SCOUR AND ENERGY DISSIPATION
BELOW CULVERT OUTLETS

By

George L. Smith

Colorado Agricultural and Mechanical College
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FOREWORD

The work reported herein was conducted in the Hydraulics Laboratory of Colorado State University under contract with Agriculture Research Service, Beltsville, Maryland. It is a continuation of experimental work initiated in 1950 by Mr. Doddiah Doddiah and carried on in 1953 by Mr. R. K. Thomas and in 1955 by Mr. D. E. Hallmark. Mr. G. L. Smith was the principal investigator and his studies resulted in a thesis leading to the degree of Master of Science in Irrigation Engineering.

ACKNOWLEDGEMENTS

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Many thanks are due to all of the fluid mechanics staff members of the Civil Engineering Department of the Colorado State University for contributions during the progress of this study. In particular, acknowledgments are made to Dr. M. L. Albertson, Professor of Civil Engineering, for suggesting the study and for general advice and direction, to Dr. D. F. Peterson, Jr. and E. W. Lane for their helpful suggestions and criticisms, to Professor J. R. Barton for assistance in the preliminary planning and designing of the experimental equipment, to R. V. Asmus of the Hydraulics Laboratory staff for his assistance in the design and construction of equipment, to Mr. Kersi Davar for his valuable assistance in collecting and analysis of data, to Lucien Duckstein for his advice on the theoretical analysis, and to Dr. A. R. Chamberlain for his advice throughout the project and for his editing of this report.

Acknowledgement is made to Professor T. H. Evans, Dean of Engineering and Dr. D. F. Peterson, Jr., Head of the Department of Civil Engineering for their support and assistance.

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FIGURES

NOMENCLATURE

Symbol	Definition	Unit
A	Area of the jet	L^2
a	Length characteristic	L
a_1	The y-intercept at $x = o$ for Eq 17	
a*	Major axis of sediment particle	L
B	Width of pool	L
b	Depth of tailwater from the original bed level to the top of the water surface	L
b_c	Critical tailwater depth	L
b*	Intermediate axis of sediment particle	L
C	Degrees centigrade	
C_s	Concentration of sediment in the jet	
c*	Minor axis of sediment particle	L
D_t	Coefficient of turbulent diffusion in the pool	
d	Mean diameter of bed material in mm	L
d_B	Diameter of preshaped scour hole taken at the bottom	L
d_{90}	Grain diameter so chosen that 90 per cent of the bed material is finer than d_{90}	L
d_m	Median diameter on the log-probability plot	L
d_n	Nominal diameter of sediment	L
d_s	Depth of sediment	L
d_T	Diameter of preshaped scour hole taken at original bed level	L

Symbol	Definition	Unit
d_{max}	Diameter of maximum size of graded aggregate to be used in armorplating	L
d_{min}	Diameter of minimum size of graded aggregate	L
E_o	Energy flux of water jet at the point of impingement of the tailwater surface	FL/T
F	Net gravitational force on the particle falling in the fluid, $F = \pi/6\ d_n^3 (\rho_p - \rho_f)g$	F
g	Acceleration due to gravity	L/T^2
H	Height of fall from the bed level upstream to the bed level downstream	L
H_c	Height from center line of area of flow to original bed level	L
H_1	Height of fall measured from the pipe invert to the initial bed	L
h	Depth of scour from the original bed level to the bottom	L
h_s	Maximum depth of scour below water surface in feet	L
h_1	Elevation difference between upstream and downstream water surfaces in feet	L
h^*	cube root of volume of scour $(V_s)^{1/3}$	L
h^*_t	cube root of volume of scour $(V_s)^{1/3}$ at time t	L
L	Length of pool	L
M_F	Momentum flux of water jet at the point of impingement of the tailwater surface	F
m	Representing the slope of the graph of Eq 17	

Symbol	Definition	Unit
n	Porosity of the bed material	
Q	Pipe discharge	L^3/T
q	Discharge per unit width	L^2/T
sf	Shape factor	
T , t	Time of scour	T
t_p	Time for a fluid particle to travel from the point of discharge to point of impact	T
V	Mean velocity of flow	L/T
V_o	Velocity of jet at point of discharge from pipe	L/T
V_s	Volume of scour	L^3
W, w_s	Fall velocity of sediment particles	L/T
w_m	Geometric mean fall velocity of particles	L/T
x_b	Horizontal distance traversed to point of impingement on bed.	L
α	Natural angle of repose of the bed material when submerged, indicating shear dapacity	
γ_s	Specific weight of the bed material	F/L^3
γ_w	Specific weight of the fluid (water)	F/L^3
ϵ	Thickness of armorplating	L
θ	Angle which the central streamline of the jet makes with thesurface of the pool	
K	Geometrical constant for determining dimensions of scour hole = $\sqrt[3]{(\frac{\pi}{4})(1 - \frac{\psi}{\tan\alpha})^2}$	
λ	Longitudinal roughness spacing	L

NOMENCLATURE --Continued

Symbol	Definition	Unit
μ	Dynamic viscosity of fluid	FT/L^2
ν	Kinematic viscosity of fluid	L^2/T
π	Mathematical constant pi (3.1516)	
ρ, ρ_f	Density of the water	FL^2/T^4
ρ_s, ρ_p	Density of the fluid	FL^2/T^4
σ_w	Geometric standard deviation	
ψ	Geometrical constant for determining dimensions of scour hole h/d_T	

1. DISSIPATION OF KINETIC ENERGY

Introduction

From the time the first irrigation system was developed to the present day, the irrigation engineer has been confronted by an ever-increasing number of design problems involving erosion and the dissipation of excessive kinetic energy of flowing water. The problems are usually concerned with scour prevention either in the conveyance system or around some structure located in the waterway. In either situation, the objective of the designer is to dissipate the energy efficiently and economically. Therefore, it is the purpose of this chapter to present and discuss principles, as well as types of energy dissipation structures, which can be employed to accomplish these objectives.

There are three methods for studying the problem of the dissipation of energy. The first is engineering experience gained in the field by each hydraulic or irrigation engineer. The second is the laboratory method of studying each problem by means of scale models and generalized research. The third is the process of theoretical analysis. All three methods of approach can be combined to find the most effective solution to the problem.

The first section of this chapter presents the fundamentals of energy dissipation as demonstrated in the laboratory and by theoretical analysis. The second section presents the contributions of engineering experience in a general summary of the factors which cause the local concentration of excessive kinetic energy. In the light of the first two sections, the last section reviews the types of structures now employed for energy dissipation.

The first section introduces the concept of kinetic energy dissipation as a function of the effects of viscosity on fluid motion. The relation of viscosity and turbulence (the intensity of which is an indication of the scale of energy dispersion) is then presented in terms of the three basic types of turbulent flow: (a) quasi-smooth (or skimming) flow, (b) wake-interference flow, and (c) isolated-roughness flow.

In general, the economy of most energy-dissipation structures is directly related to the fluid volume within which the energy dissipation takes place; the smaller the dissipation volume is the less expensive the structure. In this respect, principles applicable to an economical design are discussed in the second part of the first section as: (a) horizontal dissipation of energy, and (b) vertical dissipation of energy.

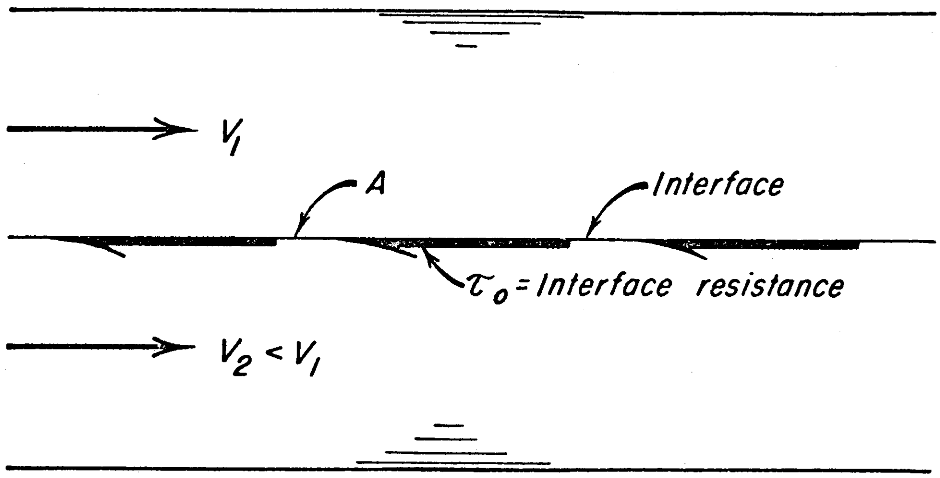
The second section, which considers the concentration of excessive kinetic energy as learned from engineering experience, consists of the general classifications: (a) eroding velocities in conveyance systems; (b) control structures installed in conveyance systems; and (c) outlet structures, as culverts and tunnels, used to by-pass water between conveyance systems.

The third and final section reviews the various types of energy dissipation structures which have been developed on the basis of knowledge gained from experience, experiment, and theoretical analysis. These structures, employing the concepts and principles of energy dissipation, are used for the conveyance, storage, or control of water. In conveyance systems the energy is dissipated by artificial roughness, overfall structures, or control structures placed in the system; for storage and control structures the energy is dissipated in some type of stilling basin. The structures generally used are: (a) overfall structures, such as spillways and drops, (b) valve-controlled structures, such as Howell Bunger or needle valve, (c) jet deflectors, such as "flip buckets", (d) cantilevered outlets, such as pipe culverts, (e) by-pass structures, such as tunnels, inverted siphons, and box or pipe culverts, and (f) manifold-type structures.

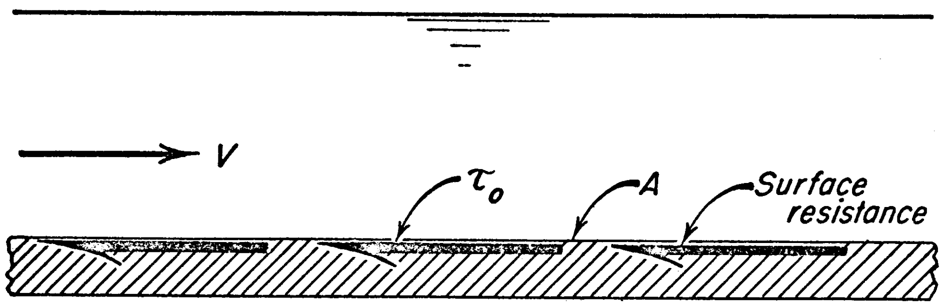
Basic Concepts of Kinetic Energy Dissipation

The basic concepts of excessive kinetic energy dissipation of interest to the designer of irrigation structures or conveyance systems are dependent upon the types of resistance and the types of turbulent flow.

Two types of fluid resistance are: (a) interface resistance, Fig. 1, and (b) form resistance, Fig. 2. Interface resistance is caused by viscous and turbulent shear which dissipates the kinetic energy of flowing water. Dissipation is brought about by the resistance to fluid deformation which is produced by the interchange of forces between the stream of water and a surface over which it flows; by the interchange of forces between an active and passive water interface; or by the action and reaction of water and air.



(a) Resistance at an interface of two fluids



(b) Resistance at boundary — fluid interface

Fig. 1 Interface resistance

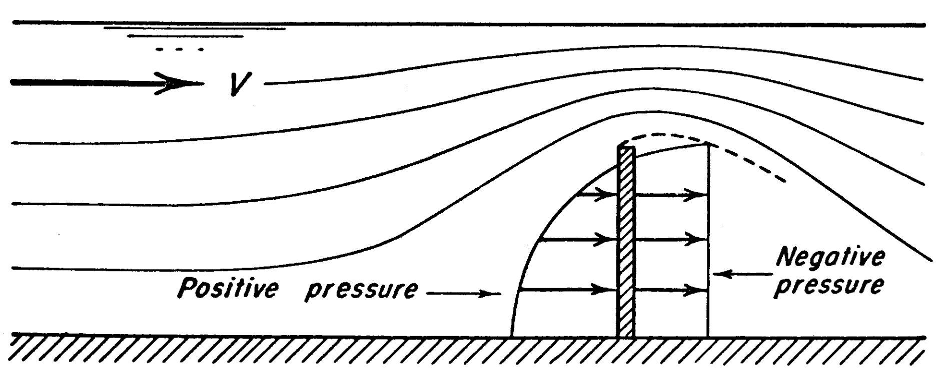


Fig. 2 Form resistance

Interface resistance may be: (a) internal shear at a fluid interface, or (b) shear at the interface of a liquid and a solid boundary. See page 4. Internal shear is exemplified by the water jet, which loses its kinetic energy through reaction with the medium surrounding it. For example, a jet of water plunging into a pool of water will diffuse, both inwards and outwards, until it reaches a boundary or is dissipated through shear. Thus, the difference of the velocity between a submerged jet and the region into which it is discharged gives rise to a zone of intense shear at the interface, and the kinetic energy of the oncoming flow is steadily converted into kinetic energy of turbulence -- the latter steadily decaying through viscous shear downstream. The diffused jet, as it moves downstream, exhibits a decrease in energy, an increase in discharge (by entraining water), and a constant momentum flux.

Analogous to the submerged jet is the jet of water discharged into the air, where it entrains air, is disintegrated, and dissipated by internal turbulence, and surface tension. Thus, due to the shear at the boundary of the jet, its kinetic energy is rapidly dissipated -- while its center, which is conical in shape, also gradually disintegrates. In summary, the fluid resistance between an active and passive fluid interface gives rise to internal shear which causes entrainment of the surrounding fluid, a decrease in energy, and a constant momentum flux along the jet.

Shear at a liquid-solid boundary interface is exemplified by flow in open channels, where the channel boundary (wetted perimeter) transmits a shearing force to the flow. The shearing force converts the kinetic energy into heat. Boundary shear results in a drag force, transmitted from the fluid to the boundary, in the direction of motion. The boundary in turn transmits to the fluid a force equal in magnitude, but opposite in direction, to the drag force. In principle, the surface may be defined as either smooth or rough. The fluid in immediate contact with the boundary has a velocity of zero.

While interface resistance is important in the dissipation of kinetic energy, form resistance is equally important and is probably more familiar to the irrigation engineer. An example of shapes or forms causing form resistance is baffle piers used in a stilling basin for the purpose of creating a hydraulic jump. When flow takes place past a boundary which is not parallel to it, a drag on the object and a resistance to the flow is created -- this condition depending upon the shape or form of the boundary. This is form drag or form resistance and is due to the difference in pressure created on the upstream and downstream sides of the object or boundary. The pressure on the upstream side is essentially all positive while on the downstream side the pressure is negative relative to surrounding piezometric pressure.

Form resistance may occur with either laminar or turbulent flow, but the flow pattern is markedly different for each. In canals and ditches, however, laminar flow is not a consideration.

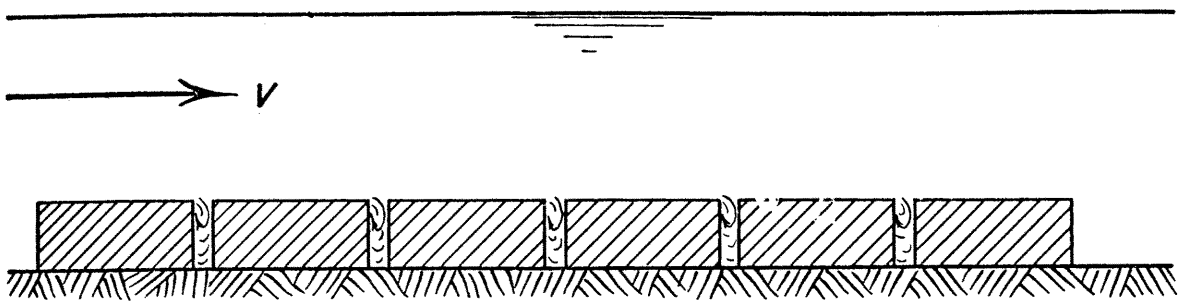
Fluid resistance in open channels usually involves both interface and form resistance. Water flowing through canals and ditches normally encounters surface resistance offered only by the canal lining, and form resistance offered by baffle piers and end sills in spillway stilling basins. This fluid resistance will, under favorable flow conditions, cause three basic types of turbulent flow: (a) quasi-smooth (skimming) flow, (b) wake-interference flow, and (c) isolated-roughness flow. These are shown in Fig. 3.

Fundamental to the three basic types of turbulent flow is the fact that the chief source of energy loss in a fluid flowing over a rough surface is the generation, spreading, and subsequent dissipation of vortices from the wake and separation zones behind each roughness element. Each element is thus a source of turbulence, indicating that the longitudinal roughness spacing λ is of importance in rough-channel flow.

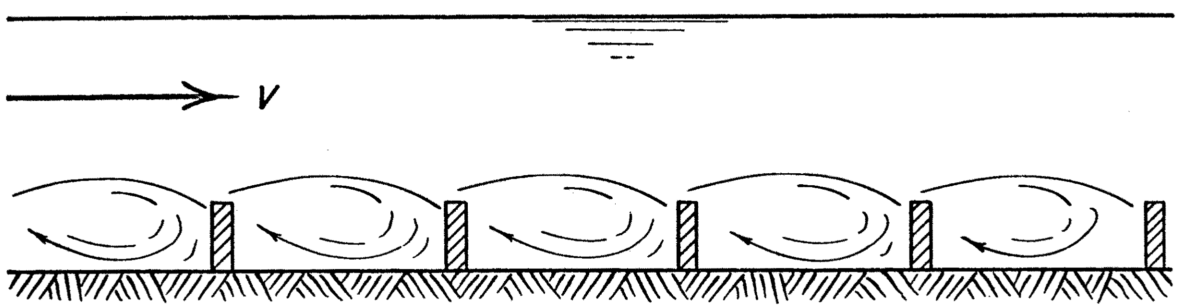
When the roughness elements are so close together that the flow (essentially) skims the crest, there will be regions of dead water containing stable vortices in the grooves between the roughness elements. The bulk of the flow is over a pseudo-wall composed of the roughness crests and the upper extent of the groove vortices. Large roughness projections are absent from the pseudo-wall; and the flow, similar to smooth-conduit flow, is of the first type or quasi-smooth (skimming) flow (14)[1]. Much of the energy loss in such flow can probably be attributed to the maintenance of the groove vortices, the size of which are controlled by the width, or the depth, of the groove whichever is smaller; the number of such vortices depends on λ .

The second type of flow results when the roughness elements are placed sufficiently close together. In this case the zone of

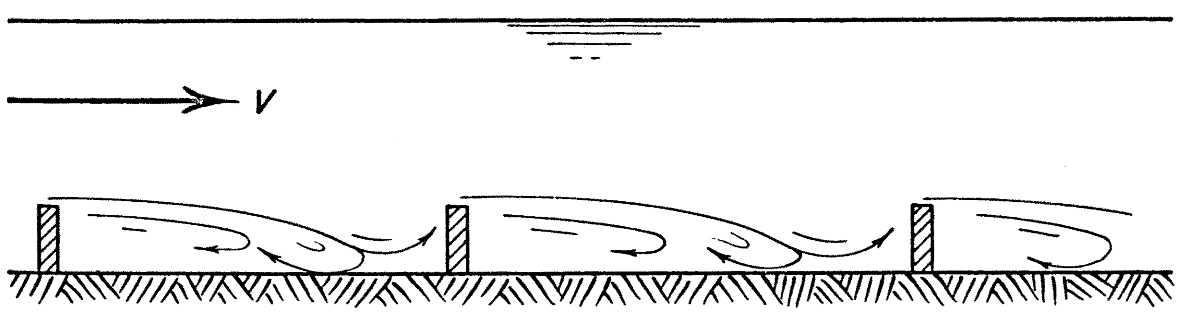
[1] Numbers in the parenthesis refer to corresponding numbers in the bibliography.



