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TRANSPORT OF MATERIAL BY FLUIDS IN PIPES

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Presented to ASCE Hydraulics Division
Conference, Seattle, Washington
17-19 August 1960

Civil Engineering Section
Colorado State University
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Note: This paper is a draft of a chapter to be included in the ASCE Sediment Manual. Suggestions for changes are solicited and may be sent to A. R. Chamberlain, Chief, Civil Engineering Section, Colorado State University, Fort Collins, Colorado.

LIST OF FIGURES

TRANSPORT OF MATERIAL BY FLUIDS IN PIPES

by

A. R. Chamberlain, N. Yotsukura, S. S. Karaki and M. L. Albertson

INTRODUCTION

The transportation of sediment in pipelines is finding an ever increasing number of applications in our technology oriented society. Applications in the field of civil engineering include dredging and transporting materials for hydraulic fills. Fluid transport is also of importance in obtaining, transporting, and placing construction materials such as sand, gravel and cement. Designers of sewer systems or well-drilling operations profit from a knowledge of sediment transport in pipes. Mining engineers are interested in the fluid transport of ore as it is mined, the processed ore, and the tailings. Coal and gilsonite are transported through pipes. Thermal power generating firms are interested in the transport of coal and ashes through pipes. Pneumatic conveyance of products such as whole grain, processed grain, and ensilage is almost an indispensable procedure in agricultural feed handling. The chemical industry utilizes fluid transport through pipes to handle raw materials, materials in process, and finished products. The paper industry is very concerned with the fluid transport of pulp slurries.

It is unfortunate, considering the many applications of fluid transport of sediment in pipes, that no unified theory has been developed to form a solid foundation for experimental and design work. The lack of an adequate theory rests on the fact that inadequate knowledge is available on the flow mechanisms involved in these multi-phase systems. The chapters to follow, however, outline the present state of the fragmented knowledge currently available.

The presentation is limited, in general, to the turbulent flow regime in pipes flowing full. Horizontal transport is emphasized. Only cursory mention is made of slug or plug flows, laminar flows and unusual materials. Fluidized beds are not considered herein. It does not seem possible, because of the paucity of information, to consider fluid transport in which the several phases undergo chemical reactions; or temporary or permanent coagulation.

While all the literature is not included in these pages, it is hoped that a representative coverage is included, sufficient to lead one needing the information to more references.

MATERIALS, CONDUITS AND FLUIDS CONSIDERED

The sediments, types of conduits and fluids frequently encountered in research reports and industrial applications are summarized below.

1. Sediments

Types of materials transported in pipes can be divided into three categories. The materials listed are those most commonly noted in the literature.

a) Non-cohesive sediments with specific gravity approximately equal to 2.65; silt, sand, gravel and some ores.

b) Non-cohesive sediments with specific gravity other than 2.65; ash, grain, seeds, ensilage, plastic, steel shots, catalysts, coal, gilsonite, and gas in a liquid.

c) Cohesive sediments; clay, sewage sludge, and pulp.

Although the above classification of sediment materials is generally adequate, at least from an experimentalist's viewpoint, it does not necessarily provide a good indication of the behavior of the sediment in a flow field. From a flow mechanisms viewpoint, sediment factors such as size, concentration, size gradation, shape factor and resistance to abrasion have a significant influence on the flow and transport characteristics of sediment-fluid mixtures.

2. Conduits

The conduits utilized in sediment transport in pipelines are usually made of metal, concrete, plastic or glass. The cross-sectional shape of the conduits has been predominantly circular. Some modified types of circular pipes have been used for the purpose of increasing transport efficiency and structural strength. These latter include rifled, Howard (26); elliptical, Zenz (52); corrugated, Chamberlain (9); and helically corrugated pipe, Chamberlain (8) -- some of which are commercially available. The surface finish of pipes is usually smooth, at least in physical appearance.

3. Fluids

Air and water are the two main types of carrier fluids used in sediment transport in pipes. In some industries, however, other gases and liquids such as carbon dioxide and hydro-carbon products are employed. It is common in long pipeline systems to find that the properties of the homogeneous phase change as fine material is released into the system by attrition of the coarser fractions.

MECHANICS OF SEDIMENT TRANSPORT IN PIPES

In the following sections the modes of transport, analysis of the flow system and available literature on the mechanics of sediment transport in pipes are discussed. The literature summary, designed to lead one to information on specific problems which might arise, is divided into several subject areas.

1. Modes of Sediment Transport

There are two basic conditions for economically transporting sediments in pipes. These are: the flow must be turbulent in nature and excessive sediment deposition should not take place on the bottom of the pipes.

It is possible, as in open channel flow, to list three quasi-distinct modes of time-steady sediment transport, i.e., suspended load, saltation load and bed load. In actual flows the three modes are usually all present to some degree. The various modes of transport are dependent on the difference in specific gravity of sediment and fluid, the physical properties and concentration of sediments, the flow velocity field, the boundary form, the size of pipe and possibly other variables.

One simplified standard, which relates the modes of transport in water to sediment sizes has been proposed by Durand (18). Under the usual ranges of concentration of sediment, and mean velocity of flow, it is found that clay, fine ash and fine coal slurry (up to 20 or 30 microns in diameter) are transported in suspension as a homogeneous mixture with the fluid. Fine sand, powdered coal and slurry (30 microns to 0.2 mm in diameter) form a heterogeneous mixture transported in suspension. Gravel and pebbles with sizes larger than 2 mm usually travel as saltation load. According to Durand the above classification is correct only for uniformly graded solids, but can be used as a crude guide for sediments which have a wide range of size distribution. Smith (39) discusses the appropriate diameter to use in Durand's equation when a size range exists. The above standard does not apply to the transport in pipes having artificially deformed boundaries, since, in such pipes, even larger particles can be picked up and travel as suspended load due to the induced secondary flow.

2. Basis of Analysis

No adequate theory of the multi-phase flow mechanism in sediment transport in pipes based on the principles of hydrodynamics has so far been developed, primarily due to a lack of understanding of the flow mechanisms involved. From the nature of the problem, however, the resistance equation for the flow of homogeneous fluids in pipelines and the sediment transport theories in open channel flow are useful and adaptable to sediment-fluid flow systems in pipelines. The one-dimensional method of analysis has led to several useful theories, some differing only in detail. Boundary layer theory, turbulence theory, the energy conservation equation, and plastic flow theory are also valuable aids in analysis. Dimensional and inspectional considerations, supported by the insight obtained from the above-mentioned analytical theories, seem to provide the only direct approach to a complete analysis of this complicated multi-phase flow phenomena.

The variables involved in a sediment-fluid flow can be divided into four categories: fluid, sediment, flow and geometry. Tabulating for a straight uniform pipe flowing full:

VARIABLES	SYMBOLS	DIMENSIONS
Fluid		
Mass density	ρ ($\gamma = \rho g$)	M/L^3
Dynamic viscosity	μ ($\nu = \frac{\mu}{\rho}$)	M/LT
Acceleration of gravity	g	L/T^2
Sediment		
Characteristic size (diameter)	d	L
Size distribution (standard deviation)	σ_d	---
Mass density	ρ_s ($\gamma_s = \rho_s g$)	M/L^3
Shape factor	S.F.	---
Flow		
Spatial mean velocity of mixture	V	L/T
Local time-averaged velocity	u	L/T
Hydraulic gradient of mixture flow	J	---

VARIABLES	SYMBOLS	DIMENSIONS
Flow (continued)		
Mean concentration	C_t	---
Local concentration	c	---
Sediment discharge	Q_s	L^3/T
Geometry		
Diameter of pipe	D	L
Slope of pipe	S	---
Surface roughness and shape characteristics of pipe	ϕ	L

Assume one-dimensional flow, so that local flow factors can be considered of secondary importance. Sediment size distribution is neglected. The characteristic settling velocity of sediment in still water (w) may be used to combine the effect of size and shape factors. Dimensional analysis leads to the functional relation:

$$\psi\left(J, \frac{VD}{\nu}, \frac{V}{\sqrt{gD}}, \frac{\gamma_s - \gamma}{\gamma}, \frac{w}{V}, C_t, \frac{\phi}{D}, \frac{Q_s}{Q}, S\right) = 0 \qquad (1)$$

Variation of these dimensionless parameters are made depending on the type of problem under study, any further assumptions, and personal preference.

