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MISSISSIPPI RIVER REVETMENT STUDIES

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PREFACE

The experimental investigations concerned with factors affecting the stability of articulated concrete revetment described in this report were conducted at the St. Anthony Falls Hydraulic Laboratory under contract DA-22-079-eng-12, sponsored by the Mississippi River Commission and the Waterways Experiment Station, Vicksburg, Mississippi.

The tests were made by R. M. Olson and T. Timar of the St. Anthony Falls Hydraulic Laboratory staff and L. F. Ingram of the Waterways Experiment Station, under the general supervision of Dr. Lorenz G. Straub, Director of the St. Anthony Falls Hydraulic Laboratory.

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MISSISSIPPI RIVER REVETMENT STUDIES

I. SYNOPSIS

Articulated concrete revetment mattresses have been and are being laid on the bed and banks of the Lower Mississippi River to stabilize bends and prevent recession of the banks. Exploratory experiments have been conducted at the St. Anthony Falls Hydraulic Laboratory to study some of the factors believed to contribute towards revetment instability and to explore the process of initial failure of the revetment as indicated by a movement or settling of the revetment mattress.

Two revetment installations were studied. One consisted of a relatively smooth 32-ft length of full-scale articulated concrete revetment mattress over an 18-in. bed of sand installed in the 9-ft main testing channel of the Laboratory. The sand was representative of that found in many stretches of the Lower Mississippi. Flow conditions simulated, as far as practicable, those indicated by field measurements in the Lower Mississippi made by the Waterways Experiment Station prior to the laboratory tests. Tests on the full-scale revetment included the following:

(a) Measurements of pressure fluctuations above and below the mattress blocks.

(b) Measurements of differential pressure pulsations between the top and bottom of the revetment blocks, which accompany turbulence.

(c) Measurements of steady-state pressure differences in the sand bed beneath the revetment blocks due to slight irregularities in the mattress surface.

(d) Observations over short- and long-duration tests of revetment settlement due to sand scour.

Supplementing and as a guide to the full-scale tests, a 4-ft length of a model revetment at a 1:18 scale was tested in a 6-in. glass-walled portable demonstration channel. The blocks were of Lucite weighted with lead and were laid over a 1-1/2-in. sand bed. Factors affecting the rate and degree of sand removal from between the interstices of the mattress were observed with this model revetment as a qualitative guide in planning the full-scale tests.

For the full-scale laboratory tests, the measured amplitude of the pressure fluctuations above the revetment were of the same order of magnitude and similar in pattern to those measured in various stretches of the Lower Mississippi River. The magnitudes of the differential pressure pulsations, measured between the top and bottom of a revetment block, were between 15 and 74 per cent of the simultaneous pressure pulsations measured above the block. The greatest change in this differential pressure, as compared with changes above the revetment, occurred when sand completely surrounded the sides and bottom of the test block; conversely, the smallest change occurred when sand did not surround the block.

Revetment failure, as defined by the removal of the sand bed from beneath the blocks and a resulting settlement of the mattress, occurred as a result of sand scour from the interstices between blocks. The scour tests were limited to studies of effects over the revetment mattress. Upstream, downstream, and talweg edge effects were not explored experimentally.

II. TEST FACILITIES AND REVETMENT INSTALLATION

All full-scale revetment tests were conducted in the 9-ft main testing channel of the Laboratory. Water for test purposes was diverted through this channel from the Mississippi River above St. Anthony Falls and discharged into large volumetric measuring basins. These basins were used for initial discharge measurements in the test program. These data were also used to calibrate the weir at the downstream end of the channel and this weir was used for controlling the water depth and measuring the discharge in subsequent tests. Water depth over the revetment was generally about 3 ft with velocities as high as 7.7 fps.

A 32-ft length of the articulated concrete revetment was installed over an 18-in. level sand bed spanning the 20-ft glass observation section of the main channel. The revetment was eight blocks long and seven blocks wide. Special test blocks for observing hydrodynamic pressure pulsations were installed along the center in the fourth and seventh rows as shown in Fig. 1. Each test block contained a differential pressure cell and two absolute pressure variation cells, one to detect pressure fluctuations above the revetment block and the other to detect these fluctuations below the block. The assembly of these cells in the test blocks is shown in Fig. 2. A photograph of the revetment prior to testing is shown in Fig. 3.

The bed material was obtained by intercepting sand from the Upper Mississippi when diverted through the test channel at very large flow rates. This sand was removed and stored outside the channel on one side for future use in the test program. The size distribution of this sand was similar to that of bed materials found in various stretches of the Lower Mississippi River. Figure 4 shows the size distribution of the sand used in the laboratory tests and comparisons with sands found at Vicksburg, Mississippi; at Memphis, Tennessee; and at Reid Bedford Bend.

Turbulent flow conditions were obtained by a simple channel contraction just upstream of the revetment installation as shown in Figs. 1 and 3. Previous tests in the main test channel and in a 6-in. portable demonstration channel indicated that vertical boards used to constrict the flow would furnish a simple method of providing turbulence pulsations that would agree most closely with field observations made in the Lower Mississippi. The data obtained in one phase of these tests indicated that the region of greatest turbulence extended to about 30 to 40 ft downstream of the contraction. These preliminary tests are described in Appendix A.

Instruments for detecting and recording the pressure pulsations were furnished by the Waterways Experiment Station and were identical with those used to make similar measurements in the field on the Lower Mississippi River.

III. PRESSURE FLUCTUATION TESTS ON FULL-SCALE ARTICULATED CONCRETE REVETMENT

A. Introduction

Field measurements by the Waterways Experiment Station had established the magnitude and the approximate frequencies of the pressure and velocity fluctuations on the river bottom resulting from natural turbulence at numerous revetted areas of the Lower Mississippi. It was the object of one phase of the laboratory investigations to simulate these measured flow conditions over the full-scale revetment installation and to measure the differential pressure pulsations across the top and bottom of the revetment blocks which might result from the pressure fluctuations over the top surface of the mattress. The pulsating differential pressures associated with turbulence, rather than steady-state differential pressures due to a normal misalignment of the mattress surface with resulting flow separation, were of primary interest in this phase of the tests.

B. Instrumentation

Two test blocks, shown in Figs. 1 to 3, were installed in the full-scale concrete mattress. Each contained one pressure differential cell and two absolute pressure variation cells furnished by the Waterways Experiment Station and were of the type used by WES in previous field measurements of pressure fluctuations. In order that the cells could be used to measure pressures in sand, the usual rubber diaphragm was protected by a plate with 45 holes each of 1/8-in. diam, and a 45-mesh screen. The time constant of this combination when used to measure abrupt pressure changes through sand was of the order of 0.1 sec. This indicates that the cell, when used to measure fluctuating pressures beneath the revetment in contact with sand, responded reliably to pressure changes of frequencies of 10 cycles per sec and less. The tests which led to these results and more details concerning the pressure cells are described in Appendix B.

The pressure fluctuations detected by each pressure cell were recorded simultaneously on a six-channel Brush oscillograph. Brush strain analyzers type BL-310 and BL-320 were used for amplifying and rectifying the signals.

C. Test Procedure

All pressure cells were calibrated statically before each day's tests, as described in Appendix C. Then the test channel was filled with water to an arbitrary level above the revetment and the recording circuits were adjusted when the pool was quiet so that the static differential pressure across the differential cells was recorded as a zero differential. Any change from this static differential was recorded during tests in such a way that if the pressure above the block decreased more than the pressure below the block (indicating positive buoyancy), the records indicated a negative differential. For the absolute pressure variation cells, the circuits were adjusted so that both cells in a given test block indicated the same pressure when only the true static pressure of the pool existed. Each record from the variation cells would then indicate pressure fluctuations about an arbitrary datum, and the algebraic differences between the two in a given test block at any time would indicate the differential pressure across the blocks by an amount greater or less than the static differential.

The zero settings were checked both before and after a series of runs and often between each run in order to compensate for a slight drift in the recording circuits.

Tests were made at mean velocities of 1.1 to 7.7 fps. For nearly all runs, all records were analyzed statistically by determining the mean pressures and the standard deviation from this mean over a 1- to 2-min period. It was found that this was a sufficiently long record to give representative results, since nearly identical values were obtained for different portions of a pressure record from a given test run. In determining these values, the recorded pressures were read at 1/10- or 1/5-sec intervals over the 1- to 2-min period; the values were averaged and the standard deviation computed in the usual manner. Examples of pressure-frequency distributions obtained by this method are shown in Fig. 5.

Runs were made on August 18, 25, and 30 and on September 8 and 14, 1950. Differential pressure fluctuations and pressure variations above and below the test blocks were recorded simultaneously for all runs. On August 18 and 25, only five Brush strain analyzers were available for use in the recording circuits, and only five simultaneous records were possible.

D. Summary of Laboratory Test Data

The significant data obtained were:

(1) The mean differential pressure across the test blocks. This was measured directly with a differential cell and computed by differences between the measured mean pressures above and below the block.

(2) The standard deviation from the mean pressure above the block, σ_a. This was compared with similar values obtained from sample field records to ensure similarity.

(3) The total variation in pressure above the block, also to compare with similar field data.

(4) The ratio of the standard deviation from the mean differential pressure to the standard deviation from the mean pressure above the block, σ_d/σ_a, hereafter called $\underline{R}$. This ratio was essentially the same as the ratio of a given change in differential pressure to the change in pressure above the block occurring simultaneously.

Good pressure fluctuation records were obtained for all runs and, in general, excellent agreement existed between differential pressures measured directly and those obtained by taking algebraic differences between measured pressure variations recorded above and below the revetment block (see Tables VI, VIII, and IX and sample records in Figs. 24 to 41).

Appendix C gives tabulations of data from each series of runs in detail and a discussion of individual tests. The significant data are summarized in Table I.

TABLE I

PRESSURE FLUCTUATION DATA FROM FULL-SCALE REVETMENT TESTS IN MAIN TESTING CHANNEL

Run or Time	Date 1950	Mean Velocity fps	Test Block 1				Test Block 2			
			Mean Diff. Press. ft	σ_a ± ft	Total Press. Variation above, ft	R*	Mean Diff. Press. ft	σ_a ± ft	Total Press. Variation above, ft	R*
1	Aug. 18	1.1	+0.003	0.021	0.12	0.15	0.0	0.012	0.06	0.17
2		1.9	-0.005	0.031	0.19	0.58	-0.003	0.031	0.17	0.26
3		2.5	-0.011	0.034	0.22	0.62	-0.005	0.033	0.17	0.46
4		4.0	-0.065		0.21				0.14	
1	Aug. 25	3.7	+0.010	0.017	0.09	0.33	+0.017	0.020	0.11	0.55
2		5.2	+0.018	0.041	0.25	0.18	+0.006	0.034	0.21	0.63
3		5.2	+0.039	0.033	0.22	0.52	-0.001	0.028	0.18	0.74
1	Aug. 30	7.7	+0.066	0.061	0.36	0.33	-0.041	0.061	0.36	0.25
1	Sept. 8	4.0								0.61
10:25	Sept. 14	4.0				0.34				0.55
11:00		4.0				0.32				0.51
11:10		6.0								0.25
11:15		6.0				0.50				0.22
11:30		6.0				0.42				0.19
2:25		6.0				0.40				0.15
Waves		0								0.65
3:50		6.0				0.35				0.33
3:56		6.0				0.35				0.25

$$^{*}\ R = \frac{\sigma_d}{\sigma_a} = \frac{\text{Standard deviation of differential pressures}}{\text{Standard deviation of pressures above block}}$$

$$\text{or } = \frac{\Delta P_d}{\Delta P_a} = \frac{\text{Change in differential pressure}}{\text{Change in pressure above block}}$$

The values of R for tests of September 8 and 14 were obtained by comparing changes in differential pressure with simultaneous changes in pressure above the block. Values of R for tests in August are ratios of standard deviations as described above.

Table I indicates that the mean differential pressure across the block never exceeded 0.065 ft of water additional positive buoyancy, this value being obtained on test block 1 on August 18 following considerable settling of blocks upstream of this test block in run 4. This additional buoyancy was about 1/6 the differential needed to overcome the weight of the revetment block. Instantaneous values greater than 0.065 ft were recorded, however. The maximum recorded instantaneous value of differential pressure which increased the block buoyancy was about 0.1 ft of water during run 4 of August 18, 1950.

Ratios of changes in differential pressure to changes in pressure above the revetment varied between 15 and 74 per cent. It was indicated that this ratio depended upon the amount of sand around the revetment block as well as the rate of change of pressure above the block. When the test block was well surrounded by sand the ratio was highest, and when sand was removed from around the block the ratio was lowest.

An examination of many records taken when the revetment test blocks were completely surrounded by sand indicated that when the rate of pressure change above the block was of the order of 0.02 ft of water per sec or less, a minimum effect of creating differential pressures occurred. Such was the case for run 1 for both test blocks and run 2 for test block 2 on August 18 (Figs. 24, 25, and 27). Values of R for these runs were 0.15, 0.17, and 0.26, respectively, from Table I. When the rate of change of pressure was about 0.06 to 0.10 ft of water per sec or greater, the maximum effect of creating pressure differentials existed. Examples of this are shown in Figs. 26 and 28 for test block 1 on August 18 and Figs. 31, 32, 33, 34, and 37 for test block 2 on August 25 and September 14. These correspond to highest values of R, the ratio of a change in differential pressure corresponding to a change in pressure above the block, from Table I.

E. Field Data

Seven sample records of pressure fluctuations measured in the water at various points in the Lower Mississippi were forwarded to the St. Anthony

Falls Hydraulic Laboratory by the Waterways Experiment Station as enclosures to a letter dated July 7, 1950. The records were analyzed and standard deviations from the mean pressure and the total pressure variations for each 2-min record were determined. The results are shown in Table II.

TABLE II

PRESSURE FLUCTUATION DATA FROM MEASUREMENTS MADE IN LOWER MISSISSIPPI RIVER

(Ref: WES letter dated July 7, 1950)

Location	Date 1950	Depth ft	Mean Velocity fps	σ_a ± ft	Total Pressure Variations ft
Reid Bedford No. 33	Feb. 15	53	4.0	0.069	0.69
Huntington Point No. 18	Feb. 3	53	4.9	0.043	0.35
False Point No. 40	Feb. 21	33	5.0	0.032	0.20
Yellow Bend No. 2	Feb. 6	55	4.2	0.041	0.40
Yellow Bend No. 7	Feb. 10	28	9.0	0.078	0.44
Yellow Bend No. 1	Feb. 6	50	5	0.01	0.05
Yellow Bend	May 23	57	3	0.098	0.46

Standard deviations of pressures above the block, σ_a, ranged from about ± 0.01 ft of water to ± 0.098 ft of water in these field measurements. Comparable values for the laboratory tests varied from ± 0.012 ft of water to ± 0.061 ft of water (Table I). Thus the magnitude of pressure fluctuations above the revetment in the laboratory tests were of the same order of magnitude as those measured in the Lower Mississippi, being greater in some instances and less in others.

The record for Reid Bedford No. 33 indicated a negative change in pressure above the revetment of 0.37 ft of water from the preceding 5-sec mean pressure. At Yellow Bend No. 2, a similar change of 0.30 ft of water occurred. These were the maximum pressure decreases recorded in this set of data, and in both instances the decreased pressures persisted for less than 1 sec—about 0.2 sec at Reid Bedford and about 0.8 sec at Yellow Bend.

An analysis of field measurements presented in "Turbulence in the Mississippi River," by J. B. Tiffany, Jr., a Waterways Experiment Station publication dated 13 May 1950, indicates that the maximum negative change in pressure from a preceding 5-sec mean was about 0.5 ft of water (Fig. 28 of that publication). This negative pressure also persisted for less than 1 sec.

F. Discussion of Results

The greatest change in differential pressure across a revetment block as compared with changes above the revetment occurred when sand completely surrounded the block. The magnitude of this greatest change in differential pressure was of the order of 74 per cent of the change above the block.

These results appeared to be independent of the magnitude of pressure variations in the water above the block and on the flow velocities, but depended more upon the rate of change of pressure at that point.

The 74 per cent figure, when applied to pressure variation data obtained in river measurements with the hydrodynamic pulsimeter, would give an indication of maximum instantaneous differential pressures expected to exist which would tend to lift or depress a revetment block.

It is significant that in the laboratory tests, failure of the revetment, as indicated by settlement of the mattress, was not a result of pulsating differential pressures lifting the blocks. Whether or not pulsating differential pressures can become great enough under natural conditions to cause failure of revetment installations in the Lower Mississippi has not been established.

Pulsating differential pressures resulting from turbulence rather than steady-state differential pressures across revetment blocks due to flow separations resulting from undulations or normal misalignments in the mattress surface were of primary interest in these tests. Those steady-state differential pressures which did result during the full-scale tests did not cause movement of the blocks; however, they were effective in the production of flow through the interstices between blocks and below them and the removal of sand, with a sinking of the revetment thereby.

IV. PRESSURE MEASUREMENTS IN SAND BED

A. Introduction

Revetment blocks, in an otherwise smooth mattress surface, can be slightly higher or lower than adjacent blocks due to the inherent flexibility of the mattress. The amount one block can be higher or lower than an adjacent block is limited by the restraint provided by connecting wire linkages. Points of step-up and step-down result in stagnation points or flow separations such that pressure differences exist around the blocks and can result in pressure gradients in the sand bed beneath them.

B. Test Procedure

Measurements were made at three mean flow velocities of the steady-state pressure differences which existed beneath the ends of blocks raised and lowered 1-1/2 in. from the mean mattress surface. These specific conditions were chosen simply as idealized typical minor irregularities in the revetment profile. Data were taken at mean velocities of 3-1/4, 4, and 5 fps with the water 3 ft deep over the revetment. The location of the test blocks, the position of the piezometer tubes, and the manometer circuits are shown in Fig. 6. The ends of the 3/8-in. copper piezometer tubes were 1 in. above the bottom of the lowest block (see Fig. 6) and were capped with 45-mesh screens. Carbon tetrachloride under water was used in the manometers.

C. Test Results

The results of the measurements are plotted on Fig. 6, those for both the raised and lowered blocks being equal within the accuracy of the measurements. The measured mean pressure difference between the ends of the blocks in feet of water was about one-sixth the mean velocity head.

V. REVETMENT SETTLING DUE TO SAND SCOUR

A. Introduction

In many instances sand was removed from the revetted area of the main test channel. This often resulted in a settlement of the revetment mattress. Movies taken during tests have shown somewhat the manner in which sand was removed and these movies, as well as photographs and bed profiles included in this report, show the effects of sand removal by scour upon the revetment mattress.

B. Test Results

Figure 7 shows profiles of the revetment surface and the sand bed after the tests of August 18, 1950 (see Table V). These were the result of 3 hr and 10 min of runs at 1.4 to 4.0 fps mean velocities. Figures 8 to 10 are photographs of the revetment under the same conditions. Figure 8 indicates that much sand was deposited between the downstream blocks.

Figure 11 shows profiles of the revetment and sand bed after a 40-min test run at 7.7 fps mean velocity. Considerable removal of sand is indicated, with an accompanying settling by the revetment mattress. Figure 12 shows the revetment after this test and after additional low-velocity runs. The overall appearance of the revetment mattress was not changed as a result of these latter low-velocity runs. A view of the voids below the revetment between the sixth and seventh runs from the upstream end is shown in Fig. 13.

A 17-hr test run at a mean velocity of about 5-1/2 fps was made in November, 1950. The revetment surface did not change appreciably during the first 6 hr. Profiles of the revetment along the glass wall of the test channel after 12, 15, and 17 hr of run are shown in Fig. 14. That the results were not essentially edge effects is indicated in Figs. 15 and 16. It may be noted that a board lining protected the upstream portion of the revetment.

The effect of only slight discontinuities in the surface of adjacent revetment blocks was quite pronounced. When a block was lower than the one immediately upstream, an underpressure existed at the transverse opening between the blocks, and sand particles were drawn into the opening from both directions along the adjacent longitudinal openings. At lower velocities this sand would accumulate just downstream of the transverse opening, while at higher velocities the particles were carried away. When a step-up occurred, an overpressure was created and sand particles were forced out, both upstream and downstream, along the adjacent longitudinal openings.

Figure 17 shows the area around raised and lowered blocks after a 25-min test run at 3.2 fps mean flow velocity. The accumulation of sand at the step-down and the removal of sand by scour at the step-up are apparent. Figures 18 and 19 show views through the glass wall of the test channel of the effects of irregularities in the block level on sand scour from a 5-hr test run at 5 fps.

