# CAVITATION DAMAGE OF ROUGHENED CONCRETE SURFACES

by Donald Colgate

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The vigorous campaign against the damage of hydraulic installations caused by cavitation erosion continues apace. Technical personnel in the hydraulic laboratories of our universities, private concerns, and those operated by the Government have clearly defined what cavitation is, and have, in the past 30 years, advanced several divergent and unrelated plausible explanations as to just how this harmless appearing vapor cloud can inflict such unbelievable damage to construction materials. The very process that encourages these different opinions to be aired before all who are interested in the problem is largely responsible for the remarkable advances made thus far in the methods of protecting our hydraulic installations from the ravages of cavitation erosion.

The common construction material most readily damaged by cavitation is concrete. Since this material is so relatively inexpensive, and so handily shaped to the desires of the designer, its use will continue to be wide and varied. However, due to its susceptibility to cavitation erosion, the specifications regulating the configuration of, and the very texture of, concrete surfaces which will be subjected to high velocity flow have become extremely stringent. This trend is proper.

At Grand Coulee Dam the forms on the spillway face bulged outward permitting the concrete to "hump" about 3 inches in at least one of the 5-foot lifts. An examination of the spillway face after about 9 seasons of

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[1] Hydraulic Engineer, Bureau of Reclamation, Denver Federal Center, Denver, Colorado.

operation disclosed that the concrete downstream from this hump had been damaged by cavitation (Figure 1). In this instance the designers had specified that the spillway section conform in all respects to the "lines, grades, and dimensions" shown on the drawings. In practice, some deviation from true lines is to be expected, but the permissible limits of such deviation to prevent damaging cavitation have not been accurately determined.

During the building of Davis Dam on the Colorado River, discharges were made into the side of the spillway bucket. Debris of varied origin was washed about until quite an area was scoured, some places to a depth of 3 inches or more below the finished surface (Figures 2 and 3). When the bucket was dewatered and the scoured area inspected, the question arose as to whether or not these roughened surfaces would induce cavitation. The answer was not readily apparent, and since spillway releases were imminent, the repair of the scoured area to the original contours was authorized and performed.

It is common practice to evaluate extensive damage where cavitation is a factor by explaining that the initial erosion is caused by cavitation, and that the large eroded areas downstream are the result of jet action. From a practical viewpoint, the mechanics of the total damage is of secondary importance--the damaged area is repaired and the cause of the cavitation ascertained, if possible, and corrected. It is likely, however, that damaging cavitation forms on the roughened surfaces and continues its destruction far downstream from that area affected by the initial cavitation pocket. This does not mean that jet action is to be discounted as a damaging agent.

A test of the relative destructiveness of a jet and of cavitation was inadvertantly performed at a large dam. Shortly before water was released over the spillway a workman, who had been patching small bug holes and other surface blemishes, dumped about 1/3 cubic foot of unused grout onto the spillway apron. A general inspection some time later disclosed that the 4-inch-high carelessly placed lump, which had been subjected to the full jet force of the stream, was as originally deposited, but cavitation caused by its presence had eroded a hole 12 feet long, 3 feet wide, and 1 foot deep.

When damage is detected in a prototype installation laboratory investigations are often undertaken to resolve the problem, such as the Bureau of Reclamation's limited exploratory program to devise a means of evaluating various roughened surfaces as regards their cavitation potential. The Bureau's program envisioned eventual classification of surface texture for specifications for new installations and for repairing roughened surfaces.

The laboratory apparatus (Figure 4) permitted a stream 6 inches wide and 3 inches deep to pass over the test surface. The test section top was made transparent for visually determining the presence of cavitation (Figure 5). The laboratory pumps were capable of producing a stream velocity up to about 100 fps, and the discharge piping was so installed that the pressure head at the test section could be lowered to about a negative 17 feet of water.

For the initial study plaster molds were made of several different damaged areas at Davis Dam, and from these molds concrete casts were made in the laboratory for installation in the test apparatus.

A study of the test surfaces showed that the surface texture could be classified roughly in terms of the average size or radius of the exposed aggregate. The vertical distance between the highest and lowest points averaged about 0.4 times the thickness of the exposed stone, and the horizontal distance between high points was nearly the stone thickness. For lack of descriptive nomenclature the surfaces have been referred to as Specimen No. 2 and Specimen No. 3. The average exposed aggregate of Specimen No. 2 extended about 3/4 inch above the lowest point of the roughened surface, and that of No. 3 about 1/4 inch.

