[redacted]Y OF VARIABLES AFFECTING FLOW CHARACTERISTICS AND SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS*

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Introduction

The U. S. Geological Survey has been studying sediment transport and resistance to flow at Colorado State University, Fort Collins, Colorado, since 1956. The study has largely been done in laboratory flumes with only limited collection of field data.

The characteristics of the flumes used in the investigations are tabulated in table 1. The principle studies have been completed in the 2 ft and 8 ft flumes.

The characteristics (size and gradation) of the bed materials which have been studied, the range of mean velocity, depth, slope, temperature, bed material and fine sediment concentration and forms of bed roughness investigated and the flume in which each study was made are indicated in table 2.

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TABLE 1. --Characteristics of flumes used

No.	Type	Length (ft)	Width (ft)	Depth (ft)	Range of Slope (%)	Range of Discharge (cfs)
1	Recirculating adjustable slope	150	8	2	0-1.5	0-22
2	do	60	2	2.5	0-2	0-7.5
3	do	40	2/3	2/3	± (0-15)	0-1.0
4 [1/]	do	200	8	4	0-3	0-100

[1/] Under construction.

TABLE 2. --Flume studies

Flume	No. of Runs	Bed Material d_{50} (mm)	Gradation coefficient σ	Velocity range (fps)	Depth range (ft)	Slope x 10^2 range (ft/ft)	Bed material concen-tration range (ppm)	Fine sediment concen-tration range (ppm)	Temper-ature range (C^0)	Range of bed forms*
1	41	0.19	1.30	0.74-4.62	0.43-1.09	0.005-0.95	0-47,300	--	16-19	B-A
1	21	0.27	1.54	0.73-4.60	0.45-1.13	0.005-1.022	0-35,800	--	11-18	B-A
1	38	0.28	1.68	0.53-4.93	0.40-1.07	0.005-1.007	0-42,400	--	10-17	B-A
1	46	0.45	1.60	0.65-6.18	0.25-1.00	0.015-1.01	0-15,100	--	9-20	B-A
1	54	0.47	1.54	1.13-5.32	0.30-1.33	0.084-0.96	1.6-17,700	0-42,000	11-22	R-A
1	44	0.93	1.54	1.00-5.86	0.43-1.11	0.0129-1.28	0-10,200	--	16-21	B-SW
2	30	0.32	1.57	0.86-5.73	0.51-0.63	0.054-.983	0-29,600	--	8-33	B-A
2	39	0.54	1.52	0.89-6.21	0.59-0.91	0.016-1.928	0-50,000	0-102,000	16-23	B-A
2	15	0.33	1.27	1.02-5.93	0.49-0.52	0.016-1.14	0-18,400	--	19.8-20.3	B-A
2	17	0.33	2.07	1.06-6.34	0.48-0.52	0.022-.98	0-22,500	--	18.3-23.4	B-A

*B = Beginning of motion, R = Ripples, SW = Standing Waves, A = Antidunes.

The investigations conducted in flume 1 with the 0.19, 0.27, 0.28, 0.45 and 0.93 mm bed materials were conceived principally to provide a better understanding of the gross mechanics of flow and sediment transport using a range of sizes of natural alluvial sands with a gradation coefficient σ, ranging from 1.5 to 1.6 where

$$\sigma = \frac{1}{2}\left(\frac{d_{50}}{d_{16}} + \frac{d_{84}}{d_{50}}\right)$$

Special studies have been completed to help understand:

(1) The effect of temperature (viscosity).

(2) The effect of large concentrations of fine sediment (bentonitic and kaolin clays).

(3) The effect of the gradation of bed material.

(4) The effect of specific weight of bed material.

For each of the runs for the regular as well as the special studies the basic data collected included velocity, depth, slope, the size characteristics of the bed material, water temperature, bed roughness [obtained by direct measurement and by the sonic sounder measurements (Richardson, 1961)], and bed material discharge.

Forms of Bed Roughness

Based upon the general studies, the following regimes of flow and forms of bed roughness, see figure 1, were suggested by Simons and

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Figure 1.--Forms of bed roughness in alluvial channels

Richardson (1961) and (1962).

I Lower Regime
- Ripples
- Ripples on dunes
- Dunes

II Transition

III Upper Regime
- Plane bed
- Standing waves
- Antidunes

Resistance to flow is relatively large and bed material discharge is small in the lower regime and conversely, resistance to flow is small and bed material discharge large in the upper regime.

The principle reasons for differentiating between ripples and dunes are:

1. Ripples are relatively small, have lengths from 0.25-1.50 ft and a maximum amplitude of about 0.1 ft, move downstream more or less in the plane of the bed as a result of bed load movement, do not increase in amplitude with increasing depth, have a rather uniform length and amplitude, and did not form under the test conditions when the d_{50} of the bed material was larger than about 0.7 mm.

2. Dunes are similar in appearance to ripples but are much more irregular in form and of considerably greater length and amplitude than ripples. Also, dunes move through a channel at very different elevations with time and are less uniform than ripples. In general, the dimensions of the dunes are quite intimately related to the characteristics of the bed material, particularly, fall velocity, but also slope and depth. Dunes can attain a maximum amplitude approximately equal to the mean depth of flow under ideal conditions. Dunes can occur with any size of bed material so long as the flow brings sufficient tractive forces to bear on the particles to move them at $F_r < 1$. Dunes formed of material with a median diameter of about 2 in., with lengths over 100 ft and amplitudes of about 3 to 4 ft have been observed on the lower Rio Grande.

The relation between length of dunes and median fall diameter of bed material for nearly constant depth, figure 2, shows that the length of dunes

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Figure 2. --Relation of length of dunes to median fall diameter of bed material.

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increases as size of bed material decreases. Also, the data shows that with the smaller sizes of bed material the dunes are less angular.

The resistance to flow caused by the ripples exceeds that for dunes when d_{50} is smaller than about 0.30 mm under flume conditions. The converse is true for $d_{50} > 0.30$. For field conditions (depths greater than about 2 ft) the resistance to flow with dunes probably always exceeds that of ripples because of the small relative roughness associated with large depths and ripples. Consequently, resistance to flow caused by ripples and dunes is also a function of their lengths.

Variables Affecting Bed Roughness

Principle variables which affect the fall velocity and the fall diameter of a given bed material in natural flow and hence the form of bed roughness, are temperature (viscosity) as reported by Al-Shaikh Ali (1961) and concentration of fine sediment (apparent viscosity) as reported by Haushild, Simons and Richardson (1961). Figure 3 indicates

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Figure 3. --Variation in fall velocity of median particle size of Elkhorn River, Nebraska, sand with temperature in distilled water and in five percent by weight, dispersions of kaolin and bentonite.

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the effect of large concentrations of fine sediment (bentonite and kaolin) and temperature on the fall velocity of a river sand with a standard fall diameter of 0.28 mm.

A complete change in form roughness can be accomplished by the introduction of a large concentration of fine sediment (an increase in apparent viscosity of the water-sediment mixture) and, under favorable conditions, by a large reduction in stream temperature (an increase in viscosity of the water). The fact that radical changes in bed form can be caused by large changes in stream temperature or large concentrations of fine sediment, or both, can easily be verified in the laboratory flumes. The same effect has been observed in the field. For example, the Loup River near Dunning, Nebraska, has dunes as bed roughness in the summer when the stream fluid is less viscous; whereas, in contrast, the bed is essentially plane during the cold winter months. Similarly, two sets of data collected by Fahnestock[1/] in a stable reach of the Rio Grande at similar discharges show that when the water was cold the bed of the stream was plane, the resistance to flow was small, the depth was relatively small and the velocity was large; whereas, when the water was warm the bed roughness was dunes, the resistance to flow was large, depth was larger and the velocity was smaller (see table 3).

[1/] Fahnestock, R. K., U. S. Geological Survey, General Hydrology, Data collected on the Rio Grande, 1962, written communication.

TABLE 3. --Rio Grande River data collected on a stable reach for two different stream temperatures at similar discharge

Temperature F^0	Velocity ft/sec	Depth ft	Slope	Bed material d_{50}	Bed roughness	Manning n
50^0	4.25	2.45	.00049	0.30	Plane	0.014
80^0	2.53	3.66	.00053	0.30	Dunes	0.034

Changes in the form of bed roughness and, hence, the resistance to flow are reflected in depth and stage-discharge curves. Figure 4 shows a

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Figure 4. --Typical depth-discharge relation involving lower and upper regime flow.

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typical break in a depth-discharge relation caused by a change in bed form from dunes to plane bed. The Manning n for the dune bed was approximately 0.03; whereas, with the plane bed condition the Manning n was 0.012.

As a further verification of the significance of fall velocity experiments were conducted using as bed material an expanded clay (idealite) with a specific gravity of about 1.7, a median sieve diameter of 0.7 mm and a fall diameter of 0.35 mm. For a given flow condition this light weight bed material was shaped into essentially the same bed form as was observed using the 0.33 mm sand as the bed material.

To determine, in a preliminary way, the role of gradation of bed material with respect to resistance to flow and sediment transport in alluvial channels, two sets of runs were completed in flume 2 using two different bed materials and holding depth and temperature constant. The two bed materials had the same median fall diameter but one was quite uniform (σ = 1.27) and the other was graded (σ = 2.07). The effects of gradation on form of bed roughness are qualitatively illustrated in figure 5.

Figure 5. --Comparison of resistance to flow for various bed forms for both sands.

To further illustrate the effect of gradation of bed material on resistance to flow in alluvial channels, figures 6 and 7 [after Daranandana

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Figure 6. --Comparison of total bed friction factor, friction factor pertaining to grains, and friction factor pertaining to form roughness for uniform and graded bed material sands.

Figure 7. --Variation of bed friction factor f_b with slope.

(1962)] relate f_b to V and f_b to S, respectively, for the runs made with the uniform and the graded bed material, d_{50} = 0.33 mm. These relations follow logically from figure 5. The large scatter in these relations, when the bed form is ripples and dunes, and the bed material is graded, indicates that continual sorting and remixing takes place with time. This suggests that the representative fall velocity and gradation of the bed material also varies with time adding to the complexity of the mechanics of flow and transport in alluvial channels.

Prediction of Form of Bed Roughness

A completely satisfactory method of predicting form of bed roughness has apparently never been developed. Various methods of predicting form roughness (Albertson, Simons and Richardson, 1958; Simons and Richardson, 1961; and Garde, 1959) have been proposed; however, none of the methods are applicable for both laboratory and field conditions. A relatively simple relation, see figure 8, which relates stream power, median fall velocity of

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Figure 8. --Relation of stream power and median fall diameter of bed material to form of bed roughness.

