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BEDLOAD TRANSPORT IN A MODEL GRAVEL STREAM

by

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DISCLAIMER

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory.

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lakes and streams; and the development of predictive models on the movement of pollutants in the biosphere.

The present report is devoted to a consideration of the possibility of modeling gravel streams at reduced scale. If this can be done, then the model can provide a powerful tool for determining the effect of non-point source pollution on gravel spawning grounds of salmon and related species.

Thomas A. Murphy
Director, CERL

PREFACE

The U. S. Environmental Protection Agency is investigating the potential effects of increased erosion in the coastal mountain range of the Pacific Northwest on the spawning and reproduction of salmonidae in the streams which discharge into the ocean. Changes in surface runoff may be caused by future land development, road construction, and changes in logging practices. Inceased runoff may lead to local degradation of stream beds and/or local increases in fine materials in the runoff. These changes in the stream environment pose a threat to the reproduction of salmonidae, and the Environmental Protection Agency is investigating means to anticipate stream changes. To accomplish this objective it has been necessary to study the mechanics of coarse bedload transport in mountain streams, such as found in the Northwest.

Field studies have been conducted on several gravel streams in the coastal mountain range of Oregon in order to document the size distributions of bed materials and bedload transport rates, and their relationship to hydraulic and stream morphologic parameters.

The study described herein involved the use of a 1:8 scale laboratory representation of a typical gravel stream reach. The erosion and bedload transport mechanics of a gravel stream bed were studied, and similarity criteria between the laboratory measurements and the field measurements were established. Laboratory simulation of gravel streams is of interest because the bedload transport and bed degradation in such streams usually occur only during or after major storm events, and field observations can be made only during those short periods. Also, laboratory experiments may be conducted for conditions that have not yet occurred in the field. A quantitatively accurate method for modeling gravel-bed reaches containing spawning gravels would allow for the identification, at an acceptable cost, of major sediment pollution problems before they occur.

ABSTRACT

The presence of a natural pavement consisting of coarse materials in gravel streams is of great interest with regard to fluvial hydraulics and stream ecology. Very little information is available on the mechanics of pavement formation and its characteristics.

In this study, insight into the characteristics of sediment transport and pavement evolution in gravel streams was gained by means of a physical model of a gravel stream in the Pacific Northwest. The results from the geometrically undistorted Froude model (scale 1:8) agreed well with the field data.

The agreement was further improved when laboratory data and field data were compared in terms of dimensionless bedload W^* and relative Shields shear stress ϕ. The $W^* - \phi$ plots allow for the quantification of differences in Reynolds number and roughness which were not or could not be scaled by means of Froude similarity. The study leads to the conclusions that bedload transport in natural gravel streams can be simulated in the laboratory and that prototype behavior can be predicted from laboratory data.

The experiments also illustrate that pavement can form under conditions of continuous equilibrium transport of all available sizes of interest.

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The authors are also indebted to Thomas Winterstein and Alec Fu, Graduate Students and Research Assistants at the St. Anthony Falls Hydraulic Laboratory, for their help in conducting the experiments.

SECTION 1

OBJECTIVES

There exists an enormous amount of data and a large variety of equations which describe the mechanics of sediment transport in waterways, the beds of which consist mainly of uniformly graded homogeneous sand. In contrast, much less information exists for gravel streams and rivers. The presence of a distinct natural pavement consisting of coarse materials in gravel streams is of great importance both with regard to fluvial hydraulics and stream ecology.

To obtain insight into the characteristics of pavements in gravel streams, it is useful to study how the pavement is actually formed by the flowing water. As in many fields of science, one rational avenue of investigation consists of conducting experiments under well-controlled conditions in the laboratory. If, in addition, these experiments can be shown to simulate a typical prototype gravel stream in the field, two goals can be achieved simultaneously.

1) Modeling criteria for gravel streams in general, and for the formation of pavement layers in particular, can be determined.

2) Current understanding of the mechanics of pavement formation, and bedload transport in the presence of pavements, can be increased.

The objectives of this study were to achieve the two goals mentioned above. A particular gravel stream called Oak Creek, located in the Mary's River Drainage Basin of the Oregon Coast Range, was selected for study. Extensive field data have been collected from Oak Creek during the last decade, both by Oregon State University and the U.S. Environmental Protection Agency at Corvallis, Oregon. Using a 1:8 undistorted geometrical scale ratio and Froude similarity, experiments were conducted at the St. Anthony Falls Hydraulic Laboratory, University of Minnesota, to determine if the field data from Oak Creek could be simulated under laboratory conditions. In addition, experiments were conducted to study the effect of a small admixture of fine suspendible sand in a gravel stream. This material could be considered to simulate the product of erosion in the watershed due to road construction or logging, for example.

SECTION 2

CONCLUSIONS

The results of the research program described herein show that the formation of pavement in a gravel stream can be simulated in the laboratory, and that the presence of pavement is related to the rate of bedload transport.

The modeling criteria developed herein are based on geometrically undistorted Froude scaling but are modified to incorporate distortions between natural streams and laboratory conditions which cannot be scaled by the Froude law. It is shown that the criteria developed can be used with confidence to predict prototype behavior.

The experiments demonstrate that pavement can form under conditions of continuous equilibrium transport of all available grain sizes. Thus pavement, as opposed to the armor that may form immediately downstream of a dam, is a mobile-bed phenomenon.

The study results indicate that the thickness of the moving layer from which particles are entrained into the bedload in the presence of a pavement is on the order of d_{50} to d_{65} of the pavement layer, and is concentrated at the sediment surface. Bulk creep of layers below was not observed.

The result of one experiment reveals that when fine suspendible sand is fed into a clean gravel stream some of that sand goes into the stream bed, tending to concentrate just below the pavement. Further experiments are needed to obtain more information on this process for a wide range of variables.

SECTION 3

INFORMATION ON RELATED STUDIES

Research in Oak Creek

Oak Creek, a typical gravel stream in the Pacific Northwest, was selected for study because extensive research on this stream has been carried out since 1969 by Klingeman (personal communication, 1979), Milhous (1)*, and Shirazi and Weim (2). Most of the field data were made available to the investigators. During the initial stage of this study the investigators visited Oak Creek and its research facilities to obtain first-hand information on the prototype stream. During this field visit extensive photographic documentation, including motion pictures, was obtained for further study.

Oak Creek is located in the McDonald State Forest in the Mary's River drainage basin just west of Corvallis, Oregon. The drainage area tributary to the study reach is approximately 6.7 sq km (2.6 sq mi). The mean annual runoff is about 460 mm (18 in.). The main surface geologic formation in the watershed is the Siletz River volcanic (Ecocene), and the main earth materials in the watershed are dense basalts and their weathering products.

The bed material of the stream is predominantly basaltic gravel of specific gravity 2.85. A distinct pavement layer exists in the stream bed. The top layer appears to consist of stones of fairly uniform size. The material below the pavement layer is relatively smaller in size and is usually poorly sorted. A typical pavement layer in Oak Creek in shown in Fig. 3.1+.

A straight reach approximately 53 m (175 ft) in length was chosen for the study. The bedload has been sampled by Klingeman using a vortex

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* See list of references on page 40.

\+ All figures are included at the end of the text, beginning on page 41.

trough in the stream bed at the downstream end of the study reach. The trough transports the bedload material into a sampling pit adjacent to the stream. The vortex sampler is shown in Fig. 3.2. A plan view of the study reach upstream of the vortex sampler is shown in Fig. 3.3; for more details about the research facilities at Oak Creek, the reader is referred to Milhous (1).

Milhous' bedload data were taken in three sets. The first set was taken during the winter of 1969-70, the second set during the winter of 1971, and the third set during the fall of 1971. It is indicated by Milhous that the winter 1971 set are the most complete. These data are herein used for modeling and later verification.

A plot of hydraulic radius (which is assumed to be approximately equal to flow depth) versus stream discharge in Oak Creek for the winter 1971 data is shown in Fig. 3.4. Bedload in Oak Creek as a function of water discharge for the winter 1971 data is shown in Fig. 3.5. Milhous gives the median (d_{50}) size of the pavement layer in Oak Creek as 63 mm and that of the material below the pavement, which is here called subpavement, as 20 mm. Milhous used 3.66 m (12 ft) as the average width of the Oak Creek bed for bedload discharge calculations. Table 3.1 gives a summary of sizes for pavement and subpavement material in Oak Creek as obtained by Milhous in July 1971. One of the main conclusions of Milhous' work is that the pavement layer is the most important single factor in limiting the availability of sediment and in controlling the relationship between streamflow and bedload discharge.

Klingeman (pers. comm., 1979) collected extensive bed material samples during 1978 in Oak Creek. The results of the size distribution of the bed material of all the samples composited together are given in Fig. 3.6.

There have been other studies of pavement layers and of armoring in gravel streams. Gomez (3) provides the summary reproduced in Table 3.2. His distinction between pavement layers and armored river beds is too long to reproduce herein. He argues that armored surfaces are intrinsically stable to all flows, that they are formed by erosion of the finer particle sizes, and that they are found in river reaches

TABLE 3.1. SUMMARY OF SIZES FOR PAVEMENT AND SUBPAVEMENT MATERIAL SAMPLES OBTAINED IN JULY 1971 IN OAK CREEK (after Milhous, 1973)

	Average		Limits			
			Pavement		Subpavement	
Size	Pavement	Subpavement	Maximum	Minimum	Maximum	Minimum
	mm	mm	mm	mm	mm	mm
d_{10}	32	1.6	40	28	1.7	1.6
d_{35}	52	8.6	56	46	9.4	9.8
d_{50}	60	20	64	53	23	14
d_{65}	68	33	72	61	40	29
d_{90}	86	65	98	80	80	51
d_{65}/d_{35}	13.1	38.4	---	---	---	---

TABLE 3.2. FIELD STUDIES OF ARMORED OR PAVED SURFACES* (after B. Gomez, 1980)

Author		Reach & Location
Borland & Miller, 1960	Below	dams on Lower Colorado River
Gamal, 1955		Hoover Dam, Colorado River
Hales et al, 1970		Cavins Point, Fort Randall and Garrison Dams
Hammad, 1972		Aswan High Dam, River Nile
Hathaway, 1948		dams on various U. S. rivers
Jansen et al, 1979		Maastricht Weir, River Maas
Kellerhals, 1967		lake outlets, British Columbian rivers
Lane & Carlson, 1953		head gate, irrigation canal, San Luis Valley
Livesey, 1965		Fort Randall Dam, Missouri River
Milhous, 1972	In	Oak Creek, Oregon
Milhous & Klingeman, 1973		Oak Creek, Oregon
Mustafa, 1955	Below	Hoover Dam, Colorado River
Pemberton, 1976		Glen Canyon Dam, Colorado River
Shulits, 1934		dams on various European rivers
Williman, 1975		head gate, irrigation race, Canterbury, N.Z.

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*Purely theoretical studies are excluded where upstream flow controls are operative. An armored surface then reflects the coarsest material available to the flow. According to Gomez' description, paved erosional surfaces are found "in reaches where external controls are inoperative. The particle size distribution of a paved surface reflects the transporting ability of the most recent flow capable of moving individual particles."

Parker and Klingeman (4) have distinguished between pavement and armor as follows: pavement is a mobile-bed phenomenon which is present even during transport of all available sizes; armor is a static limiting case when load vanishes completely.

Charlton, Brown, and Benson (5) studied the hydraulic geometry of some gravel rivers in Britain to develop criteria for the hydraulic design of shallow gravel bed channels. The study includes streams that are quite similar to Oak Creek.

Little and Mayer (6) have done laboratory experiments on the stability of channels by armoring. It is to be noted that when the bed is armored, bed movement ceases. Little and Mayer developed empirical equations (a) to determine whether a given sediment bed will armor and (b) to determine the geometric mean diameter and standard deviation of the armored surface particles.

Parker and Klingeman (4) using data from Oak Creek and the Elbow River, Alberta, Canada, another typical gravel stream, have determined an empirical bedload relationship for prototype paved gravel rivers. The empirical relationship is shown in Fig. 3.7. It consists of a plot of a dimensionless bedload W^* versus relative Shields stress $\phi = \tau^*/\tau_r$, where $\tau^*_r = 0.0876$ is a reference Shields stress at which $W^* = 0.0025$ or Einstein bedload $q^*_B = 6.48 * 10^{-5}$. This reference value corresponds to conditions not far above critical conditions for breaking of the pavement. Thus, τ_r^* serves as a surrogate for a somewhat lower critical Shields stress. These terms are defined as:

$$\text{Shields Stress} \quad \tau^* = \frac{HS}{\beta d_{50}}$$

Dimensionless bedload $W^* = \frac{q_B \beta}{\sqrt{g}\ (HS)^{1.5}} = \frac{q^*_B}{(\tau^*)^{1.5}}$

Einstein bedload $q^*_B = \frac{q_B}{\sqrt{\beta g\ d_{50}}\ d_{50}}$

Symbols are defined in a separate listing at the beginning of this report. The parameter d_{50} is the median subpavement grain size in the above terms.

SECTION 4

RESEARCH APPROACH

As stated earlier, the two main objectives of the research program described herein were:

1) Verification of modeling criteria for gravel streams in general and for the formation of pavements in particular.

2) Elucidation of the mechanics of pavement formation and bedload transport in the presence of pavements, with and without fine infeed.

It was decided to build a geometrically undistorted Froude model of Oak Creek to eliminate any uncertainties with regard to distortion. Based on the range of variables and the capacity of the tilting flume/ sediment recirculating facility at the Laboratory, a scale ratio (L_r) of 1:8 was chosen. From the cross-sections presented by Milhous (1), a width of 4.27 m (14 ft) was determined to be a representative average width (not water-surface width) for Oak Creek.

According to Klingeman (pers. comm., 1979) the ratio of the values of d_{90} to d_{50} of the subpavement in Oak Creek is about three and the d_{50} value is about 20 mm. Preparation of a scaled bed material is a difficult task. The model sediment distribution, obtained by careful mixing of different selected sands and gravels in predetermined percentages, is shown in Fig. 4.1. The d_{50} of this distribution is about 2.25 mm, and the d_{90} to d_{50} ratio is about 2.5. From Fig. 3.6 it can be seen that the bed material size in Oak Creek goes as low as about 0.1 mm and d_{10} is about 1.6 mm. In the model a scaled value for d_{10} would be about 0.2 mm. Recognizing that any material below 0.2 mm will be mostly in suspension for the flow conditions to be tested, and considering the nature of the flume which cannot consistently recirculate suspended material, it was decided to cut off the size distribution of the model bed material at about 0.2 mm. An experiment involving feeding in suspendible sand with a median size of 0.12 mm was also planned. The size distribution of this fine sand is given in Fig. 7.18.

It was hypothesized that in a laboratory experiment with a bed material similar to that of a natural gravel stream, a pavement should eventually form naturally under conditions of continuous bed movement if the hydraulic conditions are right. Milhous (1) stated that 1.13 m^3/sec (40 cfs) is the critical discharge for bed movement in Oak Creek. Based on this information, it was decided to run the experiments corresponding to prototype steady-state discharges of 1.7 m^3/sec (60 cfs), 2.55 m^3/sec (90 cfs), 3.40 m^3/sec (120 cfs), and 4.25 m^3/sec (150 cfs). At these discharges the total time required to reach equilibrium was not excessive. The winter 1971 data of Milhous contain flows only up to 3.40 m^3/sec (120 cfs) and, hence, for 4.25 m^3/sec (150 cfs) the data field was extrapolated. When the bedload transport and water surface slope stay fairly constant over time, the channel is said to have reached an equilibrium condition. A high steady-state discharge in Oak Creek does not last more than an hour or so. Nevertheless the information obtained in laboratory experiments with a steady-state discharge was considered valuable. Furthermore, there are no reliable prototype data on the stream's behavior during the passage of a flood wave (hydrograph). Consequently no unsteady-state experiments could be conducted and verified from the prototype.

The specific gravity of the bed material used in the model was 2.63, while that in Oak Creek is 2.85. It was decided to accept this distortion in specific gravity rather than search for basaltic materials for the model bed.

The mechanics of pavement formation have been described in Milhous (1). The process is one of segregation of material. This is, if a material of a relatively wide range of grain sizes is subjected to a flow velocity, the fines will be moved first and faster while the coarse materials are relatively slow or stationary. Some of the fines find a hiding place between the coarse particles. As the fines are removed below the pavement, the rate of transport is reduced, but does not reach zero, and a mobile-bed pavement forms. In a recirculating system, the bed material is constantly fed back to maintain a mobile-bed equilibrium. In order to see the evolution of mobile-bed pavement into true static armor, experiments were also conducted with no recirculation and thus no replenishment of sediment washed out of the flume.

Shirazi and Weim (2) indicate that excess fine sediments in the spawning gravel of streams are a cause for embryo and larvae mortality of salmonidae. In particular silvicultural activities in the Pacific Northwest have introduced various levels of fine sediment and debris into the streams, often degrading riffle habitats critical for salmonid reproduction and for the production of invertebrate food organisms necessary for rearing juvenile fish. With this critical problem in mind, an experiment was planned in which fine sand is fed in (but not recirculated) at a constant rate, to find out how much of the fines go into the gravel bed and how much remain in suspension.

To collect separate samples of pavement and subpavement layers a core sampler, 127 mm (5 in.) high and 102 mm (4 in.) in diameter, made of plexiglass, is driven into the bed at the desired location. A piston made of hard plexiglass, 96 mm (3.8 in.) in diameter and about 330 mm (13 in.) in height, is filled with wet clay at one end. The piston with clay on its bottom is inserted into the larger core sampler already in the bed. A slight uniform pressure is applied at the top such that the wet clay and the layer of bed particles in immediate contact with it form a bond. The piston is then withdrawn and then the bed material withdrawn is separated from the clay by washing. A size analysis of the bed material is subsequently made. The equipment is shown in Fig. 5.10; the sampler is used for taking pavement samples only. Once the pavement is separated, the subpavement sample underneath is taken in bulk using a spoon. When the subpavement sample itself is required in layers, the layer for required thickness is separated carefully using a putty knife and a spoon, starting from the top layer of the subpavement. A typical pavement sample still attached to the core sampler is shown in Fig. 5.11.

