U. S. DEPARTMENT OF COMMERCE NATIONAL BUREAU OF STANDARDS

RESEARCH PAPER RP907

Part of Journal of Research of the National Bureau of Standards, Volume 17, August 1936

EXPERIMENTAL STUDY OF THE SCOUR OF A SANDY RIVER BED BY CLEAR AND BY MUDDY WATER [1]

By Chilton A. Wright

ABSTRACT

At the request of the U. S. Bureau of Reclamation, an experimental comparison was made of the scour produced in a bed of fine sand in a sloping flume by muddy water and by clear water, in attempted simulation of the conditions existing in the Colorado River at the Boulder Dam before and after construction.

Critical velocities of the water were determined for incipient movement of the sand bed in the form of riffles and were found to be greater for muddy water, that is, water containing an appreciable amount of clay in suspension, than for clear water. With the muddy water an increase of about 10 percent in mean velocity was necessary to scour out the same amount of Colorado sand as was scoured by clear water under otherwise similar conditions. For coarser sands this increase was greater.

It was concluded that when clear water is discharged at the Boulder Dam it will cause greater scouring away of the sand bed than did the muddy water under previous conditions.

CONTENTS

	Page
I. Introduction	193
1. Purpose of the investigation	193
2. Nature of the laboratory investigation	194
3. Materials used	194
II. Apparatus	196
III. Experiments	197
1. General procedure	197
2. Preliminary experiments	198
3. Final experiments	198
IV. Results	199
1. Roughness coefficient	199
2. Sand movement	200
3. Quantity of material scoured—scour	201
4. Effect of silt on the flow of water	204
5. Velocity distribution	205
V. Conclusions	205
VI. References examined	206

I. INTRODUCTION

1. PURPOSE OF THE INVESTIGATION

This investigation arose from the problems of the U. S. Bureau of Reclamation in connection with the design and construction of the Boulder Dam on the Colorado River. The Colorado River has

[1] Paper presented before the Section of Hydrology, at the 17th Annual Meeting of the American Geophysical Union, Washington, D. C., April 30, 1936.

always been heavily charged with fine silt, clay, and colloids up to a maximum of 10 percent by weight. It was expected that all of this material would be trapped in the new Boulder Reservoir, so that only clear water would be drawn off through the intake towers and discharged by the turbines into the river below. The Bureau of Reclamation wished to determine whether this clear water would cause a greater scour in the river bed than that caused by the original muddy water.

2. NATURE OF THE LABORATORY INVESTIGATION

Although it was not expected that this problem could be solved quantitatively in the laboratory, it was hoped that the experimental measurement of the difference in the scour produced in a bed of fine sand in a flume by clear water, and that produced by water containing clay in suspension, would throw some light on the problem. In this paper the clay suspension will be referred to as "muddy water" for brevity.

In establishing a criterion that would serve for both the clear- and muddy-water tests it was found necessary to distinguish between the ability of the water to *scour* its bed and its ability to *transport* bed load under constant conditions; that is, with the sand fed into the water upstream from the test bed at the same rate as that at which it is being carried away by the flowing water. In the actual river, prior to the construction of the dam, the conditions had to do with the transportation of sediment, whereas now the existing conditions have to do with the scour of the bed. Formerly the river not only carried suspended material, but also moved a considerable quantity of bed load; now it presumably carries neither suspended load nor bed load immediately below the dam. Strictly these same conditions should have been duplicated in the laboratory tests, but the difficulties involved in trying to determine and to feed into a stream of muddy water the same amount of sand that this stream is capable of transporting under given conditions appeared to be of such magnitude as to preclude the possibility of obtaining results on the particular comparison desired. It was therefore decided to restrict the problem still further and attempt merely to compare the scour that would result from passing a stream of muddy water over a sand bed with that which would be produced by a similar stream of clear water. Consequently no sand was fed into the flume during the investigation. This method of attack differs from that used by most investigators of sediment transportation, and accordingly the results obtained are not comparable with theirs.

3. MATERIALS USED

A quantity of typical Colorado River sand from Yuma, Ariz., was sent to the laboratory for the tests. As this sand appeared too fine to be used in developing the experimental procedure, a local commercial fine sand, referred to here as "asphalt sand", was obtained also. The asphalt sand was later divided into coarse and fine portions, as required by the experiments, by means of a large U. S. Standard no. 70 sieve (opening 210 microns).

The average size distribution of the particles of the suspended load or mud carried by the Colorado River was estimated from the records of the U. S. Bureau of Reclamation and publications of the U. S. Geological Survey [4] [2]. After considerable search for a material for use in simulating this suspended load, a quantity of kaolin was obtained from Georgia. It was necessary for the kaolin to be finer than the actual suspended load in order to be maintained in suspension in the experimental flume. However, it was found later that a sufficient concentration of the undispersed kaolin could not be maintained in suspension until sodium carbonate was added as a dispersing agent. Particle-size distribution curves of the kaolin were determined by the pipette method [5], and are shown in figure 1.

For making the mechanical analyses of the materials, sieves 3 inches in diameter were constructed, and the weight of the samples was limited to 80 grams. At the beginning of the experiments the sieves were shaken by hand in accordance with ASTM practice [7],

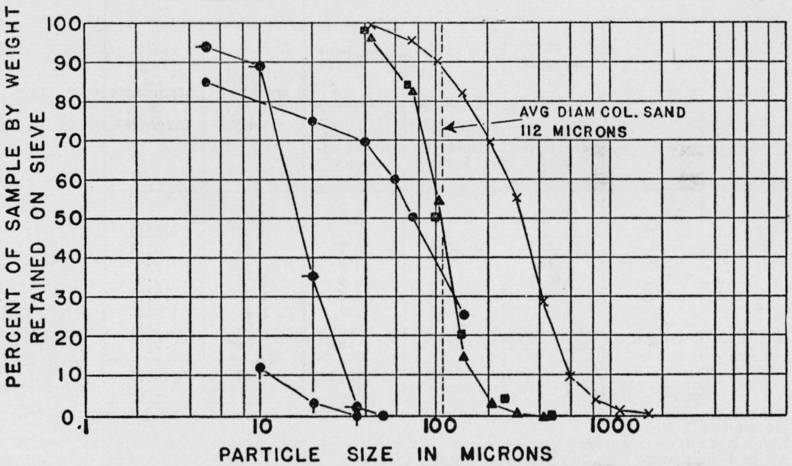

FIGURE 1.—*Particle size of materials.*

▲ Colorado River sand.
■ Typical Colorado River bed silt, analysis furnished by U. S. Bureau of Reclamation.
× Asphalt sand.
● Typical Colorado River suspended load.
-● Kaolin, undispersed.
† Kaolin after dispersion.

and later a machine was developed which produced results agreeing within plus or minus 2 percent of those obtained by hand. Analyses of the bed sands are shown in figure 1.