Summarizing the literature from dimensional consideration, commonly used functions to correlate data are as follows:

Function	Reference
$\psi(J, V, C_t) = 0$	O'Brien & Folsom (34) Newitt & others (33)
$\psi(f, R_e, C_t) = 0 \; : \; f = \frac{2J}{\frac{V^2}{g D}}, \; R_e = \frac{VD}{\nu}$	Chamberlain (8)
$\psi\left(\frac{J - J_e}{J_e}, \frac{V}{\sqrt{gD}}, \frac{\gamma_s - \gamma}{\gamma}, C_t\right) = 0$	Durand (18)
$\psi\left(R_e\sqrt{f}, \left[\frac{I}{\frac{d}{D}}\right]^{\frac{1}{5}} C_t^{\frac{1}{3}}\right) = 0$	Chamberlain (9)

The work of Banister (5) seems to be about the only research available in which an attempt is made to consider the flow system from a micro-scopic, versus the macro-scopic or one-dimensional approach. The case is discussed for which the mass of suspended sediment per unit volume is approximately equal to the mass of air per unit volume. Since the volume of the dust is small, the fluid is considered to have its usual equation of state. It was further assumed that all sediment particles were identical and exerted no static pressure. Equations were presented for the conservation of mass, momentum and energy.

3. One-dimensional Analysis

Completely suspended flow is considered herein, with the solid phase consisting of material larger than 30 microns.

Durand (18) presented an equation of the functional form:

$$\frac{J - J_e}{J_e C_t} = \psi\left(\frac{V^2}{gD} \frac{\sqrt{C_D}}{\frac{\rho_s - \rho}{\rho}}\right), \tag{2}$$

where C_D is a drag coefficient for the sediment particles.

Worster (49) extended Durand's correlation and expanded the formulation to read:

$$\frac{J - J_e}{J_e C_t} = 121 \left[\frac{gD}{V^2} \frac{(\rho_s - \rho)}{\rho} \frac{w}{\sqrt{gd \frac{(\rho_s - \rho)}{\rho}}} \right]^{\frac{3}{2}} \tag{3}$$

Newitt (33) considered analytically the case of heterogeneous suspensions of one and two sizes of materials. For one size it was concluded that

$$\frac{J - J_e}{J_e C_t} = K_1 \cdot \left(\frac{\rho_s - \rho}{\rho}\right) \frac{gD}{V^2} \frac{w}{V}. \tag{4}$$

It should be noted that in the last two of the above equations the mean velocity enters to the third power. The power of the diameter, however, is different. The term K_1 is a constant of proportionality.

Wilson (47) derived an expression for the total energy gradient by making the assumption that the total energy gradient could be divided into two parts: a) a term expressing the rate at which energy is being expended in maintaining the turbulent pipe flow and, b) a term which measures the rate at which energy is being transferred in order to maintain the particles in suspension.

Albertson (1) presented a correlation in the form

$$Re\sqrt{f} = \psi\left(\left[\frac{I}{\frac{d}{D}}\right]^{\frac{1}{s}} \cdot C_t^{\frac{1}{3}}\right). \tag{5}$$

The I and s are determined from supplemental plots. Vogt and White (44) derived the equation

$$\frac{J - J_e}{J_e} = A\left(\frac{D}{d}\right)^2 \left(\frac{\rho}{\rho_s}\,\frac{r}{Re}\right)^{K_2}, \tag{6}$$

where r is the weight ratio of the solids to fluid in the flow. The A and K_2 are functions of the solids and fluid. Their work, combined with that of Segler (38) and Gästerstadt (22), is summarized in Fig. 6.

4. Laminar Flow in Circular Pipes

Laminar transport of sediment is of significance due to the fact that this represents one extremity of flow regimes and is a good starting point for a theoretical approach to the problem.

If the flow is laminar and the distribution of sediment concentration is uniform over the entire flow section, the mixture can be considered as forming a plastic body or a homogeneous fluid. This type of flow occurs only for the transport of very fine sediments with diameters less than 20 to 30 microns. The equations of plastic flow or of viscous fluid flow are applicable. Babbitt and Caldwell (4) studied this type of flow using sewage sludges and clay slurries in water, and confirmed that these latter mixtures behave as true plastics. In plastic flow, yield stress and coefficient of rigidity are the two important coefficients to solve the equation $\tau = \tau_y + \eta \frac{du}{dy}$. Babbitt and Caldwell observed that τ_y and η were dependent on mean concentration C_t, size and other characteristics of the sediments, fluid, temperature, thixotropy, slippage, agitation, and gas constant of the sludge, but independent of size and roughness of the pipes. Clifford (10) applied the theory of viscous flow and computed head loss on the basis of estimated kinematic viscosity of the mixture. The measured head loss checked closely with the estimate. Clifford concluded that sewage sludge acted as a viscous fluid.

The flow, whether it is considered as plastic flow or viscous flow, may be analyzed by established theories -- except for the difficulties of determining the viscosity of the mixture, which is not constant in the case of plastic flow. The head loss is proportional to the mean velocity. The upper limit of this flow regime corresponds to a lower critical Reynolds number of approximately 2000. From a practical viewpoint, the transport of very fine sediments up to 30 microns in diameter by laminar flow should be avoided because the flow is not stable and eventual clogging of pipe may take place. A "critical velocity" at transition from laminar to turbulent flow then serves as a criterion of design.

5. High-turbulence Flow in Circular Pipe

When the flow is turbulent enough so that the distribution of sediment concentration over the flow section is relatively uniform, it is a good approximation to treat the mixture as a homogeneous fluid, with its mass density corrected to account for the presence of the sediment. Then, the resistance equation in turbulent flow can be applied immediately to this homogeneous fluid. Thus, the resistance equation of pipe flow formed the basis of analysis for early investigators. In the Darcy-Weisbach equation $J = \frac{fV^2}{2gD}$ the resistance coefficient f is known to be a function of pipe roughness for large Re -- J is the head loss per unit length of pipe. The head loss J must be expressed in feet of mixture. However, as pointed out by Durand (18), the specific weight of the mixture has little direct effect on the head loss for heterogeneous mixtures. Normally, then, for preliminary design purposes, no distinction needs to be made between head loss in terms of mixture and that in terms of fluid, at least for inert non-interlocking sediments.

Gregory (23) in tests of clay slurry transport through 4-inch pipe, assumed that both the Darcy-Weisbach equation and the Hagen-Poiseuille equation hold at transition from laminar to turbulent flow. Then, the critical velocity is inversely proportional to the density of mixture. The tests of Gregory showed the opposite results, possibly due to questionable values of viscosity of mixture. The pressure drop, furthermore, was not proportional to velocity in the laminar regime. The qualitative conclusion was that the assumption of homogeneity may not be correct. The head losses in the high velocity range were, however, identical with those of clear water flow.

O'Brien and Folsom (34) tested flows of sand-water mixtures and concluded that the Darcy-Weisbach equation is valid for the flow regime where the apparent viscosity has little influence on the flow. According to O'Brien, the principal differences between flows with and without sediments are:

a) effect of settling solids on velocity fluctuation,

b) secondary flow induced by the variation of concentration across horizontal planes,

c) addition of turbulence by settling particles, and

d) breaking of the laminar sublayer by settling particles.

The validity of the Darcy-Weisbach equation in turbulent flow with relatively high velocity and fine sediments in homogeneous suspension was also confirmed by Mikumo (31), Durepaire (19), and Babbitt and Caldwell (4).

6. Low-turbulence Flow in Circular Pipes

When the turbulence is such that it cannot maintain an approximately uniform concentration of the sediment over the flow section, the relationship discussed in the previous section does not hold since the effect of particle settling becomes important. From the early tests made by Blatch (7), it has been observed that the head loss curves of a mixture deviated further from that of pure fluid flow at low velocities and high concentration of sediment. Typical curves of this kind are illustrated in Fig. 1, in which J is plotted against V with C_t as a third variable. The head loss becomes a minimum at a certain velocity. This point was named "the most economical velocity" by Blatch, since it is the velocity at which sediment is transported with the least energy expenditure. Several investigators indicated that this point also represents the start of incipient deposition.

Blatch concluded that the additional head loss for a given velocity is proportional to C_t and was due to the settling of the sediments. Gregory (23) considered that the additional loss is due to interlocking of particles.

A more general presentation of test results than the $J = \psi(V, C_t)$ can be obtained by plotting $f = \psi(Re, C_t)$. This type of plot is shown in Fig. 2. Wilhelm and others (46) reported that fairly good correlation was obtained by the use of apparent viscosity in place of fluid viscosity. Howard (27) also used this diagram and found that f would decrease with an increase in V, and it would increase with an increase in C_t. Minimum head loss occurred when a jerking motion of sediments existed on the bed.

When the particle sizes are increased, the settling velocity of the particles becomes appreciable relative to the mean flow velocity V. This causes a higher concentration of sediment in the lower part of the pipe and some portion of the sediment may be deposited on the bottom. When such a sediment concentration gradient becomes pronounced and is combined with a wide range of size distribution, analysis of the flow system becomes extremely difficult. Quantitative analyses have been made by correlation of significant parameters which have been derived by dimensional or inspectional analysis. As the range of test variables became wider in recent years, various correlation parameters have been proposed to unify all the available test data; such as those of Vogt and White (44), Durand (18), Newitt (33) and Gästerstadt (22).

