# MEASUREMENT OF SEDIMENT TRANSPORTATION

by

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Sediment moves in fluids in three manners: suspension, rolling-sliding, and saltation. Everyone is familiar with muddy streams, in which sediment is being transported in suspension, and with dust being carried in the air, but it is only in the last few years that any satisfactory scientific analysis of this phenomenon has been made. In suspension the particles of sediment are kept up by the vertical components of the velocity of the fluid while being moved forward by the horizontal components. In general it is only the finer particles which are moved in suspension in air or water.

The larger particles of sediment move by rolling or sliding along the bed of the fluid streams, practically always in contact with it. Strangely enough there is no commonly-accepted term to designate the material thus moving, but it is believed that the best term is "contact load." Material moving in this manner sometimes reaches the size of large boulders.

The third class of movement is saltation, a sort of bouncing along of the particles on the stream bed. This phenomenon has not been as thoroughly studied as the other two forms of motion. Its action in air has been investigated by a British engineer, Bagnold [1],[1] and Gilbert [2] has reported a similar action in water. In water, however, it is very difficult to distinguish saltation from suspension, and recent studies by Kalinske [3], adapting the quantative studies of Bagnold to water by means of fluid-mechanics relations, seem to indicate that saltation is probably of little importance in water streams. In air, however, it is often of major importance.

In most rivers sediment is moving at the same time in two or three of these modes. On the bottom large particles are moving

[1] References appear at the end of the article.

along in contact with the bed. Just above the bottom there is a layer in which the concentration of the moving material is relatively high, and comparatively coarse material is transported in suspension or saltation or both. Above this is a thick layer extending to the surface in which the sediment is carried in suspension and is generally fine. In most streams the fine material is the greater part of the total, but the coarse material is usually more important from the standpoint of the formation of the bed and banks.

Observations at a great number of places have shown that the fine material in suspension is very uniformly distributed in the water from the surface to the bottom, but the coarse material, usually sand, travels at much higher concentration near the bottom. In suspension, the coarser the material the greater the part of it which travels close to the bottom.

If it is desired to determine the total quantity of sediment discharged in a unit time, a difficulty arises because the different parts of the load cannot be measured with the same instrument. To determine the amount of material being carried in suspension it is necessary to sample the flowing water in such a way as to obtain a representative sample of known weight and measure the weight of sediment in it in proportion to the weight of the sample. It is also necessary to determine the water discharge. From these data it is possible to compute the weight of sediment discharged per unit time. It is not possible to measure in this manner the amount of the heavy material moving on the bed, however, as it does not move at the same velocity as the water. For this material the procedure is to measure the quantity of sediment moving per unit time for a known width of the stream, at enough points across the stream so that the total quantity can be computed. For this purpose a sort of a trap is used which catches the material moved for a known length of time over a definite width of the river bed. It will thus be seen that there are two types of device for measuring sediment discharge, one called a suspended-sediment sampler, which secures a typical sample of the water in the stream with its suspended sediment, and the other called a bed-load sampler, which secures a sample consisting of the sediment carried along the stream bed and for a short distance above it over a definite width of channel in a known time.

In measuring both bed load and suspended load there are two general divisions of problems: (1) those concerned with selecting the points of measurement in the stream at which the sediment load can most accurately be related to the mean of the stream, and (2) those involving the design of the device to obtain the truest possible sample of the material at these measuring points. For bed load little seems to have been done to develop a science of locating sampling points. The customary procedure is to observe the rate of movement at a sufficient number of points across a stream to observe with reasonable accuracy the variation between the sampling points. The rate of sediment discharge per unit width of stream is then plotted as ordinate and the position of the observing point across the stream as abscissa, and the total sediment discharge is determined from the area under the curve thus obtained.

Most of the work on bed-load measurement has been done in Europe and the devices for sampling have been largely developed there. The simplest form consists of a sort of basket or box of screen material, open at the end, which is placed on the bed of the stream with the open end upstream to catch the coarse sediment which is swept into it. Fig. 1 represents probably the most highly developed form of this device, which was designed by a Swiss Government agency. It consists of a steel box frame with three sides and top covered with wire mesh. It is open on the fourth side and the bottom is covered with a flexible-link mesh-like chain mail, which will fit closely on the bottom. The side opposite the open one is hinged so that the material collected may be discharged through it. The sampler is raised and lowered by means of a portable derrick and is held in place in the

