TRANSPORT OF SEDIMENT IN HELICAL CORRUGATED PIPE

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Prepared for the
February 18-22, 1957 meeting
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SYNOPSIS

Helical-corrugated, standard-corrugated and smooth 12-inch diameter pipes were tested under varying regimes of total sediment load. The pipelines were 100-ft long, set at zero slope, with piezometers located on 10-ft centers. The sediments had a median sieve diameter of 0.20-mm and 0.65-mm. Hydraulic gradient, discharge of mixture, total load, temperature and concentration profiles were measured.

The resistance coefficient f was found to vary with both Reynolds number and total load when the 0.65-mm sand was being transported. The f - Re plot for 0.20-mm sand transport was nearly identical to the corresponding curve for clear water. Plots are also presented of hydraulic gradient versus mean velocity and total load. Several researchers data are correlated by means of the boundary layer concept of alluvial channel roughness of Ali and Albertson. It was demonstrated that under some conditions the helical-corrugated pipe conveyed more sediment per unit time with less horsepower input than the standard-corrugated or smooth pipes. A new exact criterion is presented for determining incipient deposition. Horizontal and vertical concentration profiles indicate that secondary circulation has a profound influence on the form of these profiles.

INTRODUCTION

Design, operation, and maintenance of pipelines that transport sediment has required the best abilities of engineers for many years. Hardly a major city or harbor exists that has not had very serious problems caused by sediment deposition and difficulty of transport in their storm sewers or dredge pipelines. Difficulties have ranged from flooded areas to costly dredging as a result of pipelines inadequately designed.

That sediment in pipeline problems will continue to be important is evident from the dirth of quantitative information for design that is available for the increasing number of engineering jobs which could be solved best by transporting a given sediment material through a pipeline.

Typical installations where sediment is transported through a pipe are sanitary sewers, harbor and river dredges, catalyst transport, coal transport, pneumatic conveyers, ash disposal, and storm sewers. A very recent installation transports gilsonite in a water medium for many miles.

This paper is limited to the horizontal transport of sand in water --probably the major application of the principles of conveying solids in a fluid medium. The concern herein is not only to determine the hydraulic characteristics of a given sand-water-pipeline system, but to compare several types of systems from the standpoint of energy losses, water conservation and the small-scale mode of transport.

Since the late 1920's engineers have been considering the possibility of installing artificial roughness in a pipeline to improve its characteristics for conveying a sand-sediment mixture. This concern stems from the fact that engineers recognized that dispersed clays and silts were carried in water as essentially a medium of uniform density while coarse sand and pebbles traveled along the bottom of the pipe. Sand distributed itself over the whole pipe cross-section with the concentration increasing near the bottom of the pipe. Reasoning led them to conclude that perhaps some artificial roughness could be introduced which would increase the concentration that could be carried without plugging the pipeline, and at the same time decrease the pipeline frictional resistance for certain ranges of velocity.

Probably the most important work with an artificial roughness placed in a pipeline was that of Howard (9), who reported in 1941 on tests in 4-inch and 2-inch pipelines. His research utilized 0.023-, 0.39-, and 2.48-mm sand. The artificial roughness consisted of three riflings spaced at 120 degrees around the pipe. These riflings had a pitch of 10 pipe diameters and were installed at intervals such that one-third of the pipeline was rifled. The height of the rifles was D/8, where D is the diameter of the pipe.

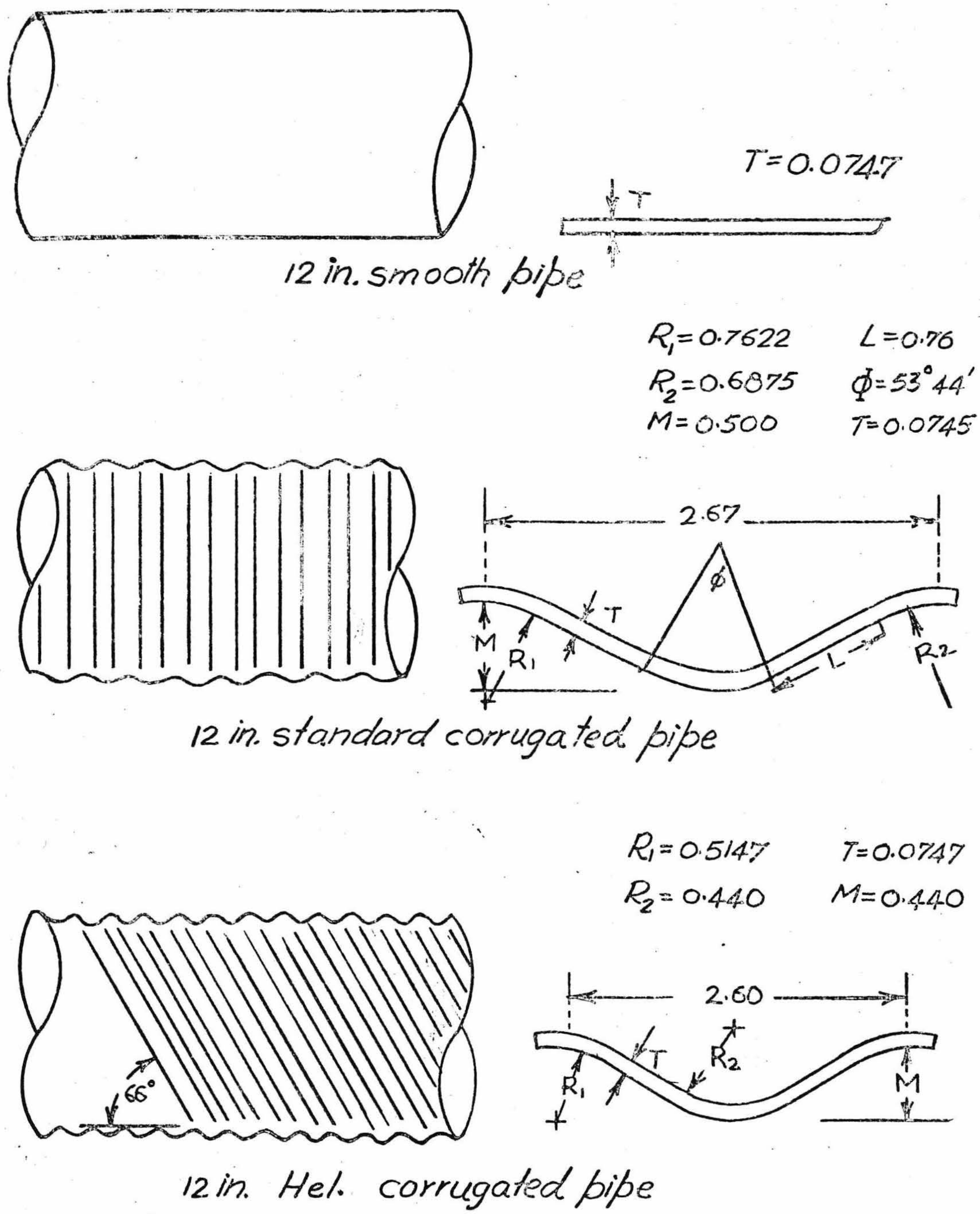
The work by Howard led him to conclude that frictional losses can be reduced in pipelines transporting coarse sand and gravel, up to velocities such that the form drag of the rifles overcomes the benefits derived from having the artificial roughness assisting the sediment transport. In general, system efficiency of rifled pipelines is reduced for installations conveying dispersed clay, silts, or fine sands.

Because the transport of sediment is continually assuming greater importance, and pipes analogous to a smooth pipe with an installed artificial roughness are now available commercially, it was believed that tests comparing several of these commercial pipes conveying sand and water were needed.

SCOPE OF RESEARCH REPORTED HEREIN

During the period from September 1952 and June 1956, studies were made on three 100-ft sections of horizontal pipeline transporting two different sediments. The pipes were all 12-inch in diameter. The three sections tested were: (1) smooth longitudinal seam-welded 14-gage steel pipe, (2) standard corrugated zinc-coated riveted pipe and (3) helical corrugated pipe. Fig. 1 gives a detailed description of the three boundaries. The two sediments utilized were: (1) a 0.20-mm median diameter sand obtained from the Loveland Lake Inlet, Loveland, Colorado and (2) a 0.65-mm median diameter washed sand purchased from a commercial plant. Fig. 2 gives the results of typical sieve analyses of the sediments. A recirculating pumping system was employed.

Data taken consisted of discharge of the sand-water mixture, total load sediment concentration, piezometric gradient along the pipelines on both the trough and crest of the corrugations, horizontal and vertical concentration profiles at a downstream cross-section, sieve analyses of the sediment for various elevations along a vertical diameter and temperature of the mixture.



NOTE: all length dimensions are in inches
Section views are normal to corrugation.

Fig 1 Boundary forms under investigation.