SECTION 6

EXPERIMENTAL PROCEDURE

A layer of model bed material about 50 mm (2 in.) deep is laid in the tilting flume. The bed material is thoroughly mixed and then screeded using a template whose mount is fixed on the carriage that runs atop the flume. This ensures that the bed slope is the same as the flume slope. The flume slope is set at a value (about 0.80 per cent) which is estimated to be close to the equilibrium slope value; previous trail runs provide guidance. The channel is then backfilled with city water, with the tailgate set at a relatively high level. Water is turned on slowly in the main line. When sediment movement is noticed, the sand slurry recirculating pump is turned on and the backfill water supply turned off. Noting the supply of water through the recirculation system, the flow in the main line is set to the required value. Depth of flow is then set using the tailgate. Tailgate setting is adjusted until the water surface slope is about the same as the bed slope. This is done by using a point gauge mount on the carriage. This procedure expedites the attainment of equilibrium.

Water surface slope and bedload are measured at the zero hour of the run. From then on, the water surface slope and bedload measurements are taken at specified intervals. This interval is about 20 minutes to one hour. It is very difficult to ascertain exactly when the channel attains equilibrium, as the approach is asymptotic. An empirical criterion is used for this purpose. If the water surface slope for 3 or 4 consecutive readings is constant and if the corresponding measured bedload variation is minimal, then the flume is said to have reached equilibrium and the run is terminated. Before the termination of the run, a bedload sample is collected for size analysis.

After the run, the flume is drained and bed profile measurements recorded using a manual point gauge. Bed profile data are taken at about every 0.1 m across the width and 0.5 m along the length. Photographs are also made. Using the bed sampler described earlier, the pavement samples at 9 m, 10 m, and 11 m from the upstream end of the flume are taken. At these locations the subpavement samples are also collected. These samples are then oven-dried, and a sieve analysis is made for size distribution. A listing of the experiments is given in Table 6.1.

One experiment (No. 111) was done without recirculation of the sediments. First, the experiment corresponding to 3.4 m^3/sec (120 cfs) in the Oak Creek model was run until it had reached equilibrium. Then the run was continued without recirculating the sediments. The sediments were pumped out of the trap and stored in a large tank. The tailgate setting and discharge were kept unchanged. Water surface slope and bedload measurements were taken every 15 minutes. Samples of the pavement and subpavement at 5 m, 8 m, and 11 m distances and at 3 hr, 6 hr, 9 hr, and 12 hr running times were taken for size analysis.

One experiment (No. 114) was done with the addition of fine sand at a known percentage of the bedload transport rate. Before feeding in the fines, the experiment corresponding to 2.55 m^3/sec (90 cfs) in Oak Creek was run to equilibrium. Several bedload samples, water surface slopes, and bedload measurements were taken to determine when the pavement had reached equilibrium conditions. Several suspended sediment concentration measurements were also made. After the channel had reached equilibrium, samples of pavement and subpavement were taken to determine the amount of fines that had gone into the bed. Subpavement samples were taken in several layers to see whether there was any stratification in the percentage of fines in the bed.

A total of 15 experiments were performed; see Table 6.1.

TABLE 6.1. LIST OF EXPERIMENTS

Run No.	Water Discharge m^3/s (cfs)	Water Temperature °C (°F)	Remarks
100	0.0114 (0.403)	25.2 (77)	Trial and preliminary experiments.
101	0.0114 (0.403)	21.0 (70)	
102	0.0187 (0.663)	20.5 (69)	
103	0.0187 (0.663)	21.0 (70)	
104	0.0187 (0.663)	22.0 (72)	
105	0.0187 (0.663)	22.0 (72)	
106	0.0187 (0.663)	22.0 (72)	
107	0.0140 (0.497)	22.0 (72)	Main experiments.
108	0.0093 (0.331)	19.0 (66)	
109	0.0187 (0.663)	20.0 (68)	
110	0.0187 (0.663)	20.0 (68)	Time extension of Run 109. Collection of detailed bed data.
111(a)	0.0187 (0.663)	13.0 (55)	Recirculation of sediments halted after equilibrium. Measurements of 3 hour intervals after equilibrium.
111(b)	0.0187 (0.663)	9.8 (50)	
111(c)	0.0187 (0.663)	8.0 (46)	
111(d)	0.0187 (0.663)	5.0 (41)	
112	0.0234 (0.829)	2.2 (36)	Main experiment
113	0.0140 (0.497)	3.6 (39)	Repeat run. Pavement for Run 114.
114	0.0140 (0.497)	1.0 (34)	Admixture of fines.

TABLE 7.1. OBSERVED PROTOTYPE (P) AND MODEL (M) PARAMETERS

Run No.	Discharge		Depth		Froude Number		Slope		Bedload				Water Temperature	
	Q_p	Q_m	H_p	H_m	F_p	F_m	S_p	S_m	Q_{sp}		Q_{sm}		T_p	T_m
	m^3/sec (cfs)	m^3/sec (cfs)	m (ft)	m (ft)					kg/hr	m^3/sec (cfs)	kg/hr	m^3/sec (cfs)	°C (°F)	°C (°F)
108	1.7	$9.37\text{x}10^{-3}$	0.335	0.0399	0.66	0.70	0.01	0.0082	57.1	$5.57\text{x}10^{-6}$	0.636	$6.72\ \text{x}10^{-8}$	4.5	19
	(60)	(0.331)	(1.10)	(0.131)						$1.97\text{x}10^{-4}$)		($2.37\text{x}10^{-6}$)	(40)	(66)
107	2.55	$1.41\text{x}10^{-2}$	0.393	0.0512	0.77	0.73	0.01	0.0072	501	$4.88\text{x}10^{-5}$	4.97	$5.25\text{x}10^{-7}$	4.5	22
	(90)	(0.497)	(1.29)	(0.168)						($1.72\text{x}10^{-3}$)		($1.86\text{x}10^{-5}$)	(40)	(72)
109	3.40	$1.88\text{x}10^{-2}$	0.445	0.0549	0.86	0.87	0.01	0.0071	2430	$2.37\text{x}10^{-4}$	18.2	$1.92\text{x}10^{-6}$	4.5	20
	(120)	(0.663)	(1.46)	(0.180)						($8.36\text{x}10^{-3}$)		($6.79\text{x}10^{-5}$)	(40)	(68)
112	4.25	$2.35\text{x}10^{-2}$	0.503	0.0674	0.89	0.80	0.01	0.0068	7910	$7.71\text{x}10^{-4}$	51.0	$5.39\text{x}10^{-6}$	4.5	2
	(150)	(0.829)	(1.65)	(0.221)						($2.72\text{x}10^{-4}$)		($1.90\text{x}10^{-4}$)	(40)	(36)

composite sediment characteristics. Size distribution curves thus obtained are shown in Figs. 7.4, 7.5, 7.6, and 7.7 for runs 108, 107, 109, and 112, respectively. In Table 7.2 are listed the average and the range of the sediment characteristics for the four runs. The ratio d_{90}/d_{50} for the pavement is 2.4, and for the subpavement it is 3.25. These values are typical of Oak Creek in particular and gravel streams in general. The ratio of pavement d_{50} to subpavement d_{50}, 1.64, is also fairly typical, although slightly on the low side.

7.2. SCALING OF MODEL DATA

Froude Scaling

The measured model values of Table 7.1 can be directly scaled up according to Froude similarity. Since the facility was designed to be at a 1:8 geometrical scale model, the scale ratio L_r is eight. Thus, where the subscript m denotes measured model values and the subscript pm denotes the result of scaling up the model values, the following conversions apply.

Discharge: $Q_{pm} = 8^{5/2} Q_m = 181 Q_m$

Depth: $H_{pm} = 8 H_m$

Froude No.: $F_{pm} = F_m$

Slope: $S_{pm} = S_m$

Bedload: $Q_{spm} = 8^{5/2} Q_{sm} = 181 Q_{sm}$

Grain Size: $d_{pm} = 8d_m$

These values, along with actual prototype values obtained from Milhous (1), are listed in Table 7.3; the actual prototype values are denoted with the subscript p. It can be seen that slope in the model is consistently low compared to the prototype by a factor of about 25 per cent. Model bedload ranges from about 1.2 to 2.2 times the corresponding prototype value. While it is clear that an approximate Froude number has been obtained, the modeling is not exact.

TABLE 7.2

COMPOSITE OF GRAIN SIZES (mm) FROM SAMPLES

at 9m, 10m, and 11m of Runs 107, 108, 109, and 112

Grain Size	Average		Pavement		Subpavement	
	Pavement	Subpavement	Max.	Min.	Max.	Min.
d_{10}	1.04	0.73	1.50	0.55	1.10	0.58
d_{16}	1.42	0.95	1.75	0.89	1.05	0.75
d_{35}	2.30	1.54	2.70	2.05	1.80	1.30
d_{50}	3.37	2.05	4.20	2.80	2.25	1.80
d_{65}	5.66	2.80	6.50	4.90	3.20	2.35
d_{84}	7.03	5.95	8.30	6.80	6.50	4.90
d_{90}	8.19	6.68	9.30	7.30	7.20	6.20

TABLE 7.3. MODEL DATA SCALED TO FROUDE SIMILARITY - COMPARISON TO OAK CREEK DATA

Run No.	Water Discharge		Q	Flow Depth			Froude No.			Slope			Bedload			Grain Size		
	Q_m	Q_{pm}	Q_p	H_m	H_{pm}	H_p	F_m	F_{pm}	F_p	S_m	S_{pm}	S_p	Q_{sm}	Q_{spm}	Q_{sp}	d_m	d_{pm}	d_p
	m^3/sec (cfs)	m^3/sec (cfs)	m^3/sec (cfs)	m (ft)	m (ft)	m (ft)							m^3/sec (cfs)	m^3/sec (cfs)	m^3/sec (cfs)	mm	mm	mm
108	$9.37x10^{-3}$	1.7	1.7	0.0399	0.319	0.335	0.70	0.70	0.66	0.0082	0.0082	0.01	$6.72x10^{-8}$	$1.22x10^{5}$	$5.57x10^{-6}$	2.25	18	20
	(0.331)	(59.9)	(60)	(0.131)	(1.05)	(1.10)							$(2.37x10^{-6})$	$(4.29x10^{-4})$	$(1.97x10^{-4})$			
107	$1.41x10^{-2}$	2.55	2.55	0.0512	0.410	0.393	0.73	0.73	0.77	0.0072	0.0072	0.01	$5.25x10^{-7}$	$9.50x10^{-5}$	$4.88 x10^{-5}$	2.25	18	20
	(0.497)	(90)	(90)	(0.168)	(1.34)	(1.29)							$(1.86x10^{-5})$	$(3.37x10^{-3})$	$(1.72x10^{-3})$			
109	$1.88x10^{-2}$	3.40	3.40	0.0549	0.439	0.445	0.87	0.87	0.86	0.0071	0.0071	0.01	$1.92x10^{-6}$	$3.48x10^{-4}$	$2.37x10^{-4}$	2.25	18	20
	(0.663)	(120)	(120)	(0.180)	(1.44)	(1.46)							$(6.79x10^{-5})$	$(1.23x10^{-2})$	$(8.36x10^{-3})$			
112	$2.35x10^{-2}$	4.25	4.25	0.0674	0.539	0.503	0.80	0.80	0.89	0.0068	0.0068	0.01	$5.39x10^{-6}$	$9.76x10^{-4}$	$7.71x10^{-4}$	2.25	18	20
	(0.829)	(150)	(150)	(0.221)	(1.77)	(1.65)							$(1.90x10^{-4})$	$(3.44x10^{-2})$	$2.72x10^{-4})$			

Subscripts: m = value observed in model.
p = value observed in prototype.
pm = value scaled up from model results.

shown in Table 7.4.

Equation 7.1 can be cast in the form

$$F/\sqrt{S} = 2.5 \ln 11\tilde{H} \tag{7.2}$$

where F is Froude number. For perfect Froude and geometric modeling, F, S, and $\tilde{H}$ must be the same in both model and prototype. It is seen from Tables 7.1 and 7.4, however, that even though F is nearly identical in model and prototype, S and $\tilde{H}$ show some systematic deviation. For example, based on the average of the slopes for the four model runs, the slope distortion can be approximately written as

$$(S)_p = \alpha_1 (S)_m$$

where

$$\alpha_1 \simeq 1.365$$

Presumably part of this distortion is due to the four trivial factors discussed previously. In order to detect more fundamental distortions, it is necessary to relate k independently to some grain size parameter. It is customary to use the relationship

$$k = \gamma\, d_{p90}$$

for gravel-bed streams, where d_{p90} refers to a pavement grain size and γ is a constant approximately equal to two; see Parker and Peterson (9). However, since d_{p90} is a dependent variable in the present study, it is more useful to relate k to subpavement (≃ mix) d_{90} for the prototype values and mix d_{90} in the model values. (These values do not differ greatly from d_{p90}.) In Oak Creek, subpavement d_{90} is about 68 mm; an average value of γ from the prototype data of Table 7.4 is

$$\gamma = 2.90$$

If there are no fundamental distortions, then the model data should obey the same resistance relation, i.e.

$$\frac{F}{\sqrt{S}} = 2.5 \ln 11 \frac{H}{\gamma d_{90}}$$

TABLE 7.4. ROUGHNESS PARAMETERS

Run No.	k (model, cm)	k (proto., m)	$\tilde{H}$ (model)	$\tilde{H}$ (proto.)
108	1.96	0.279	2.04	1.21
107	1.82	0.195	2.82	2.01
109	0.949	0.159	5.78	2.80
110	1.50	0.156	4.49	3.21

TABLE 7.5. DIMENSIONLESS PARAMETERS AND OTHER VALUES FOR OAK CREEK (PROTOTYPE)

Q		τ^*	R^*	ϕ	W^*	q_B^*
m^3/s	cfs					
1.70	60	0.0905	2340	1.034	4.63×10^{-3}	1.26×10^{-4}
2.55	90	0.106	2540	1.213	3.20×10^{-2}	1.10×10^{-3}
3.40	120	0.120	2700	1.373	0.130	5.42×10^{-4}
4.25	150	0.136	2870	1.552	0.350	1.75×10^{-2}

TABLE 7.6. DIMENSIONLESS PARAMETERS AND OTHER VALUES FOR THE MODEL RESULTS

Run No.	Q		τ^*	R^*	q^*_B	W^*	ϕ	ϕ
	cm^3/sec	cfs						(+)
108	9370	0.331	0.0892	122	2.95×10^{-4}	0.0111	1.018	1.169
107	14100	0.497	0.101	140	2.31×10^{-3}	0.0724	1.147	1.317
109	18800	0.663	0.106	137	8.43×10^{-3}	0.243	1.213	1.393
112	23500	0.829	0.125	90	2.37×10^{-2}	0.536	1.427	1.638

+Value of ϕ in this column is after making 13% reduction in the value of τ^*_r .

where $\gamma = 2.9$. This is shown on Fig. 7.9. The laboratory data is again slightly, but consistently, high in terms of $F/\sqrt{S}$, as shown by the squares; this indicates some fundamental distortion. The data can be brought into correspondence by reducing γ for the model data to 2.22; this is shown by the diamonds in Fig. 7.9. The lower value of γ in the model may be tentatively attributed to the same reasons that $\tau_r{}^*$ is low in the model, i.e., bank roughness or Reynolds effects.

The values of various dimensionless parameters in the prototype are shown in Table 7.5; corresponding model values are shown in Table 7.6.

Mildly-distorted Froude Modeling

It is now possible to develop a mildly-distorted Froude scale-up procedure which accounts for both trivial distortions and fundamental scale effects.

The trivial distortions can be described by four distortion factors; where p denotes prototype and m denotes model,

$$\alpha_2 = \frac{(\beta)_p}{(\beta)_m} = \frac{1.85}{1.63} = 1.135$$

$$\alpha_3 = \frac{\left(d_{50}\right)_p}{L_r\left(d_{50}\right)_m} = \frac{20}{8*2.25} = 1.111$$

$$\alpha_4 = \frac{\left(B_s\right)_p}{L_r\left(B_s\right)_m} = \frac{12}{8*1.75} = 0.857$$

$$\alpha_5 = \frac{\left(D_{90}/D_{50}\right)_p}{\left(D_{90}/D_{50}\right)_m} = \frac{3.4}{3.11} = 1.093$$

The two fundamental distortions can be described by

$$\alpha_6 = \frac{\left(\tau_r{}^*\right)_p}{\left(\tau_r{}^*\right)_m} = 1.148$$

$$\alpha_7 = \frac{\gamma_p}{\gamma_m} = 1.306$$

Discharge Q, depth H, and water surface width B could be set independently to satisfy a 1:8 Froude model; thus, they scale up without distortions.

$$(Q)_p = L_r^{2.5} (Q)_m = 181(Q)_m \qquad (7.3)$$

$$(H)_p = L_r (H)_m = 8(H)_m \qquad (7.4)$$

$$(B)_p = L_r (B)_m = 8(B)_m \qquad (7.5)$$

Grain size and bed sediment width are distorted by the factors α_3 and α_4 .

$$\left(d_{50}\right)_p = \alpha_2 L_r \left(d_{50}\right)_m = 8.89 \left(d_{50}\right)_m \qquad (7.6)$$

$$\left(B_S\right)_p = \alpha_3 L_r \left(B_S\right)_m = 6.86 \left(B_S\right)_m \qquad (7.7)$$

A strict derivation of the slope distortion can be obtained from Eq. 7.2. Writing

$$k = \gamma d_{90} = \gamma \left(\frac{d_{90}}{d_{50}}\right) d_{50}$$

it is seen that

$$(k)_p = \alpha_8 L_r (k)_m$$

where

$$\alpha_8 = \alpha_7 \alpha_5 \alpha_3 = 1.586$$

Since $S = F^2/(2.5 \ln 11H/k)^2$, slope scales up as

$$(S)_p = \alpha_1 (S)_m \qquad (7.8)$$

where strictly speaking

$$\alpha_1 = \left\{ \frac{\ln\left[11\left(\frac{H}{k}\right)_m\right]}{\ln\left[\frac{11}{\alpha_8}\left(\frac{H}{k}\right)_m\right]} \right\}^2$$

The predicted bedload discharges as a function of water discharge are plotted in Fig. 7.10, along with Oak Creek winter 1971 data. The predicted values from the model results agree very well with Oak Creek data.

