DESIGN CHARACTERISTICS OF THE VORTEX-TUBE SAND TRAP

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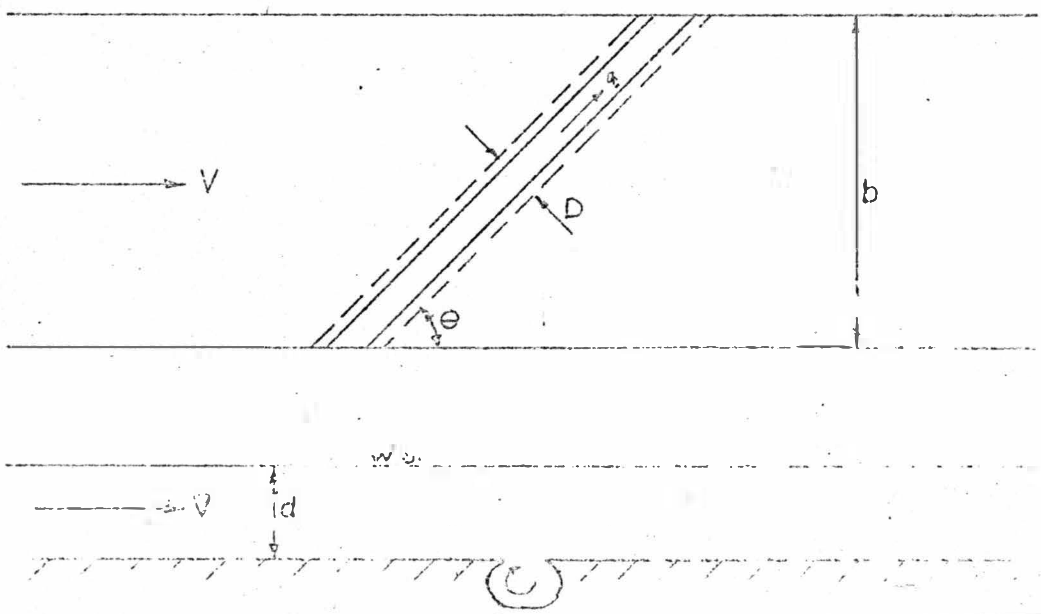
The problem of preventing sediment from depositing in a canal and choking it is one which is frequently encountered in the design and operation of irrigation and power canals. Various means have been devised for trapping the sediment once it has entered the canal. One system which is gaining increasing usage in the United States and in Mexico and South America is the vortex-tube used either alone or in combination with riffle deflectors -- the design being originated by Mr. Ralph L. Parshall*** (1), (2). The vortex tube consists of an open-top tube placed across the bottom of the canal. The tube is placed in a transverse direction to the flow either normal to it (90°) or at some other angle down to 30°. To control the rate of flow out of the tube, the downstream end is regulated by a valve. The upper portion of the tube is cut away in order to receive the sediment to be trapped. As the water passes over the tube, a shearing action across the open portion sets up a



Schematic layout of typical vortex tube

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vortex motion within the tube which has sufficient velocity to prevent lodging of sediment of considerable size (3-in. cobbles have been successfully trapped and carried by a 6-in. tube).

In order to obtain more complete design information for the vortex tube, a generalized research program was set up by the senior author under the direction of the junior author. The influence of sediment concentration, flow conditions, and tube size and arrangement were investigated.

Dimensional Analysis:

As a guide to the desirable range of variables, a dimensional analysis was made of the problem. The variables describing the channel and tube are the width b, the tube diameter D, the angle of inclination of the tube θ, and the difference in lip elevation p. The variables describing the flow are the depth d, the mean velocity V, the sediment concentration C, the extractor ratio R, and the efficiency of trapping E. The water is described by the density ρ, the difference in specific weight of the water and air $\Delta\gamma$, and the viscosity μ. The sediment may be described by the density ρ_s, the fall velocity ω or the sedimentation diameter S, and the standard deviation σ of the fall velocity or the sedimentation diameter. These variables may be expressed in a general function as:

$$\phi_1 \left(b, d, p, D, \theta, C, E, V, \rho, \Delta\gamma, \mu, \rho_s, S, \sigma\right) = 0 \qquad (1)$$

By choosing D, V, and ρ as repeating variables, dimensional analysis yields:

$$\phi_2 \left(\frac{b}{D}, \frac{d}{D}, \frac{p}{D}, \theta, C, E, \frac{\rho}{\rho_s}, \frac{V}{\sqrt{gd}}, \frac{S}{D}, \frac{\sigma}{S}, \frac{Vd\rho}{\mu}\right) = 0 \qquad (2)$$

As a first step, a tube of 0.2 ft. diameter was used at a 45° angle across the bottom of a 2-ft laboratory flume. The elevation of the downstream lip of the tube was varied from 0.02 ft. higher to 0.02 ft. lower than the upstream lip.