Practically all of the Colorado sand was coarser than the openings in the U. S. Standard no. 325 sieve (44 microns), while practically all of the kaolin particles were finer. Consequently throughout the experiments the material coarser than the openings in this screen were classed with the sand or scoured material that moves as bed load, while all particles finer were classed with the clay or suspended load.

Photomicrographs of typical samples of asphalt and Colorado sand are shown in figures 2 and 3. Both sands are seen to have fairly sharp grains differing mainly in size. The kaolin was found to consist of flat particles with rounded edges. The particles of kaolin

---

[2] The figures given in brackets throughout the text correspond to the numbered references at the end of this paper.

coated and adhered to the sand grains in the test, as indicated in the photomicrographs.

A convenient average grain diameter for each sand was computed from curves similar to those in figure 1. The area to the left of the analysis curve bounded by the coordinate axes and the 100-percent line was computed. The size in microns indicated on the x-axis, which corresponded to the equivalent *rectangular* area bounded by these lines was called the "average diameter" of the material. Values for the materials used are summarized in table 1. This method of determining average diameter was found to correspond generally with that used by other investigators.

TABLE 1.—*Sand movement and roughness*

Average diameter	Sand movement			Roughness factor	
	No movement of sand	Critical movement of sand			
	Tractive force, upper limit	Critical tractive force	Critical mean velocity	Corresponding mean velocity (average)	Manning's n (average)
Microns	lb /ft ^{2}	lb /ft ^{2}	fps	fps	
(a)	----------	----------	----------	0.98	0.0112
336 b	0.0032	0.0100	1.2	1.32	.0110
204 c	.0058	.0080	1.0	.96	.0167
384 d	.0060	.0088	1.0	1.12	.0128
342 e	----------	.0125	1.2	1.21	.0120
398 f	----------	.0125	1.4	1.41	.0127
107 g	----------	.0077	.8	.96	.0118
109 h	----------	.0087	.9	.98	.0115
			Average---	1.12	.0124

a No sand in flume.
b Asphalt sand, clear water.
c Asphalt sand passing no. 70 sieve, clear water.
d Asphalt sand retained on no. 70 sieve, clear water.
e Asphalt sand retained on no. 70 sieve with undispersed kaolin.
f Asphalt sand retained on no. 70 sieve with dispersed kaolin.
g Colorado sand, clear water.
h Colorado sand, with dispersed kaolin.

II. APPARATUS

The principal piece of apparatus used in this investigation was a wooden flume, adjustable in slope and supplied by an independent circulating system.

The flume itself, shown in figures 4 and 5, was 20 inches wide, 18 inches deep, and 40 feet long and was supported by adjustable steel jacks upon the lower steel return channel or forebay. The test sand bed was placed in the flume opposite a glass panel section 8 feet long. Water levels were controlled by means of the inclined tail gate at the end of the flume and were measured by means of a point gage traveling on the top of the flume. Most of the sand scoured from the bed was caught in the sand trap placed at the end of the flume, but any fine sand that passed the trap was caught in the forebay below leading to the measuring weir. Provision was made for draining and drying the material caught in these traps. For the muddy-water experiments, the kaolin was added to the supply basin and was thoroughly stirred into the water being pumped up to the sand bed.

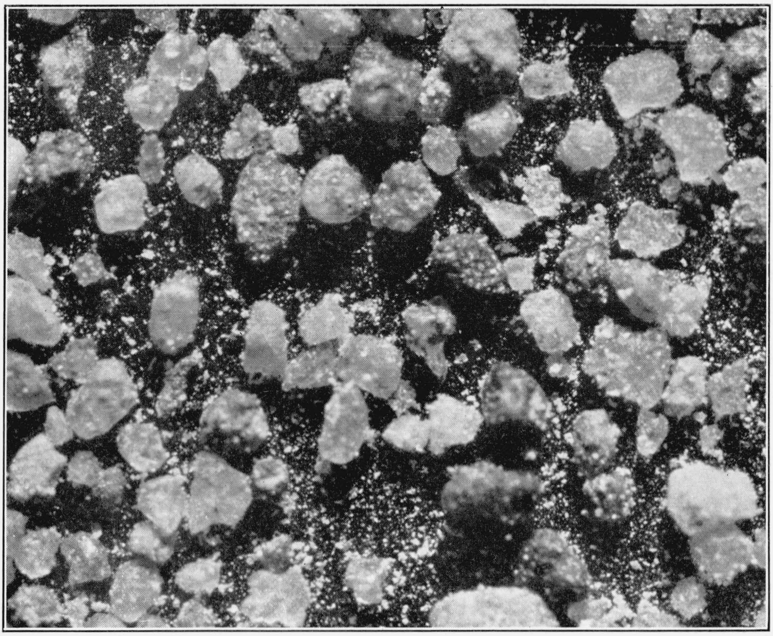

FIGURE 2.—*Asphalt sand with kaolin, typical sand-trap sample.*
Magnification ×25.

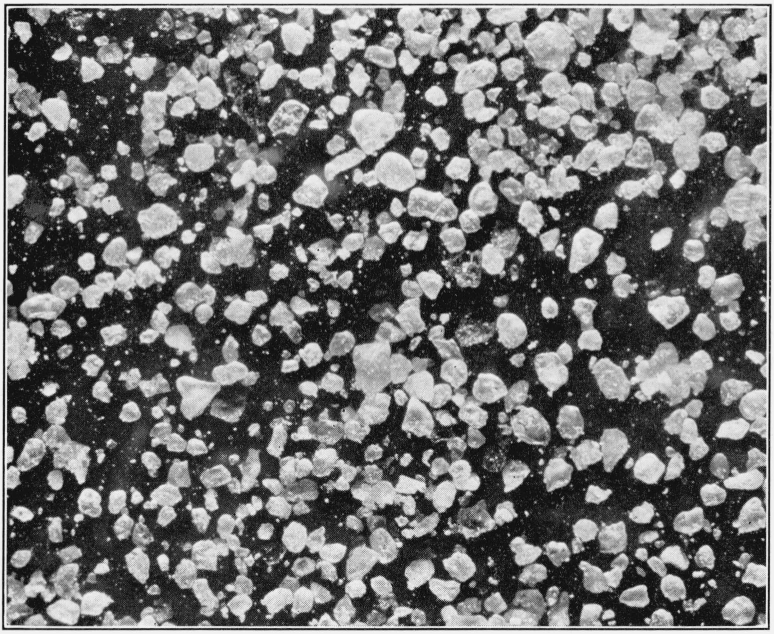

FIGURE 3.—*Colorado sand with kaolin, bed before experiment 103.*
Magnification ×25.