7.3. FLUCTUATIONS IN BEDLOAD

Run 109, corresponding to a prototype discharge of 3.4 m^3/sec (120 cfs) was continued as run 110 for an additional time of about 21 hours. The bedload discharge at the end of run 110 was 3.1 cm^3/sec and water surface slope was 0.0068 whereas the respective values for run 109 were 2.8 cm^3/sec and 0.00706. Samples of bed materials taken at 9 m, 10 m, and 11 m locations for both the runs are analysed. The geometric mean diameters d_g for run 109 are: subpavement - 2.45 mm; pavement - 3.55; composite - 2.55 mm; and the respective values for run 110 are 2.25 mm, 3.45 mm, and 2.36 mm. These data show that under steady-state discharge and after the pavement has been formed fully, i.e. when equilibrium conditions have been reached, there is very little further change in the hydraulic conditions of the flume as well as sediment characteristics.

7.4. THICKNESS OF MOVING LAYER

During run 110, an attempt was made to obtain an estimate of the thickness of the moving layer close to the bed. At the 8 m location, the entire bed material for a longitudinal length of 2.5 cm over the whole width of the flume was taken out separately as pavement and several vertical layers of subpavement. The particles were then colored with orange fluorescent spray paint in batches corresponding to layer and put back into their original location layer by layer. After about 2.75 hours of run, the channel was drained. A layer of uncolored particles had occupied the top layer of previously colored particles. The thickness of the layer of uncolored particles approximates the thickness of the moving layer near the bed. In order to obtain a value for the thickness of the uncolored particle layer, the following procedure was applied: three transects across the width of the channel, one at each edge of the original trench and one at the center were selected. Elevations were recorded on all three transects at every 1.25 cm (0.5 in.).

Then all uncolored particles on the top were very carefully removed one by one by hand using tweezers. After removal, the elevations of the colored particles beneath it were recorded again. The difference in elevation between the two sets of readings should give a good estimate of the thickness of the moving layer for the entire width. The difference in elevation at the three transects is graphically shown in Fig. 7.11. The mean difference in elevation for the whole set of readings is about 5.89 mm (0.0193 ft) with a standard deviation of 3.9 mm (0.0128 ft). For this particular run the pavement layer has a d_{50} of 4.1 mm and d_{65} of 5.9 mm. The experiment described above suggests that the thickness of the layer from which moving grains are entrained is about equal to the d_{65} of the pavement layer on the average, under a steady-state discharge equivalent to 3.4 m^3/sec (120 cfs) in the prototype.

A time lapse movie of the above experiment, taken from the starting of movement of the top layer of colored particles until about 150 minutes later, gives a qualitative idea of the movement of the particles. In another experiment during run 110, between the 6.5 m and 7 m location and at about 5 cm from the left wall, a portion of the top layer was sprayed with fluorescent yellow colored paint for a width of about 23 cm. After the flow was turned on, a time lapse movie for about 45 minutes was taken to obtain a qualitative idea of the movement of the particles outside this colored area. Extensive still photos were also taken over the entire length of the channel to document the location of the colored particles.

7.5. ALTERNATE BAR FORMATION

There is evidence from Milhous' (1) work in Oak Creek, and also from the field visits by the investigators to Oak Creek, that there are weak but easily discernible alternate bars in the stream bed. In the model, during run Nos. 109 and 112, which correspond to 3.4 m^3/sec (120 cfs) and 4.25 m^3/sec (150 cfs) in the prototype, the formation of very weak alternate bars was also noticed and documented. The final bed profiles for these two runs are shown schematically in an isometric view in Figs. 7.12 and 7.13. A first look at Figs. 7.12 and 7.13 reveals that the channel has a generally uniform slope (absence of meandering tendency). A closer look allows for the discernment of weak alternate bars in the flume.

7.6. EXPERIMENT WITHOUT SEDIMENT RECIRCULATION

Run 110, which corresponds to a prototype discharge of 3.4 m^3/sec (120 cfs) was continued further under the designation run 111. The main difference was that run 111 had no recirculation of sediment. Run 111 was stopped every 3 hours for measurements but lasted for a total period of 12 hours. At the end of run 110, i.e. before starting the run with no sediment recirculation, the bedload rate was 3.14 cm^3/sec. At the end of run 111(a), i.e. at the end of 3 hours of the run with no sediment recirculation, the bedload rate dropped to 0.79 cm^3/sec. At the end of 6 hrs - run 111(b), 9 hrs - run 111(c), and 12 hrs - run 111(d), the respective bedload rates were 0.41 cm^3/sec, 0.26 cm^3/sec, and 0.22 cm^3/sec, respectively. Thus, it is evident that the bedload rate was steadily decreasing to an almost negligible value, as sediment was continuously taken out of the system. The finer range of sediment sizes which was available earlier under a recirculation system are no longer available, and the pavement in effect became denser and acted to protect the subpavement. In this fashion a true armor tended to form. The pavement at the end of runs 111(a), 111(b), 111(c), and 111(d) is photographically shown in Figs. 7.14 through 7.17, respectively. These figures show the tendency of the pavement to become coarser as time progresses. The bed profile data at the end of each run show that there is a general degradation of the bed starting from the head of the channel. The fact that the tailgate has been kept at a fixed position from the beginning to the end of the four runs, while the bed has been constantly degrading, has in effect imposed a constantly varying Froude number with respect to time. This fact rather prevents us from doing any further analysis of the data at this point.

7.7. REPEATABILITY

Run 113, corresponding to a prototype discharge of 2.55 m^3/sec (90 cfs) was primarily designed to allow for the formation of pavement and the attainment of equilibrium before starting run 114, into which very fine sand was fed. The final results obtained at the end of run 113 could be compared for repeatability with run 107, in which the hydraulic conditions are identical. The flow depth, slope, and bedload discharge for run 107, respectively, are 5.12 cm, 0.0072, and 0.525 cm^3/sec, while the corresponding values for run 113 are 5.21 cm, 0.006, and 0.633 cm^3/sec. The values agree to within about 1 per cent to 20 per cent, which is a fair verification for repeatability of runs.

7.8. EXPERIMENT WITH FINE SAND ADDITION (Exp. No. 114)

The channel was run to equilibrium condition (run 113) corresponding to a prototype discharge of 2.55 m^3/sec (90 cfs). At the end of run 133 the bedload rate was 0.904 cm^3/sec and the pavement had been fully formed. After the termination of run 113, with the same steady-state discharge of 2.55 m^3/sec (90 cfs) the experiment was continued as run 114. Fine sand was fed into the water at the head of the flume. Agsco No. 2/0 quartz sand with a median size of 0.12 mm and specific gravity of 2.65 was fed into the water at the head of the flume. The size distribution of this sand is given in Fig. 7.18. This fine sand, which has a mean fall velocity of about 0.8 cm/sec, is easily transported in suspension. In the experiment the bedload material was recirculated, while the fines were not. Details on the experimental setup are given in Section 6 of this report.

The average feed rate of the fines was about 0.313 g/sec, which is about 18 per cent of the bedload rate at the beginning of the run and about 30 per cent of the bedload rate at the end of the run. Hence, the average feed rate of the fines for the entire run could be estimated as 24 per cent of the bedload rate.

Run 114 was run until it reached "equilibrium." The equilibrium condition was verified by checking the relative constancy of both bedload rate and suspended sediment concentration. The suspended sediment concentration was measured by using a rack of pitot tubes as described earlier in Section 6. The suspended sediment concentration as an average over the flow depth of 5.43 cm (0.178 ft) and at 3 hours before the termination of the run was 17.03 mg/ℓ and about an hour before the termination of the run was 17.63 mg/ℓ. The total run time was about 18 hours for run 114.

Bedload samples were taken frequently to see whether any of the added fines were recirculated. Close visual examination after drying in the oven showed that there were no fines in the bedload, except at the time of termination of the run, at which time the bedload contained about 1.48 per cent fines by weight. This can be considered to be negligible.

As the experiment progressed, one could visually observe that a sizable percentage of the fines was being trapped in the bed. After termination of the run, bed material samples were taken at the center of the flume at 9 m, 10 m, and 11 m locations. In order to quantify the stratification of fines in the bed, the subpavement samples were taken in three layers. The content of fines in percentage by weight in each of the layers at the three locations is given in Table 7.8.

TABLE 7.8. PERCENTAGE OF FINES BY WEIGHT IN THE BED

	Percentage of fines		
Location/Layer	9 m	10 m	11 m
Pavement	9.26	4.18	6.77
Subpavement			
Top	7.3	8.70	8.11
Middle	3.65	1.76	1.93
Bottom	2.35	1.07	1.34
For the Whole Subpavement	3.45	2.73	2.78
For the Whole Bed	3.43	2.85	3.22

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At the 9 m location, there is a strong stratification of fines from the pavement layer to the bottom subpavement layer. At the 10 m and 11 m locations, the stratification is dominant only within the subpavement. Contents of fines in the pavement, top, middle and bottom layers of the subpavement at the 9 m location, can be observed qualitatively in Figs. 7.19, 7.20, 7.21, and 7.22, respectively. A lateral cross-section view of the bed with the fines is shown in Fig. 7.23. A bed sample for the entire width of the flume between 8 m and 8.33 m locations was taken. Analysis of this sample reveals that the percentage of fines for the entire bed as an average for the whole width is 2.33 per cent. This value is a little lower than the values obtained by taking samples at the center. At any rate, one could say that the fines content in the bed is about 2.3 per cent by weight for the bed as a whole.

In order to find what percentage of fines went into the bed for the whole channel, samples were taken at every 1 m along the length of the channel and fines contents were determined. Knowing the bed profile and bottom of the flume elevations, the total weight of bed material was also determined. Out of a total 20.65 kg of fines fed over the period of 18 hours, 9.27 kg of fines were trapped in the bed.

Table 7.9 shows the values of the various parameters obtained at the end of runs 113 and 114.

TABLE 7.9. COMPARISON OF RESULTS FOR EXPERIMENTS WITHOUT AND WITH ADMIXTURE OF FINE SAND

		Run 113	Run 114
Water Discharge	Q (cm^3/sec)	14,100	14,100
Water Depth	H (cm)	5.21	5.43
Slope	S (-)	0.006	0.0056
Bedload Discharge	Q_s (cm^3/sec)	0.904	0.57

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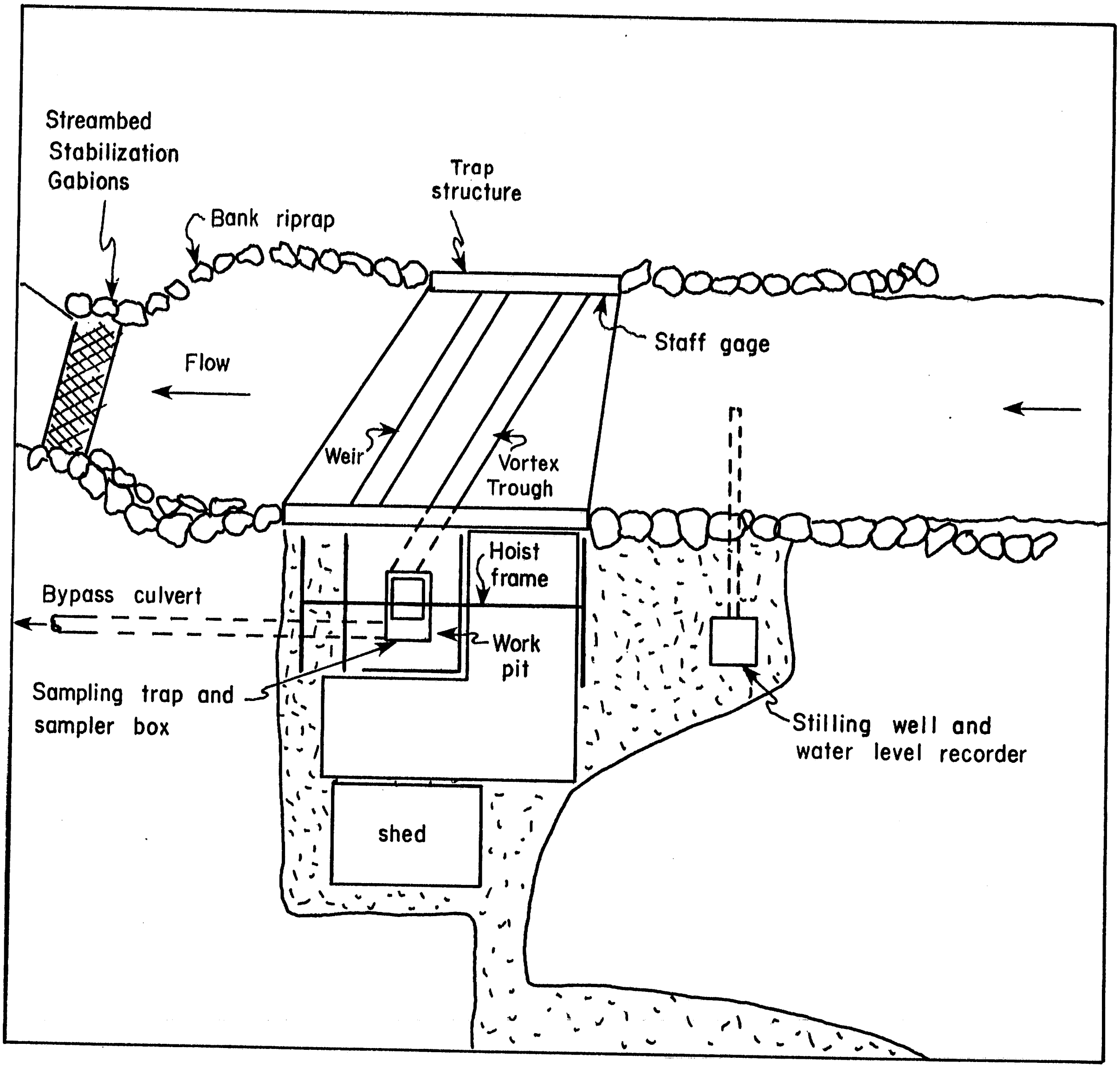


Figure 3.2. Oak Creek field installation.

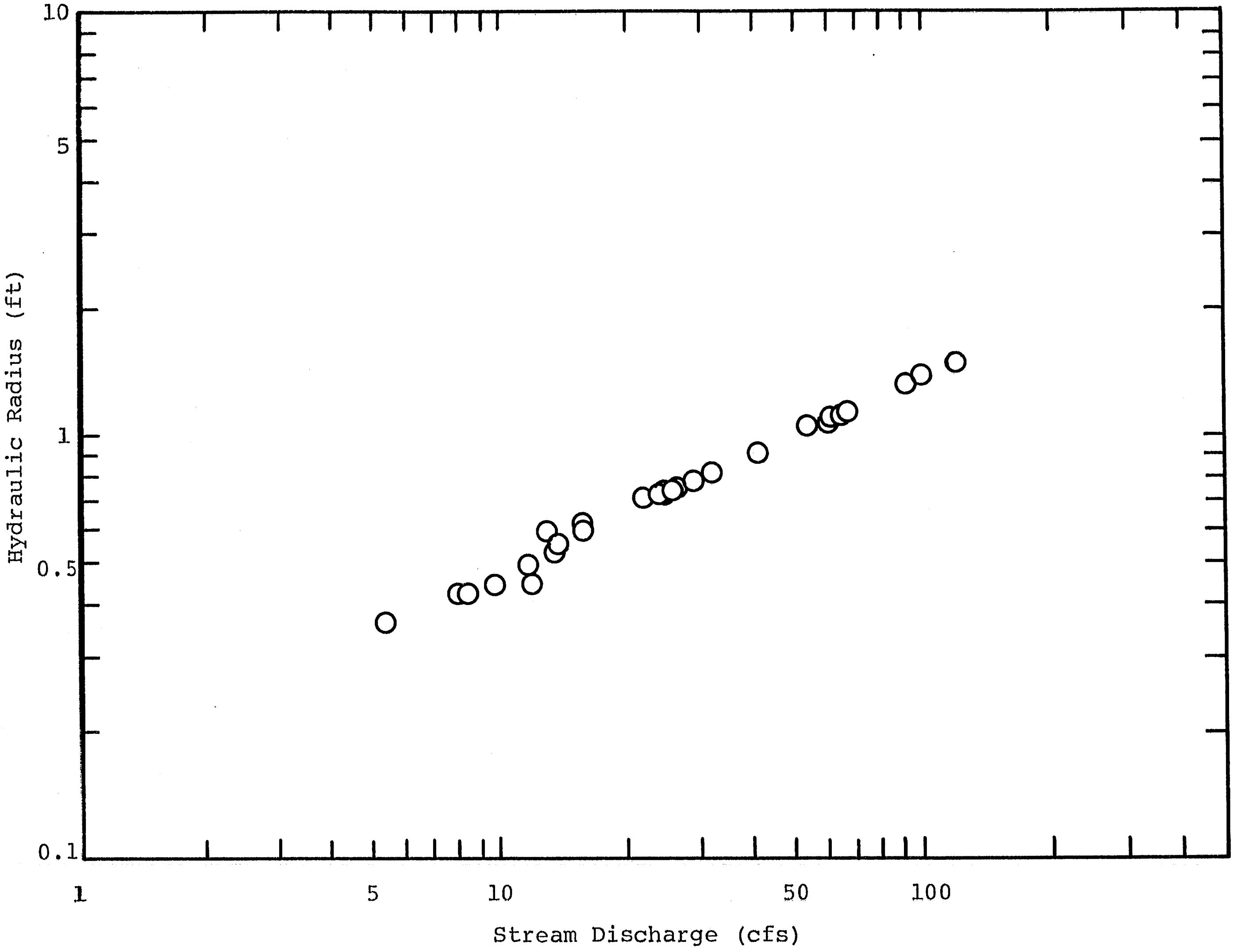


Figure 3.4. Hydraulic radius versus stream discharge in Oak Creek – winter 1971. (after Milhous [1]).