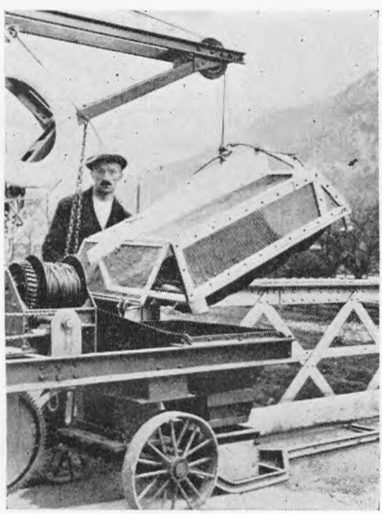

FIG. 1.—BED-LOAD SAMPLER OF THE BASKET TYPE DEVELOPED BY THE SWISS FEDERAL AUTHORITY FOR WATER UTILIZATION.

stream by cables extending upstream. It is permitted to remain on the bed of the stream for a time of known length, sufficient to collect a considerable quantity of sediment, and is then raised and the weight of the sediment determined. Experiments have shown that this device does not collect all of the material which would ordinarily pass the space it occupies, and it must therefore be calibrated to determine the relation of the material collected to that moving. This form of sampler is adapted to measurement where the load is coarse, such as pebbles and cobbles.

A second group of bed-load samplers are of what is known as the pressure-difference type. Of these the Arnhem sampler, devised by the Dutch Government (Fig. 2) is the most highly developed. It consists of a collecting assembly held in a large frame, the function of which is to place this assembly carefully into position on the stream bed with the mouth resting on the bottom and pointing upstream. Downstream from the mouth is a flexible rubber connection to an expanding section which leads in turn into a wire-mesh bag. The expanding section sets up a suction which is designed to balance the resistance to flow through the device and thus enable all the material approaching the mouth to pass into it without obstruction and be screened out by the mesh bag. As developed, this device used a 0.3-millimeter mesh in the screen, indicating that it is suitable for all material larger than fine sand.

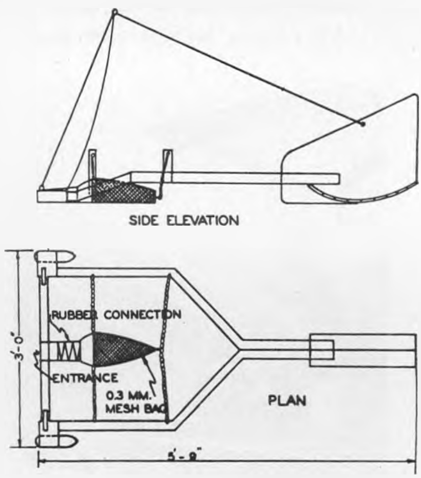


FIG. 2.—BED-LOAD SAMPLER OF THE PRESSURE-DIFFERENCE TYPE DEVELOPED BY THE HYDRAULIC STRUCTURES BUREAU OF THE DUTCH GOVERNMENT.

In measuring the discharge of suspended sediment, considerable study has been given to finding the best points in the stream cross section to take the samples. The methods worked out resemble those used in measuring stream discharge, in that they involve the location of the sampling sections both across the stream and in a vertical line at each of these stations. The method used may be better understood from Fig. 3. In measuring streams, the velocity is distributed across the stream as shown by the vectors of part (a), the length of the vectors representing the magnitude of the velocity. The discharge is represented by the volume bounded by the surface passed through the vector points, the plane of the cross section, and the bottom and surface of the stream. In (b) is represented the variation of concentration across the stream, with the

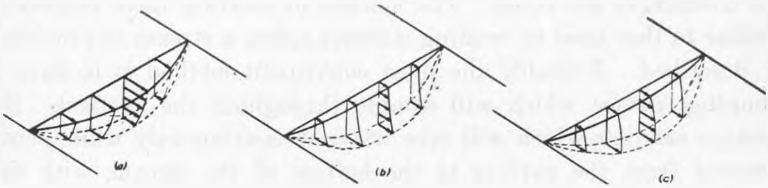


FIG. 3.—VELOCITY AND SEDIMENT DISTRIBUTION IN A FLOWING STREAM.

length of the vectors representing the concentration of sediment. In (c) the vectors represent the product of the velocity and the concentration and are proportional at each point to the discharge of sediment per unit area. The sediment discharge of the stream is proportional to the volume of the "solid" bounded by the surface formed by the vector points, the plane of the cross section, and the surface and bed of the stream.