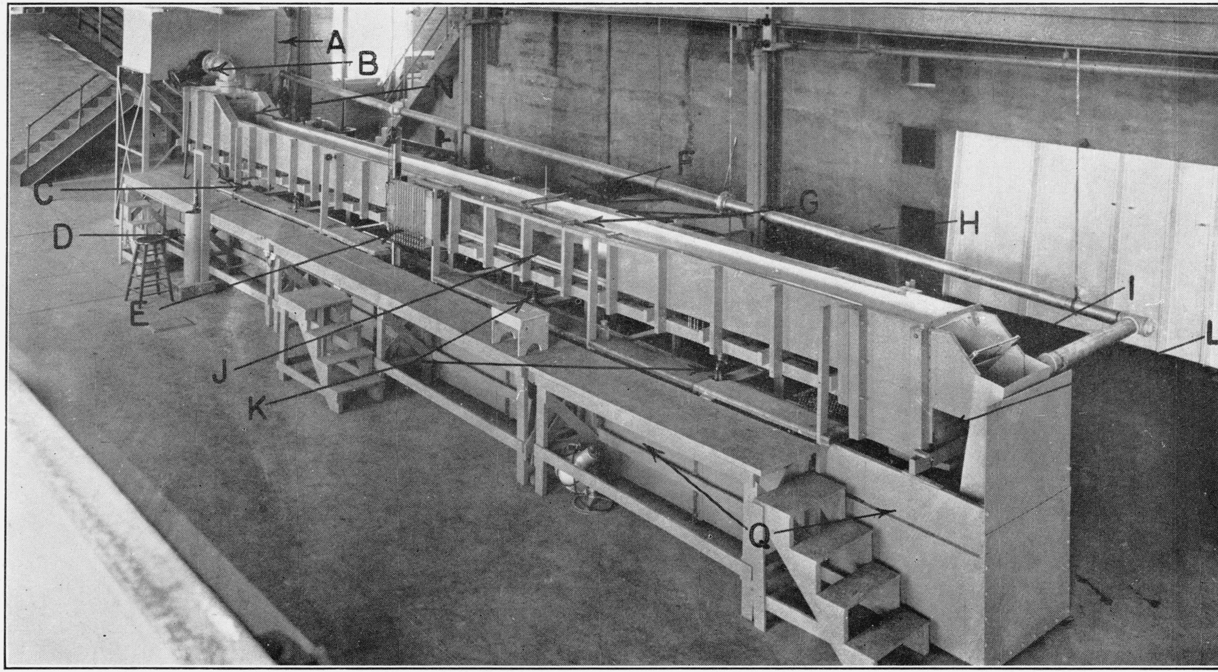

FIGURE 5.—*General view of apparatus.*

A.—Constant level tank.
B.—Supply valve.
C.—Weir.
D.—Weir gage.
E.—Gages.
F.—Point gage.
G.—Brass rails.
H.—By-pass pipe.
I.—Tail gate.
J.—Glass-panel section.
K.—Jacks.
L.—Coarse sand trap.
M.—Stone baffle.
N.—Radiator baffle.
O.—Sediment settling can.
P.—Raft.
Q.—Settling basin and weir fore-bay.
R.—Foot valve—pump.
S.—Supply basin.
T.—Supply pipe—pump to tank.
U.—Gage connections and drains.
V.—Sand bed.
W.—Approach floor.
X.—Overflow troughs leading to overflow pipe.

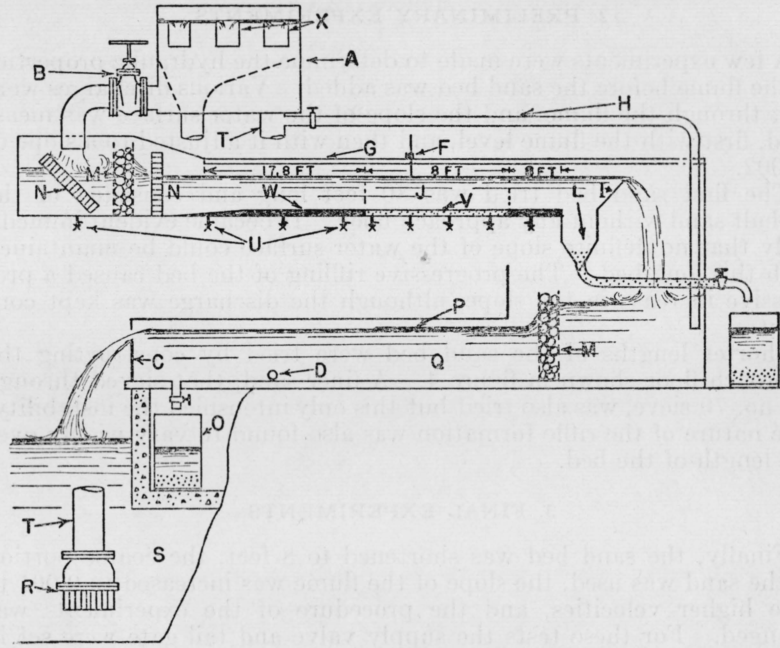

FIGURE 4.—*Sketch of sediment flume.*

A. Constant level tank.
B. Supply valve.
C. Weir.
D. Weir gage.
F. Point gage.
G. Brass rails.
H. By-pass pipe.
I. Tail gate.
J. Glass panel section.
L. Coarse sand trap.
M. Stone baffle.
N. Radiator baffle.
O. Sediment settling can.
P. Raft.
Q. Settling basin and weir forebay.
R. Foot valve—pump.
S. Supply basin.
T. Supply pipe—pump to tank.
U. Gage connections and drains.
V. Sand bed.
W. Approach floor.
X. Overflow troughs leading to overflow pipe.

III. EXPERIMENTS

1. GENERAL PROCEDURE

The general procedure was the same for most of the experiments. The sand bed was settled under water to eliminate air bubbles, and enough of the water was drained through the bed to allow the surface to be smoothed with a steel trowel. The tail gate was set, and the supply valve was adjusted until the slope of the water surface was approximately parallel to that of the bed. The scouring and riffling of the sand bed were studied through the glass panel. At the end of an hour the experiment was stopped, the flume slowly drained and the characteristics of the bed sketched and photographed. Samples of sand were taken from the bed, and the material in the traps was dried and sampled.

For the muddy-water experiments, the sand bed in the flume was settled in muddy water, and the clay in the supply basin was stirred thoroughly before each experiment. Four samples of the suspended load were taken during the experiment.

2. PRELIMINARY EXPERIMENTS

A few experiments were made to determine the hydraulic properties of the flume before the sand bed was added. Various discharges were sent through the flume, and the slope of the water surface was measured, first with the flume level, and then with it adjusted to a slope of 0.0002.

