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Part I

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CRITICAL VELOCITY FOR SOLID-LIQUID MIXTURES; THE LEHIGH EXPERIMENTS

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CRITICAL VELOCITY FOR SOLID-LIQUID MIXTURES; THE LEHIGH EXPERIMENTS

ABSTRACT

The critical (deposit) velocity for solid-liquid mixture is this velocity below which solid particles settle out and form a stationary bed (not moving bed).

First an analysis is presented which considers the hydraulics of such a system. Then experimental data reported in the literature and the ones obtained at Lehigh are used to test the validity of the analysis.

The present findings will be helpful for design purposes.

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1. INTRODUCTION

The present investigation is a search for the mixture flow velocity in a closed conduit which separates the "deposit free" regime from the "deposit" regime. This boundary velocity will be referred as the "critical velocity", V_C (sometimes it is called the minimum transport velocity).

Of all the dimensionless parameters used in hydraulics, it seems reasonable to expect that the Froude number, N_F, presents a good criterion for solid-liquid flow through pipes. In the present investigation numerous experiments, reported by different researchers, have been examined with the help of a modified Froude-number. The general relation is given with equation (4) and summaries of the experimental data are given with Figures 2 to 5. The quality of the relation depends upon desired accuracy as well as upon the desired range of the information.

2. ANALYSIS

Moving a solid-liquid mixture through a horizontal closed conduit one may expect the following variables to be of importance:

$$f\ (V,D,\epsilon,\rho,\nu,g,\rho_s,d,d_{90}/d_{50},C) = 0 \qquad (1)$$

in which V is the mixture's flow velocity, D is the conduit diameter, ϵ is the conduit roughness value, ρ and ρ_s are the density of water and of particles, respectively, ν is the viscosity of water, g is the gravitational constant, d is the (average) particle diameter, d_{90}/d_{50} is a grain size nonuniformity parameter, and C is the volumetric particle concentration. Proper grouping results in:

$$f\left[\frac{V}{\sqrt{gD}}, (s_s-1), \frac{d}{D}, \frac{\epsilon}{D}, \frac{d_{90}}{d_{50}}, \frac{VD}{\nu}, C\right] = 0 \qquad (2)$$

It is expected that the flow Reynolds number, $(VD)/\nu$, does not play a significant role in the problem, and equation (2) may be simplified to read:

$$f\left[\frac{V}{\sqrt{gD}}, (s_s-1), \frac{d}{D}, \frac{\epsilon}{D}, \frac{d_{90}}{d_{50}}, C\right] = 0 \qquad (3)$$

Replacing the critical velocity, V_C, for the general flow velocity, V, and further rearranging equation (3), one obtains:

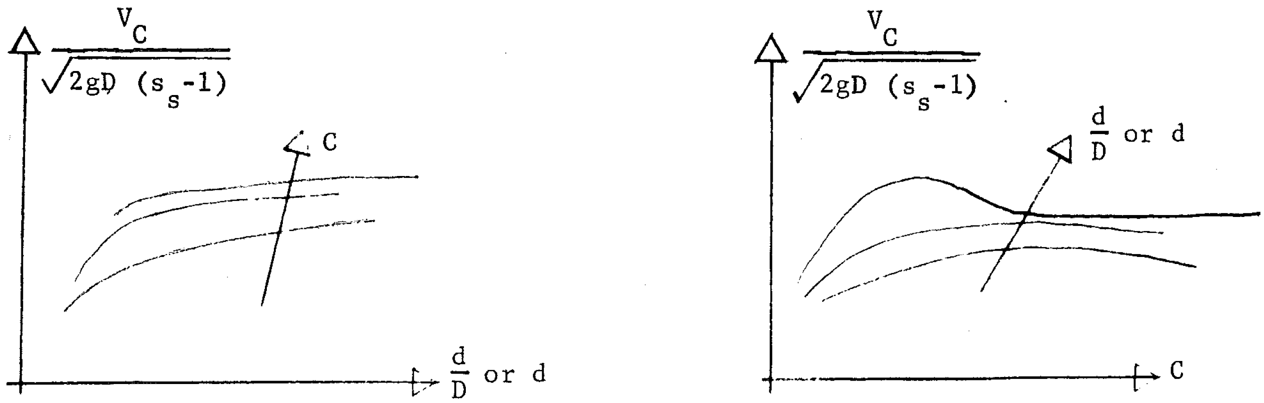
$$f\left[\frac{V_C}{\sqrt{2gD\ (s_s-1)}}, \frac{d}{D}, \frac{\epsilon}{D}, \frac{d_{90}}{d_{50}}, C\right] = 0 \qquad (4)$$

Note that the above equation is somewhat similar to relations proposed by DURAND (1953) and BARR et al. (1968).

The applicability of equation (4) shall be tested with experimental data. An attempt will be made to summarize the data on a plot, such as:

$$\frac{V_C}{\sqrt{2gD\ (s_s-1)}} = f\left[\frac{d}{D}, C\right] \qquad (5)$$

as given in Figure 1, and stated over what range of roughness, ϵ/D, and of nonuniformity, d_{90}/d_{50}, they are applicable. Note, the left-side of equation (5) is a modified Froude number. Further note that without loss of generality it may become frequently important to replace the relative particle diameter, d/D, by the particle diameter, d, itself. In the subsequent discussion we have chosen to represent the data in the way suggested with Figure 1a.



(a) $\frac{V_C}{\sqrt{2gD\ (s_s-1)}}$ vs. $\frac{d}{D}$ or d

with C as parameter

(b) $\frac{V_C}{\sqrt{2gD\ (s_s-1)}}$ vs. C

with d/D as parameter

Figure 1 Plot of equation (5)

3. EXPERIMENTS

3.1 Gibert's Experiments

GIBERT (1960) has presented a relationship which is the best-fit curve to about 250 data points. As such, this study represents to date the most exhaustive experiment. Unfortunately, the raw data themselves are not available, and it is therefore that only the best-fit curve was replotted and studied. This is done in Figure 2, where the modified Froude number, $V_C/\sqrt{2gD\ (s_s-1)}$, is plotted against the particle diameter, d, with the concentration, C, as parameter. The range of parameters of the data used to establish Figure 2 is given in Table 1. While the experiments are limited to sand-water mixture only, there exists a good reason to believe - from a detailed study of GIBERT (1960) - that other solid-liquid mixtures are represented by the modified Froude number. The range of sand size is considerable but all are rather uniform. Two different conduits were investigated. From Figure 2 it is apparent that both concentration and particle diameter are in functional relationship with the modified Froude

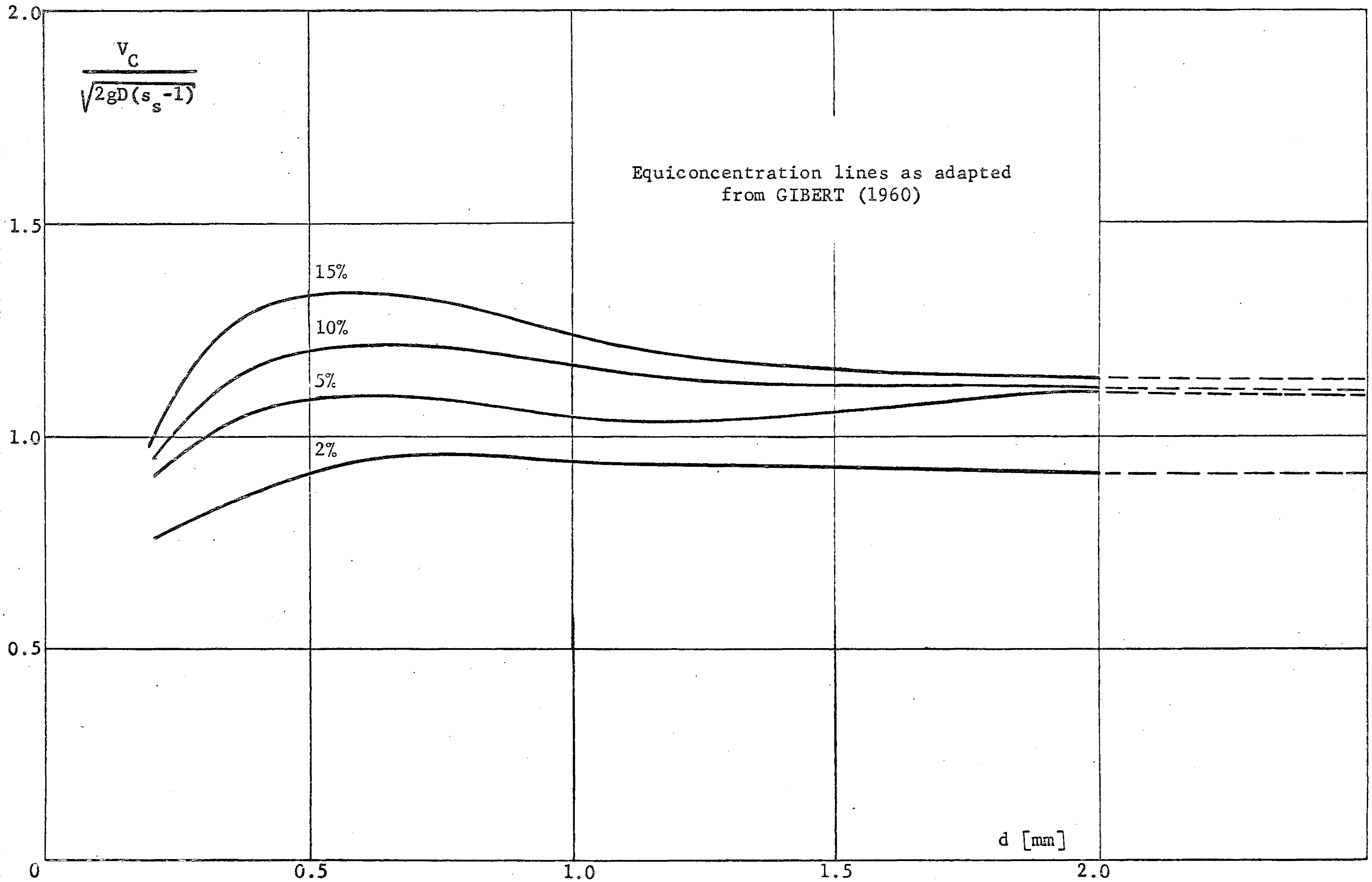


Figure 2 Modified Froude number versus particle diameter, concentration as parameter (after GIBERT (1960))

	Pipe Size D	Pipe Material	Flow Velocity V	Sediment Size d [mm]	Sediment Uniformity d_{90}/d_{50}	Sediment Concent. C	Relative Density ρ_s/ρ	Remarks
GIBERT (1960)	40.2, 150.0 mm	ε=0.00015	1.3 to 5.6 m/s	0.20, 0.39, 0.89, 2.05, and 4.20	1.2 all	up to 15%	2.65 Sand/Water	
BLATCH (1906) △ ⧍	1"	Brass and Galv. Iron	1.0 to 18.0 fps	0.180 and 0.590	1.10 1.16	up to 42%	2.64 Sand/Water	V_C is obtained from head-loss curves
NEWITT et al. (1955) ⧏	1"	Brass	2.0 to 12.0 fps	0.208, 0.762, and 3.81	1.10 all	up to 35%	2.64, 2.55 Sand/Water	V_C is obtained from head-loss curves
FÜHRBÖTER (1961) ⬡	0.3 m	Metal	2.0 to 6.0 m/s	0.19, 0.27, 0.53, 0.88	1.7 to 2.7	up to 25%	2.64 Sand/Water	V_C is reported
SINCLAIR (1962) ○ ○ ○	0.5, 0.75, 1.0"	Brass	—	0.35, 0.68, 0.42, 0.53	1.35 1.40 1.19 1.11	up to 20%	2.61 Sand/Water	V_C is reported
SASSOLI (1963) D D	0.08, 0.05 m	Steel, Plastic, Vetro-flex	1.1 to 3.7 m/s	0.22, 0.32, 0.83	1.45 1.56 1.50	up to 18%	2.65 Sand/Water	V_C is obtained from head-loss curves
LEHIGH EXPERIMENTS	4" 6"	Galv. Iron ε=0.0001 Black Steel ε=0.00065	2.4 to 11.4 fps	0.88 0.45	1.20 1.07	up to 15%	2.65 Sand/Water	V_C is obtained from observation through plastic test section and from head-loss curves

Table 1: Range of parameters of the data used by GIBERT (1960) and other investigators; for sand/water mixtures; data are used to establish Figures 3 and 5 to 8.

number. In what follows we shall try to investigate as to how other experimental data compare with GIBERT's (1960) findings.

3.2 Sand-Water Mixtures

Researchers like BONNINGTON (1961) and CONDOLIOS et al. (1963) and others quote general agreement with the relationship given with Figure (2); they do, however, not report their findings. However, some researchers report their findings and we shall compare these with GIBERT's (1960) relation. It must be said in all fairness that many researchers have reported on sand-liquid studies, but from all of these only the studies by BLATCH (1906), NEWITT et al. (1955), FÜHRBÖTER (1961), SINCLAIR (1962), and SASSOLI (1963) rendered useful data for the present investigation. The ranges of parameters under consideration are listed in Table 1, while the data are plotted in Figure 3.

3.3 Other Solid-Liquid Mixtures

To show the general usefulness of the modified Froude number data from other solid-liquid mixtures were studied. WORSTER et al. (1955) and SINCLAIR (1962) reported on coal-water mixtures, WILSON (1965) on nylon-water mixtures, and SINCLAIR (1962) on iron-kerosene mixtures. Again, the data are compared with GIBERT's (1960) results as shown in Figure 4; the ranges of parameters are summarized in Table 2.

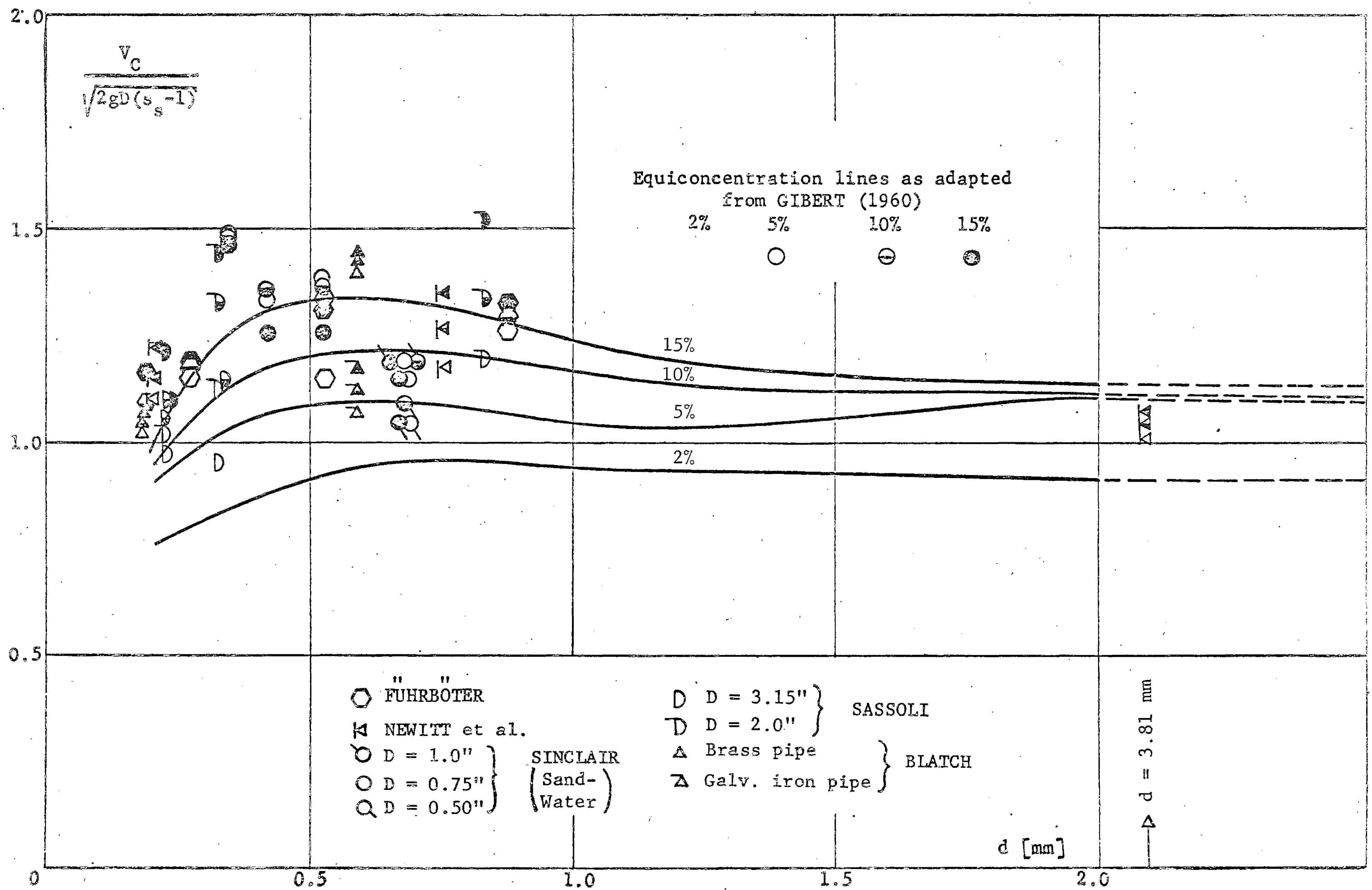


Figure 3 Modified Froude number versus particle diameter, concentration as parameter (data from sand/water mixtures)