At the onset it was determined that, under certain conditions, cavitation did form on the protruding aggregate (Figure 6). The test apparatus had sufficient range to permit visible cavitation to be formed for stream velocities as small as 25 fps with low back pressure, and up to 97 fps with high back pressure. The only measurements made were (a) the discharge, (b) pressures at various points on the viewing window, and (c) single leg Pitot tube pressures to calculate the velocities at various distances above the specimen.

In the analysis the data are applicable to either closed conduits or open channels. The laboratory study was made in a closed conduit rectangular in cross section, and computations were made using circular pipe formulae. These approximations appear to be permissible since the boundary shear, and the stream velocity near the boundary, are affected by a given surface in the same manner for either closed conduit or open channel flow. The computations regarding the velocity distribution in the stream above the surface recognize that the Prandtl universal logarithmic velocity-distribution law for pipes applies equally well for an infinitely wide open channel.

The analysis considered that the tested surface was a full scale specimen, and that the boundary shear, or shear velocity, of the surface could be determined directly from measurements made in the laboratory apparatus. A plot on semilog paper of the velocity profile perpendicular to the test specimen produced a straight line for the elements of flow affected only by the roughened surface (Figure 7). From this plot the shear velocity for the specimen was determined from the Karman-Prandtl equation for rough surfaces:

$$\frac{V}{\sqrt{\frac{\tau_0}{\rho}}} = 5.75 \log_{10} \frac{Y}{K} + 8.5 \qquad (1)$$

where:

$Y$ = distance from the specimen

$V$ = velocity at $Y$

$K$ = von Karman constant (about 0.4)

$\sqrt{\frac{\tau_0}{\rho}}$ = shear velocity

Substituting values for two points ($V_1$,$Y_1$) and ($V_2$,$Y_2$) and solving simultaneously, the shear velocity was determined:

$$\sqrt{\frac{\tau_0}{\rho}} = \frac{V_2 - V_1}{5.75 \log_{10} \frac{Y_2}{Y_1}} \qquad (2)$$

or the boundary shear:

$$\tau_0 = (0.0586) \left( \frac{V_1 - V_2}{\log_{10} \frac{Y_1}{Y_2}} \right)^2 \qquad (3)$$

The discharge through the test apparatus and the pressure at the specimen were adjusted to produce a small, but visible cavitation cloud, and the velocity profile measured above the specimen. This procedure was followed for several combinations of velocity and pressure. A plot was then made showing the relationship between the shear velocity and the pressure on the viewing window (Figure 8).

This curve is readily obtainable from the test apparatus, but the possibility is remote that flowing water in a field installation will have been in contact with the roughened surface long enough to establish uniform turbulent flow, and an accurate determination of the shear velocity would be virtually impossible.

A study of the velocity profiles (Figure 9) reveals that, for the same average velocity, the velocity near the boundary is appreciably greater for a smooth surface than for a rough one. If the approach to the roughened area was a reasonably smooth surface sufficiently long to establish uniform flow, the average velocity of the approaching stream necessary to cause cavitation on the rough surface would be less than that computed from the shear velocity curve (Figure 7). Since the velocity near the boundary is the one which would attack the roughened surface, it is the one which must be computed to ascertain whether cavitation would exist on the damaged or roughened area.

For illustration, assume that a roughened surface of Specimen No. 2 texture existed on the floor of a channel with water flowing 5 feet deep, and that this surface prevailed for a considerable distance upstream. From Figure 8 the minimum shear velocity to produce cavitation would be 4.2 fps. Consider the velocity about 0.3 inch from the mean surface to be critical. This velocity may be computed (for this surface) from the relation:

$$V_{0.3}^2 = 110\ (H_p + H_B)$$

(determined from the average of the results of the study)

where:

$V_{0.3}$ = velocity 0.3 inch from the mean surface

$H_p$ = pressure head or depth

$H_B$ = barometric pressure in feet of water

so:

$$V_{0.3} = \sqrt{110\ (5 + 27)} = 59.3 \text{ fps}$$

The average velocity exists at:

$Y = (0.37)(5) = 1.85$ feet from the bottom

(from Vanoni, Velocity Distribution in Open Channels, Civil Engineering, June 1941, p. 357)