(a) Quasi-smooth (skimming) flow



(b) Wake interference flow



(c) Isolated roughness flow

Fig. 3 Basic types of boundaries and resulting turbulent flow separation, vortex generation, and dissipation associated with each element is not completely developed before the next element is encountered. This type of flow can be termed wake-interference flow, involving as it does the interference of the wake of each element by the elements immediately downstream, which are partly or totally enclosed within the vortex downstream from the preceding element. The drag of the individual elements is obliterated and the entire region near the wall is replete with intense and complex vorticity and turbulent mixing. The height of the element is relatively unimportant in this type of flow but the spacing is obviously of major importance.

The third type of flow occurs when the channel-roughness elements are far apart. In this case the individual elements will act as isolated bodies. The wake zone and the vortex-generating zone at each element are completely developed before the next element is reached. The form drag on any one element depends primarily on the height of the projection of the element and the total form drag in a given length of conduit depends on λ . This type of flow can be termed isolated-roughness flow.

Principles of Kinetic Energy Dissipation Applicable to Design Problems

Attention in the foregoing section has been centered upon means of evaluating the dissipation of excessive kinetic energy through fluid resistance and by various methods of turbulent flow. Fluid resistance and turbulence are to a great extent an integral part of the various methods of energy dissipation. Broadly speaking, these methods are: (a) the horizontal dissipation of energy, (b) the vertical dissipation of energy, or (c) some combination of both. The methods of energy dissipation are illustrated in Fig. 4.

Horizontal dissipation:- The horizontal dissipation of energy may be due to external resistance (surface drag) between the water and the channel -- the roughness or drag on the boundary causing a reduction in velocity and an increase in depth. The boundary of the channel, in this instance, transmits a shearing force to the flow and converts the kinetic energy into potential energy and thermal heat.

External resistance in the horizontal direction may also be between water and the surrounding air. In the case of a jet spread out by a deflector over a wide area, the air drag causes the jet to disintegrate through air-entrainment and surface tension. Here the kinetic energy of the jet is dissipated through viscous shear.

The distance required to decrease the velocity head and dissipate energy in the horizontal direction can be reduced appreciably if the flow can be brought quickly into a state of intense turbulence with the greater part of the energy being transformed into heat. Such a transformation can generally be accomplished by introducing strong internal resistance into the flow -- the change in kinetic energy being brought about by the interaction between the active and passive water interface. Common methods generally employed are: (a) vortices, indicated by rollers, (b) hydraulic jump, and (c) jet diffusion in a radial direction, which results in small-grain turbulence.

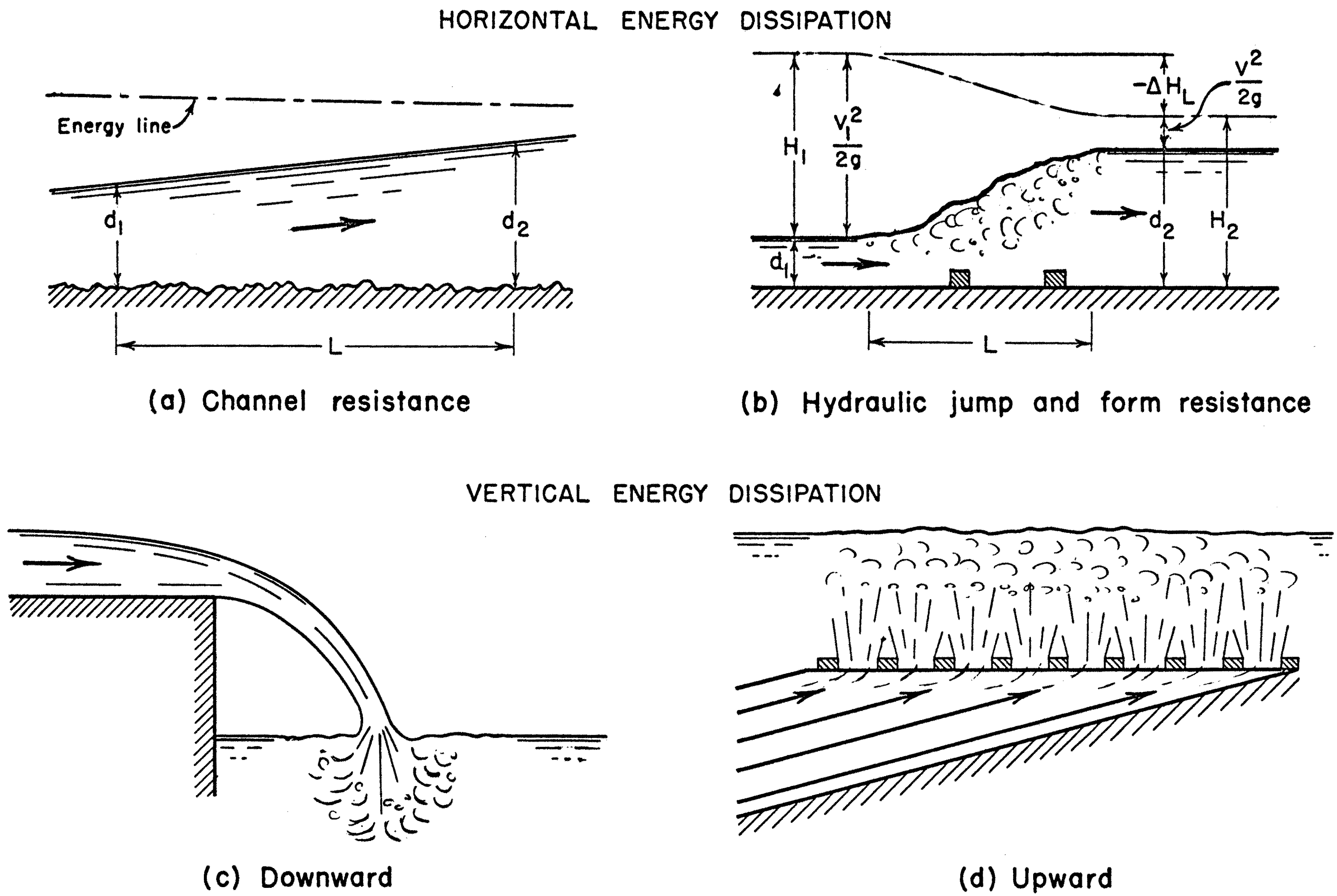


Fig. 4 Methods of dissipation of kinetic energy

As previously mentioned, rollers indicate the regions of vortex formation within the flow. In these regions there are large differences of velocity within the fluid -- that is, regions of considerable fluid resistance. To the eye there are three types of rollers: (a) surface roller above the jet which is a horizontal vortex; (b) ground roller under the jet which is also a horizontal vortex; and (c) side roller which is a vertical vortex.

The efficiency of the roller depends on its size and shape, on the velocity (the difference between the jet velocity and the velocity of the surrounding water), and on the boundary or interface proximity -- the interface being caused by the surrounding water, the bed, or the structure. The amount of energy dissipated increases directly with velocity difference and volume of the roller. The dissipation decreases when the roller approaches a circular form. These properties were found in model studies on roller-type stilling basins (16).

A particular case of a surface roller is the hydraulic jump, which occurs when flow conditions are favorable for its formation. The hydraulic jump is the classical type of a horizontal energy dissipator, because of its efficiency and smooth action, and as such is used very extensively. It may be explained by the momentum principle of basic mechanics which is derived from Newton's well-known equation $F = Ma$. Fundamentally, at any section through the jump normal to the flow the sum of the momentum flux and the hydrostatic pressure are constant, but between sections parallel to the flow there is a change in the momentum flux and the hydrostatic pressure.

The hydraulic jump is a sensitive phenomenon which may move easily upstream or downstream and thereby become ineffective by having the stilling basin; therefore, resistance elements, such as blocks or sills, are usually placed on the floor of the channel to help stabilize the location of the hydraulic jump and to help reduce the length required for it to take place. The St. Anthony Falls stilling basin is an excellent example of the use of these principles.

Another type of internal resistance is jet diffusion. Small-grain turbulence is achieved when a jet, discharged from an outlet above or below the tailwater, is guided by means of deflectors into the tailwater where it produces eddies. Diffusion of the jet is both vertical and horizontal.

Vertical dissipation:- The second method of kinetic energy dissipation involves the vertical direction. Vertical dissipation may be accomplished by discharging the water as a jet from an outlet high above the tailwater, with the jet disintegrating through air-entrainment as it falls. Vertical dissipation may be achieved by means of the flip-bucket where the flow is given a trajectory that has a component of velocity upward and then downward.

A jet also may be travelling vertically upward, as from a manifold type stilling basin; or vertically downward, as from a drop or a cantilevered outlet. However, the effective dissipation of the excessive kinetic energy in the jet is dependent upon the jet being submerged. A basic concept of energy dissipation applicable here is that turbulence is created by viscous shear which diffuses the jet with an increase in discharge, a decrease in energy, and a constant momentum flux in the direction of flow. The remaining energy is spread radially and then dissipates as it moves downstream.

Dissipation by impact:- A fallacy often associated with energy dissipation is that of water impact upon resistance elements such as floor blocks. It is rather obvious that energy dissipation can occur only by means of the turbulence produced by the shear at the interface of water and water, water and air, or water along a boundary, since no energy can be transmitted to a stationary solid surface simply by the static condition of pressure acting against it. Obtaining energy dissipation requires turbulence produced by fluid resistance and viscous shear, not impact.

Another type of flow phenomenon that is misleading in the concept of energy dissipation is the roller (horizontal vortex) which represents not the source but the locale of energy dissipation.

General Cause of Problems Involving Energy Dissipation

In the foregoing section consideration has been given to the concepts and principles of energy dissipation applicable to hydraulic design involving excessive kinetic energy. Consideration is now given to the general cause of problems associated with this kinetic energy.

Most problems involving energy dissipation in flowing water are associated with either a conveyance system, natural or man made, or a hydraulic structure of some type located in the conveyance system. When resistance to flow in conveyance systems is reduced, the velocity increases and there results a tendency toward erosion.

For example, overgrazed land under intense rainfall will be subject to eroding velocities, typified by a sheet of water moving overland. The sheet of water becomes a myriad of tiny rivulets which eventually cause gullies and bad lands, unless the erosion is curtailed by conservation measures. A gully that is permitted to form will continue to enlarge in the region of steep slopes where the eroding velocities are the greatest. Even in natural canals and laterals, when precaution is not exercised, the problem of eroding velocities will increase in magnitude with each growing season. This is especially true of neglected irrigation or drainage ditches, where erosion is often a slow but consistent process which increases on a grand scale during floods.

Structures in conveyance systems provide the greatest variety of problems involving energy dissipation to avoid excessive scour of the conveyance channel. They are generally classified as either: (a) control structures, or (b) outlet structures. The control structure, such as a spillway or a sluice gate, is used principally for regulating the flow of water. Whereas the outlet structure, such as a culvert or a tunnel, is used principally as a by-pass for water.

Control structures:- One of the most common type of control structure used in conveyance systems is the spillway or overfall structure. The water discharged over the spillway usually falls, with only slight resistance, through a height corresponding approximately to the difference of headwater and tailwater elevations. Thus it acquires a velocity which is generally much greater than the natural stream velocity at the given site and upsets the equilibrium of the stream by the concentration of excessively high velocities and abnormal underground pressure gradients. This presents a large potential for serious erosion.

Another familiar overfall structure in irrigation systems is the vertical or inclined drop. Water passing over the drop is accelerated by the drawdown of the water surface. A serious effect often occurs when the width, or crest length, of the drop is so large that the depth of water on the crest is very low. Then the drop in the water surface causes a decrease in the cross-sectional area of the water, with a significant increase in the velocity, and this may have a marked effect for considerable distance upstream, resulting in erosion of the channel bed and banks. Furthermore, downstream at the base of the drop there is the problem of energy dissipation. The vertical drop acts as a free overfall, with the energy a function of the height of fall; and the inclined drop acts as a spillway with its energy a function of the difference of headwater and tailwater elevations. The problem of energy dissipation associated with vertical drops is likewise found where sills and check dams or gates are used.

Another type of control structure frequently used in irrigation and drainage systems is the sluice gate. With it, the high-velocity flow that is developed through the sluice-gate opening must be controlled and dissipated. Often at flood stage, when the water is high enough to pass over as well as under the gate, there is an additional energy factor of excessive gate vibration which endangers both the gate and the gate structure.

In structures with valve-controlled outlets, the jet formed by the valve becomes the source of the energy problem. The extent of the energy available for scour below the outlet is dependent upon whether the jet is divergent, such as in the Howell-Bunger valve, or convergent, such as in the needle valve. The divergent jet has the lesser concentration of energy since it is dissipated over a much larger area than the convergent jet.

Outlet structures:- Outlet structures in irrigation and drainage systems that incur energy dissipation problems are conveyance structures such as tunnels and culverts. The problem is usually confined to the drainage culvert in a waterway having an erodible bed. Since the flow is unregulated, the amount of energy available for scour is dependent on the upstream discharge -- which, with many cross drainage culverts, is generally unknown and frequently excessive at flood times. The problem is complicated further when such a culvert is cantilevered above the downstream bed. Thus, the problem may be manifold at large discharges with a vortex formation at the submerged inlet. This condition results in surge flow through the pipe, as well as eddies and energy waves near the entrance and outlet of the culvert. These can be of sufficient magnitude to erode easily the channel banks and bed. There is also the problem of dissipating the impinging jet at the outlet.

Types of Energy Dissipation Structures

The purpose of this section is to present the application of the principles of energy dissipation now being used in hydraulic design for solving problems of excessive kinetic energy. In brief, it is a review of the types of energy dissipation structures of the following classification: (a) structures employing horizontal dissipation of energy, and (2) structures employing the vertical dissipation of energy.

Structures employing the horizontal dissipation of energy:- Water flows in open channels through the action of gravity and the expenditure of potential energy to overcome the resistance to flow. It is the magnitude of the velocity head, which represents the kinetic energy, that must be considered in the kinetic energy dissipation.

To reduce the velocity head some form of resistance must be provided to the flowing water. The form of the resistance will depend upon the flow conditions either created or existing in the conveyance system. For steady flow, where velocity head is not significant, the resistance may be provided by the surface in contact with the flowing water. Artificial resistance of some form is usually added to the wetted surface (wetted perimeter) if it is significant. Adding artificial resistance to the channel bed and banks is one of the most universal forms of horizontal energy dissipators.

For the open channel, the extent of bed and bank protection will depend on such factors as velocity magnitude and depth of flow, as well as the general condition of the bed and banks. Types of artificial elements frequently used are wattles, fascines, rock sausages, and concrete tetrahedrons. In larger channels sills and check dams are often employed to reduce the slope of the channel (hydraulic gradient), to prevent erosion of the bed, and to stabilize the toe of the slope by raising the valley floor. The extent of energy dissipation by the roughness elements is measured by the amount of turbulence created within the flow as evidenced by rollers and eddies.

However, the most common method of providing channels with artificial roughness is the use of riprap or rock aggregate. It is not always available in large quantities, but can be made most effective if a graded material is used with a size range varying from the maximum size of the bed and bank material to the largest size of riprap available not to exceed those sizes in the cobble classification.

The design for horizontal dissipation of energy below overfall structures generally is more complex than that for the open channel itself. Energy dissipation below overfall structures is most commonly and efficiently accomplished by using some type of stilling basin, which is a structure so designed as to transform most of the kinetic energy of the high-velocity flow into turbulence, and eventually into heat.

In the problem of designing energy-dissipation features of a stilling basin, the engineer is confronted with many variables in addition to those pertaining to the nature of the stream bed. Among these may be the frequency and intensity of flood, the degree of protection to be provided for very infrequent floods, the elevation of tailwater at various discharges, and the flow downstream from the basin on the erodable stream bed.

Furthermore, because of the interrelation of these variables, it is difficult to standardize spillway apron designs, or to be assured of satisfactory results by simply copying existing structures which operate satisfactorily. This is particularly true because certain energy dissipating devices are especially sensitive to tailwater elevations -- slight differences in tailwater depth being sufficient to change the type of performance from excellent to destructive. Not infrequently it is necessary to have the design checked by a model test.

Experiments on spillway models invariably demonstrate that energy dissipation can be achieved in the models by the use of aprons -- horizontal, sloping or upturned -- and by interposing baffle piers, or sills -- dentated, solid or stepped -- in the path of the main jet. In this way the super-critical flow is transformed into sub-critical flow. If the basin is improperly designed, the energy may be only slightly dissipated and a high velocity jet will then be diverted farther downstream where it will dissipate itself in the form of large waves and eddies.

One of the simplest and most effective methods available for throwing a large mass of water into extremely violent turbulence and dissipating its energy is the use of the horizontal hydraulic jump. The jump is usually formed in stilling basins by interposing baffle piers, sills, or other resistance elements in the path of the main jet. The flow in the jump is changed from super-critical to sub-critical. The hydraulic jump, however, is a sensitive phenomenon which may move easily upstream or downstream and thereby become ineffective. Therefore, blocks or sills are usually placed on the floor of the channel to help stabilize the location of the jump and to help reduce the length of the stilling basin. A very effective and efficient design of a structure utilizing the hydraulic jump is the SAF stilling basin. This basin was developed by Blaisdell and is an energy dissipator with a horizontal apron, together with chute blocks, floor blocks and dentated end sills.

In designing basins for outlet works, the method used for energy dissipation depends on the relation of the center line of the outlet to the downstream bed elevation. When the outlet is above tailwater elevation and the channel bed is comparatively stable, a free jet may be discharged into the tailwater which acts as a stilling pool. Where conditions downstream do not permit the use of the tailwater as a stilling pool, stepped basins with dividing walls or chutes of combined circular and sloping sections are often used.

Other forms of external resistance used for outlet elevations between river-bed and tailwater are chute basins, in which the jet flows down a trajectory-curved chute onto a level apron where a hydraulic jump is formed. Transitions with chute blocks, floor blocks and sill may be used if necessary.

When outlets are lower than bed elevation, either an upturned apron or a hump, or a combination of both, is used to raise the high-velocity flow to the proper elevation, so that a jump may be formed on another apron downstream. Dividing walls and floor blocks are frequently used with the upturned apron, while the hump has a simple curve on its upstream side, and its downstream side is curved to fit the trajectory of the maximum jet.

Structures employing the vertical dissipation of energy:- When a jet is discharged horizontally over a stilling pool, its impact on the water in the pool and its scour effect on the bottom of the pool will be greatly reduced if the jet is flared out laterally through a jet deflector, before it strikes the pool. Such an opportunity exists if the jet is from an outlet where the width of the issuing stream is much less than that of the tailwater channel. The thin, fan-shaped sheet of water tends to skip along the tailwater surface at the point of impact, and has only slight penetration. In this case energy dissipation is accomplished by internal interface resistance provided by air drag on the dispersed jet and shear between the skimming water and tailwater.

A high-velocity flow in a conduit loses much of its kinetic energy by external resistance of the walls; but when more complete dissipation is necessary, artificial elements, such as flow-guides and baffle plates, are placed in the conduit. The flow-guide breaks up the jet and improves flow distributions. The baffle-plates break up the jet further, and by acting as weirs, provide backwater which submerges the jet.

When the tailwater below a spillway is too shallow for the formation of a hydraulic jump and construction of a stilling pool is considered undesirable, the flip or upcurved spillway bucket should be used, so that the jet is deflected upward into the air and strikes the tailwater some distance downstream from the bucket. The method of energy dissipation of the impinging jet is best accomplished in the vertical direction and involves the diffusion of the submerged jet into the surrounding flow or tailwater. Obviously the effectiveness of the dissipation will depend on the extent of jet submergence.

