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# FLOW SURFACE TOLERANCES ON THE INVERT BETWEEN STATIONS 20+20.08 AND 46+61, NEVADA SPILLWAY

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## INTRODUCTION

Plaster of paris casts of the invert roughness were obtained from the Nevada spillway tunnel near stations 22+50 and 32+60. Most of the invert has suffered extensive erosion. This probably occurred during the diversion flows while the dam was being constructed. The cast at station 22+50 is representative of areas that have not suffered extensive erosion damage. The cast at station 32+60 is located downstream of the horizontal bend in the spillway tunnel. Due to secondary currents as the diversion discharges passed around the bend, the erosion at this location is more severe.

Estimation of the cavitation characteristics of the two areas was made by testing the casts in the LAPC (low ambient pressure chamber) in the Hydraulics Laboratory. The purpose of the tests was to determine if the invert requires any special repair treatment or if it can remain in its present state. Since flow conditions in the chamber are significantly different from those in the field, a method was developed to predict the performance of the prototype from the model observations.

The cavitation characteristics of the test samples as determined in the LAPC were compared to the cavitation index of the flow in the spillway tunnel. The flow index is determined from a computer program which needs the surface roughness as an input parameter. If the cavitation index of the roughness is greater than the index of the flow, then the roughness will cavitate. Whether the cavitation will produce damage is a function of the quantity of air in the water, the severity of the cavitation as indicated by the cavitation indices, and the exposure time of the surface to cavitation.

The purpose of this memorandum is to describe the test facility, to provide detailed descriptions of methods used to determine the surface resistance of the plaster casts, to show how the model results are scaled to the prototype values and to provide recommendations for the repair of the tunnel invert considering the cavitation potential and the beneficial effects of aeration.

## TEST FACILITY

A test tunnel was constructed within the LAPC which allowed for the determination of both the surface resistance of the plaster casts and their cavitation characteristics, figure 1. The test tunnel consisted of a 4-inch by 6-inch rectangular section about 10 feet long. The flow enters the tunnel after passing through a stilling chamber, which contains baffles and a metal transition. The combination of the stilling chamber and the metal transition produces a blunt velocity profile at the upstream end of the tunnel.

The tunnel is constructed from Plexiglas and has the provision for insertion of test samples about 6-feet downstream from the entrance of the tunnel. The size of the samples which can be tested are 4 inches by 11 inches. At the site of the test section, the boundary layer is about 1 inch thick.

Velocities in the tunnel are measured with a laser doppler anemometer. Pressures are measured with either piezoelectric or diaphragm type pressure transducers. The piezoelectric transducers cannot measure the static pressure but they have a very high frequency response. Therefore, they are very useful in detecting cavitation.

The LAPC can achieve pressures as low as 1.0 lb/in$^2$ absolute. The maximum average velocity used in these investigations was about 33 ft/s.

## SURFACE ROUGHNESS

In order to determine the water surface profile, the boundary layer thickness, and the cavitation index of the flow, an accurate value of the surface roughness must be input into the computer program. In the past it has been practice to calculate the water surface profile using Manning's "n". However, estimation of Manning's "n" is very difficult. In addition, Manning's "n" does not account for flow in the transition range between smooth and fully rough turbulent flow. Therefore, the current computer program uses the more modern concept of sand grain roughness and a modified form of the Colebrook-White equation as applied to open channel flow to calculate the boundary resistance.

Two methods of determining the sand grain roughness are possible. One is to determine the surface resistance from observations of the flow in the LAPC. The other is to determine the sand grain roughness from physical measurement on the plaster cast. The two methods should yield the same result.

The following sections describe the techniques to determine the sand grain roughness from the flow observations in the LAPC and from physical measurements of the plaster casts. The results are used in the computer program to calculate the water surface profiles and the cavitation index of the flow for the case of no aerator in the spillway tunnel.

Determination of Sand Grain Roughness from Flow Measurements. - The surface resistance of the plaster casts was determined in the LAPC from measurements made with and without the sample placed in the test section. Then through application of the momentum equation the shear stress on the sample can be determined, figure 1.

The momentum equation for the test section without the sample is given by

$$A*(P1 - P2) - 2*L*(Tp*H + Tp*W) = \rho*Q*(\beta 2*V2 - \beta 1*V1) \tag{1}$$

where A = Cross-sectional area of test section
P1 = Upstream pressure
P2 = Downstream pressure
L = Length between pressure taps
Tp = Wall shear stress
H = Height of test section
W = Width of test section
$\rho$ = Density of the water
$\beta 1$ = Upstream momentum correction factor
$\beta 2$ = Downstream momentum correction factor
V1 = Upstream average velocity
V2 = Downstream average velocity
Q = Discharge

Since from continuity V1 = V2, the shear stress is given by

$$Tp = R*(P1 - P2)/L - \rho*R*V^2*(\beta 2-\beta 1)/L \tag{2}$$

where R = Hydraulic radius

Similarly the momentum equation for the test section with the plaster cast installed is given from

$$A*(P3 - P4) - 2*L*Tp*H - L*Tp*W - (L - Ls)*Tp*W - Ls*Ts*W = \rho*Q*(\beta 4*V4 - \beta 3*V3) \tag{3}$$

where P3 = Upstream pressure with sample
P4 = Downstream pressure with sample
Ls = Length of sample
Ts = Shear stress on sample
$\beta 3$ = Upstream momentum correction factor
$\beta 4$ = Downstream momentum correction factor
V3 = Upstream average velocity
V4 = Downstream average velocity

The points 1 and 3 refer to conditions at the same upstream station but without and with the test sample, respectively. Similarly, points 2 and 4 refer to conditions at the same downstream station.