Sand having a mean diameter of 0.7 mm and a size range of from 0.4 to 1.1 mm was introduced far enough upstream so that it would all be on the bed of the flume when it reached the tube. Concentrations varied from 0.1% to 0.3% by weight. Each run was made after the discharge of both water and sediment had reached equilibrium. The water discharging thru the vortex tube and that leaving the downstream end of the flume were both measured by means of calibrated weirs. The sediment was trapped in a box for a certain period of time and then weighed.

To determine the influence of flow conditions upon the operation of the tube, the velocity was varied from 1.3 fps to 5.5 fps, and the depth was varied from 0.2 ft. to 0.6 ft. This gave a range of Froude number of from 0.5 to 1.5 where $F_r = \frac{V}{\sqrt{gd}}$.

From the foregoing limitations, Eq. 2 was simplified to

$$E = \phi_3 \left(\frac{d}{D}, \frac{p}{D}, C, F_r \right) \qquad (3)$$

the Reynold's number being considered relatively insignificant in the immediate vicinity of the tube $\frac{b}{D}$, θ, $\frac{\ell}{\rho s}$, $\frac{S}{D}$, and $\frac{\sigma}{S}$ being kept constant throught the tests.

Although the authors recognized that the effect of the Reynolds number cannot be considered entirely insignificant (because of its influence on the profile of the approach velocity and the distribution of turbulence), it was considered of secondary importance since essentially all of the material was found to be moving as bed load under conditions of maximum efficiency. With this assumption, the velocity profile influences only the rate of rotation of the vortex in the tube.

Preliminary tests indicated that for maximum efficiency the two lips of the tube should be kept at the same elevation so that Eq. 3 simplified to

$$E = \phi_4 \left(\frac{d}{D}, C, F_r \right) \qquad (4)$$

Discussion of Experimental Data:

The tests which were made for equal lip evaluations are summarized in Table 1 and shown graphically in the figures. Fig. 1 is a plot of the efficiency as a function of the concentration of sediment for various depths of flow when Fr = 1.0 (critical flow). From this figure it may be seen that as the concentration increases beyond a certain point the efficiency decreases rapidly. By observing the tests, one could see that this reduction resulted from plugging of the tube -- the sediment arriving at the tube faster than it could be carried away. This point of reduction occurred at a concentration of about 0.42% for d/D = 1, 0.22% for d/D = 2, and 0.17% for d/D = 3. As the depth of flow increased for a given concentration, the rate of sediment flow increased but the capacity of the tube did not increase proportionately resulting in decreased efficiency.

The principal loss of bed load past the tube occurred at the quarter points of the transverse cross section regardless of the concentration or flow conditions. The vortical action appeared to be somewhat disturbed at these points and some of the sand was thrown out of the tube. At low velocities, when sediment was deposited in the tube, the clogging began at the upstream quarter point, extended to the upstream end of the tube, and then continued down stream to about the center of the tube. In this condition the downstream half of the tube did not clog but acted as a sluice with little or no vertical action.

Reference to Fig. 1 shows that for concentrations less than the critical concentrations just named the efficiency remained essentially constant. For $d/D = 1$ the constant efficiency was 92%, for $d/D = 2$ it was 76%, and for $d/D = 3$ it was 65%. This efficiency decrease with increased depth probably resulted from the greater quantity of sediment being moved and the increased percentage in suspension with increased depth velocity.

Fig. 2 is a plot of efficiency against the velocity ratio v/ω with sediment concentration $C = 0.1\%$ for various values of relative depth d/D, extraction ratio q, and Froude number Fr. This plot shows that as the Froude number changes from 1.0 (either an increase or decrease) the efficiency always decreases. Therefore, most of the studies were made with Fr = 1 -- the condition for maximum efficiency. For the lower values of Fr the vertical action was poor and material was deposited in the tube. When the Froude number was greater than one, the bed load was carried over the tube opening. Fig. 2 also shows that as the velocity of flow increases relative to the fall velocity the efficiency is generally reduced. This apparently results from an increase in the per-cent of sediment in suspension thereby reducing the bed load available to be trapped. As the velocity ratio decreases for a given value of d/D, the efficiency decreases because of poor vertical action in the tube.

