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VORTEX TUBE SAND TRAP[a]

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SYNOPSIS

Tests were made on a device that can be used for the removal of large sediments from canals. This material must be traveling as bed load in order to be trapped by the tube. Data from several investigations have been combined in order to develop the general design information that is presented.

INTRODUCTION

The accumulation or movement of gravel and sand in irrigation, power, and municipal canals presents problems that are usually common in the operation of water conveyance systems. When coarse sediments enter the canal through diversion structures or because of unstable channel conditions and are eroded from the canal itself, many difficulties may arise. Some of the problems encountered are: (1) the depositing of material in some reaches of the channel thereby reducing the carrying capacity and making frequent cleaning necessary, (2) gravel or sand entering the turbines in a power canal, (3) municipalities requiring the construction of elaborate desilting facilities for removal

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of this material, and (4) materials carried in irrigation canals ultimately depositing in a detrimental manner on farmlands when the water is applied.

A properly designed diversion works can exclude a portion of the material before it enters the channel. However, many diversion works were constructed before much was known about proper design for excluding or bypassing sediment. Many diversion dams act as sediment traps so that much more material than is necessary enters the canals. An overabundance of this material usually causes difficulties and must be removed.

In the case of earth canals, the channels should be designed to remain as stable as possible for all conditions of flow. Here again, a lack of knowledge of proper design has resulted in many unstable situations. Material is eroded in certain reaches to be deposited at others. Canals that infrequently act as floodways may also catch material that must later be removed.

Successful design of a device for extracting sediments involves many engineering aspects. Some of these are stable channel theory, mechanics of sediment transport, and the hydraulic principles governing operation of the device as well as structural design. For this problem, interest in sediment transport is confined to that material near the bed.

Extensive studies have been conducted in India on development of sediment excluders and extractors. In the United States, the development of the vortex tube sand trap as an extractor has been noteworthy. Pioneer development of this device was made by Carl Rohwer and Ralph L. Parshall. Considerable experimental work was done to develop the device for specific installations. However, general design criteria to assist field engineers in designing the vortex tube has been lacking.

This report summarizes the results of a study initiated to correlate the results of past studies and to conduct further investigations for developing needed design information.

Notation.—The letter symbols adopted for use in this paper are defined where they first appear, in the illustrations or in the text, and are arranged alphabetically, for convenience of reference, in Appendix I.

REVIEW OF LITERATURE

Sediment ejectors usually consist of slots or apertures in the bed of a canal through which coarser material moving as bed load can be removed along with a small quantity of the flow. Uppal (14)[2] described a device used in India to remove bed load that consisted of a series of small tunnels facing into the flow. The height of these tunnels was about one-fourth the depth of water in the canal. Flow entering the tunnels along with bed load was diverted out of the canal; also described was the use of large tunnels that passed under the canal proper. Slots were provided in a canal structure for larger sand fractions to drop through into the lower tunnel. One end of the tunnel was blocked. The other end was provided with a gate that, when opened, caused the tunnel to function as an ejector discharging into a cross drainage system.

Tests of the vortex tube sand trap along with a riffle deflector device were first reported by Parshall (8). The vortex tube sand trap was described as a tube with an opening along the top and placed in the bed of a canal at an angle of about 45° to direction of flow. As flow passed over the opening, a spiral

[2]Numerals in parenthesis—thus; (1)—refer to corresponding items in the Appendix, Bibliography.

motion was set up within the tube. Material traveling along the canal bed was drawn or dropped into the tube and carried to an outlet at which it was discharged into a return channel. The device was observed to be very effective in removing large material even to the size of cobblestones. The riffle deflector sand trap was described as consisting of a series of curved metal plates, each the shape of the quadrant of a circle fastened to the channel floor. Bed load was caused to move to one side of the channel at which it was removed through an opening. A combination of riffles and tubes was also tested with considerable success.

Rohwer, et al. (10) reported the results of tests conducted on vortex tubes installed in channels 8 ft and 14 ft wide. The tubes used were 4 in. and 6 in. in diameter set at various angles to the flow. Conclusions from these tests were given as: (1) the tubes were most active when the depth of water in the channel was slightly less than critical; (2) straight or tapered tubes were equally efficient in removing sand; (3) angle of tube for angles less than 90° to the direction of flow had little effect on efficiency; (4) efficiencies of trapping were conspicuously better when elevations of the upper and lower lips were the same; (5) the tubes would remove from 70% to 90% of bed load carried by the flume; (6) tubes in a channel that was 8 ft wide seemed to be more efficient in sand removal than ones installed in a channel 14 ft wide; and (7) when the Froude number of the flow immediately upstream from the tube exceeded 1.3 a considerable amount of sand and gravel was thrown out of the tube and reentered the channel.

The amount of flow from the tube was regulated for some of these tests. This was accomplished by controlling the water level at the tube outlet so that the percentage of flow removed could be varied. It was found that the wasted flow could be reduced by 40% to 50% with a corresponding smaller reduction in the trapping efficiency.

Measurements of velocity of translation and rate of rotation of the flow within the vortex tube were attempted. The maximum translation velocity was found to be approximately 0.4 times the mean velocity in the channel. Because of the number of variables introduced into the study, it was not possible to determine the relationship of translation velocity and rotation to other factors.

Further tests on the vortex tube are also reported by Rohwer (11). For these tests, tube shape was varied as well as size of sand. The tubes were installed at an angle of 45°. By testing a number of tubes a shape was found that gave the highest trapping efficiency. This efficiency varied with the size of material, being near 90% for material with a median diameter of 1.75 mm and 45% for 0.38 mm median diameter sands. These efficiencies were nearly constant for a range in Froude numbers from 0.4 to 1.3 (velocities 2.3 to 7.9 fps). The percentage of total flow removed by the tube varied from 3.8 to 13.0.

The amount of flow from the tube was also controlled in a limited number of tests. It was found that a reduction of tube discharge of 40% to 50% caused only a slight decrease in trapping efficiency. In both series of tests reported by Rohwer (10), (11) the sand was instantaneously dumped into the channel; thus, a constant rate of sediment inflow was not maintained.

Parshall (9) stated that the optimum action of the vortex tube occurred when the water passing over the lip was at or near critical velocity. He also stated that field installations of the device had been both successful and unsuccessful. In installations that were ineffective it was noted that the velocity in the canal was low and the tube was set below channel grade. Trapping efficiencies of 90% were claimed for the device when operating properly.

A tube 0.2 ft in diameter with one-quarter of the circumference cut away and installed in a flume 2 ft wide was studied by Koonsman (3), (4). The sand used for the tests had a size range of 0.4 to 1.1 mm with a median diameter of 0.7 mm. Concentrations of sand ranged from 0.09 to 0.68 in percent by weight. Velocity of flow varied from 1.3 to 5.5 fps while depth ranged from 0.2 ft to 0.6 ft (Froude number, **F**, 0.5 to 1.5). The elevation of the downstream lip was varied relative to the upstream one. Results from these tests showed that: (1) highest trapping efficiencies (92%) were noted near a Froude number of 1.0; (2) efficiencies decreased as the depth of flow increased; (3) efficiencies decreased as concentration was increased beyond a certain point depending also on the depth of flow; (4) optimum operation was noted when the lips were at the same elevation; and (5) percentage of flow removed from the tube varied from 2.7% to 15.5% depending on velocity and depth of flow over the tube. The reason given for the apparent decrease in efficiency with increasing depth was that greater quantities of sediment were being moved and more of this material was in suspension at the greater depths.

Model studies of sediment control structures for diversion dams have been reported by Martin and Carlson (7). Included in the studies of the Republic diversion dam was a vortex tube that was installed upstream from the radial gate at the headworks. Various arrangements of guide walls alone and in combination with the vortex tubes were tried in order to exclude sand from the canal. The inclusion of the vortex tube in the model design gave the greatest improvement in exclusion of any individual change. A unique innovation of the design was the installation of a tapered horizontal vane over the vortex tube. The tapered vane increased the velocity directly over the tube causing the vortex in the tube to be more active that in turn increased its ability to move sand.

In a design study by Ahmad (1), the vortex type ejector was found to be superior to the frontal type and was, therefore, preferable to the common ones used in Pakistan. The vortex type gave greater efficiencies at less discharge extractor ratios (percent of total flow removed) under similar operating conditions. The following recommendations were made regarding the design of the vortex tube.

(1) The structure should be designed so that the Froude number of flow at the tube is equal to 0.8.

(2) Diameter of the tube should be equal to water depth in the channel at a Froude number equal to 0.8.

(3) The two lips of the opening slit should be at the same elevation.

(4) Opening of the slit should be one-sixth of tube circumference.

(5) Under conditions of heavy silt concentration, a long tube may not work efficiently. In this case, shorter tubes should be used, each equipped with an independent discharge pipe.

Review of past studies indicates that the vortex tube type of sand trap has been found to be superior to other types of sediment ejectors. The following design features are indicated based on findings of previous investigators.

(1) The Froude number of the flow in the section containing the vortex tube should be near 1.0.

(2) Amount of flow removed by the tube depends on slot opening as well as depth and velocity of flow. An average extractor ratio of about 10% was indicated.

(3) The shape of tube was not particularly important as long as area was sufficient and shape such that sediment would not escape from the tube once it had entered. Rohwer (11), however, developed and tested a particular shape that had almost constant efficiencies regardless of rate or depth of flow.

(4) Efficiency of trapping increases as size of material increases.

(5) Straight tubes performed equally as well as tapered ones.

(6) There seems to be a limiting length of tube for optimum operation.

(7) The angle of tube should be in the range of 45° to 65° from the direction of flow.

ANALYSIS OF THE PROBLEM

As stated previously, the successful design of a bed load extractor must necessarily consider stable channel design, the mechanics of sediment transport, and the hydraulic principles governing the operation of the device.

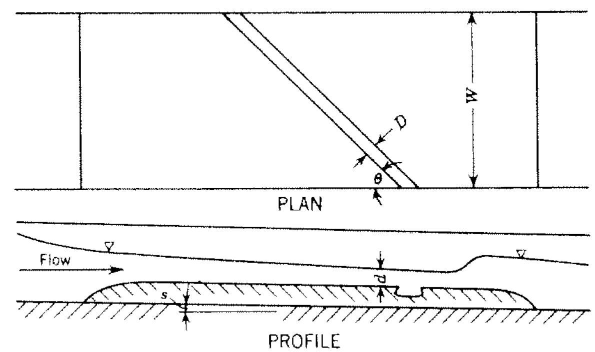


FIG. 1

Dimensional Analysis.—In order to group the pertinent variables involved in the operation of a vortex tube and to arrange these variables for a systematic approach to the problem, dimensional analysis can be used. By using the dimensionless parameters that result, a study covering a maximum range of operating conditions can be made.

