Study of Transportation of Fine Sediments by Flowing Water

By

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STUDY OF TRANSPORTATION OF FINE SEDIMENTS
BY FLOWING WATER
A. A. Kalinske and C. H. Hsia

I. INTRODUCTION

1. Object and Scope of Investigation.—The problem of suspended sediment transportation like many other engineering problems has been studied by more or less empirical methods in order to develop working formulas from field measurements. Needless to say, it is too much to expect that such formulas will be universally applicable, as it is almost impossible to study enough field data to establish a truly general law.

In recent years great progress has been made in studying the problem of suspended sediment transportation by flowing water from the rational side by using the knowledge relating to the mechanism of turbulent flow. However, the experimental work that has been carried on to date has been limited largely to fairly coarse sediments, and the sediment concentrations have been rather low. It is of considerable importance, especially from the Chinese viewpoint, that experimental work on suspended sediment be extended to sediments of very fine sizes and high concentrations. For instance, the rivers in China carry tremendous amounts of relatively fine sediment and the development of methods of estimating the kind and amount of material in suspension for a given river flow and bed condition would be valuable in the planning of any kind of irrigation and engineering works on these rivers.

The purpose of this investigation was to obtain information relating to the movement of very fine sizes of sediment. Special attention was given to the development of a relationship between the bed composition and the amount of material in suspension for given hydraulic conditions in an open water channel.

2. Acknowledgments.—This paper is based on a doctoral dissertation of the same title submitted by Chen Huan Hsia. The investigation was conducted under the direction of A. A. Kalinske,

—Submitted to the Department of Mechanics and Hydraulics, University of Iowa, in July, 1943.
Associate Professor of Hydraulics and Associate Director of the Iowa Institute of Hydraulic Research. The authors are indebted to F. M. Dawson, Dean of the College of Engineering, for providing funds to carry on the experimental work, and to E. W. Lane, Professor of Hydraulic Engineering, for his encouragement and advice.

II. THEORY OF SUSPENDED SEDIMENT TRANSPORTATION

3. Vertical Distribution of Sediment in Turbulent Water.— Turbulence makes it possible for streams to carry non-colloidal sediments in suspension. The eddies present in turbulent flow are capable of transferring heat, mass, momentum, foreign particles, etc., from one region of the fluid to another. By assuming that the general nature of the two-dimensional diffusion process due to the turbulence eddies is similar to molecular diffusion, the basic equation of convection due to the turbulence can be written as:

$$q = -D \frac{d\Theta}{dy}$$

This states that the rate of transfer, $q$, of any local characteristic of the fluid or material present in the fluid is equal to the product of a diffusion coefficient and the negative gradient of the fluid characteristic, or foreign matter, in a specified direction. This general expression applies to the transfer of momentum, heat, salinity, sediment, etc., in a turbulent fluid.

Schmidt$^2$ first developed this basic relationship for the vertical transfer of dust particles by atmospheric turbulence. In the case of particles heavier than the fluid, and for the condition of equilibrium, the net convection due to turbulence is equal to the rate of settling of the particles due to gravity,

$$cN = -D \frac{dN}{dy}$$

where $c$ is the settling velocity of the particle, $N$ the concentration of the suspended matter, and $y$ is the distance in the vertical direction.

O'Brien$^3$ first presented the theory of sediment distribution for streams. By integrating Eq. (2), we have,

---


This gives the concentration of sediment at any distance $y$ above the channel bottom in terms of that at some reference distance $a$. By measuring the diffusion coefficient $D$ directly, the writers demonstrated the general validity of this equation. If $D$ remains constant with respect to $y$, then integration of Eq. (3) gives:

$$N/N_a = e^{-c(y-a)/D}$$

(4)

However, in natural streams and flumes the diffusion coefficient is far from constant throughout a stream cross-section.

For fully developed turbulent flow, the intensity of fluid shear, $\tau$, due to the turbulent mixing process can be expressed as:

$$\tau = \varepsilon \rho \frac{dU}{dy}$$

(5)

where $\varepsilon$ is the coefficient of momentum transfer, $\rho$ the fluid density, and $dU/dy$ the mean velocity gradient.

In the case of flow in a wide channel, the unit shear is equal to $\gamma S(h-y)$ and, therefore, the shear varies linearly, thus:

$$\tau = \tau_0 \left(1 - \frac{y}{h}\right)$$

(6)

where $\tau_0$ is the bottom shear, $\gamma$ the unit weight of the fluid, $h$ the total depth and $S$ the energy gradient.

