measuring Devices

Discharge in the flume was measured with a venturi-meter which was constructed at the downstream end of the return tunnel open to the tail box. The venturi-meter was calibrated with a Cipolletti weir. Provision for temporary installment of such measuring devices was made at the original construction of the flume.

Water surface slope was measured with two static head tubes connected to the manometer board situated at the downstream end of the flume. Both of these static head tubes were placed upstream from the turnout and they were 48.83 feet apart. Similarly, differential head measurements were made to determine discharge through the turnout.

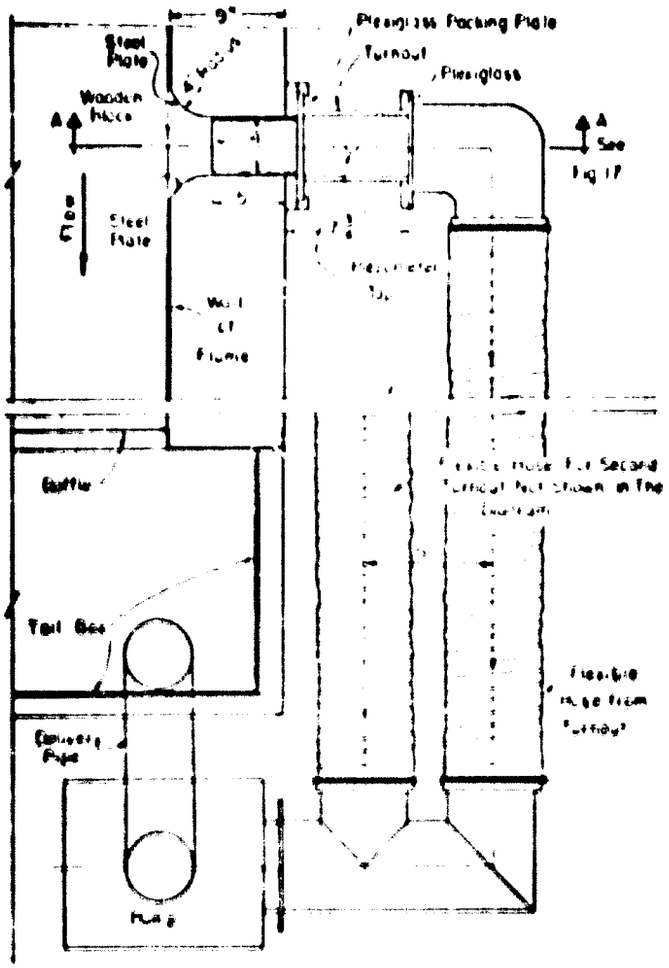


Figure 4-2. General layout of turnouts (after Kalha).

Sediment Samplers

Sediment samples were taken both from the flume and from the turnout. The sampler for the flume (see Fig. 4-3) was fixed in the return pipe at the upstream end of the flume, that for the turnout (see Fig. 4-4) was fixed in the return pipe from the turnout to the flume located at the downstream end of the flume. In both cases, the samples were taken in 3 locations, one at the center of the pipe and the other two each a quarter away out from both sides of the center line. Sampling time for the turnout was 9 minutes--that is, 3 minutes at each location--while that for the flume was a total of 6 minutes. The sampling time was determined from the discharge capacity of the samplers. In each case, the water-sediment mixture was passed through a 200 mesh sieve and the volume of the sediment caught in the sieve was measured in a graduate cylinder. There was very little fine material that passed #200 seive and it was neglected in this study.

Sonic Depth Sounder

Bed profiles of the flume were observed with a sonic depth sounder over a distance of 10 feet, that is, 5½ feet upstream and 4½ feet downstream from the turnout. The output from the sonic depth sounder was obtained on a strip chart recorder and consisted of a continuous reproduction of the sand-bed profile. The device responded to waves reflected from the sand-bed, heavy sediment concentration in the body of water, and the exposed concrete bed. Its response to the latter two consisted of a series of spikes which in the case of exposed concrete bed went beyond the limits of calibration. Most of the bed profiles obtained were free of spikes. The spikes usually occurred at profiles taken near the turnout.

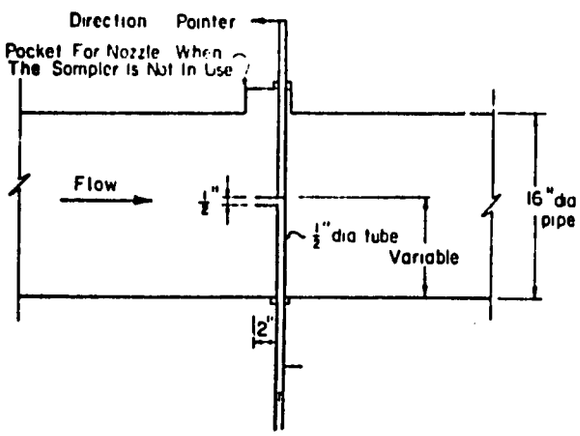


Figure 4-3. Sediment sampler in the delivery pipe of flume pump (after Rakha).

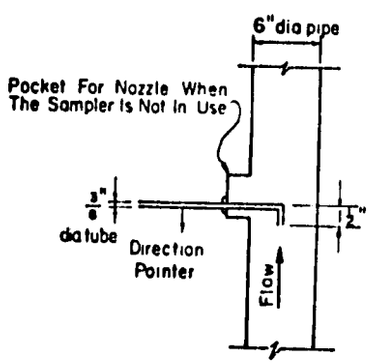


Figure 4-4. Sediment sampler in the delivery pipe of turnout pump (after Rakha).

The sonic depth sounder was calibrated for an average depth of flow in the flume. The calibration was checked whenever the bed profiles were to be observed. Brief instructions for the operation and maintenance of this model 1024 Sonic Depth Sounder are included in the Appendix. More detailed information is contained in the Manual of Automation Instruments, Incorporated, Boulder, Colorado.

Data Taking Procedure

Through a number of special runs made, it was found that it takes a maximum of 20 hours for steady state to be reached for any changes of flow conditions in the flume. The maximum amount of time required for equilibrium to be achieved for any changes in the discharge through the turnout was found to be about 4 hours. The amount of time actually given for any changes in flow conditions, both in the flume and the turnout, was in all cases more than what was considered to be the maximum requirements. Whenever conditions for equilibrium flow both in the flume and the turnout were satisfied, the following steps were made for each run in an orderly way.

1. All the tubes coming to the manometer board were flushed with clean water to make sure that the flow of water through them was not hampered by trapped air or sand.
2. Both sediment sampler tubes were flushed back to make sure there was free flow of the water sediment mixture through them.
3. Static elevation gages used for slope measurement were checked for alignment.

4. Manometer board was observed for:
   a. Venturi-meter reading for flume discharge
   b. Reading on static elevation gages
   c. Piezometer reading for the turnout discharge
5. Water temperature was recorded.
6. Sediment samples were collected both at turnout and flume.
7. Bed profiles were observed over a distance of 10 feet, that is, 5½ feet upstream from the turnout and 4½ feet downstream from the turnout. Plots of bed profiles were taken at 3, 6, 9, 12, 15, 18, 21, 24, 36, and 48 inches from the turnout side of the flume respectively.
8. Depth of flow over the concrete bed was measured at four points over the width of the flume 2 feet upstream from the center line of the turnout.
9. Necessary changes were made in the flow conditions to make the setup ready for the next experiment.
10. V. A. tube analysis of the samples was made.

The following quantities were derived from the data obtained in steps 1 to 10.

1. Discharges in the flume and the turnout were read from the calibration curves.
2. Water slope was computed.
3. Bed profiles were analyzed for the following quantities:
   a. Depth of sand
   b. Height and length of sand bed forms
   c. Scour pit geometry

4. Sediment concentration by weight was computed.

5. Values for D_{50} and σ for the bed material load in the flume and in the turnout.

An effort was made to study the effect of each variable seperately on the variation of sediment concentration through the turnout. For example, at any particular depth of flow and discharge in the flume, a series of discharges through the turnout were passed with the assurance that the depth of flow and discharge in the flume remained unchanged for that whole series.

Any variation in the depth of flow and discharge in the flume would have introduced an additional variable beside the variation of discharge through the turnout which would have added to the complexity of the already complex problem. Variation in the elevation of turnout which also could enter as a second variable was not a problem. It was well fixed in its place. The variables which needed constant attention were the depth of flow in the flume and discharge in the flume. These two variables are so related that changes in one bring changes in the other.

Probable Sources of Error in Data

The data obtained for this study might have been affected by many factors. Only those factors which attracted attention during the course of this study will be discussed.

1. Difficulties involved in maintaining constant depth of flow in the flume required for each series of runs. This difficulty was mainly due to the changes in pressure of the cooling and lubricating water supply which after passing through the pump was making its way to the flume. Since there was no sump in the recirculating flume,

therefore, the lubricating water was constantly adding to the depth of flow in the flume. Efforts were made to adjust the lubricating water supply such that it will make up only for the losses due to leakage and evaporation but an exact balance between the two was not always achieved. The error due to this factor was measurable but not significant.

2. The wooden partition built in the flume to reduce width from 8 feet to 5 feet was not a stable structure. It assumed different positions under different flow conditions. In other words, it seldom remained vertical as it should have. There was also a continuous flow of sand through the partition to the 3-foot section. Several attempts were made to stabilize the structure, the situation was improved but the problem was not completely solved. The error due to this will not be considered very significant because that section of the flume where the measurements were made remained fairly stable during the entire study.

3. Sediment concentration in the turnout was significantly affected by turbulence in the flume and bed form movement. Both of these factors, based on visual observation were found to take place irregularly in time and space. Their effect on the variation of sediment concentration through the turnout was observed to be very significant. The duration of 9 minutes sediment sampling in the return pipes was adequate to average out high frequency sediment concentration fluctuations. This duration was, however, not enough for the extremely low frequency fluctuations associated with the movement of the bed form passing the turnout.

Chapter V

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

As indicated previously, data at two different elevations of the turnout were obtained and variation of the amount and size distribution of bed material withdrawal through the turnout was studied. For each location of the turnout, the depth of flow and discharge in the flume were varied up to the limits of the flume dimensions. Depth of flow in the flume was varied from 0.89 feet to 1.89 feet. The range of variation for the discharge per unit width of the flume was from 1.04 cfs to 2.44 cfs.

For each depth and discharge in the flume, a series of discharges were passed through the turnout. The discharge in the turnout was varied from minimum to maximum in several steps. The number of steps in each series was determined by the flow conditions in the flume. For higher depth of flow and lower velocity in the flume, there were less chances of air entrainment at the turnout. In such cases the discharge through the turnout was varied from its minimum value of 0.23 cfs to a maximum of 1.70 cfs in four or five steps. Because of air entrainment, it was not possible to obtain a representative sample at higher discharges through the turnout for lower depth of flow and higher velocity in the flume.

Depth of flow and discharge in the flume and turnout elevation and discharge through the turnout, are unfortunately not the only variables affecting variation of sediment withdrawal through the turnout. Another most important variable is the sediment concentration in the flume which in turn is affected by the slope of channel, bed material size, particle

size distribution, bed roughness, bed form movement, scour formation, size of scour pit, etc.

In this study which is based on 126 laboratory tests (data for the tests are included in the Appendix), attention was focused on the variation of sediment withdrawal through the turnout with respect to the following changes:

1. Effect of flume and turnout characteristics.
2. Bed form movement in the flume.

Analysis of Flume and Turnout Data

The data collected under various flow conditions in the flume and the turnout was analyzed extensively. Almost all possible combinations of the parameters in the phenomena were studied. Efforts were made to find a relationship between sediment concentration through the turnout and the other related parameters. Various plots of the data were made. None of those plots showed an obvious relation between the variables. One example of these attempts is shown in Fig. 5-1. In this figure, the ratio of sediment concentration through the turnout over the sediment concentration in the flume is plotted against the ratio of discharge through the turnout over the discharge in the flume with the ratio of the total depth minus the turnout crest elevation from the concrete bed of the flume over the total depth minus the depth of sand as a third variable. The range of variation for the third variable Y_t is from 0.6 to 0.96. This range is divided into nine equal intervals and each interval is indicated by a letter A, B, C, etc.

At the start of this study, it was assumed that the turnout elevation from the bed of the flume and the discharge ratio in the turn-

Range of Y_t	Symbols	Range of Y_t	Symbols
0.0 to 0.6	Q	0.80 to 0.84	F
0.6 to 0.64	A	0.84 to 0.88	G
0.64 to 0.68	B	0.88 to 0.92	H
0.68 to 0.72	C	0.92 to 0.96	P
0.72 to 0.76	D	0.96 to 1.00	R
0.76 to 0.80	E		

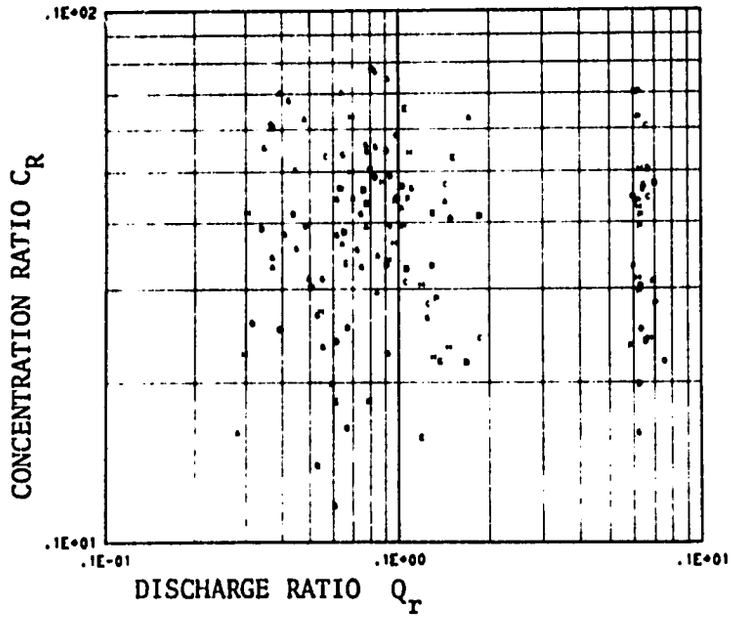


Figure 5-1. Plot of concentration ratio versus discharge ratio with the depth ratio Y_t as a third variable.

out and the flume are important factors for the sediment withdrawal through the turnout.

