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EROSIONAL AND DEPOSITIONAL CHARACTERISTICS OF COHESIVE SEDIMENTS FOUND IN ELEPHANT BUTTE RESERVOIR, NEW MEXICO

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The Bureau of Reclamation undertook this study to help solve sediment management and water delivery problems at Elephant Butte Reservoir, near Socorro, New Mexico, associated with sediment deposition in the river and conveyance channels. As part of building a mathematical model to predict the erosion and deposition of clays in the Rio Grande, hydraulic modeling to determine the erosional and depositional characteristics of Rio Grande clay samples was identified as a critical element. Laboratory flume tests and rotating cylinder erosion tests were performed on clay samples collected from the upper end of Elephant Butte Reservoir. Critical shear stress for erosion, particle erosion rates, and mass erosion rates were determined in the flume tests. An independent set of rotating cylinder erosion tests was performed to determine the critical shear stress for erosion and the particle erosion rate. Also, flume tests were conducted to determine the threshold shear stress for clay depostion.

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Water Resources Research Laboratory
Water Resources Services
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Denver, Colorado

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INTRODUCTION

Elephant Butte Dam is located about 125 miles north of El Paso, Texas, on the Rio Grande. The dam is part of the multipurpose Rio Grande Project that provides flood control, power, and irrigation water. The reach of river upstream from Elephant Butte is known as the Middle Rio Grande, which extends about 200 miles north of the headwaters of Elephant Butte. Sedimentation problems have long plagued the Middle Rio Grande Valley (Bureau of Reclamation, 1953 and 1967). The Middle Rio Grande has one of the highest sediment loads of any river in the world. A study by Janson et al. (1979) compared the average sediment concentration of the major rivers in the world. Of the 38 rivers compared, 27 have mean sediment concentrations less than 1000 mg/L. According to Janson et al. (1979), the four rivers with the highest sediment concentrations are: (1) Hwang Ho (Yellow River, China) - 15,000 mg/L, (2) Waipapa (New Zealand) - 7,500 mg/L, (3) Ganges (India) - 3,600 mg/L, and (4) Missouri (United States) - 3,200 mg/L. The rate of annual sediment inflow into Elephant Butte has been as high as 13,000 mg/L from 1966 to 1977, and currently is about 5,000 mg/L. The gaging station records of Rio Grande floodway at San Marcial indicate that about 50 percent of the total sediment load carried by Rio Grande to Elephant Butte Reservoir is silt and clay. Inflow of silt and clay amounts to about 2,500,000 tons/yr (Slater and Baird, 1991). The silts and clays are deposited on the overbanks and in the reservoir where velocities are low and the detention period of sediment laden water is long. When the reservoir is high, these fine sediments deposit farther upstream. When the reservoir pool recedes and a defined river channel flows into the reservoir, channel degradation occurs as the delta deposits are transported farther into the reservoir.

From 1951 through 1959, the Rio Grande Conveyance Channel was constructed into the upper 15 miles of Elephant Butte Reservoir. The channel extended an additional 60 miles upstream from the reservoir. The purpose was to improve conveyance of reservoir inflows, which would conserve about 60,000 acre-ft of water annually. The river reach above the reservoir has been aggrading because of high sediment loads for about the last 11,000 to 22,000 yr (Leopold et al. 1964; Hawley et al. 1976), and most recently during this century (Bureau of Reclamation, 1967).

In the early 1980s, Elephant Butte Reservoir filled and inundated the lower reaches of the conveyance channel, and the channel went out of full operation in April 1981. The conveyance channel was operated only occasionally between 1980 and 1985, and has been out of full operation continually since 1985 because of sediment deposition in the conveyance channel and in the Rio Grande channel within the reservoir headwaters. Riverside levees in the Rio Grande upstream from the reservoir have nearly been overtopped several times since 1985 because of sediment deposition attributable to the delta sediment deposits in Elephant Butte Reservoir. Failure of the levee would result in the destruction of about $14,000,000 worth of infrastructure.

PURPOSE

This study was undertaken to help solve sediment management and water delivery problems at Elephant Butte Reservoir, near Socorro, New Mexico, associated with sediment deposition in the river and conveyance channels upstream from the reservoir. As part of building a mathematical model to predict the erosion and deposition of clays in the Rio Grande, hydraulic testing to determine the erosional and depositional characteristics of Rio Grande clay samples was identified as a critical element. Laboratory flume tests and rotating cylinder erosion tests were performed on clay samples collected from the upper end of Elephant Butte Reservoir. Critical shear stress for erosion, particle erosion rates, and mass erosion rates were determined in the flume tests. An independent set of rotating cylinder erosion tests was performed to determine the critical shear stress for erosion and the particle erosion rate. Also, flume tests were conducted to determine the threshold shear stress for clay deposition.

CONCLUSIONS

The erosion test results show that clay from the upper end of Elephant Butte Reservoir has a high critical shear stress. Good agreement was found between the critical shear stress obtained by rotating cylinder tests and flume tests for samples collected from the same location. In general, critical shear stresses for erosion varied from 0.10 to 0.90 lb/ft^2 with the exception of one sample, which had a critical shear stress of nearly zero.

Empirical equations developed by Smerdon and Beasley (1959) were found to be a good predictor of critical shear stress when either the percentage of the clay or the plasticity index of the sample are known. The Bingham shear strength values were lower than the critical shear stress values obtained from rotating cylinder and flume tests.

The clay erosion rates varied widely from sample to sample. This inconsistency was likely caused by various degrees of consolidation and embedded organic debris which caused significant localized erosion. With the exception of two samples, the shear stress at which particle erosion changes to mass erosion could not be clearly defined. Mass erosion was often identified by the removal of discrete layers. For other tests, mass erosion occurred suddenly and would erode the majority of the sample over a short duration.

Particle erosion rates determined from the flume and rotating cylinder erosion tests differed substantially. For the rotating cylinder tests, the slopes of particle erosion rate curves were 6 times and 2 times larger than the slopes of similar erosion rate curves obtained from the flume tests for samples collected at River Sites No. 1 and 2, respectively. A possible explanation for this discrepancy may be the short duration (60 to 90 seconds) of the individual rotating cylinder tests, whereas the flume tests were 2 to 3 hours long. A higher erosion rate would be expected during the start of a test; as a result, the rotating cylinder tests may overpredict erosion rates because of the relatively short test duration. Another factor may be differences in how the shear stress is applied to the sample. The rotating cylinder tests apply shear stress to a cross section of depositional layers in the cylindrical sample. The flume tests apply shear stress to a uniform sediment layer. For example, an erosion resistant layer on the surface of a flume sample will prevent erosion from the underlying sediment layers, unlike the rotating cylinder tests, which can erode the underlying layers. Furthermore, Dr. Ray B. Krone, UCD (University of California at Davis), mentioned in a letter that the rotating cylinder test is insensitive to vertical variations in soil erodibility over the 3-inch sample length.

Rapid deposition of clay particles occur as average channel velocities reach a critical value of about 0.5 ft/s. The bed shear stress at the point of rapid deposition was determined to be 0.021 lb/ft^2 for both spring and summer sediment concentrations because rapid deposition initiated at the same average channel velocity for both tests.

SEDIMENT SAMPLE COLLECTION

Sediment samples were collected with assistance from Reclamation's Socorro Field Division. Samples were collected in February 1994 when Elephant Butte Reservoir was drawn down. Sampling sites were chosen at representative locations in the Rio Grande channel, along the overbanks, and in the delta. Ten samples were collected.

Collection of Clay Samples

The sample collection area extended several river miles upstream from the reservoir headwaters and downstream into the reservoir about 0.25 mi. Ten clay samples were collected from the study reach. Three samples were taken from Rio Grande's overbanks, three samples were taken from the river channel, and four were taken from the reservoir pool. Sampling depth varied from near-surface deposits to about 5 ft below the channel bed.

Sample size was partially dictated by flume size and the maximum sample weight that could be measured by the precision scale. A sample with the largest surface area possible, given the flume facility constraints, was desired to minimize the influence of sample-flume interfaces on erosion rates. A 4-ft-long sample was desired for flume testing. However, this size was considered too large to extract and handle. Therefore, test samples were collected as two 2-ft-long samples, collected side by side.

Collection of minimally disturbed samples was preferred for the erosion tests. Preserving sediment bedding layer integrity of test samples is important when the presence of fine scale bedding layers is likely. Materials deposited in the Rio Grande delta area are distinctly bedded. Likewise, location, depth, and layering of clays, silts, and sands vary throughout the delta area. The wide variability of deposited materials reflects historical changes in reservoir elevation and river alignment at the reservoir delta. In addition to the river sediments deposited in the delta area, layers of organic material are intermixed with delta deposits. These organic deposits result from rapid growth of woody vegetation in the reservoir riparian zone, which is inundated and dies during periods of high reservoir.

Collection of minimally disturbed clay samples was a goal of this study. Consideration was given to in situ freeze core methods and rigid pan sampling. A rigid pan method was selected because of the complexity of freeze core sampling techniques and possible effects on sample consolidation from freezing. Rectangular, 16-gauge sheet metal pans were fabricated to collect each 2-ft sample. Pans were designed with removable end caps to allow sample collection, sample storage, and supporting the sample during erosion testing.

A pontoon-mounted backhoe was used for sample collection. The ability to extract undisturbed samples varied at each site. Samples extracted above the water table were taken by first digging a pit with a vertical face and then pushing a sample pan horizontally into the exposed face (fig. 1). The back side of the backhoe bucket was used to slide pans into the exposed clay. Material surrounding the pans was then trimmed away until the pan and sample could be removed. The top and end surfaces of each sample were trimmed using fine piano wire. Samples were sealed in plastic and placed in an insulated shipping crate. Samples collected at or above free-standing water showed only minor edge disturbance during sampling. Samples taken from within the reservoir or below the water table were collected by sampling from backhoe bucket spoils. Clay material brought to the surface by the backhoe was minimally disturbed in the center of the bucket. Therefore, samples were taken from the center of the bucket spoils using the rigid pan method (fig. 2).

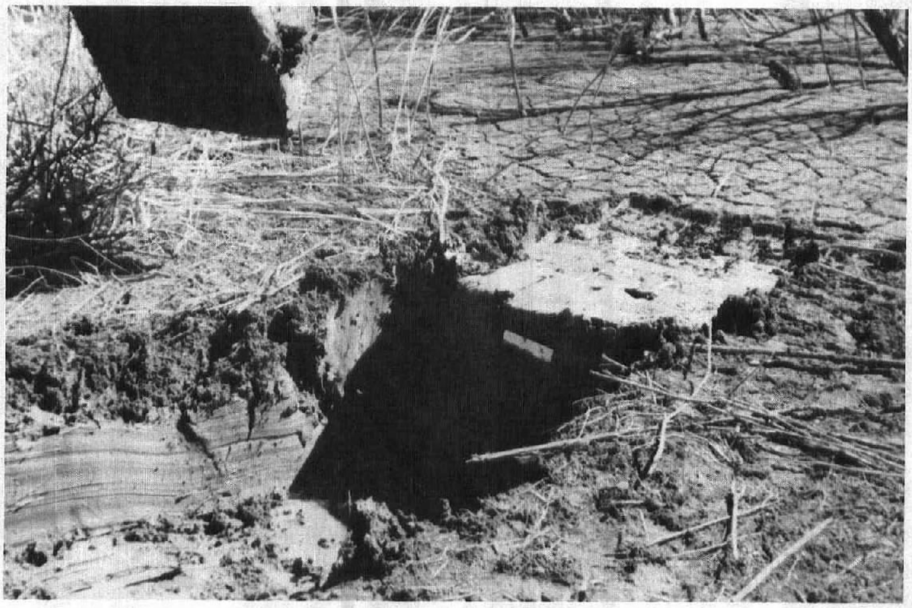


Figure 1. - Photograph of a sample pan driven into an overbank clay deposit using the bucket of the backhoe.