Typical is the work of Durand (18). Pipe diameters ranged from $1\frac{1}{2}$ inches to 28 inches, uniformly graded sediment sizes varied from 20 microns to 100 mm, concentration from 50 to 600 gram per liter of mixture and the materials included clay, coal powder, sands, gravels, corundum and plastic. Starting with the parameters $\frac{J-J_e}{J_e C_t}$ and V, the final correlation is

$$\psi\left(\frac{J-J_e}{J_e C_t}, \frac{V^2}{gD} \cdot \frac{\sqrt{C_D}}{\frac{\rho_s-\rho}{\rho}}\right) = 0, \text{ Eq 2},$$

which combines the data onto a single curve. Fig. 3 shows this curve for the case of sand and gravel transported in water through pipes. The parameter $\frac{J-J_e}{J_e C_t}$ may be difficult to interpret when the flow has infinitely small concentration of sediment. The theoretical basis for this correlation can be well understood by comparing it with the equations derived by Newitt (33) and Vogt and White (44) -- Eqs 4 and 6.

One of Durand's conclusions is that the drag coefficient C_D corresponding to the terminal settling velocity is the best parameter to represent sediment size. This was deduced from the fact that head loss became independent of grain size when the size exceeded 2 mm.

Chamberlain (9), observing a marked resemblance of the f-Re-C_t curves to the form of the curves presented by Albertson and Ali (1) in an analysis of sediment transport in alluvial open channels, derived the correlation parameters

$$Re\sqrt{f} \propto \frac{V_* D}{\nu} \quad \text{and} \quad \left[\frac{I}{\frac{d}{D}}\right]^{\frac{1}{5}} \cdot C_t^{\frac{1}{3}}$$

mentioned earlier -- Eq 5. Data were correlated as shown on Fig. 5. Even though this correlation did not cover as wide a range as Durand's, the significance lies in the use of $Re\sqrt{f}$, which is proportional to $\frac{V_* D}{\nu}$, thus to D/δ, which is the relative thickness of the laminar sublayer. Thus, a possible step toward unification of sediment-laden flow in pipes and that in open channels has been proposed.

7. Effects of Concentration Gradient on the Transport Characteristics

When the solids are large and the difference in mass density of the fluid and sediment is large, or the mean velocity is small, there will exist a pronounced increase in concentration as the bottom of the pipe is approached. Suspended load theory in open channels supplies background for the analysis of this type of pipe flow, at least in a qualitative sense. There has not been any attempt made to apply quantitatively various equations of suspended load theory. Ismail (28), Chamberlain (8) and Daily and Bugliarello (14) directed some effort toward experimentally evaluating parameters such as the sediment exchange coefficients, the momentum exchange coefficient, the Rouse number, and the Karman universal constant.

Some observations concerning the vertical distribution of sediment concentration and of local velocities are reported by Howard (26), Durand (18) and Chamberlain (8). Integral interpretation of these results remains to be difficult, even though it is apparent that the existence of a mixture mass density gradient has a profound effect on the magnitude of the deviation of head loss curve of the mixture from that of clear water.

Danel (15) discussed the effect of mass density gradient on turbulence. It was proposed that a marked density gradient causes damping of turbulence in the pipeline in the same way as in "evening calm" in the atmosphere. He also points out that the small particles of less than 0.1 mm will also damp the turbulence in the course of settling, whereas larger particles will induce turbulence. Thus, it is predicted that under certain conditions the head loss for sediment flow with marked density gradient may be less than that for clear water, since the decrease of energy dissipation due to damping of turbulence may be more than the increase of energy dissipation to keep the sediment in suspension.

8. Incipient Deposition and Minimum Head Loss

It has been generally accepted that the point of minimum head loss for non-homogeneous flows closely coincides with the point of incipient deposition. The latter point, however, is only loosely confirmed since the visual judgment by the observer of tests is the only criterion. As an example of the possible results, in Gregory's (23) tests, J became constant after the velocity was decreased to a certain point. The highest velocity for which J was a constant for a given C_t was called a "critical velocity". O'Brien and Folsom (34) defined the "critical velocity" as the one at which the head loss began to differ appreciably from that of clear water. The "velocity of incipient deposition" was also defined by O'Brien and Folsom. Below the "critical velocity", an increasing portion of sediments is transported by rolling along the bed as the velocity decreases, eventually resulting in plugging of pipe by accumulated deposition.

Howard (27) concluded that the type of material is the most pertinent factor in determining the point of minimum loss. In tests, the minimum loss occurred when the jerking motion of sediment exists. Durepaire (19) discussed the results of Howard and stated that the jerking motion and the sudden clogging of the entire pipe are problems involving the stability of the flow, which depends on the kinetic head. No jerking motion of sediments occurred in Durepaire's specially designed pumping system.

In the partial deposition range it was observed that J and the depth of deposit increased as discharge decreased for a given C_t. The phenomenon of the incipient deposition was not a reversible process.

Wilson (47) considered that the condition of incipient deposition can be given as $\frac{w}{\sqrt{gRJ}} = \frac{w}{V_*} = 1.$

Durand (18) proposed

$$\frac{V_L}{\sqrt{2gD \frac{\rho_s - \rho}{\rho}}} = \psi(C_t, d)$$

where V_L is the velocity at which deposition starts. For given sands less than 1 mm, V_L varies as C_t and d, while for coarse sands and pebbles $\psi(C_t, d)$ remains constant at a value of 1.34.

Chamberlain (8), derived the function relation

$\frac{V}{\sqrt{gD}} = \psi(C_t, \frac{\phi}{D})$ from dimensional consideration of the incipient deposition. Correlation of the vertical distribution of sediment concentration in a given size of pipe revealed that the diagram of c/C_t versus C_t with $\frac{V}{\sqrt{gD}}$ as the third variable can serve as an absolute criterion of incipient deposition. The concentration c refers to the local concentration at distance 0.06D from the bottom of pipe. Incipient deposition occurs at the maximum point of the curves. A single curve of V_L versus C_t can be prepared for a given d and D. It was suggested that this criterion is particularly useful for fine sand, while, for coarse sands and pebbles, the conventional J-V-C_t diagram is adequate for the purpose.

9. Effects of Size Distribution on Transport

In many engineering applications of sediment transport in pipes, it is quite common that the size of material is not uniform. In spite of the practical importance, the effects of size distribution on the transport characteristics are known only qualitatively at present.

Durand (18) observed that a functional relationship can be extended to a case of mixed size, if the equivalent diameter of the mixture is determined on the basis of a weighted average. The fine solids seem to play an important role in reducing head loss.

Smith (39) considered three definitions of equivalent diameter for mixed size material:

a) diameter of a particle whose volume is equal to the average volume of all the particles;

b) diameter of a particle whose surface area is equal to the average surface area of all the particles;

c) diameter of a particle whose surface area per volume is the average of surface area per volume of all the particles.

The definition (c) gives better results than the other two. The functional relation of the form

$$\frac{J - J_e}{J_e C_t} = K \left(\frac{g D}{V^2} \frac{\frac{\rho_s - \rho}{\rho}}{\sqrt{C_D}} \right)^{1.5}$$

after Durand was not, however, satisfactory for the mixed size sands.

Newitt (33) analyzed a case of two sizes of material. Assuming that the finer component of the mixture contributes to increase the density of the fluid, the equivalent fall velocity of the mixture is always less than the average fall velocity obtained by the independent falling of two solids. In presenting tests of binary mixtures Newitt observed that with 25% concentration of a mixture of sand and gravel for which the size ratio is 1 to 40 the maximum carrying capacity for the gravel was obtained when the mixture contained 15% of sand. This capacity was about 10% higher than that for the 25% concentration of all gravel under the same head loss. The phenomenon is of importance in many applications.

10. Sediment Transport as Saltation Load and Bed Load

For water-sediment mixtures, very few experimental data are available which deal primarily with the saltation regime of transport. Fortunately, however, a considerable amount of knowledge has been accumulated in the field of pneumatic conveyance in which sediments are frequently transported as saltation load.

In general, two basic equations are employed in analyzing penumatic conveyance:

a) the Darcy-Weisbach equation, and

b) the equation of fluid drag on the particles.

Experimental data are usually presented as correlations of the head loss parameter $\frac{J-Je}{C_t\ Je}$ and the rate of total sediment discharge Q_s. Early investigations, such as those of Gästerstadt (22), were based on the assumption of linearity between $\frac{J-Je}{Je}$ and Q_s. Gästerstadt concluded that $\frac{J-Je}{Je} = \frac{G_s}{G_a} \tan \alpha$ for wheat grains transported in 3-inch pipe. Segler (38) investigated the effect of diameter. A linear equation was obtained on a log-log plot of $\frac{J-Je}{Je} \cdot \frac{1}{r}$ against $Re \cdot \left(\frac{d}{D}\right)^2 \cdot \left(\frac{\gamma_s}{\gamma_a}\right)$. Wood and Bailey (48) confirmed the linear relationship of $\frac{J-Je}{Je}$ and $\frac{G_s}{G_a}$. Vogt and White (44) derived the relation

$$\frac{J-Je}{Je} = A\left(\frac{D}{d}\right)^2 \left(\frac{\rho_a}{\rho_s} \cdot \frac{r}{Re}\right)^{K_2}$$

taking into account the turbulent drag force. A and K_2, from analogy of free settling of particles in the fluid, were assumed to be functions of $\frac{\sqrt{1/3(\rho_s - \rho_a)\rho_a g d^3}}{\mu_a}$.

