UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PROGRESS REPORT

AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM

Report No. Hyd-521

Hydraulics Branch
DIVISION OF RESEARCH

OFFICE OF CHIEF ENGINEER
DENVER, COLORADO

December 15, 1965

CONTENTS

CONTENTS--Continued

LIST OF SYMBOLS

v = velocity at a point (y), fps

y = perpendicular distance from the flow boundary, ft

v_* = shear velocity, fps

C = constant of integration

τ_o = boundary shear, lb/sq ft

ρ = mass density, slugs/cu ft

y' = boundary displacement (y where theoretically $v = 0$)

k_s = equivalent sand roughness (Nikuradse), ft

r = inside radius of Pitot tube, ft

n = constant, Manning's equation

P = total pressure, psf

P_o = static pressure, psf

N_R = Reynolds' number

D = pipe diameter of circular section or four times the hydraulic radius of noncircular sections

ν = kinematic viscosity, ft^2/sec

V = mean velocity, fps

y_o = y distance to point of maximum velocity, ft

g = acceleration of gravity, $ft/\overline{sec}^2$

m = value or measurement

σ = standard deviation = $\sqrt{\frac{1}{n_s} \Sigma (m - \overline{m})^2}$

n_s = number of values, measurements, or sample size

f = Darcy-Weisbach friction factor

V_c = $(100\ \sigma\ /\ \overline{m})$ = coefficient of variance

ABSTRACT

Laboratory tests evaluating the ability of velocity distribution and shear tube methods to determine Nikuradse's equivalent sand roughness as a measure of the fluid dynamic roughness of a concrete canal lining were not conclusive. A closed-conduit test duct with top and sides of transparent plastic and bottom (test surface) of wood float finished concrete used air as the fluid. Random mechanical measurements of test surface texture were made for statistical comparison of surface roughness at three measuring stations. The velocity distribution method is a direct application of the Prandtl-von Karman equation to measured vertical velocity profiles. The shear tube method is Preston's method for boundary shear determination applied to fluid pressures near test surface. Both methods indicated an increase in equivalent sand roughness as the standard deviation of mechanical measurements increased. Equivalent sand roughness values determined by velocity distribution method averaged 2.5 times greater than those determined by the shear tube method. Reason for such a discrepancy is not known, but further improvements in instrumentation and measuring techniques and more data will be needed to evaluate the two methods and to derive possible correlations between statistical parameters representing physical roughness and those representing fluid dynamic roughness.

DESCRIPTORS-- hydraulics/ *fluid friction/ roughness coefficients/ shear/ velocity distribution/ aerodynamics/ research and development/ boundary shear/ fluid flow/ Manning formula/ Reynolds number/ hydraulic similitude/ hydraulic models/ velocity/ *roughness/ concrete/ concrete finishing/ surfaces/ capacity reduction/ canals/ turbulent flow/ boundary layer/ air

IDENTIFIERS-- Prandtl-von Karman equation/ Preston technique/ fluid dynamic roughness/ shear tube method/ velocity distribution method/ conveyance capacity/ Nikuradse/ equivalent sand roughness

FOREWORD

The studies discussed in this report were performed during the period November 1960 to July 1963 under the direction of J. C. Schuster. The experiments were performed by Donald Colgate and J. M. Bergmann and the data were analyzed with the assistance of R. A. Dodge.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Office of Chief Engineer
Division of Research
Hydraulics Branch
Denver, Colorado
December 15, 1965

Hydraulics Branch Report
No. Hyd-521
Written by: J. M. Bergmann
R. A. Dodge
Checked by: J. C. Schuster
Reviewed by: A. J. Peterka
Submitted by: H. M. Martin

AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM--PROGRESS REPORT

SUMMARY AND CONCLUSIONS

The flow of fluid on a fixed boundary produces frictional or shearing forces which oppose the local relative motion. The total resisting shear force exerted by the boundary on the fluid depends on fluid properties, rate of motion, flow section geometry, and the physical roughness of the boundary surface. This investigation is primarily concerned with the laboratory determination of fluid dynamic roughness associated with concrete surfaces and aerodynamic flow. The laboratory test facility shown in Figures 1 and 2A is essentially a rectangular air duct having a top and two sides made of transparent plastic and the bottom formed of cement-sand mortar.

As part of a continuing program a series of typical concrete surface finishes will be installed and tested in the facility with the expectation of correlating the tested surfaces with surfaces encountered in the field. Thus far, two wood-floated concrete test surfaces have been prepared and aeordynamic tests and random mechanical measurements have been made of the test surface irregularities. Analyses of laboratory data indicate that the two surfaces were similar in roughness. Because the series of tests on the second surface, Figure 2B, were more complete, only these test results are discussed in this progress report.

One method used to determine the fluid dynamic roughness of the test surface, herein called the velocity distribution method, was a direct application of the Prandtl-von Karman velocity distribution equation to measured vertical velocity profiles. Nine profiles measured at each of three measuring stations near the downstream end of the test section were analyzed by this method. The roughness values k_s are listed in Column 3 of Table 1 in terms of equivalent sand grain roughness. For the farthest downstream measuring station

the values of k_s range from 7.68×10^{-3} foot to 10.3×10^{-3} foot with an average value of 8.72×10^{-3} foot. The corresponding average Manning's n value is 1.41×10^{-2}, Column 5.

The other method used to determine the fluid dynamic roughness, herein called the shear tube method, was the Preston method for boundary shear determination applied to fluid pressures measured near the test surface. Both a smaller range and magnitude of k_s were obtained by this method and are listed in Column 3 of Table 2. The range of k_s values for the downstream station is from 2.5×10^{-3} foot to 3.8×10^{-3} foot. The average k_s is 3.4×10^{-3} foot and the corresponding average Manning's n value is 1.21×10^{-2}, Column 4. Fourteen hydraulic engineers were asked to inspect the test surface and then make independent estimates of Manning's n values. The average for all of these estimates was 1.5×10^{-2}.

Both the shear tube and velocity distribution methods indicated that the equivalent sand roughness decreased as the velocity and the Reynolds number decreased. Also, both methods resulted in values of equivalent roughness tending to increase as the standard deviation increased for the random vertical linear measurements of surface irregularities.

Studies are continuing on the same concrete surface. Further improvements in instrumentation and technique, as well as more data, are necessary to evaluate the ability of velocity profile and shear tube methods of determing equivalent sand roughness of a concrete surface. Studies on other types of concrete finishes are also required in order to derive possible correlations between statistical parameters of physical roughness and equivalent sand roughness. Successful correlation between laboratory and prototype concrete surfaces in terms of either statistical parameters or by a description of concrete finishing techniques would be a worthwhile contribution to the field of hydraulic design.

INTRODUCTION

The design of canals is complex. Besides size, shape and grade, the cumulative resistive effects of minor factors such as bridge piers or structures crossing the canal, curves, inlets, outlets and checks have not been fully appraised by field or laboratory research studies. Despite this lack, experienced engineers have developed and applied design procedures that have given acceptable results for the usual canal. However, experience with large lined canals on flat slopes has clearly demonstrated deficiencies in conveyance capacity. Deficiencies of as much as 20 percent have been measured in the field.

The implications and the impact of these clearly demonstrated under-capacities led to a review and evaluation of design practices and to a program to refine methods of determing flow resistance.

The program contains the following objectives:

1. Develop explanations for the hydraulic behavior of canals known to be deficient in capacity.

2. Develop corrective hydraulic design procedures for interim use while field and laboratory investigations are conducted.

3. Pursue comprehensive field and laboratory research investigations to acquire data to provide a firm basis for refinement of design procedures.

For this program, flow resistances of canals designed to convey 700 to 13,200 cubic feet per second have been measured for flows ranging from 700 to 6,800 cubic feet per second. About 144 miles of operating canals of various sizes have been used in the tests. Also, measurement of head loss caused by different types of structures within the canal flow have been made to establish their effects in regard to the flow retardance. These field measurements definitely show that the usual small canal design techniques are unsatisfactory when applied to large lined canals on flat slopes.

The studies described in this report concern only laboratory research conducted in an air facility used to investigate two possible methods of determing fluid dynamic roughness associated with concrete surfaces.

INVESTIGATIONS

The Test Facility

The principal features of the test facilities are the rectangular air duct, three measuring stations and equipment, pressure measuring instrumentation, and the air supply and control system.