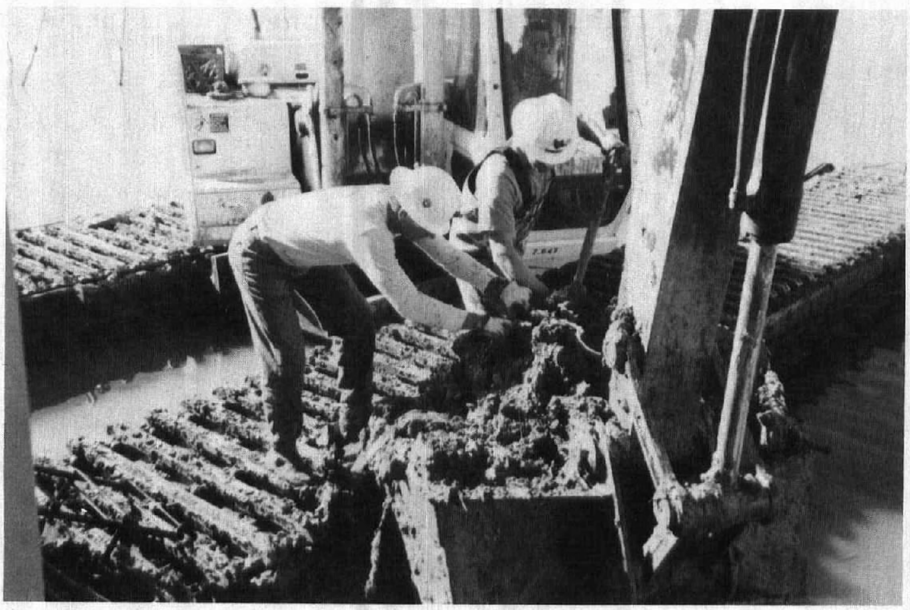


Figure 2. - Photograph of a reservoir sample being collected from the backhoe bucket.

In addition to collection of samples for flume erosion testing, 3-in.-diameter cylindrical samples were also collected for rotating cylinder erosion tests. These samples were collected in a method similar to the rigid pan sampling. A thin-wall cylinder with sharpened edges was pressed into the clay deposits. The cylinder was cut free and the ends were trimmed to a smooth surface using piano wire. The cylinders were capped, wrapped in plastic, and stored in an insulated cooler. Lastly, several samples were collected so the sediment properties could be identified.

A description of each sampling location and the samples collected are as follows:

- **Overbank Site No. 1. -** This site was located about 3,000 ft upstream from the Fort Craig low-flow channel bridge (river mile post 64.7). One sample was taken on the Rio Grande's right overbank (looking downstream) near the low-flow channel levee. An undisturbed, saturated sample was taken about 12 in. below grade (2 pans).

- **Overbank Site No. 2. -** This site was located about 1,000 ft upstream from the Fort Craig low-flow channel bridge. Two samples were taken on the Rio Grande's right overbank (looking downstream) near the low-flow channel levee: 1) an undisturbed, saturated clay sample was taken about 12 in. below grade (2 pans); 2) an undisturbed, very consolidated, saturated clay sample was taken about 60 in. below grade (this sample was pulverized and used for the deposition tests).

- **River Site No. 1. -** This site was located near river mile 59.2. Three samples were taken on the Rio Grande's right overbank (looking downstream) at the end of conveyance channel levee road: 1) an undisturbed, saturated clay sample was taken about 48 to 60 in. below grade; 2) a 6-in.-diameter sample was taken from the same material—this material was used to determine the physical properties on the sample; 3) a 3-in.-diameter sample was taken from the same material for rotating cylinder testing at UCD.

- **River Site No. 2. -** This site was located about 2,500 ft upstream from river mile 59.2. Four samples were taken on the Rio Grande's left overbank about 100 ft upstream from a breach in a levee: 1) an undisturbed, saturated clay sample was taken about 24 in. below grade (2 pans); 2) an undisturbed, saturated clay sample was taken about 60 in. below grade (2 pans); 3) a 6-in.-diameter sample was taken of the same material as sample 2—this material was used to determine the physical properties on the sample; 4) a 3-in.-diameter sample was taken from the same material as sample 1 for rotating cylinder testing at UCD.

- **Reservoir Site No. 1. -** This site was located about 1.0 mile downstream from river mile 59.2. Three samples were taken from Elephant Butte Reservoir; this site was located farther downstream than any other sampling location: 1) An undisturbed, saturated clay sample was taken about 24 in. below surface; 2) a 6-in.-diameter sample was taken from the same material as sample 1—this material was used to determine the physical properties on the sample; 3) a 3-in.-diameter sample was taken of the same material as sample 1 and was sent to UCD for rotating cylinder testing.

- **Reservoir Site No. 2. -** This site was located 1,000 ft upstream from Reservoir Site No. 1. Five samples were taken in an area behind a dredge pile levee in Elephant

Butte Reservoir: 1) a disturbed, saturated, unconsolidated clay sample was taken about 12 in. below grade; 2) an undisturbed, saturated, consolidated clay sample was taken about 8 to 10 ft below grade; 3) an undisturbed, saturated, silty-clay sample was taken about 12 in. below grade; 4) a 6-in.-diameter sample was taken of the same material as sample 3—this material was used to determine the physical properties on the sample; 5) a 3-in.-diameter sample was taken from the same material as sample 2 and was sent to UCD.

Sample Storage and Preparation

Clay samples sealed with plastic were stored in an environmental chamber which maintained a constant temperature of 40 °F and a relative humidity of 99.5 pct. Prior to testing, samples were submerged in simulated Rio Grande water for at least 24 hours to re-saturate the surface material. Sample installation required removing the end caps of the sample tray and using fine wire to remove material projecting above the edges of the pan. Two pans were then placed in the flume end to end. Gaps between the two samples and at the floor joints were filled with excess clay removed during sample preparation. The gaps were filled to prevent erosion from initiating at surface discontinuities. Upon completing the sample installation, the flume was filled to a 9-in. depth with simulated Rio Grande water.

Analysis of Sediment Samples

Reclamation's Earth Sciences and Research Laboratory determined the physical properties of samples collected at the River Sites No. 1 and 2 and Reservoir Sites No. 1 and 2. Index properties, unconfined compression tests, and vane shear tests were performed. Index properties include dry unit weight, gradation analysis with hydrometer, Atterberg limits, and specific gravity. A summary of the sediment properties is presented in table 1.

FLUME TESTING

The hydraulic erosion and the deposition of cohesive sediments are extremely complex processes. Numerous field and laboratory investigations over the last three decades have provided a great deal of insight into the fluid and soil characteristics which influence the processes, as well as the mechanisms of erosion and deposition. In studies by Smerdon and Beasley (1959), data were obtained to predict erosion characteristics using relatively simple empirical models based on properties like plasticity index, dispersion ratio, mean particle size, and critical bed shear stress. Empirical models for the rates of erosion and deposition of cohesive sediments are often used in numerical sediment transport models. Studies by Partheniades (1962 and 1965) concentrated on the development and application of erosion rate models based on bed shear stresses. However, all these advancements have not produced any universally accepted methods to predict the rates of erosion and deposition that do not require field or laboratory evaluation of empirical model parameters.

Laboratory flume studies are considered to be the most dependable tests to determine empirical model parameters. However, flume studies are difficult to conduct and results must be extrapolated to field conditions. The most dependable erosion tests are carried out in flumes in which sediment forms a significant portion of the bottom (Partheniades and Paaswell, 1970). Sediment samples should be collected and tested in a state representative of the natural bed conditions. Likewise, research has demonstrated that the chemical quality of the eroding fluid should be representative of field conditions.

Table 1. - Results of index properties, unconfined compression tests, and laboratory vane shear tests for samples collected at River Site No. 1, River Site No. 2, Reservoir Site No. 1, and Reservoir Site No. 2.

Index Properties					Unconfined Compression Test			Laboratory Vane Shear					
									Break Bond	360° Rotation	720° Rotation	1080° Rotation	1440° Rotation
Sample Location	Classification	Specific Gravity	Sample Moisture Content %	Sample Dry Unit Weight lbf/ft³	Strain %	Unconfined Compressive Strength lbf/in²	Undrained Shearing Strength lbf/in²	Trial	Maximum Undrained Shearing Resistance lbf/in²	Maximum Undrained Shearing Resistance lbf/in²	Maximum Undrained Shearing Resistance lbf/in²	Maximum Undrained Shearing Resistance lbf/in²	Maximum Undrained Shearing Resistance lbf/in²
River Site No. 1	Fat Clay	2.69	61.4	58.9	1.7	2.4	1.2	1	0.550	0.242	0.207	0.177	0.170
								2	0.847	0.486	0.436	0.417	0.418
								3	0.709	0.358	0.332	0.377	0.306
								4	0.955	0.563	0.518	0.494	0.496
River Site No. 2	Fat Clay	2.68	58.7	56.8	14.2	2.2	1.1	1	0.991	0.400	0.335	0.304	0.285
								2	0.773	0.355	0.299	0.282	0.264
								3	0.651	0.327	0.258	0.237	0.230
								4	0.628	0.237	0.184	0.164	0.149
								5	0.849	0.352	0.271	0.238	0.225
Reservoir Site No. 1	Fat Clay	2.58	83.8	49.4	15.3	1.6	0.8	1	0.268	0.176	0.137	0.128	0.118
								2	0.263	0.142	0.123	0.117	0.108
								3	0.257	0.135	0.120	0.111	0.108
Reservoir Site No. 2	Silt	2.67	30.1	81.6	8	8.8		1	0.784	0.130	0.088	0.056	
								2	0.439	0.179	0.105	0.211	0.061
								3	0.587	0.185	0.162	0.150	
								4	0.792	0.301	0.334	0.242	0.266
								5	0.590	0.063	0.048		

A recirculating flume is normally used for erosion and deposition studies. Recirculating systems present several problems. Turbulence generated by pumps and piping can shear the cohesive bed material, resulting in a decreased particle size distribution and reduced settling velocities. The storage volume of the flume should be small to minimize the loss of sediment by deposition in the return conduits. Hydraulic considerations during test design should include the ability to control the channel slope to obtain uniform depths across the sample. The headbox and tailbox should be designed to minimize entrance and exit disturbances.

The Recirculating Flume

The flume (fig. 3) has a channel length of 12 ft, a depth of 1.5 ft, and a width of 11.5 in. The flume walls were constructed from clear acrylic sheets. The flume floor was made of a high density, closed-cell urethane and has a surface roughness similar to fine sand. Water is recirculated using a 15-hp centrifugal pump with a capacity of 5 ft^3/s under 10 ft of pressure head. Flow rate was regulated using a variable speed, programmable motor controller. Flow rates were measured using a strap-on acoustic flow meter. The inlet consisted of a constant head tank with flow straightening vanes. In addition, tube-type diffusers were used to improve the velocity distribution entering the flume. Return flows were taken from a slightly oversized tank attached to the end of the flume. Vanes were used to minimize air entrained by flow entering the tank. Recirculating water in the system was not stored, so deposition could only occur in the flume and not in the conveyance system.