Failure of the revetment, as defined by a settlement of the mattress, occurred as a result of removal of the sand bed from beneath the revetment by scour. This occurred in a relatively short time--from less than an hour to less than a day.

VI. COMMENTS ON TEST RESULTS AND CONCLUDING REMARKS

The experimental studies of articulated concrete revetment conducted at the St. Anthony Falls Hydraulic Laboratory during the past year are noteworthy in a number of ways, although this program has thus far been of short duration and held to a limited but well-defined program to stay within the expenditures of funds allotted for this purpose.

Special note is made of the fact that the studies showed that full-scale revetment experiments can be made under laboratory controlled conditions to simulate closely corresponding conditions in the Lower Mississippi River. There is thus provided an additional very promising adjunct in the study of revetment behavior and in the eventual establishment of optimum designs.

Field observations made by the Waterways Experiment Station on the revetment of the Lower Mississippi River were satisfactorily reproduced to full scale, particularly as regards magnitude and pattern of pressure pulsations over the revetment in consequence of turbulent flow in the river. The establishment of these relationships has provided a firm basis for further revetment studies to full scale under controlled conditions simulating occurrences in the field. The observations of the Waterways Experiment Station by direct measurement of characteristic flow conditions at various revetment installations on the Lower Mississippi River during the past two years are invaluable in providing the necessary information for establishing criteria for the full-scale laboratory tests.

The program of revetment studies thus far undertaken and described in this report has included detailed consideration of only a limited number of the many factors which affect revetment stability. Some of the factors which have been considered have been explored more thoroughly than others. No final answers to the overall revetment problem have been obtained; however, certain trends have been indicated as results of the tests. Some discussion is offered here as an aid in crystallizing contemporary thinking and as a guide to planning future test programs.

Measurements indicated that in general the pressure beneath revetment blocks did not follow the fluctuating pressures above the blocks when the blocks were completely surrounded at the edges and bottom by the sand bed. When voids existed around the blocks, the bottom pressures followed the upper surface pressures and little or no differential pressure existed across the block as a result of pressure fluctuations above the block. The differential pressures which did occur when voids existed around the blocks were essentially steady-state pressure differentials and were probably due to separation effects from the undulations in the bed. No special emphasis was placed on the study of separation effects in the test program with full-scale revetment; these observations were incidental and occurred in conjunction with other tests.

Revetment settlement occurred as a result of the removal of sand from the openings between blocks by scour. No tests were made of upstream, downstream, or talweg edge effects. Some trends were indicated from both the pilot tests and the full-scale tests. These trends were only qualitative; thus, positive conclusions are not warranted at this time concerning critical conditions, magnitudes, or relative importance of the various factors contributing to revetment failure. However, the limited test program gave some indications here listed.

(a) As the mean velocity of flow increased, the intensity of scour increased.

(b) At a given mean velocity, higher turbulence levels resulted in increased scour.

(c) Discontinuities between blocks in an otherwise essentially smooth revetment surface resulted in stagnation points and flow separations which affected the manner and rate at which sand scour occurred. These conditions may be classified as sharp variations in the steady-state pressure gradient along the revetment, both longitudinally and transversely to the general direction of flow of the main stream.

(d) When sand was artificially introduced into the flow upstream of the revetment installation, the rate of scour was decreased and in some instances deposition occurred.

(e) A double layer of revetment reduced the amount of sand removed by scour in the pilot model tests. (These tests have thus far not been repeated in the full-scale experiments.)

Several other observations probably of less direct importance have been made, particularly as regards instrumentation, but are left to a reading of the full report.

APPENDICES

APPENDIX A

TURBULENCE GENERATION AND TESTS ON REVETMENT MODEL

Prior to the full-scale tests, studies were made in a 6-in. glass-walled portable demonstration channel to establish a method of producing a turbulence pattern most closely resembling patterns observed in the Lower Mississippi River. Two pressure variation cells were mounted 5 ft apart in a false bottom of the channel to record the pressure fluctuations produced by various means at the upstream end of the channel.

The pressure fluctuations and turbulence patterns were initiated by different methods singly and in various combinations. These methods included the use of paddles on a vertical shaft at controllable rotational speeds, cyclic variations in discharge by changing the head and opening of the sluice gate inlet, pulsating wakes shed from an oscillating horizontal airfoil section submerged at about mid-depth in the flow stream, surface waves produced manually, and partial vertical channel obstructions. The latter method seemed to give the best agreement with river conditions as indicated by both the recorded pressure fluctuations and the observed turbulence conditions. It was also considered to be the simplest method to apply to the full-scale tests. The other methods resulted in pressure fluctuations which were more cyclic and less random than those recorded in the river measurements.

In order to determine the approximate attenuation in turbulence along the 9-ft main testing channel, pressure fluctuations along the bottom in the center of the channel were made at various distances downstream of an obstruction with the WES hydrodynamic pulsimeter. The results, which are shown in Fig. 20, indicated that the attenuation in the turbulence pattern along the channel was not unduly serious.

Pilot tests were made to small scale as a guide to the full-scale tests. The small scale revetment blocks were made of Lucite weighted with lead. A view of this revetment model in the portable demonstration channel is shown in Fig. 21.

APPENDIX B

INSTRUMENTATION STUDIES

The WES pressure cell was originally designed to measure pressure variations on the river bottom of revetted areas of the Lower Mississippi. The cell was mounted in a large iron disc, the hydrodynamic pulsimeter, with its active surface exposed directly to the water. A thin rubber diaphragm was used to keep foreign matter from the moving bellows, and the pressures in the water were transmitted through this diaphragm to the bellows inside the cell through castor oil in the intervening volume. The movement of the bellows is detected electrically by the movement of a transformer core, supported directly by the bellows, with respect to the fixed windings of the transformer. The minute signals are amplified and rectified and recorded either as a 60-cycle trace or a single-line trace with an amplitude proportional to changes in pressure from an arbitrary datum, usually near the ambient static pressure. The back volume of the bellows is exposed to air at a pressure corresponding to the ambient static pressure in the pressure variation cell. This cell was modified so that this back volume was also an active side. Thus, the motion of the bellows, and hence recorded signals, was proportional to the differential pressure existing across the two faces of the cell.

The WES pressure cells are of a displacement type, with a 1 in. of water change in pressure producing a movement of about 0.001 in. of the 2-in. bellows. Their use to measure pressure fluctuations in sand is limited by the ability of the water in the sand-water mixture to flow freely with changes in pressure which should result in proportionate motions of the bellows.

Tests were made with a 2-in. tube mounted on a pressure variation cell wherein sand was supported by the rubber diaphragm. The cell recorded the true change in water level when no sand was on the diaphragm, but recorded only about 40 per cent of the change in water level in the tube with 9 in. of sand above the cell. This percentage increased for smaller amounts of sand over the diaphragm. Similar results were observed when a cell was placed beneath a larger expanse of sand in the 9-ft main testing channel.

A flat plate with a 1/8-in. hole was then used to support various depths of different types of sand. The cell recorded accurately the static pressure changes in the water column above the sand, but a time lag occurred in the case of abrupt changes. This delay was measured in the same manner as in an electrical circuit; that is, the time required to reach (1 - 1/e) or 63 per cent of the final value was determined from pressure-time records taken.

The results of tests made with three types of sand are given in Table III. The abrupt pressure changes were applied by raising or lowering a rod into the column of water above the sand very quickly, or by applying a slight pressure or vacuum to the air space above the water and releasing it suddenly. A highly damped high frequency oscillation was often superimposed upon the step-function pressure change because of the natural vibrations of the moving parts of the cell.

TABLE III

WES PRESSURE CELL RESPONSE TO ABRUPT PRESSURE CHANGES IN WATER ABOVE A SAND STRATUM

(Sand Supported by Plate with One 1/8-in. Hole)

Type of Sand	Mean Size mm	Sand Height ft	Abrupt Pressure Change ft	Delay Time Constant sec
Missouri River	0.17	0.05	0.10	1.2 Trial 1* 4.3 Trial 4 3.4 Trial 5 5.5 Trial 7
		0.25	0.10	5.6
		0.25	0.20	3.2
Mississippi River	0.4	0.05	0.023	1.2
		0.05	0.10	0.8
		0.05	0.20	0.8
		0.25	0.023	0.9
		0.50	0.023	0.9-1.2
		0.75	0.023	1.0-1.2
Eau Claire	1.5	0.05	0.10	0.20
		0.25	0.10	0.20
		0.50	0.10	0.20
		0.75	0.10	0.20
Missouri River Sand above 0.02 ft Eau Claire sand		0.06	0.10	0.16
		0.25	0.10	0.72
		0.50	0.10	0.78
		0.50	0.20	0.74

* All trials made without changing sand or test setup.

Table III indicates that the delay in response was reasonably independent of sand height for a given sand and of the magnitude of the pressure change. The delay was greater for a finer sand. The use of a coarse sand immediately above the sand-supporting plate brought the delay time constant nearer the value for this coarser sand than that for the finer sand in the strata above.

A second series of tests was made with a differential cell wherein a plate with nine 1/8-in. holes supported sand on each side of the cell, with a larger volume of water between the plates and the cell diaphragms. Mississippi River sand 0.5 ft deep was placed over one plate and 0.1-ft abrupt pressure changes were applied first to one side of the cell and then to the other. Then an equal amount of the same sand was placed over the other plate and the test repeated. These tests were with water at 72° F. The tests with sand on both sides were repeated with water at 120° F. Results are shown in Table IV.

TABLE IV

WES DIFFERENTIAL CELL RESPONSE TO 0.1-FT ABRUPT PRESSURE CHANGES IN WATER THROUGH A SAND STRATUM

(One-half Foot of Mississippi River Sand--
Supported by Plate with Nine 1/8-in. Holes)

Condition	Water Temperature deg F	Dynamic Viscosity lb sec/sq ft	Delay Time Constant sec
Sand on one side	72	2.0×10^{-5}	0.34
Sand on both sides	72	2.0×10^{-5}	0.49
Sand on both sides	120	1.2×10^{-5}	0.36

The delay time constant for sand on one side (comparable to data of Table III) was reduced from about 1.0 sec with one 1/8-in. hole to 0.34 sec with nine 1/8-in. holes. It was increased from 0.34 to 0.49 sec with sand on both sides of the cell. The effect of water at 120° F was to reduce the delay time constant from 0.49 at 72° F to 0.36 sec.

A third series of tests was made with a plate with 45 holes, each of 1/8 in. diam, in combination with a 45-mesh screen on one side of a differential cell. This side was placed downward directly on Mississippi River sand

and the 2-in. tube was mounted on the top side of the cell and abrupt pressure changes of 0.34 to 0.44 ft of water were applied to the column of water inside the tube. The resulting delay time constant was 0.10 to 0.12 sec. This was the arrangement used later in the full-scale revetment tests for those cells which had an active side exposed to the sand beneath the revetment blocks. Typical oscillographs showing the response of the cells to abrupt pressure changes in sand for these first three series of tests are given in Fig. 22.

A fourth series of tests was made to compare the response of the WES pressure cell with a Statham pressure cell. The Statham cell is a bellows-type cell with a 1/2-in. bellows connected to wire strain gages. Figure 23 shows the test apparatus. The delay time constant for an abrupt pressure change was of the order of 0.01 to 0.02 sec when recording an abrupt pressure change of 0.2 ft of water above 1/2 ft of Mississippi River sand.

It is indicated that when the WES pressure cell was used to measure pressure changes with the active surface exposed to water, the response to abrupt pressure changes was limited only by the natural frequency of the bellows and transformer core assembly and by any viscosity effects of the castor oil used in the back volume of the differential cell. (A high-dielectric fluid is necessary because electrical wires and terminals are exposed in this space.) When the cell was used with one or both active surfaces in contact with sand, contact of sand with the rubber diaphragm resulted in erroneous results for recording of passive pressures as well as transient pressures. With a perforated plate to support or separate the sand from the diaphragm, the cell response was apparently a function of the sand permeability. As used in full-scale tests at the St. Anthony Falls Hydraulic Laboratory, the delay time constant was of the order of 0.1 sec.

APPENDIX C

DETAILS OF PRESSURE FLUCTUATION TESTS ON FULL-SCALE REVETMENT

A. Calibration of Pressure Cells in Revetment Block

The pressure differential cells and the two absolute pressure variation cells with active surfaces upwards were each calibrated with a 2-in. tube attached to the top of the cells. Gain settings of the electronic recording instruments were adjusted to produce the desired deflection on the Brush six-channel recording oscillograph for a given change in water level in the tube.

All four pressure variation cells had their back volumes connected to a common air pressure tank. Pressure in this tank was adjusted to compensate for ambient static pressures. Thus a decrease in this back pressure was equivalent to an increase in pressure on the active surface of the cell. This feature was used to calibrate the two cells whose active surfaces were below the blocks. Water was pooled in the channel and the back air pressure was varied. The amount of variation was measured by the two cells already calibrated; by a proper control of the changes in air pressure, the recording circuits for the two uncalibrated cells could be adjusted.

B. Discussion of Individual Tests

1. August 18, 1950

Four runs were made under conditions given in Table V. Sample records are given in Figs. 24 to 30. Data from the original oscillograph records are shown in Table VI. In run 1, low differential pressures were recorded because of the slow rate of change of pressures. In runs 2 and 3 the rate of change of pressures above the blocks increased, and larger differential pressures were recorded, as indicated in the sample records and in Table VI. After run 3 the test channel was drained. Blocks along the glass side of the channel in the first four rows had settled due to removal of sand from beneath them. All blocks in the first two rows had voids beneath them, up to 5 in. deep in some instances. This was near the contracted section where velocities were about 2, 3.4, and 4.5 fps, respectively, for runs 1, 2, and 3. The total elapsed time of tests at this point was 55 min at 1.1 fps, 45 min at 1.9 fps, and 75 min at 2.5 fps mean velocity.

TABLE V

REVETMENT TESTS - AUGUST 18, 1950

Run	Duration min	Discharge cfs	Mean Depth ft	Mean Velocity fps	Contraction per cent
1	55	21	2.25	1.1	45
2	45	52	3.0	1.9	45
3	75	67	3.0	2.5	45
4	15	117	3.2	4.0	22*

* 45 per cent for 5 min.

TABLE VI

RESULTS OF PRESSURE FLUCTUATION TESTS OF AUGUST 18, 1950

(Pressures in feet of water)

Run	Mean Velocity fps	Pressure	Measured Mean Pressure	Computed Mean Pressure	Standard Deviation $\pm\sigma$	Total Variation	$R = \frac{\sigma_d}{\sigma_a}$
1	1.1	Diff block 1	+.003	+.012	.003	.017	0.15
		Above block 1	+.065		.021	.12	
		Below block 1	+.053		.021	.12	
		Diff block 2	.00	.00	.002	.015	0.17
		Above block 2	+.065		.012	.060	
		Below block 2	+.065		.010	.055	
2	1.9	Diff block 1	-.005	-.010	.017	.090	0.58
		Above block 1	-.025		.031	.19	
		Below block 1	-.015		.018	.080	
		Diff block 2	-.003	-.004	.008	.062	0.26
		Above block 2	+.015		.031	.17	
		Below block 2	+.019		.025	.095	
3	2.5	Diff block 1	-.011	-.005	.021	.096	0.62
		Above block 1	-.050		.034	.22	
		Below block 1	-.045		.018	.096	
		Diff block 2	-.005	+.010	.016	.086	0.46
		Above block 2	+.055		.033	.17	
		Below block 2	+.045		.016	.076	

Run 4 was short and records obtained were inadequate for detailed analysis. A sample record is shown in Fig. 30. At the initial contraction, the velocity was about 7.2 fps for 5 min; then the contraction was decreased so that this velocity was about 5.1 fps. Sand was scoured considerably through the third row of blocks. Much sand was washed downstream of the revetment installation and had also been deposited upstream, indicating that sand was carried in from the river to the test channel. Sand had also been deposited between the interstices of the revetment downstreamward from the fourth row so that test block 2 was well surrounded by sand.

Figure 30 indicates that there existed a mean differential of about 0.07 ft of water tending to lift the block. This was probably due to the flow separation effects caused by irregularity in the revetment profile.

2. August 25, 1950

Three runs were made, as indicated in Table VII.

TABLE VII

REVETMENT TESTS - AUGUST 25, 1950

Run	Duration min	Discharge cfs	Mean Depth ft	Mean Velocity fps	Contraction per cent
1	120	103	3.1	3.7	22
2	45	146	3.1	5.2	11
3	35	146	3.1	5.2	11

Because of the severe loss of sand by scour in the upstream portion of the revetment in the previous tests, the approach slope was changed to 1:4 and the first two and one-half rows of blocks were underlaid by 2-in. boards to prevent scour just below the channel contraction and approach, as was shown in Fig. 1.

Sample records are shown in Figs. 31 to 34. Tabulated results are given in Table VIII. Differential pressure changes compared to changes above the block (ratio R) were 0.33 and 0.55 for test blocks 1 and 2 in run 1, from Tables I and VIII. At the end of run 1, the channel was drained. Some sand had scoured out near test block 1 and along the sides of the channel in the center of the revetment. Figures 31 and 32 indicate relatively small differential pressure fluctuations for block 1. Some sand had been added to the upstream end. In the time between 11:20 and 11:55, the gain in sand around block 2 resulted in an increase in differential pressure fluctuations as shown in Figs. 31 and 32. In run 2, the value of $\underline{R}$ for test block 1 decreased to 0.18. In run 3, the value of $\underline{R}$ increased to 0.52 for test block 1 and to 0.74 for test block 2 (Fig. 34). At the end of these runs, both blocks were well surrounded with sand, although considerable scour occurred along the side walls of the revetment. Some settling of the mattress occurred at these points, but the main part of the revetment was still intact.

TABLE VIII
RESULTS OF PRESSURE FLUCTUATION TESTS OF AUGUST 25, 1950
(Pressures in feet of water)

Run	Mean Velocity fps	Pressure	Measured Mean Pressure	Computed Mean Pressure	Standard Deviation $\pm\sigma$	Total Variation	$R = \frac{\sigma_d}{\sigma_a}$
1	3.7	Diff block 1	+.010	-.012	.006	.035	0.33
		Above block 1	-.002		.017	.090	
		Below block 1	+.010		.017	.095	
		Diff block 2	+.017		.011	.063	0.55
		Above block 2	+.030		.020	.105	
		Below block 2	-		-	-	
2	5.2	Diff block 1	+.018		.007	.045	0.18
		Above block 1	+.027		.041	.25	
		Below block 1	-		-	-	
		Diff block 2	+.006	-.005	.022	.115	0.63
		Above block 2	-.033		.034	.21	
		Below block 2	-.028		.012	.065	
3	5.2	Diff block 1	+.039	+.078	.017	.095	0.52
		Above block 1	+.030		.033	.225	
		Below block 1	-.048		.025	.145	
		Diff block 2	-.001		.021	.12	0.74
		Above block 2	-.061		.028	.185	
		Below block 2	-		-	-	

3. August 30, 1950

The revetment was refurbished and one 40-min run was made at a mean velocity of 7.7 fps over the revetment. (Discharge was 173 cfs at a mean depth of 2.5 ft.) An 11 per cent contraction was used. A sample record is shown in Fig. 35, and detailed tabulations are listed in Table IX. It is seen that pressures below the block followed those above the block quite well, and only small differential pressures existed. Ratios of R were 0.33 and 0.25 for test blocks 1 and 2, respectively. Profiles of the revetment and sand bed at the conclusion of the test (Fig. 11) indicated that some voids apparently existed around the test blocks.

TABLE IX

RESULTS OF PRESSURE FLUCTUATION TESTS OF AUGUST 30, 1950

(Pressures in feet of water)

Run	Mean Velocity fps	Pressure	Measured Mean Pressure	Computed Mean Pressure	Standard Deviation $\pm\sigma$	Total Variation	$R = \frac{\sigma_d}{\sigma_a}$
1	7.7	Diff block 1	+.066	+.004	.020	.13	0.33
		Above block 1	+.112		.061	.36	
		Below block 1	+.108		.060	.35	
		Diff block 2	-.041	-.017	.015	.105	0.25
		Above block 2	-.013		.061	.36	
		Below block 2	+.004		.036	.19	

4. September 8 and 14, 1950

Short test records were made on these dates to verify the indications that the variation in differential pressure fluctuations was a function of the amount of sand around the block. Figure 36 shows a record taken at a mean velocity of 4 fps over the revetment. Test block 2 appeared to be well surrounded by sand; a 2-hr run at a mean velocity of 2 fps was made just prior to the run at 4 fps. From Table I, the value of R was 0.61.