Fig. 3 is a general design curve for $\theta = 45°$, $b/D = 10$, $C = 0.1\%$, $p/D = 0.0$, and $s/D = 0.008$. From this plot the designer may determine the magnitude of any desired variable provided the foregoing parameters remain at the values just stated. For example, if 5% of the flow can be wasted, an efficiency of slightly over 75% may be attained with Fr = 1, $d/D = 1.8$, and $v/\omega = 18$. On the other hand removal of only 60% of the bed load from the canal may be sufficient to prevent degradation downstream, thus $E = 60\%$. With Fr = 1.0 the desired efficiency could be realized with d/D somewhat greater than 3, wasting about 2% of the total flow, and v/ω of about 25. As another example, if the depth of the flow is three times as great as the tube diameter ($d/D = 3$) a 65% efficiency may be attained with Fr = 1.0, $v/\omega = 23.8$ and 2.8% of the water being wasted.

If v/ω is changed because of the different fall velocity of sediment, a plot similar to Fig. 3 is necessary for each fall velocity. To illustrate, assume $d/D = 2$ and Fr = 1, then $R = 4.4\%$ and $v/\omega = 19$. Should a sand with a greater fall velocity be used, the efficiency would increase because more sediment would fall into the tube and a smaller value would exist for v/ω, say 16. By decreasing v/ω from 19 to 16, the efficiency increases from 75% to 82% but this indicates a nonexistent change in d/D as well as an increase in the extractor ratio.

When $p/D = 0$, material is deposited in the tube if the Froude number is somewhat less than 1. This is noted in Fig. 3 as the zone of clogging.

Summary:

When the concentration of sand or bed load in a canal was excessive, the vertical action in the vortex tube was destroyed and deposition in the tube resulted, leading to low efficiencies. Slightly better efficiency was found for values of Fr greater than 1 than for values less than 1, and the critical depth (Fr = 1) gave the highest efficiency when $p/d = 0$. Lowering the downstream lip of the tube seemed to have the disadvantage of allowing the bed material to be carried over rather than falling into the tube when Fr = 1. As the downstream lip was lowered, increased efficiency was attained with Fr less than 1. Efficiency increased with relative tube size.

References:

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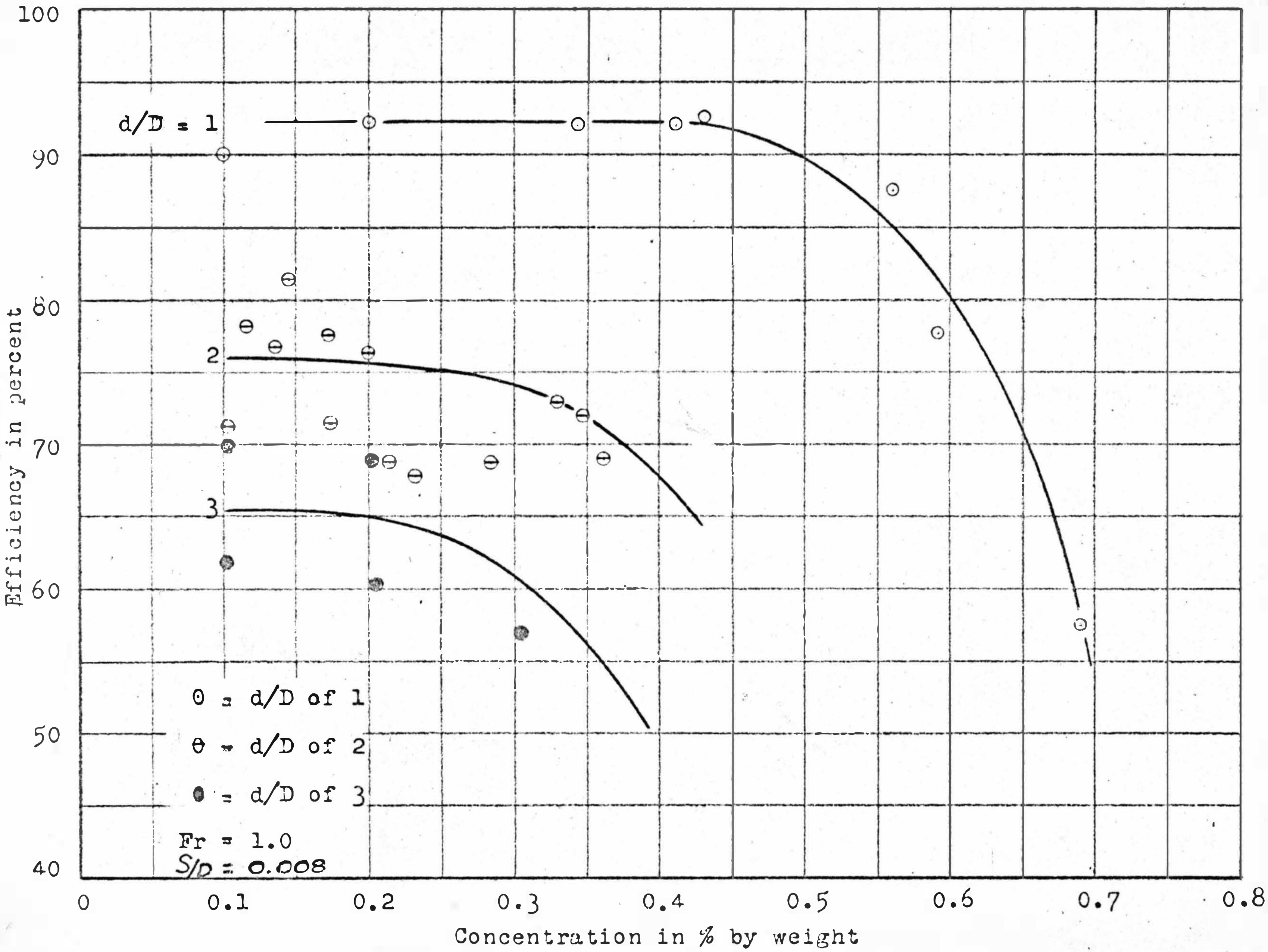