If a series of tests are conducted with and without a sample at constant values of discharge, then for each value of discharge 1 = 3, and V1= V2= V3= V4. Under these conditions the average shear stress over the sample is given from

$$Ts = 1/(Ls*W)*[A*(P3 - P4) + (R*Ls*W/L - A)* [(P1 - P2) - \rho*V*V*(\beta 2 - \beta 1)] - \rho*A*V^2 (\beta 4 - \beta 3)] \qquad (4)$$

The tests have shown that for all practical purposes, β1= β2= β3= β4. Therefore the equation can be simplified to

$$Ts = A/(Ls*W)*[(P3 - P4) - (P1 - P2)] + R/L*(P1 - P2) \qquad (5)$$

The values thus obtained can be expressed in terms of an average resistance coefficient over the length of the sample, which is defined as

$$\lambda = \frac{8*Ts}{\rho*V^2} \qquad (6)$$

The sand grain roughness is determined from correlations given by Schlichting (6) for fully rough flow over flat plates with a developing boundary layer. The equation is

$$1/\lambda = 2*\log(r/k) + 1.74 \qquad (7)$$

where k = sand grain roughness
r = pipe radius

For a developing boundary layer, the pipe radius was replaced with the boundary layer thickness, h.

The values obtained from the tests are summarized in table 1.

Table 1. - Effective sand grain roughness measured in the LAPC

| Station | Velocity ft/s | λ | k ft |
|---|---|---|---|
| 22+50 | 18.44 | 0.073 | 0.024 |
| | 22.54 | 0.067 | 0.017 |
| | 29.72 | 0.063 | 0.015 |
| 32+60 | 18.44 | 0.110 | 0.035 |
| | 22.54 | 0.090 | 0.019 |
| | 29.72 | 0.080 | 0.017 |

Scaling Measured Sand Grain Roughness to Prototype Values. - The surface roughness is described by a parameter called the "sand grain roughness." The correlation between this parameter and the velocity distribution was determined by Nikuradse (1). In his experiments sand grains of various sizes were glued to a pipe and the velocity distributions were obtained. These distributions were then correlated with the resistance to flow. The technique was good. However, to keep the sand grains on the pipe it was necessary for him to cover the grains with a coating of lacquer. This coating essentially decreased the height of the individual grains.

Kamphius (2) studied the effect of the coating by repeating the tests using better glues which did not require the lacquer coating. The problem was also studied by Brown and Chu (3) of the Corps of Engineers, and by Riedel (4). The results of these studies show that the equivalent sand grain roughness is actually larger than a characteristic dimension of the sand. Since the sand is not of uniform size, the characteristic dimension is usually taken to be the size of sieve which will pass 90 percent of the sand.

Kamphius showed that the relative sand grain roughness (k/D) is a function of the relative flow depth (d/D) and the Reynolds number of the flow, figure 2. For flow in the fully rough zone, the Reynolds number is not a significant parameter. In the above ratios, the values are defined as follows:

d = flow depth
D = 90 percentile grain size
k = equivalent sand grain roughness

The parameters in the analysis of Kamphius were modified slightly for this study. With a developing boundary layer, the significant parameter is actually the boundary layer thickness and not the flow depth. For this reason, the dimensionless plot shows boundary layer thickness and not the flow depth as the independent variable, figure 2.

From the above discussion it should be apparent that scaling refers to accounting for the boundary layer thickness. The effective sand grain roughness with a thin boundary layer is much less than the effective sand grain roughness with a thick boundary layer. Thus, values of the effective sand grain roughness determined in the laboratory with thin boundary layers need to be corrected to prototype values where the boundary layer is generally much thicker.

To use the curves of Kamphius, it is necessary to know the boundary layer thickness and the 90 percentile grain size. The boundary layer thickness is determined from physical measurements in the model. Whereas in the prototype, the boundary layer thickness must be estimated by appropriate equations. The appropriate equations have been coded into the water surface profile program used to investigate the occurrence of cavitation in the spillway. The 90 percentile size of the grains on the surface is determined from physical measurements.

Measurements taken from the centerline of the plaster casts at even 1/2-inch intervals were used to determine the 90 percentile size of the grains, figure 3. In this case it was assumed that the deviations from a plane were equivalent to the size distribution obtained by passing the aggregate through a sieve, figure 4.

The pertinent parameters for the two plaster casts are given in the following table:

Table 2. - Determination of effective sand grain roughness in the prototype

| Station | D ft | $h^*$ ft | h/D | k/D** | $k_p$ ft |
|---|---|---|---|---|---|
| 22+50 | .0154 | 5.2 | 338 | 2.5 | .038 |
| 32+60 | .0292 | 9.6 | 329 | 2.5 | .073 |

*Estimated by the computer program
**From figure 2

The equivalent sand grain roughness for the prototype, $k_p$, given in table 2 is about twice the value measured in the model, table 1. The model values compare favorably with the curves presented by Kamphius, figure 2.