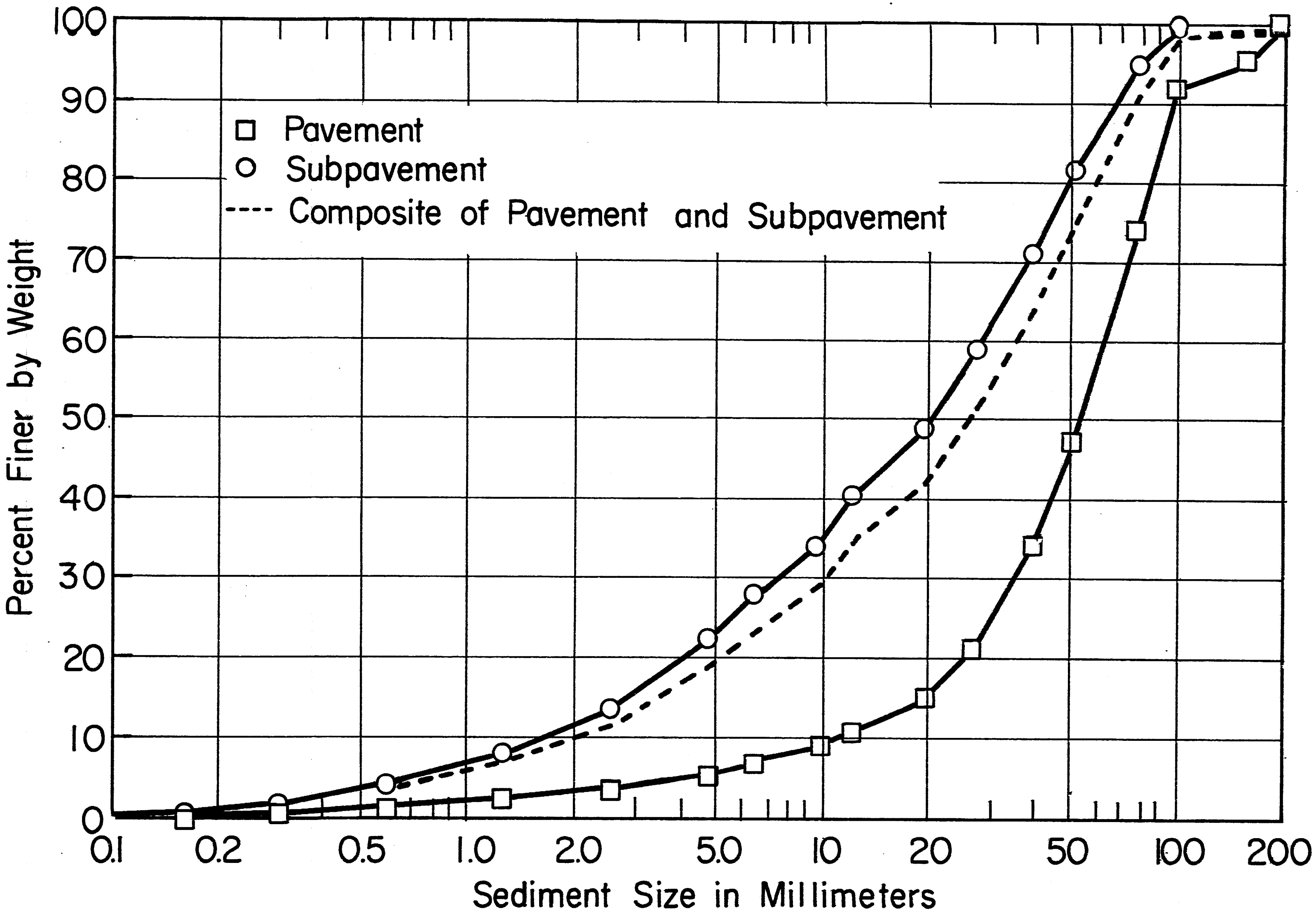


Figure 3.6. Size distribution of bed material samples in Oak Creek.

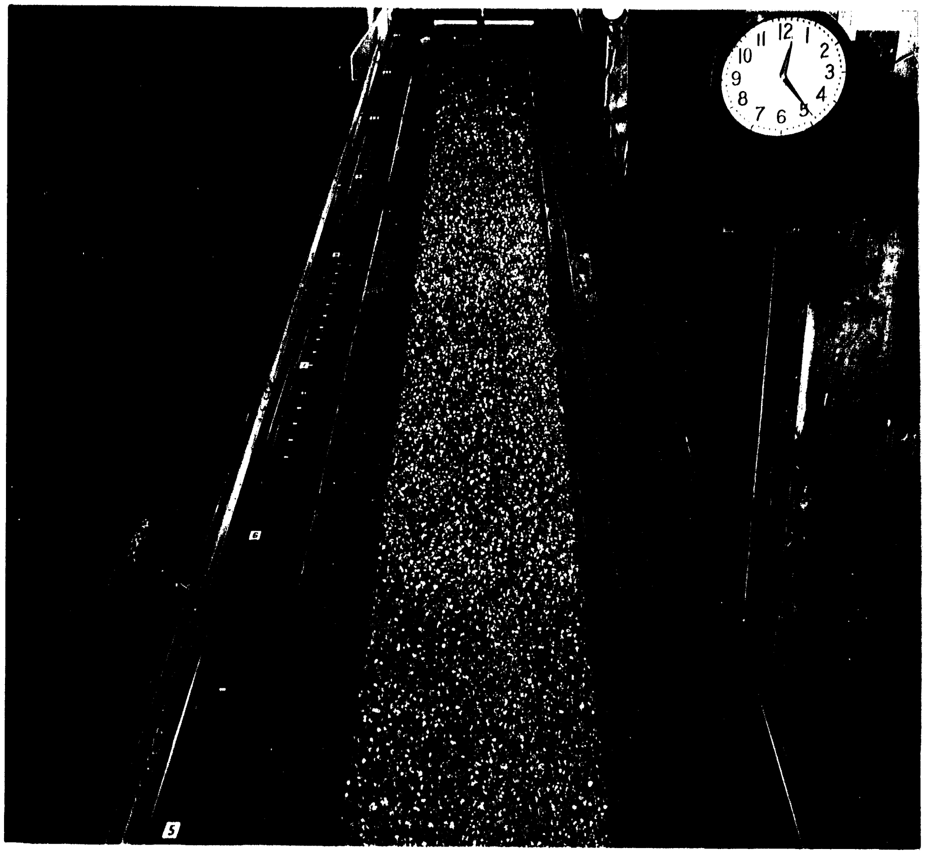


Figure 5.1. View of tilting flume from upstream.

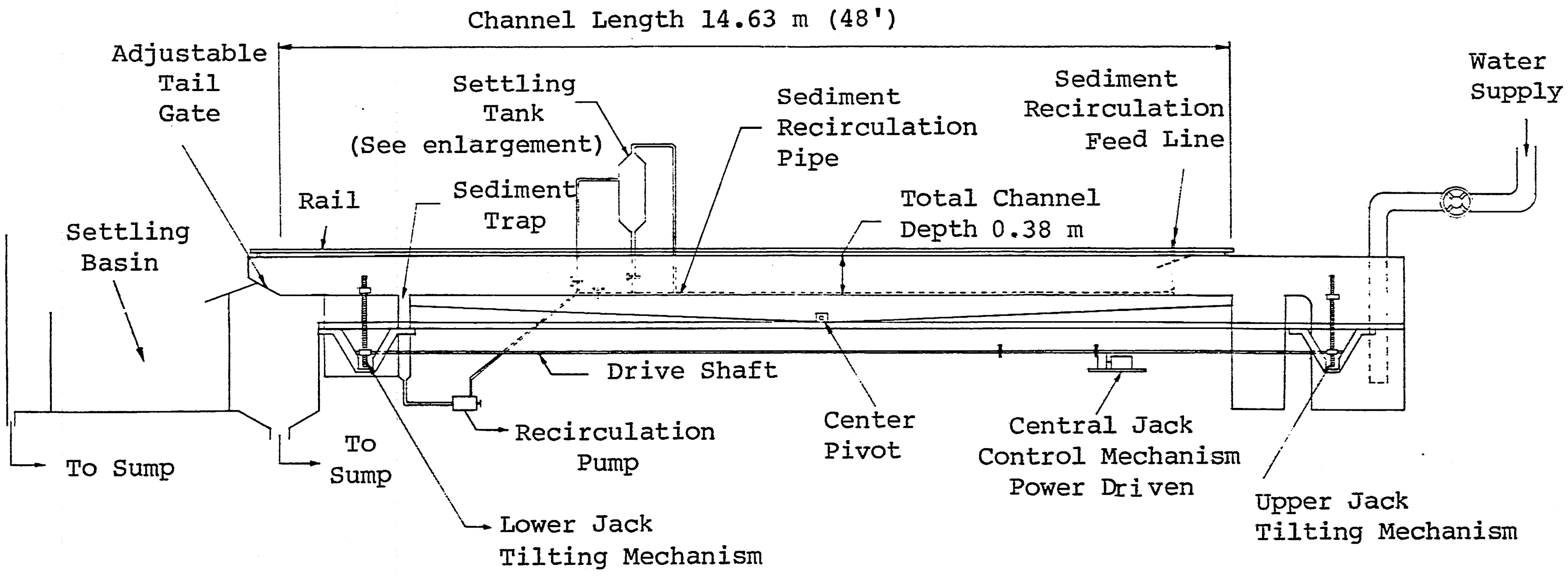


Figure 5.2. Schematic of the tilting flume. Flow is from right to left.

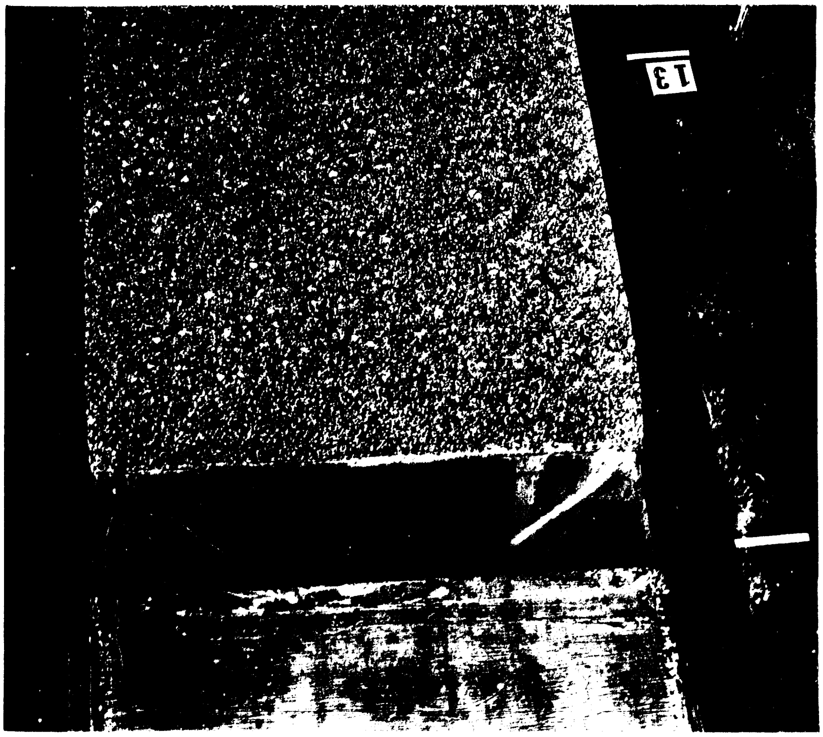


Figure 5.3. View of bedload trap from downstream. (Gravel bed is shown in upper half of picture.)

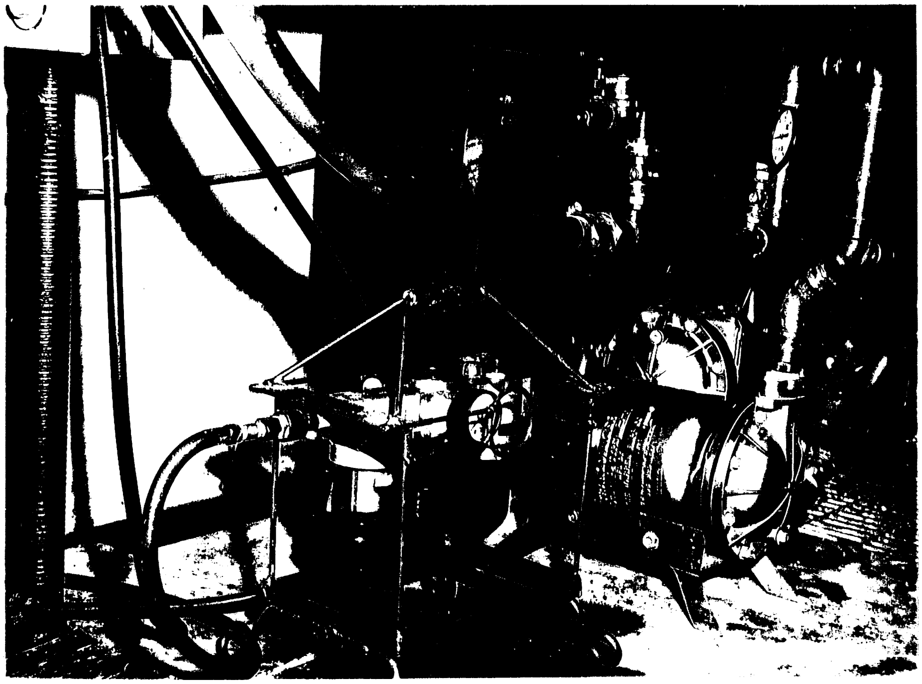
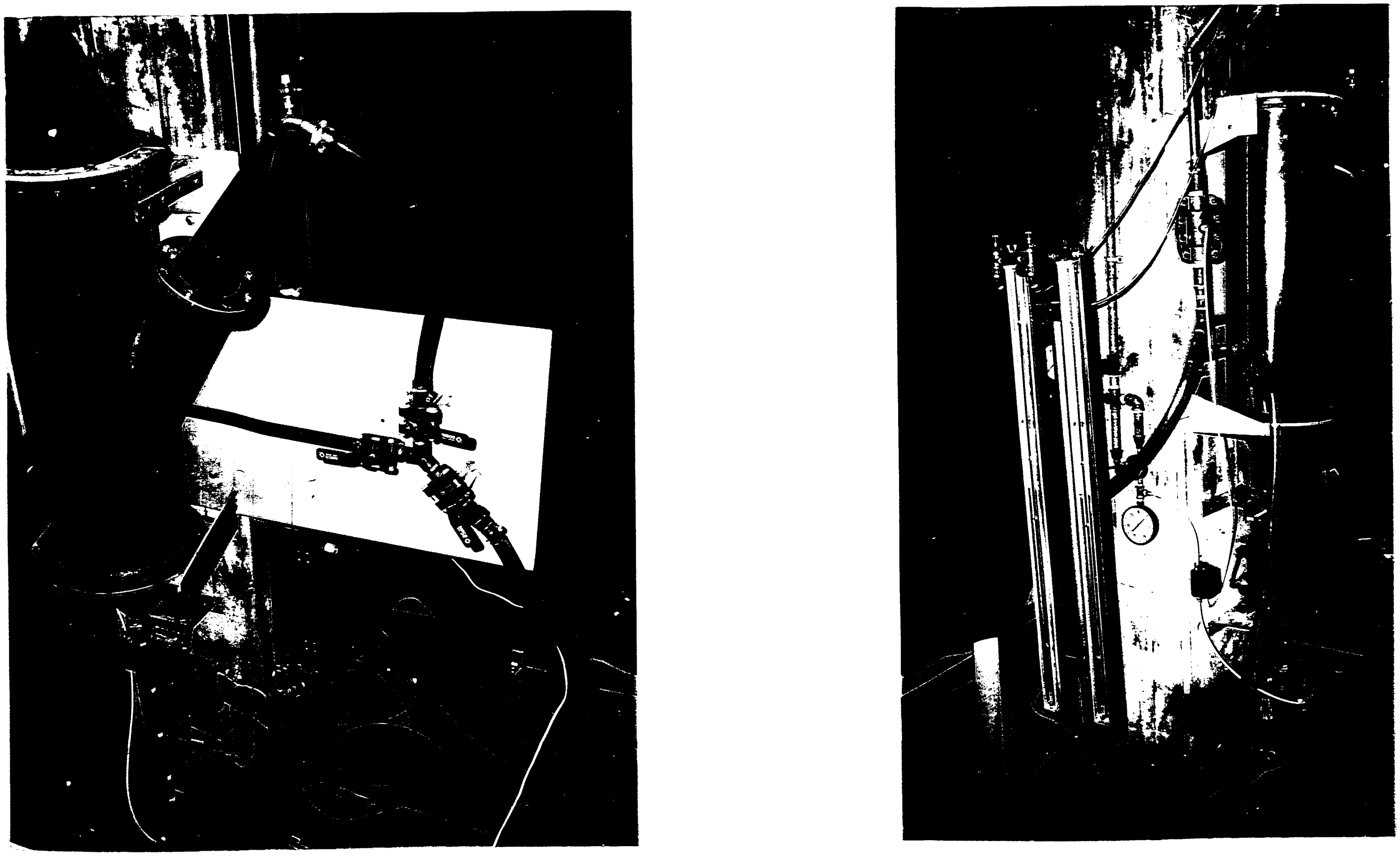


Figure 5.4. Air-powered diaphragm pump for recirculating gravel slurry.