Substituting in Equation (2):

$$4.2 = \frac{V_{avg} - 59.3}{5.75 \log_{10} \frac{1.85}{0.025}}$$

$V_{avg} = 104.4$ fps

(average stream velocity at which cavitation will occur on Specimen No. 2 with rough approach surface)

Now assume that the approach channel to the roughened surface is smoother and has about one-quarter the boundary shear of the roughened area. Then:

$$2.1 = \frac{V_{avg} - 59.3}{5.75 \log_{10} \frac{1.85}{0.025}}$$

$V_{avg} = 81.9$ fps

(average stream velocity at which cavitation will occur on Specimen No. 2 with smoother approach)

In the case of flow with a blunt velocity profile, the average velocity can be considered to exist near enough to the boundary to affect the roughened area. If the average velocity is critical, then cavitation will occur on Specimen No. 2 at

$V_{avg} = 59.3$ fps

Comparing the approach conditions and average stream velocities for incipient cavitation to exist on the roughened surface in the illustration:

| Approach conditions | Average stream velocity |
|---|---|
| Specimen No. 2 texture | 104.4 fps |
| Relatively smooth approach | 81.9 fps |
| Blunt velocity profile | 59.3 fps |

From the data obtained in the laboratory a chart was made by plotting the average velocity near the roughened surface versus depth of flow (or pressure head) for the condition of incipient cavitation for the two tested surfaces (Figure 10). A family of curves of this type for various surface textures would be extremely valuable to the designer, or to the field engineer, since the values for the chart can be readily computed from known flow conditions.

On the basis of average velocity and stream depth, the flow conditions at Davis Dam would induce cavitation on the damaged surfaces (see Figure 10).

This exploratory study on cavitation of roughened surfaces demonstrated that a simple laboratory test can be made to determine and evaluate the cavitation potential of any surface. There is a need for the collection, evaluation, and classification of information from the field concerning roughened surface problems, and further laboratory studies must be made so that criteria may be established to enable the designer or field engineer to state with confidence that a given surface texture will or will not induce cavitation.

Figure 1. Spillway, Grand Coulee Dam, showing "humped" concrete surface and cavitation erosion.

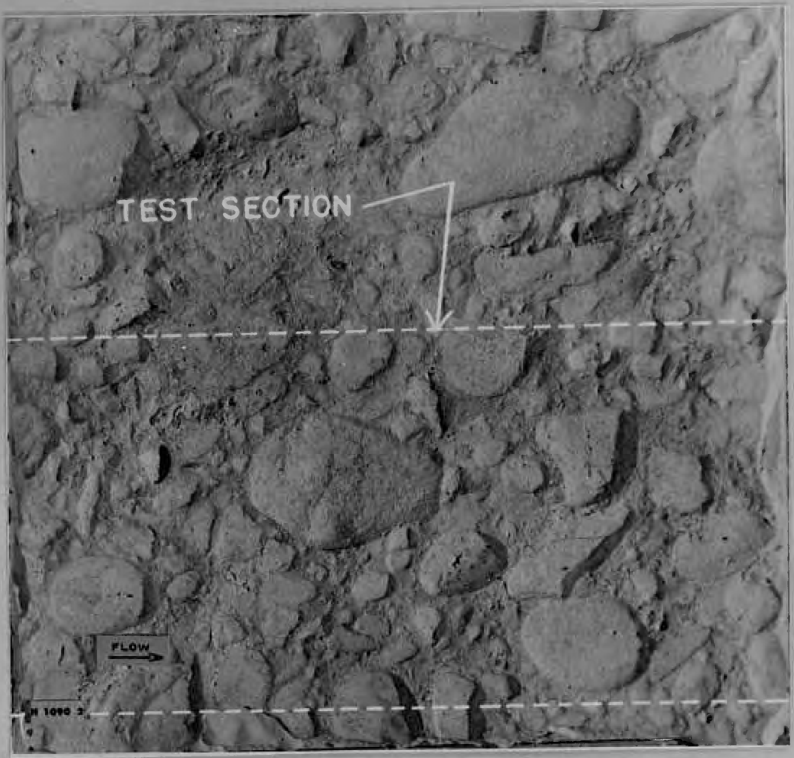

Figure 2. 1-foot-square plaster mold of eroded surface at Davis Dam (Specimen No. 2).