Another type of structure employing the vertical dissipation of energy is the simple drop in an irrigation canal, a roadside ditch, or a gully. This drop may be equipped with a permanent type of stilling basin with resistance elements, such as baffle piers and sills, which will force the horizontal dissipation of energy. Instead, it may be equipped with a semipermanent stilling basin armorplated with graded riprap, and with a tailwater of depth at least one-third the height of fall, which dissipates the kinetic energy vertically downward. The vertical dissipation of the energy in this instance is accomplished by shear against the graded aggregate (external resistance), and through jet diffusion (internal resistance).

A cantilevered pipe outlet, such as a culvert under a roadway, is another example of a situation where the kinetic energy may be dissipated vertically downward.

The dissipation of energy vertically upward may be accomplished by a manifold type structure. In this case the water is turned in the structure from horizontal to vertically upward and lack of the jets is dissipated by diffusion as it flows upward through the tailwater. When the jets have reached the surface, the kinetic energy has been largely dissipated. The energy which remains is diffused radially outward so that it too is rapidly dissipated as it travels downstream.

II. PREVIOUS INVESTIGATIONS ON SCOUR AND SCOUR CONTROL IN MOVABLE BEDS

Research into the problem of scour by jets has been carried on more extensively for the past two decades than in any previous years. Significant to the 1935-45 decade was the fact that model and field investigations were concerned with the effect of scour by a two-dimensional jet, as, for example, the jet from a simple drop in a canal.

Among the early investigators were Einwachter (8), Escande (9), Jaeger (12), Muller and Eggenberger (16), Schoklitsch (20), and Veronese (24). Their work has been notable in the broadening of the concept of the phenomenon of scour. In 1940 Rouse (18) made a study of scour, which has since proved to be a primary contribution of the 1935-45 era.

The first part of this chapter considers briefly the contributions of the early investigators to the study of scour; the latter part is a summary of an extension of Rouse's work by Doddiah (6), Thomas (23), and Hallmark (11). In this respect, Doddiah considered the three-dimensional case of scour; and Thomas and Hallmark considered the two-dimensional case of scour. Because of its singularity as the only investigation of the three-dimensional case, the study by Doddiah will be considered last.

Investigations by European and American Scientists

The study of localized scour by jets in sand beds have been relatively few in comparison to other studies of hydraulic phenomenon.

Schoklitsch in 1935 studied the scour depth in an unprotected river bed below a free overfall and developed the following equation

$$h_s = (3.15/d_n^{0.32})\ h_1^{0.2}\ q^{0.57} \qquad (1)$$

where h_s is the maximum depth of the scour hole in feet below the water surface, over the entire width of the stream after an extended period of time at a constant discharge q in cfs per linear foot;

h_1 is the elevation difference between upstream and downstream water surfaces in feet; and

d_n is the diameter of bed material in millimeters of which 10 per cent by weight is coarser.

In 1937 Veronese derived a general equation from model tests of the erosion of a sediment bed below a weir (overfall) structure. It is

$$h_s = (2.56/d^{0.42})\ h_1^{0.225}\ q^{0.54} \qquad (2)$$

where h_s is the maximum depth of scour;

h_1 is the velocity head; and

q is the discharge in cfs per linear foot.

The diameter d, however, is mean diameter of the gravel bed.

Observations of flow conditions downstream of a fixed step were made by Einwachter in 1930 and later by Escande in 1939. They found four conditions and types of flow to occur downstream of the fixed step:

(a) Free flow, rising jet (undular jet),

(b) Free flow, diving jet,

(c) Submerged flow, rising jet, and

(d) Submerged flow, diving jet.

In 1939 Jaeger conducted research on the problem of scour downstream of a fixed step or apron and found that these four main types of flow occur equally as well in an erodible bed. In addition he found that, at least at the beginning, certain forms of scour holes appear to be unstable, and different profiles are obtained alternately. His conclusions were that the final form of scour pattern depends on the shape of the fixed step upstream, on the tailwater level, on the duration of the experiment, and on the amount of bed load carried by the upstream flow.

In 1944 Eggenberger made model studies similar to those conducted by Veronese and from these studies he derived the following formula

$$h_s + b = 15.9 \left(h_1^{0.5} q^{0.6} / (d_{90})^{0.4} \right) \tag{3}$$

where h_s , h , and q are as defined for Eq 2;

b is the depth of tailwater; and

d_{90} is the grain diameter chosen, meaning that 90 per cent of the bed material is finer than d_{90} .

The significant factor of the studies by Eggenberger was that he considered the scour depth to be a function of the tailwater depth.

In 1940 Rouse, in his experimental study on scour, provided the basis for more recent studies on scour and scour control. In this study, Rouse expressed the depth of scour as a function of time T, mean velocity of inflow V, particle fall velocity w_m, and the geometric standard deviation σ_w, in the following equation

$$h/a = \phi_1 \ (w_m T/a \ ; \ V/w_m \ ; \ \sigma_w) \qquad (4)$$

where a is a length characteristic of the boundary geometry. Rouse made experimental studies with a vertical, deeply submerged two-dimensional jet with the upstream face against a wall, striking a level bed of sand. On the basis of experimental data he derived the following equation

$$h/b = \phi_2 \ (\log (w_m T/a) \ (w_m/V)^3 \ ^{(V/w_m - 1)} \ . \qquad (5)$$

Rouse demonstrated that in localized scour, caused by an impinging jet, the important variables are w_m, σ_w, tailwater depth, time of scour, and the velocity and area of the impinging jet.

On the basis of the research by Rouse and others, Thomas, in 1953, studied the scour resulting from a two-dimensional jet or sheet of water issuing from a free overfall and impinging on an alluvial bed also covered by a pool of water having various depths. More recently Hallmark studied the influence of graded riprap on the control of scour when applied to those conditions studied by Thomas.

Fundamental Principles of Two-dimensional Scour

The study of scour at the base of a free overfall made by Thomas was essentially a study of two-dimensional scour. Scour at the base of a free overfall is a complex phenomenon. It represents, in fact, the most extreme degree of unsteady, non-uniform flow, since the stream bed as well as the water surface may be continuously changing in form. Therefore, an analysis of the scour phenomenon can be obtained only by so simplifying the boundary conditions that only the most significant variables need be considered. Obviously this is an oversimplification of the problem, in that the phenomenon as analyzed bears little relation to actuality. Nevertheless, by following this procedure a basic understanding of at least the most essential aspects of the problem is gradually attained. In this respect, Thomas approached the problem by making proper simplifications for his laboratory investigation, and then, by dimensional analysis, determined the significant variables pertinent to his study.

Theoretical Considerations of Two-dimensional Scour

For the study of Thomas and Hallmark reported herein, the physical arrangement of the free overfall was a sudden drop in elevation from one horizontal bed to a lower horizontal bed. The drop occurred over a sharp edge with ventilation under the nappe. With such physical conditions, the depth over the edge of the crest was controlled only by the discharge per unit length of crest. Furthermore, for the experimental tests the tailwater was varied. The geometric mean size w_m of the bed material was held constant, but the deviation σ_w of sizes about this mean size was varied, except for series B sand of Hallmark's studies.

Based upon the foregoing assumptions, the following relationship was assumed to exist:

$$h = \emptyset_3 (H , b , q , T , w_m , \sigma_w) . \qquad (6)$$

This relationship was simplified and a number of variables were reduced by means of the Pi-theorem to give

$$h/b = \emptyset_4 (H/b , q/w_m H , qT/H^2 , \sigma_w) \qquad (7)$$

where h is the depth of scour from the original bed level to the bottom of the scour hole,

b is the tailwater depth from the original bed level to the top of the water surface,

H is the height of fall from the bed level upstream to the bed level downstream,

q is the discharge per unit width of crest,

T is the time of scour,

w_m is the geometric mean fall velocity of the bed material being scoured, and

σ_w is the standard deviation of fall velocity about the mean fall velocity.

Using the same physical arrangement as Thomas and using two different gravel mixtures, Hallmark conducted an extensive experimental program in order to determine the relative depth of scour as a function of the parameters, as specified in the foregoing general functional relationship, Eq 7.

The two gravels selected for testing were referred to as Series A and Series B. Series A gravel had the same fall velocity w_m, but a different standard deviation σ_w, than the gravels tested by Thomas. Series B gravel was a natural stream sand, having nearly the same σ_w as Series A, but a different w_m. This gravel was representative of fine sands of natural stream beds. Further tests were made on this gravel as bed material to establish the effects of armorplating a scour hole with larger size particles. The armorplating material was selected so that all the particles were larger than the largest particle size of the bed material. To establish the influence of size gradation of armorplating material on the rate of scour, several uniform sizes were tested; after which a graded mixture was tested. The choice of armorplating was limited to material between 1/4-in. and 2-in. in diameter.

Experimental Results of Research on Localized Scour for Two-dimensional Flow

The experimental studies by Thomas and Hallmark both verified and enhanced the investigations of Rouse, Doddiah, and others on scour by jets. Specifically, they considered the factors affecting the depth of scour to be the rate of flow, height of fall, tailwater depth, rate of scour, gravel size, sorting process, and armorplating. Their findings and observations on the foregoing factors are presented briefly as follows:

Rate of flow:- The rate of flow q has two important effects on scour, its initial penetration of the bed material and its continuous movement of the bed material out of the scour hole. The energy and momentum flux are related to the ability of q to penetrate or strike the bed material. This momentum and energy must be diverted or dissipated by the force from the bed and by the turbulent action, or else the particles are rapidly put in motion until a balance is established by the shearing forces within the pool. The movement of the particles from the scour hole is a function of q and the tailwater depth b. This relation will be explained in the discussion of the tailwater depth in a following section.

Height of fall:- The height of fall is related to the velocity and energy of the impinging jet. By determining an empirical relationship between h/b, H/b, and q/w_mH, it was shown that the tendency for decreased h with increased H, indicated by q/w_mH, is more than offset by the opposite effect of H in H/b. Thus, the depth of scour was found to increase slowly as H increases.

Tailwater depth:- In studying the tailwater depth b, several important characteristics were noted. First, for a minimum tailwater depth there is a high rate of scour. At a shallow tailwater depth an optimum depth is reached which, if varied (either increased or decreased), causes a greater depth of scour. By further increasing the tailwater depth a critical tailwater depth is encountered where an increase in tailwater depth decreases the amount of scour. Doddiah was one of the first to observe and discuss critical tailwater depth.

Optimum and critical depths were found to occur only for the greater heights of fall and lower rates of flow.

The optimum tailwater depth appears to represent approximately the dividing point between two conditions of scour. At tailwater depths less than optimum, the jet was deflected vertically upward with a high carrying capacity. The mechanism of scour at b values less than optimum is comparable to the condition of maximum jet deflection described by Rouse (18). At tailwater depths greater than optimum, the jet was more widely diffused causing a broad curved scour hole. Under the more active conditions, where the carrying capacity of the jet was large, the particles were carried out of the scour hole in suspension. In general, this mechanism is comparable to the condition of minimum jet deflection described by Rouse.

Rate of scour:- The depth of scour in all gravels increased directly with a geometric progression of time. Therefore, an equilibrium depth of scour cannot be expected in either the bed material or in armorplating tests.

Gravel size:- The importance of the gradation of aggregate in the control of scour was established by the standard deviation σ_w. As σ_w increases the rate of scour decreases, for bed material of the same w_m. For low values of the parameter qT/H^2 of Eq 7, the influence of σ_w is not great, but increasing qT/H^2 to 3×10^5 indicates the scour with material having a large σ_w is almost eliminated as compared with the scour of the material of small σ_w. In general a 50 per cent increase in σ_w will give a 50 per cent decrease in scour.

Sorting process:- Selective sorting of graded material occurs, so that with a wide variation in size of bed material the bottom of the hole gradually becomes paved with a progressively coarser material, thus decreasing the effective fall velocity of the sediment and reducing the scour rate.

Armorplating:- The use of armorplating materials considerably decreased the rate of scour. Four different size-ranges of armorplate gravel were used, each decreasing scour with increasing amounts of armorplate material applied to the scour hole.

The larger size aggregate used as armorplate was found to decrease the rate of scour less than the smaller size. By using a graded mix of these sizes a still greater decrease in the rate of scour was obtained than for any of the separate sizes tested alone.

An explanation of the foregoing phenomenon is as follows: When only large size aggregate is placed on the bed material, there are large interstices between the piers of aggregate. Thus, the small relatively high velocity jets, which are formed as the falling jet strikes the large aggregate, are dissipated while scouring the bed material exposed by the interstices. These jets, with a velocity component predominantly vertical, lift the finer bed material through the interstices. At the same time a roller, which marks the development of a ring-vortex as the main jet diffuses, sweeps over the surface of the developing scour hole and carries the scoured bed material into the main stream flow. Furthermore, the scouring action around the large aggregate causes its subsidence and eventual disappearance into the bed material. Therefore, the large aggregate does not function as armorplate.

In contrast to the large aggregate, a graded mixture, with sizes ranging from that of the bed material to the largest sizes of riprap used as armorplate, has its interstices filled by the smaller sizes of the mixture. By this means each particle of riprap is protected by smaller particles underneath so that it does not become undermined. Therefore, the graded aggregate functions as an armorplate against scour, and proved to be the best type of armorplate material tested.

It was also found that an increase in the amount of armorplate applied produced a corresponding decrease in the rate of scour. Since an increase in the amount of armorplate material would increase w_m of the bed material, it is evident that the ratio V/w_m, where V is the velocity of the impinging jet, would approach unity. Furthermore, the relative rate of scour produced by a given jet depends only on the ratio V/w_m, approaching zero as this ratio becomes unity. Also, as V/w_m becomes unity, any further increase in the amount of armorplate would not give a significant decrease in the rate of scour.

Thus, for the conditions tested, Thomas and Hallmark concluded that:

1. The depth of scour increased rapidly as the discharge was increased.
2. The depth of scour increased slowly as the height of fall increased.
3. In the zone of high tailwater, scour depths increased as the depth of tailwater increased until a critical depth was reached, beyond which further increases in tailwater depths resulted in smaller scour depths. At low tailwater depths an optimum depth of tailwater occurred which resulted in a minimum depth of scour.
4. The depth of scour continues to increase with a geometric progression of time.
5. A 50 per cent decrease in the standard deviation of the size distribution resulted in a 50 per cent increase in depth of scour when $qT/H^2 = 3 \times 10^5$.
6. Only a relatively small amount of armorplating material is necessary for a relatively large decrease in the rate of scour.
7. The rate of scour decreases with a decrease in the size of the armorplate material when the armorplate material remains larger than the largest size of the bed material.
8. The rate of scour decreases with an increase in the amount of armorplate placed in the scour hole.
9. Graded armorplate material decreases the rate of scour more effectively than uniform material.

Fundamental Principles of Three-Dimensional Scour

Doddiah (8) was among the first to consider the problem of scour by a three-dimensional jet, when, in 1949, he made a study of scour depth, in relatively uniform gravel beds, caused by hollow and solid jets of water flowing vertically downward.

His investigation is summarized in this section. In the analysis of the problem, Doddiah considered the fundamental principles to be (a) the factors that influence such scour, and (b) the analytical or functional relationships between these factors. The results of quantitative studies of localized scour, by Doddiah, are discussed briefly as a final part of this section.

Theoretical Considerations of Scour

One of the most important factors affecting scour is the energy of the jet, which can be expressed by its area and velocity. Also of importance is the angle of inclination of the jet and the distance the jet travels before it reaches the pool which is being scoured. Over the bed is the stilling pool where the lateral extent of the pool is important, as well as the depth of water over the bed.

Finally, the characteristics of the bed material must be given consideration. Rouse has demonstrated that for completely alluvial material, the geometric mean fall velocity and the standard deviation of this fall velocity about the mean adequately characterize the erodibility of the sediment. These variables together with the density completely describe the sediment. As for the two-dimensional case, it is essential that the large number of variables involved be reduced in order that a systematic study can be made of scour by jets. Therefore, in order to simplify the problem, Doddiah imposed the following limitations:

1. The jet issued from a point sufficiently close to the bed that no appreciable disintegration of the jet occurred prior to striking the pool.
2. The scour resulting from the discharge from both a hollow jet and a solid jet of water was compared.
3. The depth of pool above the original bed was varied.
4. The lateral extent of the pool was made sufficiently great that the pool was effectively infinite in size.
5. Two sizes of bed material having a narrow size range were used.
6. The angle of inclination of the jet was held at 90° with the horizontal.
7. During any single run the discharge from the jet was held constant and the elevation of the pool remained fixed.
8. The turbulence within the pool was sufficiently great that any laminar zone near the boundary was ineffective and the influence of viscosity was reflected solely on the fall velocity of the particles.

By dimensional analysis, Doddiah determined the functional relationship between these factors to be

$$\phi_5 \,(b \,,\; V \,,\; A \,,\; T \,,\; \rho \,,\; \rho_s \,,\; w_m \,,\; \sigma_w \,,\; h) = 0 \,. \quad (8)$$

This relationship was simplified and the number of variables were reduced by means of the Pi-theorem to give

$$\phi_6 \,(b/\sqrt{A} \,,\; V/w_m \,,\; w_m T/\sqrt{A} \,,\; \rho_s/\rho \,,\; \sigma_w \,,\; h/\sqrt{A}) = 0 \,, \quad (9)$$

where b is the depth of the pool above the original bed,

V is the velocity of efflux of the jet,

A is the area of the jet,

T is the time,

ρ is the density of the water,

ρ_s is the density of the sediment,

w_m is the geometric mean fall velocity of the sediment,

σ_w is the standard deviation of the fall velocity, and

h is the depth of scour below the original bed level at the particular time T .

The relationship of Eq 9 was further reduced by making certain variables constant. Since natural materials were used, the density ratio was considered constant; and since a narrow size range was used, the standard deviation was also considered a constant. Therefore, the problem resolved itself into

$$h/b = \phi_7 \,(b/\sqrt{A} \,,\; V/w_m \,,\; w_m T/b) \,. \quad (10)$$

In Eq 10 it is seen that the three parameters $b/\sqrt{A}$, V/w_m , and w_m/b form the independent variables and control the variation of

h/b . It is evident that different values for these parameters may be obtained by changing any one of the quantities constituting the parameters. Doddiah conducted his experimental study by varying systematically the six factors, h , b , A , V , w_m , and T .

Experimental Results of Research on Localized Scour for Three-dimensional Flow

Results of this study indicate that for a relatively uniform material the depth of scour depends upon b , A , V , w_m , and T . A comparison of depths of scour obtained by using the hollow jet with those obtained by using the solid jet under similar conditions reveals that scour is influenced also by the shape of the jet.

Experimental data showed that with a 50 per cent increase in discharge with the area remaining constant, there was a marked increase in the depth of scour. Also it was noted that with the discharge held constant and the area decreased 50 per cent, there was also a marked increase in scour. Therefore, other factors remaining constant, the scour increases with velocity whether this velocity increase is brought about either by decreasing the area and keeping the discharge constant, or by increasing the discharge while the area remains constant.

From empirical relationships involving $b/\sqrt{A}$ and V/w_m , it was found that:

1. With given values of $b/\sqrt{A}$ and V/w_m , the increment of scour remains constant with time increasing in geometric progression. In other words, a state of equilibrium in the process of scour cannot be expected at any depth or after any period of time.

2. The rate of scour approaches zero as $(V/w_m - 1)$ approaches zero. This infers that if the bed material were graded the larger size particles would gradually line the scoured hole; thereby decreasing the value of V/w_m and the rate of scour.