(a)

(b)

Figure 5.5. Sediment trap (left) and bedload measuring installation (right).

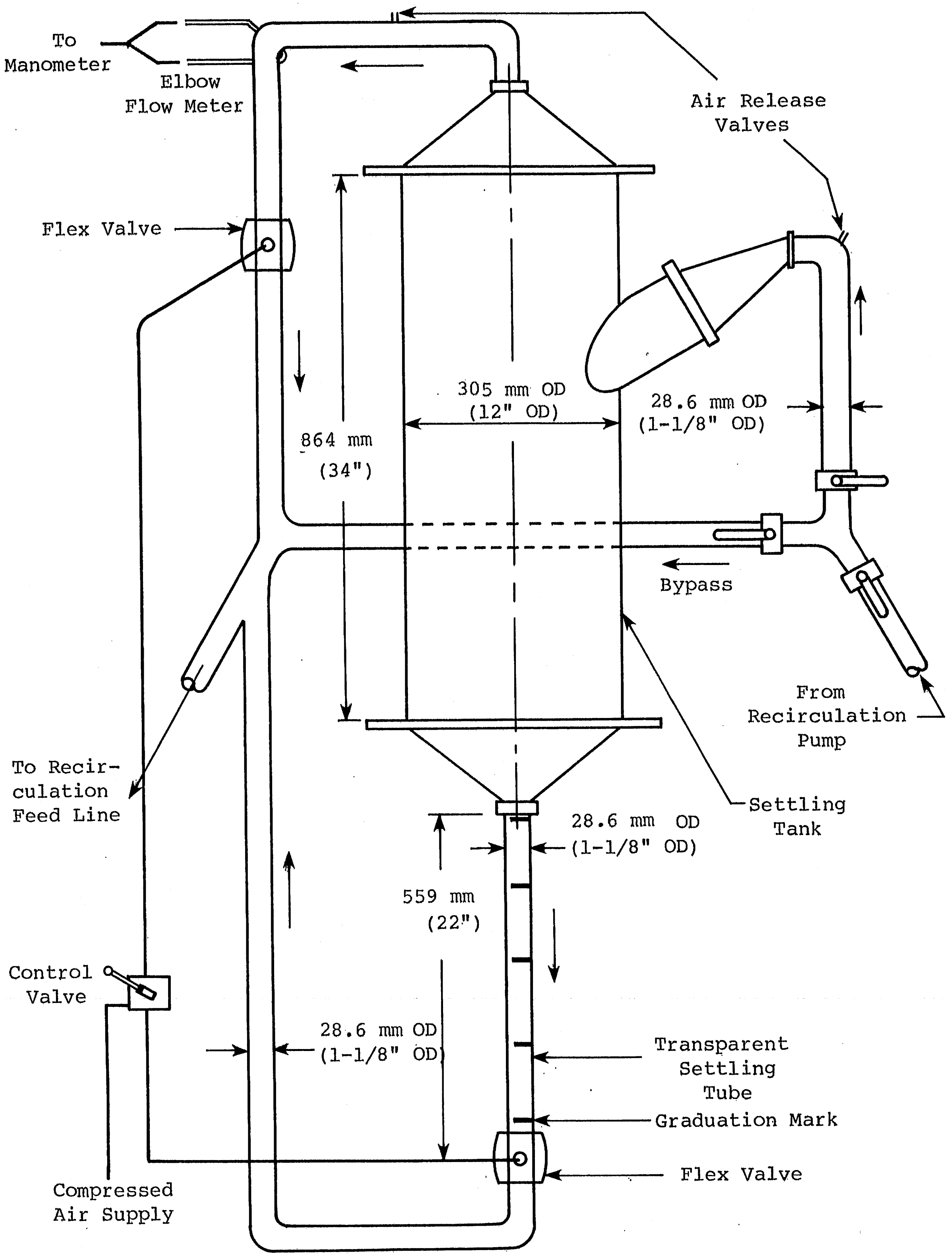


Figure 5.6. Schematic of the sediment trap and bedload measuring installation.

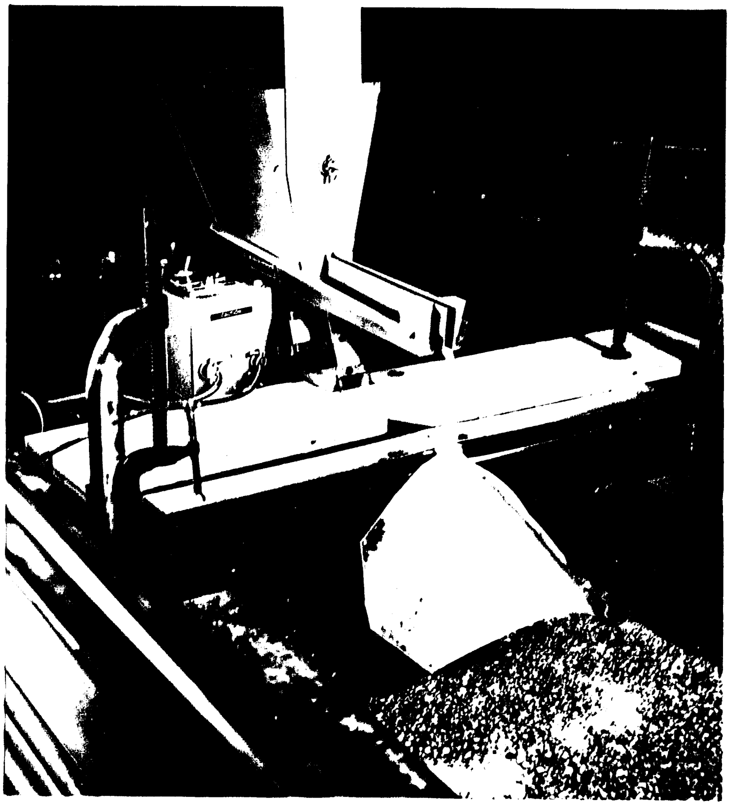


Figure 5.7. Syntron vibrating feeder.

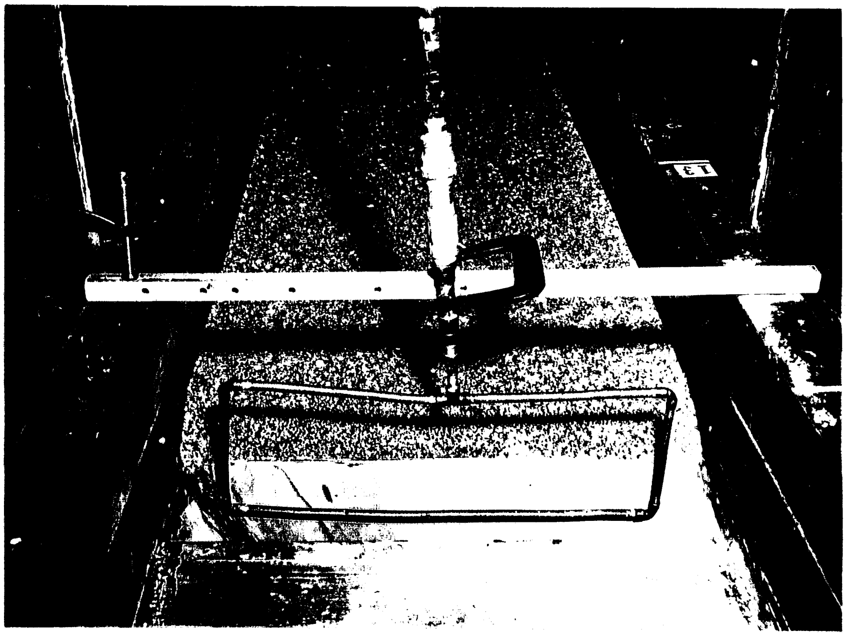
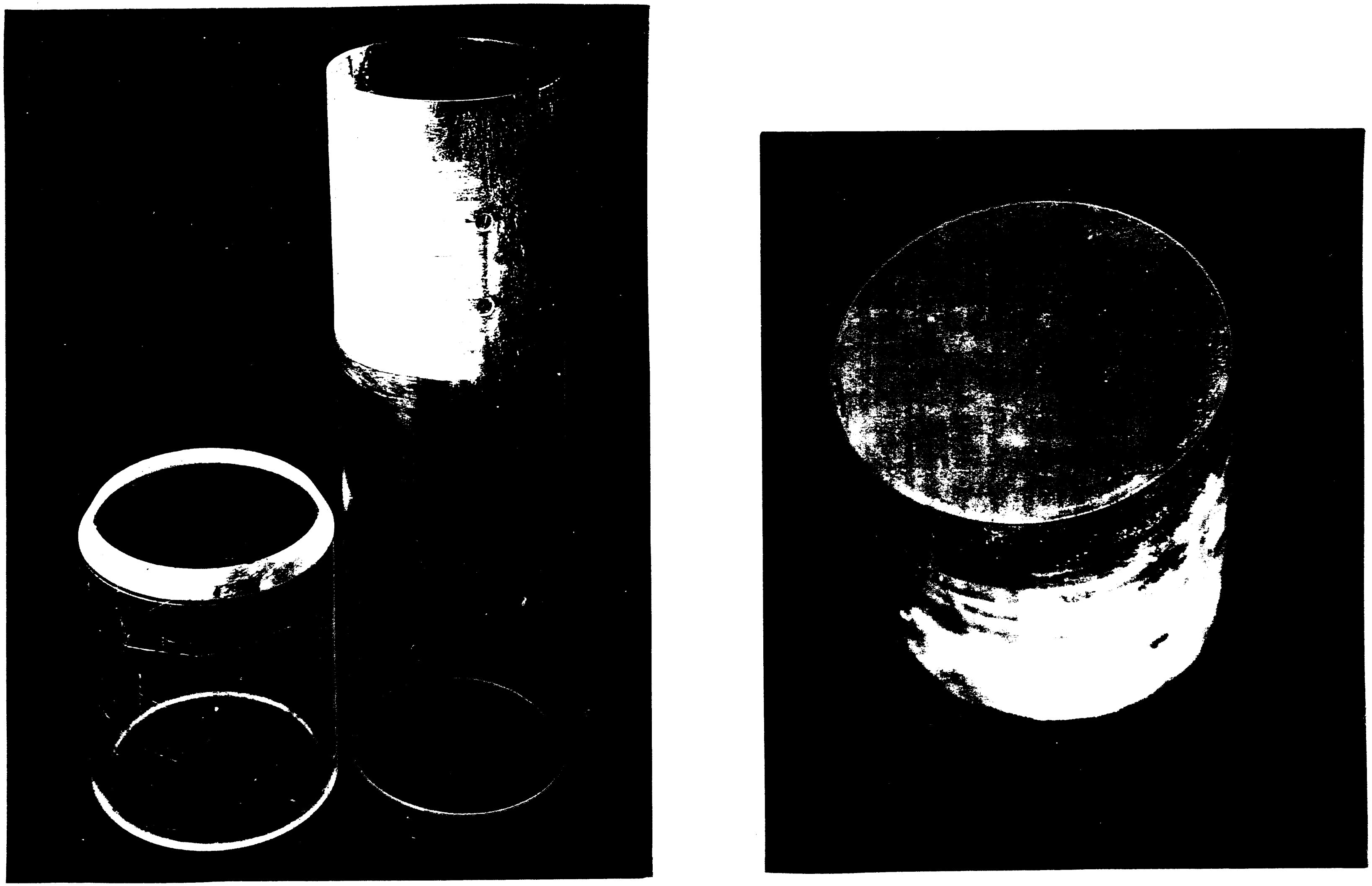


Figure 5.8. Bedload trap with air-bubbler (Exp. 114).

(a)

(b)

Figure 5.9. Suspended sediment sampling facility.



(a) (b)

Figure 5.10. Sampler used for taking pavement samples. Corer on left, piston on right.

Figure 5.11. A typical pavement sample.
Piston with soft clay surface.

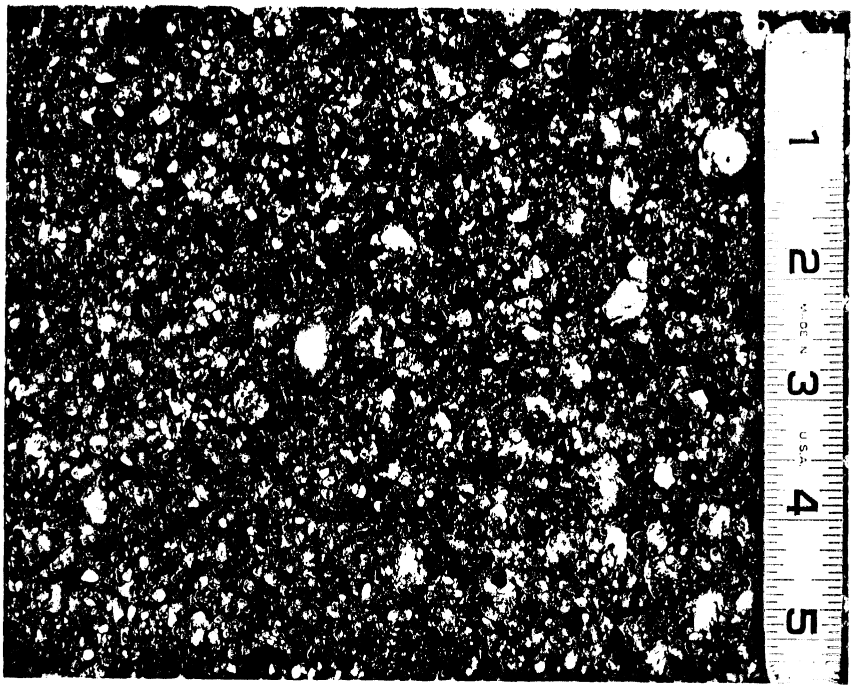


Figure 7.1. Bed surface at beginning of a typical experiment.

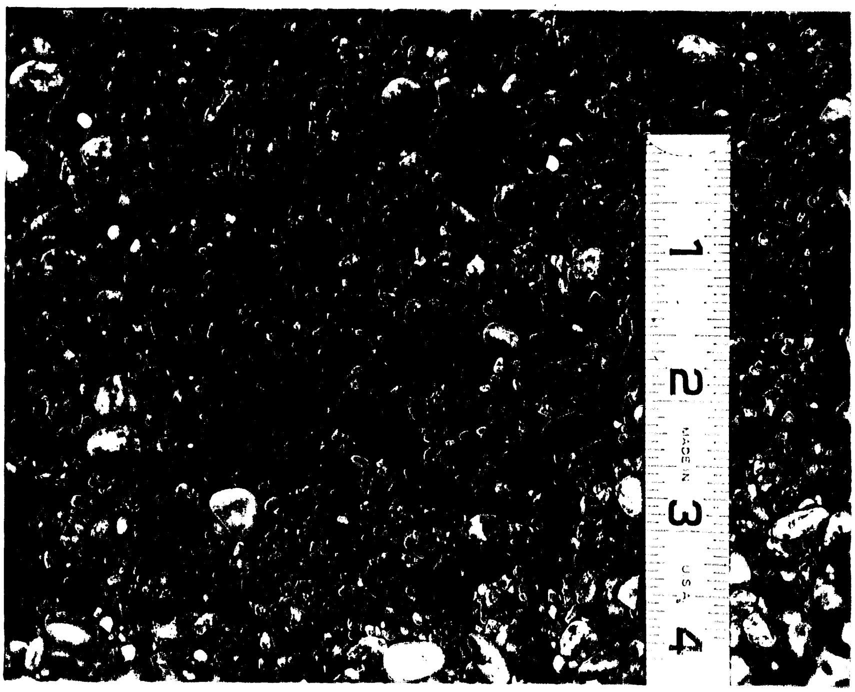


Figure 7.2. Bed surface (pavement layer) at end of the experiment (Run No. 107).

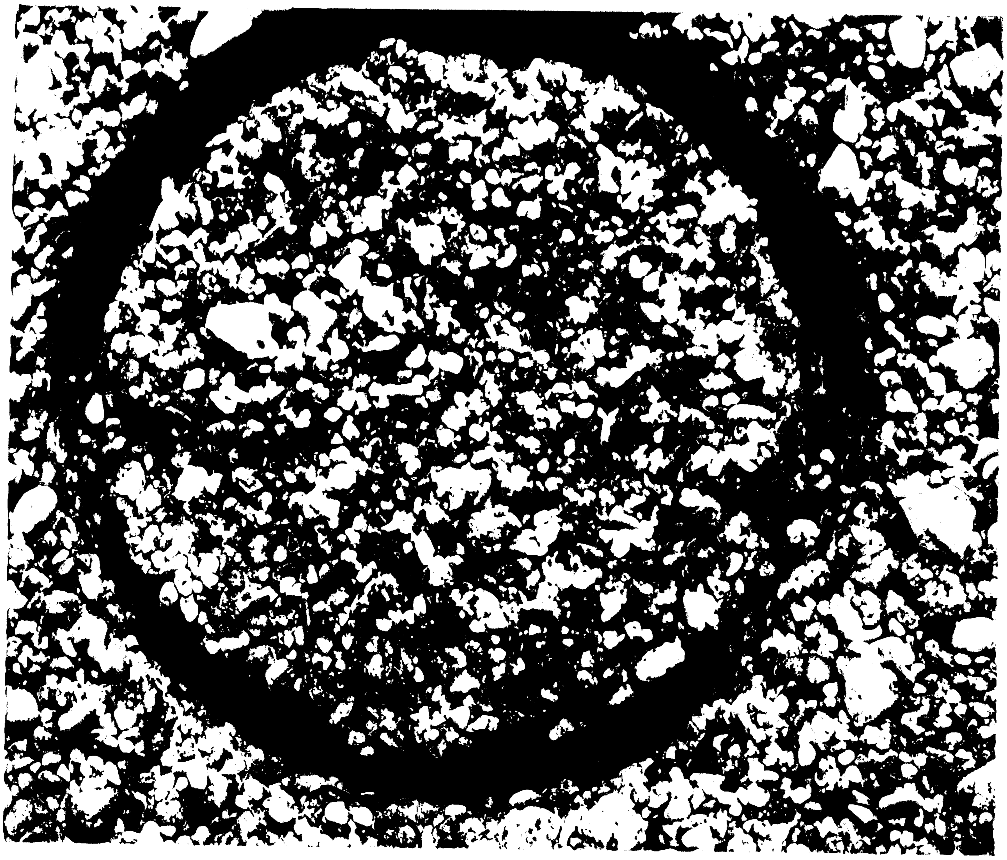


Figure 7.3. Pavement and subpavement for Run 109.