Due to lack of an obvious relationship between the sediment concentration through the turnout and the other related parameters, it was found necessary to use regression analysis. Even then, the correlation was poor when the parameters were used in their dimensional form. Finally, all the parameters were transformed into dimensionless form and then the correlation techniques were applied.

The statistical analysis of data was done at the Colorado State University Computer Center where the computer program for such analysis is available on permanent file. This program computes a sequence of multiple linear regression equations in a stepwise manner. At each step one variable is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently, it is the variable which has highest partial correlation with the dependent variable partialed on the variables which have already been added, or it is the variable which, if it were added, would have the highest F-value. In addition, variables can be forced into the regression equation. Non-forced variables are automatically removed when their F values become too low.

From the many statistical equations so obtained, the following equation was considered to be the best of what was available.

$$C_t = (0.1336)(C_f)^{0.863}\ (Z)^{2.14}\ (Fn)^{2.0}\ (Re)^{1.0}\ (1/C_*)^{2.44} \qquad (5\text{-}1)$$

in which

C_f = Sediment concentration in the flume

Z = Rouse number

Fn = Froude number

Rn = Reynolds number

C_* = $\frac{V}{u_*}$, in which V = flow velocity in the flume, and

u_* = shear velocity

Equation (5-1) in simplified form is:

$$C_t = (0.1336) \left(\frac{W_{50}}{4.u^*}\right)^{2.14} \left(\frac{V^{0.56}}{\nu g}\right) \left(u_*\right)^{0.3} \qquad (5\text{-}2)$$

in which

W_{50} = fall velocity (average size bed material)

ν = kinematic viscosity of the water

The summary table for the free variables given to the computer and their corresponding regression coefficient R and F (F-Test for Significance of Regression) values taken from the computer output for Eq. (5-1) are the following:

Step number	Variables entered	Control Status	Multiple R	R_{sq}	Increase in R_{sq}	F value to enter
1	C_f	Free	.95986	.92133	.92133	1452.23731
2	Fn	Free	.96176	.92499	.00366	5.99955
3	Rn	Free	.96259	.92658	.00159	2.63433
4	C_*	Free	.96288	.92714	.00056	0.93627
5	Z	Free	.96423	.92974	.00260	4.44293
6	Q_r	Free	.96428	.92983	.00009	0.15559
7	D_r	Free	.96430	.92987	.00003	0.05660

in which

$$Dr = \frac{\text{Turnout elevation - Depth of sand}}{\text{Total depth - Depth of sand}} = \frac{E_t - D_{ms}}{d_t - D_{ms}} \quad \text{and}$$

$$Q_r = \frac{\text{Discharge through the turnout}}{\text{Discharge in the flume}} = \frac{Q_t}{Q_f}$$

The other variables are defined previously.

The coefficient of determination for this equation is 0.93. In other words, this equation explains the total variation of sediment concentration through the turnout within 93 percent of its actual value. From the range of variation of the parameters on the right side of the forementioned equation, it is clear that the variation of sediment concentration through the turnout is basically a function of the sediment concentration in the flume. The sediment concentration through the turnout computed by the equation plotted versus the sediment concentration found in laboratory experiments is shown in Fig. 5-2.

Discussion of Results

One possible explanation for the disappearance of turnout elevation from the bed of the channel and the discharge ratio in the final statistical equation could be that the turnout was not sufficiently raised. The original elevation of the turnout from the bed of the channel was 0.74 feet and it was raised 4 inches in one step during the course of the study.

The plot of bed material distribution throughout the depth of the flow computed by the Einstein Bed Load Function is shown in Fig. 5-3. It is clear from this graph that the variation of bed material concentration at higher elevations from the bed of the channel

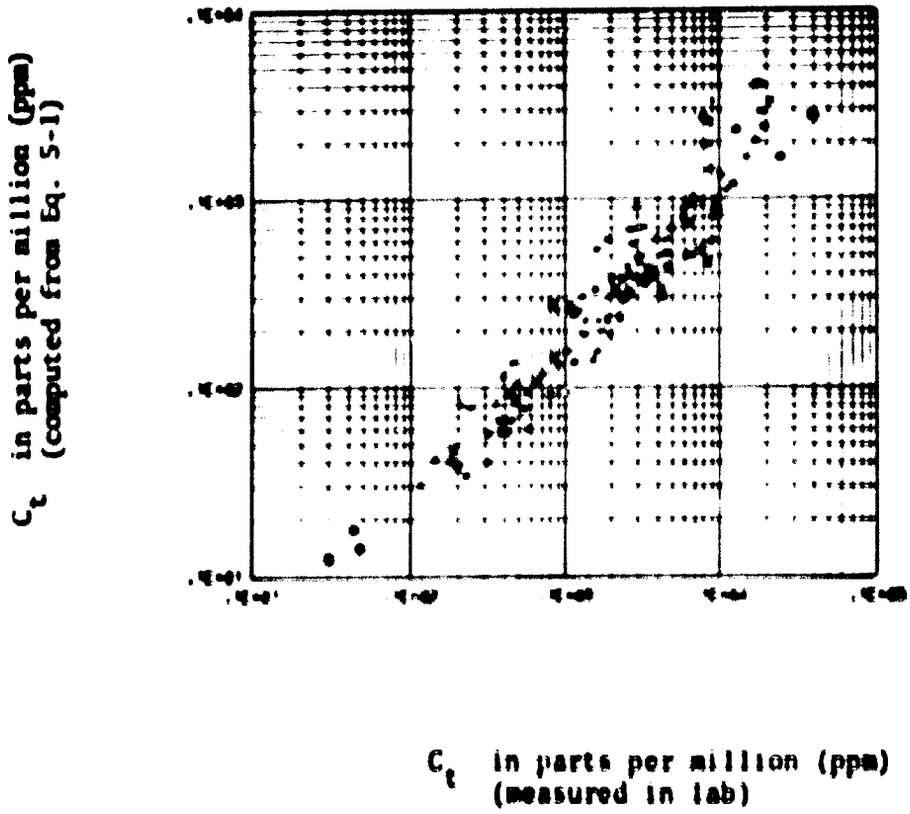


Figure 5-2. Plot of sediment concentration through the turnout (measured versus computed).

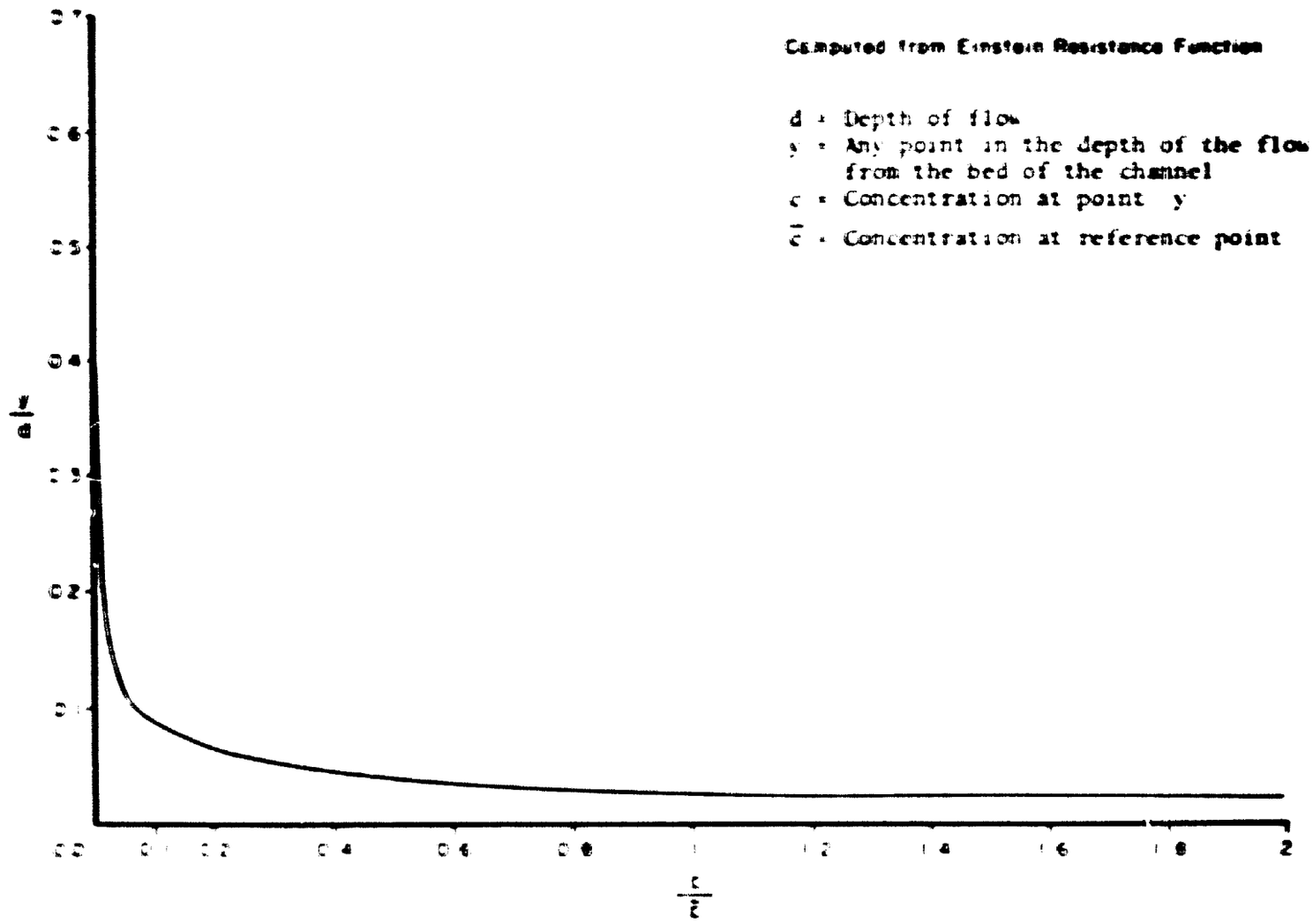


Figure 3-6 Variation of bed material concentration throughout the depth of flow in the laboratory flume used for this study.

is insignificant. Assuming that Fig. 5-3 is applicable, then most of the sediment load in this laboratory flume was transported as bed load.

Effect of Bed Form Movement

Three sets of special runs were made to determine the time variation of sediment concentration through the turnout and its relation to the bed form movement in the flume. In each case, sediment samples were taken both from the flume and the turnout at equal intervals of time and the bed profile was observed at a distance of one foot from the turnout side of the flume. The data for these three sets of special runs is given in a brief form in Table 5-1.

Table 5-1. Summary of the data for the special runs

	set 1	set 2	set 3
Discharge in the flume (cfs)	8.70	10.20	9.50
Discharge in the turnout (cfs)	0.67	0.66	1.15
Total depth (sand + water) (ft)	1.996	1.930	1.926
Water temperature (C^0)	26.5	29.0	28.5
Slope of channel	6.98×10^{-4}	5.24×10^{-4}	5.24×10^{-4}
Total time (hours)	6.0	3.0	2.5
Number of samples	12	10	10
Sediment concentration in the flume (ppm)			
Maximum	17	70	53
Average	15	59	48
Minimum	12	51	44
Sediment concentration in the turnout (ppm)			
Maximum	68	516	225
Average	54	347	174
Minimum	32	190	128

According to these figures, the variation in sediment concentration with time through the turnout has a greater range than the variation of sediment concentration in the flume. Great variation in sediment concentration through the turnout was also visually observed through the transparent section (observation window) of the turnout. The variation of sediment concentration through the turnout was greater whenever there was a collapse of sharp peaks or unstable bed formation in the vicinity of the turnout. This was also visually observed. In fact, the water in the flume was so clear sometimes that one could easily see through it to observe the changes taking place in the bed of the channel.

The longitudinal areas of the sand thickness over distances of one depth of flow, two depths of flow (about 1½ feet and 3 feet), and the entire length of 5½ feet upstream from the center line of the turnout were determined from the analysis of the bed profile which was observed and recorded with each sample at a distance of 1 foot away from the turnout side of the flume (see Fig. 5-4). These areas and the sediment concentration through the turnout are plotted versus time in the order the samples were obtained. The plots for each set as shown in Fig. 5-5a, b, and c indicate that the sand thickness on the bed of the flume is generally small when sediment concentration through the turnout is large, and is large when the sediment concentration through the turnout is small. From the analysis of the special runs plus visual observations, it appears that the sediment concentration through the turnout is significantly affected by the bed movement in the flume.

