

## SEDIMENT INVESTIGATIONS FOR MISSOURI RIVER PROJECTS

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Engineers of the Missouri River Division, Corps of Engineers, are engaged in a sediment investigation program which is believed to be unparalleled, both in scope and in the nature of the study. The purpose of the work is to provide practical solutions to the sediment problems involved in the construction and operation of the comprehensive program for flood control and water use in the Missouri River Basin. Specifically, the objective of the program is to explore the basic functions of sediment activity in streams and adapt them to practical usage in the solving of specific problems for controlling or utilizing sediment phenomena.

The entire history of the Missouri River and of works for its control has been dominated by sediment. When the Corps of Engineers was assigned the first general project for channel control, the basic tools utilized were the erosion, transportation, and deposition of sediment. The channel was shifted into a predetermined position, moulded into proper dimensions and held in place by the construction of carefully planned permeable pile dikes which guided the flow, pushed the river into place by forcing erosion of opposing banks, and induced deposition of sediment behind the dikes to form the new bank lines and contain the flow. Material eroded from the original banks in one bend was transported by the river to form the new banks in a downstream reach.

The engineers who accomplished the earlier portion of this work knew little of sediment transport theory, but with experience they gained a practical qualitative knowledge which enabled them to recognize and predict the occurrence of many sediment phenomena. It also gave them an appreciation of the need for further knowledge and led to the first general sediment study of the Missouri River, which was accomplished during the period 1928-1931 in connection

with a comprehensive investigation of the Missouri River for flood control and water use. This study provided invaluable groundwork for determination of the nature and scope of the sediment aspects of river control, and permitted planning and construction of the present projects for flood control and water use to proceed without delay. It also established the necessity for further specific investigations and identified the character of the studies needed.

It was with this background of sediment experience that plans were laid for a detailed program of study in connection with the design and construction of Corps of Engineers projects in the comprehensive basin plan. Since the basic sediment functions involved were common to all the projects and, particularly, since the effects of several major projects on a single stream would be overlapping, the first step was to set up a strong organization which would be explicitly coordinated under a single administration to insure full development of the study and to prevent duplication. A sediment section was established in the Missouri River Division Office, with a similar group in the office of each District within the Division. Control of the planning and execution of all phases of the work was centered in the Division Office. Physical surveys are assigned individually to Districts, with correlation between Division and District offices in planning the work, interpretation and correlation of data, and the dissemination of results. Functional studies are generally accomplished in the Division Office, but portions are assigned to Districts in accordance with specially qualified personnel available. An advisory board of specialists in the field of sediment was set up for consultation collectively or individually for aid in maintaining an intelligent and balanced program and for advice in specific problems.

An analysis of the problems to be anticipated revealed that they can be almost entirely classified under the dynamics of sediment movement. The formation of reservoir deltas and possible aggradation in the backwater reach above results from deposition as the power of the stream to transport sediment is reduced. Degradation downstream depends on the ability of the stream to erode the bed and banks and to transport the eroded material, and, finally, the regimen of the stream in its lower reaches will depend on the ability of the regulated flows to transport the sediments brought in by tributaries. All these items may be of greater or lesser importance, depending upon conditions existent on a given stream. On the

Missouri River each of these phases is important, although the problems arising from degradation appear to be most critical.

Actually, the Missouri River does not carry a very heavy concentration of sediment, its tawny appearance being the result of light reflected from the fine silts and clays which form more than 70 percent of the suspended load. Concentrations of suspended sediment during normal flows average about five grams per liter (5000 parts per million). During moderate flood discharges concentrations may reach twenty grams per liter, but with larger floods the proportion of sediment decreases again, particularly if the flow is derived from snowmelt. During the unprecedented flood of April 1952, the concentration of suspended sediment at Omaha, Nebraska, was less than 5 gpl, and during the flood of July 1951 at Kansas City was less than 10 gpl. The problem of loss of reservoir storage is not nearly as acute on the Missouri River as it is on many other streams. The major sediment problems arise from the fact that the Missouri River is an alluvial stream with strong tendencies toward meandering and an unstable channel in its natural state. The river flows over an alluvial fill varying up to more than 100 feet in depth.