Some of the variables describing the physical features of the vortex tube are shown in Fig. 1.

The variables describing the channel and tube are width of opening, D; the difference in upstream and downstream lip elevations, P; the contraction ratio between the channel and section containing the vortex tube, Z; the width of vortex tube section, W; the slope of channel, s; the shape of tube (may also describe relative area), λ; and the angle of tube to direction of flow, θ.

Variables describing the flow are the depth of flow upstream from tube, d; the mean velocity of flow immediately upstream from tube, V; the water discharge through tube, Q_T; the total sediment discharge through channel, G; and the sediment discharge through the tube, G_T.

The sediment may be described by the density, ρ_s; the size of sand fraction, d_s; and the fall velocity, ω.

Variables describing the fluid are the dynamic viscosity, μ; the density, ρ; and the specific weight of fluid, γ. The general relationship that exists between the variables is

$$\phi_1 (D, P, Z, W, S, \lambda, \theta, d, \overline{V}, Q_T, G, G_T, \rho_s, \omega, d_s, \mu, \rho, \gamma) = 0. \qquad (1)$$

Choosing $\overline{V}$, ρ and D as repeating variables and combining yields

$$\phi_2\left(\frac{P}{D}, Z, \frac{W}{D}, s, \lambda, \theta, \frac{d_u}{D}, \frac{Q_T}{\overline{V}\, D^2}, \frac{G}{\overline{V}\, D^2}, \frac{G_T}{\overline{V}\, D^2}, \frac{\rho}{\rho_s}, \frac{\omega}{\overline{V}}, \frac{d_s}{D}, \frac{\overline{V}\, D\, \rho}{\mu}, \frac{\overline{V}}{\sqrt{g\, D}}\right) = 0 \ldots (2)$$

By replacing d_u for D and W d_u for D^2 in the flow parameters, Eq. 2 can be written as

$$\phi_3\left(\frac{P}{D}, Z, \frac{W}{D}, s, \lambda, \theta, \frac{d}{D}, \frac{Q_T}{Q}, \frac{G}{Q}, \frac{G_T}{Q}, \frac{\rho}{\rho_s}, \frac{\omega}{\overline{V}}, \frac{d_s}{D}, \frac{\overline{V} d \rho}{\mu}, \frac{\overline{V}}{\sqrt{g\, d_u}}\right) = 0 \ldots (3)$$

with Q representing the quantity of flow, $\overline{V}$ W d_u.

On the basis of known relationships, and from previous studies, certain delimitations can be made to reduce the number of variables involved. Some terms can be eliminated from Eq. 3 for the present study. The term s can be eliminated because it is related to velocity and depth, θ because it will be constant at 45° from direction of flow, $\frac{\rho}{\rho_s}$ because it will be essentially constant for sand and water, and $\frac{\overline{V}\, d_u\, \rho}{\mu}$ (Reynolds number $\mathbf{R}$) because it should be of minor importance in a problem of this nature. The parameter Z will be varied in order to obtain a range of $\overline{V}/\sqrt{g\, d_u}$ (Froude number) for flow over the tube. For this reason, Z will be eliminated, because the variation of $\mathbf{F}$ is of primary interest. With these limitations, Eq. 3 reduces to

$$\phi_4\left(\frac{P}{D}, \frac{W}{D}, \lambda, \frac{d_u}{D}, \frac{Q_T}{Q}, \frac{G}{Q}, \frac{G_T}{Q}, \frac{\omega}{\overline{V}}, \frac{d_s}{D}, \frac{V}{\sqrt{g\, d_u}}\right) = 0 \ \ldots\ldots\ldots \ (4)$$

Combining $(G/Q)^{-1}$ with G_T/Q and retaining G/Q results in a parameter G_T/G that is the efficiency of trapping, E. The ratio of water removed by the tube to the total flow is represented by Q_T/Q and may be termed the extractor ratio R. The Froude number relates inertia to gravity forces and should be of prime importance in a problem of this nature. The parameter G/Q is the concentration of sediment and will be termed C. The length of tube L is needed rather than channel width so that W will be replaced by L. Eq. 4 then becomes

$$\phi_5\left(\frac{P}{D}, \frac{L}{D}, \lambda, \frac{d}{D}, R, C, E, \frac{\omega}{\overline{V}}, \frac{d_s}{D}, \mathbf{F}\right) = 0 \ \ldots\ldots\ldots\ldots (5)$$

and presents all known variables involved in the problem.

Flow Analysis.—Because efficiency of trapping E is probably dependent on extractor ratio R, but R is independent of E, the problem should be separated into a flow analysis and sediment removal analysis. Assuming that the tube will remove the same amount of water whether clear or sediment laden and

using R as the dependent variable, the sediment factors may be omitted to yield

$$R = \phi_6\left(\frac{P}{D}, \frac{L}{D}, \lambda, \frac{d}{D}, \mathbf{F}\right) \ \ldots\ldots\ldots\ldots\ldots (6)$$

For a particular series of tests, three of the independent parameters in Eq. 6 can be held constant while varying the other two. In this case, P/D (relative downstream lip elevation), L/D (relative tube length), and λ (tube shape) can be held constant for one test series and then changed and again held constant for another series. In this manner, the effect of all five variables can be determined.

The functional relationship implied in Eq. 6 can be determined analytically. The amount of flow that will be removed by the tube may be governed to some extent by width and length of slot as well as cross-sectional area of the tube. If a circular orifice is assumed then the discharge will be given by

$$Q_T = c\ A_T\ \sqrt{2\ g\ H} \ \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

in which A_T is the cross-sectional area and H is the effective head on the tube, that is

$$H = d + \frac{B}{2} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

in which d is the depth of flow in the channel at the tube, and B is depth of tube. The term c would be a modified coefficient of discharge due to tube geometry and approach velocity.

The condition of continuity in the channel over the tube section is

$$Q = A\ \overline{V} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

in which Q is channel discharge and A the area of flow, that is (W d). Dividing Eq. 7 by Eq. 9 results in

$$R = \frac{Q_T}{Q} = \frac{c\ A_T\ \sqrt{2\ g(d + B/2)}}{A\ \overline{V}} \ \ldots\ldots\ldots\ldots (10)$$

or

$$R = \frac{c\ A_T\ \sqrt{2}\ \sqrt{1 + B/2\ d}}{A\ \overline{V}/\sqrt{g\ d}} \ \ldots\ldots\ldots\ldots (11)$$

Multiplying and dividing by width of opening D, and substituting A = W d results in

$$R = \frac{c\ \left(A_T/D\right)\ \sqrt{2}\ \ \sqrt{1 + B/2\ d}}{W\ (d/D)\ \ (\mathbf{F})} \ \ldots\ldots\ldots\ldots (12)$$

Because W = L sin θ

$$R = \frac{c\ \sqrt{2}\ \sqrt{1 + B/2\ d}}{\left(D\ L\ \sin\theta/A_T\right)\ (d/D)\ \ (\mathbf{F})} \ \ldots\ldots\ldots\ldots (13)$$

For a particular design

$$R = \frac{c' \sqrt{1 + B/2\ d}}{(d/D)\ (\mathbf{F})} \qquad (14)$$

in which

$$c' = \frac{c\ \sqrt{2}}{\left(D\ L\ \sin\ \theta / A_T\right)} \qquad (15)$$

For the analysis of flow, Eq. 14 can be used together with Eq. 6. It should be emphasized that these relationships apply only when the tube is discharging freely. When the outflow is controlled, other variables are introduced into the basic relationships.

Sediment Removal Analyses.—The parameters that determine the operation of the device in the removal of sediments are given in Eq. 5. Because E is now the dependent variable,

$$E = \phi_7 \left(\frac{P}{D}, \frac{L}{D}, \lambda, \frac{d}{D}, R, C, \frac{\omega}{\bar{V}}, \frac{d_s}{D}, \mathbf{F}\right) \qquad (16)$$

Of major importance is the effect of particle size on the efficiency of trapping. Because the parameter d_s/D is more easily obtained than $\omega/\bar{V}$ in describing the sediment, it will be retained. The sediment concentration C is probably important only for large concentrations since it is conceivable that with large amounts of bed load, the tube would become overloaded. If the extractor ratio R approaches the upper limit of 100%, then the efficiency must also approach the same limit. For this reason, the efficiency must be partially dependent on the amount of water removed. Previous investigators (1), (3), (10), (11) have shown that the Froude number is particularly important. Koonsman and Albertson (4) found that the efficiency of trapping decreased as the ratio of depth to slot opening (d/D) increased.

For a particular tube design, the parameters describing the tube geometry may be held constant. For this condition, Eq. 16 reduces to

$$E = \phi_8 \left(\frac{d}{D}, R, C, \frac{d_s}{D}, \mathbf{F}\right) \qquad (17)$$

The Froude number and the resultant depth will be varied. The sediment load will be divided into different size ranges so that the relationship of size to efficiency will be determined.

Stable Channel Design and Sediment Transport.—Although the vortex tube sand trap may be installed in both lined and unlined canals, the unlined section is of primary importance. Here the purpose of the ejector is to assist in stabilization of a channel that is otherwise unstable. A stable channel is defined as an unlined earth canal for carrying water, the banks and bed of which are not scoured by moving water, and in which deposits of sediment do not occur. Many investigators have developed design criteria for stable channels. Notable among the recent studies have been those of Blench (2), Lane (5), and Simons (12). Relationships have been developed using both regime and tractive force theories for determining width, depth, and slope of a stable channel in erodable material.

The purpose of sand ejectors is to remove a portion of the sediment that is moving as bed load rather than suspended load. Bed load is defined as that portion of the sediment load, usually coarse material, that is moving on or near the channel bed. There is no distinct dividing line separating suspended and bed load. Size of material that may be transported either as bed or suspended load covers a fairly broad range and depends on many factors. Any given channel is capable of transporting a certain quantity of sediment depending on related factors such as shape of channel, size of sediment, slope of the energy gradient, and amount of wash load. The effect of reducing the sediment load of an otherwise stable channel is to initiate scour and hence non-equilibrium. Conversely, deposition will occur if the sediment load is increased above the stability level. The balance between stability of a channel and charge has been given by Lane (6). The relationship he presents is

$$G\ d_s \sim Q\ s_e \qquad (18)$$

in which G is the quantity of sediment being discharged, d_s the mean particle diameter, Q the water discharge, and s_e the slope of the energy gradient. This expression shows that, if a stream in equilibrium has its sediment load decreased equilibrium can be restored by decreasing Q and s_e or a combination of the two.