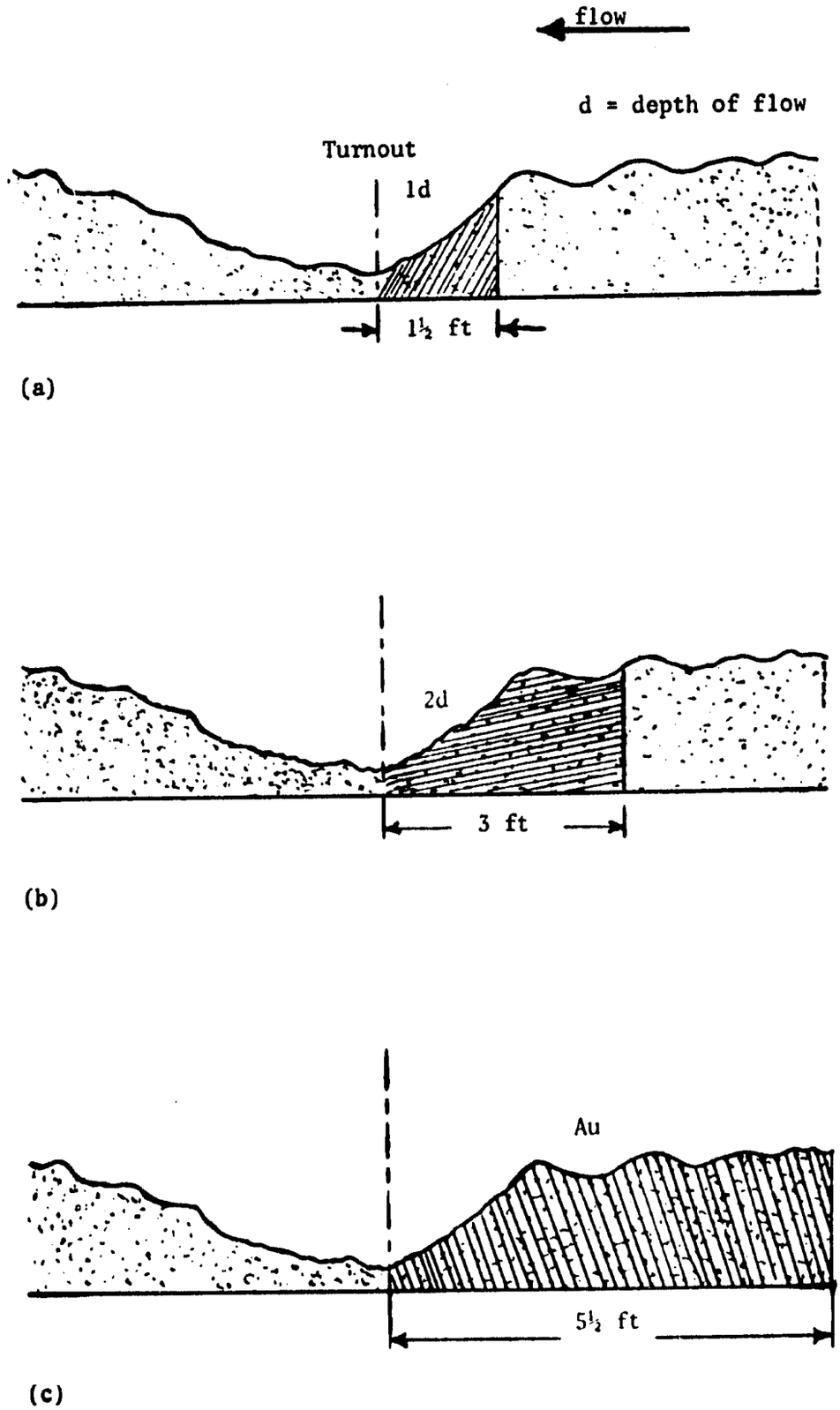


Figure 5-4. Hypothetical sand-bed profiles, indicating the longitudinal areas referred to in the text.

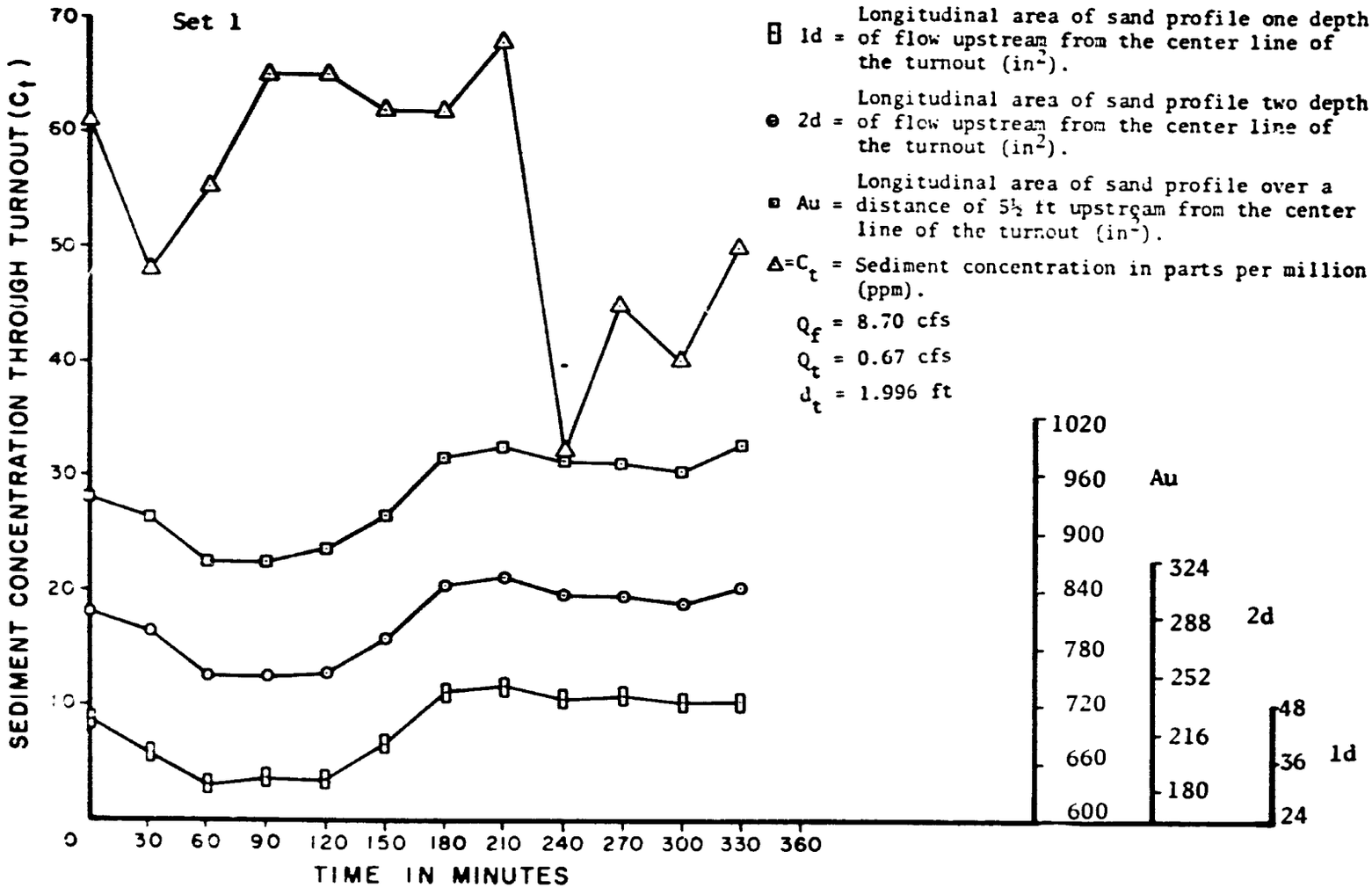


Figure 5-5a. The effect of bed form movement in the flume on the variation of sediment concentration through the turnout.

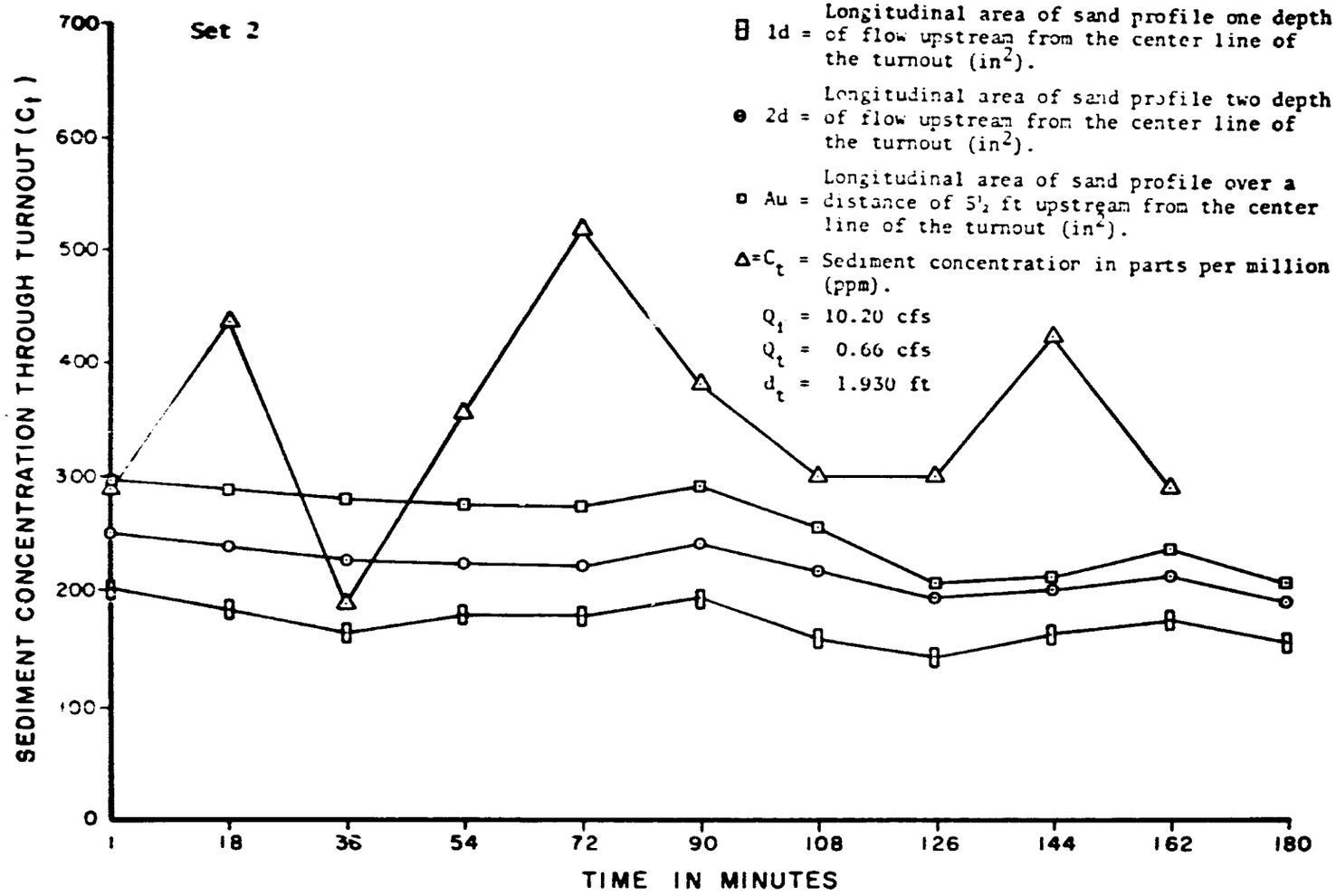


Figure 5-5b. The effect of bed form movement in the flume on the variation of sediment concentration through the turnout. Note: The relative magnitudes of the longitudinal areas are about the same as for Figure 5-5a.

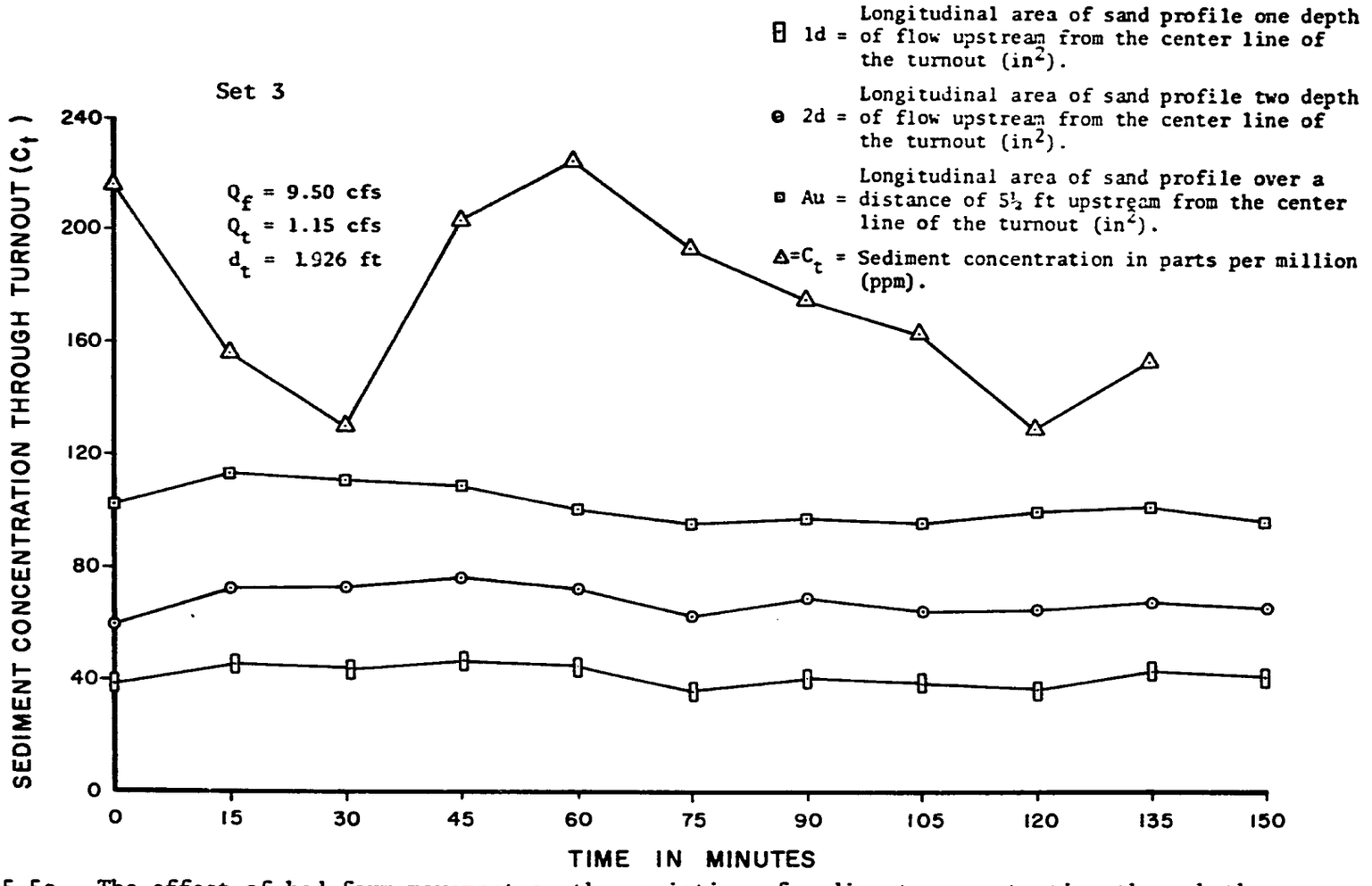


Figure 5-5c. The effect of bed form movement on the variation of sediment concentration through the turnout. Note: The relative magnitude of the longitudinal areas are about the same as for Figure 5-5a.