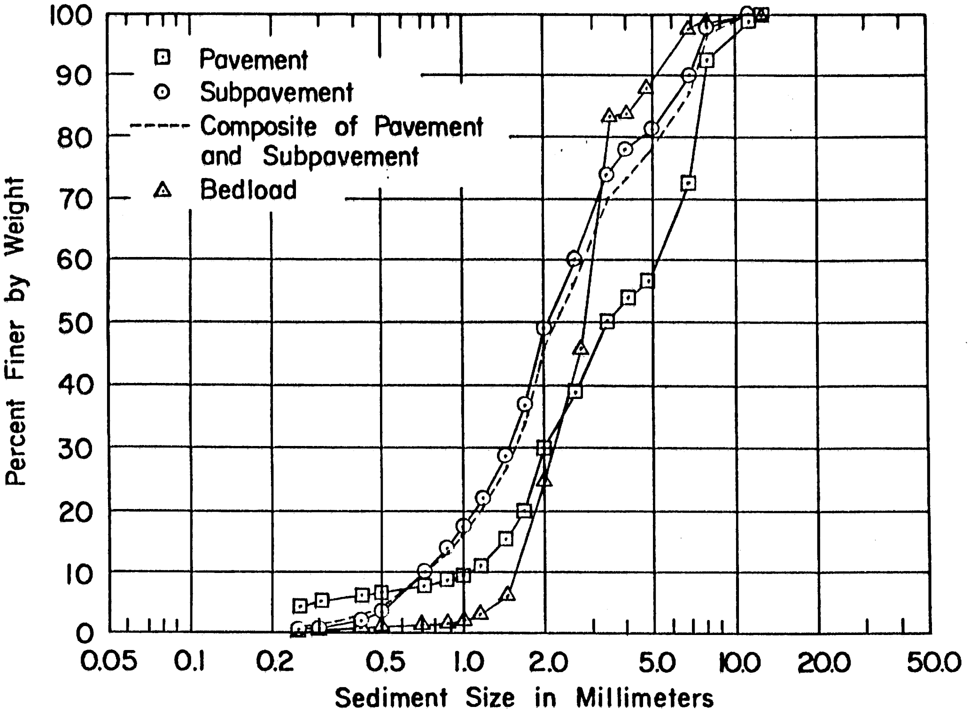


Figure 7.4. Composite size distribution curve for Run 108.

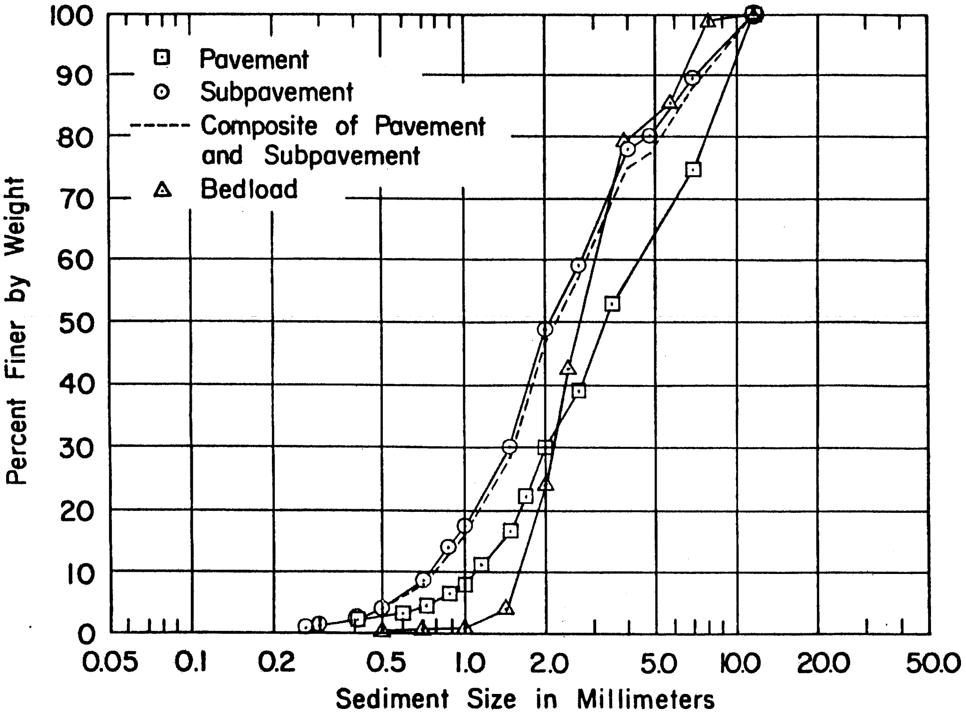


Figure 7.5. Composite size distribution curve for Run 107.

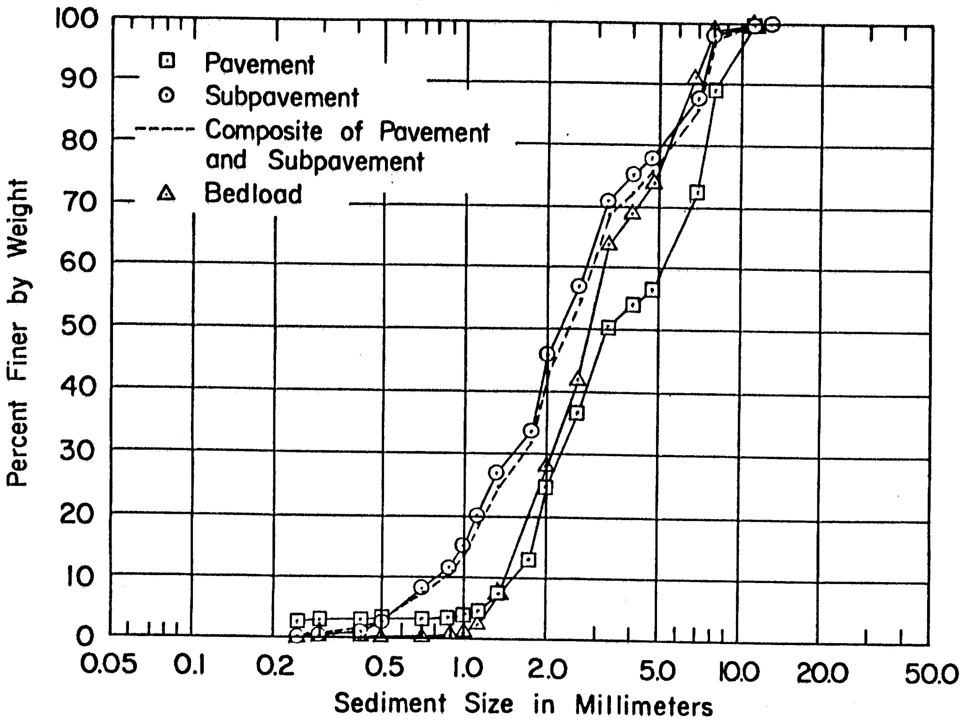


Figure 7.6. Composite size distribution curve for Run 109.

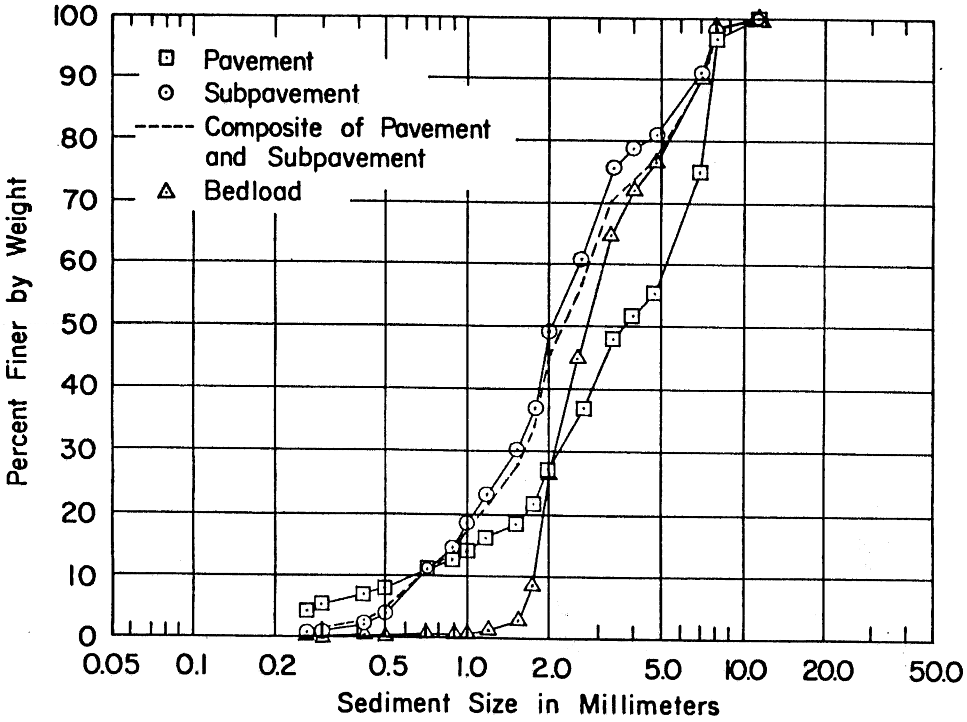


Figure 7.7. Composite size distribution curve for Run 112.

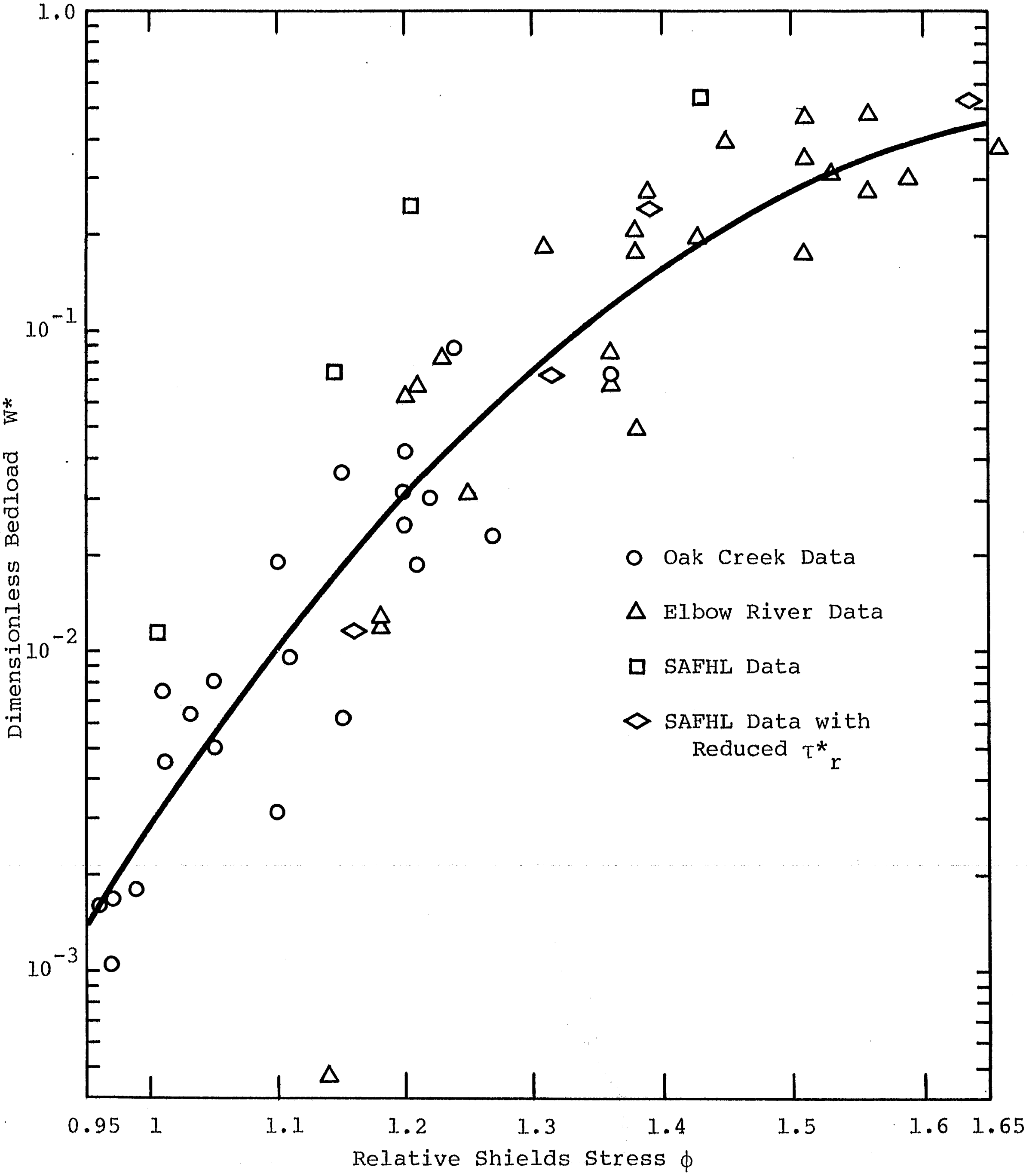


Figure 7.8. Plot of dimensionless bedload W* versus relative Shields stress ϕ.

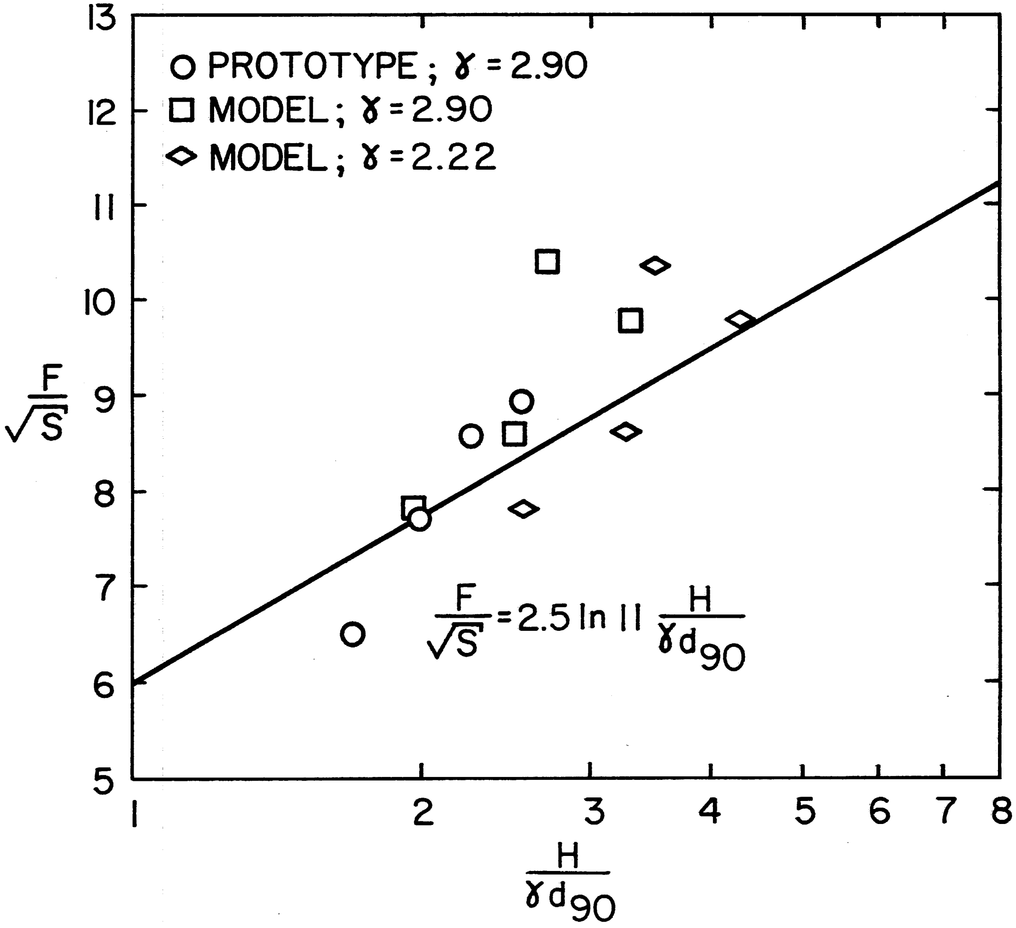


Figure 7.9. Resistance relation.