On September 14, short runs were made with no change in the revetment installation following tests on September 8. Again, at 4 fps similar values of R were obtained for test block 2 as on September 8 and for test block 1 on August 30 (see Table I). Figure 37 shows a typical record made at 11:00. The velocity was increased to 6 fps and three short records were analyzed to compare values of R at 11:10, 11:15, and 11:30. For test block 2, the values decreased from 0.51 for the 4-fps run to 0.19. Figure 38 is a sample record taken at 11:30 when the ratio of differential pressure changes to those above the block was 0.19. When the channel was drained, it was seen that test block 2 was quite free of sand, and a slight void existed beneath it. Sand was then completely removed from beneath the center of test block 2, and the records of Fig. 39 were obtained. The value of R was 0.15. Then the void was completely filled and sand placed all around test block 2 and the neighboring blocks. Surface waves with still water resulted in a value of R of 0.65 (see Table I). Water at a mean velocity of 6 fps progressively scoured sand from around test block 2, and the values of R at 3:50 and 3:56 were 0.33 and 0.25, respectively. Sample records of these latter runs are shown in Figs. 40 and 41.

APPENDIX D

TESTS OF HYDRODYNAMIC PULSIMETER

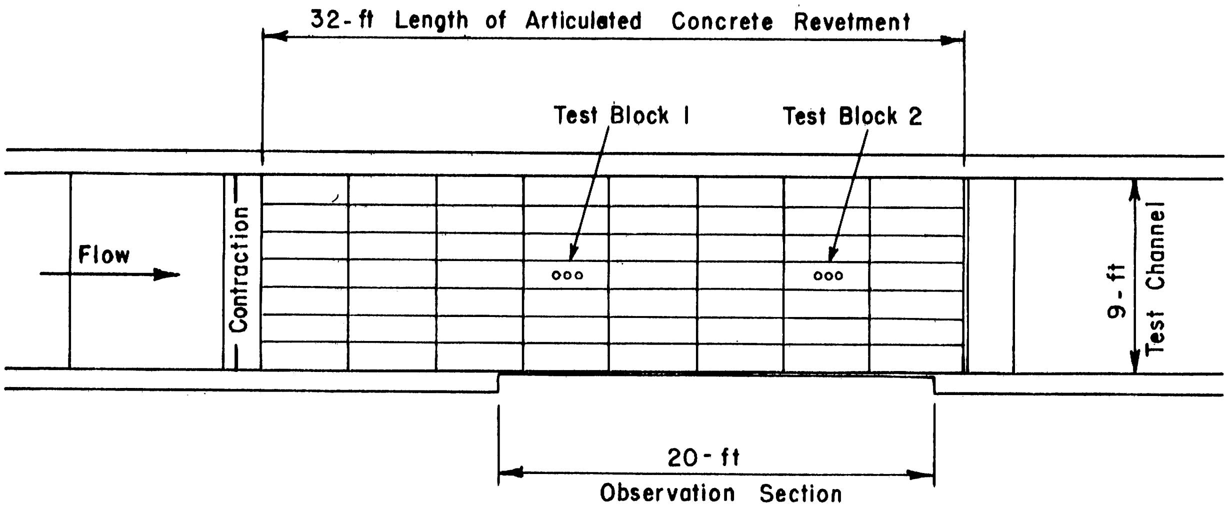
Tests were conducted in the 9-ft main testing channel to compare the magnitude of pressure fluctuations resulting from turbulence as measured with pressure-variation cells in the Waterways Experiment Station hydrodynamic pulsimeter and with cells mounted in the channel floor. Measurements were made in the center of the channel at a point 29 ft downstream from a channel contraction used to produce the turbulence patterns. Records were not taken simultaneously but those for a given test were made without changing the flow. Mean flow velocities varied between 1.3 and 5.0 fps at water depths of 3.0 to 4.8 ft. The mean pressure over a 1- to 3-min period was determined with respect to an arbitrary datum, and the standard deviation of pressures from this mean was then computed. The standard deviation was used as an index of pressure fluctuations. The magnitudes of these standard deviations for a given run were compared to determine any effect of the presence of the hydrodynamic pulsimeter. Results are shown in Table X, and are plotted in Fig. 42. The pulsimeter is shown in the test channel in Fig. 43.

TABLE X

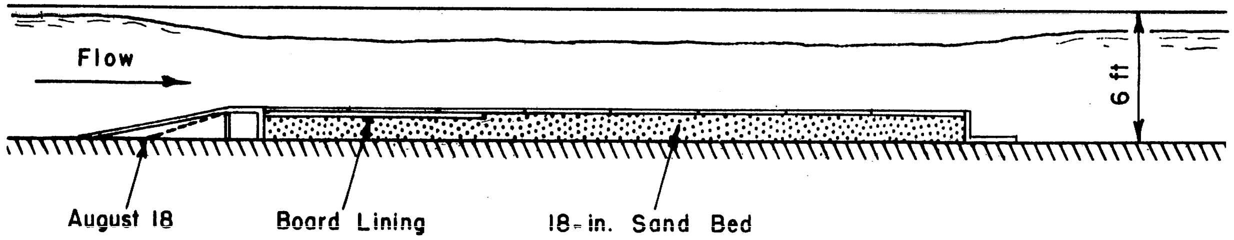
TESTS OF HYDRODYNAMIC PULSIMETER

Date 1950	Mean Velocity fps	Water Depth ft	Cell in Pulsimeter	σ_p ± ft	Cell in Channel Floor	σ_f ± ft	$\frac{\sigma_p}{\sigma_f}$
15 June	1.3	3.1	5-V	0.0114	6-V	0.0157	0.73
	1.3	3.0	5-V	0.029	6-V	0.0360	0.80
	2.5	3.1	5-V	0.035	6-V	0.045	0.78
18 July	2.5	3.1	5-V	0.0366	6-V	0.052	0.70
	2.5	3.1	6-V	0.0362	5-V	inoperative	
19 July	2.5	3.1	6-V	0.045	7-V	0.045	1.00
25 July	3.7	4.8	6-V	0.026	7-V	0.028	0.93
26 July	5.0	4.8	6-V	0.042	7-V	0.041	1.02

Results with variation cells 5-V and 6-V indicate that pressure fluctuations measured with the pulsimeter disc on the channel floor were 20 to 30 per cent less than those measured directly on the channel floor without the disc. When cell 6-V was installed in the pulsimeter in place of 5-V, fluctuations compared within 2 per cent of those previously measured with cell 5-V. This would indicate that the techniques and results were valid. However, tests with cells 6-V and 7-V indicate that pressure fluctuations measured with the pulsimeter were essentially the same as those measured directly on the channel floor. Installation of the revetment in the main testing channel precluded the continuation of this phase of the investigations.