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bed material and form roughness gives an indication of the form of bed roughness one can anticipate given the depth, slope, velocity, and fall diameter of bed material. Flume data were utilized to establish the boundaries separating (1) plane bed and ripples, (2) ripples and dunes for all sizes of bed material, and (3) dunes and transition for the 0.93 mm bed material. The lines dividing (1) dunes and transition, and (2) transition and upper regime are based upon the following field data: (1) Elkhorn River (Beckman and Furness, 1962); (2) Rio Grande 20 miles above El Paso (see table 3); (3) Middle Loup River at Dunning (Hubbell and Matejka, 1959); (4) Rio Grande at Cochiti; (5) Rio Grande near Bernalillo; (6) Rio Grande - Angostura heading (Culbertson and Dawdy, 19__); (7) the canal data reported by Simons (1957); and (8) canal data collected in Pakistan by Tipton and Kalmbach, Denver, and Harza Engineering Company, Chicago, during 1961-62. If only the flume data were used, the dividing line between dunes and transition would occur at about 10 percent less stream power than the field data indicates. In figure 8, note that the range of stream power for which dunes occur becomes smaller with decreasing fall diameter of bed material. Hence, when the median fall diameter of the bed material is relatively small, stable channels must be designed with care. For example, if large resistance to flow is anticipated, stable channel design concepts indicate a relatively small average velocity, large depth and steep slope. However, the channel may not function as anticipated. If the stream power is sufficiently large, the bed form will not be dunes but will be plane resulting in a small resistance to flow, a high average velocity, a small depth and an unstable channel with high transport capacity. A good example is the Marala-Ravi Canal in Pakistan[2/]. This canal has bed material with a median diameter of 0.29 mm and was designed to carry 15,500 cfs. When it was put into operation its bed depth was 9.1 ft, its slope was 1/3,460 and an average velocity of 4.51 ft/sec resulted. The stream power for these conditions was 0.71, which was sufficient for a plane bed, channel instability, and a bed material discharge of 132 tons per day per foot of width.

[2/] Data collected 1961-62 by Tipton and Kalmbach, Inc., Engineers, Denver, Colorado, written communication.

The measurement as well as the prediction of average velocity in alluvial channels is a complex problem. Observing velocity data it is immediately noted that error can be introduced into the measurement by any change in bed configuration during the measurement. Also, as the water-sediment mixture flows over the crests of the ripples and dunes a separation occurs, see figure 1. Taking measurements of velocities within the zone of separation shows that upstream velocities exist that are one-half to two-thirds average stream velocity and the boundary shear is sufficient to form ripples that are oriented opposite to the direction of the flow in the channel.

Prediction of Average Velocity

Various methods of determining average velocity and resistance factors for alluvial channels have been suggested. The Manning and Chezy equations developed for channels with rigid boundaries, the regime equations (Inglis, 1948) quite commonly referred to when attempting to design stable alluvial channels and Einstein's and Barbarosa's (1952) treatment of alluvial river channel roughness have all been used to estimate channel resistance and average velocity. The latter two methods are probably the most successful of those cited.

The flume data referred to in table 2 follow Einstein's river curve, which relates V/V_*'' to ψ' , with reasonable success within the range of ψ' values for which ripples and dunes occur. However, for both large and small values of ψ' , the data departs somewhat systematically and radically from the proposed curve. Hence, some modification is required when it is applied to laboratory data, see figure 9.

Figure 9. --Flume resistance data for various sands in relation to Einstein's bar resistance diagram.

The occurrence of the separation zones downstream of the ripples and dunes suggests that the cross sectional area through which the flow is assumed to occur should be reduced to eliminate the separation zones. This reduces the actual depth D to an effective depth D' and increases the average velocity V to an effective velocity V'. Using these concepts of depth and velocity a useful method of predicting the average velocity in alluvial channels has been devised (Simons and Richardson, 1962a). The method involved establishing a relation between V and V_* for the plane bed runs for each median fall diameter and neglecting the difference in resistance to flow and relative roughness with and without sediment movement for the plane bed. The resultant relation (figure 10a) which is essentially a straight line that passes

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Figure 10.--Relation of V and V' to V_* and V'_*, respectively, for bed material with a median fall diameter of about 0.29 mm and dunes

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through the origin, implies that for plane bed

$$V \alpha V_* = \frac{C}{\sqrt{g}} \sqrt{g DS}$$

With forms of bed roughness other than plane bed, the points relating V and V_* fall to the right of the relation for plane bed indicating a greater resistance to flow, the magnitude of which is proportional to the displacement to the right of the line. Assuming that this displacement is related to the volume of the flow within the separation zones downstream of the ripples or dunes, a correction to depth and velocity can be made based upon the assumed magnitude of the separation zones which yields an effective depth D' and velocity V'. Replotting the relation between

V and V_* for each run with similar bed roughness, using V' in place of V and $\sqrt{g D'S}$ in place of $\sqrt{g DS}$ puts the new points essentially on the line representing plane bed conditions. This indicates that if the depth correction ΔD can be determined such that $D' = D - \Delta D$ and $V' = V D/D'$ a useful method of predicting average velocity results provided the form of bed roughness and median fall diameter of the bed material are known. The complexity of predicting form roughness has already been discussed. Also, the usefulness of this method is limited when dealing with a situation where a small change in stream power will cause a change in bed roughness and a large change in average velocity.

The method applied to stable irrigation canals with dunes having median fall diameters of about 0. 28 mm is illustrated in figure 10a. The straight line passing through the origin is based upon plane bed flume runs using bed materials with median fall diameters of 0. 27 and 0. 28 mm. Figure 10b relates the depth D to the correction ΔD which is assumed to be related to the volume of the separation zones relative to the total flow and slope of energy gradient. The method of estimating average velocity, using figure 10, is illustrated in table 4. Also in table 4 the estimated average velocity is given for comparison with the measured average velocity. For most of the canals, agreement is within 10 percent illustrating the effectiveness of the method.

Certainly the source of considerable error in determining velocity and sediment transport is in evaluating the magnitude and effect of each significant variable - only a few have been discussed here. Future fundamental studies of the variables to more precisely define their effects on flow in alluvial channels, are essential.

Bed Material Discharge

The mechanics of sediment transport are very complex - many empirical and semi-empirical methods of estimating bed material discharge have been proposed. Of these many methods, two of the most commonly used are the Einstein method (1950) and the modified Einstein method (Colby and Hembree, 1955). Although the latter method is the most accurate, its usefulness is limited because computations are based on actual suspended sediment and velocity data; hence, it is not particularly useful for design problems.

TABLE 4. --Comparison of measured average velocity to computed average velocity using figure 10 for stable canals with dune bed and median diameter of bed material of approximately 0.29 mm

Depth D	Slope $S \times 10^3$	ΔD	D'	$\sqrt{g D'S}$	V'	Computed V	Measured V	Percent error
				Punjab Data, Simons (1957)				
2.6	.33	0.9	1.7	.135	2.44	1.59	1.4	+13.6
3.45	.22	0.75	2.70	.138	2.40	1.88	2.16	-12.9
2.24	.31	0.76	1.48	.122	2.10	1.39	1.53	- 9.15
2.20	.26	0.50	1.70	.119	2.05	1.58	1.50	+ 5.3
3.74	.17	0.54	3.20	.132	2.30	1.97	2.28	-13.6
5.10	.15	0.66	4.44	.146	2.50	2.17	2.27	- 4.4
5.42	.15	0.70	4.72	.151	2.60	2.26	2.30	- 1.8
5.43	.14	0.52	4.91	.154	2.65	2.40	2.25	+ 6.7
4.97	.15	0.64	4.33	.145	2.50	2.18	2.14	+ 1.9
4.53	.15	0.57	3.96	.138	2.40	2.10	2.14	- 1.9
6.36	.13	0.53	5.83	.156	2.70	2.47	2.49	+ 0.8
5.44	.16	0.75	4.69	.155	2.70	2.33	2.32	+ 0.4
2.46	.28	0.70	1.76	.126	2.20	1.57	1.56	+ 0.7
3.50	.20	0.67	2.93	.137	2.40	2.01	2.16	- 7.0
3.78	.20	0.71	3.07	.140	2.40	1.95	1.88	+ 3.7
5.47	.14	0.54	4.93	.149	2.60	2.34	2.15	+ 8.8
4.16	.20	0.77	3.39	.148	2.55	2.08	2.12	- 1.9
4.73	.16	0.65	4.08	.145	2.50	2.16	2.12	+ 1.9
10.80	.13	1.25	9.55	0.20	3.45	3.08	2.84	+ 8.5
10.90	.12	1.20	9.70	0.194	3.35	2.99	2.87	+ 4.2
				West Pakistan Data, Tipton and Kalmbach, Inc. (1961-62)				
7.0	.132	0.63	6.37	.169	2.92	2.66	2.74	- 2.9
10.0	.149	1.40	8.60	.203	3.51	3.02	3.36	-10.1
9.0	.15	1.27	7.73	.193	3.34	2.87	3.02	- 5.0
8.1	.158	1.15	6.95	.188	3.25	2.79	2.86	- 2.4
8.7	.183	1.39	7.31	.208	3.60	3.03	2.97	+ 2.01
6.0	.193	1.04	4.96	.175	3.03	2.51	2.67	- 6.0
9.1	.181	1.46	7.64	.211	3.65	3.06	3.10	- 1.3
9.0	.182	1.45	7.55	.210	3.64	3.06	3.10	- 1.3
9.3	.20	1.57	7.73	.223	3.85	3.20	3.15	+ 1.6

The relation between measured bed material discharge and the bed material discharge computed by the Einstein (1950) procedure is given in figure 11. It was found that agreement between the computed

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Figure 11. --Measured sediment discharge compared to sediment discharge computed by Einstein's function

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and measured sediment discharge varied appreciably with size of bed material and the form of bed roughness. Best results occurred in the transition zone connecting lower and upper regime flow. The largest variation occurred within the lower regime particularly near beginning of motion and with ripples where bed material discharge was relatively very small. Of course, success hinges on beginning with a known average velocity for each run. For design purposes, where it is necessary to estimate the average velocity, results would be less impressive.

A study of the Einstein method by Bishop (1961) using the flume data cited in table 2 resulted in a rather simple method of estimating bed material discharge. It involves:

1. Using the first nine steps as described by Einstein (1950) to determine ψ' except that R' was determined by a more direct graphical method developed by Vanoni and Brooks (1957) where

$$\psi' = \frac{\rho_s - \rho_f}{\rho_f} \quad \frac{d_{35}}{R' S}$$

2. Entering figure 12 with ψ' to determine ϕ_T from which the

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Figure 12. --Composite ϕ_T - ψ' curves for various sands from flume data.