For flow in a wide, open channel, the mean velocity distribution expression is:

$$U/U_m = 1 + \frac{\sqrt{\tau_0}}{k \ U_m} \left(1 + \ln \frac{y}{h}\right)$$

(7)

On differentiating the above equation, the velocity gradient is:

$$\frac{dU}{dy} = \frac{\sqrt{\tau_0}}{k \ y}$$

(8)

In these expressions $U_m$ is the mean velocity in the entire vertical section and $k$ is von Kármán's universal constant which is equal to 0.40, approximately. Substituting $\varepsilon$, as given by Eq. (5), for $D$ in Eq. (3), and for $\tau$ and $dU/dy$ as given by Eqs. (6) and (8), and then integrating Eq. (3), there is obtained:


Field and laboratory measurements of suspended sediment distribution in wide channels, under equilibrium conditions, follow Eq. (9) quite well.

4. Relation Between Bed Material and Suspended Material. — The theory reviewed above provides a means of determining the relative sediment distribution; the absolute amount of sediment in suspension, however, is still undetermined. It remains to develop a function which governs the relationship between the sediment in suspension, the bed composition, and the flow characteristics.

Lane and Kalinske⁶ made a step in this direction by indicating such a relationship. They reasoned that an instantaneous vertical velocity on the bed equal to or greater than the fall velocity of a particle will tend to pick it up from the bed. They stated that the average rate at which particles, characterized by fall velocity \( c \), are picked up from the bottom is proportional to the amount of that material in the bed, to the magnitude of the vertical velocity capable of picking them up, and to the relative amount of time during which the vertical velocities capable of picking up particles of that size exist. Their analysis reduced to an expression which stated that the quantity \( N_s/N_b \) is a function of \( c/\sqrt{\tau_0/Q} \), where \( N_s \) is the concentration of material having a fall velocity \( c \) in suspension just above the bed, and \( N_b \) is the concentration of that material in the bed. They plotted values of \( N_s/N_b \) against the values of \( c/\sqrt{\tau_0/Q} \) from field data and drew a mean curve through the plotted data. Though there was considerable scatter of data, a functional relationship seemed to be indicated.

Owing to the intricate nature of flow conditions near the bed, the problem of predicting the amount of material that will be picked up from the bed is still largely unsolved. Therefore, the ideas reviewed above should be looked upon only as the beginning of the final solution of the problem.

III. EXPERIMENTAL APPARATUS

5. Channel and Appurtenances. — The experiments were conducted in an existing recirculating system consisting of a rectangu-

lar-shaped steel flume in which the tests were made, a V-shaped approach channel, two interconnected tanks, and a pump. The general arrangement of the apparatus is shown in Fig. 1.

The steel rectangular flume was 2 ft.—3 in. wide, 1 ft.—1½ in. deep and 80 ft. long. It was supported on jacks so that the slope of the channel could be adjusted. The V-shaped channel served as an approach channel to quiet the flow from the discharge pipe of the pump. It was of the same length as, and was built parallel to, the steel flume. The slope of the V-shaped channel was always kept much greater than that of the rectangular flume so that no sediment would deposit in this channel. A transparent section, 8 in. in width, was built into the sides of the steel channel at a distance of several feet above the sampling section. The purpose of this transparent section was to make observations of the conditions near and at the bed.

The two interconnected tanks each of 150 cubic feet capacity located at the end of the two flumes were used as a reservoir. The water from the test flume was discharged into one of the tanks from which it was pumped by the centrifugal sand pump into one end of the V-shaped channel, through which it flowed into the rectangular test flume.

The slope of the water surface along the rectangular flume was
determined by 6 point-gages which were distributed along the center line of the channel. The gages could be read to 0.001 foot. The depth of the water in the test channel was controlled by a tailgate at the discharge end of the test channel.

6. Sediment Samplers. — Samples of the sediment-laden water were obtained from the freely falling nappe at the end of the rectangular flume by means of a trough, 1\(\frac{1}{2}\) in. wide and 4 in. deep, which extended horizontally at right angles to the nappe, and which was moved at a uniform rate across the entire width of the nappe. After the water sample was collected by the moving trough, it flowed to a stationary trough, and then into the sample cans. The point sampler for suspended sediment was made from a glass tube, the open end of which was ground to a sharp edge and bent to extend 2 in. upstream into the flow. This tube was mounted on a frame so that it could be adjusted vertically and the sampler could be moved along a horizontal bar across the sampling section. A rubber tube was connected to the sampler and extended over the side of the flume. The sample collected flowed through the rubber tube by siphonic action, the velocity of flow being adjusted by moving the sampling jar up or down so that the entrance velocity into the sampler was equal to the water velocity in the flume at the sampling point.

7. Discharge and Velocity Measuring Devices. — An elbow meter was installed in the pipe line from the pump, and was used to determine the rate of discharge. The pressure difference between the sides of the bend was measured by either a mercury-water gage or a water-air gage depending on the magnitude of the discharge. To prevent the sand in the water from getting into the gage tubes, sand traps were installed between the manometers and the elbow meter. The elbow meter was calibrated in place by use of a calibrated weir.