PLAN



ELEVATION

Fig. 1 — Revetment Layout in Main Testing Channel

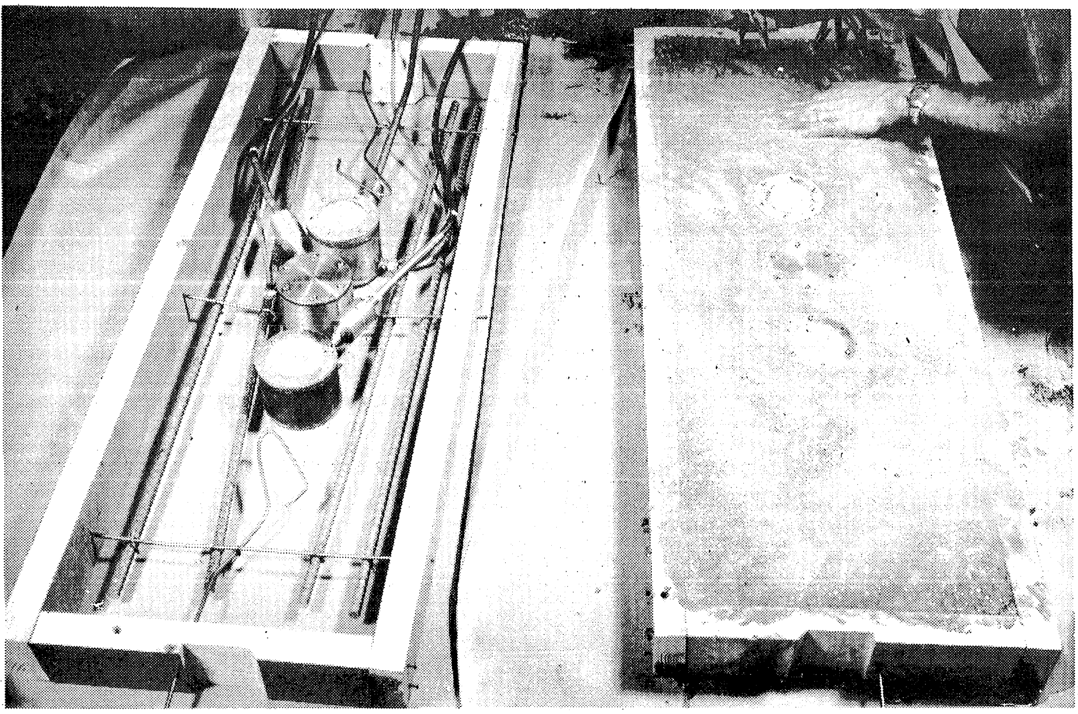


Fig. 2— Fabrication of Test Blocks

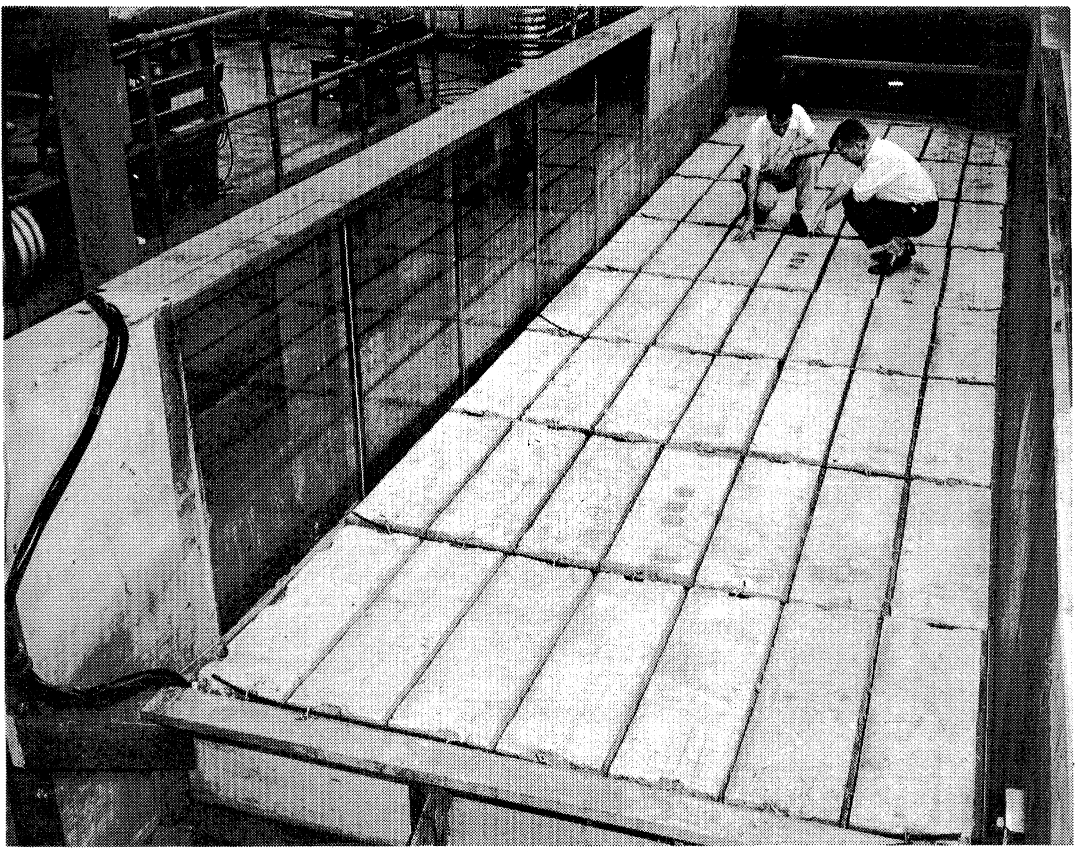


Fig. 3— Revetment Installation in Main Testing Channel

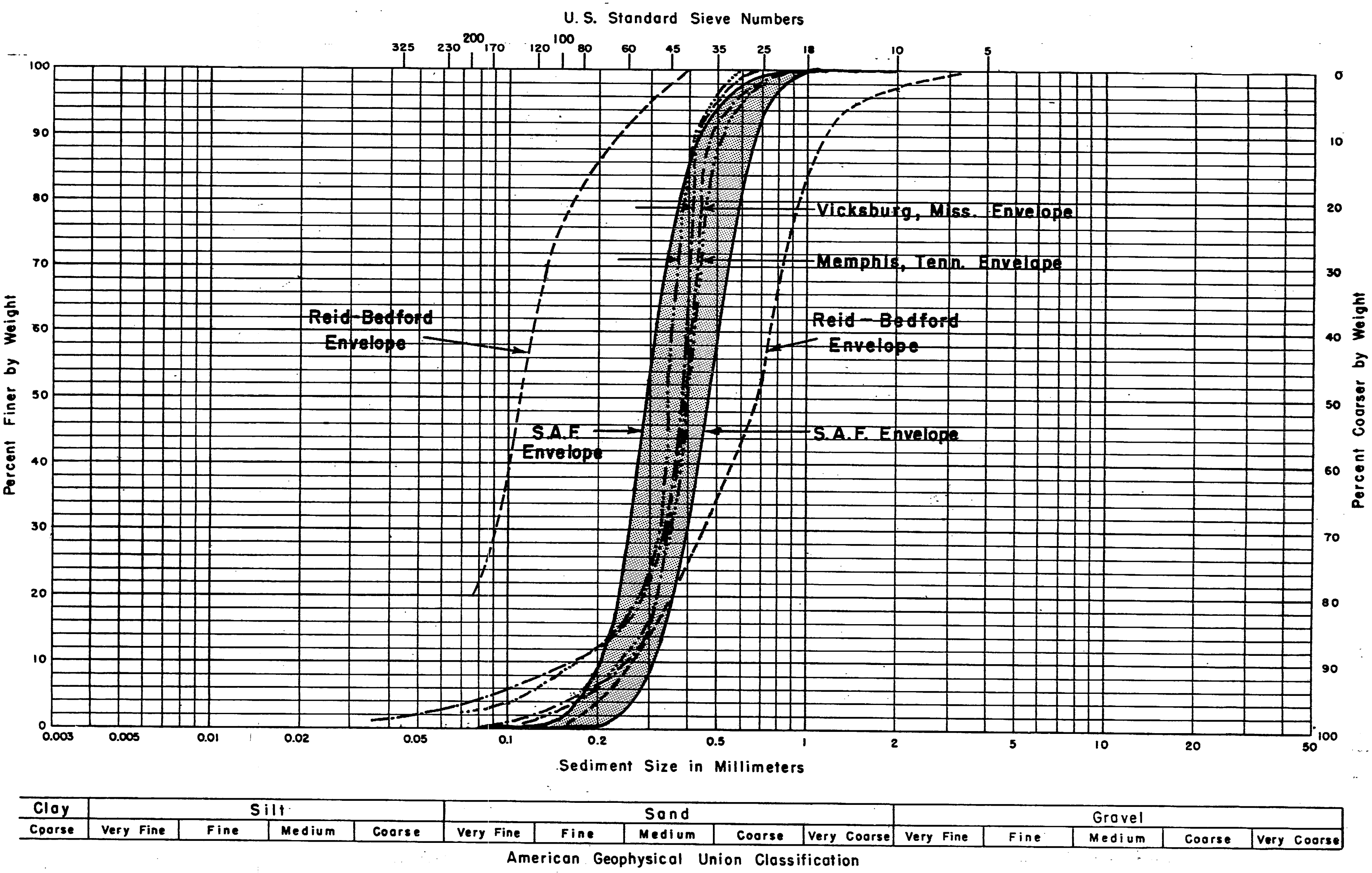


Fig. 4— Sediment Size Distribution

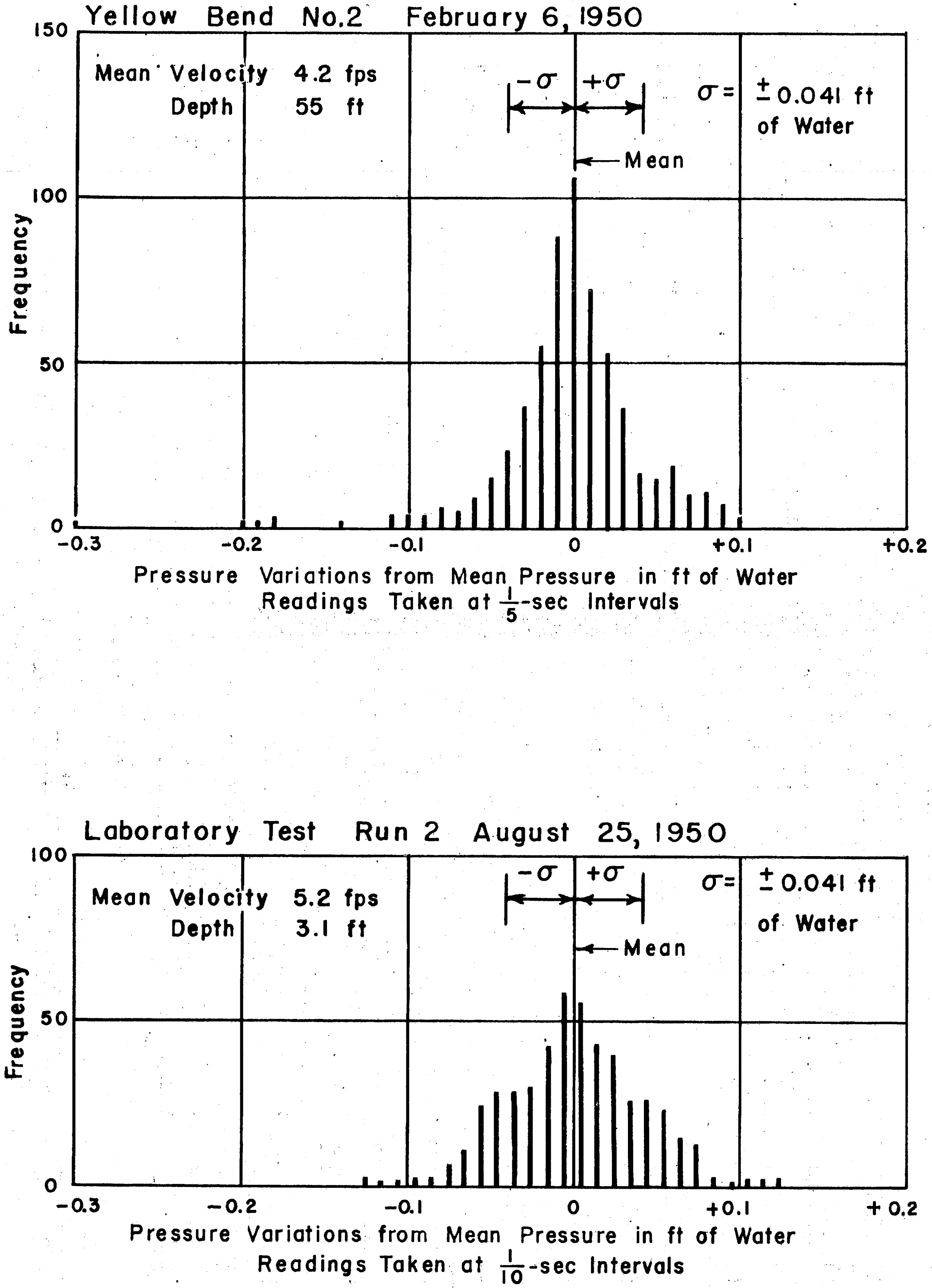


Fig. 5— Distribution of Pressures from Sample Field and Laboratory Records

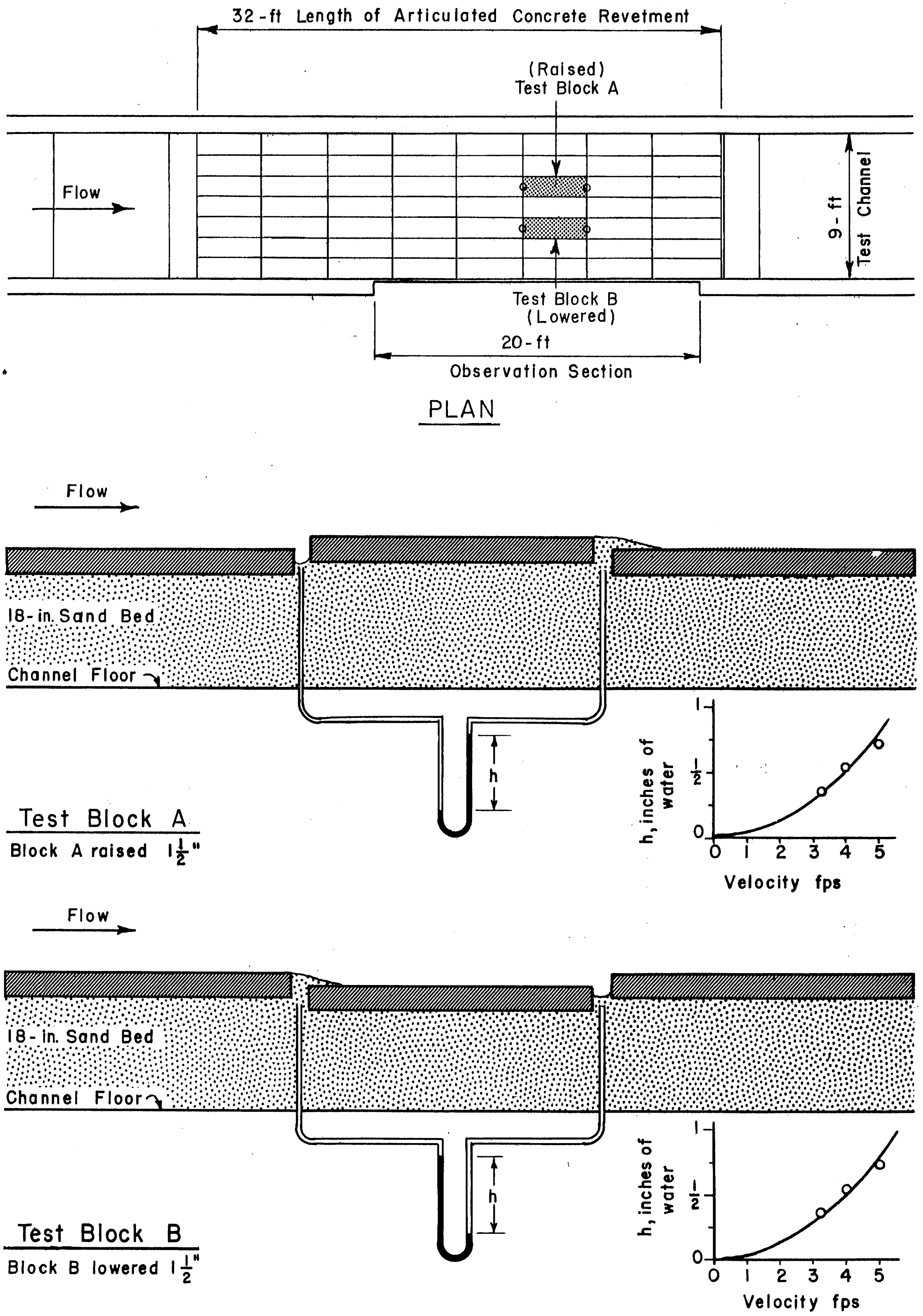
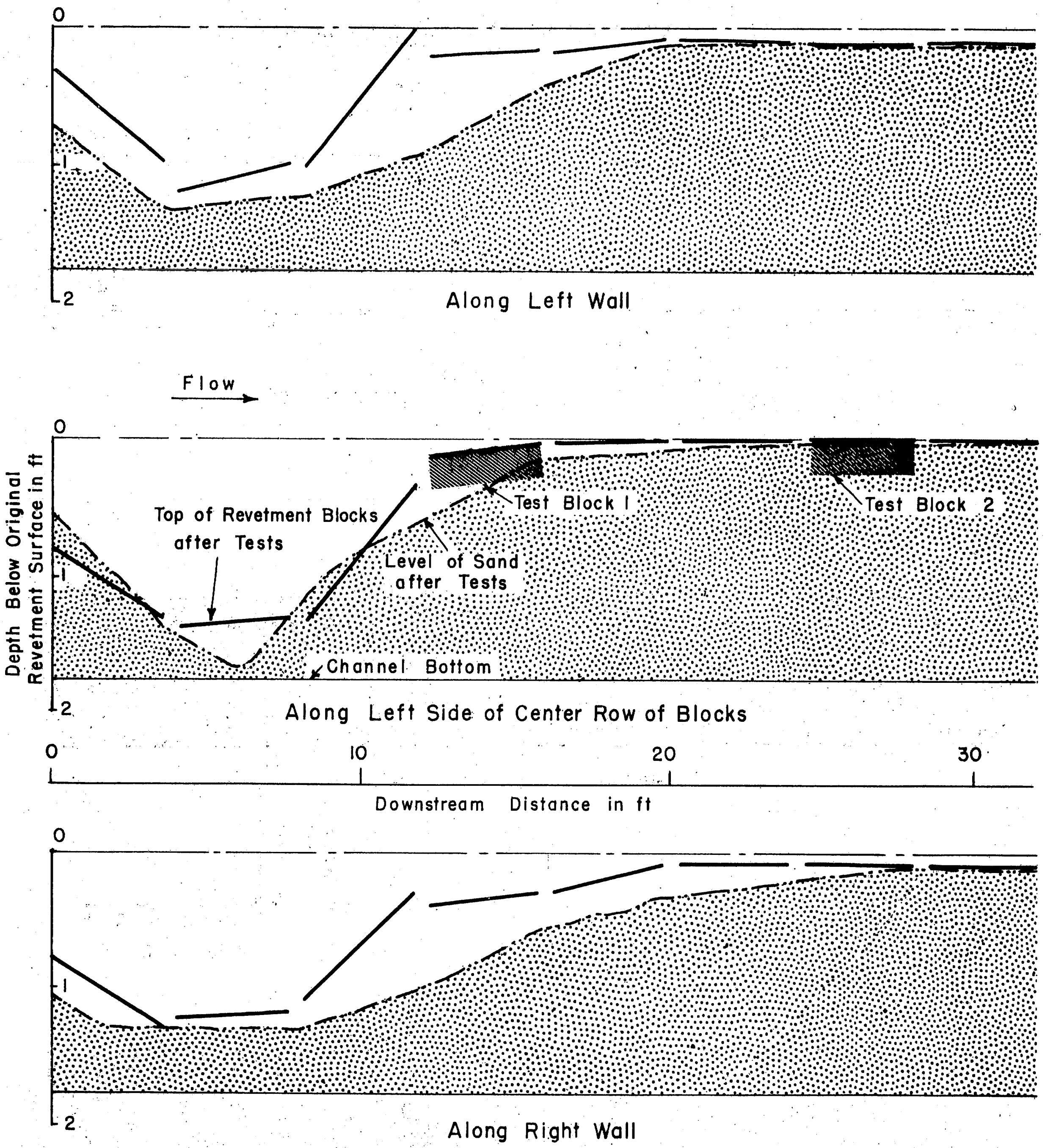