Scour Pit Formation

The bed profiles taken with each run were analyzed for the size and shape of the scour pit which is usually formed at the vicinity of the turnout. The data so derived indicate that the depth of scour is proportional to the size of the scour. The two plots which show this relationship are shown in Fig. 5-6a and 5-6b. Fig. 5-6a indicates this relation for the data taken at the turnout elevation from the bed of the channel equal to 0.74 feet and Fig. 5-6b shows this relation for that part of the data which were taken at the turnout elevation equal to 1.073 feet above the concrete bed of the flume.

An effort was made to find a relationship for the depth of scour in terms of the other related parameters. By using correlation techniques on the data at hand, the following equation was obtained.

$$D_{rs} = C(Q_r)^{1.34}(V_r)^{-0.9}(1/C_r)^{0.06}(C_t)^{0.03} \qquad (5\text{-}3)$$

in which

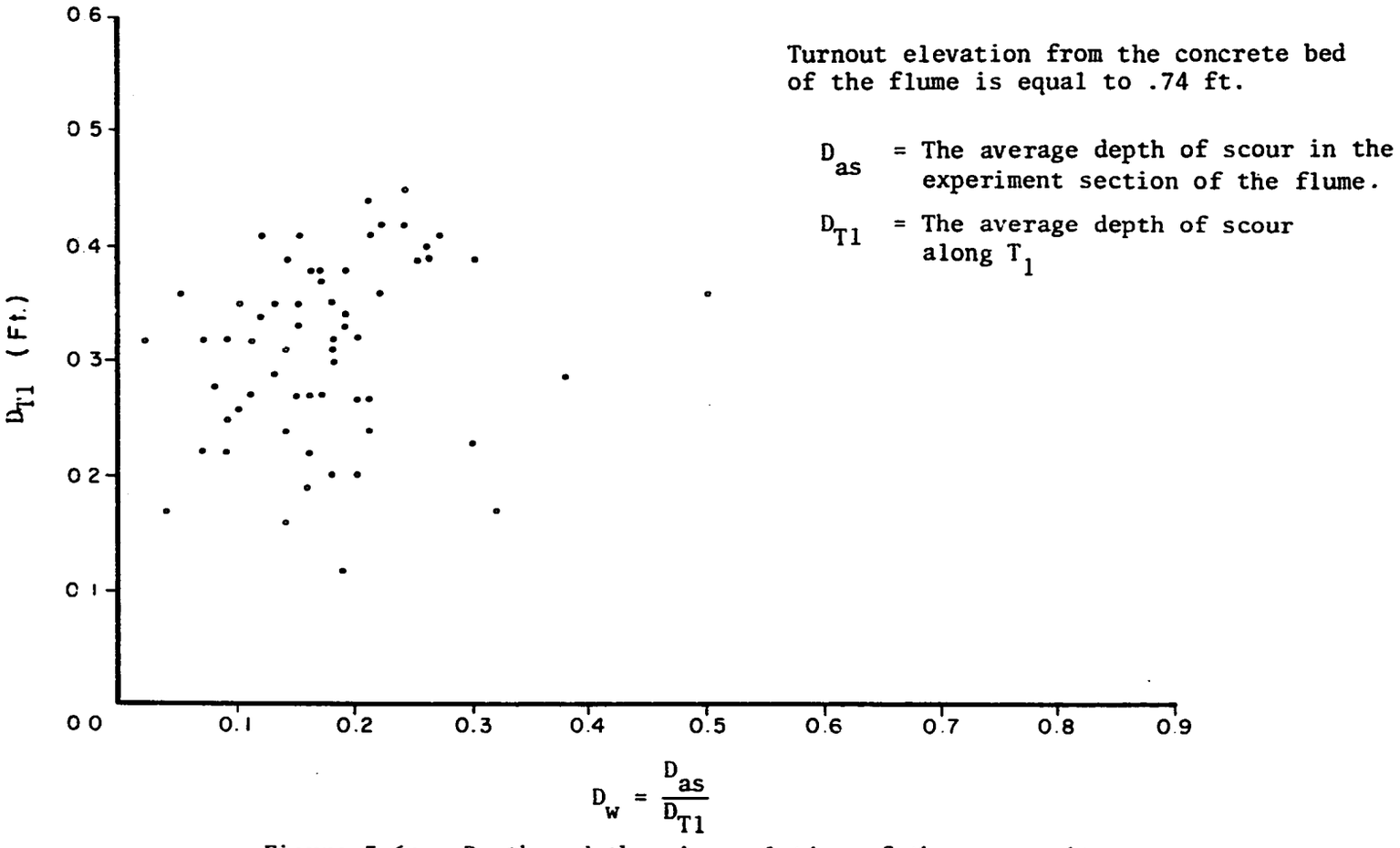
$D_{rs} = \dfrac{\overline{D}_{T_1}}{d_f}$, $\overline{D}_{T_1}$, and d_f are previously defined

C = a constant

$$Q_r = \frac{\text{Discharge in the turnout}}{\text{Discharge in the flume}} = \frac{Q_t}{Q_f}$$

$$V_r = \frac{\text{Velocity in the turnout}}{\text{Velocity in the flume}} = \frac{V_t}{V_f}$$

$$C_r = \frac{\text{Sediment concentration through the turnout}}{\text{Sediment concentration in the flume}} = \frac{C_t}{C_f}$$



Turnout elevation from the concrete bed of the flume is equal to .74 ft.

D_{as} = The average depth of scour in the experiment section of the flume.

D_{T1} = The average depth of scour along T_1

Figure 5-6a. Depth and the size relation of the scour-pit.

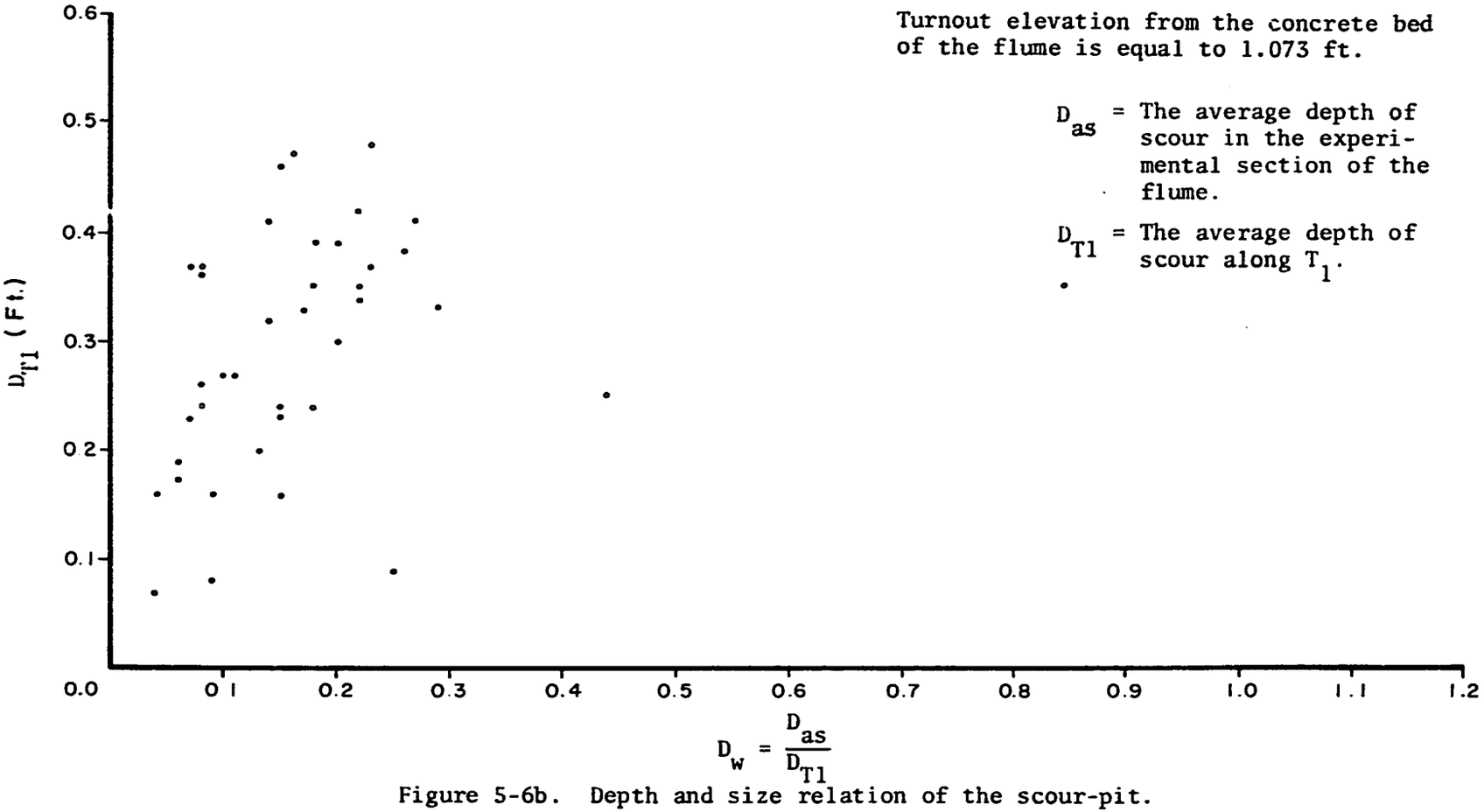


Figure 5-6b. Depth and size relation of the scour-pit.

The coefficient of determination for this equation is 0.41. In other words, this equation explains the total variation of scour within 41 percent of its actual value. According to this equation, the depth of scour is mainly a function of the discharge ratio Q_r .

From Model to Prototype

The variation of bed material concentration throughout the depth of flow in the flume and an assumed irrigation canal was computed by the Einstein Bedload Function. The following values were used in the computation:

		Canal	Flume
Average depth of flow	=	9 ft	1.5 ft
Average bed material size (D_{50})	=	0.25 mm	0.19 mm
" " " " "	=	0.35 mm	
" " " " "	=	0.45 mm	
" " " " "	=	0.55 mm	
Grain size distribution (σ)	=	1.30	1.30
Froude number	=	0.30	0.30

The results of this computation are plotted and shown in Figures 5-7a, 7b, 7c, and 7d. For reason of comparison, in each case the distribution of bed material concentration in the flume is plotted on the same graph with the concentration of the different bed material sizes used in the canal. The plots indicate that the variation of bed material concentration in the flume is almost the same as the variation in the canal with the average bed material size equal to 0.35 mm. This means that

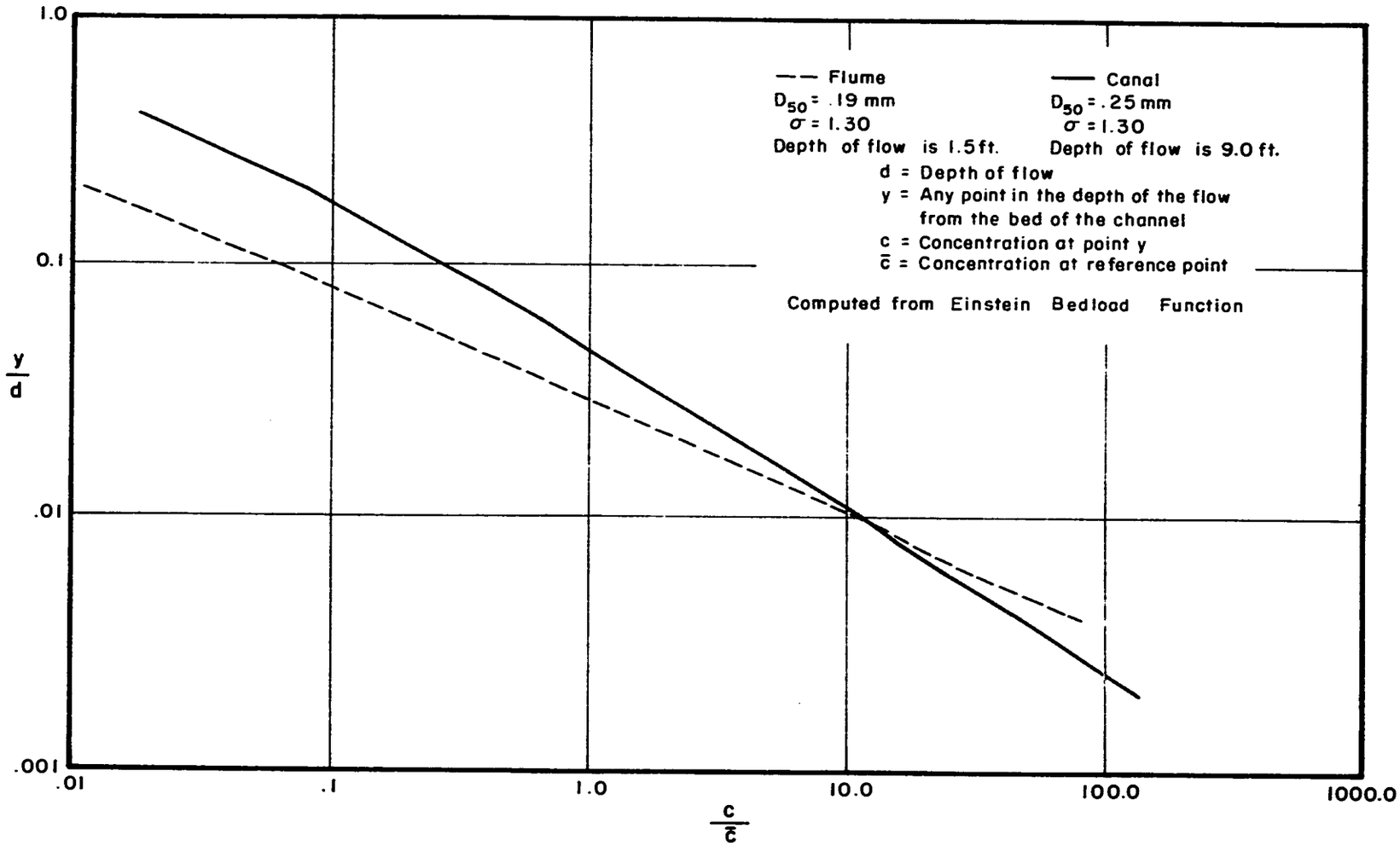


Figure 5-7a. Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.25 mm).

