Apparatus and Techniques for Measuring Bedload

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By D. W. HUBBELL

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APPARATUS AND TECHNIQUES FOR MEASURING BEDLOAD

By D. W. Hubbell

ABSTRACT

The need for accurate determinations of the total sediment discharge of particles of bedload size has prompted this investigation of available and possible measuring apparatus and procedures. The accuracy of measurements of sediment discharge made with trap-type samplers is affected by the variability of sampler efficiency, by the oscillatory variation of bedload discharge, and by sampler placement. Equations that were developed for determining total discharge from measured bedload discharge and measured suspended-sediment discharge are simplest if the bedload apparatus measures only the true bedload.

Early bedload samplers are generally unsatisfactory. Recently developed or suggested apparatus include various improved samplers of the pressure-difference type, a pumping sampler, a magnetic sampler, acoustical instruments that measure the magnitude of the sound of particle collisions, an ultrasonic bedload sampler designed to measure and integrate electronically the concentration and velocity, and a tiltmeter designed to measure the total sediment discharge from the ground tilt that results from the passage of flow. All the pressure-difference samplers are improvements over early samplers, but none are void of the inherent shortcomings of trap-type apparatus; probably the Sphinx (Dutch) and VUV (Hungarian) samplers are the most satisfactory. The acoustical instruments are capable of measuring only the relative discharge. The ultrasonic sampler and the tiltmeter are not adequate without further development.

Some new possible apparatus and means for measuring or aiding in measuring bedload discharge are small pit samplers, ultrasonic sounders, pressure transducers, and photography. A small pit sampler for measuring bedload discharge was designed to provide self-placement and portability; however, its practicability and efficiency are undetermined. Exploratory films show that by using slow-motion photography the discharge of particles larger than about pea size can be determined provided the flow is clear; however, photography generally is not practical. Ultrasonic sounders provide continuous and accurate data on bed configuration and dune movement for use in equations that were developed for computing the bedload discharge. Computations with the equations indicate that the interpretation of the sounding data needs further study. Pressure transducers placed beneath the bed surface possibly can be used to provide information on dune movement; however, their installation would be difficult. The time required for collecting data on bed configuration and dune movement throughout a cross section could be substantially reduced by using several transducers simultaneously in conjunction with an ultrasonic sounder. A modified ultrasonic sounder that provides information on the shape and velocity of large particles and a method for determining the discharge of such particles were proposed; the method seems most feasible for particles of high sphericity.

INTRODUCTION

One of the principal concerns in studies of sediment transport is the determination of the total sediment discharge of coarse sediments—those particles of bedload size. Such particles do not always move as bedload but sometimes move as suspended-sediment load. Because the suspended sediment can easily be measured, the main problem is the determination of bedload—the sediment that slides, rolls, or skips along in almost continuous contact with the streambed.

In the past, attempts have been made to determine the bedload discharge in three general ways: By direct measurement with some type of apparatus; by definition of physical relations from which the bedload could be estimated; and by quantitative measurements of the results of some sedimentation process, such as erosion or deposition. Unfortunately, direct-measuring apparatus have been useful for only a very limited range of sediment and hydraulic conditions; the definition of physical relations has not been complete enough to estimate precisely the bedload discharge; and the quantitative measurements have supplied information only on the characteristics of the reach that was studied. As a result, no single apparatus or procedure, whether theoretical or empirical, has been universally accepted as completely adequate for the determination of bedload discharge over the wide range of sediment and hydraulic conditions in nature.

The need for adequate determinations of bedload discharge prompted an investigation on the measurement of bedload. This report presents the results of a review and evaluation of the existing and contemplated apparatus and techniques that were studied as a part of the investigation.

Because the majority of previous development work and study on the measurement of bedload was done outside the United States, much of the literature had to be reviewed through translations. Many of the translations of publications on early bedload samplers were furnished by the U.S. Waterways Experiment Station, the U.S. Soil Conservation Service, the U.S. Bureau of Reclamation, the National Bureau of Standards, and the University of California. Publications and other informational material on some of the recently developed measuring apparatus were kindly supplied by some foreign laboratories of the International Association for Hydraulic Research, by the U.S. Corps of Engineers, and by Mr. Sam Shulits. The publication by Smoltczyk (1955) was translated partly by Dr. A. N. Zervins and partly by Mr. Donald Steinmetz. Mr. William Thordarson of the Geological Survey and Mr. Istvan Takacs translated the articles by Juniet (1952) and Ivicsics (1956), respectively.

SOME ASPECTS OF MEASURING SEDIMENT DISCHARGE

The total sediment discharge of any size fraction includes the suspended-sediment discharge and the bedload discharge of the size fraction. Theoretically, both of these discharges can be determined either by measuring the weight of sediment that passes a section in a given time or by combining the concentration, the area of flow, and the velocity of the particles. However, in practice, the suspended-sediment discharge is usually computed by the concentration method, and the bedload discharge is usually computed by the weight method. Different methods are used because suspended-sediment particles are transported for sustained periods of time at about the same velocity as that of the flow, and bedload particles usually are transported intermittently at velocities less than that of the flow. Thus, suspended-sediment discharge can be computed from a concentration and a water discharge (the product of particle velocity and area of flow equals water discharge), whereas the bedload cannot.

Seemingly, the simplest and most practical method for measuring the weight of bedload passing a section in a given time would be to collect the sediment for a given time in some kind of portable sampler; this method has been used in most efforts to measure the bedload discharge. However, because with this method the sampler must rest on the bed, the flow pattern and the bedload discharge in the vicinity of the sampler are altered to some extent. The degree to which the bedload discharge is altered by any particular sampler depends on many factors, such as the stream velocity and depth, the magnitude of the bedload discharge, and the particle size of the bedload. For accurate bedload discharge measurements, the sampler must be designed so that the bed-load discharge is virtualy unaltered. Also, it must be designed to sample the largest and the smallest bedload particles, to accumulate and retain the bedload particles, to be stable on the bed, and to orient vertically and horizontally so that all particles have an equal opportunity for entrance. These criteria, collectively cannot be completely satisfied. As a result, samplers must be calibrated to determine their efficiencies. The efficiency of any given sampler may vary with any or all of the following factors: velocity, depth, particle size, bedload magnitude, degree of filling, and bed configuration. Inasmuch as all these factors vary in a natural stream, efficiencies are highly variable and uncertain.

The bed configuration is a particularly important factor because its effect on efficiency is superimposed, through sampler orientation and stability, on the other factors. Although discussions of the effects of bed configuration on efficiency are not available from the literature, certain effects seem probable. If the bed relief is formed by dunes that are large relative to the sampler, the sampler location and orientation with respect to the dunes would cause the efficiency to vary radically. Thus, variability in efficiency is the least when the bed relief is low, except possibly if high velocity makes the sampler unstable. Also, if the bed relief is formed by antidunes, which are usually unstable, sampler stability, and therefore efficiency, probably will be affected adversely. Inasmuch as bed relief can be approximated roughly according to the Froude number, certain generalities about the variability of efficiency can also be made according to the Froude number. Tranquil flow over movable material generally forms, successively, ripples, dunes, a so-called transition bed, and possibly antidunes as the Froude number increases. Rapid flow generally forms a transition bed and then antidunes as the Froude number increases. Hence, in tranquil flow, sampler efficiencies might be expected to be least variable at low Froude numbers, highly variable at Froude numbers from about 0.3 to 0.6, only fairly variable at Froude numbers from about 0.6 to 0.8 (if the sampler remains stable), and highly variable at Froude numbers from about 0.8 to 1.0 and throughout the rapid-flow regime.

Besides variable and uncertain efficiencies, other factors cause inaccuracy in bedload sampling. Probably the factor that contributes most to inaccuracy is the oscillatory variation in the bedload discharge. This phenomenon has been commented on by many investigators. From measurements made with bedload samplers, Ehrenberger (1931) was able to characterize the variations in the Danube and Inn Rivers with an almost constant period of oscillation, ΔZ_m. (See fig. 1.) Einstein (1937) also measured variations during his laboratory calibration tests of the Nesper bedload sampler (fig. 2). The significance of the variations in the measurement of bedload lies in the fact that short-term measurements at a point are very likely to be unrepresentative of the mean bedload discharge at the point. Thus, each sampling point must be sampled many times over a long period in order to achieve any reasonable accuracy. Ehrenberger concluded that greater accuracy can be achieved by measuring a few verticals for a long time than by measuring many verticals for a short time. Also, Einstein (1948) has pointed out that many samples at each point are required and that, consequently, sampling a single cross section may take as much as a whole day. Because of the time element, bedload sampling with an apparatus that measures the load at a point for only short periods of time is not accurate with changing flow conditions.

Another factor that contributes to inaccuracies in bedload sampling is the inadvertent collection of bed material. Because of hy-

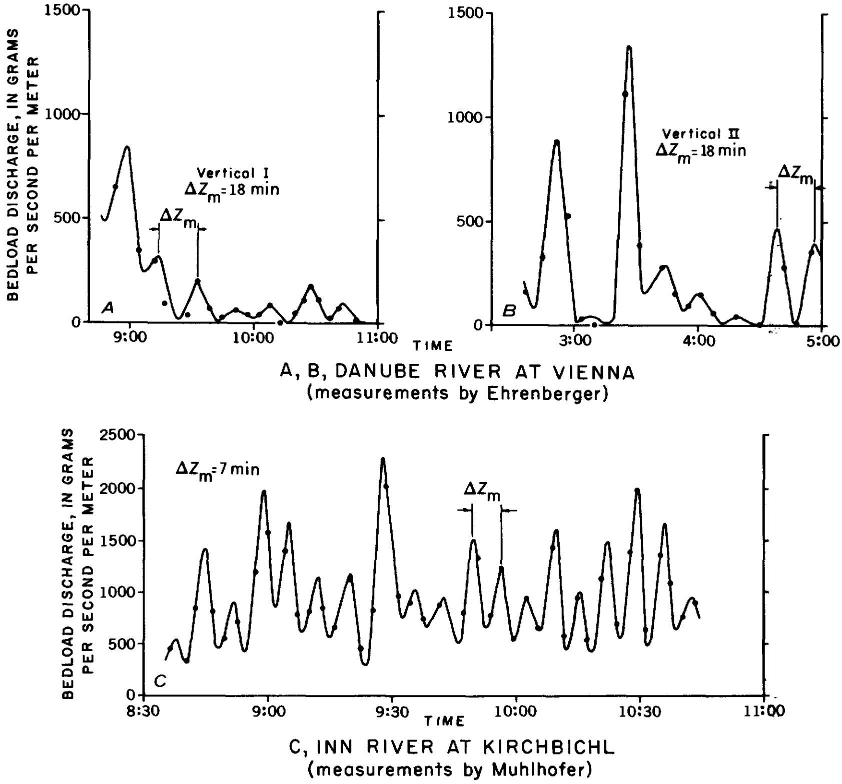


FIGURE 1.—Variation of sampled bedload discharge (from Ehrenberger, 1931).

draulic resistance, most samplers are subjected to a large downstream drag force and must be supported by an elaborate cable system. As the sampler is lowered into layers of progressively decreasing velocity, the drag force continuously decreases. As a result, the sampler achieves an upstream motion from its own weight and from the elasticity of the front stay lines. If the motion is not arrested before the sampler reaches the bed, the sampler may scoop up bed material. Also, once the sampler is on the bed, the turbulence causes the drag force to fluctuate; as a result, the net force on the sampler oscillates and may cause the sampler to move back and forth and scoop up bed material. The scooping of bed material is probably most likely if the sampler is inadvertently lowered into a trough in the bed.

CALIBRATION OF BEDLOAD SAMPLERS

The sampling efficiency of a bedload sampler can be defined as the ratio of the weight of bedload collected during any single sampling time to the weight of bedload that would have passed through the

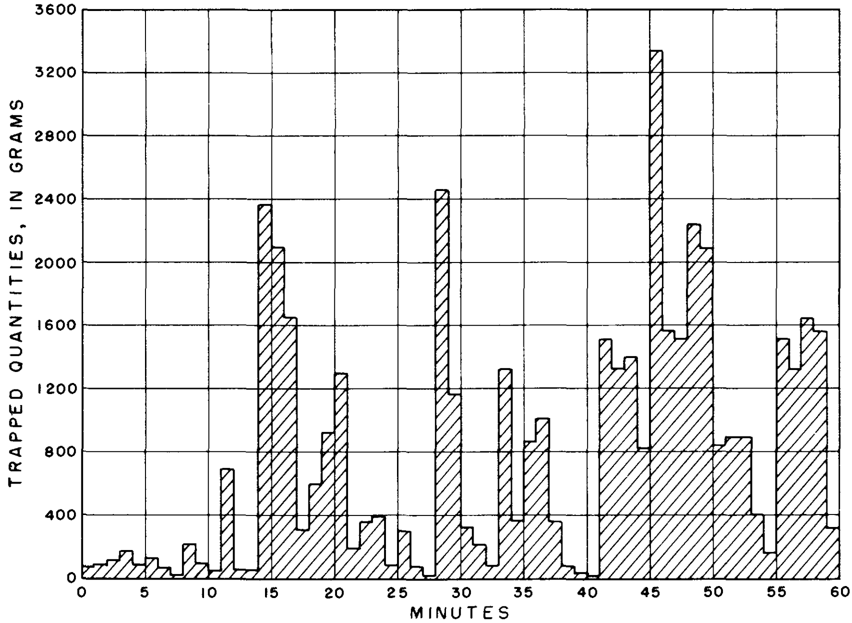


FIGURE 2.—Results of bedload collections during one hour in a laboratory flume (from Einstein, 1937).

sampler width in the same time had the sampler not been there. Needless to say, truly representative sampling efficiencies for prototype samplers are extremely difficult, if not impossible, to determine. Ordinarily, the sampling efficiency of a sampler can be determined most easily and accurately through tests in a laboratory flume; however, even under controlled conditions in a flume, several difficulties are encountered. The difficulties result not only from the variation of efficiency with several hydraulic and sediment variables (see under "Some aspects of measuring sediment discharge") but, also from several other physical restrictions. One difficulty is the determination of the bedload that would have passed through the width occupied by the sampler had it not been there. Because the magnitude of the bedload discharge oscillates and varies laterally across the flume, a bedload discharge that is measured at a particular time across the end of the flume or across some part of the end will not necessarily reflect the bedload discharge for the same time and the same lateral location at a given cross section in the flume. Thus, some corrective procedure must be applied to the measured loads so that they will be representative of the discharge at a given place upstream in the flume. Another difficulty arises because full-size samplers are generally so large that they alter the flow pattern in common-size laboratory flumes to such an extent that the calibration is invalid; therefore, scale models must be used. However, the use of models produces the problem inherent in most sediment model studies—the lack of similarity.

Bedload samplers have been calibrated both in flumes with fixed beds and in flumes with movable beds. Ehrenberger (1932) calibrated his sampler in a flat-bottomed laboratory flume by placing models of the sampler in the middle of the flume at a point downstream from the sediment injecting device where the sediment was assumed to be transported along the flume bottom in a normal manner and evenly distributed across the width of the flume. By knowing the amount of sediment injected into the flow, G_t, the amount retained in the sampler, G, and the ratio of the flume width to sampler width, W/w, Ehrenberger computed the efficiency, in percent, from Eff.$=$ $(G\ W/G_t w)100$. With this type of calibration, the following facts are ignored: The bed material, the bed shape, and the vertical orientation of the sampler may affect the efficiency; the sediment and flow conditions are not mutually related as they are in a natural stream; the sediment probably is not transported at the same rate everywhere across the flume; and the bedload discharge may vary along the flume.

Einstein (1937) used a calibration procedure that was intended to indicate, as nearly as possible, the efficiency a sampler would have in a natural stream. The procedure differed from Ehrenberger's procedure in several respects—the flume contained bed material scaled to the river material in approximately the same proportion as the model-prototype ratio, the lateral distribution of bedload discharge upstream in the flume was determined by special measurements, and individual measurements were treated as statistical quantities. The efficiency was determined by comparing the average bedload discharge measured at the end of the flume with the average local bedload discharge determined from sampler measurements that were adjusted in accordance with the lateral distribution to represent the load for the entire width.

DETERMINING THE TOTAL LOAD

The determination of the total sediment discharge is not necessarily the simple summation of the measured suspended-sediment discharge and the discharge from a bedload measuring apparatus. For many conditions, the determination of total load becomes somewhat complicated and is dependent on theoretical considerations. The reasons for the complications are that the measured suspended-sediment discharge is not necessarily the total suspended-sediment discharge and that some bedload measuring apparatus measure more than the bedload discharge. Normally, the measured concentration, which with present-day suspended-sediment samplers represents only the concentration from the water surface to 0.3 or 0.4 foot from the streambed, is multiplied by the total flow and a constant to give the measured suspended-sediment load. Consequently, if the concentration of a particular size range in the unsampled depth is greater than that in the sampled depth (if a concentration gradient exists), some of the load in the unsampled depth will not be included in the computation. Therefore, if the measured suspended-sediment load for the size range is summed with the results of a bedload measurement that represents only the bedload, the total load of the range will be low. Whereas, if the measured suspended-sediment load is summed with the results of a bedload measurement that represents the bedload plus some of the suspended-sediment load, the total load of the range may be either too large or too small; the direction of error depends on how much of the unsampled depth (depth from lowest point measured with suspended-sediment sampling equipment to streambed) is measured by the bedload apparatus.

For all conditions the following general formula is applicable for determining the total sediment discharge of a size range:

$$T = D/e + Q_{sM} + Q_{usM_1} - FQ_{sM} + (1 - E/e)Q_{ts_2}$$

where

- T is the total sediment discharge of the size range.
- D is the discharge of the size range as measured with the bedload apparatus. If the apparatus measures more than the bedload discharge, D includes some of the suspended-sediment discharge. If the apparatus measures only the bedload discharge, $D=B$.
- e is the efficiency of the bedload apparatus in measuring the bedload discharge of the size range.
- Q_{sM} is the measured suspended-sediment discharge of the size range. It equals the product of the total water discharge, a units conversion constant, and the velocity-weighted mean concentration in the sampled zone.
- Q_{usM_1} is the unmeasured suspended-sediment discharge of the size range in the depth between the lowest point measured by the supsended-sediment sampler and the highest point measured by the bedload apparatus. It equals the product of the water discharge in this depth, a units conversion constant, and the difference between the velocity-weighted mean concentrations in the sampled zone and in this depth.
- F is the fraction that the flow in the depth measured by the bedload apparatus is of the total flow.
- E is the efficiency of the bedload apparatus in measuring the suspended-sediment discharge of the size range that passes through the depth measured by the apparatus.
- Q_{ts_2} is the total suspended-sediment discharge of the size range through the depth measured by the bedload apparatus.

Simplifications of the general formula can be made for different combinations of particle-size ranges (expressed as bedload or suspended load), vertical distribution of suspended-sediment concentration, and type of bedload measuring apparatus. Table 1 shows, for each combination, the equivalent of each factor in the general equation and the simplified formula. The formulas in table 1 indicate that for particle-size ranges transported only as suspended load, the least effort is involved in the computation if a bedload apparatus that measures only the bedload is used; for particle-size ranges transported only as bedload, any type of bedload measuring apparatus is equally convenient; and for particle-size ranges transported as both bedload and suspended load, the apparatus that measures only the bedload is possibly the most convenient. These facts for individual size ranges lead to the following general conclusion: For all streams, regardless of how any particle-size range is transported, an apparatus that measures only the bedload is preferable.

EARLY BEDLOAD-MEASURING APPARATUS

Before about 1940, most bedload measurements were made with direct-collecting samplers. Many of the samplers developed up to that time have been described in detail in Report 2, "Equipment Used for Sampling Bed Load and Bed Material," of the Federal Inter-Agency River Basin Committee (1940) and will be mentioned only briefly here. In general, all these samplers can be classified according to one or a combination of the following types: box or basket, pan or tray, pressure difference, and slot or pit.

BOX OR BASKET SAMPLERS

Box or basket samplers operate by retaining sediment that is deposited in the sampler because of a reduction in the flow velocity and (or) that is screened from the flow. Usually, box samplers are open only at the front and top; and basket samplers are open, but screened, on all sides except the front and possibly the bottom. In general, the basket type has been adopted in preference to the box type. Several of the most highly developed and tested basket samplers are those designed by Mühlhofer (Ehrenberger, 1932), Ehrenberger (1932), Nesper (1937), and the Swiss Federal Authority (1939). (See figs. 3–6.) All these samplers are similar in design, but each is an improvement over its predecessor. The Mühlofer sampler had a solid bottom; each of the others had a bottom of loosely woven iron rings that conformed to the shape of the bed.

In general, the average efficiency of a basket sampler is about 45 percent. However, Einstein (1937) measured efficiencies with the Nesper sampler from about 90 to 20 percent, depending on the particle size and discharge of the bedload; Ehrenberger (1932) determined efficiencies for his sampler from about 92 to 80 percent, depending on

TABLE 1.—*Simplified formulas for computing the total sediment discharge of a size range*

[β, bedload; s, suspended sediment having a uniform vertical distribution; σ, suspended sediment having a nonuniform vertical distribution; W, measures only bedload; Y, measures bedload plus suspended sediment in all of unsampled depth; Z, measures bedload plus suspended sediment in part of unsampled depth]

Particle-size range transported as—	Type of bedload measuring apparatus	Equivalent					Simplified formula (T equals—)
		D/e	Q_{sM}	Q_{usM_1}	F	Q_{ts_2}	
s	W	0	Q_{sM}	0	0	0	Q_{sM}
s	Y	$(E/e)Q_{ts_2}$	Q_{sM}	0	F	FQ_{sM}	Q_{sM}
s	Z	$(E/e)Q_{ts_2}$	Q_{sM}	0	F	FQ_{sM}	Q_{sM}
σ	W	0	Q_{sM}	Q_{usM_1}	0	0	$Q_{sM}+Q_{usM_1}$
σ	Y	$(E/e)Q_{ts_2}$	Q_{sM}	0	F	Q_{ts_2}	$D/e+Q_{sM}-FQ_{sM}+(1-E/e)Q_{ts_2}$ [1]
σ	Z	$(E/e)Q_{ts_2}$	Q_{sM}	Q_{usM_1}	F	Q_{ts_2}	$D/e+Q_{sM}+Q_{usM_1}-FQ_{sM}+(1-E/e)Q_{ts_2}$ [1]
β	W	B/e	0	0	0	0	D/e
β	Y	B/e	0	0	F	0	D/e
β	Z	B/e	0	0	F	0	D/e
β, s	W	B/e	Q_{sM}	0	0	0	$D/e+Q_{sM}$
β, s	Y	$B/e+(E/e)Q_{ts_2}$	Q_{sM}	0	F	FQ_{sM}	$D/e+Q_{sM}-(E/e)Q_{ts_2}$
β, s	Z	$B/e+(E/e)Q_{ts_2}$	Q_{sM}	0	F	FQ_{sM}	$D/e+Q_{sM}-(E/e)Q_{ts_2}$
β, σ	W	B/e	Q_{sM}	Q_{usM_1}	0	0	$D/e+Q_{sM}+Q_{usM_1}$
β, σ	Y	$B/e+(E/e)Q_{ts_2}$	Q_{sM}	0	F	Q_{ts_2}	$D/e+Q_{sM}-FQ_{sM}+(1-E/e)Q_{ts_2}$
β, σ	Z	$B/e+(E/e)Q_{ts_2}$	Q_{sM}	Q_{usM_1}	F	Q_{ts_2}	$D/e+Q_{sM}+Q_{usM_1}-FQ_{sM}+(1-E/e)Q_{ts_2}$

1 or $Q_{sM}+Q_{usM}$ where Q_{usM} is unmeasured suspended-sediment discharge in unsampled depth.