The first sand bed tried was 30 feet long and consisted of the asphalt sand without any approach floor. It became evident immediately that no definite slope of the water surface could be maintained with this long bed. The progressive riffling of the bed caused a progressive increase in the slope, although the discharge was kept constant.

Shorter lengths of the sand bed were tried by constructing the approach floor shown in figure 4. A finer sand, that sieved through the no. 70 sieve, was also tried but this only intensified the instability. The nature of the riffle formation was also found to vary widely over the length of the bed.

3. FINAL EXPERIMENTS

Finally, the sand bed was shortened to 8 feet, the coarse portion of the sand was used, the slope of the flume was increased to 0.001 to give higher velocities, and the procedure of the experiments was changed. For these tests the supply valve and tail gate were set in fixed positions at the beginning of each test and kept unchanged throughout its duration. The slope was measured with the point gage every 15 minutes during the test, which was allowed to run for an hour. Typical changes in the slope are shown in figure 6 for experiments 59, 70, 71, and 72.

Even with the short sand bed, as soon as scouring began at the upstream end of the bed and riffles began to form at its lower end, the slope of the water surface became steeper over the downstream end of the bed. In order to maintain this slope, the water backed upstream and consequently increased in depth. A typical development of the slope is shown in figure 6 for experiment 59. It is seen that the steep part of the slope tended to move down toward the end of the bed, the water surface finally becoming somewhat curved in profile. This tendency was less pronounced when the amount of scour was small and when the mean velocity of the water was low.

Since the computed values of the mean velocity and tractive force depend on both the slope of the water surface and the depth of the water, both of which changed during a test, the method used to select representative values for the slope and depth was of considerable importance. When the coarse asphalt sand was used, the changes in slope and depth during a given experiment were small enough to justify selection of their average values for use in analyzing the results. However, for similar experiments made with the fine Colorado sand, these changes were too great to allow the use of the average. Consequently the assumption was made that the initial conditions would determine the characteristic scouring of the sand bed, and values of the initial slope and depth were determined from curves similar to those shown in figure 6. These values were used in the computations.

After the clear-water experiments had been completed similar experiments were made with the muddy water. In all, 101 preliminary and 91 final experiments were made.

Vertical-velocity curves were measured occasionally with a simple glass Pitot tube.

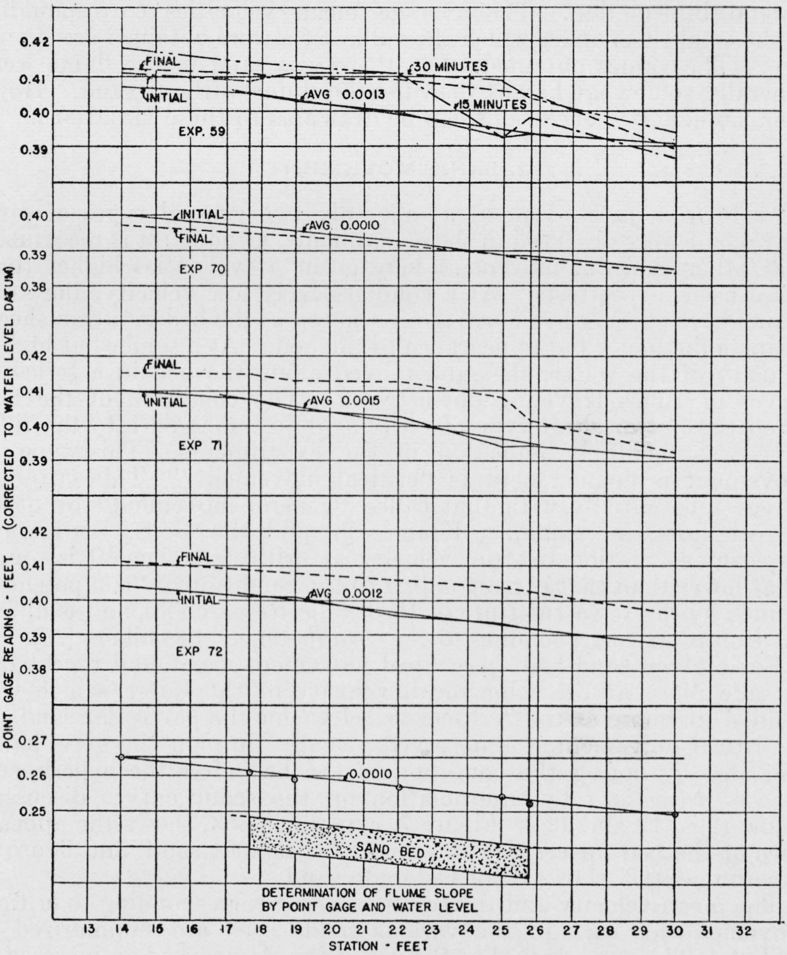

FIGURE 6.—*Typical water surface slopes.*

IV. RESULTS

The results were divided into (1) a study of the roughness coefficient (Manning's n); (2) types of sand movement as affected by the presence of clay in the water; (3) a quantitative study of the sand scoured; and (4) effect of silt on the flow of water.

1. ROUGHNESS COEFFICIENT

For each of the preliminary experiments the average slope of the energy line was determined, together with values of the depth and the hydraulic radius. By substitution in the Manning formula for flow in open channels, the corresponding roughness coefficient n was determined. For each final experiment, values of the average *initial* slope were determined from diagrams similar to those given in figure 6, and the corresponding initial value of Manning's n determined. These values, which varied quite widely for the various sand beds, were averaged, and the results are shown in table 1 for general information. The average mean velocities corresponding to the conditions under which the values of n were obtained are shown also. The values obtained when there was sand in the flume were generally somewhat higher than for the flume without sand. However, no definite conclusions can be drawn as to these variations.

2. SAND MOVEMENT

Aside from no movement at all, only two general types of sand movement were observed in the experiments, although it is recognized that other types of movement may occur at velocities higher than those used in the tests. At a comparatively low velocity, the sand grains were observed to move along the top of the bed in a thin sheet, giving a distinctly flat appearance to the bed. At a somewhat higher velocity of the water, the sand moved along the bed in a series of waves or riffles traveling downstream. The condition of the bed when the flat or sheet type of movement just merged into the riffle type was definitely indicated in the experiments. This type of movement is defined here as "critical movement." This criterion agrees substantially with that called "general movement" by other investigators, for example, Kramer [8] and the U. S. Waterways Experiment Station [2]: the velocity at critical movement is somewhat lower than that corresponding to the condition of "competence" defined by the Iowa Institute of Hydraulic Research [3], and is different from that corresponding to the "competence" of Gilbert [25].

For a given sand bed the critical movement was found repeatedly to take place at the same mean velocity of the water, which was defined therefore as the "critical velocity" for the particular sand.