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total bed material discharge q_T can be estimated from the relation

$$q_T = \phi_T \; \rho_s \; g \; d_{50}^{\;3/2} \left(\frac{\rho_s}{\rho_f} - 1 \right) \quad 43.2\, w$$

The ϕ_T - ψ' curves (figure 12) are very similar to Einstein's $\phi_* - \psi_*$ curves, except that the transport intensity factor

$$\phi_T = q_s \Big/ \rho_s \, g^{3/2} \, d_{50}^{\;3/2} \left(\frac{\rho_s}{\rho_f} - 1 \right)^{1/2}$$

is calculated from the total bed material load assuming i_B and i_b are equal to unity. The lower leg of each ϕ_T - ψ' curve has been fit by the probability function defined by Einstein. However, A_* and B_* were found to vary systematically with median fall diameter of bed material as shown in figure 13. The upper legs of each of the ϕ_T - ψ' curves do not

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Figure 13. --Values of A_* and B_* for theoretical probability curves from laboratory data.

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follow the probability relation and have been extended to fit the data empirically. The bed material discharge computed accordingly is compared with the measured bed material discharge in figure 14. The relation is

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Figure 14. --Measured sediment discharge compared to sediment discharge computed using modified ϕ_T - ψ' relation.

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consistently improved throughout the entire range of flow conditions investigated.

To illustrate the possible utility of Bishop's (1961) method for estimating bed material discharge in canals and rivers, the total bed material discharge was computed for the (1) canals investigated by Simons (1957), (2) the Niobrara River, (3) the Loup River, (4) the Colorado River, (5) the Solomon River, and (6) the Rio Grande. The computed values are related to a comparable total bed material discharge obtained by (1) direct measurement of the total bed material load in the canals, (2) direct measurement at a contracted section for the Niobrara River, (3) by direct measurement at the turbulence flume (Benedict, Albertson, and Matejka, 1953) on the Loup River and by the modified Einstein method for the Colorado River, the Solomon River and the Rio Grande, see figure 15. The agreement is best for

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Figure 15.--Comparison of bed material load estimated from laboratory curves with measured bed material load.

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shallow streams but offers good possibilities for all streams. However, as is the case for the flume data success achieved, when applying the method to field conditions, is dependent on the accuracy with which the stream velocity can be estimated or measured.

Future Studies

A series of so-called critical experiments are being considered, oriented toward:

1. A study of the mechanics of the formation of bed roughness in alluvial channels and a statistical analysis of their occurrence.

2. Determination of the magnitude of lift and drag on sediment particles.
3. Determination of fall velocity of gravel particles.
4. Measurement and evaluation of the role of turbulence on resistance to flow and sediment transport in alluvial channels.

The study of bed roughness will be initiated in flume 3 using a light weight bed material (Vestyron) with a specific gravity of 1.04-1.06. Using this facility, dune like roughness elements can be generated by the flow at very small Reynolds numbers. Actually, the individual motion of a single particle can be followed and studied over an appreciable distance.

The magnitude of the lift and drag forces on particles is being studied using individual beads mounted on a fine wire. The force on the bead is measured with calibrated semi-conductor strain gages. This method of measuring drag on a wire was originated by Sharp (1962) to determine velocity in pipes and open channels.

The measurement of turbulence in water has been a difficult task because of many factors--principally inadequate turbulence measuring equipment. However, preliminary work done in flume 3 using the electrokinetic probe reported by Chuang and Cermak (1962) indicates the feasibility of measuring turbulence in both pipes and open channels. The probe by Chuang (1962) has also been used in flume 3 to measure the frequency of shedding of vorticies downstream of cylinders. The results thus obtained are in excellent agreement with those obtained by Roshko (1953) in a wind tunnel using a hot wire anemometer.

Symbols and Units

Symbol	Definition	Units
A_*	Constant for ϕ_T	--
B_*	Constant for	--
$C/\sqrt{g}$	Chezy coefficient	--
D	Water depth	ft
ΔD	Correction to depth	ft
D'	Effective depth, $(D - \Delta D)$	ft
d_{50}	Size of bed material for which 50 percent is finer, etc.	ft
f_b	Friction factor of the bed	--
F_r	Froude number	--
i_b	Fraction of the bed material in a given size range	--
i_B	Fraction of bed load in a given grain size	--
q_s	Corresponding suspended load rate	lbs/sec/ft
q_t	Total sediment discharge	tons/day
R	Hydraulic radius	ft
R'	Hydraulic radius with respect to the grain	ft
R''	Hydraulic radius with respect to channel irregularities	ft
S	Slope	--
V	Average velocity	ft/sec
V'	Effective velocity	ft/sec
V_*	Shear velocity, $\sqrt{g\,DS}$	ft/sec
V'_*	Effective shear velocity	ft/sec
w	Width of channel	ft
ρ_s	Density of fluid	slugs/ft^3

Symbol	Definition	Units
ρ_f	Density of solids	slugs/ft^3
τ	Shear stress	lbs/ft^2
ϕ	Intensity of sediment transport	--
ϕ_*	Intensity of transport for individual grain size	--
ϕ_T	Intensity of transport for total bed material load	--
ψ'	Intensity of shear on representative particle	--
ψ_*	Intensity of shear for individual grain	--

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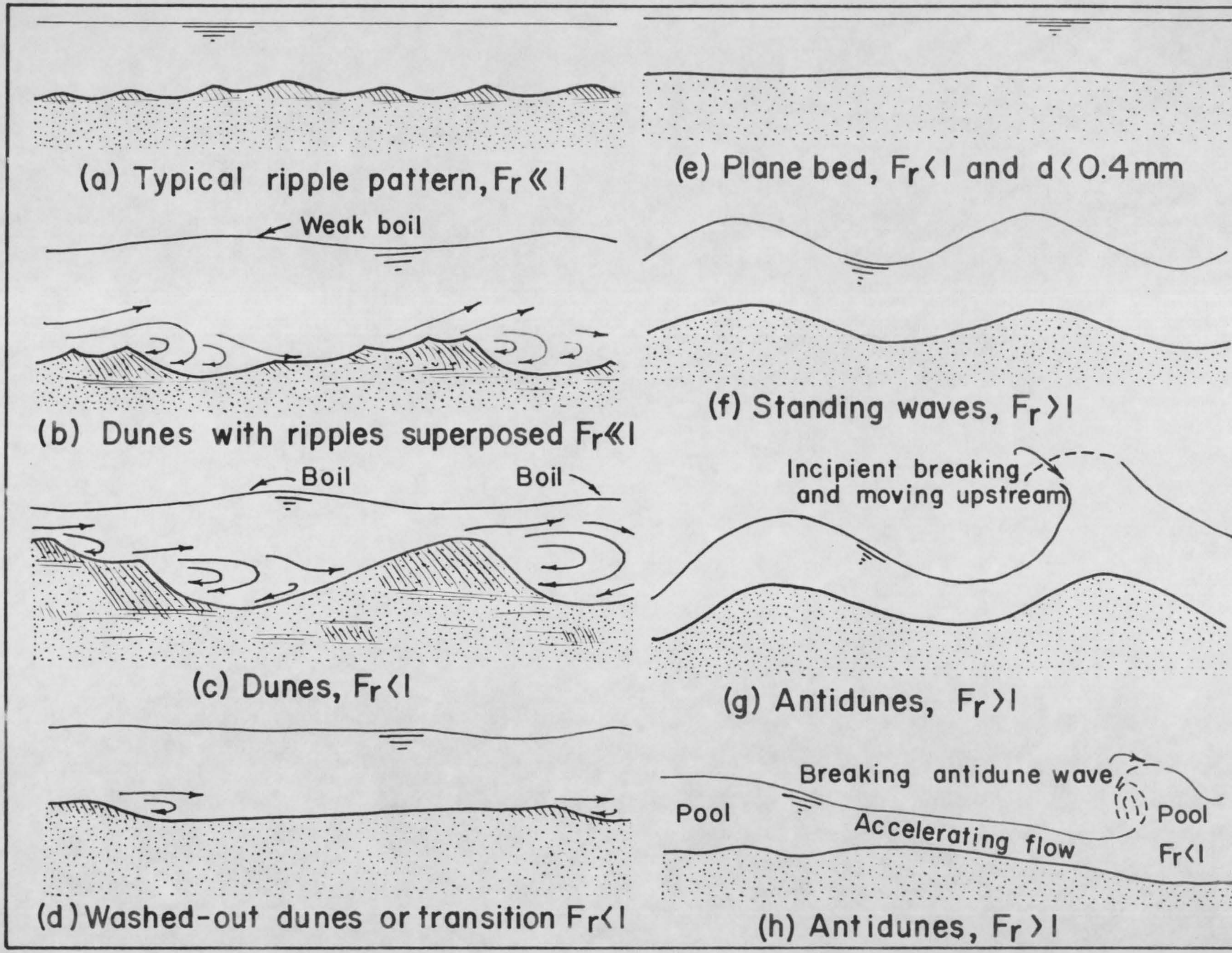