Fig. 6— Pressure Measurements in Sand



Along Left Wall

Along Left Side of Center Row of Blocks

Along Right Wall

Fig. 7 — Profiles of Revetment and Sand Bed After Tests on August 18, 1950

Maximum Mean Velocity 4.0 fps for 15 min

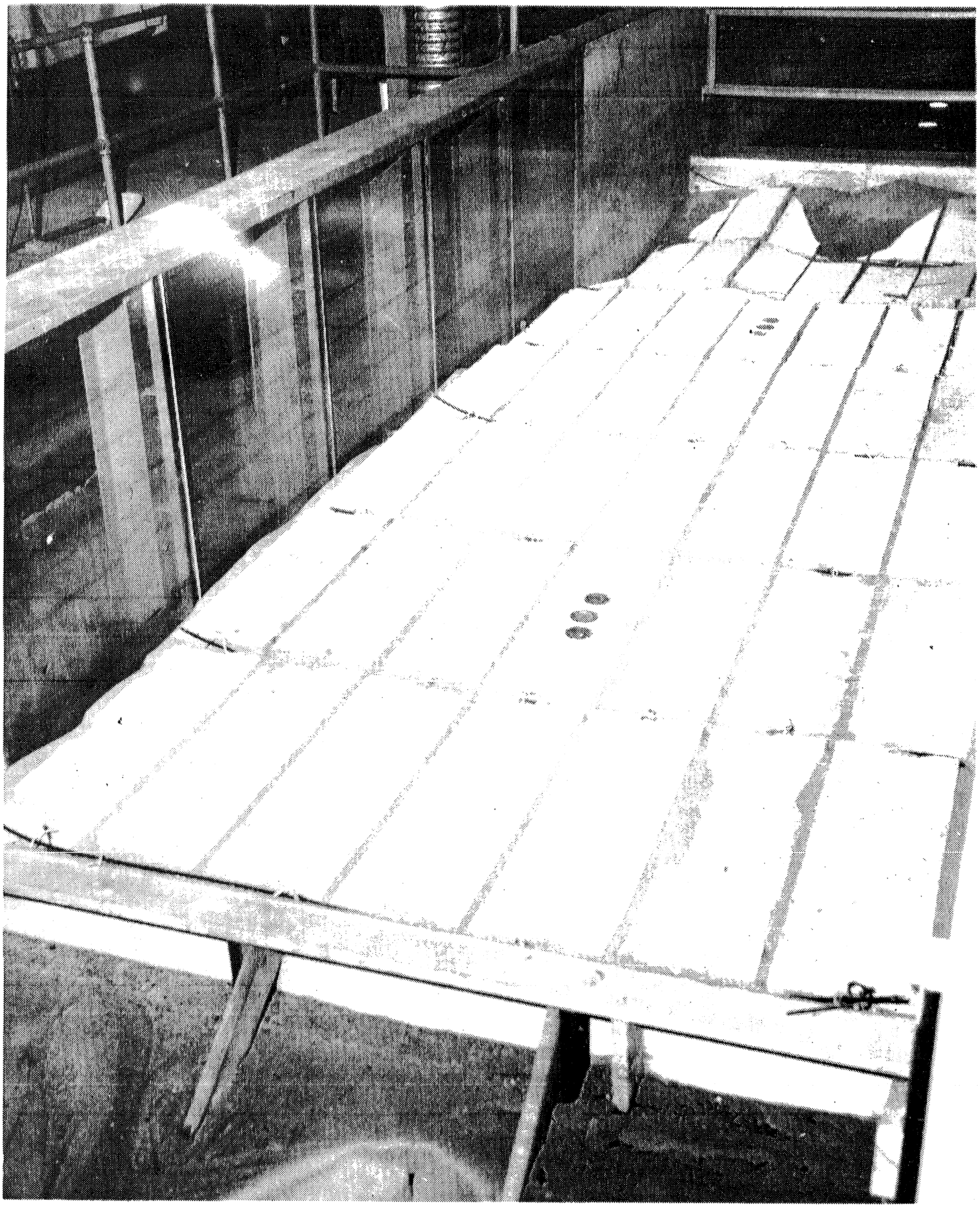


Fig. 8— Revetment After Tests on August 18, 1950

Mean Velocity 1.4—4.0 fps for 3 hr

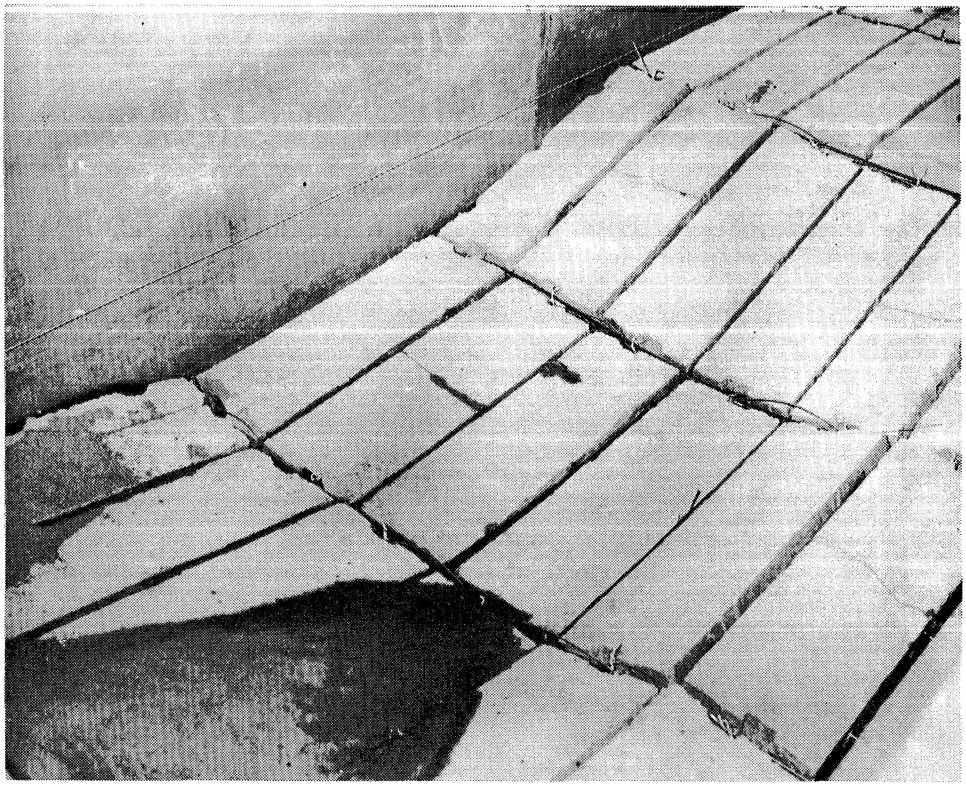


Fig. 9— Upstream Area of Revetment After Tests on August 18, 1950

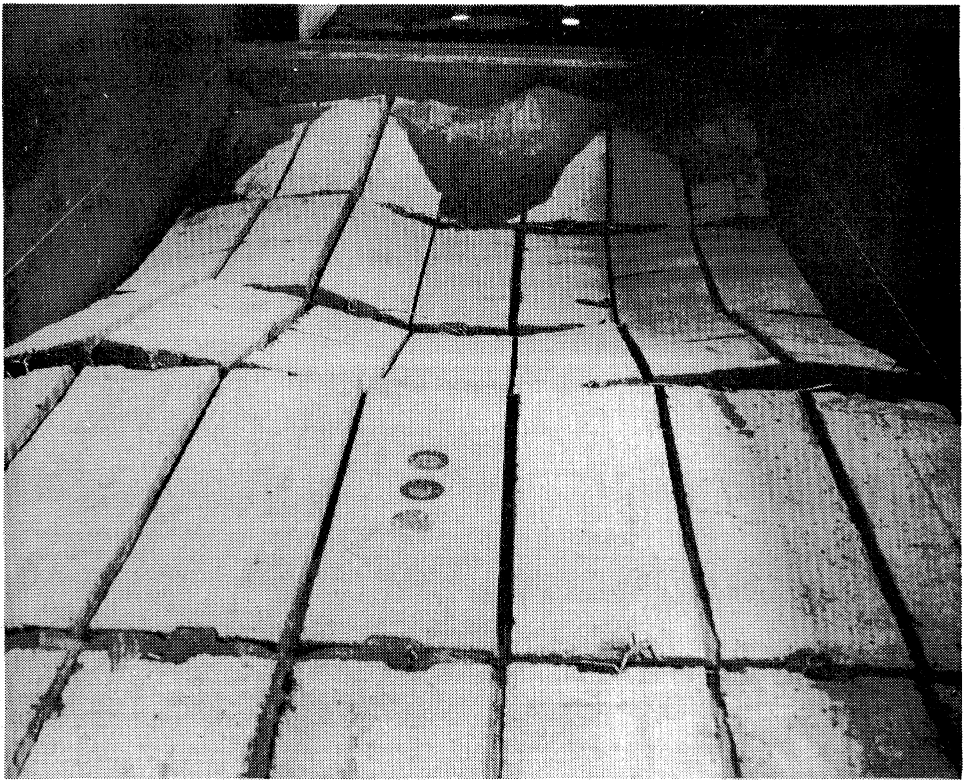


Fig. 10— Upstream Area of Revetment After Tests on August 18, 1950

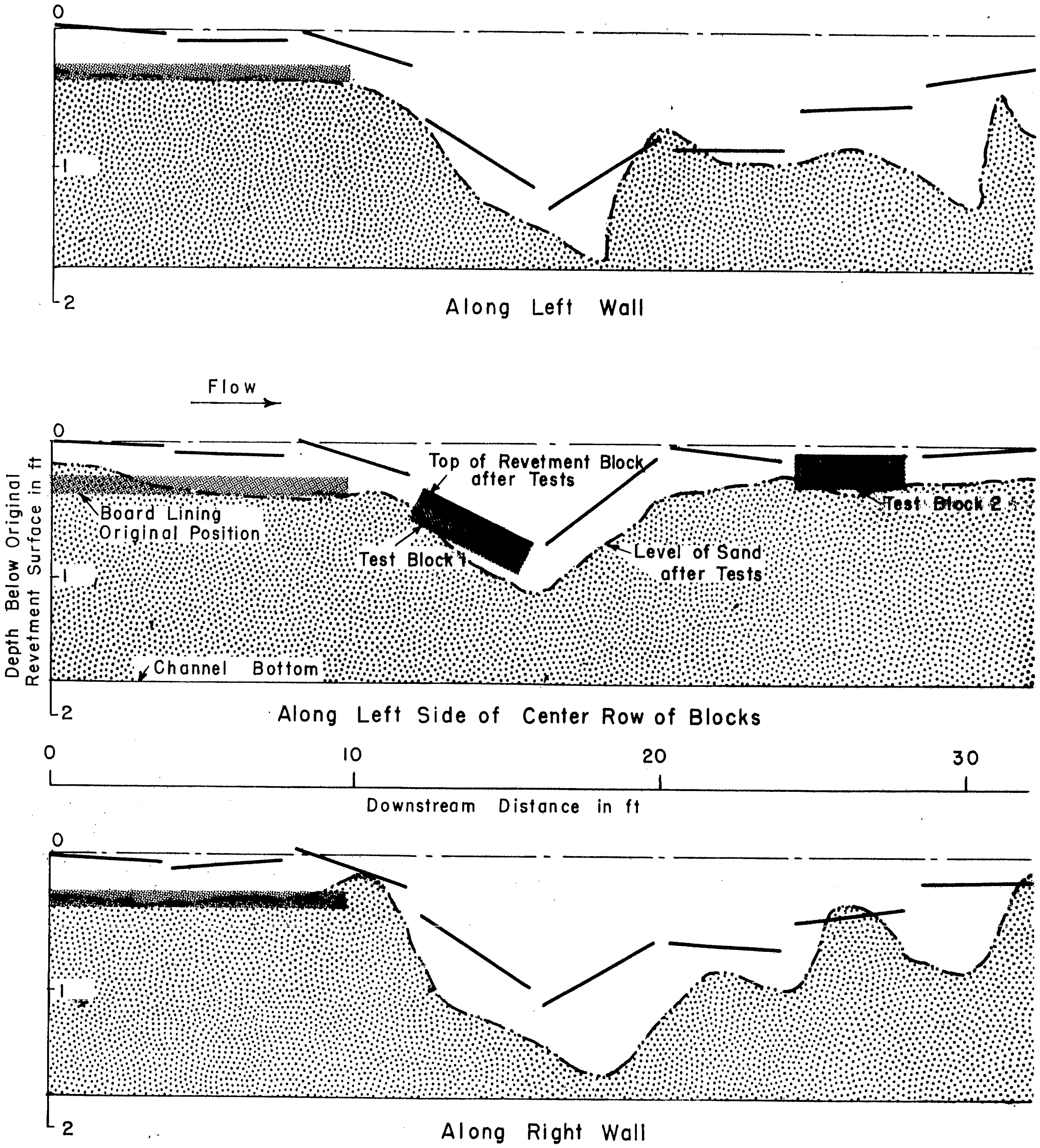


Fig. 11 — Profiles of Revetment and Sand Bed After Tests on August 30, 1950

Maximum Mean Velocity 7.7 fps for 40 min

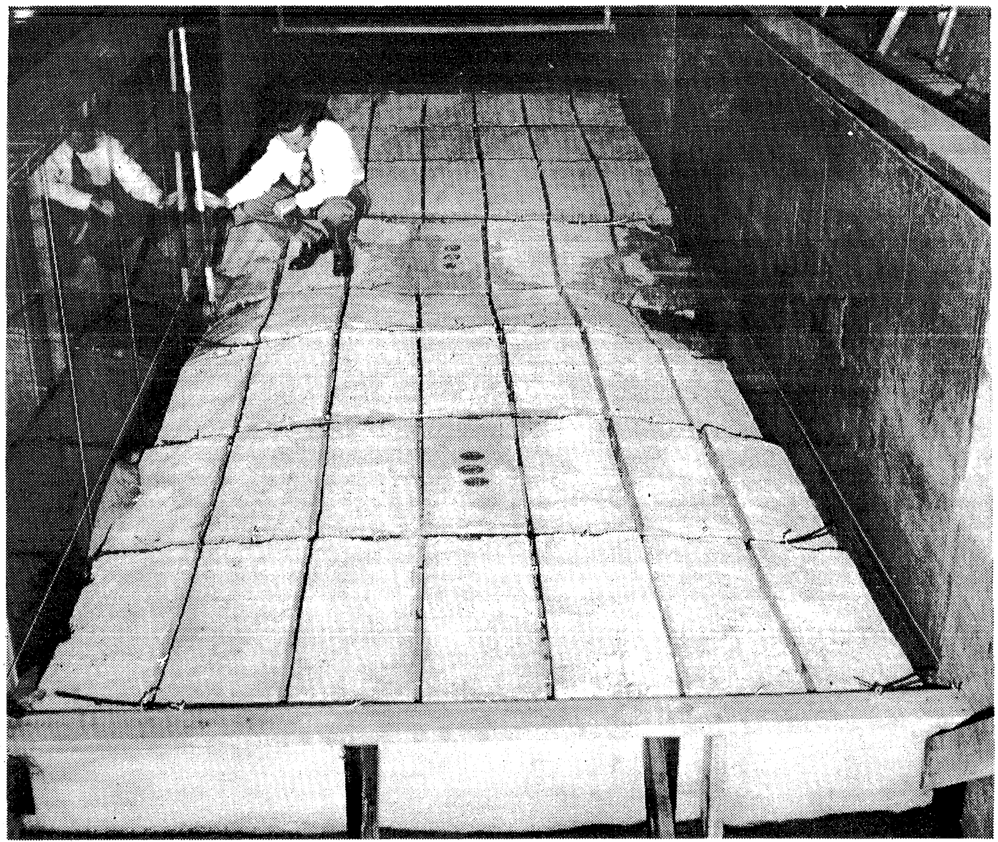


Fig. 12 — Revetment After Tests on August 30 and September 8, 1950

Maximum Mean Velocity 7.7 fps for 40 min

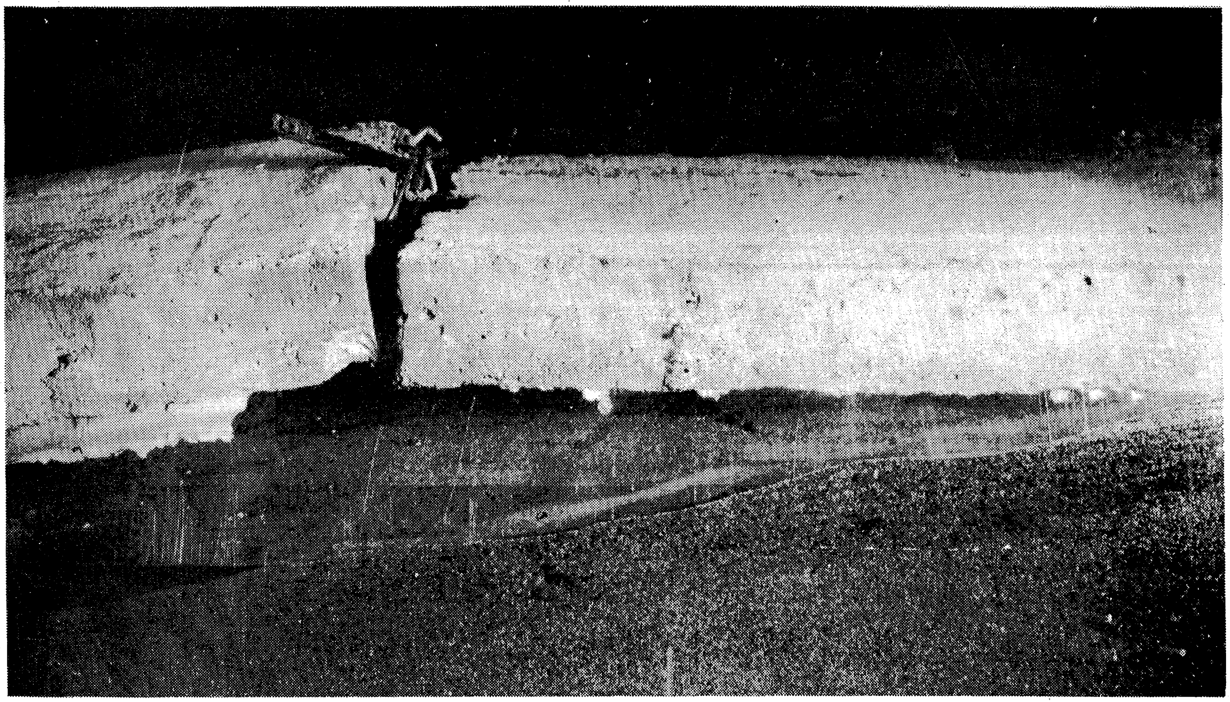
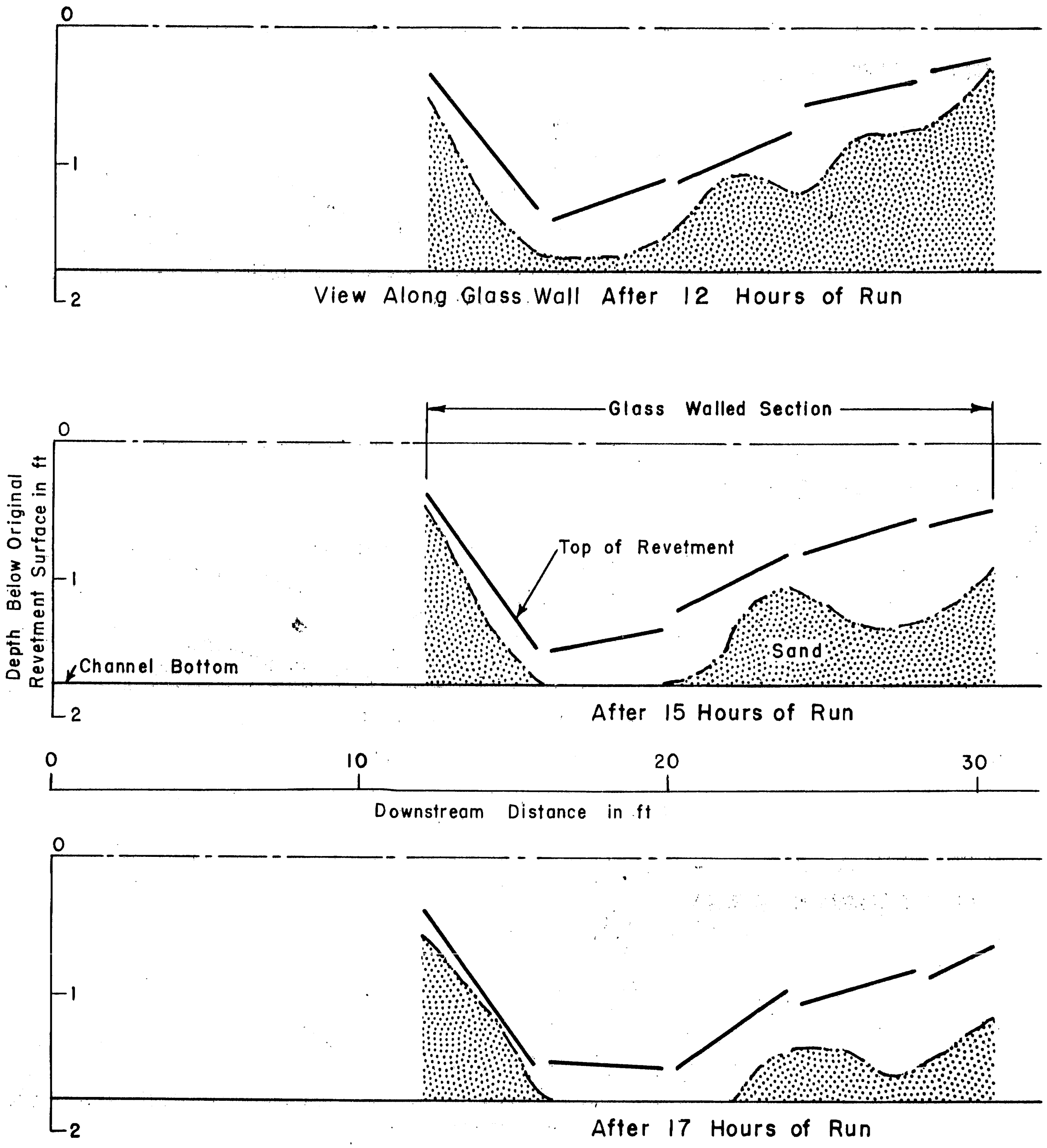


Fig. 13 — Voids Below Revetment After Tests on August 30 and September 8, 1950


View Along Glass Wall After 12 Hours of Run

After 15 Hours of Run

After 17 Hours of Run

Fig. 14 — Profiles of Revetment and Sand Bed During Test in November 1950

Mean Velocity $5\frac{1}{2}$ fps

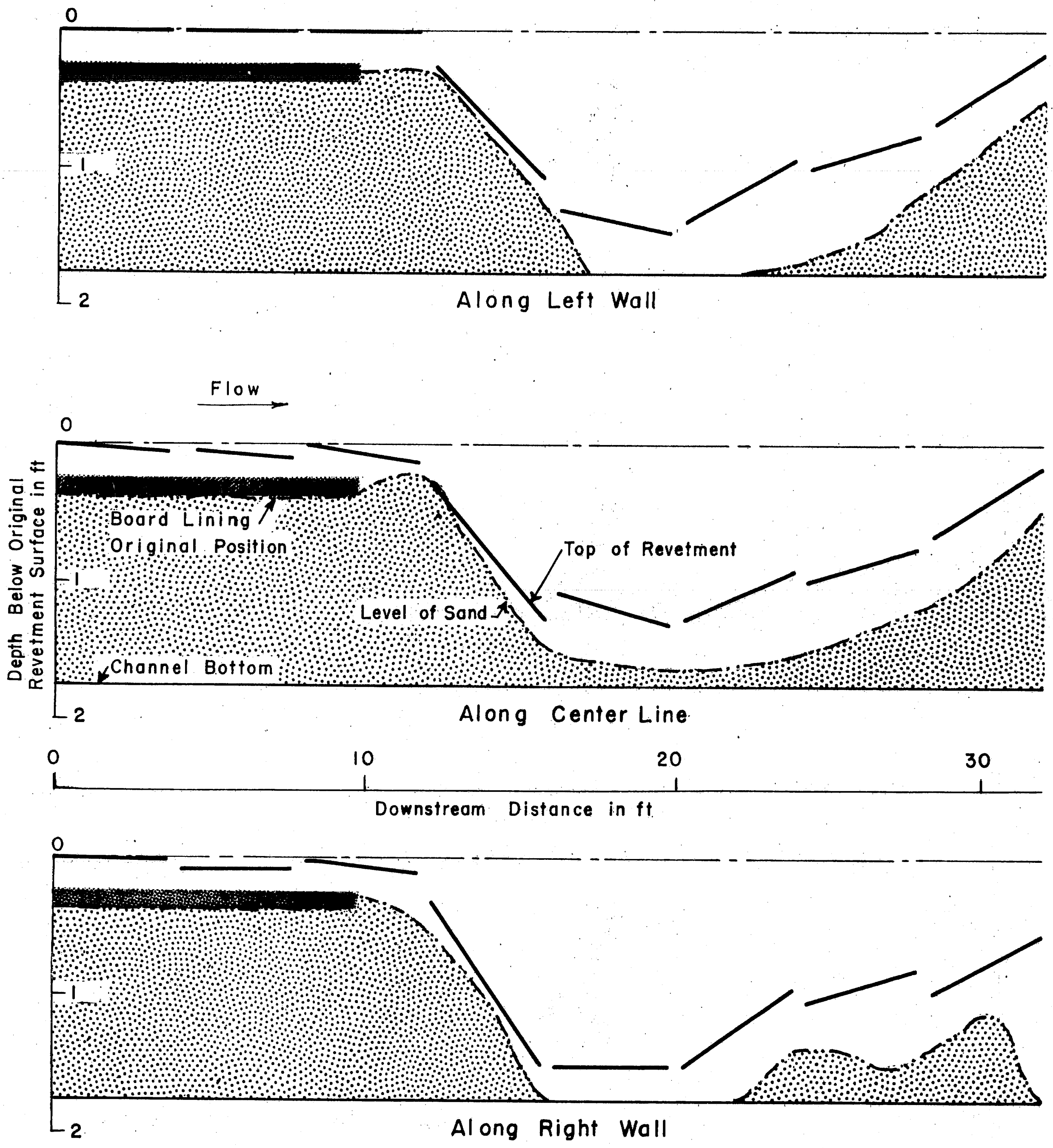


Fig. 15— Profiles of Revetment and Sand Bed After 17-hr Test in November 1950

Mean Velocity $5\frac{1}{2}$ fps

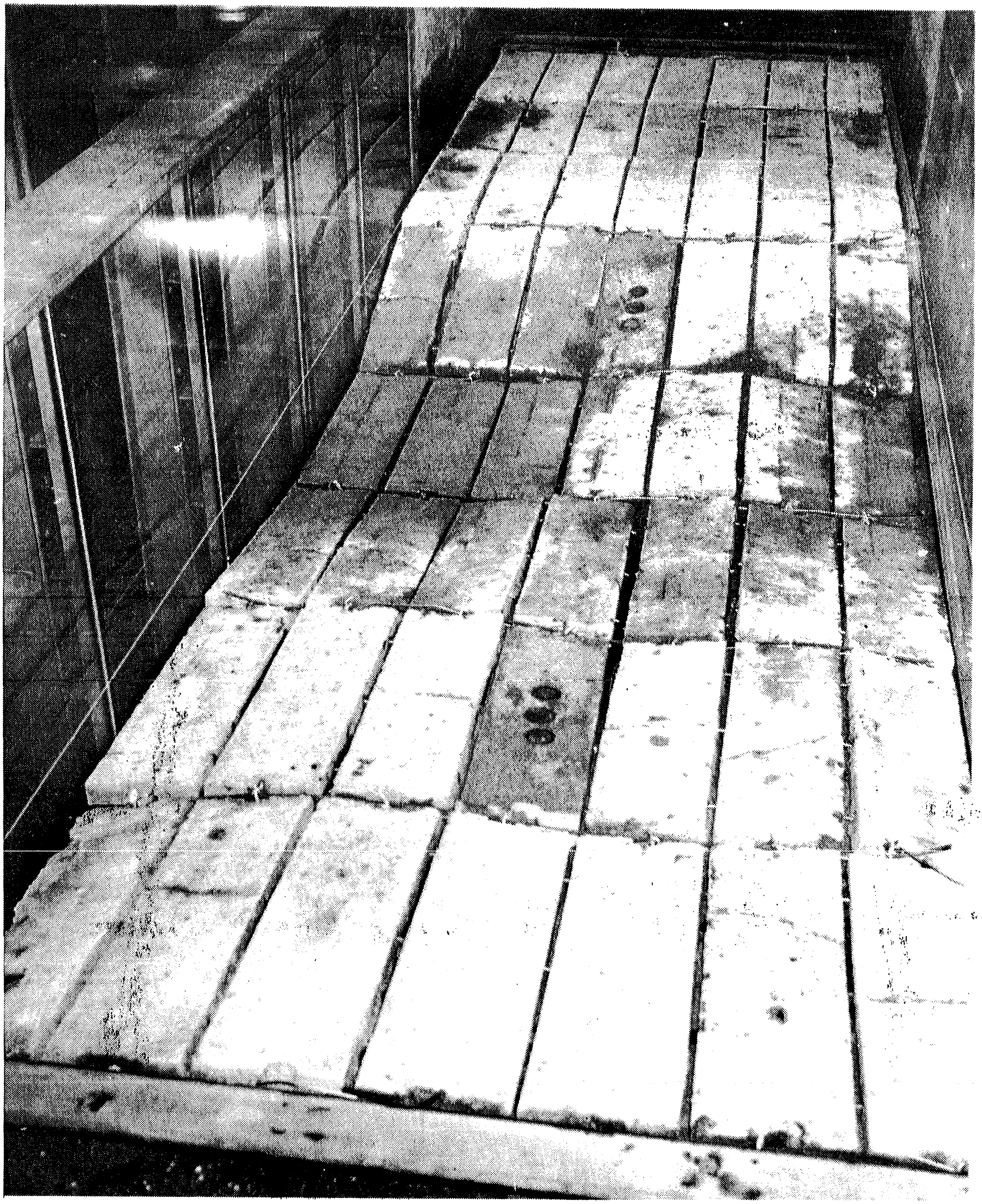


Fig. 16 — Revetment After 17-hr Test in November 1950

Mean Velocity $5\frac{1}{2}$ fps

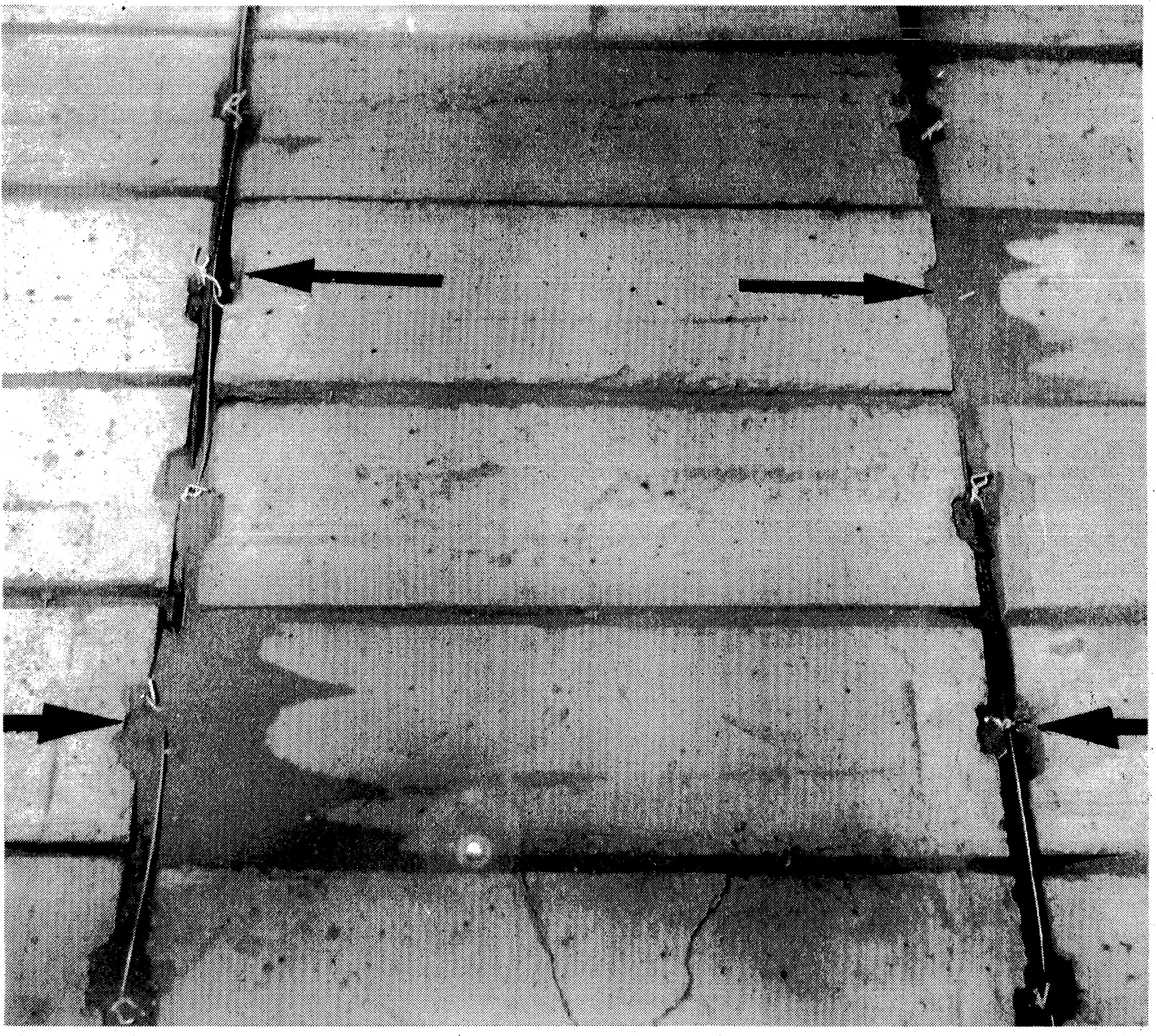


Fig. 17— Area Around Raised (Upper) and Lowered (Lower) Revetment Blocks Showing Accumulation of Sand at Step-down and Scouring at Step-up