Their tests used sand, steel shots, clover seed, and wheat conveyed in a 1/2-inch pipe and are reproduced in Fig. 6.

Farbar (20) used pyrex conduit to observe the motion of sediments in pneumatic conveyance. At low concentration, the solids seemed to travel in clusters following a sinuous path, striking the wall and deflecting back into the main flow. For higher C_t, there was a tendency for the pressure drop to be independent of concentration. The correlation was J versus G_s with G_a as a third variable.

For the pure saltation flow, reference is made to Durand's relationship $\frac{J-J_e}{J_e \cdot C_t} = \psi\left(\frac{V^2 \sqrt{C_D}}{gD \frac{\rho_s - \rho}{\rho}}\right)$.

The empirical correlation which led to this equation included some data in the saltation regime. The sediment size varied from 2.3 mm to 25 mm, and the pipe size from 104 mm and 150 mm. The flows were in the saltation regime, without any deposition on the bottom of pipe. Durand found that the suspension regime and the saltation regime can be unified onto a single curve at least for the limited range of test variables.

Craven (12) published a paper dealing with bed load transport of sediment in pipes. Various bed load formulas were summarized and after combining with the Darcy-Weisbach formula the following formula was derived:

$$J = \psi\left(\frac{Q_s}{\sqrt{g}\, D^{2.5}}, \frac{\Delta\gamma}{\gamma}, \frac{y_s}{D}, \frac{d}{D}, R_e, \frac{K}{D}\right) \tag{7}$$

where y_s is the depth of deposition layer and K the equivalent roughness height for pipe. Even though tests were not extensive enough to cover all the parameters, a correlation of the results was obtained as

$$\frac{y_s}{D} = \psi\left(\frac{Q}{D^{2.5}}\sqrt{\frac{\rho}{\Delta\gamma}}\left(\frac{Q_s}{Q}\right)^{-\frac{1}{3}}\right) \tag{8}$$

The tentative criterion for design was that $\frac{Q}{d^{1/2} D^2}\sqrt{\frac{\rho}{\Delta\gamma}}$ should exceed 2.5 to prevent the gradual accumulation of permanent deposit. For clay materials, the recommendation was made that $$\frac{Q}{D^{2.5}}\sqrt{\frac{\rho}{\Delta\gamma}}\left(\frac{Q_s}{Q}\right)^{-\frac{1}{3}} \tag{9}$$

should exceed 5 to keep material in motion at all times.

Ambrose (2) extended Craven's work to free surface flow in pipes. A transport function was defined as:

$$\frac{Q}{D^2}\,\frac{1}{Q_s^{1/5}\,g^{2/5}} = \psi\left(\frac{y-y_s}{D}, \frac{y_s}{D}, \frac{d}{D}, \frac{K}{D}, \frac{\gamma_s}{\gamma}, R_e\right) \tag{10}$$

and a discharge function as:

$$\frac{Q}{g^{1/2}\,D^{5/2}\,J^{1/2}} = \psi\left(\frac{y-y_s}{D}, \frac{y_s}{D}, \frac{d}{D}, \frac{K}{D}, R_e\right) \tag{11}$$

Analysis of data showed that the transport function appeared to be solely dependent on the mean geometry $\frac{y-y_s}{D}$. For the discharge function, $\frac{y-y_s}{D}$ and $\frac{d}{D}$ were used as two additional parameters. Correlations were found to be fairly good. This work of Ambrose and Craven was conducted in 5.55-inch and 2-inch pipes transporting quartz sands of 0.25 mm, 0.58 mm and 1.62 mm.

Another discussion is found in Colliery Engineering, October 1956. A stable equilibrium was assumed between the amounts of sediment applied onto the stationary bed by the flow and the amounts transported away from the bed. A probability p was introduced with which a particle on the bed is picked up in a second, and the leaping distance of a particle is ℓ. Since p has a dimension of time and is dependent on the ratio of the hydraulic force on a particle to the resistance of a particle the probability p may be expressed as $p = \frac{V_*}{\ell} \cdot \psi\left(\frac{V_*^2}{gd} \cdot \frac{\gamma_s - \gamma}{\gamma}\right)$.

After simplification and with correlations of test data supplied by Turtle (42), using the Chezy coefficient in place of the hydraulic gradients, the final relationship is

$$\frac{Che - Ch}{\sqrt{g}} \propto \frac{Che}{\sqrt{g}} \left(\frac{w}{V}\right)^{0.173} \cdot \left(\frac{C_t g D}{V^2} \cdot \frac{\rho_s - \rho}{\rho}\right)^{0.413} \qquad (12)$$

The tests by Turtle were carried out in 1-inch pipe. The sediment sizes varied from 1/50 inch to 1/8 inch and the concentration from 6 - 40%.

11. Sediment Transport in Vertical Pipes

For sediment transport in vertical pipes, the basic method of analysis is the same as in horizontal pipes. Some features which are of particular importance for vertical pipes will be briefly discussed. Most of the literature can be found in the field of pneumatic conveyance. Considerable information about sediment behavior in vertical pipes also has been compiled from the rapidly developing field of fluidization.

One of the main features involved in the mechanics of sediment transport in a vertical pipe is the pronounced "slippage" between the particles and the fluid. This slippage is usually expressed as the difference between the fluid velocity and the sediment velocity. If it is assumed that the particles are moving upward with constant velocity, the slip velocity is equal to the settling velocity. In actual transport, however, it has been observed that the particles are subject to accelerations which have some effects on head loss. Energy losses in this type of transport were divided into four parts by Hariu and Molstad (24):

$$h = h_{fg} + h_{fs} + h_s + h_{as},$$

in which h_{fg} is the resistance loss of fluid along pipe wall,

h_{fs} is the resistance loss caused by collision of the solids with the pipe wall and other solids,

h_s is the solids static head loss due to supporting of solids in upward motion, and

h_{as} represents the loss due to acceleration of solids.

In a vertical pipe the solids static head is generally the most important term. If the fluid is accelerated, an additional loss h_{ag} must be considered.

Reports by Vogt and White (44) and Farbar (20) include correlation of vertical transport data, in which the same parameters are used as in horizontal transport. Belden and Kassel (6) confirmed the linear relationship between the relative head loss term $\frac{J-Je}{Je}$ and the term $Re \frac{Ga}{Gs}$ on a log-log plot. By generalizing the Darcy-Weisbach equation, it was concluded that $\frac{f V D \rho_a}{2/d}$ is a linear function of $\frac{G_a G_s}{(G_a + G_s)^2}$. Hariu and Molstad (24) derived analytically an equation of head loss; test results were mostly of a qualitative nature. Acceleration loss in the lower part of a vertical pipe made up a significant portion of the total loss.

12. Effects of Artificial Roughness on the Transport Characteristics

This section summarizes work on some artificial roughnesses, particularly spiral roughness, introduced for the specific purpose of increasing sediment transport in circular pipes.

The U. S. Corps of Engineers has long been experimenting on the design of rifling of pipe. A summary of such a study is given in Howard (26). Using 4-inch and 2-inch pipes, optimum rifling was determined to be 1/3 of the total pipe length. These three rifles were spaced at 120 degrees around the pipe with a pitch of 10D, and the height of rifles was D/8. The qualitative conclusion was that the rifling in the discharge line of a dredge increases the efficiency of the line in cases where the material being dredged would, in a plain pipe, settle out along the bottom in appreciable quantities. Thus rifling increases the efficiency of the line when coarse sands and gravels are transported, and reduces it in other situations when silts and clays are the only phase transported. The efficiency is decreased by introducing rifles in pipe if the velocity and turbulence are already great enough to keep all sediments in suspension. Introduction of rifling gives rise to two opposing effects on the head loss of the flow:

a) it induces additional turbulence which helps to keep the sediment in suspension, thus reducing the head loss,

b) it introduces additional roughness on the boundaries, thus increasing the resistance loss. Effectiveness of rifling is dependent on the balance of these two effects.