The Air Duct.--The test facility, similar to one used by H. Schlichting1/ in 1936, is a rectangular duct with top and sides made of smooth, transparent plastic and the bottom test surface formed of concrete, Figures 1 and 2A. The duct is 48 feet long and 0.3 foot deep by 1.8 feet wide in cross section. The upstream 24 feet of the duct is an approach section fabricated entirely from 1/4-inch-thick transparent plastic. To aid in developing the boundary layer, an 18-inch-wide wire screen was placed and centered on the bottom along the full length of the approach section. The fine wire screen has 18 meshes per inch transverse to the direction of flow and 14 meshes per inch in the direction of flow. The downstream 24 feet of duct was the test section; the top and sides were formed from transparent plastic and the concrete test surface was placed in the bottom, Figure 2A.

Test Surface. --For convenience and economy the 1.8- by 24-foot bottom test surface was formed of concrete in the laboratory. In preparation the three plastic sides of the air duct test section were removed and mortar was placed in a form built into the facility. The form consisted of steel screed bars along the outside edges (Figure 3) and a plywood bottom. The steel screed bars were used to support a wood float during the finishing process and to establish test surface elevation. After placing the cement-sand mortar in the form, the surface was finished by placing the wood float on the steel screed bars and gently moving it back and forth transversely to the centerline on the wet mortar surface. Care was taken to be sure that the float rested on the top of the steel screed bars. At the same time the float was moved transversely it was slowly but uniformly moved downstream. This finishing action produced the surface shown in Figures 2 and 4.

Air Supply and Control. --Air is drawn into the duct from the atmosphere through a rectangular bell-mouth inlet transition and leaves the duct through a 260-cubic-foot plenum chamber, Figure 1. A centrifugal blower with about a 3-foot-diameter impeller, driven by a constant-speed 20-horsepower motor, forces air from the plenum chamber back to the atmosphere.

The discharge through the air duct may be varied by clamping various orifice plates to the 10-inch-diameter discharge opening of the air pump. The back pressure created by the orifice restrictions regulates the flow. No attempts have been made to measure the blower discharge with the orifice plates.

Measuring Stations, Pressure Probes and Referencing. --Three measuring stations are located approximately 15, 19, and 23 feet from the upstream edge of the 24-foot-long test surface, Figure 1. On the top of each pressure station there is a plastic block for mounting the bracket used to support a point gage assembly with a linear scale and vernier, which holds a total head pitot tube instead of the usual hook or point, and a piezometer through the mounting block and top plastic surface, Figure 3. The piezometer for measuring the pressure head in the duct was a 1/32-inch hole drilled through the top of the duct in the same cross-sectional plane as the total head tube opening. The total head tube was made from 0.065-inch-outside-diameter, by 0.046-inch-inside-diameter, stainless steel tubing. The tube has a 1-1/4-inch horizontal leg in the direction of flow and a square cut tip. The right angle between the horizontal leg and the vertical stem was stiffened by a trapezoidal fillet, Figure 3. The vertical stem of the tube passed through a hole in the plastic block and top surface of the duct at the measuring station; an airtight seal was made between the duct wall and the tube stem by a rubber O-ring seal.

The positioning of the total head tube and the measuring of the distance of the openings from the test surface were done by manipulating the point gage assembly control wheel, Figure 3. The vernier gage was capable of reading to the nearest 0.001 foot.

To relate the velocity measurements and the elevation above the test surface a convenient and permanent reference elevation relative to the rough boundary was established. To do this a reference pad, approximately 1/4 inch in diameter and 1/32 inch in thickness, was cemented to the rough surface directly under the total head tube. The elevation of the pad was related to the elevation of the rough boundary of the flow surface using the equipment shown in Figure 4. The reference pad was centered within the 8-inch-diameter sampling ring. The spaced bars on top of the ring were moved until they were centered directly over the pad. A sufficient number of point gage readings were obtained over the surface of the pad to establish a firm average point gage reading for the pad. Without moving the sampling ring, point gage readings were then obtained on the test surface, randomly placing the spaced bars on the ring and randomly placing the point gage on the bars for each reading. Enough random point gage readings were obtained on the rough surface (peak or valley entirely at random) to determine a statistically meaningful average point gage reading of the test surface irregularities. The average point gage reading on the rough surface was subtracted from the average point gage reading on the pad to obtain the elevation of the pad relative to the rough surface. This relative elevation of the pad plus one-half the outside diameter of the total head tube was then subtracted from the linear gage reading when the total head tube was placed on the reference pad. With this method of "zeroing" the linear gage, the average height of the surface irregularities is defined as the plane of the effective test surface.

Pressure Transducer Instrumentation.--The velocity head at the elevation of the total head tube opening was measured as the differential pressure between the total head on the pitot tube and the piezometer head at the roof tap, Figure 3. The differential pressure was measured by one of two different bidirectional, differential pressure transducers.

The transducer that was used for measuring the velocity head when applying the velocity distribution method is a differential transformer type with an armature linked between the sensing diaphragms of two pressure chambers. The transducer has an operating pressure range of ± 0.8 pound per square inch, and was operated from a 5-volt, 2,400-cps carrier-amplifier system having a circuit for direct-current output. The accuracy of the transducer for hysteresis and nonlinearity, was specified as ± 1.5 percent full scale.

The transducer that was used when applying the shear tube method is a variable-reluctance type with a built-in transistorized carrier-demodulator. This transducer was energized with 28 volts direct current and had a 5-volt, direct-current, full-scale output for the operating range of ± 0.1 pound per square inch. The accuracy of the transducer was specified as one-half percent of full scale.

Direct-current voltages, representing the differential pressure across either of the two transducers, were fed in to a voltage-to-frequency converter. The converter has a linear 100,000-cps output for the full range of each of four input scales, namely of 0.1-, 1.0-, 10-, or 100-volt input. The frequency or pulse output of the converter, proportional to a fractional part of the 100,000 cps, was registered on an event per unit-time meter, then recorded on a digital tape printer, Figure 5.

The entire pressure measuring system was calibrated by using a double well and hook gage arrangement. The larger of the two wells was open to atmosphere and was equipped with an ordinary hook gage to measure the water surface within it. The other, or smaller well, was firmly anchored in an inverted and partially inserted position within the larger well. Another hook gage was arranged so that the shank of an elongated hook was in the larger well and the point of the elongated hook in the inverted well. When the tubing connection between inverted well and one chamber of the pressure transducer was opened to atmosphere, the water surface elevation in both wells would be the same and the verniers of the two hook gages could be related to each other by taking several readings with each. Then the inverted well was reconnected to the pressure transducer and some water was drained from the larger well. In effect, a column of water was supported by a negative pressure with respect to atmosphere and was applied to both the water surface in the inverted well and one side of the pressure transducer. This negative pressure in terms of waterhead was equal to the difference of water surface elevation between the two wells.

By this means known subatmospheric pressures were applied to one chamber of the transducer with the other chamber open to the atmosphere. The output was registered by the counting meter for several 1-second time periods. The output of the transducers was found to be linear for the differential pressure range of the tests. Thus, to measure the differential pressure across the transducer, the unit-time interval of the counting meter was adjusted or scaled to give a direct reading either in feet of water or in pounds per square foot.

Velocity Distribution Method for Obtaining Equivalent Sand Roughness

Theory.--Boundary layer theory and experimental work indicate that a Prandtl-von Karman logarithmic velocity distribution exists in fully developed turbulent flow near a fixed boundary. This velocity distribution relationship may be stated as:

$$v/v_* = 5.75 \log y + C \qquad (1)$$

The variables of equation (1) are defined in the list of symbols. If the boundary conditions of $(v = 0)$ at $(y = y')$ are substituted in equation (1), the constant of integration C may be evaluated and equation (1) then becomes:

$$v/v_* = 5.75 \log (y/y') \qquad (2)$$

Experiments of Nikuradse and others indicate that for the fully developed rough-turbulent flow regime, y' can be expressed as:

$$y' = k_s/30 \qquad (3)$$

Substituting equation (3) into equation (2) and solving for v results in:

$$v = 5.75\, v_* \log (30y/k_s) \qquad (4)$$

Since v_* is constant for one steady flow condition over a given surface and k_s is constant, equation (4) may be written as:

$$v = A \log y + B \qquad (5)$$

where:

$$A = 5.75\, v_* \qquad (6)$$

$$B = 5.75\, v_* \log (30/k_s) \qquad (7)$$

If the variables v and y are measured at two or more locations and substituted into equation (5), the constants A and B may be determined by simultaneous solution. With A and B known, k_s may be computed from equations (6) and (7).