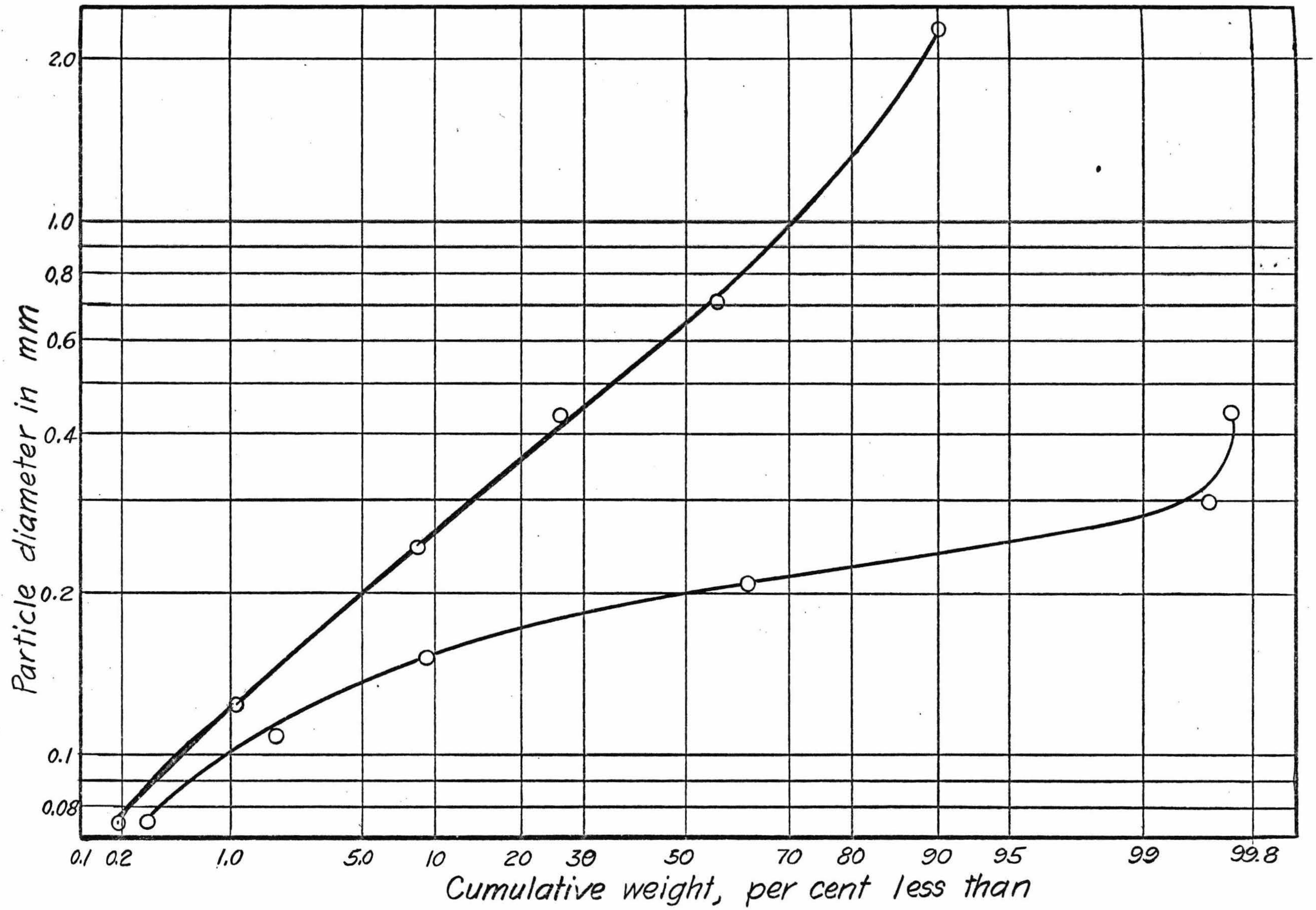


Fig. 2 Size distribution of sediment

EXPERIMENTS

The experimental work may be divided into two parts, although all tests utilized essentially the same recirculating piping system. The first series of tests was with a 0.20-mm sand, employed in all three pipes. The second series of experiments was with 0.65-mm sediment. In the first series a non-deposition regime persisted throughout the majority of the runs; in the second series a deposit of sand was usually present on the bottom of the pipe. While the experimental procedure was essentially the same throughout, the recorded data differed somewhat in the two series of experiments.

Discussion of the experiments will follow this order: (A) experimental equipment installation, (B) preliminary tests, (C) tests with 0.20-mm sediment and, (D) tests with 0.65-mm sediment.

A. Experimental Equipment Installation

The recirculation system employed for the tests is shown schematically in Fig. 3. Sediment was recirculated with the water. The 100-ft section of 12-inch test pipe was readily removable so the change from smooth pipe to helical-corrugated pipe to standard corrugated pipe could be made very quickly. The two sediment concentration sampling stations shown on Fig. 3 are presented in detail in Fig. 4. Total load sampling was done in the vertical section of pipeline near the 10-inch orifice. Horizontal and vertical concentration profiles were taken at the downstream end of the 100-ft test pipe.

The piezometer installation for determining head loss was the same in both series of runs, but the piezometer taps on the crests of the corrugations (as seen by an observer outside the pipe) were not utilized for the

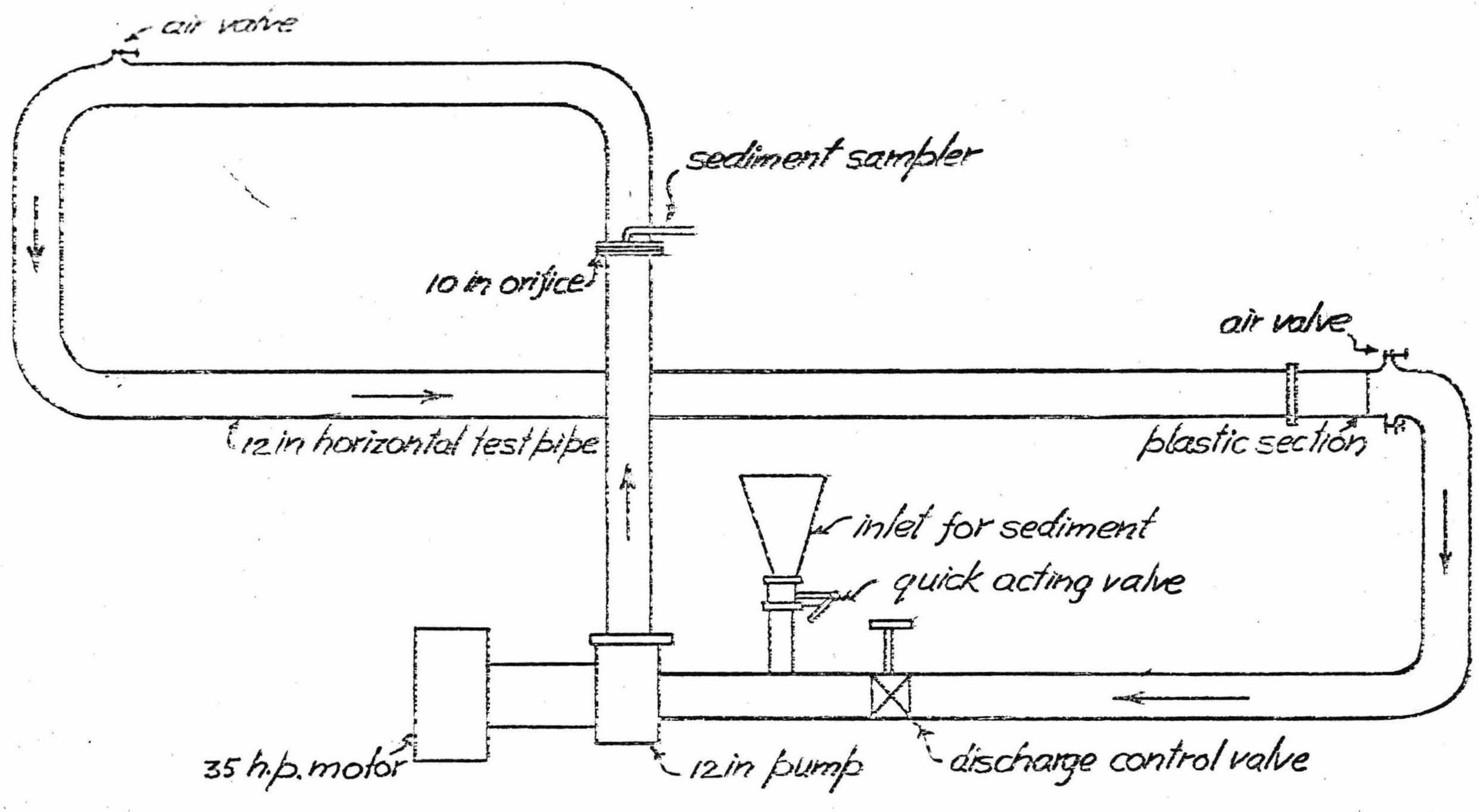


Fig.3 General lay-out of the recirculation system.

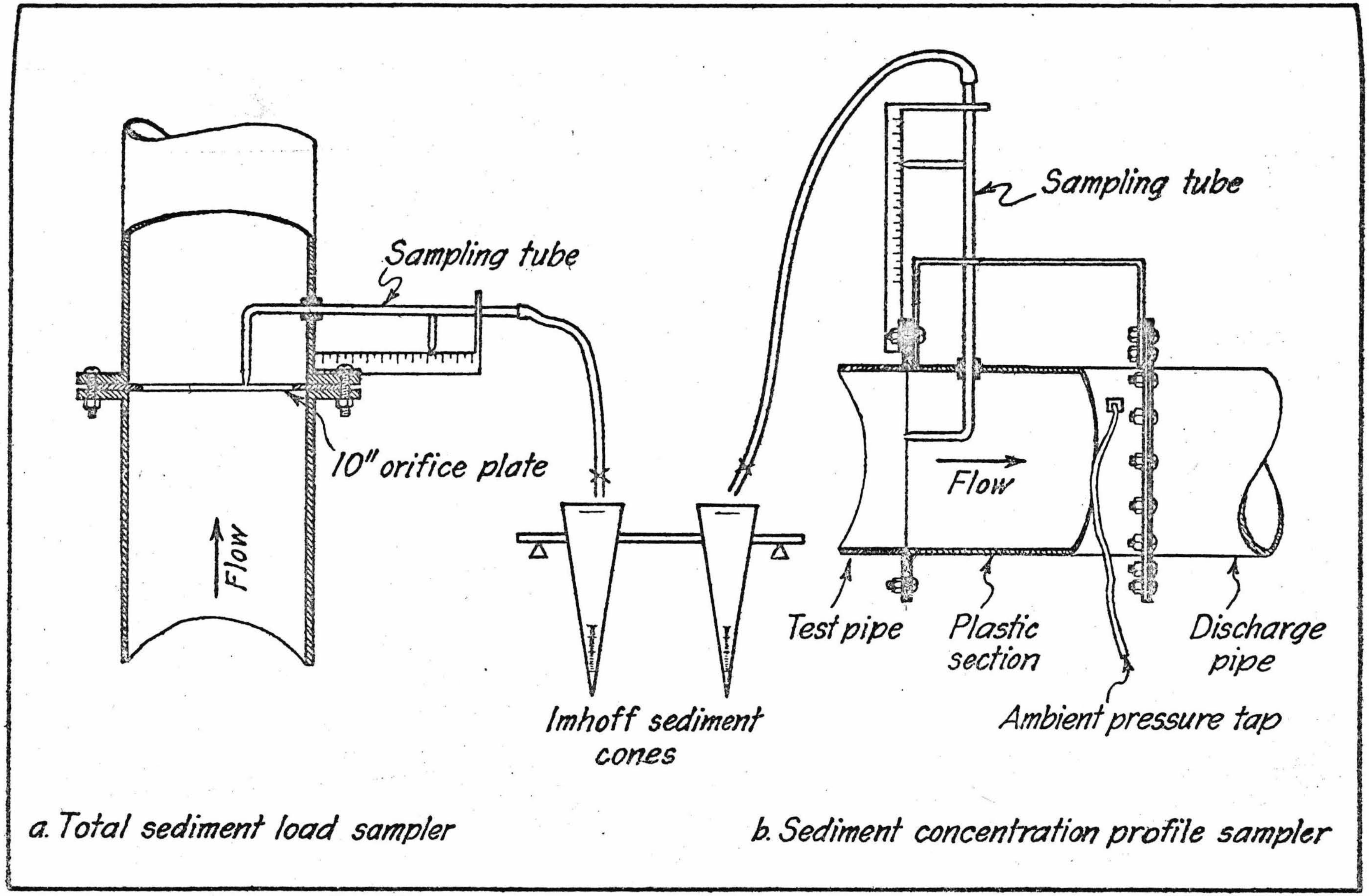


Fig. 5 Schematic diagram of sampling equipment.

second series of tests. The piezometer system for recording the hydraulic gradient differed somewhat for each boundary. Piezometer taps were installed on the corrugations at the point nearest to the axis of the pipe in every case. Some taps were installed on the troughs of the corrugations of the corrugated pipe in order to check the effect of location.