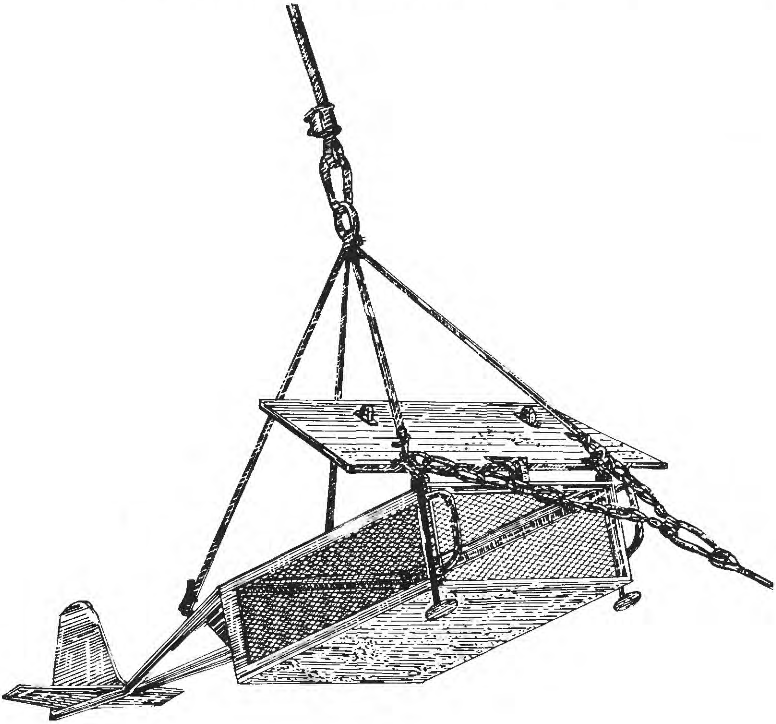


FIGURE 3.—Mühlhofer sampler (from Ehrenberger, 1932).

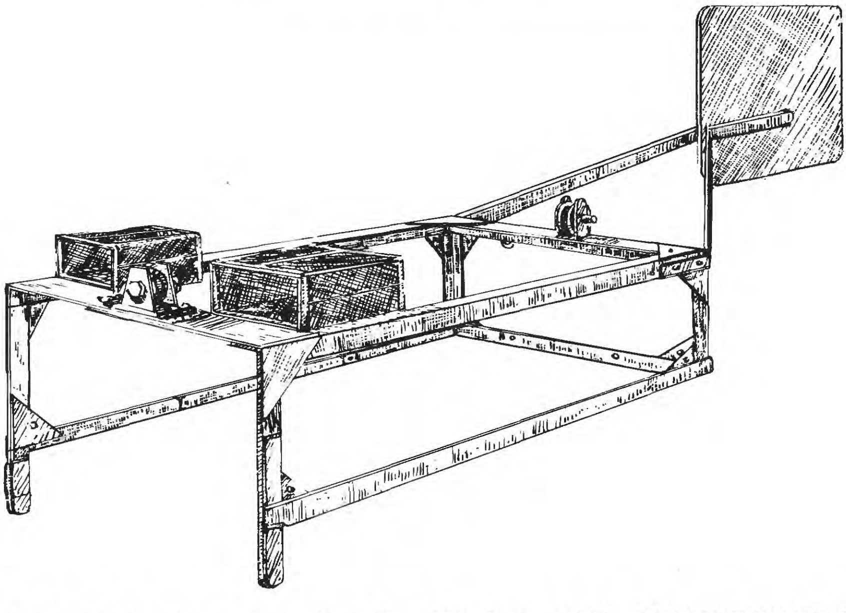


FIGURE 4.—Ehrenberger sampler frame (from Ehrenberger, 1931). Mesh basket is inserted into frame.

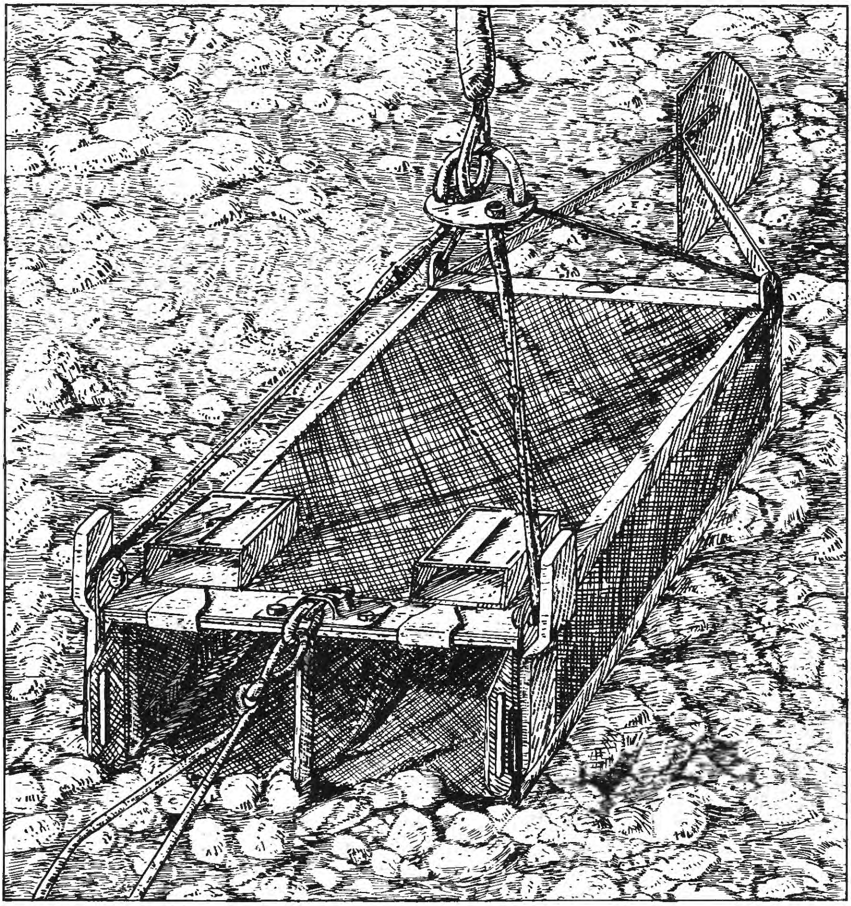


FIGURE 5.—Nesper sampler (from Einstein, 1937).

the bottom velocity, the particle sizes of bedload, and the degree of filling of the sampler (he later revised these efficiencies downward after recalibrating his sampler in a flume having a movable bed rather than a metal floor); and the Swiss Federal Authority (Federal Inter-Agency River Basin Committee, 1940) computed efficiencies for their sampler and found that they varied with the sampling time and the bedload discharge.

Because basket samplers have a large capacity, they are suited for measuring large particles. However, small particles, including suspended-sediment particles, can also be collected if the screen openings are sufficiently small.

The most extensive use of basket samplers was in Europe in the 1930's. Although the samplers were used primarily as an aid in the

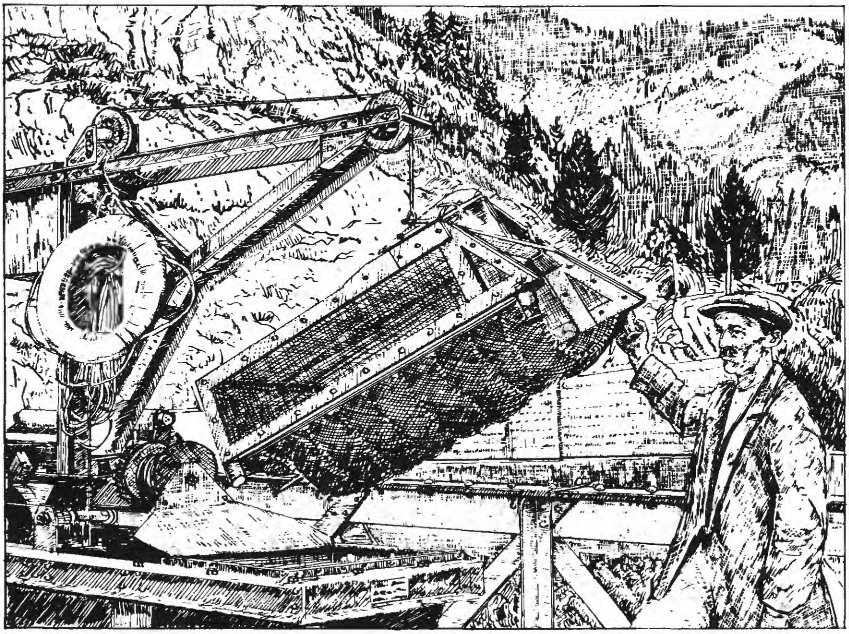


FIGURE 6.—Swiss Federal Authority sampler (from Swiss Federal Authority, 1939).

solution of specific river problems, they also were used for checking the validity of bedload formulas. The Schoklitsch formula was checked by both Ehrenberger (1931) and Schoklitsch (1934), who used the data from Ehrenberger's sampling of the Danube River at Vienna, where particle sizes from about 5 to 75 mm were collected. An early form of the Meyer-Peter and Müller equation was checked with bedload measurements and other field data by Müller (1937) as a part of a study of the Rhine River, where the coarse sediment is mainly from 5 to 100 mm. The study, which was proposed by Meyer-Peter, also included the calibration of the Nesper sampler by Einstein (1937) and the use of the sampler in the field by Nesper (1937).

PAN OR TRAY SAMPLERS

Pan or tray samplers operate by retaining the sediment that drops into a slot or slots after it has rolled, slid, or skipped up an entrance ramp. Hence, this type of sampler collects mainly bedload. Shamov (1935) has described and tested the operation of several different models of pan samplers that have been used principally in Russia for measuring the bedload discharge of sands. He found that average efficiencies for the Losiebsky (fig. 7), Polyakov (fig. 8), and Scientific Research Institute of Hydrotechnics (SRIH) (fig. 9) samplers were 38 percent, 46 percent, and 75 percent, respectively, and that the effi-

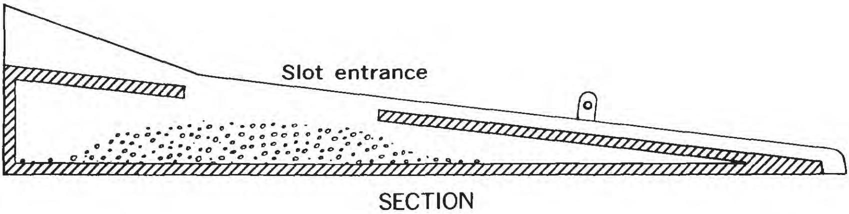


FIGURE 7.—Losiebsky sampler (from Federal Inter-Agency River Basin Committee, 1940).

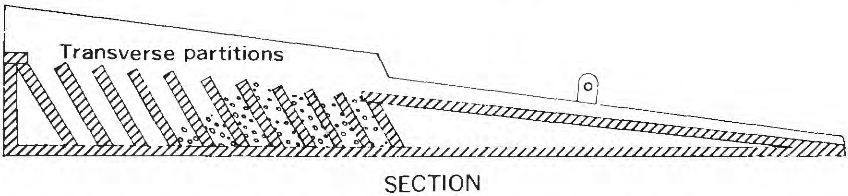


FIGURE 8.—Polyakov sampler (from Federal Inter-Agency River Basin Committee, 1940).

ciencies increased as velocities increased from 1.3 to 1.75 feet per second but decreased markedly when the velocities were greater than 2.1 feet per second (partly because some of the bedload moved as suspended sediment). He concluded that the upstream ramps of the Losiebsky and Polyakov samplers contributed to their low efficiencies by creating mounds of sediment in front of the ramps, whereas the SRIH sampler with its conelike entrance did not create this condition. The tests also showed that the series of slots in the Poyakov and SRIH samplers were superior to the single slot of the Losiebsky sampler because they did not create a large eddy over the slots.

Several writers (Polyakov, 1932; Einstein, 1948) have recommended that this type of sampler be limited to applications in streams having low velocities and low bedload discharges.

PRESSURE-DIFFERENCE SAMPLERS

In the operation of ordinary basket and pan samplers, the flow resistance of the sampler produces a decrease in the velocity at the

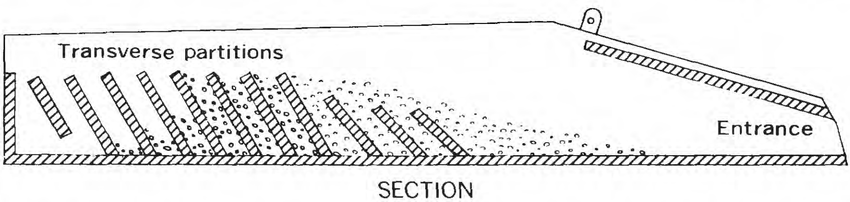


FIGURE 9.—Scientific Research Institute of Hydrotechnics (SRIH) sampler (from Federal Inter-Agency River Basin Committee, 1940).

sampler entrance. This velocity decrease causes some sediment to be diverted from or deposited at the sampler entrance; as a result, efficiencies are extremely variable. The pressure-difference sampler is designed so that the entrance velocity and the stream velocity are approximately the same. The equalization of velocity is accomplished through the creation of a pressure drop at the sampler exit by constructing the sampler walls so that they diverge toward the rear. Because the internal arrangement of pressure-difference samplers is not fixed, samplers can be designed to measure particles as small as fine sand or as large as 199 mm.

The first pressure-difference sampler was made by Goncharov; the SRIH sampler and the sampler developed by J. M. Terry of the U.S. Geological Survey also are of the pressure-difference type (Federal Inter-Agency River Basin Committee, 1940). Probably the best known of this type of sampler is the Arnhem or Dutch sampler (fig. 10). This sampler is composed of a rigid rectangular entrance

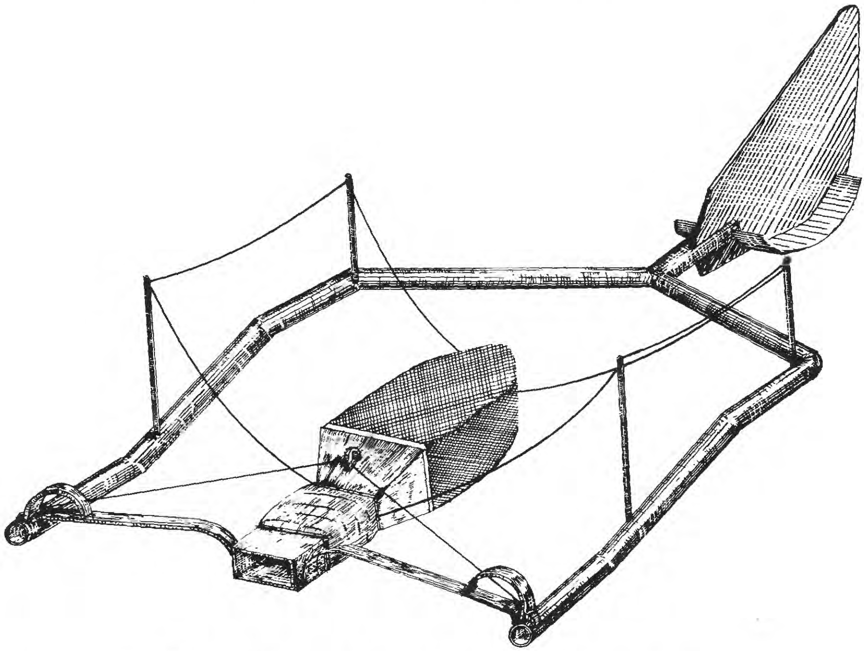


FIGURE 10.—Arnhem sampler (from Einstein, 1948).

that is connected by a diverging rubber neck to a basket of 0.2- to 0.3-mm mesh. Because of the mesh size, the sampler is capable of measuring the discharge of particles as small as medium sand. The sampling efficiency of the Arnhem sampler is about 70 percent (Meyer-Peter, 1937).

Although the results of specific measurements with the Arnhem sampler are not readily available, this author is familiar with some measurements that were made by L. C. Fowler (written communication) in 1954 on the Middle Loup River at Dunning, Nebr. In these measurements the computed average bedload discharge was low in comparison with the difference between the total sediment discharge as measured at the turbulence flume (Benedict, Albertson, and Matejka, 1955) and the suspended-sediment discharge as measured at a normal stream cross section. However, the most striking thing about the measurements was the variability in the sampling rate, which ranged from 11 to 112 cc per minute at one point. The variability of the sampling rate probably accounts in a large part for the low computed discharge and confirms the fact that numerous bedload samples are required for an accurate determination of the bedload discharge.

SLOT OR PIT SAMPLERS

Slots or pits that catch the sediment as it moves along the streambed have been used by several investigators to determine characteristics of the bedload transport. Mühlhofer (Federal Inter-Agency River Basin Committee, 1940) trapped sediment with the arrangement shown in figure 11, to determine the size distribution of the bedload. Other investigators have determined the bedload discharge by measuring the time required for a pit of known volume to fill. Probably the most elaborate installations were those of the Soil Conservation Service on the Enoree River and Mountain Creek near Greenville, S.C. (Federal Inter-Agency River Basin Committee, 1940; Einstein, 1944). Although the Enoree River apparatus (fig. 12) is a permanent installation and the Mountain Creek apparatus is semiportable, both operate on the same principle—the continuous withdrawal and weighing of the bedload after it falls into the slot or pit.

Experiments have shown that samplers having slot widths of 100- to 200-grain diameters are capable of collecting nearly 100 percent of the bedload (Einstein, 1944). The disadvantage of slot or pit samplers is that they must be placed into the streambed and cannot be emptied except by pumping or digging.

RECENT BEDLOAD-MEASURING APPARATUS

Recently developed bedload equipment generally can be classified as direct- or indirect-measuring apparatus. With the exceptions of a pumping sampler and a magnetic sampler, the direct-measuring

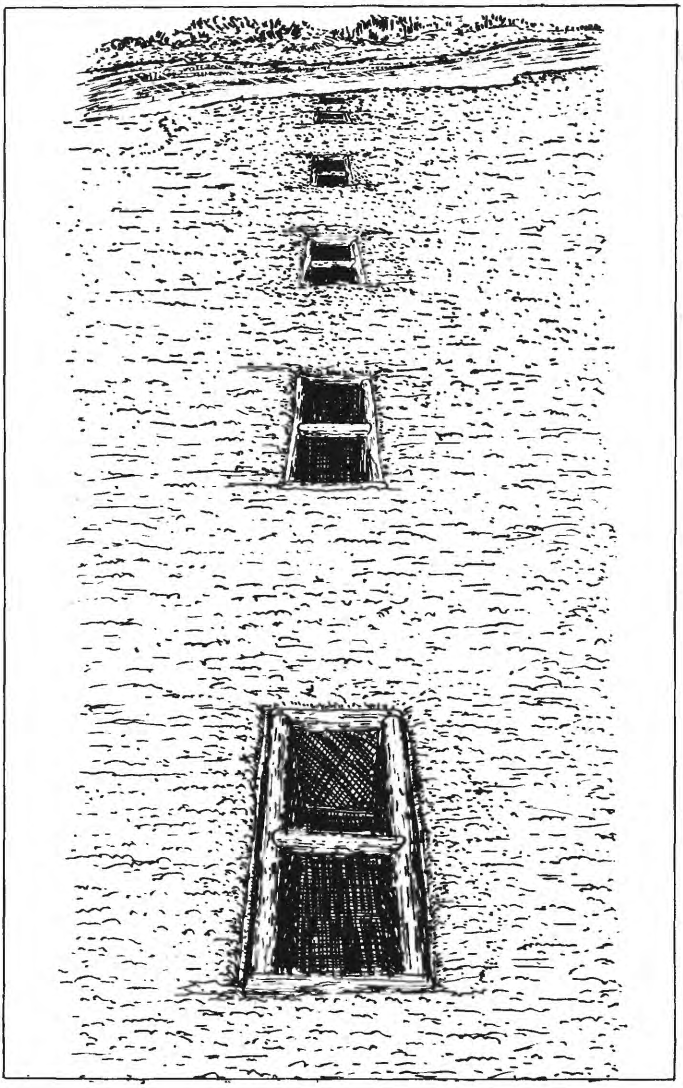


FIGURE 11.—Mühlhofer pit sampler (from Federal Inter-Agency River Basin Committee, 1940).

apparatus basically are improved models of the early pressure-difference samplers. On the other hand, the indirect-measuring apparatus, which measure some consequential characteristic of sediment movement rather than bedload discharge directly, are radical departures from any type of early sampler. Inasmuch as the indirect approach to the determination of bedload discharge is relatively new, some of the apparatus are not fully developed. Also, some of the apparatus are intended only as aids in studying the nature of bedload movement.

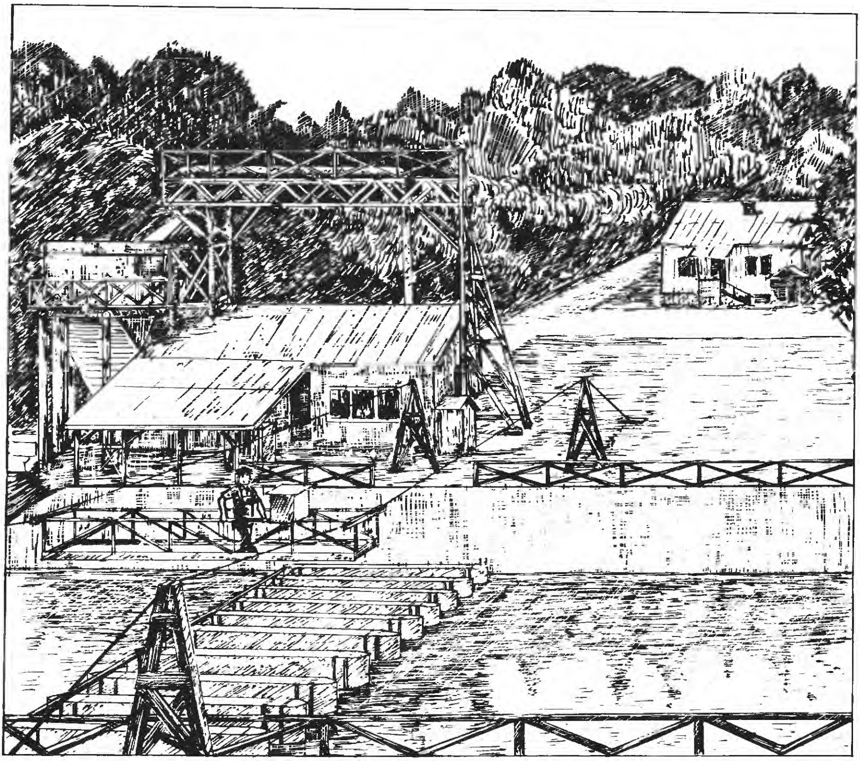


FIGURE 12.—Enoree River sampling installation (from Dobson and Johnson, 1940).

