

SUSPENDED-LOAD CONTROL AND THE PROBLEM  
OF CHANNEL STABILIZATION

by

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The purpose of this paper is to present the factors which control the load of sediment which is carried in suspension by streams of flowing water and the application of the laws governing these factors to the stability of water-conveying channels. Within the time available it is not possible to go into the mathematical and quantitative relations; all that can be accomplished is to present a word picture of the actions and relations involved.

There have been a number of ideas of how solid material is carried in suspension in flowing water, but it is now quite generally agreed that it is carried because of turbulence. There is no widely accepted definition of turbulence, but for the purpose of this paper, it may be said that water is turbulent when at a given point the flow changes rapidly and erratically both in velocity and direction. Solid particles in suspension are kept in suspension by currents having an upward component, where the upward component is sufficiently large to overcome the force of gravity. Particles of solid matter of greater than colloidal sizes in a stream tend to settle to the bottom, the rate of settlement being greater for those of larger size or greater specific gravity. If these particles are moving in a stream in which the water is in a turbulent condition, they are continually meeting with currents which flow upward or downward or from side to side, but always with a component in the general downstream direction. When they encounter a current whose upward component of velocity is greater than their settling rate, they move upward, and if they meet such currents with sufficient frequency, they will stay in suspension a long time without reaching the bottom.

When these particles meet with currents having a downward component of velocity they of course move downward at a rate greater than this component by an amount equal to their settling rate. When they meet with upward velocities having smaller components than their settling rate they move downward at a rate equal to the excess of their settling velocity over the upward component of the fluctuating velocity. This analysis neglects the inertia effects of the particles which tend to keep them moving in the direction in which they start, but since these inertia effects are small and tend to prevent particles both from speeding up and slowing down, they tend to balance each other and may be neglected.

The amount of water moving upward in a stream must equal the amount of water moving downward, or in other words, the upward velocity components must equal the downward ones on an average. If this were not so, part of the water moving upward from the bottom of the stream would not be replaced by water moving downward and a void space in the water would occur. Since a particle in suspension is as likely to meet a downward current as an upward one and since in addition all of the particles tend to move downward continuously because of their own weight, at first glance it would appear that it would be impossible for material to be carried in suspension. It has long been known, however, that in the lower part of a stream there is more sediment being carried per unit of volume of water than is carried in the upper part of the stream. Fig. 1, for example, shows the results of measurements made by Dr. Straub on the material being carried in suspension in the Missouri River. Dr. Straub found that very fine material was carried in nearly equal amounts near the surface and near the bottom of the river, but that coarser material was carried in larger quantities near the bottom, the excess in quantity near the bottom over that at the top increasing with the increase in particle size. The total silt concentration, being a composite of various sizes, would also show a greater concentration near the bottom than at the top. Since this is true, currents of water moving upward come from regions of higher concentration than currents moving downward. Since the upward and downward currents are equal, the upward currents would carry upward more material than the downward currents would carry downward. Thus, we find in a stream carrying sediment in suspension there are particles moving upward due to the upward currents, fewer particles moving downward due to the downward currents,

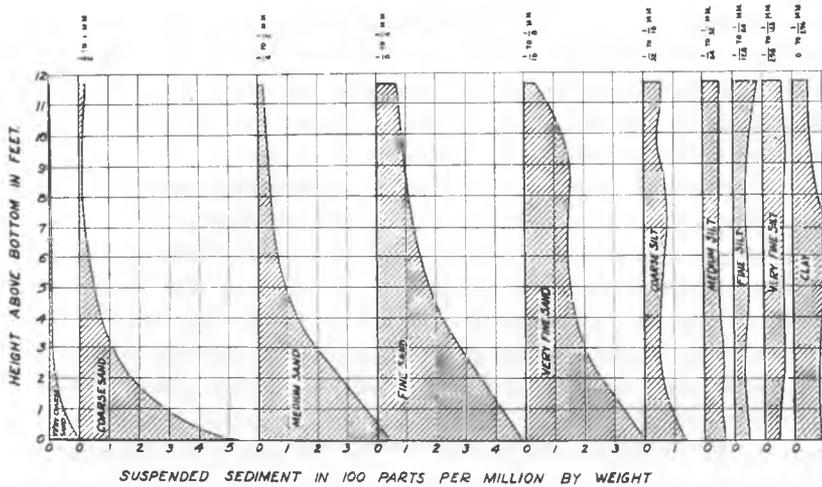


FIG. 1.

and all of the particles tending to move downward due to the excess of their specific gravity over that of water.