(a) Typical ripple pattern, $F_r \ll 1$

(b) Dunes with ripples superposed $F_r \ll 1$

(c) Dunes, $F_r < 1$

(d) Washed-out dunes or transition $F_r < 1$

(e) Plane bed, $F_r < 1$ and $d < 0.4$ mm

(f) Standing waves, $F_r > 1$

(g) Antidunes, $F_r > 1$

(h) Antidunes, $F_r > 1$

Fig. 1 Forms of Bed Roughness in Alluvial Channels

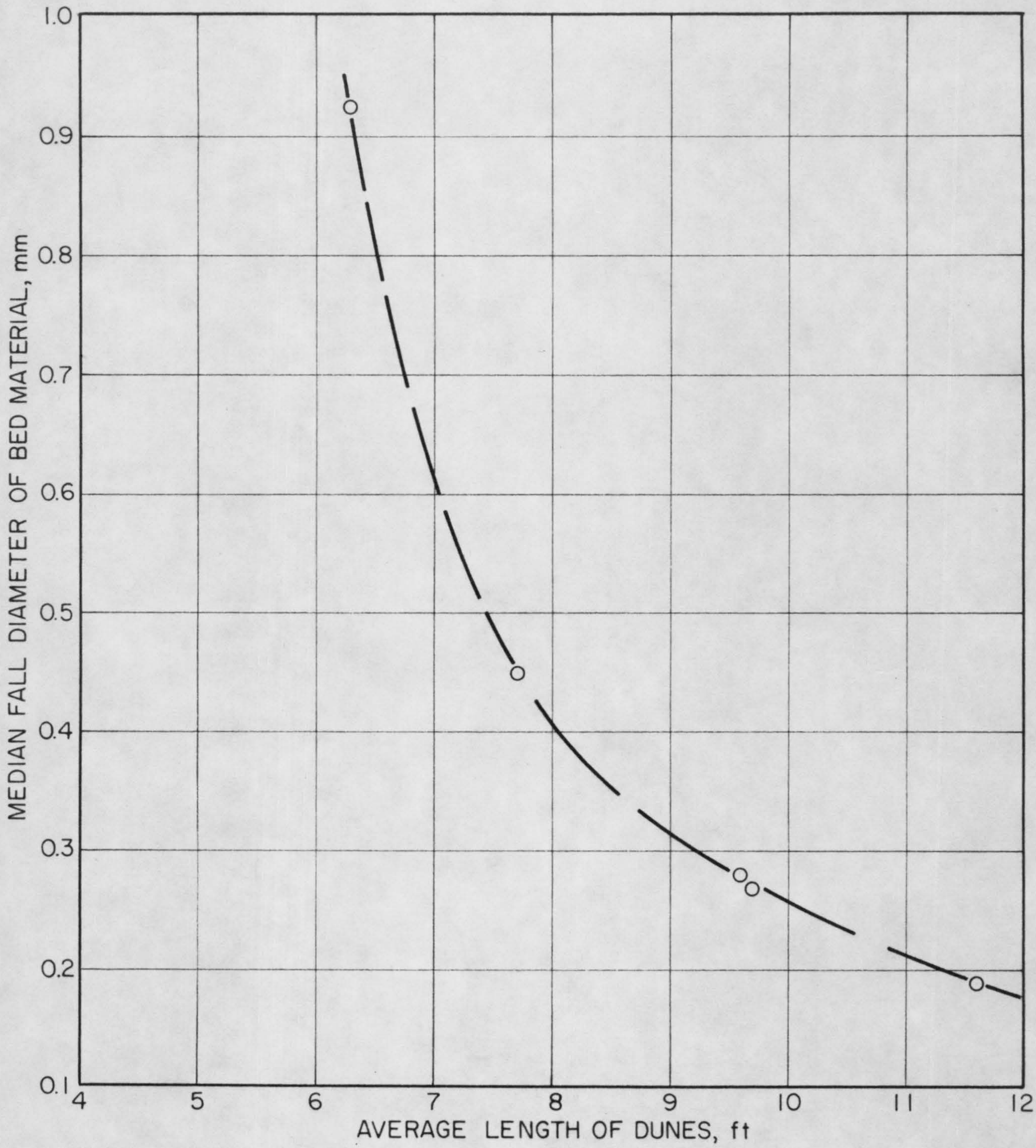


FIG. 2 APPROXIMATE RELATION OF LENGTH OF DUNES TO MEDIAN FALL DIAMETER OF BED MATERIAL FOR CONSTANT DEPTH

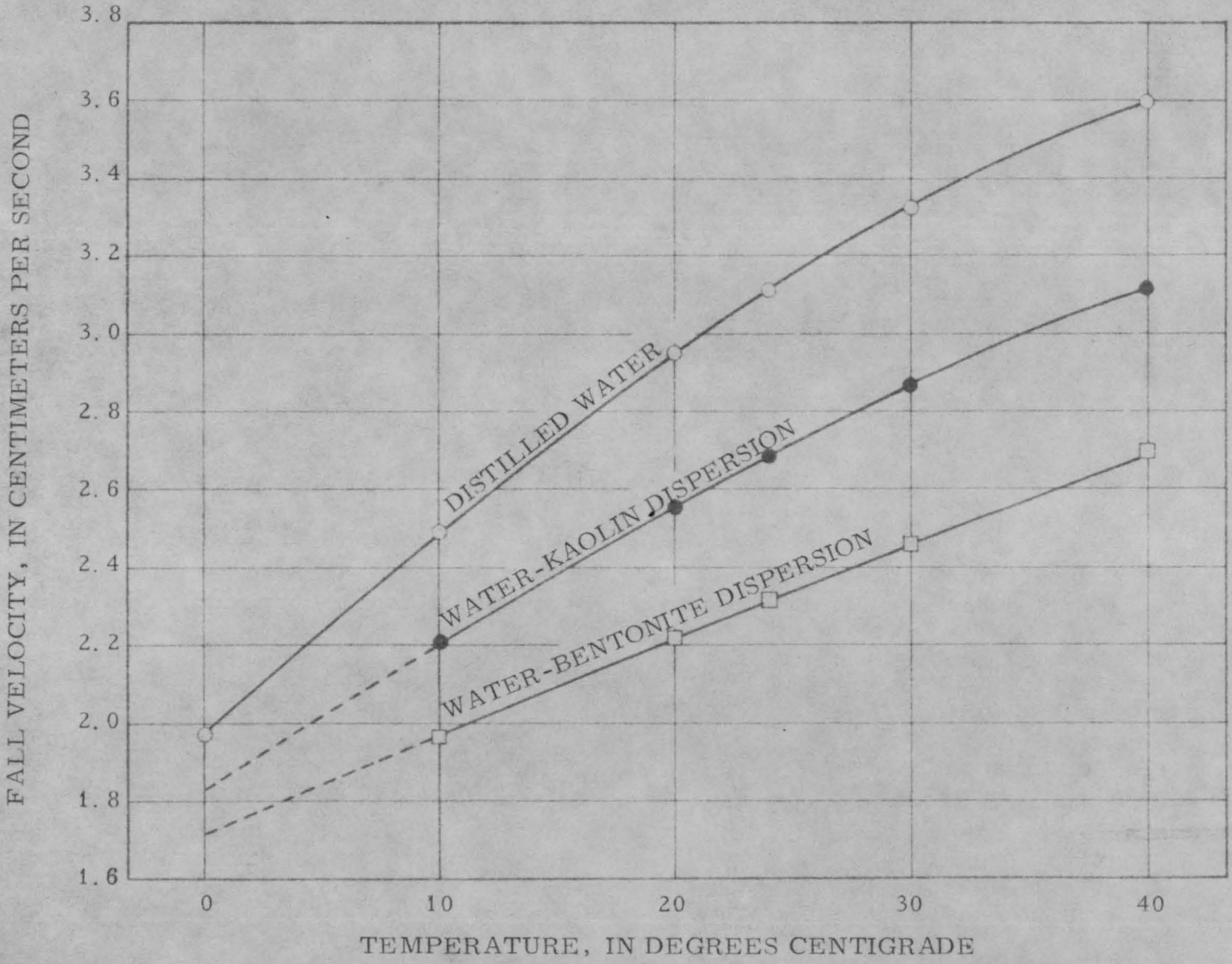


Figure 3. --Variation in fall velocity of median particle size of Elkhorn River, Nebraska sand with temperature in distilled water and in 5 percent, by weight, dispersions of kaolin and bentonite.