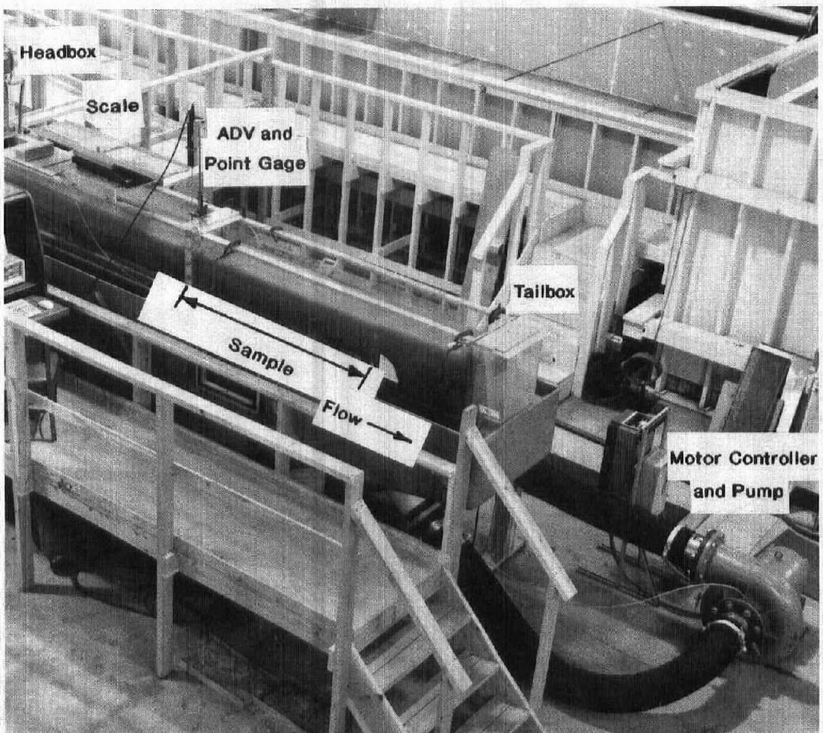


Figure 3. - Photograph of recirculating flume, scale and carriage, ADV (acoustic Doppler velocimeter) probe, and point gage. The pump and motor controller are positioned in the lower right side of the photograph.

Clay samples were installed in the flume flush with the urethane floor. Samples were located 7 ft downstream from the inlet and 1 ft upstream from the end of the flume. Each sample pan was 2 ft long, 2.5 in. deep, and 11.5 in. wide, and two pans were installed end to end to form one sample. The clay sample covered 33 pct of the flume length. The entire flume can be tilted from horizontal to an 8-pct slope. An instrumentation carriage, movable over the entire length of the flume, was used to position a precision scale. The scale was used to measure the sample's submerged weight.

Reclamation's Sedimentation and River Hydraulics Group determined a typical water quality using U.S. Geological Survey water quality data. The primary constituents and concentrations in Rio Grande water are sodium (58.6 mg/L), magnesium (10.2 mg/L), calcium (56.4 mg/L), chloride (34.8 mg/L), bicarbonate (96.0 mg/L), and sulfate (119.2 mg/L). A typical pH for Rio Grande water was reported to be 8.1. Water quality analyses were performed by Reclamation's Water Treatment Engineering and Research Group, and they provided a chemical mixture used to produce Rio Grande quality from our laboratory water supply. The water was prepared in a separate tank and pumped into the flume at the beginning of each test. Flume water was monitored with a pH meter to maintain a pH of 8.1. Temperature control features were not incorporated into the flume.

DATA COLLECTION

Data collected for this study consisted of vertical velocity profiles, discharge, water surface elevations, water temperature, and sample weights. Typically, these data were collected at the beginning and end of each individual erosion test.

Velocity Measurements

Velocity measurements were collected using an ADV (acoustic Doppler velocimeter). An ADV uses remote sensing techniques to measure simultaneously three components (u, v, and w) of water velocity from a single sampling volume. Sampling volume is located 2 in. below the probe head and is cylindrical in shape (0.08-in. diameter and 0.24-in. length). Consequently, the probe has minimal impact on the flow field surrounding the measurement volume. Velocity data were sampled at an output rate of 20 Hz. The ADV's horizontal velocity range is ±8 ft/s. Probe operation and data storage were controlled using a personal computer.

Velocity profiles were collected by mounting the ADV probe to a point gage. The point gage's point was positioned at the same level as the ADV's measurement volume location. The point gage was located about 3 in. behind the measurement volume. Profiles were collected by starting with the point gage resting on the floor and moving the gage upward at set increments. Velocities were collected every 0.04 in. within the boundary layer and at least every 0.4 in. thereafter. Individual velocity measurements were taken as the average value of 200 ADV measurements. Velocities within 2 in. of the water surface could not be measured by the ADV because the probe must be completely submerged to operate.

Discharge Measurements

Discharge measurements were taken with a strap-on acoustic flowmeter. The flowmeter was mounted to an 8-in.-diameter return flow pipe. Discharge measurements were used to check the average channel velocities measured by the ADV. However, discharge could not be measured at high flows because air entrainment would interrupt the acoustic signal.

Water Surface Elevations

Water surface elevation measurements were determined by the same point gage used for velocity profiling. Water depths were only used to determine the average channel velocities using continuity. The flow was often very rapid and wavy; therefore, measuring an average water depth was difficult.

Submerged Sample Weights

Submerged sample weights were determined using an electronic scale accurate to the nearest 0.001 lb. Prior to and after each test run, the clay sample was lifted using a hydraulic jack and placed on the scale, and the submerged weight was measured. Specific gravity and temperature of the water were measured and used to correct for the small change in the sample's submerged weight caused by change in water density.

Erosion Tests

Typically, erosion tests were 3 hours long and were conducted at a constant flow rate. Subsequent tests were always conducted at a higher flow rate. Initially, water depths were relatively constant over the length of the horizontal flume for lower flows. At higher flows, water depths were adjusted to be nearly uniform by adjusting the slope of the flume. However, uniform flow was rarely achieved because of the relatively short flume length. Clay erosion rates were determined using an electronic scale. After the submerged weight was established, the sample was lowered into a position flush with the floor of the flume and the next erosion test was started. Erosion rates were calculated by dividing the change in sample weight by the elapsed time of the test and the sample's surface area. Erosions tests were terminated when the sample was eroded sufficiently to expose the bottom of the sheet metal pan. Two velocity profiles were measured for each erosion test, one upstream from the sample and the second just downstream from the sample. Profiles were not measured directly over the sample because of the difficulty in locating the sample's surface during the erosion process. A typical set of velocity profile data is shown on figure 4.

Deposition Tests

Deposition tests were conducted to determine the depositional characteristics of silt and clay particles carried by the Rio Grande. Material for deposition tests was obtained from an extra erosion sample collected at Overbank Site No. 2. The dried sample was mechanically pulverized and sieved. Only material passing the No. 200 U.S. Standard sieve (particle diameters less than 0.075 mm) was used for these deposition tests. Clay and silt were thoroughly mixed into simulated Rio Grande water and pumped into the flume. Typically, deposition tests were 24 hours long and were conducted at a constant flow rate. Subsequent tests were always conducted at a lower flow rate. Reclamation's Sedimentation and River Hydraulics Group used historical suspended sediment records to determine the average Rio Grande spring, summer, and fall suspended sediment concentrations to be 2,600 mg/L, 8,500 mg/L, and 2100 mg/L, respectively.

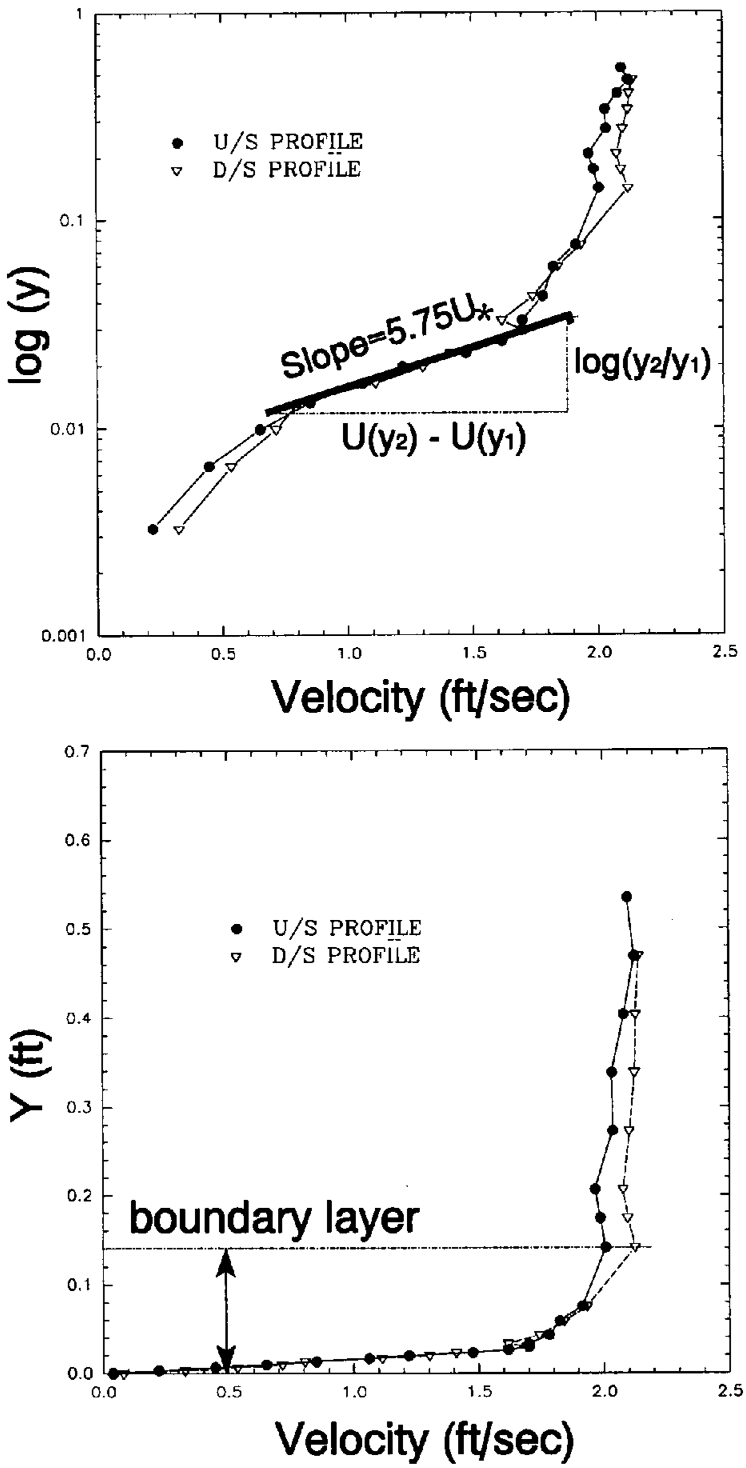


Figure 4. - A typical velocity profile is shown in the lower plot. The upper plot was used to determine the shear velocity, U_*. Velocity profiles were collected upstream (U/S) and downstream (D/S) from the sediment sample.

Two deposition tests were conducted for initial concentrations similar to average spring and summer suspended sediment concentrations. For the deposition tests, initial suspended sediment concentrations for spring and summer deposition tests were analyzed and reported to be 2,300 and 10,800 mg/L, respectively. Deposition tests were started at average channel velocities near 1.5 ft/s, which was sufficient to keep the silt and clay particles in suspension. A clay sample was installed in the flume in the same manner as described for the erosion tests to simulate a clay river bottom. Clay deposition rates for a 24-hour period were determined by taking total suspended solid samples at the beginning of each test. Similarly, the ADV signal strength, which indicates sediment concentration, was continuously measured. Water temperatures were measured and were nearly constant over the entire test. No appreciable temperature gain occurred because pump speeds were low. Average channel velocities were measured using the six-tenths-depth method. The ADV was positioned to measure the velocity at six-tenths of the depth from the water surface. Velocity profiles were only measured at flows where rapid deposition occurred. Velocity profiles were used to determine the bed shear stress using the same procedure as described for the erosion tests.