PREDICTION OF CAVITATION INDEX OF SURFACE IN FIELD

The cavitation indices of the two casts were determined in the LAPC for free stream water velocities of 18.44, 22.54, and 29.72 ft/s. It was observed that cavitation began at isolated points on each surface which corresponded to high points on the large individual pieces of aggregate. As seen from a distance, these pieces of aggregate give the appearance of an almost uniform surface, figure 5a. However, when examined at close range the surface texture is characterized more by a uniformly rough surface having almost hemispherical protrusions, figure 5b.

A theory to predict cavitation over an irregular surface has not been developed. Previous investigations have concentrated on either a uniformly rough surface or on isolated irregularities protruding from a smooth surface. Therefore, these studies were used for guidance in interpreting the results from the LAPC.

Arndt, et. al. (5) reported on investigations of the cavitation characteristics of hemispheres protruding from a smooth surface, The correlation, which has a theoretical basis, to predict the inception of cavitation is of the form:

$$\sigma_r = 0.439*(Ho/h)^{0.30} * (V*h/Nu)^{0.01} \qquad (8)$$

where Nu = kinematic viscosity of water
Ho = height of hemisphere
h = boundary layer thickness
V = velocity outside of boundary layer

To obtain a correlation for the irregular surfaces, it was assumed that the height of the offset could be replaced by the 90 percentile grain size. In addition, it was assumed that only the value of the constant multiplier had to be changed to account for the difference in the definition of the height of the irregularity. Thus it is necessary to determine from model tests the value of the coefficient "a" in the equation

$$a = \frac{\sigma_m}{(D/h)^{0.30} * (V*h/Nu)^{0.01}} \qquad (9)$$

where $\sigma_m$ = cavitation index from model tests.

The experimental investigation gave the following values:

Table 3. - Experimental values of constant in cavitation index

| Station | Velocity ft/s | $\sigma_m$ | | a |
|---|---|---|---|---|
| 22+50 | 18.44 | 1.26 | | 1.88 |
| | 22.54 | 1.15 | | 1.71 |
| | 29.72 | 1.34 | | 1.99 |
| | | | Average | 1.86 |
| 32+60 | 18.44 | 1.41 | | 1.73 |
| | 22.54 | 1.39 | | 1.70 |
| | 29.72 | 1.37 | | 1.67 |
| | | | Average | 1.70 |

Thus the equation for the cavitation index of the plaster casts $\sigma_r$ is

$$\sigma_r = a*(D/h)^{0.30} * (V*h/Nu)^{0.01} \qquad (10)$$

where a is determined from the above table

By inserting the proper values for the velocities and boundary layer thicknesses at the two stations into equation 10 it was found that the cavitation index of the surface is given by:

Table 4. - Incipient cavitation indices for prototype surface

| Station | Discharge $ft^3/s$ | $\sigma_r$ |
|---|---|---|
| 22+50 | 20,000 | 0.36 |
| | 50,000 | 0.37 |
| | 100,000 | 0.38 |
| | 200,000 | 0.39 |
| 32+60 | 20,000 | 0.38 |
| | 50,000 | 0.38 |
| | 100,000 | 0.37 |
| | 200,000 | 0.37 |

EVALUATION OF THE RESULTS

The results of the study seem to indicate that damage to the invert of the diversion tunnel should have occurred between stations 20+00 (the P.T.) and station 25+50 during the flood of 1983. [1] In this region the cavitation index of the flow is less than the cavitation index of the surface roughness in the invert for discharges up to 20,000 $ft^3/s$, figure 6. There were a couple of mitigating circumstances which prevented the damage. First, sweepout of the tunnel occurs for flows between 5,000 and 10,000 $ft^3/s$. Thus, for discharges less than the sweepout discharge, no cavitation damage to the invert would be expected.

For flows between 10,000 and 20,000 $ft^3/s$, natural aeration enters the flow through the water surface. The air entrainment starts near the P.T. and continues on past station 25+50. Thus, for all of the flows which were passed through the tunnel, natural aeration was occurring. The cavitation damage which had occurred in the elbow probably contributed to the aeration. The reason is that the flow depth was approximately equal to the depth of the damage. Therefore the flow through the damaged area would be highly turbulent, appearing very much like the flow through a steep mountain stream.

Another equally important mitigating factor is the small difference between the cavitation indices of the flow and of the surface roughness. Even though the surface will cavitate, the intensity of the

[1] Note: The diversion tunnel stationing does not correspond to the stationing on the inclined section of the spillway. The equation connecting the two is Spillway Station 12+09.71 = Diversion Tunnel Station 20+02.09. The stations given on figure 6 refer to the spillway stations.

cavitation will be low and hence its potential for producing damage will be small. This effect cannot be quantified at the present time although research promises some definitive answers in the near future.

Above 20,000 $ft^3/s$ natural aeration does not occur. Without an aerator, damage would be expected to develop in the invert. In the past, the repair criteria would have required the complete removal and replacement of all of the invert which had suffered erosion type damage. However, the tests at Glen Canyon Dam and the experience gained during the spill at Hoover in 1983 both demonstrate the protection air provides to damage from cavitation.