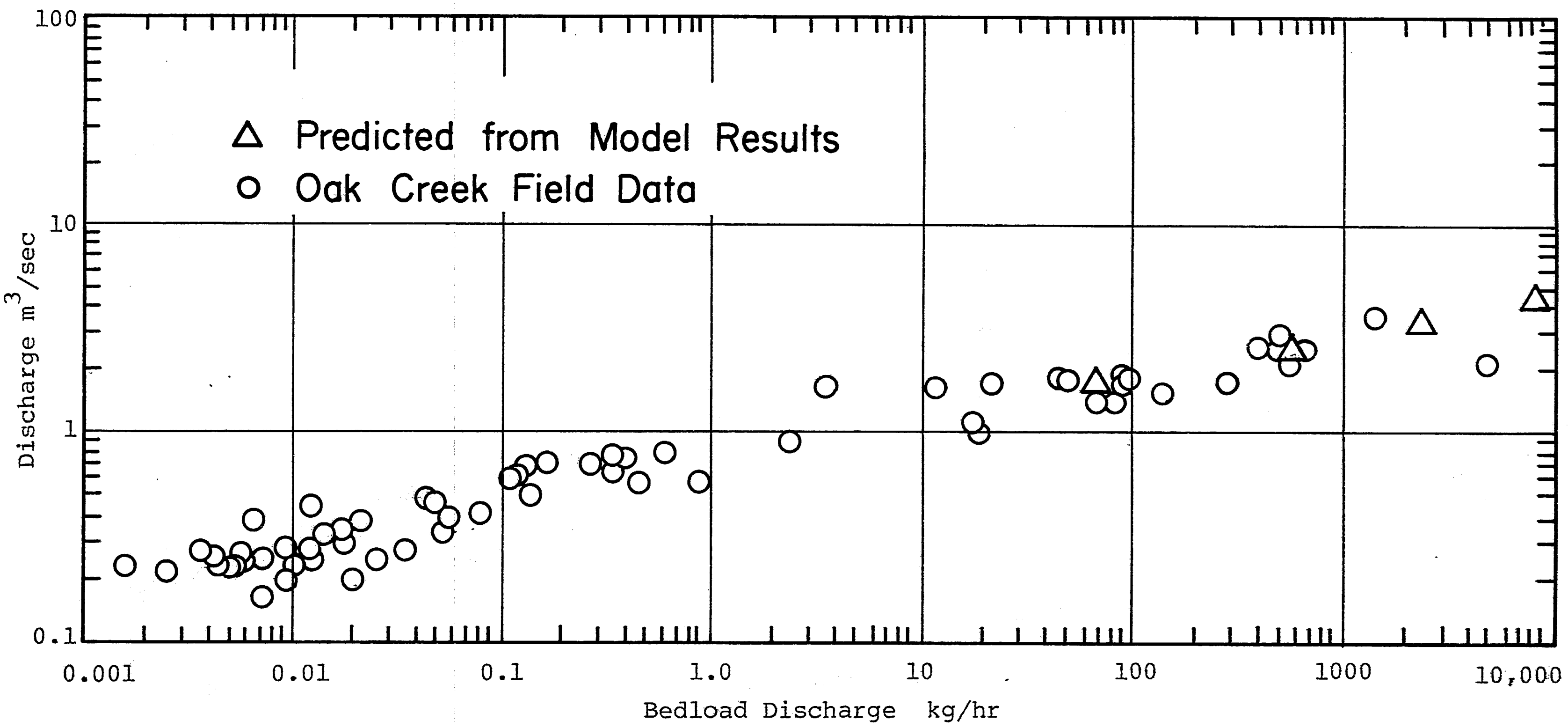


Figure 7.10. Bedload discharge versus water discharge in Oak Creek.

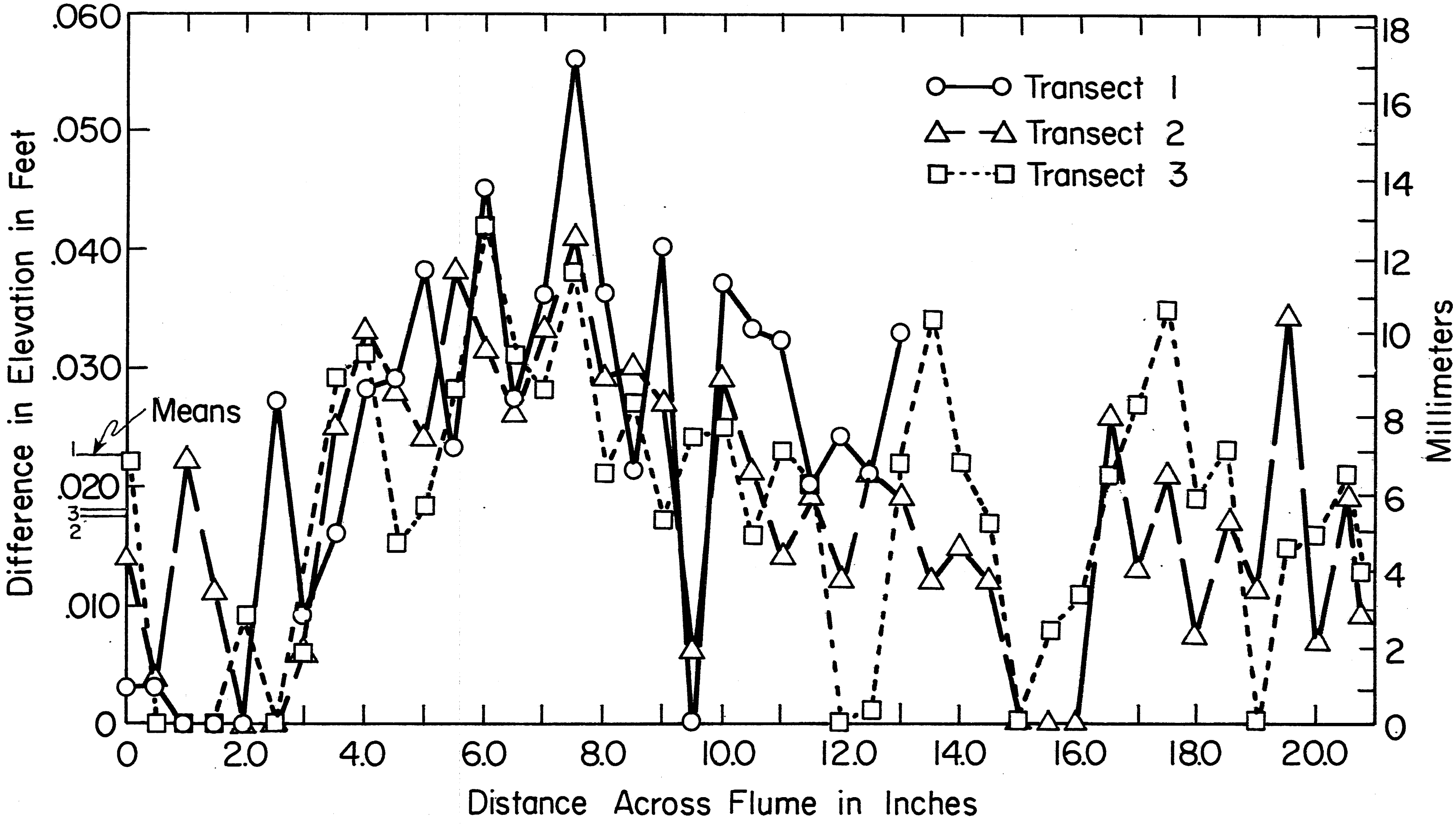


Figure 7.11. Difference in elevation between bed surface and surface of colored layer after 2.75 hours for Run 110.

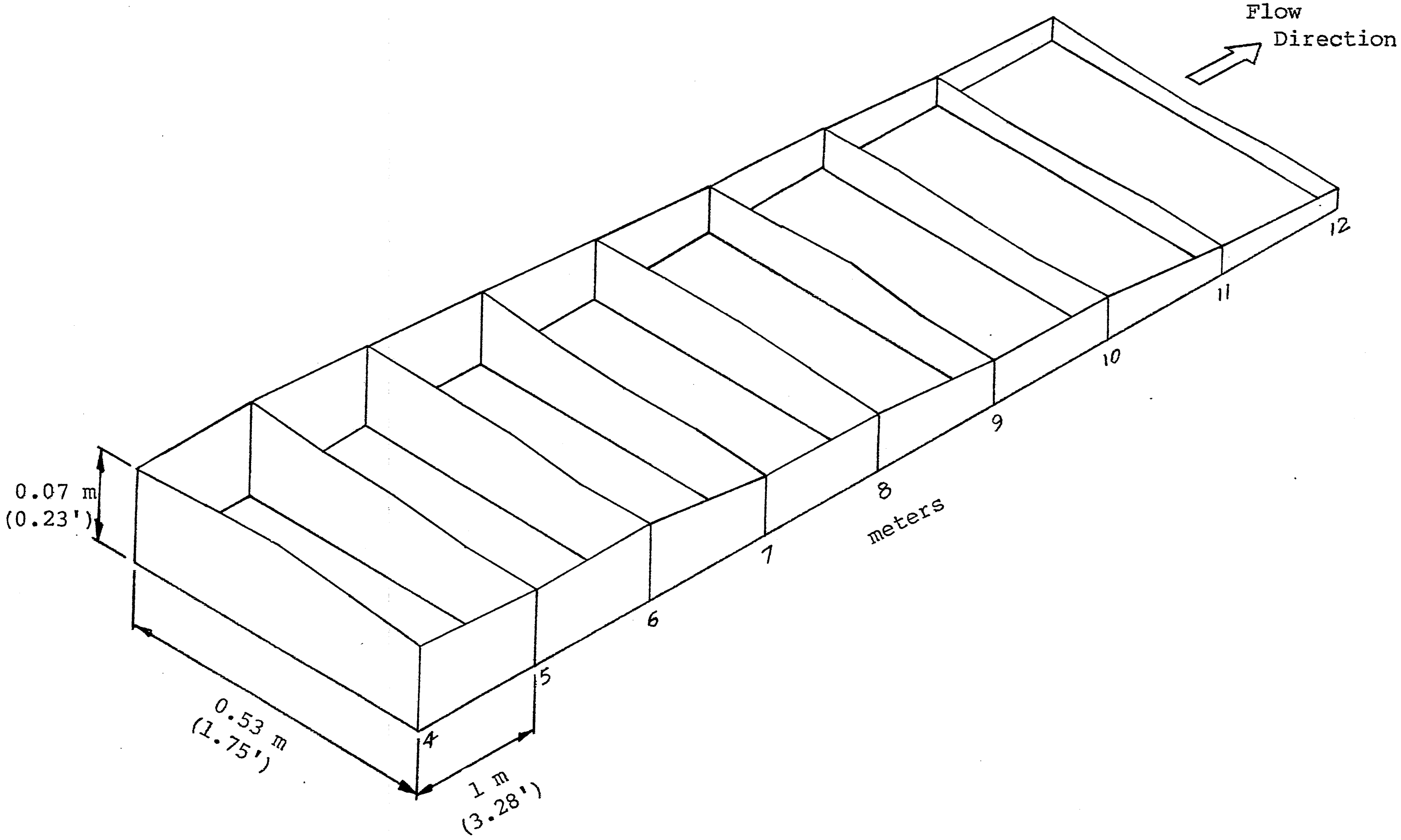


Figure 7.12. Schematic of bed elevations at the end of Run 109.

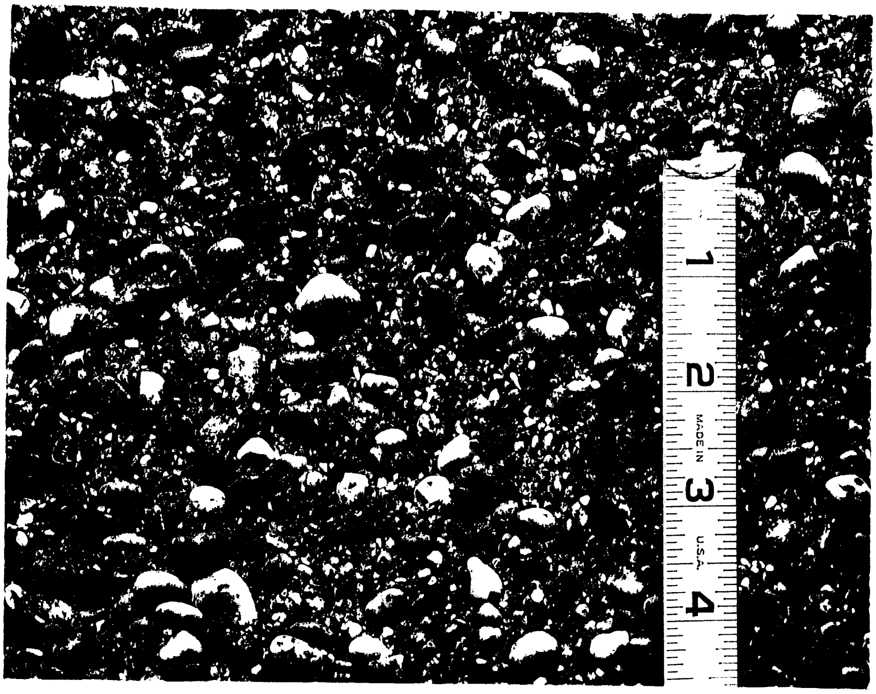


Figure 7.14. Pavement at the end of Run 111(a).

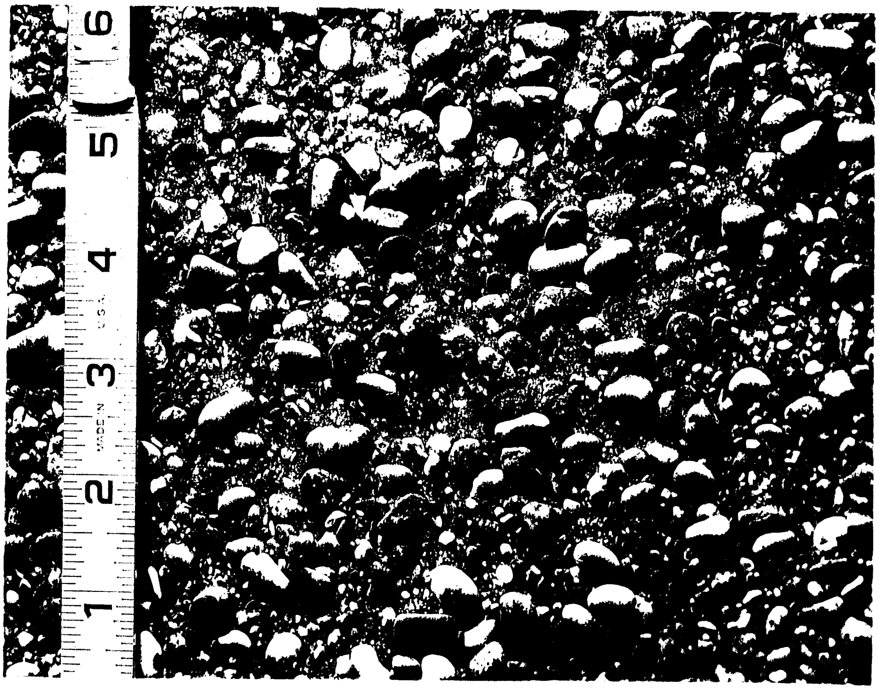


Figure 7.15. Pavement at the end of Run 111(b).

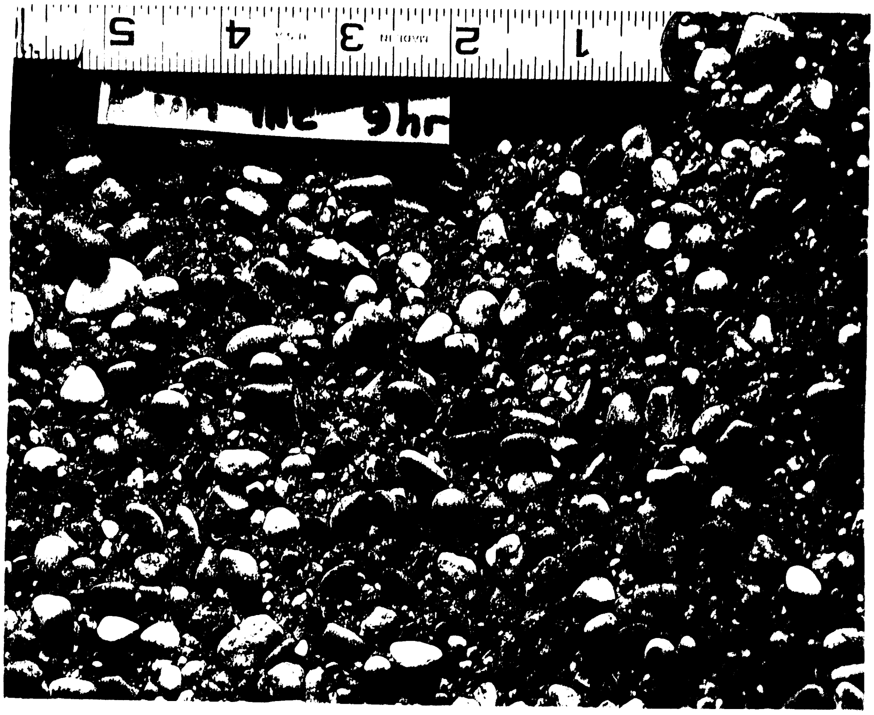


Figure 7.16. Pavement at the end of Run 111(c).