The velocity of the water was measured by a Pitot tube of a modified Prandtl type, and had a coefficient equal to unity. The differential head was measured by a slanting water-air differential gage.

8. Sediment Used. — The sediment used in the tests was a commercial product known as Barnsdall Admix, and sold by the Barnsdall Tripoli Company of Seneca, Mo. It is a finely ground silica and has a light, buff color. Particles are more or less spherical in shape. The specific gravity of the material was determined in ac-
cordance with the standard procedure recommended by "Laboratory Procedure in Testing Earth Dam Materials" (U. S. Bureau of Reclamation, Technical Memorandum No. 533). The entrapped air was removed by applying a vacuum to the sample for a duration of about 30 minutes. A balance accurate to .0001 gram was used in determining the weight and the temperature during the test was recorded so that the correct absolute density of the water would be known. The specific gravity of the material was 2.67.

The size composition of the material was determined by pipette analysis, the results being shown in Fig. 2. From the size composition curve it can be seen that the material is uniformly graded and has a median diameter of about .011 mm.

For purposes of analyzing the data obtained in these experiments, the sediment used was arbitrarily divided into 13 size intervals, each size interval being characterized by the mean size of that range. The size intervals and mean sizes are shown in Table I.

**TABLE I**

<table>
<thead>
<tr>
<th>Size Interval (mm)</th>
<th>Mean Size (mm)</th>
<th>Size Interval (mm)</th>
<th>Mean Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.0442 - .0312</td>
<td>.0377</td>
<td>.0039 - .00276</td>
<td>.00333</td>
</tr>
<tr>
<td>.0312 - .0221</td>
<td>.0266</td>
<td>.00276 - .00195</td>
<td>.00236</td>
</tr>
<tr>
<td>.0221 - .0156</td>
<td>.0189</td>
<td>.00195 - .00138</td>
<td>.00167</td>
</tr>
<tr>
<td>.0156 - .0110</td>
<td>.0133</td>
<td>.00138 - .000975</td>
<td>.00118</td>
</tr>
<tr>
<td>.0110 - .0078</td>
<td>.0094</td>
<td>.000975 - .00069</td>
<td>.000833</td>
</tr>
<tr>
<td>.0078 - .0055</td>
<td>.00665</td>
<td>.00069 - .000488</td>
<td>.000589</td>
</tr>
<tr>
<td>.0055 - .0039</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IV. EXPERIMENTAL PROCEDURE

9. Details of Test Run.— Since sediments of very fine sizes are cohesive, it was important not to let the material in the channel bed become compacted; otherwise, the sediment behavior would be entirely different from that of a sediment having discrete particles. It was noted that if the bed material was allowed to dry up, the particles stuck together to form big lumps, and even after soaking under water for a few days, the particles would not separate unless some other means was used to break up the lumps. For this reason, before each test, the bed material was thoroughly stirred up and well mixed by a rake. The lumps were broken up, and the bed was leveled approximately and left under water.

At the start of a run the water was introduced into the flume gradually, so as to prevent local washing away of the bed material. To attain the predetermined value of water surface slope and the desired depth, the discharge and the tailgate were adjusted until the required conditions were reached. It took considerable time to reach equilibrium condition so far as sediment transportation was concerned; from trial runs it appeared that the equilibrium condition was approached only after four or five hours of running. Hence every test run lasted about eight hours and sediment samples were taken at intervals of one hour for the purpose of ascertaining when the equilibrium condition was reached. During the first several hours, although equilibrium so far as the suspended sediment was concerned might not be reached, the flow was sufficiently stable so the velocity measurements could be made during those hours.

Velocity measurements were taken at points beginning .02 ft. below the water surface and at intervals of .05 ft. down to the sand bed. This was done at seven verticals in the sampling section which was located about ten feet upstream from the end of the test flume. The seven verticals were located at the center line of the section and symmetrically at 4 in., 9 in., and 11½ in. distances from it.

Point sediment samples of about 800 cc. in volume were taken about 7 hours after the beginning of the run. These samples were taken at three verticals which were located at the center line and at symmetrical distances 9 inches from the center. In each vertical, sediment samples were taken at .02 ft. below the water surface and at intervals of 0.10 ft. down to the bottom.
After the run, special efforts were made to drain the water away slowly so that the bed formation would not be disturbed. After stopping the pump, the tailgate was lowered slowly so that the water would flow away gradually, but not so slowly as to cause excess deposition of the suspended material on the bed. A slight deposition was, however, unavoidable. The top layer of the bed material was carefully sampled in order to determine the bed composition, and the bed configuration was photographed.