Simons (12) found that stable earth canals through soils in the sandsilt range generally carried less than 500 ppm of total load exclusive of wash load. In effect, this would mean that canals in this material, carrying heavier loads, could be stabilized if the load were reduced below the 500 ppm level.

From this information, it would seem that the primary purpose of a sand ejector is not to remove all the sediment but rather to reduce the load to a level that can be carried under stable conditions. The difference between the load being carried in the unstable condition and that necessary to establish a stable channel is the amount that the extractor would be required to remove.

The forms of bed roughness in an alluvial channel are dependent on the bed material, sediment in transport, and characteristics of the flow (13). Laboratory studies by Simons and Richardson for the United States Geological Survey (USGS), at Fort Collins, Colo., and a field study by Simons (12) have shown that the following approximate relationship exists for channels in sandy material having a mean diameter of 0.45 mm.

Flow Regime and Form of Bed Roughness	Total Sediment Load in Percent
Tranquil Flow Regime ($\mathbf{F} < 1$)	
(1) Plane bed without movement of the bed material	----
(2) Ripples	0.0 - 0.0075
(3) Dunes	0.0075 - 0.1
(4) Transition from dunes to rapid flow	0.1 - 0.3
(5) Plane bed with movement of bed material	0.3 - 0.4

Rapid Flow Regime ($F > 1$)

(6) Standing water waves and sand waves	0.4 - 0.6
(7) Antidunes	> 0.6

The forms of bed roughness in the foregoing table are arranged in order of increasing Froude numbers.

Of importance in the design of the vortex tube sand trap is the manner in which the bed load will be traveling. In the case of dune bed roughness, bed material is traveling in waves or slugs, and the suspended load is relatively large. The amount moving past a certain point will vary with time. In this case, it is foreseeable that at the time a dune reaches the tube, the tube would become completely covered with sediment and would be rendered inoperative. This phenomenon has been observed on both field structures and laboratory studies. With the plane bed form of roughness, movement of bed load is reasonably continuous and at fairly constant rate.

With these factors in mind, the section containing the tube should be designed so that flow conditions in the section are in the regime in which a plane bed will exist. According to Simons and Richardson, this form of roughness exists at a Froude number range of 0.4 - 0.5 for material with a mean diameter of 0.28 mm and 0.6 - 0.7 for a mean diameter of 0.45 mm. From these ranges, it is logical to assume that as size of material is increased, the Froude number must also be increased in order to maintain plane bed condition.

EQUIPMENT AND PROCEDURE

The flume used for the study was available in the Hydraulics Laboratory at Colorado State University, Fort Collins, Colorado. This flume is 160 ft long, 8 ft wide, and is adjustable for slope. A system of large centrifugal pumps recirculates the water and sediment. Maximum flows near 20 cfs are possible. Sand of desired gradation can be placed to depths of 6 in. to 8 in. throughout the length of the flume. The field situation of sediment transport is simulated because of the recirculation feature and size of flume.

For tests of the vortex tube, a section containing the tube was placed in the flume near the downstream end [see Figs. 2, 3(a), and 3(b)]. This section was constructed so that tubes of different shapes and sizes could be inserted. The sediment and water discharge from the tube was conveyed by pipe into a head box and thence through a Parshall measuring flume [Fig. 3(c)]. Periodically, this flow was diverted into a weighing tank for determining the amount and size of sediment being removed. The sediment discharge past the tube was determined using a sampler that traveled across the overfall from the flume [Fig. 3(d)]. Several traverses were made to obtain a single representative sample. Duplicate samples were usually taken from both the tube and traversing samplers.

The total water discharge through the flume was determined using calibrated orifices in the pump discharge lines. Depths of flow were measured using a point gage mounted on a movable carriage. The water surface profile was determined beginning at a point several feet upstream from the vortex tube section and extending downstream from the section. The depths of flow were adjusted using the movable tailgate [Fig. 3(b)].

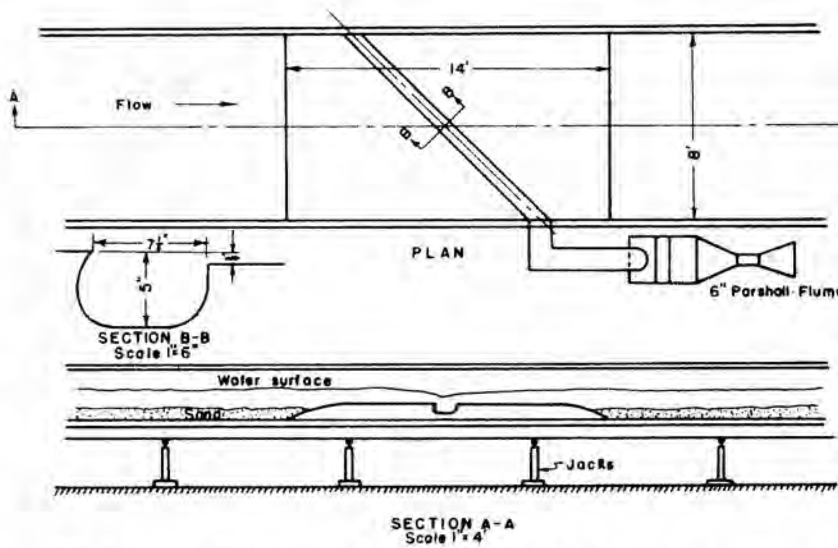
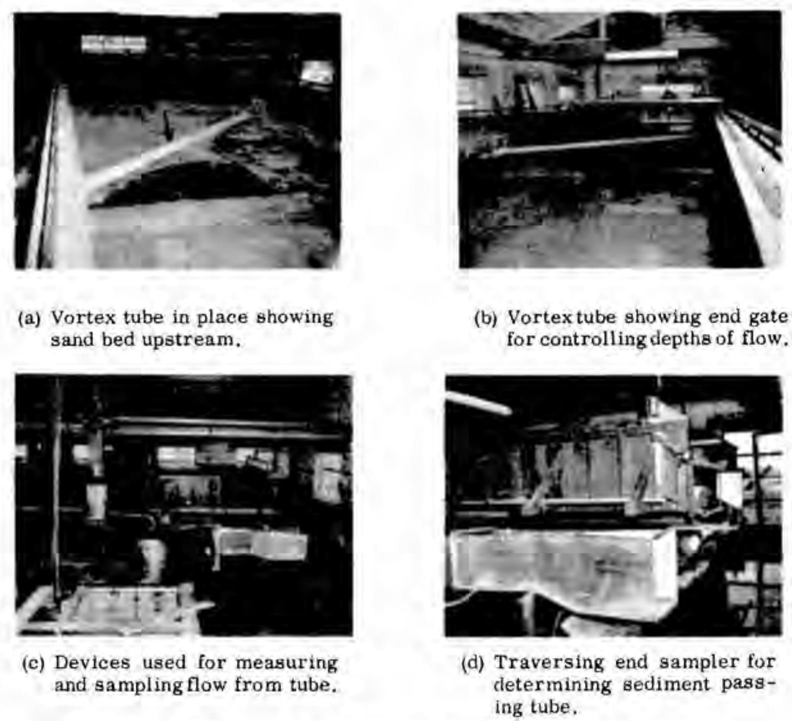


FIG. 2.—LAYOUT OF VORTEX TUBE SAND TRAP FOR LABORATORY STUDY



(a) Vortex tube in place showing sand bed upstream.

(b) Vortex tube showing end gate for controlling depths of flow.

(c) Devices used for measuring and sampling flow from tube.

(d) Traversing end sampler for determining sediment passing tube.

FIG. 3.—DETAILS OF EQUIPMENT USED FOR LABORATORY STUDY OF VORTEX TUBE

The bed material used in these tests was a granitic sand having a median size of 0.53 mm. Of the entire sand fraction, 22%, by weight, was finer than 0.30 mm, and 25% was larger than 0.83 mm. For the purpose of determining the relationship of size of material to efficiency of trapping the samples were broken into size ranges consisting of fraction > 0.83 mm, fraction 0.59-0.83 mm, fraction 0.30-0.59 mm, and fraction < 0.30 mm.

Basically, the procedure followed in conducting the tests was as follows:

(1) A flow was established and allowed to stabilize for a period of 2 hr. to 4 hr.

(2) After this period, the total water discharge and that from the tube was determined.

(3) Water surface profiles and depths were measured using the traveling point gage.

(4) Samples for sediment analyses were taken.

(5) The depth of flow for the particular discharge was then changed, and the procedure repeated after the 2 hr to 4 hr stabilization period.

A range of Froude numbers of from 0.3 to 1.4 was covered for a constant discharge. On completion of this range, the discharge was changed and the procedure repeated.

A limited number of additional tests were also made utilizing tubes installed in a flume that was 4 ft wide. In this case, sediment was not used, since the purpose was to study only the characteristics of flow from the tube. With the 4-ft width, it was possible to observe the action of tubes that were one-half the length of those in the 8-ft flume. For these tests, the amount of flow from the tubes was controlled by submerging the tube outlet. Piezometers were installed in one tube to observe the distribution of piezometric head around the periphery of the tube. Particles of the same specific gravity as sand were injected into the tube to measure the translation velocities.

Designs of the different tubes used in this study are shown in Table 1. In these tests, the design listed for series 1 is identical in shape to the one found to be superior in trapping by Rohwer (series 6). The tube listed for series 4 to 10 was modified from 0.5 ft ID steel pipe. Also shown in Table 1 are designs used by Rohwer (11) and the one used by Koonsman (3) because data from these tests are also presented in this report.

Two field installations of vortex tubes designed by Ralph L. Parshall are shown in Fig. 4. These two structures have each been termed highly successful although quantitative measurements have not been made. Because of large quantities of bed load involved, two parallel tubes were used in the structure shown in Fig. 4(a). The sides of the structure were contracted and the bottom raised to increase the velocity across the tubes. Shown in Fig. 4(a) is the outlet works to convey the removed flow back to the river. Two tubes were also used in the installation shown in Fig. 4(b) to reduce the length of a single tube. Each tube discharges into a catchment basin in the center, which, in turn, discharges through a buried pipe under the structure into the return channel.