Once the nature of the problems to be encountered had been clarified, it appeared evident that existing knowledge of sediment phenomena was inadequate for their solution and that a completely new attack was required. Several formulae for computation of bed load movement had been developed by various individuals, and there were several excellent references on transportation of suspended load, but these were based primarily on flume tests and on fluid mechanics analyses, in which the extraneous influences of cross currents, meanders, and other phenomena of natural streams could not be taken into account. The adequacy of these formulae and theoretical concepts for application to natural streams had not been established. It was decided, therefore, that an investigation for the solution of problems in natural streams should logically be directed toward a study of the application of existing knowledge of transport and a derivation of additional knowledge as necessary to make such application successful. It was also believed that detailed observations of phenomena occurring at existing projects should be made both for application to the theoretical analyses and for qualitative application. The program was thus planned in four general phases (1) sampling to obtain more data on sediment loads and to provide data on sediment characteristics, (2) a review of

data from existing projects, (3) detailed observations of phenomena occurring at existing projects, and (4) investigation of fundamental transport theory and formulae. There are, of course, interrelationships between these phases which require explicit correlation to insure that each portion of the study provides all necessary data without duplication.

In planning the sediment-sampling program, consideration was given to prior sampling programs as well as future. The earliest regular sampling, accomplished during the study of 1928-1930, was designed primarily to provide data on total suspended load, although many samples were analyzed to determine distribution of sediments within the sample. The samplers then available were probably not very accurate insofar as the sand load was concerned, but were adequate in the silt and clay range. Since the sands proved to be less than one-fourth of the total suspended load, any error involved in that fraction would not be important in total suspended load values. The sampling period of slightly more than two years was not adequate, however, so in 1937 and in ensuing years numerous stations were established to augment the total suspended load data. Improved sampling techniques, which were somewhat more accurate in sampling sand sizes, were developed, but emphasis remained primarily on total suspended loads. Altogether, at the inception of the present expanded investigation, there were available records from stations at critical locations for periods up to 12 years, not enough to develop firm average values, but adequate to provide indexes from which reasonable averages could be developed.

The availability of these prior records made it unnecessary to concentrate on record stations, and thus permitted a high degree of flexibility in continued station operation. Stations at critical locations were retained, both to extend the total suspended load record and to provide data on sediment characteristics. Some stations at less critical locations were dropped; new stations were added to broaden the range of information; and a group on the Missouri River and near the mouths of major tributaries were designated for intensive observation for transport studies and for control data. About one-half of the 74 stations initially set up were intended only to provide short-term records which could be extended by reference to index stations. They were operated during the first three years of the program, and have now been suspended so that efforts may be concentrated on investigations of transport fundamentals.

The second phase of the program, the review of available data on existing reservoirs, was disappointing. There are numerous survey data available, but most of the surveys were made solely to measure loss of storage. They provide very few data on delta formation, backwater deposits, degradation, or characteristics of the original channel and bed material. In addition, very few existing reservoirs are located on streams having the alluvial characteristics of the Missouri River. By far the most valuable information from such projects was obtained visually during a reconnaissance of a group of southwestern reservoirs at a time when pool levels were unusually low and a thorough inspection could be made. Results of this reconnaissance are presented in the paper by Mr. A. S. Harrison contained in this volume.

The third phase, observation of phenomena occurring at existing reservoirs, provided some disappointments, but has generally yielded data of considerable value. A typical disappointment was met in an attempt to measure total load at a small channel reservoir which is flushed frequently and thus appeared to offer an excellent opportunity to check bed load movement. Unfortunately the accuracy with which the pool could be surveyed in the limited time available before and after flushing was sadly short of requirements.

A much more successful study is that of the degradation below Fort Peck Reservoir. A few ranges were established in the reservoir area and in the river downstream prior to completion of the project, from which were obtained data on original conditions. As soon as the sediment program was initiated, these were supplemented by additional permanent ranges which are further supplemented by temporary ranges maintained at approximately one-mile intervals in the reaches where deposition or degradation is currently active. Since sediment inflow into Fort Peck Reservoir is very light, sediment accumulations are insufficient as yet for accurate measurement except in limited areas, but the results obtained from detailed observations of degradation have provided extremely gratifying data on the formation of bed armor and degradation barriers.

Initially, the degradation observations consisted of biannual observation at the ranges with surface samples of the bed material taken at three points on each. These observations gave a measure of the volume of material removed by degradation and a picture of variations in river bed level, but gave little information as to the factors controlling the degradation. The bed samples were very

erratic, possibly showing fine sand for a given range at one time, coarse gravel on the next survey, and medium sand the next. One or two ranges appeared to indicate a rise and fall over a certain portion of the bed, as if sand bars were moving across them. Dr. H. A. Einstein, one of our consultants, noted this behavior, and suggested a more detailed inspection of the river bed. It was this suggestion that led to our most successful observations.