Critical movement was observed visually through the glass panel and also by noting the condition of the bed after the experiment. It was *determined* by interpolation on the scour curves discussed below (figs. 12 and 13). Figure 7, experiment 53, shows the appearance of the bed for critical movement for asphalt sand, and figure 8, experiment 106, shows it for Colorado sand.

The mean velocity and the tractive force [3] corresponding to critical movement for each of the various sands used are summarized in table 1. The data show that the use of the clay caused an increase in the value of critical mean velocity and critical tractive force.

At higher velocities a definite scour took place in the sand bed, usually with its maximum depth just downstream from the beginning of the bed, with the edges of the scoured area rounded. The scoured material traveled smoothly on a slight upgrade to the center of the bed, and thereafter in the form of riffles to the end of the bed. The scour for the muddy water differed somewhat in that the sand bed scoured away in small areas, leaving the edges sharp instead of rounded.

[3] Tractive force, F_t is defined as follows:

$$F_t = wds,$$

where F_t is the tractive force exerted by the flowing water on the bed, in pounds per square foot.
w is the specific weight of the water, in pounds per cubic foot.
d is the depth of the water, in feet, in uniform flow.
and s is the slope of the water surface.

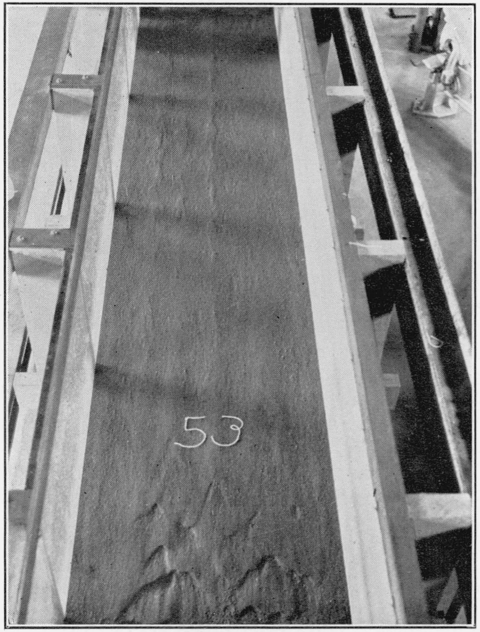

Figure 7.—*Bed after experiment 53, looking upstream.*

Asphalt sand, clear water, mean velocity 1.03 fps.

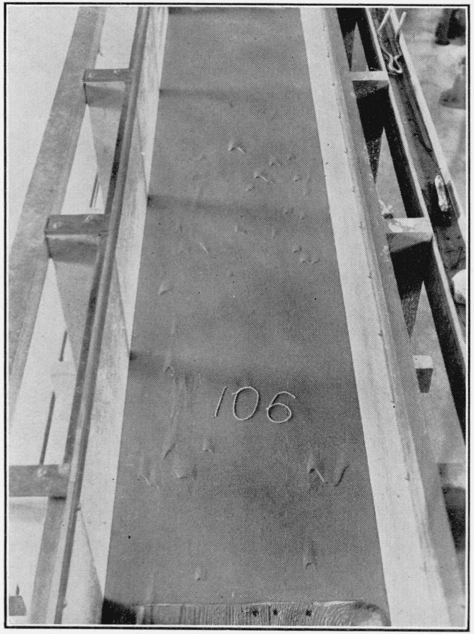

Figure 8.—*Bed after experiment 106, looking upstream.*

Colorado sand, clear water, mean velocity (initial) 0.81 fps.

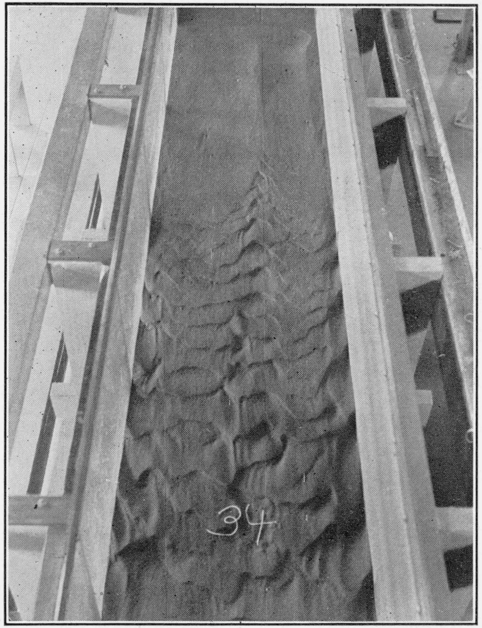

FIGURE 9.—*Bed after experiment 34, looking upstream.*

Asphalt sand, clear water, mean velocity 1.28 fps.

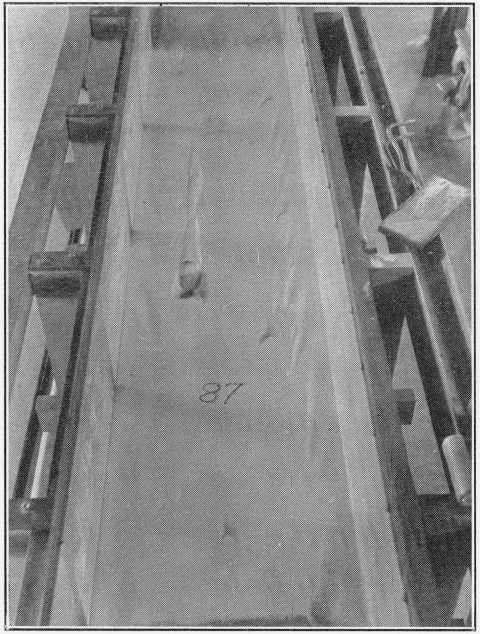

FIGURE 10.—*Bed after experiment 87, looking upstream.*

Asphalt sand, muddy water, mean velocity 1.28 fps.

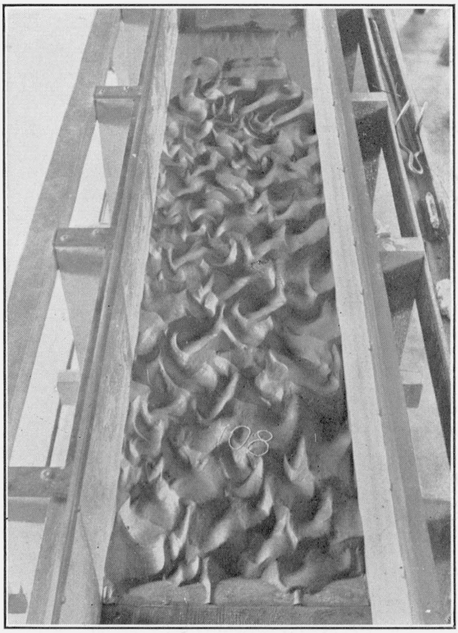

FIGURE 11.—*Bed after experiment 108, looking upstream.*

Colorado sand, clear water, mean velocity (initial) 1.04 fps.