As in water-discharge measurements, sediment discharge is usually obtained by collecting samples considered to give the mean sediment concentration in the vertical, and these are weighted according to the values indicated by the position selected for the verticals. Depending on the accuracy desired, the number of verticals at which samples are taken is varied from one to many. In general they are located so as to make the verticals typical of equal portions of the stream discharge, or equal proportions of the solids in (a) of Fig. 3. Where high accuracy is not required, they are taken at arbitrary distances from the banks, such as the center and the quarter points, or the center and the sixth points from the ends, which are assumed to give samples of equal weight. For greater accuracy, however, they should be spaced at the center of equal increments of discharge, the points being located from the results of stream discharge measurements previously made at the

measuring station. The selection of measuring points in the verticals is also a matter for consideration. The simplest method is to take them at one point, usually 0.6 depth. Other simple methods involve surface and bottom, and surface, mid-depth and bottom, with the mid-depth weighted either one or two. One of the best methods is that proposed by Dr. Straub of taking samples at two-and the 8/10 depth at 3/8. Another is the Luby method in which
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samples are taken at the centers of increments of depth for which the discharges are equal. The method of locating these centers is similar to that used in locating stations across a stream as previously described. Probably the most convenient method is to have a sampling device which will sample throughout the vertical. By using a sampler which will take water in continuously while being lowered from the surface to the bottom of the stream, with the amount being taken in proportional to the velocity at each point, it is possible to secure a sample which is the average for the entire depth. As will be described later, samplers of this type have been devised.

The development of a device for securing a true sample of the sediment in suspension in water has been going on for many years, and a great deal of ingenuity has been exercised by a large number of individuals. In the study of this problem, which has been carried on at the University of Iowa in cooperation with the U. S. Government agencies having sediment problems, (Tennessee Valley Authority, Corps of Engineers, Department of Agriculture, Geological Survey, Bureau of Reclamation, Office of Indian Affairs)[1] descriptions have been found of more than seventy different forms of samplers. A number of these are shown on Fig. 4. Time will not permit more than a very brief summary of these devices.

Most of these forms of sampler fall into one of three general

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[1] The results of this work are presented in nine reports: Report No. 1, "Field Practice and Equipment Used in Sampling Suspended Sediment"; Report No. 2, "Equipment Used for Sampling Bed-Load and Bed Material"; Report No. 3, "Analytical Study of Methods of Sampling Suspended Sediment"; Report No. 4, "Methods of Analyzing Sediment Samples"; Report No. 5, "Laboratory Investigation of Suspended Sediment Samplers"; Report No. 6, "The Design of Improved Types of Suspended Sediment Samplers"; Report No. 7, "A Study of New Methods for Size Analysis of Suspended Sediment Samples"; Report No. 8, "The Measurement of the Sediment Discharge of Streams"; Report No. 9, "The Density of Sediments Deposited in Reservoirs."

classifications: (1) instantaneous, (2) integrating, and (3) intermediate. The instantaneous types take a sample over a very short time interval and therefore reflect the conditions which exist in the vicinity of the sampler at that time. If these conditions

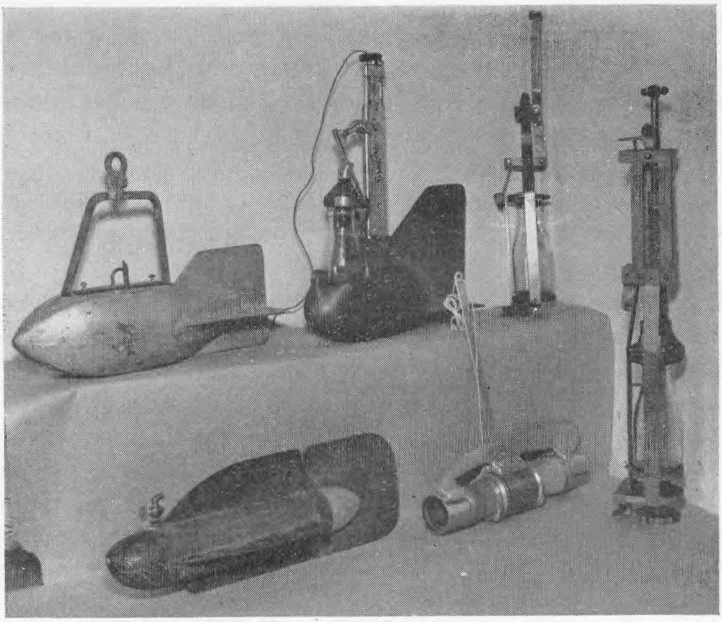

FIG. 4.—A NUMBER OF FORMS OF SUSPENDED-SEDIMENT SAMPLERS.