The Fort Peck District personnel had developed a scoop-type sampler which had a spring mounted cover and which was mounted on a long handle. With this sampler excellent samples could be taken rapidly in water up to 15 feet in depth, so that large numbers of samples could be obtained economically. A group of samples taken at one of the fluctuating ranges showed the bed surface to consist of dense clay or shale on one side, gravel on the other, and sand near the center where the fluctuation had been noted. A check of several other ranges which had apparently stabilized showed either clay or gravel, while intermediate ranges which appeared to be still active had bed surfaces of sand. With these data as guides, a complete reconnaissance survey was made of the river bed from the dam to the lower end of the reach to which degradation had extended. A map prepared from this survey showed several locations where either gravel or clay had been exposed to form local barriers to further degradation.

One of these locations was at a range immediately downstream from the spillway outlet channel, which had been opened as a pilot cut and then permitted to be eroded to full channel dimensions by the spillway discharge. This range had degraded sharply, then aggraded again to a level which has since remained fairly constant. It was noted that the period of aggrading had occurred during the time the spillway channel was being eroded, and that the bed survey showed a long curving tongue of gravel extending across the river from the mouth of the spillway channel. These gravel barriers were unusually interesting, because no information indicating any extensive gravel deposits had been obtained either during the construction period or subsequently. A review of the data from foundation and borrow-area investigations showed widely scattered lenses of gravel, seldom more than a few feet in thickness and a few hundred square feet in area. One employee recalled that the spillway pilot channel had cut through such a lens near its mouth. These small, widely scattered gravel lenses, together with a few clay or

shale outcrops, have been surprisingly effective in controlling degradation.

After these data had been developed, the study was extended to include sub-surface as well as surface investigations of bed materials in the river downstream from the present limits of degradation. Core borings were found to be too expensive for extended coverage, and other available means of subsurface sampling were inadequate in the water depths encountered; but the ingenuity of Fort Peck personnel again provided a solution. A jet probe was made of one-inch pipe with a flexible hose leading from a small gasoline-powered pump mounted in an outboard-motored skiff. This probe went through sand readily but was stopped by gravel or clay. Gravel was identified readily by the characteristic "ring" when struck by the probe, while clay was equally easily identified by the "feel". A few checks by core borings verified the interpretations of the probing. All locations which have subsequently been exposed by the flow as degradation barriers and a number which will be exposed in the future were readily identified in advance.

An interesting situation was noted at one reach. Here a loop of the river is perched on a shale shelf, which forms an excellent degradation barrier. This shelf does not extend across the neck of the loop, however, and if a cut-off occurred there the flow would encounter only sand. Since there is a sharp drop in the bed profile at the lower end of this loop, a cut-off would result in several feet of additional local degradation. At this location, neither the cut-off nor the degradation would be important, but, in a similar situation, should it be desirable to prevent further lowering of the profile, advance knowledge would permit steps to prevent any possible cut-off and to hold the stream on the shelf.

A similar study is underway at the Kanopolis Reservoir in Kansas, but the period of operation there has not yet been long enough to provide much information. The bed material of the channel downstream is a mixture of sand with some gravel. Maximum degradation for the maximum release to be expected appears to have occurred at the first downstream range. A check of critical bed-load transport at the presently existing slope at that range and maximum discharge experienced to date indicates that the largest material which will be transported is about 0.75 mm., and that the amount of larger material available in the present bed would be almost enough to form a thin protective layer over the bed. This check may be merely

fortuitous, because the length of reach used for the computation was too short to be really conclusive and the conditions at that range are complicated by shale slabs remaining from the construction. However, the case is illustrative of one of the phases of the investigation which will be extended as data become available. Studies of bank caving, temperature gradients, water quality, and possible density currents at both Fort Peck and Kanopolis Reservoirs offer considerable promise, but have not yet progressed sufficiently to warrant description. Similar studies are being initiated at the Harlan County Reservoir and will be started elsewhere as other reservoirs are completed. Sediment ranges for observation of reservoir sedimentation, aggradation, and degradation will be established and surveyed at all Corps of Engineers reservoirs within the Missouri River Basin and adequate samples to define the original bed characteristics will be obtained prior to completion of the projects.