ANALYSIS OF DATA

One objective of this study was to correlate the results of past investigations with the current experiments. These studies were all essentially laboratory studies since no field evaluations have been made. However, except for

TABLE 1.—TEST DESIGNS OF VORTEX TUBES

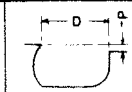
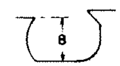
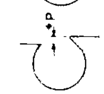
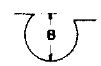
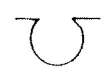
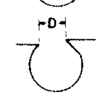
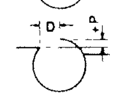
Series No.	Tube Shape	Area (A) ft^2	Length (L) ft.	Depth (B) ft.	Opening (D) ft.	Downstream Lip Position (P) ft
Robinson 1		0.244	11.31	0.417	0.625	-0.062
2		.261	11.31	.417	.561	+.005
3		.280	11.31	.417	.520	+.064
4		.170	11.31	.440	.375	-.062
5		.184	11.31	.440	.308	+.020
6		.197	11.31	.440	.287	+.091
7		.170	11.31	.440	.375	-.062
8		.182	11.31	.440	[illegible]	+.009
9		.194	11.31	.440	.232	+.080
10		.196	11.31	.440	.204	+.080
11	Same as 1	.244	5.48	.417	.625	-.062
12	Same as 4 & 7	.170	5.48	.440	.375	-.062

TABLE 1. –*CONTINUED*

Series No.	Tube Shape	Area (A) ft.²	Length (L) ft.	Depth (B) ft.	Opening (D) ft.	Downstream Lip Position (P) ft.
Rohwer 1		.234	11.31	.417	.625	-.125
2		.238	11.31	.417	.625	.000
3		.256	11.31	.417	.625	-.062
4		.256	11.31	.417	.583	-.083
5		.184	11.31	.417	.583	-.083
6		.262	11.31	.416	.625	-.062
7		.138	11.31	.292	.469	-.042
Koonsman	 Dia. 0.2'	.0286	2.83	.172	.142	.000

Note - Rohwer Series 1-7 tubes tapered. Average dimensions shown except for length.

the work of Koonsman (3), the laboratory studies were made on large structures comparable to the sizes used in the field.

An understanding of the hydraulics of flow in the tube is essential in order to analyze the efficiency of trapping. For this reason, the problem has been broken down into a flow and sediment removal analysis so that these phases will be dealt with separately and then combined to show the total effect.

Flow-Analysis.—The general relationship presenting the parameters that are of importance in the hydraulic behavior of the vortex tube are given in Eq. 6. Eq. 14 was developed by assuming that the flow from the tube can be determined by the general orifice equation. This was the case for free flow from the tube. Fig. 5 illustrates the validity of this relationship. Fig. 5 shows the results of five series of tests made with tubes of two different designs. Values of c' in Eq. 14 are shown for each series. Note that extractor ratio R is inversely proportional to the parameter d/D and the Froude number. For a constant depth, the percentage of flow removed would be increased if the opening D is increased or the velocity decreased.

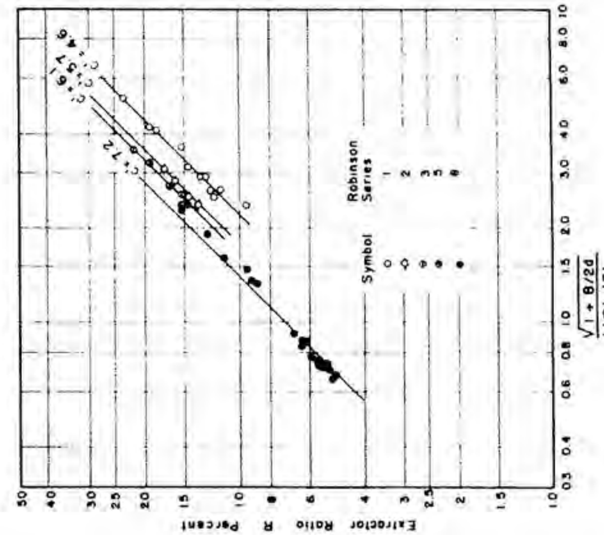


FIG. 5.—EXTRACTOR RATIO AS A FUNCTION OF d/D AND FROUDE NUMBER

(a) Installation in the Handy Canal near Loveland Colorado using two parallel tubes.

(b) Structure in the Ish Canal near Berthoud, Colorado using two tubes discharging into a central bay.

FIG. 4.—FIELD INSTALLATIONS OF VORTEX TUBE AND SAND TRAPS

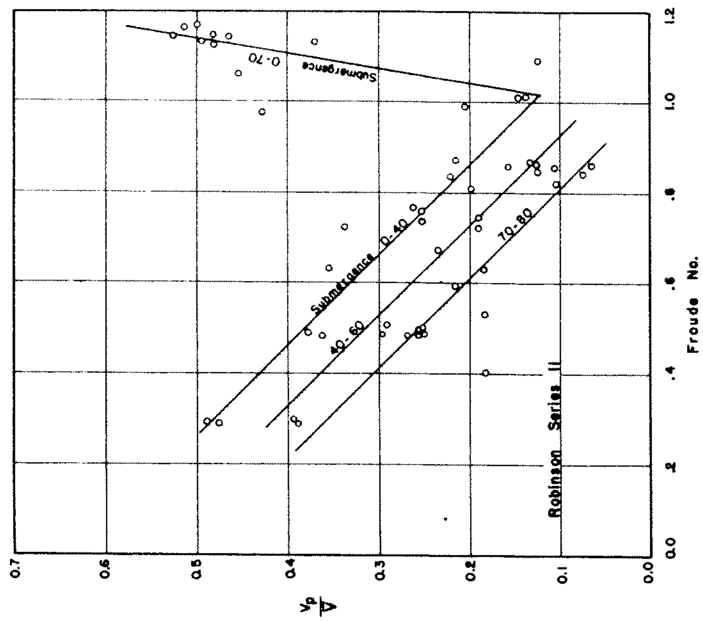


FIG. 7.—RELATIONSHIP OF PARTICLE VELOCITY AND FROUDE NUMBER

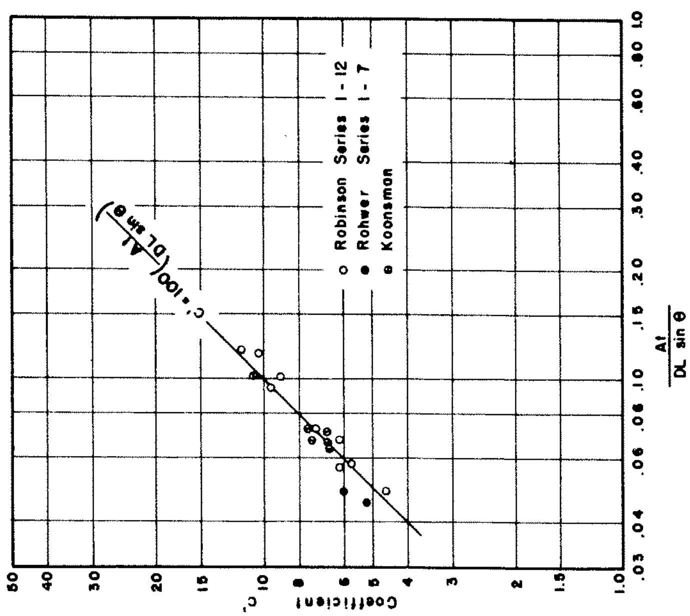


FIG. 6.—DISCHARGE COEFFICIENT AS A FUNCTION OF TUBE GEOMETRY

Values of c' are shown in Table 2 for all the present tests together with those from Rohwer (11) and Koonsman (3). These are values determined when expressing extractor ratio R in percent. Also given are the parameters describing the tube geometry. In the case of the tapered tubes (Rohwer 1 through 7), the area of tube was that at the outlet end. The relationship of this

TABLE 2.—SUMMARY OF FLOW ANALYSES OF VORTEX TUBES

Series	$\frac{P}{D}$	$\frac{L}{D}$	$\frac{A_T}{D\ L\ \sin\theta}$	c'
Robinson				
1	-0.100	18.1	0.0487	4.6
2	+ .009	20.2	.0580	5.7
3	+ .123	21.8	.0672	6.1
4 and 7	- .166	30.2	.0565	6.2
5 and 8	+ .044	35.8	.0722	7.2
6 and 9	+ .331	43.6	.095	9.6
10	+ .421	55.5	.120	11.5
11	- .100	8.8	.101	9.0
12	- .166	14.6	.117	10.4
Rohwer[a]				
1	- .200	18.1	.0650	6.7
2	.000	18.1	.0652	6.7
3	- .100	18.1	.0706	6.7
4	- .142	19.4	.0670	7.4
5	- .142	19.4	.0450	5.2
6	- .100	18.1	.0723	7.6
7	- .089	24.1	.0485	6.0
Koonsman	.000	19.9	.101	10.7

[a]Rohwer series 1-7 used tapered tubes.

parameter to the coefficient c' is shown in Fig. 6 with the equation being,

$$c' = 100\left(\frac{A_T}{D\ L\ \sin\theta}\right) \qquad (19)$$

It should be emphasized that the data shown in Fig. 6 includes that from a variety of tube shapes, lengths, and areas so that Eq. 19 is the general relationship. With Eq. 19, it is then possible to determine the coefficient c' in Eq. 14 for a tube design. For a given depth of flow and corresponding velocity, the percent of flow that will be removed can be determined with a probable accuracy of $\pm$ 10%.

One other parameter in the analysis of the free flow discharge from the tube was not considered in the foregoing discussion. This is the relative elevation of the downstream lip of the tube, that is, P/D. Because of the interrelationship of P with D and A_T in the present experiments, it was not possible to separate the effects of this variable. In general, it was noted that as the downstream lip was raised, the percent of flow removed was increased slightly. The deviation of points in Fig. 6 was not entirely due to the variation of the parameter P/D.

In the previous work by Rohwer (10) (11), tests were made to determine the relative operation of the tube when the flow from the tube was controlled. This control was accomplished by adjusting the water level in a chamber into which the tube discharged. This same scheme was used in the tests on the Robinson series 11 tests. The percent of tube submergence was determined as the ratio of depths in the channel to those in the control chamber taken from a base that was the floor of the section containing the tube. With this base, tube submergence was zero until the water level in the chamber was above the top of the tube outlet.

The tests on the effect of controlling the tube discharge by end submergence were inconclusive. Generally, the relationship for tubes operating under submergences up to 40% was the same as for free flow. For this condition, the value of the coefficient c' was 9.0. As the submergence was increased beyond 40%, the extractor ratio decreased. At 90% submergence, the percentage of flow removed was less than one-half that for the 0% through 40% condition.