DIRECT-MEASURING APPARATUS

Vinckers, Bijker, and Schijf (1953) have described a bedload sampler that measures grain sizes smaller than 0.40 mm and that was developed by the Research Department of the Rijkswaterstaat and the Hydraulic Laboratory at Delft, Netherlands. In this sampler, called "Sphinx," (fig. 13) the flow enters through a rectangular nozzle that gradually becomes circular, then through a series of settling chambers, and then out a wide exit at the rear. The sampler has been designed so that the hydraulic efficiency—the ratio of water discharge through the sampler to the product of the undisturbed mean velocity of the stream at the nozzle location and the area of the nozzle entrance—is about 1.09 for clear flow, slightly lower for fairly high loads, and between 0.9 and 1.0 for extreme conditions. Sampling-efficiency tests indicate that about 8 percent of the sediment that enters the sampler passes on through when the median grain size is slightly greater than 0.2 mm and that 12 to 15 percent passes through when the sand is finer than about 0.09 mm. However, no information is available on the absolute sampling efficiency.

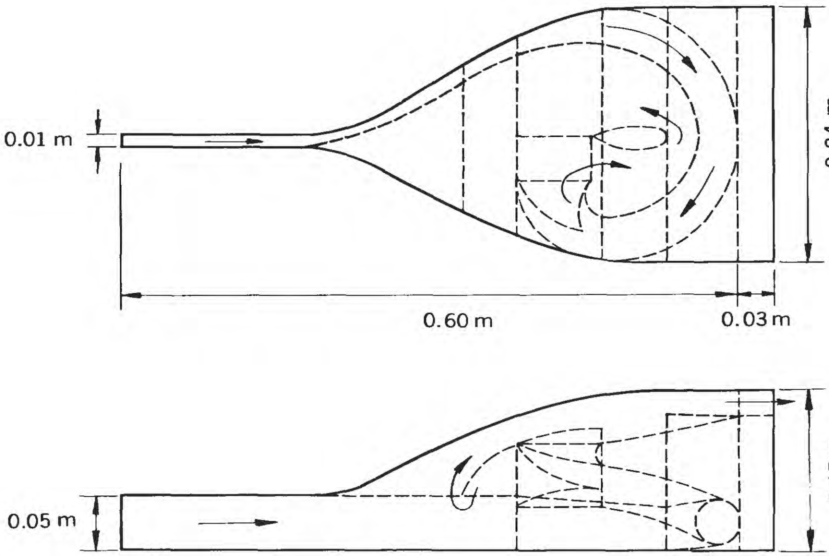
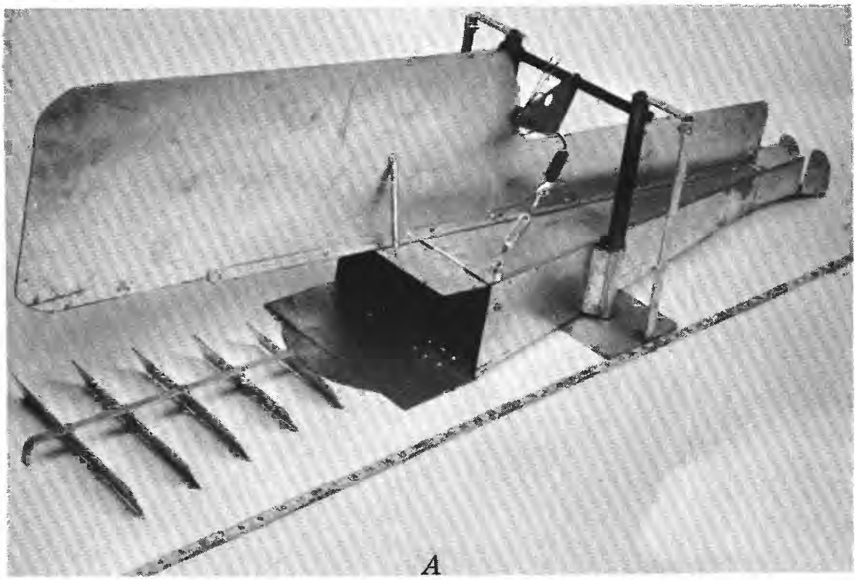


FIGURE 13.—The Sphinx sampler (from Vinckers, Bijker, and Schijf, 1953).

The Corps of Engineers, Little Rock, Ark., U.S. Army Engineer District, (written communication) have developed an experimental bedload sampler that measures sand and gravel and that contains some of the basic features of the SRIH and Terry samplers. The sampler (fig. 14) consists of a diverging rectangular box with a series of canted baffles (or slots) that retain the skipping, rolling, and sliding particles and any other sediment deposited as a result of the decrease in velocity. Mean entrance velocities have been made about equal to mean stream velocities at the sampling points by making the lower part of the rear gate, which remains in the closed position except when the sample is removed, a specific height. During sampling, the entrance ramp is pressed against the bed by means of a spring, and the supporting frame for the side weights, which is attached to the sampler with sleeves, settles into the bed independently of the sampler. Both the entrance ramp and the upper part of the rear gate automatically retract and close off the ends whenever the weight of the sampler is supported by the suspension cable. The large fin is necessary in raising and lowering the sampler in high velocity flow. Although the sampler has not been calibrated and its sampling efficiency is unknown, it has been used successfully to determine the sizes of particles transported, the stage at which appreciable movement begins, the relative amount and size of material transported at various locations on the bed, and the approximate accuracy of various tractive-force bedload formulas.



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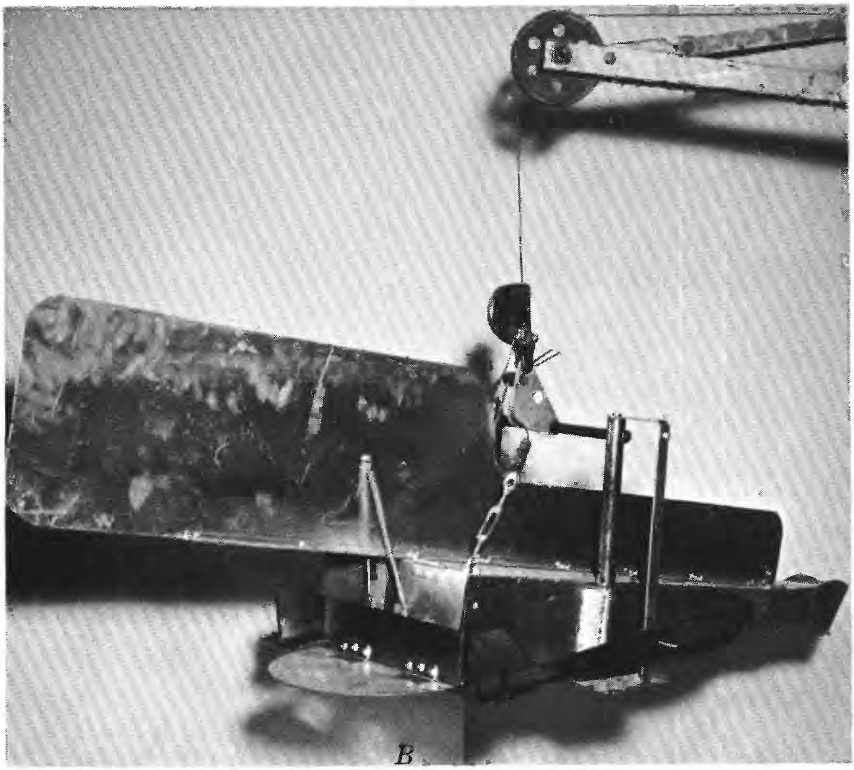

B

FIGURE 14.—Experimental sampler of U.S. Army Corps of Engineers, Little Rock, Ark. (U.S. Army photographs) : *A*, Parts diagram ; *B*, Sampler in lowering position.

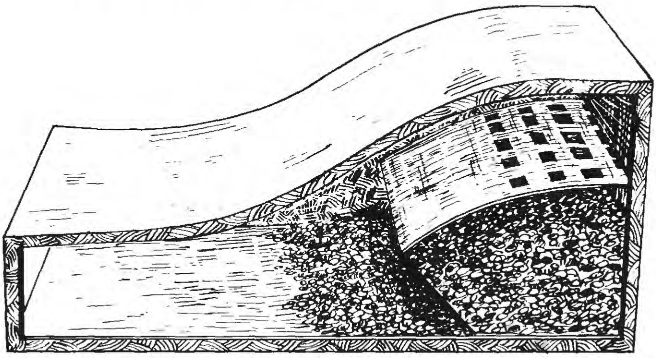

FIGURE 15.—Interior of Károlyi sampler (from Károlyi, 1947).

Károlyi (1947) developed a pressure-difference sampler (fig. 15) for measuring the bedload discharge of coarse sand and gravel. The principal feature of the sampler is a horizontal curved dividing wall that is about midway between the top and bottom of the rear of the sampler. This wall, which divides the lower sediment-retaining part of the sampler from the upper direct-flow-through part, is perforated at the rear. In the operation of the sampler, the bedload laden flow passes beneath the wall, rises through the perforations, and passes out the exist of the sampler. This action causes the load to be deposited at the rear of the sampler. (See fig. 15.) Other features of the sampler include a rubber-sheeting bottom at the entrance to insure conformation with the bed, an exit closure that operates automatically and is open only when the sampler is on the bed, signal lights to indicate the beginning and ending of sampling, and a side door for emptying the trap. In large rivers, this sampler, like most other traps, requires an elaborate suspension and anchor system to insure stability of the sampler on the bed.

Károlyi used the sampler in the field and assumed that it had a relatively high sampling efficiency if the sampling periods were short. However, Novak (1957) found in laboratory calibration tests that the hydraulic efficiency was about 80 percent and the sampling efficiency was about 45 percent. Although these efficiencies are relatively low, they do not vary radically with velocity or particle size as do the efficiencies of most other trap-type samplers.

Novak (1957) has developed a pressure-difference type sampler, called the VUV sampler, for measuring the discharge of sediment particles from 1 to 100 mm in diameter. The sampler (fig. 16), which is basically an improvement of the Károlyi sampler, is 130 cm long, 45 cm high, and 50 cm wide and collects about a 25-kg sample. Like the Károlyi sampler, the VUV sampler has a perforated dividing

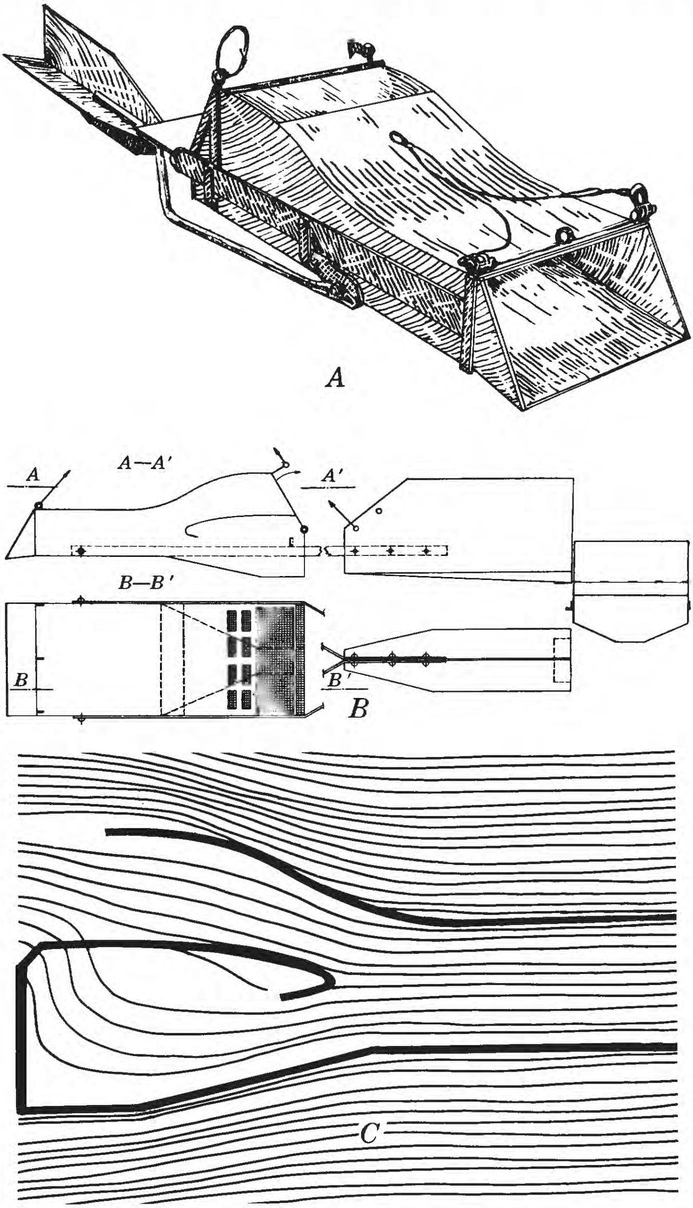

FIGURE 16.—VUV sampler (from Novak, 1957) : *A*, Sampler in operating position; *B*, Top and side views of sampler; *C*, Flow pattern through the sampler.

wall; however, the perforations consist of 1 large and 8 small mesh windows. (See fig. 16*B*.) Flow through the sampler exits from the unobstructed section above the dividing wall and from a 5.5-cm mesh-covered canted slot just below the dividing wall. The entrance and exit areas have been designed to give a hydraulic efficiency of about 100 percent. The flow pattern through the sampler is shown in figure 16*C*.

Novak determined the sampling efficiency of the VUV, Károlyi, Nesper, and Ehrenberger samplers and a wire-mesh sampler. His laboratory studies, which were extremely comprehensive, were made in flumes 60, 100, and 250 cm wide and with sampler models that had scale ratios of 1:1, 1:2, 1:4, and 1:8. Runs were made with the samplers placed on concrete floors (Ehrenberger method) and on movable beds (Einstein method), with particle-size mixtures and individual fractions of bedload that ranged from 0.1 to 100 mm, and with mean velocities that ranged from 0.6 to 2.2 meters per second. The model scales, particle-size ranges, and velocity ranges were selected so as to maintain an approximate similarity with the flume size. Sampling efficiencies were determined according to the concept used by Einstein that the efficiency is the ratio of the weight of sediment retained by the sampler to the weight of sediment that would normally pass through the area occupied by the sampler. Efficiencies for all the samplers tested are given in table 2. The field efficiencies recommended by Novak are 70 percent for the VUV sampler, 40 percent for the Nesper sampler, and 60 percent for the Ehrenberger sampler. Both the 40 percent and the 60 percent agree reasonably well with the efficiencies previously established by Einstein and Ehrenberger.

TABLE 2.—*Results from sampler calibrations by Novak (1957)*

[Sampling efficiency: 1, concrete bed; 2, movable bed]

Sampler	Scale ratio (model to prototype)	Ratio of flume width to sampler width in indicated flume			Sampling efficiency, in percent, as determined in indicated flume						Recommended overall field sampling efficiency, in percent	Hydraulic efficiency, in percent
		250 cm	100 cm	60 cm	250 cm		100 cm		60 cm			
					1	2	1	2	1	2		
VUV	1:1	5	----	----	82	52	----	----	----	----	70	----
	1:2	10	4	----	70	64	75	30	----	----		----
	1:4	----	8	4.8	----	----	93	61	----	65		101
	1:8	----	16	----	----	----	83	55	----	----		----
Wire mesh	1:1	3.9	----	----	92	64	----	----	----	----	65	----
	1:2	7.8	3.7	----	75	----	80	45	----	----		
	1:4	----	6.25	3.75	----	----	85	53	65	55		
	1:8	----	12.5	7.5	----	----	75	48	----	42		
Károlyi	1:1	5	----	----	55	40	----	----	----	----	45	----
	1:2	10	4	----	27	----	47	----	----	----		----
	1:4	----	8	4.8	----	----	67	36	50	----		81
Nesper	1:1	5	----	----	75	34	----	----	----	----	40	----
	1:4	----	8	----	----	----	65	22	----	----		
Ehrenberger	1:1	5	----	----	80	----	----	----	----	----	60	----
	1:4	----	8	----	----	----	74	49	----	----		

In addition to the information given in table 2, Novak also concluded from the sampler tests:

1. With a uniform size of bedload and with samplers that have thin lower front edges, the efficiency increases only slightly, if at all, as the particle size increases.
2. The VUV, wire-mesh, and Károlyi samplers retain particle-size distributions that agree, in general, with the distribution of the actual bedload, except for the sizes smaller than the mesh of the wire-mesh sampler and except for Károlyi samplers having blunt lower front edges.
3. For samplers having a thin lower front edge, efficiencies may increase slightly as velocity increases.
4. The height of the lower front edge of the sampler affects the efficiency materially, particularly for the particle sizes smaller than the height of the edge. The lower inlet edge should be sharp and gently sloping.
5. Hydraulic efficiency is only a qualitative index to sampling efficiency.

Uppal and Gupta (1958) have described two pressure-difference samplers that have been developed and tested at the Irrigation and Power Research Institute, Punjab. One of these samplers, sampler B, (fig. 17) has a horizontal curved wall, slotted at the rear, that divides the inside of the sampler into an upper part and a lower part in a manner similar to that of the Károlyi and VUV samplers. The other sampler, sampler A, has a rapidly expanding cross section and one vertical and one canted baffle for retaining the sediment. Laboratory tests of both of these samplers show sampling efficiencies of about 90 percent at stream velocities of 0.38 to 2.03 feet per second. The laboratory studies were made by comparing the weight of material collected in the 4-inch-wide sampler models with that collected in a 7-inch-wide box at the lower end of the flume; efficiencies were determined by assuming that the load did not vary with the width. The efficiency of the prototype of sampler B was concluded to be the same as the efficiency of the model after tests in a canal showed that the ratio of weight of material collected in the prototype to that in the model was 2.7, whereas the scale ratio was 2.5. Information is not available on the efficiencies by size ranges nor on the hydraulic efficiency. Also, information is not given as to whether the models were tested on a solid or movable bed.

Hiranandani (1943) described a proposed sampler that operates on a pumping principle. The sampler (fig. 18) consists of a nozzle attached to the suction side of a pump. Attached to the nozzle are two Pitot tubes, one of which is about 2 inches from the outside wall of

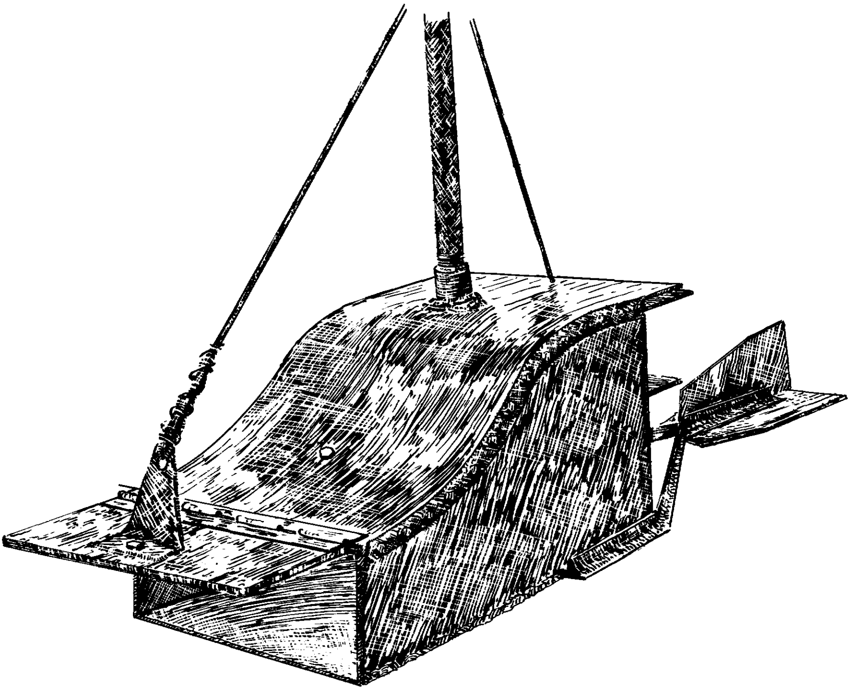

FIGURE 17.—Sampler B of the Irrigation and Power Research Institute, Punjab (from Uppal and Gupta, 1958).

the nozzle and one of which is on the inside and at the center of the nozzle. Each Pitot tube is connected to one side of a manometer so that the liquid levels in the manometer are equal when the velocities are equal. The pump discharge is regulated to attain the equal velocities. The sampler is intended as a point-integrating sampler for suspended sediment as well as a bedload sampler. Information is not available on whether or not such a sampler was ever constructed. Presumably, the sampler is limited in application to the measurement of the discharge of sands.

V. C. Kennedy (written communication, 1959) has suggested a magnetic bedload sampler for collecting particles from about 0.05 to 5.0 mm that are composed wholly or partly of magnetic minerals. The proposed sampler would consist of a series of electromagnets in the form of parallel vanes either completely or partially encased in a housing similar to that of a pan or pressure-difference sampler. The sampler and method are based on the assumption that the total bedload discharge can be computed from the discharge of magnetic-mineral particles that have the same size and shape and that behave in substantially the same way as nonmagnetic particles. Magnetic minerals have specific gravities as high as 5.2; therefore, the specific gravity a

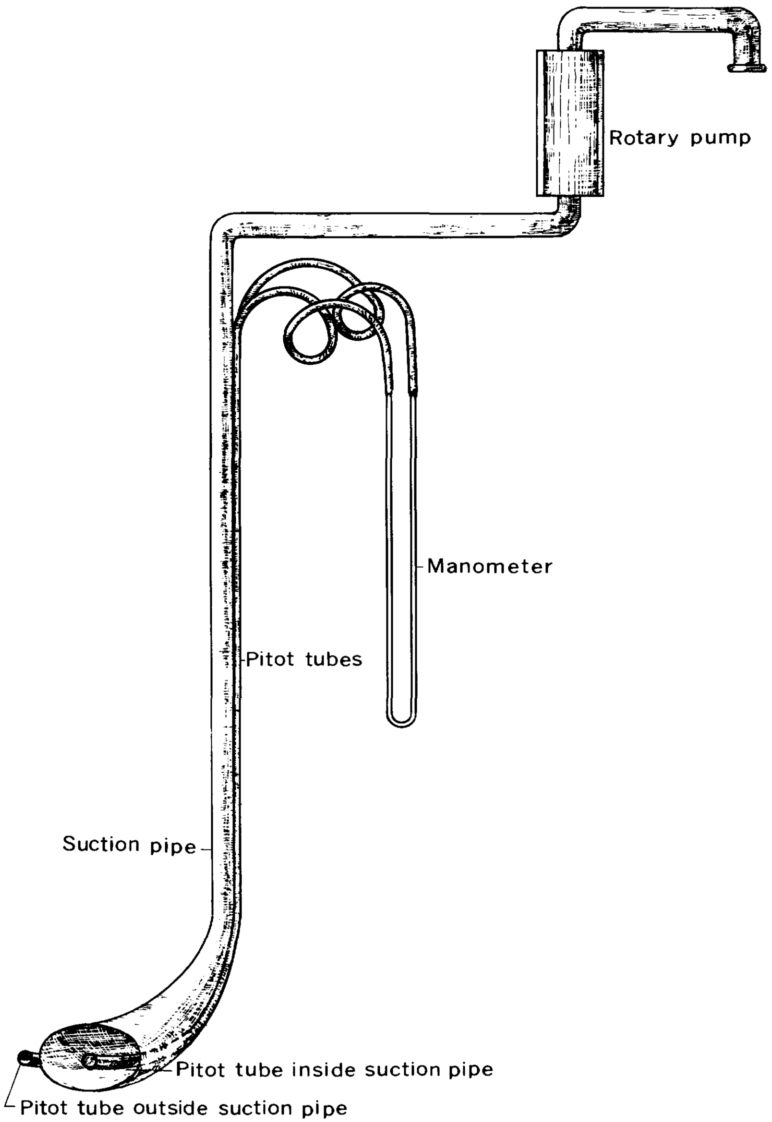

FIGURE 18.—Suction-type sampler proposed by Hiranandani (from Hiranandani, 1943).

particle must have before its behavior is significantly different from the majority of nonmagnetic particles of the same size should be considered in the method. Tentatively, Kennedy has assumed that magnetic particles have a specific gravity of less than 2.90 can be used for determining the bedload discharge. The bedload discharge would be computed for each size range by dividing the collected weight of particles having a specific gravity of less than 2.90 by the fraction of such particles in the bed material; the total bedload discharge would be the sum of the individual discharges from each size range.