Fig. 1 -- Efficiency as a function of concentration

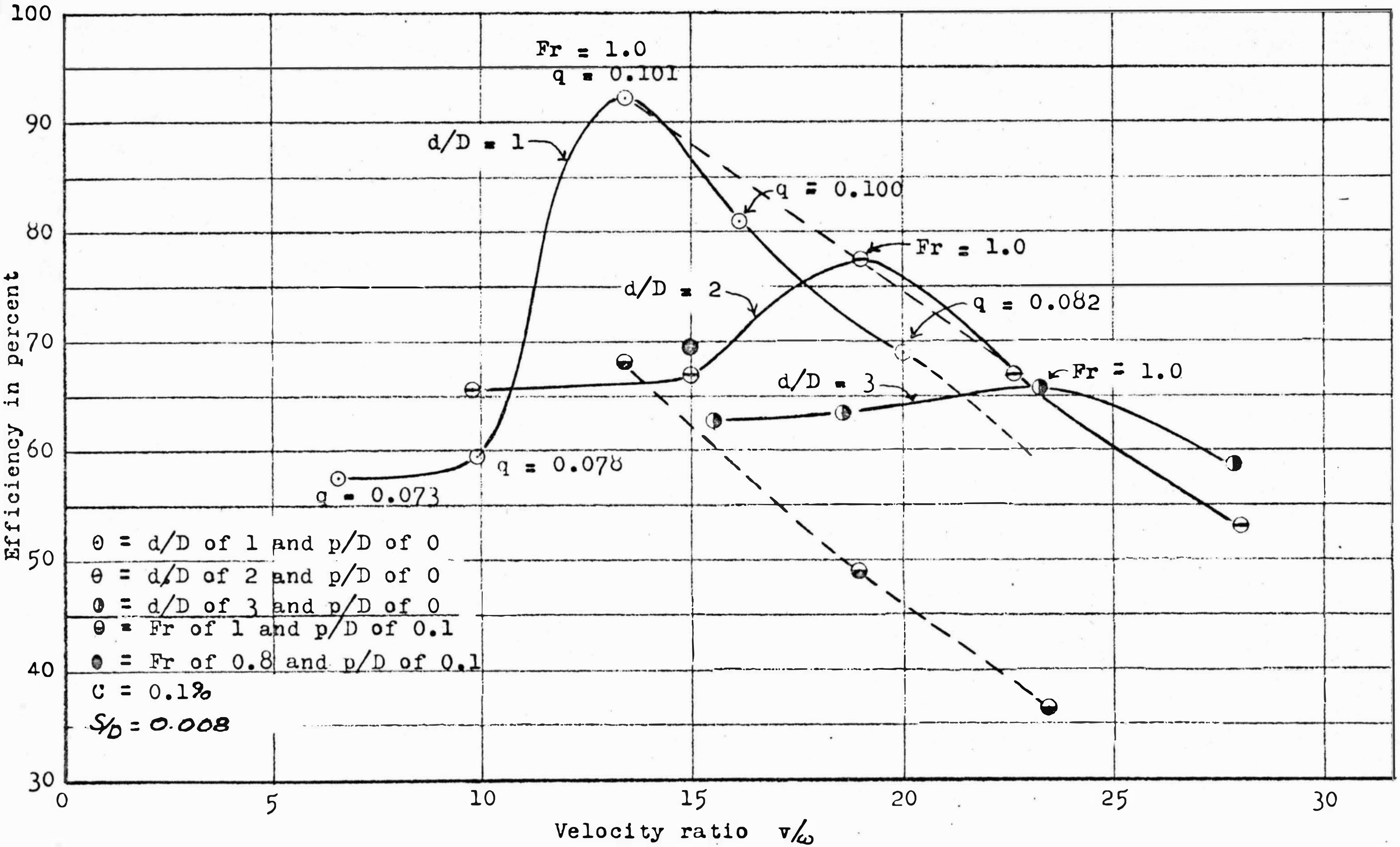

Fig. 2 -- Efficiency as a