The use of k_s directly in design formulae is rare in comparison with the use of Manning's n. Therefore to provide values for comparison, the experimentally determined k_s values were converted to Manning's n values, from a relationship presented by Ackers2/ as:

$$n = \frac{k_s^{1/6}}{32.1} \qquad (8)$$

This relationship illustrates the relative insensitivity of Manning's n as a measure of roughness compared to k_s. For example, a concrete surface may have an n value of 0.011 to 0.016. The ratio of this n range (0.016 minus 0.011) to the lower limit (0.011) is 0.45; the corresponding range of values of k_s, determined by equation (8), is 0.002 to 0.018. The corresponding ratio of the difference to the lower k_s value is 8.0. In other words the equivalent sand roughness used as a measure of fluid dynamic roughness, is nearly 18 times more sensitive than Manning's n.

Application of Velocity Distribution Method and Results.--Velocity distribution measurements were made within the test portion of the 1.8- by 0.3-foot air duct; transversely to the vertical centerline of the test section. Measurements indicated that for a distance of about 6 inches each side of the vertical centerline the total velocity decrease was about 1 percent of the centerline velocity. Therefore, the influence of the duct sides on the velocity distribution near the centerline of the air duct was considered to be small compared to the influence of the rough bottom test surface. Vertical velocity traverses were obtained by taking 10 velocity head measurements at 0.01-foot intervals between 0.05 and 0.14 foot above the test surface. Then each set of 10 velocities and corresponding elevations relative to the mean test surface elevation, was fitted to equation (5) using the method of least squares. The resulting values of the constants A and B for each set of 10 velocities, were substituted into equations (6) and (7) to determine k_s values. Manning's n was then computed from equation (8). The k_s and n values determined in this manner are listed in Table 1.

For subsequent comparison with the shear tube method, the standard deviation and coefficient of variance were computed for the nine k_s values in Table 1 determined for the downstream measuring station by the velocity distribution method. The standard deviation σ was 8.96×10^{-4} and the coefficient of variance V_c or $(100\,\sigma/\overline{k_s})$ was 10.3.

Inspection of Table 1 shows a trend at all stations for k_s and n to decrease with a decrease in velocity. Also there was a tendency for the average k_s and n to increase from the upstream to the downstream station. The implications of these trends will be considered in later sections of this report.

Shear Tube Method for Obtaining Equivalent Sand Roughness and Results

Theory.--The technique of using a pitot or total head tube to measure shear at smooth boundaries was developed by Preston3/ in 1954. Laursen4/ applied Preston's technique to shear measurements at rough boundaries. The technique used by Laursen was modified and applied to the measurement of roughness of the Bureau concrete test surfaces.

In Laursen's analysis it was assumed that (1) the pitot tube did not appreciably disturb the flow, (2) the dynamic pressure at the end of the pitot tube is an average over the open end, and (3) the Prandtl-von Karman velocity distribution defined by equation (4) is valid at the boundary. By integrating the dynamic pressure acting on the end of the pitot tube, Laursen developed the following relationship for the ratio of the dynamic pressure to shear in terms of equivalent sand roughness, k_s, distance of centerline of the pitot tube from the boundary, y, and the inside radius of the pitot tube, r.

$$\frac{P-P_o}{\tau_o} = 16.53 \left\{ \left[\log \frac{30y}{k_s}\right]^2 - \log \frac{30y}{k_s} \left[0.25\left(\frac{r}{y}\right)^2 + 0.0833\left(\frac{r}{y}\right)^4 + 0.00704\left(\frac{r}{y}\right)^6 + \ldots\right] + \left[0.25\left(\frac{r}{y}\right)^2 + 0.1146\left(\frac{r}{y}\right)^4 + 0.0586\left(\frac{r}{y}\right)^6 + \ldots\right]\right\} \quad \ldots\ldots\ldots (9)$$

Laursen's intention is to use equation (9) to determine τ_o at a surface having a known value of k_s. Since k_s is the unknown in this study, equation (9) is applied by measuring $(P-P_o)$ at two y distances above the same point on the rough surface and solving for τ_o and k_s.

Equation (9) was simplified for use in this study because the combined effects of the dimensions of pitot tube and the surface roughness caused the ratio of the inside tube radius to the distance of the centerline from the surface (r/y) to be always less than 0.7; therefore the terms in equation (9) containing (r/y) to powers of 4 or greater become insignificant and can be neglected:

$$\frac{P-P_o}{\tau_o} = 16.53 \left[\left(\log \frac{30y}{k_s}\right)^2 + 0.25\left(\frac{r}{y}\right)^2 \left(1 - \log \frac{30y}{k_s}\right)\right] \ldots\ldots (9a)$$

Application of Shear Tube Method and Results.--Values of equivalent sand roughness k_s determined by the shear tube method at each measurement station in the test facility are listed in Column 3 of Table 2. These 18 values of k_s were obtained as follows. For each k_s value determination, a series of nine differential pressures $(P-P_o)$ were measured at 0.001-foot vertical increments starting at y equal to 0.007 foot and these series of values were used to compute sets of nine values of boundary shear τ_o by equation (9a) i.e., a set of nine for each of several assumed k_s values. Since there can be only one value of shear on the boundary for a given flow condition, the nine values of τ_o in each set should be the same regardless of the distance from the boundary at which each of the nine pressure differentials $(P-P_o)$ was measured. However, there was a variance in τ_o within each set of nine because of limitations in testing and instrumentation techniques, and the value of k_s assumed. The variance of each set of the nine τ_o values was expressed as the average-absolute deviation $\left(\frac{1}{9}\sum_{i=1}^{9}\left|\bar{\tau}_o - \tau_o\right|\right)$. These average-absolute deviations and their corresponding assumed k_s values were plotted as in the example, Figure 6. In the graphs shown in Figure 6 the k_s values corresponding to the minimum average-absolute deviations were the most probable solutions of equation (9a) and are listed in Column 3 of Table 2.

For subsequent comparison with the velocity distribution method, the 12 (k_s) values for the downstream station shown in Table 2 were used to compute standard deviation and coefficient of variance values. The standard deviation σ was 3.7×10^{-4} and the coefficient of variance or $(100\ \sigma/\bar{k}_s)$ was 10.9.

Inspection of Table 2 shows a tendency for the k_s values to decrease with decreasing velocity. The highest value was obtained for the downstream station, while the lowest was for the middle station. The implications of these trends will be considered in later sections of this report.

Random Mechanical Measurements of Physical Roughness.--Hamma5/ and others have stated that there is no known relationship between the mechanical measurements of a surface's physical roughness and the surface's fluid dynamic roughness. However, to compare the physical roughness of the test surface at the three measuring stations, the data used to reference the elevation of the total head tube to the plane of the effective test surface were used to compute the standard deviation σ of the test surface irregularities.

Table 3 shows a comparison of surface roughness or σ determined by direct physical measurement, the k_s determined by the velocity distribution method, and k_s roughness determined by the shear tube method. Inspection of Table 3 shows that the values of equivalent sand roughness determined by the shear tube method for the three measuring stations in the test section progressively increased in a downstream direction, just as the statistical analyses of the physical roughness indicated they should vary. The values from the velocity distributions method also showed an increase from the upstream to downstream station but the lowest value was for the middle station. The implications of these trends will be discussed in a later section of this report.

DISCUSSION OF THE INVESTIGATIONS

Theoretical Considerations

Prandtl-von Karman Velocity Distribution. --The methods in this study were proposed and used because they could be related to the Prandtl-von Karman velocity distribution equation. The form of this equation is generally accepted by boundary layer theorists although they do not agree on the exact value of the constants in the equation. Assumptions made in this study, which are basic to the validity of the Prandtl-von Karman equation, were that the flow at the measuring stations was characterized as rough-turbulent and the boundary layer was completely developed.