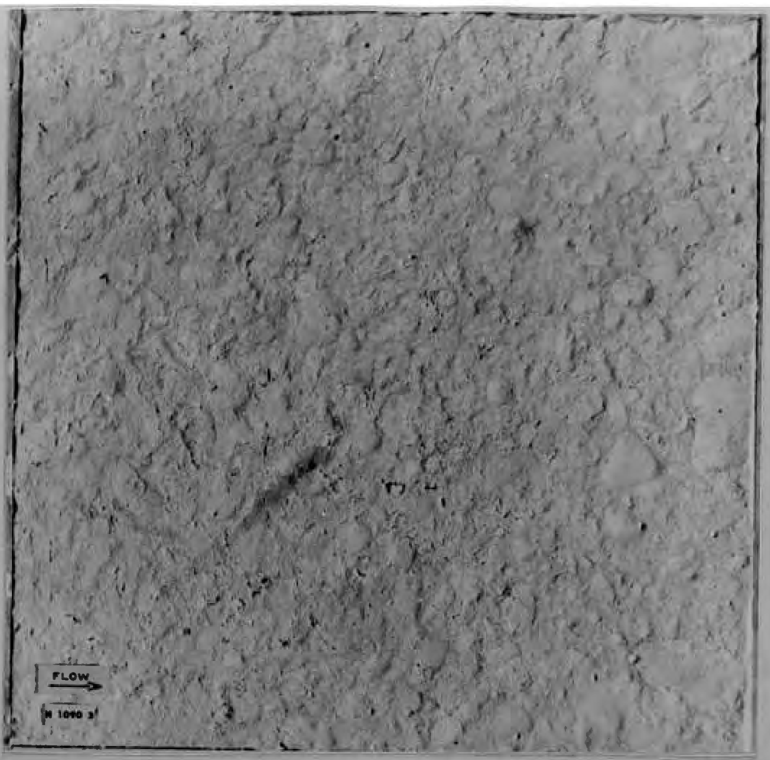

Figure 3. 1-foot-square plaster mold of eroded surface at Davis Dam (Specimen No. 3).