function of velocity ratio v/ω

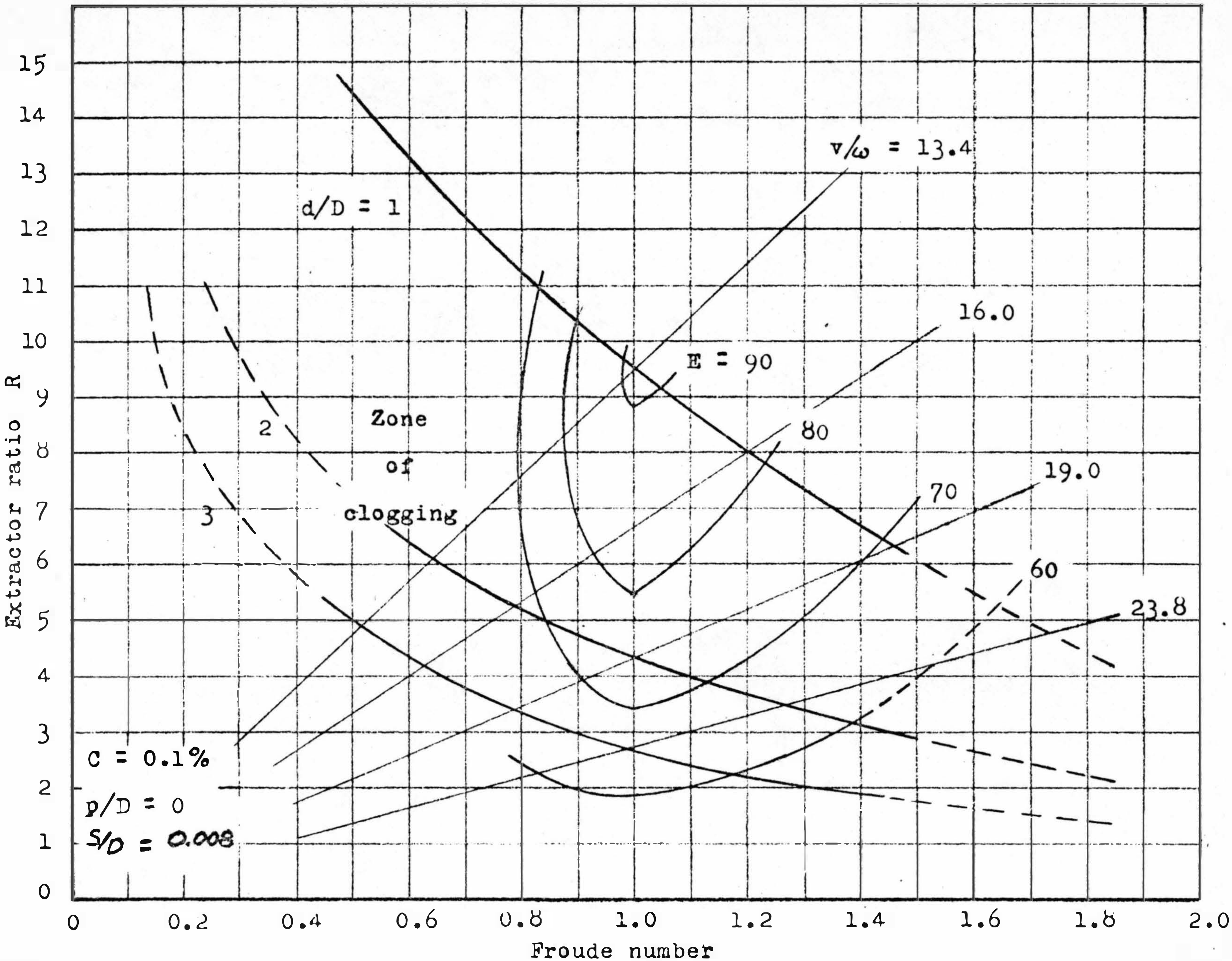

Fig. 3 -- Extractor ratio as a function of Froude number