Flow Regime. --To verify existence of rough-turbulent flow, various combinations of linear dimensions and velocities were used to compute the Reynolds Number N_R which can be used as an indicator. For a circular pipe N_R is expressed as:

$$N_R = \frac{DV}{\nu} \qquad (10)$$

where:

- D = pipe diameter or four times the hydraulic radius of the section
- V = mean velocity
- ν = kinematic viscosity

If the distance from the test surface to the point of maximum velocity, y_o on Figure 7, is considered the radius of an equivalent circular section and since Rouse6/ states that the mean velocity occurs at a point ($0\ 22\ y_o$) from the boundary, a Reynolds number may be computed that is based only on the measured profile. The distance of the maximum velocity from the test surface was found to be about 0.19 foot. The mean velocities or velocities at $0.22\ y_o$) range from 60 to 90 fps (feet per second). The mean kinematic viscosity of the air was 1.9×10^{-4}. Using the lower velocity of 60 fps results in the minimum value of N_R of 120,000 which indicates turbulent flow but not necessarily fully rough.

Another logical method of computing N_R is to consider y_o as the hydraulic radius and/or depth of an infinitely wide open channel. Mean velocity for open channel flow would occur at about $(0.4\ y_o)$ from the boundary and the mean velocity range would be from 70 to 100 fps. Again, using the lower velocity, the previously mentioned kinematic viscosity and $(4\ y_o)$ as the diameter of the equivalent circular section, N_R is computed to be about 280,000 which indicates turbulent flow but, again, not necessarily fully rough.

Minimum values of k_s required for rough flow regime were computed based on the above N_R values. Rouse7/ gives the following equations as the lower limit of rough-turbulent flow:

$$1/\sqrt{f} = 2 \log \frac{D}{k_s} + 1.14 \quad \text{.......} \quad (11)$$

$$\frac{N_R \sqrt{f}}{D/k_s} = 200 \quad \text{.......} \quad (12)$$

solving for N_R results in:

$$N_R = 400\ D/k_s \log (3.7\ D/k_s) \quad \text{.......} \quad (13)$$

where again, D is the diameter of a circular section and is equal to four times the hydraulic radius of noncircular sections. For N_R values of 5×10^4 to 5×10^5, equation 13 is approximated by a simpler form:

$$N_R = 450\ (D/k_s)^{1.18} \quad \text{.......} \quad (13a)$$

or rearranging equation (13a),

$$D/k_s = 0.0056\ N_R^{0.85} \quad \text{.......} \quad (13b)$$

Considering y_o as the radius of an equivalent circular section of diameter D and using the minimum N_R value of 1.2×10^5, the minimum value of k_s for rough-turbulent flow is computed to be 0.0033 foot. Considering y_o, the depth in very wide channel where D is replaced by ($4 y_o$) and using the minimum N_R value of 2.8×10^5, the minimum k_s is computed to be 0.0032 foot. Comparing these computed minimum values of k_s for rough-turbulent flow regime with those determined by the shear tube method, Table 2, only the surface at the downstream station is sufficiently rough to satisfy the Rouse criteria as expressed by k_s in equation (13). The values of k_s by the velocity distribution method, Table 1, indicate that the surface at all three stations can be considered in the rough-turbulent flow regime based on the Rouse criteria.

However, at the upstream and downstream stations for both test methods there is a variance of k_s with respect to the Reynolds number of the flow. The maximum values of N_R occurred during the tests with the 10-inch throat flow and the k_s values were the largest. The minimum values of N_R occurred during the tests with the smallest orifice control and the k_s values were the lowest. The fact that the k_s values when determined by the tests vary with the Reynolds number makes the existence of a complete rough-turbulent flow regime in the test section of the duct more doubtful.

Boundary Layer Development.--For smooth circular pipe, 50 diameters is usually considered a sufficient length for completely developing the boundary layer. In this study, 50 effective diameters is probably sufficient since the boundary layer would develop in a shorter distance on the rough boundary. To verify that the boundary layer was or was not fully developed, the length of duct required for development can be calculated.

As in the Reynolds number computations, the distance y_o will first be considered the radius of an equivalent circular section and, secondly, as the depth in an infinitely wide channel. In the first case the required air duct length for complete boundary layer development is 19 feet and in the second case, the length is 38 feet. The first, or upstream, pressure measuring station in the test section is preceded by 24 feet of calming section with wire screening placed on the bottom plus 15 feet of concrete. The total 39-foot length exceeds both of the computed lengths of duct required for boundary layer development. However, the hydraulic roughness of screen in the approach section may not truly represent the concrete roughness and may be insufficient to fully develop a boundary layer at any of the pressure measuring stations.

Comparison of Test Methods

The velocity distribution method and the shear tube method produced considerably different k_s values. The k_s values measured by the velocity distribution method averaged about 2.5 times greater than those by the shear tube method. There may be many mechanical reasons for this difference, but there is a question whether or not the Prandtl-von Karman equation can be applied to either method. In no case could the velocity distribution curves obtained in this test be approximated with a single equation of logarithmic form. The straightest portion of the curve, as plotted on semilog paper, was consistently between values of y equaling 0.05 to 0.14 foot above the test surface. This part of the curve was used for the velocity distribution method of determining k_s. The velocity distribution deviated from semilog straight lines for values of y less than 0.05 foot and greater than 0.14 foot.

The shear tube method is more sensitive to experimental errors than the velocity distribution method. These sources of error may be expressed as follows: (1) the relative accuracy in the y-distance measurement when close to the test surface for the shear tube method compared to the larger y distances used for the velocity distribution method, (2) the errors in not accounting for proximity effects of the pitot tube with respect to the boundary, and (3) the possible error in assuming that the effective fluid boundary is the average height of the roughness.

The shear tube method is more sensitive to errors associated with measurement of pressure because of the relatively smaller pressures compared to the greater pressures measured during the application of the velocity method. The magnitude of the pressures measured for the velocity method were two to three times greater than for the shear tube method. Based on specifications, the accuracy of the pressure transducers varied from 3 to 10 percent. However, much greater precision was attained by careful calibration of the transducers in the laboratory and making sure the cells were being used in a linear range of pressures. To minimize the effect of zero drift, the cells were checked for zero before and after each pressure measurement.

Both the velocity distribution and the shear tube methods resulted in k_s values that tended to vary in the same sense and order that standard deviations of the physical roughness measurements varied, Table 3. Despite the apparent relationship between physical and fluid roughness, correlation should not be inferred until instrumentation has been further improved and more data have been obtained on the same concrete surface and on other concrete surfaces finished by the other possible techniques.

REFERENCES

1. H. Schlichting, Experimentelle Untersuchurgen zum Rauhigkeitsproblem. Ing. Arch., 7, 1 (1936), Eng Trans by V. L. Streeter

2. P. Ackers, Resistance of Fluids Flowing in Channels and Pipes, Hydraulic Research Paper No. 1, Department of Scientific and Industrial Research, Hydraulics Research Station, Howbery Park, Wallingford, Berks, England

3. J. Preston, The Determination of Turbulent Skin Friction by Means of Pitot Tubes, Journal of the Royal Aeronautical Society, Vol 58, February 1954, p 109

4. E. Laursen and Li-San Hwang, Extension of Preston's Shear Measurement Technique to Rough Boundaries, Technical Report No. 1, NSF G-7409, National Science Foundation, Washington, D. C.

5. F. Hama, Boundary-layer Characteristics for Smooth and Rough Surfaces, Trans. SNAME, Vol 62, 1964

6. H. Rouse, Elementary Mechanics of Fluids, 1946, John Wiley and Sons, Inc.

7. Proceedings of the Second Hydraulic Conference, University of Iowa, 1942, H. Rouse, Engineering Hydraulics, 1949, John Wiley and Sons, Inc., p 405.