The fourth general phase, investigation of transport theory, cannot be described extensively at this time, since the work has only recently entered the most active stage. In this phase, extensive field measurements are being made to obtain data both to check the application of transport theory to natural streams and to develop new concepts. Laboratory flume experiments are being conducted in coordination with this work.

The first step was a computation of anticipated degradation and aggradation in order to explore the procedures. The reach selected for study extended from one dam to the head of the next downstream reservoir in the system, thus including degradation, aggradation, and delta formation in a single study. The formula adopted for this study was the bed-load formula of Dr. L. G. Straub, an adaptation of the Du Boys formula. As the work progressed, it appeared that the results would be acceptable approximations, but assumptions as to channel characteristics, selective erosion and deposition of various sizes of materials, and numerous other factors were required at every step. The identification of these assumptions, however, formed one of the bases for planning the continuing investigation.

It was evident, for instance, that in the use of a formula of this type, explicit information on the transport characteristics of the material and on the selective movement of various materials was essential and that it could be obtained only by controlled laboratory tests. Accordingly, a contract was made with the University

of Minnesota for laboratory flume tests to be made under the direction of Dr. Straub, in which material from the bed of Missouri River is being utilized. These tests are still underway and cannot be discussed at this time, but recent developments have shown a previously unexplored variation of bed material movement with changes in the bed form. It is anticipated that the tests will be extended to include a thorough investigation of this phenomenon, which is expected to be a very important phase of the anticipated aggradation and degradation.

At the same time a study was undertaken of the formulae of Dr. H. A. Einstein. A contract was made with the University of California for a flume test under Dr. Einstein's direction to explore the sortings of materials in a degrading bed, the armoring of the bed by non-moving particles, and the continuing relationship between material remaining in the bed and that being moved. This test developed important information on the manner in which particles capable of being transported by a given flow are removed from the bed and the non-transportable particles left to form an armor. It also developed that armoring against a given flow is effectively accomplished if a layer of non-transportable particles one particle thick covers approximately 60 percent of the bed surface.

A further disclosure of this test was the fact that deposition under conditions of aggradation involved an additional element, primarily because a portion of the material normally identified with the bed will continue into the aggrading reach as wash load. A further test to explore this aggrading phase is now underway at the University of California.

While these laboratory tests were being undertaken to resolve problems which could not be studied in the field, field tests were initiated to investigate the problems which could not be answered either by theory or in the laboratory. These field investigations are considered to be the most important phase of the program. They are designed to explore the factors involved in the movement of sediment in a stream with all its attendant complications of three-dimensional flow as contrasted with the two-dimensional flow of the laboratory flume.

These tests were planned with the understanding that it would ultimately be necessary to adopt average values for relatively long reaches in order to avoid the necessity of accounting for numerous individual local phenomena. It was planned to make detailed meas-

urements of all factors affecting both the hydraulics of the flow and the transport, and to analyze these data in correlation with available theory and results of laboratory tests. A few preliminary checks proved, however, that it would be necessary to isolate many local phenomena before they could logically be combined. Checks also showed that it would be necessary to make the study in an open reach of river rather than one complicated by bridge piers. Accordingly, a 10-mile river reach in the vicinity of Omaha, Nebraska, was selected for study. This reach was comparatively straight; in fact, a portion several miles in length was probably the most nearly straight reach available along the river. The plan of operation was to begin with the observation of single vertical lines in a section of the straight reach, and thence to proceed to the longer reach. The final stage will be the consideration of a long reach containing a typical meander pattern.

Work on the first stage has been underway for about one year. It was necessary to provide a boat from which samples, velocity measurements, soundings, and other data could be obtained, and to outfit the boat with the special equipment required, such as a sonic sounder for rapid depth determinations and booms for handling current meter and sampling equipment. Several experimental runs were required to develop techniques for holding the boat in position and to determine the optimum time required for each velocity measurement to secure representative results. Each set of observations is carefully planned in advance.

Results of the observations to date have verified the logarithmic distribution of velocities and sediment in stream verticals in accordance with early conclusions of Dr. Hunter Rouse. They also tend to support the conclusions of Dr. V. A. Vanoni, which are described in another paper in this bulletin. They have shown positively that the exponential functions involved in formulae for the vertical distribution of velocities and sediments cannot be established solely on the basis of the two-dimensional analyses from which these formulae were derived. It appears certain that the use of these formulae in natural streams will require the determination of factors representing the effects of three-dimensional flow, and the results of the work to date offer promise of a successful conclusion.