3. For any value of h and with V/w_m remaining constant, the magnitude of scour increases with increase in the depth of tailwater. The phenomenon of an increase in tailwater depth giving rise to increasing scour is explained as follows:

With the energy of inflow assumed constant, the extent of the turbulence increases with increase of tailwater depth because with a greater depth there is greater scope for the full development of the flow pattern. With an increase in the size of the zone of turbulence the scour area increases resulting in an increase in the total quantity of material in suspension.

For shallow depths of tailwater, the vertical component of the velocity is predominant which, while increasing the lift, will not help the lateral dispersion of the material. With an increase in depth a pronounced ring-vortex form of flow pattern develops, which increases the horizontal component of velocity. As a result, the bed material is thrown farther and farther from the center of the jet.

This development of flow pattern will result in a maximum scouring capacity at a certain depth depending upon the characteristics of the jet, pool, flow, and sediment. The scouring rates attain a maximum when the depth of tailwater reaches a certain critical value b_c . When the depth exceeds the value b_c , the scouring capacity decreases due to a greater diffusion of the jet in the deeper pool. As the energy of the jet is dissipated, its scouring capacity also decreases.

A study of the scouring capacity of the two types of jets under similar conditions lead to the following conclusions:

1. There does not seem to be any uniformity in the trend of results with respect to the scour caused by the two types of jets when the area of the jets is varied.
2. The scouring capacity, by itself, divorced from other hydraulic and structural factors, is not important enough to make one of the two types of jets superior to the other.

This study was concerned with scour caused by hollow and solid jets, and was one of the first to consider the three-dimensional case. The important findings of the experimental data were:

1. In relatively uniform gravel, scour is directly proportional to a geometric progression of time, and no equilibrium of depth can be expected. This same conclusion was made by Rouse (18).

2. The rate of scour approaches zero as $(V/w_m - 1)$ approaches zero, as also concluded by Rouse.
3. Scour increases with an increase in the depth of water over the erodible bed until the depth reaches a critical value. Any further increase in depth will diminish the resulting scour.
4. For a given area and velocity of jet the scour resulting from a hollow jet, as compared with a solid jet, appears to indicate a single trend.

III. EXPERIMENTAL INVESTIGATION OF SCOUR DEVELOPMENT BELOW A CANTILEVERED PIPE OUTLET

One of the most important tasks in the design of hydraulic structures is the determination of the stilling basin size. Most stilling basins are designed on the basis of the theory of the hydraulic jump, but the coefficients of the given equations admit to considerable differences in the stilling basin size. Because of the efforts to reduce the costs of hydraulic structures, research is faced with the problem of finding ways to reduce the calculated dimensions either by the verification of the use of decreased coefficients in the computations or by developing basin design different from the classic type. In either case it is necessary to deepen the stilling basin below the river bed and then there is the additional problem of transition from the stilling basin to the downstream river channel without the presence of excessive kinetic energy in the flowing water.

If the hydraulic jump were to be eliminated, and if economy were a major consideration, then it is rather obvious that a basin design different from the classic type must be developed. This would be particularly so where cantilevered outlets or small drops are used in irrigation or drainage systems, because both are a very common type of structure. Furthermore, a basin that is economical is usually of a simple design; consequently, the objective of the experimental study of this report was to obtain data that would provide a basis leading to such a design.

Objectives

Specifically, the objectives of this investigation were to determine and record systematically the following:

1. The development of a scour hole below a cantilevered pipe outlet for certain predetermined characteristics of the geometry, the flow, the fluid, and the sediment.
2. The effect of a systematic variation in the geometry and flow characteristics on the scour hole development.

Two fundamental principles were considered essential in the testing program for the development of a basis for design criteria for stilling basins not using the theory of the hydraulic jump. These principles were: (a) the principle of the vertical dissipation of energy, and (b) the use of graded rock aggregate in the control of the rate of scour. Primarily, the immediate objective of the use of graded riprap in armorplating the basin was the development of an empirical basis for its application to the scour hole at any stage of the development of the scour hole.

Such an empirical basis would help in the determination of the effectiveness of riprap armorplate in the scour hole below a cantilevered outlet. The empirical basis, however, would be contingent upon experimental data of armorplating of preshaped scour holes -- that is, standard scour holes based on certain flow, fluid, geometry, and sediment characteristics. The criteria for the standard scour hole would be based on the experimental data of this study on scour below cantilevered outlets.

Experimental Program

The solution to the process of movement of sediment, whether by flowing water or by the action of a jet, is a very complicated problem. It depends upon so many variables that it is generally impossible to solve the problem by using purely rational methods. A theoretical approach to the problem can be no closer to the prediction of the needed solution than the recognition of the parameters which are involved in the phenomenon and their generalized functional relationship. In experimental research, dimensional analysis offers one of the most direct means of exploring the general forms of functional relationship between the variables.

For purposes of dimensional analysis, all variables considered in this study of the phenomenon of scour by a jet from a cantilevered outlet may be arranged according to group classification as follows:

1. Geometric characteristics,
2. Flow characteristics,
3. Fluid characteristics, and
4. Sediment characteristics.

The geometric characteristics are:

- b tailwater depth - L
- V_s volume of scour - L^3
- h^* the cube root of the volume of scour - $(V_s)^{1/3}$ - L
- H_1 height of fall measured from the pipe invert to the initial bed below - L

L length of pool - L

B width of pool - L

d_s depth of sediment - L

θ angle which the central streamline of the jet makes with the surface of the pool.

The following assumptions were made to determine the characteristics of geometry to be used: the pool was considered of infinite extent, and the experiment was planned so that the depth of sediment will never be exceeded by the depth of scour. The corresponding variables, L , B , and d may be considered as constants. The dependence of θ on the factors Q , H , and b permits its omission.

The <u>flow characteristics</u> are:

V velocity of jet - L/T

A area of jet - L^2

t duration of inflow or time of test - T

C_s concentration of sediment in the jet

D coefficient of turbulent diffusion in the pool.

Of the above variables, C_s can be eliminated by using only clear water, C_s becomes a constant, and D and h^* are dependent variables. Therefore, the use of one omits the use of the other and h^* was considered significant to this study.

The <u>fluid characteristics</u> are:

μ dynamic viscosity of fluid - FT/L^2

γ_w specific weight of fluid - F/L^3

ρ mass density of fluid - FT^2/L^4 .

The viscosity μ is important only as it affects the fall velocity of the particles, and may be considered a constant. Therefore, the significant fluid characteristics are ρ and γ_w .

The sediment characteristics are:

ρ_s mass density of sediment - FT^2/L^4

w_m geometric mean fall velocity of the gravel particesl - L/T

σ_w standard deviation of the fall velocities w_s about w_m

α natural angle of repose of the bed material submerged as indicating the shear capacity

γ_s specific weight of the bed material - F/L^3

n porosity of the bed material.

Since n and α are nearly constant in natural cohesionless sediments they may be considered as constants. Of the above variables w_m , σ_w , ρ_s , and γ_s remain to be considered.

By dimensional analysis the variables selected for study may be arranged in the following function:

$$\phi_1 (H, h^* , M_F , b , t , \rho , \rho_s , w_m , \sigma_w) = 0 \qquad (11)$$

where all variables are previously defined except M_F which is the momentum flux (ρQV) of the water jet at the point of impingement of the tailwater surface.

Since there are nine physical quantities involved and since three fundamental physical dimensions are required to express them, there will be six non-dimensional parameters according to the Buckingham Pi-theorem. Choosing H , ρ , and w_m as the repeating variables, dimensional analysis yields

$$\phi_2 \; (h^*/H \; ; \; M_F/H^2 w_m^2 \rho \; ; \; b/H \; ; \; w_m t/H \; ; \; \rho_s/\rho \; ; \; \sigma_w) = 0 \; . \tag{12}$$

By using homogeneous gravel mixtures for each test and clear water at nearly constant temperatures ρ_s/ρ and σ_w were considered as constants. The relationship of Eq 12 now becomes

$$\phi_3 \; (h^*/H \; ; \; M_F/H^2 w_m^2 \rho ; \; b/H \; ; \; w_m t/H) = 0 \tag{13}$$

from which

$$h^*/H = \phi_4 \; (M_F/H^2 w_m^2 \rho \; ; \; b/H \; ; \; w_m t/H) \tag{14}$$

or

$$h^*/H = \phi_5 \; (E_o/H^2 w_m^3 \rho \; ; \; b/H \; ; \; w_m t/H) \tag{15}$$

where E_o is the energy flux (ρQV^2) of the jet of water at the point of impingement of the tailwater surface.

In the above relationship, the three parameters $E_o/H^2 w_m^3 \rho$, b/H , and $w_m t/H$ form the independent variables and control the variation of h^*/H . It is evident that different values for these parameters may be obtained by changing any one of the quantities constituting the parameter. A testing program based on the variation of these quantities is shown in Table 1 of the Appendix.

Experimental Equipment and Procedure

Scour development below cantilevered outlets is a complex problem. Its analysis in the foregoing sections indicates that limitations must be imposed on its scope to make a laboratory investigation practicable. Therefore, the range of variables was fixed for the purpose of obtaining adequate information on the most significant variables. This section describes the equipment that was necessary and the procedure that was followed in the systematic collection of data.

Experimental equipment:- The experiment was conducted in the Hydraulics Laboratory at Colorado State University. The laboratory equipment employed consisted of a cantilevered pipe outlet, bed material of a sand and gravel mixture, a water-supply system with means of regulating the discharge, and a flume to accommodate the bed material and the flow.

Fig. 5 shows the equipment assembly. Clear water was pumped from an underground sump to an 8-in. pipe line (P_1 , P_2 , P_3 , P_4 , and P_5) by a 60-horsepower Fairbanks-Morse No. 14 propeller-type pump. The discharge through the supply line was regulated by the valve V_1 located in pipe P_3 . The flow was measured by an orifice meter installed in pipe P_2 downstream from the pump.

Guide vanes were used in the 90° bends connecting pipes P_3 , P_4 , and P_5 , to prevent zones of separation from developing and to help establish uniform flow conditions in pipe P_5 . Height adjustment of pipe P_5 was provided, in 2-in. steps, over a 3-ft vertical interval. Also for height adjustment, short sections of pipe of varying length

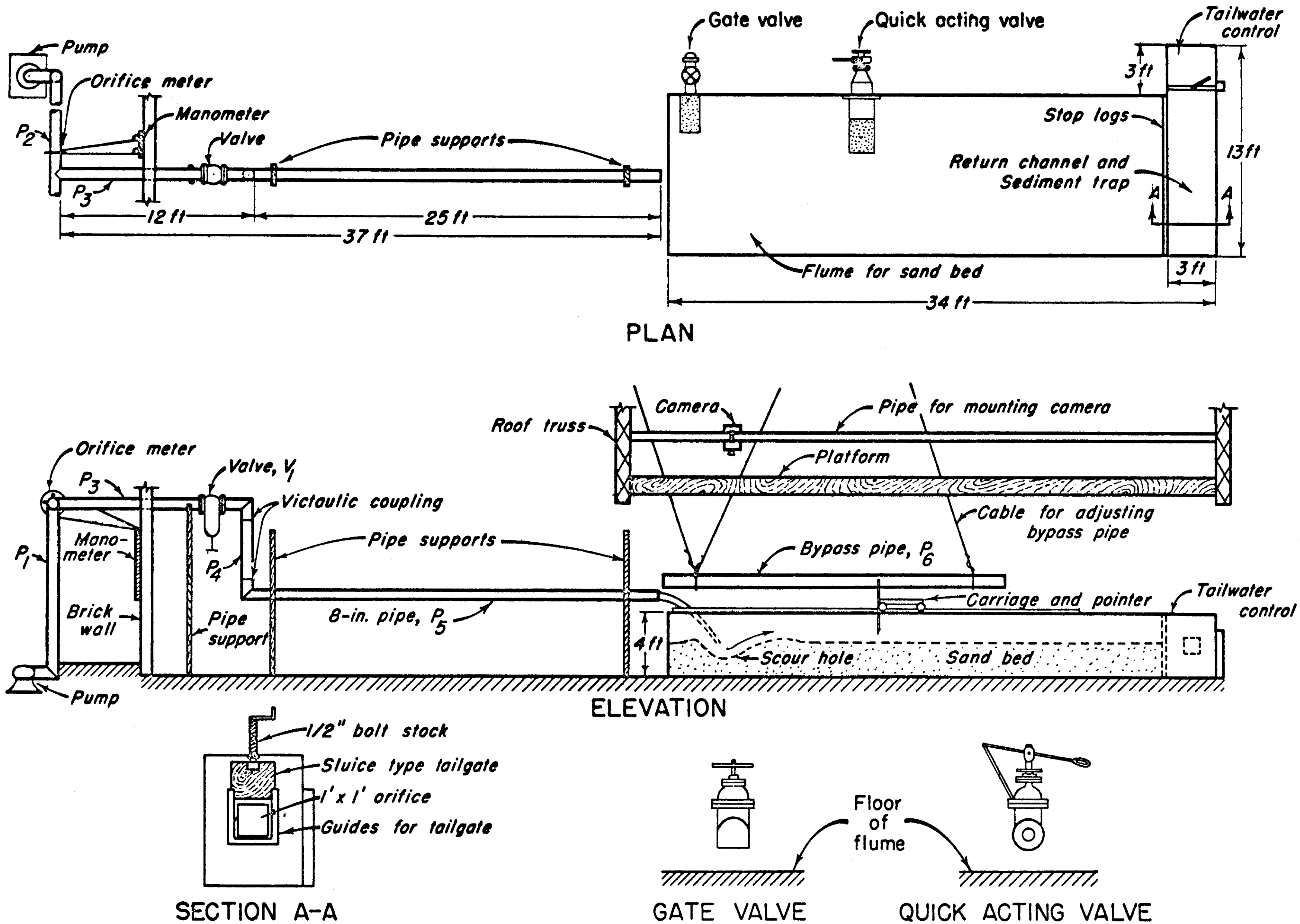


Fig. 5 Laboratory layout for study of scour below a culvert outlet

were made to interchange with pipe P_4 . Victaulic couplings between pipes P_3 , P_4 , and P_5 were used. The installation of the water supply line was such that the pipe P_5 was exactly centered over the upstream end of the flume. The trajectory of all jets started at a fixed height of 4 ft above the gravel bed during the tests conducted to date.

The flume, of dimensions given in Fig. 5, was filled to a depth of 2 ft with gravel. Three feet from the downstream end of the flume the bed material terminated in a 3-ft wide sediment trap. At the end of the trap was a 1 ft square orifice through which the water passed before spilling into the return channel to the sump.

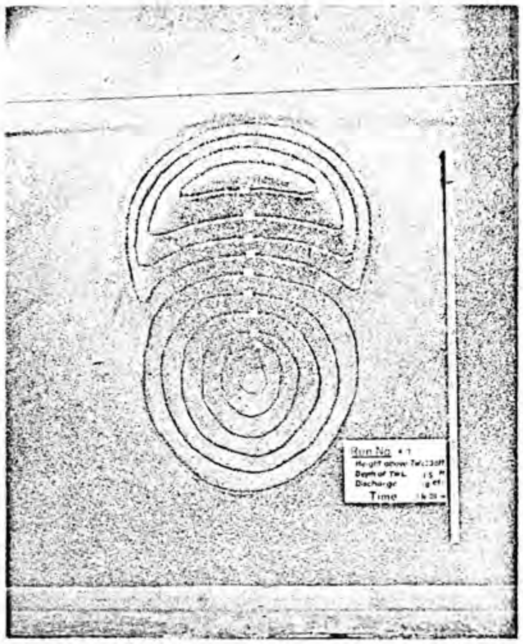
To vary the depth of water over the gravel bed, a sluice-type tailgate was used to regulate the size of opening of the orifice outlet. The tailgate was operated by means of a 3/8-in screw bolt which permitted a close adjustment in the water depth. A point gage was used to control tailwater depth. It was located at the inside corner of the flume near the point of jet impingement. Since it was necessary to have a known depth of water over the gravel before the jet was allowed to strike the pool, a pipe P_6 was used to divert the jet downstream beyond the extent of the test area. A flexible rule and a point gage were used to measure the horizontal and vertical dimensions of the scour hole.

Since time was an important variable, a quick change in the volume of water in the flume was found to be a desirable factor. It was noted that a rapid change in tailwater depth, if properly controlled, would represent a saving of several hours for each experimental run. This point will be made clear in the following section on procedure.

An installation that proved satisfactory in controlling tailwater was two 4-in outlet pipes with valves placed on the flume floor. One pipe with a gate valve was located against the end of the flume near the scouring area; the other pipe with a quick acting valve was located near the mid-point of the flume. The pipes projected one foot into the flume. To prevent undesirable flow conditions near the scour hole as well as sand from entering the sump, closed cylinders of heavy brass plate were attached to the inlet of each pipe. The cylinders, three ft long and one ft in diameter, were perforated with 1/4-in holes on 2-in centers. This fact made it necessary to wrap each cylinder with a double thickness of 1/8-in hardware cloth in order that undesirable movement of water or entry of sand into the sump be adequately curtailed. The pipe with the quick acting valve permitted rapid adjustment of tailwater depth; the other unit permitted rapid control of the water surface in the scour hole.

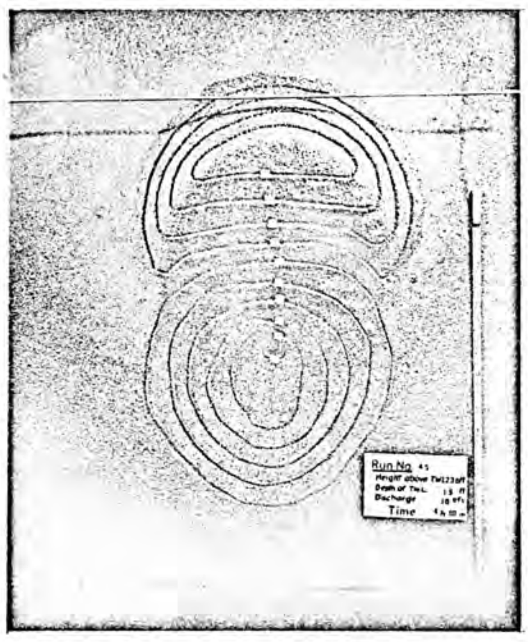
A photographic record of the scour hole development was made as illustrated in Fig. 6. To obtain a plan view of the scour hole it was necessary to construct a platform above the flume. A 2-ft by 14-ft platform bolted to the roof trusses and supported at its one-third points was sufficient for support and maneuverability without interfering with the focal area of the camera. Two cameras, a Speedgraphic 4 by 5 and a Rolleiflex 3.5, were used for taking pictures. A portable photo-flood lamp with 1000-watt photo-flood bulbs was used on either side of the

Time of scour: 0.5 hour



Time of scour: 1.0 hour

Time of scour: 2.0 hours



Time of scour: 4.0 hours

Fig. 6 Photographic record of the development of a scour hole

$Q = 1.0\,ft$ $b = 1.5\,ft$ $H = 4.0\,ft$

flume for the proper lighting effect. A bank of four 150-watt spotlights mounted directly above the outlet of pipe P_5 were used for auxiliary lights.

A carriage was essential for making measurements of the scour hole as the water surface receded. The carriage used was a 2-in. by 12-in. wooden plank with 3-in. brass wheels. Rails for the carriage were 1/8-in. by 2-in. angle iron which extended for 20 ft along the top of the flume walls. Two 1/8-in. by 2-in. angles with braces were bolted to the carriage and used to support a bed leveler consisting of a 1-in. by 4-in. wooden plank and two 1/8-in. by 2-in. angles. The leveler was secured to the carriage by means of C-clamps.

The angle of jet impingement was measured by means of a 1 ft protractor, which was held in position on a slotted 1/8-in. by 1-in. steel strap by a wing nut. An arrow held by the wing nut was used in marking the angle. The slotted strap in the form of a T-section permitted vertical and horizontal movement of the protractor.