Table 1

VELOCITY DISTRIBUTION TEST RESULTS

(1) Station	(2) Blower discharge flow restriction	$k_s \times 10^3$* (3) Each	$k_s \times 10^3$* (4) Avg	(5) $n \times 10^2$**
Upstream or Station I (Figure 1) 39 feet from entrance	10-inch throat	9.33		1.43
		7.52	7.57	1.38
		5.85		1.32
	9-inch orifice	6.81		1.35
		5.07	6.23	1.29
		6.80		1.35
	7-inch orifice	6.06		1.33
		3.46	5.18	1.21
		6.01		1.31
	Avg	6.32		1.34
Middle or Station II 43 feet from entrance	10-inch throat	6.45		1.35
		8.08	7.21	1.40
		7.09		1.36
	9-inch orifice	6.60		1.35
		8.21	7.23	1.40
		6.89		1.36
	7-inch orifice	3.39		1.20
		9.28	6.56	1.43
		7.03		1.36
	Avg	7.00		1.36
Downstream or Station III 47 feet from entrance	10-inch throat	10.26		1.45
		9.15	9.81	1.42
		10.02		1.45
	9-inch orifice	8.28		1.40
		9.06	8.38	1.42
		7.81		1.39
	7-inch orifice	8.25		1.40
		7.68	7.97	1.38
		7.99		1.39
	Avg	8.72		1.41

*k_s = Nikuradse equivalent sand roughness (ft.)

**n = Manning's coefficient = $\frac{k_s^{1/6}}{32.1}$

Table 2

SHEAR TUBE TEST RESULTS

(1) Station	(2) Blower discharge flow restriction	(3) $k_s \times 10^3$*	(4) $n \times 10^2$**
Upstream or Station I (Figure 1) 39 feet from entrance	10-inch throat	1.9	
	9-inch orifice	2.4	
	7-inch orifice	1.5	
	Avg	1.9	1.09
Middle or Station II 43 feet from entrance	10-inch throat	0.8	
	9-inch orifice	0.9	
	7-inch orifice	1.1	
		0.9	0.97
Downstream or Station III 47 feet from entrance	10-inch throat	3.7	
	9-inch orifice	3.4	
	7-inch orifice	2.5	
		3.2	1.20
	10-inch throat	3.8	
		3.5	
		3.5	
		3.6	
	***9-inch orifice	3.7	
		3.7	
		3.2	
	Avg	3.5	
	7-inch orifice	3.7	
		3.5	
		2.9	
	Avg	3.4	
	Total average for Station III	3.4	1.21

*k_s = Nikuradse equivalent sand roughness (ft.)

**n = Manning's coefficient = $\frac{k_s^{1/6}}{32.1}$.

***These values of k_s determined from Figure 6.

Table 3

STANDARD DEVIATION OF RANDOM MECHANICAL SURFACE MEASUREMENTS AND CORRESPONDING EQUIVALENT SAND ROUGHNESS

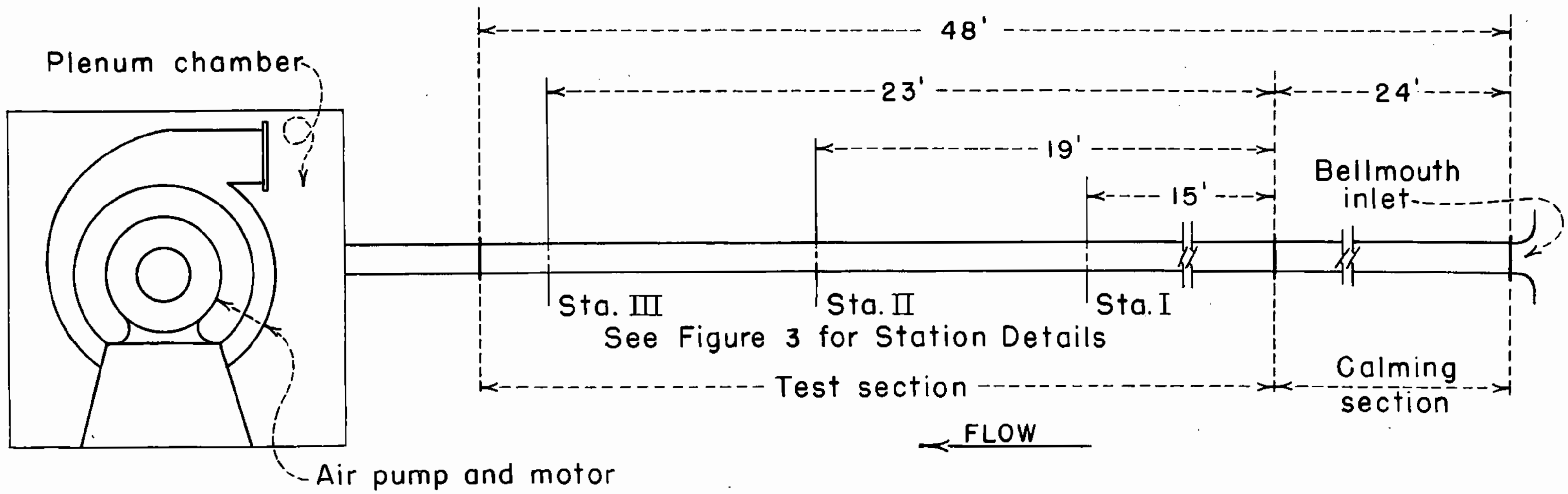
①	②	$k_s \times 10^3$**	
Station	$\sigma \times 10^3$* physical roughness	③ By velocity profile	④ By shear tube
Upstream (I)	0.94	6.32	1.9
Middle (II)	0.89	7.00	0.9
Downstream (III)	1.15	8.72	3.4

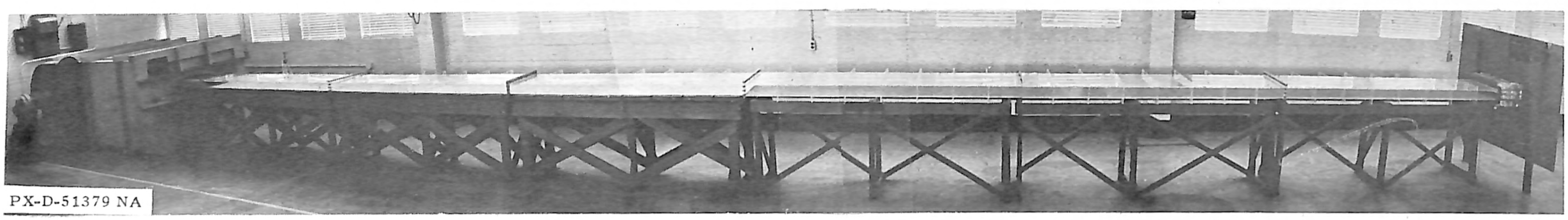
$$* \ \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (m - \overline{m})^2}$$

m = random vertical measurement from datum to surface in vicinity of station (ft).