DATA ANALYSIS

Several methods can be used to determine shear velocity and shear stress at a boundary. Researchers have successfully used boundary-layer theory and uniform flow equations to compute bed shear stress, τ_0, for turbulent flows by determining shear velocity, U_*. Graf et al. (1995) compared three methods for calculating shear velocity. Their results indicated that using the slope of the logarithmic velocity distribution was comparable to using the Reynolds-stress distribution (a direct method based on Prandtl's mixing length theory) and the uniform flow relation, $U_*=(gR_hS_b)^{1/2}$. Because ADV instrumentation allowed accurate, rapid collection of velocity measurements within the boundary layer, the logarithmic velocity distribution law was selected as the basis for calculating shear velocities for these erosion tests. Another consideration was that uniform flow did not always exist in the flume, so a boundary layer approach allowed for a consistent method of analysis for uniform and nonuniform flows.

Shear Velocity and Bed Shear Stress Calculations

Shear velocity, U_*, and bed shear stress, τ_0, were calculated from velocity data measured in the turbulent boundary layer. The logarithmic velocity distribution law (Kármán-Prandtl equation) for turbulent flow over a smooth boundary (eq 1) was used to calculate U_* assuming uniform flow.

$$\frac{U(y)}{U_*} = 5.75 \log\frac{U_* \, y}{\nu} + 5.5 \qquad \textbf{(1)}$$

where $U(y)$ is the velocity (ft/s) at a distance y (ft) from the boundary, ν is the kinematic viscosity of the fluid (ft^2/s), and ρ is the mass density of the fluid (slugs/ft^3). Using two point velocity measurements in the boundary layer, U_* can be determined by rewriting equation 1 as follows:

$$U(y_2)-U(y_1) = 5.75 \; U_* \; [\log\frac{y_2}{\nu} - \log\frac{y_1}{\nu}] \equiv$$

$$U_* = \frac{U(y_2)-U(y_1)}{5.75 \; \log\frac{y_2}{y_1}}$$

An example of this procedure is shown on figure 4.

Once U_* was known, then bed shear stress was calculated from the definition of shear velocity (eq 2):

$$U_* = \sqrt{\frac{\tau_o}{\rho}} \tag{2}$$

or the bed shear stress can be computed directly from equation 3:

$$\tau_o = \rho \left[\frac{U(y_2) - U(y_1)}{5.75 \log \frac{y_2}{y_1}} \right]^2 \tag{3}$$

Bed shear stress was then compared to the rate of clay erosion over a series of tests to establish the shear stress at incipient particle erosion, $\tau_{critical}$; shear stress at incipient mass erosion, τ_{mass}; slope of the particle erosion rate curve, ER_1; and the slope of the mass erosion rate curve, ER_2. A schematic of an ideal set of erosion characteristics is shown on figure 5.

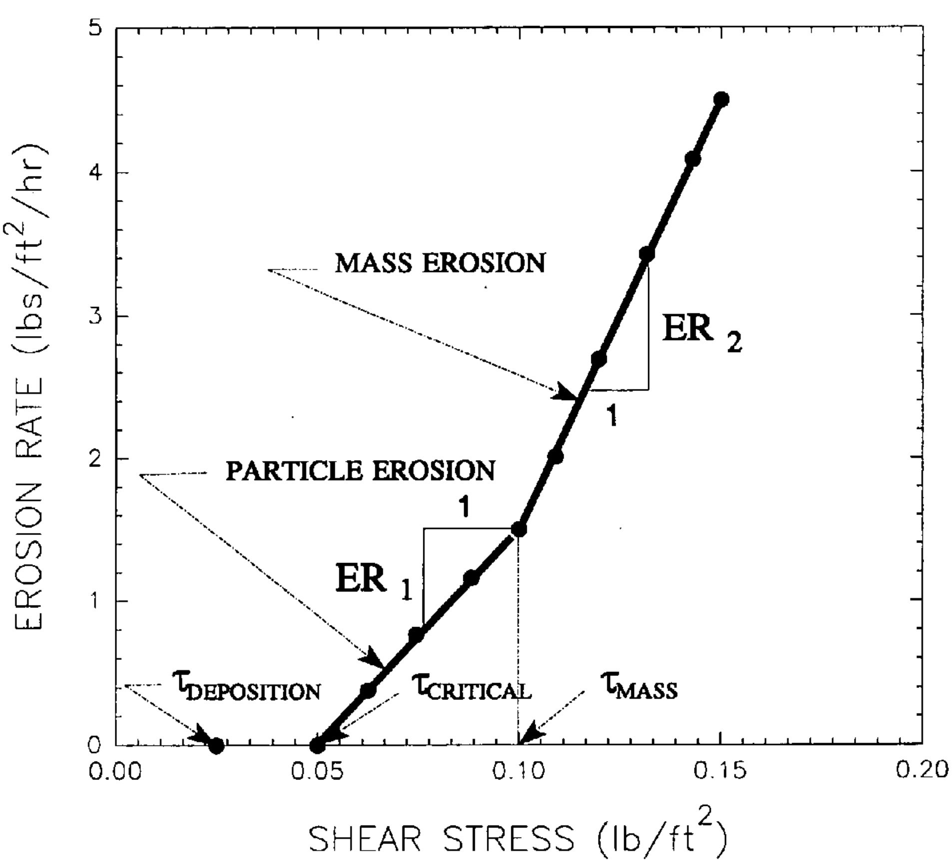


Figure 5. - This schematic illustrates the erosional characteristics that were determined from the erosion tests.

RESULTS

The results from the flume studies are presented as an evaluation of the erosional and depositional characteristics in both a quantitative and qualitative sense. Results for the UCD rotating cylinder erosion tests are also included in a separate section. Variability in test results made it difficult to combine the results of all erosion tests into one set of data which could describe the erosional characteristics of samples collected in the reservoir, river, or floodplain.

Erosional Patterns

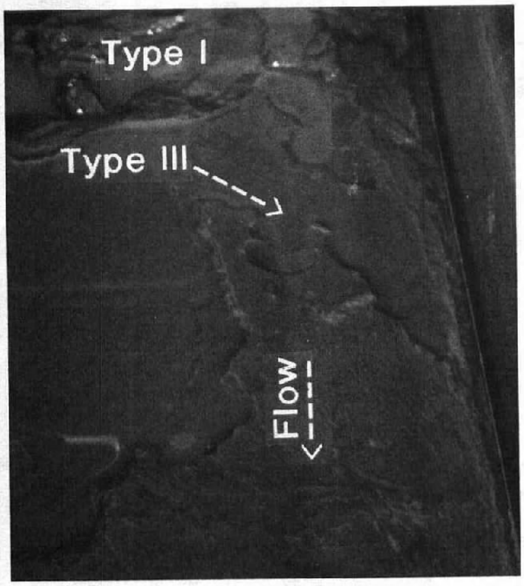
In general, all but one of the clay samples (a silty-clay sample) were very resistant to erosion. Four types of erosion were observed during tests. The initial type of erosion (Type I) occurred when the sample began to erode at the interface of the sample and the flume floor (fig. 6). Type I erosion quickly stabilized, and the next type of erosion (Type II) was initiated at locations where organic materials protruded from the sample (fig. 7). Type II erosion was by far the most destructive to the sample because deep channels would form behind the twig or reed (fig. 8). Type III erosion was the removal of discrete layers of cohesive sediment (fig. 6). This type of erosion was common in samples without organics. The eroded layers varied in thickness and appeared to form at random locations. The final type (Type IV) of erosion occurred when large pieces of material were sheared off the sample (fig. 7).

FLUME TEST RESULTS

Flume erosion tests were conducted on nine samples over a wide range of bed shear stresses. Test results were highly variable, which hindered data interpretation. Results from the nine tests are presented on figures 9 through 17 and in table 2, and more detailed test data are included in the appendix. In general, critical shear stresses for erosion varied from 0.10 to 0.90 lb/ft^2 with the exception of the silty-clay sample, which had a critical shear stress of nearly zero. Test results indicated that consolidated samples (overbank and river) were more difficult to erode than unconsolidated (reservoir) samples and a silty-clay sample. However, individual data points within each erosion test were inconsistent and added uncertainty to data quality. As a result, some data were so inconsistent that no information was obtained from those tests. Likewise, test data were difficult to analyze because of the variability of erosion rates measured throughout an erosion test. For example, some tests exhibited rapid erosion at one flow rate and reduced erosion at a higher flow rate. This behavior was most likely caused by variability in the silt and clay layers and the exposure of organic matter in the samples. Despite the variability in test data, several tests provided complete or partial erosional characteristics that will be used in the sediment transport modeling efforts.

Rotating Cylinder Erosion Tests

RCE (Resource Consultants and Engineers), in conjunction with Dr. Ray B. Krone and UCD, were contracted to test four samples to determine the erosional characteristics using the rotating cylinder erosion test. The rotating cylinder test procedure is unique and only performed at UCD. The samples were also tested for grain size distribution using the hydrometer method (as described in ASTM standard D 422-63) and to determine the cation exchange capacity. Four samples were sent to Dr. Krone at UCD to conduct rotating cylinder erosion tests. The rotating cylinder erosion test is described in a technical paper by Arulanandan et al. (1975).



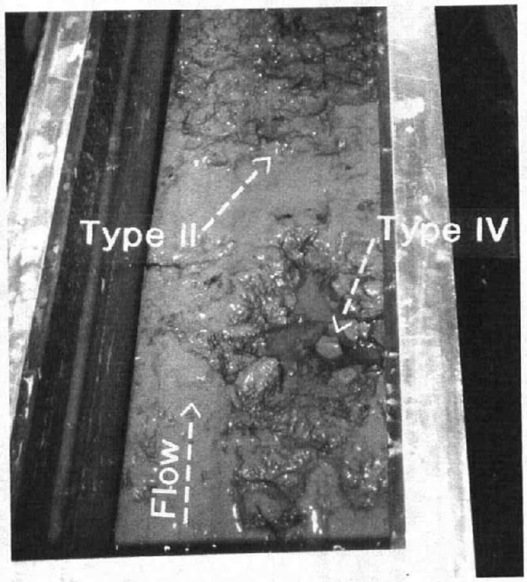


Figure 6. - A typical example of Type I and III erosion. This sample was collected about 8 ft below the surface at Reservoir Site No. 2.

Figure 7. - A typical example of Type II and IV erosion. This sample was collected near the surface at Overbank Site No. 1.

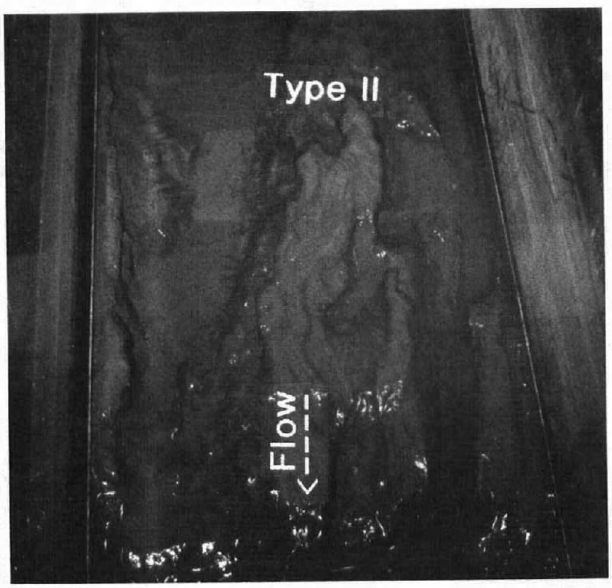


Figure 8. - Example of severe Type II erosion. This sample was collected near the surface at Reservoir Site No. 2.