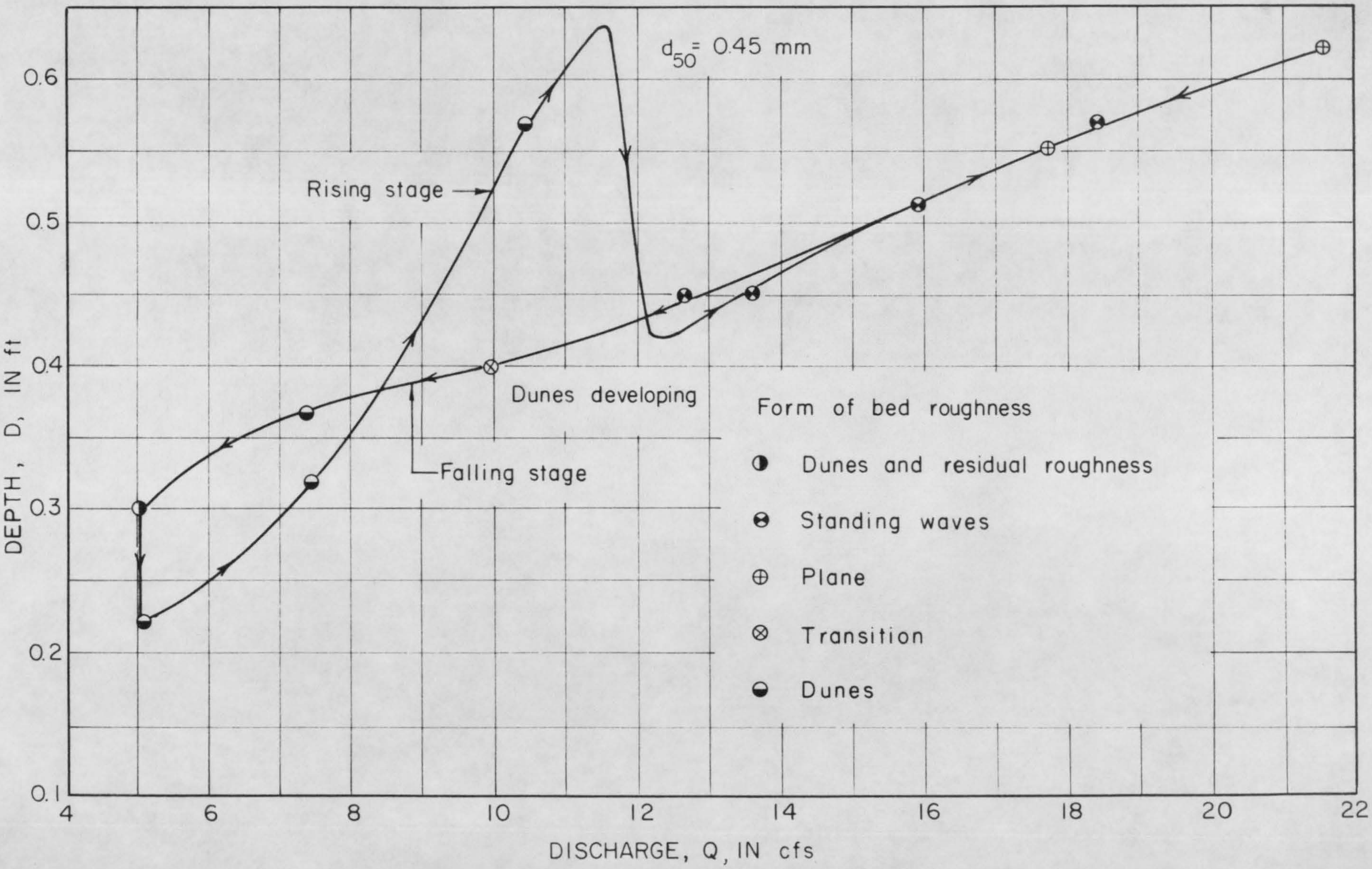


FIG. 4 RAPID AND TRANQUIL FLOW DEPTH – DISCHARGE RELATION, SLOPE VARYING WITH DISCHARGE

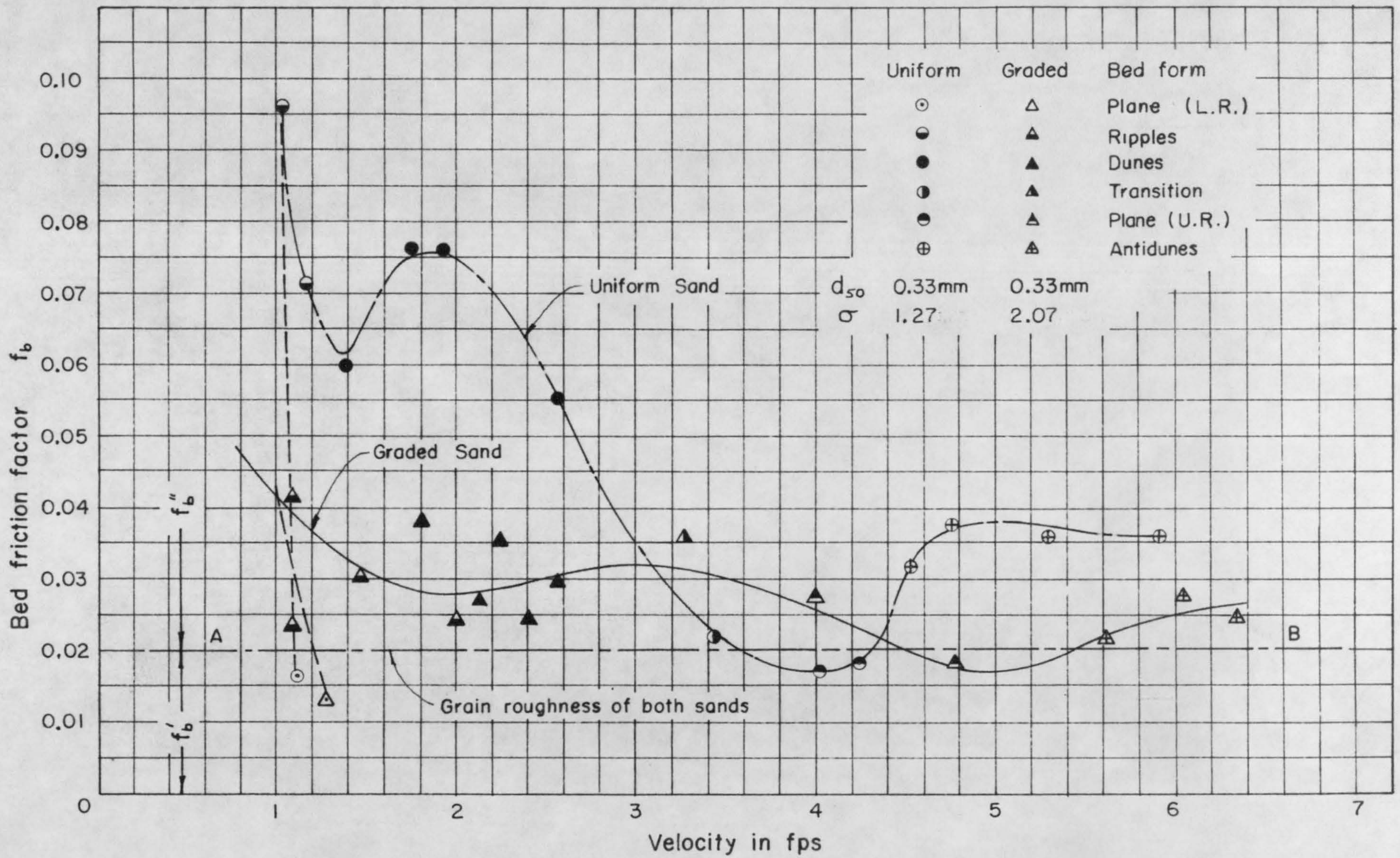


Figure 6 Comparison of total bed friction factor, friction factor pertaining to grains, and friction factor pertaining to form roughness for uniform and graded bed-material sands.

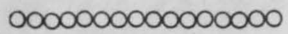
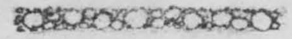
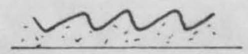
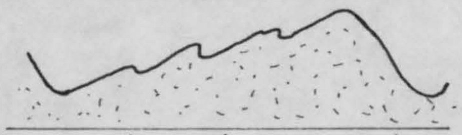
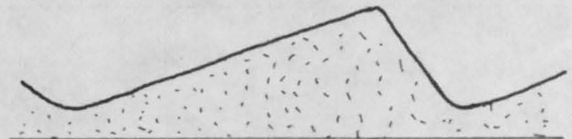
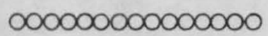
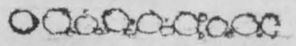
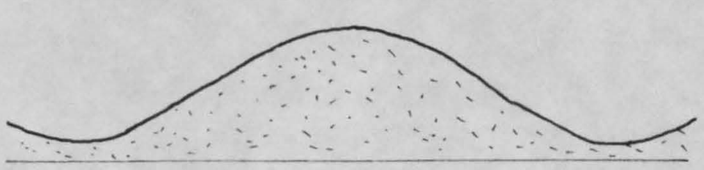
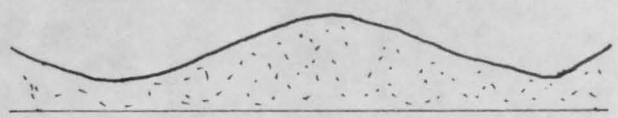
<table>
<tr><th>Bed Forms</th><th>Uniform Sand</th><th>Graded Sand</th></tr>
<tr><td rowspan="2">Plane bed & beginning of motion.</td><td></td><td></td></tr>
<tr><td colspan="2">a) Resistance to flow of the uniform sand is greater than graded sand.</td></tr>
<tr><td rowspan="2">Ripples</td><td>
l=0.86', h=0.032</td><td>
l=0.46', h = 0.025</td></tr>
<tr><td colspan="2">b) Resistance to flow of the uniform sand is greater than graded sand.</td></tr>
<tr><td rowspan="2">Dunes</td><td>
l= 3.33', h=0.095'</td><td>
l=4.00', h= 0.14'</td></tr>
<tr><td colspan="2">c) Resistance to flow of the uniform sand is greater than graded sand.</td></tr>
<tr><td rowspan="2">Plane bed Upper regime</td><td></td><td></td></tr>
<tr><td colspan="2">d) Resistance to flow of the graded sand is greater than uniform sand.</td></tr>
<tr><td rowspan="2">Antidunes</td><td>
l=5.05', h=0.15'</td><td>
l= 4.3' , h= 0.085'</td></tr>
<tr><td colspan="2">e) Resistance to flow of the uniform sand is greater than graded sand.</td></tr>
</table>

Figure 5 Comparison of resistance to flow for various bed forms for both sands.

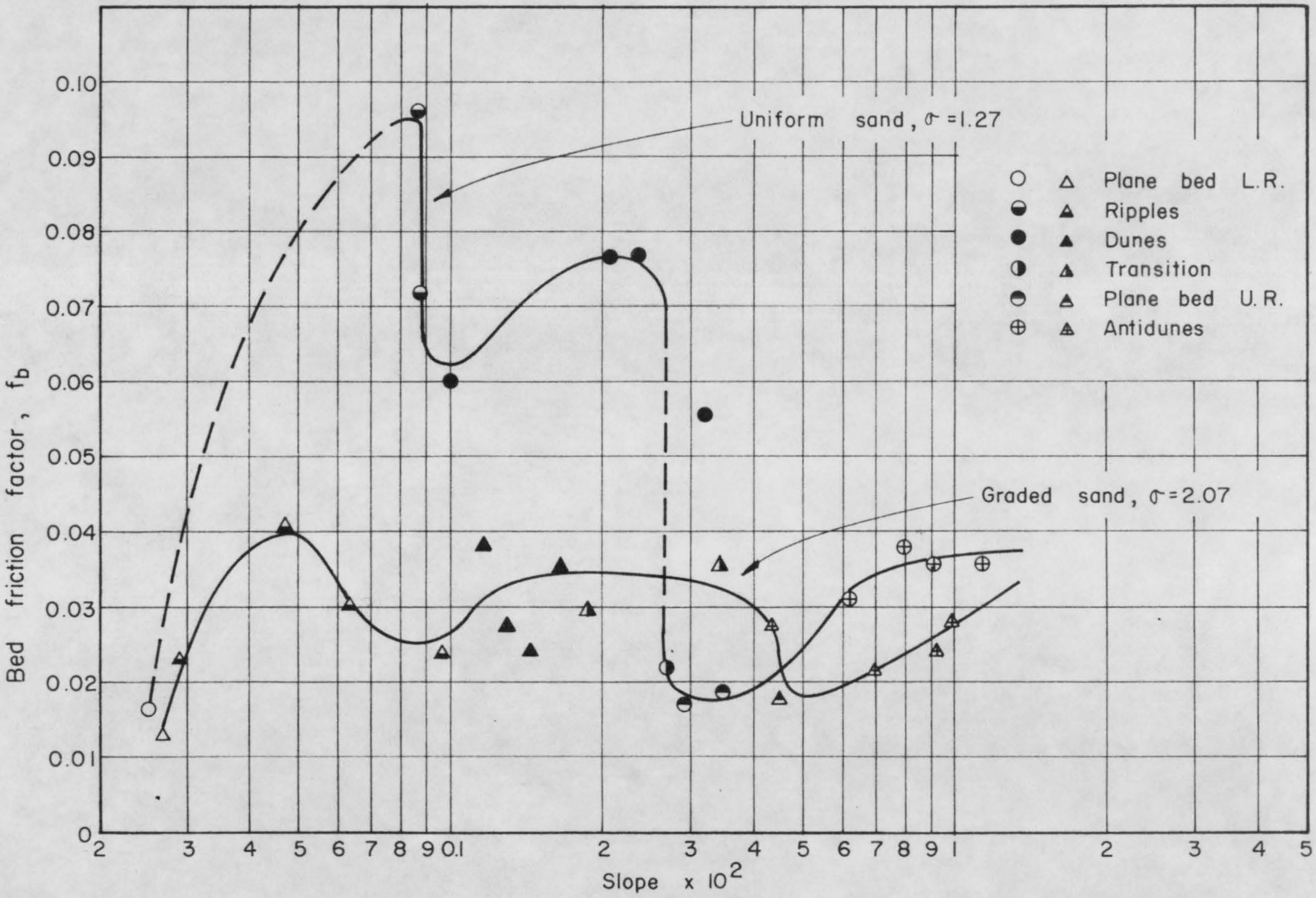


Figure 7 Variation of bed friction fraction f_b with slope.