There were ten piezometer taps located along the pipes, spaced at 10-ft intervals starting about twelve diameters from the downstream end of the test pipe. The openings into the pipe were 1/16 inch. The taps were located on a horizontal plane through the axis of the pipe..

The sediment concentration sampling equipment included an intake tube, siphoning and pumping equipment, sampling cones, stop watch, and oven-drying and weighing apparatus. The equipment installation employed is show in Fig. 4. The sampler intake tube extended 5 inches upstream from its support, normal to the direction of flow. It was made of 1/2-inch OD by 1/4-inch ID brass tubing. The nozzle section was 4 inches long, tapering to a sharp edge at the inlet.

The sediment samples ordinarily were taken by siphoning. A small horizontal centrifugal pump was used when insufficient piezometric head was available for siphoning. The pump was not used unless absolutely necessary because of its unsteady discharge characteristics.

B. Preliminary Tests

Preliminary studies were conducted before proceeding with the main problem. These studies included: (1) measurement of discharge of the mixture, (2) determination of the sampling time interval, (3) rapid determination of the local sediment concentration, (4) determination of the total sediment load, and (5) determination of the effect of piezometer location along the corrugations.

Measurement of discharge of the mixture was accomplished by means of the clear-water calibration curve for the 10-inch orifice installed in the vertical section of the 12-inch pipe. Durand's (6) paper constituted the justification for assuming this procedure to be of sufficient accuracy.

Determination of the sampling time interval at each point at which a sample was to be taken was quite time consuming. Since a sampler with a sharp edge at the opening and a 0.25-inch ID circular intake was to be used, some knowledge of the allowable ratio of intake to ambient velocity was needed; to maintain say ± 5 percent maximum error in sediment concentration. From the Corps of Engineers (11), it was found that, for the particular nozzle used, differences of ± 15 percent in intake velocity from the ambient velocity would result in concentration errors of less than ± 5 percent. Hence, rapid velocity determinations were made at each point in the flow where a point time integrated sample was to be taken. From this velocity the sampling time interval required to fill a one litre sediment cone was calculated. Each one litre sample taken to determine the local concentration was obtained on the basis of a sampling time determined in the above manner. There seems sufficient reason to expect, as far as sampling time is concerned, that concentrations are accurate, in general, to at least ± 5 percent.

A rapid determination of the local sediment concentration was devised, since it became evident in the early phases of the investigation that the classical oven-drying technique was impractical. Some 20,000 concentration determinations were to be made. The difficulty was resolved by calibrating a one litre sediment cone. Some 140 samples of known apparent volume were oven-dried in order to determine a calibration curve of apparent volume versus percent concentration for the cones. Such a calibration curve was developed for each size of material used in the research program.

The calibration curves gave very good results. However, there is a lower limiting concentration for a sediment cone. Extremely small concentrations still must be oven-dried.

Determining the total sediment load was quite simple. Thirty or more concentration samples were taken along two diameters of the 10-inch orifice installed in the vertical 12-inch riser. A weighed average (area weighing) gave the total load concentration.

The effect of piezometer location along the corrugation was investigated. While there seemed no physical reason why the hydraulic gradient as determined from a set of piezometers all located on the crests (observer inside pipe) should differ from a set located consistently at some other position, it was believed the matter should be investigated.

The Corps of Engineers, reporting on a study of large diameter corrugated pipes, included some information on the deviation in head from true ambient pressure at various locations along a corrugation. A hydraulic gradient measured by any consistent piezometer bank seemed to be satisfactory, within ones ability to read the manometer. Sediment was not present during the tests. See reference (10)

A large number of tests were conducted during the course of the program reported herein, with sediment, with piezometers on the crest and troughs of the corrugations. The conclusion was the same as that in the preceding paragraph.

C. Tests with 0.20-mm Sediment

Procedure was first, with each pipe, to run a series of tests with clear water. The piezometers, located on 10-ft centers, were read four times and the results averaged in order to obtain the clear water piezometric gradient, J_e. Temperature was recorded four times and averaged for each run. The discharge Q was likewise an average value.

Subsequent to the clear water tests for a given boundary, a small amount of sediment was added to the system. After equilibrium was established the piezometer bank readings, orifice manometer levels, and temp perature were recorded. Next, after a velocity profile along a diameter of the pipeline was made, a concentration profile along a vertical diameter of the pipeline was obtained. This profile consisted of taking three sediment samples, of one liter each, at each of ten points along the diameter. During the taking of this profile, the piezometric gradient, the temperature and the discharge were recorded twice. After the profile was completed, another reading of piezometers, manometers and thermometers was made.

The next step consisted of following the same procedure on the piezometers, thermometers and orifices while making three concentration profile traverses along each of two diameters of the horizontal 10-inch orifice in order to evaluate the total load concentration. Then, with the sediment load still held constant, the procedure of the above two paragraphs was repeated, but this time the local concentration profile was taken along the horizontal diameter of the test pipeline.

Following these tests at a constant concentration, more sediment was added to the system. The procedure outlined above was repeated again;

measuring the mixture discharge Q , the water-sediment mixture piezometric gradient J , the total load concentration C_t , the profile of the local concentration c and the temperature T . Sediment was added in increments until even at the maximum discharge that could be pumped with the available pump there was a bed of non-zero width of alluvial material formed on the bottom of the pipe. This same procedure was repeated for each of the three types of pipes.

D. Tests with 0.65-mm Sediment

The procedure for the laboratory investigations with 0.65-mm sediment was the same as it was for the 0.20-mm sediment, except that certain categories of data that were obtained during the latter tests were omitted during the studies with 0.65-mm sediment. Concentration profiles in a plane normal to the direction of flow in the pipe were omitted. No data were taken on the effect of the sediment on the piezometric gradient as recorded by piezometers on the crest and troughs of the corrugations. Data were somewhat limited for the non-deposition transport regime -- that is, in general a bed was present on the bottom of the pipe.

RESULTS OF EXPERIMENTS

In presenting the results of the experiments, the gross picture of effect of boundary form on the transport of sand is discussed first. Subsequently, a brief resume is given of certain observations on the transport mechanism and how pipe boundary form effects it. Under (A) plots of the piezometric gradient J versus the mean mixture velocity V and the transport concentration C_t is discussed. Section (B) sets forth experimental results on the fundamental resistance coefficient f versus Reynolds number Re and C_t. In (C) is presented a plot correlating various researchers data. Following this, in section (D), optimum operating conditions for pipes and their relative merits are discussed. In (E) data are presented on the intermechanics of the transport process, and section (F) briefly discusses an exact criterion for determining incipient deposition of sediment.

A. Piezometric Gradient

For turbulent flow in pipes it is anticipated that a plot of clear water piezometric gradient Jo against the mean velocity V will yield a straight line of slope two on log-log paper, and sediment introduced into the system will cause deviations from this straight line. The magnitude of the deviation depends on several factors, the most significant being the size of material being transported.

Fig. 5 is a plot of piezometric gradient J against mean velocity V, regardless of concentration C_t for the 0.20-mm sediment. Helical corrugated, standard corrugated and smooth pipes are included on this plot. The small flags indicate that a sand bed had formed on the bottom of pipeline.

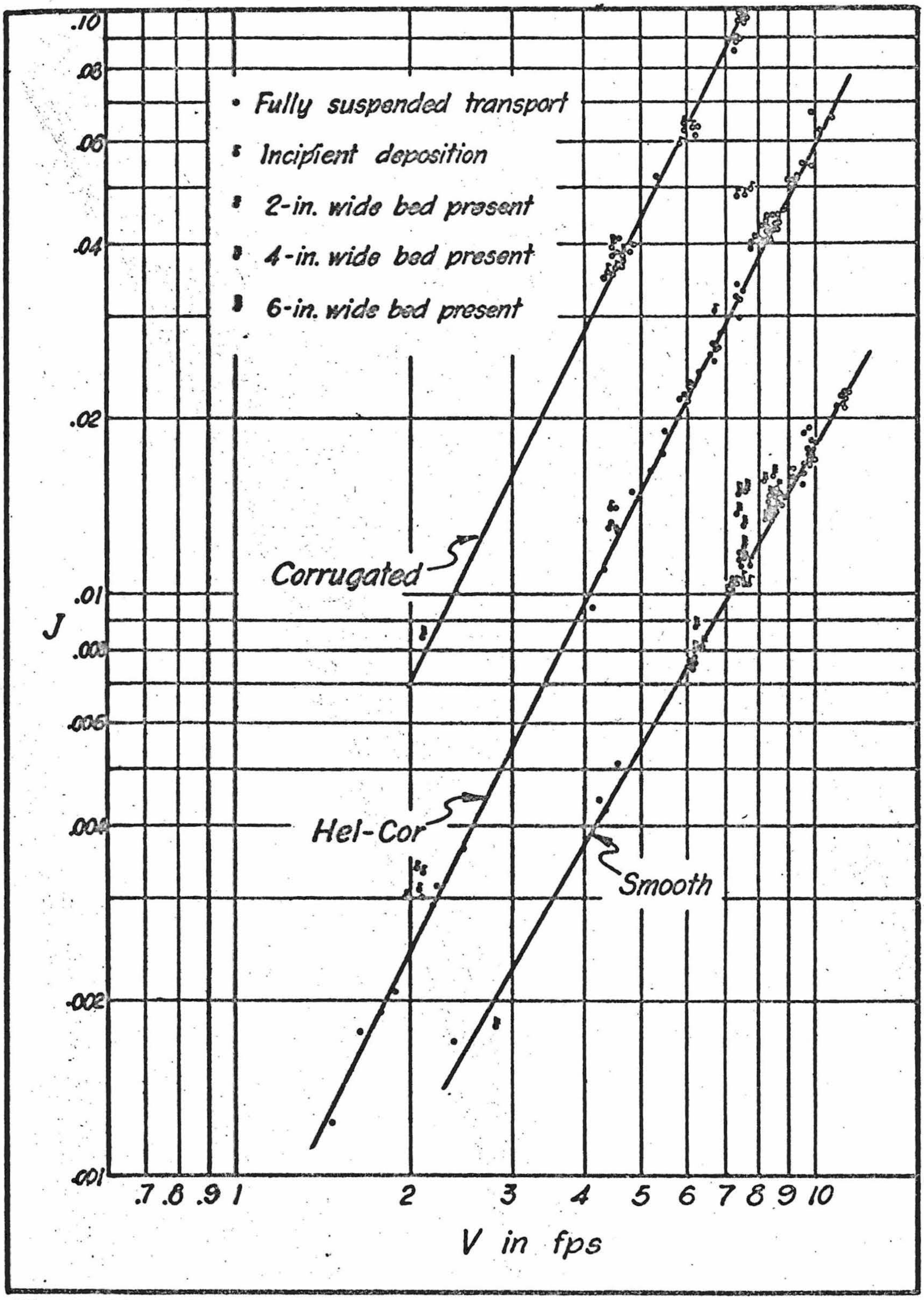


Fig. 5 Variation of hydraulic gradient with velocity and concentration.