A mercury thermometer, graduated to 1.0°C, was used to measure the temperature of the water in the flume.

Gravel:- The bed material gravel for the tests was obtained from the Big Thompson River at Evans, Colorado. It was obtained from a commercial company. It was washed once at the gravel pit before being transported and placed in the flume. The gravel was considered to be typical of river and stream bed material of eastern Colorado. Brief study under a microscope revealed that about 55 per cent of the sand particles were quartz grains, 45 per cent orthoclase, and 5 per cent flakes of mica (mostly biotite).

One bed material gravel was used throughout the experiment. The purpose here is to present those data useful in analysis and representing the behavior of the sediment during the testing program.

Seven representative samples of bed material were taken at random from the flume. To determine the size or weight of a sample to be tested, the procedure outlined on page 14 of the publication, "The Profitable Use of Testing Sieves" of the W. S. Tyler Company was followed. The size of sample to use was found to be approximately 250 grams. Tyler Standard Sieve Numbers 4, 6, 8, 10, 14, 20, 28, 35, 48 and 65, with openings having a constant ratio of 1.414, were used. Each sample was sieved for five minutes in a Ro-tap shaker.

The sieve analysis data were plotted on "log-probability" paper, thus making it possible to rapidly determine the median sieve diameter and the standard deviation of the diameter. An analysis of the seven representative samples is given in Fig. 7. By statistical reasoning, as presented by Rouse (18), the average median sieve diameter of the bed material is 2.32 mm and its standard deviation 1.71. Shown on the same figure is an analysis of five random samples taken from the flume bed after 120 hours of tests. Although the curve shows that the fine bed material has been washed away, it is noteworthy that the average median diameter and the average standard deviation of the bed material did not change. The magnitude of the standard deviation is given by the ratio of the 84.1 per cent intercept to the 50 per cent intercept, d_m .

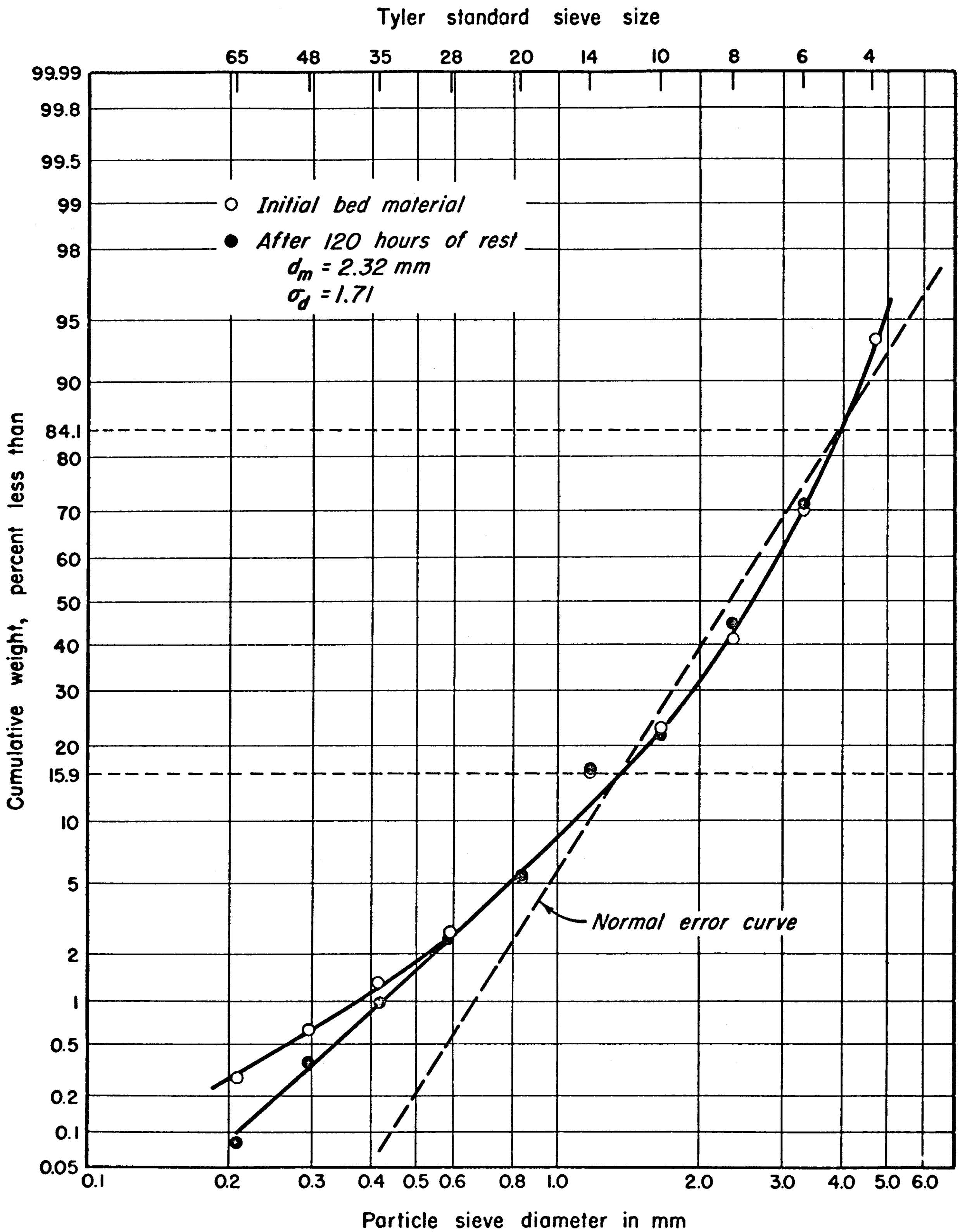


Fig. 7 Sieve analysis curve

Ten representative particles were chosen from each sieve fraction. Each particle was weighed to the neartest 0.1 milligram on a chain-o-matic balance. Since only quartz or feldspar particles were used, the specific gravity of the particles was assumed to be the average published value for these minerals - 2.65.

The mean fall-velocity of the particles was determined by two methods. The first method was to actually measure the rate of fall of the particle in a glass tube 10 in. in diameter and 10 ft long. The tube was filled with Fort Collins public water. The average temperature over the section of the tube in which the velocity measurements were taken was recorded to the nearest 0.1°C (degree centigrade) for each run. The temperature range was from 18.9°C to 20.0°C during the entire testing period of two weeks.

Acceleration to terminal velocity was found to be established in a distance of one ft for the largest size particles. A distance of 18 in. below the water surface was marked on the tube as the starting point for determination of all fall velocities. Each particle was timed independently by two observers over its distance of fall of three feet. The fall velocity of each particle was the average of two or more runs. The mean fall velocity of the bed material used in the flume was found to be 21.37 cps or 0.700 fps.

In the second method, the three mutually perpendicular axes, a* , b* and c* , were measured using an ocular micrometer. Particles were placed on a glass slide using a pair of tweezers. The long (a) and intermediate (b) axes were measured by orienting the glass slide parallel to the micrometer scale. The shortest axis (c) was then measured by grasping the particle with a pair of tweezers and turning 90° on edge and then measuring with the micrometer. The average shape factors, as defined by Corey (4) and given by

$$sf = c^*/\sqrt{a^*b^*} \tag{16}$$

were found for all particles measured. By applying the curves of Fig. 24 and Fig. 25 in the report by Schulz, Wilde, and Albertson (22), the mean fall velocity of each particle for the given shape factor was determined. By this method the mean fall velocity of the bed material used in the flume was found to be 20.56 cps, or a difference of four per cent from the measured velocity.

A log-normal plot of the measured mean fall velocity against "per cent by dry weight less than" for each sieve size is shown in Fig. 8. Again by statistical reasoning, the geometric mean fall velocity w_m, of the bed material, is 0.738 fps, and the standard deviation σ_w is 1.3. The graph gives a value of w_m that is 5 per cent greater than the measured mean.

The physical and hydraulic properties of the particles studied in this experiment are given in Table 2 of the Appendix.

Experimental procedure:- The experimental procedure was directed toward collecting data on the volume of scour and energy loss in the scour hole for different discharges, tailwater depths, and periods of scour.

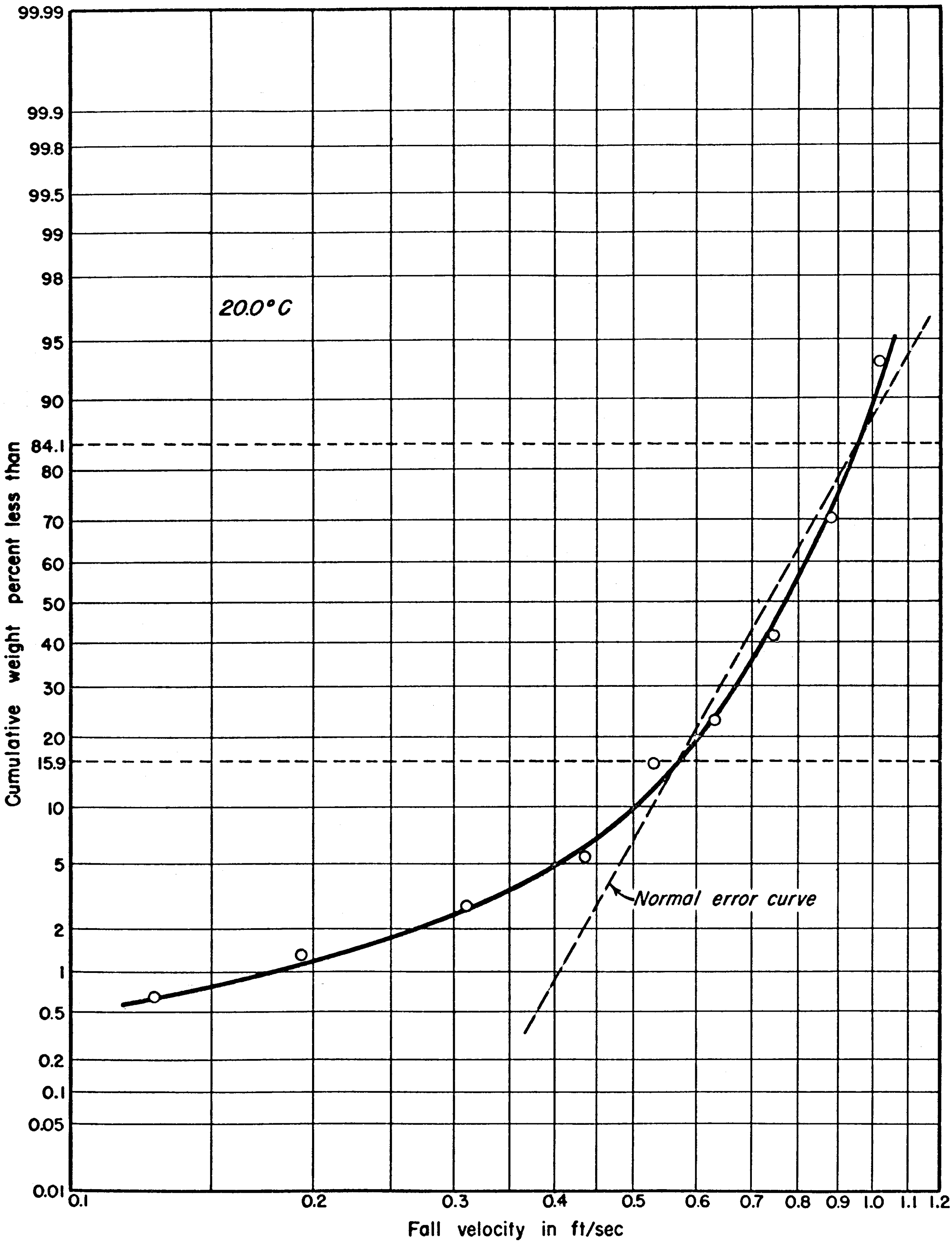
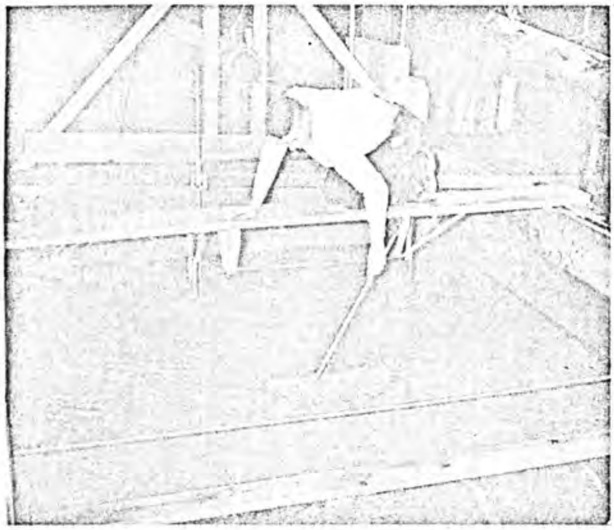


Fig. 8 Fall velocity curve

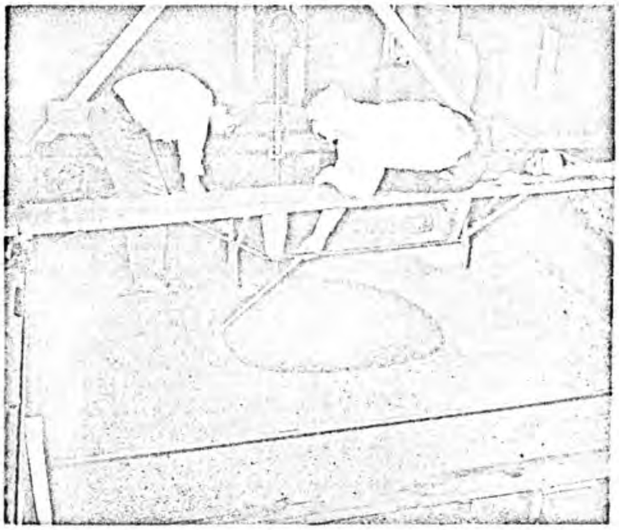
General operating procedure was first to thoroughly mix the bed material. The bed was then leveled by means of the leveler attached to the carriage. The depth from the bed to the invert of the discharge pipe was recorded. The by-pass pipe, being of a larger diameter, was placed over the discharge pipe and held, by a metal block, in a position that prevented back flow. Countertension in the supporting cables permitted split-second adjustment of the by-pass pipe. The pump was started and the depth of water over the bed was brought to the desired level with all flume outlets closed. The tailgate was raised to a predetermined orifice opening. The adjustment between inflow, outflow, and flume storage was made by the quick-acting valve. Discharge was established concurrently with tailwater. The discharge was set by the valve in pipe P_3 . A calibrated orifice meter and water manometer measured the discharge. The lines to the manometer were drained free of trapped air.

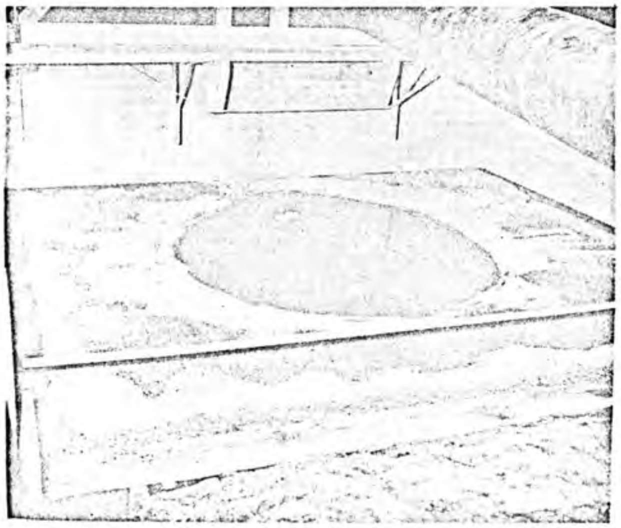
When the tailwater and discharge had remained steady for several minutes, the by-pass was withdrawn allowing the jet to strike the pool. The time of impingement was noted. The angle of jet was determined by two methods: (a) by the protractor, and (b) by measuring the x and y coordinates of the center line of the free-falling jet. After a period of scour of 15 minutes, for instance, the by-pass pipe was brought quickly into position over the discharge pipe. The pump was stopped and the drain-valves opened to lower the water level to expose the scour hole and the delta formed by the action of the jet. The water surface and a point gage, as illustrated in Fig. 9a and Fig. 9b,



(a) Contouring the dune using the point gage and water surface to locate contour.

(b) Contouring the scour hole using the point gage and water surface to contour.





(c) Filling scour hole by ground water flow. Gradual raising of water surface is essential in preventing sloughing and erosion from by-pass flow (pipe in photo is by-pass pipe).

Fig. 9 Experimental techniques

were used to establish a 0.2 ft contour interval on the delta and in the scour hole. The contoured delta and scour hole were recorded by photograph as shown in Fig. 6. An established scale on each photo and planimeter were used to determine the volume of the delta and scour hole

After the initial test it was necessary to gradually raise the ground water in the flume to bed level as illustrated in Fig. 9c. This precaution was necessary as the overland flow from the by-pass for normal flow, being of greater velocity than the ground water, would enter the scour hole first and cause sloughing. The next experiment was made for an additional 15 minutes thereby making the total time for the second experiment 30 minutes. A 30-minute run for the third time made the duration of the experiment 1 hour. The period of test was terminated when the scour pattern became distorted by the boundary. All eroded material was collected and uniformly mixed, the bed was leveled and the procedure repeated for another experiment.

All experiments pertaining to one value of Q , b , and H have been called a series. One series of experiments consisted of four to seven runs. There were four discharges, 0.5, 1.0, 1.5, and 2.0 cfs, three tailwater depths, 0.5, 1.0, and 1.5 ft, and one height of fall H , 4.0 ft. In all, 12 series totalling 66 experiments were made.

IV. EXPERIMENTAL RESULTS

Introduction:- The first section of this chapter is restricted to a discussion of the phenomenon of localized scour pertinent to three-dimensional jets from cantilevered outlets. First analysis of the phenomenon is made, followed by consideration of the practical application of the phenomenon to certain field conditions. This section is concluded with a summary of observations of experimental tests. In the second section a relation between energy and scour, as well as an empirical equation for a standard preshaped scour hole, is developed on the basis of experimental data. The standard preshaped scour hole is intended to provide a criterion for comparing the effect of different sizes of graded aggregate as armorplate on the rate of scour. The final section presents experimental studies on armorplate that definitely illustrate its effectiveness in the control of scour.

Theoretical considerations:- The phenomenon of scour is influenced by all the factors that affect the jet, the flow, the pool into which it discharges, and the sediment forming the erodible bed of the pool.

The energy contained by the jet at the point of impingement on the tailwater surface is dependent upon:

1. The amount of turbulence imparted to the jet by the pipe,
2. The height of fall, and
3. The amount of kinetic energy in the flow.

The amount of turbulence generated within the pipe is dependent upon the Reynolds number of the flow and the boundary roughness. For large

Reynolds numbers the turbulent eddies induced by the pipe roughness are carried throughout the pipe flow. For the experimental studies reported herein, the Reynolds number for minimum discharge exceeded 800,000.

