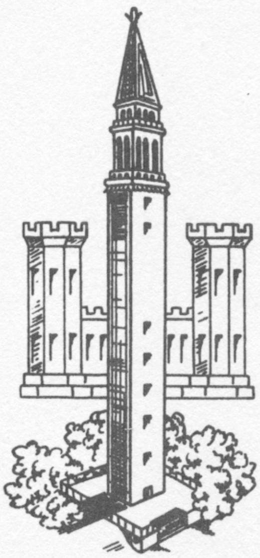
WATER JET PUMPS FOR SEDIMENT CIRCULATION

By

Ning Chien



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THE MISSOURI RIVER DIVISION
CORPS OF ENGINEERS
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M. R. D. Sediment Series No. 1

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CORPS OF ENGINEERS SEDIMENT STUDIES PROGRAM

FOR MISSOURI RIVER BASIN

MISSOURI RIVER DIVISION

FORT PECK DISTRICT	OMAHA DISTRICT
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The Corps of Engineers Missouri River Basin sediment studies program was established for the development of practical sediment engineering for rational evaluation, regulation, and utilization of fluvial sediment phenomena. It was implemented as a comprehensive, basin-wide program for coordination of studies of sediment problems in the overall basin program for flood control and allied purposes as well as for continuity and perspective in the planning and design of individual projects. The program includes both investigations for the development of sediment transport theory and observations of existent and occurring phenomena for the purpose of developing the applications of theory to practical problems, developing empirical relationships, and providing aids to judgment.

The program has been conducted during the tenures of and supported by the following Division Engineers:

Lieutenant General Lewis A. Pick
Major General Samuel Sturgis
Brigadier General Don G. Shingler
Brigadier General W. E. Potter

Mr. F. B. Slichter was Chief of the Engineering Division from the inception of the program until April 1949. Mr. W. E. Johnson has been Chief of the Engineering Division since that time. The program was formulated and organized by Mr. R. J. Pafford, Jr., Chief, Planning and Reports Branch. Planning and execution is under the immediate direction of D. C. Bondurant with technical advice and assistance provided by an Advisory Board consisting of:

Mr. G. A. Hathaway	Mr. T. H. Means
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WATER JET PUMP FOR SEDIMENT CIRCULATION

Introduction

In the laboratory study of sediment problems, it has frequently been found necessary to keep the sediment transport rate of the reach constant. This is often accomplished by reintroducing the sediment collected at the downstream traps to the flow at the upper end of the reach until the movement of detritus becomes constant. When the quantity of material involved is large, this process cannot be handled manually and some mechanical means must be provided to carry the sediment. This can be done by pumping, only most of the impellers of centrifugal pumps wear fast in pumping the sediment-laden water. The water jet pump, on the other hand, is reputed for its lack of valves and other moving parts. It is in this respect that, in spite of its smaller efficiency, the water jet pump is especially expedient for the pumping of sediment-laden water.

Figure 1 shows the sketch of a water jet pump. The power supplied by the driving pump produces a high-velocity flow, Q_1, through the nozzle. This fast-moving jet creates a local low pressure zone and thus induces a secondary flow, Q_2. These two flows mix together in the mixing chamber and through a diffuser, the combined discharge, $Q_1 + Q_2$, then being carried away by the discharge line. If such a jet pump of suitable size is installed in the downstream sediment trap of the test reach, the flow induced by the jet action carries with it also the sediment which deposits in the neighborhood of the nozzle. By this means, all the sediment moving out of the reach and caught by the trap can be pumped back to the upstream end and an equilibrium state of the test reach is thus established.

In this report, the theory of the water jet pump is briefly reviewed at first. The detailed procedures in designing a water jet pump and in selecting a driving pump are presented next. In the last part of the report, the various ways of using water jet pumps in sediment experiments are illustrated by describing three actual studies carried out at the University of California. The main purpose of this report is to indicate how the water jet pump can be employed in sediment study to best advantage. It is not the writer's intention either to develop the best design of water jet pumps, or to study the effect of sediment on the characteristics of the jet pump.

Theory of Water Jet Pump

The following notations are used to demote the different variables involved in the derivation of the theory:

A_1	Area of the driving line
Q_1	Discharge through the driving line
V_1	Velocity of flow in the driving line
A_j	Area of the nozzle tip
V_j	Velocity of flow at the nozzle tip
A_s	Annular area surrounding the nozzle tip
Q_2	Induced secondary flow
V_s	Velocity of the secondary flow entering the mixing chamber
A_3	Area of the mixing chamber
V_3	Velocity of flow at the exit of the mixing chamber
L	Length of the mixing chamber
A_4	Area of the discharge line
V_4	Velocity of flow in the discharge line
P	Pressure
K	Coefficient of energy loss
h_f	Head loss
f	Coefficient of frictional loss
D	Diameter
ℓ	Length
h	Total head
Z	Elevation above the datum plane
γ	Unit weight of the fluid
E	Efficiency of the water jet pump
g	Gravitational acceleration

In 1942, Gasline and O'Brien (1942) presented a complete theory on the water jet pump on the basis of energy considerations, and verified it by experiments. The following derivation of the theory is based on both the energy and momentum considerations. The two methods of approach give practically the same result.