The tests by Rohwer (10), (11) indicated that the flow from the tube could be reduced in the manner described, and yet high efficiencies of trapping could be maintained. In essence, this would mean that the translation velocity within the tube would be maintained under these conditions. Results of observations made during the Robinson series 11 tests are shown in Fig. 7. The relationship of the parameter $V_p/\overline{V}$ to the Froude number, with the percent of submergence as the third variable is shown. V_p is the translation velocity that was the velocity of a particle along the tube and $\overline{V}$, the mean velocity of the flow over the tube.

Although the relationships in Fig. 7 are not well defined due to scatter of data, definite trends are noted. As the Froude number increases to a value of 1 the velocity ratio decreases. Beyond a Froude number of 1 this ratio increases sharply. For a given Froude number below 1, the ratio of $V_p/\overline{V}$ decreases as the percentage of tube submergence increases, indicating that the translation velocity has decreased because the mean velocity remains constant. Examination of data from Rohwer (10) indicated almost identical trends, with the lowest value of $V_p/\overline{V}$ being near a Froude number of 1.

Water surface profiles and piezometric head distribution in the vicinity of the vortex tube is given in Fig. 8. This was for a constant discharge and tube design used in Robinson series 11 tests. The Froude numbers indicated on each profile were determined using the depth 1 ft upstream from the tube. In each case, the piezometer in the L-4 location gave a pressure greater than the water depth. This was probably due to impact or change of momentum of the jet being greater at this point. At the L-3 location, that is in the bottom of the tube, piezometric head was always lower than the water depth, being the lowest at the higher Froude number and increasing as the Froude number decreased. Of particular interest are the determinations made at the L-1 location directly under the upstream lip of the tube. Contrary to a belief that negative pressures exist at this point, the piezometric head was always greater than water depth except at the highest Froude number. The magnitude of the variation of piezometric head from water depth is an indication of the vorticity within the tube. This variation is essentially constant for the higher Froude numbers down to a value of 0.85 after which it decreases rapidly.

Sediment Removal Analysis.—Using dimensional analysis the parameters that should affect the efficiency of trapping were arranged in dimensionless form as given in Eq. 16. For a particular tube design, those terms describing the shape are held constant. For this condition, Eq. 16 reduces to Eq. 17, that

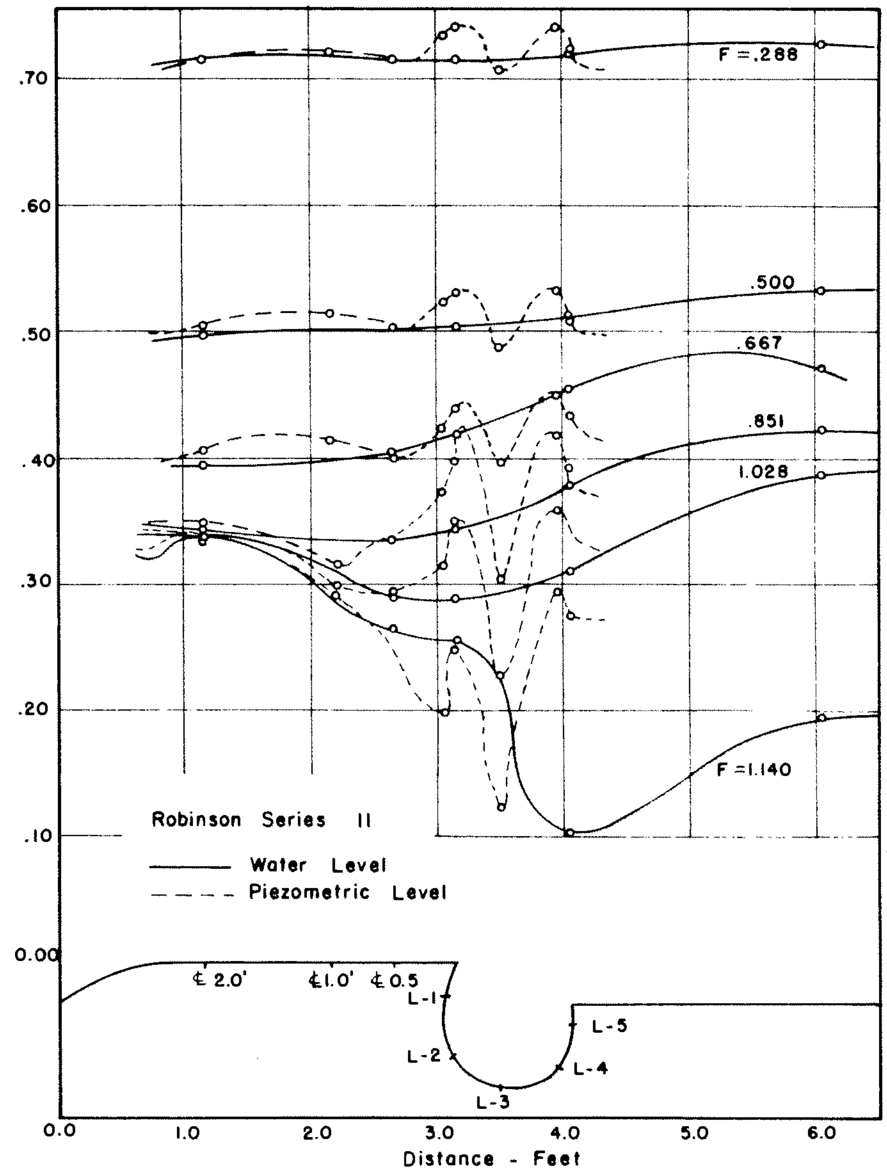


FIG. 8.—RELATIONSHIP OF FLOW DEPTH TO PIEZOMETRIC LEVEL

TABLE 3.—SUMMARY OF VORTEX TUBE EFFICIENCY—ROBINSON

Series No.	d/D range	F	Trapping efficiency in percent				
			0.83 mm	0.59 - 0.83 mm	0.30 - 0.59 mm	0.30	Total Sample
1	0.39-0.96	1.2	79.0	72.0	70.0	24.0	36.0
		1.0	85.5	77.5	75.0	26.5	41.0
		0.8	90.5	81.5	78.5	28.0	45.0
		0.6	93.5	84.0	81.5	30.0	49.5
3	.72-1.05	1.2	92.5	83.5	74.0	29.5	47.0
		1.0	92.0	84.0	75.0	31.0	49.0
		0.8	91.0	84.5	75.5	32.5	50.5
		0.6	91.0	84.5	76.0	34.0	52.0
4	.72-1.15	1.2	72.0	69.5	62.0	27.0	49.5
		1.0	62.0	59.5	58.0	28.5	42.0
		0.8	67.0	61.5	60.0	25.0	41.0
		0.6	81.5	70.0	66.0	26.0	45.0
5	1.00-1.56	1.2	89.0	78.5	65.0	25.0	47.5
		1.0	86.0	77.5	63.5	25.0	47.0
		0.8	84.5	77.5	61.5	24.0	45.5
		0.6	85.5	79.0	59.0	43.0	23.5
6	1.39-1.83	---	----	----	----	----	----
		1.0	88.5	79.0	71.0	39.5	61.5
		0.8	80.0	65.0	51.0	32.0	49.0
		0.6	78.0	61.5	40.5	24.5	37.0
7	1.23-2.50	1.2	50.0	42.5	32.5	17.5	30.5
		1.0	50.0	45.0	35.0	18.5	32.5
		0.8	61.0	54.0	45.0	23.5	38.5
		0.6	73.5	69.0	58.0	29.0	39.5
8	1.53-3.15	---	----	----	----	----	----
		1.0	73.0	67.0	58.5	34.0	54.0
		0.8	67.0	59.0	52.0	31.0	48.0
		0.6	58.0	47.5	41.0	24.0	37.5
9	2.56-4.46	---	----	----	----	----	----
		1.0	91.0	83.0	71.0	34.0	67.0
		0.8	80.0	73.0	62.0	33.0	55.5
		0.6	63.0	52.0	46.5	26.0	37.5
10	2.91-4.76	---	----	----	----	----	----
		1.0	70.5	62.5	53.0	27.5	48.0
		0.8	60.5	52.0	45.0	23.0	39.5
		0.6	42.5	32.0	26.0	18.0	23.0
Average for all tubes							
		1.0	77.6	70.6	62.2	29.4	49.1
		0.8	75.7	67.6	58.9	28.0	45.8
		0.6	74.0	64.4	54.9	28.3	38.3

will be the primary relationship examined. The parameter describing the sediment size d_s/D will be reduced to only d_s in order to make the analysis more understandable.

The efficiency of trapping as a function of Froude number and sand size are shown in Figs. 9, 10, and 11. These are representative tests on two different shapes of tubes. The results from all tests are given in Table 3. The effect of sand size on trapping efficiency is noteworthy. In each case, the