**k_s = Nikuradse equivalent sand roughness (ft).

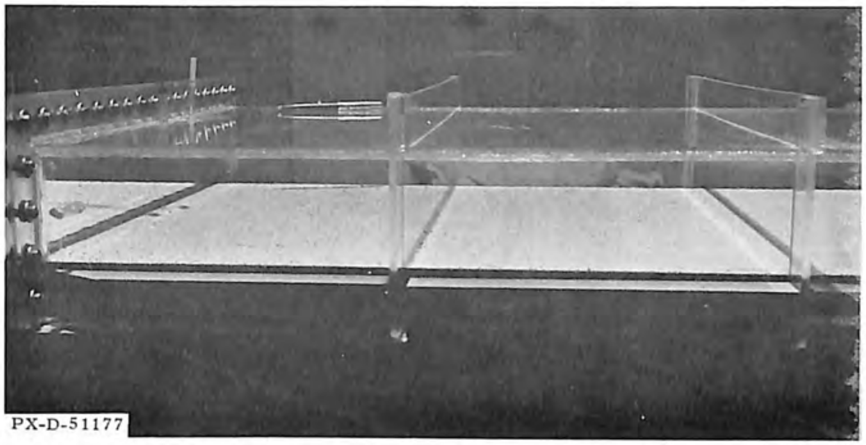
624





CONCRETE ROUGHNESS STUDY
AIR TEST FACILITY

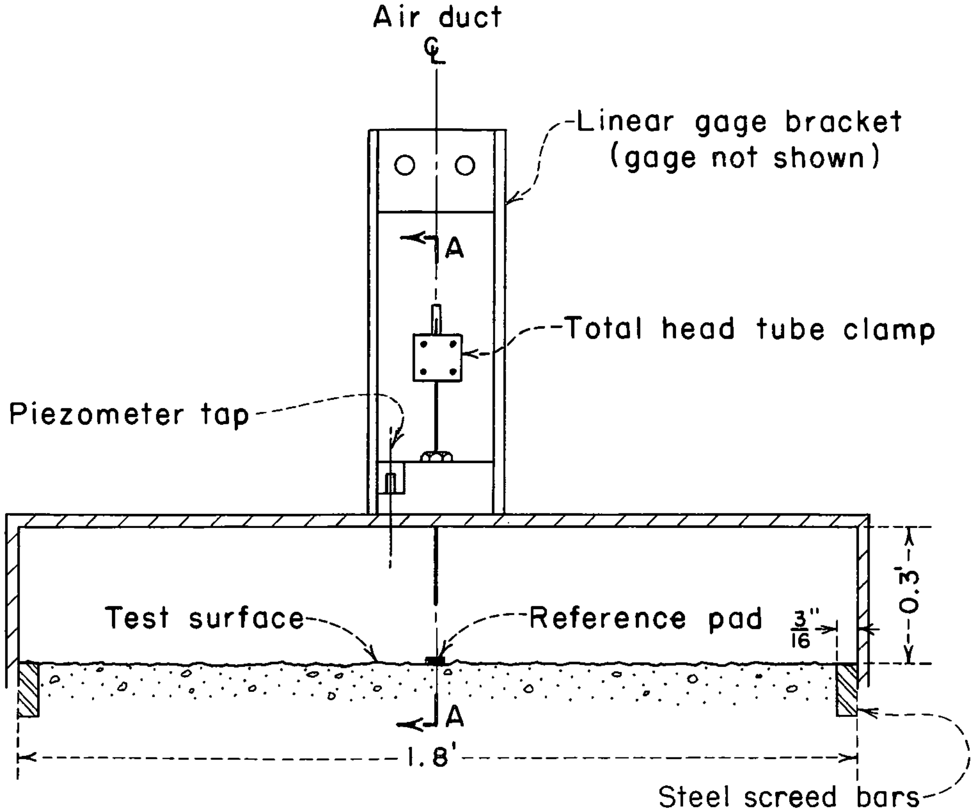
FIGURE 1
REPORT HYD-521

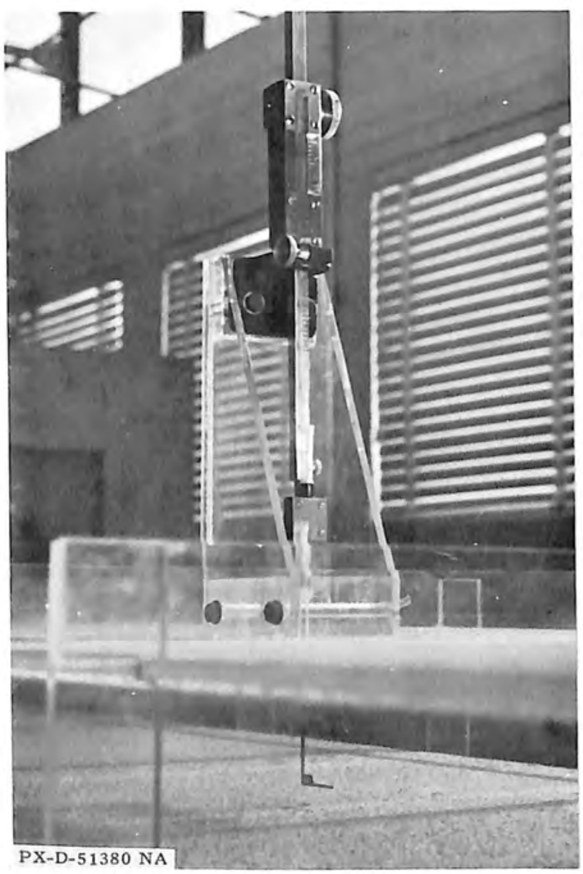


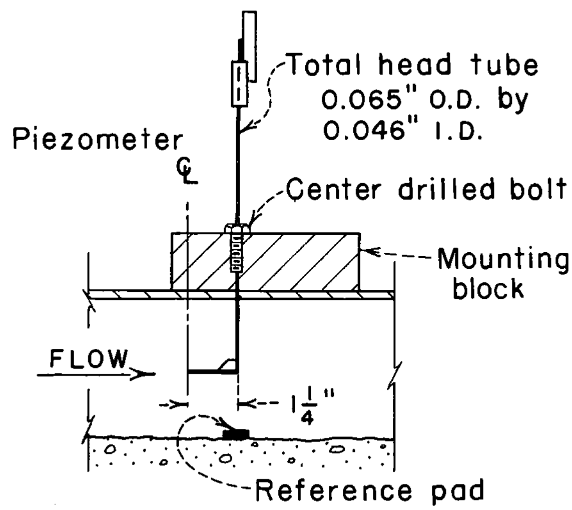
A. Closeup view of the air duct

B. Texture of concrete test surface

Concrete Roughness Studies
AIR DUCT AND TEST SURFACE



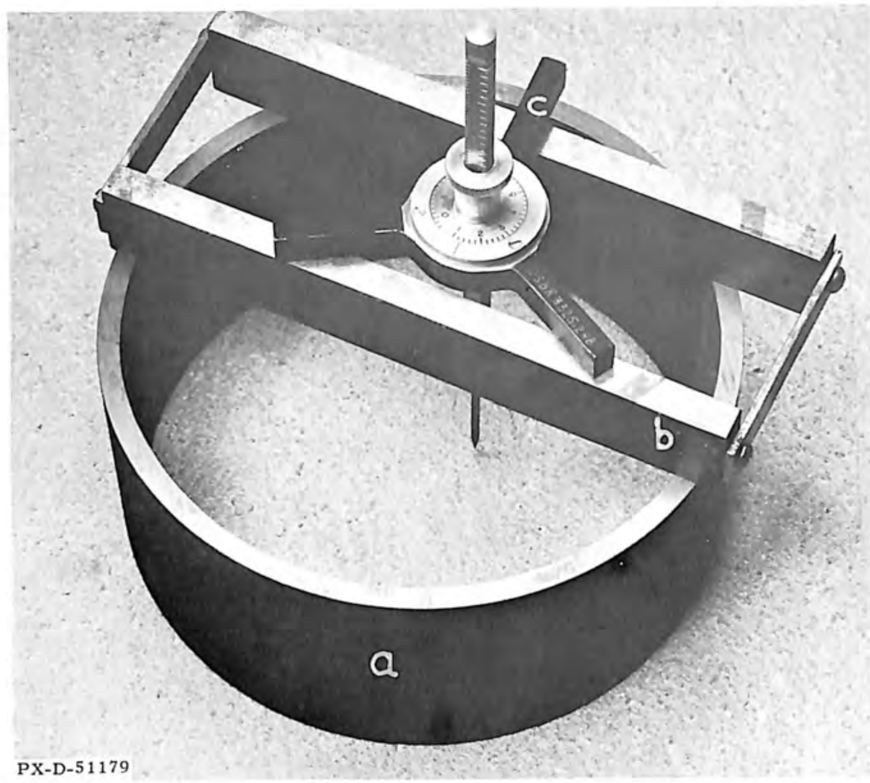




SECTION A-A

CONCRETE ROUGHNESS STUDY

PRESSURE
MEASUREMENT STATION



(a) Sampling ring
(b) Spaced bars
(c) Point gage

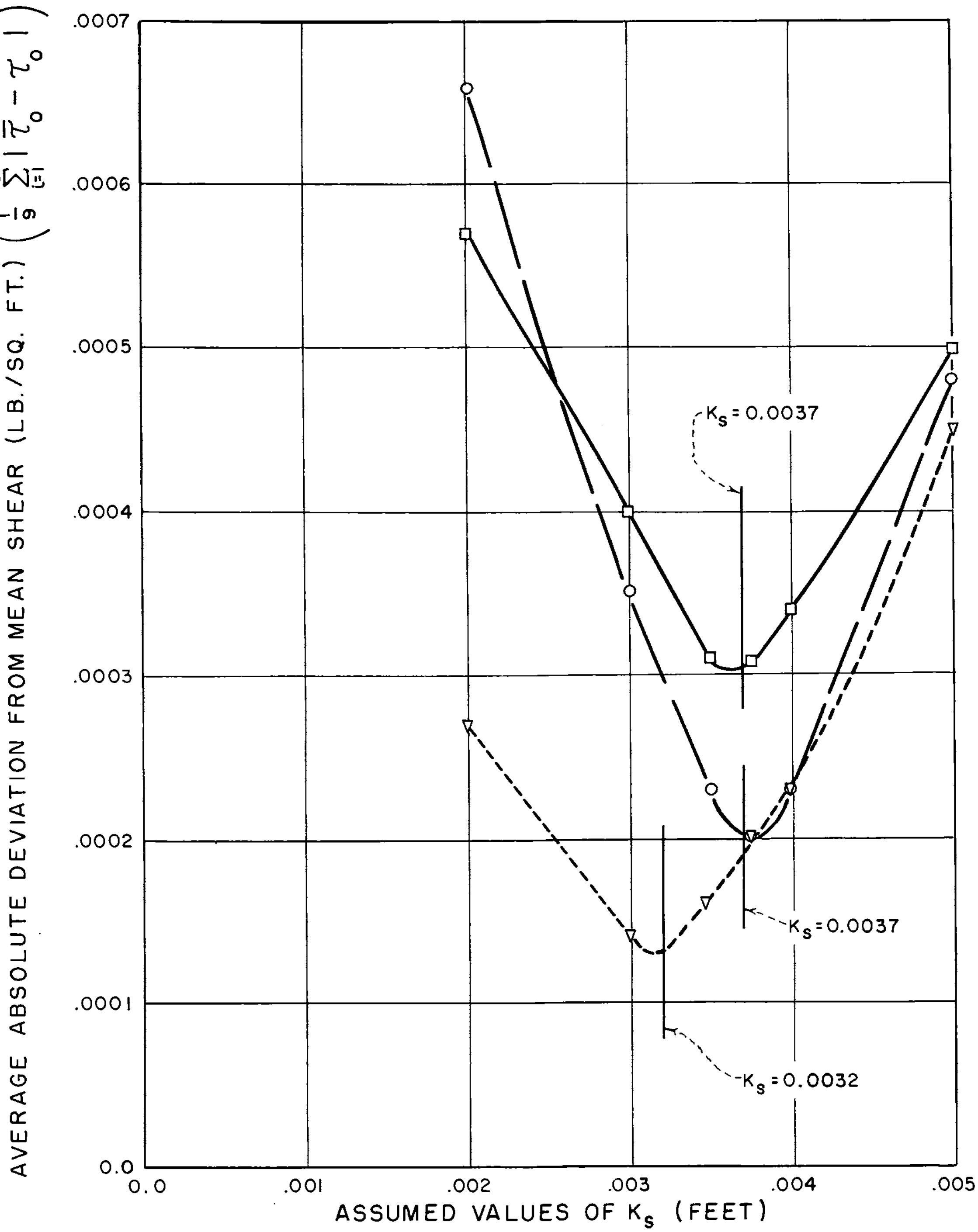
Concrete Roughness Study
DEVICE USED FOR RANDOM MECHANICAL
MEASUREMENTS OF SURFACE ROUGHNESS

PX-D-51180

(a) Insulated box for transducer
(b) Power source
(c) Voltage to frequency converter
(d) Event per unit-time meter
(e) Total head tube mounting

Concrete Roughness Study
INSTRUMENTATION USED FOR OBTAINING
PRESSURE MEASUREMENTS

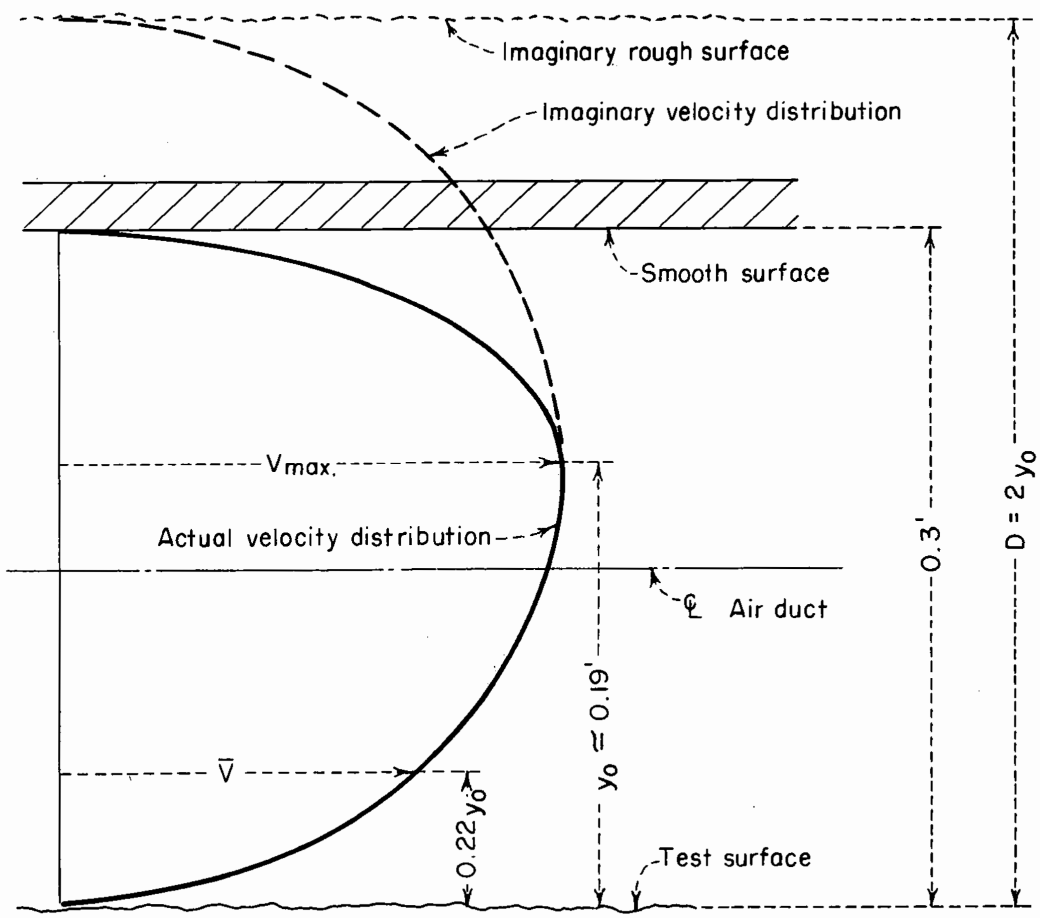
FIGURE 6
REPORT HYD-521



NOTE: (τ_o) computed from equation (9a) for station III and with 9 inch orifice restriction. (See table 2)

CONCRETE ROUGHNESS STUDY

TYPICAL CURVES USED TO DETERMINE MOST PROBABLE (K_s) VALUES BY THE SHEAR TUBE METHOD



CONCRETE ROUGHNESS STUDY

VELOCITY DISTRIBUTION

GPO 854-471

7-1750
(10-64)

CONVERSION FACTORS--BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, January 1964) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given on pages 10-11 of the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg; that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Table 1

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
	0.3048 (exactly)*	Meters
	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	929.03 (exactly)*	Square centimeters
	0.092903 (exactly)	Square meters
Square yards	0.836127	Square meters
Acres	0.40469*	Hectares