The horizontal plane through the tip of the nozzle is taken as the datum plane, and the sections under consideration are indicated in Figure 1. The Bernoulli equation between sections (1) and (2) gives

$$h_1 = \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + \frac{V_j^2}{2g} + h_{f_{12}} \quad (1)$$

Here $h_{f_{12}}$ indicates the total head loss between sections (1) and (2) including

The loss in the valve

The loss in the elbow

The loss in the U

The friction loss along the pipe

The loss in the jet

It has been suggested (Williamson, 1939) that the losses in bend, valve, U, and nozzle can be taken into consideration by adding a fictitious length of the same pipe to the actual length of the driving line. The frictional loss is then

$$h_{f_{12}} = f_1 \frac{l_1}{D_1} \frac{V_1^2}{2g}$$

where l_1 = length of the driving pipe plus the fictitious length of the pipe due to additional losses

D_1 = diameter of the driving pipe

f_1 = coefficient of frictional loss in the driving pipe

The same head loss can also be expressed in terms of the jet velocity head by the following transformation

$$h_{f_{12}} = f_1 \frac{\ell_1}{D_1} \frac{V_1^2}{2g} = K_j \frac{V_j^2}{2g}$$

such that

$$K_j = f_1 \frac{\ell_1}{D_1} \left(\frac{A_j}{A_1}\right)^2$$

Then equation (1) becomes

$$h_1 = \frac{P_1}{\gamma} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma} + (1 + K_j) \frac{V_j^2}{2g} \tag{1A}$$

The Bernoulli equation between sections (3) and (4) gives

$$h_4 = \frac{V_4^2}{2g} + Z_4 = \frac{P_3}{\gamma} + \frac{V_3^2}{2g} + L - h_{f_{34}} \tag{2}$$

Here $h_{f_{34}}$ includes the loss in the diffuser due to diversion of flow, loss in the bend, and frictional loss along the discharge line. By the same procedure as given above, one can introduce

$$K_d = f_4 \frac{\ell_4}{D_4} \left(\frac{A_3}{A_4}\right)^2$$

such that equation (2) becomes

$$h_4 = \frac{V_4^2}{2g} + Z_4 = \frac{P_3}{\gamma} + L + (1 - K_d) \frac{V_3^2}{2g} \tag{2A}$$

The Bernoulli equation between sections (2) and (5) gives

$$h_5 = Z_5 = \frac{P_2}{\gamma} + \frac{V_S^2}{2g} + h_{f_2} \tag{3}$$

Here h_{f_2} is the entrance loss at section (2), and can be expressed as

$$h_{f_2} = K_S \frac{V_S^2}{2g}$$

which gives

$$h_5 = Z_5 = \frac{P_2}{\gamma} + (1 + K_s)\frac{V_s^2}{2g} \tag{3A}$$

The momentum equation between sections (2) and (3) gives

$$\frac{1}{g}\left[Q_2V_s + Q_1V_j - (Q_1 + Q_2)\,V_3\right] = A_3\left(\frac{P_3}{\gamma} - \frac{P_2}{\gamma} + L\right) \tag{4}$$

Finally, considering the efficiency of the jet pump as the ratio of the work done over the total energy used, we have

$$E = \frac{Q_2\,(h_4 - h_5)}{Q_1\,(h_1 - h_4)} \tag{5}$$

These are the five equations on which the theory of water jet pump is based.

In designing a water jet pump, the following transformations are made to facilitate the computation

Let $R = \frac{A_j}{A_3}$ = the ratio of the nozzle-tip area to the mixing chamber area

$M = \frac{Q_2}{Q_1}$ = The ratio of the secondary flow to the primary flow of the driving pump

and assuming that the wall of the nozzle is thin so that

$$A_s + A_j = A_3$$

Then we have

$$Q_2 = M\,Q_1$$

$$Q_1 + Q_2 = (1 + M)\,Q_1$$

$$A_3 = \frac{1}{R}A_j$$

$$A_s = \frac{1-R}{R}A_j$$

$$V_3 = R\,(1 + M)\,V_j$$

$$V_s = \frac{MR}{1-R}V_j$$

Using these relationships, equations 1 to 5 can be given in the form of equations 6 to 9, reducing the number of variables from 5 to 4.