The height of fall governs the extent of the inertial effects on the jet. In leaving the pipe, the jet comes under the influence of gravity. If the height is sufficient and discharge small, the jet will eventually disintegrate into fine spray. Furthermore, the turbulence within the jet and the shear between the jet and surrounding air cause particles of water to break away from the jet. Shear and drag at the air-water interface causes the jet to spread and air to be entrained. For the smaller water elements, surface tension causes the element to approach a sphere in shape and it also resists further breakup. The amount of mixing of air and water affects the effective density ρ. The average mass density ρ will decrease as the concentration of air in the jet increases. With entrainment of surrounding air, the discharge of the air-water mixture increases. At the same time the effect of the lateral diffusion by air will reduce the water elements to smaller and smaller droplets. At a section sufficiently far from the point of discharge, the droplets become very small hence the fall velocity likewise becomes small. Therefore, the momentum of the falling jet, defined as ρQV, is a function of the droplet velocity, the total discharge, and the average density. This product becomes very small if the breakup of the jet is sufficient to reduce the droplets to a mist, so that their fall velocity approaches zero. For this experimental study the height of fall did not cause any significant change in ρ. Nor was the turbulence within the jet sufficient to be considered.

After impingement on the tailwater surface, the depth of water cushion determines the extent of jet diffusion and kinetic energy dissipation. For a depth of infinite extent, the kinetic energy of the oncoming flow is, by reaction between the active and passive water interface, steadily converted into kinetic energy of turbulence, while the latter steadily decays into heat through viscous shear. As previously mentioned, any jet issuing into a quiet body of its own fluid entrains fluid from the outside so that the discharge is increased as the energy is decreased. As a consequence, the momentum flux remains a constant. (The basic principles of diffusion of submerged jet are illustrated in Fig. 10. The distribution of volume, momentum and energy flux of a submerged jet is illustrated in Fig. 11.) For the condition of the impinging jet diffusing in the tailwater, it is generally assumed that the pressure is hydrostatically distributed throughout the flow. This means that on any horizontal plane that extends through both the jet and the surrounding medium the pressure is the same. However, for this experimental study there was a modification of the above condition of jet diffusion. The change is explained in the following paragraph.

The depth of water was not sufficient, for conditions tested, to cause perceptible jet diffusion. Furthermore, the erodible bed surface represented a boundary limit to the jet. Being erodible, the surface moved under impact by the jet, and, as a moving boundary, caused flow conditions as follows: at some point below the water surface the sediment boundary would cause a change from the momentum equation (constant momentum flux) to the energy, or Bernoulli, equation. This point

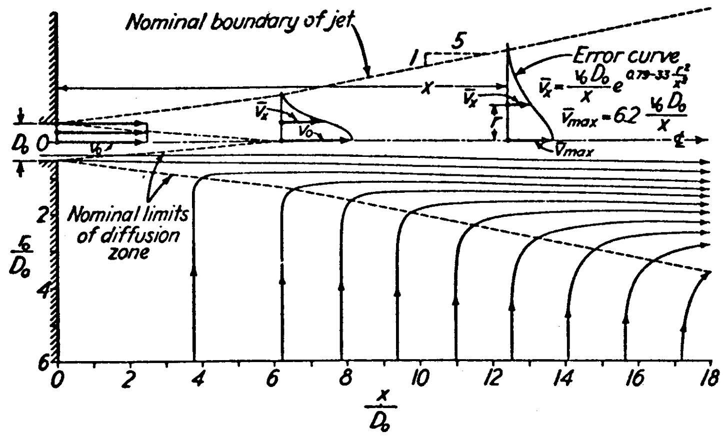


Fig. 10 Mean flow characteristics of a submerged jet

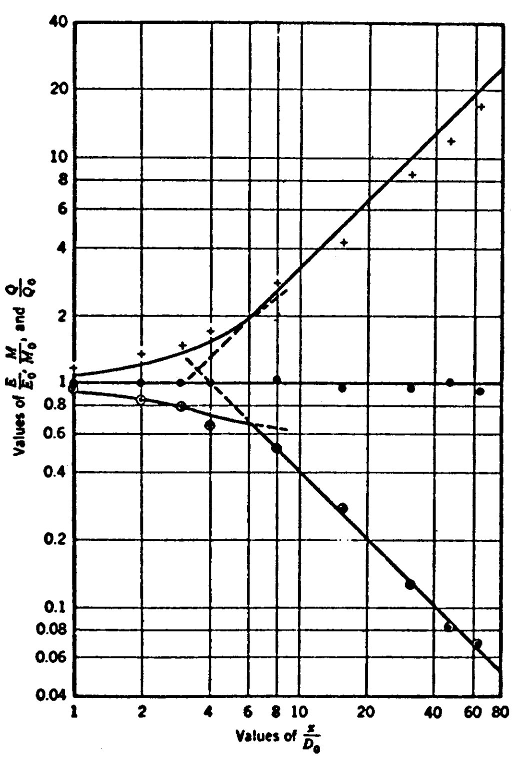


Fig. 11 Distribution of volume, momentum, and energy flux downstream from orifice

changed as the bed material eroded. For the new flow condition, an analogy, used in the study of the impact of the jet on the bed, is that of a jet striking a moving plate. At the juncture of the central stream-line and the bed (plate) the pressure is maximum and the velocity zero; this is commonly called stagnation flow. As the jet is deflected there is, within a small region, an acceleration of the flow. Beyond this region in submerged flow, the momentum equation replaced the energy equation in the analysis of jet diffusion.

The rate in change of momentum flux also begins with the development of the boundary layer. For the experimental study, there was an additional factor of an unequal division of the jet at point of impact with the bed.

The flow phenomenon downstream from the stagnation point will be considered first. By the law of the conservation of momentum, the momentum of the jet remains the same as it spreads radially. There is, however, a change in the momentum flux with the development of the boundary layer because of the surface resistance at the bed. A change in momentum flux between the stagnation point and any radial distance r_o is the summation or total shear from the stagnation point up to r_o. As the jet diffuses there is an increase in discharge caused by entrainment on the upper side of the jet, but a decrease in energy due to shear at the bed. The corresponding decrease in velocity; the velocity varies inversely with the radial distance from the stagnation point.

At the impact of the jet on the bed material, the density is changed by the intermixing of the bed material with the jet flow, the density being directly proportional to the specific weight of the mixture. Furthermore, tests show that the greater the density the greater its ability to scour. As the fine or small material is transported downstream the "local" density decreases.

The deepening scour hole, the decrease in "local" density, and the increased bed roughness will result in a decrease in the scouring ability of the jet. As the jet moves radially outward the turbulent shear and boundary shear of the bed material, along with a decrease in the velocity, establishes an equilibrium between this shear and the loss in momentum flux. Deposition begins as the reduction in velocity and momentum flux takes place. As the material is deposited, the flow tends to decrease in size and hence there is an increase in the velocity by the continuity equation; that is, the area of flow is decreased by the depositing material. The increase in velocity is not significant, but will tend to cause deposition of the fine bed material farther downstream.

The interaction of the diffusing jet and the bed material affects not only the effective density but also the effective fall velocity of the sediment. This has been shown by Rouse (18), Thomas (23), and Hallmark (11) in their studies and is given in the summary of their work in Chapter II of this report. However, for this experiment, only the downstream segment of the jet, which apparently has the greatest affect on the effective density of the fluid, caused extensive selective sorting of the sand and gravel mixture. This action increases the mean size of the bed material lining the scour hole and consequently the effective fall velocity is also increased. The net result is that the size of the scour rate is reduced and the scour hole is armorplated against jet penetration. As in the case of scour in a uniform bed material, the scour with armorplating present also depends upon the size and velocity of the impinging jet, the geometric mean fall velocity of the sediment exposed, and the duration of the scouring action.

In summary, the energy and momentum flux of the jet have the following relationships to scour. The development of the initial scour hole is a function of the momentum of the jet impinging upon the bed material. The rate of scour gradually decreases because of decreased boundary shear and the greater resistance of the bed material. Also the sorting process, which proceeds at a maximum rate in the initial stage and decreases with increased stability, will cause a slight increase in the normal rate of scour, and a larger volume of material to be held in suspension. As the shear becomes less, resistance to shear becomes greater and there is less material in suspension as well as a gradation of sediment particles from a maximum at the bottom to a mean size at bed level along the downstream surface of the scour hole.

There is a direct relation between the energy and the momentum flux of the jet and its ability to penetrate or strike the bed material. Consequently, the balance between particle motion and shearing forces within the pool depends on the extent of energy and momentum flux dissipation by the shearing stresses at the sediment bed, and the shear between the active and passive water interface.

With an assumed constant energy inflow, the lateral extent of turbulence will increase with depth of water because of the possible greater scope for full development of the flow pattern. Thus, an increase of the turbulence zone will cause an increase in the area of erosion and, consequently, an increase in the suspended sediment load. In this respect, the rate of sediment removal and its rate of dispersion would be a function of the tailwater depth.

For shallow depths the vertical velocity component (upward as well as downward) is predominant causing lift but not dispersion of the sediment. An increasing tailwater depth gives rise to a more extensive ring-vortex form of flow pattern which increases the horizontal component of velocity and consequently increases the dispersion of sediment away from the jet center.

In accordance with the foregoing explanation, the rate of scour increases with an increase in tailwater depth until a critical depth is reached, and the scour rate decreases due to the jet diffusion and energy dissipation in the deeper pool. The same conclusion was reached by Doddiah (6). Critical tailwater depth as a function of energy is shown in Fig. 13.

Practical results:- From observations and findings of previous experimental studies, the following were deemed applicable to many field conditions:

1. For shallow tailwater and small scour holes, energy waves and eddies will be of sufficient magnitude to cause erosion of the channel banks for some distance downstream.
2. For large discharges, scour holes, and tailwater depths, vortex action will cause excessive scour along the banks in the vicinity of the impinging water.

3. Armorplating by means of graded aggregate will be most effective in the control of scour if placed on the downstream surface of a preshaped scour hole.

Observations:- During each experimental run observations were made of the scour phenomena produced by a three-dimensional jet from a cantilevered outlet and of its effect on the development of the scour hole. For the purpose of discussion the scour phenomena will be classified as follows: (a) during the period of scour, and (b) after the period of scour.

During the Period of Scour

During scour, the scour hole assumed the shape which was characteristic of the particular discharge, sediment, and depth of tailwater. As the scour hole increased in volume the energy waves emanating from the area of scour decreased. The periphery of the scour hole during scour was rather well defined by a large boil on the water surface immediately downstream from the impinging jet. The boil marked by a large mass of bubbles indicated not only the region of scour but also that there was a large amount of air entrainment by the jet.

Other observations during the period of scour were that when the jet was discharging into a shallow pool the height of the boil was from 6 to 8 inches and consisted of a large mixture of gravel and water, most of which would fall or would return to the point of its removal. With an increase in depth of the tailwater or pool depth, the "boils" covered a wider area giving rise to a ring-vortex type of motion rotating in a counter-clockwise direction along the surface of the scour hole.

After the Period of Scour

After the water had been turned off, the effect of the scouring action of the jet was noted as it affected the bed material. An examination of the profile of the scour hole showed that the angle of repose of the bed sediment on the downstream side was much steeper than on the upstream side. This was an indication that the direction of maximum energy of the jet is in the downstream direction and that the shear from the jet eddies tends to support the particles on a steeper slope. The sorting action of the jet in the scour hole developed a pattern of aggregate gradation that was similar for all flow conditions tested. A typical pattern was as follows:

The coarse material of the bed material was sorted by the water action only onto the downstream surface of the scour hole, where it took the form of a triangular segment with its apex at the bottom of the hole. The angle of the triangular segment at its apex approximated the angle of impingement of the jet on the tailwater surface. The sorting action also caused a rather significant band of fine material sediment to form after several hours of scour, which was transverse to the direction of flow and always upstream from the center line cross-section of the scour hole. There was little or no sorting action by the water upstream from the band of fine material.

Several adverse conditions in the bed material were noted after either long periods of scour or large discharges. In particular it was noted that shallow channels and dunes would form along the flume walls between the scour hole delta and the wall. These were developed as a result of secondary flow, in the form of vortices, formed by the slowly moving water along the flume wall as a result of boundary shear. The normal development of the delta formed of the scoured sediment was that of a fan, whereas for large discharges or long scouring periods its growth was in a longitudinal direction, or in the direction of flow. The increase in discharge also had a marked effect on the rate of scour hole growth, with an increase of discharge causing a rapid increase in the rate of scour hole development.

The delta formed by the scoured sediment was found not only to be fan shaped for normal conditions of flow but also to have a greater volume than the scour hole. The increase in volume was attributed to the sorting action of the water resulting in an increased porosity of the bed sediment or in a "bulking" effect.

Presentation of Data

In the first part of this section empirical equations are developed from graphs giving the variation between energy and scour, and energy and critical depth. The graphs represent the data collected by conducting 66 experiments as explained in the preceding chapter. A basis for three-dimensional studies in the control of scour by graded aggregate is set forth in the second part of this section. Such a basis is a standard preshaped scour hole developed also from the experimental data.

Energy and scour relationship:- Empirical equations for expressing scour in a gravel bed as a function of the energy of the cantilevered three-dimensional jet are developed from the curves of Fig. 12, as follows:

The amount of scour

$$h^*_{100}/H = a_1 + m \log_{10} E_o/H^2 w_m{}^3 \rho \qquad (17)$$

where h^*_{100} is the cube root of the volume of scour after 100 hours of test in the model, E_o is the energy of the jet at the tailwater surface, a_1 and m are constants.

Fig. 12 shows the curves giving the variation of scour with energy for different tailwater depths tested. The variation of h^*_{100}/H with energy can be expressed by Eq 17. It also shows that there is an apparent "critical" tailwater where the amount of scour h^*_{100}/H becomes independent of tailwater depth for a given energy. Therefore, in order to evaluate the constants a and m, the empirical relation between energy and scour must be considered for two different flow conditions.

The flow condition for tailwater less than critical tailwater will be considered first. Fig. 12 shows that h^*_{100}/H increases proportionately to the logarithm of energy with the same rate m for all tailwater depths. Therefore, by Eq 17 (for the range of common values of h^*_{100}/H greater than zero), the constant m as well as the constant a for the different tailwater are determined. The general equation for the different tailwater depths is as follows:

For tailwater depth of 0.5 ft

$$h^*_{100}/H = -3.62 + 2.60 \log_{10} E_o/H^2 w_m{}^3 \rho \qquad (18)$$

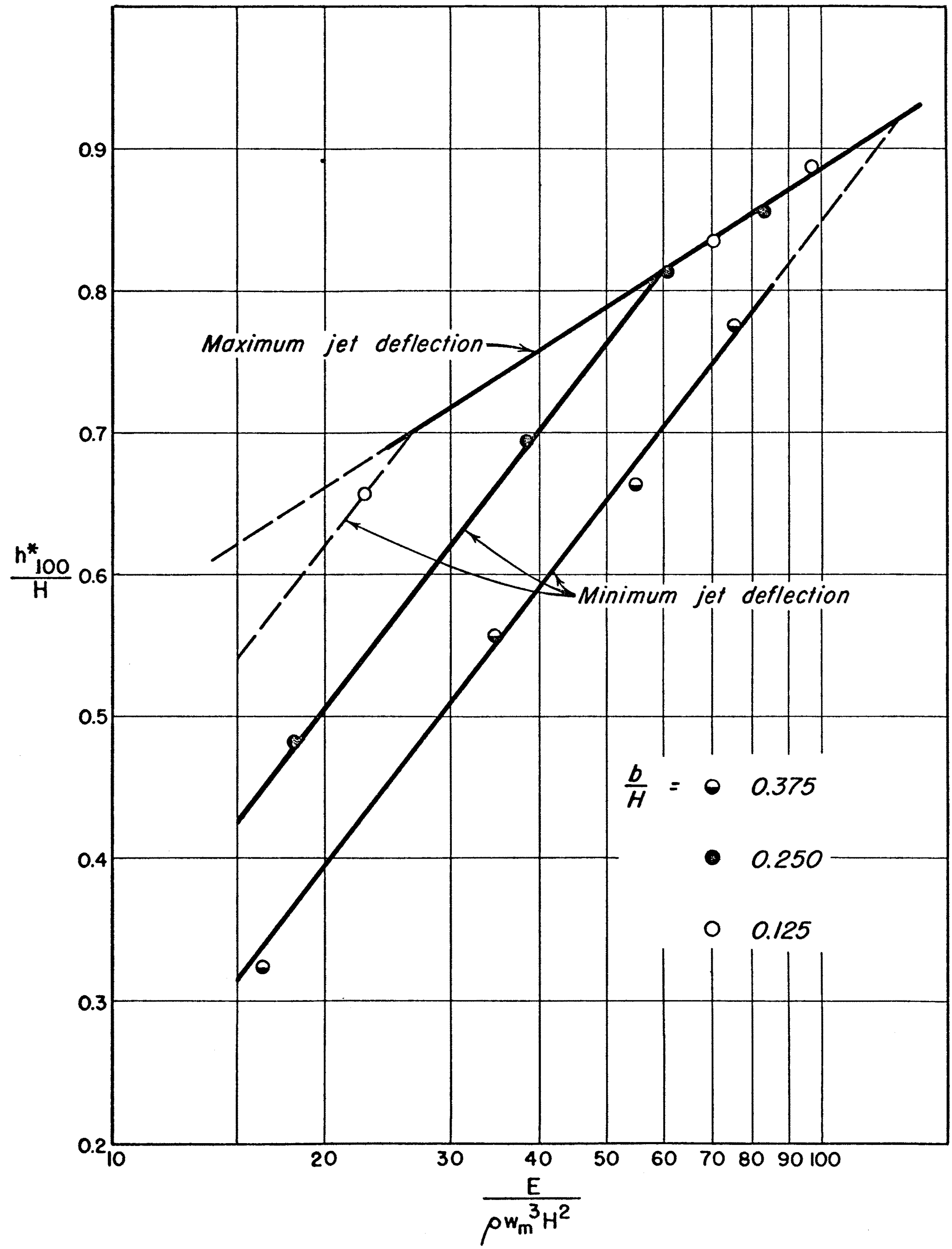


Fig. 12 Relation between energy and scour for various tailwater depths

For tailwater depth of 1.0 ft

$$h^*_{100}/H = -4.00 + 2.60 \log_{10} E_o/H^2 w_m^3 \rho \quad . \qquad (19)$$

For tailwater depth of 1.5 ft

$$h^*_{100}/H = -4.47 + 2.60 \log_{10} E_o/H^2 w_m^3 \rho \quad . \qquad (20)$$

For above critical tailwater, the general equation for h^*_{100} is given by:

$$h^*_{100}/H = -0.37 + 1.29 \log_{10} E_o/H^2 w_m^3 \rho \quad . \qquad (21)$$

This is an expression for h^*_{100}/H for any given discharge or tailwater depth above the critical tailwater depth.

The relation of energy to the critical tailwater depth b_c/H is given in Fig. 13. The general equation is:

$$b_c/H = -3.18 + 1.49 \log_{10} E_o/H^2 w_m^3 \rho \quad . \qquad (22)$$

Development of a Standard for a Preshaped Scour Hole

An experimental program on armorplating of a scour hole below a cantilevered outlet should have as a basis some standard by which the effectiveness of the graded riprap could be determined. In more explicit terms, the purpose of developing a standard would be to determine analytically, if possible, a preshaped hole, which, for given geometry, flow, fluid, and sediment characteristics, would form in the flume bed. Such a standard preshaped hole would provide also a basis for preshaping a scour hole in the field for certain given hydraulic conditions.