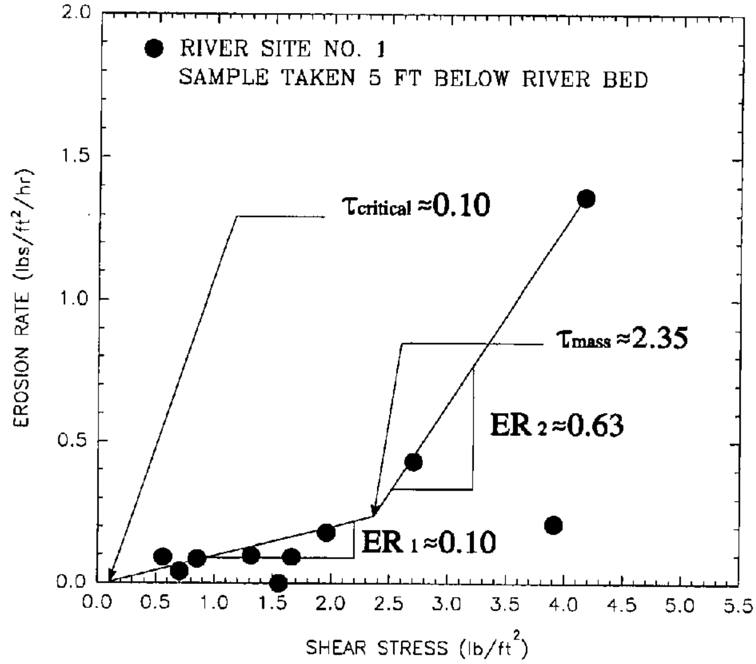


Figure 9. - Erosion characteristics for clay sample collected at River Site No. 1. This sample was collected 5 ft below the river bottom.

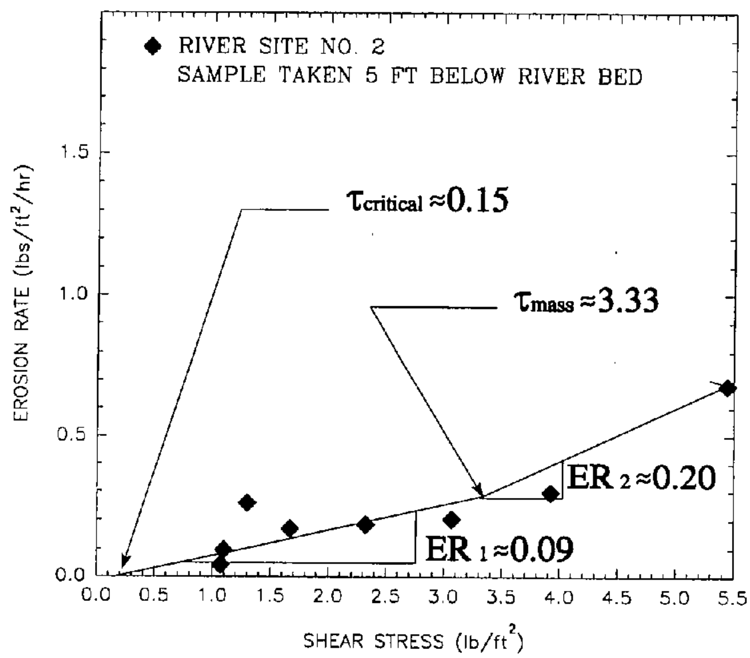


Figure 10. - Erosion characteristics for clay sample collected at River Site No. 2. This sample was collected 5 ft below the river bottom.

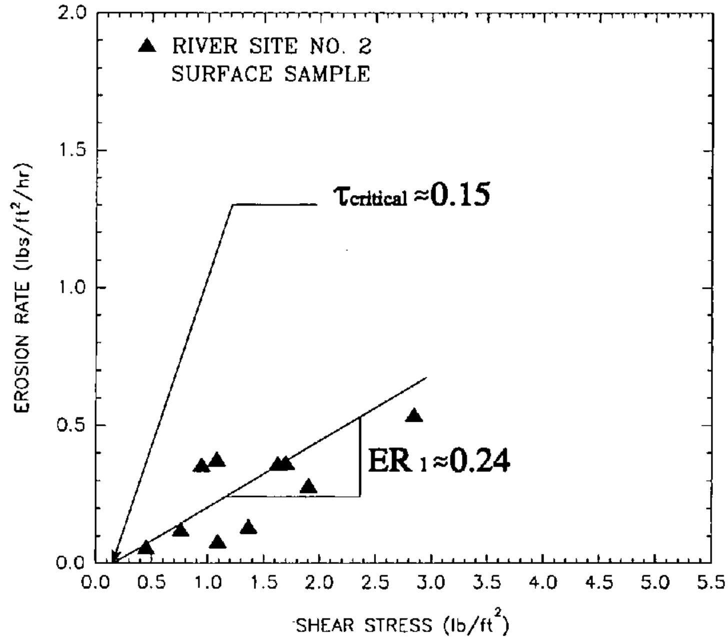


Figure 11. - Erosion characteristics for clay sample collected at River Site No. 2. This sample was collected just below the river bottom.

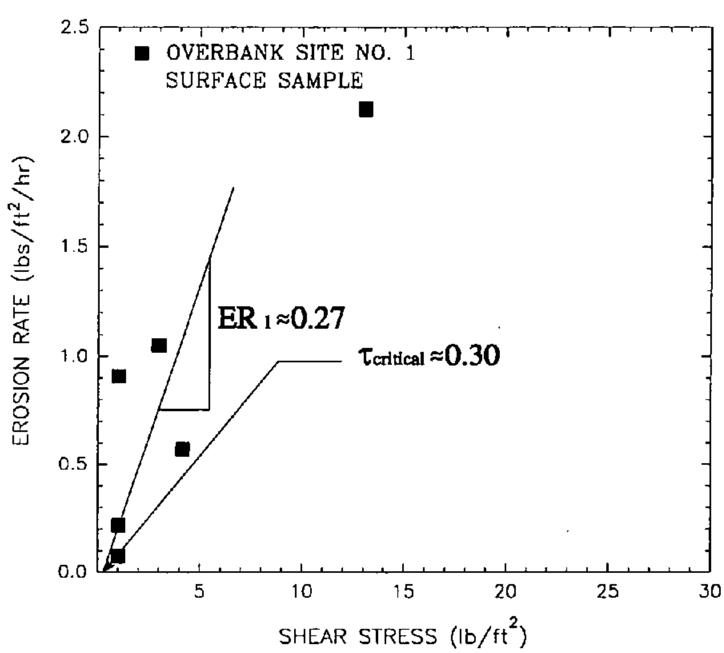


Figure 12. - Erosion characteristics for clay sample collected at Overbank Site No. 1. This saturated sample was collected 1 ft below the surface.

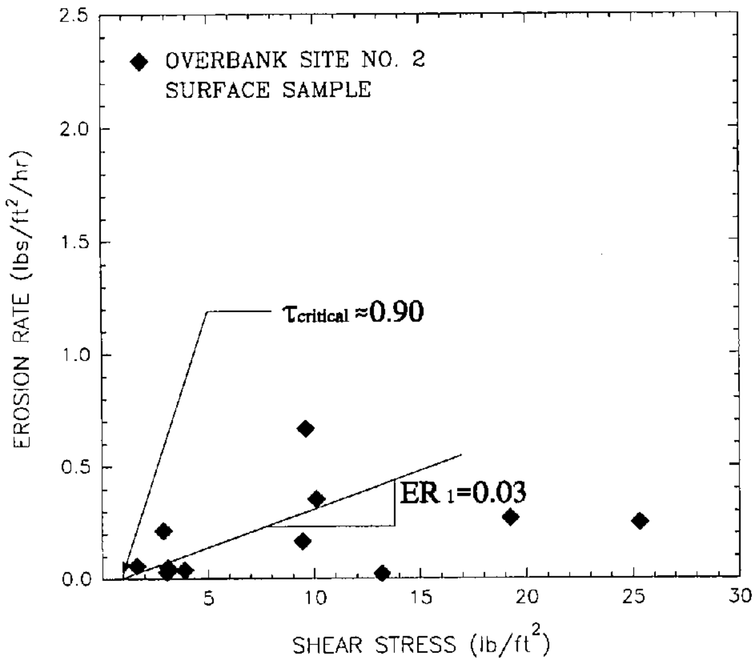


Figure 13. - Erosion characteristics for clay sample collected at Overbank Site No. 2. This saturated sample was collected 1 ft below the surface.

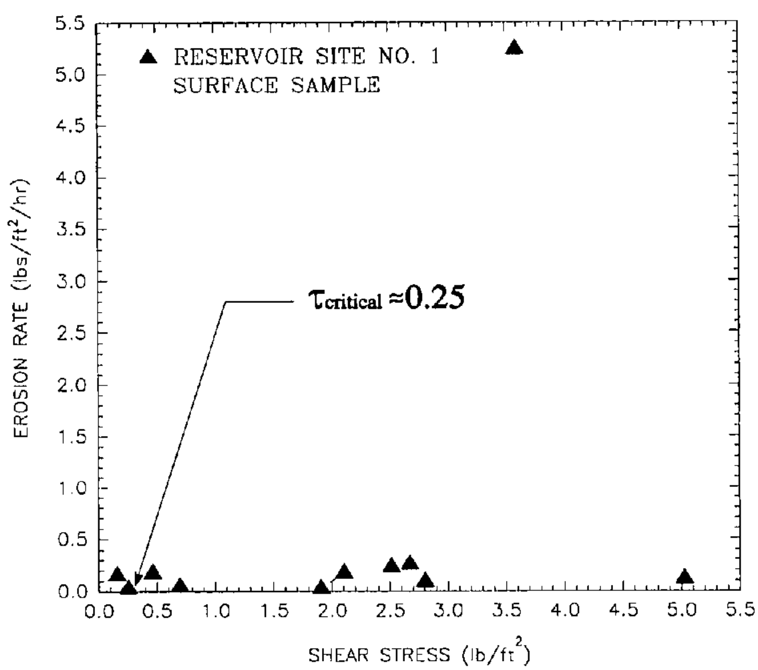


Figure 14. - Erosion characteristics for clay sample collected at Reservoir Site No. 1. This unconsolidated sample was collected about 2 ft below the reservoir bottom.