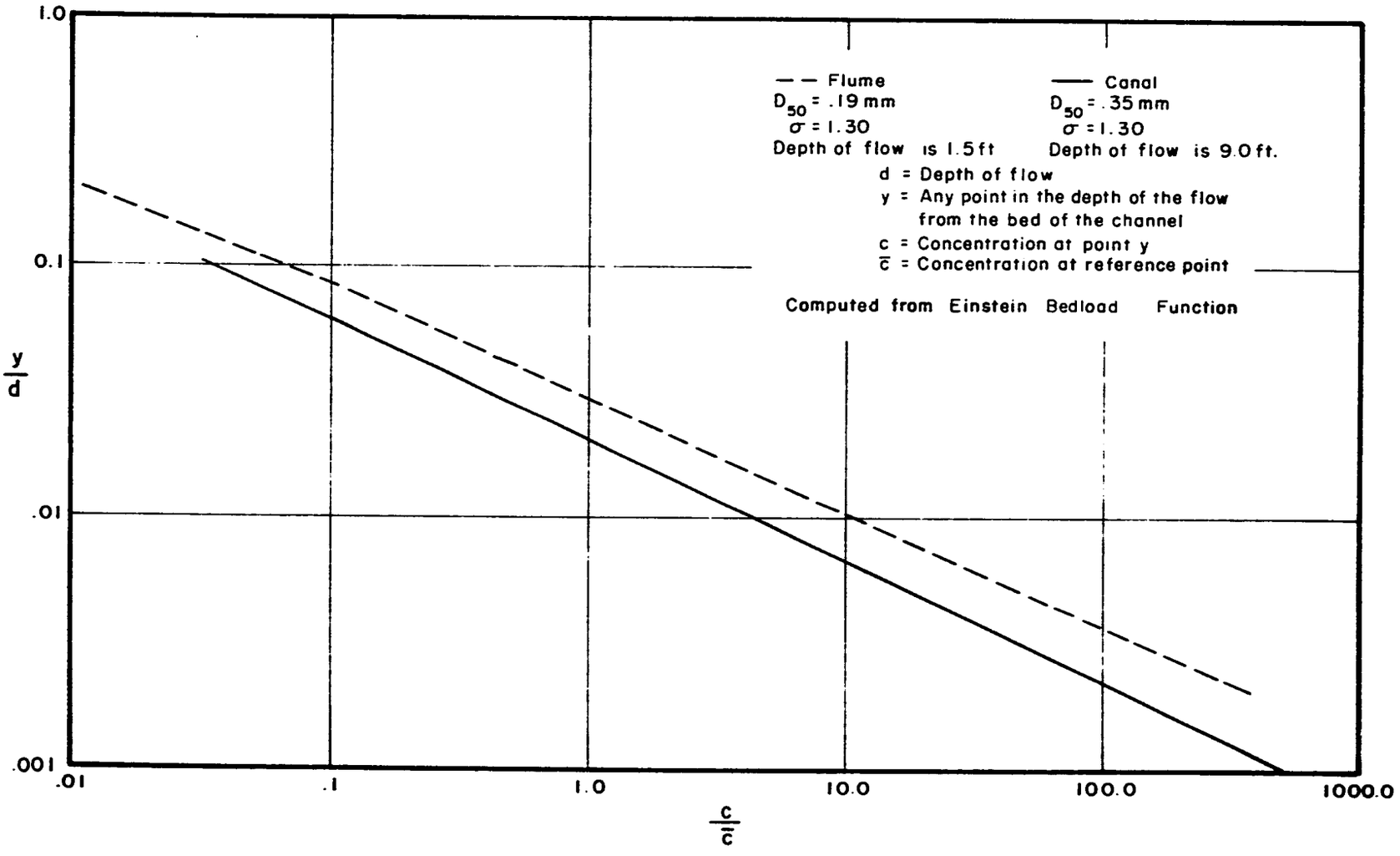


Figure 5-7b. Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.35 mm).

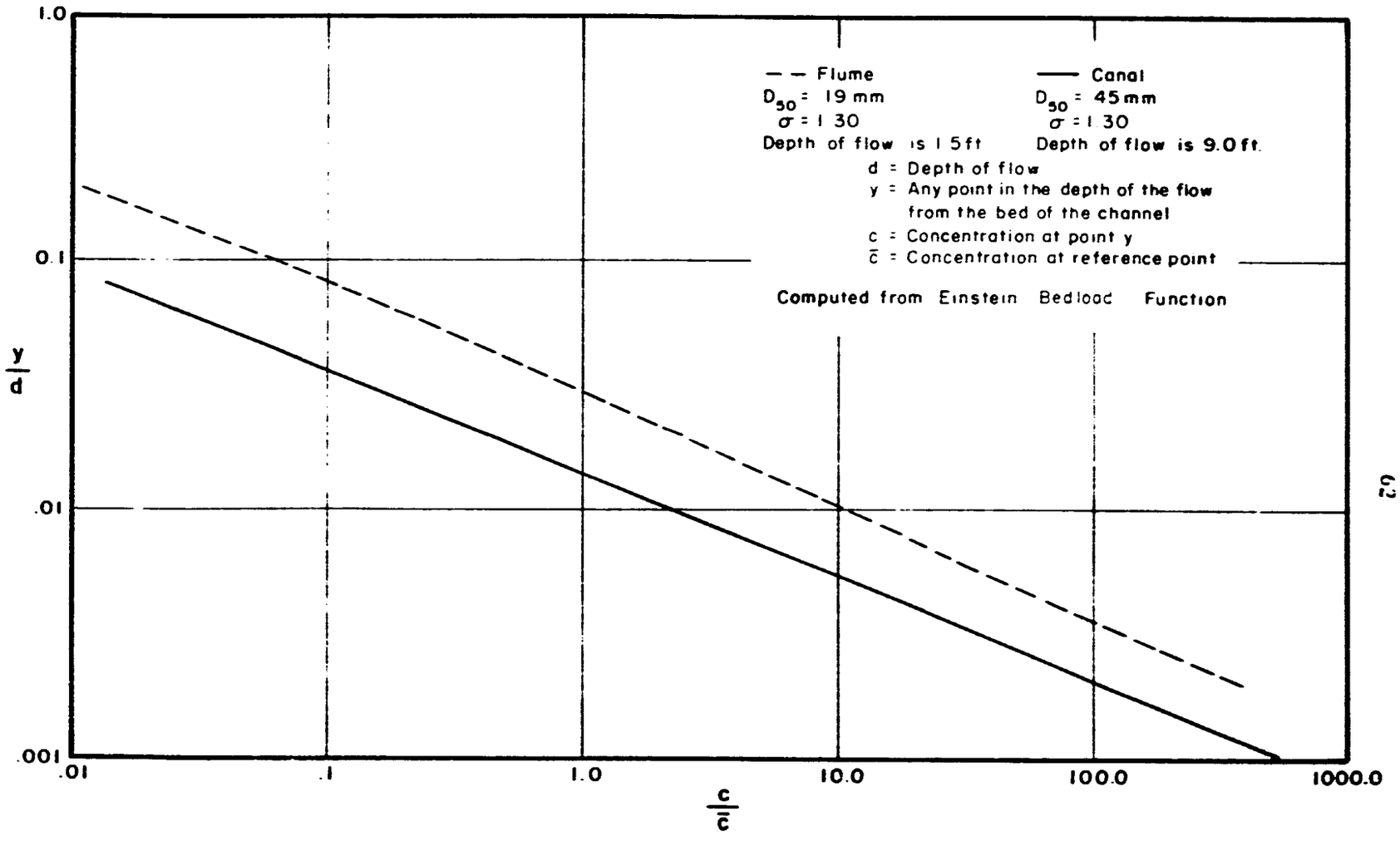


Figure 5-7c. Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.45 mm).

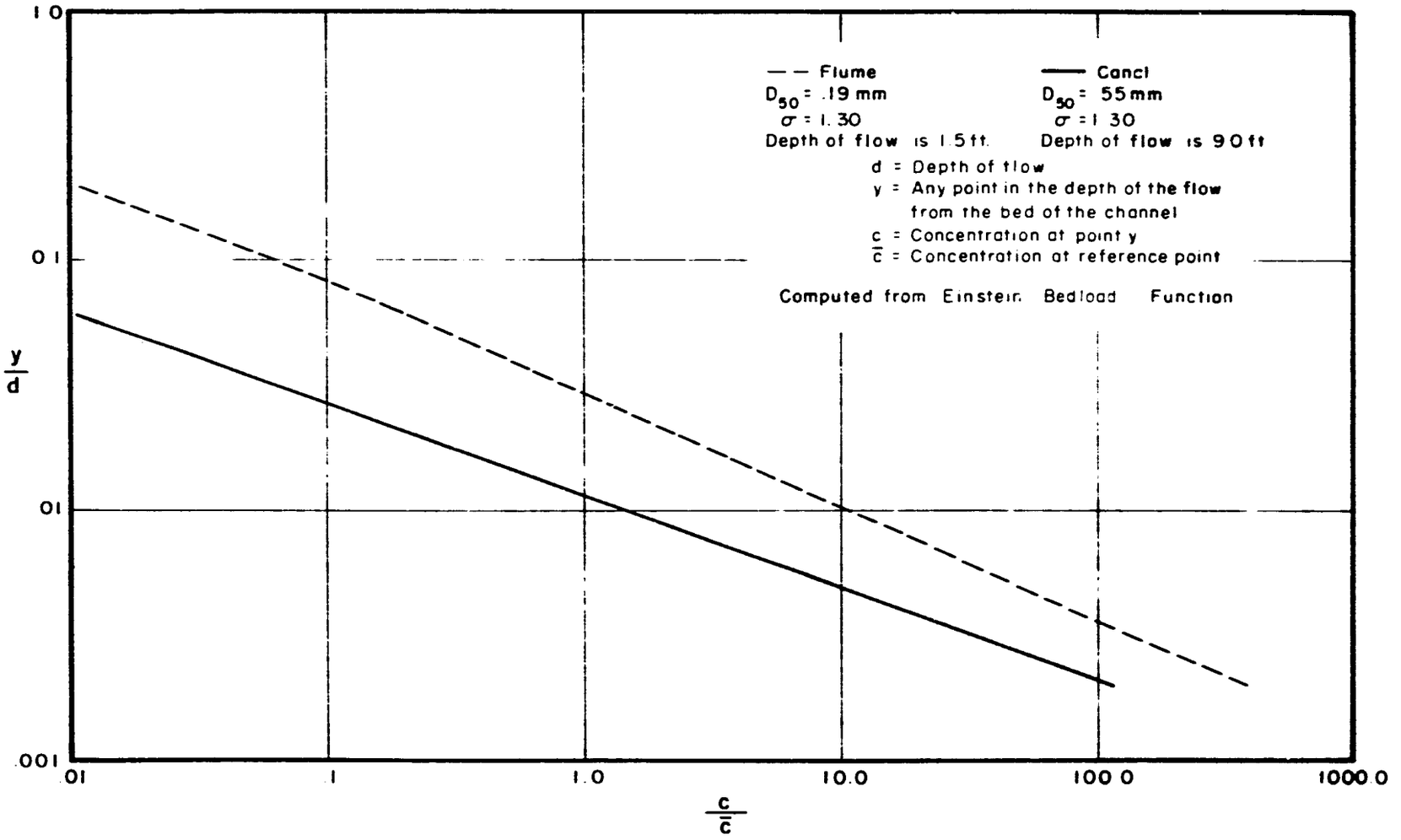


Figure 5-7d. Variation of bed material concentration throughout the depth of flow in the flume and a 9-foot deep irrigation canal (D_{50} = 0.55 mm).

if the results are to be applied to a 9-foot deep canal, then the model prototype extrapolation will be valid if average bed material size in the canal is 0.355 mm. The choice of using a 9-foot deep canal with the given flow conditions in this computation was purely arbitrary and it was not the goal of this research to study any specific problem. The plots further indicate that most of the sediment load in the flume is transported at elevations less than 10 percent of the depth ratio. In other words, the variation of sediment concentration at elevations higher than 10 percent of the depth ratio from the bed of the channel is not significant.