Chamberlain (8) compared the flow and transport characteristics of 12-inch Hel-Cor pipe, plain circular pipe and standard corrugated pipe. The results were presented both in J-V-C_t and in f-Re-C_t diagrams. Hel-Cor pipe can usually deliver more sediment discharge with less horsepower than either standard corrugated pipe or plain pipe, when transporting 0.2 mm sand with velocities less than 10 feet per second. Secondary circulation induced by a continuous helical corrugation was more effective in maintaining a nearly uniform concentration over a pipe cross-section than corrugations placed normal to the direction of the mean flow. The head loss of the sand-water mixture was the same as that of clear water flow in all of the boundary roughnesses studied, as long as the sediment was transported in suspension.

Zenz and Othmer (52) report a study using elliptical-horizontal conduits, with the major axis in successive experiments in a horizontal and vertical direction. It was concluded that the circular shape is the optimum for the saltation transport regime.

13. Flow in Elbows

Some amount of physical erosion of straight sections of pipelines occurs. This erosion is negligible compared to that which normally takes place in elbows. At the present time it seems that while some data can be presented on this erosion problem, none is available on the head loss in elbows conveying sediment-fluid mixtures.

Zenz and Othmer (52), covering the work of Schmidt (37) and Olive (35), describe erosion tests of 90 degree elbows, including ones containing a wear plate. A quarter-ellipse model seemed to be effective in decreasing the local intensity of erosion.

The most practical solution to the problem of erosion at bends, either horizontal to horizontal or horizontal to vertical, appears to be by means of a "tee" elbow. One leg of the "tee" is plugged. Sediment accumulates in the area of the plug and forms a flow-turning surface consisting of sediment.

14. Effect of Sediment on Turbulence

Experimental work by Kada (29) and Daily and Bugliarello (13) and (14) constitute sources of information that the turbulence is damped by the presence of sediment in a pipeline flow system.

Kada, working with very small inert, non-interlocking spheres in a small pipeline, concluded that the sediment did not affect the eddies responsible for turbulent diffusion unless there was considerable "slip" between the fluid and sediment. One of the most important works is that of Daily Bugliarello (14), in which measurements of the turbulence intensity and energy spectra are reported. These latter experiments, with dilute suspensions of a long and short paper pulp fiber, indicate that the dimensionless rms turbulence intensities decrease as the concentration increases, other flow conditions being equal. Furthermore, the long fibers seem, until Reynolds number becomes sufficiently high, to shift the energy to the lower frequencies. It was also observed that the friction losses for the suspensions was less than the losses for water at the same Reynolds number.

15. Flow Through Inclined Pipes

Referring only to a direction of flow up slopes of 22.5, 45 and 67.5 degrees in a 1-3/4 inch I.D. lucite pipe, Zenz (51) discusses exploratory experiments using rape seed, salt and powdered magnetite. Pressure drop versus mean air velocity is reported in which the losses were greater than those for a vertical pipe.

At sufficiently high velocities the material is conveyed upward in a well dispersed stream. As the velocity decreases, small unstable ripples or nodes form on the lower portion of the pipe. The forming and breaking of these nodes can cause vibrations or pressure surges to be present. These nodes lead to high energy losses due to their constricting effect. At near vertical slopes these ripples continually slide downward and frequently are associated with a slug flow.

As the velocity is decreased, a layer of material forms on the bottom of the pipe and all the material moving is conveyed in the area above this bed. As the velocity is further decreased, or slope increased somewhat, the bed continually slips downward and the system conveys only small amounts of solids while the rest recirculates within the inclined section.

DESIGN PROBLEMS

As can be seen from the foregoing discussion of the mechanics of fluid transport of sediments, it is rather difficult to establish generalized design criteria. In particular, when the transport is not steady with respect to the flow of the fluid-sediment mixture, as in a dredging operation, the best design criterion can be obtained mainly through scale-model tests and past experience. When the sediment transport and fluid flow are steady, on the other hand, small scale tests as well as the theoretical achievements can render a valuable aid in design. The following discussion will be limited to the case of steady transport, in which the flow velocity and the average concentration of solids remain constant with respect to time.

Since turbulent flows conveying colloidal material, or a uniform suspension, can be considered as a homogeneous fluid and systems designed by accounting for a correction in unit weight, no further reference is made herein to this type of design problem. Design data for pulps in pipelines is too inadequate to be included in the following discussion.

1. Items to Consider

The design of most large installations will involve the following items in the sequence indicated:

a) determination of the quantities of solids to be transported per unit time, the distance the sediment is to be transported, the selection of a fluid medium, and the general operational features;

Because of high fixed costs, a pipeline system does not lend itself to intermittent or occasional operation. As for the length of pipeline, many of the installations already in operation have relatively short lengths of the order of a couple thousand yards to several miles. Coal-water slurries have been successfully and economically transported for a distance of 100 miles or more.

Since pipe transport requires a large volume of fluid, the economic availability of the fluid must be taken into consideration. In many cases it turns out to be more economical to employ a closed circuit system. The operating procedure has significant effects on operation costs, and should be carefully planned so that the maximum economy of operation is achieved while the demand is adequately satisfied.

3. Design of a Pipeline System

The design of pipelines involves several important items, namely:

a) selection of the pipe material on the basis of resistance to wear, corrosion and capital cost;
b) determination of the range of operating velocities;
c) determination of the optimum range of average concentration;
d) determination of the size of pipeline;
e) design of the bends, joints and valves;

f) estimation of the head loss; and

g) design of the supporting foundations.

4. The Pipeline

The size of pipe should be determined so that the required transport rate can be obtained under the given velocity and concentration. The characteristics of the sediments or the capital cost of the pipeline may also be a factor in determining the pipe size. With a certain upper limit, the greater the pipe size, the smaller will be the annual installation costs and operating costs.

It is recommended that, when transporting large materials like rock and gravels, the minimum diameter of the pipe should be at least three times that of the average size of material.

Rifled or helical corrugated pipes are quite effective in transporting medium to large size sediment. Thus, the designer should look into the possibility of using these deformed pipes. Frictional wear by the sediment should not be overlooked. When fine sediments are transported in high concentration, a stable layer of deposited sediment can reduce the wear to a considerable extent, even in smooth pipes.

Estimation of head loss in the straight reaches of pipeline is where the theoretical and experimental work in the literature can be utilized to the maximum benefit. In brief, the head loss can be safely estimated as being equal to that of clear water flow if there is no deposition on the bottom and the velocity is very high. A deviation from the head loss curve of a clear water flow will occur if:

a) the velocity becomes less than about 4 fps;

b) the sediment size is larger than about 5 mm; and

c) a stable deposition layer may be expected to appear on the bed.

If a deviation is to be expected, reference should be made to the specific equations and curves derived by the various investigators. Some excellent references are: Durand (18), Newitt (33), Durepaire (19), Vogt and White (44), Chamberlain (9) and Zenz and Othmer (52).

If a large fraction of the sediment is very fine sand or smaller material, a substantial reduction in head loss may result. Since there is no quantitative information in this connection, a model test will usually be required.

The layout of a pipeline generally follows the topography. The slope of the pipeline should not exceed the angle of repose of the sediment; to prevent clogging during shutdowns.

5. Sediment Concentration in the Pipeline

The range of sediment concentration in relation to the operating velocity is restricted by the requirements of achieving minimum energy loss in the pipeline and preventing the pipeline from plugging. The optimum concentration for minimum head loss can be selected from $J = \psi(V, C_t)$ plots. In addition, it is important to consider:

a) the largest size sediment particle;

b) the size distribution of the sediment;

c) the submerged weight of the sediment; and

d) the characteristics of the pump to be used.

It is important to try several values of concentration, for the sake of maximum economy, since the concentration can be considered as an independent variable in the design. The common range of concentrations is 20 - 40% by volume.

A water-coal ratio (by weight) of 1:1 has been successfully handled. An important feature is the role played by the very fine portions of sediments. These fine sediments help to increase the amount of material which can be transported at a given rate of energy loss. Proper use of a dispersing agent is also helpful in cases where this will keep all the sediment in suspension.

6. Operating Velocity

In the selection of an operating velocity the first requirement is for operation without the clogging of the pipeline. Thus, the velocity should not be reduced below the critical one at which excessive deposition occurs at the bottom of pipe. In other words, some deposition may be unavoidable and perhaps desirable, but it must be stable. Since the bends are the most sensitive locations for deposition, the proper velocity should be selected with full consideration of the bend design, although very few data are available. An estimate of the point of incipient deposition will help in making a sound decision on the operating velocity.

The point of incipient deposition usually coincides with the point of lowest hydraulic loss, at least for materials coarser than fine sand. In general, a velocity of less than 4 fps, in the case of water transporting 2.65 specific gravity sediments in pipelines with a diameter greater than perhaps three inches, is ruled out. The common range is 4 to 25 fps, depending on: a) the average concentration; b) the average size of the sediments; c) the submerged weight of the sediment; and d) the diameter of the pipe.