Flow from Left to Right at 3.2 fps for 25 min

Fig. 18 — Effect of Step-up on Sand Scour

Flow from Left to Right at 5 fps for 5 hr

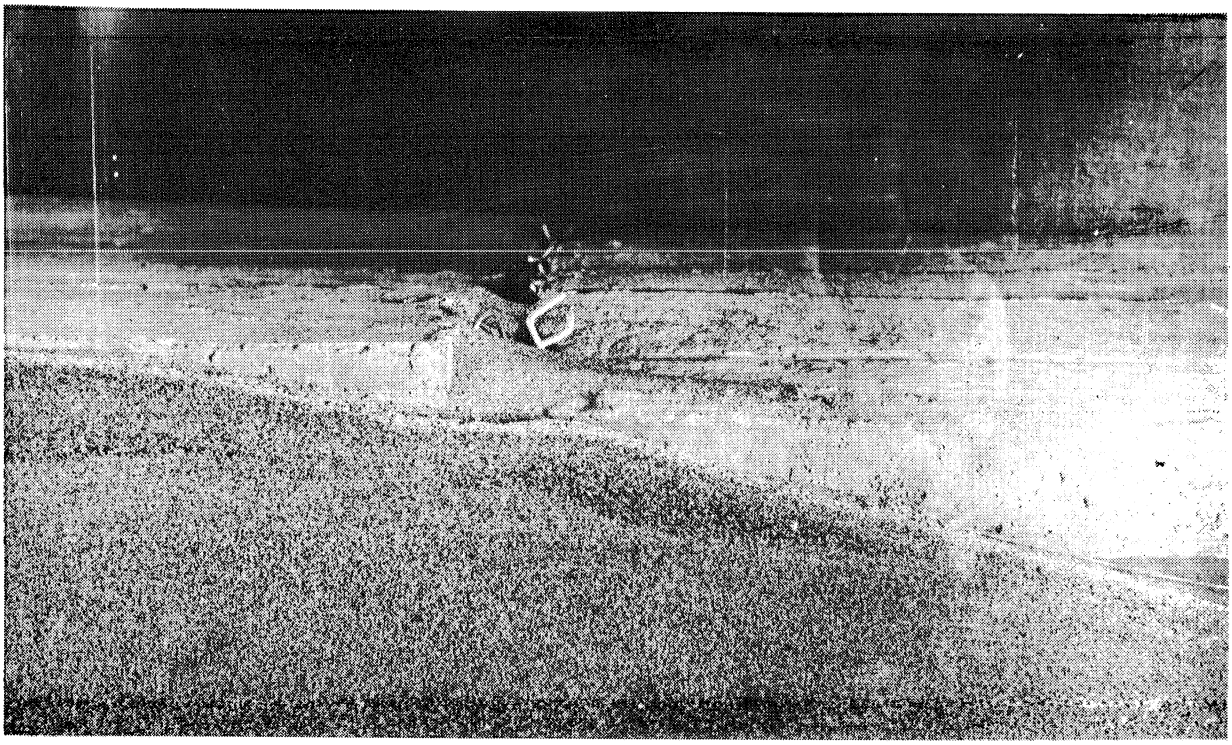


Fig. 19 — Effect of Step-down on Sand Scour

Flow from Left to Right at 5 fps for 5 hr

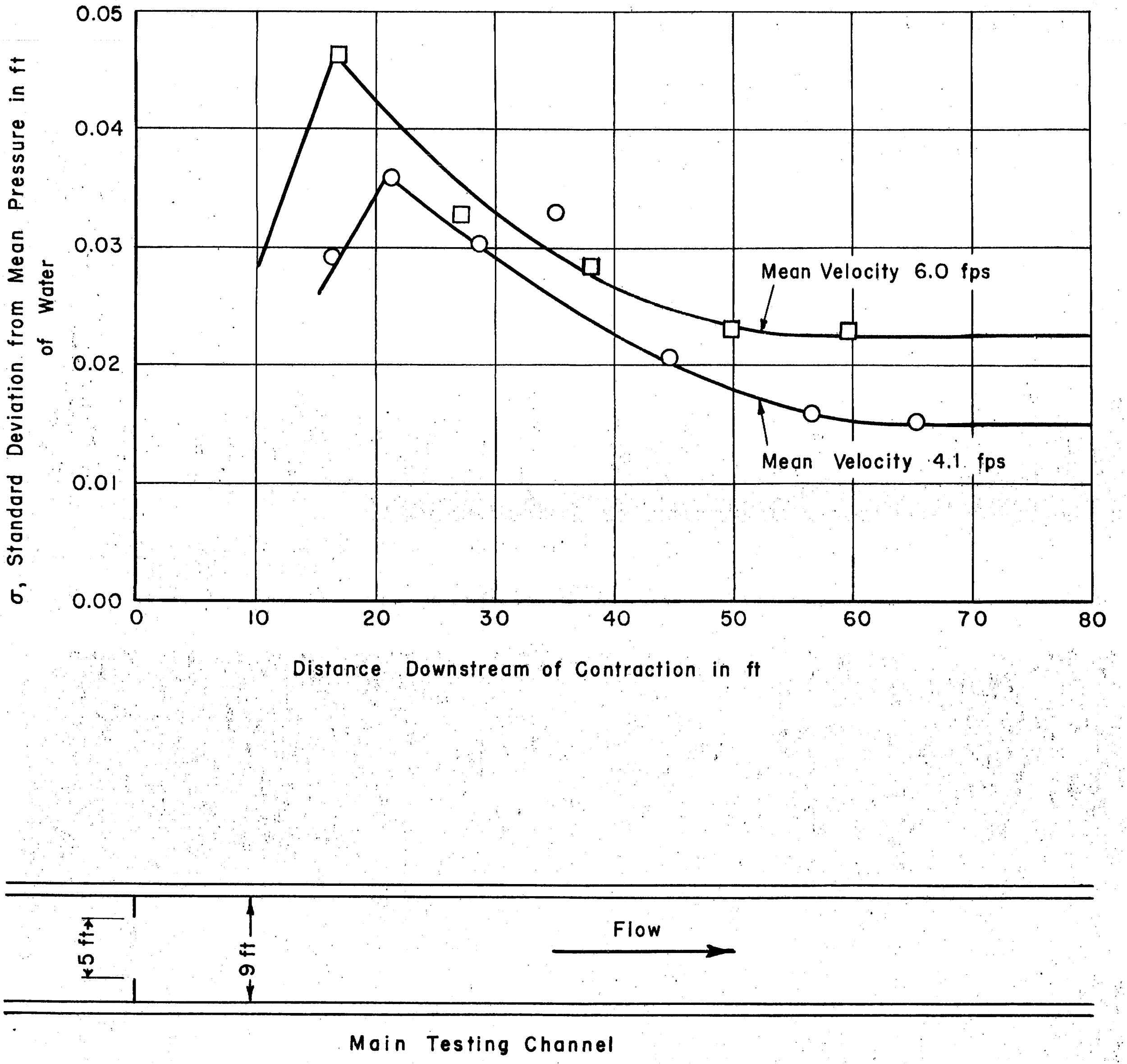


Fig. 20— Attenuation in Turbulence Pattern Downstream of Channel Obstruction

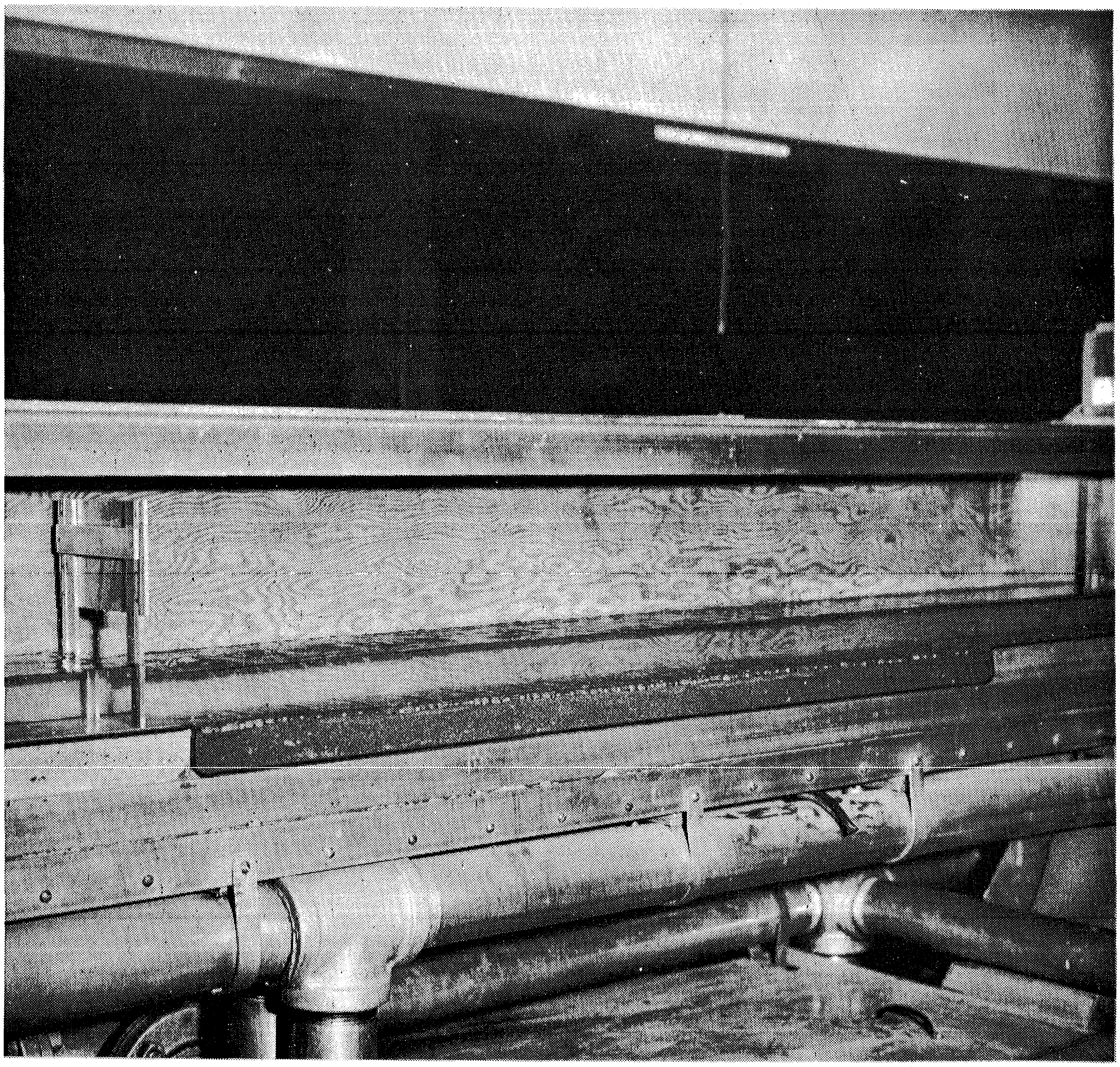


Fig. 21— Model of Revetment in 6-in. Portable Demonstration Channel

Plate with One $\frac{1}{8}$-in. Hole over Cell

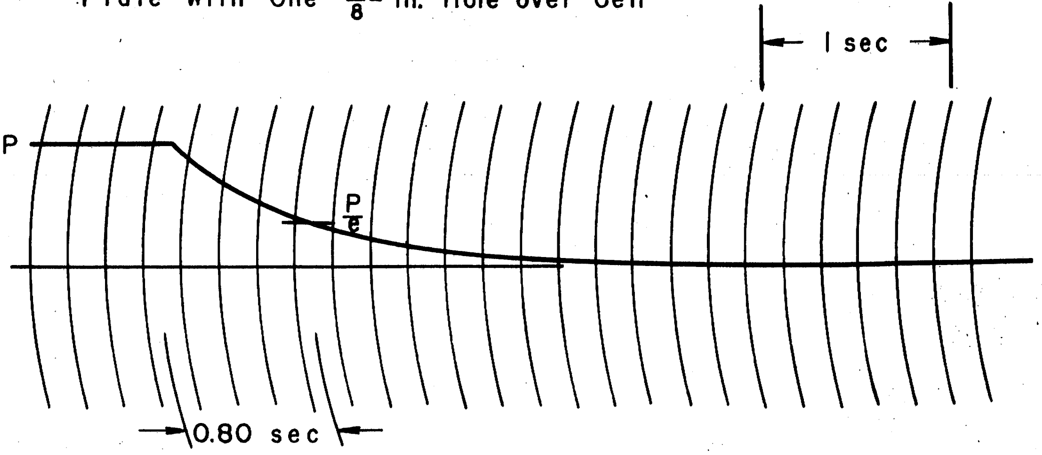


Plate with Nine $\frac{1}{8}$-in. Holes over Cell

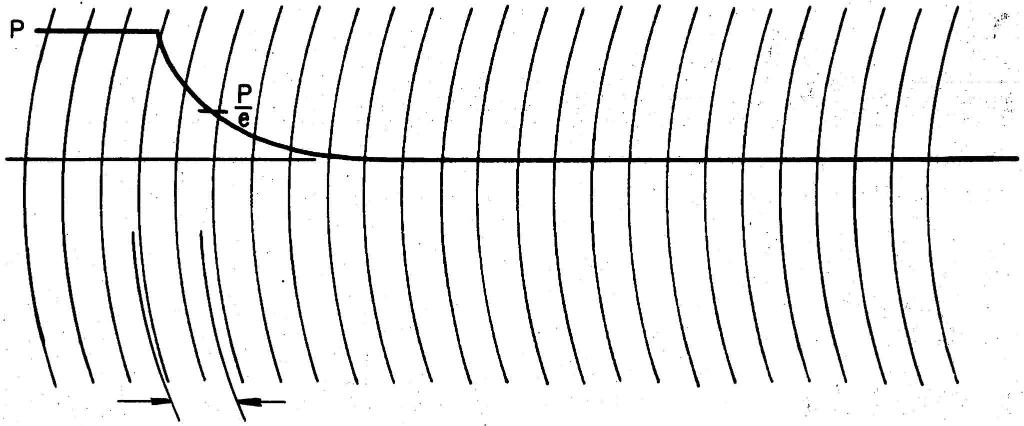


Plate with Forty-five $\frac{1}{8}$-in. Holes and 45-mesh Screen over Cell as Used in Full-Scale Tests