Since the particles of greater than colloidal size are continually settling down, sooner or later in flowing down a channel they reach the bottom. If the channel was long enough, therefore, and no particles were picked up from the bottom, all of the non-colloidal particles would settle out. Usually this does not happen, however, for the fluctuating velocities not only raise material already in suspension but also pick material up off the bottom. Frequently eddies or boils are set up in a stream which carry the bed material up into the flowing stream. If the bottom is composed of granular material, without cohesion, comparatively small currents are usually sufficient to raise up the bed material. The general picture of sediment being carried in suspension in a stream is therefore that of sediment being picked up from the bottom by turbulent currents and carried forward by the forward components of the currents, finally settling back again to the stream bed. While they are in suspension the particles are continually settling downward with respect to the water surrounding them, but this water may be moving upward or downward. If moving upward at a greater velocity than the particle settles the particle moves upward, and although the quantity of water moving upward is no greater than that moving downward, it tends to move upward more sediment, since upward-moving water

comes from a region of higher sediment concentration. In spite of the settling of the sediment particles it is thus possible to have water flow an infinite distance and still contain as much sediment in suspension as it contained at the start. From one standpoint such a channel could be said to be stable.

A stream channel may be said to be completely stable if it does not change its general position or the size or shape of its cross section. A great deal more research will be necessary before the problem of stable channels is adequately understood, for it is a very complex one. In this paper it will not be practicable to go into all phases of the stable channel problem, and only one will therefore be considered, that of the size of cross section. If in a given section of channel more material is carried out by the water than is carried into it, the average cross section of the channel must increase, and if more material is carried in than is carried out, the average size must decrease. A channel, which does not overflow its banks, will not increase or decrease its average cross section if the material carried out at the lower end is equal to that carried in at the upper end. This is independent of the process by which the material is transported; it may be carried in suspension, as bed load, or in any other manner. In this paper however we will limit our consideration to the transportation of material in suspension. From the standpoint of transportation in suspension, if more material is picked up from the bottom of a section of a channel than is deposited on the bottom, there will be more material passing out of the section in suspension than is coming into it, and therefore the average section is enlarging. If more material is being deposited on the bottom than is being picked up, the channel will be filling. To be stable from the standpoint of suspension, therefore, the amount of material picked up from the bed must be equal to that which is being deposited.

In working out the science of the transportation of material in suspension it is necessary to consider the simplest case first. If the relations cannot be solved for the simplest case, there is no hope of solving complex ones. In trying to work out the laws of sediment transportation, therefore, Mr. Kalinske and I have been studying the simplest case, which is that of a channel with level bottom of infinite width, in which steady, uniform flow occurs, the bed throughout being composed of fine non-cohesive material of uniform composition, the slope and discharge being such that the material picked up from the bed is equal to that which is deposited upon it. In such

a channel experience has shown that the curve of vertical velocities would have a shape as shown in Fig. 2. Whether or not this curve would turn back at the top is a disputed question, but since such a shape involves difficulties which we are not at present able to handle, we have assumed that it does not turn back, but comes up at right angles to the surface. As had been previously stated, the distribution of sediment of the different sizes is different, that of the finer sizes being fairly uniform from top to bottom and of the coarser sizes being much more heavily concentrated near the bottom. A mathematical equation of these distribution curves was first worked out by O'Brien<sup>1</sup> following the solution of Schmidt for turbulence in the atmosphere. That silt is actually distributed according to these relations was proved by Christiansen<sup>2</sup> and Richardson<sup>3</sup> who studied the results of actual observations.

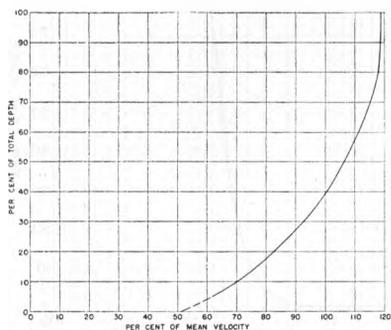


FIG. 2.

O'Brien's solution shows that the distribution of sediment of any size follows a logarithmic law which is a function of a settling rate of particles of that size, the shape of the vertical velocity curve, and the shear or tractive force at the stream bottom. With this equation it is possible to predict the concentration of sediment of any given size at any point in the vertical, if the concentration of that

size at some other point in that vertical is known. Unless the concentration at some other point is known, this relation cannot be used in a practical way.

It seemed to Mr. Kalinske and me that it should be possible to find a relation by which it would be possible to determine the concentration and size composition of material just above the bottom of the stream. We concluded that there should be a relation between three factors at this point; (a) the shear or tractive force at the bottom, (b) the composition of the bed material, and (c) the concentration of the various sizes of suspended material just above the bottom. Let us study this relation a little more carefully by considering the action which goes on at the bottom of a stream.