From this plot two things stand out. First, the slope of the line representing the smooth pipe does not have a slope of two. Second, the mean transport concentration C_t of sediment, even when a bed has formed, has only a very small effect on the head loss for any given discharge.

Turning now to similar plots for the 0.65-mm sediment in Figs. 6 and 7, the situtation is not as it was for the finer 0.20-mm sand. Here it is immediately evident that concentration C_t plays an important role when 0.65-mm sand is being transported. The head loss differs greatly from the clear water curve for a given mixture discharge as the total load C_t increases.

Briefly, the effect of sediment size on the general form of the plots of J versus V and C_t plots depends on the fact that as the sediment size increases the concentration distribution within the pipeline is such that the transported material is concentrated near the bottom of the pipe. There is no longer any semblance of a homogenous fluid in the pipe, as is the situation when dispersed colloidal clays and silts are being transported. Local sediment concentration near the bed approached 30 percent in some of the tests.

B. Resistance Coefficient

More fundamental than J versus V plots, from the viewpoint of fluid mechanics, are plots of the Darcy-Weisbach resistance coefficient f versus the Reynolds number Re and transport concentration C_t. The resistance coefficient was computed from

$$f = \frac{JD}{V^2/2g} \qquad (1)$$

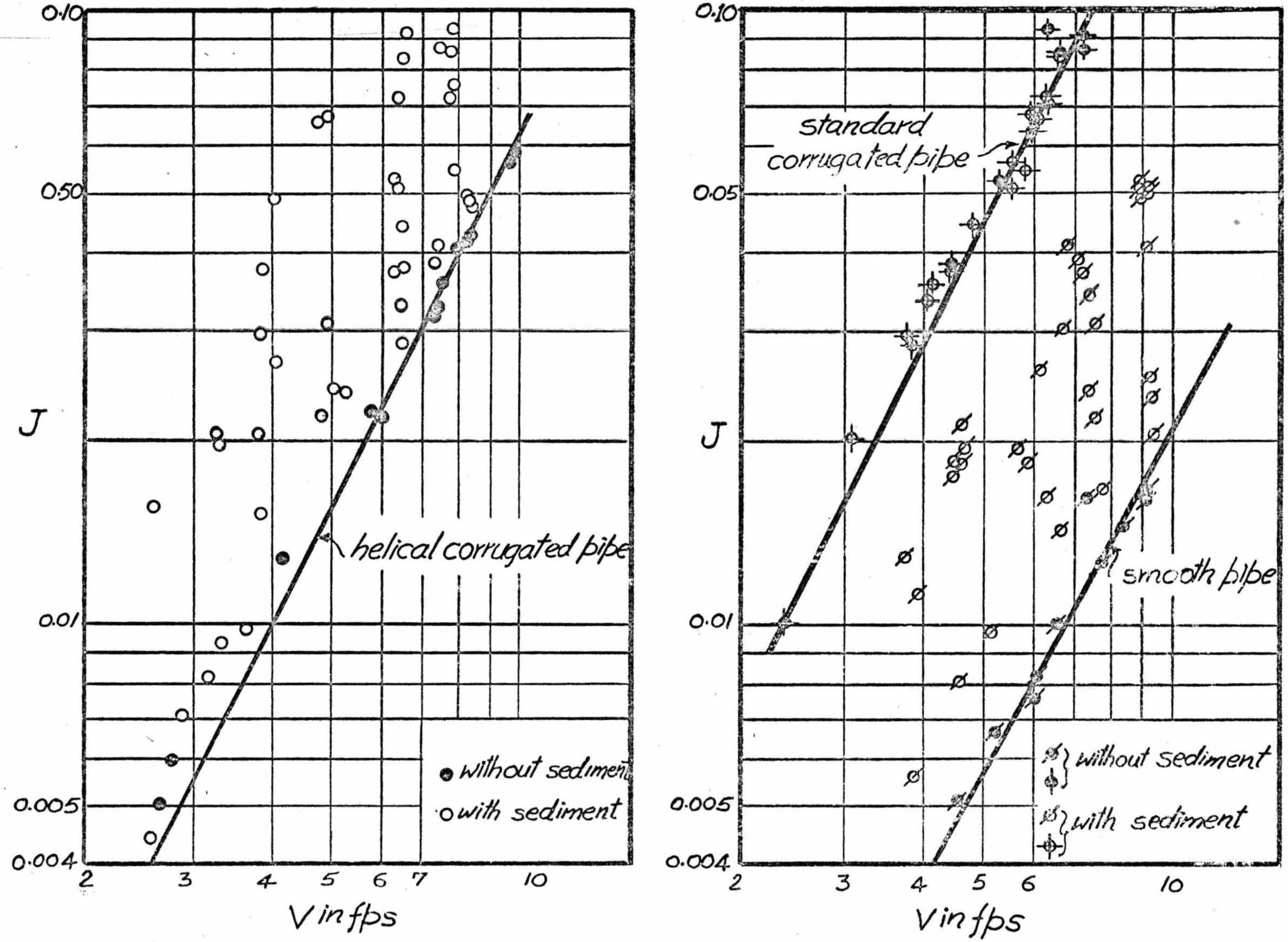


Fig. 6 Variation of J with V and C_T for all boundaries.

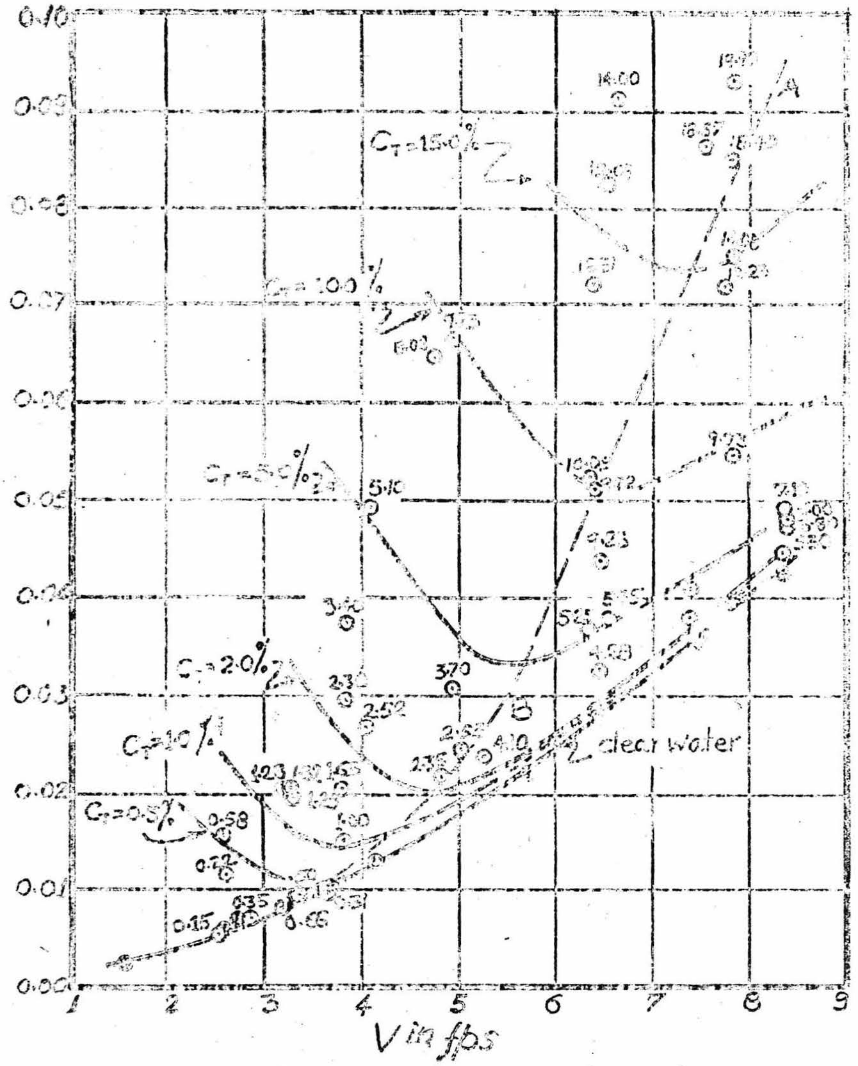


Fig. 7 Variation of J with V and C_T for helical corrugated pipe

where g is the gravitational constant and the other variables are as defined earlier, Reynolds number Re is defined as

$$Re = \frac{VD}{\mu/\rho} = \frac{VD}{\nu} \tag{2}$$

where μ is the dynamic viscosity and ν the kinematic viscosity of clear water at the temperature of the sand-water mixture and ρ is the mass density of clear water.

Fig. 8 shows the variation of the resistance coefficient with Reynolds number for all transport concentrations, with 0.20-mm sand. The downward sloping curve for the smooth pipe is the Blasius equation -- around which the smooth pipe data group quite well. As one would expect from the previous discussion on the J versus V plots, the effect of sediment concentration on the resistance coefficient is not important.

However, two points may be emphasized. The height of the artificial roughness is practically the same for the helical corrugated pipe and the standard corrugated pipe. But the resistance coefficient f for the standard corrugated pipe is nearly three times that of the helical corrugated pipe -- partially explained by the fact that a considerable proportion of the discharge of the helical pipe follows the corrugations, which is a flow pattern that can not take place in standard corrugated pipe. Furthermore, a brief calculation of an equivalent Nikuradse sand grain roughness will demonstrate that there is no relation between the sand grain size and the actual height of the artificial roughness. Conversely, employing the wake-interferance concept of Morris, Proceedings of ASCE, vol. 80, 1954, the physical size of the corrugations corresponds to that give by the theory.