Figures 9 and 10 show clearly the much greater scour produced by clear water than muddy water under otherwise similar conditions. In both of these experiments the bed was formed of asphalt sand and the mean velocity was 1.28 fps. However, in the experiment shown in figure 9, clear water flowed over the bed, while in that shown in figure 10, water containing dispersed kaolin flowed over the bed. The amount of material scoured in experiment 34 was about 26 times as great as that scoured in experiment 87. One reason for this large difference is to be found in the fact that the mean velocity in experiment 34 was above the critical velocity for asphalt sand and clear water, while in experiment 87, this same velocity was lower than the critical velocity for asphalt sand and water containing dispersed kaolin. (See table 2.)

TABLE 2.—*Comparison of scour with mean velocity*

ASPHALT SAND

Scour	Mean velocity		
	Clear water	Muddy water	Difference
lb/ft²/hr	fps	fps	fps
0.2	[a] 1.00	1.30	0.30
.5	1.10	[b] 1.40	.30
1.0	1.18	1.48	.30
1.5	1.23	1.53	.30
COLORADO SAND (SHALLOW WATER)			
.15	[a] .82	.90	.08
.2	.85	[b] .92	.07
.6	.90	.98	.08
1.5	1.05	1.10	.05

[a] Beginning of critical movement for clear water.
[b] Beginning of critical movement for muddy water.

A bed of Colorado sand is shown in figure 11, experiment 108, for clear water at an initial mean velocity of 1.04 fps. The excessive scouring and riffling shown are in great contrast to those of the corresponding muddy-water experiments. At this velocity the latter exhibit a flat bed, generally similar to that shown in figure 8, except for the small riffles.

3. QUANTITY OF MATERIAL SCOURED—SCOUR

The weight of material scoured out of the bed in 1 hour and caught in the traps divided by the area of the bed is defined as "scour." It is measured in pounds per square foot per hour.

Values of the scour for the asphalt-sand experiments with the clear water, and experiments with dispersed kaolin in the water are plotted logarithmically against the corresponding values of mean velocity in figure 12. This figure shows that, in order to cause the same scour with the muddy water as with the clear water, an increase of about 25 percent in the mean velocity is necessary. The scour tends to be proportional to the tenth, or greater, power of the mean velocity, and the steepness of the curves further shows that a great increase in the scour may occur for a small increase in the mean velocity.

The experiments in which the bed movement took place in the form of a flat sheet are indicated in figure 12 by F, while those not so marked are for movement in riffles. The critical velocity at which

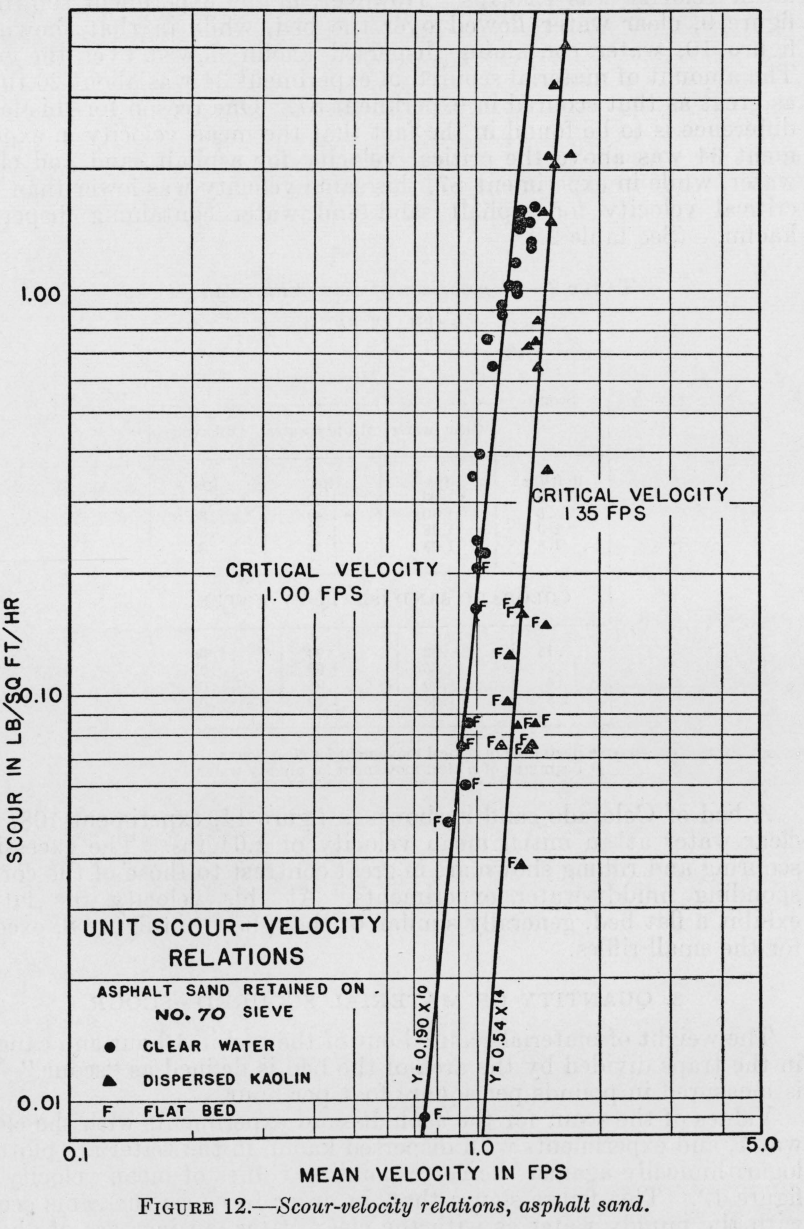

FIGURE 12.—*Scour-velocity relations, asphalt sand.*

the bed movement changes to the riffled form was determined from the figure and values of critical velocity are shown in table 1.

Figure 13 in which scour is plotted against *initial* mean velocity, shows the results for the Colorado sand. The initial mean velocity was used here instead of the average mean velocity because of the unstable slope and depth due to excessive riffling of this fine sand as previously explained.