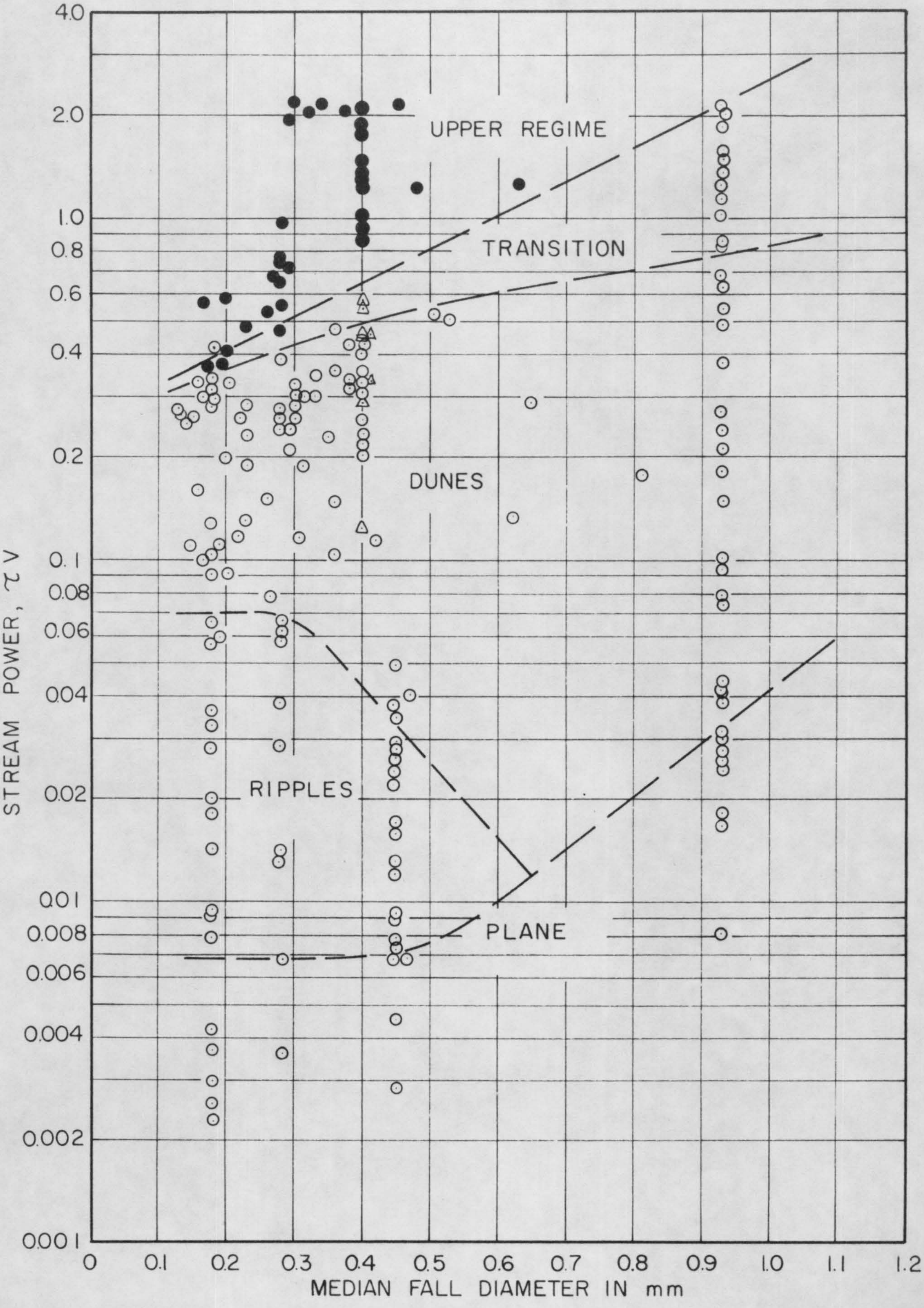


FIG. 8 RELATION OF STREAM POWER AND MEDIAN FALL DIAMETER TO FORM OF BED ROUGHNESS

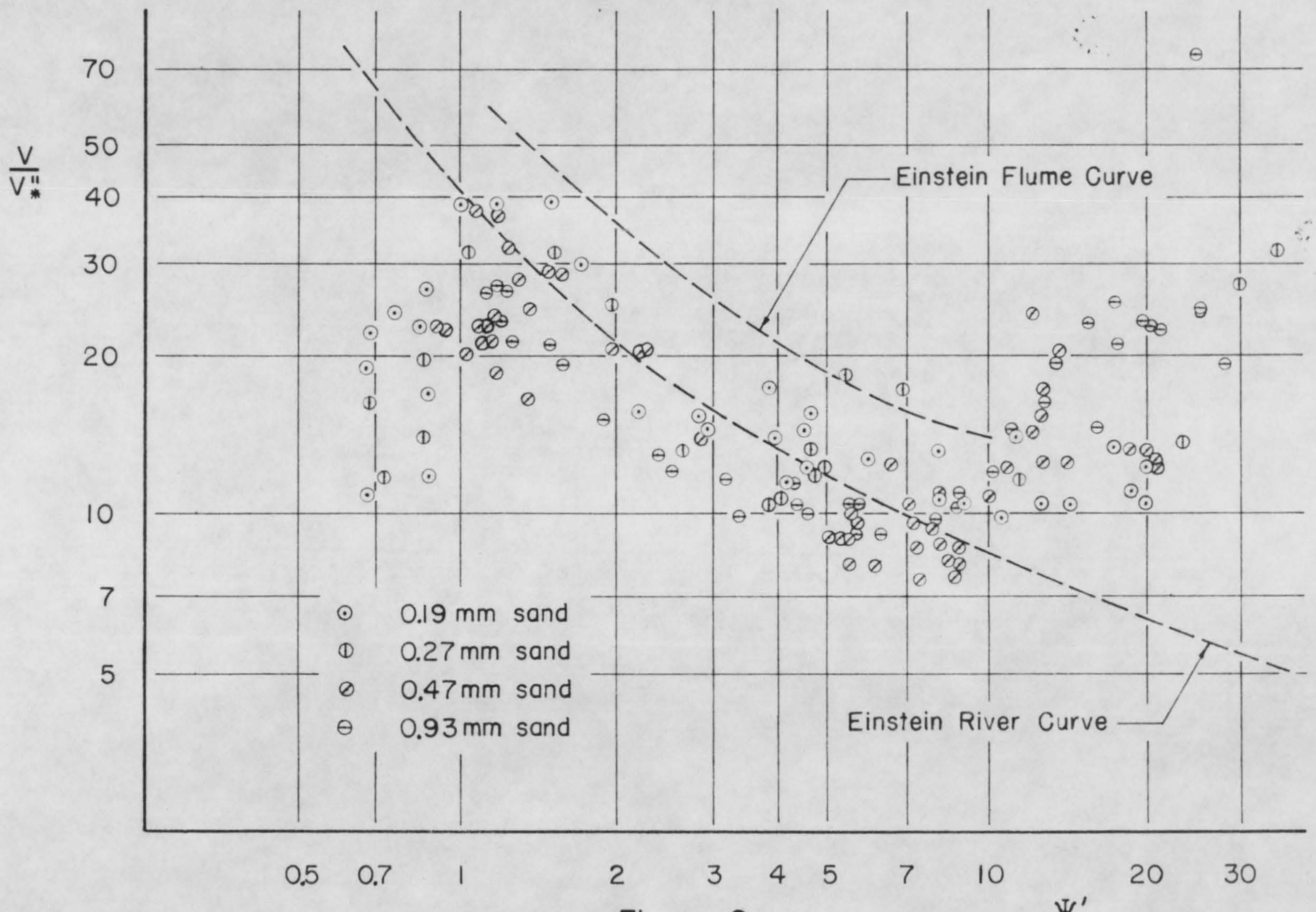


Figure 9

Flume resistance data for various sands in relation to Einstein Bar Resistance Curves

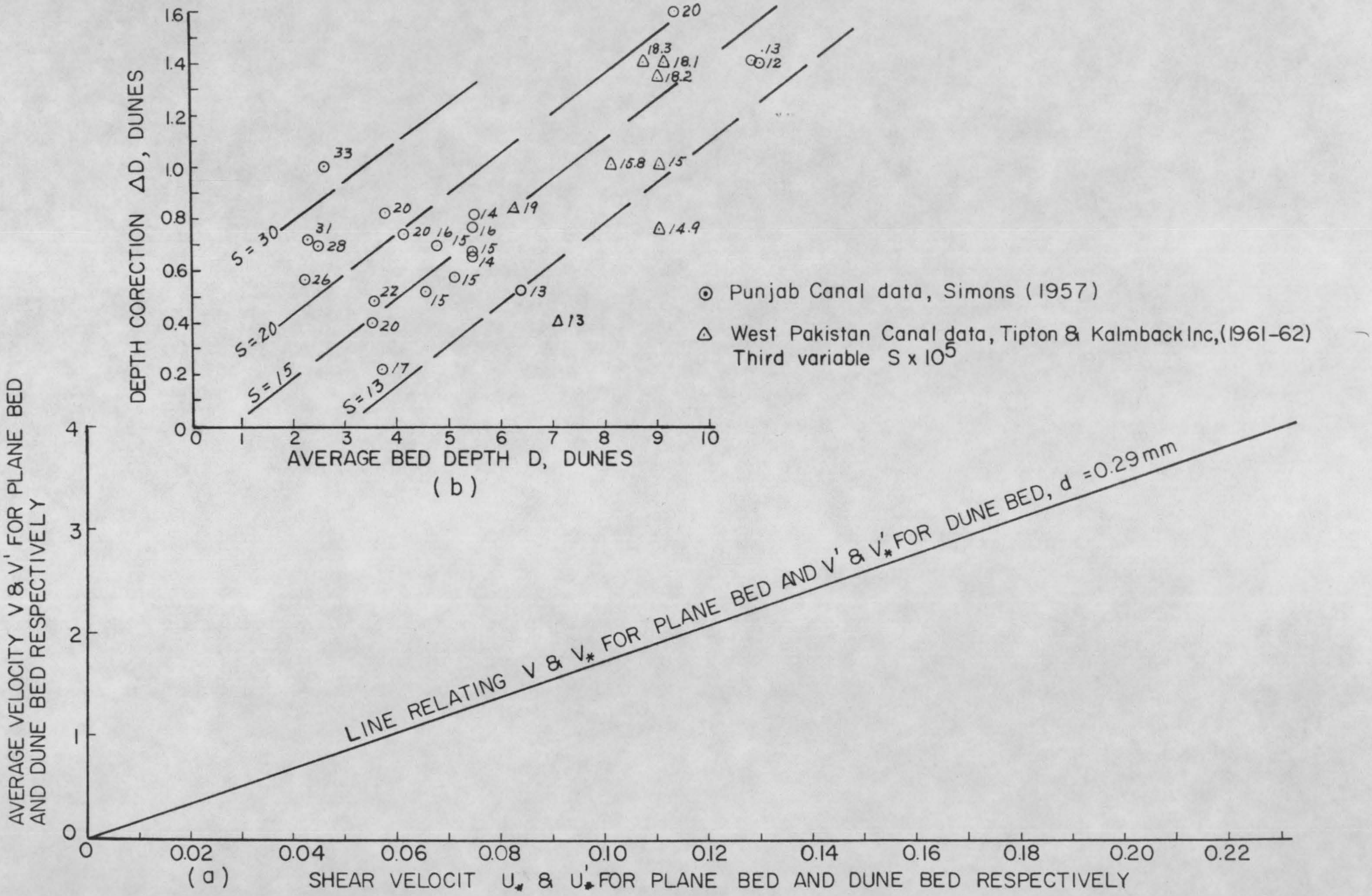


FIG. 10 RELATION OF V AND V' TO U_* AND U'_* RESPECTIVELY FOR BED MATERIAL WITH A MEDIAN FALL DIAMETER OF ABOUT 0.29 mm FOR PLANE BED AND DUNES