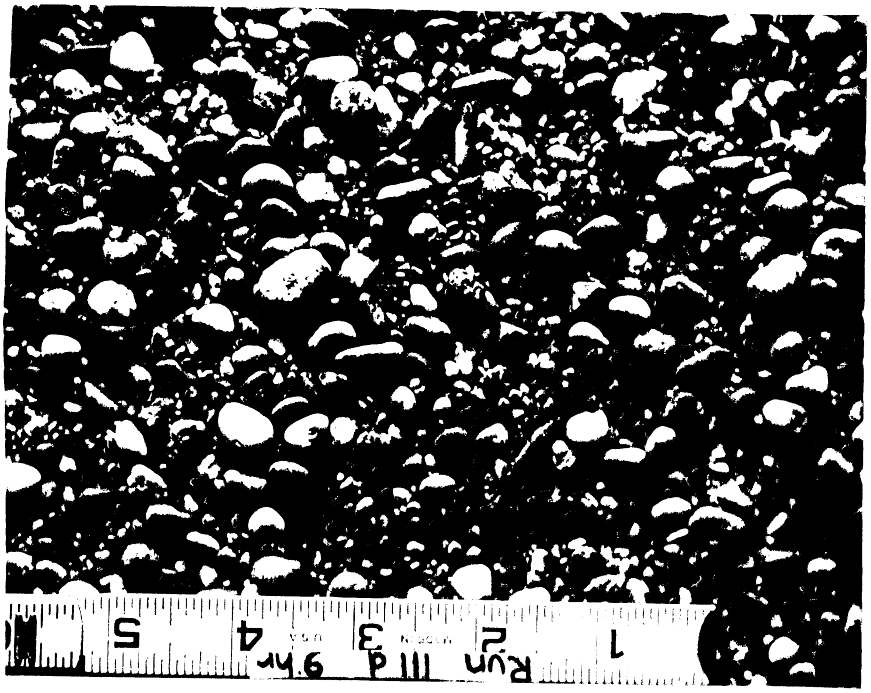


Figure 7.17. Pavement at the end of Run 111(d).

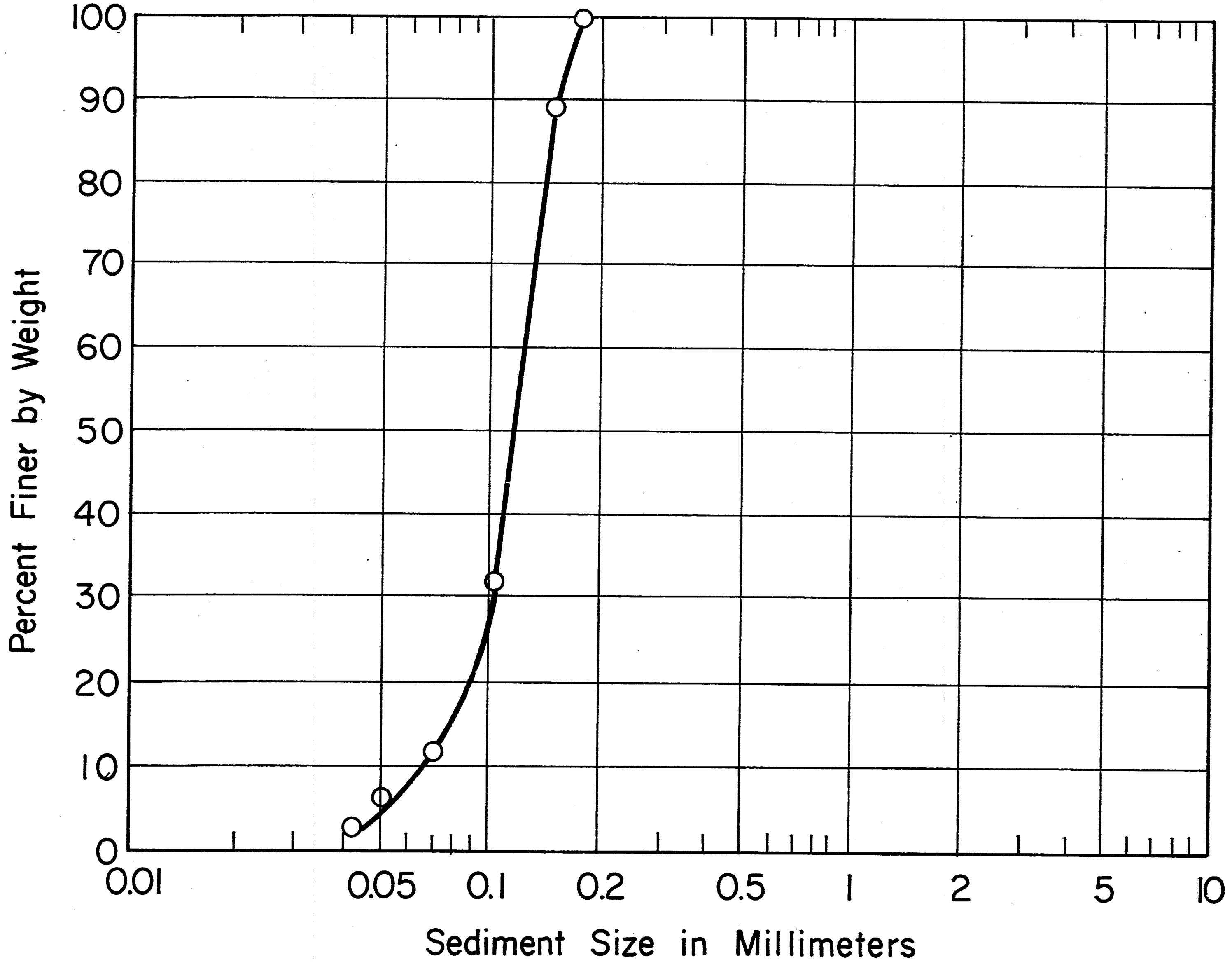


Figure 7.18. Grain size distribution for the fine sand.

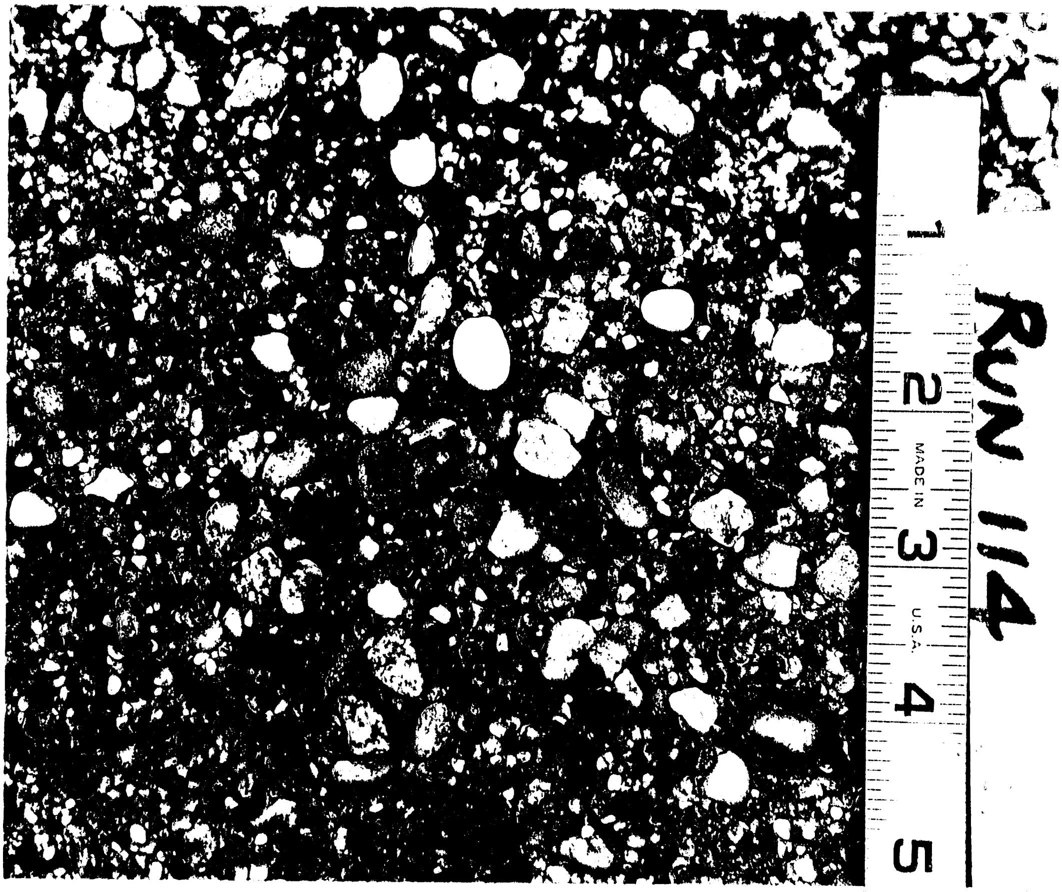


Figure 7.19. Pavement with fines for Run 114.

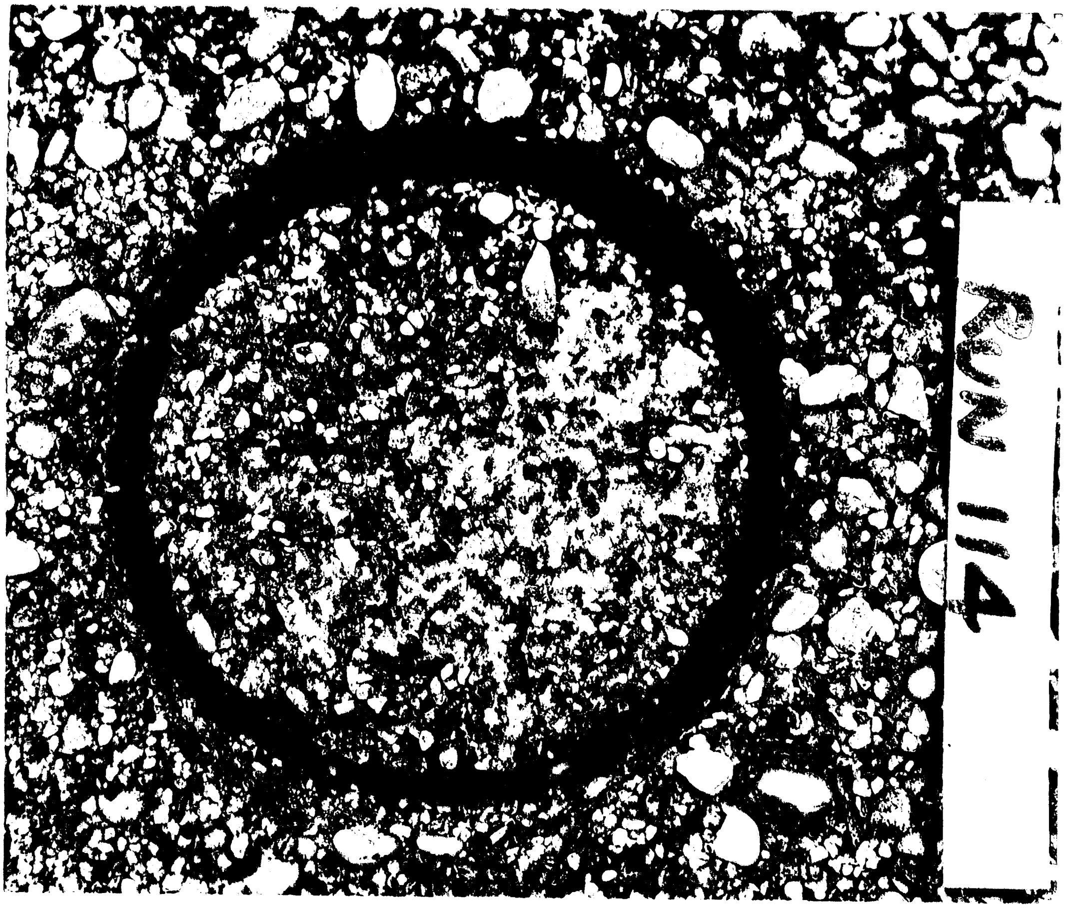


Figure 7.20. Top layer of subpavement with fines for Run 114.

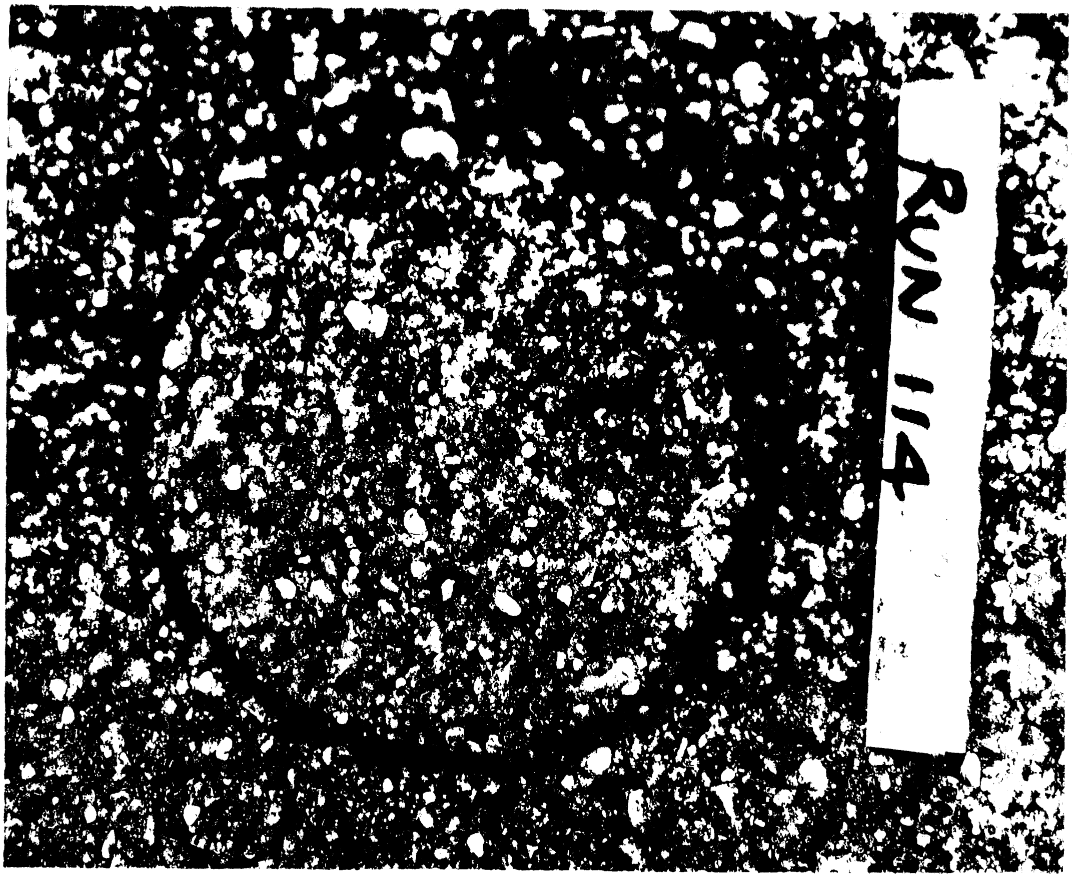


Figure 7.21. Middle layer of subpavement with fines for Run 114.

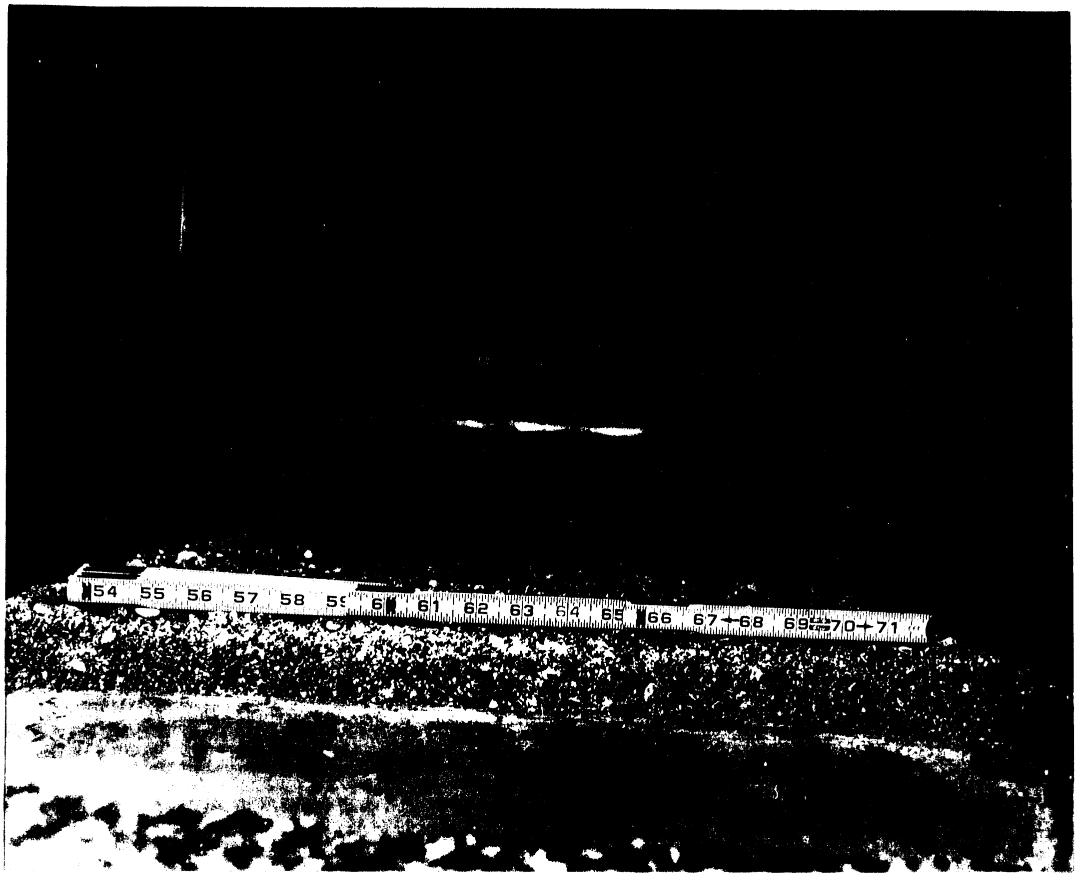


Figure 7.23. Lateral cross sectional view of the bed with fines for Run 114.