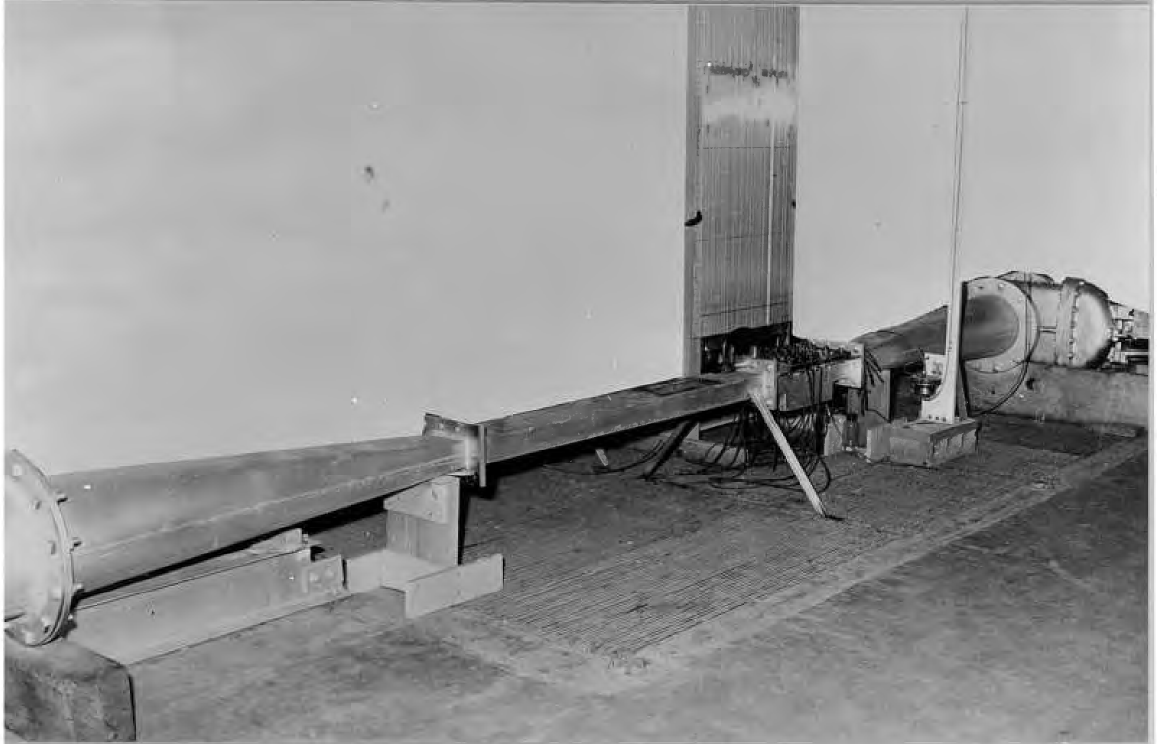

Figure 4. View of laboratory test apparatus showing approach and downstream piping.

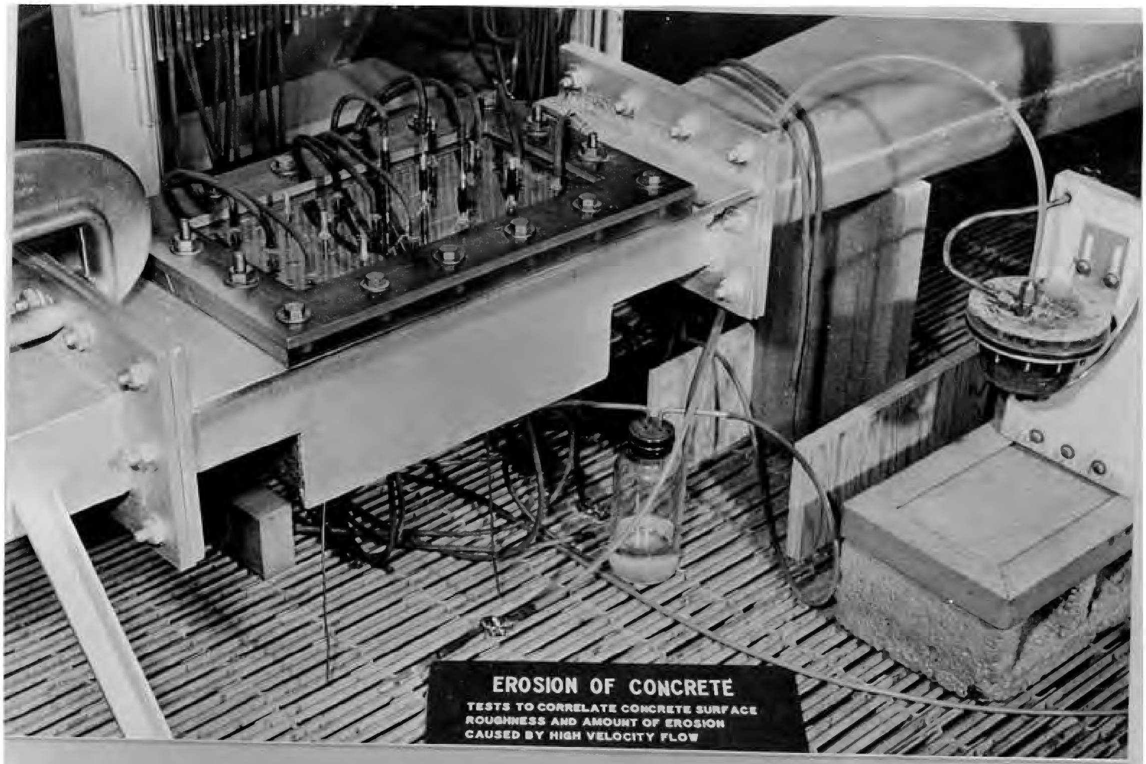

Figure 5. Closeup of test section showing transparent viewing window and pressure taps.