fluctuate rapidly, as they do in many instances, and if what is desired is an average sample, a sampler which will sample over a considerable period and thus integrate the fluctuating conditions is preferable. This is accomplished by samplers of the integrating type. The intermediate type consists largely of samplers in which there is a bottle which is lowered to the desired point and the stopper removed to take in the sample. As some time is required to fill the bottle, to some extent the sample is an integrated sample. Frequently the opening in the bottle is closed by a stopper through which there is a small hole, which causes the bottle to fill more slowly and thus integrate over a longer time period. These samplers can integrate either at a single point over a period of time or in a single vertical, from the surface to near the bottom of the stream. The integration can therefore be either time integration or depth integration. Fig. 4 shows a group containing a number of the better samplers of the intermediate and integration types developed in this country.

To practically all samplers which have been devised some objection can be made. Some of these objections are major and others minor, but until an adequate quantitative study has been made the relative importance of these objections cannot be accurately appraised, and is therefore subject to the judgment of individuals, giving rise to unending argument. To obtain some of the facts necessary to settle these arguments and to develop the most advantageous types of samplers, the cooperative study with the Government agencies was undertaken.

One of the objections to many samplers is that they deflect the stream lines of the flowing water which enters the sampler in such a way that the sediment particles tend to separate from the water and make the sample either more or less concentrated than it should be. As part of the cooperative studies the effect was investigated of drawing samples at different rates into the end of a tube pointed upstream in a current of water in which sediment was suspended. It was found that when the water directly approaching the end of the tube was drawn in, so that there was no deflection of the stream lines, the sample secured was a correct one, but that when either more or less than this amount was drawn in an error was introduced. For sediment composed of clay or silt particles this error was unimportant, but for larger particles it was appreciable, and for sizes about ½ millimeter, if the amount taken in was a small part of that directly approaching the end of the tube, an error of over 100% was possible. These results are shown quantitatively on Fig. 5. A number of other cases of intake conditions were investigated, and substantial errors were found in all cases in which the stream lines were seriously deflected at the intake and the material was coarse.

Another source of error in many forms of sampler results from what may be called "initial inrush." If the sample is taken in a rigid container which is kept closed until the sampler is lowered to the desired sampling point and is then opened, there is a considerable difference in pressure between the air inside the container and the water outside, the magnitude of which depends on the depth to which the sampler is lowered. When the container is opened, there is an initial inrush due to this pressure difference which goes on until sufficient water has flowed in to compress the air in the sampler to an amount equal to the pressure outside. The remainder of the space in the container is filled at a much slower rate, as the air in it escapes. Observations which were made on existing samplers showed that the initial inrush period was one second or less, and that the volume of this inrush could be computed by Boyle's Law. Under the severe currents set up in so short a time, not only would the deflecting action previously mentioned in the case of the intake tube occur, but the greater inertia of the solid particles would tend toward still further lessening of the concentration of the sample. If the sampler was used to integrate the concentration in a vertical of the stream, and was opened at the bottom, too large a part of the total volume of the sampler would be taken from the bottom and thus the integration would be imperfect.

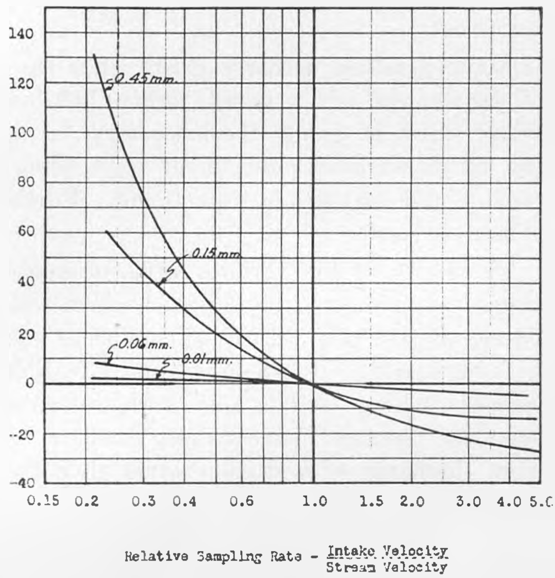


FIG. 5.—ERRORS IN CONCENTRATION RESULTING FROM VARIOUS INTAKE RATES IN TUBE INTAKE.