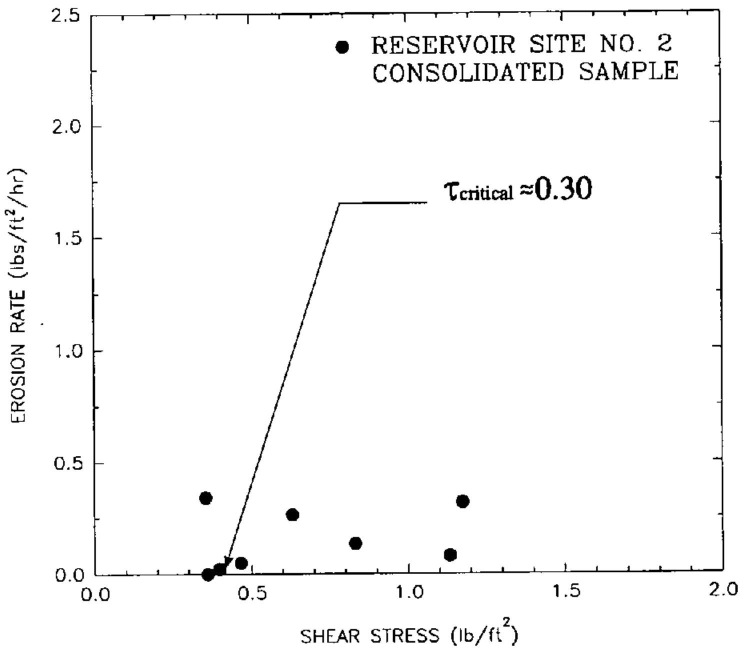


Figure 15. - Erosion characteristics for clay sample collected at Reservoir Site No. 2. This consolidated sample was collected about 8 ft below the reservoir bottom.

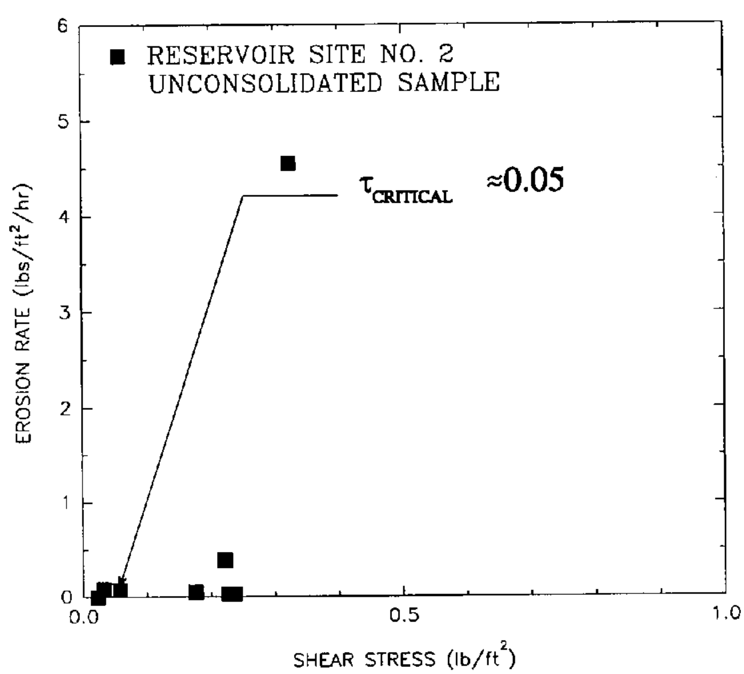


Figure 16. - Erosion characteristics for clay sample collected at Reservoir Site No. 2. This disturbed, unconsolidated sample was collected 1 ft below the reservoir bottom.

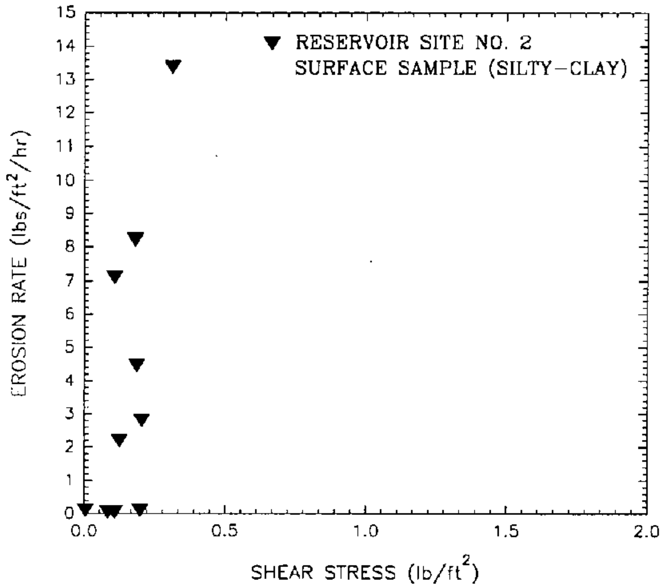


Figure 17. - Erosion characteristics for clay sample collected at Reservoir Site No. 2. This consolidated sample was collected about 1 ft below the reservoir bottom.

Table 2. - Erosional characteristics for flume tests on eight Elephant Butte Reservoir clay samples.

Sample Identification	Critical shear stress for particle erosion $\tau_{critical}$ (lb/ft^2)	Critical shear stress for mass erosion τ_{mass} (lb/ft^2)	Slope of particle erosion rate curve, ER_1	Slope of mass erosion rate curve, ER_2
River Site No. 1, deep sample	0.10	2.35	0.10	0.63
River Site No. 2, deep sample	0.15	3.33	0.09	0.20
River Site No. 2, surface sample	0.15	n/a	0.24	n/a
Overbank Site No. 1, surface sample	0.30	n/a	0.27	n/a
Overbank Site No. 2, surface sample	0.90	n/a	0.03	n/a
Reservoir Site No. 1, surface sample	0.25	n/a	n/a	n/a
Reservoir Site No. 2, consolidated sample	0.30	n/a	n/a	n/a
Reservoir Site No. 2, unconsolidated sample	0.05	n/a	n/a	n/a
Reservoir Site No. 2, surface, silty-clay sample	n/a	n/a	n/a	n/a

n/a - applies to data sets which were incomplete or too inconsistent to interpret

Of the four samples sent to be tested, two unconsolidated samples (from Reservoir Sites No. 2 and 1) fell apart during preparation for testing. Two consolidated samples were tested; one was collected from 5 ft below the river bed (River Site No. 1) and the other from 2 ft below the river bed (River Site No. 2). Physical properties, critical shear stresses, and particle erosion rates of the four samples are reported in table 3. According to Dr. Krone, rotating cylinder erosion tests are not suited to determine the mass erosion characteristics (τ_{mass} and ER_2).

Table 3. - Percent clay, CEC (cation exchange capacity), plasticity index, and soil classification for four erosion samples.

Sample identification	Percent Clay (pct)	CEC (meq/100 gm of soil)	Plasticity Index	Critical shear stress for particle erosion $\tau_{critical}$ (lb/ft^2)	Slope of particle erosion rate curve, ER_1	Unified Soil Classification
River Site No. 1	75.7	34.8	54	0.13	6.25	CH
River Site No. 2	71.8	36.4	53	0.12	10.00	CH
Reservoir Site No. 1	81.5	38.6	72	n/a	n/a	CH
Reservoir Site No. 2	89.2	38.4	n/a	n/a	n/a	n/a

The rotating cylinder erosion test results for the two samples, as interpreted by Dr. Krone, are presented on figures 18 and 19. Good agreement was found between the critical shear stress obtained by rotating cylinder erosion tests and flume erosion tests for samples collected from the same location. However, slopes of particle erosion rate curves, ER_1, for the flume and rotating cylinder erosion tests differed substantially. The rotating cylinder ER_1 values were 6 times and 2 times larger than erosion rates measured in the flume for samples collected at River Sites No. 1 and 2, respectively. A possible explanation for this discrepancy may be the short duration (60 to 90 seconds) of the individual rotating cylinder tests, whereas the flume tests were 2 to 3 hours long. An increased erosion rate would be expected during the start-up phase of a test. As a result, the rotating cylinder tests may overpredict erosion rates because of their relatively short duration. Another factor may be differences in sample collection and preparation. The rotating cylinder tests required each core sample to be shaped into a 3-inch diameter cylinder. The sample shaping may have affected the erodibility of the samples. Conversely, flume test samples were disturbed only when trimmed so that the sample surface was level with the flume floor.

Comparison of Critical Shear Stress Results

The results from the flume tests and the rotating cylinder erosion tests are compared in table 4. Also shown in the table is the critical shear stress obtained from the relations developed by Smerdon and Beasley (1959) and the Bingham shear strength equation developed by Krone (1983). Equations 4 and 5 were developed by Smerdon and Beasley using observations from a number of flume erosion tests on cohesive sediments.

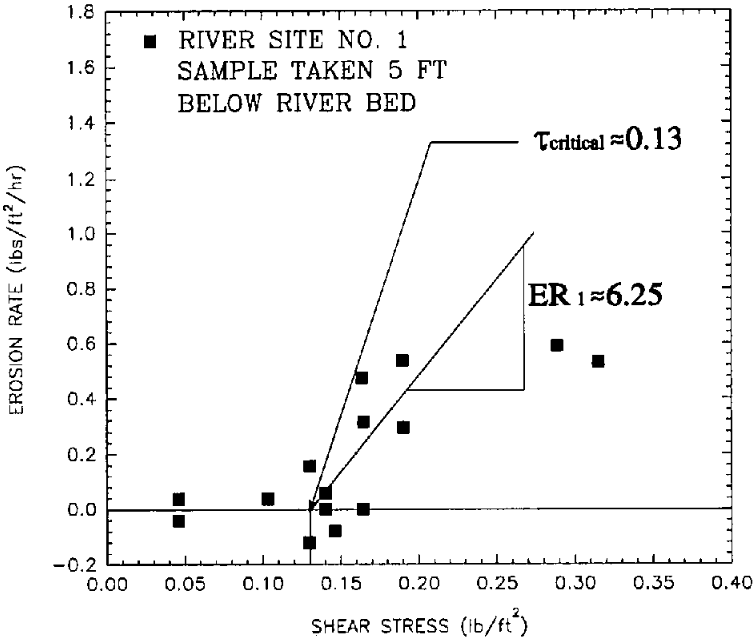


Figure 18. - Erosion characteristics for UCD rotating cylinder test No. 1. This sample was collected 5 ft below the bed at River Site No. 1.

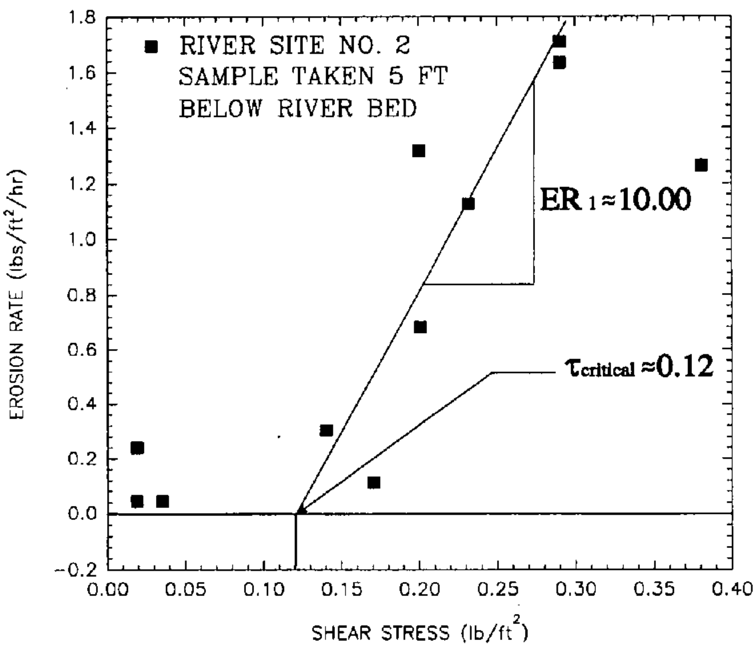


Figure 19. - Erosion characteristics for UCD rotating cylinder test No. 2. This sample was collected 5 ft below the bed at River Site No. 2.

$$\tau_{critical} = 0.0034\ (PI)^{0.84} \quad (4)$$

$$\tau_{critical} = 0.00645 * 10^{(0.0182 P_C)} \quad (5)$$

where:

$\tau_{critical}$ = critical shear stress (lb/ft^2)
PI = plasticity index
P_C = percentage of clay in a sample

Table 4. - Comparison of critical shear stress obtained by rotating cylinder tests, flume tests, and empirical equations.