## RECOMMENDATIONS

Due to the fact that aerators are being installed at Hoover and due to the small difference between the cavitation index of the flow and that of the surface irregularities, replacement of the invert is not recommended for the Nevada spillway tunnel at Hoover Dam.


## ACKNOWLEDGMENTS

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D-1532
D-1532 (Mefford)

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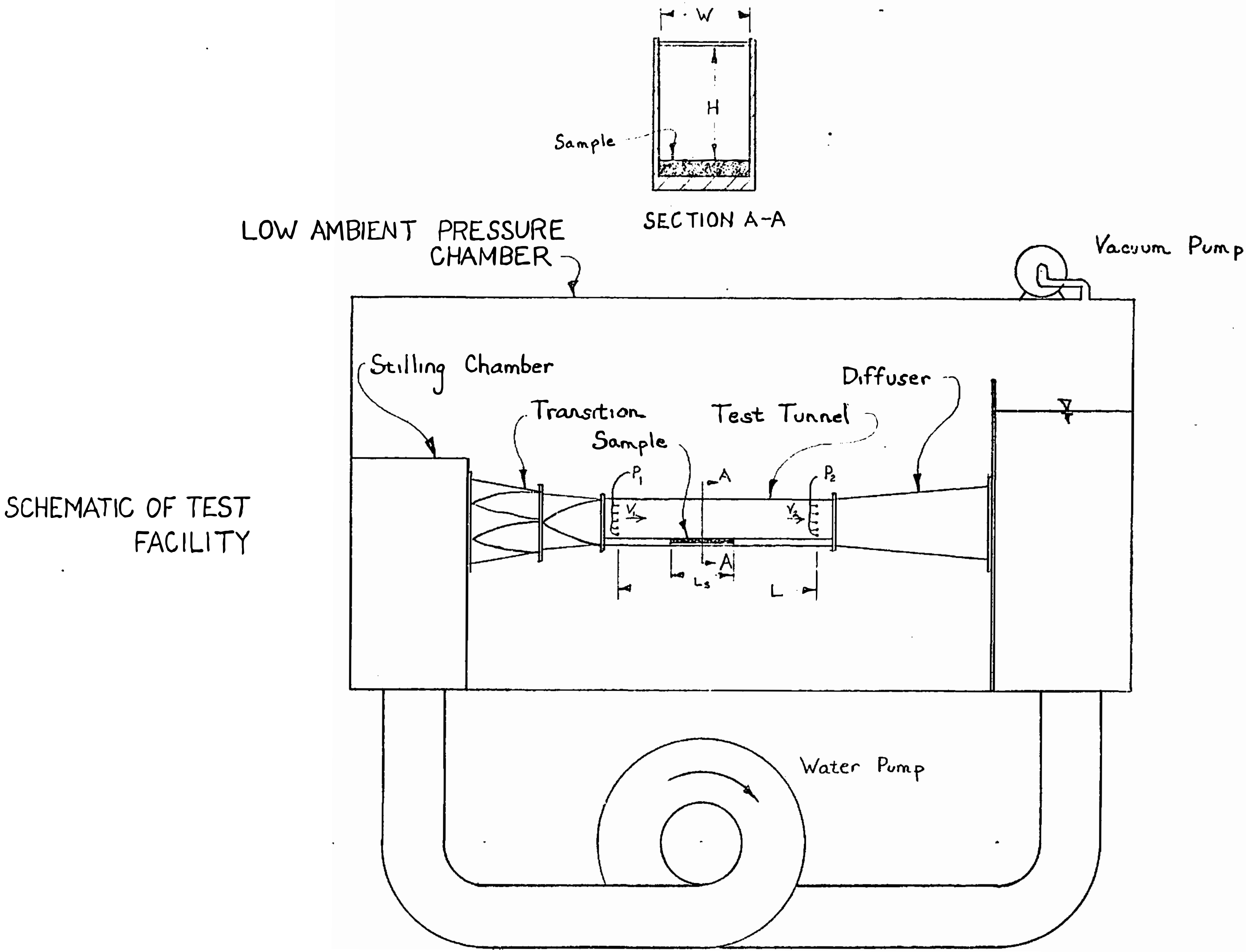



Figure 1. - Test apparatus.