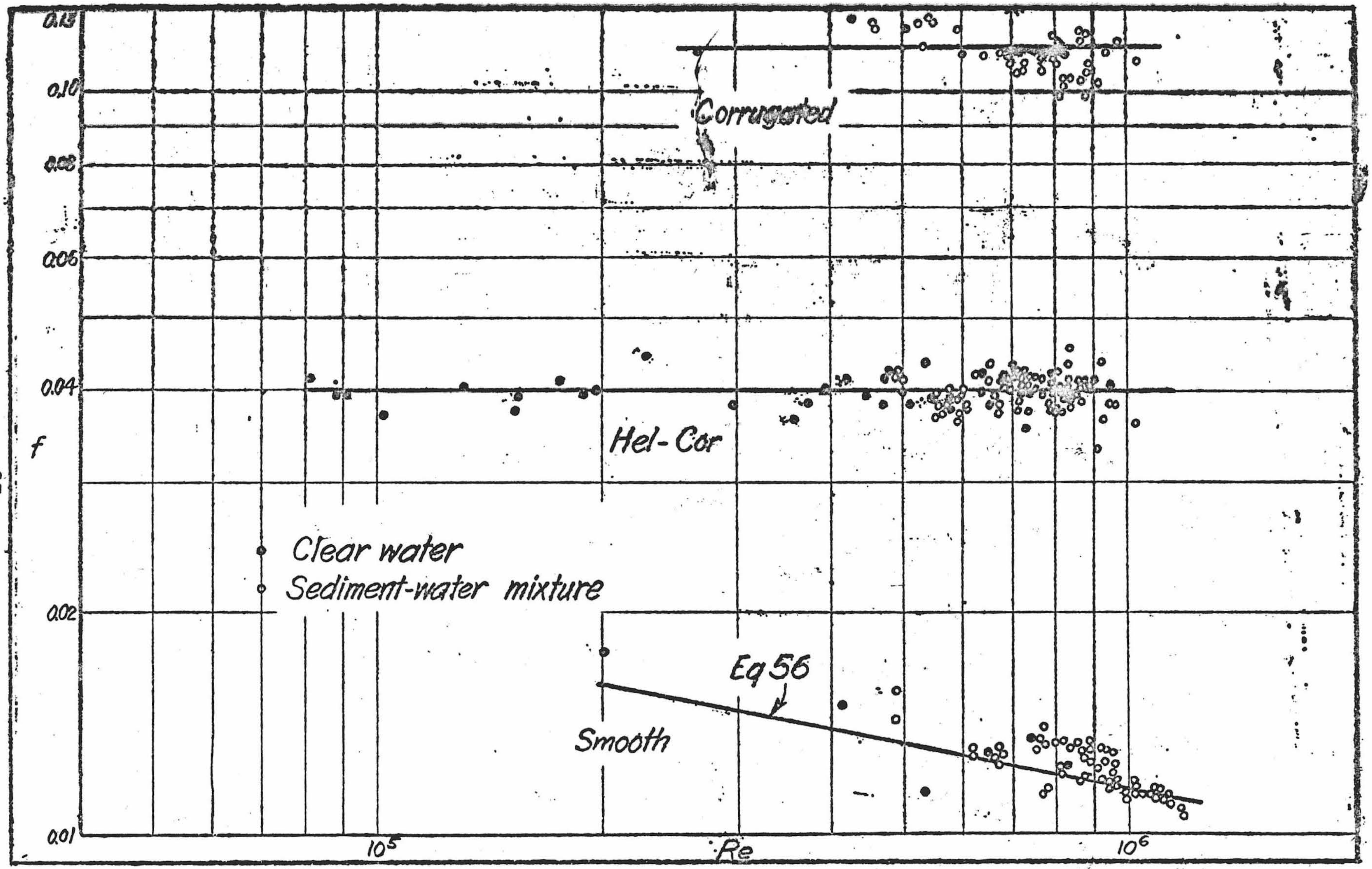


Fig. 102 Variation of resistance coefficient with Reynolds number — fully suspended transport.

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In Figs. 9 and 10, the experimental results are given for the 0.65-mm sediment. These figures clearly indicate that transport concentration plays a significant role in pipeline conveyance of larger sizes of sediment. The total load C_t must be considered when designing sewers, dredges, etc. that are to convey coarse material. For example, for a given Reynolds number it is possible that the resistance coefficient will be increased three to four times its magnitude for clear water by simply introducing a one percent concentration total load.

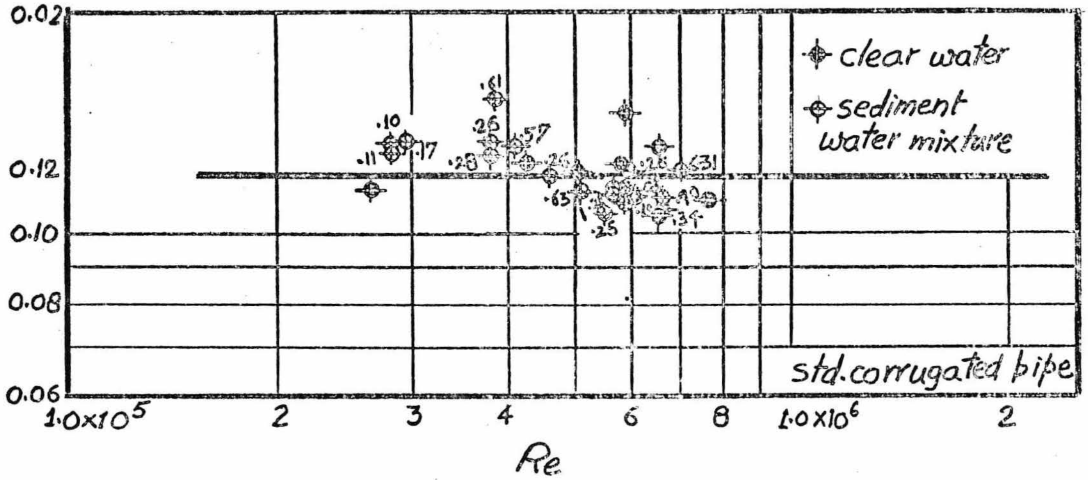
C. Correlation of Data.

The shape of the f versus Re and C_t curves of Figs. 9 and 10 yield an important clue to a generalized correlation of available data on sand conveyance through horizontal pipes by water. There is a marked resemblance to the form of the curves presented by Albertson and Ali (1) in their analysis of flow in alluvial open channels. Their approach, appropriately labeled the boundary layer approach, utilizes as a fundamental parameter $Re\text{-}\sqrt{f}$, where

$$Re\text{-}\sqrt{f} = \frac{VD}{\mu/\rho} = \frac{D}{\delta} \qquad (3)$$

This parameter is inversely proportional to the relative thickness of the laminar sublayer δ/D or directly proportional to the shear velocity V. Employing this parameter, but omitting the details of their analysis, the data of a number of researchers were correlated as shown in Fig. 11.

The correlation indicated in Fig. 11 is quite remarkable when it is considered that sediment sizes varying from 0.20-mm to 2.45-mm and pipeline diameters ranging from 1 inch to 570 mm in all regimes of flow are



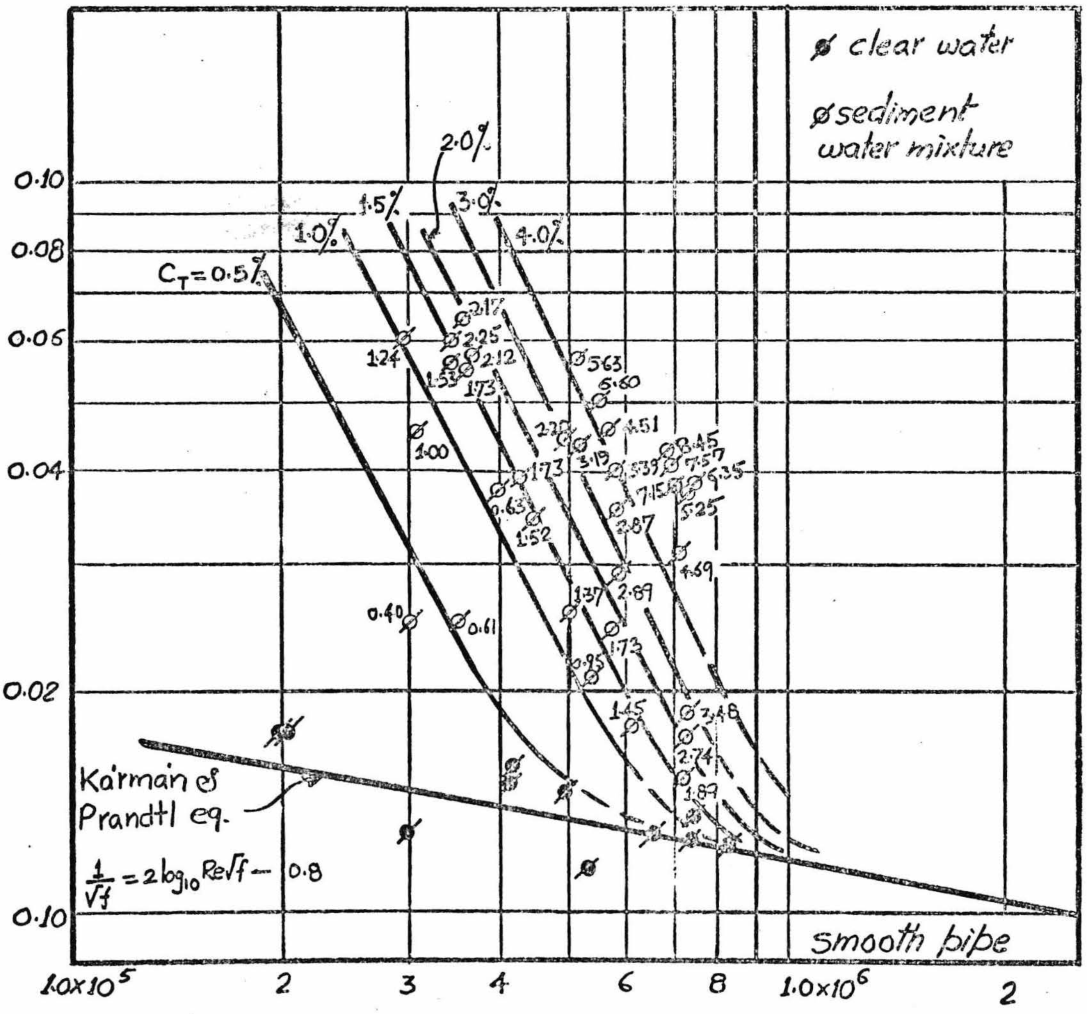


Fig. 9 Variation of f with Re and C_T for smooth and standard corrugated pipes.