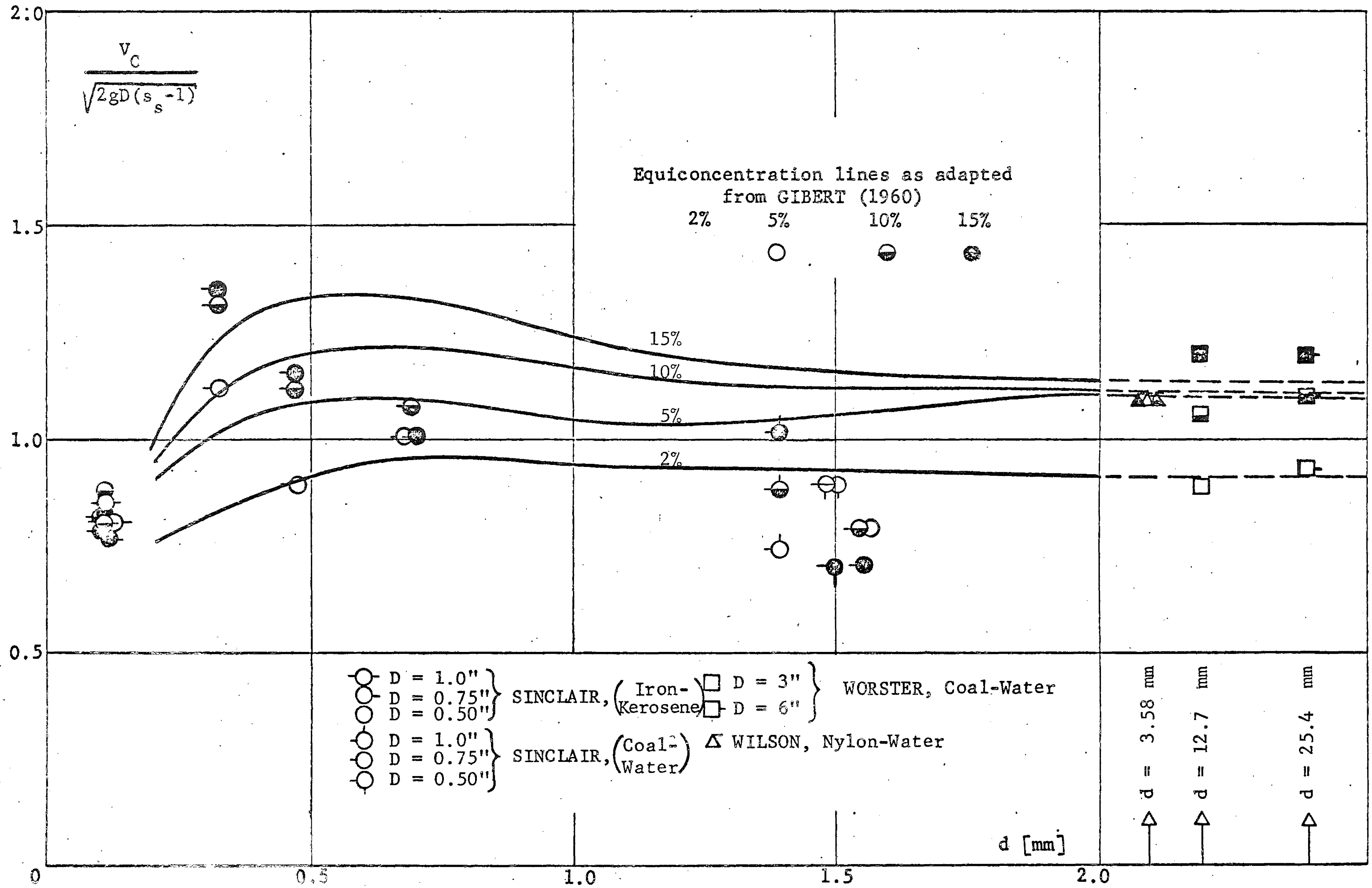


Figure 4 Modified Froude number versus particle diameter, concentration as parameter (data from other mixtures)

	Pipe Size D	Pipe Material	Flow Velocity V	Sediment Size d [mm]	Sediment Uniformity d_{90}/d_{50}	Sediment Concent. C	Relative Density ρ_s/ρ	Remarks
WORSTER et al. (1955) □ □-	3, 6"	Steel	1.0 to 8.0 fps	12.5, 25.0	1.5	up to 20%	1.5 Coal/ Water	V_C is obtained from head-loss curves
SINCLAIR (1962)	0.5, 0.75, 1.0"	Brass	—	0.33, 0.48 0.70 1.40, 1.50, 1.56	1.40, 1.25 1.42 } 1.41	up to 20%	1.41 Coal/ Water	V_C is reported
SINCLAIR (1962)	0.5, 0.75, 1.0"	Brass	—	1.19	1.16	up to 20%	10.37 Iron/ Kerosene	V_C is reported
WILSON (1965) △	3.48, *3.69"	Plastic, Alumin.	1.5 to 12.8 fps	3.88	1	up to 20%	1.138 Nylon/ Water	V_C is obtained from head-loss curves

*Square Conduit

Table 2 Range of parameters of the data used by GIBERT (1960) and other investigators; for solid/liquid mixtures; data are used to establish Figure 4.

Lehigh Experiments

To check the validity of equation (5) experimentally a laboratory setup was designed and built at Lehigh University. The equipment is most versatile and allows careful observation of the critical velocity, V_C through a transparent pipe section. The range of discharge is $0.1 < Q < 1.4$ cfs, and the system handles up to 17% of volumetric concentrations. Tests were done with two rather uniform sands of $d = 0.88$ mm and $d = 0.45$ mm for a galvanized 4" pipe and a black steel 6" pipe. The pipe slope was horizontal, downward, and upward inclined.

The experimental data are tabulated and plotted in Appendix I. The critical velocities, V_C, for the different concentrations, C, were subsequently obtained and tabulated in Appendix II, where also the modified Froude numbers, $V_C / \sqrt{2gD(s_s-1)}$, are given.

The information summarized in Appendix II allows now comparison of the Lehigh data with a plot of equation (5), such as suggested with Figures 1a and 1b. For horizontal pipe slopes this is done in Figures 5a and 5b as well as Figures 6a and 6b; for inclined pipe slopes in Figure 7a and 7b as well as Figures 8a and 8b. Also plotted on Figures 5 through 8 are the best fit curves adopted from GIBERT (1960) which were discussed earlier in Section 3.1.

It is safe to say that the Lehigh data from the horizontal pipe experiments, shown with Figures 5 and 6, are in reasonable agreement with GIBERT's (1960) best fit curves. As is exhibited by Figures 5b and 6b, the Lehigh experiments indicate - for a system where the parameters do not vary - larger V_C-values then the relation of GIBERT (1960) indicates. The maximum differences, however, never exceed 15%, whereby the Lehigh values would be on the conservative side.

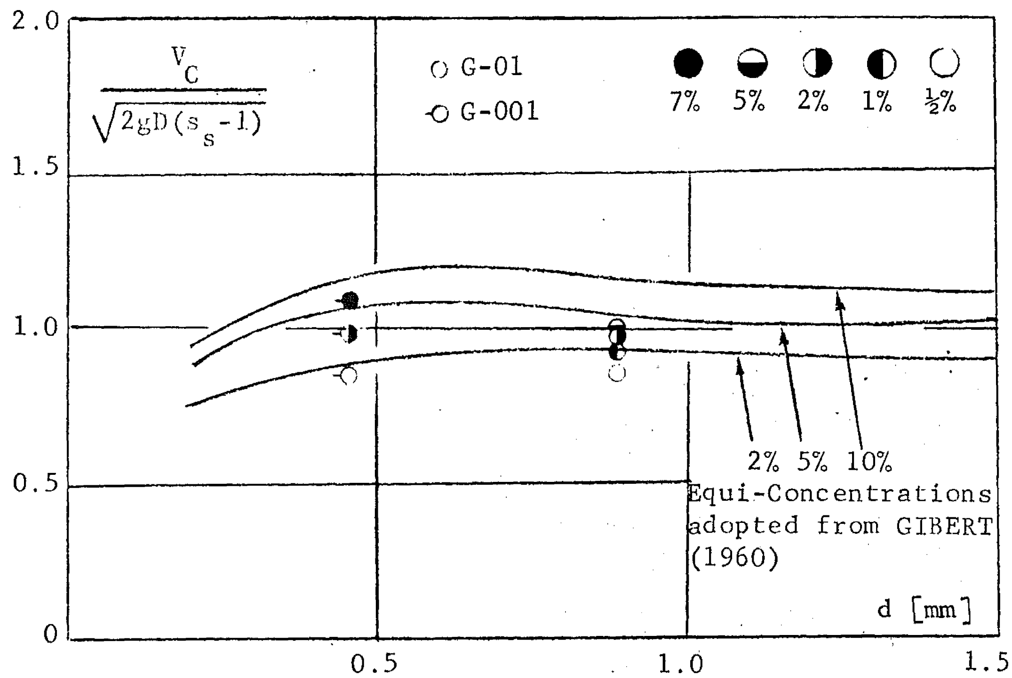


Figure 5a Modified Froude number versus particle diameter, concentration as parameter for horizontal, 4-inch galvanized pipe.

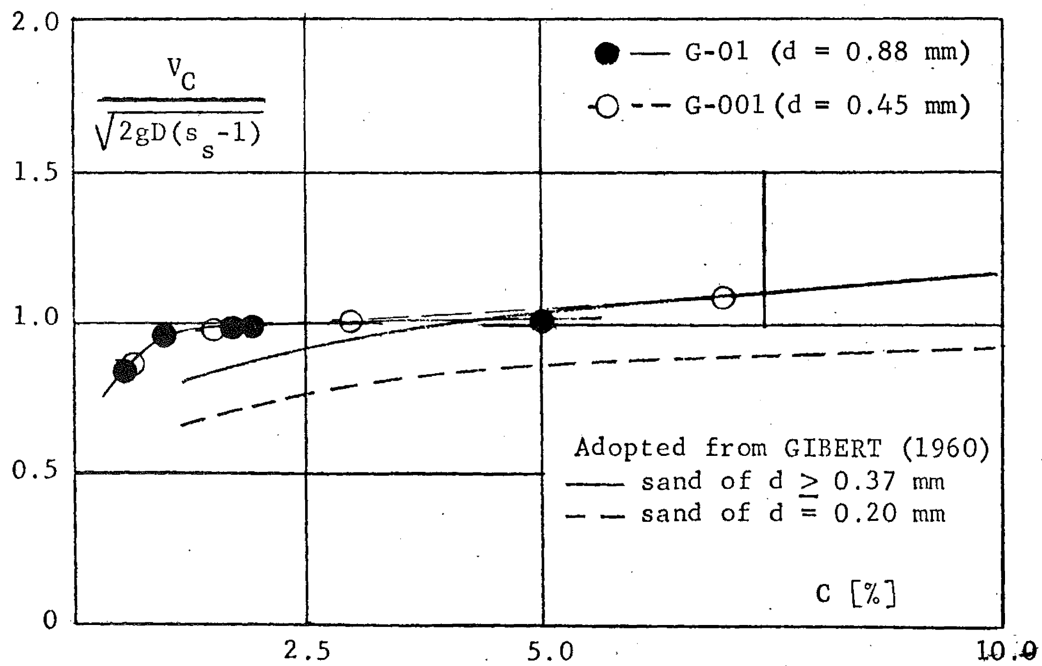


Figure 5b Modified Froude number versus concentration, particle diameter as parameter for horizontal, 4-inch galvanized pipe.

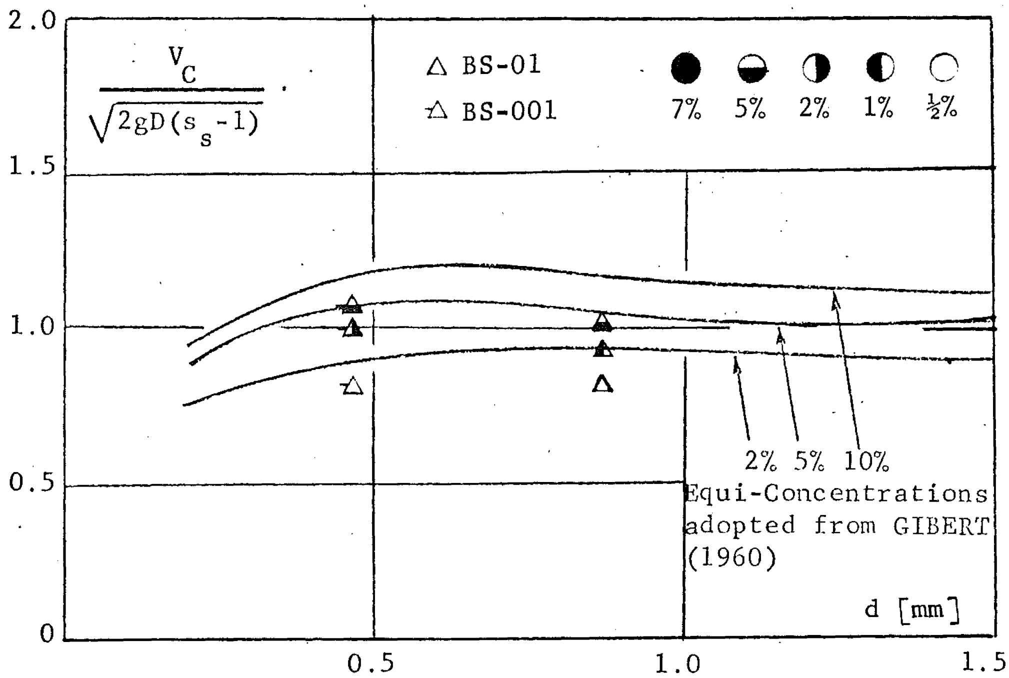


Figure 6a Modified Froude number versus particle diameter, concentration as parameter for horizontal, 6-inch black steel pipe.

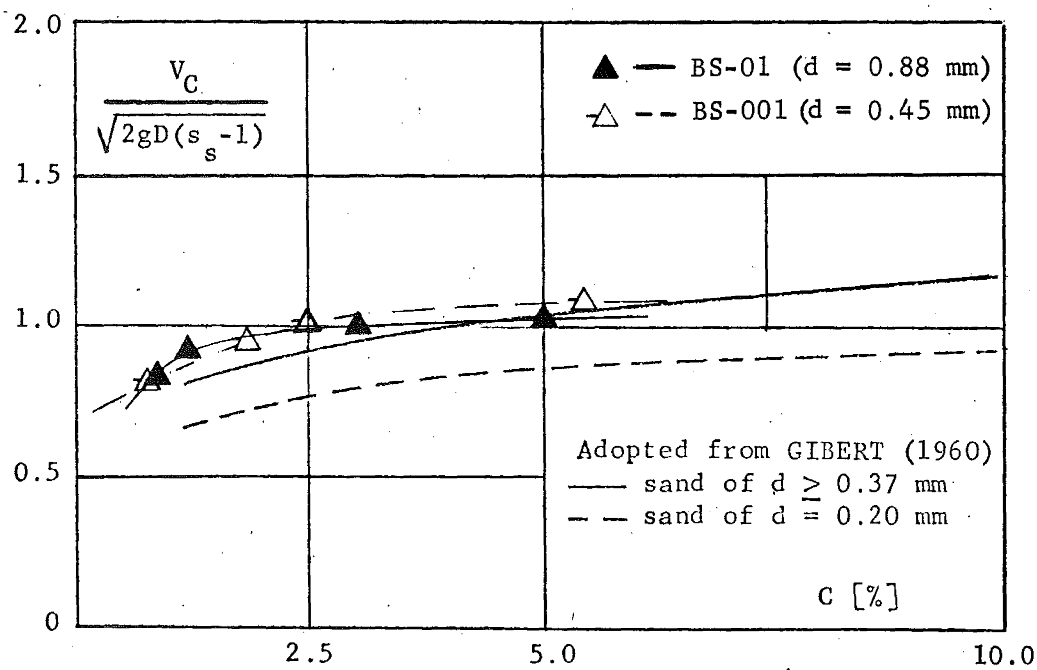


Figure 6b Modified Froude number versus concentration, particle diameter as parameter for horizontal, 6-inch black steel pipe.

The inclined pipe experiments of the Lehigh data are plotted on Figures 7 and 8 and again are compared with the best-fit curve of GIBERT.

The Lehigh data are limited to one set of tests for a downward (S = 0.060) and another one for an upward (S = 0.027) sloping pipe. While these experiments should not be generalized beyond its limits, they are in reasonable agreement with the best fit curves of GIBERT (1960).

4. DISCUSSION

The experimental data on Figures 3 through 8 have a tendancy to agree with the curves given with Figure 2 but do not exactly match with it. However, this is not at all a surprising result; it is part of the nature of any sedimentation study. At this point it should also be pointed out that a certain amount of inaccuracy is introduced into the data since it is, at times, difficult to read off the V_C-value from the reported head-loss curves.

In general, it is our feeling that the trend established by GIBERT's (1960) relation of Figure 2 is often well reflected in both the sand-water and solid-liquid mixtures data. The data used in the present study covered the following ranges: for pipe size: $0.0125 < D < 0.3$ m, for particle size: $0.18 < d < 25$ mm, for sediment uniformity: $1 < d_{90}/d_{50} < 2.7$, for sediment concentration: up to 42%, for relative density: $1.138 < s_s < 10.37$, and for different kinds of pipe materials (roughnesses).

5. CONCLUSION

As a result of this study, the following is recommended:
The critical velocity, which is the velocity which separates the "deposit free" from the "deposit" regime, may safely be obtained for design purposes from the relation given with equation (5) and with Figure 2.