In planning the overall sediment investigation it was anticipated that laboratory work, other than that to be accomplished in hydrau-

lic laboratories, would be restricted to sample analyses. However, as soon as emphasis had been shifted to studies requiring mechanical analyses of the sand fractions, it was found that available means of analysis were inadequate. The bottom-withdrawal tube, which has been generally adopted in sediment laboratories, proved to be reasonably accurate insofar as particles smaller than about one-fourth millimeter were concerned, but was too erratic in analyses of particles larger than one-quarter millimeter to permit its use for specific studies. A number of other methods for direct determination of fall velocities were tried, but none proved successful in the desired range. The use of sieves was tried and temporarily abandoned because of the difficulty of accurately weighing small fractions. A microscopic method which proved to be accurate and reasonably rapid was developed, but shortly thereafter it was recognized that the use of sieves would be satisfactory if an accumulation curve was plotted from the sieve fractions, thus compensating for errors in weighing. After thoroughly checking this method against microscopic counts, it was adopted because of the speed and economy involved. It is necessary to convert sieve diameters to equivalent fall velocities for transport studies, and a correlation curve was developed for the material found in the transport study reach by timing the fall of a number of individual particles.

Fall-velocity tests were made on samples from 10 different sources to determine the magnitude of error which would be involved in using an average correlation curve for conversion of sieve diameters to fall velocity. The error in the use of this average curve, translated into the resultant errors in transport computations, proved too large to be acceptable; an analysis of the data from the tests indicated that the variation in fall velocity was probably due solely to the shape of the grains. At that point Dr. M. L. Albertson providentially mentioned that several theses had been prepared at the Colorado Agricultural and Mechanical College on the effect of shape on fall velocity, and that he was anxious to complete the range of these studies and combine them into a report. In view of the importance of this work to the sediment program of the Corps of Engineers, a contract has been arranged for its completion. This work is summarized in a paper by Dr. Albertson which is also part of these proceedings.

One of the most serious problems involved in the sediment study has been the employment of qualified personnel. The trend of the

program and the results obtained to date leave little doubt that a competent sediment engineer must be well grounded in fluid mechanics. This problem is being partially solved in the present program by organizing night classes at a local university for training available personnel. In another instance the student who conducted one of our flume tests was employed as soon as the test was completed. The importance of sediment in river control and similar work is rapidly becoming recognized, and the field should offer an attractive future for young engineers. It is, however, no longer a field in which random sampling programs can be conducted primarily to provide filler for file cases. It is a subject which must be intelligently studied by properly qualified individuals and directed toward specific purposes.

#### DISCUSSION

Mr. Smallshaw indicated that the principal interest in sediment in the Tennessee Valley is its effect on the storage capacity of the reservoirs. The beds of the Tennessee River and its tributaries are for the most part well armored, usually by solid rock or gravel, and not subject to degradation. The 630-mile length of the main stem is in slack water and the problem of maintaining a navigation channel is not serious. A few minor deltas have formed at the mouths of tributary streams. Scattering bank caving has occurred in the upper reaches of Kentucky Reservoir, probably the result of saturation by high flows, followed by sudden withdrawal.

The effect of local barriers, he continued, is of considerable interest. A knowledge of the location and elevation of these barriers would permit a more accurate prediction of the extent of degradation. Such knowledge would be most useful to dam designers in the location of draft tubes.

Mr. Smallshaw expressed his regret that Mr. Bondurant had not expanded his discussion of use of suspended sediment data in predicting loss of life of reservoirs. He also asked what length of record of suspended sediment is considered necessary to give a good average of total suspended loads.

Mr. Warner expressed his surprise at the low concentration of sediment in the Missouri River. Observations in the field indicate that apparently some of the tributaries, for example, the White and Grand Rivers, at times carry large sediment loads. He asked about the relationship of the sediment in the tributaries to that in

the main river, and whether there is a relation between sediment loads in the Missouri River and the seasons.

Mr. Bondurant replied that the Corps of Engineers does operate sediment sampling stations on the main tributaries as well as on the river and that records are being compiled to show the relation of sediment movement. Studies are also being conducted on the relation of sediment movement in the river to the seasons.

Mr. Moore called attention to the movement of some sediments through reservoirs as density currents and raised the question of the magnitude and nature of this movement and the probable effect on the movement below the reservoir.

Mr. Bondurant replied that the density currents are composed of extremely fine sediments, probably a fixed isotropic jell, derived from the movement of clay materials. He was of the opinion that the movement of such materials would require a slope of at least 1 inch per mile (.000016).