Sample Identification	Critical Shear Stress, $\tau_{critical}$ (lb/ft^2)				
	Rotating cylinder results	Flume test results	Using Eq 4	Using Eq 5	Using Eq 6
River Site No. 1	0.13	0.10	0.10	0.15	0.070
River Site No. 2	0.12	0.15	0.10	0.13	0.073
Reservoir Site No. 1	n/a	0.25	0.12	0.20	0.077
Reservoir Site No. 2	n/a	0.30	n/a	0.27	0.076

The Bingham shear strengths for the clay samples tested at UCD were calculated using the relationship developed by Krone (eq 6):

$$S_B = 0.0021\ [3.92 + 0.8447(CEC)] \quad (6)$$

where:

S_B = the Bingham shear strength (lb/ft^2)
CEC = the cation exchange capacity of the clay material (meq/100 g)

The calculated Bingham shear strengths of the four samples are presented in table 4.

As shown in table 4, critical shear stress obtained from rotating cylinder erosion tests and the flume test for similar samples are about equal. However, only samples from River Sites No. 1 and 2 were available for a direct comparison. The critical shear stress computed using the plasticity index and equation 4 is about the same as the shear stress obtained by rotating cylinder and flume tests. The critical shear stress computed using the percentage clay and equation 5 was also in close agreement with flume and rotating cylinder tests. The Bingham shear stress values are lower than the critical shear stress values obtained in the rotating cylinder test and the flume test. For the samples tested, the best predictor of critical shear stress is the Smerdon and Beasley relationship using percent clay.

DEPOSITION TESTS

Two deposition tests were conducted for initial concentrations similar to the average spring and summer suspended sediment concentrations, which were 2,150 and 10,800 mg/L, respectively. Deposition tests were done to determine the shear stress at which the flow is unable to carry cohesive sediments in suspension. Several characteristics were observed for both deposition tests:

1. Each test had an initial settling period where silt would rapidly settle out of suspension.

2. Suspended sediment concentrations at each flow rate would decay to an equilibrium value. An equilibrium concentration was reached for each flow rate and was a function of the maximum particle size the turbulence intensity could keep in suspension.

3. As average channel velocities approach a critical value (about 0.9 ft/sec), settling rates change from minor to significant (figs. 20 and 21).

4. As average channel velocities reach a critical value of about 0.5 ft/s, rapid deposition of all remaining size fractions occurs. This observation was consistent with a range of velocities (0.47 to 0.58 ft/s) presented by Partheniades (1965).

5. The bed shear stress at the point of rapid deposition was calculated from a velocity profile measured upstream from the clay sample. The bed shear stress was determined to be 0.021 lb/ft^2, which is valid for both spring and summer concentrations because rapid deposition initiated at nearly the same average channel velocity.

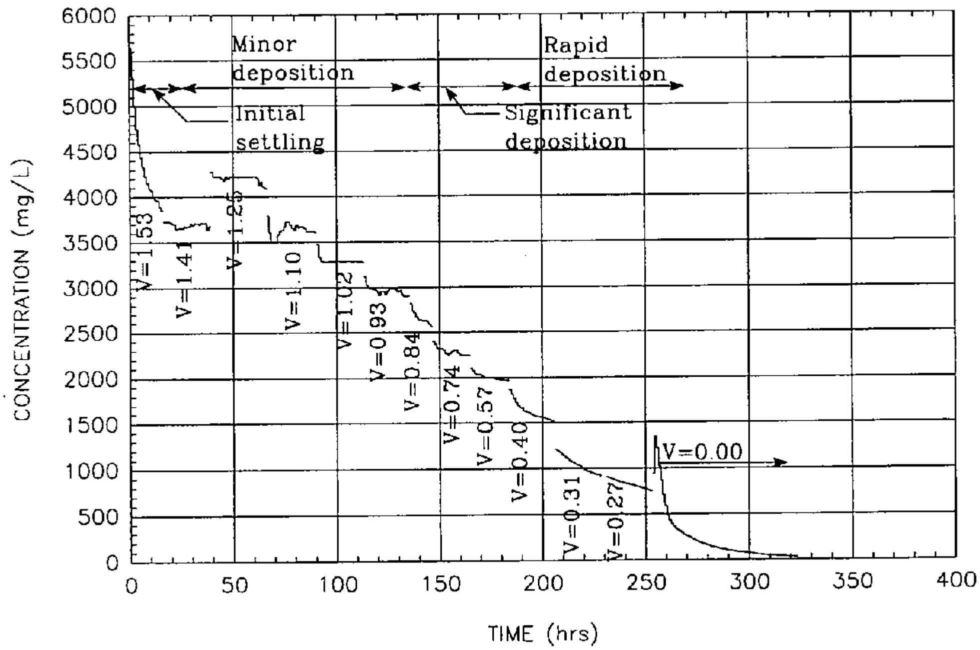


Figure 20. - Depositional characteristics for an average summer suspended sediment concentration. Rapid deposition occurs when the average channel velocity, *V*, drops below 0.57 ft/s.

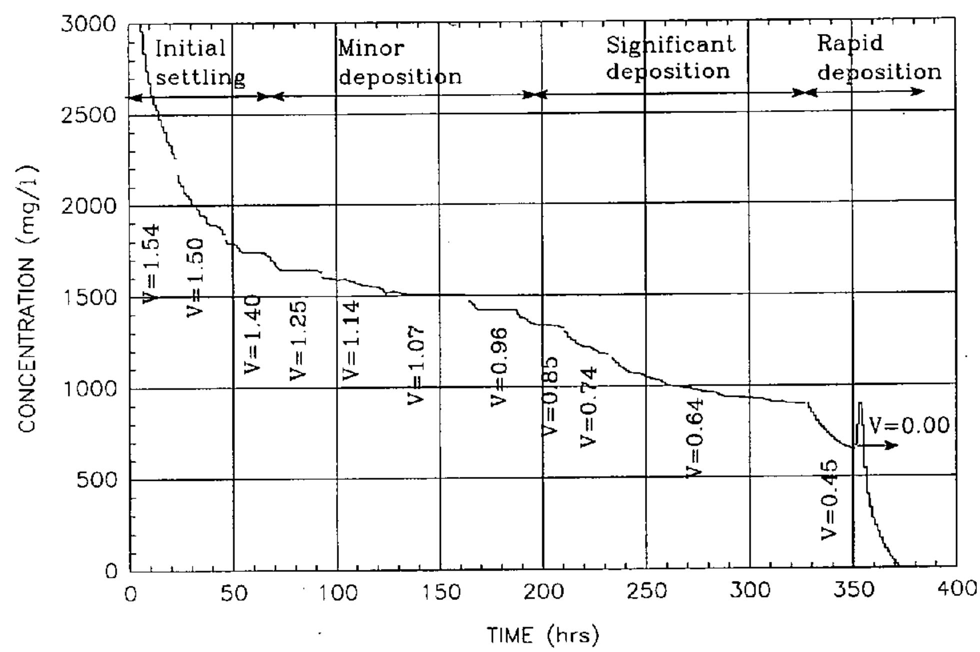


Figure 21. - Depositional characteristics for an average spring suspended sediment concentration. Rapid deposition occurs when the average channel velocity drops below 0.64 ft/s.

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APPENDIX

Summary of Flume Erosion Test Results

Table A.1. - Data summary for flume erosion tests for a surface sample collected at Reservoir Site No. 1.

Test I.D.	Q (ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. (ft^2/s)	Re	Fr	U_*	Shear Stress (lb/ft^2)	Weight Loss (lb)	Time (hours)	Erosion Rate ($lb/ft^2/h$)	Erosion Rate ($gm/ft^2/h$)
RES1S1	1.25	0.70	1.84	72	1.03e-05	5.00e+05	0.388	0.286	0.158	0.489	3	0.163	73.937
RES1S2	1.58	0.71	2.32	73	1.02e-05	6.48e+05	0.485	0.362	0.254	0.001	3	0	0.151
RES1S3	1.92	0.67	2.87	74	1 e-05	7.66e+05	0.618	0.489	0.462	0.550	3	0.183	83.160
RES1S4	2.29	0.68	3.50	80	9.34e-06	1.02e+06	0.748	0.600	0.696	0.169	3	0.056	25.553
RES1S5	2.50	0.63	3.85	78	9.57e-06	1.01e+06	0.855	1.140	2.513	0.703	3	0.234	106.294
RES1S6	2.67	0.62	4.28	83	9.02e-06	1.18e+06	0.958	0.993	1.906	0.001	3	0	0.151
RES1S7	n/a	0.66	4.41	78	9.57e-06	1.22e+06	0.957	1.044	2.105	0.542	3	0.181	81.950
RES1S8	n/a	0.67	4.36	77	9.68e-06	1.21e+06	0.939	1.203	2.803	0.296	3	0.099	44.755
RES1S9	n/a	0.56	4.72	76	9.80e-06	1.08e+06	1.112	1.612	5.025	0.364	3	0.121	55.037
RES1S10	n/a	0.53	5.32	77	9.68e-06	1.16e+06	1.288	1.175	2.671	0.791	3	0.264	119.599
RES1S11	n/a	0.50	5.50	77	9.68e-06	1.14e+06	1.371	1.363	3.591	10.480	2	5.240	2376.864

Table A.2. - Data summary for flume erosion tests for a surface sample (silty-clay) collected at Reservoir Site No. 2.

Test I.D.	Flow(ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft^2/s	Re	Fr	U_*	Shear Stress (lb/ft2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/h$	Erosion Rate $gm/ft^2/h$
RES21	0.42	0.72	0.59	70	1.06e-05	1.60e+05	0.122	0.078	0.012	0.396	3	0.132	59.875
RES22	0.83	0.72	1.11	70	1.06e-05	3.02e+05	0.231	0.216	0.091	0.308	3	0.103	46.570
RES23	1.28	0.72	1.90	70	1.06e-05	5.18e+05	0.395	0.237	0.109	2.214	23.50	0.094	42.735
RES24	1.78	0.72	2.50	70	1.06e-05	6.81e+05	0.519	0.326	0.206	0.257	1.67	0.154	69.931
RES25	1.82	0.69	2.68	73	1.02e-05	7.27e+05	0.569	0.309	0.184	1.867	0.42	4.481	2032.475
RES26	1.86	0.71	2.88	70	1.06e-05	7.74e+05	0.602	0.329	0.210	1.430	0.50	2.860	1297.296
RES27	n/a	0.61	n/a	74	1 e-05	0	0	0.451	0.394	6.750	0.23	28.970	13140.773
RES28	1.72	0.59	3.20	70	1.06e-05	7.15e+05	0.734	0.307	0.182	4.100	0.50	8.200	3719.520
RES29	n/a	0.62	2.90	70	1.06e-05	6.80e+05	0.649	0.257	0.128	0.740	0.33	2.222	1008
RES210	n/a	0.58	3.35	78	9.57e-06	8.12e+05	0.775	0.369	0.263	6.560	0.92	7.157	3246.363
RES211	n/a	0.36	4.64	86	8.71e-06	7.67e+05	1.363	0.401	0.311	6.718	0.50	13.436	6094.570

Table A.3. - Data summary for flume erosion tests for a surface sample collected at Reservoir Site No. 2. This sample was disturbed during collection.