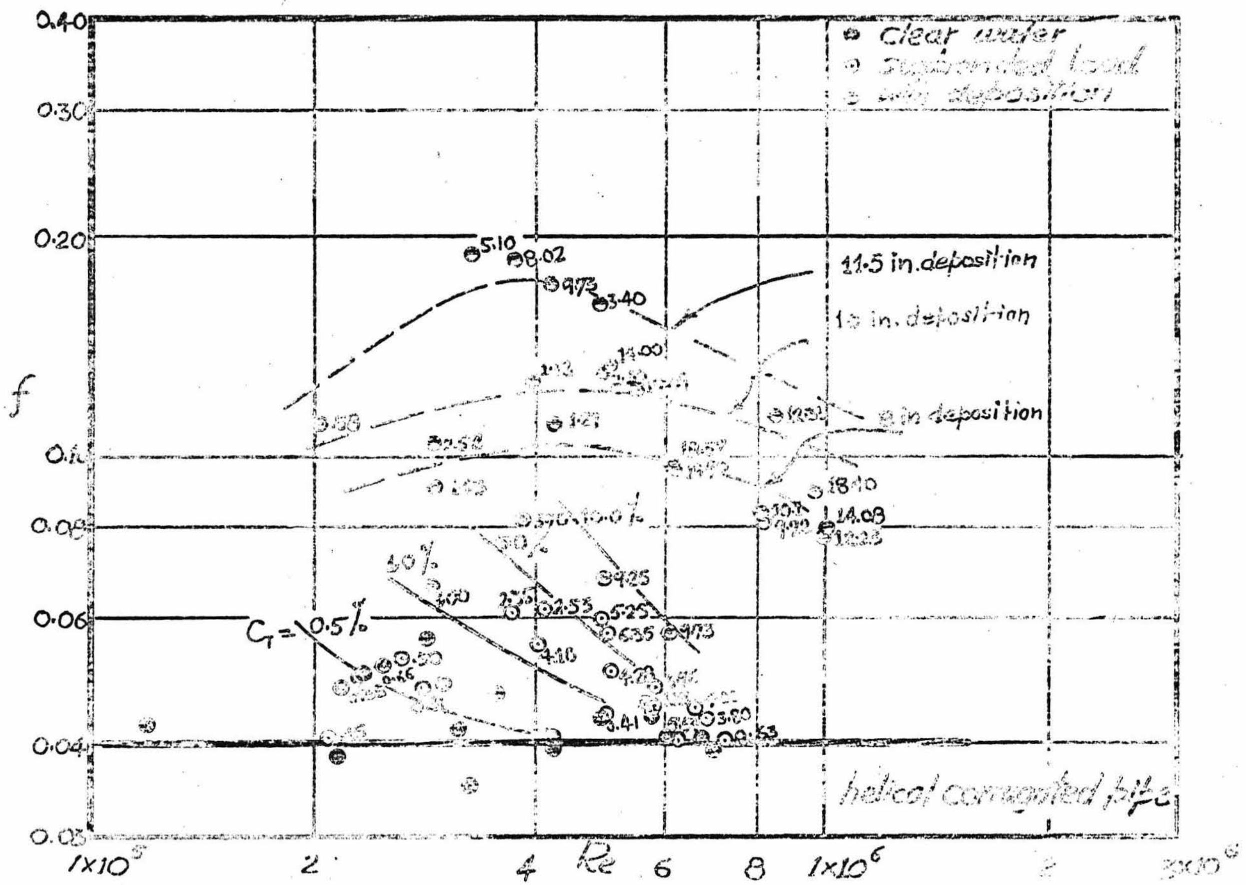


Fig. [redacted] Variation of f with Re and Cr for helical corrugated pipe.

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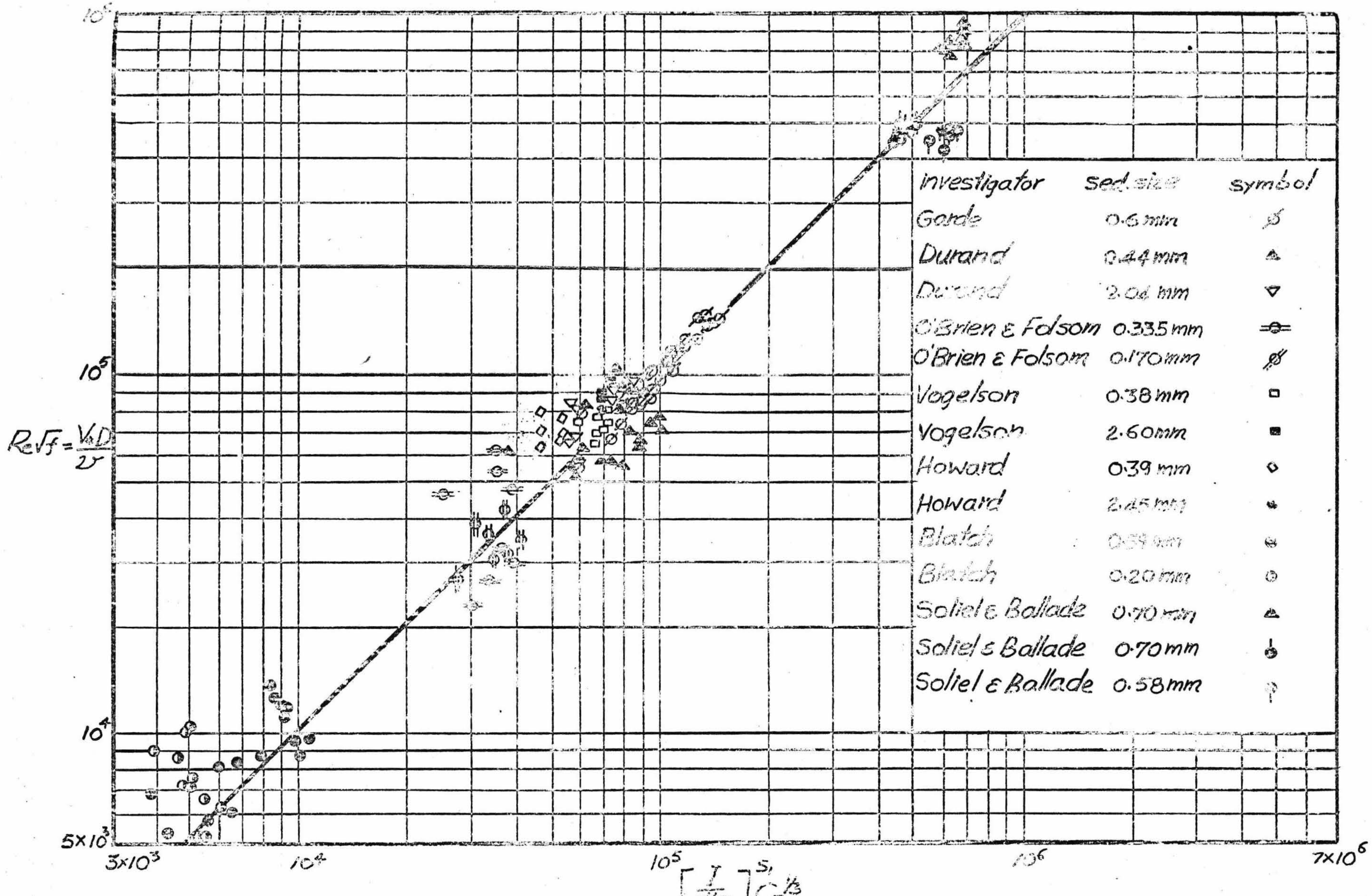

Fig. 11 Variation of $R_e\sqrt{f}$ with $\left[\frac{I}{d/D}\right]^{S_1} C_T^{1/3}$ for smooth boundary

included. Standard corrugated and helical corrugated pipes are not, however, included in this plot.

The parameter plotted along the abscissa is

$$\left[\frac{I}{d/D}\right]^{\frac{1}{S}} C_t^{1/3} \quad , \tag{4}$$

where d is the median sieve diameter of the sediment, I varies directly with d as shown in Fig. 12 and S is the slope of the curves of constant d on a plot of d/D versus p, where p is the intercept of plots of $Re\sqrt{f}$ versus C_t for a given d/D.

The excellent correlation does not indicate, however, that all the problems are resolved. The diameter d is utilized in dimensional form. Furthermore, only sand has been considered. Preliminary computation with clover seed, steel shot and wheat indicate some major difficulties are yet to be overcome.

Understanding of the phenomenon would be enhanced considerably if an adequate explanation for the total load concentration occurring to the one-third power were available. This one-third power also appears in the work of Craven (3) and in recent unpublished investigations by J. R. Barton.

At least two other major contributions toward correlating sediment transport data in pipelines for a wide range of variables have been published. The first of these, by Vogt and White (12), used the parameter of Gasterstadt (8) (J - Jo)/Jo and reduced a large number of data to a set of parallel lines. Steel shot, clover seed and wheat were included. Durand (5), using the same parameter divided by C_t, was able to reduce all of his data to a single curve. However neither of these analyses can include data involving