7. Bends and Joints

Design of the bends and joints is difficult since there is a paucity of data. A sharp bend at the bottom of a vertical pipe is the worst offender from the viewpoint of deposition. Thus, it should be avoided as much as possible. Joints may be accounted for as if a homogeneous fluid flow were present. The angle of such a bend should not be more than 90 degrees. Wear is the controlling factor in the selection of valves.

8. Economics

Since this paper is concerned with the technical phases of sediment transport, a detailed discussion of costs is not included. The importance of the economic aspect can be realized, however, from the fact that for years there has been little doubt about the technical feasibility of proposed installations, even with the paucity of design data. Whenever a pipeline conveyance plan had to be discarded it was because of some economic reason. Frequently the pipeline could not compete with other modes of transportation such as the railroads. Many patents and new ideas have been left unused, since the demands for the products which could be transported were not big or continuous enough. Such a situation has greatly retarded the development of programs for technical achievements in this field.

It is expected, however, that pipeline transport will gradually assume a greater importance in the future. It involves very low labor costs and is subject to nearly complete automation. The advancement in the knowledge of sediment transport achieved in recent years, though meager, points toward a bright future for fluid transport of sediments in pipelines.

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NOMENCLATURE

		Dimensions
A	Constant in Vogt and White head loss equation	---
c	Local concentration of sediment by volume	---
C_t	Mean concentration of sediment by volume	---
C_D	Drag coefficient of sediment particle	---
Ch	Chezy coefficient for mixture flow	$\sqrt{\frac{L}{T}}$
Che	Chezy coefficient for pure fluid flow	$\sqrt{\frac{L}{T}}$
d	Characteristic diameter of sediment	L
D	Pipe diameter, usually nominal diameter	L
f	Darcy-Weisbach resistance coefficient	---
g	Acceleration of gravity	L/T^2
G	Discharge of fluid by weight (G_a refers to air)	ML/T^3
G_s	Discharge of sediment by weight	ML/T^3
I	Non-dimensional number depending on d	---
J	Energy gradient of mixture flow	---
Je	Energy gradient of pure fluid flow	---
K	Equivalent roughness height of pipe	L
K_1	Constant in Newitt's head loss equation	---
K_2	Constant in Vogt and White head loss equation	---
Q	Discharge of mixture by volume	L^3/T
Q_s	Discharge of sediment by volume	L^3/T
R	Hydraulic radius	L
Re	Reynolds number	---
r	Weight ratio of sediment to fluid in flow	---

		Dimensions
s	Non-dimensional number depending on $\frac{d}{D}$, $Re\sqrt{f}$ and C_t	---
S	Slope of pipeline	---
S.F.	Shape factor of sediment	---
V	Mean velocity of flow	L/T
V_L	Limit deposit velocity	L/T
V_*	Shear velocity, equal to $\sqrt{gRJ}$	L/T
w	Terminal fall velocity of sediment	L/T
y	Distance from the bottom of pipe	L
y_s	Depth of deposited sediment layer	L
γ	Specific weight of fluid (γ_a for air)	M/T^2L^2
γ_s	Specific weight of sediment	M/T^2L^2
$\Delta\gamma$	Difference $\gamma_s - \gamma$	M/T^2L^2
μ	Dynamic viscosity of fluid (μ_a for air)	M/LT
ν	Kinematic viscosity of fluid (ν_a for air)	L^2/T
ρ	Mass density of fluid (Pa for air)	M/L^3
ρ_s	Mass density of sediment	M/L^3
σ_d	Standard deviation of size distribution of sediment	---
τ	Shear stress of flowing mixture	M/T^2L
ϕ	Boundary-form parameter for pipe	---
ψ	Read as "function of"	---

OUTLINE OF SELECTED INVESTIGATORS TEST CONDITIONS

Investigators		Fluids	Pipe			Sediment		Remarks
Ref.	Name		Diameter (in.)	Material	Slope	Diameter (in.)	Material	
7	Blatch	Water	1	Galv. Iron Brass	Horiz.	0.0076 and 0.023	Sand	5-35 percent concentration by volume
10	Clifford	Water	5/16		Horiz.		Sewage Sludge	
23	Gregory	Water	4	Cast Iron	Horiz.	0.00048	Clay Slurry	
31	Mikumo and others	Water	1-1/2		Horiz.	0.004	Copper Ore	
34	O'Brien and Folsom	Water	2 3	Wrought Iron	Horiz.	0.007 and 0.015	Sand	2-26 percent concentration by volume
4	Babbitt and Caldwell	Water	1,2,3	Wrought Iron	Horiz.		Sewage Sludge Clay Slurry	Laminar flow investigated. 15-20 percent concentration by weight
46	Wilhelm and others	Water	3/4 1-1/2 3	Steel Brass	Horiz.		Cement Rock Filter Gel	12 to 54 percent by weight
19	Durepaire	Water	2.05	Steel	Horiz.	0.012	Sand	
27	Howard	Water	4	Steel	Horiz.	0.015 and 0.099	Sand and Gravel	10 to 40 percent by weight
4	Babbitt and Caldwell	Water	1/2, 1, 2, 3	Steel	Horiz.		Sewage Sludge	Laminar and turbulent range tested

OUTLINE OF SELECTED INVESTIGATORS TEST CONDITIONS

Investigators		Fluids	Pipe			Sediment		Remarks
Ref.	Name		Diameter (in.)	Material	Slope	Diameter (in.)	Material	
26	Howard	Water	2, 4	Steel	Horiz.	0.0154, 0.0984 0.000906	Sand Gravel Silt	Rifled and plain pipe. 4 to 30 pounds per second
47	Wilson	Water	18 30	Wood Stave	Horiz.		Ore Tailings	Data by Climax Molybdenum Co.
50	Yufin	Water	9.85 11.8		Horiz.	0.00982 and 0.0126		
28	Ismail	Water	Rectangular 10-1/2 X 3		Horiz.	0.00394 0.00630	Sand	0.015 - 31 percent by weight
12	Craven	Water	2 and 6	Lucite	Var.	0.00984 0.0228 0.0638	Quartz Sand Sand	
2	Ambrose	Water	2 and 6	Lucite	Var.	0.00984 0.0228 0.0638	Quartz Sand Sand	
18	Durand	Water	1.57 to 22.8	Steel	Horiz.	0.00787 to 0.984	Sand and Gravel	
8	Chamberlain	Water	12	Steel	Horiz.	0.00787 0.0256	Sand	Plain, corrugated and Hel Cor pipe. 0.15 - 20 percent concentration.

OUTLINE OF SELECTED INVESTIGATORS TEST CONDITIONS

Investigators		Fluids	Pipe			Sediment		Remarks
Ref.	Name		Diameter (in.)	Material	Slope	Diameter (in.)	Material	
33	Newitt and others	Water	1	Brass	Horiz.	0.008 to 0.235	Perspex, coal, sand, gravel and man-gonese dioxide	
39	Smith	Water	2 and 3		Horiz.	0.008 0.012 0.047	Sand	Mixed Size
41	Thomas	Water	3/4	Glass	Horiz.	0.0000157	Thorium oxide	Mixed size
14	Daily and others	Water					Wood Pulp	Measured turbulence. Long and short fibers.
22	Gasterstadt	Air	3		Horiz.		Wheat	Air speed 50-60 fps
38	Segler	Air	1.77 to 16.5		Horiz.		Wheat Oats	Air speed 75 fps
48	Wood and Baily	Air	2.9		Horiz.		Sand Linseed	Air speed 50-125 fps
44	Vogt and White	Air	1/2		Horiz. and Vert.	0.0080 to 0.0287 0.0165 0.0460 0.158	Sand steel shot clover seeds wheat	Air speed 30-120 fps

OUTLINE OF SELECTED INVESTIGATORS TEST CONDITIONS

Investigators Ref.	Name	Fluids	Pipe Diameter (in.)	Pipe Material	Pipe Slope	Sediment Diameter (in.)	Sediment Material	Remarks
20	Farbar	Air	0.67	Pyrex	Horiz. and Vert.	0.000787 to 0.00866	Catalyst	Air speed 40-80 fps
6	Belden and Kassel	Air	0.473 1.023	Steel	Vert.	0.0379 0.0764	Catalyst	Air speed 12-57 fps
24	Hariu and Molstad	Air	0.267 0.532	Glass	Vert.	0.0084 to 0.0198 0.0043	Sand Catalyst	Air speed 12-40 fps
25	Hinkle	Air	2, 3		Horiz.	0.014 to 0.33	Polystyrene beads tenite pellets and others	Air speed 60-120 fps
52	Zenz and Othmer	Air	1.75		Horiz. and Vert.	0.0066 to 0.066	Rape seeds sand glass beads	Air speed 3-40 fps
45	Wen	Air	0.364 0.5 0.7 1.0		Horiz.	0.0028 to 0.011 0.0044 to 0.0297	Glass beads coal	Air speed 0.2-60 fps