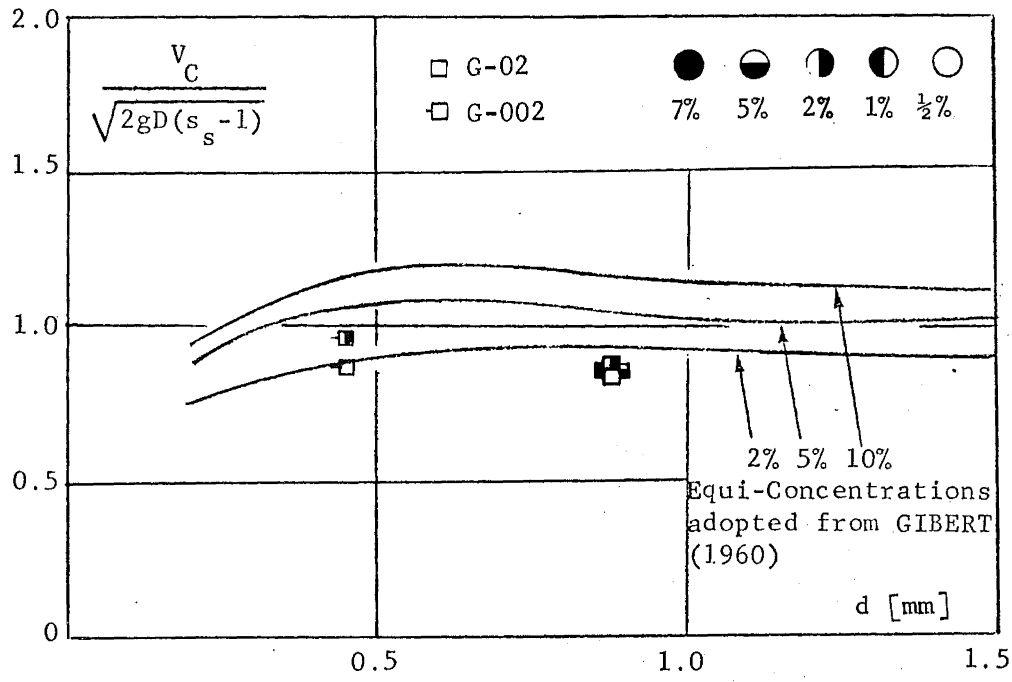


Figure 7a Modified Froude number versus particle diameter, concentration as parameter for downward sloping, 4-inch galvanized pipe.

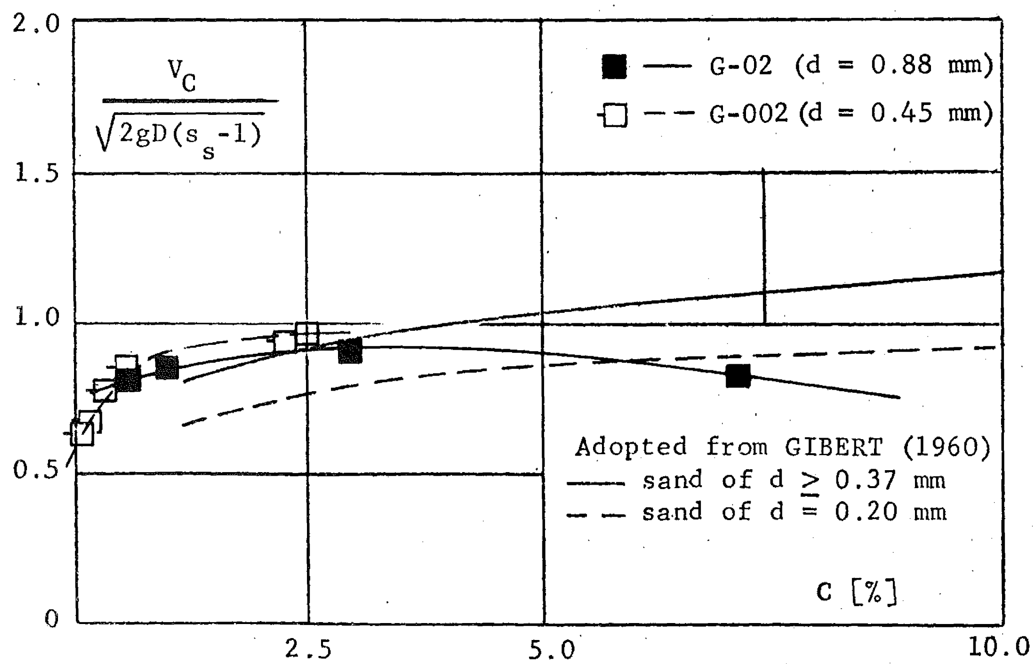


Figure 7b Modified Froude number versus concentration, particle diameter as parameter for downward sloping, 4-inch galvanized pipe.

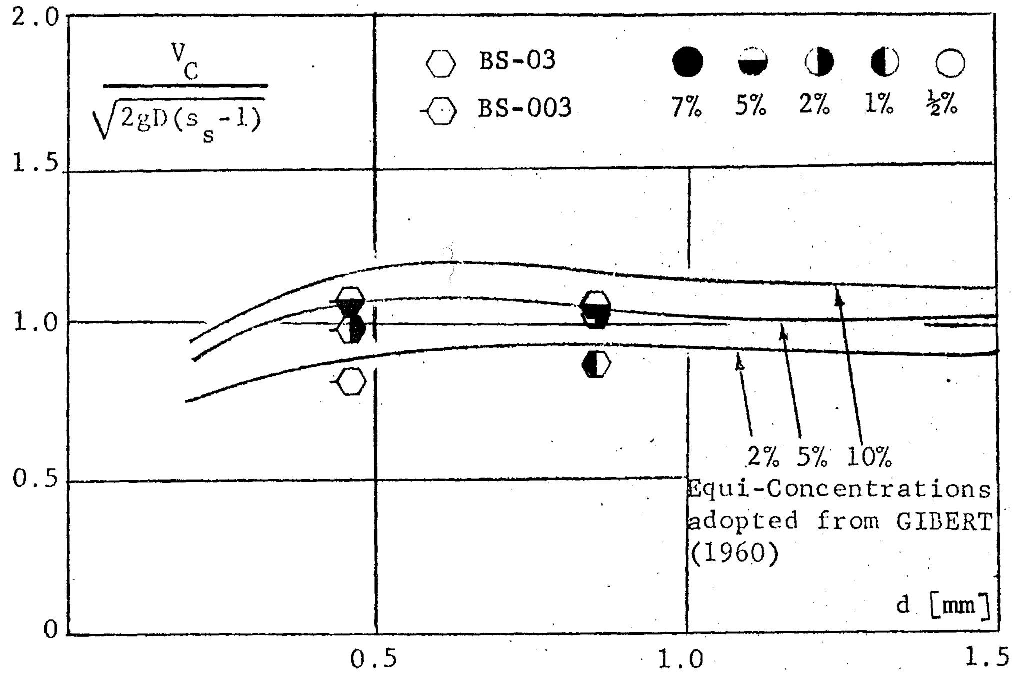


Figure 8a Modified Froude number versus particle diameter, concentration as parameter for upward sloping, 6-inch black steel pipe.

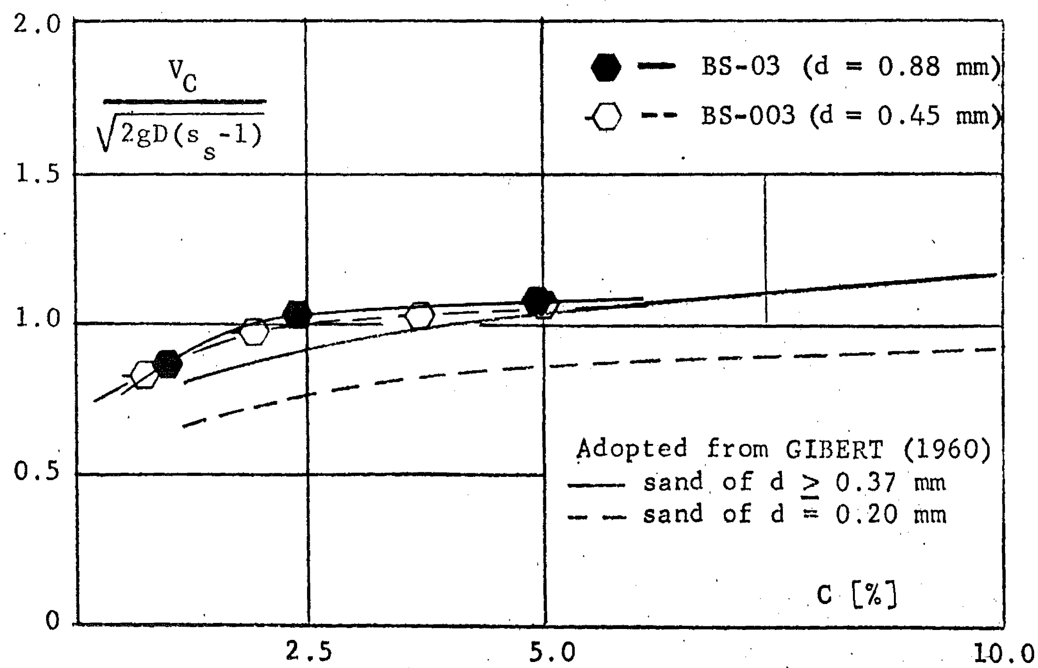


Figure 8b Modified Froude number versus concentration, particle diameter as parameter for upward sloping, 6-inch black steel pipe.

Figure 2 and/or equation (5) suggest the following trends:

The critical velocity, V_C, is-for a given particle size, d, and a given concentration, C,-directly proportional to the square root of the pipe diameter, D, and of the specific particle density of, s_s.

Further, for a given pipe-size, D, and particle density, s_s, one observes the following: The critifal velocity, V_C, increases with concentration, C, the increase being more evident at smaller particle diameters, $d \approx 0.5$ mm, than at larger particle diameters. For a given concentration, C, and a particle size of $d > 1$ mm the critical velocity, V_C, remains, in general, almost constant. However, for a particle size of $d < 0.5$ the critical velocity, V_C, increases with an increase in particle size. For particle sizes of $0.5 < d < 1$ mm there exists a transition between above discussed regions.

Apparently, neither particle size distribution nor the pipe material (roughness) affect the relationship.

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APPENDIX I

Parameters of primary significance in their effect on the critical velocity are: The inside pipe diameter, D, the pipe material roughness, ϵ, the slope of the pipe, S, and the mean sediment particle size, d_{50}, with consideration of the uniformity coefficient, d_{90}/d_{50}. These parameters have been varied to determine how each enters into the modified Froude number relationship, defined earlier. The series of tests are coded with the following convention:

G - 01 - No.
G - 02 - No.
G - 001 - No.
G - 002 - No.

BS - 01 - No.
BS - 03 - No.
BS - 001 - No.
BS - 003 - No.

RUN NUMBER (Indicates change in concentration).

SLOPE
- 1 — Horizontal
- 2 — Downward, -0.060
- 3 — Upward, +0.027

SAND
- 0 — d_{50} = 0.88 mm, $\frac{d_{90}}{d_{50}}$ = 1.21
- 00 — d_{50} = 0.45 mm, $\frac{d_{90}}{d_{50}}$ = 1.07 (highly silica sand)

PIPE
- G — 4" Ø Galvanized, ϵ = 0.0001 ft.
- BS — 6" Ø Black Steel, ϵ = 0.00065 ft.

Explanation of the Table Headings

Test Section: (Over a 3.6 m (= 141.8 in) test section the headloss was determined; U-tube manometers were used).

$\Delta h_{1.95}$: Measured mixture headloss (in inches of a liquid with a specific gravity of s = 2.95).

$(\frac{\Delta h}{\Delta \ell})_m$: Mixture headloss gradient (calculated from $\Delta h_{1.95}$).

Loop Readings: (The "loop-system" developed by Einstein and Graf (1966) was used to simultaneously determine the mixture flow rate, Q_m, and the solid phase concentration, C. The loop system consists essentially of two identical vertical pipe sections with opposite flow direction. Head differences are obtained over these vertical pipe sections, namely a "Riser" and a "Downcomer" section. Mixture flow rate, Q_m, and concentration, C, were determined with the theory advanced by Einstein and Graf (1966). A computer (CDC 6400) program was developed to expedient the solution).

$\Delta h_R;\Delta h_D$: Headlosses in the Riser and Downcomer sections (3-inch pipe, 1.5 m (= 5.91 in) long; U-tube manometers are used).

$\Delta h_R+\Delta h_D$: Sum of the headlosses.

Q_m : Mixture flow rate, according to theory of Einstein and Graf (1966), from the sum of the headlosses.

V_m : Mixture velocity in test section determined with continuity relation.

$\Delta h_R-\Delta h_D$: Difference of the headlosses

$\Delta h_R-\Delta h_D$ (cor.): Correction of above from predetermined clear water test correction curve.

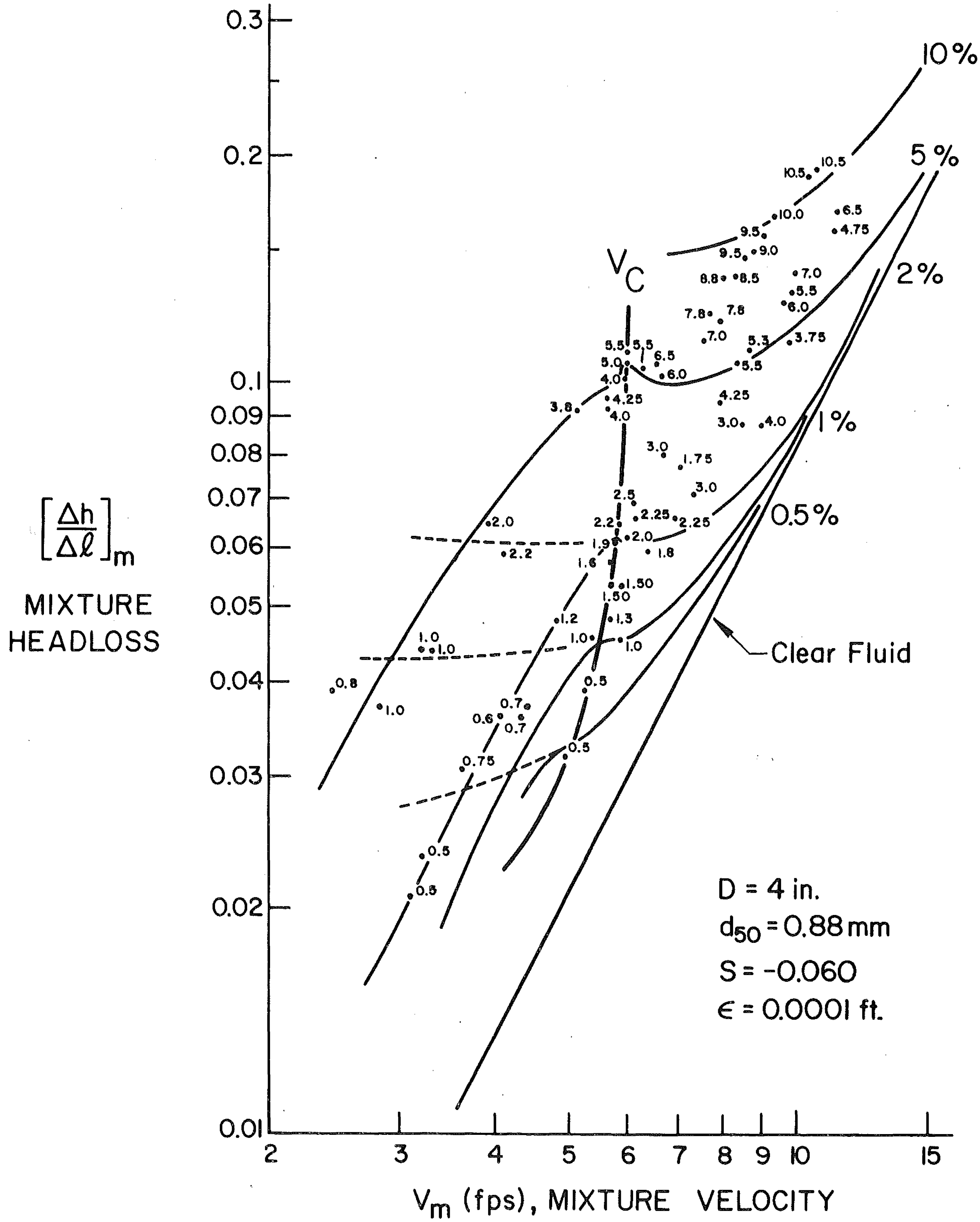
C : Concentration, determined according to theory of Einstein and Graf (1966), from the difference of the headlosses.

Comments: Commentary of observations in plexiglass section on the conditions of sediment deposit.

Each table is summarized indicating the critical condition; this is the critical velocity, V_C, for a specific concentration, C.

Some Remarks to the Figures

Plotting of the data follows on mixture headloss versus mixture velocity graphs. These graphs show the variation of critical velocity, V_C, with a change in solids concentration. Constant concentration lines are fitted to the data, and the critical velocity, subjectively observed as the velocity at which a non-moving bed forms on the bottom of the pipe, is located for each concentration. At velocities below the critical, equi-concentration (constant "moving" concentration) lines are dashed (---), while the diminishing concentration line for a particular run is drawn solid (—).


0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
$\left[\frac{\Delta h}{\Delta \ell}\right]_m$
MIXTURE
HEADLOSS
2
3
4
5
6
7
8
9
10
15
V_m (fps), MIXTURE VELOCITY
10%
5%
2%
1%
0.5%
V_C
Clear Fluid
D = 4 in.
d_{50} = 0.88 mm
S = -0.060
ϵ = 0.0001 ft.