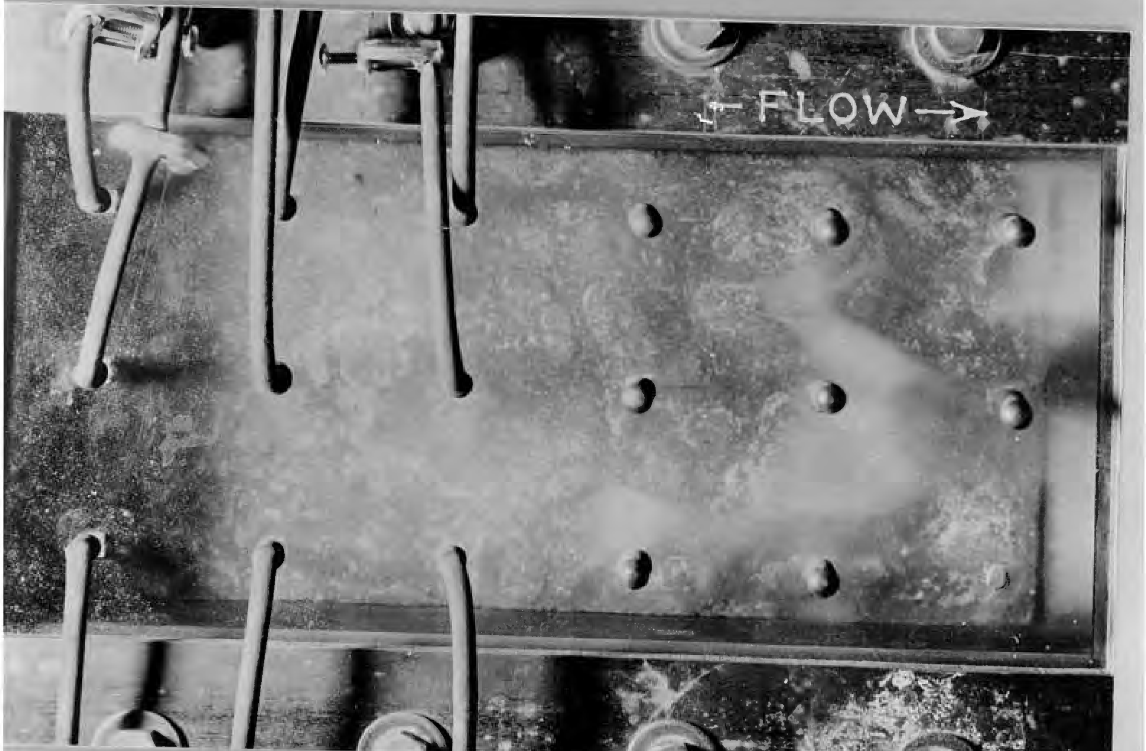

Figure 6. Visible cavitation cloud on Specimen No. 2. Head on the viewing window = +14', $\sqrt{\frac{\tau_o}{\rho}} = 5.4$.

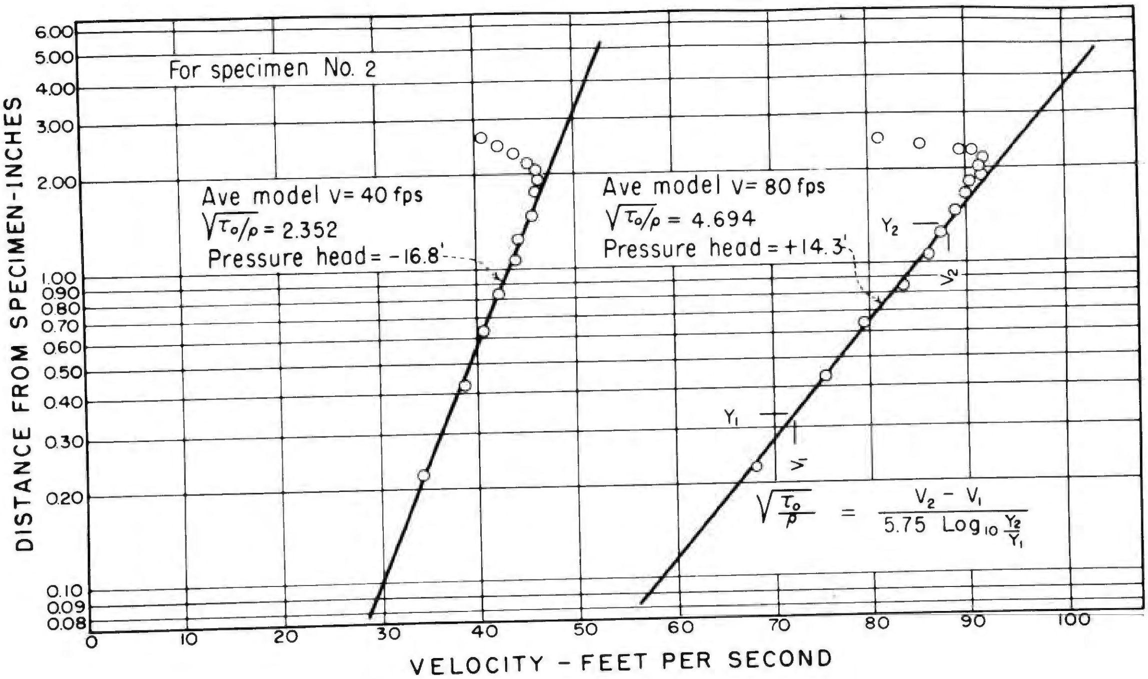

Figure 7. Graph showing representative velocity distribution for Specimen No. 2.