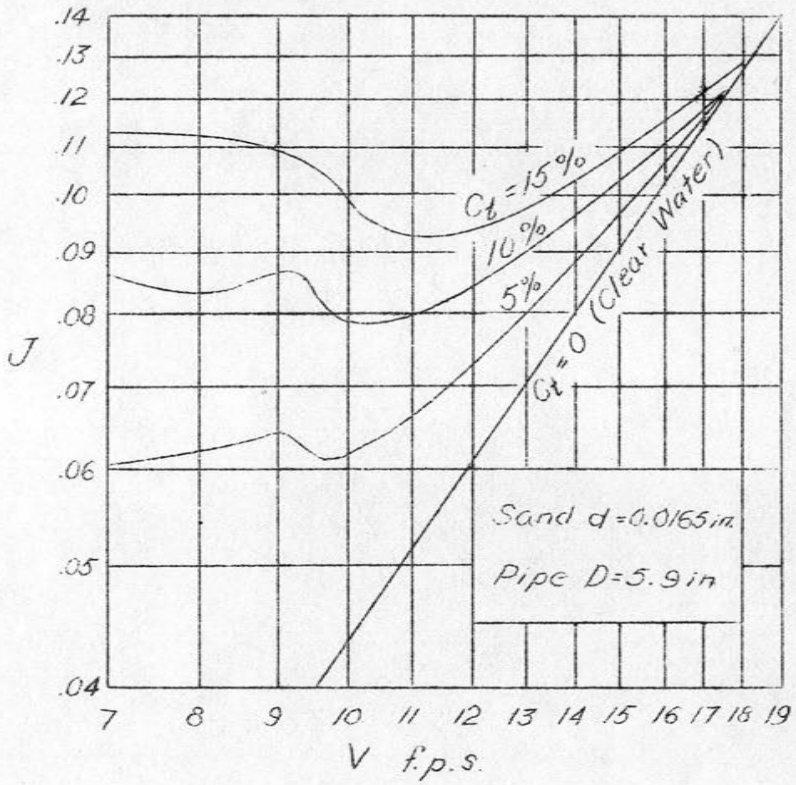


Fig. 1 Typical head loss curve for sediment transport in a horizontal pipe (Durand -- Ref. 18)

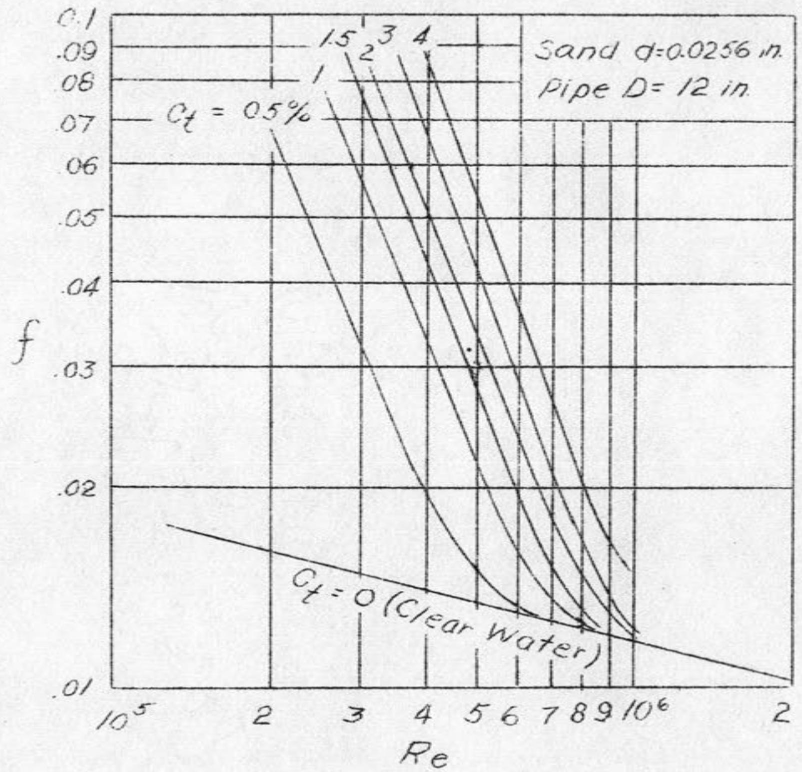


Fig. 2 Typical resistance curve for sediment transport in a horizontal pipe (Chamberlain, Garde, and Albertson -- Ref. 9)

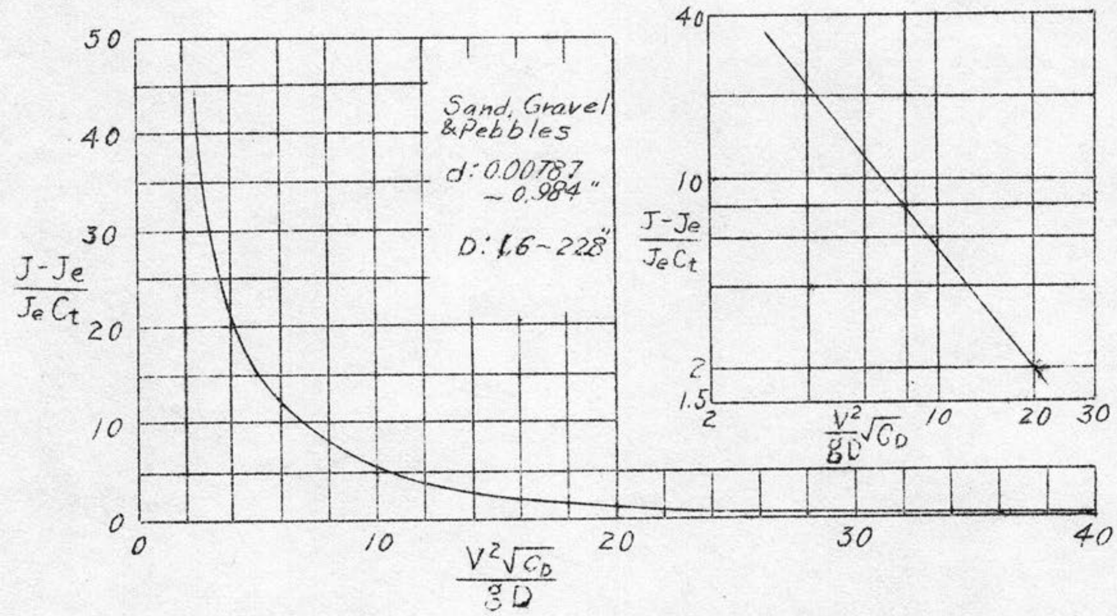


Fig. 3 Correlation of sediment transport in horizontal pipes. (Durand -- Ref. 18)