$$h_4 - h_5 = \frac{V_4^2}{2g} + (Z_4 - Z_5) \tag{6}$$

$$h_1 - h_5 = \left[1 + K_j - (1 + K_s) M^2 \left(\frac{R}{1-R}\right)^2\right] \frac{V_j^2}{2g} \tag{7}$$

$$H = \frac{h_4 - h_5}{h_1 - h_4} = \frac{(1 - 2R - K_s)\frac{M^2R^2}{(1-R)^2} + 2R - (1 + K_d) R^2 (1 + M)^2}{1 + K_j + (1 + K_d) R^2 (1 + M)^2 - \frac{2M^2R^2}{1-R} - 2R} \tag{8}$$

and

$$E = MH \tag{9}$$

Equations (6) to (9) are used in the following section to design a water jet pump and to select a driving pump which will be appropriate for sediment study.

Design of Water Jet Pump

The design of a water jet pump and the selection of a driving pump to supply the necessary power for the jet pump are outlined in the following steps:

(A) Estimate the maximum transport rate at which the sediment is to be moved.

(B) Assume a feasible sediment concentration in the discharge line such that the water jet pump is capable to carry away the sediment without clogging the line. As the theory of sediment transport in pipes is not yet fully developed, the assumption made concerning the sediment concentration must rely, to some extent, on personal judgement or past experience. For sand, and under ordinary conditions, a concentration of 10 percent by weight should prove to be adequate.

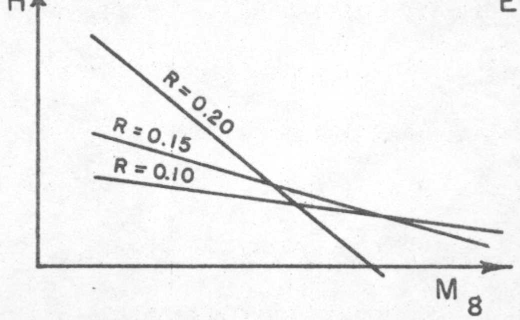
(C) The required discharge, $Q_1 + Q_2$, to carry the sediment at this concentration is determined next.

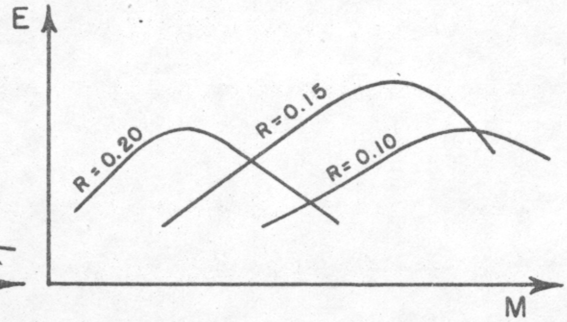
(D) The lift, $Z_4 - Z_5$, is decided on the basis that it will give a satisfactory arrangement of the laboratory equipment and provide convenient working conditions.

(E) From the pipes available, select the sizes of the pipe lines (A_1, A_3 and A_4); and also decide the general arrangement of the pipe lines.

(F) Estimate the coefficients of loss (K_j, K_s and K_d).

(G) Use equations (8) and (9) to construct the following graphs:





(H) Choose the R and M that will give the maximum efficiency.

(I) From the H value corresponding to the selected R and M, and from equations (6) and (7), determine Q_1 .

(J) Check if $Q_1 + Q_2$ is sufficient to fulfill the requirement set up in step (C). If it is not, then another pair of R-M must be selected which will provide required flow but will not perform at peak efficiency.

(K) From the finally selected value of R and the predetermined size of the mixing chamber, the size of the nozzle is fixed.

(L) Determine P_1 / γ , the pressure head on the driving pump, from equations (7) and (1A).

(M) Select a driving pump which will give the discharge Q_1 and the required head.

In designing a water jet pump, there are a few places where certain uncertainties, including the estimation of the coefficients of loss, are involved. This will be made even more difficult if some of the sediment settles in the horizontal part of the discharge line and forms a sand bed. It is advisable, therefore, to select a driving pump which will supply at least 25% more discharge and head than are required according to the computation.

The procedure used by laboratory workers is usually quite different. That is because there may be several service pumps available and the problem is then how to design a jet pump which can use the power supplied by any of the available pumps to meet the needs. This can be done without difficulty by slightly changing the sequence of the steps outlined above.

One of the jet pumps used in the University of California is shown in Figure 2. As suggested by Gasline and O'Brien (1942), the length of the mixing chamber is about twelve times the size of the nozzle, and the angle of diffuser is about $5\frac{1}{2}^{\circ}$. The distance between the tip of the nozzle and the entrance of the mixing chamber can be adjusted at will; and the best operating conditions were obtained by Gasline and O'Brien when the tip of the nozzle was back from the entrance to the mixing chamber by a distance equal to the nozzle diameter. The guide plates welded on the U and the sleeve are used to break the vortex motion, if any is developed in the sediment trap due to the jet action. This design seems to give the desired performance upon the conditions under which it is operated, but it should by no means be considered as the one which necessarily gives the best performance.