Series G-01-1

test section		loop readings									
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
10.50	0.158	29.55	18.90	48.45	440	11.15	10.65	9.05	4.75	Everything moving
8.30	0.114	23.10	14.65	37.75	385	9.7	8.45	7.35	3.75	Suspended and bed load
6.40	0.088	17.65	11.0	28.65	335	8.45	6.65	5.75	3.0	Suspended and bed load
5.60	0.077	11.60	7.70	19.30	275	7.0	3.90	3.30	1.75	Moving bed
3.30	0.0455	8.10	5.90	14.0	230	5.85	2.20	1.70	1.0	Pulsating, sliding bed
2.80	0.039	6.40	4.80	11.2	205	5.2	1.60	1.20	0.50	Pulsating, sliding bed
2.30	0.032	5.30	4.20	9.5	195	4.95	1.10	0.70	0.50	Slowly moving bed CRITICAL
2.30	0.032	5.30	4.15	9.45	195	4.95	1.15	0.65	0.50	Just below critical

CRITICAL CONDITION $\begin{cases} C = 0.50\% \\ V_C = 5.0 \text{ fps} \end{cases}$

Series G-01-2

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta l})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
6.40	0.088	19.40	10.60	30.0	350	8.9	8.80	7.80	4.0	Suspended and bed load
5.20	0.0715	13.80	7.70	21.50	290	7.35	6.10	5.30	3.0	Everything moving
4.80	0.066	11.80	6.80	18.60	270	6.85	5.00	4.40	2.25	" "
4.30	0.0592	10.40	6.40	16.80	250	6.35	4.00	3.50	1.8	Moving slowly
3.90	0.0535	8.80	5.50	14.30	230	5.85	3.30	2.80	1.50	Moving bed, thickening layer
3.30	0.0455	7.10	4.75	11.85	210	5.35	2.35	2.00	1.0	Deposit bed CRITICAL
3.50	0.0481	7.60	4.95	12.55	220	5.65	2.65	2.30	1.3	Bottom limit of moving bed
2.60	0.0358	6.0	3.90	9.90	190	4.3	2.10	1.70	0.8	Below critical

CRITICAL CONDITION $\begin{cases} C = 1\% \\ V_C = 5.5 \text{ fps} \end{cases}$

Series G-01-3

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
9.30	0.128	23.95	11.10	35.05	375	9.55	12.85	11.75	6.0	Everything moving
8.10	0.111	20.35	9.0	29.35	340	8.65	11.35	10.35	5.3	" "
6.80	0.094	16.60	7.50	24.10	310	7.9	9.10	8.30	4.25	" "
5.80	0.080	12.00	5.75	17.75	265	6.7	6.25	5.65	3.0	Sliding bed
5.00	0.069	10.30	5.10	15.40	235	6.1	5.20	4.70	2.5	Pulsating bed
4.50	0.062	8.90	4.75	13.65	230	5.95	4.15	3.75	2.0	Bed slowly moving
										CRITICAL
4.20	0.058	8.25	4.50	12.75	220	5.6	3.75	3.35	1.75	Non-moving bed
2.60	0.036	4.50	2.95	7.45	160	4.1	1.55	1.25	0.6	Flat bed
1.70	0.0235	2.90	1.50	4.40	125	3.2	1.40	1.10	0.5	Long dunes
					2nd Run					
12.20	0.168	31.85	17.70	49.55	450	11.45	14.15	12.55	6.5	Everything moving
9.50	0.131	24.55	12.50	37.05	390	9.8	12.05	10.85	5.5	" "
6.70	0.092	16.35	8.35	24.70	310	7.9	8.00	7.25	3.75	" "
4.80	0.066	10.15	5.30	15.45	240	6.05	4.85	4.35	2.25	Sliding, pulsating bed
4.20	0.058	8.75	5.10	13.85	230	5.85	3.65	3.15	1.6	Bed slowly moving
4.10	0.0565	8.55	5.75	13.5	225	5.75	3.60	3.10	1.6	Still moving CRITICAL
3.90	0.0535	7.70	5.95	12.45	220	5.65	2.95	2.65	1.5	Deposit
3.20	0.044	3.75	5.60	6.60	145	3.7	0.90	0.60	0.3	Flat bed

CRITICAL CONDITION { $C = 1\frac{3}{4}\%$; $V_C = 5.75$ fps }

G-01

Series G-01-4

test section $\Delta h_{1.95}$ [in.]	test section $(\frac{\Delta h}{\Delta \ell})_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R + \Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R - \Delta h_D$ [in.]	$\Delta h_R - \Delta h_D$ corrected [in.]	C [%]	COMMENTS
10.20	0.140	26.75	12.10	38.85	390	9.9	14.65	13.45	7.0	Suspended and bed load
7.70	0.106	20.10	8.70	28.80	330	8.35	11.40	10.50	5.5	Suspension, mostly bed load
5.90	0.081	11.85	5.50	17.35	260	6.6	6.35	5.75	3.0	Fast moving bed
4.70	0.0645	9.25	4.65	13.90	230	5.85	4.60	4.10	2.2	Sliding bed
4.40	0.0605	8.55	4.50	13.15	225	5.75	4.05	3.55	1.9	Just above V_C
4.20	0.0578	7.95	4.20	12.15	220	5.65	3.75	3.25	1.8	Non-moving bed CRITICAL
3.50	0.0481	6.65	3.85	10.50	190	4.8	2.80	2.45	1.2	Flat bed
2.20	0.0302	3.60	2.10	5.70	140	3.6	1.50	1.20	0.8	Flat bed--thinning (long dunes)
1.50	0.0206	2.40	1.50	3.90	120	3.1	0.90	0.60	0.5	6' long dunes at 2 intervals
4.40	0.0605	8.50	4.0	13.50	230	5.85	4.50	4.0	2.0	Scour (long impulse variations)

CRITICAL CONDITION: $C = 2\%$, $V_C = 5.75$ fps

Series G-01-5

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
12.10	0.167	28.55	7.95	36.50	365	9.25	20.60	19.50	10.0	Everything moving
10.70	0.148	24.85	5.80	30.65	335	8.45	19.05	18.15	9.5	" "
10.10	0.139	22.80	5.00	27.80	315	8.0	17.80	17.0	8.8	Heavy bed load
8.70	0.120	19.40	3.75	23.15	290	7.95	15.65	15.0	7.8	Quickly moving bed just above critical
7.70	0.106	15.45	2.70	18.15	255	6.5	12.75	12.15	6.5	Deposit - and immediate scour
7.60	0.1045	14.65	2.50	17.15	245	6.2	12.15	12.15	6.5	Still squirming, pulsating bed
7.90	0.109	13.60	2.35	15.95	235	5.95	11.25	10.75	5.5	Above critical
										CRITICAL
7.30	0.101	10.75	2.60	13.35	230	5.95	8.15	7.65	4.0	Non-moving bed
6.70	0.092	9.35	1.50	10.85	200	5.1	7.85	7.45	3.8	Flat bed
4.70	0.065	5.40	1.35	6.75	150	3.9	4.05	3.75	2.0	Long flat dunes
2.70	0.037	2.90	1.10	4.00	110	2.8	1.80	1.80	1.0	Long flat dunes

Series G-01-5

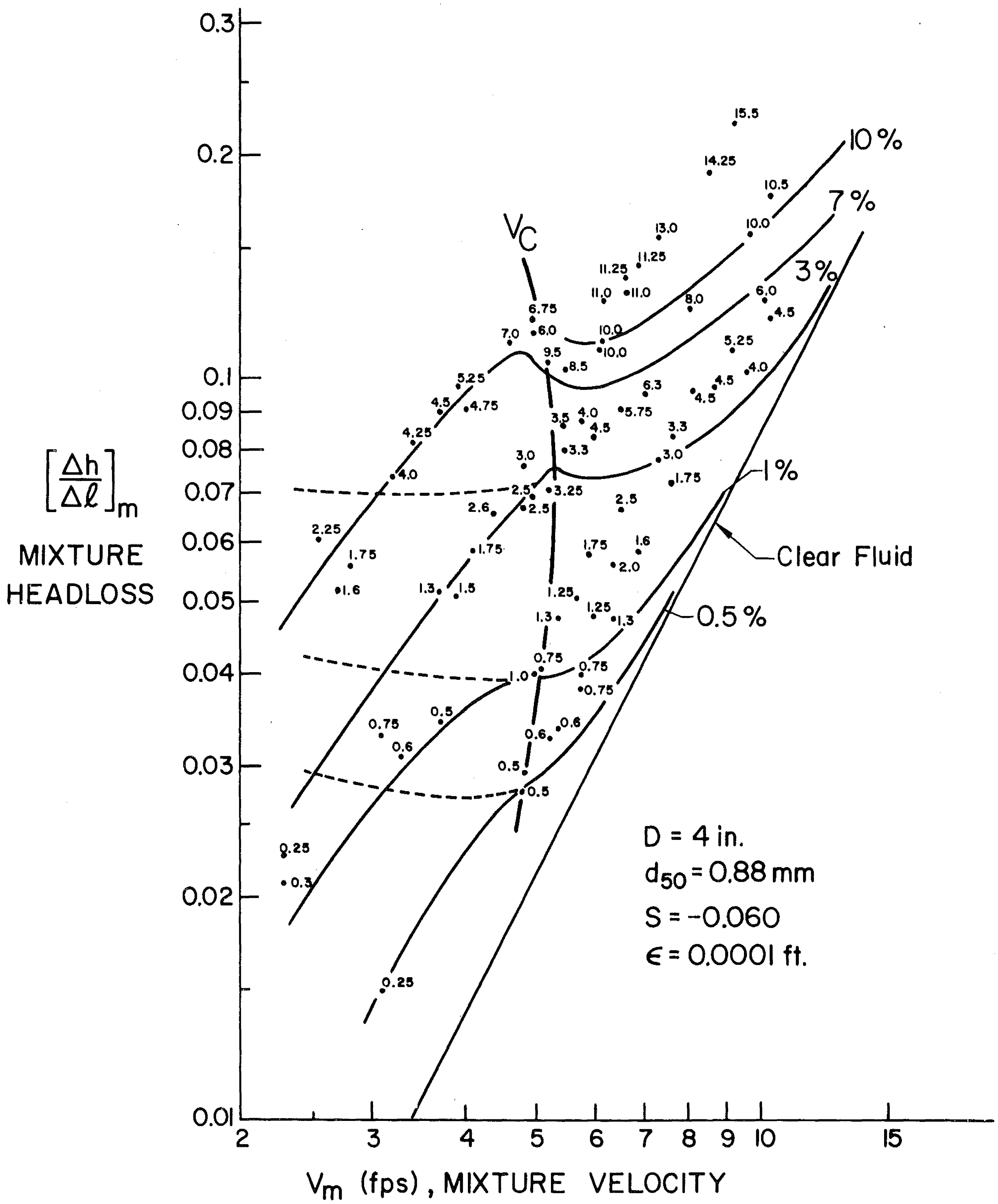
test section $\Delta h_{1.95}$ [in.]	test section $(\frac{\Delta h}{\Delta \ell})_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R + \Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R - \Delta h_D$ [in.]	$\Delta h_R - \Delta h_D$ corrected [in.]	C [%]	COMMENTS
						2nd Run				
13.90	0.191	32.90	10.70	43.60	410	10.45	22.20	20.90	10.5	All suspended
11.40	0.158	26.30	6.90	33.20	355	9.0	19.40	18.30	9.5	" "
10.70	0.139	22.25	5.30	27.55	325	8.25	16.95	16.15	8.5	Bed load
8.20	0.113	18.30	4.20	22.50	295	7.5	14.10	13.40	7.0	Slowly moving bed
7.50	0.103	15.40	2.90	18.30	260	6.6	12.50	11.90	6.0	Pulsating-sliding bed
7.80	0.1075	12.40	2.10	14.50	235	5.95	10.30	9.80	5.0	Bed just slightly moving
										CRITICAL
6.70	0.092	10.30	2.60	12.90	220	5.6	7.90	7.20	4.0	Non-moving bed just below critical
4.30	0.059	5.80	1.30	7.10	160	4.1	4.50	4.20	2.2	Flat bed, great saltation
3.20	0.044	3.50	1.20	4.70	130	3.3	2.30	2.00	1.0	Very little dune buildings
2.80	0.039	2.05	0.35	2.40	95	2.4	1.70	1.50	0.8	High dune formation

Series G-01-5

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
						3rd Run				
13.70	0.189	32.00	10.30	42.30	405	10.3	21.70	20.40	10.5	Everything moving
10.80	0.149	24.70	6.30	31.00	340	8.65	18.40	17.40	9.0	" "
9.00	0.124	20.05	4.40	24.45	300	7.6	15.65	14.950	7.75	Moving, sliding bed
7.70	0.106	13.90	2.75	16.65	250	6.35	11.15	10.55	5.5	Pulsating bed
7.90	0.109	12.10	2.35	14.45	235	5.95	9.75	9.25	5	Just slightly moving bed
										CRITICAL
6.90	0.095	10.80	2.15	12.95	220	5.6	8.65	8.25	4.25	Just below critical, non-moving bed
3.20	0.044	3.45	1.40	4.85	125	3.2	2.05	1.75	1.0	Flat bed

CRITICAL CONDITION { $C = 5\%$, $V_c = 5.95$ fps

G-02



0.3
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
$\left[\frac{\Delta h}{\Delta \ell}\right]_m$
MIXTURE HEADLOSS
V_C
10 %
7 %
3%
1%
0.5 %
Clear Fluid
D = 4 in.
d_{50} = 0.88 mm
S = -0.060
ϵ = 0.0001 ft.
2
3
4
5
6
7
8
9
10
15
V_m (fps), MIXTURE VELOCITY

Series G-02-1

test section		loop readings								COMMENTS
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
8.80	0.121	27.35	16.70	44.05	410	10.45	10.65	9.35	4.75	Everything moving
7.50	0.103	22.65	13.80	36.45	375	9.55	8.85	7.75	4.0	" "
5.20	0.072	13.65	9.40	23.05	300	7.6	4.25	3.55	1.75	" "
4.30	0.059	11.70	7.75	19.45	270	6.85	3.95	3.35	1.6	" "
3.50	0.048	8.90	6.25	15.15	235	5.95	2.65	2.15	1.25	Sliding bed
2.90	0.040	7.60	5.50	13.10	225	5.75	2.10	1.60	0.75	Pulsating bed
2.50	0.034	6.45	4.85	11.30	210	5.35	1.60	1.20	0.6	" "
2.00	0.028	5.55	4.10	9.65	190	4.8	1.45	1.05	0.5	Slowly pulsating
3.50	0.048	9.60	6.35	15.95	250	6.35	3.25	2.65	1.3	Everything moving
2.80	0.0385	7.30	5.45	12.75	225	5.75	1.85	1.35	0.75	" "
2.40	0.033	6.40	4.75	11.15	205	5.2	1.65	1.20	0.6	Pulsating
2.15	0.0295	5.45	4.20	9.65	190	4.8	1.25	0.85	0.5	CRITICAL

CRITICAL CONDITION $\begin{cases} C = 0.50\% \\ V_C = 4.8 \text{ fps} \end{cases}$

Series G-02-2

test section		loop readings									COMMENTS
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C		
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]		
9.20	0.127	25.65	12.60	38.25	400	10.2	13.05	11.85	6.0		Everything moving
8.00	0.110	21.85	10.55	32.40	365	9.2	11.30	10.25	5.25		" "
7.10	0.098	19.25	9.40	28.65	340	8.65	9.85	8.95	4.5		" "
6.10	0.084	15.50	8.0	23.50	300	7.6	7.50	6.70	3.3		" "
5.70	0.078	13.90	7.05	20.95	290	7.35	6.85	6.15	3.0		" "
4.10	0.0565	9.85	5.50	15.35	250	6.35	4.35	3.75	2.0		Sliding bed
4.20	0.058	8.80	5.0	13.80	235	5.95	3.80	3.30	1.75		Just pulsating
3.70	0.051	7.25	4.55	11.75	220	5.65	2.70	2.20	1.25		Just above critical
3.00	0.041	6.05	4.0	10.05	200	5.1	2.05	1.65	0.75		CRITICAL
2.50	0.0345	3.60	2.0	5.60	145	3.7	1.60	1.30	0.5		Deposit
					2nd Run						
7.00	0.0965	19.25	9.55	28.80	320	8.1	9.7	8.8	4.5		Everything moving
5.70	0.078	14.65	7.35	22.0	285	7.25	7.3	6.5	3.3		" "
4.90	0.067	11.40	5.85	17.25	255	6.5	5.55	4.95	2.5		" "
4.20	0.058	9.05	5.25	14.30	230	5.85	3.80	3.3	1.75		" "
3.50	0.048	7.30	4.30	11.60	210	5.35	3.0	2.6	1.3		Bed just moving
2.90	0.040	5.85	3.75	9.60	195	4.95	2.1	1.7	1		CRITICAL
1.10	0.015	2.25	1.85	4.10	120	3.1	0.4	0.2	0.25		Flat bed

CRITICAL CONDITION $\begin{cases} C = 1\% \\ V_c = 5.1 \text{ fps} \end{cases}$

Series G-02-3

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
12.90	0.178	33.00	11.05	44.05	410	10.4	21.95	20.65	10.5	Everything moving
11.50	0.158	28.90	8.45	37.35	380	9.65	20.45	19.25	10.0	" "
9.10	0.125	21.60	5.20	26.80	315	8.0	16.40	15.60	8.0	" "
7.00	0.096	16.65	3.60	20.25	275	7.0	13.05	12.35	6.3	" "
6.70	0.092	14.60	2.80	17.40	255	6.5	11.80	11.20	5.75	Sliding bed
6.10	0.084	12.05	2.70	14.75	235	5.95	9.35	8.85	4.5	Qucikly pulsating
6.50	0.089	10.65	2.45	13.10	225	5.75	8.20	7.70	4.0	Slowly moving, just above critical
5.80	0.080	9.15	2.30	11.45	215	5.45	6.85	6.35	3.3	CRITICAL
4.90	0.0675	7.40	2.0	9.40	190	4.8	5.40	5.0	2.5	Deposit
5.10	0.070	7.70	2.30	10.0	195	4.95	5.40	5.0	2.5	"
3.70	0.051	4.90	1.60	6.50	150	3.9	3.30	3.0	1.5	Flat bed
2.40	0.033	3.0	1.0	4.0	120	3.1	2.0	1.70	0.75	" "
1.70	0.023	1.45	1.0	2.45	90	2.3	0.45	0.30	0.25	Dunes
					2nd Run					
6.20	0.085	12.40	2.40	14.80	235	5.95	10.0	9.50	4.75	Quickly pulsating
6.30	0.087	9.65	2.40	12.05	215	5.45	7.25	6.85	3.5	Slowly pulsating