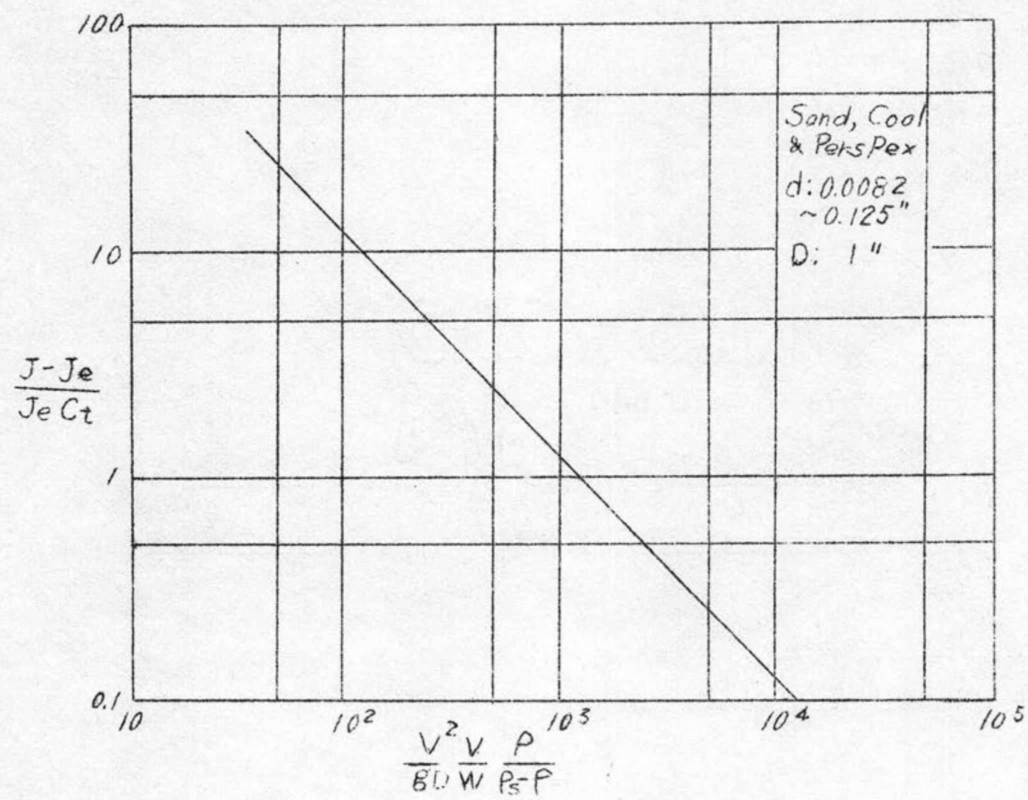
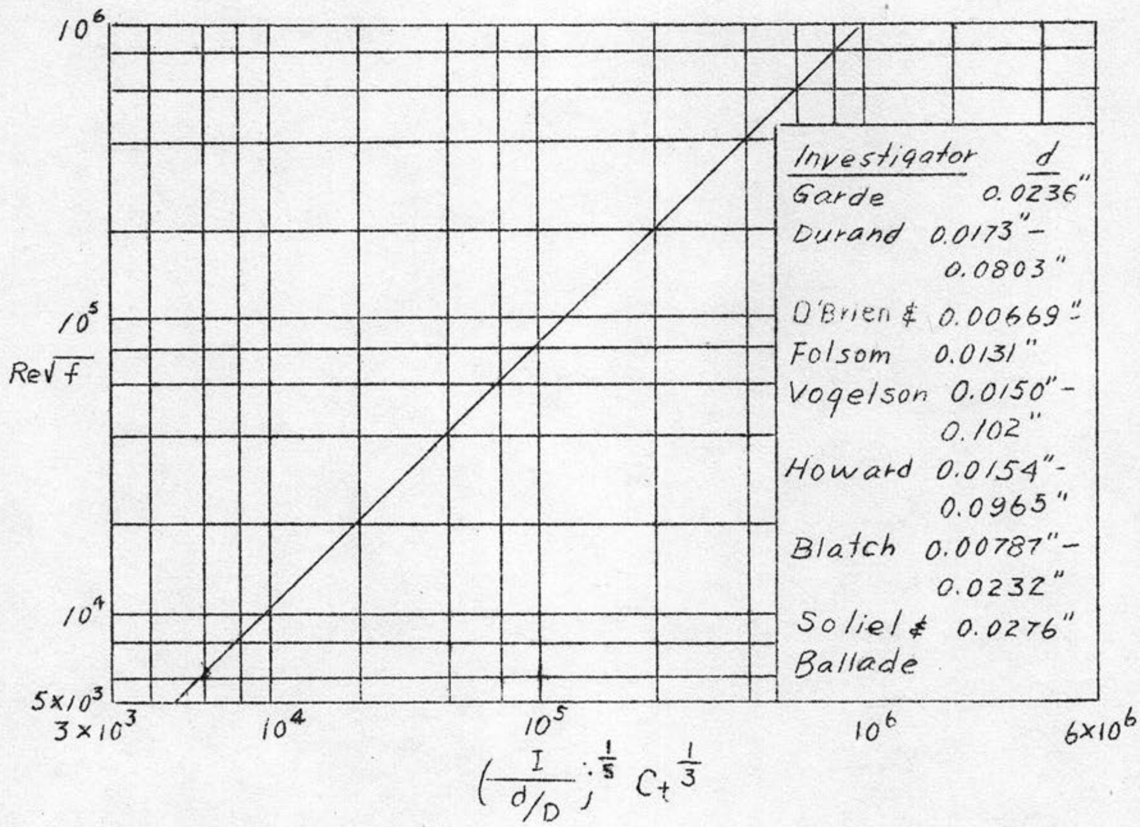
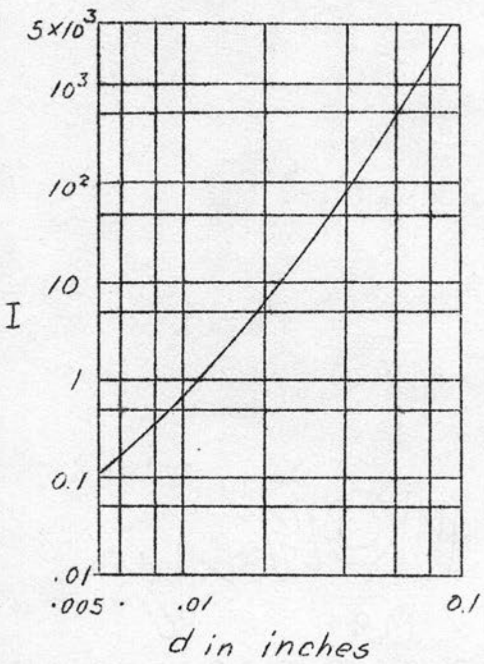


Fig. 4 Correlation of sediment transport in pipes. (Newitt, Richardson, Abbott and Turtle -- Ref. 33)





s in the above parameter is the slope of the curves of constant d on a plot of d/D vs P; where P is the intercept of plots of $Re\sqrt{f}$ vs C_t for a given d/D.

Fig. 5 Correlation of sediment transport in horizontal pipes. (Chamberlain, Garde and Albertson -- Ref. 9)

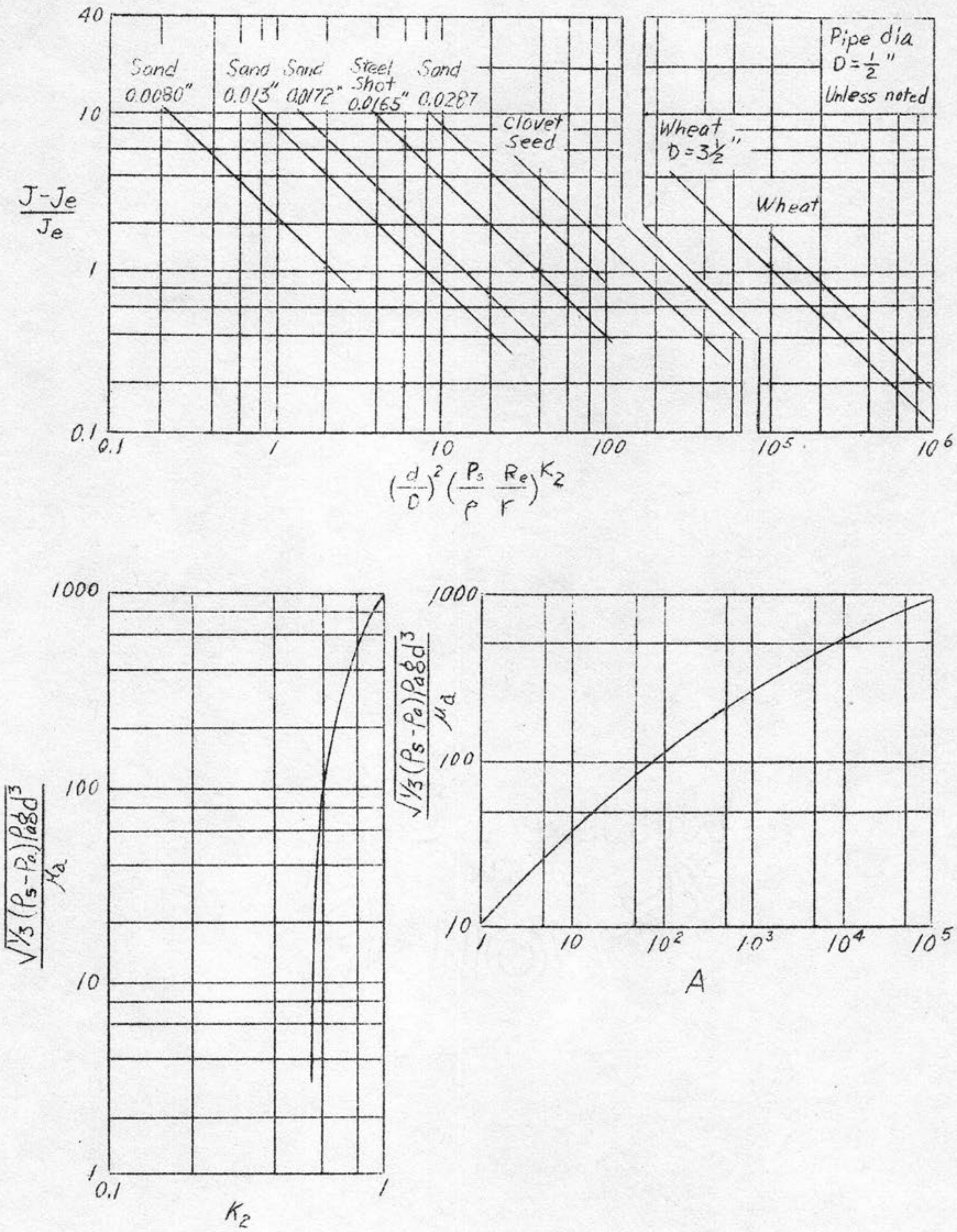


Fig. 6 Correlation of sediment transport in horizontal pipes. (Vogt and White -- Ref. 44)