Another source of error, when the average concentration at a point is desired, may result from the fluctuations of sediment concentration as previously mentioned if a so-called instantaneous sampler is used. The magnitude of this error depends upon the magnitude of the fluctuations which occur and the extent to which the sample approaches being instantaneous. Unfortunately, a determination of the magnitude of such errors requires observation under a wide range of conditions in actual rivers, and as this has not been carried out, it is still largely a matter of opinion and argument.

Another source of error exists when the sample is poured out of the sampler into a vessel, rather than being taken directly in a vessel which is sent to the laboratory. A few tests were made of the errors involved and under some conditions discrepancies of considerable magnitude were found. Further study of this error should be made.

The study of the various forms of samplers indicated that no single sampler could be designed which would be suitable for use under all the wide variety of conditions encountered in sediment-bearing streams. It does not appear feasible to develop a form of sampler which would give both instantaneous or integration samples. Because in most cases the data desired is the total sediment discharge of a stream rather than the discharge at a point at a certain instant, and because of the uncertainty of the error involved in determining the sediment discharge by means of samples taken in an instantaneous type sampler, it was decided to work out first the most desirable form of integration sampler for the most widely encountered conditions in streams. It was expected that the most desirable form of instantaneous sampler for similar conditions could later be developed and a study be made of the magnitude of the errors involved in instantaneous samplers, to see if this best form would have sufficient advantage over the integration type to more than offset any disadvantage from such inaccuracies as might occur due to concentration fluctuations.

Two types of depth-integrating samplers were developed, one suitable for moderate depths and one for large depths. Both use a milk bottle enclosed in a torpedo-shaped weight as shown in Fig. 6. From the nose of the torpedo, an intake tube extends upstream and an exhaust is located on the side of the head, from which the air escapes. The exhaust is so designed that the water is taken in at the rate which will produce no deflection of stream lines, and therefore a true sample will be obtained. For moderate depths the sampler is lowered to the bottom and immediately raised to the surface again, taking in the sample on both the lowering and the rising trip. The movement is at such a rate that the bottle is nearly but not entirely filled, in order to insure that a portion of the sample was obtained from all depths. For greater depths a sampler was devised which takes in the sample only on the downward trip, and is closed when the bottom is reached by a foot-like trigger which actuates a valve on the intake tube.

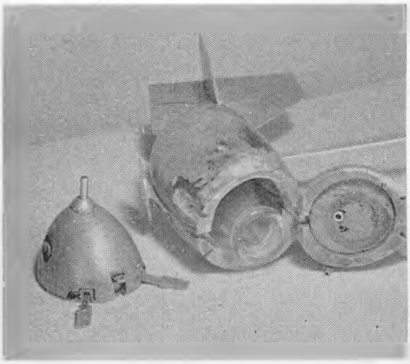

Fig. 6.—Improved Depth-Integrating Type of Suspended-Sediment Sampler.

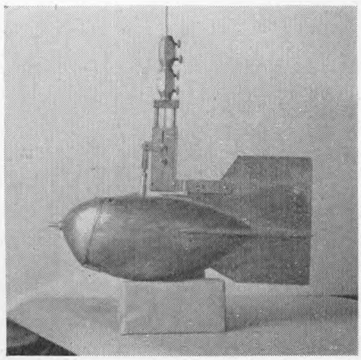

Fig. 7.—Improved Point-Integrating Type of Suspended-Sediment Sampler.

For taking a sample at a point, a sampler was devised which is opened at the desired point by a weight dropped down the suspension cable, and is closed, when desired, by a second weight. The initial inrush is prevented by a "diving bell" air chamber inside the weight, which compresses the air in the sample container as the sampler descends, and therefore the initial inrush does not occur (Fig. 7).

It should be stated that these samplers are largely the result of a combination of features found in many other samplers. Time is not available to enumerate each of these features, but indebtedness must be acknowledged. It was felt that a bringing together of the best ideas of a large group, insofar as they could be combined in a single device, would result in a more perfect instrument than would be produced by any single person or group.

REFERENCES

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[2] Gilbert, G. K., ''The Transportation of Debris by Running Water,'' *U.S.G.S. Professional Paper* No. 86, p. 26.
[3] Kalinske, A. A., ''Criteria for Determining Sand Transport by Surface Creep and Saltation,'' *Trans. A.G.U.*, 1942.