Because the number of particles that will be collected by the sampler depends on the attractive forces of the electromagnets and on the forces that act on the particles, the sampler will have to be calibrated for different flow conditions, rates of bedload movement, gradations of particle size, and particle density. Herein lies a primary difficulty with the method. Also, particles must be separated according to specific gravity. However, Kennedy has suggested and used the simple heavy-liquid flotation method of separation.

Kennedy made preliminary studies of several streams and found sufficient quantities of light magnetic-mineral particles to make the method feasible. In addition, Mundorff (written communication, 1955), who also conceived a magnetic sampler, made similar studies of several Nebraska sandhill streams in 1954, and found significant amounts of magnetic particles.

INDIRECT-MEASURING APPARATUS

Of the indirect-measuring apparatus recently developed, several are acoustic instruments, one is an ultrasonic sampler, and one is a tiltmeter. All the acoustic instruments and the ultrasonic sampler have transducers, which convert acoustical energy to mechanical energy, or vice versa. The acoustic instruments are designed to pick up the sounds produced by interparticle or particle-instrument collisions and convert them to a variable electric current that is amplified and reproduced as sound or some other sensible phenomenon. The ultrasonic sampler is designed to give the bedload discharge by measuring the flow velocity and the sediment concentration through the sampler; the concentration is determined from the absorption of ultrasonic energy. The tiltmeter, the only nonelectric apparatus, is designed to give the total sediment discharge by measuring the ground tilt that results from the passage of sediment loads.

ACOUSTIC INSTRUMENTS

Acoustic apparatus have been used in sediment investigations for some time. As early as 1936 a microphone placed close to the water surface was used to listen to the sediment movement during the formation and passage of large-scale boils (Reitz, 1936), and in 1942 a hydrophonic detector was constructed at Grenoble, France (Braudeau, 1951).

The Beauvert Laboratory hydrophonic detector, which is a modification of the original Grenoble instrument, was adopted and somewhat altered by Braudeau (1951) and others at the Service des Études et Recherches Hydrauliques, d'Électricité de France. The Beauvert Laboratory detector consists of a triangular base plate of brass (75 cm on a side), which rests on the bed; a watertight case, which is supported 15 cm above the base by three acoustically insulated uprights; and a microphone, which is housed in the case and is actuated by a plate spring attached to the base. Braudeau's apparatus (fig. 19) is the same as the Beauvert Laboratory detector except that the

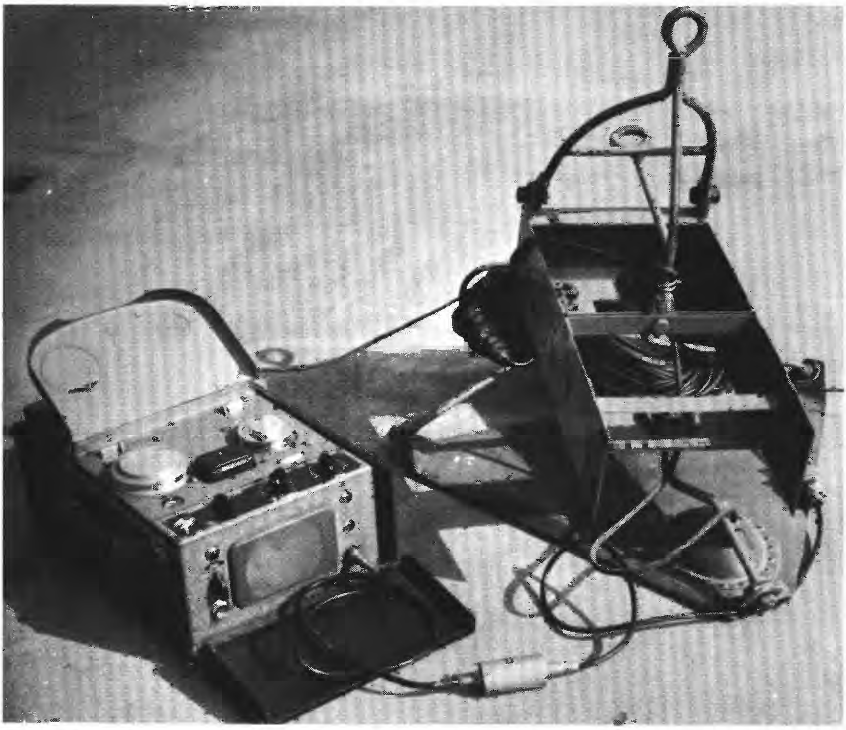

Figure 19.—Hydrophonic detector of Électricité de France (from "Détecteur Hydrophonique," Électricité de France, Direction des Études et Recherches, Département Essais, written communication, 1960).

microphone rests directly against the base plate and is housed in a small watertight, streamlined cupola. In both instruments, the sound of the interparticle collisions and of the particle impact on the base plate is picked up by the microphone, amplified, and transmitted to headphones or a magnetic tape recorder.

Braudeau (1951) states that during tests on the Isère River when the flow was regulated to give an increase and then a decrease in the bedload discharge—

The phenomena could be "heard" with an accuracy comparable to that of purely visual sensations. Each sound could be distinguished: at the outset, the murmuring of the water, the impacts and the sliding of individual grains of sand; then, the progressive arrival of pebbles of different sizes, their rolling or their repeated impacts on the plate; finally, as the discharge slowly decreased, the more and more frequent sliding of the pebbles and the very gradual return to the initial condition.

Juniet (1952) has commented that instruments such as the hydrophonic detector give good results in streams having coarse bed material. However, in streams having fine bed material, the sound level is weak, and the presence of a relatively large instrument may disturb the flow sufficiently to alter materially the local bedload transport. Juniet has developed a much smaller instrument for monitoring the bedload movement. The instrument, called L'Arénaphone, (figs. 20, 21) consists of a rod, which is about 20 cm long and is forkshaped at the lower end; a transducer of some piezoelectric material, to which the rod is attached; a cylindrical housing for the transducer, sealed at the lower end by a watertight membrance through which the rod passes and at the upper end by a cap through which an insulated cable passes; a tripod, which is fitted with stability discs; and a regulator, which is fixed at the top of the tripod and adjusts the vertical position of the cylinder and rod. During sediment movement, particles collide with each other and with the fork-shaped part of the rod, which is inserted a few centimeters into the bed. The vibrations engendered by the collisions are transmitted by the rod to the transducer, which is stressed and thereby produces a variable electric current that is selectively amplified to filter out the bass frequencies created by the interparticle collisions. The amplifier has outputs for headphone, oscilloscope, and magnetic tape recorder.

Ivicsics (1956) has presented an acoustic instrument that is somewhat different from the other acoustic instruments already described. This instrument, which was developed at Epitoipari Es Kozlekedesi Müszak Egyetem, measures the intensity of sound of only the interparticle collisions. Its unique feature is that it can be suspended several meters above the bed; thus, it does not influence the bedload movement. The instrument (fig. 22) consists of a streamlined torpedo-shaped body, which is made of 3.5-mm iron plate and weighted at the front and rear with lead ballast, and a 70-mm crystal microphone, which is housed in the body. The microphone (see fig. 22B) faces downward, and a 0.3-mm brass plate seals the microphone cavity at the bottom wall of the instrnument. Because the microphone is insulated on the sides and above by felt and cotton batting, only sound originating directly below the instrument is picked up. The sound, in turn, is amplified, and its intensity is registered on an am-

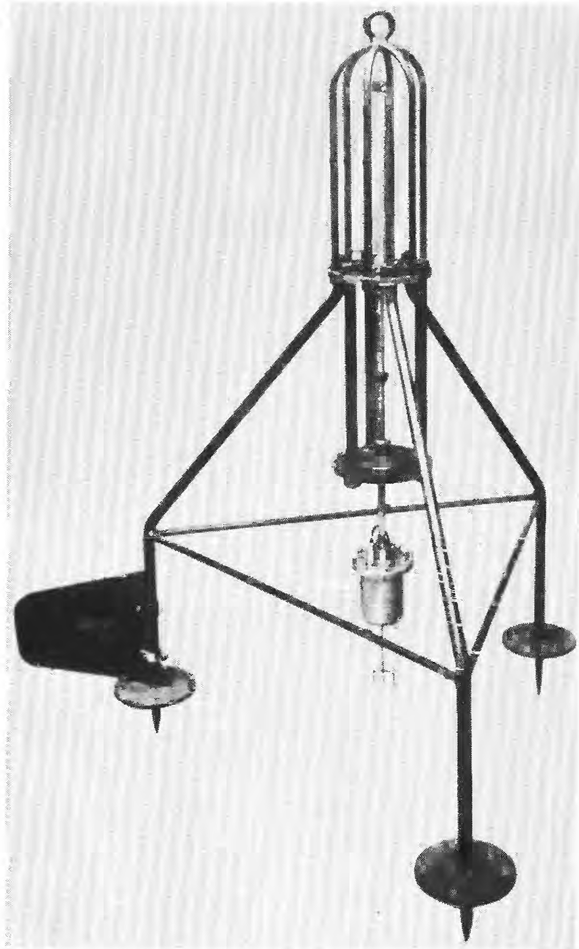

FIGURE 20.—L'Arénaphone (from Juniet, 1952): Operating position.

meter. The sound can also be transmitted to headphones. The intensity of sound does not change significantly when the instrument is raised or lowered within a 5-meter interval because the microphone is extremely sensitive.

The instrument is used to determine the relative sediment transport in cross sections and the relative variation of transport with time. Also, the instrument is used to determine the location and number of verticals to be used in bedload sampling with bedload samplers of the trap type. Field studies indicate that the relative difference in bedload discharge from one place to another as measured with samplers of the trap type sometimes differs greatly from the relative difference

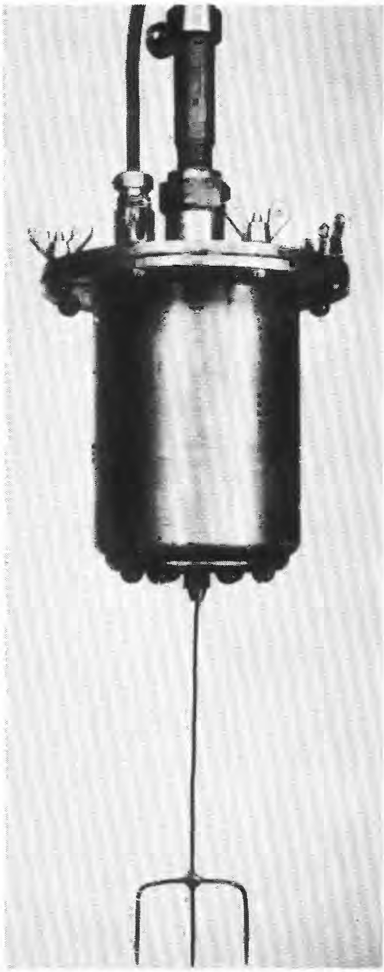

FIGURE 21.—L'Arénaphone (from Juniet, 1952) : Fork and transducer.

as measured with the instrument. (See fig. 23.) The discrepancies are assumed to be caused by inaccuracies in the samplers.

ULTRASONIC BEDLOAD SAMPLER

Smoltczyk (1955) has commented in detail on various existing methods for measuring the bedload discharge and has experimented with several different electronic methods for measuring sediment concentration. The experiments were made as a prelude to the development of a device for measuring the bedload discharge of streams that have bed material of fine sand. One method for determining concentration was based on the measurement of the electrical resistance

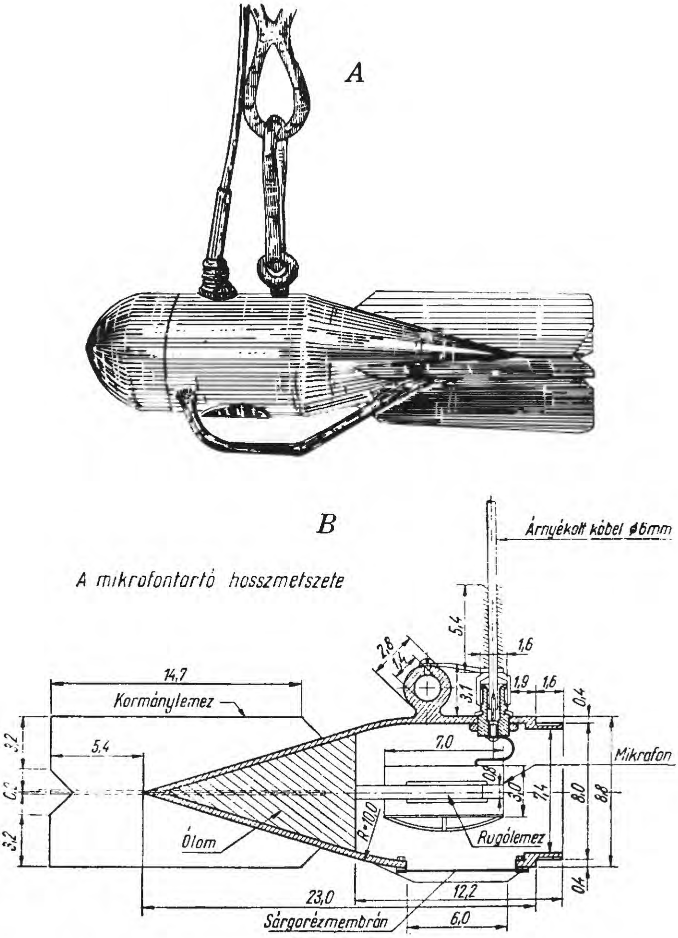

Figure 22.—Ivicsics' acoustic bedload recorder (from Ivicsics, 1956): *A*, Operating position; *B*, Plan view.

of water-sediment mixtures. However, this method was rejected because the resistance varied with the particle size and because impurities in the water caused a polarization effect that hindered the reproducibility of the results. Measurement of concentration by high frequency (ultrasonic) sound waves proved to be very satisfactory and was employed in the design of a bedload sampler. Smoltczyk intimates that some experiments were performed with a sampler, but he presents no results.

The basis for the ultrasonic method is that different amounts of transmitted acoustic energy are absorbed by transmitting mediums of different sediment concentrations. Thus, by measuring the degree of absorption in a medium of unknown concentration relative to that

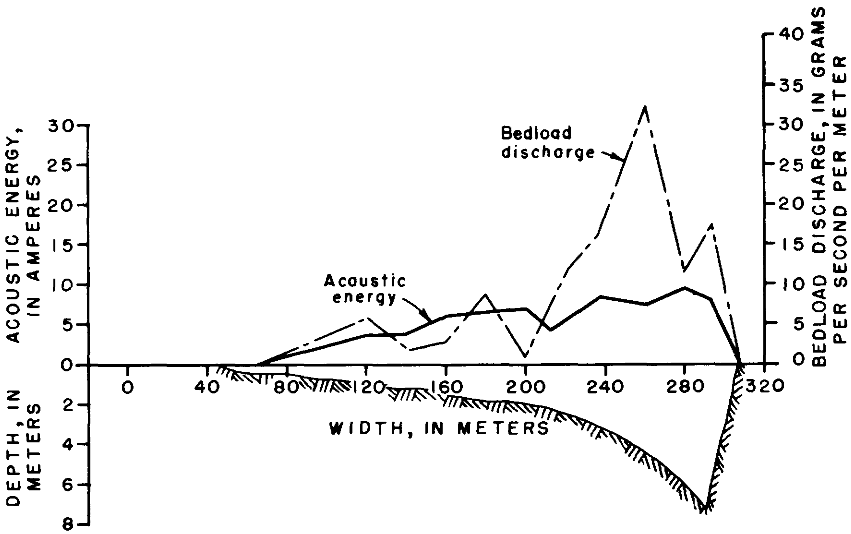

FIGURE 23.—Variation of acoustic energy and sampled bedload discharge, Rajka gaging section (from Ivicsics, 1956).

in a medium of known concentration, the unknown concentration can be determined.

Absorption phenomena are characterized by the function

$$y = y_0 e^{-\alpha x}$$

where

- y is the magnitude of a quantity after absorption.
- y_0 is the magnitude of the quantity at some initial condition.
- e is the natural logarithm base.
- α is the absorption coefficient.
- x is the independent variable (such as time, distance, concentration).

For the change in sound-wave amplitude with concentration,

$$A = A_0 e^{-\alpha C_p}$$

or

$$\ln A/A_0 = -\alpha C_p$$

where

- A is the amplitude.
- C_p is the concentration.

Smoltczyk, by measuring sediment of different sizes and concentrations, determined that the absorption coefficient was a constant for any given size but that it varied from size to size. From measurements, Smoltczyk also determined that the relation between particle size and absorption coefficient[1] was given by

$$\alpha = pd_m^2 + q$$

where

p and q are constants for the particular sediment and frequency.
d_m is the characteristic particle size of the size range.

Thus, for any particular kind and size of sediment

$$A = A_0 e^{-(pd_m^2+q)C_p}$$

or

$$E = E_0 e^{-2(pd_m^2+q)C_p}$$

where

E is the sound energy, which is proportional to the square of the amplitude.

Because

$$E_1 = E_0 e^{-2(pd_{m_1}^2+q)C_{p_1}}$$

and

$$E_2 = E_1 e^{-2(pd_{m_2}^2+q)C_{p_2}}, \text{ etc.}$$

for a mixture of k different particle-size ranges

$$E_k = E_0 e^{-2C_{p_t}(p\Sigma_1^k C d_m^2 + q)}$$

where

E_k is the energy received after the sound waves pass through a mixture that contains k different size ranges, each of which has a concentration $C_{p_1}, C_{p_2}, \ldots C_{p_k}$.
C_{p_t} is the total concentration and equals $C_{p_1} + C_{p_2} + \ldots + C_{p_k}$.
d_m is the characteristic particle size for each size range.
C is the fraction, for each size range, that the concentration of the range is of the total concentration ($C_{p_1} = C_1 C_{p_t}$).

Smoltczyk's sampler (fig. 24) is virtually an open-end rectangular tube whose interior walls and top are convex toward the inside. The convexity causes an increase in the flow velocity and provides side walls thick enough to accommodate, on opposite sides, a reflector and a quartz crystal transducer, which transmits and receives high frequency sound waves. In addition, one wall of the tube contains a control crystal that is near the floor of the instrument and that indicates when the floor is covered with an appreciable amount of sediment. Also, Smoltczyk describes, but does not show in the figure, a flow-

[1] Studies made as a part of the research project, "Methods used in measurements and analysis of sediment loads in streams," of the Federal Inter-Agency Committee on Water Resources (written communication) indicate that this equation is valid for only a limited range of particle sizes and frequencies.

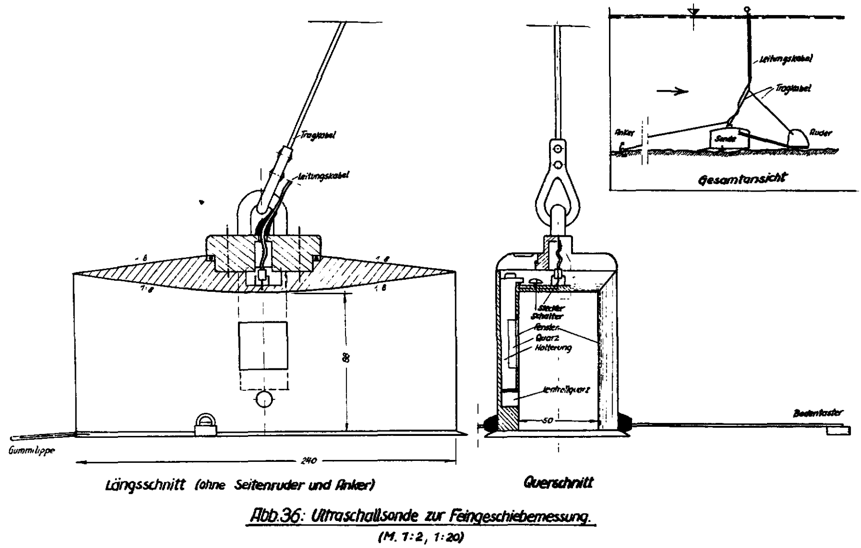

FIGURE 24.—Smoltczyk's ultrasonic bedload sampler (from Smoltczyk, 1955).

velocity measuring apparatus consisting of two transducers which are fixed at opposite ends of the tube in such a way that each receives the signals transmitted by the other. The basis of operation for this velocity apparatus is that sound waves traveling downstream will have a velocity of V_s+V_f, and those traveling upstream will have a velocity of V_s-V_f; thus, $V_f=V_s\ (t_u-t_d)/(t_d+t_u)$, where V_s and V_f are the velocities of sound and flow, respectively, and t_u and t_d are the times required for a sound wave to pass between the transducers in an upstream and downstream direction, respectively.

The sampler measures continuously the parameters required for the determination of the flow velocity and the amplitudes of the reflected sound waves. By installing modulating and integrating elements into the electronic system, the logarithms of the amplitudes are electronically determined and converted to concentrations, the flow velocity is determined, and these data are combined to give a continuous record of accumulated weight with time.

The method, of course, cannot be applied without a knowledge of the size distribution of the load. Smoltczyk states that the sensitivity of the sonic measurements is sufficient for predicting accurate loads only at concentrations greater than about 1 percent and that, for streambeds composed of fine sand, such concentrations reflect a condition of the movement of all particle sizes in the bed. As a result, Smoltczyk assumes that the particle-size distribution of the bed material is equal to the size distribution of the bedload and that the size distribution of the bed material, therefore, can be used in determining the concentration.

In addition to the assumption that the size distribution of the load is the same as that of the bed material, several other important assumptions seem to be inherent in the method: All particles are transported at the velocity of flow; the load passing through the sampler can be determined from the product of the mean concentration and the mean velocity (that no velocity and concentration gradients exist); the bedload is transported for some distance above the bed; the suspended sediment that enters the sampler does not change the absorption or the absorption coefficient; and the instrument has hydraulic and sampling efficiencies very close to 100 percent.