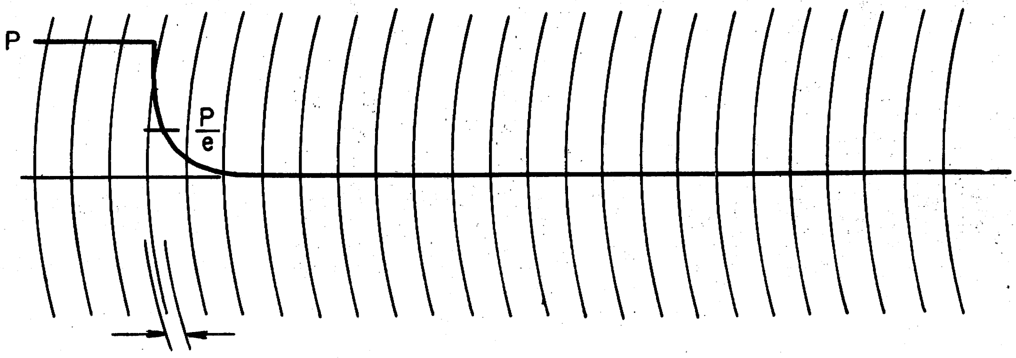


Fig. 22— Response of WES Pressure Cells to Abrupt Pressure Changes in Sand

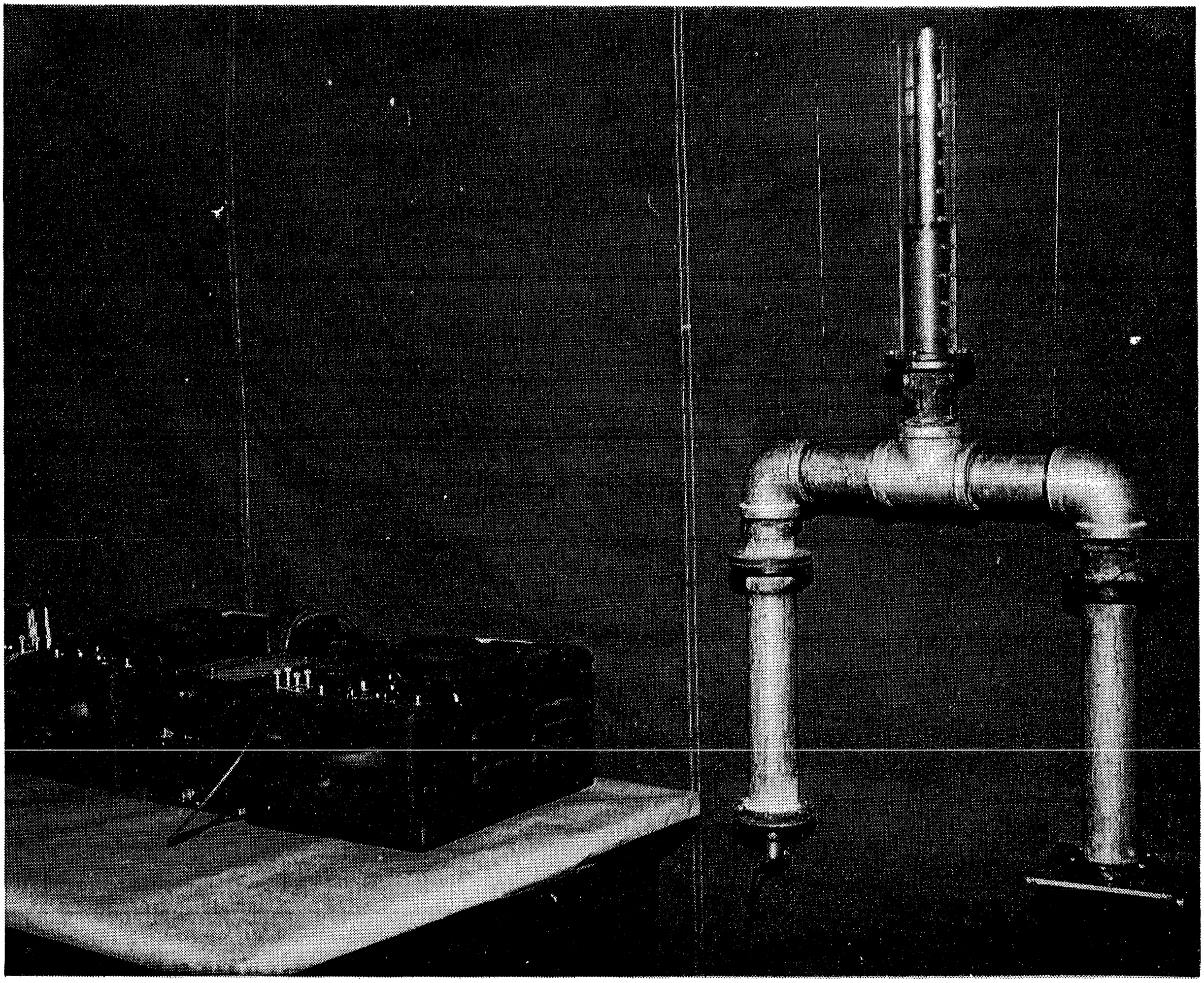


Fig. 23— Apparatus for Comparison of WES Pressure Cell with Statham Cell

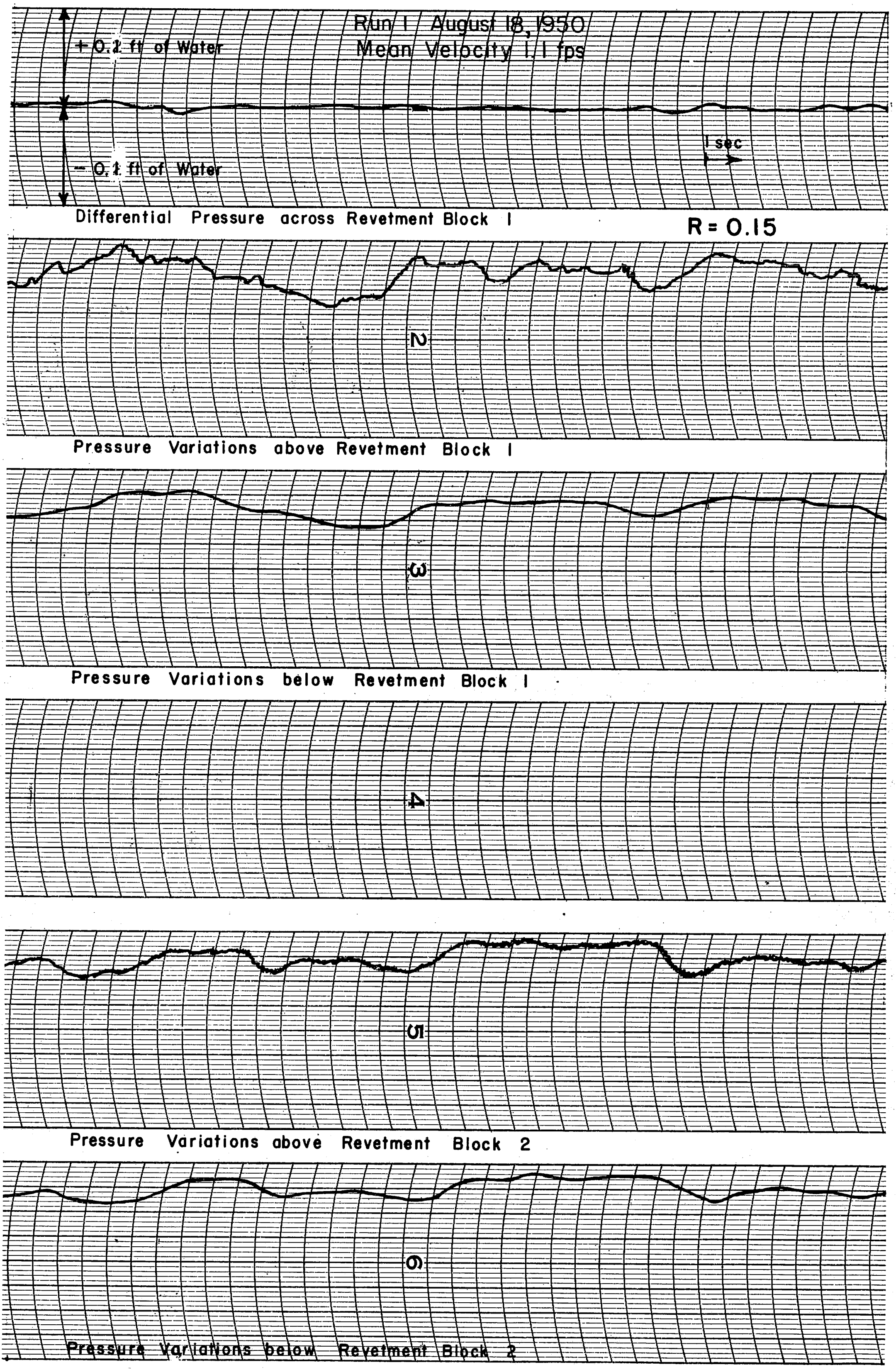


Fig. 24 — Sample Pressure Fluctuation Record

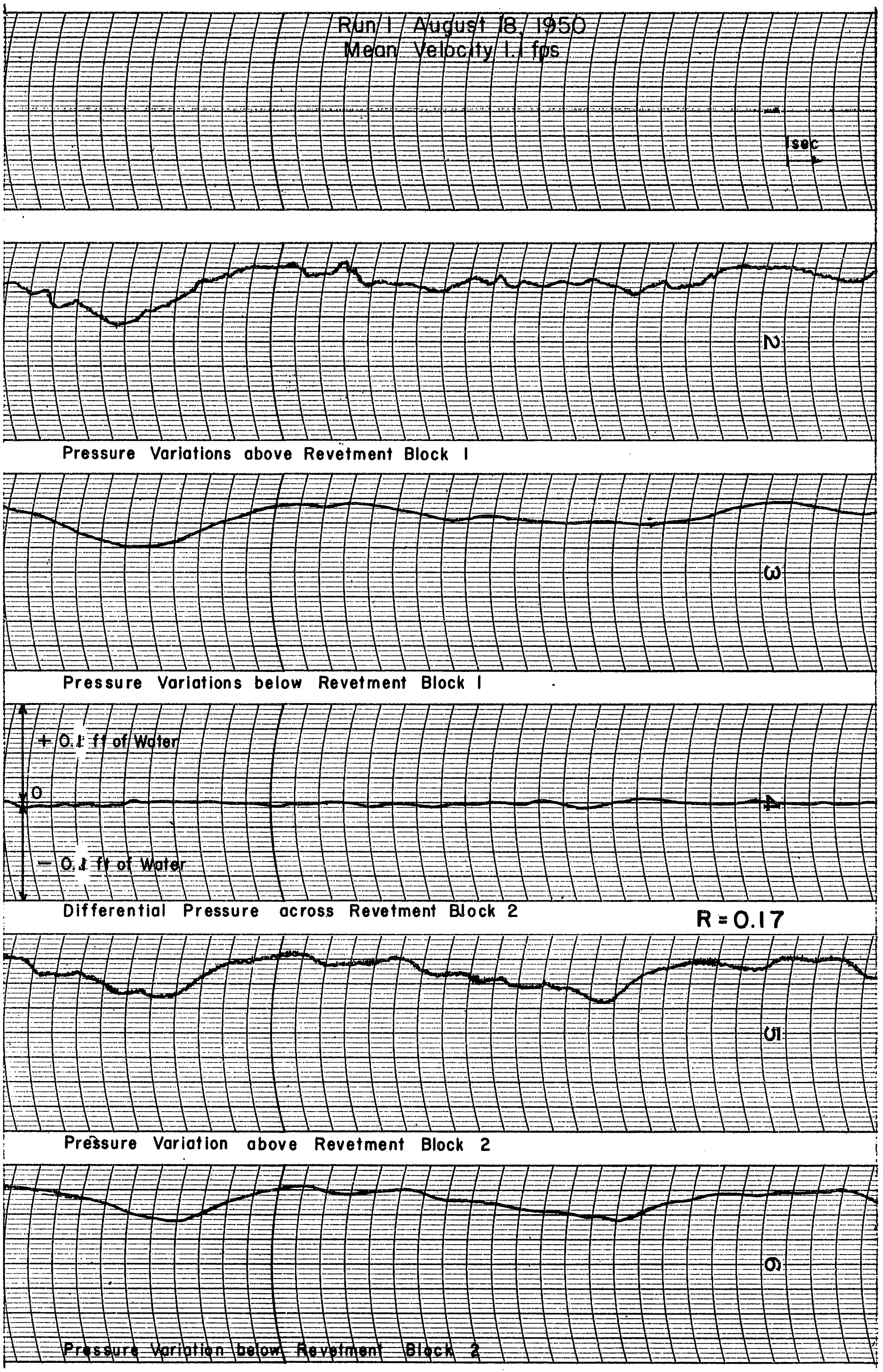


Fig. 25 — Sample Pressure Fluctuation Record

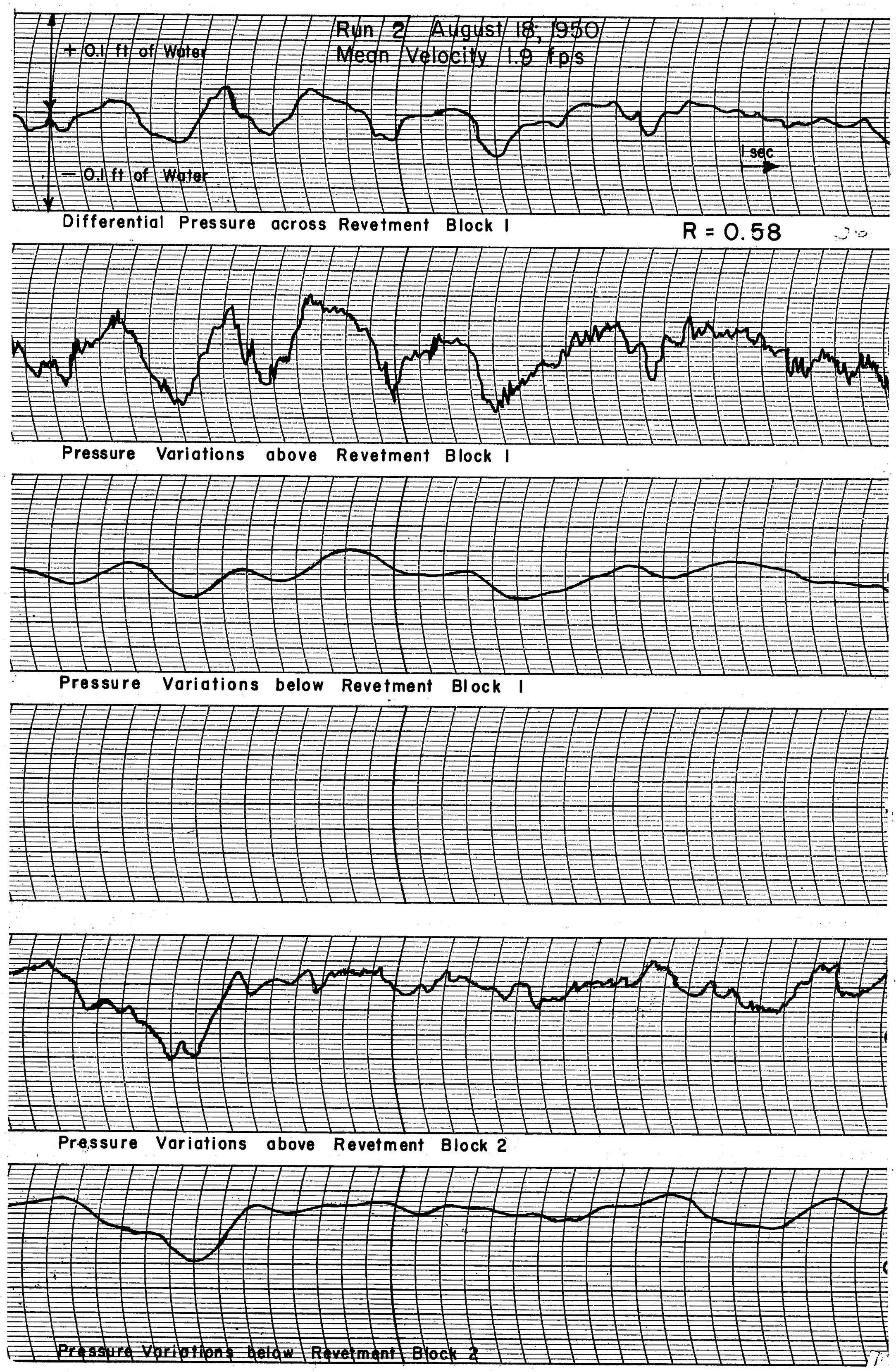


Fig. 26 — Sample Pressure Fluctuation Record

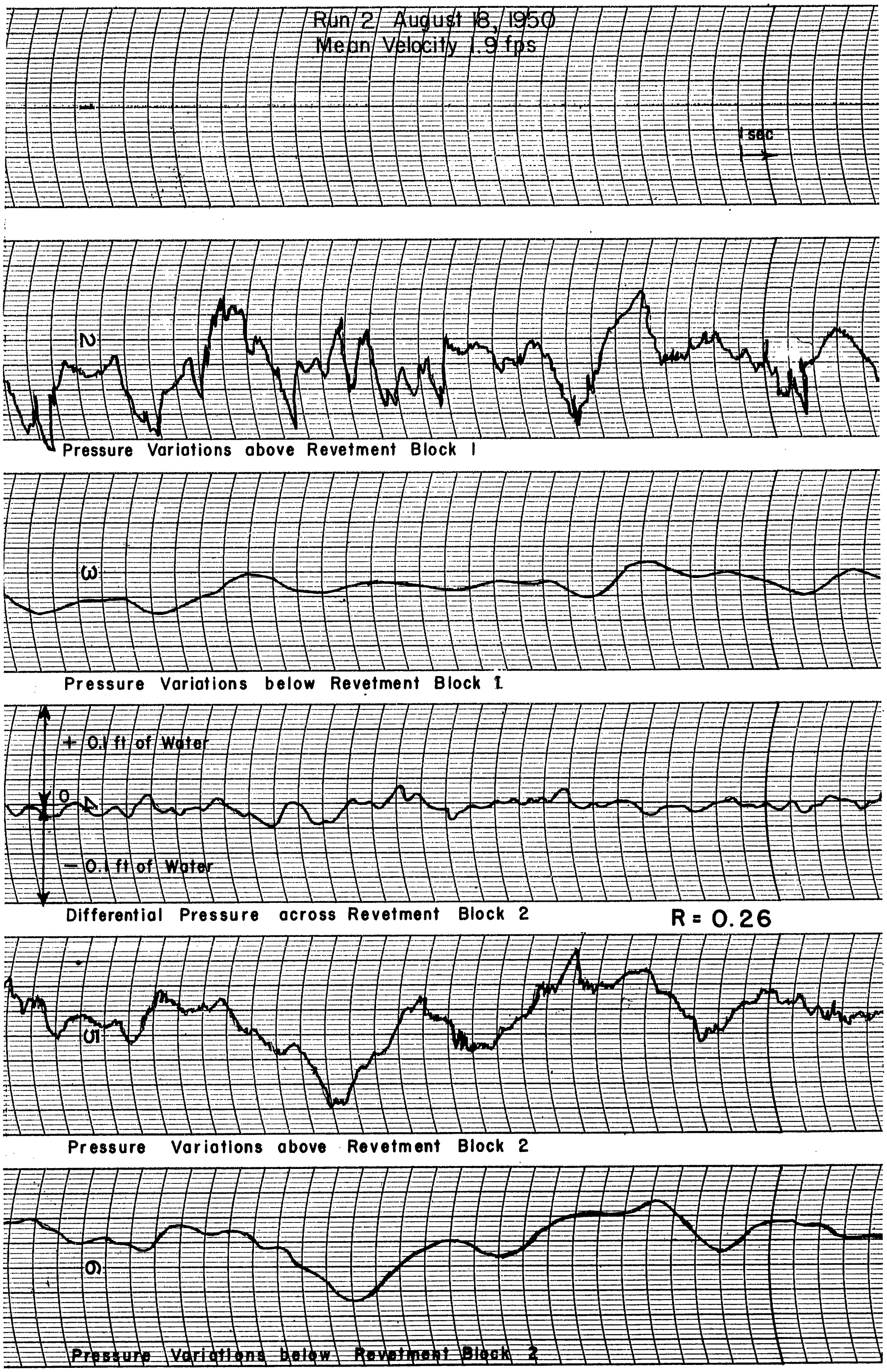


Fig. 27 — Sample Pressure Fluctuation Record

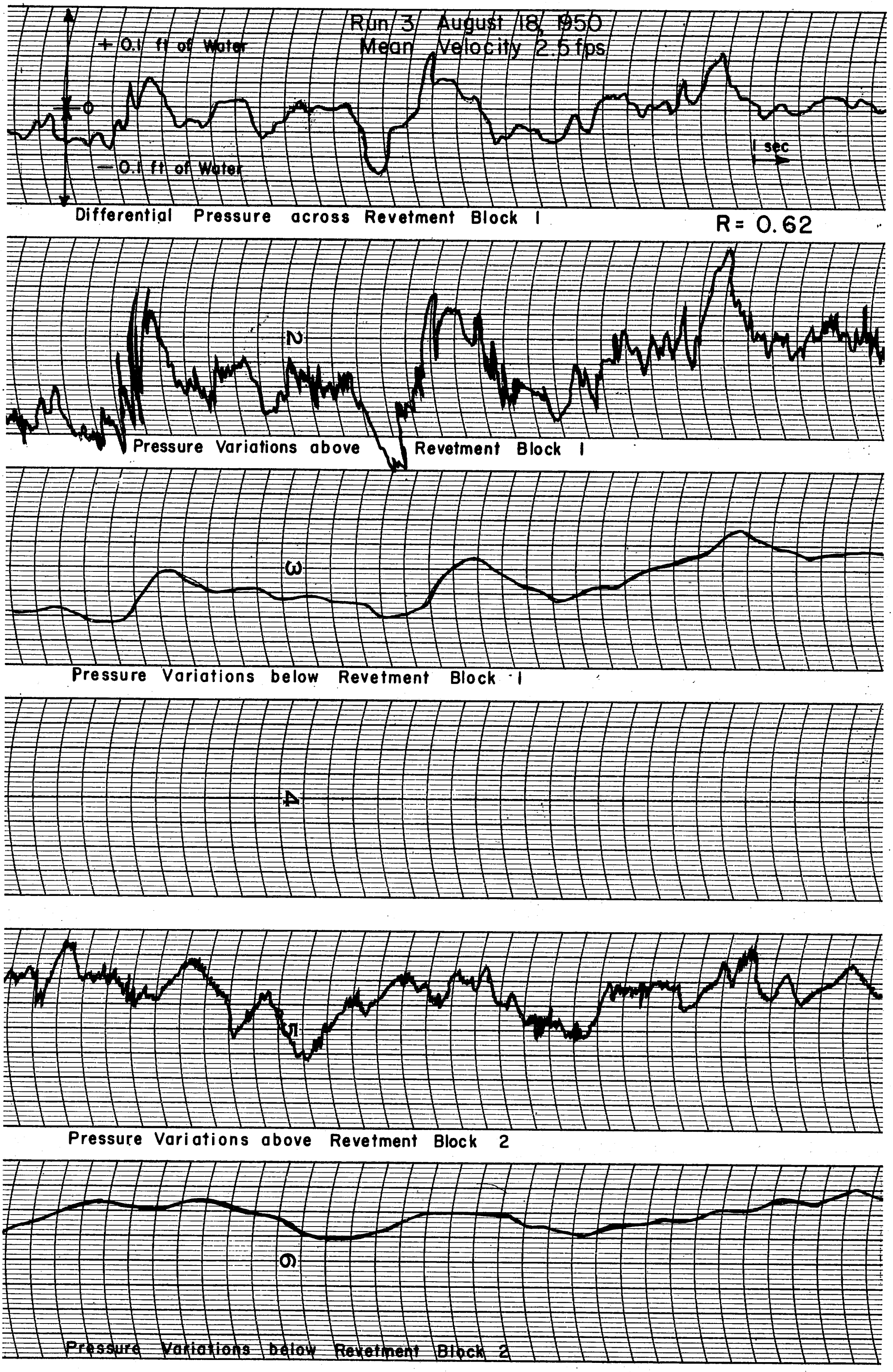


Fig. 28 — Sample Pressure Fluctuation Record

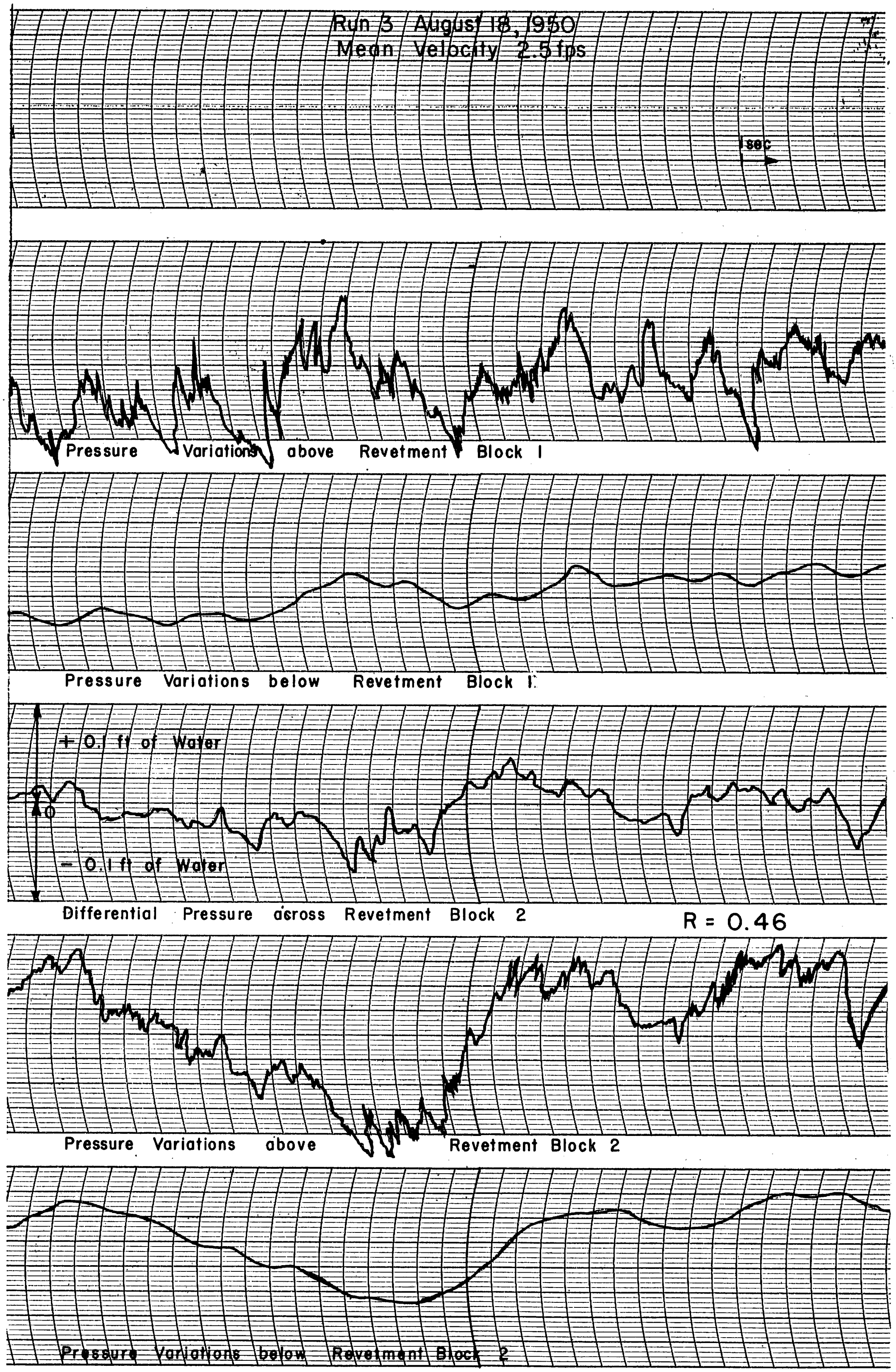


Fig. 29 — Sample Pressure Fluctuation Record