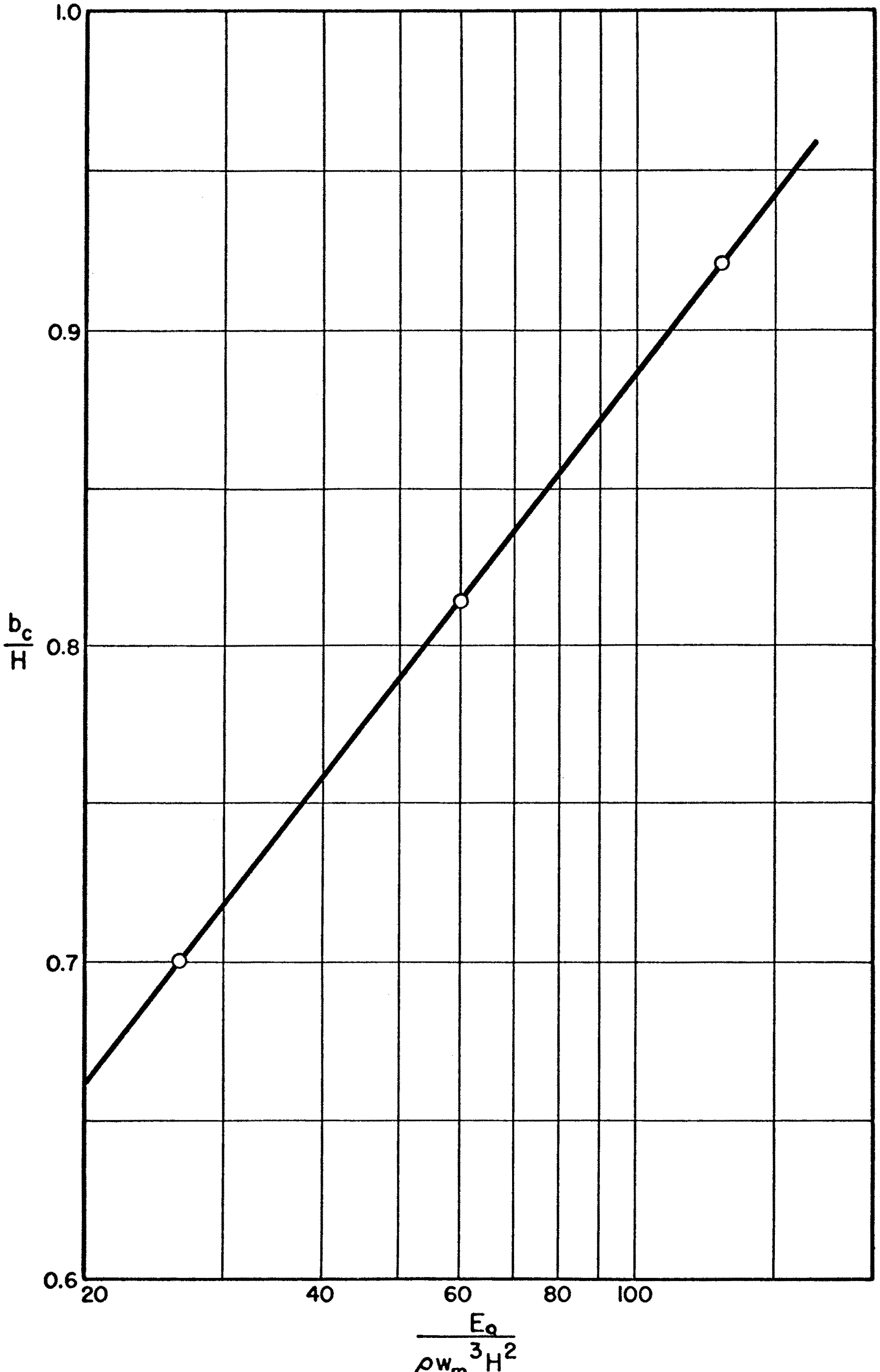


Fig. 13 Variation of critical tailwater depth coefficient $\frac{b_c}{H}$ with energy coefficient $\frac{E_o}{\rho w_m^3 H^2}$

In the analytical development of a standard preshaped scour hole the variables that should be considered are:

Q discharge - L^3/T,

b depth of tailwater - L,

w_m geometric mean fall velocity of the sediment of the bed material - L/T,

σ_w standard deviation of fall velocity w_s of sediment particles about w_m,

t time of scour - T,

H height of fall - L, and

θ angle which center streamline of impinging jet makes with the tailwater surface.

The analytical approach in determining a standard preshaped scour hole was accomplished in two steps, namely: (a) the development of an analytical method of locating the center of the scour hole, and (b) the development of an analytical method for determining the pertinent characteristics of the scour hole for given flow, fluid, sediment, and geometry characteristics.

The equation for locating the center of a standard preshaped scour hole was determined for a cantilevered pipe outlet by making use of the law of continuity and the trajectory method of flow measurement. The law of continuity being

$$Q = V_o A \quad \text{or} \quad V_o = Q/A \tag{23}$$

where Q is the pipe discharge - L^3/T,

A is the area of flow of jet at point of discharge - L^2, and

V_o is the velocity of jet at point of discharge from pipe - L/T.

The trajectory method of flow measurement is that by measuring the position of a point on the trajectory of a free jet downstream from its source (vena contracta of a full flowing pipe) the actual velocity may be determined if air resistance is neglected. The x-component of velocity does not change; therefore,

$$V_o t_p = x_b \tag{24}$$

where x_b is the horizontal distance from the source, or end of the pipe, to the point of impingement on the bed - L, and

t_p is the time for a fluid particle to travel from the point of discharge to point of impact - T.

The time for a fluid particle to drop a distance H under the action of gravity when it has no initial velocity in that direction is given by

$$t_p = \sqrt{2H_c/g} \tag{25}$$

where H_c is the height from the center line of area of flow to the original bed level - L, and

g is the acceleration due to gravity - 32.2 ft/sec^2 - L/T^2.

Eliminating t_p in the two relations,

$$V_o = x_b/\sqrt{2H_c/g}$$

or

$$x_b/H_c = \sqrt{2}\, V_o/\sqrt{gH_c}\ . \tag{26}$$

An adjustment of Eq 1, on the basis of experimental data of this study, will give an empirical expression for the distance to the center line of the standard preshaped scour hole. It is

$$x/H_c = x_b/H_c + 0.6\ h^*/H_c, \tag{27}$$

where x is the horizontal distance from the end of the pipe to the center of the scour hole - L ,

h^* is the cube root of the volume of scour - $(V_s)^{1/3}$ - L ,

x_b is the horizontal distance from the source, or end of the pipe, to the point of impingement on the bed - L , and

H_c height of fall - L .

The analytical approach used in determining expressions for the standard preshaped scour hole characteristics, such as depth, width at top and bottom, and angle of repose of bed material, was based on two assumptions:

1. That the general relationship expressing the phenomenon of scour below a cantilevered outlet is given by

$$\phi_1\ (h^*\ ,\ H\ ,\ b\ ,\ Q\ ,\ w_m\ ,\ \sigma_w) = 0 \tag{28}$$

or,

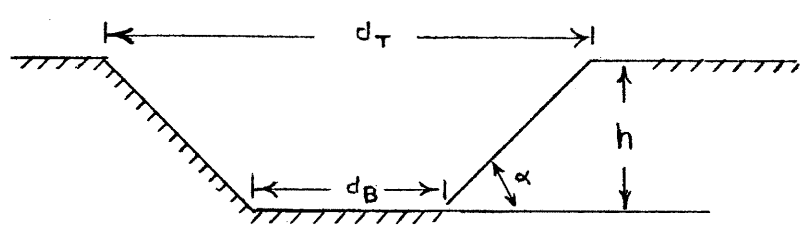
$$h^* = \phi_2\ (H\ ,\ b\ ,\ Q\ ,\ w_m\ ,\ \sigma_w) \tag{29}$$

Since only one type bed material was used in the experiment and since it was thoroughly mixed between runs, w_m and σ_w were considered as constants. The elevation of the pipe invert was four feet above the original bed level for all runs; consequently, H was constant. Therefore, the relation expressing the phenomenon of scour was reduced to

$$h^* = \phi\ (Q\ ,\ b)\ .$$

The experimental tests consisted of a systematic variation of the independent variables Q and b .

2. That the standard scour hole can be represented by a truncated cone as shown in the following sketch.



where d_T = diameter at the top,

d_B = diameter at the bottom,

h = depth, and

α = angle of repose of the bed material.

On the basis of the foregoing assumptions, as well as experimental data of this study, empirical expressions for d_T , d_B , and h were developed as follows:

The volume of a truncated cone is given by

$$V_S = \pi/4 \quad (d_T + d_B)^2 \; h \tag{30}$$

and,

$$\tan\alpha = h \; / \; 1/2 \; (d_T + d_B) \tag{31}$$

or

$$d_T/2 + d_B/2 = \psi \, d_T/\tan\alpha \tag{32}$$

where

$$\psi = h/d_T \quad .$$

By substitution, we have

$$V_S = \pi/4 \quad (1 - \psi/\tan\alpha)^2 \quad d_T^3 \, \psi \tag{33}$$

and

$$d_T = h_t^*/k \tag{34}$$

where

$$k = \sqrt[3]{(\pi/4) \quad (1 - \psi/\tan\alpha)^2} \tag{35}$$

The diameter at the bottom is given by

$$d_B = h^*/k \quad (1 - 2\psi/\tan\alpha) \tag{36}$$

and, the depth h by

$$h = (h^*/k)\psi. \tag{37}$$

From the experimental data of the study of this report an empirical expression for d_B , d_T , and h was obtained as follows:

The angle of repose α of the bed material and the ratio h/d_T were first determined, with the experimental data giving for the values of 25° and for h/d_T a value of 0.20.

Since $\tan\alpha = 0.47$ and $h/d_T = 0.20$, k can be solved by substitution in Eq 10, or

$$k = \left[(\pi/4)\,(0.20)\,(1 - 0.20/0.47)^2\right]^{1/3} = 0.40 .$$

Substituting the value for k in Eqs 9, 11, and 12 gives:

$$d_T = 2.5\ h_t^* \tag{38}$$

$$d_B = 0.4\ h_t^* \tag{39}$$

$$h = 0.5\ h_t^* \tag{40}$$

where, as before, h_t^* is the cube root of the volume of scour ($\sqrt[3]{V_s}$) at time t .

To indicate the extent of agreement between the computed values of h_t^* and those from experimental data, Fig. 14 has been prepared. The points in Fig. 14 represent values of the cube root of the volume

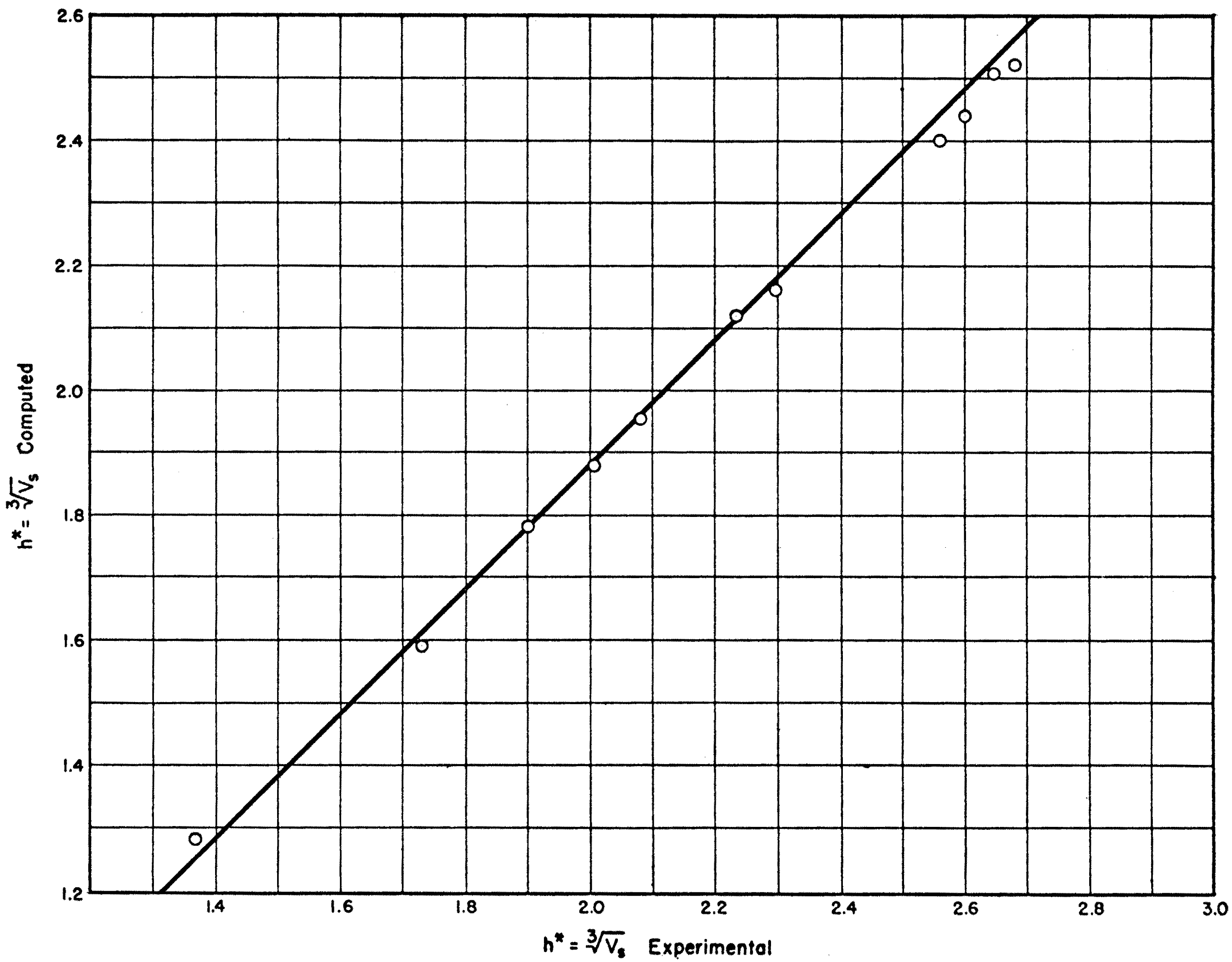


Fig. 14 Variation of h^* from data with computed h^* for given flow conditions

V_s ($h^* = \sqrt[3]{V_s}$) computed by Eq 8 plotted against the corresponding values of the cube root of the volume V_s determined from experimental data, for the same flow conditions and time of scour.

Control of Scour by Graded Riprap Used as Armorplate

The relative rate of scour produced by a given jet at a given stage depends only upon the ratio of the jet velocity V to the geometric mean fall velocity w_m of the bed material. In a word, the ratio V/w_m indicates the sorting capacity of the impinging jet, for as w_m increases, the ratio V/w_m approaches unity and the rate of scour approaches zero.

As the selective sorting of graded material occurs, the bottom of the scour hole gradually becomes paved with progressively coarser material. Thus, the effective fall velocity of the sediment is decreased and the rate of scour reduced.

Using this precept, an experimental study was made with graded aggregate being applied as armorplate to an eroding scour hole. The results proved that graded riprap used as armorplate will decrease considerably the rate of scour. However, the primary objective of the experimental program was to obtain information on the use of graded aggregate as an armorplate against scour in stilling basins.

The variables considered essential to the fulfillment of the objective of the experimental program were as follows:

Q - rate of flow - L^3/T ,

t - time of duration of scour - T ,

H - height of fall - L ,

b - tailwater depth - L ,

d_{max} - diameter of maximum size of graded aggregate to be used in armorplating - L ,

d_{min} - diameter of minimum size of graded aggregate to be used in armorplating - L , and

W - weight of armorplate - F/L .

The experimental procedure was to study the effect of four different size-ranges of armorplate gravel. It was found that each size range decreased scour with increasing amounts of armorplate material applied to the scour hole. The size-ranges used were

1-in. to 2-in. gravel

$\frac{1}{2}$-in. to 1-in. gravel

$\frac{1}{4}$-in. to $\frac{1}{2}$-in. gravel graded or $\frac{1}{4}$-in. to 2-in. gravel.

In studying armorplating, a constant time parameter qT/H^2 was chosen as 0.486. This allowed time for the development of the scour hole with a layer of coarser particles sorted from the bed material. Further, the tests were limited to only one flow condition, this limitation was due to the time limit for this study. In holding the time parameter and flow conditions constant for all of the armorplating studies, very good correlation of the effects of the various armorplate was obtained.

An important part of this study was the relation of the size gradation of the armorplate to the extent the scour was reduced. The larger size particles decreased the rate of scour less than the smaller