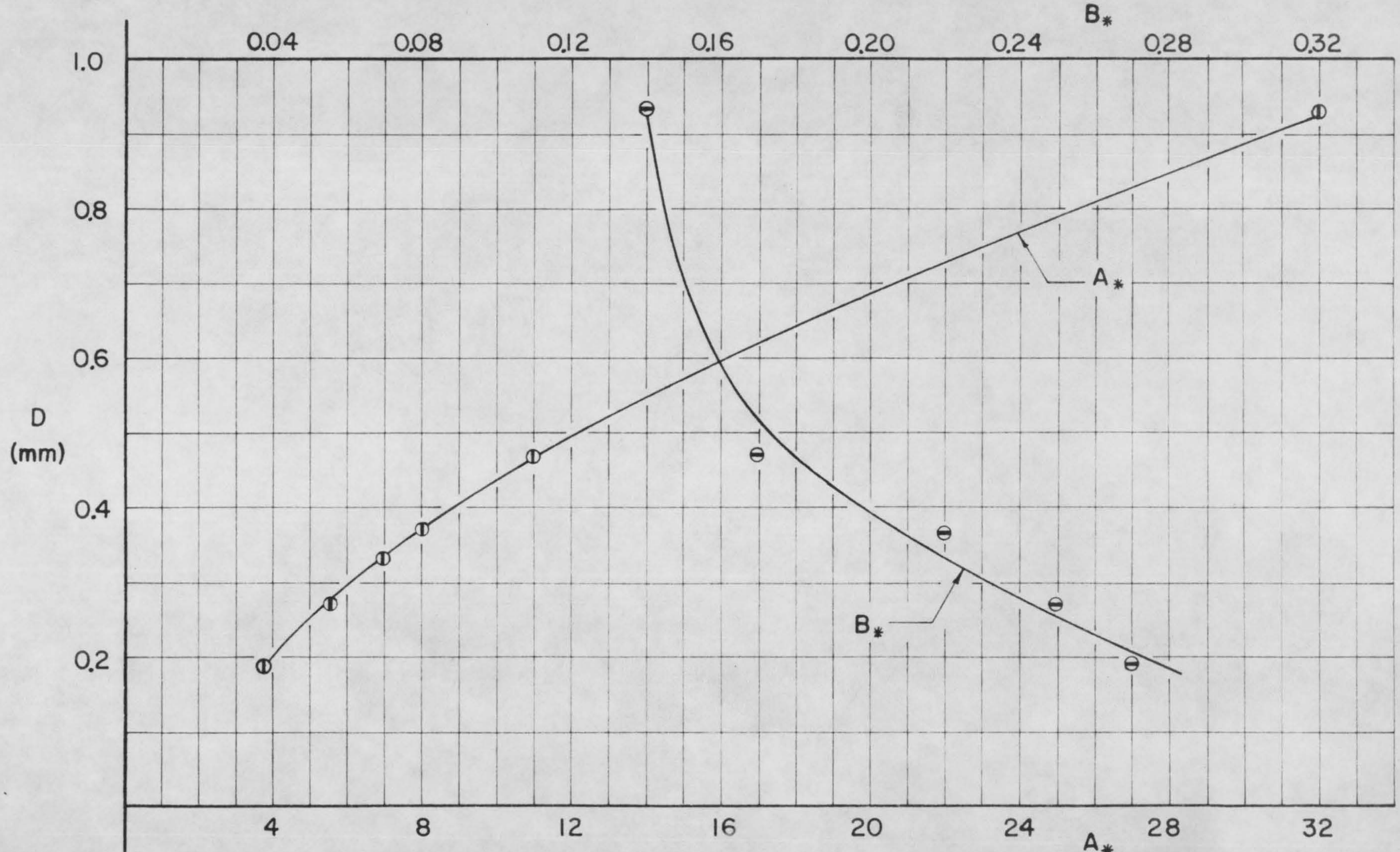


Figure 11
Values of A_* and B_* for Theoretical Probability Curves from Laboratory Data