Continued

Series G-02-3

test section $\Delta h_{1.95}$ [in.]	test section $\left(\frac{\Delta h}{\Delta \ell}\right)_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R+\Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R-\Delta h_D$ [in.]	$\Delta h_R-\Delta h_D$ corrected [in.]	C [%]	COMMENTS
5.20	0.0715	8.60	2.05	10.65	205	5.2	6.55	6.15	3.25	CRITICAL
5.60	0.077	7.95	1.50	9.45	190	4.8	6.45	6.05	3.0	Flat bed
4.80	0.066	6.70	1.30	8.0	170	4.35	5.40	5.10	2.6	" "
4.30	0.059	5.70	1.70	7.40	160	4.1	4.0	3.60	1.75	" "
3.80	0.052	4.45	1.60	6.05	145	3.7	2.85	2.55	1.3	" "
2.40	0.033	2.95	1.40	4.35	120	3.1	1.55	1.25	0.6	" "
1.50	0.021	1.50	0.65	2.15	90	2.3	0.85	0.65	0.3	Dunes

CRITICAL CONDITION $\begin{cases} C = 3\% \\ V_C = 5.35 \text{ fps} \end{cases}$

Series G-02-4

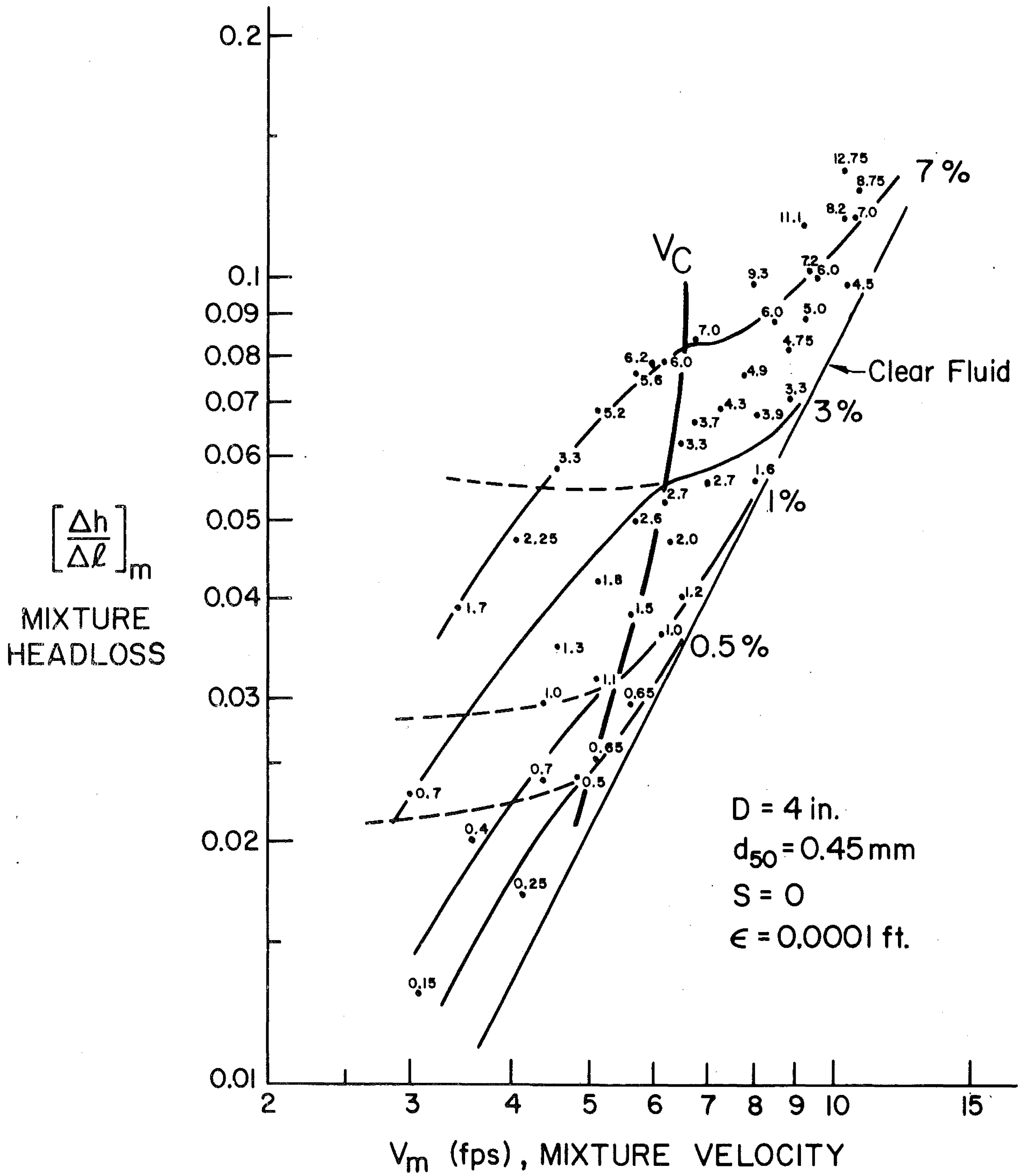
test section: $\Delta h_{1.95}$ [in.]	test section: $(\frac{\Delta h}{\Delta \ell})_m$	loop readings: Δh_R [in.]	Δh_D [in.]	$\Delta h_R+\Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R-\Delta h_D$ [in.]	$\Delta h_R-\Delta h_D$ corrected [in.]	C [%]	COMMENTS
10.40	0.143	21.40	-1.05	20.35	270	6.85	22.45	21.85	11.25	Sometimes stopping
9.60	0.132	20.25	-1.65	18.60	260	6.6	21.90	21.30	11.0	" "
8.20	0.113	17.70	-2.0	15.70	240	6.1	19.70	19.20	10.0	" "
7.60	0.105	14.90	-2.20	12.70	215	5.45	17.10	16.70	8.5	Quickly pulsating
8.40	0.116	11.30	-0.95	10.35	200	4.95	12.25	11.85	6.0	CRITICAL
6.70	0.092	8.30	-1.50	6.80	155	4.0	9.80	9.40	4.75	Flat bed
6.60	0.091	7.85	-1.60	6.25	145	3.7	9.45	9.15	4.5	" "
6.00	0.0825	7.10	-1.70	5.40	135	3.4	8.80	8.50	4.25	" "
3.80	0.052	3.35	+0.05	3.40	105	2.7	3.30	3.10	1.6	" "
					2nd Run					
16.00	0.221	36.45	5.35	41.80	365	9.2	31.10	30.0	15.5	Everything moving
13.80	0.190	31.10	2.50	33.60	335	8.55	28.60	27.70	14.25	" "
11.30	0.156	25.65	-0.10	25.55	290	7.35	25.75	25.05	13.0	" "
10.00	0.138	21.55	-1.05	20.45	260	6.6	22.60	21.95	11.25	" "
8.00	0.110	18.35	-1.85	16.50	240	6.05	20.20	19.70	10.0	Slowly pulsating
7.70	0.106	15.10	-2.30	12.80	215	5.45	17.40	17.0	8.75	" "
8.80	0.121	12.0	-1.70	10.30	195	4.95	13.70	13.30	6.75	CRITICAL fluctuating with scour-deposit mechanism
4.40	0.061	4.10	-0.60	3.50	100	2.55	4.70	4.40	2.25	Flat bed

Continued

Series G-02-4

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
					3rd run					
9.30	0.128	19.95	-2.20	17.75	245	6.15	22.15	21.65	11.0	Deposit·scour
7.80	0.107	16.30	-2.90	13.40	205	5.2	19.20	18.80	9.5	" "
7.80	0.107	16.15	-2.75	13.40	205	5.2	18.90	18.50	9.5	" "
										CRITICAL
8.20	0.113	11.40	-2.10	9.30	180	4.6	13.50	13.10	7.0	Just deposited, thick bed
7.10	0.098	8.70	-1.90	6.80	150	3.9	10.60	10.30	5.25	Flat bed
5.40	0.074	6.50	-1.50	5.0	125	3.2	8.0	7.70	4.0	" "
4.00	0.055	3.60	+0.20	3.80	110	2.8	3.40	3.20	1.75	" "

CRITICAL CONDITION $\begin{cases} C = 7\% \\ V_C = 5.0 \text{ fps} \end{cases}$


0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
[Δh/Δℓ]m
MIXTURE
HEADLOSS
2
3
4
5
6
7
8
9
10
15
Vm (fps), MIXTURE VELOCITY
VC
7 %
3 %
1%
0.5 %
Clear Fluid
D = 4 in.
d50 = 0.45 mm
S = 0
∈ = 0.0001 ft.

Series G-001-1

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta l}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
7.15	0.098	24.45	14.35	38.80	415	10.55	10.10	8.70	4.45	Everything moving
5.20	0.0715	17.00	10.10	27.10	345	8.75	6.90	6.00	3.10	" "
4.10	0.0563	13.15	9.25	22.40	315	8.00	3.90	3.10	1.60	" "
2.95	0.0405	8.75	5.90	14.65	255	6.45	2.85	2.40	1.20	" "
2.65	0.0364	7.90	5.45	13.35	240	6.10	2.45	2.00	1.02	Bed particles visible
2.15	0.0296	6.75	4.70	11.45	220	5.60	2.05	1.65	0.85	Pulsating, almost deposited, just above critical
1.85	0.0254	5.60	3.95	9.55	200	5.10	1.65	1.25	0.65	CRITICAL
1.75	0.0240	5.10	3.70	8.80	190	4.80	1.40	1.00	0.50	Flat bed
1.15	0.0172	3.50	2.70	6.20	160	4.10	0.80	0.45	0.25	" "
0.95	0.0130	2.15	1.60	3.75	120	3.10	0.55	0.30	0.15	" "

CRITICAL CONDITION $\begin{cases} C = 0.65\% \\ V_C = 5.10 \text{ fps} \end{cases}$

Series G-001-2

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
8.65	0.119	30.45	15.25	45.70	435	10.60	15.20	13.70	7.0	Everything moving
7.35	0.101	25.30	12.35	37.65	395 (400)	9.50	12.95	11.65	6.0	" "
6.45	0.089	21.20	10.30	31.50	360	9.15	10.90	9.90	5.0	Bed load
5.95	0.082	19.55	9.25	28.80	345	8.75	10.30	9.30	4.75	" "
4.95	0.068	16.05	7.55	23.60	315	8.05	8.50	7.70	3.9	Sliding bed
4.05	0.056	12.05	6.20	18.25	275	7.00	5.85	5.35	2.7	" "
3.45	0.0475	9.60	5.40	15.00	245 (250)	6.30	4.20	3.80	2.0	Pulsating bed
2.75	0.038	7.90	4.70	12.60	225	5.70	3.20	2.80	1.5	Just above critical
2.85	0.039	7.85 7.75	4.30 4.40	12.15 12.15	220	5.60	3.55 3.35	3.15 3.05	1.6 1.5	CRITICAL
2.35	0.032	6.20	3.80	10.00	200	5.10	2.40	2.10	1.1	Flat bed
1.75	0.024	4.55	3.00	7.55	170	4.40	1.55	1.25	0.7	" "

CRITICAL CONDITION $\begin{cases} C = (1.50)\% \\ V_C = 5.6 \text{ fps} \end{cases}$

Series G-001-3

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
9.35	0.129	31.90	13.40	45.30	430	10.95	18.50	17.00	8.75	Everything moving
8.65	0.119	28.75	11.50	40.25	410	10.45	17.25	15.95	8.2	" "
7.45	0.103	23.85	8.80	32.65	365	9.30	15.05	13.95	7.2	Heavy bed load
6.45	0.089	20.00	7.40	27.40	330	8.40	12.60	11.80	6.0	" " "
5.55	0.0765	16.40	6.15	22.65	305	7.75	10.25	9.55	4.9	" " "
5.05	0.0695	14.35	5.35	19.70	285	7.25	9.00	8.40	4.3	Sliding bed
4.85	0.067	12.25	4.80	17.05	265	6.75	7.45	7.05	3.7	Quickly pulsating
4.55	0.0625	11.45	4.75	16.20	255 (260)	6.50	6.70	6.30	3.3	" "
3.85	0.053	9.75	4.25	14.00	245	6.20	5.50	5.20	2.7	CRITICAL
3.65	0.050	8.90	3.50	12.40	225	5.70	5.40	5.10	2.6	Flat bed
3.05	0.042	6.80	3.05	9.85	200	5.10	3.75	3.50	1.8	Thickening flat bed
2.55	0.035	5.45	2.70	8.15	180	4.55	2.75	2.55	1.3	Saltating bed load
2.15	0.0295	4.90	2.70	7.60	170	4.40	2.20	2.00	1.0	Saltating bed load
1.45	0.020	2.95	2.00	4.95	135	3.60	0.95	0.80	0.4	Thick bed, little moving

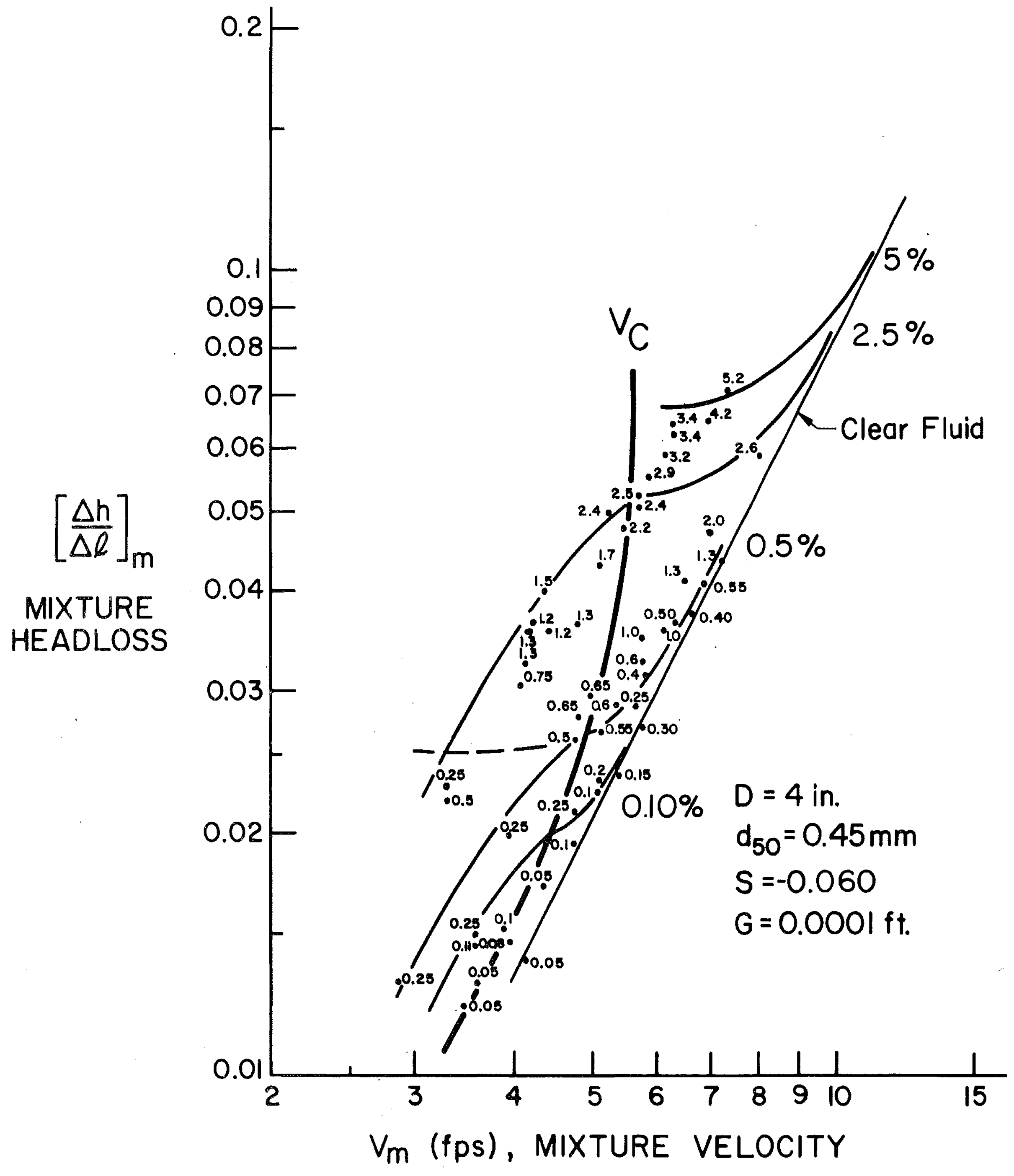
CRITICAL CONDITION $\begin{cases} C = 3\% \\ V_C = 6.25 \text{ fps} \end{cases}$

Series G-001-4

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
9.85	0.136	34.25	8.40	42.65	400	10.20	26.15	24.85	12.75	Everything moving
8.55	0.1175	28.05	5.45	33.50	360	9.15	22.60	21.60	11.1	" "
7.15	0.0985	21.95	3.05	25.0	310	7.90	18.90	18.20	9.3	Mostly bed load
6.15	0.0845	16.00	1.70	17.7	265	6.75	14.30	13.80	7.0	Slowly moving bed, just above critical
										CRITICAL
5.75	0.079	13.80	1.70	15.5	245	6.20	12.10	11.70	6.0	Just below critical, thickening bed
6.45	0.089	16.05	1.80	17.85	270	6.85	14.25	13.75	7.0	Just below critical, thickening bed
5.75	0.079	13.50	1.05	14.55	235	5.95	12.45	12.05	6.2	Deep flat bed
5.55	0.0765	12.20	0.90	13.10	225	5.70	11.30	10.90	5.6	" " "
5.05	0.0695	10.05	0.70	10.75	200	5.10	10.35	10.05	5.2	" " "
4.25	0.0585	7.60	0.85	8.45	175	4.55	6.75	6.45	3.3	Still suspension load
3.45	0.0475	5.65	1.00	6.65	155	4.05	4.65	4.35	2.25	Saltation load
2.85	0.039	4.30	0.80	5.10	130	3.45	3.50	3.30	1.7	Flat bed
1.65	0.023	2.35	0.85	3.20	110	3.00	1.50	1.30	0.7	" "

CRITICAL CONDITION $\begin{cases} C = 7\% \\ V_C = 6.5 \text{ fps} \end{cases}$

G-002


0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
[Δh/Δℓ]m
MIXTURE
HEADLOSS
2
3
4
5
6
7
8
9
10
15
Vm (fps), MIXTURE VELOCITY
VC
5%
2.5%
Clear Fluid
0.5%
0.10%
D = 4 in.
d50 = 0.45mm
S = -0.060
G = 0.0001 ft.