Consider first the composition of the bed material. Most engineers are familiar with the mechanical-analysis chart such as that

shown in Fig. 3a. Such a chart shows the percentage of particles with diameters greater than any specified size. Since the relation of the size of particles to the settling rate is known with reasonable accuracy it is possible to convert such a curve to one showing the percentage of sizes having various settling rates such as that in Fig. 3b. This curve, for example, shows that more than fifty per cent of the material would have a settling rate greater than 6 cm. per sec.

When a turbulent current with an upward component of a cer-

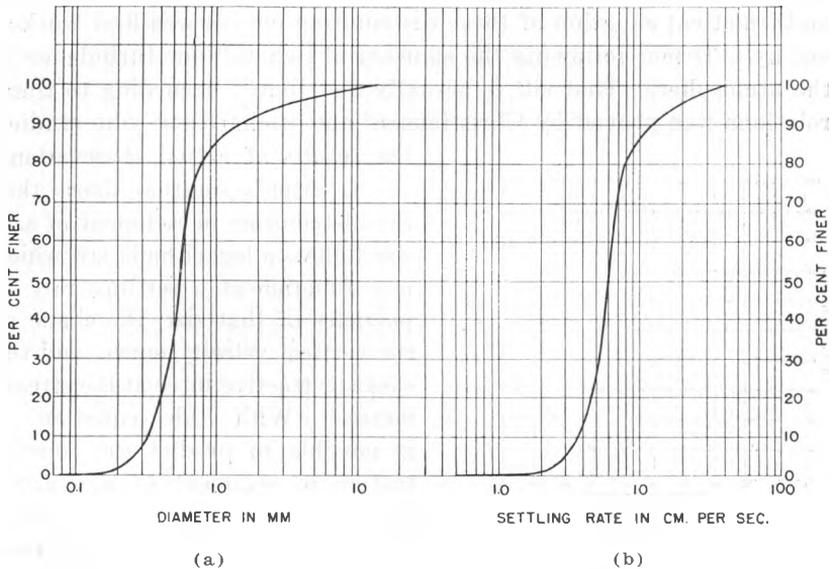


FIG. 3.

tain amount contacts the bottom, it carries upward the particles which have a settling rate less than its upward component. For example, upward components of 8 cm. per sec. carry up about 80 per cent of the material shown by the curve in Fig. 3.

The amount of the material which would be carried up by such currents depends upon the percentage of time various upward velocities occur. No satisfactory apparatus has yet been devised to measure these upward currents. However, measurements of horizontal variation of currents have been made. They show that the horizontal component of a current varies in a stream according to the normal error law. For example, Fig. 4 shows a variation of velocities at a given point in the Mississippi River and Fig. 5 shows

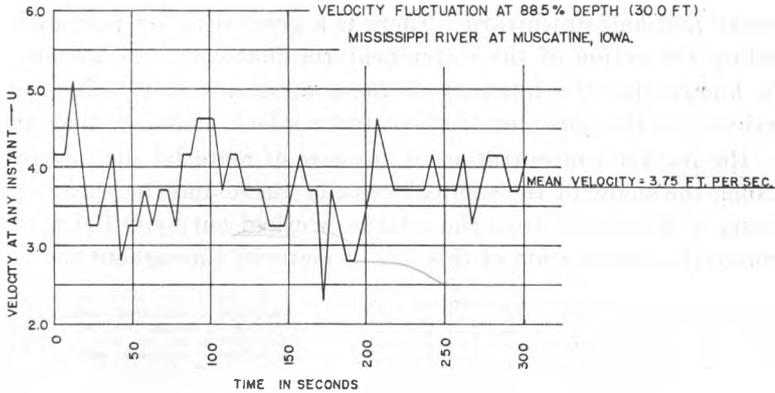


FIG. 4.

how these agree in distribution with the normal error law. We can represent the normal error law in the more familiar form of the distribution diagram, as shown in Fig. 6. For example, this diagram indicates that 25 per cent of the time the velocity would exceed 3.3 ft. per sec. Fifty per cent of the time it would exceed 3.75 ft. per sec., the mean velocity, and of course fifty per cent of the time it would be less than the mean velocity. Experiments have shown that the upward components of flow vary in proportion to the horizontal fluctuations and also follow the normal error law, half the time being

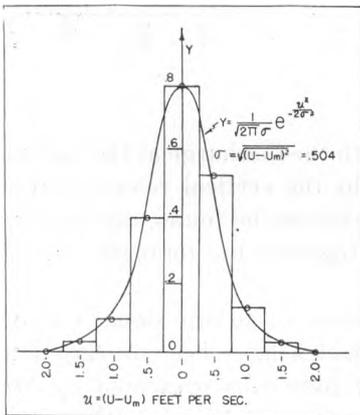


FIG. 5.