Test I.D.	Flow(ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft^2/s	Re	Fr	U_*	Shear Stress (lb/ft2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/h$	Erosion Rate $gm/ft^2/h$
RES2d1	0.76	0.73	1.04	70	1.06e-05	2.87e+05	0.215	0.110	0.023	0	3	0	0
RES2d2	0.95	0.74	1.15	70	1.06e-05	3.22e+05	0.236	0.130	0.033	0.250	3	0.083	37.800
RES2d3	1.16	0.73	1.50	72	1.03e-05	4.25e+05	0.309	0.172	0.058	0.224	3	0.075	33.869
RES2d4	1.29	0.73	1.76	72	1.03e-05	4.99e+05	0.363	0.301	0.175	0.150	2.92	0.051	23.328
RES2d5	1.42	0.72	1.96	76	9.80e-06	5.76e+05	0.407	0.342	0.227	0.171	5	0.034	15.513
RES2d6	1.52	0.69	2.30	72	1.03e-05	6.17e+05	0.489	0.350	0.237	0.093	3	0.031	14.062
RES2d13	2.29	0.67	3.38	72	1.03e-05	8.79e+05	0.727	0.338	0.221	0.388	1	0.388	175.997
RES2d14	2.52	0.63	4.17	76	9.80e-06	1.07e+06	0.926	0.561	0.608	4.550	1	4.550	2063.880
RES2d15	n/a	n/a	n/a	72	1.03e-05	0	ERR	0.996	1.921	4.379	0.13	32.851	14901.083

Information for tests 7-12 were lost due to a computer problem

Table A.4. - Data summary for flume erosion tests for a sample collected 8 feet below the bottom at Reservoir Site No. 2.

Test I.D.	Flow (ft^3/s)	Depth (ft)	Ave. Vel (ft/s)	Temp. (°F)	Kin. Viscos. ft^2/s	Re	Fr	U_*	Shear Stress (lb/ft^2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/h$	Erosion Rate $gm/ft^2/h$
RES2C1	1.25	0.65	2.05	72	1.03e-05	5.17e+05	0.448	0.432	0.360	0.003	3	0.001	0.454
RES2C2	1.49	0.65	2.40	74	1 e-05	6.21e+05	0.525	0.453	0.397	0.069	3	0.023	10.433
RES2C3	1.73	0.69	2.52	77	9.68e-06	7.18e+05	0.535	0.490	0.465	0.153	3	0.051	23.134
RES2C4	1.94	0.67	2.92	75	9.92e-06	7.89e+05	0.629	0.765	1.133	0.245	3	0.082	37.044
RES2C5	n/a	n/a	2.20	82	9.12e-06	n/a	n/a	0.428	0.354	1.028	3	0.343	155.434
RES2C6	1.93	0.75	2.69	74	1 e-05	8.03e+05	0.547	0.571	0.630	0.530	2	0.265	120.204
RES2C7	2.12	0.56	3.95	76	9.80e-06	9.03e+05	0.930	0.655	0.831	0.271	2	0.136	61.463
RES2C8	2.24	0.56	4.17	86	8.71e-06	1.07e+06	0.982	0.779	1.174	0.638	2	0.319	144.698

Table A.5. - Data summary for flume erosion tests for a surface sample collected at Overbank Site No. 1.

Test I.D.	Flow (ft³/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft²/s	Re	Fr	U_*	Shear Stress (lb/ft²)	Weight Loss (lb)	Time (hours)	Erosion Rate lb/ft²/h	Erosion Rate gm/ft²/h
OBS1S1	1.57	0.72	2.13	71	1.04e-05	5.88e+05	0.442	0.724	1.013	0.231	3	0.077	34.927
OBS1S2	1.94	0.70	2.72	73	1.02e-05	7.49e+05	0.573	0.729	1.028	0.654	3	0.218	98.885
OBS1S3	2.31	0.68	3.40	74	1 e-05	9.20e+05	0.727	0.724	1.014	2.725	3	0.908	412.020
OBS1S4	2.64	0.69	3.80	73	1.02e-05	1.03e+06	0.806	1.465	4.152	1.718	3	0.573	259.762
OBS1S5	2.79	0.67	4.34	76	9.80e-06	1.19e+06	0.934	1.241	2.975	3.154	3	1.051	476.885
OBS1S6	3.13	0.69	4.74	74	1 e-05	1.30e+06	1.006	2.602	13.068	4.253	2	2.127	964.580

Table A.6. - Data summary for flume erosion tests for a surface sample collected at Overbank Site No. 2.

Test I.D.	Flow (ft³/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft²/s	Re	Fr	U_*	Shear Stress (lb/ft²)	Weight Loss (lb)	Time (hours)	Erosion Rate lb/ft²/h	Erosion Rate gm/ft²/h
OBS2S1	1.51	0.69	2.04	70	1.06e-05	5.33e+05	0.433	0.846	1.638	0.172	3	0.057	26 6
OBS2S2	1.87	0.75	2.50	76	9.80e-06	7.65e+05	0.509	1.253	3.040	0.090	3	0.030	13.548
OBS2S3	2.23	0.70	3.04	79	9.45e-06	9 e+05	0.640	1.264	3.090	0.148	3	0.049	22.378
OBS2S4	2.57	0.65	3.90	78	9.57e-06	1.06e+06	0.852	1.222	2.887	0.645	3	0.215	97.524
OBS2S5	n/a	0.60	4.10	86	8.71e-06	1.13e+06	0.933	1.417	3.877	0.116	3	0.039	17.539
OBS2S6	n/a	0.58	4.49	80	9.34e-06	1.12e+06	1.039	2.222	9.451	0.502	3	0.167	75.902
OBS2S7	n/a	0.43	5.43	78	9.57e-06	9.76e+05	1.459	2.611	13.181	0.063	3	0.021	9.541
OBS2S8	n/a	0.50	4.85	78	9.57e-06	1.01e+06	1.209	2.286	10.102	1.067	3	0.356	161.330
OBS2S9	n/a	0.52	5.22	75	9.92e-06	1.09e+06	1.276	3.155	19.240	0.811	3	0.270	122.623
OBS2S10	n/a	0.50	5.12	75	9.92e-06	1.03e+06	1.276	2.228	9.597	2 2	3	0.667	302.702
OBS2S11	n/a	0.49	n/a	76	9.80e-06	0	0	3.616	25.320	0.751	3	0.250	113.551

Table A.7. - Data summary for flume erosion tests for a surface sample collected 2 feet below the river bottom at River Site No. 2.

Test I.D.	Flow (ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft^2/s	Re	Fr	$U*$	Shear Stress (lb/ft^2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/hr$	Erosion Rate $gm/ft^2/h$
RIV2S1	1.64	0.70	2.28	72	1.03e-05	6.20e+05	0.480	0.482	0.450	0.164	3	0.055	24.797
RIV2S2	2	0.65	2.94	74	1 e-05	7.61e+05	0.643	0.626	0.759	0.358	3	0.119	54.130
RIV2S3	2.35	0.65	3.50	78	9.57e-06	9.51e+05	0.765	0.752	1.093	0.230	3	0.077	34.776
RIV2S4	2.71	0.62	4.12	78	9.57e-06	1.07e+06	0.922	0.748	1.082	1.119	3	0.373	169.193
RIV2S5	n/a	0.71	4.10	84	8.92e-06	1.31e+06	0.857	0.700	0.946	1.057	3	0.352	159.818
RIV2S6	n/a	0.62	5.21	75	9.92e-06	1.30e+06	1.166	0.991	1.901	0.833	3	0.278	125.950
RIV2S7	n/a	0.48	4.78	75	9.92e-06	9.25e+05	1.216	0.840	1.366	0.390	3	0.130	58.968
RIV2S8	n/a	0.53	4.50	75	9.92e-06	9.61e+05	1.089	0.917	1.627	1.070	3	0.357	161.784
RIV2S9	n/a	0.49	n/a	75	9.92e-06	0	0	n/a	n/a	-0.173	2	n/a	0
RIV2S10	n/a	0.50	5.00	75	9.92e-06	1.01e+06	1.246	0.937	1.697	1.081	3	0.360	163.447
RIV2S11	n/a	0.52	5.20	75	9.92e-06	1.05e+06	1.222	1.212	2.844	1.602	3	0.534	242.222

Table A.8. - Data summary for flume erosion tests for a sample collected 5 feet below the river bottom at River Site No. 1.

Test I.D.	Flow (ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp. (°F)	Kin. Viscos. ft^2/s	Re	Fr	$U*$	Shear Stress (lb/ft^2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/hr$	Erosion Rate $gm/ft^2/h$
RIV1D1	1.64	0.73	2.11	73	1.02e-05	6.06e+05	0.435	0.538	0.559	0.275	3	0.092	41.580
RIV1D2	1.92	0.71	2.57	74	1 e-05	7.26e+05	0.537	0.602	0.702	0.125	3	0.042	18.900
RIV1D3	2.29	0.72	3.08	73	1.02e-05	8.72e+05	0.640	0.664	0.852	0.257	3	0.086	38.858
RIV1D4	2.64	0.68	3.94	75	9.92e-06	1.08e+06	0.842	0.824	1.315	0.292	3	0.097	44.150
RIV1D5	n/a	0.67	4.34	76	9.80e-06	1.19e+06	0.934	1.006	1.960	0.541	3	0.180	81.799
RIV1D6	n/a	0.57	5.09	77	9.68e-06	1.20e+06	1.188	0.896	1.553	0.002	3	0.001	0.302
RIV1D7	n/a	0.54	4.37	77	9.68e-06	9.75e+05	1.048	0.927	1.662	0.279	3	0.093	42.185
RIV1D8	n/a	0.49	5.60	72	1.03e-05	1.07e+06	1.410	1.421	3.910	0.636	3	0.212	96.163
RIV1D9	n/a	0.51	5.50	75	9.92e-06	1.13e+06	1.357	1.182	2.704	0.863	2	0.432	195.728
RIV1D10	n/a	0.51	n/a	76	9.80e-06	0	0	1.467	4.166	4.091	3	1.364	618.559

Table A.9. - Data summary for flume erosion tests on a subsurface sample collected 5 feet below the surface at River Site No. 2.

Test I.D.	Flow (ft^3/s)	Depth (ft)	Ave. Vel. (ft/s)	Temp (°F)	Kin. Viscos. ft^2/s	Re	Fr	U^*	Shear Stress (lb/ft^2)	Weight Loss (lb)	Time (hours)	Erosion Rate $lb/ft^2/hr$	Erosion Rate $gm/ft^2/h$
RIV2D1	2.33	0.71	3.24	73	1.02e-05	9.04e+05	0.678	0.744	1.071	0.131	3	0.044	19.807
RIV2D2	2.50	0.71	3.60	74	1 e-05	1.02e+06	0.753	0.753	1.097	0.292	3	0.097	44.150
RIV2D3	2.77	0.69	4.19	73	1.02e-05	1.14e+06	0.889	0.819	1.299	0.780	3	0.260	117.936
RIV2D4	n/a	0.62	4.51	73	1.02e-05	1.10e+06	1 9	0.929	1.670	0.513	3	0.171	77.566
RIV2D5	n/a	0.53	4.82	73	1.02e-05	1 e+06	1.167	1.096	2.323	0.555	3	0.185	83.916
RIV2D6	n/a	0.50	5.60	71	1.04e-05	1.07e+06	1.396	1.258	3.066	0.611	3	0.204	92.383
RIV2D7	n/a	0.52	5.72	74	1 e-05	1.18e+06	1.398	1.423	3.919	0.894	3	0.298	135.173
RIV2D8	n/a	0.53	5.70	74	1 e-05	1.20e+06	1.380	1.677	5.444	2.046	3	0.682	309.355

Mission

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American Public.