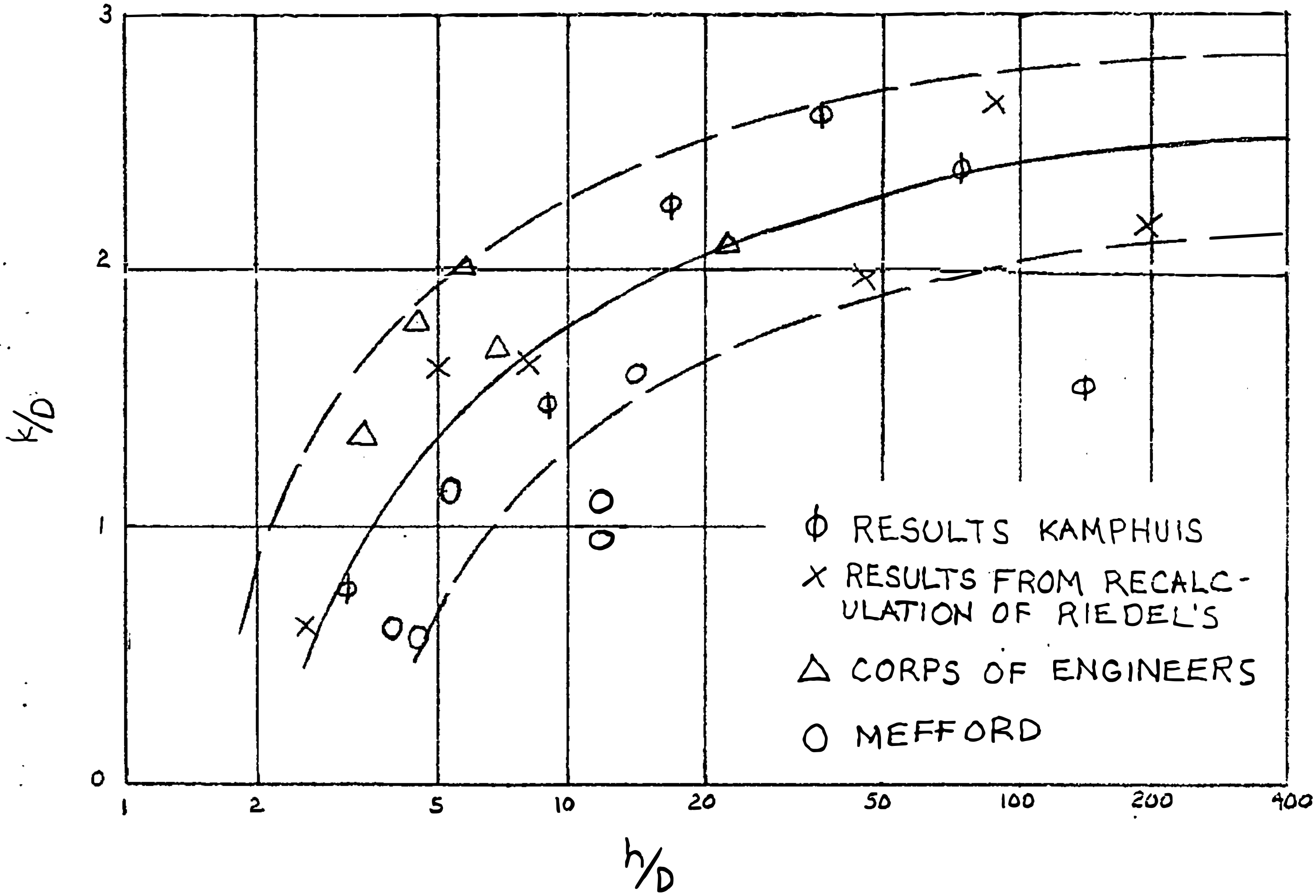
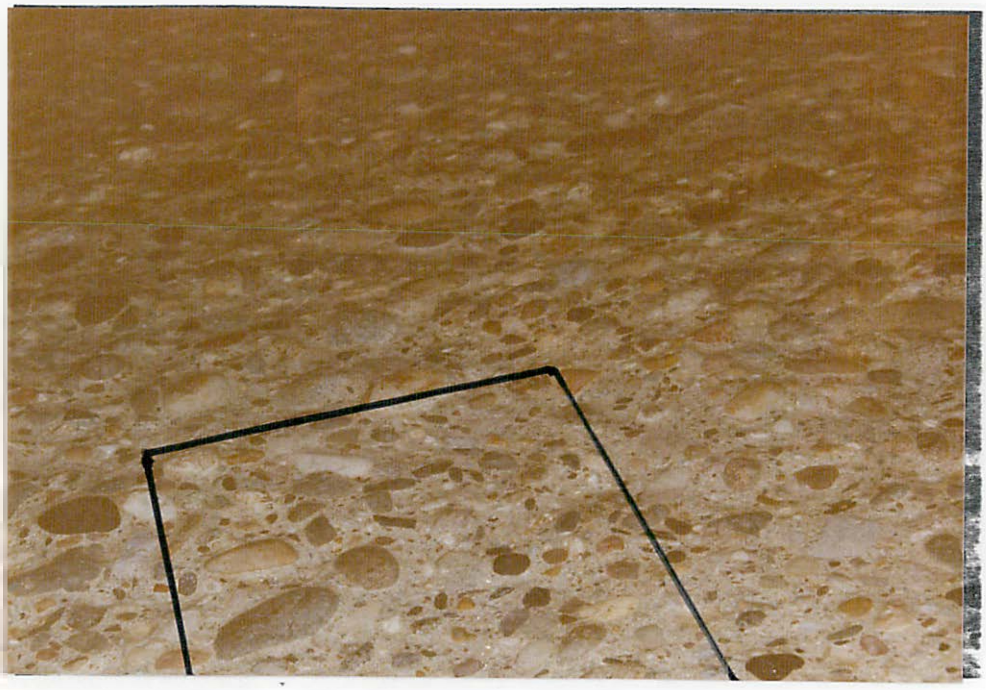
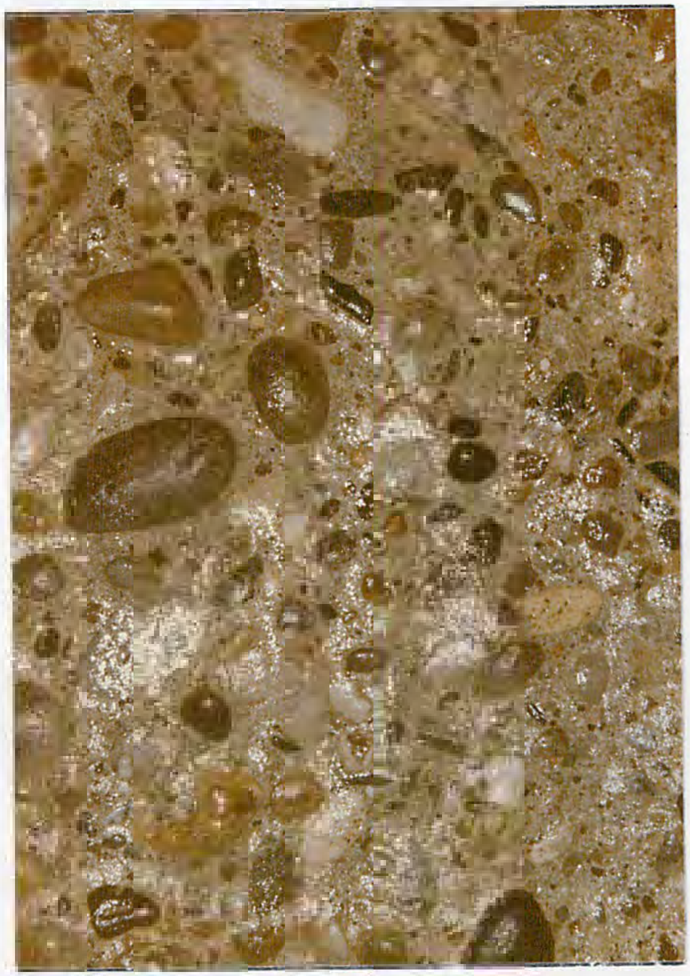