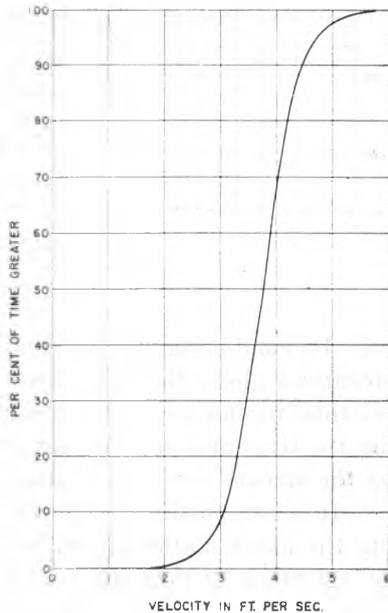


FIG. 6.

upward and half downward. There is a great deal yet unknown regarding the action of the water near the bottom of the stream but it is known that the intensity of these variations in velocity is proportional to the shear or tractive force which exists at that point.

Having the concentration of any size of material just above the bottom, the shape of the vertical velocity curve and the shear at the bottom, it is possible from the relation worked out by O'Brien to determine the distribution of this size of material throughout the verti-

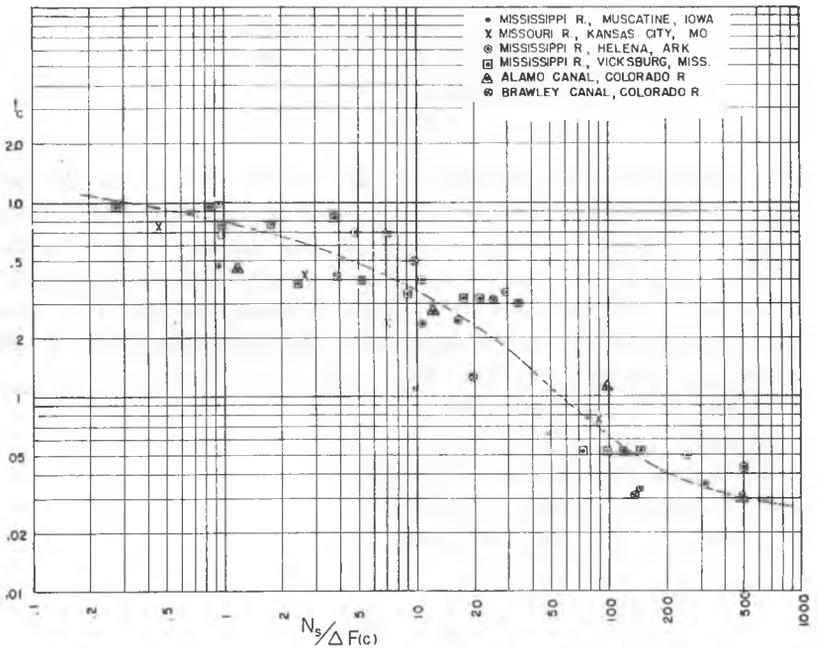


FIG. 7.

cal. By combining this distribution with the discharge at the various elevations above the bottom as shown by the vertical velocity curve the total discharge of that size of material can be found, and by adding the discharge of the various sizes together the total silt carried by the stream can be computed.

It is not possible in the time available to go into detail regarding the exact mathematical relations which have been worked out. A statement of them in mathematical form was presented by Mr. Kalinske and me to the American Geophysical Union meeting this

spring and will be published in their proceedings. We hope in the near future to work up a longer paper giving these points in more detail and written in a form readily understandable to engineers as well as to scientists. The agreement which has been found between these relations and the available observed results is shown in Fig. 7. This is a logarithmic diagram and although there is considerable spread of points, considering the nature of the data it is believed that the plotting shows that the agreement between theory and fact is quite satisfactory. Except in a few instances, the data were not complete and the missing parts had to be applied in a roundabout manner. The discharges ranged from a few hundred second feet to nearly two million second feet, the data used being that taken in small canals and in the Mississippi River at flood stage. The sizes of material varied over a considerable range. There is no assurance that in any one of the conditions observed the stream was actually in equilibrium which probably accounts for a large part of the spread of the observed points.

A great deal more study is necessary in this field in order to work out more exactly the relations indicated by this curve. The results, however, indicate that progress is being made toward a reasonably accurate quantitative solution of the simplest cases of suspended load, and that in the near future reasonably accurate engineering solutions will be found for problems of this type.

#### REFERENCES

- (1) *Trans., American Geophysical Union, Part II, 1933, p. 487.*
- (2) *Trans., American Geophysical Union, Part II, 1935, p. 478.*
- (3) *Proceedings of Royal Society of London. Vol. 162, 1937, p. 583.*