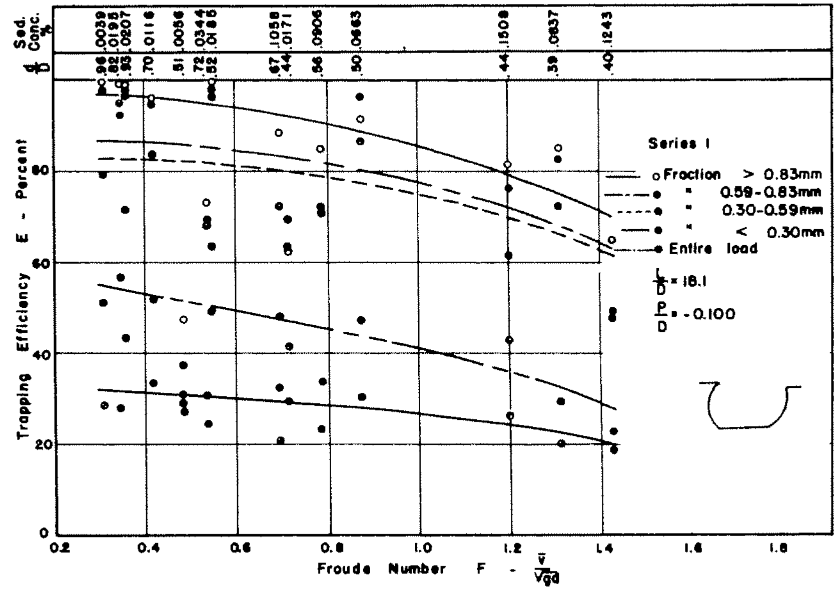


FIG. 9.—TRAPPING EFFICIENCY AS A FUNCTION OF FROUDE NUMBER AND SAND SIZE

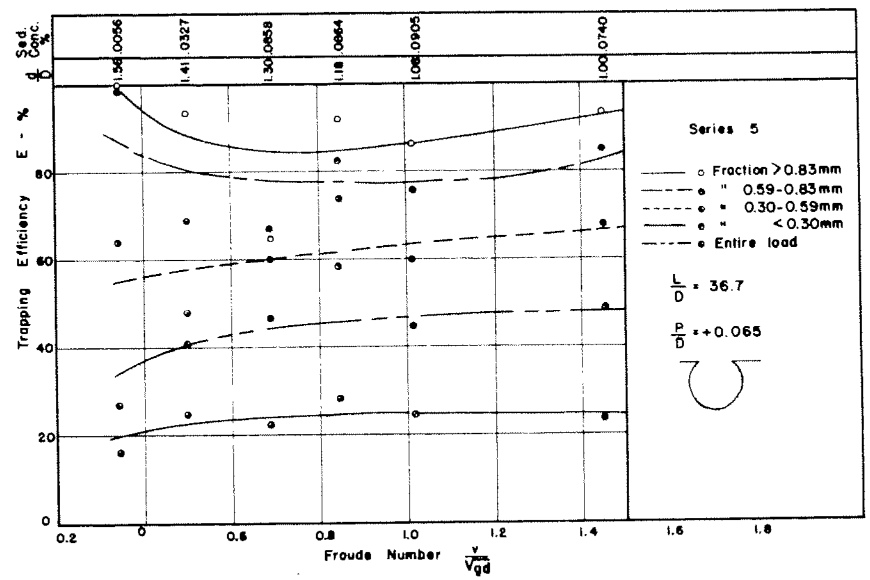


FIG. 10.—TRAPPING EFFICIENCY AS A FUNCTION OF FROUDE NUMBER AND SAND SIZE

highest efficiency was obtained for coarser material, that is, greater than 0.83 mm. As the size was decreased to 0.30 mm, the efficiencies correspondingly dropped. For that material smaller than 0.30 mm, the efficiency of trapping was very low. If the entire sand sample was considered the efficiency was low but higher than that for the finest fraction of material.

The amount of total load for each run is also given in Figs. 9, 10, and 11. These concentrations varied from 0.004 to 0.28 in percent by weight (40 ppm to 2800 ppm). No effect of concentration on efficiency was noted, probably because the maximum concentration was relatively low. In fact, those tests shown in Fig. 11 indicate an increase in efficiency with an increasing sediment load. It is conceivable that for very high concentrations the tube would

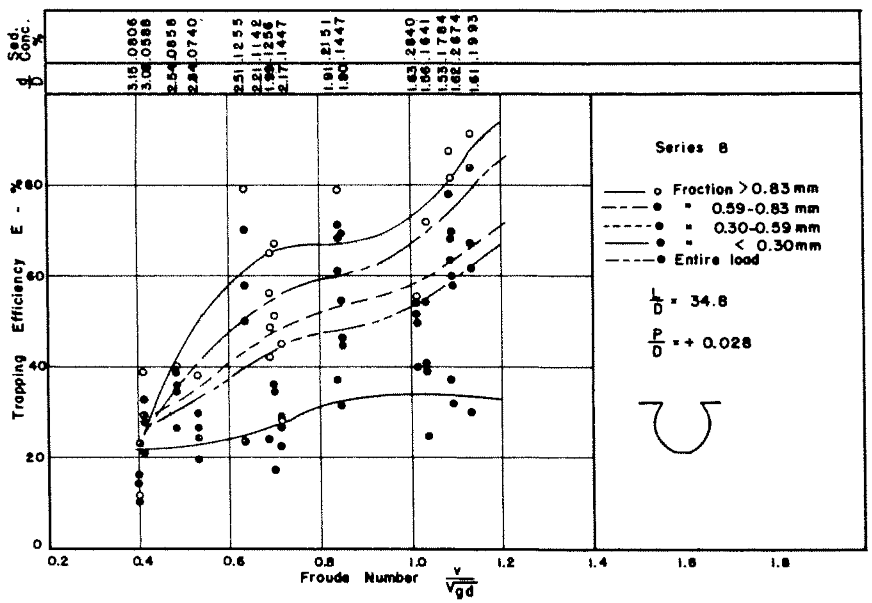


FIG. 11.—TRAPPING EFFICIENCY AS A FUNCTION OF FROUDE NUMBER AND SAND SIZE

become plugged or overloaded so that the efficiency would be reduced. Koonsman (3) found that this was the case with the maximum concentration at which the tube became overloaded varying with the depth of flow. When the depth of flow was equal to diameter of the tube, this critical concentration was 0.45% (4500 ppm). When the depth was three times the diameter of the tube, the efficiency began to drop at a concentration of 0.20%.

The parameter d/D, or depth divided by width of opening, is shown for each set of data plotted in Figs. 9, 10, and 11. In Fig. 9 this value varies from 0.39 to 0.96. Test results on tubes of almost identical shapes are given in Figs. 10 and 11. In Fig. 10, the magnitude of d/D varied from 1.00 to 1.56. The efficiencies are relatively constant over the entire range of Froude numbers. However, in Fig. 11 the efficiencies are very low at the low Froude numbers and higher values of d/D. This plot shows a range of d/D from 1.53 to 3.15.

From these data it seems that the efficiency generally decreases as depth is increased for a given tube design. A similar conclusion was reached by Koonsman (3). In general, it can be said that the Froude number seemed to have very little effect on the trapping efficiencies when the value of d/D was below approximately 1.5.

Table 3 gives the average efficiencies for different sand fractions as well as for the total sample for a range of Froude numbers. For the series 1 and 3 tests, efficiencies of trapping were high and relatively constant over the entire range of Froude numbers. The physical design of tubes used in these tests is given in Table 1. The range of d/D values for these tests was 0.39 to 1.05. Series 4 and 7 utilized tubes of the same shape, but the values of d/D were greater in series 7, that evidently resulted in lower efficiencies. Series 10, in which d/D ratios were largest, gave the lowest overall efficiencies. In general, the tubes tested using the lowest d/D values gave almost constant efficiencies for a given gradation regardless of Froude number. For all series, the efficiency of trapping material smaller than 0.30 mm was very low.

TABLE 4.—SUMMARY OF VORTEX TUBE EFFICIENCY—KOONSMAN

$\frac{d}{D}$	F	Trapping Efficiency Total Sample[a] percent
1.41	1.2	80
	1.0	88
	0.8	60
	0.6	49
2.82	1.2	64
	1.0	70
	0.8	62
	0.6	--
4.23	1.2	--
	1.0	61
	0.8	57
	0.6	--

[a]Median diameter 0.65 mm. - Size range 0.3-2.0 mm.

A summary of tests by Koonsman (3) is given in Table 4. The highest efficiency in trapping was noted at a Froude number equal to 1 (critical velocity) and decreased when this parameter was either greater or less than 1. Higher efficiencies were noted at lower d/D ratios, that is, flow depths, because the opening width D remained constant. The indicated efficiencies are for the entire sample used in the test, that had a median diameter of 0.65 mm and a size range of from 0.3 to 2.0 mm.

The results of tests by Rohwer (11) are given in Table 5. The tube shapes and dimensions are given in Table 1. For series 1-5, the efficiencies generally decreased as the Froude number decreased with no conspicuous difference between the different tube shapes. The tube used in series 6 tests was identical in shape to that used in Robinson series 1 with the exception that it was tapered rather than straight. For each sand size this tube gave almost constant trapping efficiencies regardless of magnitude of Froude number. These efficiencies were also higher on the average than those for the other tubes. Again efficiency decreased as sand size decreased. Values of d/D ranged from 0.62 to 4.00 for these tests. For those tests in series 7, the tube had the

TABLE 5.—SUMMARY OF VORTEX TUBE EFFICIENCY—ROHWER

Series	$\frac{d}{D}$ range	F	Trapping efficiency		
			River sand[a]	Fine sand[b]	Blow sand[c]
1	1.04-3.71	1.4	75		
		1.2	72		
		1.0	70		
		0.8	67		
		0.6	65		
2	1.10-2.98	1.4	--		
		1.2	93		
		1.0	81		
		0.8	69		
		0.6	57		
3	0.66-3.09	1.4	94		
		1.2	82		
		1.0	70		
		0.8	59		
		0.6	47		
4	0.65-2.25	1.4	92		
		1.2	80		
		1.0	67		
		0.8	54		
		0.6	41		
5	0.69-1.34	1.4	75		
		1.2	73		
		1.0	69		
		0.8	62		
		0.6	53		
6	0.62-4.00	1.4	85	73	41
		1.2	87	74	43
		1.0	88	76	45
		0.8	89	77	46
		0.6	90	78	48
7	0.85-4.40	1.4	79	57	33
		1.2	78	59	34
		1.0	77	61	35
		0.8	76	64	36
		0.6	76	66	38

[a]Median diameter 1.75 mm - 1.2% < 0.3 mm and 30% > 2.8 mm (by weight).
[b]Size unknown but smaller than river sand and larger than blow sand.
[c]Median diameter 0.38 mm - 26% < 0.3 mm and 0.0% > 0.59 mm (by weight).

same relative shape as in series 6 but was smaller in area. The efficiencies were lower than those in series 6 but remained constant throughout the Froude number range.

The effect of depth of flow divided by the width of opening (d/D) on the efficiency of trapping is shown in Figs. 12 through 17 for the Robinson tests.