Series G-002-1

test section		loop readings								COMMENTS
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
2.75	0.0378	8.75	7.50	16.25	265	6.7	1.25	0.75	0.40	Everything moving
1.95	0.0268	6.30	5.35	11.65	230	5.85	0.95	0.55	0.30	" "
1.65	0.0227	5.05	4.45	9.50	200	5.1	0.60	0.20	0.10	" "
1.25	0.0172	3.90	3.45	7.35	170	4.35	0.45	0.10	0.05	Rapid Pulses
0.95	0.0130	2.80	2.40	5.20	140	3.6	0.40	0.10	0.05	Deposit when there's enough sand
										CRITICAL
1.07	0.0147	3.20	2.70	5.90	155	3.95	0.50	0.15	0.08	Deposit
1.00	0.0137	3.20	2.75	5.95	160	4.1	0.45	0.10	0.05	Deposit mostly in larger pipe

CRITICAL CONDITION $\begin{cases} C = 0.05\% \\ V_C = 3.7 \text{ fps} \end{cases}$

Series G-002-2

test section		loop readings								
$\Delta h_{1.95}$ [in.]	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R [in.]	Δh_D [in.]	$\Delta h_R+\Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R-\Delta h_D$ [in.]	$\Delta h_R-\Delta h_D$ corrected [in.]	C [%]	COMMENTS
3.00	0.0405	9.10	7.55	16.65	270	6.85	1.55	1.05	0.55	Everything moving
2.10	0.0288	6.25	5.30	11.55	220	5.65	0.95	0.50	0.25	" "
1.70	0.0233	5.00	4.45	9.45	200	5.1	0.55	0.10	0.05	" "
1.40	0.0192	4.25	3.60	7.85	180	4.8	0.65	0.30	0.15	Very slowly moving
1.10	0.0151	3.00	2.50	5.50	150	3.9	0.50	0.20	0.10	Deposit CRITICAL
0.90	0.0124	2.35	2.10	4.45	135	3.45	0.25	-	-	Flat bed, no moving concentration
0.20	0.00274	0.65	0.65	1.30	65	1.65	0.0	-	-	Small dunes
					2nd Run					
3.15	.0439	10.20	8.05	18.25	280	7.35	3.15	2.60	1.33	Everything moving
2.65	.0369	8.25	6.80	15.05	250	6.35	1.45	1.00	0.52	" "
2.25	.0313	7.10	5.90	13.00	230	5.85	1.20	0.80	0.42	" "
1.95	.0271	6.05	5.10	11.15	215	5.45	0.95	0.55	0.30	" "
1.70	.0237	5.30	4.50	9.80	200	5.1	0.80	0.40	0.20	Pulses
1.55	.0215	5.00	4.20	9.20	195	4.59	0.80	0.40	0.20	Bed particles visible
1.48	.0206	4.50	3.75	8.25	185	4.75	0.75	0.40	0.20	" " "
0.95	.0132	3.10	2.60	5.70	150	3.9	0.50	0.20	0.10	Almost deposit, moves CRITICAL
1.05	.0146	3.10	2.45	5.55	150	3.9	0.65	0.30	0.15	Deposit

Continued

Series G-002-2

test section		loop readings								
$\Delta h_{1.95}$ [in.]	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R [in.]	Δh_D [in.]	$\Delta h_R + \Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R - \Delta h_D$ [in.]	$\Delta h_R - \Delta h_D$ corrected [in.]	C [%]	COMMENTS
1.05	.0146	3.15	2.50	5.65	150	3.9	0.65	0.30	0.15	Deposit, bed less thick
1.05	.0146	3.15	2.60	5.75	150	3.9	0.55	0.20	0.10	(Deposit, bed less thick)
0.70	.0097	2.00	1.65	3.65	115	2.95	0.35	0.05	0.02	Deposits a while then washes away
0.35	.00049	1.20	0.95	2.15	90	2.3	0.25	0.05	0.02	Single dunes

CRITICAL CONDITION $\begin{cases} C = 0.10\% \\ V_C = 3.9 \text{ fps} \end{cases}$

Series G-002-3

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta L})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.35	0.0597	14.00	8.35	22.35	315	8.0	5.65	4.95	2.55	Everything moving
3.45	0.0474	11.05	6.60	17.65	275	7.0	4.45	3.95	2.00	" "
2.55	0.0350	7.55	5.20	12.75	225	5.75	2.35	1.95	1.00	Slowing down, bed particles visible
1.95	0.0268	5.50	4.05	9.55	200	5.1	1.45	1.10	0.55	Pulsating bed
2.15	0.0295	5.50	3.85	9.35	195	4.95	1.65	1.30	0.65	Pulsating slowly
2.05 1.95	0.0282 0.0268	5.30	3.70	9.00	190	4.8	1.60	1.30	0.65	Deposits for a while then slides again
1.55	0.0212	4.20	3.35	7.55	175	4.75	0.85	0.50	0.25	Deposit
										CRITICAL
1.35 1.55 1.45	0.0185 0.0212 0.0199	3.45 3.45	2.65 2.60	6.10 6.05	155	3.95	0.80 0.85	0.50 0.55	0.25 0.30	Deposit, bed thickens
1.15 1.05	0.0158 0.0143	2.75	2.15	4.90	140	3.6	0.60	0.45	0.25	Deposit, first thinner, then thicker
0.95	0.0130	1.90	1.25	3.15	110	2.8	0.65	0.45	0.25	First flat bed, then dunes
0.40 0.60	0.0055 0.0082	1.20	0.95	2.15	90	2.3	0.25	0.05	0.03	1' long dunes

CRITICAL CONDITION
$C = 0.25\%$
$V_C = 4.5$ fps

Series G-002-4

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta l})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.00	0.0411	9.00	6.10	15.10	255	6.5	2.90	2.45	1.30	Everything moving
2.60	0.0357	7.75	5.50	13.25	240	6.1	2.25	1.85	0.95	" "
2.40	0.0327	6.95	5.05	12.00	225	5.75	1.90	1.50	0.80	Rapid pulses
2.10	0.0288	5.90	4.40	10.30	210	5.35	1.50	1.10	0.57	Slow pulses, bed particles visible
1.90	0.0261	5.50	4.20	9.70	205	5.2	1.30	0.90	0.47	Very slow pulses, almost deposit
2.10	0.0288	5.30	3.90	9.20	198	5.1	1.40	1.05	0.55	Deposit CRITICAL
2.10	0.0288	5.50	3.75	9.25	200	5.1	1.75	1.30	0.67	
1.90	0.0261	5.30	4.05	9.35	200	5.1	1.25	0.85	0.45	
1.87	0.0357	5.00	3.70	8.70	190	4.8	1.30	1.00	0.50	Deposit
1.90	0.0261	4.90	3.65	8.55	185	4.75	1.25	0.90	0.47	Deposit (with pulses)
1.65	0.0226	4.45	3.40	7.85	175	4.75	1.05	0.75	0.40	Deposit
1.05	0.0144	2.60	2.10	4.70	140	3.6	0.50	0.20	0.10	"
0.55	0.0075	1.40	1.30	2.70	95	2.45	0.10	-	-	" long dunes forming

CRITICAL CONDITION $\begin{cases} C = 0.55\% \\ V_C = 5.1 \text{ fps} \end{cases}$

G-002

Series G-002-5

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
5.15	0.0707	15.50	4.90	20.40	290	7.35	10.60	10.00	5.15	Everything moving
4.80	0.0658	13.20	4.45	17.65	275	7.0	8.75	8.20	4.20	" "
4.70	0.0644	11.15	4.05	15.20	250	6.35	7.10	6.60	3.40	Bed particles visible
4.30	0.0590	10.45	3.85	14.30	240	6.1	6.60	6.25	3.20	Slow bed motion
3.70	0.0508	8.65	3.60	12.25	225	5.75	5.05	4.65	2.40	Very slow pulsation, almost deposit
										CRITICAL
3.55	0.0487	8.00	3.35	11.35	215	5.45	4.65	4.30	2.20	Deposit
3.15	0.0431	6.70	3.10	9.80	200	5.1	3.60	3.20	1.65	Flat bed
2.65	0.0364	5.70	2.90	8.60	190	4.8	2.80	2.45	1.25	" "
2.75 2.55	0.0378 0.0350	5.25	2.50	7.75	165	4.2	2.75	2.40	1.22	" "
2.20	0.0302	4.10	2.35	6.45	160	4.1	1.75	1.50	0.75	" "
1.65	0.0226	2.70	1.90	4.60	130	3.3	0.80	0.50	0.25	" "
0.65	0.00895	0.70	0.60	1.30	65	1.65	0.10	-	-	1' long dunes, no moving concentrations

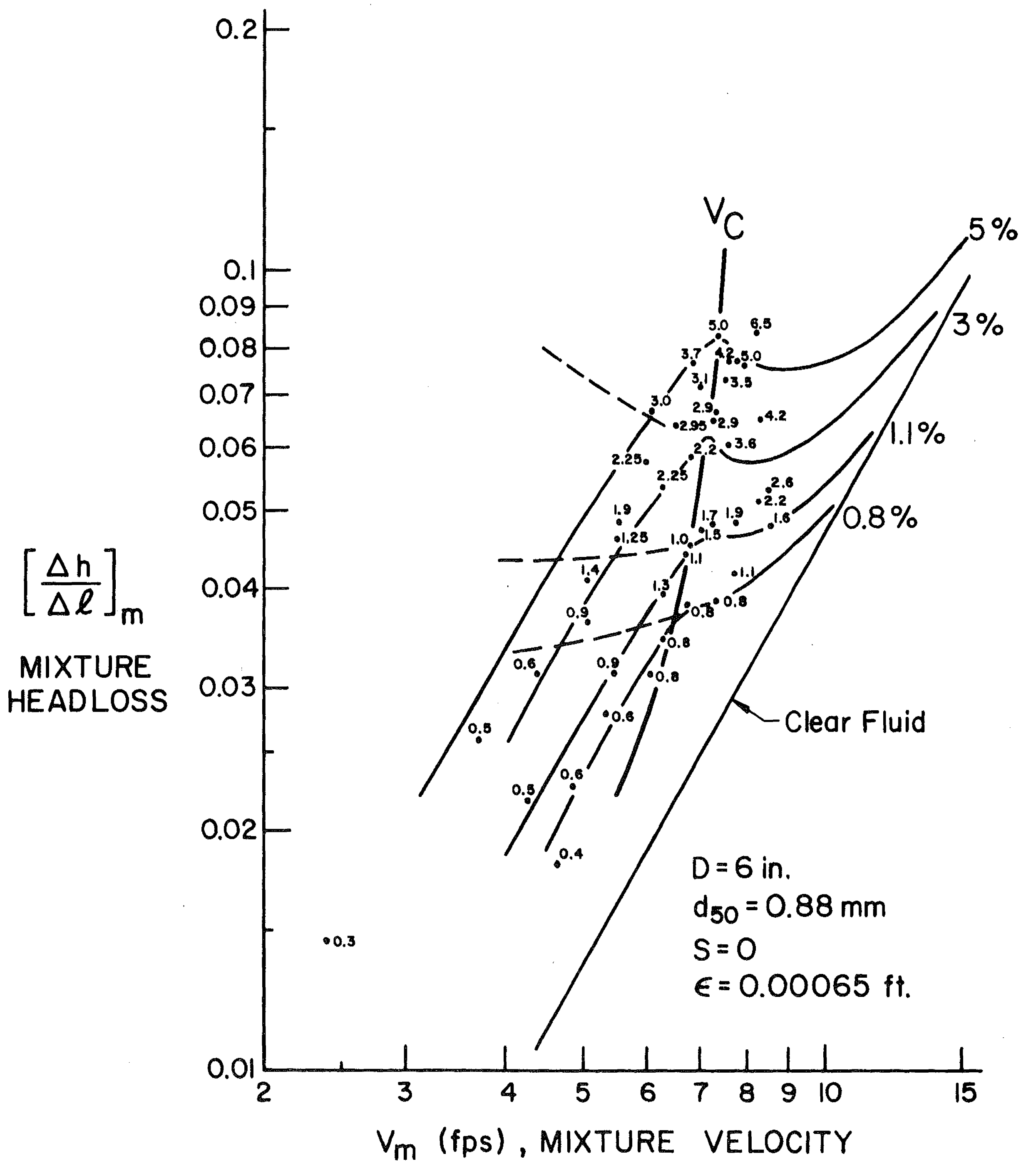
CRITICAL CONDITION $\begin{cases} C = 2.25\% \\ V_C = 5.5 \text{ fps} \end{cases}$

Series G-002-6

test section $\Delta h_{1.95}$ [in.]	$(\frac{\Delta h}{\Delta \ell})_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R + \Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R - \Delta h_D$ [in.]	$\Delta h_R - \Delta h_D$ corrected [in.]	C [%]	COMMENTS
4.70	0.0645	13.60	4.45	18.05	270	6.85	9.15	8.60	4.40	Everything moving
4.50	.0626	11.00	3.90	14.90	250	6.35	7.10	6.65	3.45	Bed particles often visible, strong pulses
4.00	.0556	9.65	3.70	13.35	230	5.85	5.95	5.50	2.85	Bed particles visible, slower pulses
3.80 3.70 3.90	.0530 .0515 .0542	8.80	3.50	12.30	225	5.7	5.30	4.90	2.50	Deposit CRITICAL
3.60	.0500	8.40	3.40	11.80	220	5.25	5.00	4.60	2.35	Flat bed
3.00 3.10	.0417 .0432	6.65	3.00	9.65	195	4.95	3.65	3.30	1.68	" "
2.57	.0358	5.35	2.70	8.05	175	4.4	2.65	2.30	1.18	" "
3.00 2.60 2.80	.0417 .0362 .0390	5.50 5.35 5.45	2.30 2.50 2.40	7.80 7.85 7.95	170 170 175	4.35 4.35 4.4	3.20 2.85 3.05	2.85 2.50 2.80	1.45 1.25 1.42	" "
2.30 2.40	.0320 .0334	5.00 4.90	2.05 2.00	7.05 6.90	165 160	4.2 4.1	2.95 2.90	2.65 2.60	1.35 1.32	" "
1.60	.0222	2.90	1.70	4.60	130	3.30	1.20	1.00	0.50	" "

CRITICAL CONDITION $\begin{cases} C = 2.50\% \\ V_C = 5.7 \text{ fps} \end{cases}$

BS-01



V_C
5%
3%
1.1%
0.8%
Clear Fluid
$\left[\frac{\Delta h}{\Delta \ell}\right]_m$
MIXTURE HEADLOSS
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
2
3
4
5
6
7
8
9
10
15
V_m (fps), MIXTURE VELOCITY
D = 6 in.
d_{50} = 0.88 mm
S = 0
ϵ = 0.00065 ft.

test section		loop readings							Series BS-01-1	
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.54	0.0480	64.2	55.0	119.2	750	8.50	9.2	3.1	1.6	Everything moving
3.05	0.0420	53.8	46.8	100.6	680	7.75	7.0	2.2	1.1	" "
2.82	0.0388	46.6	41.0	87.6	640	7.30	5.6	1.6	0.8	Heavy bed load
2.79	0.0385	40.6	35.5	76.1	595	6.75	5.1	1.6	0.8	Sliding bed
										CRITICAL
2.54	0.0349	35.3	30.9	66.2	550	6.25	4.4	1.6	0.8	Just below critical
2.36	0.0324	32.8	28.5	61.3	530	6.05	4.3	1.6	0.8	Deposit
2.05	0.0282	26.2	23.2	49.4	470	5.35	3.0	1.2	0.6	Flat bed
1.33	0.0183	19.2	17.0	36.2	410	4.65	2.2	0.8	0.4	" "

CRITICAL CONDITION $\begin{cases} C = 0.8\% \\ V_C = 6.40 \text{ fps} \end{cases}$

BS-01

Series BS-01-2

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.90	0.0535	68.2	57.0	125.2	750	8.50	11.2	5.1	2.6	Everything moving
3.74	0.0515	62.4	52.6	115.0	725	8.25	9.8	4.2	2.2	" "
3.54	0.0487	55.2	46.7	101.9	680	7.75	8.5	3.7	1.9	Heavy bed load
3.54	0.0487	48.2	41.0	89.2	630	7.20	7.2	3.3	1.7	Sliding bed
3.46	0.0477	44.0	37.4	81.4	615	7.00	6.6	3.0	1.5	Just above critical
3.34	0.0459	42.4	37.0	79.4	600	6.80	5.4	2.0	1.0	Just above critical
3.26	0.0448	41.4	35.8	77.2	590	6.70	5.6	2.2	1.1	CRITICAL
2.87	0.0394	36.6	31.0	67.6	555	6.30	5.6	2.6	1.3	Thin bed
2.28	0.0314	28.4	24.6	53.0	480	5.45	3.8	1.8	0.9	Flat bed
1.67	0.0229	21.6	19.0	40.6	425	4.85	2.6	1.2	0.6	" "
1.59	0.0219	17.0	15.2	32.2	375	4.25	2.2	1.1	0.5	" "

CRITICAL CONDITION $\begin{cases} C = 1.1\% \\ V_C = 6.70 \text{ fps} \end{cases}$