All the point samples, except three samples taken at the center-line vertical, were used for total concentration determinations. After the samples were allowed to stand for some time, all the material would settle down, leaving clear water at the top. The clear water was then siphoned away into a graduated cylinder where the volume of water could easily be determined. The condensed sample, after determining its weight, was then washed into an evaporating dish and dried in the oven under constant temperature. The weight of the material was determined from the dried sample. The total concentration of the sediment obtained at any point was given by the ratio of the weight of dried sediment to the total weight of the water sample.

Three samples from the center vertical obtained at approximately the top, mid-depth and the bottom of that vertical were used for size analysis. The pipette method was chosen for this purpose because of its simplicity and accuracy.

10. Summary of Tests Conducted. — Two runs were made in the test flume with clear water and nine with sediment. In the nine sediment runs, four different slopes were used; they were: .00025, .0005, .001, and .0013. Three different depths were used for slopes of .00025 and .0005, two depths for the .001 slope, and one depth for the .0013 slope. A brief summary of all the experiments made is presented in Table II.

Note that the depth of flow varied from 0.30 to 0.66 ft., the discharge from 0.70 to 3.20 c.f.s., the average sediment concentration from 0.64 to 11.1 per cent by weight, and the mean velocity from 0.84 to 2.73 ft. per sec.

V. VELOCITY AND SEDIMENT DISTRIBUTION

11. Velocity Distribution. — The data on velocity distribution were studied with respect to vertical distribution at the channel
<table>
<thead>
<tr>
<th>Run No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope</td>
<td>.0005</td>
<td>.0005</td>
<td>.00025</td>
<td>.00025</td>
<td>.00025</td>
<td>.0005</td>
<td>.0005</td>
<td>.0005</td>
<td>.001</td>
<td>.001</td>
<td>.0013</td>
</tr>
<tr>
<td>Average depth, ft.</td>
<td>.305</td>
<td>.505</td>
<td>.37</td>
<td>.49</td>
<td>.66</td>
<td>.36</td>
<td>.52</td>
<td>.64</td>
<td>.35</td>
<td>.56</td>
<td>.52</td>
</tr>
<tr>
<td>Discharge, cfs.</td>
<td>1.01</td>
<td>2.05</td>
<td>.70</td>
<td>1.26</td>
<td>1.95</td>
<td>1.01</td>
<td>1.81</td>
<td>2.60</td>
<td>1.32</td>
<td>2.70</td>
<td>3.20</td>
</tr>
<tr>
<td>Av Sediment Concentration %</td>
<td>0</td>
<td>0</td>
<td>.64</td>
<td>1.29</td>
<td>1.67</td>
<td>1.95</td>
<td>2.24</td>
<td>2.27</td>
<td>3.36</td>
<td>6.81</td>
<td>11.1</td>
</tr>
<tr>
<td>Mean Velocity $V = Q/A$ ft./sec.</td>
<td>1.47</td>
<td>1.81</td>
<td>.841</td>
<td>1.14</td>
<td>1.31</td>
<td>1.25</td>
<td>1.54</td>
<td>1.805</td>
<td>1.68</td>
<td>2.14</td>
<td>2.73</td>
</tr>
<tr>
<td>$\sqrt{\tau/Q}$ ft./sec.</td>
<td>.062</td>
<td>.075</td>
<td>.046</td>
<td>.054</td>
<td>.061</td>
<td>.069</td>
<td>.080</td>
<td>.084</td>
<td>.098</td>
<td>.125</td>
<td>.128</td>
</tr>
</tbody>
</table>
center and the distribution in the entire cross-section. The logarithmic velocity distribution, as adapted from von Kármán's equation for circular pipes, can be written as:

\[ U = U_m + \sqrt{gh} \left(1 + 2.3 \log \frac{y}{h}\right) \]

(10)

**Fig. 3. Velocity Distribution at Center of Channel.**

**Fig. 4. Velocity Distribution at Center of Channel.**
The validity of this equation as applied to wide, open channels was confirmed by Vanoni\(^7\) in an experimental flume.

The results of the present studies are shown in Figs. 3 and 4 for the nine different runs. The curves drawn correspond to Eq. (10), and the good agreement between the curves and the measured values provide further evidence of the validity of Eq. (10) for relatively wide channels where the side-wall effect has not extended into the center of the flow.

It was of interest to see whether the sediment in suspension, at the high concentrations, had any effect on the velocity distribution. The velocity data obtained for Run No. 11 where the total concentration of sediment was over 11 per cent by weight seemed to follow the theoretical curve as well as the data for zero sediment load.