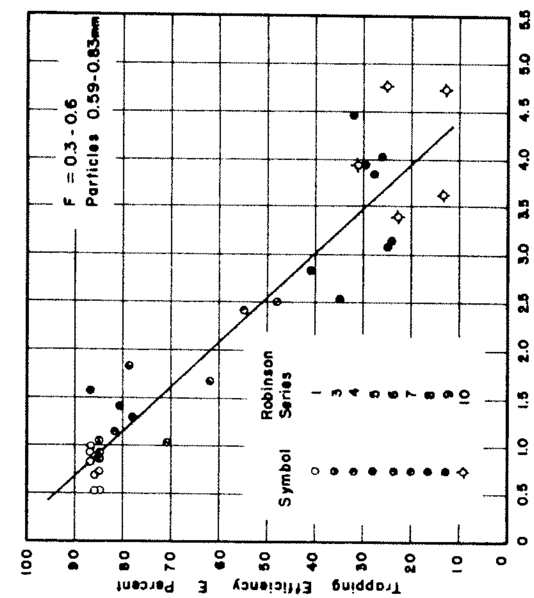


FIG. 13.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZE RANGE OF 0.59-0.83 mm AND FROUDE NUMBER RANGE 0.3-0.6

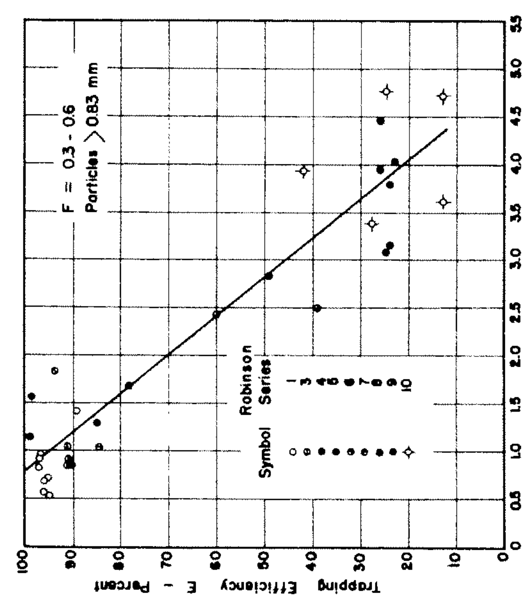


FIG. 12.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZES GREATER THAN 0.83 mm AND FROUDE NUMBERS IN THE RANGE OF 0.3 - 0.6

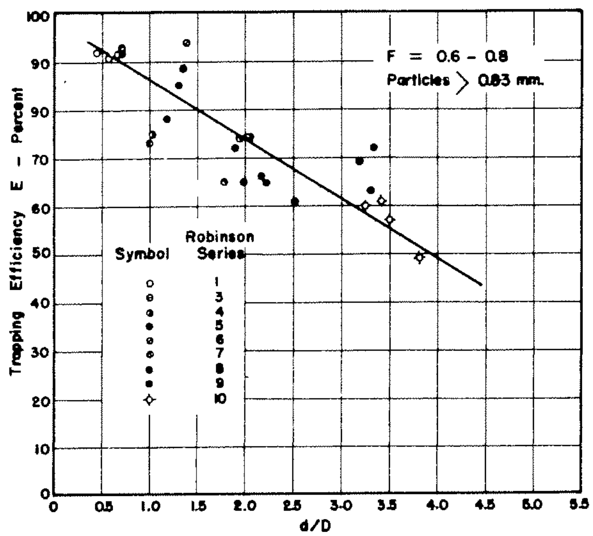


FIG. 14.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZES GREATER THAN 0.83 mm AND FROUDE NUMBERS IN THE RANGE OF 0.6-0.8

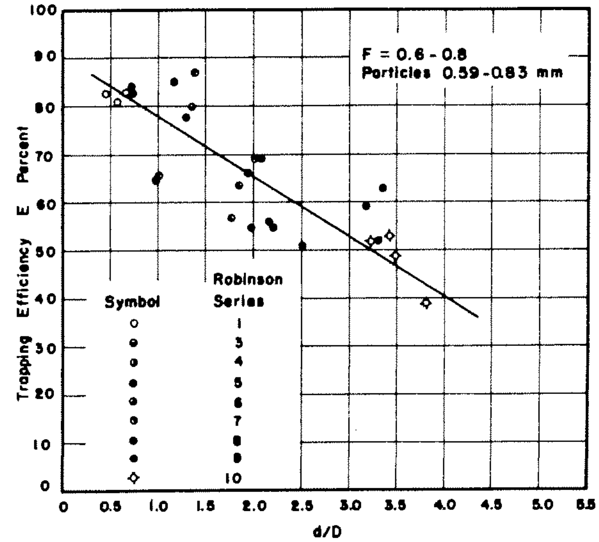


FIG. 15.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZE RANGE OF 0.59-0.83 mm AND FROUDE NUMBER RANGE 0.6 - 0.8

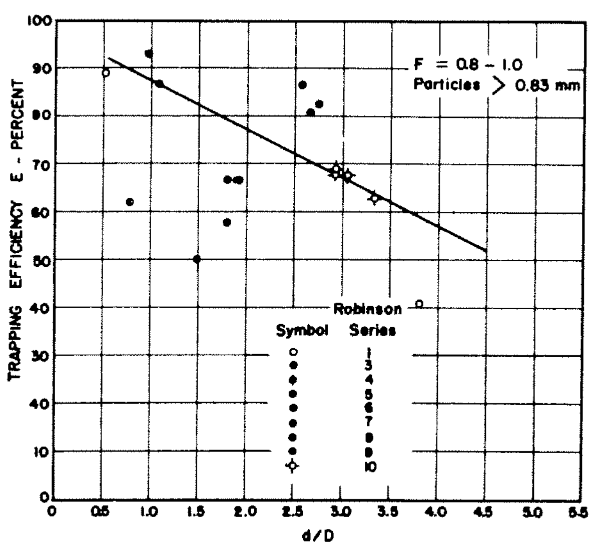


FIG. 16.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZES GREATER THAN 0.83 mm AND FROUDE NUMBERS IN THE RANGE OF 0.8 - 1.0

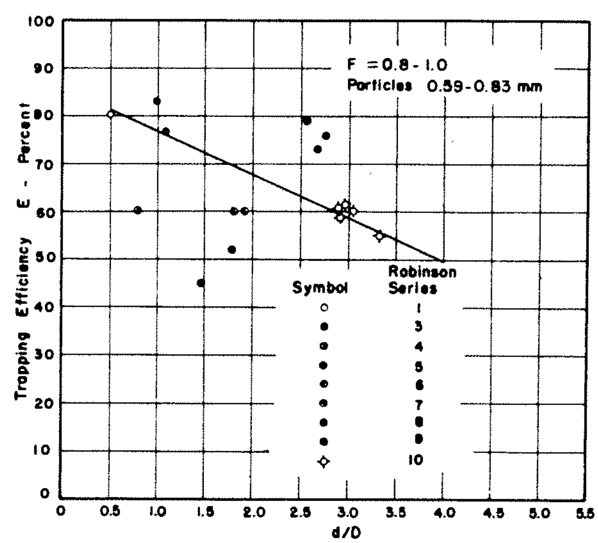


FIG. 17.—TRAPPING EFFICIENCY AS A FUNCTION OF d/D FOR PARTICLE SIZE RANGE OF 0.59-0.83 mm AND FROUDE NUMBER RANGE OF 0.8 - 1.0

Two sizes of material have been considered, that greater than 0.83 mm. and the fraction in the range of 0.59 to 0.83 mm. The range of Froude numbers has been divided into three categories: from 0.3 to 0.6, 0.6 to 0.8, and 0.8 to 1.0. For the range of Froude numbers of 0.3 to 0.6, and for both sand fractions (Figs. 12 and 13), the efficiency drops sharply as the value of d/D increases. It should be pointed out that the data from all tests and corresponding tube designs for the present experiment are included on these plots.

In Figs. 14 and 15 are shown the relationships in the range of Froude numbers of 0.6 to 0.8. Here the effect of the relative depth d/D is not as pronounced as in the **F** range of 0.3 to 0.6. The data in Figs. 16 and 17, that are for higher Froude numbers (0.8 to 1.0), do not show a definite trend. Generally, it can be observed that efficiency also decreases as relative depth increases but to a smaller magnitude than for the other cases. For the largest material, the highest trapping efficiencies were those for the Froude number range of 0.3 to 0.6 and d/D values less than 2.

The effect of variation in the parameter L/D, that is the length of tube divided by the slot opening, on the trapping efficiency was noted. In general, the trapping efficiency decreased as the length or L/D ratio was increased. From field observations, it has been noted that there is a limiting length for a given size tube for optimum operation. From these data and the field observations, it might be said that the length over opening ratio should not exceed 20 if an efficiency of greater than 80% is to be expected for the larger materials. Several successful field installations have L/D ratios in the range of 11 through 15. In general, the lengths have not exceeded 17 ft in the field structures.

As stated in the analysis, the extractor ratio, or percentage of flow removed by the tube, must be important because if all the flow was removed then the efficiency would be 100%. In Figs. 18 and 19, the efficiency as a function of extractor ratio is given for the data from the present experiment. Lines of constant values of d/D and the Froude number are also shown. These relationships were determined from interpolation of values for each point, use of Figs. 12 through 17 and from Eq. 14. In the use of Eq. 14 and the figures, it was necessary to determine average values for c' and $\sqrt{1 + B/2\ d}$. The variation in c' was in the order of 20% from the mean with $\sqrt{1 + B/2\ d}$ approximately 6%.

The results shown in Figs. 18 and 19 indicate that the efficiencies are high for all values of d/D less than 1.5 and are almost independent of extractor ratio in this range. As the value of d/D increases, higher Froude numbers must be maintained in order that efficiencies remain at a high level. At large values of d/D and low Froude numbers, the efficiency is very low. As in the previous discussion, efficiencies are lower for the smaller sizes of material.

One variable given in Eq. 16 that has not yet been considered in trapping efficiency, is relative elevation of the downstream lip of the tube given by the parameter P/D. From plots of constant Froude number and sediment size, it was determined that there was no effect depending on the location of the downstream lip other than that previously discussed in the flow analysis. This indicated that as the lip was raised the percentage of total flow was increased.