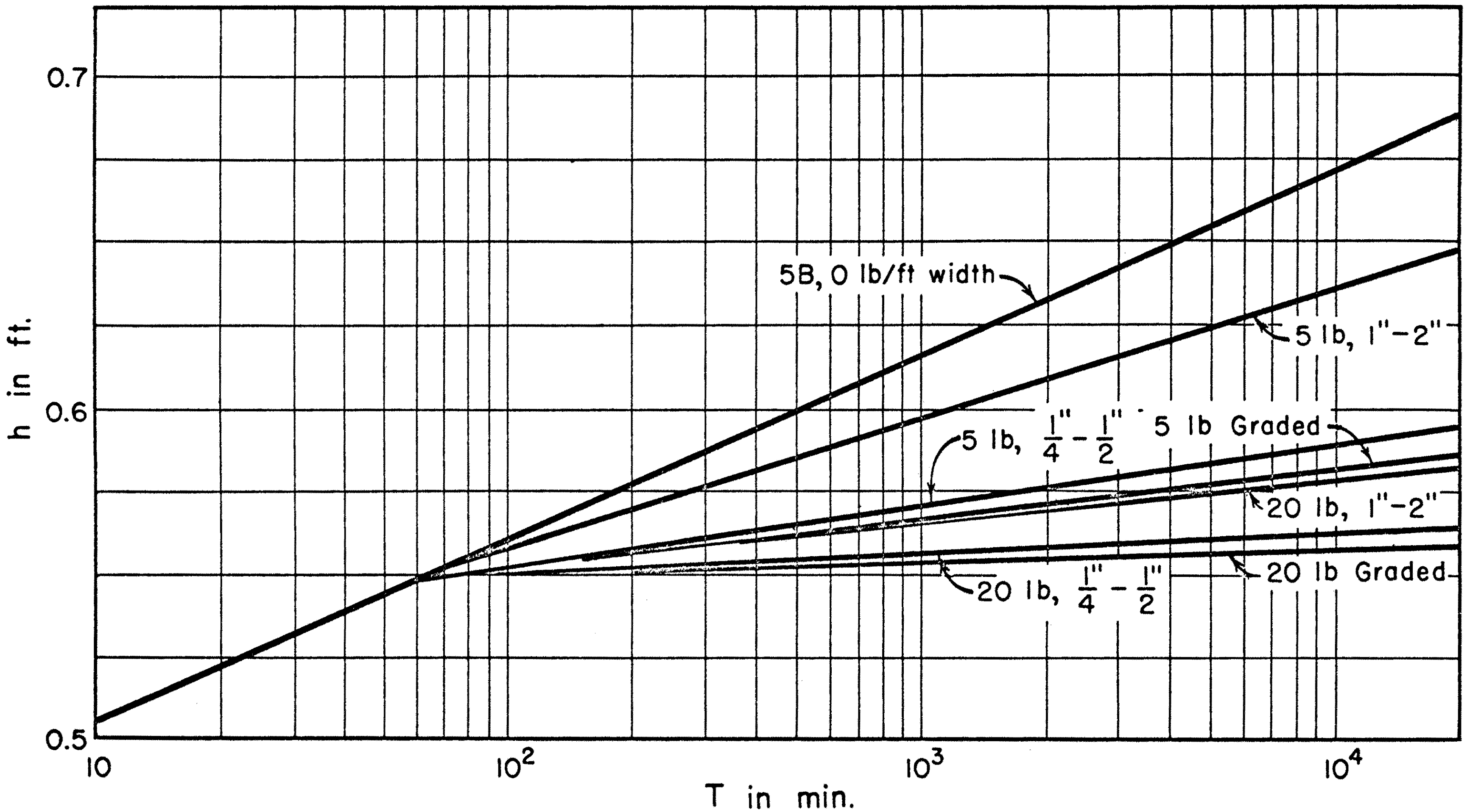


Fig.15 Variation of rate of scour with size and quantity of armorplate

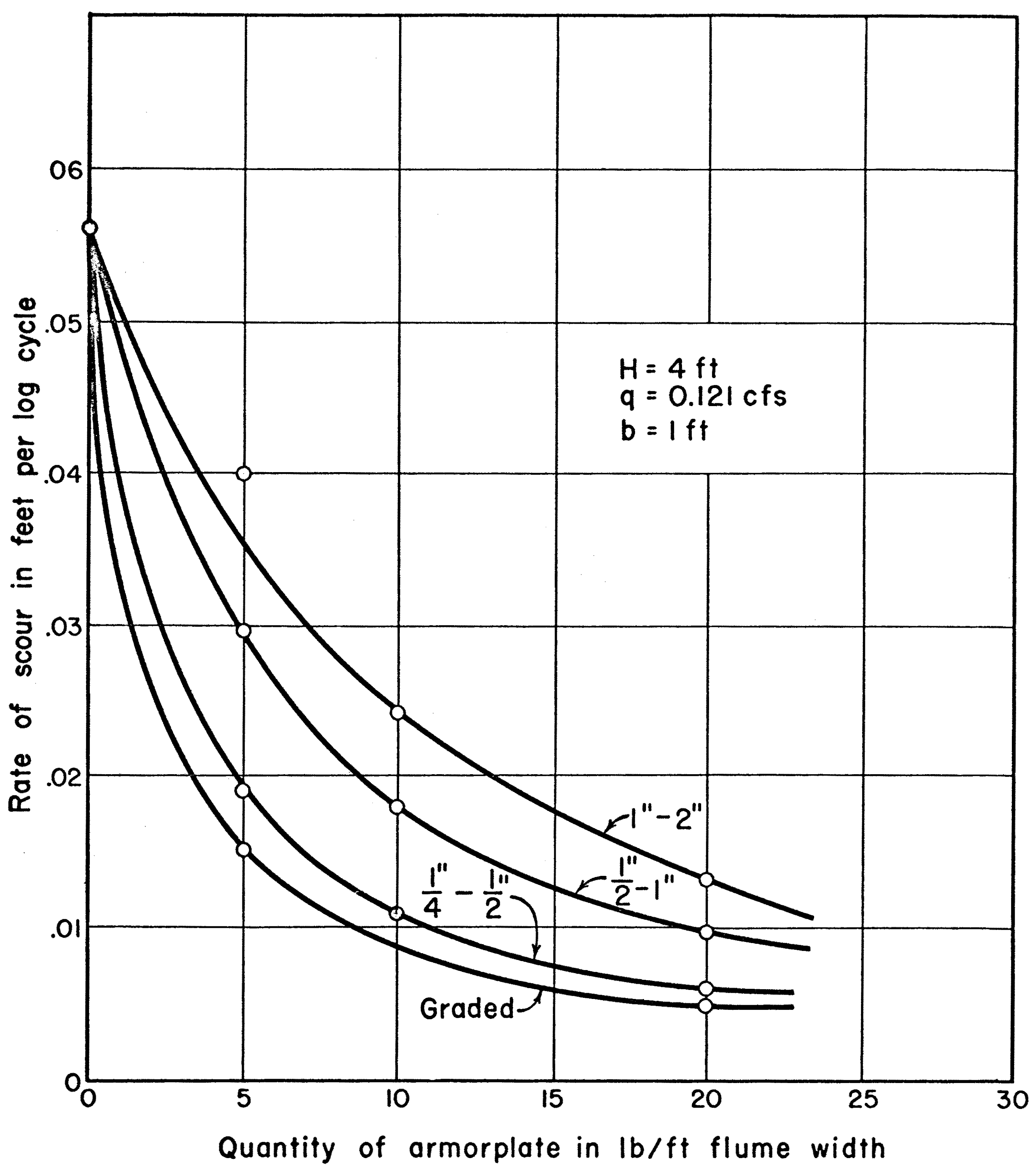


Fig. 16 Effect of armorplate on rate of scour

size as shown by Fig. 15 and Fig. 16. By using a graded mix of these sizes a still greater decrease in the rate of scour was obtained than for any of the separate sizes tested alone.

An increase in the amount of armorplate applied, produced a corresponding decrease in the rate of scour. Fig. 15 clearly indicates the decrease in the rate of scour by increasing the amount of armor-plating material. As the armorplate is increased, the scour decreases so that any greater increase in amount of armorplate would not give a sufficient decrease in scour to be practical from the economic viewpoint. From Fig. 16 it is evident that a very low rate of scour can be obtained with relatively small amounts of armorplate which have the proper size and size gradation.

V. CONCLUSIONS

An analysis of experimental study of scour below a cantilevered outlet leads to the following conclusions:

1. The amount of scour h^*_{100} increases proportionately to the logarithm of the energy of the jet at the tailwater surface with the same rate for all tailwater depths less than the critical tailwater depth.
2. As tailwater increases more energy input is required for the same amount of scour h^*_{100} until the critical tailwater depth is reached.
3. Above the critical tailwater depth the amount of scour h^*_{100} is independent of discharge and tailwater depth for any given energy.
4. Above the critical tailwater depth, an incremental increase in scour requires a greater increase in energy.

An analysis of armorplating studies reported herein leads to the following conclusions:

1. Only a relatively small amount of armorplating material is necessary for a relatively large decrease in the rate of scour.
2. The rate of scour decreases with a decrease in the size of the armorplate material when the armorplate material remains larger than the largest particle size of the bed material.

3. The rate of scour decreases with an increase in the amount of armorplate placed in the scour hole.
4. Graded armorplate material decreases the rate of scour more effectively than uniform material.

VI. PROPOSED FUTURE RESEARCH

Because of the period of time required for each test series, the study of scour caused by a three-dimensional jet from a cantilevered pipe was of only a preliminary nature. Therefore, a few of the factors that should be examined further are:

1. A continuation of the present systematic study to determine more completely the critical tailwater depth and the effect of discharge on scour and energy dissipation when the tailwater is above or below critical depth.
2. To investigate systematically the effect of bed material of different mean diameters on the relation of jet diffusion, energy dissipation and scour.
3. To determine a theoretical equation relating rate of scour to the momentum flux of the jet.

It is also proposed that an experimental study should be made of the control of scour by graded riprap using the preshaped scour hole. Furthermore, the experimental program should be based on the following variables:

Q - discharge - L^3/T

b - tailwater depth - L

t - time of scour - T

h_t^* - the cube root of the volume of the scour hole for a given Q and b at time t - L.

d_{max} - diameter of the maximum size of graded riprap to be used in armorplating - L

ϵ - thickness or quantity of armorplate in terms of d_{max} ($\epsilon = nd_{max}$, where $n = 0, 1, 2, 3$ and 4) - L .

The testing program should be systematized to determine the following:

1. The influence of size gradation of the riprap on the rate of scour.
2. The influence of quantity or thickness of the graded riprap on the rate of scour.
3. The influence of tailwater depth and discharge on the armorplating and rate of scour.

In summary it is proposed that the experimental program be a study of systematic combinations of the following:

Q - 0.5, 1.0 and 2.0 cfs

$\%h_t^*$ - 25%, 50% and 75% of $\sqrt[3]{V_{s_t}}$ where V_{s_t} is the volume of scour at time t

b - 0.5, 1.0 and 1.5 ft

t - 0.5, 1.0, 2.0 and 4.0 hrs.

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T A B L E S

TABLE 1 TESTING PROGRAM COMPLETED

Test Series	Test No.	Variables Held Constant Per Test Series Q cfs	b ft	H ft	t hrs	$h^* = (V_s)^{1/3}$ [1] ft	Remarks
I	1	0.5	0.5	4.0	0.25	1.18	
	2				0.50	1.40	
	3				1.00	1.54	
	4				2.00	1.72	
	5				6.00	1.90	Boundary effects noted.
II	6	1.0	0.5	4.0	0.25	1.27	
	7				0.50	1.41	
	8				1.00	1.55	
	9				2.00	1.66	Overland flow from by-pass caused
	10				4.00	1.87	sloughing.
	11				8.00	2.08	
III	12	2.0	0.5	4.0	0.25	2.14	
	13				0.50	2.34	
	14				1.00	2.48	Boundary effects begin.
	15				2.00	2.68	Boundary effects significant experiment terminated.

Notes: By Boundary Effects is meant the influence of the side-walls of the flume in distorting shape of scour-hole.
By Sloughing is meant slight slippage of the side of the scour hole into the bottom.

[1] V_s is the volume of scour in cubic feet.

TABLE 1 --Continued

Test Series	Test No.	Variables Held Constant Per Test Series Q cfs	b ft	H ft	t hrs	$h^* = (V_S)^{1/3}$ [1] ft	Remarks
IV	16	1.5	0.5	4.0	0.25	1.67	
	17				0.50	1.89	
	18				1.00	2.20	Boundary effects noted.
	19				2.00	2.44	" "
	20				4.00	2.56	Boundary effects significant - experiment terminated.
V	21	0.5	1.0	4.0	0.25	1.22	
	22				0.50	1.31	
	23				1.00	1.33	
	24				2.00	1.60	
	25				4.00	1.57	
	26				8.00	1.65	
	27				16.00	1.73	
VI	28	1.0	1.0	4.0	0.25	1.50	
	29				0.50	1.59	
	30				1.00	1.64	
	31				2.00	1.87	
	32				4.00	2.06	
	33				8.00	2.30	

TABLE 1 --Continued

Test Series	Test No.	Variables Held Constant Per Test Series Q cfs	b ft	H ft	t hrs	$h^* = (V_s)^{1/3}$ [1] ft	Remarks
VII	34	1.5	1.0	4.0	0.50	2.18	
	35				1.00	2.33	Boundary effects noted.
	36				2.00	2.44	" "
	37				4.00	2.60	Boundary effects significant - experiment terminated.
VIII	38	2.0	1.0	4.0	0.25	2.29	Boundary effects noted.
	39				0.50	2.35	" "
	40				1.00	2.49	" "
	41				2.00	2.65	Boundary effects significant - experiment terminated.
IX	42	1.0	1.5	4.0	0.50	1.56	
	43				1.00	1.68	
	44				2.00	1.80	
	45				4.00	1.85	
	46				8.00	1.94	
	47				16.00	2.01	
X	48	1.5	1.5	4.0	0.50	1.76	
	49				1.00	1.91	
	50				2.00	1.99	
	51				4.00	2.09	Boundary effects noted.
	52				8.00	2.16	" "
	53				16.00	2.21	" "
	54				32.00	2.23	Boundary effects significant - experiment terminated.

TABLE 1 --Continued

Test Series	Test No.	Variables Held Constant Per Test Series Q cfs	b ft	H ft	t hrs	$h^* = (V_s)^{1/3}$ [1] ft	Remarks
XI	55	2.0	1.5	4.0	0.25	1.94	
	56				0.50	2.04	
	57				1.00	2.20	Boundary effects noted.
	58				2.00	2.29	" "
	59				4.00	2.42	" "
	60				8.00	2.55	Boundary effects significant - experiment terminated.
XII	61	0.5	1.5	4.0	1.00	0.95	
	62				8.00	1.05	
	63				16.00	1.14	
	64				64.00	1.29	
	65				128.00	1.31	
	66				223.00	1.37	

TABLE 2

PHYSICAL AND HYDRAULIC PROPERTIES OF SEDIMENT PARTICLES REPRESENTATIVE OF EXPERIMENTAL BED MATERIAL

Particle Number	Axis (mm) a^*	b^*	c^*	sf $c^*/\sqrt{a^*b^*}$	Particle Weight (mg)	Nominal Diameter (mm)	Fall Velocity $w_{cm/s}$	$w_{ft/s}$	With Nominal Dimensions $\frac{wd_n}{\nu}$	$\frac{F/d_n^2}{\rho w^2/2}$
Retained on 4-mesh sieve										
1	7.52	5.68	3.30	0.51	176	4.97	25.2	0.826	1114	1.33
2	10.41	5.55	2.64	0.35	251	5.60	26.8	0.879	1286	1.32
3	5.94	5.81	3.69	-	188	5.09	-	-	-	-
4	6.60	4.62	4.48	0.81	184	5.05	29.6	0.971	1330	0.98
5	6.06	5.27	4.61	0.82	162	4.83	30.6	1.004	1326	0.88
6	6.60	5.55	4.48	0.74	220	5.36	35.2	1.157	1682	0.74
7	6.86	5.15	4.87	0.82	200	5.19	32.6	1.070	1500	0.83
8	6.60	5.41	3.44	0.57	166	4.88	34.4	1.130	1492	0.70
Retained on 6-mesh sieve										
1	5.41	4.88	3.69	0.715	141	4.62	28.2	0.924	1160	0.99
2	5.41	4.48	2.38	0.484	74	3.73	26.2	0.858	870	0.92
3	5.15	4.35	2.77	0.582	83	3.87	26.0	0.852	895	0.97
4	5.67	4.35	2.77	-	101	4.13	-	-	-	-
5	6.60	4.62	3.30	0.595	127	4.46	29.8	0.976	1182	0.86
6	4.62	3.96	3.96	0.926	72	3.69	24.8	0.813	814	1.02
7	5.67	3.69	2.24	0.490	58	3.44	23.4	0.766	716	1.07
8	5.41	4.22	3.56	0.745	103	4.16	31.2	1.024	1157	0.73
9	5.80	3.96	3.96	0.828	101	4.14	26.0	0.853	956	1.04
10	5.02	3.30	3.16	0.776	68	3.63	27.4	0.898	885	0.82
11	7.00	5.15	3.16	0.525	131	4.51	26.8	0.879	1078	1.07

TABLE 2 --Continued

Particle Number	Axis (mm) a^*	b^*	c^*	sf $c^*/\sqrt{a^*b^*}$	Particle Weight (mg)	Nominal Diameter (mm)	Fall Velocity w cm/s	w ft/s	With Nominal Dimensions $\frac{wd_n}{\nu}$	$\frac{F/d_n^2}{\rho w^2/2}$
Retained on 8-mesh sieve										
1	4.48	3.16	1.98	0.526	28.9	2.72	-	-	-	-
2	4.62	3.04	2.64	0.702	40.7	3.38	-	-	-	-
3	4.08	3.16	1.85	0.514	25.5	2.61	18.4	0.604	427	1.31
4	4.35	3.69	2.90	0.723	47.8	3.22	24.7	0.810	795	0.90
5	3.96	3.16	2.24	0.633	28.0	2.70	22.8	0.748	755	0.88
6	4.35	3.30	2.90	0.763	43.2	1.14	-	-	-	-
7	5.14	3.30	2.77	0.673	62.4	3.52	27.5	0.901	969	0.79
8	3.04	2.77	1.58	0.545	18.7	2.36	19.3	0.633	456	1.08
9	4.35	2.90	1.58	0.444	26.2	2.64	23.2	0.761	612	0.83
10	5.54	3.43	1.85	0.424	44.1	3.13	-	-	-	-
Retained on 10-mesh sieve										
1	2.78	2.31	2.24	0.883	21.1	2.46	23.5	0.771	515	0.76
2	3.04	2.64	1.45	0.511	13.5	2.11	16.6	0.545	312	1.30
3	2.97	2.24	1.92	0.745	12.5	2.16	17.0	0.558	311	1.21
4	3.10	2.18	2.11	0.812	16.2	2.25	22.8	0.748	456	0.74
5	2.51	2.38	1.52	0.623	11.5	2.01	20.5	0.673	367	0.81
6	3.17	2.24	1.92	0.722	13.1	2.09	17.1	0.561	318	1.22
7	3.10	1.85	1.45	0.604	9.3	1.87	17.5	0.574	291	1.04
8	3.04	2.18	1.98	0.767	10.1	1.92	16.6	0.545	284	1.19
9	2.84	2.44	1.59	0.602	12.1	2.04	18.9	0.620	343	0.97
10	2.71	2.44	1.78	0.690	12.4	2.06	23.1	0.757	424	0.66

TABLE 2 --Continued

Particle Number	Axis (mm) a*	b*	c*	sf $C^*/\sqrt{a^*b^*}$	Particle Weight (mg)	Nominal Diameter (mm)	Fall Velocity $w_{cm/s}$	$w_{ft/s}$	With Nominal Dimensions $\frac{wd_n}{\nu}$	$\frac{F/d_n^2}{\rho w^2/2}$
Retained on 14-mesh sieve										
1	2.38	2.05	1.98	0.895	8.6	1.82	17.8	0.584	288	0.98
2	3.17	1.98	1.25	0.496	8.8	1.83	17.2	0.564	280	1.05
3	2.51	1.65	1.59	0.780	6.9	1.69	20.3	0.666	306	0.70
4	3.90	1.65	1.52	0.599	10.2	1.93	14.0	0.459	240	1.67
5	3.76	1.52	1.59	0.665	14.1	2.14	16.1	0.528	306	1.41
6	2.28	1.92	1.19	0.567	5.6	1.58	15.7	0.515	221	1.09
7	2.97	1.78	1.39	0.604	7.75	1.76	16.5	0.561	258	1.10
8	2.44	1.85	1.39	0.656	5.2	1.54	13.9	0.456	191	1.36
9	2.51	1.72	1.19	0.578	6.4	1.65	15.7	0.515	231	1.14
10	2.48	1.98	0.90	0.424	5.3	1.55	14.4	0.472	199	1.27
Retained on 20-mesh sieve										
1	Note: Measurements were				3.45	1.34	16.3	0.537	194	0.86
2	not made of particles				1.35	0.98	12.1	.398	106	1.14
3	passing the 14 mesh				2.2	1.15	14.5	.477	148	0.93
4	sieve.				3.3	1.32	13.7	.450	161	1.19
5					1.2	0.94	10.6	.348	89	1.43
6					5.2	1.54	13.6	.448	185	1.42
7					2.6	1.22	11.6	.382	126	1.55
8					4.65	1.48	14.7	.483	194	1.17
9					1.0	0.89	11.9	.392	94	1.07
10					4.15	1.43	14.6	.480	186	1.13

TABLE 2 --Continued

Particle Number	Axis (mm) a*	b*	c*	sf $C^*/\sqrt{a^*b^*}$	Particle Weight (mg)	Nominal Diameter (mm)	Fall Velocity $w_{cm/s}$	$w_{ft/s}$	With Nominal Dimensions $\frac{wd_n}{\nu}$	$\frac{F/d_n^2}{\rho w^2/2}$
Retained on 28-mesh sieve										
1	Note: Measurements were				1.05	0.90	9.00	0.295	72	1.89
2	not made of particles				0.80	0.82	9.45	0.310	69	1.56
3	passing the 14 mesh				1.15	0.93	9.55	0.313	79	1.74
4	sieve.				-	-	-			
5					0.85	0.84	10.23	0.335	77	1.36
6					0.80	0.82	10.72	0.351	78	1.22
7					0.57	0.735	9.19	0.301	60	1.40
8					0.60	0.74	9.22	0.302	61	1.49
9					0.55	0.73	8.13	0.267	53	1.88
10					-		-			
Retained on 35-mesh sieve										
1-10					0.25[1]	0.56	5.9[2]	0.193	29	0.27
Retained on 48-mesh sieve										
1-10					0.11[1]	0.425	3.9[2]	0.128	15	0.47
Retained on 65-mesh sieve										
1-10					0.04[1]	0.300	2.0[2]	0.066	5	1.28

[1] The average weight of 10 representative particles was determined for all material passing the 28 mesh sieve.

[2] Fall velocities were taken from Fig. 25 of the report by Schulz, Wilde and Albertson (22). The fall velocity was taken as the value corresponding to the sieve size and for a water temperature of 20°C.