Chapter VI

SUMMARY AND CONCLUSIONS

The phenomena of bed material withdrawal at farm turnouts was studied in a sand bed laboratory flume. The average size of the sand used as bed material was 0.19 mm , and the grain size distribution was 1.30. It was the purpose of this study to determine the effect of depth of flow in the flume, discharge in the flume, turnout elevation, and the discharge through the turnout on the variation of sediment concentration through the turnout. The ranges of variation for these variables were:

Depth of flow in the flume, d_f from 0.89 feet to 1.89 feet.

Discharge in the flume, Q_f from 5.2 cfs to 12.2cfs.

Turnout elevation d_c from .74 feet to 1.073 feet.

Discharge through the turnout Q_t from .23 cfs to 1.70 cfs.

The results of the analyses are as follows:

1. The four inches increase in turnout elevation from its original elevation of 0.74 from the concrete bed of the flume did not prove to have considerable effect on the amount of sediment withdrawal through the turnout. The reason for this is that most of the sediment load was transported as bed load and the variation in sediment concentration at higher elevation from the bed of the channel was insignificant.
2. Sediment concentration through the turnout was found to be mostly affected by the concentration in the flume as shown by the statistical equation (Eqs. 5-1, 5-2).

3. The bed form movement in the flume has a significant effect on the variation of sediment withdrawal through the turnout. A collapse of sharp peaks or unstable bed formation as bed form moves by the turnout increases sediment discharge through the turnout tremendously. The support for this statement is based on visual observation and the results of three sets of special runs presented in Chapter V.
4. The scour pit remains geometrically similar under different conditions of flow in the flume and the turnout. The average depth of scour was found to be predominantly a function of the discharge ratio and velocity ratio of the flow in the turnout and flume respectively.

Chapter VII

RECOMMENDATIONS FOR FUTURE STUDY ON THIS SUBJECT

The following suggestions may increase the amount and range of design information for a better understanding of the sediment withdrawal phenomena at the farm turnout.

1. The phenomena should be studied at a greater range of turnout elevation from the bed of the channel.
2. Having two turnouts of different sizes located at a reasonable distance from each other along the length of the flume will provide a better basis for the study of this problem.
3. Having transparent sections both in the flume and the turnout would help to understand the changes that take place in the bed of the channel and the variation of co centration both in the flume and the turnout.
4. It will be better to study the problem with at least two different sizes of bed materials.
5. The time for taking the sediment samples from the turnout and the flume should be more than what was used in this study. If possible both samples should be taken at the same time.
6. It will be a worth while effort to investigate the similarity and scaling criteria for suspended load in sediment laden flows.

REFERENCES

REFERENCES

Alam, Abu M. Z. and Kennedy, John F., "Friction Factors for Flow in Sand Bed Channels," Journal of Hydraulic Division, ASCE, Vol. 95 pp. 1973-1933. November 1969.

Albertson, Maurice L., Barton, J. R., and Simons, D. B., "Fluid Mechanics for Engineering," pp. 487-512. January 1963.

Applied Sedimentation, Edited by Parker D. Trask. John Wiley & Sons, Inc. 1950.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Transport Mechanics: Erosion of Sediment," Progress Report, Journal of Hydraulic Division, ASCE, Vol. 88, pp. 109-129. July 1962.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Transport Mechanics: Suspension of Sediment," Journal of Hydraulic Division, ASCE, Vol. 89, pp. 45-77, September 1963.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Transport Mechanics: Initiation of Motion," Journal of Hydraulic Division, ASCE, Vol. 92, pp. 291-315. March 1966.

ASCE Task Committee on Preparation of Sedimentation by Task Force on Bed Forms in Alluvial Channels, "Nomenclature for Bed Forms in Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 92, pp. 51-64. May 1966.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Economic Aspect of Sedimentation," Journal of Hydraulic Division, ASCE, Vol. 95, pp. 191-209. January 1969.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Control Methods: Introduction and Watershed Area," Journal of Hydraulic Division, ASCE, Vol. 95, pp. 649-677. March, 1969.

ASCE Task Committee on Preparation of Sedimentation Manual, "Sediment Measurement Techniques: F. Laboratory Procedure," Journal of Hydraulic Division, ASCE, Vol. 95, pp. 1477-1543. September 1969.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Sources and Sediment Yields," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 1283-1331. June 1970.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Fundamentals of Sediment Transportation," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 1979-2022. December 1971.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Transportation Mechanics: F. Hydraulic Relations for Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 101-143. January 1971.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Transportation Mechanics: Sediment Discharge Formulas," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 523-567. April 1971.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Control Methods: B. Stream Channels," Journal of Hydraulic Division, ASCE, Vol. 98, pp. 1295-1326. July 1972.

ASCE Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation, "Sediment Control Methods: C. Control of Sediment in Canals," Journal of Hydraulic Division, ASCE, Vol. 98, pp. 1647-1691. September 1972.

Bishop, Avery A., Simons, Daryl B. and Richardson, Everett V., "Total Bed Material Transport," Journal of Hydraulic Division, ASCE, Vol. 91, pp. 175-193. March 1965.

Blench, Thomas, "Coordination in Mobile Bed Hydraulics," Journal of Hydraulic Division, ASCE, Vol. 95, pp. 1871-1899. November 1969.

Blench, Thomas, "Mobile-Bed Fluviology," University of Alberta Press, Edmonton, Alberta, Canada. 1969.

Carstens, Marion R. and Altinbilek, Hilmi D., "Bed Material Transport and Bed Forms," ASCE, Vol. 98, pp. 787-804. May 1972.

Chang, F. M., "Ripple Concentrations and Friction Factors," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 417-431. February 1970.

Chang, F. M. and Richards, Dennis L., "Deposition of Sediment in Transient Flow," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 837-349. June 1971.

Chin, Chao-Lin and McSparran, John E., "Effect of Secondary Flow on Sediment Transport," Journal of Hydraulic Division, ASCE, Vol. 92, pp. 57-71. September 1966.

Einstein, H. A., "Needs of Sedimentation," Journal of Hydraulic Division, ASCE, Vol. 87, pp. 1-7. March 1961.

Einstein, H. A. and Abdul-Aal Farouk, "Einstein Bed-Load Function at High Sediment Rate," ASCE, Vol. 98, pp. 137-152. January 1972.

Einstein, Hans Albert, "The Bed-Load Function for Sediment Transportation in Open Channel Flows," Technical Bulletin No. 1026, USDA, Soil Conservation Service, Washington, D.C. September 1950.

Engineering Hydraulics, Edited by Hunter Rouse, John Wiley & Sons, Inc. New York, New York. London. pp. 6-15; 774-786. 1950.

Garde, R. J. Subramanya, K., and Nambudripad, K. D., "Study of Scour Around Spur-Dikes," Journal of Hydraulic Division, ASCE, Vol. 87, pp. 23-39. November 1961.

Garde, R. J. and K. G. Ranga Raju, "Resistance Relationships for Alluvial Channel Flow," Journal of Hydraulic Division, ASCE, Vol. 92, pp. 77-100. July 1966.

Graf, Walter H., "Hydraulics of Sediment Transport," McGraw-Hill Book Company, 1971. pp. 27-70; 238-241.

Gary, Satya P., Agrawal, A. K. and Prem Raj Singh, "Bed Load Transportation in Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 653-665. May 1971.

Grass, Anthony, J., "Initial Instability of Fine Bed Sand," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 619-633. March 1970.

Grigg, Neil S., "Motion of Single Particles in Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 2501-2519. December 1970.

Grill, Mohammad Adram, "Rationalization of Lacey's Regime Flow Equation," Journal of Hydraulic Division, ASCE, Vol. 94, pp. 983-997. July 1968.

Grill, Mahammad Akram, "Height of Sand Dunes in Open Channel Flows," Journal of Hydraulic Division, ASCE, Vol. 98, pp. 2067-2074. December 1971.

Guy, Harold P., Ratbun, Ronald E., and Richardson, E. V., "Recirculation and Sand-Feed Type Flume Experiments," Journal of Hydraulic Division, ASCE, Vol. 93, pp. 97-115. September 1967.

Henderson, F. M., "Open Flow Channel," The Macmillan Company, New York, 1966.

Hydraulics and Fluid Mechanics, Edited by Richard Silvester, The Macmillan Company, New York. 1964.

Jobson, Harvey E. and Sayre, William W., "Predicting Concentration Profiles in Open Channels," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 1973-1997. October 1970.

Kivi, A. J. Raud, "Loose Boundary Hydraulics," Pergamon Press. 1967.

Leliavsky, Serge, "Irrigation and Hydraulic Design," Chapman and Hall, Ltd., 37 Essex Street, W.C., London. 1955.

Leopold, L. B., Wolman, M. G. and Miller, J. P., "Fluvial Processes in Geomorphology." W. H. Freeman and Company, 1964.

Lovera, Federico and Kennedy, John F., "Friction-Factors for Flat Bed Flows in Sand Channels," Journal of Hydraulic Division, ASCE, Vol. 95, pp. 1227-1235. July 1969.

Mahmood, Khalid, "Sediment Equilibrium Considerations in the Design of Irrigation Canal Networks." Proceedings International Symposium on River Mechanics," IAHR, Bangkok, 1973.

Mahmood, Khalid, "Flow in Sand-bed Channels," Ph. D. Dissertation, Colorado State University, 1971.

Mao, Shien Wen and Rice, Leonard, "Sediment Transport Capability in Erodible Channels," Journal of Hydraulic Division, ASCE, Vol. 89, pp. 69-97. July 1963.

Mathematical Methods for Digital Computers, Part V, (17), Edited by A. Ralston and H. S. Wilf, Wiley, 1960.

Mogridge, Geoffrey R., "Testing Sediment Movement Due to Wave Action," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 1587-1604. July 1970.

Nordin, Carl F. Jr., "Study of Channel Erosion and Sediment Transport," Journal of Hydraulic Division, ASCE, Vol. 90, pp. 173-193. July 1964.

Rakha, Allah, "Sediment Conduction of Turnouts," M.S. Thesis. Colorado State University. December 1971.

Raudkivi, A. J., "Analysis of Resistance in Fluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 93, pp. 73-85. September 1967.

Rathbun E., and Nordin, Carl F. Jr., "Tracer Studies of Sediment Transport Processes," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 1302-1318. September 1971.

Richardson, E. V. and Simons, D. B., "Resistance to Flow in Alluvial Channels," Geological Survey Professional Paper. 1966.

River Mechanics Volume I and II. Edited by H. W. Shen. Available at P. O. Box 606, Fort Collins, Colorado 80521. U.S.A.

Sedimentation (Einstein) Edited and Published by Hsieh Wen Shen, 1972. Available at P. O. Box 606, Fort Collins, Colorado 80521. U.S.A.

Seventh Congress on Irrigation and Drainage. Central Office: 48, Nyaya Marg, Chanakyapuri, New Delhi - 11 (India). 1969.

Shen, Hsieh W. and Komura, Saburo, "Meandering Tendencies in Straight Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 94, pp. 997-1017. July 1968.

Shen, Hsieh W., "Development of Bed Roughness in Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 88, pp. 45-89. May 1962.

Simons, Daryl B. and Albertson, Maurice L., "Uniform Water Conveyance Channels in Alluvial Material," Journal of Hydraulic Division, ASCE, Vol. 86, pp. 33-73. May 1960.

Simons, D. B. and Richardson, E. V., "Forms of Bed Roughness in Alluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 87, pp. 87-107. May 1961.

Sixth Congress on Irrigation and Drainage. Central Office: 48, Nyaya Marg, Chanakyapuri, New Delhi - 11 (India). 1966.

Smith, Kenneth V. H., "Alluvial Channel Resistance Related to Bed Form," Journal of Hydraulic Division, ASCE, Vol. 94, pp. 59-71. January 1968.

Sonic Depth Sounder. Automation Instruments, Incorporated. Boulder, Colorado.

Squarer, David., "Friction Factors and Bed Forms in Fluvial Channels," Journal of Hydraulic Division, ASCE, Vol. 96, pp. 995-1019. April 1970.

Tarapore, Z. S., "Effect of Bed Load Supply on Equilibrium Conditions of Local Scour in Alluvial Channels," Sixth Congress on Irrigation and Drainage. Central Office: 48, Nyaya Marg, Chanakyapuri, New Delhi - 11 (India). 1966.

Taylor, Brend D. and Vanoni, Vito A., "Temperature Effects in Low-Transport Flat-Bed Flows," pp. 1427-1445. August 1972.

Tuffaleti, Fred B., "Sedimentation Aspect in Diversion at Old River," Journal of Hydraulic Division, ASCE, Vol. 86, pp. 37-47. June 1960.

Tywoniuk, Nick, "Sediment Discharge Computation Procedure,", pp. 521-540. March 1972.

Vanoni, V. A., N. H. Brook, and J. F. Kennedy, Lecture Notes on Sediment Transportation and Channel Stability. California Institute of Technology, Report No. KH-R-1. January 1961.

Vanoni, Vito A. and Nomicos, George N., "Resistance Properties of Sediment Laden Streams," Journal of Hydraulic Division, ASCE, Vol. 85, pp. 77-109. May 1959.

Vanoni, V. A. and N. H. Brooks, Laboratory Study of Roughness and Suspended Load of Alluvial Streams. Sedimentation Laboratory, California Institute of Technology, Report No. E-68. December 1957.

Willis, Joe C., Coleman, Neil L., Ellis, Wilbert M., "Laboratory Study of Transport of Fine Sand," pp. 489-502. March 1972.

Young, Ted Chih and Sayre, William, "Longitudinal Dispersion of Bed-Material Particles," Journal of Hydraulic Division, ASCE, Vol. 97, pp. 907-923. July 1971.

Ziekinski, Paul B. and Villemonte, James R., "Effect of Viscosity on Vortex - Orifice Flow," Journal of Hydraulic Division, ASCE, Vol. 94, pp. 745-752. May 1968.