TILTMETER

Taniguchi (1958) has developed a method for computing the total sediment load by using a tiltmeter, which measures the variations in ground tilt near the channel that result from the passage of different weights of water and sediment through the channel. The tiltmeter consists of a Zöllner pendulum suspension and asociated recording equipment. The Zöllner pendulum suspension (fig. 25) is a bar, weighted at one end, that is supported by a 30-micron-diameter superinvar thread attached near the center of the bar and held in a horizontal position by another similar thread attached at the end of the bar opposite the weight. The upper or supporting thread is attached to an inverted J-shaped vertical support, and the lower or counterbalancing thread is attached to the base into which the vertical support is fixed. If the vertical support (and base) is tilted parallel to a plane that is perpendicular to the horizontal bar, the bar rotates in approximately a horizontal plane. Very small tilting angles produce relatively large turning angles. In the tiltmeter, a mirror, which is attached to the horizontal bar, reflects light from an electric bulb in a small collimated beam so that the beam strikes photographic paper and produces a continuous record of turning angle with time. An electric water-stage recorder and thermograph are also arranged to record on the same photographic paper.

According to Taniguchi, if the titlting angle, which can be computed from the turning angle, is plotted against the stage, a curve similar to *OB* in figure 26 will result from a sediment-laden flow. Also, Taniguchi states that a straight line (see *OA* in fig. 26) must result from a sediment-free flow. Thus, the sediment load at any stage is the weight that will produce a tilting angle equal to the difference between the curve and the straight line at that stage.

Taniguchi has reported on two different field measurements with the tiltmeter. In both these measurements, two tiltmeters were used

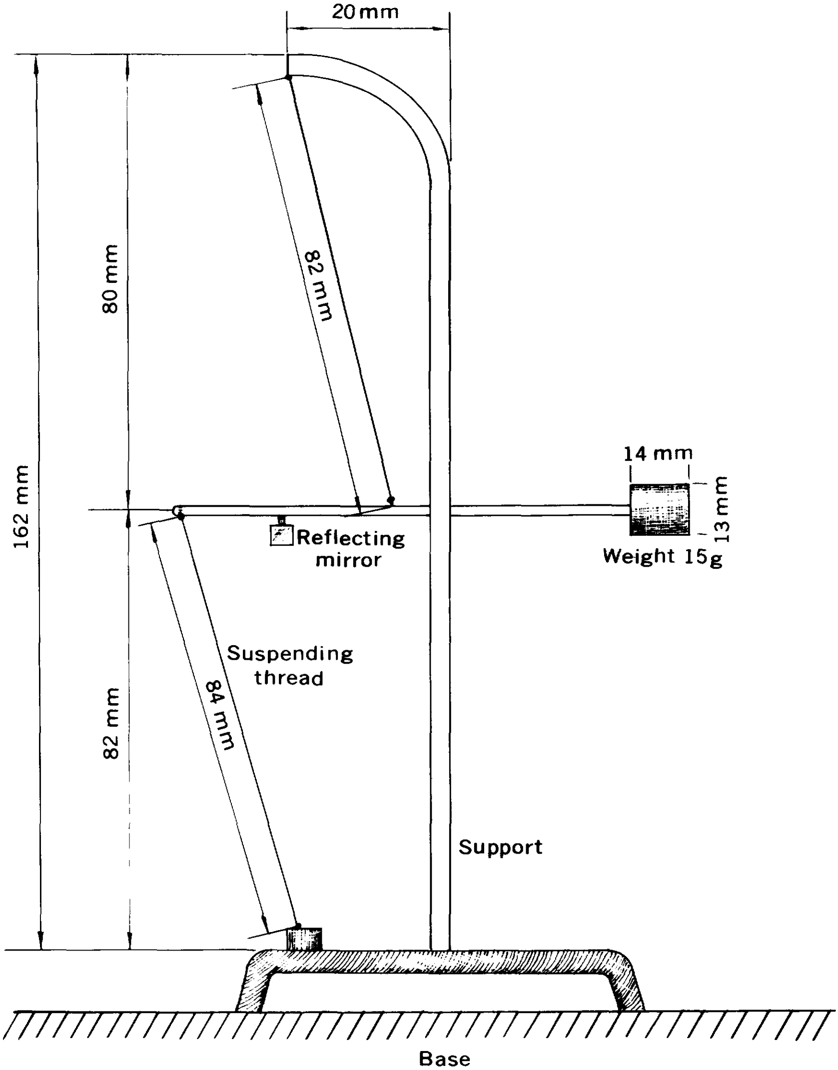

FIGURE 25.—Diagram of Zöllner pendulum suspension (from Taniguchi, 1958). Drawing not to scale.

and placed so that they were perpendicular to each other. In the first measurement, the tilting angles registered by the two meters were greater after the subsidence of a high flow than they were prior to the flow. The difference in tilting angle was attributed principally to sediment deposition in the channel and somewhat to a decrease in ground resistance as a result of bank saturation. Subsequent computations showed that the depth of deposit required to cause the difference in tilt was about the same as the measured depth of deposit in the channel. In the second measurement, a power failure and equip-

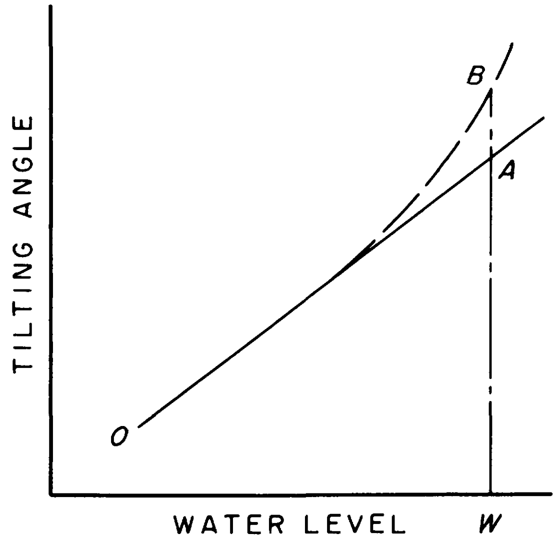

Figure 26.—Relation between water level and tilting angle (from Taniguchi, 1958).

ment damage limited the data; however, the information plotted in figure 27 was obtained. The tilt angle and stage curves in figure 27

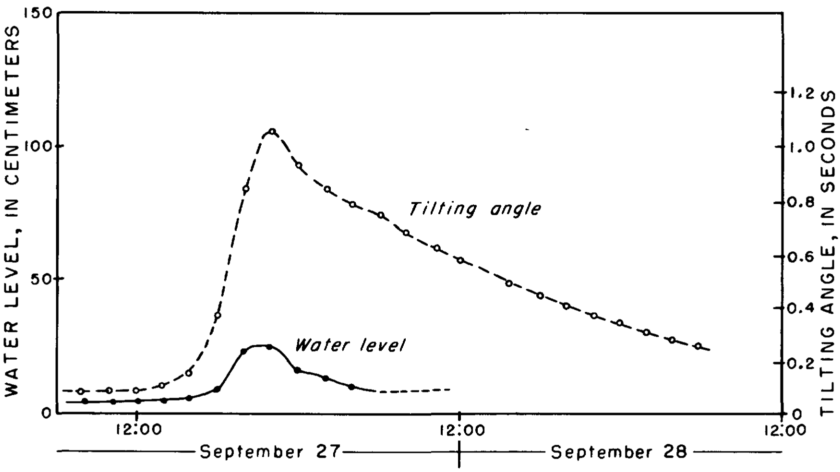

FIGURE 27.—Tiltmeter chart, Kokidaira in Tone River System, September 27–28 (from Taniguchi, 1958).

are combined in figure 28 to show the tilt-stage relation. The dashed straight line is the presumed relation between tilting angle and sediment-free flow stage. The conclusion from this second measurement

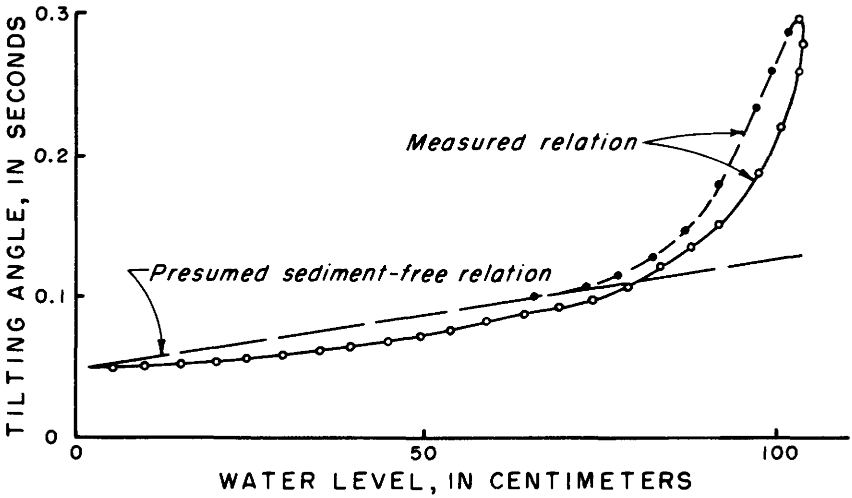

FIGURE 28.—Relation between water level and tilting angle, Kokidaira in Tone River System, September 27–28 (from Taniguchi, 1958).

was that the variation in tilting angle was influenced by something besides the flow and the sediment load.

One of several vague points about the tiltmeter method is the use of a linear relation between tilting angle and stage for sediment-free flow. Taniguchi has not discussed this point except to say that the relation must be linear. Because the weight distributions in alluvial channels are variable with time, because the bank stability probably varies with the degree of saturation, and because channels are usually not rectangular, the linear relation between tilting angle and stage seems questionable. Another vague point is the determination of the sediment discharge from the weight at a given stage. Regardless of how the discharge is determined, the accuracy would seem to depend on the degree to which the velocity of the sediment particles approaches the velocity of the flow.

Probably, the tiltmeter method is applicable only to streams that have relatively large variations in sediment discharges and that flow through unconsolidated materials.

SOME NEW POSSIBLE APPARATUS AND METHODS FOR MEASURING BEDLOAD

None of the recently developed apparatus seem to be completely adequate for measuring bedload discharge or total sediment discharge accurately. Therefore, some new apparatus and methods have been investigated insofar as possible. These apparatus and methods include a portable pit sampler; photography; tracking of dune movement, particularly by ultrasonic sounding; pressure transducers; and ultrasonic sounding of large particles.

PORTABLE PIT SAMPLER

The most accurate of all the retaining-type bedload samplers is the slot or pit sampler. Some preliminary investigations were made on possible designs for a small portable pit sampler. The most practical design seems to be for one that is modeled after Einstein's Mountain Creek sampler, which was semiportable and consisted mainly of a hopper and a pumping unit. The sampler, however, would be considerably smaller than the Mountain Creek sampler and would have the additional features of portability and automatic placement by dredging. Figure 29 shows the contemplated design. The essential features are as follows: A hopper that can slide vertically along the suction pipe and can be dropped and locked in position after the suction pipe has been inserted into the bed a distance sufficient to offer horizontal support against the drag force on the hopper; a small motor-pump unit; an automatic valve that closes the lower end of the suction pipe after dredging is completed; an automatic valve that opens the sides of the suction pipe at the bottom of the hopper so that the accumulated bedload can be continuously removed by pumping; and a fixed rim at the top of the hopper to insure that the hopper rests flush with the bed surface. The practicability and efficiency of such a sampler, of course, are subject to question; and the sampler could be used only in streams that have predominantly sand beds and low velocities, unless stay lines are used. Figures 30 and 31 show that if slurry (bed material and water) concentrations of about 100,000 parts per million were pumped during placement, a hopper with a volume of 2.0 cubic feet could be placed into the bed in about 5 minutes with a 2-inch pump that discharges 50 gallons per minute and a motor that delivers about 3 horsepower (30-foot head).

PHOTOGRAPHY

Motion pictures of bedload movement in several different streams and in one canal have been taken to determine if it is possible to estimate the bedload discharge by counting the number and measuring the nominal diameter of particles as they move downstream into or out of the field of view. Unfortunately, neither an industrial high-speed camera nor a projector that could be used to show individual frames at a manually operated speed was available. However, exploratory films, which were taken through a glass-bottom box that was fixed to a tripod (see fig. 32), were viewed at one-sixth normal motion (64 frames per sec exposure speed and 10.7 frames per sec projection

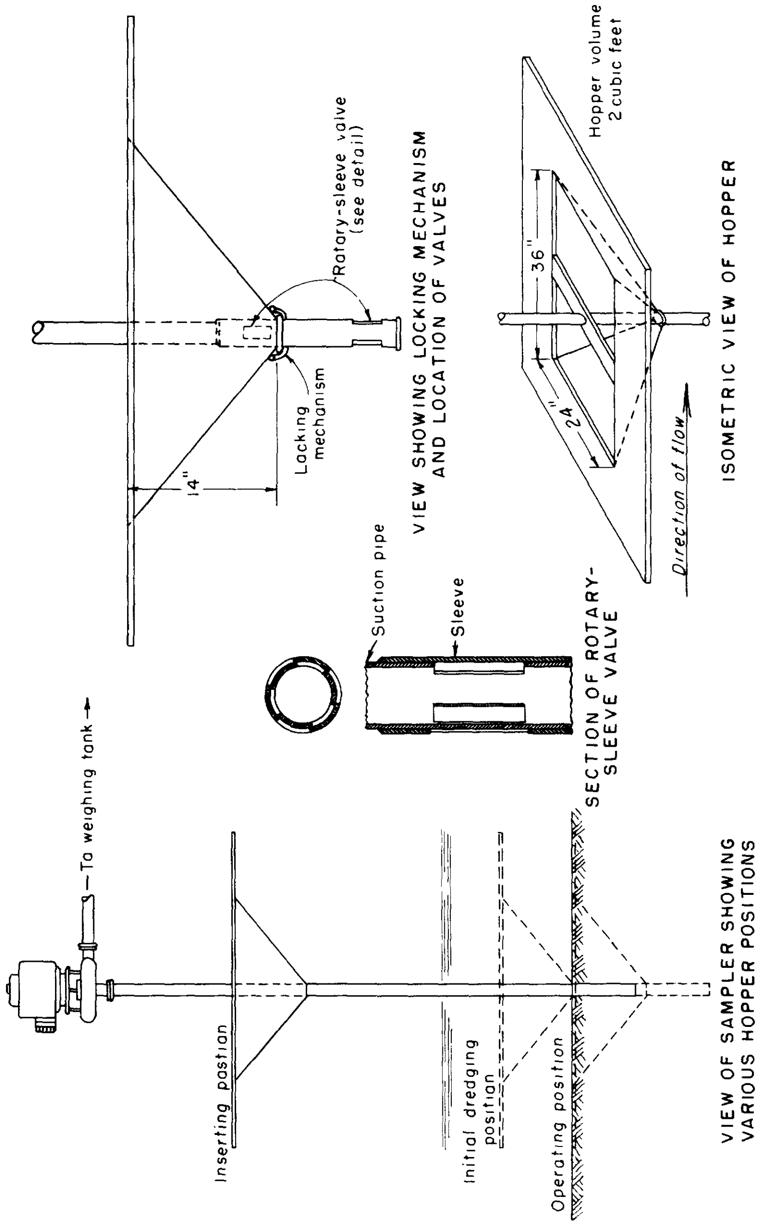

Figure 29.—Diagrammatic sketch of portable pit-type bedload sampler.

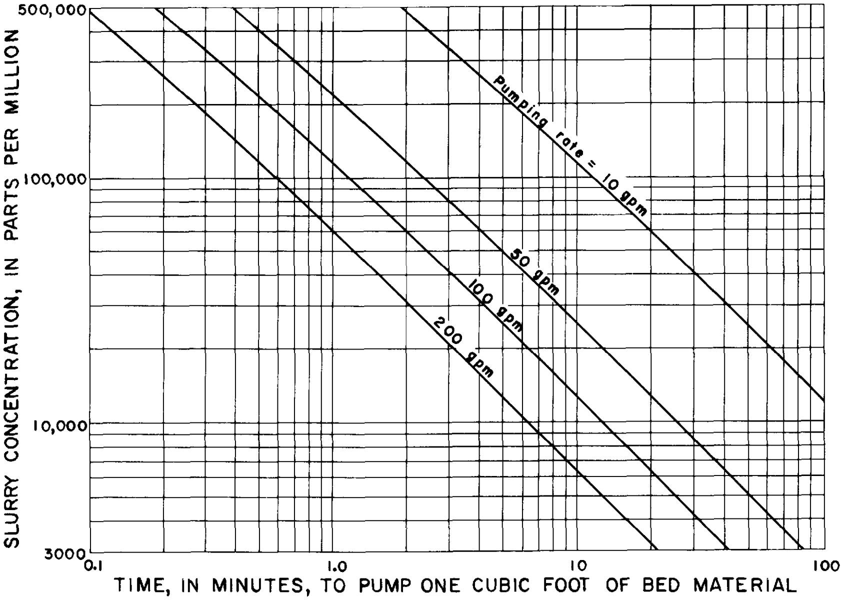

FIGURE 30.—Time required to pump material from the bed at different slurry concentrations and pumping rates. Based on a specific weight for bed material of 103 pounds per cubic foot.

speed). At this speed, particles larger than about pea size can be readily counted if the field of view is divided into lateral segments and if the film is projected repeatedly; however, particle diameters can be measured only if the motion is further reduced.

In addition to motion reduction, one of the major problems connected with photography is visibility. In order to prevent any disturbance to the bed and bedload movement, the photographic equipment must be placed about 2 feet from the bed. However, limited field experience indicates that at a distance of 2 feet, the visibility is poor, with concentrations as low as 600 ppm (parts per million) of suspended sand; it is probably even poorer with silt and clay suspensions. As a result, the use of photography for estimating bedload discharge is limited to streams having low suspended-sediment concentrations and transporting particles about pea size or larger. Also, because of the enormous amount of film that would be required if bedload movement were photographed for a reasonably long time, the method seems generally impractical.

TRACKING OF DUNE MOVEMENT, PARTICULARLY BY ULTRASONIC SOUNDING

In 1894, Deacon (Goncharov, 1929) observed in the laboratory that the discharge of sediment along the streambed could be determined

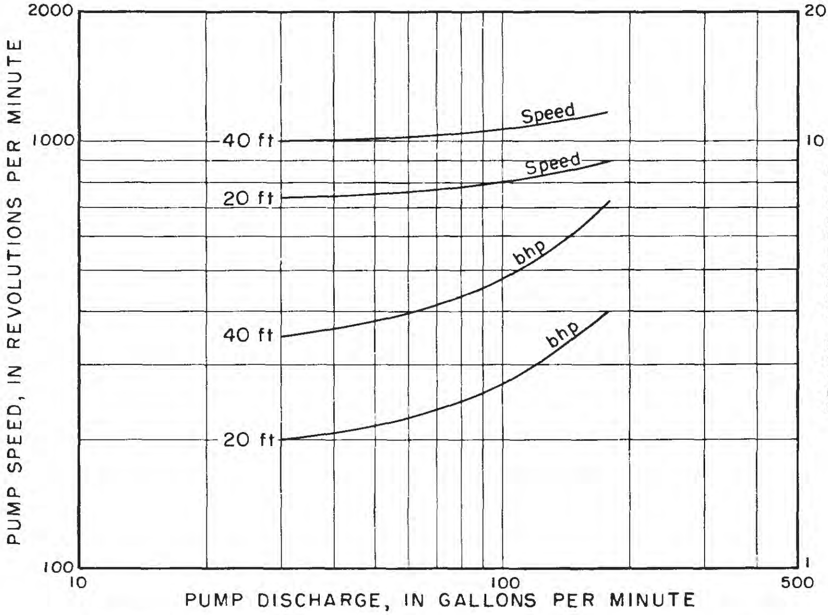

FIGURE 31.—Relation of pump speed and brake horsepower to the discharge of a 2-inch pump for 20- and 40-foot heads.

from the volume of the sand waves and their crest velocities if the stream velocity was less than some critical value. Benedict, Albertson, and Matejka (1955) applied this idea in the field and computed the bedload discharge of a sand-bed stream from the average dune height and the average dune velocity. In the computation, the dune height and velocity were determined from maps of the streambed that had been defined by 1-hour interval soundings over a short reach of the stream. However, the soundings were difficult to obtain and only fairly accurate because they had to be made manually. Richardson, Simons, and Posakony (1961) developed the following equation for the bedload discharge from a differential equation by assuming a constant dune shape:

$$q_b=(1-\lambda)\frac{Vh}{2}+C$$

where—

q_b is the volume of bedload discharge per unit of width per unit of time.

λ is the porosity of the bed material.

V is the average velocity of dune crests determined by timing the movement of individual crests for a known distance.

h is the average of individual dune heights determined by measuring the difference in elevation between the crests of individual dunes and the adjacent downstream troughs.

C is a constant of integration that, according to the boundary conditions, is equal to zero.

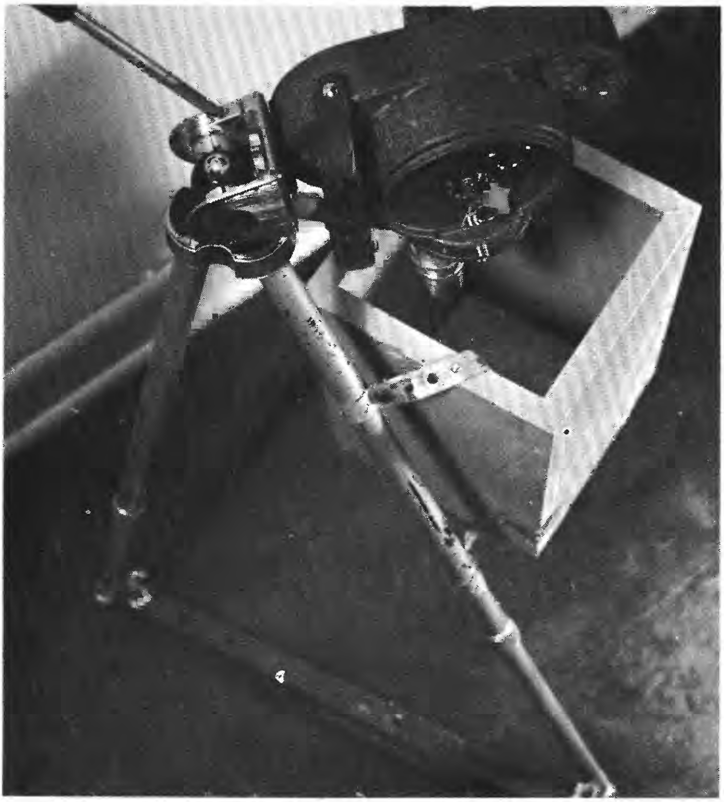

FIGURE 32.—Motion-picture apparatus.

Computation of the bedload discharge from dune movement has been deterred in the past by an inability to obtain accurate data. Recently, however, studies (op. cit.) made as a part of a research project by the U.S. Geological Survey on channel roughness at Colorado State University, Fort Collins, Colo., indicate that very accurate and meaningful records of dune shape and movement can be obtained with ultrasonic sounders (Richardson, Simons, and Posakony, 1961).

Ultrasonic sounders operate by means of a transducer, placed under the water surface, which transmits short bursts of ultrasonic energy at a constant frequency. The energy travels through the water and is reflected back to the transducer by the streambed. The electronic system measures the time interval, which is proportional to the depth, between the transmission and receipt of the energy and converts the time into a voltage that is graphed by a strip recorder as depth.

In the movement of bedload, particles are alternately eroded and deposited. Because the erosion and deposition have unequal rates over the bed area, bed configurations develop and continuously change their absolute position. Thus, the erosion and deposition determine the character and magnitude of the bedload movement and also the specific form and rate of movement of the bed configuration. In the tranquil-flow regime, erosion predominates on the upstream side of the bed forms, and deposition predominates on the downstream side; consequently, the bed forms move in the direction of flow.