Figure 2. - Sand grain roughness versus boundary layer thickness.



a. Overall View of Invert



b. Closeup of Invert

Figure ~~5.~~ 6.1 concrete SURFACE NEAR STATION ~~32+60~~ 994.
Nevada Spillway - Hoover Dam

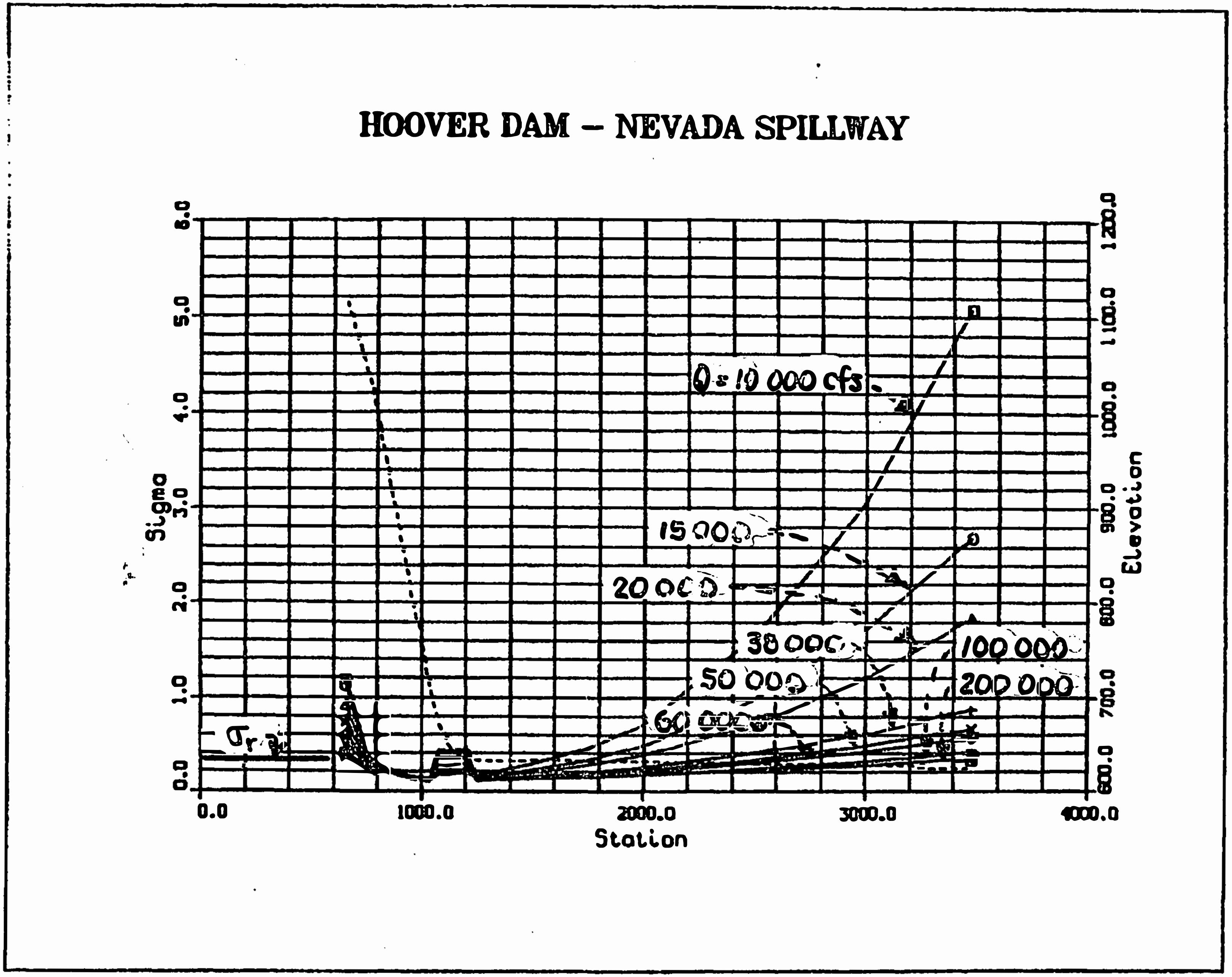



Figure 6. - Cavitation index of flow.

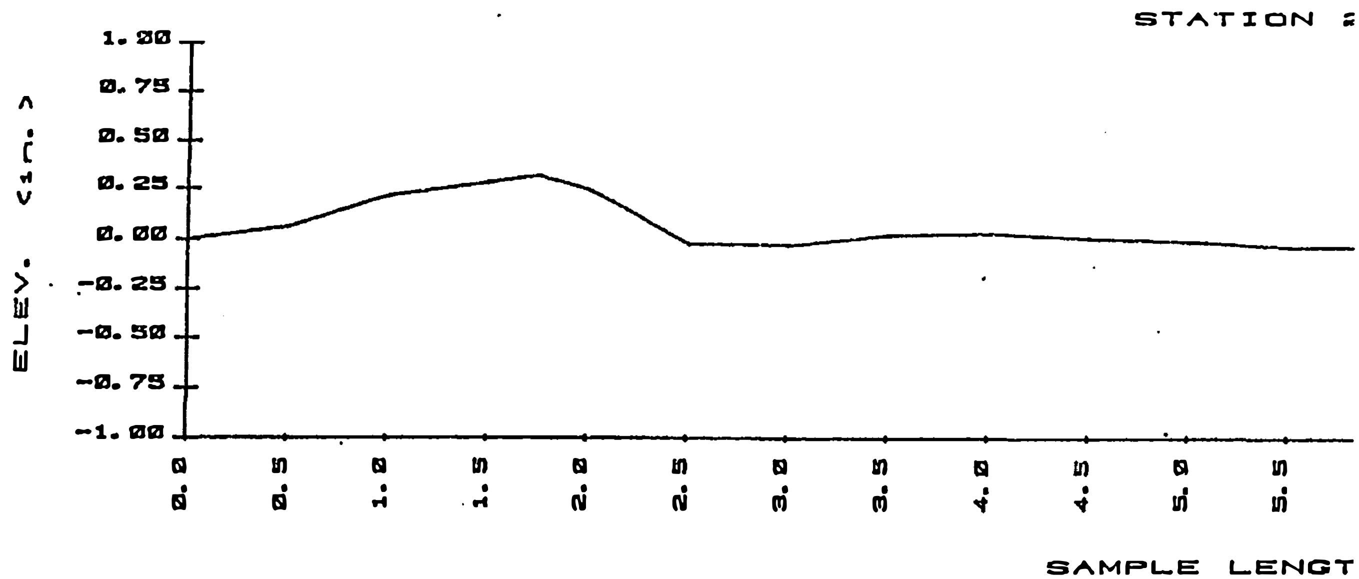
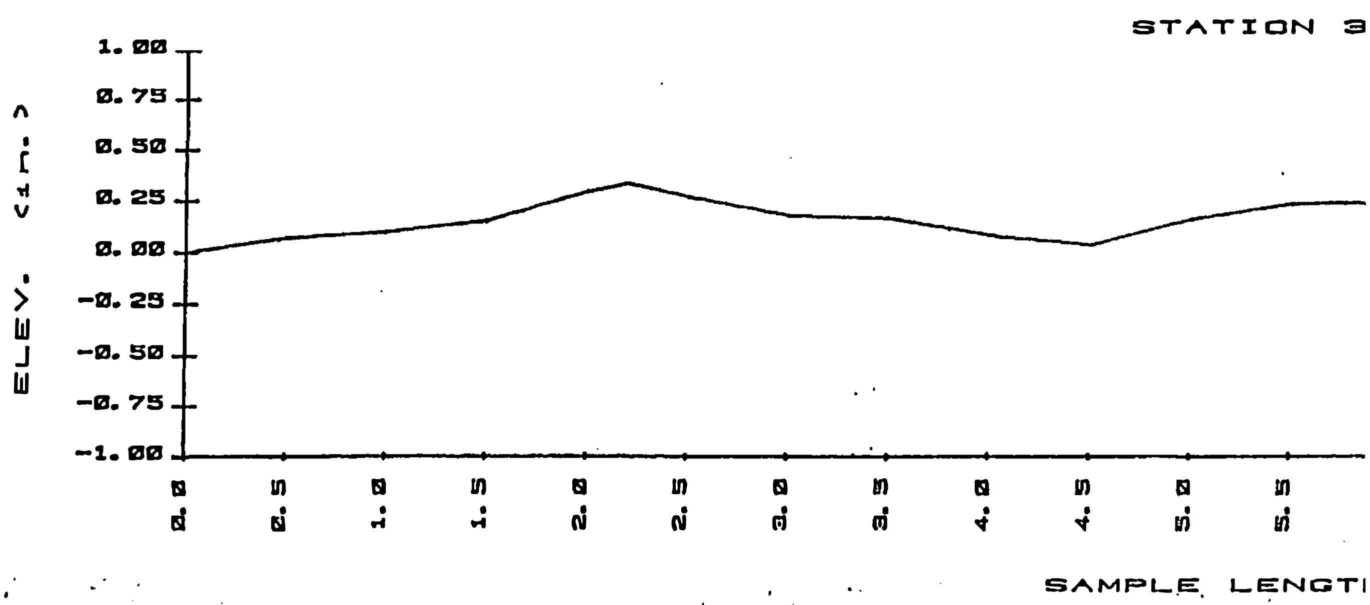