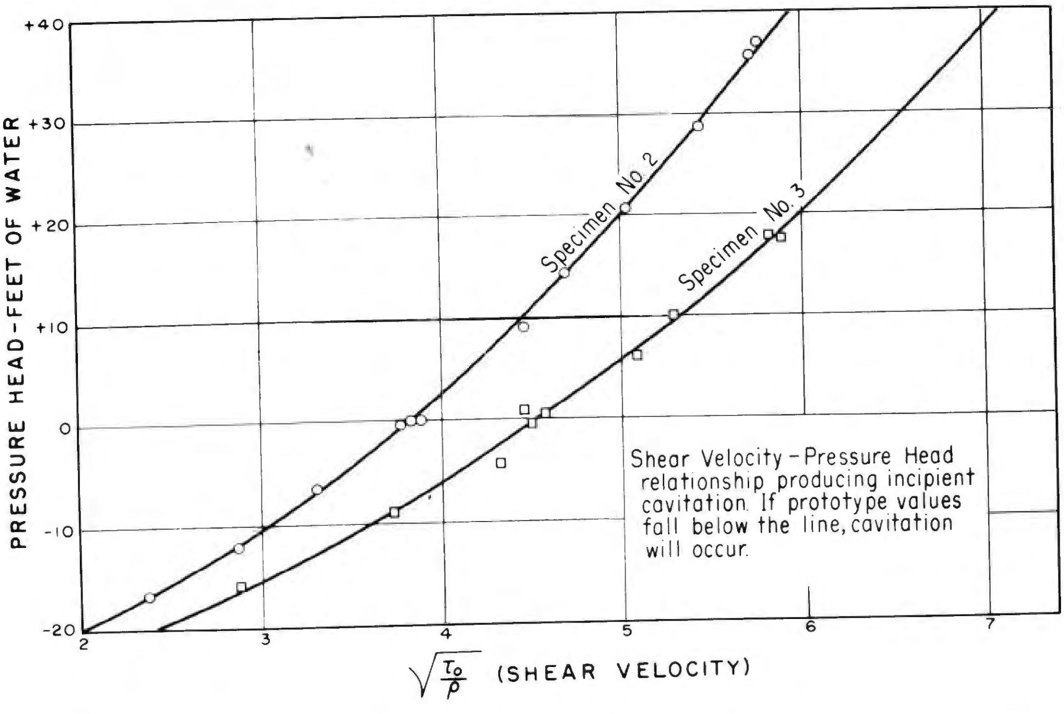

Figure 8. Relationship between stream depth (or pressure head) and shear velocity, feet per second.