	4,046.9*	Square meters
	0.0040469*	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
	0.473166	Liters
Quarts (U.S.)	9,463.58	Cubic centimeters
	0.946358	Liters
Gallons (U.S.)	3,785.43*	Cubic centimeters
	3.78543	Cubic decimeters
	3.78533	Liters
	0.00378543*	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	764.55*	Liters
Acre-feet	1,233.5*	Cubic meters
	1,233,500*	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
	0.3048 (exactly)*	Meters per second
Feet per year	0.965873×10^{-6}*	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	0.3048*	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	0.028317*	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	0.453592*	Kilograms
	4.4482*	Newtons
	4.4482×10^{-5}*	Dynes
WORK AND ENERGY*		
British thermal units (Btu)	0.252*	Kilogram calories
	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	1.35582*	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 deg F (k, thermal conductivity)	1.442	Milliwatts/cm deg C
	0.1240	Kg cal/hr m deg C
Btu ft/hr ft^2 deg F	1.4880*	Kg cal m/hr m^2 deg C
Btu/hr ft^2 deg F (C, thermal conductance)	0.568	Milliwatts/cm^2 deg C
	4.882	Kg cal/hr m^2 deg C
Deg F hr ft^2/Btu (R, thermal resistance)	1.761	Deg C cm^2/milliwatt
Btu/lb deg F (c, heat capacity)	4.1868	J/g deg C
Btu/lb deg F	1.000*	Cal/gram deg C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
	0.09290*	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	304.8*	Liters per square meter per day
Pound-seconds per square foot (viscosity)	4.8824*	Kilogram second per square meter
Square feet per second (viscosity)	0.02903* (exactly)	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	35.3147*	Millicuries per cubic meter
Milliamps per square foot	10.7639*	Milliamps per square meter
Gallons per square yard	4.527219*	Liters per square meter
Pounds per inch	0.17858*	Kilograms per centimeter