From the velocity data obtained, velocity contours were plotted for the various flow sections; some typical data are shown in Fig. 5. There does not appear to be any peculiarity in the velocity pat-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{TYPICAL DATA ON VELOCITY IN TEST CHANNEL.}
\end{figure}

tern and the contours correspond to those obtained for a wide channel. Note that Run No. 11 is for a sediment concentration of over 11 per cent by weight. In the center portion of the channel the contours are parallel and thus the condition of two-dimensional flow is approached. So far as these data are concerned, and for the range of sediment concentrations covered, it must be concluded that sus-

\(^7\) V. A. Vanoni, "Velocity Distribution in Open Channels," Civil Engineering, Vol. 11, No. 6, p. 356, June, 1941.
TABLE III
VALUES OF Von KÁRMAÁN k AND MANNING n

<table>
<thead>
<tr>
<th>Run No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Av. Sediment Concentration, %</td>
<td>0</td>
<td>0</td>
<td>0.64</td>
<td>1.29</td>
<td>1.67</td>
<td>1.95</td>
<td>2.24</td>
<td>2.27</td>
<td>3.36</td>
<td>6.81</td>
<td>11.1</td>
</tr>
<tr>
<td>Values of k</td>
<td>.41</td>
<td>.43</td>
<td>.40</td>
<td>.34</td>
<td>.32</td>
<td>.40</td>
<td>.33</td>
<td>.40</td>
<td>.40</td>
<td>.34</td>
<td>.44</td>
</tr>
<tr>
<td>Appearance of Bed Surface</td>
<td>Steel Bed</td>
<td>Steel Bed</td>
<td>Ripples</td>
<td>Ripples</td>
<td>Ripples</td>
<td>Rugged &amp; Irregular</td>
<td>Rugged &amp; Irregular</td>
<td>Rugged &amp; Irregular</td>
<td>Rugged &amp; Irregular</td>
<td>Smooth</td>
<td></td>
</tr>
<tr>
<td>Manning n</td>
<td>.0091</td>
<td>.0094</td>
<td>.0119</td>
<td>.0106</td>
<td>.0105</td>
<td>.0117</td>
<td>.0112</td>
<td>.0101</td>
<td>.0119</td>
<td>.0114</td>
<td>.0098</td>
</tr>
</tbody>
</table>
pended sediment does not have any noticeable effect on the velocity distribution in the flow cross-section.

12. **Hydraulic Characteristics of Flow and Bed Appearance.** — By plotting $\frac{U}{\sqrt{ghS}}$ against $y/h$ on semi-logarithmic paper, Eq. (10) will become a straight line with the slope inversely proportional to the value of $k$, the universal constant. The values of $k$ thus obtained are given in Table III together with the average sediment concentrations, Manning’s $n$, and the form of the bed surface. It is seen that the value of $k$ deviates from the accepted value of 0.40 without any definite trend with respect to the sediment concentration. It is interesting to note that the bed roughness is in good accord with the value of Manning’s $n$.

The problem of the effect of the suspended sediment on the mean velocity in a cross section has been studied by Vanoni,8 Chang,9 Buckley,10 and others. Contradictory conclusions have been formed from different observations made in natural streams and laboratory flumes. Some believed that the suspended sediment would increase the mean velocity of the flow, while the results obtained by others gave a contrary indication.

For instance, in the present investigation, for conditions of identical discharge and slope the mean velocity was 1.47 ft./sec. for clear water and 1.25 ft./sec. for water having a sediment concentration of 1.95% by weight. Thus one might conclude that the sediment decreases the mean velocity.

It seems from observations made in these tests that the bed roughness has considerable bearing on the mean velocity and probably exerts more influence than the suspended sediment. Different bottom shears produce different sediment concentrations, but may also cause considerable change in the bed formation; thus, it becomes difficult to isolate the cause of the change in velocity. In Figs. 6 and 7 are shown the type of bed formations obtained at different shears. For Run No. 4 the shear was .0056 lb. per sq. ft. and for Run No. 7 it was .0124. Table III indicates the bed appearance for all the runs; note that for the highest shear (Run No. 11) the bed became smooth.

---

In engineering literature relating to observations on streams carrying high sediment concentrations, it has often been said that the appearance of the flow is different from that of ordinary stream flow. Some have said that when a river carries a very high sediment load it has a smooth oily movement, such as a stream of molten metal, instead of the usual rough, turbulent surface. Others have stated that when a river gets more than five per cent of silt by weight, all eddy currents become damped, and the water flows in a straight-line motion which one never sees when the water is clear.

From the observations made throughout all the present experiments, there was no such phenomenon as straight-line, oily movement of the fluid. In the case of the highest concentration, which was about 11%, there still were many eddies and surface fluctuations. It is rather doubtful that eddies can be damped out because of high sediment concentrations and still have the sediments remain in suspension. However, in this connection, it should be pointed out that fine sediments in high concentrations may be flocculated, and it is well known that the laws that govern ordinary suspended sediments would not apply to sediments in a flocculated state.