BS-01

Series BS-01-3

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.75	0.0653	65.8	52.2	118.0	725	8.25	13.6	8.1	4.2	Everything moving
4.38	0.0604	56.8	45.3	102.1	670	7.60	11.5	7.0	3.6	Pulsating bed, just above critical
4.87	0.0670	52.4	42.6	95.0	650	7.35	9.8	5.6	2.9	Just above critical
4.76	0.0656	50.6	40.8	91.4	635	7.25	9.8	5.6	2.9	CRITICAL
4.28	0.0589	44.0	36.4	80.4	600	6.80	7.6	4.2	2.2	Thin bed
3.92	0.0540	38.6	31.4	70.0	550	6.25	7.2	4.3	2.25	Flat bed
3.36	0.0462	29.4	24.9	54.3	485	5.50	4.5	2.5	1.25	" "
2.66	0.0368	24.6	21.2	45.8	445	5.05	3.4	1.8	0.9	" "

CRITICAL CONDITION $\begin{cases} C = 3\% \\ V_C = 7.25 \text{ fps} \end{cases}$

Series BS-01-4

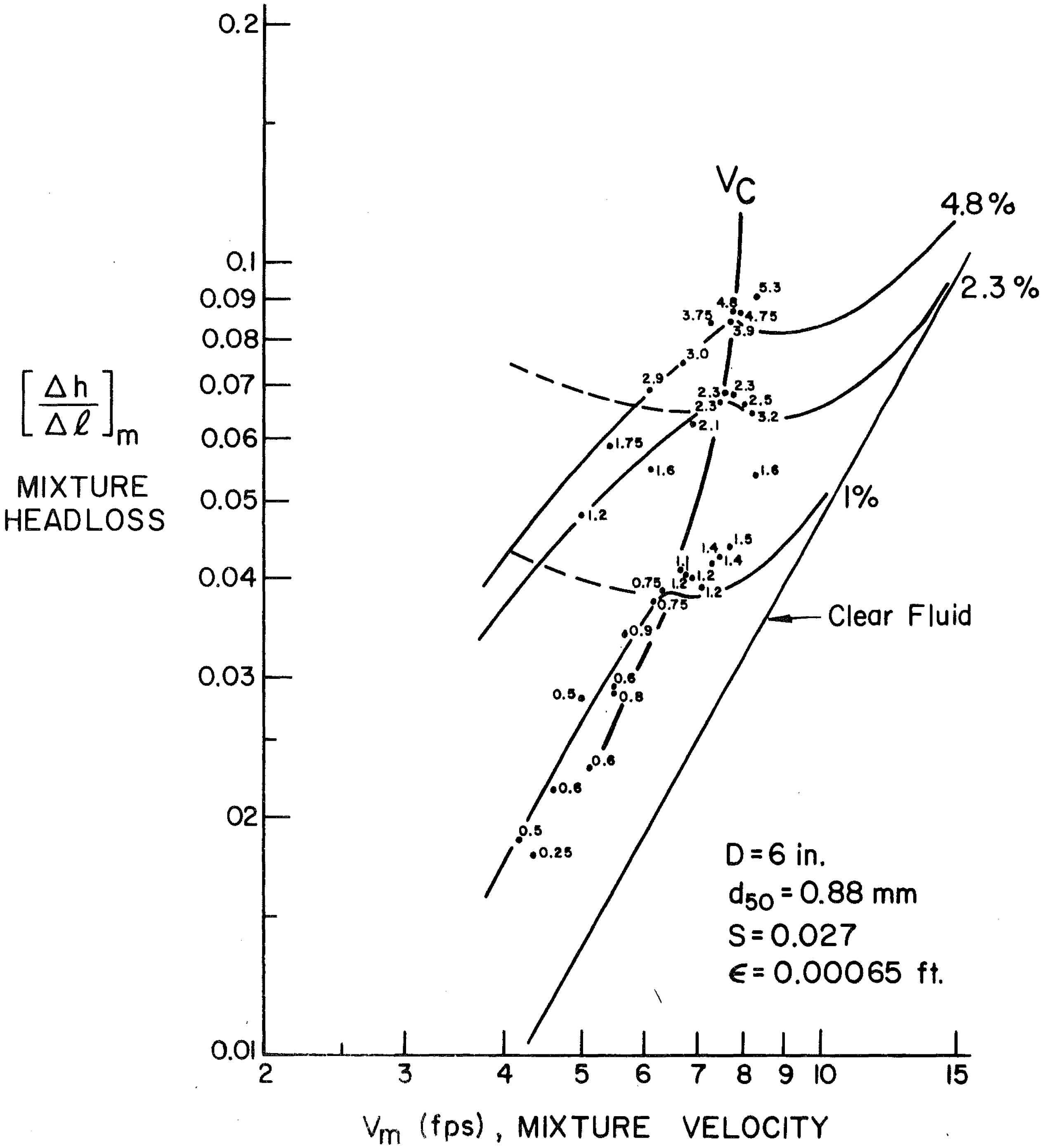
test section $\Delta h_{1.95}$	test section $\left(\frac{\Delta h}{\Delta \ell}\right)_m$	loop readings Δh_R	loop readings Δh_D	loop readings $\Delta h_R+\Delta h_D$	loop readings Q_m	loop readings V_m	loop readings $\Delta h_R-\Delta h_D$	loop readings $\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
5.54	0.0762	59.0	45.2	104.2	700	7.95	14.8	9.8	5.0	Pulsating
5.56	0.0765	57.0	44.1	101.1	690	7.85	12.9	8.2	4.2	Just about critical
5.56	0.0765	54.1	41.4	95.5	670	7.60	12.7	8.5	4.35	CRITICAL
5.33 5.39	0.0738	50.7	39.7	90.4	655	7.45	11.0	6.8	3.5	Deposit
5.23	0.0720	45.7	35.9	81.6	615	7.00	9.8	6.1	3.1	Deposit
4.66	0.0642	39.7	31.0	70.7	565	6.45	8.7	5.7	2.95	"
4.15	0.0571	33.6	26.6	60.2	525	6.00	7.0	4.5	2.25	Flat bed
3.51	0.0484	28.4	22.6	51.0	480	5.55	5.8	3.8	1.9	" "
2.98	0.0410	24.1	19.8	43.9	445	5.05	4.3	2.7	1.4	" "
2.26	0.0310	17.6	15.2	32.8	385	4.40	2.4	1.2	0.60	Flat bed, saltating
1.64	0.0260	13.4	11.5	24.9	325	3.70	1.9	1.1	0.5	Flat bed, saltating

Series BS-01-4

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
						2nd Run				
6.05	0.0834	69.5	51.4	120.9	720	8.20	18.1	12.6	6.5	Heavy bed load
5.68	0.0783	64.2	47.4	111.6	685	7.80	16.8	12.0	6.1	Sliding bed
5.59	0.0769	62.0	46.3	108.3	680	7.75	15.7	11.0	5.7	" "
6.07	0.0835	55.4	41.6	97.0	650	7.40	13.8	9.7	5.0	CRITICAL
5.64	0.0775	47.4	36.8	84.2	600	6.85	10.6	7.2	3.7	Deposit bed
4.87	0.0670	35.8	27.5	63.3	530	6.05	8.3	5.8	3.0	Thick flat bed
1.05	0.0145	5.8	4.8	10.6	210	2.40	1.0	0.6	0.3	Dunes

CRITICAL CONDITION $\begin{cases} C = 5\% \\ V_C = 7.40 \text{ fps} \end{cases}$

BS-03



0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
02
0.01
[Δh/Δℓ]m
MIXTURE HEADLOSS
Vc
4.8%
2.3%
1%
Clear Fluid
D=6 in.
d50 = 0.88 mm
S = 0.027
ε = 0.00065 ft.
2
3
4
5
6
7
8
9
10
15
Vm (fps), MIXTURE VELOCITY

Series BS-03-1

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.22	0.0440	54.0	46.4	100.4	675	7.70	7.6	2.9	1.5	Everything moving
3.05	0.0420	49.4	42.5	91.9	645	7.35	6.9	2.8	1.4	" "
2.92	0.0401	43.7	37.9	81.6	610	6.95	5.8	2.3	1.2	Heavy bed load
3.00	0.0412	40.5	35.2	75.7	585	6.65	5.3	2.1	1.1	Pulsating, just above critical
2.82	0.0388	36.4	32.0	68.4	560	6.35	4.4	1.5	0.75	CRITICAL
2.74	0.0377	33.4	29.2	62.6	540	6.15	4.2	1.5	0.75	Deposit, thin bed
2.13	0.0292	27.0	23.9	50.9	485	5.50	3.1	1.1	0.6	Flat bed
2.05	0.0282	21.4	19.0	40.4	440	5.00	2.4	0.9	0.5	" "
1.31	0.01800	16.8	15.1	31.9	380	4.35	1.7	0.5	0.25	" "
					2nd Run					
3.95	0.0542	61.4	52.4	113.8	730	8.30	9.0	3.2	1.6	Everything moving
3.08	0.0422	50.8	43.6	94.4	660	7.50	7.2	2.8	1.4	" "
2.97	0.0394	45.2	39.1	84.3	625	7.10	6.1	2.3	1.2	Heavy bed load
2.95	0.0405	41.8	36.1	77.9	595	6.80	5.7	2.3	1.2	Pulsating, just above critical
2.82	0.0387	39.0	33.8	72.8	570	6.50	5.2	2.2	1.1	CRITICAL
2.54	0.0349	33.6	29.1	62.7	530	6.05	4.5	2.0	1.0	Deposit
2.49	0.0342	30.4	26.4	56.8	500	5.70	4.0	1.8	0.9	Thin bed

Continuation

Series BS-03-1

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
2.10	0.0289	28.2	24.6	52.8	485	5.50	3.6	1.6	0.8	Flat bed
1.69	0.0232	24.0	21.2	45.2	455	5.15	2.8	1.2	0.6	" "
1.59	0.0218	20.4	17.6	38.0	410	4.65	2.8	1.3	0.6	" "
1.36	0.0187	16.85	14.7	31.55	370	4.20	2.15	1.0	0.5	" "

CRITICAL CONDITION $\begin{cases} C = 1.0\% \\ V_C = 6.40 \text{ fps} \end{cases}$

Series BS-03-2

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.77	0.0655	59.5	47.9	107.4	720	8.20	11.6	6.1	3.2	Everything moving
4.83	0.0662	56.15	46.0	102.15	705	8.00	10.15	4.95	2.5	Heavy bed load
4.97	0.0683	53.4	43.1	96.5	685	7.80	9.3	4.5	2.3	Pulsating, just above critical
4.94	0.0680	51.0	41.9	92.9	670	7.60	9.1	4.5	2.3	CRITICAL
4.81	0.0662	49.8	40.8	90.6	660	7.50	9.0	4.6	2.3	Deposit, thin bed
4.56	0.0627	42.7	35.1	77.8	610	6.95	7.6	4.1	2.1	Flat bed
4.00	0.0550	33.6	28.0	61.6	540	6.15	5.6	3.1	1.6	" "
3.51	0.0483	27.8	13.80	41.6	440	5.00	4.0	2.3	1.2	" "

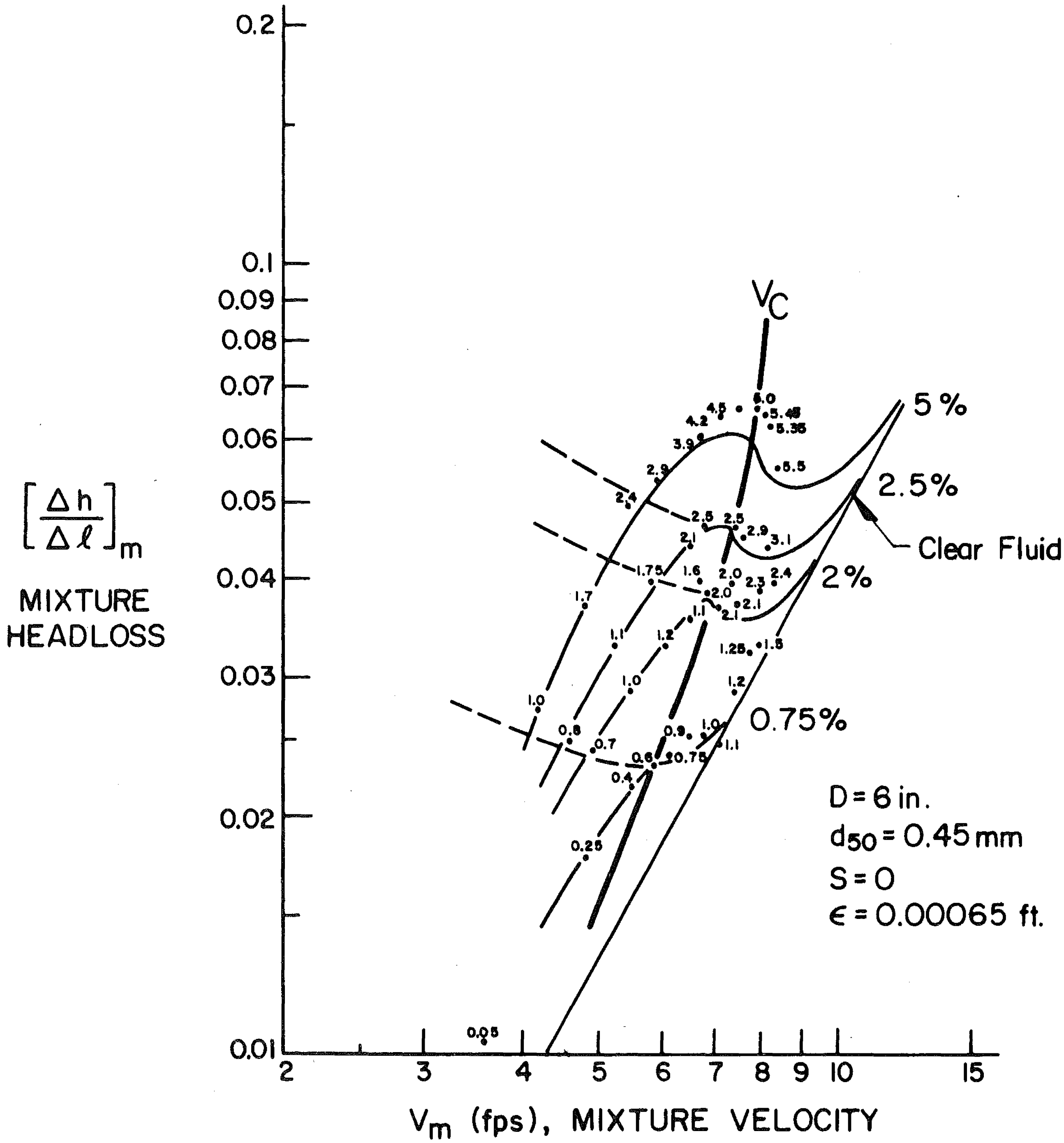
CRITICAL CONDITION $\begin{cases} C = 2.30\% \\ V_C = 7.60 \text{ fps} \end{cases}$

BS-03

Series BS-03-3

test section $\Delta h_{1.95}$ [in.]	test section $(\frac{\Delta h}{\Delta \ell})_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R+\Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R-\Delta h_D$ [in.]	$\Delta h_R-\Delta h_D$ corrected [in.]	C [%]	COMMENTS
6.56	0.0902	68.0	51.4	119.4	755	8.30	16.6	10.4	5.3	Everything moving
6.36	0.0874	58.7	44.5	103.2	700	7.95	14.2	9.1	4.75	Pulsating, just above critical
6.36	0.0874	56.8	42.7	99.5	690	7.85	14.1	9.2	4.8	CRITICAL
6.29	0.0864	53.7	41.3	95.0	675	7.75	12.4	7.7	3.9	Deposit
6.13	0.0842	48.3	37.0	85.3	640	7.30	11.3	7.3	3.75	Flat bed
5.44	0.0746	41.6	32.4	74.0	590	6.70	9.2	5.9	3.0	" "
5.07	0.0697	34.4	26.1	60.5	535	6.10	8.3	5.8	2.9	" "
4.26	0.0585	27.0	21.5	48.5	480	5.45	5.5	3.5	1.75	" "

CRITICAL CONDITION $\begin{cases} C = 4.8\% \\ V_C = 7.85 \text{ fps} \end{cases}$



$\left[\frac{\Delta h}{\Delta \ell}\right]_m$
MIXTURE HEADLOSS
0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
2
3
4
5
6
7
8
9
10
15
V_m (fps), MIXTURE VELOCITY
V_C
5 %
2.5%
2%
0.75%
Clear Fluid
D = 6 in.
d_{50} = 0.45 mm
S = 0
ϵ = 0.00065 ft.