Figure 3. - Profile on centerline of pl



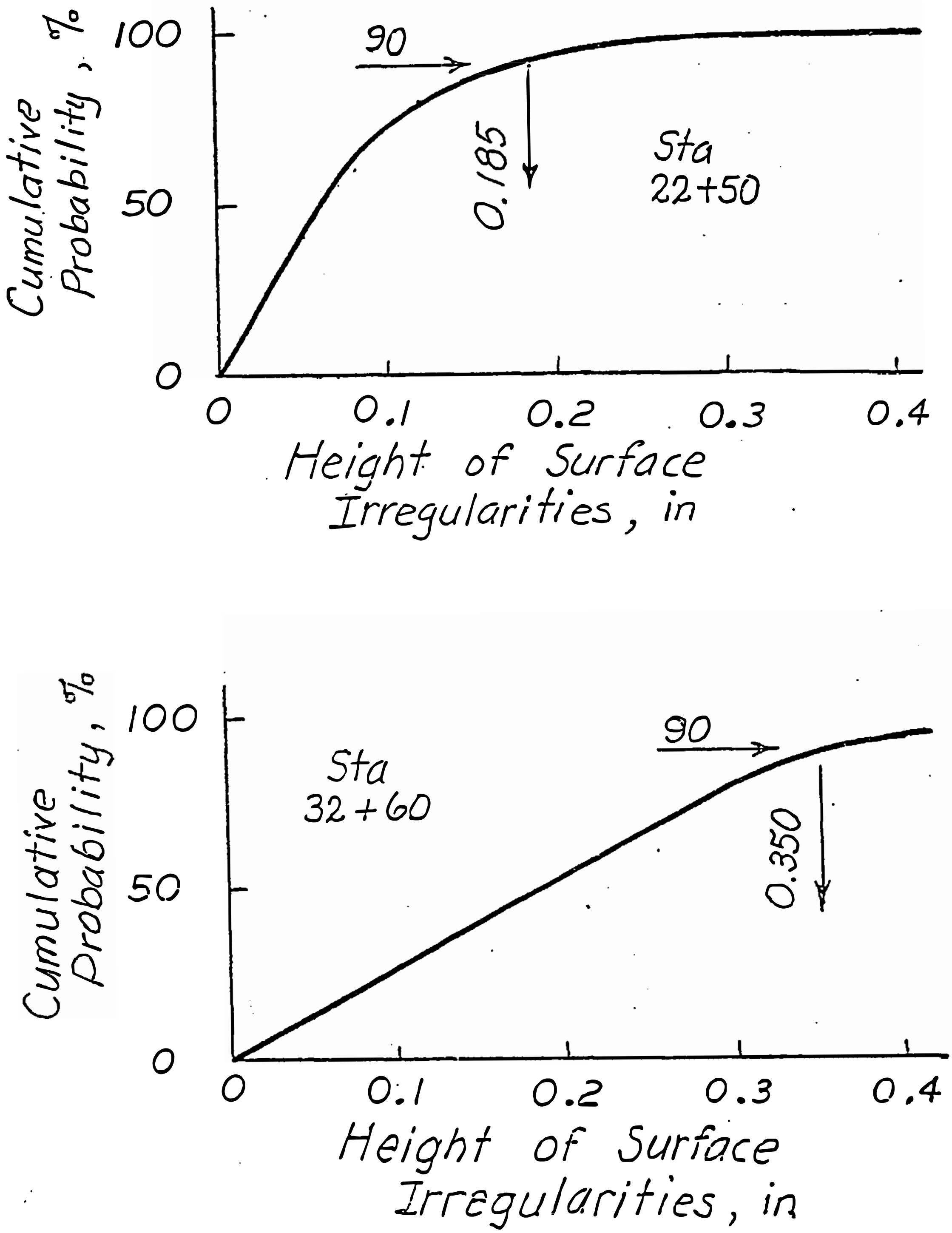



Figure 4. - Cumulative distribution of surface roughness of casts.