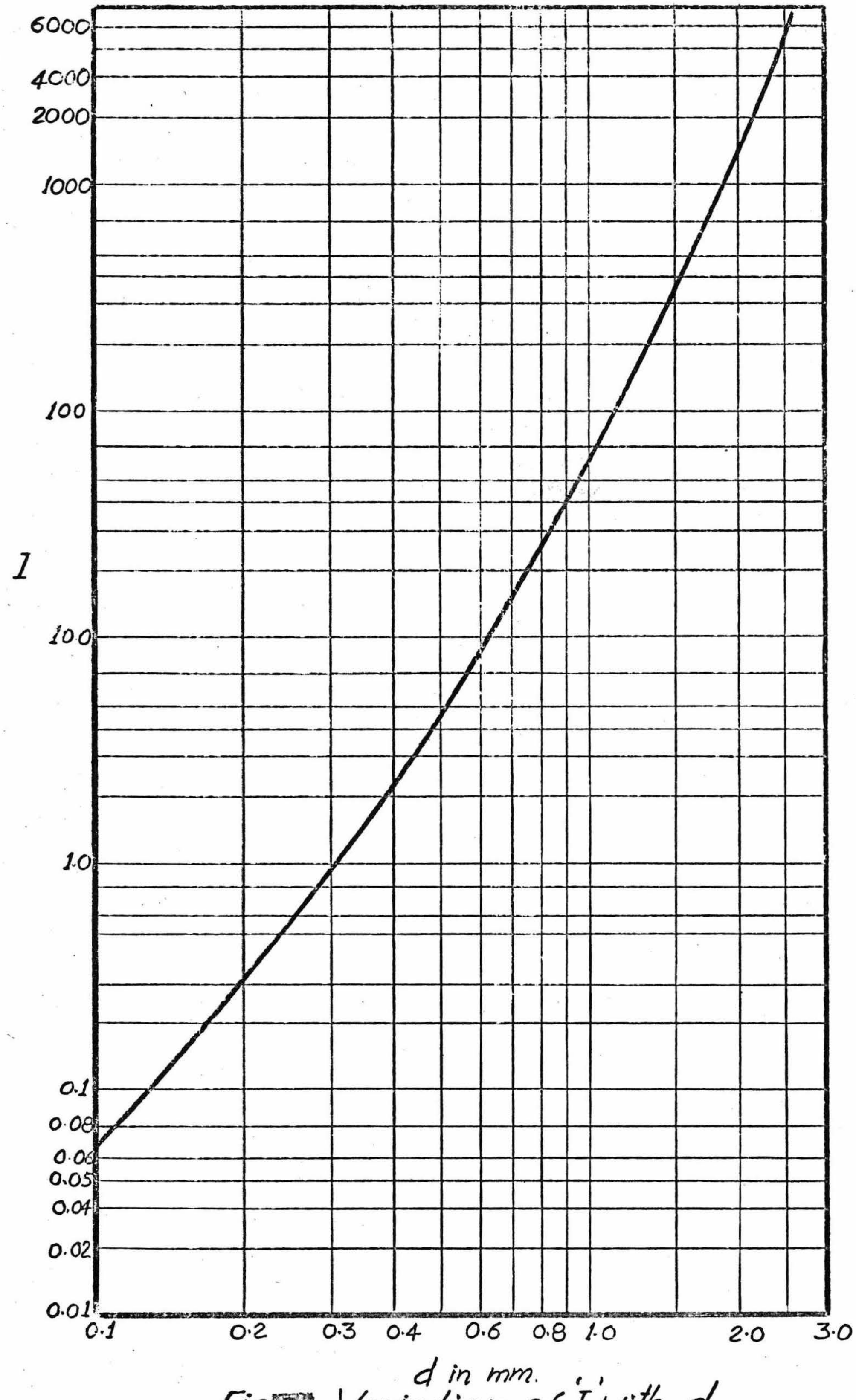

Fig. 12 Variation of 'I' with d.

fine sand; since $(J - Je)$ is always positive in their analysis, but actually is found frequently to be negative for fine materials such as fine sands and silts. Danel (4) gave the explanation for negative $(J - Je)$ as a damping of the turbulence by the fine material — the mixture acting as an essentially homogenous fluid.

D. Optimum Design Conditions

From emmination of J versus V and C_t plots one sees that the minimum energy required to transport a given concentration corresponds to the minimum of the C_t equal constant curves on the $J - V$ plots. This minimum also corresponds to a velocity, usually labeled the limit deposit velocity, at which deposition begins for the material in question. This limit deposit velocity can also be determined from V versus C_t diagrams.

Assuming the minimum energy consumption to transport a given total load C_t as the optimum design condition, Fig. 13 was prepared. On this figure the sediment discharge G in cfs is plotted against HP for all three boundaries. Also prepsented on this graph is a plot of G versus the mixture discharge Q. This figure is limited to 0.20-mm sediment.

It follows that for a given G (less than about 0.1 cfs) the helical corrugated pipe will transport the sediment with less water and less horsepower than either smooth or standard corrugated pipe, thus demonstrating that important economies can be realised for certain jobs by using pipelines containing an artificial roughness. However, for large G, when the amount of water available to carry the sediment is unlimited and of no economic value, the horsepower requirements will be less with smooth pipe. In general, the standard corrugated pipe is not economical to employ because the power

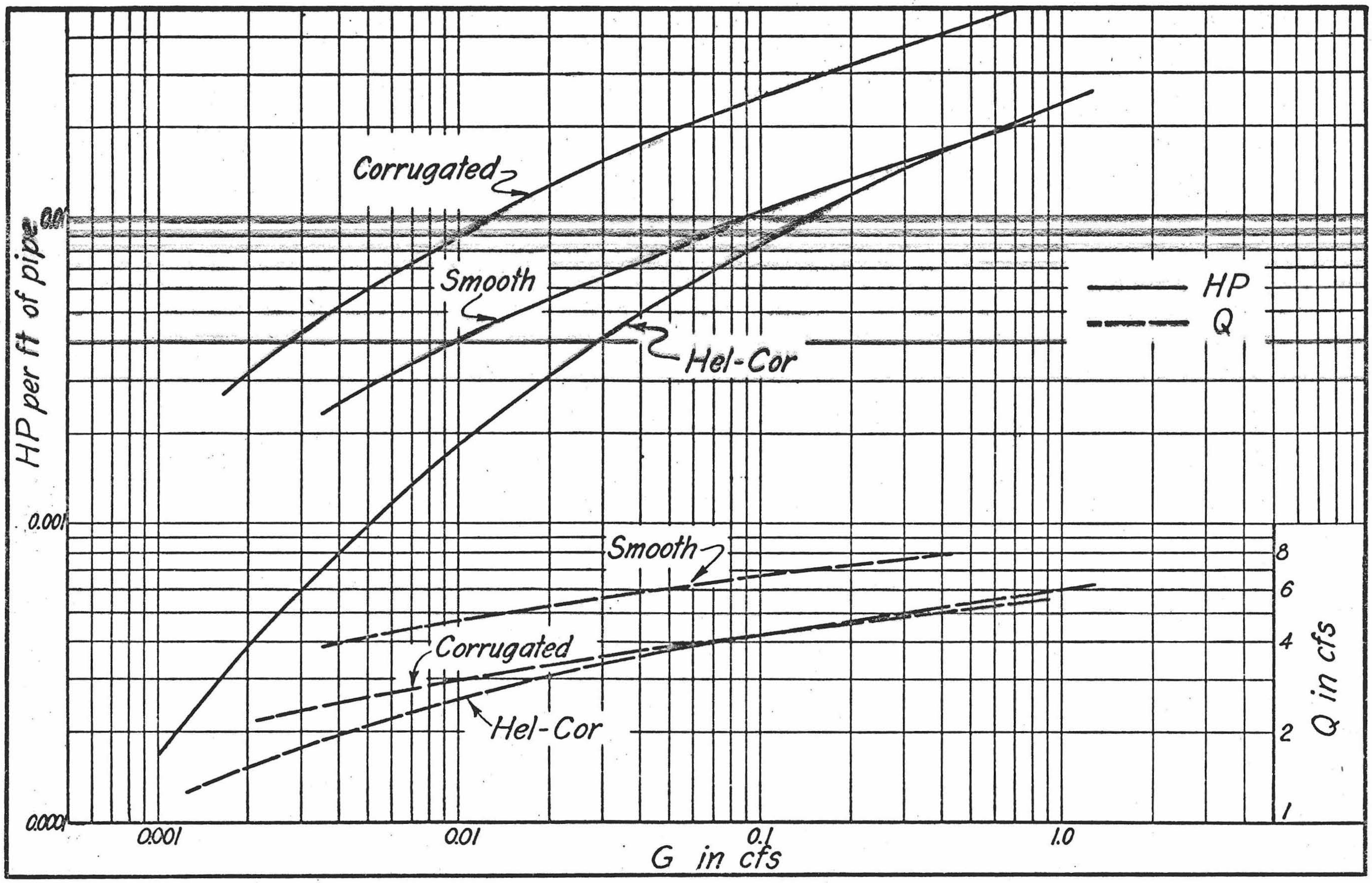

Fig. 13 Variation of horsepower and discharge of mixture with sediment discharge.

consumption is very high. Other combinations of HP , G and Q can be considered for specific design problems that present themselves.

The size of sediment has an affect on the location of G versus Q plots, as determined by the tests with 0.65-mm sand. The G versus Q curve in the case for helical corrugated pipe transporting 0.65-mm sand was the same as that for the 0.20-mm sand, but in the case of smooth and standard corrugated pipes the curves for the coarse sand were shifted upward. The curves in these latter cases merged with the curves for 0.20-mm sand for G of about 0.2 cfs.

E. Internal Mechanism of Transport

Remarks on the internal mechanism of the transport phenomenon as influenced by boundary form, sediment concentration, discharge velocity and Reynolds number will be very brief. The discussion is limited to 0.20-mm sand and extensive detail is given by Chamberlain (2).

Profiles of the local sediment concentration C were obtained along the horizontal and vertical diameters of a section normal to the direction of flow for the three boundaries, when conveying 0.20-mm sand. Along the horizontal diameter, the concentration was practically a constant for all the combinations of temperature, concentration, and mixture discharge tested. However, in the case of the helical corrugated pipe a pronounced deviation from a constant concentration was evident in the immediate proximity of the boundary. Here the secondary helical circulation induced by the helical corrugation carried sediment up one wall of the pipeline.

Fig. 14 is a typical set of data illustrating the basic difference in the vertical sediment concentration profiles for the three boundaries