In regard to the manner in which the sediments were carried by the flow, it was noted that the sediment was not evenly distributed
in the fluid. At the water surface, it could be seen that there were patches of low concentration and also almost clear water separating patches of high concentration. Such a phenomenon has also been seen in natural streams.

Little is known about the stability of a bed formed of fine sediments. Through the transparent section of the flume in the present study, it was possible to make some observations of the bed. In all the experiments, it was noted that there was a definite demarcation between the bed and the flowing fluid, and the bed seemed to be quite stable.

13. **Total Concentration of Suspended Sediment.**—Because of the very fine sediment used, the total concentration was very uniform throughout any section, and, therefore, the total suspended load discharge could be obtained by multiplying the water discharge by the total concentration at any point in a section. The total concentration determined from the water falling over the tailgate and that obtained by point sampling were identical. This indicates that all the material was transported in suspension, and bed-load transport was insignificant.

Fig. 8 shows the relation between total concentration of the sediment and the bottom shear. It is interesting to note that the total concentration is a function of the shear; however, due to the variation in the composition of the sediment for each shear, it is not possible to generalize this relationship. It is merely presented as a point of interest.

14. **Vertical Sediment Distribution of Different Size Ranges.**—

![Graph showing the relation between bottom shear and total sediment concentration.](http://ir.uiowa.edu/uisie/29)
The composition of the sediment samples in the center vertical were divided into several size intervals in order to investigate the distribution of various sizes. The size intervals selected were given in Table I. From the size-analysis data of the suspended material at various distances above the bed, the concentration of various size intervals could be computed.

In Figs. 9 to 17 the size analysis data for the various runs are shown; it will be noted that the variation in the type of material present from top to bottom is very small. In other words, even for the larger sizes of material the concentration was quite uniform from top to bottom. This is, of course, to be expected for a material as fine as that used in these experiments. Use of Eq. (9) indicated that the theoretical variation in concentration vertically was in accord with the data obtained; that is, the concentration curves were practically vertical lines. The coarser sizes were distributed vertically somewhat more uniformly than Eq. (9) indicated. This was attributed to the fact that the actual fall velocity, \( c \), of the large sizes was probably smaller than that used in the theoretical relation, due to the fact that the settling rate of the coarser particles was reduced due to interference with the many small particles present.

VI. RESULTS ON RELATION OF SUSPENDED TO BED MATERIAL

15. Preliminary Analysis. — From the size-analysis data of the suspended sediment and the bed material used in the present study as shown in Figs. 9 to 17, it was possible to furnish experimental data for checking the relationship between suspended load and bed material proposed by Lane and Kalinske. As was mentioned in Part II of this paper, according to these writers the ratio of \( N_s/N_b \) should be a function of \( c \sqrt{\tau_0/\rho} \) where \( N_s \) is the concentration of suspended material at the bed, characterized by the fall velocity \( c \), and \( N_b \) is the concentration of this material in the bed. The values of \( N_s/N_b \) and \( c/\sqrt{\tau_0/\rho} \) were calculated from the present data and were plotted together with the mean curve from the field data presented by Lane and Kalinske.

The units of \( N_s \) and \( N_b \) used herein are different from those used originally by Lane and Kalinske; \( N_s \) and \( N_b \) are the weight of material of a certain size interval, in suspension and in the bed re-
Fig. 9. Size Composition of Suspended and Bed Materials.

Fig. 10. Size Composition of Suspended and Bed Materials.

Fig. 11. Size Composition of Suspended and Bed Materials.
spectively, expressed in pounds per cubic foot of the samples. By using the latter unit, it is obvious that the value of $N_s/N_b$ should vary from zero to unity. The value of $N_s$ for any size range can be obtained from the size analysis and the total concentration expressed in weight per unit volume of the liquid mixture. The value of $N_b$ for any size range is obtained from the size analysis curve for the bed and the weight of bed material per unit volume. For sand, this weight of bed material is about 100 lbs. per cubic foot, a value which does not change much for different flow conditions. For fine material, like that used in the present study, the weight of the material per unit volume of bed sample may vary appreciably with the flow conditions. That is, the weight of material per unit volume may be less for flow with high bed shear than for flow with low shear, since the material tends to loosen up under high shear. In the present study, a constant value of 65 lbs. per cubic foot was used throughout. This value was determined experimentally by mixing water with the dry material until the mixture had a consistency approximating that of the bed material.