ABSTRACT

Laboratory tests evaluating the ability of velocity distribution and shear tube methods to determine Nikuradse's equivalent sand roughness as a measure of the fluid dynamic roughness of a concrete canal lining were not conclusive. A closed-conduit test duct with top and sides of transparent plastic and bottom (test surface) of wood float finished concrete used air as the fluid. Random mechanical measurements of test surface texture were made for statistical comparison of surface roughness at three measuring stations. The velocity distribution method is a direct application of the Prandtl-von Karman equation to measured vertical velocity profiles. The shear tube method is Preston's method for boundary shear determination applied to fluid pressures near test surface. Both methods indicated an increase in equivalent sand roughness as the standard deviation of mechanical measurements increased. Equivalent sand roughness values determined by velocity distribution method averaged 2.5 times greater than those determined by the shear tube method. Reason for such a discrepancy is not known, but further improvements in instrumentation and measuring techniques and more data will be needed to evaluate the two methods and to derive possible correlations between statistical parameters representing physical roughness and those representing fluid dynamic roughness.

ABSTRACT

Laboratory tests evaluating the ability of velocity distribution and shear tube methods to determine Nikuradse's equivalent sand roughness as a measure of the fluid dynamic roughness of a concrete canal lining were not conclusive. A closed-conduit test duct with top and sides of transparent plastic and bottom (test surface) of wood float finished concrete used air as the fluid. Random mechanical measurements of test surface texture were made for statistical comparison of surface roughness at three measuring stations. The velocity distribution method is a direct application of the Prandtl-von Karman equation to measured vertical velocity profiles. The shear tube method is Preston's method for boundary shear determination applied to fluid pressures near test surface. Both methods indicated an increase in equivalent sand roughness as the standard deviation of mechanical measurements increased. Equivalent sand roughness values determined by velocity distribution method averaged 2.5 times greater than those determined by the shear tube method. Reason for such a discrepancy is not known, but further improvements in instrumentation and measuring techniques and more data will be needed to evaluate the two methods and to derive possible correlations between statistical parameters representing physical roughness and those representing fluid dynamic roughness.

ABSTRACT

Laboratory tests evaluating the ability of velocity distribution and shear tube methods to determine Nikuradse's equivalent sand roughness as a measure of the fluid dynamic roughness of a concrete canal lining were not conclusive. A closed-conduit test duct with top and sides of transparent plastic and bottom (test surface) of wood float finished concrete used air as the fluid. Random mechanical measurements of test surface texture were made for statistical comparison of surface roughness at three measuring stations. The velocity distribution method is a direct application of the Prandtl-von Karman equation to measured vertical velocity profiles. The shear tube method is Preston's method for boundary shear determination applied to fluid pressures near test surface. Both methods indicated an increase in equivalent sand roughness as the standard deviation of mechanical measurements increased. Equivalent sand roughness values determined by velocity distribution method averaged 2.5 times greater than those determined by the shear tube method. Reason for such a discrepancy is not known, but further improvements in instrumentation and measuring techniques and more data will be needed to evaluate the two methods and to derive possible correlations between statistical parameters representing physical roughness and those representing fluid dynamic roughness.

ABSTRACT

Laboratory tests evaluating the ability of velocity distribution and shear tube methods to determine Nikuradse's equivalent sand roughness as a measure of the fluid dynamic roughness of a concrete canal lining were not conclusive. A closed-conduit test duct with top and sides of transparent plastic and bottom (test surface) of wood float finished concrete used air as the fluid. Random mechanical measurements of test surface texture were made for statistical comparison of surface roughness at three measuring stations. The velocity distribution method is a direct application of the Prandtl-von Karman equation to measured vertical velocity profiles. The shear tube method is Preston's method for boundary shear determination applied to fluid pressures near test surface. Both methods indicated an increase in equivalent sand roughness as the standard deviation of mechanical measurements increased. Equivalent sand roughness values determined by velocity distribution method averaged 2.5 times greater than those determined by the shear tube method. Reason for such a discrepancy is not known, but further improvements in instrumentation and measuring techniques and more data will be needed to evaluate the two methods and to derive possible correlations between statistical parameters representing physical roughness and those representing fluid dynamic roughness.

Hyd-521
AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM--PROGRESS REPORT
Bureau of Reclamation, Denver, 18 p, including 7 fig, 4 tab, 7 ref, 1965

DESCRIPTORS-- hydraulics/ *fluid friction/ roughness coefficients/ shear/ velocity distribution/ aerodynamics/ research and development/ boundary shear/ fluid flow/ Manning formula/ Reynolds number/ hydraulic similitude/ hydraulic models/ velocity/ *roughness/ concrete/ concrete finishing/ surfaces/ capacity reduction/ canals/ turbulent flow/ boundary layer/ air
IDENTIFIERS-- Prandtl-von Karman equation/ Preston technique/ fluid dynamic roughness/ shear tube method/ velocity distribution method/ conveyance capacity/ Nikuradse/ equivalent sand roughness

Hyd-521
AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM--PROGRESS REPORT
Bureau of Reclamation, Denver, 18 p, including 7 fig, 4 tab, 7 ref, 1965

DESCRIPTORS-- hydraulics/ *fluid friction/ roughness coefficients/ shear/ velocity distribution/ aerodynamics/ research and development/ boundary shear/ fluid flow/ Manning formula/ Reynolds number/ hydraulic similitude/ hydraulic models/ velocity/ *roughness/ concrete/ concrete finishing/ surfaces/ capacity reduction/ canals/ turbulent flow/ boundary layer/ air
IDENTIFIERS-- Prandtl-von Karman equation/ Preston technique/ fluid dynamic roughness/ shear tube method/ velocity distribution method/ conveyance capacity/ Nikuradse/ equivalent sand roughness

Hyd-521
AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM--PROGRESS REPORT
Bureau of Reclamation, Denver, 18 p, including 7 fig, 4 tab, 7 ref, 1965

DESCRIPTORS-- hydraulics/ *fluid friction/ roughness coefficients/ shear/ velocity distribution/ aerodynamics/ research and development/ boundary shear/ fluid flow/ Manning formula/ Reynolds number/ hydraulic similitude/ hydraulic models/ velocity/ *roughness/ concrete/ concrete finishing/ surfaces/ capacity reduction/ canals/ turbulent flow/ boundary layer/ air
IDENTIFIERS-- Prandtl-von Karman equation/ Preston technique/ fluid dynamic roughness/ shear tube method/ velocity distribution method/ conveyance capacity/ Nikuradse/ equivalent sand roughness

Hyd-521
AERODYNAMIC STUDY OF CONCRETE SURFACE ROUGHNESS FOR CANAL CAPACITY PROGRAM--PROGRESS REPORT
Bureau of Reclamation, Denver, 18 p, including 7 fig, 4 tab, 7 ref, 1965

DESCRIPTORS-- hydraulics/ *fluid friction/ roughness coefficients/ shear/ velocity distribution/ aerodynamics/ research and development/ boundary shear/ fluid flow/ Manning formula/ Reynolds number/ hydraulic similitude/ hydraulic models/ velocity/ *roughness/ concrete/ concrete finishing/ surfaces/ capacity reduction/ canals/ turbulent flow/ boundary layer/ air
IDENTIFIERS-- Prandtl-von Karman equation/ Preston technique/ fluid dynamic roughness/ shear tube method/ velocity distribution method/ conveyance capacity/ Nikuradse/ equivalent sand roughness