Series BS-001-1

test section		loop readings								COMMENTS
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
2.40	0.0330	53.7	45.7	99.4	700	7.95	8.0	3.0	1.5	Everything moving
2.35	0.0324	49.8	42.8	92.6	675	7.7	7.0	2.5	1.25	Heavy bed load
2.10	0.0289	46.7	40.0	86.7	650	7.4	6.7	2.4	1.2	" " "
1.80	0.0248	43.1	37.1	80.2	625	7.1	6.0	2.1	1.1	Rapidly moving bed
1.85	0.0255	40.1	34.7	74.8	600	6.8	5.4	1.9	1.0	Pulsating bed
1.80	0.0255	36.0	31.2	67.2	570	6.5	4.8	1.8	0.9	" "
1.75	0.0241	32.3	28.0	60.3	540	6.15	4.3	1.5	0.75	Slowly pulsating bed
1.70	0.0234	29.7	26.2	55.9	515	5.85	3.5	1.2	0.6	CRITICAL
1.60	0.0220	25.8	23.0	48.8	485	5.5	2.8	0.8	0.4	Thin bed
1.30	0.0179	20.2	18.0	38.2	420	4.8	1.8	0.4	0.25	Flat bed
0.75	0.0103	11.5	10.6	22.2	315	3.6	0.9	0.1	0.05	" "

CRITICAL CONDITION $\begin{cases} C = \frac{3}{4}\% \\ V_C = 5.85 \text{ fps} \end{cases}$

BS-001

Series BS-001-2

test section $\Delta h_{1.95}$ [in.]	$(\frac{\Delta h}{\Delta \ell})_m$	loop readings Δh_R [in.]	Δh_D [in.]	$\Delta h_R + \Delta h_D$ [in.]	Q_m [gpm]	V_m [fps]	$\Delta h_R - \Delta h_D$ [in.]	$\Delta h_R - \Delta h_D$ corrected [in.]	C [%]	COMMENTS
2.90	0.0399	61.8	51.2	113.0	730	8.3	10.6	4.7	2.4	Everything moving
2.80	0.0386	56.4	46.6	103.0	700	7.95	9.8	4.5	2.3	Heavy bed load
2.70	0.0371	50.0	41.4	91.4	655	7.45	8.6	4.1	2.1	Pulsating, sliding bed
2.85	0.0392	47.0	39.0	86.0	645	7.35	8.0	3.8	1.95	Pulsating, sliding bed
2.70	0.0371	44.0	36.4	80.4	620	7.05	7.6	3.8	1.95	Just above critical
										CRITICAL
2.80	0.0386	41.4	34.8	76.2	600	6.85	6.6	3.1	1.60	Deposit
2.60	0.0358	35.8	30.7	66.5	570	6.5	5.1	2.1	1.10	Thin bed
2.40	0.0330	31.4	26.6	58.0	530	6.05	4.8	2.3	1.20	Flat bed
2.10	0.0289	26.9	23.0	49.9	485	5.5	3.9	1.9	1.0	" "
1.75	0.0241	21.7	18.8	40.5	430	4.9	2.9	1.4	0.7	" "
0.55	0.0076	6.0	5.2	11.2	220	2.5	0.8	0.4	0.2	Dunes

CRITICAL CONDITION $\begin{cases} C = 1.9\% \\ V_C = 6.95 \text{ fps} \end{cases}$

BS-001

Series BS-001-3

test section		loop readings								COMMENTS
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.20	0.0440	59.9	48.2	108.1	715	8.15	11.7	6.1	3.1	Heavy bed load
3.30	0.0454	53.0	42.8	95.8	670	7.6	10.2	5.5	2.85	Quickly moving bed
3.40	0.0469	49.7	40.4	90.1	655	7.45	9.3	4.8	2.45	CRITICAL
3.40	0.0469	42.8	34.4	77.2	600	6.8	8.4	4.9	2.47	Thin bed
3.20	0.0440	38.0	30.9	68.9	570	6.5	7.1	4.1	2.10	Thickening bed
2.90	0.0399	31.1	25.4	56.5	510	5.8	5.7	3.4	1.75	" "
2.40	0.0330	24.85	21.0	45.85	460	5.25	3.85	2.15	1.10	" "
1.80	0.0248	19.4	16.5	35.9	410	4.65	2.9	1.50	0.80	Flat bed
0.60	0.0083	6.0	5.3	11.3	220	2.5	0.7	0.30	0.15	Very little saltation, dunes

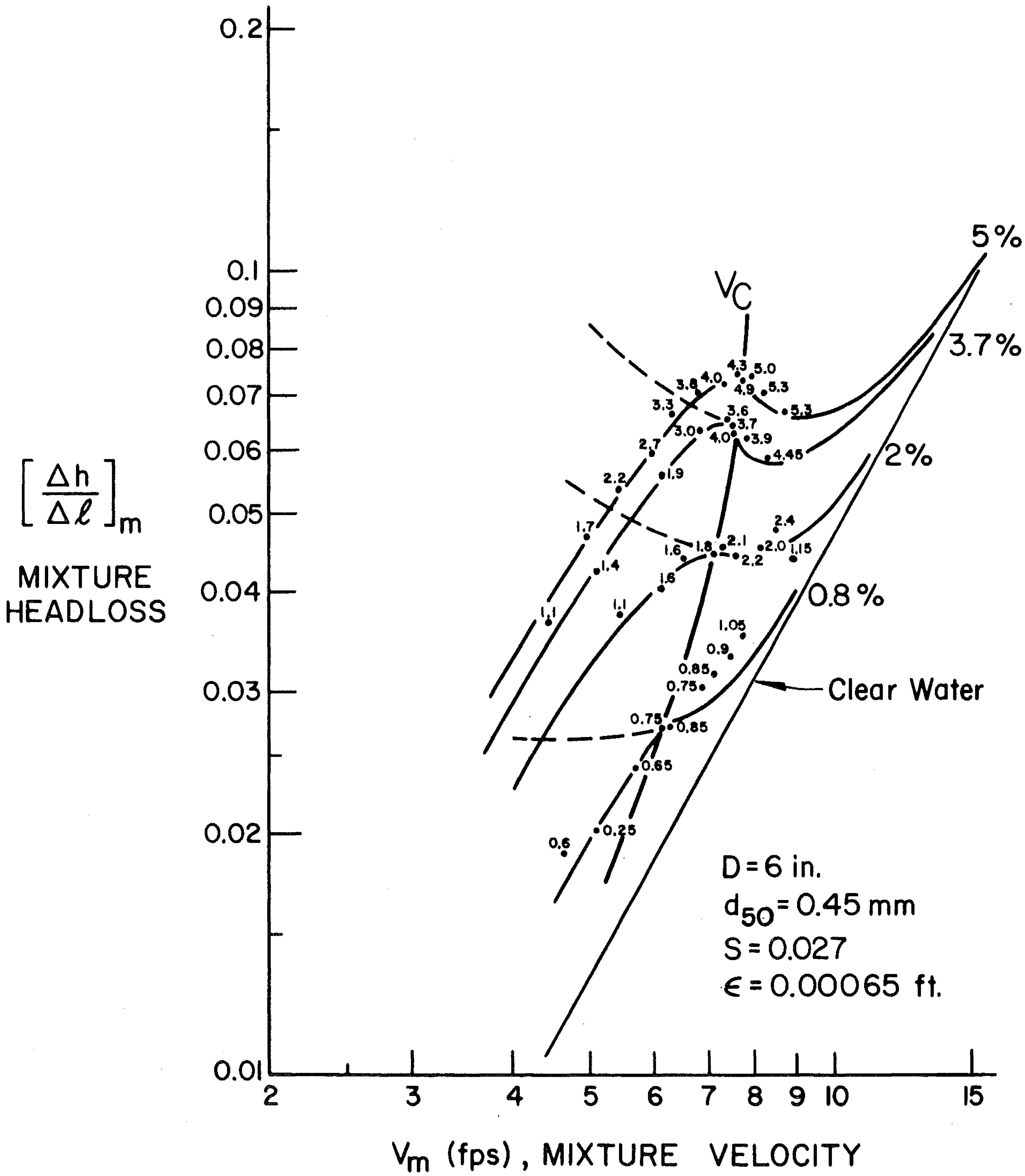
CRITICAL CONDITION $\begin{cases} C = 2.5\ \% \\ V_C = 7.45\ \text{fps} \end{cases}$

Series BS-001-4

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.10	0.0555	68.10	51.30	119.40	740	8.4	16.80	10.70	5.5	Above critical, slowly pulsating
4.60	0.0631	64.40	48.20	112.60	720	8.2	16.20	10.50	5.35	Just above critical
4.70	0.0645	62.10	45.90	108.00	710	8.1	16.20	10.70	5.45	Sliding
										CRITICAL
4.80	0.0660	58.40	43.40	101.80	690	7.85	15.00	9.90	5.05	Just below critical
4.80	0.0660	53.00	39.60	92.60	660	7.5	13.40	8.80	4.50	Flat bed
4.70	0.0645	48.80	36.80	85.60	620	7.05	12.00	8.3	4.2	" "
4.40	0.0605	42.80	32.00	74.80	585	6.65	10.80	7.5	3.85	" "
3.90	0.0536	33.40	25.30	58.70	520	5.9	8.10	5.70	2.90	" "
3.60	0.0495	28.90	22.25	51.15	480	5.45	6.65	4.65	2.40	" "
2.70	0.0371	21.90	17.30	39.20	420	4.8	4.60	3.20	1.65	" "
2.00	0.0275	16.50	13.50	30.00	370	4.2	3.00	1.90	1.00	Flat bed, little bed load
0.70	0.0096	5.90	5.10	11.00	215	2.45	0.80	0.40	0.20	Dunes

CRITICAL CONDITION $\begin{cases} C = 5.4\% \\ V_C = 7.95 \text{ fps} \end{cases}$

BS-003


0.2
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
$\left[\frac{\Delta h}{\Delta \ell}\right]_m$
MIXTURE
HEADLOSS
2
3
4
5
6
7
8
9
10
15
V_m (fps), MIXTURE VELOCITY
V_C
5%
3.7%
2%
0.8%
Clear Water
D = 6 in.
d_{50} = 0.45 mm
S = 0.027
ϵ = 0.00065 ft.

Series BS-003-1

test section		loop readings									COMMENTS
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C		
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]		
3.20	0.0440	63.8	55.0	118.8	775	8.84	8.8	2.3	1.15		Heavy bed load
2.56	0.0352	49.2	42.5	91.7	675	7.70	6.7	2.1	1.05		" " "
2.44	0.0335	46.2	40.2	86.4	655	7.45	6.0	1.8	0.9		Sliding bed
2.31	0 0317	43.0	37.5	80.5	625	7.10	5.5	1.7	0.85		Pulsating bed
2.20	0.0304	40.0	35.0	75.0	605	6.87	5.0	1.5	0.75		" "
2.0	0.0274	33.0	28.6	61.6	550	6.25	4.4	1.7	0.85		Just above critical
1.97	0.0271	31.8	27.7	59.5	540	6.15	4.1	1.5	0.75		CRITICAL
1.77	0.0243	27.6	24.2	51.8	500	5.70	3.4	1.3	0.65		Deposit
1.49	0.0204	21.4	19.3	40.7	450	5.10	2.1	0.5	0.25		Thin bed

CRITICAL CONDITION $\begin{cases} C = 0.75\% \\ V_C = 6.15 \text{ fps} \end{cases}$

Series BS-003-2

test section		loop readings								COMMENTS
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R+\Delta h_D$	Q_m	V_m	$\Delta h_R-\Delta h_D$	$\Delta h_R-\Delta h_D$ corrected	C	
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
3.49	0.0480	63.4	52.6	116.0	745	8.50	10.8	4.8	2.4	Heavy bed load
3.31	0.0455	57.4	48.2	105.6	710	8.10	9.2	3.9	2.0	" " "
3.26	0.0448	53.8	44.4	98.2	670	7.60	9.4	4.5	2.2	Sliding bed
3.31	0.0455	47.4	39.2	86.6	635	7.25	8.2	4.2	2.1	Pulsating bed
										CRITICAL
3.23	0.0444	44.2	37.0	81.0	620	7.05	7.2	3.5	1.8	Just below critical
3.21	0.0441	38.6	32.4	71.0	575	6.55	6.2	3.1	1.6	Thin bed
2.95	0.0405	34.0	28.2	62.2	540	6.15	5.8	3.1	1.6	Flat bed
2.72	0.0374	27.0	23.0	50.0	480	5.45	4.0	2.1	1.1	" "
2.61	0.0190	19.8	17.2	37.0	410	4.65	2.6	1.2	0.6	" "
0.66	0.0092	5.8	5.4	11.2	210	2.40	0.4	0.1	0.05	Dunes

CRITICAL CONDITION $\begin{cases} C = 2.0\% \\ V_C = 7.10 \text{ fps} \end{cases}$

BS-003

Series BS-003-3

test section		loop readings								
$\Delta h_{1.95}$	$\left(\frac{\Delta h}{\Delta \ell}\right)_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.23	0.058	65.4	51.0	116.4	730	8.30	14.4	8.7	4.45	Everything moving
4.51	0.062	57.8	45.3	103.1	685	7.80	12.5	7.6	3.9	Sliding bed
4.56	0.0627	55.3	43.0	98.3	665	7.55	12.3	7.8	4.0	Pulsating bed
4.62	0.0640	55.2	43.5	98.7	665	7.55	11.7	7.2	3.7	Just above critical
										CRITICAL
4.75	0.0652	53.0	41.8	94.8	655	7.45	11.2	7.0	3.6	Just below critical
4.59	0.0630	44.6	35.25	79.85	605	6.90	9.35	5.85	3.0	Flat bed
4.07	0.0560	34.6	28.30	62.90	540	6.15	6.3	3.7	1.9	" "
3.08	0.0422	24.0	19.60	43.60	450	5.10	4.4	2.7	1.4	" "

CRITICAL CONDITION $\begin{cases} C = 3.70\% \\ V_C = 7.50 \text{ fps} \end{cases}$

Series BS-003-4

test section		loop readings								
$\Delta h_{1.95}$	$(\frac{\Delta h}{\Delta \ell})_m$	Δh_R	Δh_D	$\Delta h_R + \Delta h_D$	Q_m	V_m	$\Delta h_R - \Delta h_D$	$\Delta h_R - \Delta h_D$ corrected	C	COMMENTS
[in.]		[in.]	[in.]	[in.]	[gpm]	[fps]	[in.]	[in.]	[%]	
4.82	0.0663	69.2	52.7	121.9	760	8.65	16.5	10.3	5.3	Sliding bed
5.10	0.0702	64.0	48.2	112.2	720	8.20	15.8	10.3	5.3	" "
5.39	0.0741	60.4	45.7	106.1	700	7.95	14.7	9.6	5.0	Pulsating bed
5.35	0.0738	58.8	44.5	103.3	680	7.75	14.3	9.5	4.9	CRITICAL
5.46	0.0752	55.6	42.6	98.2	670	7.60	13.0	8.5	4.3	Deposit
5.46	0.0738	50.2	38.4	88.6	635	7.25	11.8	7.9	4.0	Thin bed
5.13	0.0706	44.8	34.0	78.8	600	6.80	10.8	7.4	3.8	Flat bed
4.82	0.0663	39.5	30.1	69.6	560	6.35	9.4	6.5	3.3	" "
4.34	0.0596	34.0	26.2	60.2	525	6.00	7.8	5.4	2.7	" "
3.90	0.0536	28.2	22.1	50.3	475	5.40	6.1	4.3	2.2	" "
3.41	0.0470	23.7	18.8	42.5	435	4.95	4.9	3.4	1.7	" "
2.64	0.0364	19.0	15.7	34.7	390	4.45	3.3	2.1	1.1	" "

CRITICAL CONDITION $\begin{cases} C = 5.0\% \\ V_C = 7.75 \text{ fps} \end{cases}$

APPENDIX II

This is a summary of the effective parameters and data tabulated and plotted in Appendix I.

Tables A-1 to A-8 summarize each series of tests.

Table A-9 is a tabulation of all the critical velocities determined. The critical velocities underlined at 1, 2, 3, and 5% concentrations are interpolated from the critical velocity curves for a rapid visual comparison of the results at those respective concentrations.

The data tabulated in Appendix II are plotted in Figures 5 to 8.

G-01	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 4 in	0.50	5.00	0.845
d_{50} = 0.88 mm	1.00	5.50	0.930
	1.75	5.75	0.970
S = 0	2.00	5.75	0.970
ε = 0.0001 ft	5.00	5.95	1.005

Table A-1

G-02	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 4 in	0.50	4.80	0.812
d_{50} = 0.88 mm	1.00	5.10	0.862
S = -0.060	3.00	5.35	0.904
ε = 0.0001 ft	7.00	5.00	0.845

Table A-2

G-001	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 4 in d_{50} = 0.45 mm S = 0 ε = 0.0001 ft	0.65 1.50 3.00 7.00	5.10 5.60 6.25 6.50	0.862 0.947 1.056 1.100

Table A-3

G-002	C (%)	V_C (fps)	$\frac{V_D}{\sqrt{2gD(s_s-1)}}$
D = 4 in d_{50} = 0.45 mm S = -0.060 ε = 0.0001 ft	0.05 0.10 0.25 0.55 2.25 2.50	3.7 3.9 4.5 5.1 5.5 5.7	0.625 0.660 0.760 0.862 0.930 0.964

Table A-4

βS-01	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 6 in d_{50} = 0.88 mm S = 0 ε = 0.00065 ft	0.8 1.1 3.0 5.0	6.40 6.70 7.25 7.40	0.829 0.920 0.995 1.016

Table A-5

BS-03	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 6 in	1.0	6.40	0.879
d_{50} = 0.88 mm	2.3	7.60	1.043
S = +0.027	4.8	7.85	1.078
ϵ = 0.00065 ft			

Table A-6

BS-001	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 6 in	0.75	5.85	0.805
d_{50} = 0.45 mm	1.9	6.95	0.955
S = 0	2.5	7.45	1.025
ϵ = 0.00065 ft	5.4	7.95	1.095

Table A-7

BS-003	C (%)	V_C (fps)	$\frac{V_C}{\sqrt{2gD(s_s-1)}}$
D = 6 in	0.75	6.15	0.845
d_{50} = 0.45 mm	2.0	7.10	0.975
S = +0.027	3.7	7.50	1.030
ϵ = 0 00065 ft	5.0	7.75	1.064

Table A-8

C (%)	G-01	G-02	G-001	G-002
0.05				3.70
0.01				3.90
0.25				4.50
0.50				
0.55	5.00	4.80		5.10
0.65			5.10	
(1)	5.50	5.10	5.40	5.30
1.50			5.60	
1.75	5.75			
(2)	5.75	5.25	6.00	5.45
2.25				5.50
2.50				5.70
3.00		5.35	6.25	
4.00				
(5)	5.95	5.25	6.40	
6.00				
7.00		5.00	6.50	

Table A-9 Summary of Results (Critical Velocities)

C (%)	BS-01	BS-03	BS-001	BS-003
0.75 0.80	6.40		5.85	6.15
(1)	6.65	6.40	6.10	6.40
1.10	6.70			
1.90			6.95	
(2)	6.90	7.40	7.00	7.10
2.30		7.60		
			7.45	
3.00	7.25			
3.70				7.50
4.00				
4.80		7.85		
(5)	7.40	7.90	7.80	7.75
5.40			7.95	
6.00				
7.00				

Table A-9 (Contd.)