From this preliminary analysis it was noted that $N_s/N_b$ is not a function of $c/\sqrt{\tau_0/\varrho}$ alone. Allowing for scatter of the points due to experimental error, there was no question that the experimental points fell on a set of curves which had different values of shear. Mean curves were drawn through the points for constant shear and the tendency of the experimental data to form a set of distinct curves was clearly indicated. It appeared that the bottom shear, or $\sqrt{\tau_0/\varrho}$, had more influence on the value of $N_s/N_b$ than had been taken into consideration, and it was therefore concluded that the relationship proposed by Lane and Kalinske is not sufficiently general, or else the behavior of fine sediments is entirely different from that of coarser materials. Detailed examination of the original field data used by Lane and Kalinske indicates that their points may have had a tendency to fall on different curves, also, but because of the limited range of particle sizes and values of shear this tendency was not apparent and consequently disregarded.

16. Generalized Analysis.—In the development of their relationship, Lane and Kalinske assumed that in the turbulent flow the turbulence penetrated down to the bed, or in other words, the turbulence is assumed to be fully developed right down to the sand particles. Though this is probably true for high values of shear
Fig. 12. Size Composition of Suspended and Bed Materials.

Fig. 13. Size Composition of Suspended and Bed Materials.

Fig. 14. Size Composition of Suspended and Bed Materials.
and large particles, it is not true for small shears and very fine particles. A thin boundary layer may exist which greatly influences the ability of the turbulence to pick up this material from the bed. The thickness of this layer is dependent on the shear and the fluid viscosity. Thus, this problem may be affected by viscosity in a manner not considered by Lane and Kalinske in their analysis. To show how the different variables entering this problem are related it is of interest to make a simple physical analysis which throws considerable light on this whole problem of transfer of material from the bed into the fluid above. In common with analyses of other transfer or diffusion phenomena, assume that the rate of transfer of sediment from the bed can be expressed as equal to \( T(N_b - N_s) \), where \( N_b \) and \( N_s \) have the definitions already mentioned and \( T \) is a sort of "diffusion coefficient." Under equilibrium conditions, this rate of transfer must be equal to the rate of settling or:

\[
T(N_b - N_s) = cN_s \tag{11}
\]

We note that Eq. (11) states that the ratio \( N_s/N_b \) is function of \( c/T \). The value of \( T \) should, of course, depend on the intensity of the turbulence and, as Lane and Kalinske showed, this depends on the value of \( \sqrt{\tau_0/\varphi} \). In addition, its value is influenced by the thickness of the boundary layer, \( \delta \). Since \( T \) has the dimension of velocity it seems that it should be proportional to \( \sqrt{\tau_0/\varphi} \) and a function of the ratio of particle size and boundary layer thickness, \( d/\delta \). We know from fluid mechanics that the value of \( \delta \) is proportional to \( v/\sqrt{\tau_0/\varphi} \), hence

\[
T \propto \sqrt{\tau_0/\varphi} \varphi \left( \frac{d/\sqrt{\tau_0/\varphi}}{v} \right), \tag{12}
\]

where \( v \) is the kinematic viscosity, and \( \varphi \) indicates a "function of." Putting this expression for \( T \) into Eq. (11), it is then apparent that \( N_s/N_b \) can be expressed as a function of two dimensionless terms, thus:

\[
\frac{N_s}{N_b} = \varphi' \left( \frac{c}{\sqrt{\tau_0/\varphi}}, \frac{d/\sqrt{\tau_0/\varphi}}{v} \right), \tag{13}
\]

or by letting \( t = c/\sqrt{\tau_0/\varphi} \) and \( P = d/\sqrt{\tau_0/\varphi}/v \) we have:

\[
\frac{N_s}{N_b} = \varphi'(t, P) \tag{14}
\]

In a problem involving three parameters such as those indicated
Fig. 15. Size Composition of Suspended and Bed Materials.

Fig. 16. Size Composition of Suspended and Bed Materials.

Fig. 17. Size Composition of Suspended Material.
by Eq. (13), the convenient method of developing the relationship experimentally is to keep one of the parameters constant and study the variation of the other two. The present experiments were not carried out according to this procedure and consequently the experimental data could not be used directly to prove the validity of the indicated relationship. However, the data could be arranged so that for a constant value of \( P \), the values of \( N_s/N_b \) corresponding to different values of \( t \) can be obtained indirectly. The values of \( N_s/N_b \) were plotted on logarithmic paper against the diameter of the particles for different values of \( \sqrt{\tau_0/\rho} \), and mean curves were drawn through each set of points having a same value of \( \sqrt{\tau_0/\rho} \). In the same way values of \( t \) were plotted against the particle diameter for various values of \( \sqrt{\tau_0/\rho} \), and curves were drawn through each set of points (in case the particles were within range of the Stokes law, these curves become straight lines on logarithmic plots). Choosing then any constant value of \( P \), the value of \( d \) could be computed by substituting the corresponding values of \( v \) and \( \sqrt{\tau_0/\rho} \) for a particular test run. Then from the curves, corresponding to that particular value of \( d \), the values of \( N_s/N_b \) and \( t \) could be read off. By taking another set of values of \( v \) and \( \sqrt{\tau_0/\rho} \) from a different run, another pair of values of \( N_s/N_b \) and \( t \) could be obtained. Thus, for any constant value of \( P \), nine pairs of values of \( N_s/N_b \) and \( t \) were obtained, since there were nine different experimental test runs. The points obtained were plotted and are shown in Fig. 18. It is apparent that for a constant value of \( P \), the points do form a smooth curve. Though the curves have a rather complicated form when the value of \( P \) becomes small, nevertheless, it seems that the analysis as expressed by Eq. (14) is confirmed.