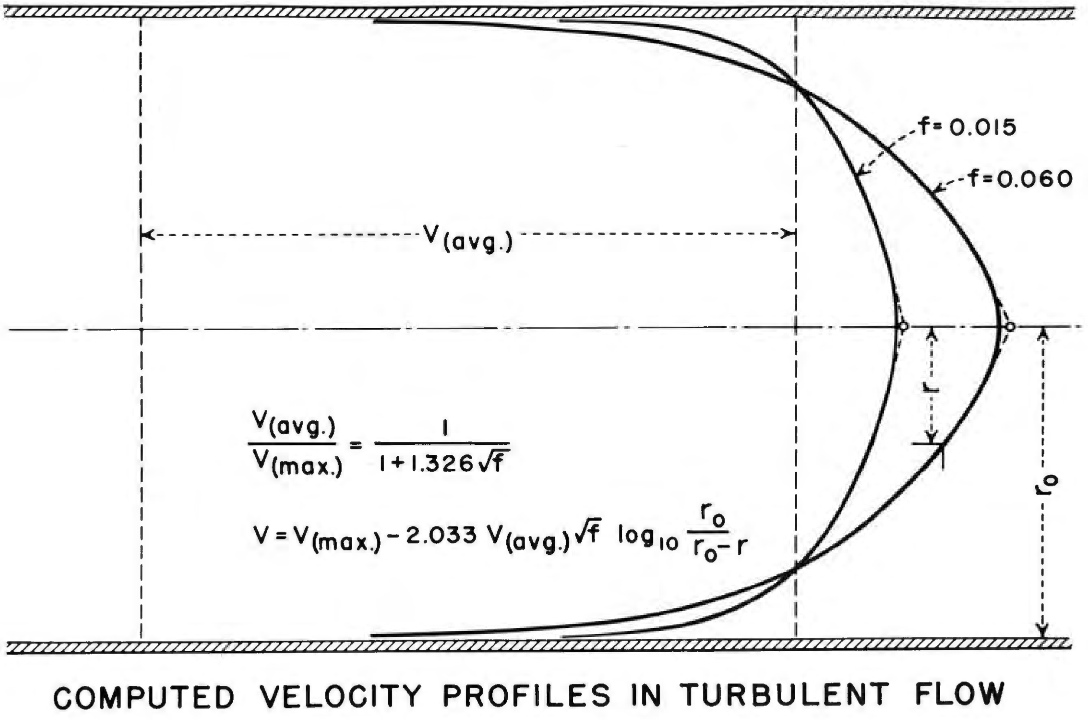

Figure 9. Computed velocity profiles for smooth and rough surfaces in turbulent flow.

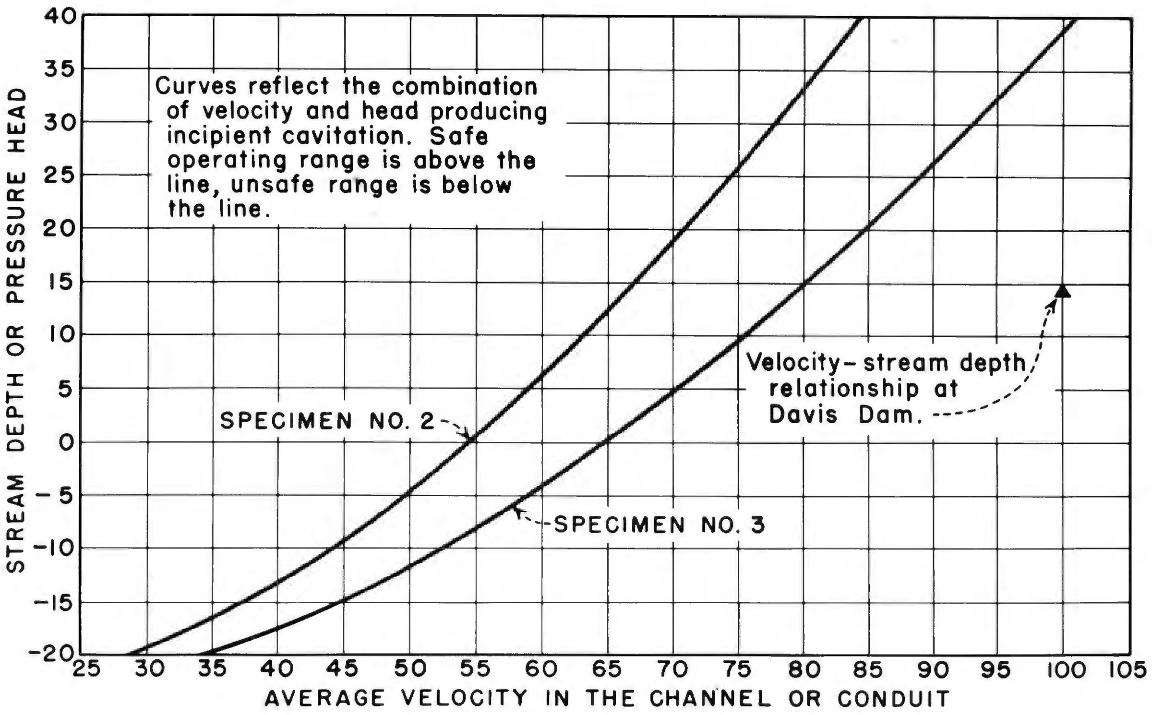

Figure 10. Relationship between stream depth (or pressure head) and average stream velocity, feet per second.