For those tests in which the depth of the water was small, a clear-cut contrast exists between the results for clear water and those for

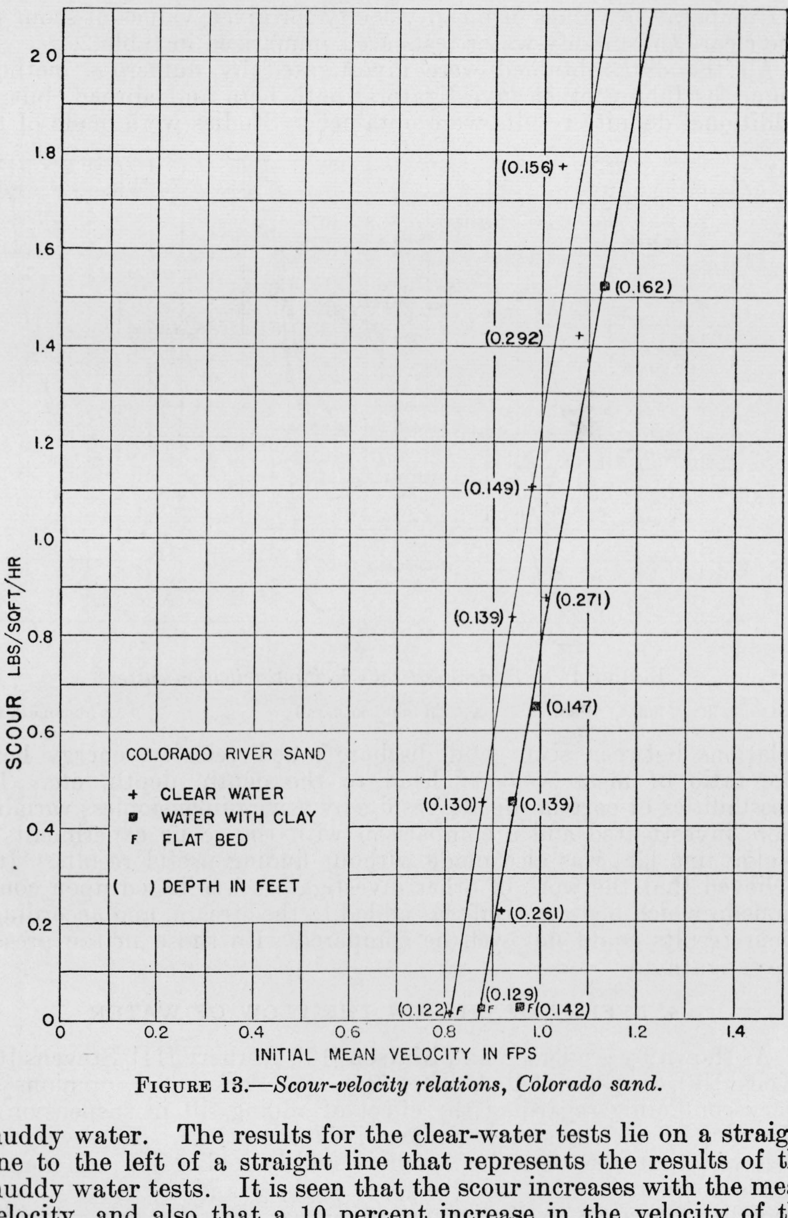

FIGURE 13.—*Scour-velocity relations, Colorado sand.*

muddy water. The results for the clear-water tests lie on a straight line to the left of a straight line that represents the results of the muddy water tests. It is seen that the scour increases with the mean velocity, and also that a 10 percent increase in the velocity of the muddy water is necessary to cause the same scour that occurred with the clear water. However, for depths about double those for which the above-mentioned curves were obtained, the points for the tests with clear water tend to become superimposed on the curve representing values for the tests with muddy water. Comparative data for muddy water at these depths are unfortunately not available, since the experiments had to be stopped because of loss of clay through a leak in the supply basin.

Comparative values of mean velocity for given values of scour for the clear- and muddy-water tests are summarized in table 2.

All the data obtained were investigated by numerous methods found useful by other investigators, both here and abroad, but no additional definite results were obtained. Studies were made of the

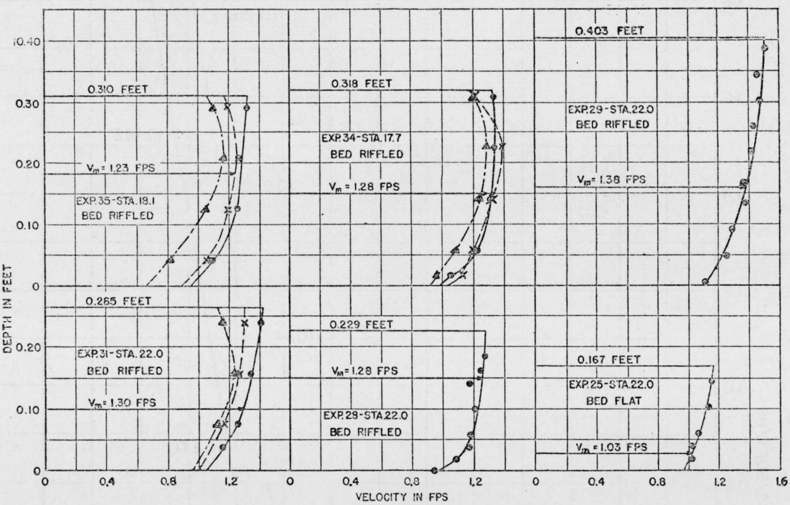

FIGURE 14.—*Typical vertical velocity-distribution curves.*

● Center line of flume. ▲ 0.2 ft from south wall. × 0.2 ft from north wall.

relations between scour and discharge, bed velocity, energy head, the ratio of mean velocity head to the depth, depth, etc. The possibilities of correlating the results by using dimensionless variables were investigated and a comparison with the scour experiments of Nakayama [28] was also made without finding useful results. It is believed that the work of other investigators was based upon conditions in which bed material was added to the stream, and accordingly their results could not well be compared with those in the present investigation.

4. EFFECT OF SILT ON THE FLOW OF WATER

As shown by Anderson and Matson [10], Rothery [11], Stevens [12], Kelly [16], Buckley [24], Gilbert [25], and Parker [27], opinions are very conflicting regarding the effect of adding silt in suspension on the flow of a clear stream under given conditions. However, it is believed that the resulting small increase in viscosity and density tends to increase the tractive force slightly and to cause a corresponding increase in the scouring power. On the other hand, a heavy load of suspended silt in the water lays down a protecting mat of cohesive particles which fill the interstices at the top of the bed and thus enable it to resist scour. However, in the experiments with the asphalt sand and the coarser undispersed kaolin, when this mat was once broken through by the water, a greater scour resulted with the muddy water than with clear water. Nevertheless, in general, it was found that the clay tended to restrict the scour, as shown by the data in tables 1 and 2.

5. VELOCITY DISTRIBUTION

A few typical vertical velocity-distribution curves obtained by means of the Pitot tube are shown in figure 14. The shape of the curves indicates that the distribution of the velocity in the flume is similar to that usually found in a typical open channel. Data for the studies with bed velocity and velocity ratios mentioned above were obtained from curves similar to these.