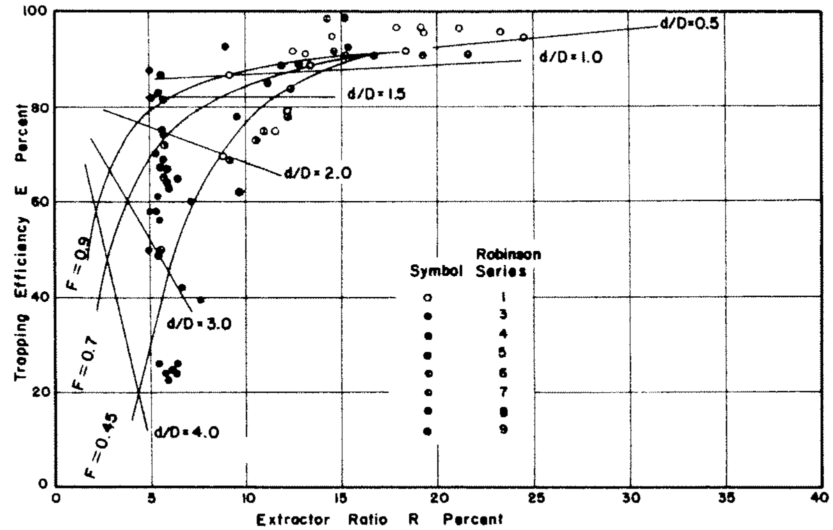


FIG. 18.—TRAPPING EFFICIENCY AS A FUNCTION OF EXTRACTOR RATIO, FROUDE NUMBER AND d/D RATIOS FOR PARTICLE SIZES > 0.83 mm

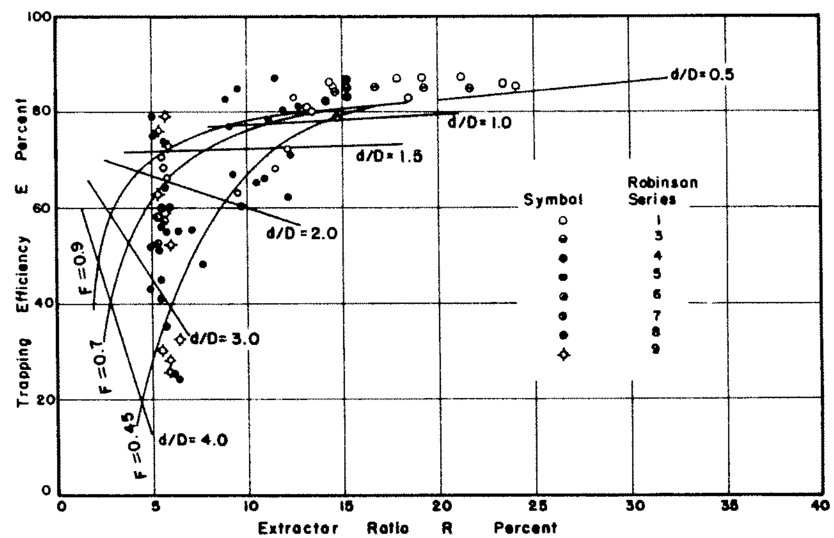


FIG. 19.—TRAPPING EFFICIENCY AS A FUNCTION OF EXTRACTOR RATIO, FROUDE NUMBER AND d/D RATIOS FOR PARTICLES SIZES IN THE RANGE OF 0.59 - 0.83 mm

Any increase in efficiency would probably be due to the increase in amount of water removed.

ANALYSIS OF RESULTS AND DESIGN RECOMMENDATIONS

In the analysis of flow from the tube, it was found that percentage of flow removed was a function of tube geometry and angle, as well as depth and velocity of flow across the section. Parameters describing the tube were the length, width of slot, and area. With the other factors that effect the sediment removal characteristics of the tube being considered, it was noted that tubes with values of c' in the range of 4.6-7.6 were most successful. For design purposes this would limit the range of the geometry parameter $A_T/D\ L \sin\theta$ from approximately 0.05-0.07 (see Fig. 6). In the section on sediment removal, it was pointed out that the parameter L/D should not exceed a value of 20 for optimum operation. Successful field structures exist with L/D values as low as 11. For practical purposes, as well as past experiences, the width of slot D should probably be in the range of 0.5 through 1.0 ft. Past studies have indicated that an angle of 45° for the tube is desirable. With the range of these factors known, it is then possible to compute the area of tube needed.

A study of the data revealed that there was no discernible difference when having the two lips of the tube level, or the downstream lip lower. It was noted that, when the downstream lip was higher, the trapping efficiency was materially reduced. For simplicity in construction then, it is recommended that the two lips be at the same elevation.

Many of the existing field structures contain tubes that are tapered along the length L. According to Rohwer (10), straight tubes are equally as efficient in removing material. All of the tubes in the present tests were straight. Straight tubes are simpler to construct and install so that these are recommended. Tube shapes such as those shown in Table 1 for Rohwer series 6 and Robinson series 1 and 5 were very effective. Those made from commercially fabricated pipe (Robinson series 5) seem as effective as the others and are easily constructed. Shapes such as those shown in Table 1 for Rohwer series 1 through 3 have been widely used in existing field installations. However, Rohwer (11) noted that material was frequently thrown out of these, particularly at the higher channel velocities. This would result in material returning to the channel.

Tests made to determine efficiency of trapping when the outflow was controlled indicated that the efficiency would be reduced to some extent with a reduction in outflow. Reduction in translation velocity within the tube was used as a measure of this effect. The reduction in velocity was not in direct proportion to reduction in percentage of flow removed, however, so that if the flow was reduced by one-half, the velocity was only reduced a portion of this. With lower concentrations of bed load, it is possible that there was sufficient movement within the tube so that high removal efficiencies were maintained. The results shown in Fig. 7 indicate that translation velocity (V_p) was relatively constant for a range of mean channel velocities below a Froude number of 1. Beyond this point, the translation velocity increased rapidly.

Effect of material size on efficiency of trapping was noteworthy. Under optimum operating conditions, material of a size > 0.83 mm was effectively trapped and removed. For material < 0.30 mm, the trapping efficiency was very low, usually less than 35%. In general, those sizes greater than 0.50 mm

will be removed. Essentially, only that material that is moving at or near the bed will be trapped by the device.

The amount of sediment moving as bed load is of importance in the operation of the tube only for high concentrations. When the flow depth is great, relative to the width of opening, then the concentration should not exceed 0.20% (2,000 ppm) if optimum operation is to be maintained. For shallower depths, the concentration may reach 0.45%. In channels when the load may exceed these values, two parallel tubes should be installed.

The effect of velocity and depth of flow on the trapping efficiency are interrelated. Tests by Koonsman (3), shown in Table 4, indicated that the highest efficiencies existed near a Froude number of unity, that is at critical depth. The studies by Rohwer (10), given in Table 5, show that the efficiency generally increased as the Froude number increased. However, series 6 and 7 of these tests gave almost constant efficiencies for a Froude number range of 0.6 through 1.4. The results from the study being presented, as given in Table 3, indicate almost constant efficiencies for the entire Froude number range except for series 7 through 10. In general, when considering the Froude number alone it would seem that the range should be from 0.6 through 1.0. Values lower than this might result in the tube being inoperative whereas those higher would result in material being thrown out of the tube as well as the problems in scour downstream from the structure due to higher exist velocities.

As was discussed in the section on sediment transport, the section containing the vortex tube should be designed so that flow conditions are in the regime in which plane bed type of sediment movement will exist. This was found to be in a Froude number range of 0.6 to 0.7 for material with a mean size of 0.45 mm. Indications are that, for larger material, the Froude number must be increased to maintain the plane bed. For sand sizes > 0.50 mm, it would seem that the velocities and depths of flow in the section should be in a range of Froude numbers between 0.7 and 0.9.

The relationship of efficiency to depth of flow for a range of Froude numbers was presented in Figs. 12 through 17. For lower values of Froude number, efficiency decreased rapidly as depth increased. For **F** in the range of 0.8 through 1.0 efficiency seemed to be almost independent of depth. Because most operating canals will generally have depths that are large relative to slot opening, it would seem that the section should be designed to maintain the 0.8 through 1.0 range.

The importance of maintaining the higher range of Froude number is also illustrated in Figs. 18 and 19. As the value of d/D increased, the Froude number must be increased to maintain higher efficiencies. At a d/D value of 4, the Froude number must be increased to 0.9 as compared to 0.7 for d/D equal to 3, to maintain an efficiency of 60% for material > 0.83 mm.

There are other points to consider relative to design and location of the vortex tube section. Most of the structures now in existence have been located near canal headworks. Generally, they are located between the headworks and the measuring structure. In this manner, the extra amount of water necessary in the operation of the tube can be returned to the river before it reaches the measuring device in the canal. Sufficient grade is necessary in returning this flow together with the material that has been removed. A collection chamber needs to be provided outside the section such as shown in Fig. 4(a). A gate valve may be necessary to control flow from the tubes. This should be on the outlet from the chamber rather than from the tubes as shown in Fig. 4(a).

When used in an unlined canal, the section should be approximately the same width as the canal but with the bottom raised. Contracting the sides will lead to additional problems in bank scour downstream from the vortex tube section.

Problems may arise in determining the amount of rise to be provided in the bottom of the vortex tube section in order to maintain the Froude number of the flow near 0.8. For canals that operate at almost constant stage, the problem is simplified. For those in which the flow varies widely, a design flow should be selected that will exist for a greater portion of time. The amount of rise in the floor can then be determined for this design flow and normal depth. Flows greater than this design flow will result in Froude number less than 0.8, whereas those less than the design flow will increase the Froude number. In the latter case, the upstream depth will also be increased over normal depth to provide additional needed energy.

SUMMARY

Tests have been made on a type of bed load ejector termed the vortex tube sand trap. These tests have shown that the following design criteria are necessary for the successful operation of the device:

(1) The velocity and depth of flow across the section containing the tube should be such that the Froude number approximates 0.8.

(2) The percentage of flow removed by the tube is a function of the depth and velocity of flow in the channel as well as width of opening, area, angle, and length of tube. The flow removed usually ranges from 5% to 15% of the total.

(3) The width of opening should usually be in the range of 0.5 ft to 1.0 ft.

(4) The ratio of length of tube to width of opening (L/D) should not exceed 20 with the maximum length of tube being approximately 15 ft.

(5) The tube angle should be 45°.

(6) Straight tubes operate as well as tapered ones.

(7) The elevation of the upstream and downstream lips of the tube can be the same rather than having the downstream one lower.

(8) The shape of the tube does not seem to be particularly important as long as this shape is such that material entering the tube is not allowed to escape back into the channel. A pipe with a portion of the circumference removed seems to operate as well as other prefabricated shapes.

(9) The required area of the tube can be approximated by the relationship $A_T = 0.06\ D\ L \sin\theta$.

(10) With the foregoing design specifications, the tube can be expected to remove approximately 80% of the sediment with sizes greater than 0.50 mm. The trapping efficiency of smaller sizes will be considerably lower.

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APPENDIX II.—NOTATION

A_T = cross sectional area;

A = area of flow;

B = depth of tube;

C = concentration of sediment, G/Q;

c = coefficient of discharge due to tube geometry and approach velocity;

D = width of opening;

d_u = depth of flow upstream from tube;

d = depth of flow in channel at tube;

d_s = size of sand fraction;

E = efficiency of trapping;

$\mathbf{F}$ = Froude number;

G = total sediment discharge through channel;

G_T = sediment discharge through channel;

H = effective head;

L = length of tube;

P = difference in upstream and downstream lip elevations;

Q_T = water discharge through tube;

Q = channel discharge;

$\mathbf{R}$ = Reynolds number;

R = extractor ratio;

s = slope of channel;

s_e = slope of energy gradient;

V = mean velocity of flow immediately upstream from tube;

V_p = velocity of a particle along the tube, translation velocity;

W = width of vortex tube section;

Z = contraction ratio between the channel and section containing the vortex tube;

γ = specific weight of fluid;

θ = angle of tube to direction of flow;

λ = shape of tube;

μ = dynamic viscosity;

ρ_s = sediment density;

ρ = density; and

ω = fall velocity.