In natural streams, generally, the bed profile along any longitudinal line lacks symmetry and shows no consistent dune shape. Also, the dunes differ radically in height and probably differ in velocity. Therefore, a relation between the bedload discharge and dune movement would seem to be the most realistic if dune shape and average heights and velocities are not critical parameters. Some simplified examples of dune movement will serve to explain the development of a relation that uses as the critical parameter the volume of material presumed to pass through an incremental width in a total time.

For the first example, consider the idealized longitudinal profile of a thin increment of the width, dw, shown in figure 33. During the time period t_2-t_1, volume $(abcd)\mathrm{d}w$ progresses the distance ab and, in doing so, moves volume $(abc)\mathrm{d}w$ past line X–X'. The movement is accomplished through the erosion of particles from $(abc)\mathrm{d}w$ and the deposition of the particles on the downstream side of $(adc)\mathrm{d}w$. During the time t_3-t_2, particles are similarly eroded from $(efg)\mathrm{d}w$ and deposited on the downstream side of $(ebf)\mathrm{d}w$ so that the volume $(ebf)\mathrm{d}w$ passes line X–X'. Thus, during the total time required to move one dune length, $t_3-t_1=t$, volumes $(abc)\mathrm{d}w$ and $(ebf)\mathrm{d}w$ pass line X–X'. Inasmuch as the bedload moved only in this manner, the bedload discharge in the incremental width, dw, that passed line X–X', or any other line, can be expressed by

$$b=\frac{(abcd)}{t}\mathrm{d}w$$

or

$$b=\frac{v(abcd)}{p}\mathrm{d}w$$
$$=vH\ \mathrm{d}w$$

where—

- b is the volume rate of bedload discharge in the incremental width.
- v is the dune velocity $(v=p/t)$.
- p is the dune length bd.
- H is the mean height of the dune and is computed so that $Hp=(abcd)$.

However, bedload does not necessarily move according to the above concept. Some particles probably are eroded from one dune and are not deposited until they reach some other downstream dune.

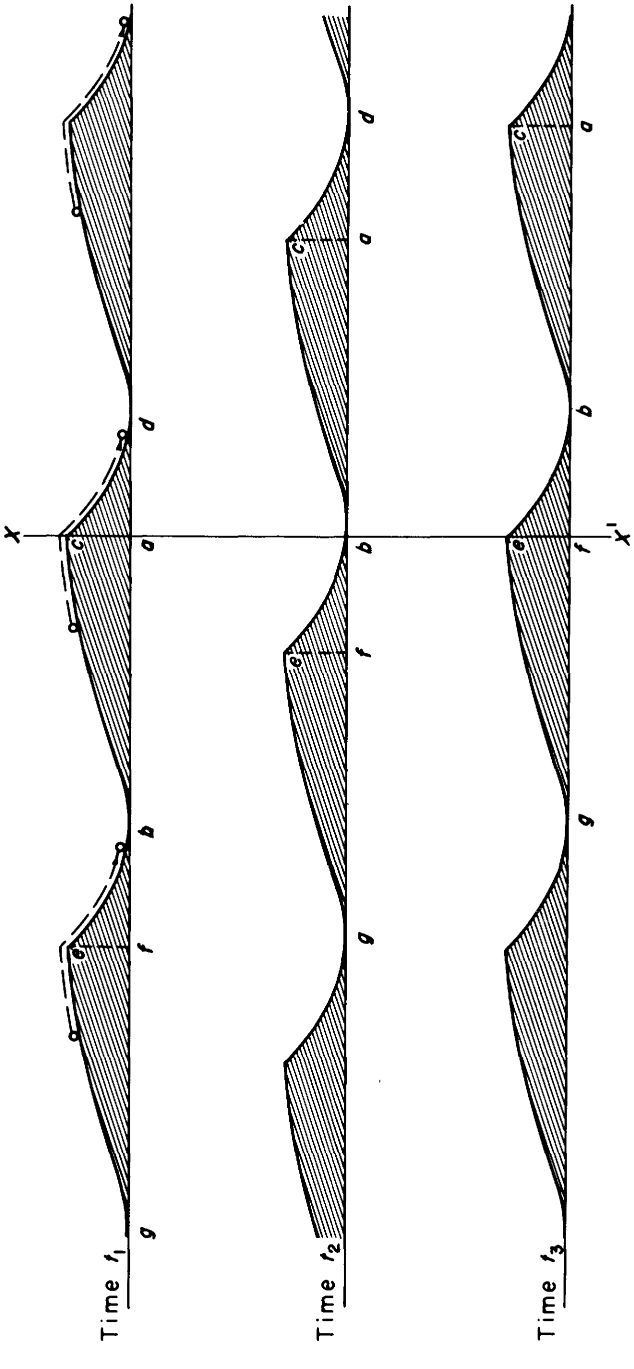

FIGURE 33.—Idealized diagram of dune movement if particles are transported only from the upstream to the downstream side of a dune.

Consider the simplified example of this phenomenon as shown in figure 34. In this figure, the assumption is made that for every three particles eroded from a dune, only one is deposted on the downstream side of the same dune and the other two pass to the next dune. (This assumption probably does not reflect a natural condition, but it does facilitate the explanation.) During the time t_2-t_1, the dune progresses the distance ab and, in doing so, moves the volume $(abc)dw$ past line X–X'. However, for every particle in $(abc)dw$, two others also pass line X–X'. Thus, the total volume passing line X–X' in time t_2-t_1 is $(abc)dw+2(abc)dw=3(abc)dw$. During the time t_3-t_2, volume $(ebf)dw$ passes line X–X'; but, again, for every particle in $(ebf)dw$, two others also pass line X–X' so that the total volume is $(ebf)dw+2(ebf)dw=3(ebf)dw$. Hence, in time t, volumes $3(abc)dw$ and $3(ebf)dw$ pass line X–X'. Because ebf equals adc, the volume rate of bedload discharge is expressed by

$$b=3\frac{(abcd)}{t}dw$$

or

$$b=3vH\ dw$$

In nature, the ratio of the number of particles eroded from the upstream side of a dune to those deposited on the downstream side is probably not extremely variable. However, the following equation should be applicable:

$$b=K\,\frac{(abcd)}{t}\,dw$$

$$=KvH\,dw$$

where

K is a variable coefficient that probably is very close to unity, except possibly at times when the bedload discharge is high or when the bed relief is low.

For the entire stream width

$$B=\int_0^w K\,\frac{(abcd)}{t}\,dw \tag{1}$$

or

$$B=\int_0^w KvH\,dw \tag{2}$$

However, because the variations in K and $(abcd)/t$ (or vH) between elemental widths are indeterminant, equations 1 and 2 must be approximated. These equations probably can best be approximated by using a K that is an average for all dunes and all parts of dunes within some width interval and by summing into one total area, A, all the $abcd$-like areas that pass a representative point within the

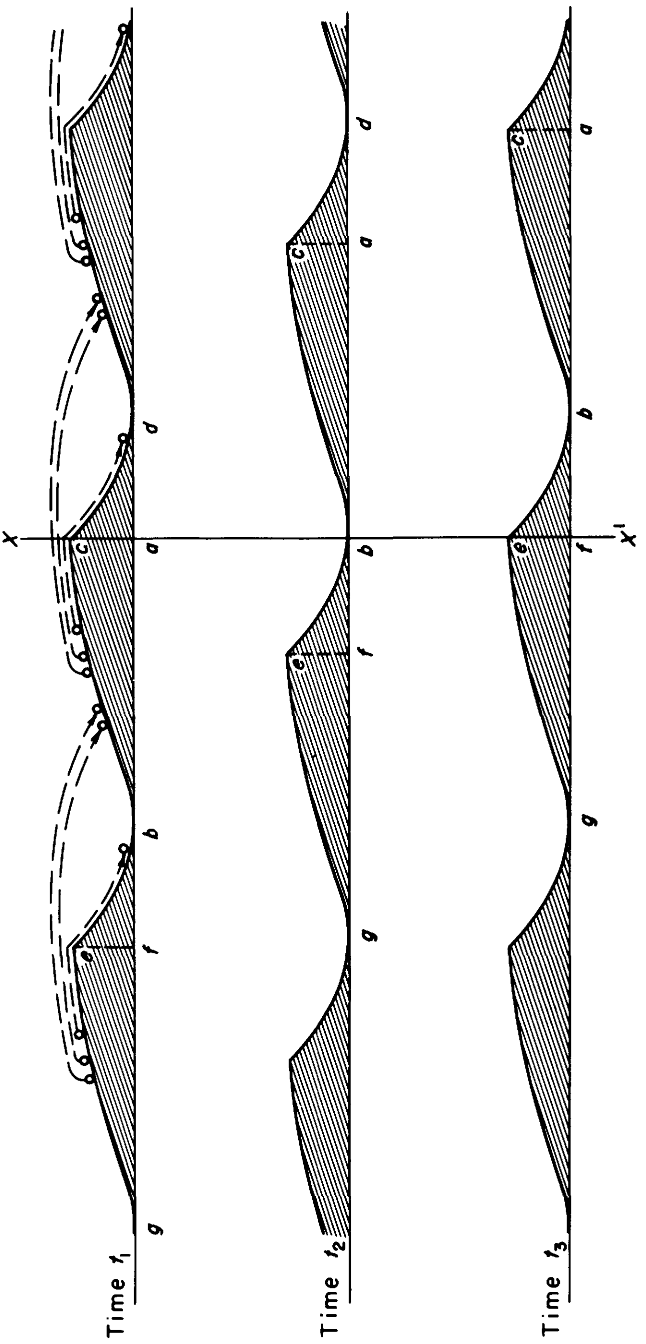

FIGURE 34.—Idealized diagram of dune movement if only one of every three particles eroded from a dune is deposited on the downstream side of the same dune and the other two pass on to the next dune.

width interval in a reasonably long time, T. For these approximations

$$B=\sum B'$$

where

$$B'=\overline{K}\frac{A}{T}\Delta w \tag{3}$$

or

$$B'=\overline{K}\overline{v}\overline{H}\Delta w \tag{4}$$

in which

Δw is the width interval.
$\overline{K}$ is the average K for all dunes and all parts of dunes within Δw.
$\overline{v}$ is the mean velocity of the part of the dunes that passes the representative point ($\overline{v}=\Sigma p/T=\overline{p}N/T$).
$\overline{H}$ is the mean height of the part of the dunes that passes the representative point ($\overline{H}=A/\Sigma p=A/\overline{p}N$).
$\overline{p}$ is the mean dune length.
N is the number of dunes that passes the point in time, T.

If the bedload discharge is expressed as a weight rate rather than a volume rate, the foregoing equations become:

$$Q_B=\sum(1-\lambda)\gamma_s\overline{K}\frac{A}{T}\Delta w \tag{5}$$

or

$$Q_B=\sum(1-\lambda)\gamma_s\overline{K}\overline{v}\overline{H}\Delta w \tag{6}$$

where

Q_B is the weight rate of bedload discharge for the entire width of the stream.
γ_s is the specific weight of solid sediment without voids.

Equations 5 and 6, which apply only if the bed is formed of ripples and dunes, can be solved if data within each width interval are available on the shape of a representative longitudinal profile and on the change in bed elevation with time at a representative point. The first kind of data is required so that a relation can be established between the height of the dunes along the line and the associated vertical areas that are subject to movement (the *abcd*-like areas). The second kind of data is required so that the total time, T, for a number of dunes to move past the point can be determined and so that the height of the dunes that actually move past a point can be measured and converted to vertical areas with the height-area relation.

Three different computations of bedload discharge have been made from field data by using equation 5. In these computations, the relation between the dune height and vertical dune area was established by defining the vertical area as the area that would move if the entire profile were to progress downstream without changing its shape and by defining the height of the dune as the maximum height associated with the area. Thus, the vertical area for any single dune was taken as the area bounded by the bed surface and a line, called the dune base, that was parallel to the water surface (assuming uniform flow) and that passed through the lowest point on the upstream face of the dune. Correspondingly, the dune height was taken as the distance, perpendicular to the dune base, between the highest point on the surface of the dune and the dune base. (Bed elevations were measured relative to the water surface so that the dune baselines are drawn in subsequent figures as horizontal.) If the total configuration of a large dune appeared to be several dunes, one on top of the other, only the uppermost apparent dune was considered as a separate dune and all lower parts were considered to be one lower dune. The vertical areas that were presumed to have actually moved were determined by converting the dune heights, which were measured on the graphs of change in elevation with time, to areas by using the height-area relation. Separate dunes were distinguished on the graphs of elevation change with time in the same manner as they were on the profiles, and their heights were determined by measuring the distance that the bed elevation dropped with the passage of the dune. Whenever the drop in bed elevation was irregular so that some parts of the graph were horizontal, the configuration was considered to be a dune on top of a dune, the uppermost drop was considered to be the height of the uppermost dune, and the total of all lower drops was considered to be the height of the lower dune. The total time that was used in each computation started when the first completely defined dune began to pass the sounding point and ended when the last completely defined dune had just passed the point. However, in some graphs this rule was waived and the time was started with the first sounding even though part of the downstream side of the dune did not appear on the time graph; the rule was waived in order to extend the total time period, but only if the missing time appeared to be insignificant. The value of $\overline{K}$ was necessarily assumed to be equal to 1.0 for all computations.

The first computation was made for a part of the width of the Little Blue River near Fairbury, Nebr. Data for the computation were collected by sounding manually with wading rods in a grid system 25 feet long and 12 feet wide. The sounder always stood at least 1.5 feet from the point of measurement so that the bed was not disturbed any more than necessary. Sufficient soundings were made to define the bed contours (see fig. 35) and the change in bed elevation with time at five points on each of five different longitudinal lines.

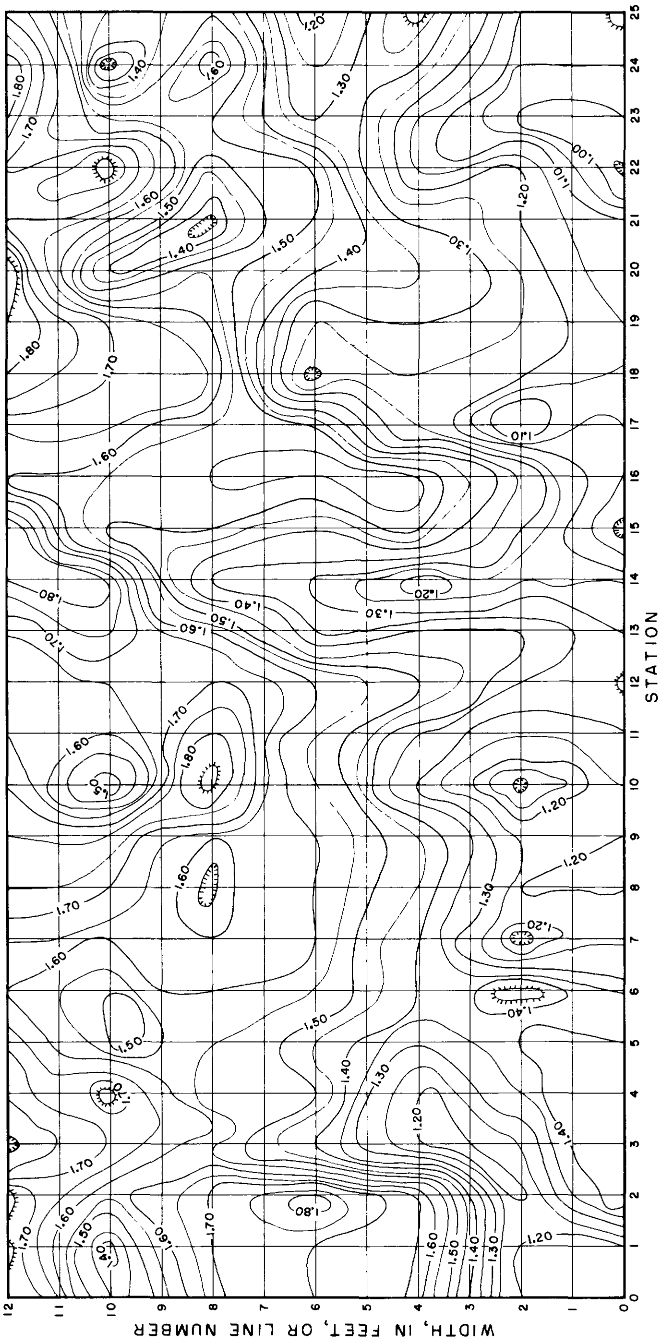

FIGURE 35.—Bed-contour plat, Little Blue River near Fairbury, Nebr., May 28, 1958. Contour interval is 0.05 foot; datum is 3 feet below water surface; and direction of flow is to the right.

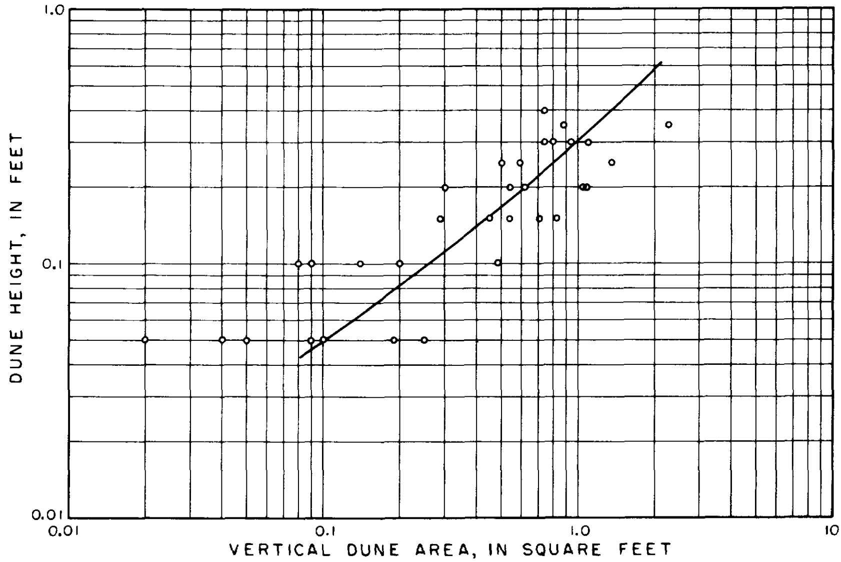

FIGURE 36.—Relation between the dune height and the vertical dune area, Little Blue River near Fairbury, Nebr., May 28, 1958.

The height-area relation (see fig. 36) was defined by means of dune heights and areas that were computed from six profile lines (see fig. 37) that had been determined from the contour map. Dune heights were determined from each of the 25 graphs of elevation change with time (see fig. 38) and converted into areas by using the height-area relation. The areas were summed, multiplied by the width interval and $\overline{K}$, and divided by the total time. The resulting B' values from each station on a common line were then averaged. The averages were summed to give the total volume discharge, which was converted to a weight discharge in tons per day with the factor 74.16 ton minutes per cubic foot day (based on $\gamma_s=166$ lbs per cu ft and $\lambda=0.38$). The computation is shown in table 3 together with a comparable bedload discharge computed with the Meyer-Peter and Müller equation (1948).

The second and third computations were made for the Middle Loup River at Dunning, Nebr., on August 7 and 8, 1958, at a section about 300 feet upstream from the turbulence flume (Benedict, Albertson, and Matejka, 1955). Manual soundings were made to define the bed profiles along five longitudinal lines which were 50 feet long and spaced approximately according to water discharge across the entire width of the channel. Soundings were also made at a single point on each line periodically for about 3 hours. Graphs of some of the data from these measurements are given in figures 39 to 44. The

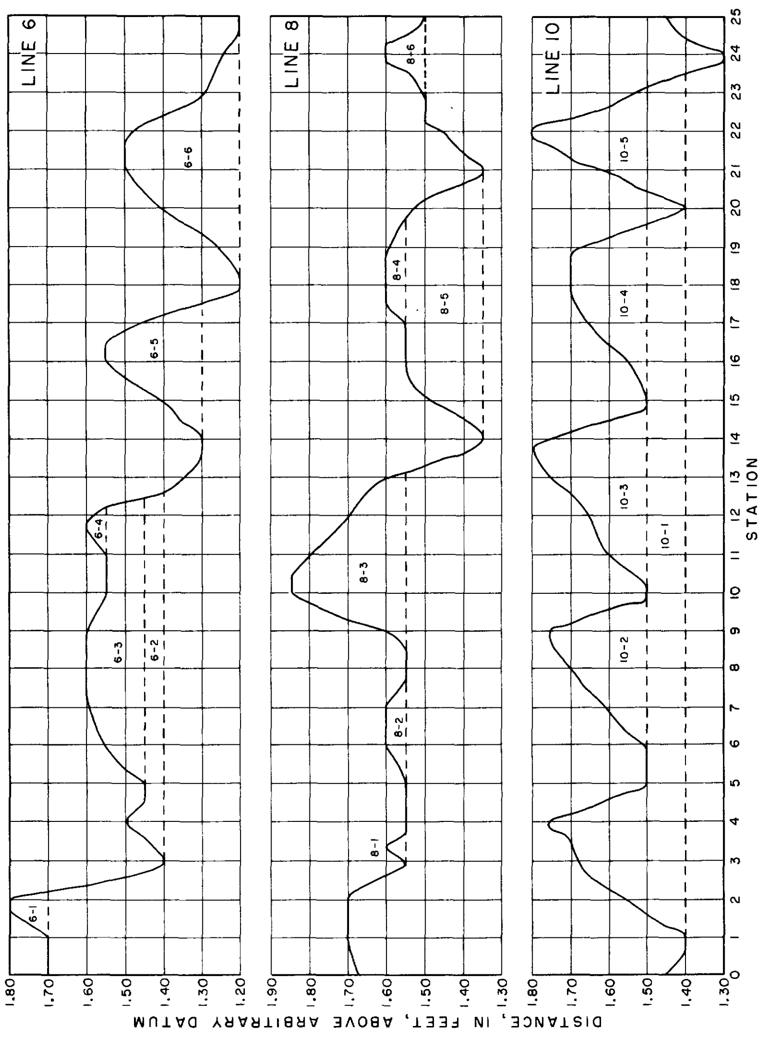

FIGURE 37.—Longitudinal profiles, Little Blue River near Fairbury, Nebr., May 28, 1958. Dune numbers are indicated; direction of flow is to the right.