V. CONCLUSIONS

The results of the laboratory tests show that, in order to scour a given amount of sand when the water contains fine clay in suspension, a greater velocity is necessary than when the water is clear. For the asphalt sand this increase in velocity amounted to 25 percent, while for the Colorado River sand it was much less, about 10 percent. It was also shown that a very considerable increase in scour resulted from a very small increase in mean velocity above the critical velocity for the given sand.

Admittedly the laboratory results cannot be applied quantitatively to the Colorado River for many reasons. In the first place, the laws by which the results of the small-scale tests can be converted to the corresponding values for the full-sized river are not known for the complicated phenomena involved. Prior to the construction of the dam, large floods, with their relatively great scouring of the river bed, occurred periodically; whereas now that the dam has been constructed, the flow downstream will be regulated. The velocities in the actual river (4 to 10 fps) are much higher than in the test flume, while the river bed is practically the same. Material which could only be transported as bed load in the laboratory tests may be transported partly as bed load and partly as suspended load in the actual river. However, the qualitative statement may be made that large volumes of clear water discharged onto a bed of Colorado River sand just below the Boulder Dam will tend to cause a greater scouring of the bed than did muddy water prior to the construction of the dam, first because the muddy water brought sand and silt with it to compensate somewhat for the material scoured and carried away, and second because, as the laboratory tests have shown, clear water scours the bed more easily than does muddy water. It may be mentioned also, as pointed out by Rothery [11] and Stevens [12], the clear-water stream may require a smaller gradient for a given flow than the muddy stream and consequently may have additional capacity for cutting and transporting the sand from its bed. Since there is no large tributary for 80 miles below the Boulder Dam to provide additional bed load, this scour will probably tend to progress gradually downstream.

A complete report on this investigation is available for loan.

Many valuable suggestions, together with editorial assistance, were furnished in this investigation by H. N. Eaton, Chief of the Hydraulic Laboratory Section. The apparatus for the mechanical analyses was

designed and the analyses were made by B. H. Monish. J. M. Buswell and C. W. Elliot of the laboratory staff were responsible for the design and construction of the sediment flume and drying apparatus.

VI. REFERENCES EXAMINED

[1] W. N. Weigel. Size and Character of Grains of Non-Metallic Mineral Fillers. Tech. Pap. 296, U. S. Bur. Mines, Washington, D. C. (1924).

[2] Studies of River Bed Materials and Their Movement, With Special Reference to the Lower Mississippi River. Pap. 17, U. S. Waterways Experiment Station, Vicksburg, Miss. (January 1935).

[3] F. T. Mavis, Chitty Ho, and Y. C. Tu. The Transportation of Detritus by Flowing Water. Pt. I, Studies in Engineering, University of Iowa, Iowa City, Iowa, [294] Bul. 5 (March 1, 1935).

[4] C. S. Howard. Sizes of Particles of Suspended Matter Carried by the Colorado River. Office Mem. U. S. Geol. Survey, Washington, D. C. (Aug. 12, 1932).

[5] C. E. Jackson and C. M. Saeger, Jr. *Use of the pipette method in the fineness test of molding sand.* J. Research NBS **14,** 59 (January 1935) RP757.

[6] C. S. Howard. Quality of Water in the Colorado River, 1928–1930. Water Supply Pap. 639–D, U. S. Geol. Survey, Washington, D. C.

[7] *Standard method of test for sieve analysis of aggregates for concrete.* Stand. C 41–33, Am. Soc. Testing Materials, Pt. II, 240 (1933).

[8] Hans Kramer. *Sand mixtures and sand movements in fluvial models.* Trans. Am. Soc. Civil Engrs. **100,** 798 (1935).

[9] M. P. O'Brien. *Review of the theory of turbulent flow and its relation to sediment transportation.* Trans. Am. Geophys. Union, Sec. Hydrol. 487 (1933).

[10] M. S. Anderson and S. Matson. Properties of the Colloidal Soil Material. Dept. Bul. 1452, U. S. Dept. Agr., Washington, D. C. (Nov. 1926).

[11] S. L. Rothery. *A problem of soil in transportation in the Colorado River* Trans. Am. Soc. Civil Engrs. **99,** 530 (1934).

[12] J. C. Stevens. *The silt problem.* Proc. Am. Soc. Civil Engrs. pt. I, **60,** 1206 (Oct. 1934).

[13] B. H. Hendrickson. *The choking of pore space in the soil and its relation to runoff and erosion.* Trans. Am. Geophys. Union, Sec. Hydrol. 500 (1934).

[14] C. E. Ramser. *Dynamics of erosion in controlled channels.* Trans. Am. Geophys. Union, Sec. Hydrol. 488 (1934).

[15] E. S. Bellasis. Hydraulics. p. 198 (Spon & Chamberlain 1924).

[16] *Prevention of silt deposits in conduits.* Report of Subcommittee of Hydraulic Power Committee. Pacific Coast Elec. Assn. Elec. West, **60,** 399 (May 15, 1928).

[17] William Kelly. *The Colorado River problem.* Discussion by J. C. Hill. Trans. Am. Soc. Civil Engrs. **88,** 415 (1925).

[18] R. G. Hemphill. *Silting and life of southwestern reservoirs.* Trans. Am. Soc. Civil Engrs. **95,** 1072 (1931).

[19] O. A. Faris. The Silt Load of Texas Streams. Tech. Bul. 382, U. S. Dept. Agr. (Sept. 1933).

[20] L. R. Fiock. *Records of silt carried by the Rio Grande and its accumulation in Elephant Butte Reservoir.* Trans. Am. Geophys. Union, pt. II, 472 (1934).

[21] A. H. Gibson. Hydraulics and its Applications, p. 339 (D. Van Nostrand Co. New York, N. Y., 1925).

[22] H. J. Casey. Über Geschiebebewegung. Dissertation. Technische Hochschule, Berlin, Germany (Mar. 11, 1935).

[23] J. C. Stevens. *The Silt Problem.* Discussion by E. W. Lane. Proc. Am. Soc. Civil Engrs. **61,** 409 (Mar. 1935).

[24] A. B. Buckley. *The influence of silt on the velocity of water flowing in open channels.* Min. Proc. Inst. Civil Engrs. **216,** pt. II, 183 (1922–1923).

[25] G. C. Gilbert. The transportation of Debris by Running Water. Prof. Pap. 86, U. S. Geol. Survey (1914).

[26] J. M. Lacey. *Some problems connected with the rivers and canals in southern India.* Min. Proc. Inst. Civil Engrs. **216,** pt. II, 150 (1922–1923).

[27] P. A. M. Parker. The Control of Water. (George Routledge & Sons, Ltd., London, Eng., 2nd ed. 1932).

[28] H. Nakayama. *Some model investigations about the motion of sand along a self-formed channel.* J. Tokyo Faculty Eng. **13,** (Mar. 1923).

WASHINGTON, May 25, 1936.