APPENDIX

Table I. Flume data

Run number	Discharge in the flume	Total depth (water + sand)	Mean depth of sand	Slope of water surface	Concentration in the flume	Average diameter of sand in the flume	Gradation of sand in the flume	Water temperature	Discharge in the turnout	Elevation of turnout crest from the concrete bed	Concentration in the turnout	Average diameter of sand through the turnout	Gradation of sand through the turnout
	Q_f	d_t	D_{ms}	S	C_f	D_{50_f}	σ_f	T	Q_t	E_t	C_t	D_{50_t}	σ_t
	(cfs)	(ft)	(ft)	(·)	(ppm)	(mm)	(·)	(C°)	(cfs)	(ft)	(ppm)	(mm)	(·)
A-3	[illegible]	1.632	.422	6.480	80.0	[illegible]	1.340	[illegible]	.41	.740	308.0	.164	1.350
A-4	4.21	1.647	.333	6.110	81.0	[illegible]	[illegible]	29.0	.46	.740	256.0	.160	1.350
A-5	4.22	1.972	.571	4.040	12.0	.177	[illegible]	30.0	.74	.740	47.0	.173	1.320
A-6	4.25	1.500	.404	7.130	75.0	.144	1.380	30.0	.72	.740	373.0	.148	1.300
A-7	4.14	1.571	.411	5.400	74.0	.168	1.400	30.0	.84	.740	344.0	.164	1.290
A-8	8.30	1.575	.448	7.400	50.0	.145	1.350	29.0	.97	.740	432.0	.190	1.280
A-9	8.22	[illegible]	.340	5.140	81.0	.161	1.370	29.0	.32	.740	854.0	.196	1.360
A-10	[illegible]	[illegible]	.603	3.080	24.0	.189	1.180	29.0	.22	.740	100.0	.185	1.260
A-11	[illegible]	[illegible]	.558	4.300	59.0	.167	1.260	29.0	.35	.740	232.0	.210	1.260
A-12	[illegible]	[illegible]	.347	6.010	58.0	.162	1.350	24.0	.60	.740	264.0	.167	1.300
A-13	3.50	2.098	.651	3.660	44.0	.208	1.220	25.5	.70	.740	87.0	.157	1.320
A-14	3.45	2.068	.637	3.310	16.0	.165	1.440	26.0	.99	.740	65.0	.160	1.300
A-15	4.30	2.117	.653	3.300	47.0	.129	1.360	27.0	1.22	.740	82.0	.139	1.320
A-16	[illegible]	2.074	.615	5.660	14.0	.160	1.430	27.0	.55	.740	106.0	.167	1.280
A-17	12.30	2.072	.573	[illegible].400	68.0	.146	1.440	24.0	.80	.740	242.0	.153	1.310
A-18	12.30	2.090	.557	7.700	58.0	.136	1.400	26.0	.58	.740	155.0	.157	1.320
A-19	12.20	2.071	.567	6.790	93.0	.135	1.460	27.0	.41	.740	622.0	.158	1.300
A-20	12.15	2.077	.703	7.120	66.0	.140	1.450	27.0	1.07	.740	233.0	.152	1.290
A-21	12.25	2.066	.618	7.740	40.0	.123	1.460	28.0	1.20	.740	222.0	.154	1.360
A-22	11.80	1.869	.624	9.140	66.0	.159	1.300	25.0	.34	.740	203.0	.168	1.280
A-23	10.30	[illegible]	.661	7.230	95.0	.152	1.450	27.0	.49	.740	314.0	.190	1.380
A-24	10.50	1.917	.653	6.970	67.0	.152	1.500	28.0	.70	.740	372.0	.160	1.360
A-25	10.10	1.924	.593	6.890	67.0	.128	1.440	29.0	.90	.740	352.0	.160	1.330
A-26	9.90	1.935	.622	6.470	58.0	.155	1.470	29.0	1.09	.740	261.0	.160	1.410
A-27	5.30	1.598	.561	4.360	23.0	.141	1.420	25.0	.35	.740	82.0	.153	1.530
A-28	5.10	1.701	.591	6.250	102.0	.120	1.420	26.0	.47	.740	158.0	.139	1.350
A-29	5.50	1.598	.372	6.180	21.0	.150	1.270	27.0	.61	.740	115.0	.188	1.290
A-30	5.60	1.701	.437	6.100	119.0	.158	1.500	27.0	.80	.740	187.0	.169	1.420
A-31	6.40	1.697	.459	6.280	32.0	.164	1.360	27.0	.97	.740	170.0	.180	1.350
A-32	9.50	1.673	.397	8.790	152.0	.142	1.420	27.0	.33	.740	595.0	.147	1.310
A-33	9.70	1.675	.419	9.410	149.0	.161	1.380	28.0	.43	.740	619.0	.179	1.360
A-34	9.10	1.631	.381	8.710	177.0	.151	1.400	29.0	.52	.740	946.0	.180	1.390
A-35	10.10	1.628	.232	8.700	102.0	.175	1.360	30.0	.94	.740	760.0	.170	1.480
A-36	5.10	1.644	.404	4.640	9.0	.161	1.420	30.0	.43	.740	44.0	.282	1.660
A-40	5.50	1.632	.272	4.810	11.0	.178	1.380	30.0	.94	.740	24.0	.179	1.360
A-9	4.41	1.489	.567	6.980	13.0	.209	1.41[illegible]	30.0	.31	.740	80.0	.223	1.340
B-13	9.50	1.490	.517	2.620	53.0	.163	1.320	25.1	.67	.740	265.0	.157	1.350
B-15	9.70	1.469	.673	6.550	41.0	.166	1.350	[illegible]	1.18	.740	118.0	.168	1.310
B-19	12.00	1.910	.596	10.450	569.0	.167	1.2[illegible]	26.7	.36	.740	*85.0	.165	1.340
51	7.50	1.839	.603	3.490	7.5	.168	1.51[illegible]	26.0	.23	.740	31.3	.210	1.243
52	7.50	1.662	.614	3.230	38.0	.140	1.369	26.0	.34	.740	136.0	.170	1.370
53	7.20	1.508	.634	5.240	96.3	.172	1.310	27.0	.46	.740	449.6	.187	1.381
54	7.50	1.535	.625	8.730	62.3	.153	1.320	27.5	.59	.740	339.5	.167	1.367
55	9.00	1.554	.594	8.470	87.7	.156	1.461	29.0	.34	.740	302.2	.149	1.332
56	9.00	1.575	.600	8.850	118.4	0.000	0.000	29.2	.56	.740	449.2	0.000	0.000
57	9.00	1.601	.615	8.910	211.3	.148	1.350	29.8	.68	.740	697.1	.133	1.360
58	9.20	1.605	.606	9.170	114.5	0.000	0.000	30.0	.77	.740	882.7	0.000	0.000
59	9.20	1.657	.610	3.910	142.1	.150	1.374	29.9	.86	.740	322.6	.140	1.371
60	4.40	1.605	.615	5.910	57.9	0.000	0.000	24.0	.35	.740	220.3	0.000	0.000

61	8.35	1.672	.602	6.110	67.8	.159	1.271	29.0	.52	.740	301.0	.161	1.286
62	8.10	1.652	.610	6.980	79.9	0.000	0.000	29.8	.65	.740	448.4	0.000	0.000
63	8.40	1.689	.627	6.980	73.1	.161	1.293	29.9	.75	.740	349.7	.152	1.279
64	8.10	1.740	.625	6.110	37.6	0.000	0.000	30.0	.80	.740	165.3	0.000	0.000
65	8.00	1.671	.625	6.980	61.6	.139	1.424	30.0	.88	.740	334.3	.165	1.244
66	9.50	1.744	.550	6.540	164.2	0.000	0.000	30.0	.33	.740	911.1	0.000	0.000
67	8.20	1.624	.488	10.460	580.0	.149	1.444	30.0	.55	.740	*46.4	.179	1.318
68	10.00	1.588	.638	10.900	259.7	.138	1.859	27.0	.64	.740	*07.5	.144	1.324
69	10.10	1.725	.600	8.300	136.0	0.000	0.000	27.0	.74	.740	484.2	0.000	0.000
70	10.00	1.650	.543	9.600	445.5	.151	1.293	28.0	.80	.740	817.3	.169	1.425
71	5.60	1.727	.580	4.800	4.2	0.000	0.000	28.0	.37	.740	22.3	0.000	0.000
72	5.57	1.782	.598	3.930	5.2	.162	1.200	28.5	.52	.740	17.7	.180	1.251
73	5.31	1.895	.599	3.490	1.5	.174	1.311	29.0	.64	.740	4.7	.183	1.258
74	5.45	1.857	.590	3.050	2.0	0.000	0.000	27.8	.72	.740	4.4	0.000	0.000
75	5.65	1.878	.587	3.490	1.3	0.000	0.000	28.0	.84	.740	3.0	0.000	0.000
76	7.00	1.862	.560	4.360	5.9	0.000	0.000	28.9	.39	.740	18.5	0.000	0.000
77	7.20	1.850	.544	4.800	8.9	.170	1.346	29.0	.54	.740	37.1	.180	1.291
78	7.10	1.896	.540	4.360	7.6	0.000	0.000	29.2	.60	.740	42.2	0.000	0.000
79	6.90	1.867	.538	4.800	99.5	.176	1.341	29.5	.76	.740	462.0	.182	1.319
80	6.50	1.892	.545	4.800	5.3	0.000	0.000	29.7	.82	.740	14.0	0.000	0.000
81	12.70	1.982	.551	9.600	375.7	0.000	0.000	26.4	.54	.740	*62.2	0.000	0.000
82	12.20	1.957	.605	9.600	317.5	.158	1.341	28.0	.67	.740	864.9	.173	1.265
83	12.70	1.972	.519	5.230	665.1	0.000	0.000	25.5	.78	.740	777.5	0.000	0.000
84	12.70	1.980	.523	10.470	377.6	.140	1.322	28.0	1.20	.740	*88.9	.166	1.310
85	12.70	1.971	.553	10.200	662.1	0.000	0.000	30.0	1.26	.740	*61.2	0.000	0.000
86	12.00	2.397	.503	6.980	41.2	.147	1.339	25.0	.69	.740	110.6	.156	1.299
87	12.00	2.385	.559	6.980	31.1	0.000	0.000	27.5	.84	.740	147.4	0.000	0.000
88	12.10	2.352	.739	5.230	53.2	.167	1.304	29.5	.99	.740	414.4	.156	1.299
89	12.00	2.361	.582	3.490	52.8	.154	1.317	29.5	1.17	.740	193.5	.150	1.271
90	12.00	2.332	.641	4.360	70.2	.163	1.298	29.5	1.26	.740	276.5	.169	1.256
91	12.00	1.975	.524	5.230	384.1	.160	1.267	25.0	.58	1.073	*12.9	.161	1.306
92	12.10	1.959	.646	8.720	205.5	.159	1.404	27.5	.80	1.073	*91.7	.160	1.373
93	12.10	1.978	.539	5.230	295.0	.154	1.311	28.0	1.04	1.073	*21.8	.176	1.305
94	12.10	1.976	.575	5.230	176.4	.160	1.319	27.0	1.12	1.073	588.5	.160	1.324
95	11.70	2.016	.599	5.230	118.1	.139	1.367	24.0	1.26	1.073	386.9	.149	1.327
96	12.25	1.827	.430	8.720	727.2	.172	1.279	25.0	.39	1.073	283.1	.152	1.268
97	12.35	1.814	.593	5.230	479.1	.168	1.299	27.0	.80	1.073	*51.9	.162	1.270
98	12.25	1.828	.438	5.230	*49.8	.160	1.346	24.5	.82	1.073	*22.4	.158	1.332
99	12.05	1.784	.736	3.490	838.9	.160	1.377	27.0	.82	1.073	*32.5	.160	1.369
100	12.00	1.828	.325	5.230	620.8	.123	1.168	25.5	.64	1.073	865.5	.114	1.427
101	8.40	2.357	.699	6.980	11.4	0.000	0.000	25.5	.52	1.073	21.0	0.000	0.000
102	8.40	2.362	.649	5.230	7.7	0.000	0.000	27.5	.80	1.073	37.7	0.000	0.000
103	8.40	2.355	.787	6.980	9.0	0.000	0.000	28.5	.92	1.073	39.9	0.000	0.000
104	8.00	2.388	.638	3.490	13.1	.168	1.253	23.5	1.05	1.073	43.7	.129	1.367
105	8.00	2.357	.847	6.980	11.7	.167	1.310	24.0	1.21	1.073	47.6	.158	1.284
106	9.40	2.365	.665	8.720	17.4	.176	1.318	24.5	.46	1.073	68.5	.194	1.263
107	9.40	2.150	.693	8.720	24.4	.154	1.359	20.0	.74	1.073	106.3	.185	1.270
108	9.40	2.358	.749	3.490	24.5	.168	1.355	27.0	1.00	1.073	161.4	.179	1.262
109	8.70	2.365	.704	5.230	31.1	.213	1.489	27.0	1.15	1.073	130.0	.168	1.288
110	8.70	2.350	.677	5.230	20.6	.160	1.355	27.5	1.22	1.073	45.0	.160	1.274
111	12.10	1.966	.573	6.980	109.8	.145	1.346	26.0	.48	1.073	276.1	.136	1.322
112	12.00	1.951	.563	8.720	135.4	.155	1.379	26.5	.72	1.073	269.1	.153	1.329
113	11.70	1.980	.585	6.980	206.9	.149	1.403	26.0	.90	1.073	956.2	.153	1.307
114	11.80	1.949	.616	8.720	236.1	.148	1.397	26.0	1.23	1.073	*08.2	.156	1.361
115	10.20	1.968	.624	5.230	38.2	.165	1.357	27.5	.38	1.073	232.5	.173	1.278
116	10.00	1.946	.634	6.980	45.6	.163	1.319	28.0	.62	1.073	108.9	.169	1.290
117	9.90	1.955	.655	6.980	37.1	.151	1.368	28.5	.80	1.073	187.1	.159	1.301
118	9.60	1.962	.653	5.230	54.4	.180	1.274	28.0	.96	1.073	242.4	.149	1.278
119	9.00	1.988	.647	3.490	52.6	.164	1.305	28.0	1.70	1.073	127.1	.166	1.298
120	6.20	1.983	.529	3.490	3.7	0.000	0.000	24.0	.31	1.073	11.5	0.000	0.000
121	6.20	1.993	.529	1.745	4.7	0.000	0.000	24.0	.64	1.073	20.0	0.000	0.000
122	6.20	1.992	.532	1.745	4.6	0.000	0.000	24.5	.90	1.073	20.0	0.000	0.000
123	6.20	1.992	.530	3.490	5.0	.152	1.631	24.5	1.08	1.073	31.7	.182	1.300
124	6.20	2.007	.552	8.720	4.8	0.000	0.000	25.0	1.17	1.073	20.0	0.000	0.000
125	8.70	1.994	.551	6.980	14.1	.158	1.388	26.5	.68	1.073	55.2	.161	1.300
126	8.61	2.004	.550	8.720	11.5	.160	1.361	27.5	.44	1.073	35.0	.167	1.306
127	8.60	1.970	.649	6.980	15.1	.160	1.352	28.0	.92	1.073	47.2	.190	1.269
128	8.50	1.974	.721	6.980	43.4	.173	1.349	28.0	1.08	1.073	122.1	.182	1.288
129	8.40	1.965	.715	6.980	39.7	.150	1.309	28.5	1.22	1.073	187.7	.176	1.263
130	9.00	1.881	.575	3.490	16.7	0.000	0.000	23.5	.50	1.073	39.1	0.000	0.000
131	9.10	1.851	.580	6.980	21.4	0.000	0.000	25.5	.36	1.073	150.9	0.000	0.000
132	8.90	1.859	.559	5.230	19.9	0.000	0.000	26.0	.63	1.073	88.4	0.000	0.000
133	7.40	1.869	.613	6.980	6.1	0.000	0.000	27.5	.63	1.073	18.2	0.000	0.000
134	7.60	1.856	.610	6.980	8.0	0.000	0.000	28.0	.49	1.073	56.7	0.000	0.000
135	7.60	1.881	.615	5.230	10.7	0.000	0.000	26.0	.34	1.073	54.0	0.000	0.000
136	12.00	1.901	.548	8.720	183.3	0.000	0.000	27.5	.34	1.073	294.0	0.000	0.000
137	12.00	1.909	.538	10.470	193.1	0.000	0.000	27.5	.45	1.073	638.3	0.000	0.000