The Use of Water Jet Pumps in Sediment Studies

In the past few years, three water jet pumps have been designed and used at the University of California in three different experimental studies, all of which involve sediment motion. Following is a brief description of these studies so as to illustrate the various situations under which a water jet pump can be employed to great advantage:

1. River Training Structures Study (Einstein, 1950):

The purpose of this study was to develop design criteria for the use of Jacks for bank protections in bends. The efficiency of the Jacks depends, to a large degree, on the sand deposits behind them. Since sand deposits will develop only in locations on the bed where the bed-load transport is intense, the sediment transport is an important phase of the problem.

The model study was conducted in a basin 18 inches deep, 30 feet long, 15 feet wide at one end, and 7½ feet wide at the other (Figure 3). It was shaped purposely asymmetric in order to accommodate long sweeping bends. Two centrifugal pumps supplied water from a storage basin to a constant-head tank, from which a 5-inch pipeline led the water to the upper end of the basin with a capacity of about 1 cfs. A sand trap was located at the downstream end to separate the sediment from the flow which returned through an underground water return to the storage basin. The sediment was pumped by means of a water jet pump through a 2-inch pipe directly into the upper end of the flume and mixed there with the discharge. The sizes of the nozzle and the mixing chamber were ½-inch and 1¼-inch respectively. A centrifugal booster pump was used as the driving pump which obtained its discharge from the constant-head tank. The sediment used had an average diameter of 0.36 mm.

2. Flood Channel Grade Stabilizers Study (Einstein and Banks, 1951):

The purpose of this study was to investigate various types of energy-dissipating structures and their spacing in flood channels with loose sediment bottoms such that no excessive scour or deposition will take place.

The experiment was conducted in a 1:24 model of the proposed structure. The flume was 40 feet long and had a trapezoidal cross section with 20-inch bed width and 1-3/4 : 1 side slopes. The side walls were composed of 1/2-inch painted plywood. Two types of bed material were used; one was sand with average size of about 0.6 mm. which simulated gravel in the prototype, the other was polystyrene pellets (1/8" x 3/16" x 3/32" in size and 1.052 in density) which simulated sand in the prototype.

Figure 4 shows the general arrangement of the experimental apparatus. Water from the storage basin was pumped by the main pump to the fore-basin of the channel. There the main flow joined the sediment return flow from the water jet pump and entered the channel. This combined flow transported sediment according to its capacity and deposited the entire transport into a hopper at the end of the flume. The discharge passed over an adjustable weir into the storage basin where it was re-circulated. The sediment, settling into the hopper bottom, was removed continuously by the water jet pump (Figure 2) and returned to the fore-basin through the sediment return line. The jet pump was supplied by a pump whose suction end was in a second storage basin. These two storage basins were separated by a weir, and the water level in the basins was maintained at the crest of the weir.

3. <u>The Littoral Barrier Study</u> (Chien and Li, 1952):

The purpose of this study was to investigate experimentally the effect of a littoral barrier on a sandy coast. An equilibrium beach was established at first, and a littoral barrier was then installed near the downcoast end of the beach to intercept the littoral drift along the beach. Observations were made upon the effect of the littoral barrier on the changes of the coast line and beach profile, when the same constant sediment drift still entered the reach from the upcoast end.

A 1-foot by 6-foot by 12-foot wave tank (Figure 5) was used for this study. A wave machine was located at one end of the basin, and a sand beach was molded at the other. A sand trap of triangular section was installed at the downcoast end of the beach. The sediment which settled at the bottom of the hopper was pumped continuously by a jet pump into the return-pipe and brought back to the upcoast end of the beach. The sizes of the nozzles and mixing chamber were 3/8" and 1" respectively. The jet flow was supplied by a centrifugal booster pump which drew water from the basin near the wave machine. A settling tank was provided in its suction line to ensure that no sediment would pass through the driving pump and cause damage to the pump impeller. With this arrangement the sediment was immediately returned into the basin as it left the downcoast end, and the total amount of sediment in the basin was constant unless sediment was added or removed purposely.

Attention should be called to the fact that the systems described above can best be applied in cases where the sediment moves mainly as bed load. If suspended load is also an appreciable part of the sediment motion, then an efficient settling basin must be provided to separate sediment from the flow. This is often impracticable, if not altogether impossible.

Acknowledgment

The water jet pumps described above were developed under the direction of Professor H. A. Einstein of the University of California at Berkeley.

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