TABLE 3.—*Computation of bedload discharge by the dune-tracking method, Little Blue River near Fairbury, Nebr., May 28, 1958*

[Height and measured vertical area used to define height-area relation]

Dune No.	Height (ft)	Measured vertical area (sq ft)	Dune No.	Height (ft)	Measured vertical area (sq ft)	Dune No.	Height (ft)	Measured vertical area (sq ft)
0–1	0.20	1.05	4–3	0.35	0.88	8–5	0.20	1.09
0–2	.15	.45	4–4	.10	.20	8–6	.10	.09
0–3	.05	.25	6–1	.10	.08	10–1	.35	2.27
2–1	.20	.54	6–2	.10	.48	10–2	.25	.59
2–2	.05	.02	6–3	.15	.83	10–3	.30	.79
2–3	.05	.10	6–4	.05	.04	10–4	.20	.62
2–4	.05	.05	6–5	.25	.50	10–5	.40	.74
2–5	.30	1.10	6–6	.30	.93	12–1	.10	.14
2–6	.05	.10	8–1	.05	.02	12–2	.15	.71
2–7	.15	.54	8–2	.05	.09	12–3	.15	.29
4–1	.25	1.35	8–3	.30	.74	12–4	.10	.19
4–2	.20	.30	8–4	.05	.10			

[Point-time data from graphs of the change in bed elevation with time. Vertical area from height-area relation]

Station No.	Line 0							Line 2							Line 6						
	Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)	Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)	Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)
	Dune No.	Height (ft)	Time (min)					Dune No.	Height (ft)	Time (min)					Dune No.	Height (ft)	Time (min)				
1	0– 1–1	0.10		0.26				2– 1–1	0.05		0.10				6– 1–1	0.10		0.26			
	2	.10		.26				2	.20		.62				2	.20		.62			
	3	.05		.10				3	.10		.26										
Total			114	0.62	1.0	1.0	0.00544			143	0.98	3.0	1.0	0.0206			91	0.88	4.0	1.0	0.0387
7	7–1	0.05		0.10				7–1	0.10		0.26				7–1	0.10		0.26			
	2	.05		.10				2	.05		.10										
	3	.05		.10				3	.05		.10										
								4	.10		.26										
Total			100	0.30	1.0	1.0	0.00300			153	0.72	3.0	1.0	0.0141			50	0.26	4.0	1.0	0.0200

13	13-1	0.10		0.26				13-1	0.05		0.10				13-1	0.25		0.80			
	2	.05		.10				2	.10		.26				2	.05		.10			
	3	.05		.10											3	.05		.10			
	4	.10		.26											4	.10		.26			
	5	.10		.26																	
Total			155	0.98	1.0	1.0	0.00632			90	0.36	3.0	1.0	0.0120			141	1.26	4.0	1.0	0.0358
19	19-1	0.05		0.10				19-1	0.10		0.26				19-1	0.05		0.10			
	2	.05		.10				2	.10		.26				2	.30		.98			
	3	.05		.10				3	.05		.10										
	4	.15		.44																	
Total			135	0.74	1.0	1.0	0.00548			90	0.62	3.0	1.0	0.0207			89	1.08	4.0	1.0	0.0486
25	25-1	0.05		0.10				25-1	0.05		0.10				25-1	0.05		0.10			
	2	.10		.26				2	.10		.26				2	.05		.10			
	3	.05		.10				3	.15		.44				3	.20		.62			
	4	.10		.26											4	.10		.26			
Total			134	0.72	1.0	1.0	0.00538			123	0.80	3.0	1.0	0.0195			139	1.08	4.0	1.0	0.0311
Average							0.00512							0.0174							0.0348

TABLE 3.—*Computation of bedload discharge by the dune-tracking method, Little Blue River near Fairbury, Nebr. May 28, 1958*—Continued

Station No.	Line 10							Line 12						
	Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)	Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)
	Dune No.	Height (ft)	Time (min)					Dune No.	Height (ft)	Time (min)				
1	10- 1-1	0.10		0.26				12- 1-1	0.05		0.10			
	2	.15		.44				2	.15		.44			
	3	.15		.44				3	.10		.26			
Total			118	1.14	3.0	1.0	0.0290			100	0.80	1.0	1.0	0.00800
7	7-1	0.25		0.80				7-1	0.05		0.10			
	2	.05		.10				2	.15		.44			
Total			100	0.90	3.0	1.0	0.0270			80	0.54	1.0	1.0	0.00675
13	13-1	0.05		0.10				13-1	0.05		0.10			
	2	.15		.44				2	.10		.26			
								3	.35		1.17			
Total			71	0.54	3.0	1.0	0.0228			109	1.53	1.0	1.0	0.0140
19	19-1	0.30		0.98				19-1	0.10		0.26			
	2	.20		.62				2	.20		.62			
Total			138	1.60	3.0	1.0	0.0348			119	0.88	1.0	1.0	0.00739
25	25-1	0.25		0.80				25-1	0.20		0.62			
	2	.05		.10				2	.10		.26			
	3	.10		.26				3	.10		.26			
Total			128	1.16	3.0	1.0	0.0272			117	1.14	1.0	1.0	0.00974
Average							0.0282							0.00918

Total of B' averages	0.09470.
Computed bedload discharge (74.16) (0.09470)	7.0 tons per day
Bedload discharge computed with Meyer-Peter and Müller equation	13.9 tons per day

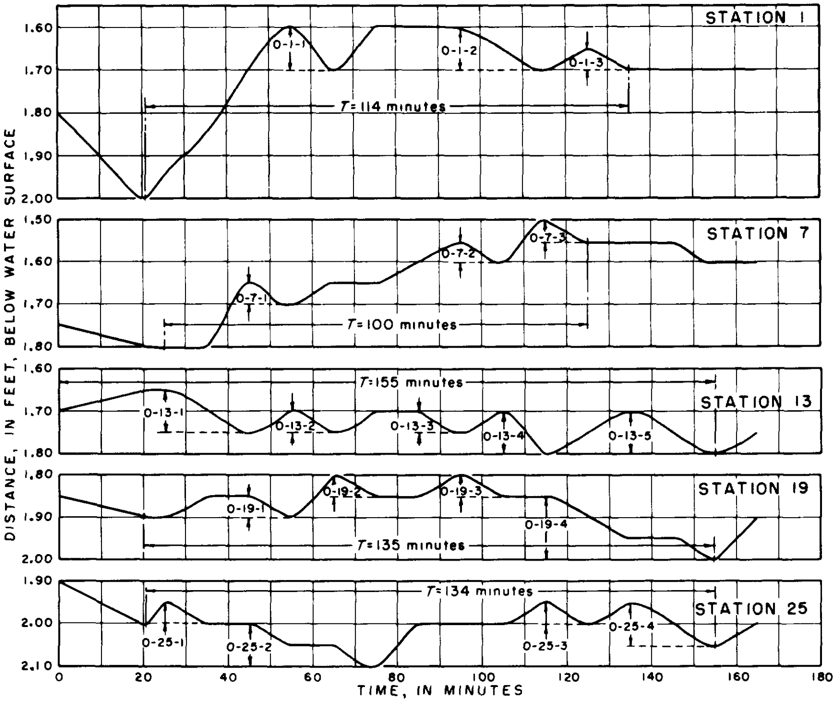

FIGURE 38.—Change in bed elevation with time at stations along line *O*, Little Blue River near Fairbury, Nebr., May 28, 1958. Vertical arrows indicate the height of the numbered dune.

computations, which are identical in basic method to the Little Blue computation, are shown in tables 4 and 5. Also included in the tables are unmeasured sediment discharges that were determined as the difference between the total load measured at the turbulence flume and the suspended-sediment discharge measured at the sounding section. The computed bedload discharge for August 7 seems to be slightly low in comparison with the unmeasured sediment discharge, and the discharge for August 8 seems to be too high. Both of these computations have time-sounding periods that were too short; consequently, many of the major dune forms were undefined. On August 8 especially, the time period was so short that the soundings reflected mostly a lowering of the bed elevation.

In addition to the field computations, three computations have been made using data from ultrasonic soundings made by D. B. Simons and E. V. Richardson of the U.S. Geological Survey in a flume at Fort Collins, Colo. The procedure and the assumptions of these computations were the same as those for the field computations except that λ was assumed to be equal to 0.35. Table 6 shows the computed

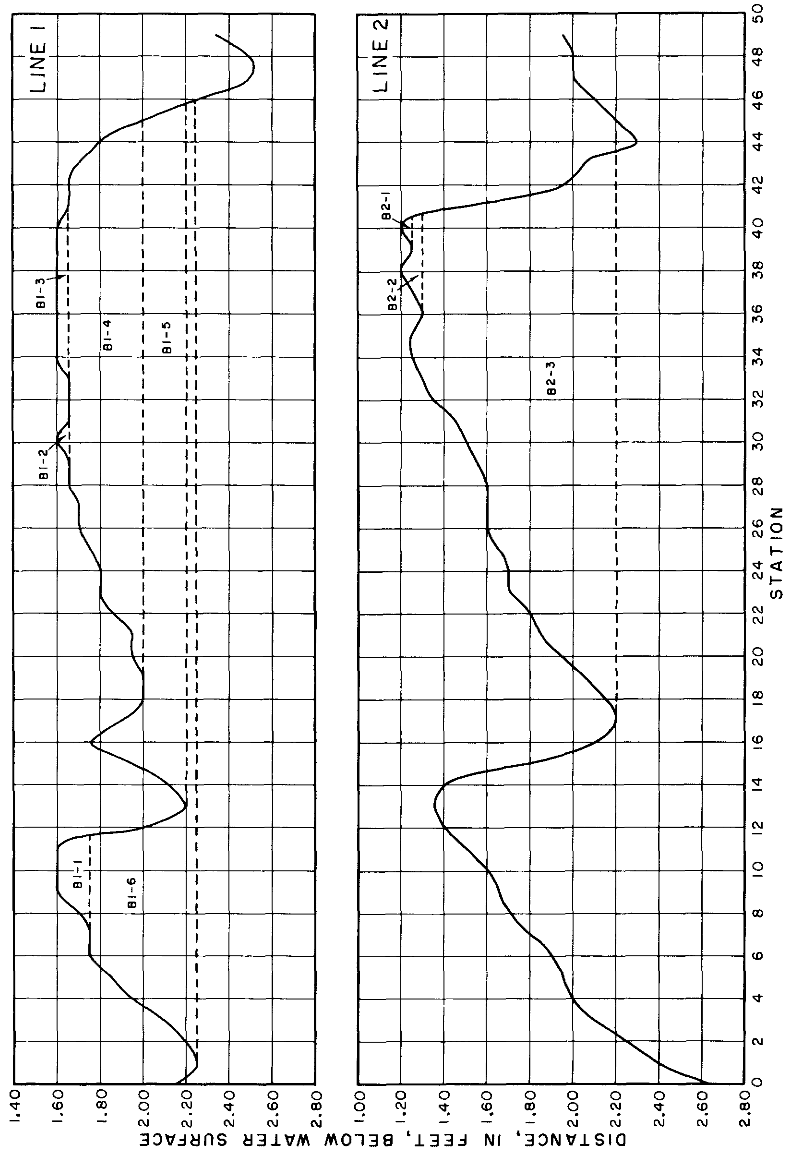

FIGURE 39.—Longitudinal profiles, Middle Loup River at Dunning, Nebr., August 7, 1958. Dune numbers are indicated; direction of flow is to the right.

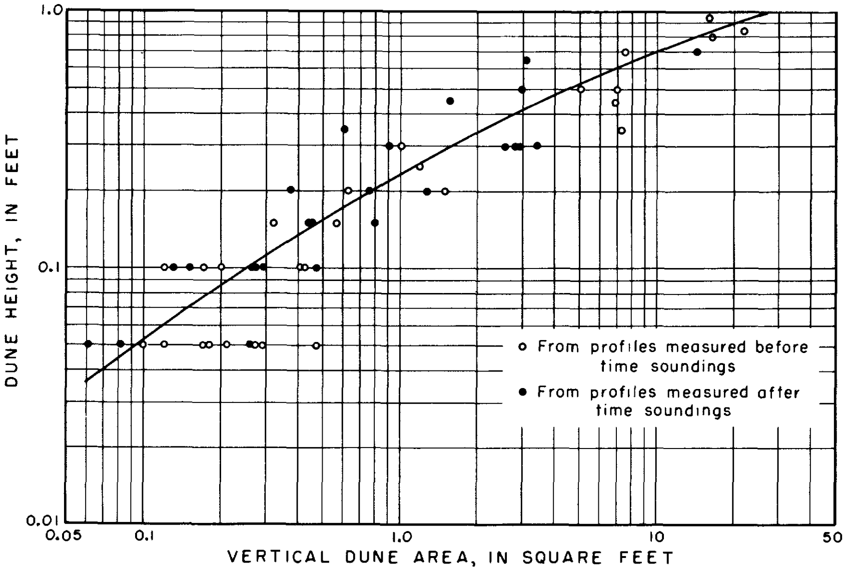

FIGURE 40.—Relation between the dune height and the vertical dune area, Middle Loup River at Dunning, Nebr., August 7, 1958.

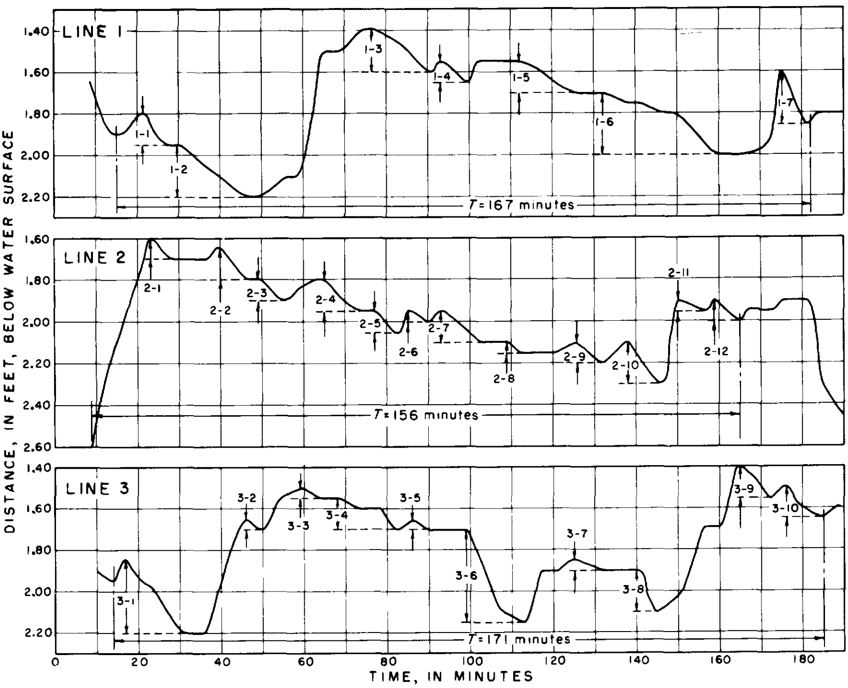

FIGURE 41.—Change in bed elevation with time at single points, Middle Loup River at Dunning, Nebr., August 7, 1958. Vertical arrows indicate the height of the numbered dunes.

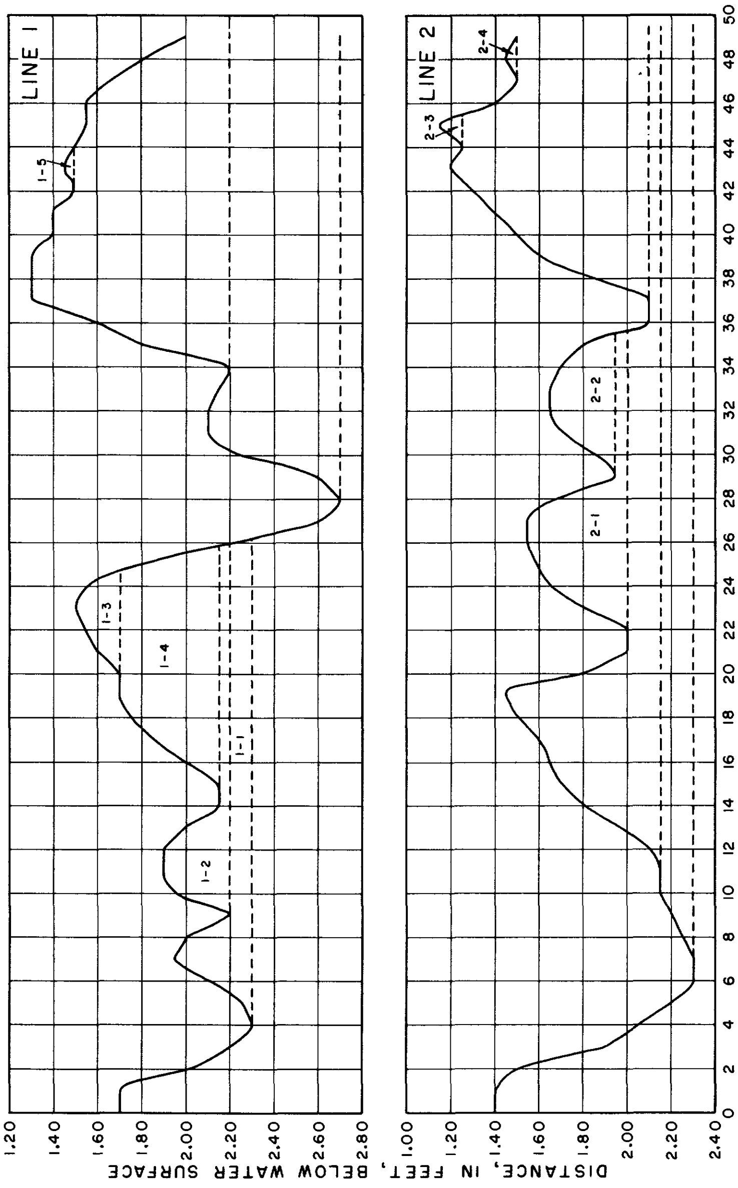

FIGURE 42.—Longitudinal profiles, Middle Loup River at Dunning, Nebr., August 8, 1958. Dune numbers are indicated; direction of flow is to the right.

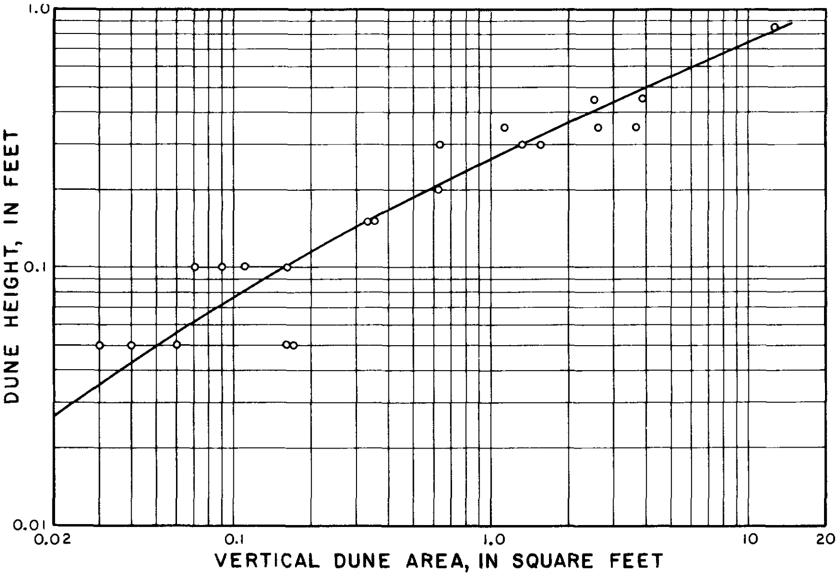

FIGURE 43.—Relation between the dune height and the vertical dune area, Middle Loup River at Dunning, Nebr., August 8, 1958.

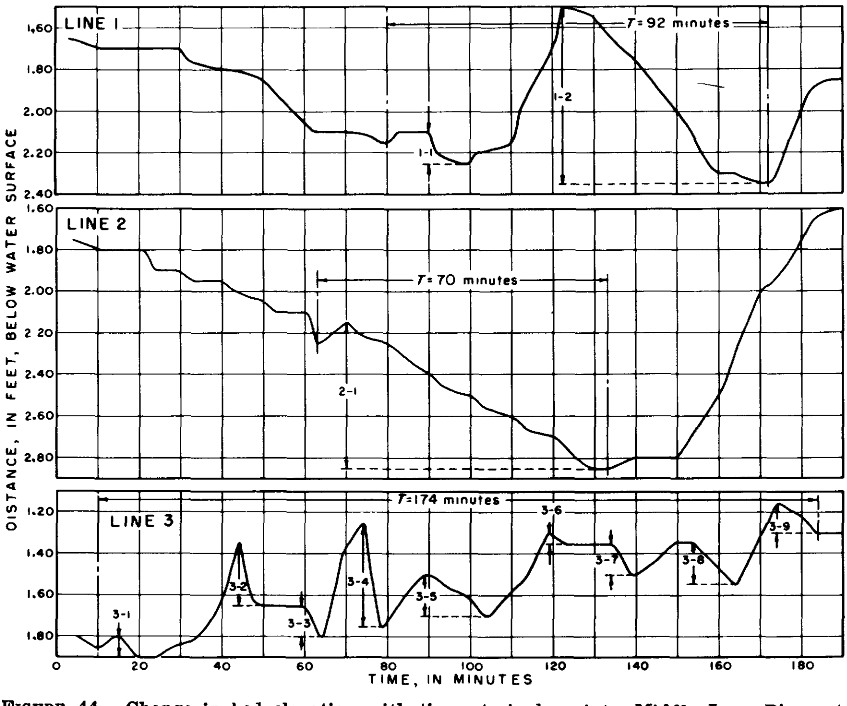

FIGURE 44.—Change in bed elevation with time at single points, Middle Loup River at Dunning, Nebr., August 8, 1958. Vertical arrows indicate the height of the numbered dunes.