Table 11. Scour pit data

Run number	Volume of scour upstream from the turnout V_{u_3} (ft^3)	Volume of scour downstream from V_{d_3} (ft^3)	Average depth of scour along T_1 $\bar{D}_{T1}$ (ft)	Average depth of scour in the entire experimental section D_{as} (ft)
A05	.8130	2.1495	.3810	.0658
A06	.8198	1.7535	.2700	.0570
A07	.8385	1.5387	.2970	.0528
A08	1.1123	1.7275	.3200	.0531
A09	.3754	1.2533	.2240	.0362
A09	.7913	.9803	.3090	.0394
A10	.1891	.7469	.1560	.0211
A11	.4811	.1009	.1640	.0129
A12	.7515	1.2030	.3040	.0434
A13	.7669	1.5950	.3470	.0525
A13	.2753	1.3490	.3540	.0361
A14	.7545	1.5250	.4090	.0507
A15	.8470	3.7270	.4250	.1020
A15	1.1410	3.0460	.4350	.0930
A16	.7420	2.0910	.3740	.0630
A17	-.4350	1.4020	.3210	.0215
A18	.7540	1.6510	.2660	.0537
A19	-.1550	1.4970	.0210	.0409
A19	.7016	.8980	.2000	.0354
A20	.4990	3.9240	.4500	.1094
A21	1.0040	3.0190	.4160	.0894
A22	.3626	1.4820	.2030	.0410
A23	.7793	.4060	.2640	.0263
A24	.7376	.8109	.3230	.0344
A25	.5134	2.0190	.3900	.0563
A26	.6693	2.1615	.4080	.0629
A27	.8250	7.3540	.3600	.1818
A28	.1065	1.1535	.3170	.0280
A29	.6293	-1.1770	.2520	-.0122
A30	1.0920	1.7990	.3500	.0643
A31	.9170	1.9230	.3310	.0631
A32	.2123	.4425	.3190	.0051
A33	.3810	.4490	.3550	.0193
A34	.6510	1.6620	.2430	.0514
A36	.2367	.1031	.1690	.0076
A38	-.0131	1.3950	.2720	.0307
A40	1.0760	-.1549	.2250	.0205
A41	.7445	2.0610	.3350	.0624
51	.3214	1.7450	.2740	.0459
52	.7174	1.1415	.2710	.0413
53	.3015	.4200	.2230	.0150
54	.2410	2.3100	.3210	.0574
55	.4910	.8570	.1900	.0300
57	.3450	1.4750	.4590	.0404
59	.9900	2.2150	.3780	.0712
61	.3195	1.2600	.2450	.0351
63	.5370	1.3760	.3430	.0425
65	1.0730	2.8520	.4130	.0872
67	-1.0240	3.4350	.1670	.0536

68	.5072	.5850	.2460	.0243
70	-.5490	1.5010	.2780	.0212
72	.9500	3.5670	.3870	.1004
73	.9175	3.8020	.4010	.1027
75	.4690	3.8400	.3910	.0960
77	-.1710	1.8120	.2890	.0365
79	.4770	1.4930	.3470	.0436
81	-.5050	1.5260	.1200	.0226
82	.1676	2.8920	.2260	.0680
83	2.1900	.5190	.3810	.0602
84	2.6180	2.7370	.3940	.1190
85	-1.1030	5.8750	.2780	.1060
86	.7640	1.0170	.2670	.0423
87	2.4740	1.0200	.3580	.0780
88	.3950	4.5390	.4120	.1100
89	1.3350	.8220	.3300	.4790
90	.8470	3.2800	.4210	.0920
91	-.7650	-.9220	.0690	-.0370
92	.4610	1.4560	.3020	.0426
93	.3110	1.2950	.2410	.0357
94	.3210	.5210	.2390	.0187
95	.5250	2.8680	.3440	.0754
96	1.9300	-.5340	.3680	.0310
97	.7700	4.2690	.2520	.1120
98	-1.1200	-1.3940	.0780	-.0560
99	.5490	12.9300	.3530	.3000
100	-2.5900	-.6060	-.2120	-.0710
101	.6590	2.0180	.3030	.0595
102	1.0780	.0791	.3720	.0257
103	1.0610	3.8360	.4750	.1090
104	.7050	2.7430	.3540	.0770
105	.6500	3.1820	.3740	.0850
106	.6610	.4580	.1950	.0249
107	.4550	1.0910	.2860	.3440
108	.7680	2.5490	.4670	.0737
109	.8280	2.2820	.4620	.0691
110	.4120	3.0450	.3910	.0770
111	-.0270	.1650	.0730	.0031
112	-.3720	-.2310	.1900	-.0140
113	.7760	2.0020	.3530	.0618
114	.4660	2.6290	.3890	.0688
115	.5270	-.0458	.1670	.0107
116	.4550	.2300	.2300	.0152
117	.4740	1.9880	.3260	.0547
118	.0980	1.1380	.3580	.0274
119	.5130	2.0650	.4080	.0573
120	-.2330	-.2310	.1125	-.0103
121	.1090	-.1900	.1405	-.0020
122	.1460	-.0380	.1580	.0024
123	.2280	.0470	.1640	.0061
124	.4695	1.0418	.2280	.0336
125	.5595	.7046	.2710	.0281
126	.4669	.0278	.1910	.0110
127	.4238	3.7940	.3260	.0937
128	.4148	4.4966	.4060	.1092
129	.3150	4.2709	.3840	.1019
130	.2920	-.4260	.0910	-.0030
131	.2870	.7320	.0920	.0226
132	.7580	.1790	.2630	.0208
133	1.4300	.5820	.2440	.0447
134	.4550	.9150	.2720	.0304
135	.5310	.1050	.1620	.0141
136	.2330	.1130	.0810	.0077
137	.3290	-1.7090	.0680	-.0372
	-0.0000	-1.7090	.0680	-.0372

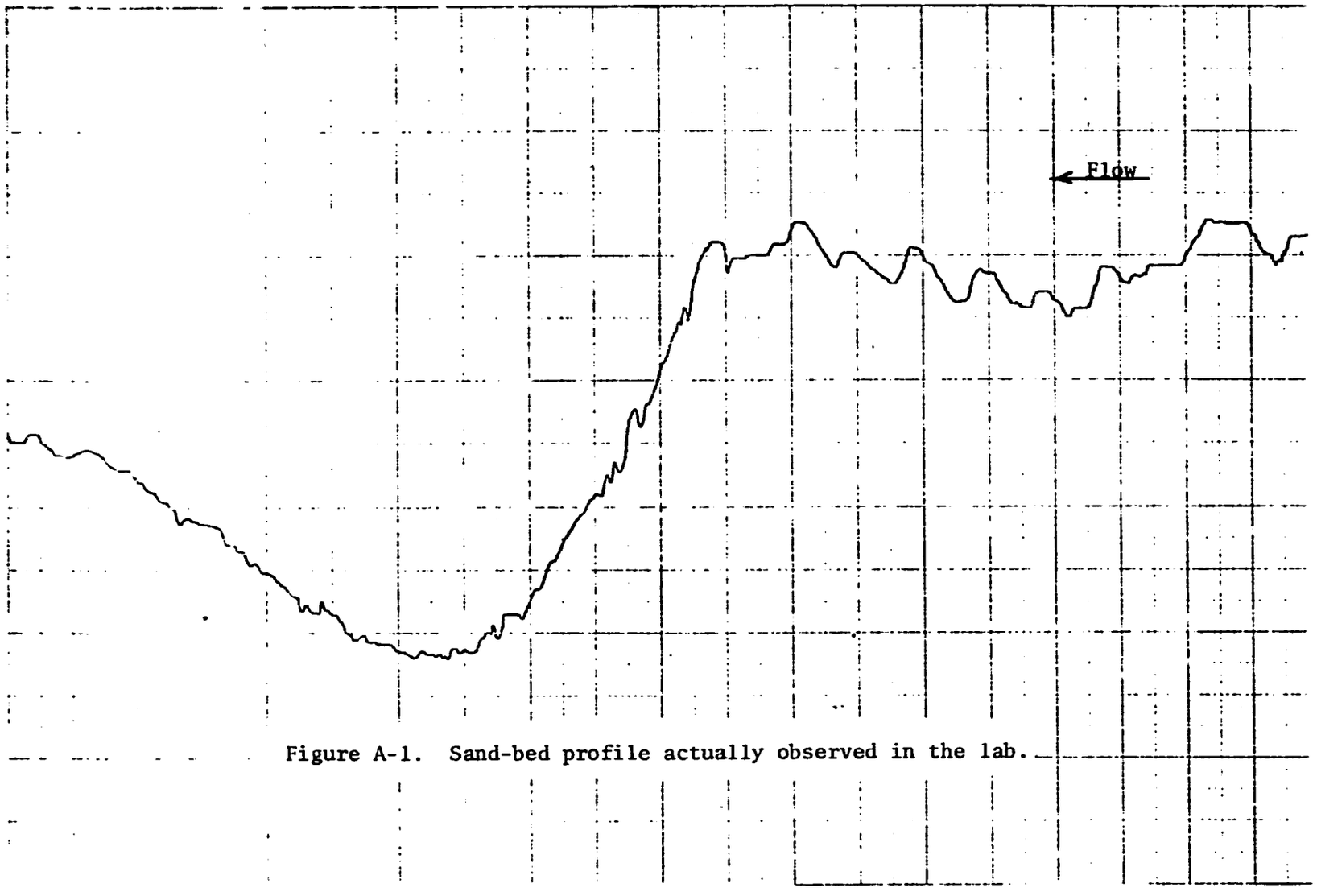


Figure A-1. Sand-bed profile actually observed in the lab.

APPENDIX B

Sonic Depth Sounder

"Sonic depth sounder is an instrument which can see through water by means of sound waves. To operate sonic depth sounder properly, it is necessary to understand the principles upon which it works.* The human ear can hear sound waves whose frequencies range from 20 cycles to 20,000 cycles per second. Sound waves oscillating at a frequency greater than 20,000 cycles per second are inaudible and are known as ultrasound. The ultrasonic waves which the sonic depth sounder utilizes have frequencies not of thousands of cycles but millions of cycles per second. In speaking of these frequency waves, the term "megacycles" meaning millions of cycles per second is used. Sound waves are used to obtain information about the depth of water by studying the echoes that are reflected from the interface between the water and an obstruction. It is possible to determine distance by the length of time required to receive an echo from an obstruction. The instrument always measures the distance from the transducer to the obstruction.

The sound waves are produced by a piezoelectric crystal. The crystal is electrically pulsed after which it vibrates at its own natural frequency. These very short sound waves will not, for all practical purposes, travel through air. They will, however, travel through most liquids. The crystal vibrates at its natural frequency for only a few cycles. The result is a very short burst of energy which travels through the water to an obstruction. Most of the sound is immediately reflected back toward the transducer.

After the crystal has given off its short burst of sound waves and stopped vibrating it "listens" for returning echoes. When the echoes are received they cause the crystal to vibrate and produce an electric current which could be displayed as a pip or cathode ray tube screen or plotted on paper with x - y plotter."

---

*Instructions for the operation and maintenance of Model 1024 Sonic Depth Sounder could be obtained from: Automation Instruments, Incorporated in Boulder, Colorado. Reference to this has also been mentioned in the List of References.