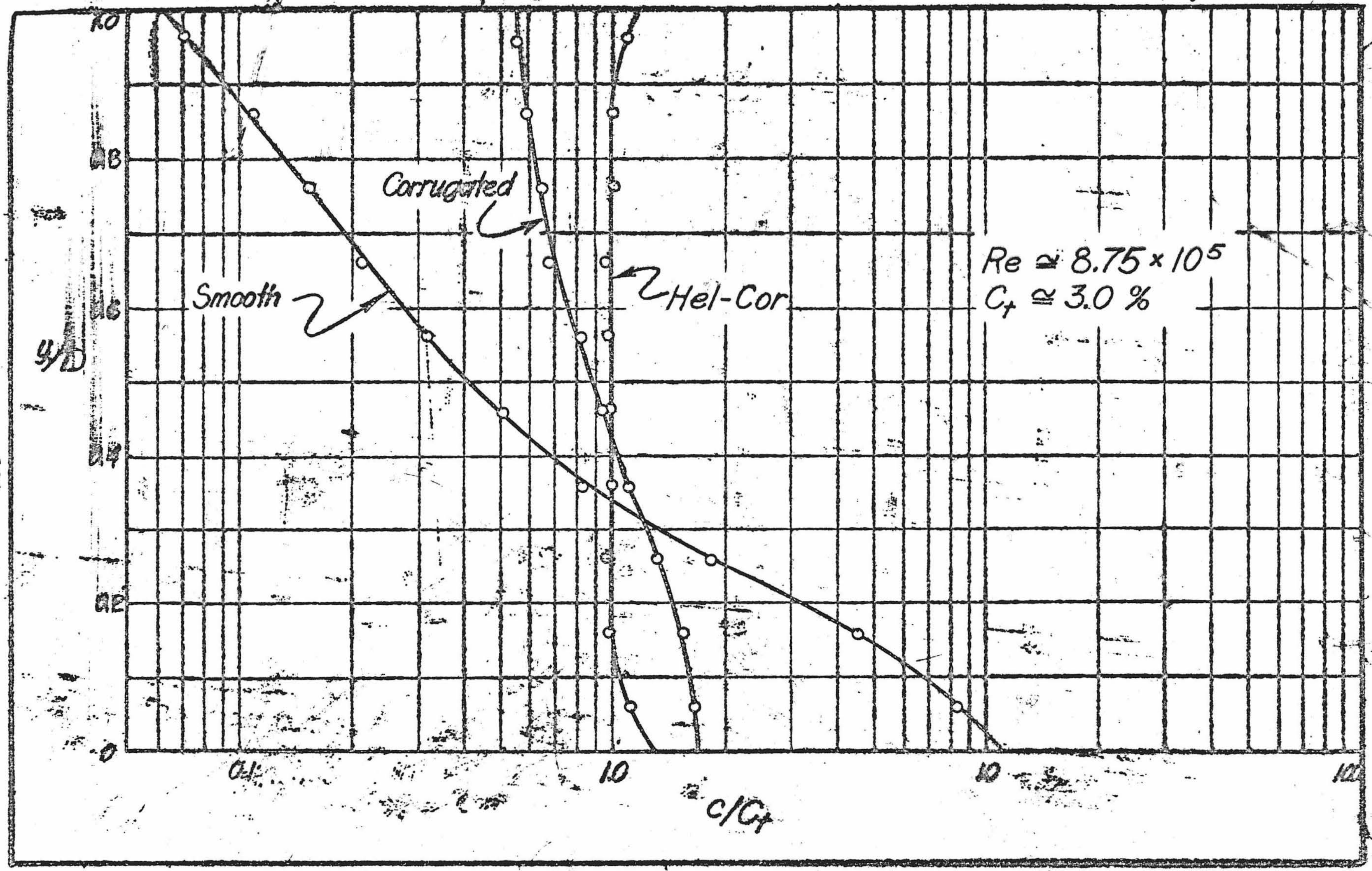

Fig. [redacted] Comparison of vertical sediment concentration profiles.
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considered. This is a graph of y/D against C/C_t, with Re and C_t constant, where y is the elevation above the bottom of the pipe. The concentration profile in a smooth pipe is very similar to that found in open channel flow. The standard corrugated pipe boundary creates a much more uniform concentration profile -- although concentration still increases near the bottom of the pipeline.

The helical corrugated pipe induces a very pronounced secondary circulation in the flow field. A "shell" of fluid and sediment circulates around the pipe, lagging somewhat the helical corrugation. This secondary circulation transports sediment up one wall of the pipe and sometimes completely over the top of the pipe. As a consequence, the concentration profiles in this pipe may have a maximum local concentration on the side or top of the pipe, and a minimum on the bottom. When the total load is increased sufficiently, the secondary circulation is damped as the bed begins to form. Once this circulation is damped, the concentration profile becomes similar to that of the corrugated pipe.

The limit deposit velocity for helical-corrugated pipe is determined, for a given C_t, by decreasing the velocity from that sufficient to keep all the sediment in suspension. In the other two boundaries it can be approached from velocities either less or greater than the limit deposit velocity -- the same result will be obtained.

F. Exact Criterion for Incipient Deposition.

In pipeline experiments, as in open channel flume experiments, the critical tractive force is of somewhat indefinite magnitude since observers must rely on personal judgement to tell when the critical regime

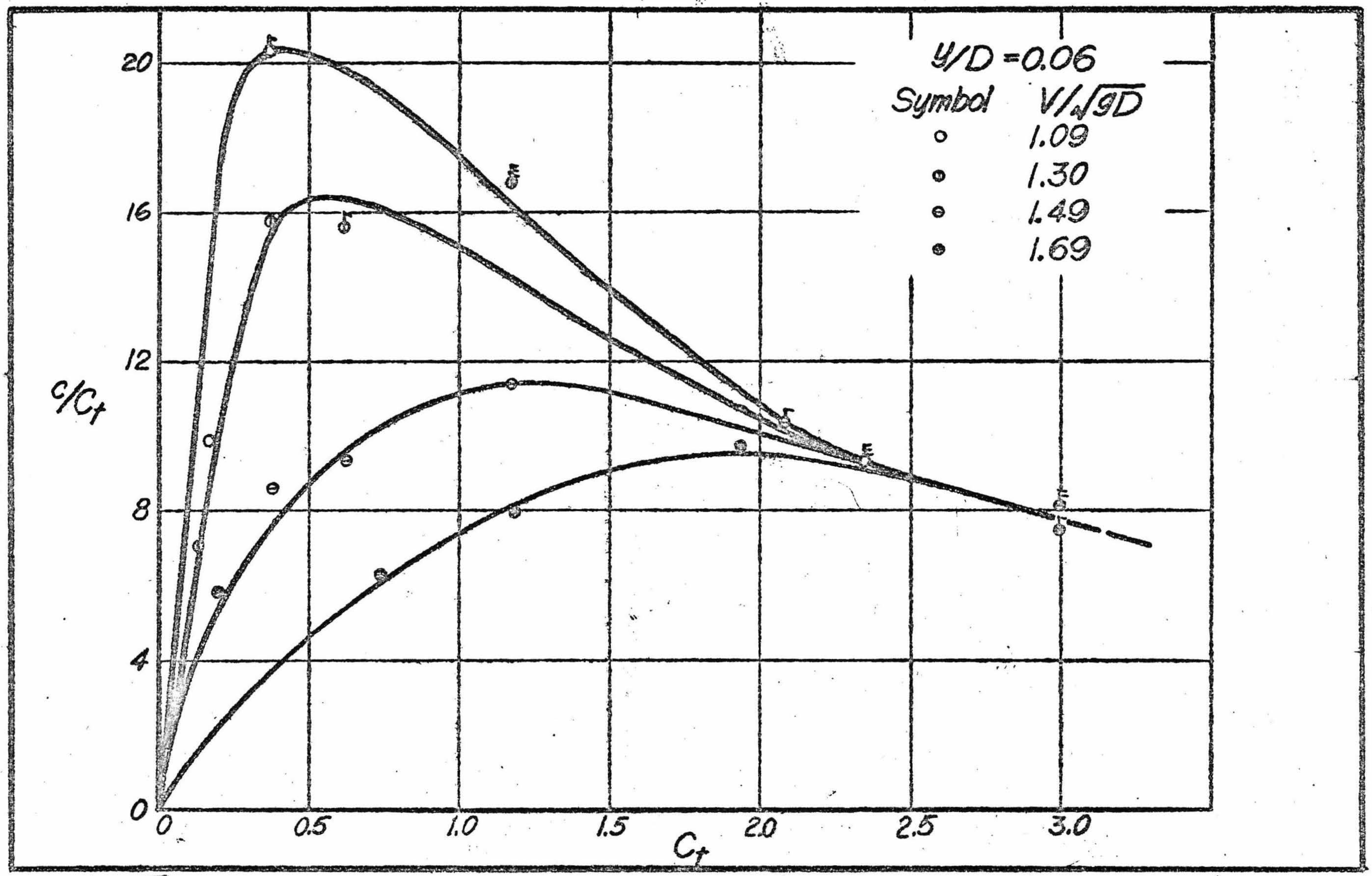

Fig. 23 Absolute criterion for incipient deposition—12-in. smooth pipe.

1 5

exists. However, in pipelines the limit deposit velocity can be used in place of the critical tractive force -- the two being intimately related to each other. Examination of the vertical concentration profiles for the smooth boundary unveiled a possible means of developing a new exact criterion for determining the limit deposit velocity. Letting $y/D = 0.06$ (this number was used only for convenience), Fig. 15 was prepared by plotting c/C_t versus C_t with $V/\sqrt{gD}$ as a third parameter. The flow regime (fully suspended transport, very slight deposition, small bed present and large bed present) was also marked on the plot. Seen immediately is the fact that a maximum occurs, for each $V/\sqrt{gD}$ = Constant, very near, if not at, the point of incipient deposition, i.e. where V is equal to the limit deposit velocity.

Therefore, it follows that by drawing a curve through the maximum of a plot such as Fig. 15 one has all the essential information for preparing a graph of limit deposit velocity versus total load C_t that is independent of the observer -- i.e. one has a new exact criterion for determining the limit deposit velocity for a given C_t. This means that the regime corresponding to limit deposit velocity, critical tractive force and incipient deposition are uniquely defined.

If the conclusions drawn from the very limited data are justified, a means is available for eliminating the personal judgement factor from the determination of incipient deposition regime. It should be noted that the method proposed is most useful for fine sand transport in smooth pipe and perhaps to open channel flows. Plots of J versus V and C_t are usually adequate for determining incipient deposition when coarse sand and pebbles are being transported in pipes.

CONCLUSIONS

It has been demonstrated that both boundary form and sediment size are significant variables in the pipeline transport of sand. A pronounced secondary circulation induced by an artificial roughness in the pipe can make it possible to transport, at the optimum regime, larger amounts of sediment with less water than is possible in smooth pipes. It is also shown that under some conditions it is possible to convey sediment at a given rate with a minimum horsepower by means of pipe containing an artificial roughness. An upper limit of transport is reached, however, beyond which smooth pipe is the most economical to use in conveying sediment. The design of pipelines to transport fine sand (0.20-mm) can be based for practical purposes on the same resistance coefficient as that for clear water. However, for coarser sand (0.65-mm), the resistance coefficient varies greatly with the total load, which must be considered in pipeline design.

There is some promise that the boundary layer approach, which has been used to study alluvial open channel roughness, can lead to a correlation of various researchers' data on pipeline sediment transport. It has been shown that a parameter inversely proportional to the relative thickness of the laminar sublayer δ°/D helps correlate many data.

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NOMENCLATURE

		Units
$C_t = G/Q$	Total load concentration, also referred to as transport concentration	percent
G	Discharge of mixture	L^3/T
Q	Discharge of mixture	L^3/T
V	Mean velocity of mixture	L/T
C	Local sediment concentration	percent
μ	Coefficient of dynamic viscosity	FT/L^2
ρ	Mass density of clear water	$\frac{FT^2/L}{L^3}$
Re	Reynolds number defined by $VD/\mu/\rho$	dimensionless
f	Darcy-Weisbach resistance coefficient	dimensionless
g	Gravitational acceleration constant	L/T^2
J	Piezometric gradient, sediment-water mixture	dimensionless
Jo	Piezometric gradient, clear water	dimensionless
d	Median sieve diameter	L
I	Intercept obtained from Fig. 12	dimensionless
$S = 1/S_1$	Defined by $S = 0.89\ d^{1/3}$, empirical	dimensionless

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