In connection with the value of \( v \), it should be mentioned that the viscosity of the fluid changes with the temperature, and undoubtedly also with the concentration of the suspended sediment. The change of viscosity of a fluid due to the high concentrations of fine suspended sediment has not been taken into account, since there is no way of determining it unless by direct measurement. This involves considerable difficulty, since the viscosity will tend to vary with the rate of shear.

In Fig. 18, the data from Pien's experiments\(^{11} \) were also plotted.

---

\(^{11}\) C. L. Pien, "Investigation of Turbulence and Suspended Material Transportation in Open Channels," Doctoral Dissertation, University of Iowa, 1941.
Due to the narrow range of particle size and shear in his experiments, only a few points could be obtained. However, these few points are significant since they represent results from an entirely different experiment and seem to fit into the general picture.

The mean curve for the field data presented by Lane and Kalinske is also shown. The values of $P$ for these data vary from about
3 to 40; however, since the water temperature was not known, the value of \( v \) was assumed equal to that for a temperature of 15° C.; actual temperatures may have varied considerably from this.

17. **Practical Applications.** — A set of curves such as shown in Fig. 14, when verified further, can be used to predict the amount of material in suspension. In making such a prediction the value of \( P \) must be computed first, and the curve corresponding to this value used. Then knowing \( N_b \) and \( t \), \( N_s \) can be obtained, which gives the amount of material, characterized by the fall velocity \( c \), and diameter \( d \), that will be present in suspension just above the bed. From the sediment distribution theory, it is then possible to find the amount of that material in suspension at any other point in the vertical, and also the total amount in suspension. Another application of information such as given in Fig. 18 is the determination of the possibility of silting or scouring action for any given values of \( N_s \) and \( N_b \) and the hydraulic conditions. The data in Fig. 18 are for conditions in which there is neither settling nor scouring, and any appreciable deviation from the relationship indicated will mean that conditions are not those of equilibrium.

**VII. CONCLUSIONS AND FUTURE WORK**

18. **Summary and Conclusions.** — This investigation was concerned with the transportation of material in suspension by flowing water in a rectangular flume 2.25 ft. wide. The material used was silica which had a median diameter of 0.011 mm. and a specific gravity of 2.67. Observations were made on the hydraulic characteristics of the water flow, and data were obtained regarding the concentrations of suspended material and bed composition for 9 different discharges.

1. Concentrations of the suspended sediment up to 11 per cent by weight, did not seem to have any definite effect on the open channel flow characteristics in these tests.

2. The mean velocity distribution in the center of the flume follows the logarithmic curve very well. The velocity distribution in the entire flow section was regular and symmetrical.

3. The value of von Kármán's universal constant \( k \) varied from 0.32 to 0.44 without any regular variation with respect to sediment concentration.

4. The appearance of the water flow with respect to turbu-
lence and surface fluctuations resembled that of normal open-channel flow for all sediment concentrations.

5. The suspended sediment distribution for all sizes (maximum size was about 0.04 mm.) was practically uniform throughout the entire cross-section.

6. The data indicated that no measurable amount of sediment was transported as bed-load.

7. In regard to the relation between suspended and bed material under equilibrium conditions, the data indicated that the relationship proposed previously by Lane and Kalinske, based on field data, was not sufficiently general. A more general relationship, which takes into account the influence of the laminar boundary layer on the picking up of sediment, was developed, and the experimental data seemed to confirm this relationship.

8. The general relationship developed would permit prediction of suspended load from a knowledge of bed conditions and the hydraulic factors of the flow. Also, it should aid in the general solution of the stable channel problem.

19. Future Work. — It would be desirable in the future to investigate flows with higher sediment concentrations than were used in the present investigation, in order to obtain a more complete understanding of the characteristics of such flows. Further laboratory studies are necessary for definitely confirming and for extending the relationship governing the suspended sediment concentration, bed composition, and the sediment and flow characteristics under equilibrium conditions. Further investigation should be made with coarser materials and with a wide range of bottom shear and particle sizes, and, if possible, with varying fluid viscosities. The effect of sediment characteristics and concentration on fluid viscosity should be taken into consideration if very high sediment concentrations are used.
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