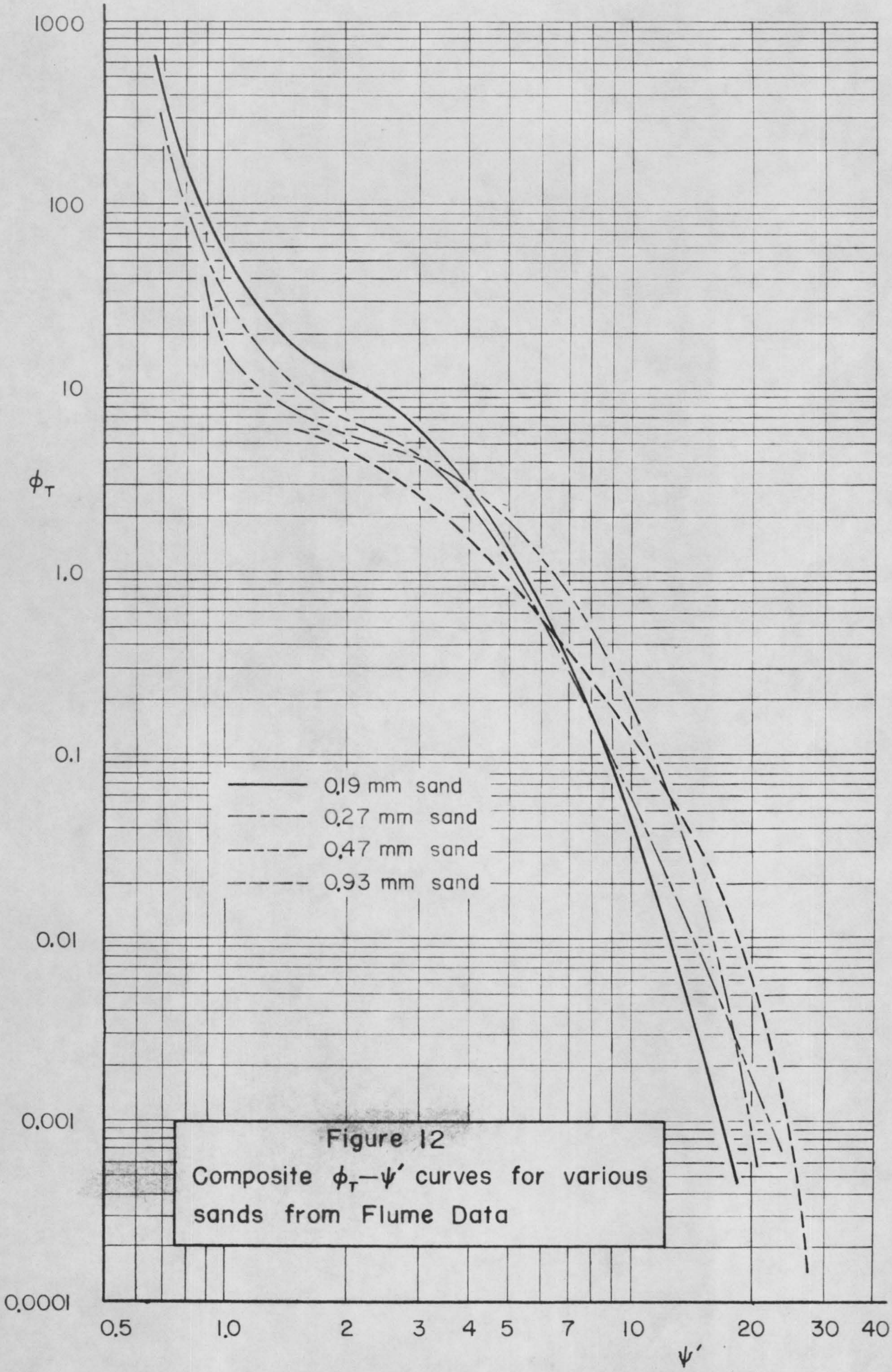


Figure 12

Composite $\phi_T - \psi'$ curves for various sands from Flume Data

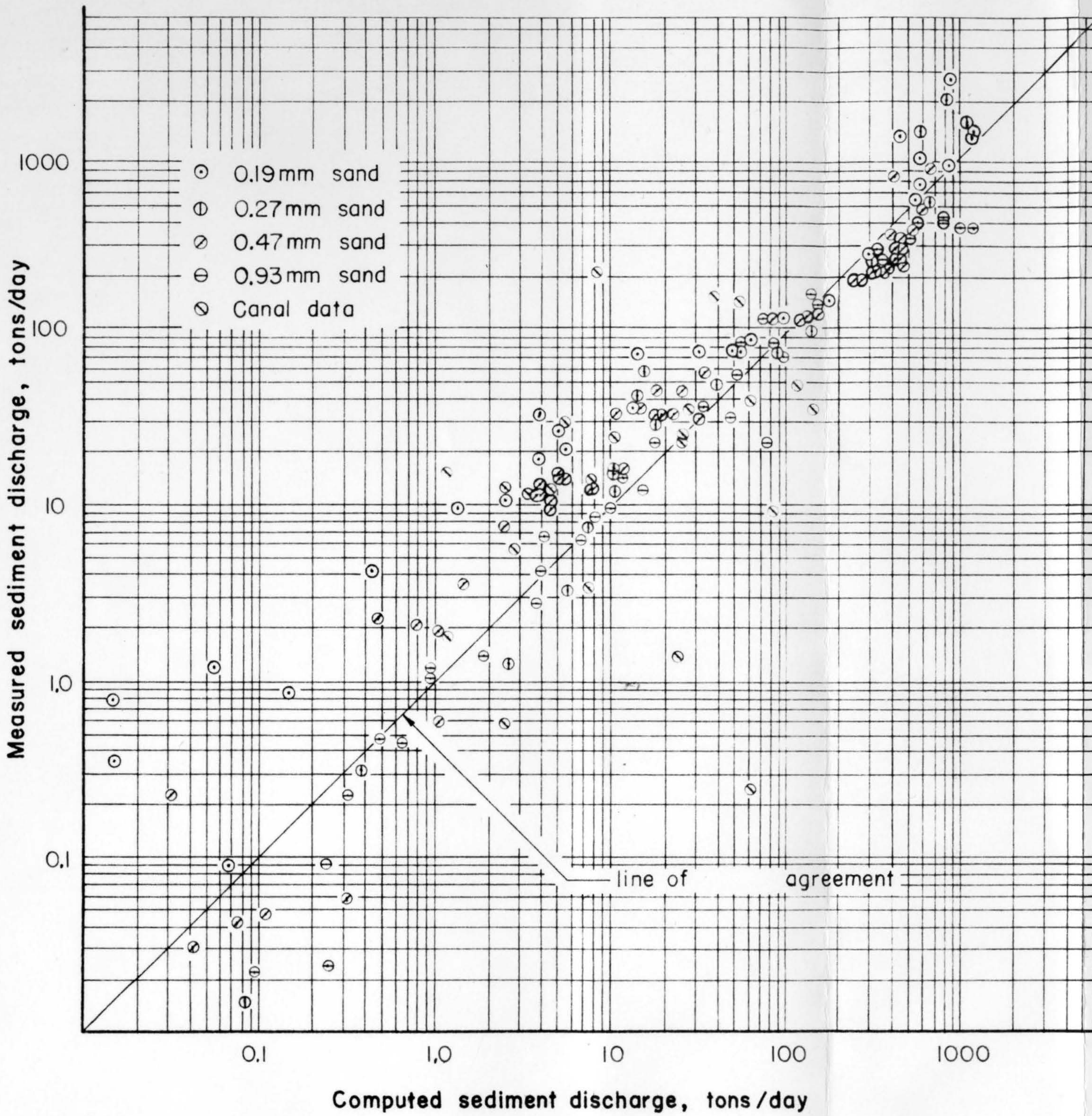


Figure 13

Measured sediment discharge compared to sediment discharge computed by Einstein's function.

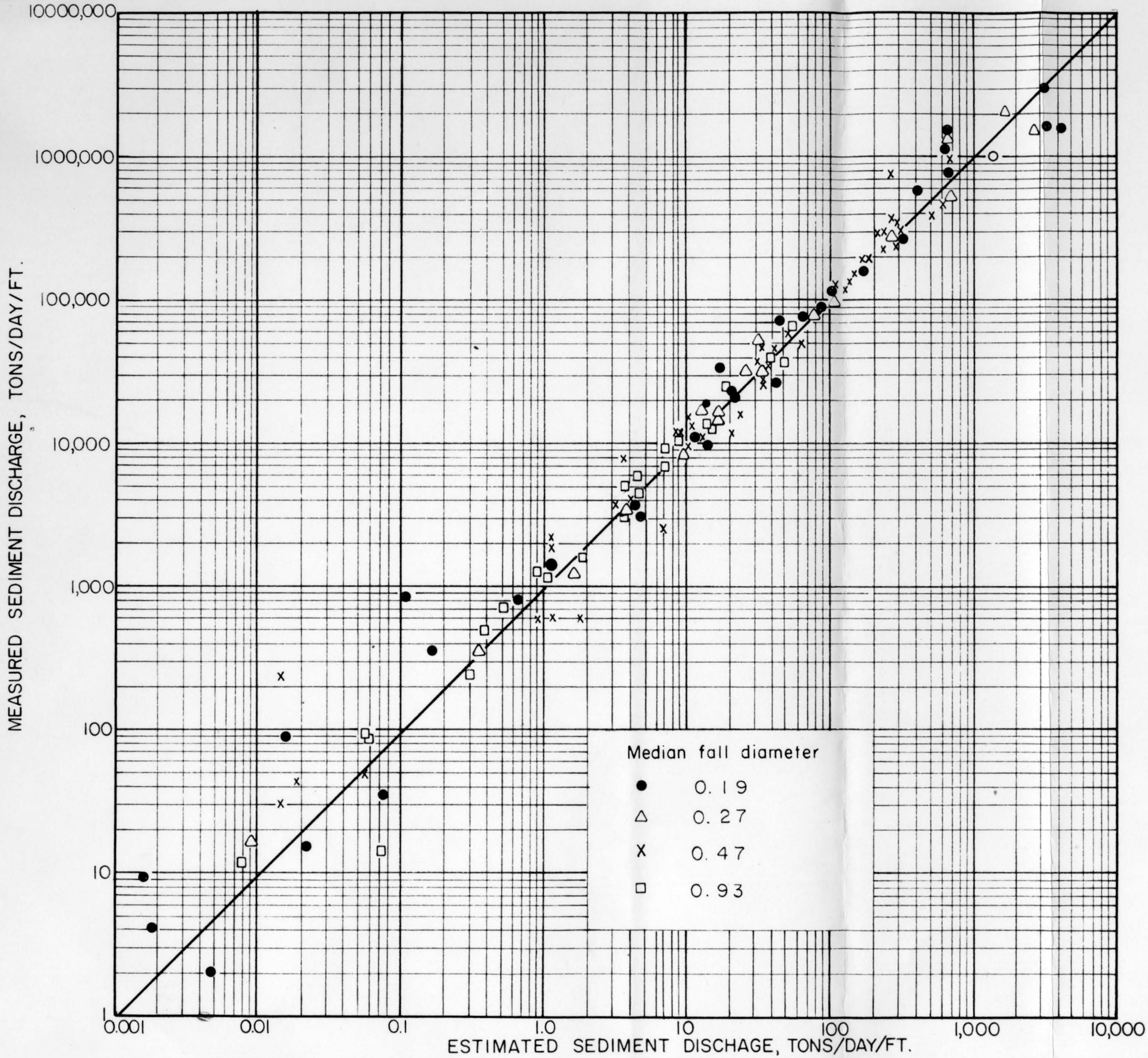


FIG. 14 MEASURED SEDIMENT DISCHARGE COMPARED TO SEDIMENT DISCHARGE COMPUTED USING MODIFIED $\phi_T - \psi$ RELATION, AFTER BISHOP, 1960.

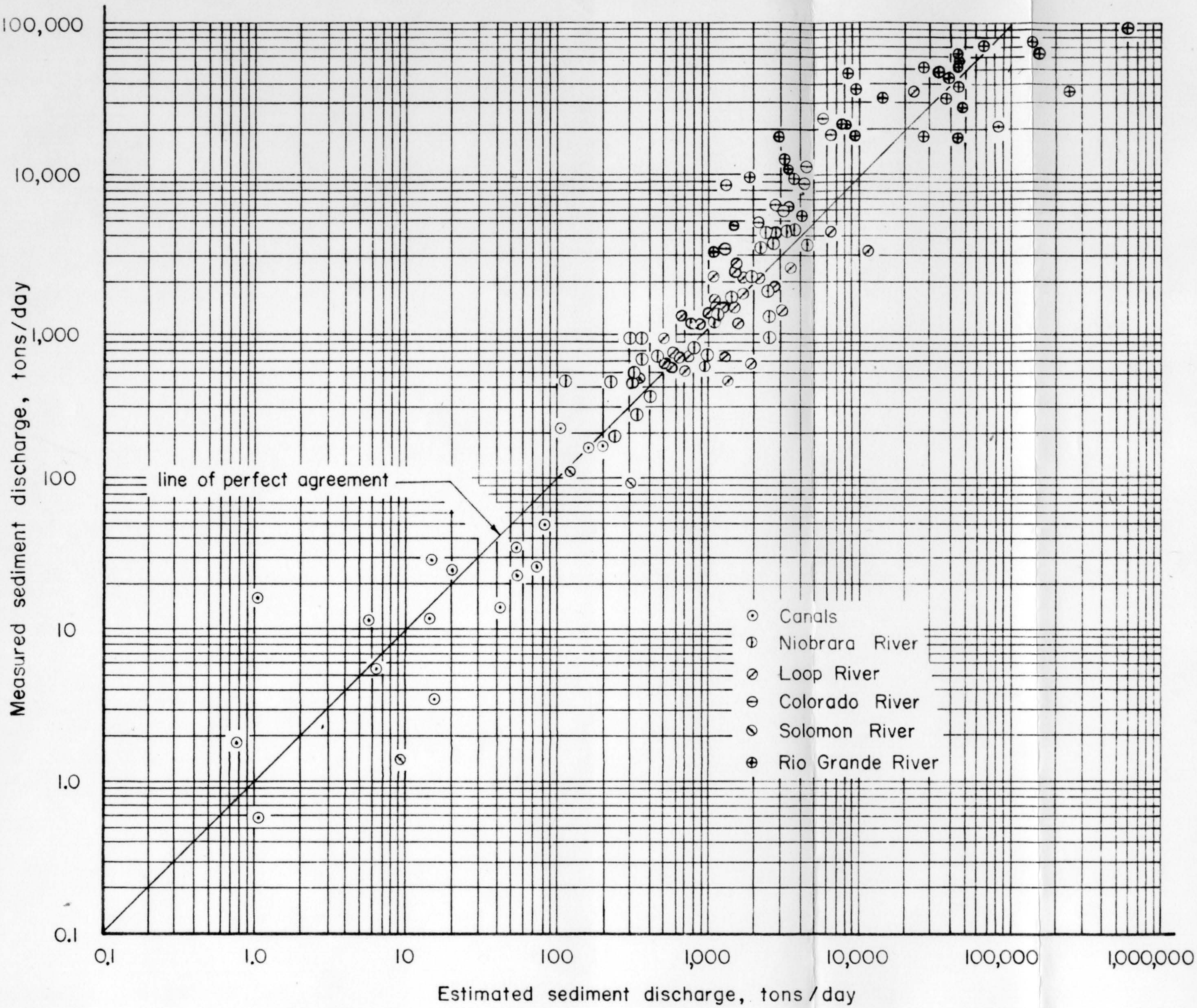


Figure 15

Comparison of bed material load estimated from Laboratory Curves with measured bed material load