TABLE 4.—*Computation of bedload discharge by the dune-tracking method, Middle Loup River at Dunning, Nebr., August 7, 1958*

[Longitudinal-profile data used to establish height-area relation. Point-time data from graphs of the change in bed elevation with time. Vertical area from height-area relation]

Longitudinal-profile data			Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)
Dune No.	Height (ft)	Vertical area (sq ft)	Dune No.	Height (ft)	Time (min)				
B1-1	0.15	0.56	1-1	0.15		0.47			
2	.05	.18	2	.25		1.12			
3	.05	.47	3	.20		.75			
4	.35	7.17	4	.10		.25			
5	.45	6.80	5	.15		.47			
6	.50	4.99	6	.30		1.61			
			7	.25		1.12			
B2-1	.05	.21							
2	.10	.42			167	5.79	15.0	1.0	0.520
3	.95	15.81							
B3-1	.05	.17	2-1	.10		0.25			
2	.30	1.00	2	.15		.47			
3	.05	.29	3	.10		.25			
4	.50	6.93	4	.15		.47			
			5	.10		.25			
B4-1	.10	.41	6	.05		.09			
2	.05	.10	7	.15		.47			
3	.20	.62	8	.05		.09			
4	.20	1.47	9	.10		.25			
5	.85	21.40	10	.20		.75			
			11	.05		.09			
B5-1	.15	.32	12	.10		.25			
2	.05	.27							
3	.25	1.18			156	3.68	15.0	1.0	.354
4	.10	.17							
5	.10	.12							
6	.10	.20	3-1	.35		2.18			
7	.80	16.14	2	.05		.09			
8	.05	.12	3	.05		.09			
9	.70	7.35	4	.15		.47			
			5	.05		.09			
A1-1	.45	1.53	6	.45		3.70			
2	.50	2.95	7	.05		.09			
3	.10	.29	8	.20		.75			
4	.10	.13	9	.15		.47			
5	.10	.47	10	.15		.47			
A2-1	.65	3.04			171	8.40	16.0	1.0	.786
2	.30	2.85							
3	.05	.26							
4	.10	.26	4-1	.05		0.09			
			2	.05		.09			
A3-1	.05	.06	3	.10		.25			
2	.30	2.53	4	.20		.75			
3	.30	3.32	5	.20		.75			
4	.20	1.26	6	.05		.09			
5	.10	.15	7	.05		.09			
			8	.05		.09			
A4-1	.30	2.80							
2	.30	.89			125	2.20	15.0	1.0	.264
3	.15	.79							
4	.70	14.05							
5	.15	.44	5-1	.20		0.75			
6	.35	.60	2	.35		2.18			
			3	.05		.09			
A5-1	.10	.27							
2	.05	.08			143	3.02	15.0	1.0	.317
3	.20	.75							
4	.20	.37							2.241

Computed bedload discharge (74.16)(2.241) .... 166 tons per day
Unmeasured sediment discharge .... 461 tons per day

TABLE 5.—*Computation of bedload discharge by the dune-tracking method, Middle Loup River at Dunning, Nebr., August 8, 1958*

[Longitudinal-profile data used to establish height-area relation. Point-time data from graphs of the change in bed elevation with time. Vertical area from height-area relation]

Longitudinal-profile data			Point-time data			Vertical area (sq ft)	Width (ft)	$\overline{K}$	B′ (cfm)
Dune No.	Height (ft)	Vertical area (sq ft)	Dune No.	Height (ft)	Time (min)				
1-1	0.35	2.60	1-1	0.15		0.33			
2	.30	1.56	1-2	.85		13.00			
3	.20	.62							
4	.45	3.86			92	13.33	15.0	1.0	2.17
5	.05	.04							
2-1	.45	2.50	2-1	.70	70	8.50	15.0	1.0	1.82
2	.30	1.31							
3	.10	.07							
4	.05	.06	3-1	.10		.16			
			3-2	.30		1.30			
3-1	.35	1.12	3-3	.15		.33			
2	.10	.16	3-4	.50		4.00			
3	.05	.17	3-5	.20		.56			
4	.05	.16	3-6	.05		.05			
5	.15	.35	3-7	.15		.33			
6	.85	12.59	3-8	.20		.56			
			3-9	.15		.33			
4-1	.30	.63							
2	.05	.03			174	7.62	16.0	1.0	.70
5-1	.10	.11							
2	.15	.33	4-1	.05		.05			
3	.10	.09	4-2	.05		.05			
4	.35	3.64	4-3	.80		11.60			
			4-4	.45		3.16			
			4-5	.15		.33			
			4-6	.10		.16			
					172	15.35	15.0	1.0	1.34
			5-1	.05		.05			
			5-2	.15		.33			
			5-3	.50		4.00			
			5-4	.60		6.00			
			5-5	.05		.05			
					158	10.43	15.0	1.0	.99
									7.02

Computed bedload discharge (74.16)(7.02) .... 521 tons per day
Unmeasured sediment discharge .... 222 tons per day

discharges and data for comparison, including bed-material discharges, which were measured at the end of the flume, and bedload discharges, which were estimated from suspended-sediment sampling to be one-half of the bed-material discharges. Also given in the table are the values of $\overline{K}$ required to give the measured bed-material discharge and the estimated bedload discharge. In each computation, the computed discharge was greater than the bed-material discharge; and the required values of $\overline{K}$, which would be expected to be about equal or greater than 1.0, were less than 1.0.

Computations with the flume data have also been made by using equation 6 (p. 49). For these computations, the mean dune velocity was determined by dividing the mean dune length (obtained from the longitudinal profile) by the total time and then multiplying the quo-

TABLE 6.—*Bedload discharges computed by the dune-tracking method from flume data*

Discharge (lb per sec per ft)			Computed discharge as percentage of—		Required $\overline{K}$ for—	
Computed	Measured bed-material	Estimated bedload	Measured bed-material discharge	Estimated bedload discharge	Measured bed-material discharge	Estimated bedload discharge
0.0637	0.0273	0.0136	233	467	0.428	0.214
.0792	.0423	.0212	187	375	.534	.267
.1220	.0715	.0358	171	342	.587	.293

tient by the number of dunes that passed the measuring point in the total time, and the mean height was determined by dividing the area subject to movement (obtained from the longitudinal profile) by its corresponding length. By using equation 6, the height-area relation is eliminated, but the results were less accurate than those listed in table 6 in two out of three computations.

Although the results of the computations are inaccurate, they do not necessarily reflect adversely on the procedures nor on equations 5 and 6. The inaccuracies could have resulted from inaccuracies in the estimates of the vertical areas and in the values used for porosity and specific weight of dune material. One important assumption in the computations with equations 5 and 6 is that the area that is actually eroded is equal to the area that would have to be eroded if the profile were to move downstream without changing form. This assumption, which inherently includes as load all the material that lies above the elevation of the lowest upstream trough, apparently is invalid. If the material that lies beneath discernible dunes is ignored, as it can be by any of the many different arbitrary means, the computed bedload discharges will agree much more closely with the measured discharges. However, the arbitrary selection of area seemed unwarranted at this point in the project, particularly because so few data are available. Only after special studies have been made on the nature of dune movement can any realistic conclusion be made on the specific areas that should be treated or, for that matter, on the suitability of the area concept.

The principal attributes of dune-tracking methods for computing bedload discharge are that the flow is not disturbed and that the statistically distributed short-term variations in discharge are ignored. On the other hand, an important shortcoming of the methods is the requirement of sounding for relatively long periods of time in order to obtain representative data. This requirement somewhat limits the application of the methods because constant flow conditions usually persist only at times of normal flow. In addition, application of any method, at least for the present, is limited to the tranquil-flow regime.

PRESSURE TRANSDUCERS

Pressure transducers, which generally operate with strain gages, may be an aid in determining bedload discharge by measuring dune movement (change in bed elevation at a point with time). Although no actual measurements have been made, the application of pressure transducers can be visualized. By placing transducers beneath the bed surface, the variations in weight above the transducers could be measured and recorded. If a dual transducer having one strain gage to measure the total weight above the transducer (combined weight of the flowing water-sediment mixture, the pore water, and the bed material) and another gage to measure only the weight of the water-sediment mixture and the pore water was used; then, a continuous record of the difference between the weights registered by the two strain gages would define the weight, hence the height, of bed material above the unit.

One possible design for a dual transducer is shown diagrammatically in figure 45. In this design, the pressure-sensitive section of the transducer is divided into two parts so that each part actuates a separate strain gage. One of the parts is covered with a mesh capable of supporting the bed material; this part is sensitive only to the weight of the water-sediment mixture and the pore-space water. Such a design is somewhat similar to one used by Bagnold (1955) for measuring the weight of sediment in suspension.

By using several pressure transducers to measure dune movement simultaneously at different places in a cross section and by using a portable ultrasonic sounder for measuring the bed configuration, the time required for collecting the data necessary for a bedload computation would be substantially less than the time required for collecting all the data by using only an ultrasonic sounder. However, at least two factors hinder the use of the pressure transducers for measuring dune movement. The installation of the transducers would be difficult, particularly in deep water, and would probably have to be permanent because the transducers would have to be placed below the lowest elevation of scour. Also, the electrical leads would have to be buried the distance from the transducer to the bank unless a vertical support sufficiently strong to withstand ice, flood, and debris was provided.

ULTRASONIC SOUNDING OF LARGE PARTICLES

Ultrasonic depth sounders, in addition to being able to define dune movement, may provide a means for determining the discharge of bedload particles that are about 3 inches or larger in diameter. However, for the measurement of large particles, certain modifications

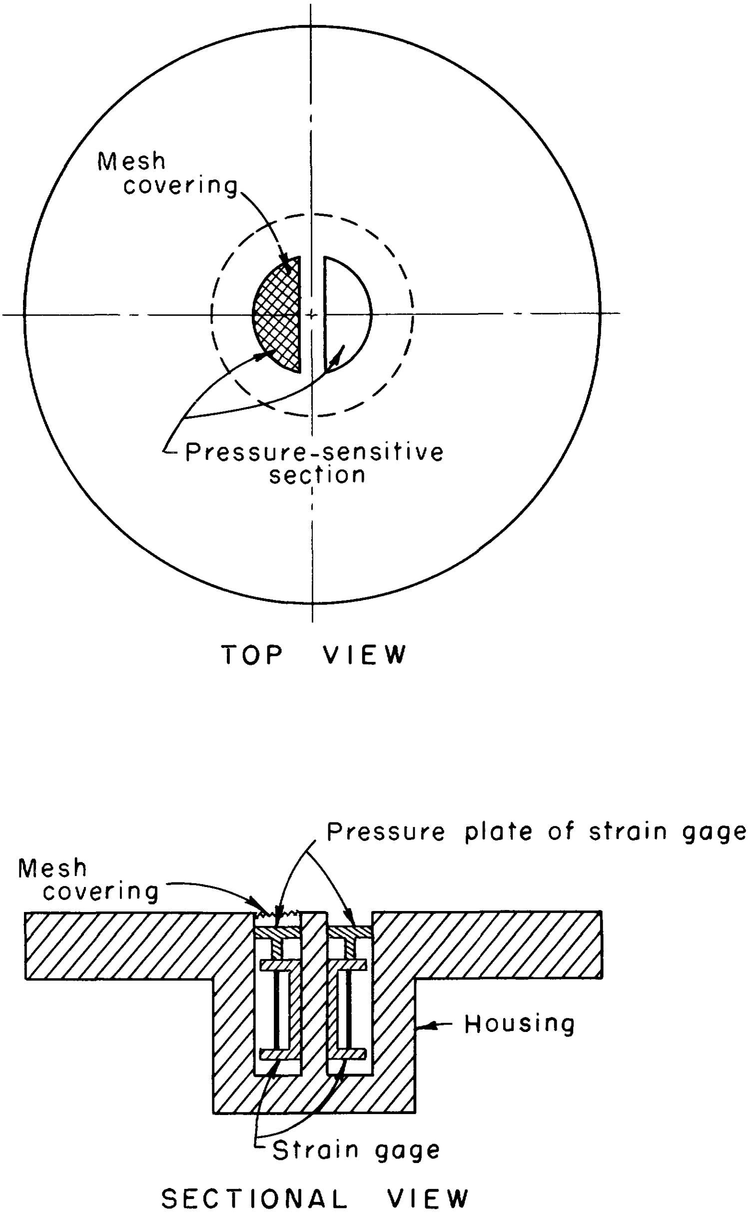

FIGURE 45.—Diagrammatic sketch of a dual pressure transducer.

must be made to the ultrasonic sounders available at present. These modifications consist of providing one rapid-scanning transducer, at least two stationary transducers, and some sort of distributor system, which would allow a single electronic unit to operate all the transducers and a multiple-channel recorder.

The theory of measurement with this system is based on the idea that the scanning transducer will define the shape of the particles, the stationary transducers will define the particle velocities, and information from both types of transducers can be used to determine the particle dimensions. Consider a transducer that scans back and forth in a plane and a particle that is moving in a direction pependicular to the scan. As the particle passes beneath the transducer, the ultrasonic sounder will measure and record the elevation of the upper part of the particle along some line that is defined by the intersection of the particle and a vertical plane. Thus, the recorder trace of each particle, particularly if it includes several scans across the particle, will define reasonably well the shape of the particle. However, the scanning record alone will not be a measure of the particle size because the scan lines across the particle are vector resultants that are neither parallel to each other nor perpendicular to the direction of particle movement. The particle size can only be determined by knowing V_p, the particle velocity, V_t, the scanning velocity, and L, the scan distance. Both V_t and L can be predetermined and fixed, but V_p must be determined for each particle. V_p can be determined by measuring the time required for the particle to move between stationary transducers that are arranged a known distance apart along the line of particle movement. With a knowledge of V_p, V_t, L, and θ, which is the angle between the scan line across a particle and a perpendicular to the direction of particle motion ($\theta = \arctan V_p/V_t$), some particle dimensions can be determined. The particle dimensions and the estimate of shape can then be converted to an estimated particle volume. By computing the total volume of all particles passing in a given time, the bedload discharge is established.

For spherical particles, only one scan across each particle is necessary for determining the particle volume. Consider a spherical particle moving on a flat bed. The recorder trace would show the elevation of the flat bed until the transducer started to scan across the particle, at which time the upper half of an ellipse whose minor axis equals $d \cos \theta$ (where d is the diameter of some circle of the sphere) would be recorded. By finding d and then the center of the circle of the sphere, the center of the spherical particle is established; the distance from this center to the bed is the radius of the particle. (See fig. 46*A*.) For spherical particles moving on an irregular bed, the computation is the same as that for the flat bed except that the radius of each particle is determined from the points of support on the bed

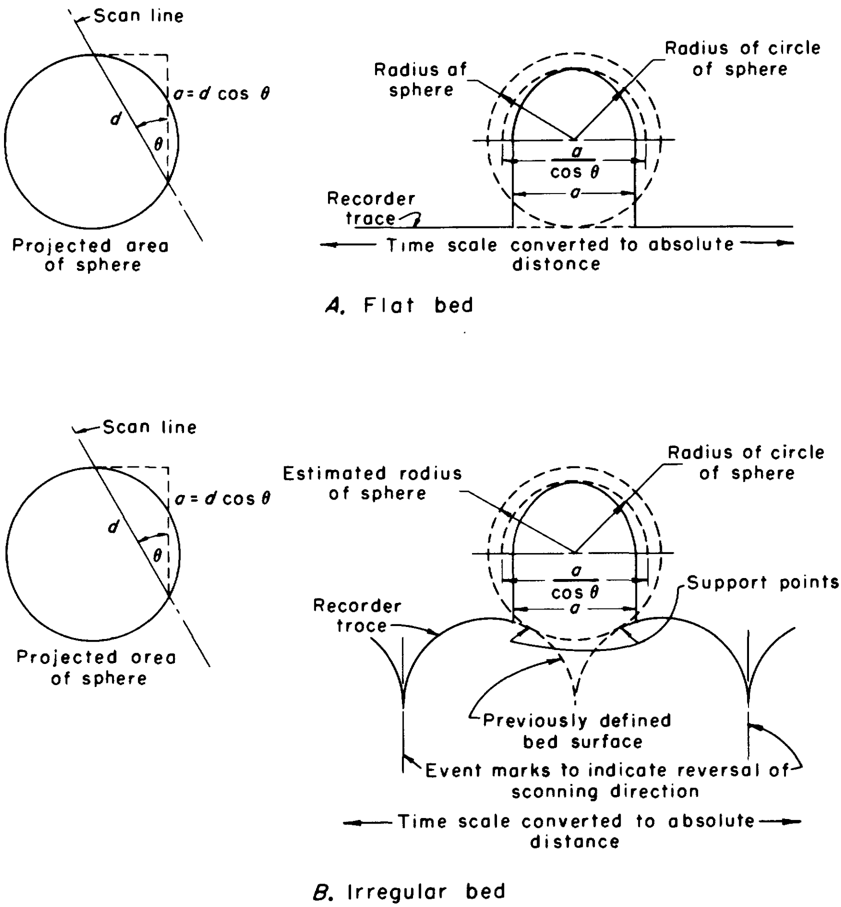

Figure 46.—Determination of radius of spherical particle from a recorder trace by ultrasonic sounding.

which would have been recorded at a time when no particles were passing through the scanning distance. (See fig. 46*B*.)

For particles of a nonspherical shape, the computation of the volume of an individual particle is considerably more tedious and less accurate because the particle volume must be determined from estimates of the projected and cross-sectional areas of the particle.

For particles that have a high degree of sphericity, regardless of the mode of movement, the scanning method for computing bedload discharge seems plausible and should give reasonably accurate results. However, for particles that have a low degree of sphericity and that move by rolling or skipping, rather than by sliding, the recorder trace would not indicate the true cross-sectional shape of the particle. Consequently, computed particle volumes would be inaccurate unless some characteristic of the recorder trace would indicate the mode of movement and furnish information from which volume corrections could be made.

For nonspherical particles, the accuracy of the computation depends to a large extent on the number of scans across each particle. Figure 47 shows the minimum number of times a spherical particle will be

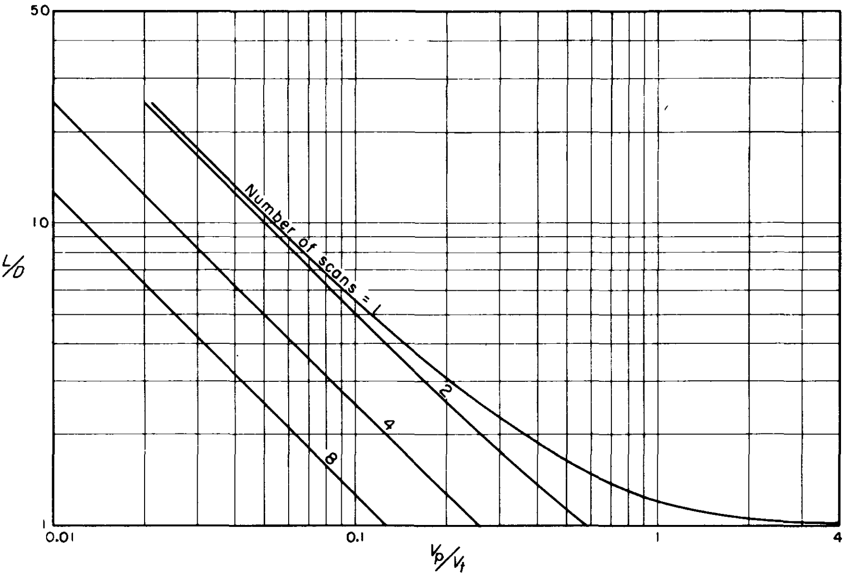

FIGURE 47.—Minimum number of times a spherical particle will be scanned. Whenever L/D for a given V_p/V_t is less than that shown by the curves, a spherical particle will be scanned at least the indicated number of times.

scanned for different ratios of V_p/V_t and L/D, where D is the sphere diameter. In order to use the graph for nonspherical particles, substitute for D the particle dimension in the direction of particle movement. The graph shows that for a reasonable number of scans at large L/D ratios, V_t must be large in relation to V_p. Herein lies one of the shortcomings in present instrumentation. According to the manufacturer of ultrasonic sounders available at present (oral communication), scanning velocities could not exceed about 1.5 feet per second and still maintain an accurate record. Thus, even at the maximum scanning velocity, particles that have velocities as high as about 1.0 foot per second will be scanned only about once when the L/D ratio is greater than 1.0.

CONCLUSIONS

The bedload discharge at any given point varies in an oscillatory manner with time. Thus, a bedload discharge defined by a single short-term measurement is not necessarily representative of the mean bedload discharge, and the discharge through an entire stream cross section can be determined only by measuring many times at each of several points.

Any bedload apparatus in which sediment accumulates or through which sediment passes must be calibrated to determine its efficiency for a given condition.

The efficiency of a bedload sampler is difficult to determine and only fairly reliable because samplers can be calibrated only in laboratory flumes by using sampler models, which are not likely to be hydraulically similar to the prototype sampler in the field.

The efficiency of apparatus that trap and accumulate sediment, except pit samplers, varies widely with different velocities, particle sizes, bedload magnitudes, degrees of filling, and bed configuration. The effect of bed configuration on efficiency is superimposed on the other factors by affecting sampler orientation and stability. Probably, efficiencies are least variable when the bed relief is low except when the velocity is sufficiently high to make the sampler unstable.

Efficiencies average about 45 percent for basket and pan samplers and about 65 percent for pressure-difference samplers. In general, efficiencies of pressure-difference samplers vary less than those of basket or pan samplers. Pit samplers have high and relatively constant efficiencies. However, they have limited application because they must be placed into the stream-bed.

Because samplers usually have high hydraulic resistances and because sampler orientation and stability are important to efficient operation, sampler suspensions and placement are paramount considerations.

The total sediment discharge is not necessarily the simple summation of the measured suspended-sediment discharge and the discharge from a bedload measuring apparatus. The expression for determining the total sediment discharge depends on the particle size, the sediment distribution, and the kind of discharge measured by the apparatus. For any given set of conditions, the determination is easiest if the apparatus measures only the bedload discharge.

The Sphinx and VUV samplers probably represent the most advanced accumulating-type apparatus for determining the discharge of material that moves close to the streambed. The efficiency of the Sphinx, which is designed to measure fine sand, has not been determined exactly; however, it probably remains fairly constant and averages about 80 percent. The efficiency of the VUV sampler, which is designed to measure sediments from 1.0 to 100 mm, averages about 70 percent. The principal advantage of the VUV sampler is that it usually gives a good representation of the actual bedload size distribution.

The magnetic bedload sampler proposed by Kennedy has not been constructed and tested. The sampler and the method may have merit.

Acoustic apparatus that record the sound engendered by interparticle or particle-instrument collisions measure the relative bedload discharge and not the actual bedload discharge; therefore, they are valuable only as an aid in certain kinds of studies or in association with other apparatus. Ivicsics' apparatus is the only device of this type that operates in a suspended position above the bed.

Taniguchi's tiltmeter method, which is intended to give the total sediment discharge from measurements of the ground tilt, may prove to be useful for some kinds of river studies; however, in its present state of development, it does not seem to be satisfactory for determining sediment discharge.

Smoltczyk's ultrasonic instrument for determining concentration and the associated instrumentation and procedures for determining bedload discharge do not seem to be sufficiently developed for practical field application. However, with modifications and improvements, the method might provide an acceptable means for determining the discharge of sediment that moves close to the bed of streams transporting fine sand. The present instrumentation incorporates some of the objectionable characteristics of samplers that accumulate sediment, and the bedload discharge cannot be determined unless several unverified assumptions are made.

Although substantial advances have been made in the design of direct-measuring apparatus and although some of the indirect-measuring apparatus are based in ingenious ideas, no completely satisfactory apparatus exists at this time for measuring the bedload or total sediment discharge of coarse sediments.

A suggested portable pit sampler may provide an acceptable means for determining bedload discharge. However, its application is limited to shallow sand-bearing streams that have velocities less than about 4 feet per second.

The discharge of particles larger than about pea size probably can be determined by using motion-reduction photographic techniques provided the flow is clear. However, photography is generally not practical.

Recently developed ultrasonic sounders provide a means of obtaining accurate and meaningful records of bed configuration and dune movement for use in mapping the streambed and computing bedload discharge.

A proposed method for computing bedload discharge from bed configuration and dune movement is based on equations in which the product of A (the summation of vertical areas presumed to move in a long time), dw (an incremental width), and the reciprocal of T (a long time) is a critical parameter. Although the method nullifies the effects of the oscillatory variation of bedload discharge with time, soundings must be made for relatively long times in order to provide adequate information. Several actual computations with the method were inaccurate, possibly because of inaccurate values for porosity and specific weight and very probably because of inaccurate estimates of the vertical areas. Much additional laboratory and field study is required before any method can be selected as the most valid and practical for determining the bedload discharge from dune movement.

A dual pressure transducer for measuring the weight of bed material above a point in the bed may provide an acceptable means for determining dune movement. However, the installation of such a transducer would be difficult and would probably have to be permanent. If several transducers are used simultaneously to measure dune movement at several places in a cross section and a portable ultrasonic sounder is used to define the bed configuration, the data necessary for bedload computations could be collected in substantially less time than if an ultrasonic sounder is used to collect all the data.

A proposed modified ultrasonic sounder, which contains one rapid-scanning transducer and two stationary transducers, and a proposed computational method might provide a means for determining the discharge of particles larger than about 3 inches in diameter. The method seems to be plausible for particles having a high degree of sphericity; however, it probably is unsuitable for particles having a low degree of sphericity.

Of the new possible apparatus and methods for determining bedload discharge, dune tracking with ultrasonic sounders seems to offer the greatest potential for general application; and the portable pit sampler, photography, the dual pressure transducer, and ultrasonic sounding of large particles seem most suited for special applications.

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