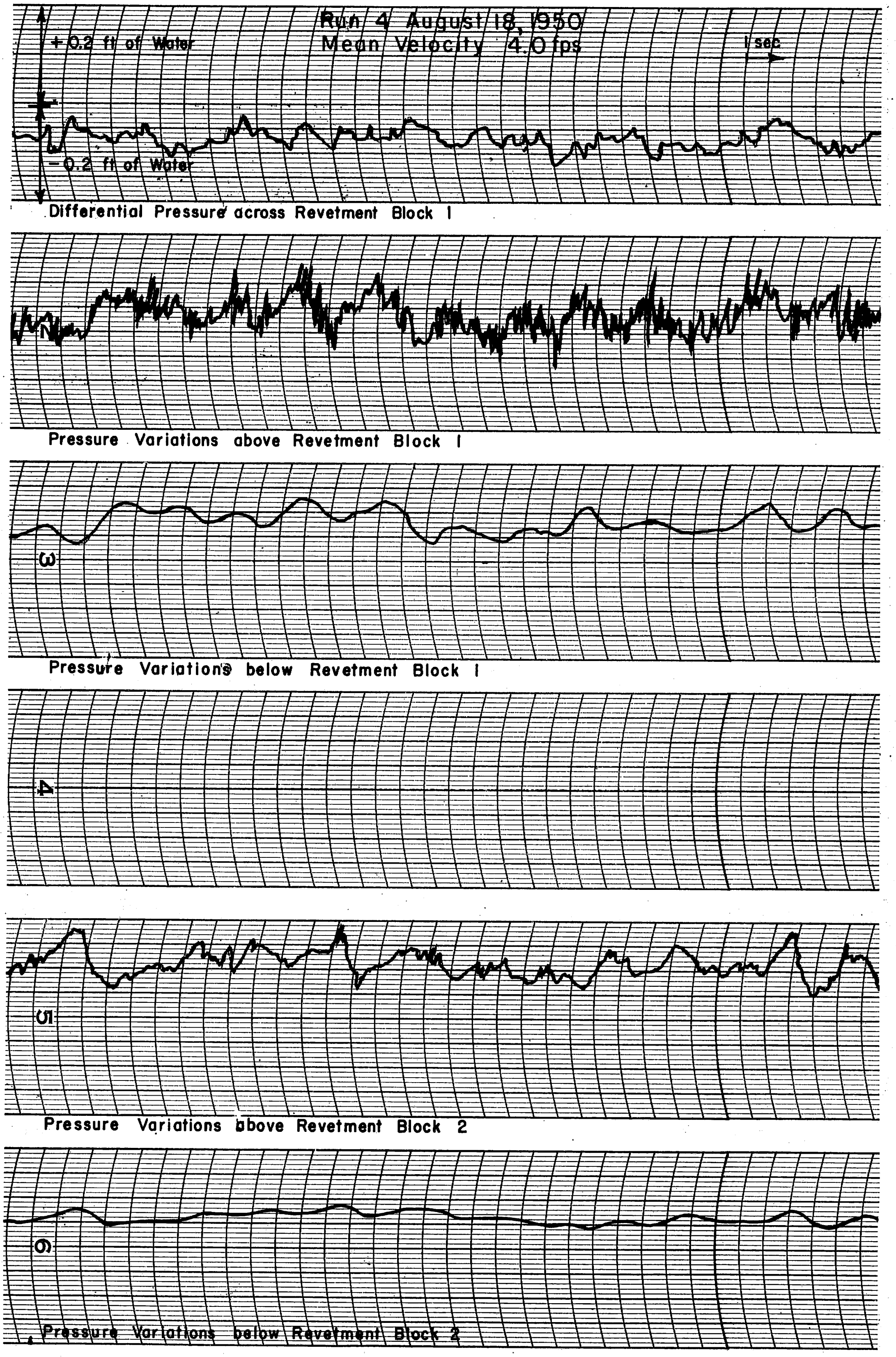
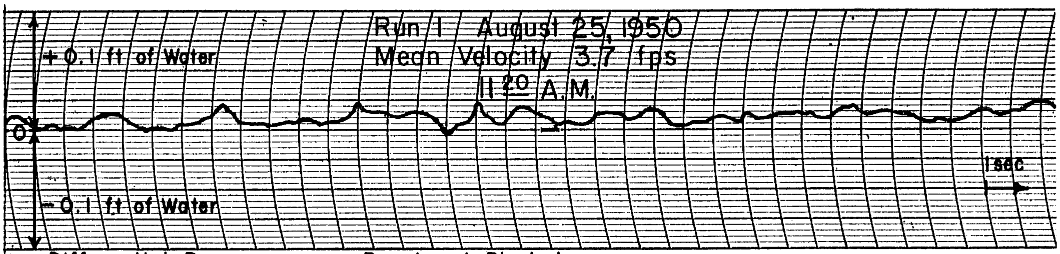
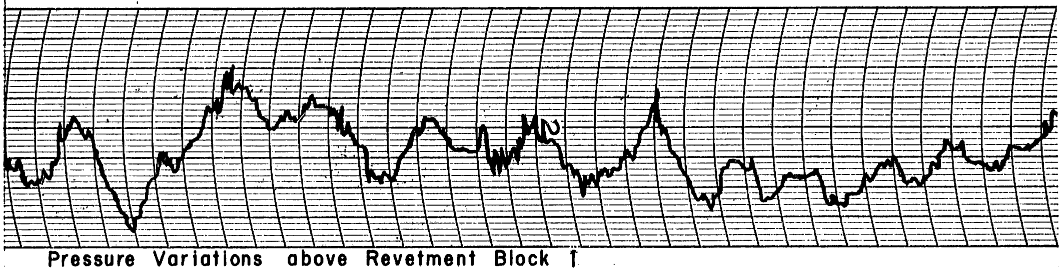


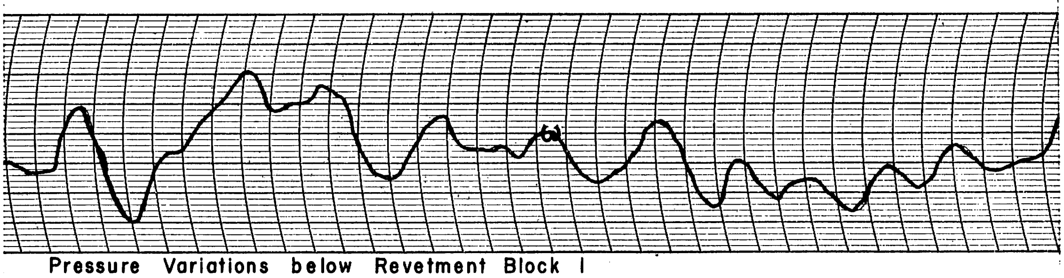
Fig. 30— Sample Pressure Fluctuation Record



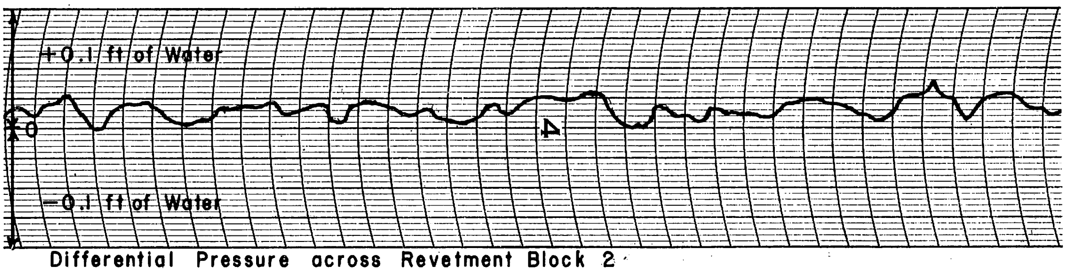
Differential Pressure across Revetment Block 1



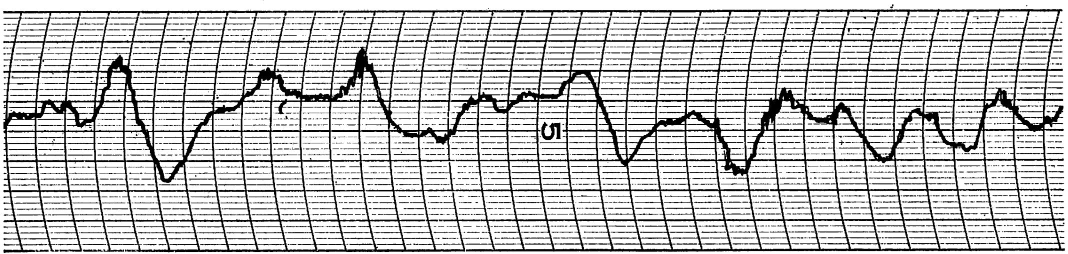
Pressure Variations above Revetment Block 1



Pressure Variations below Revetment Block 1



Differential Pressure across Revetment Block 2



Pressure Variations above Revetment Block 2

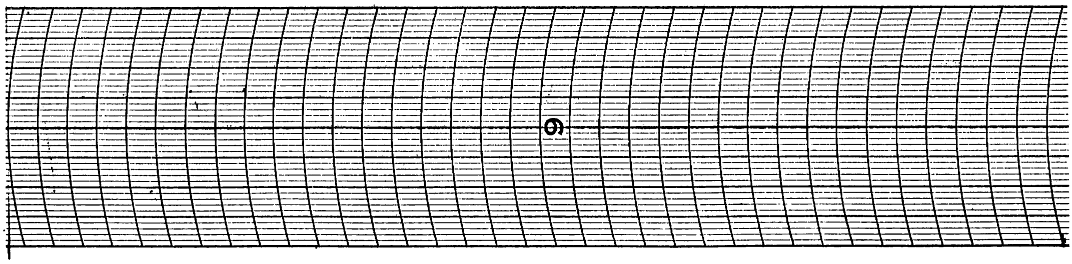


Fig. 31 — Sample Pressure Fluctuation Record

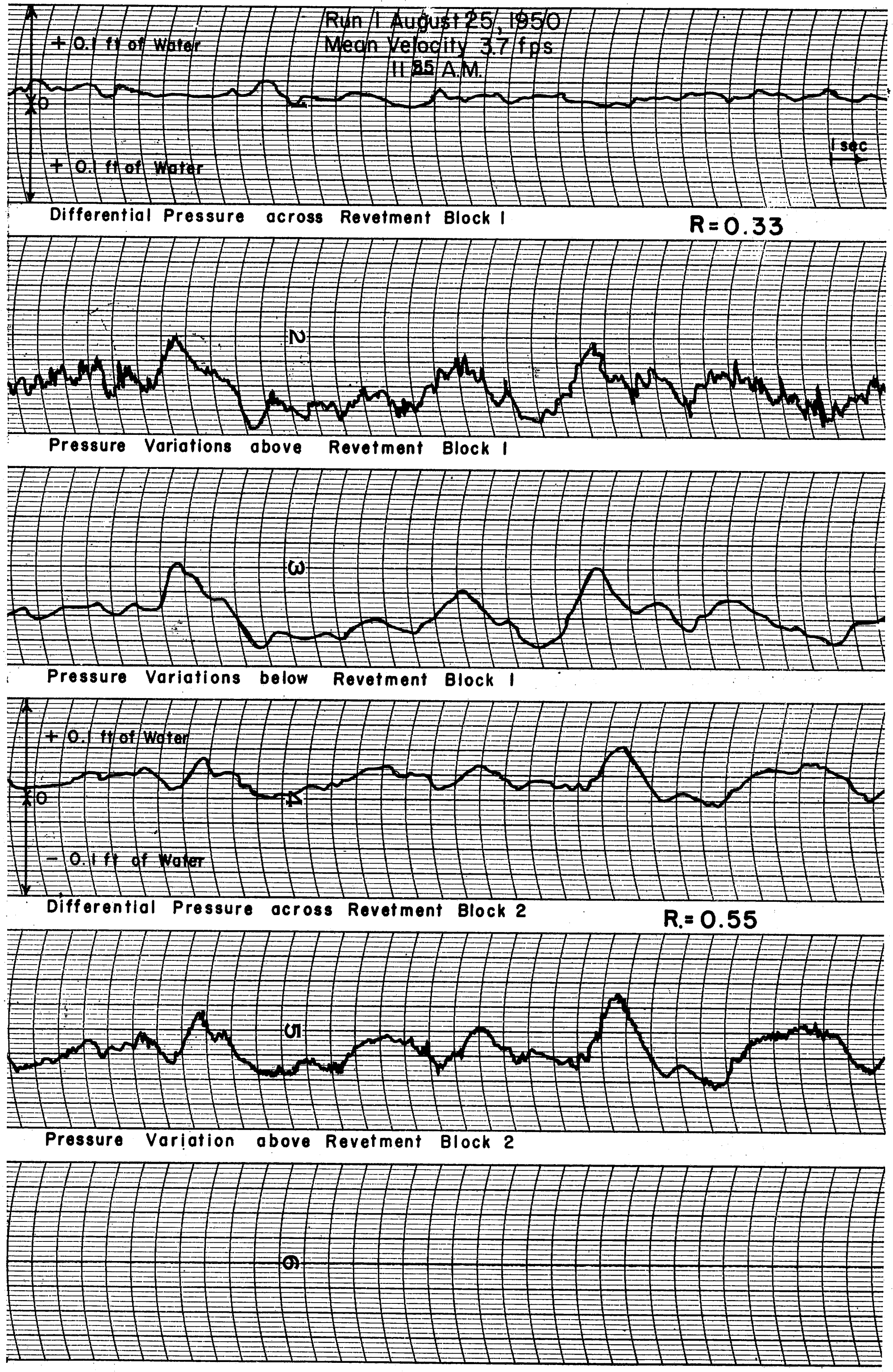


Fig. 32 — Sample Pressure Fluctuation Record

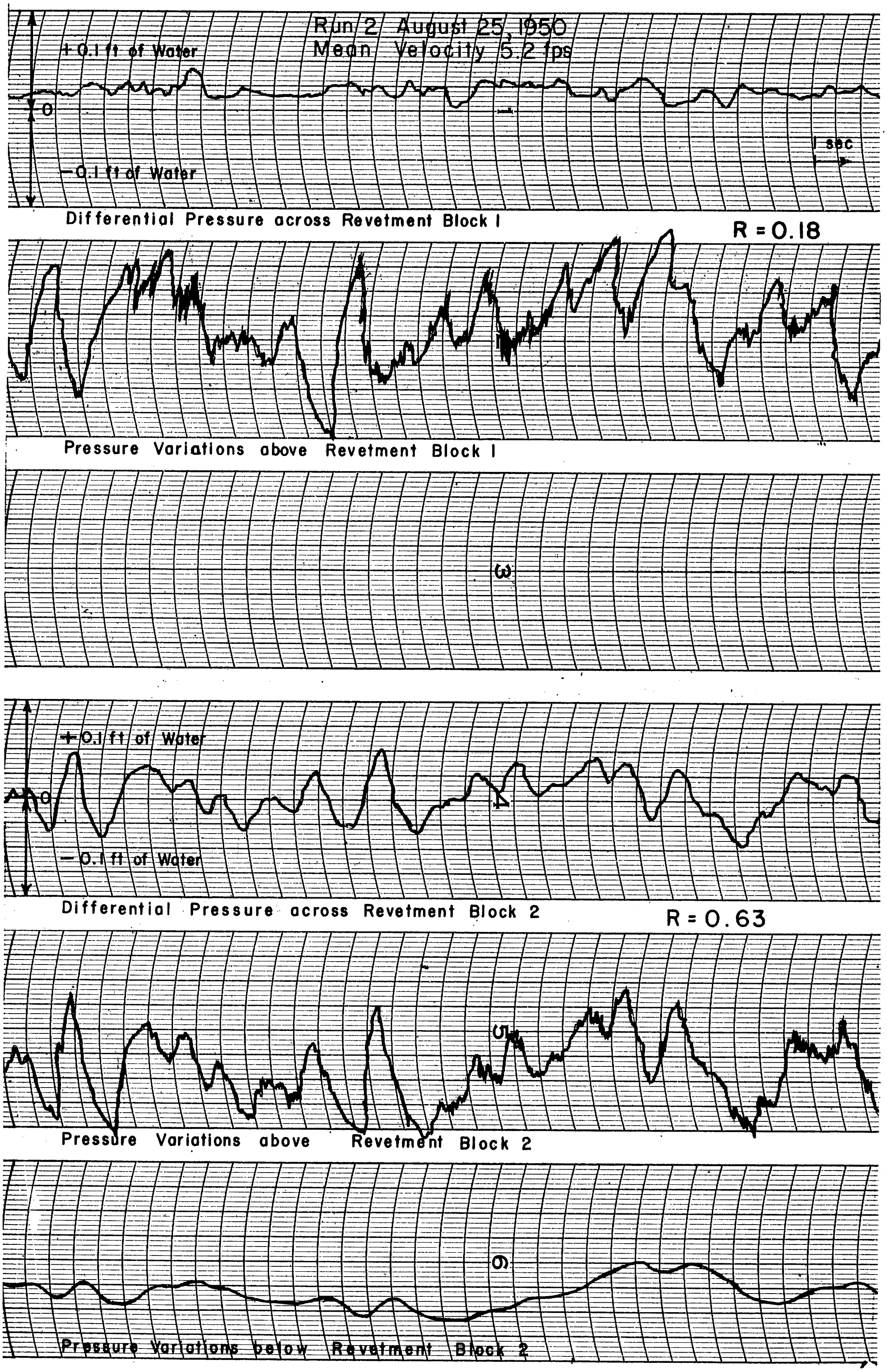


Fig. 33 — Sample Pressure Fluctuation Record

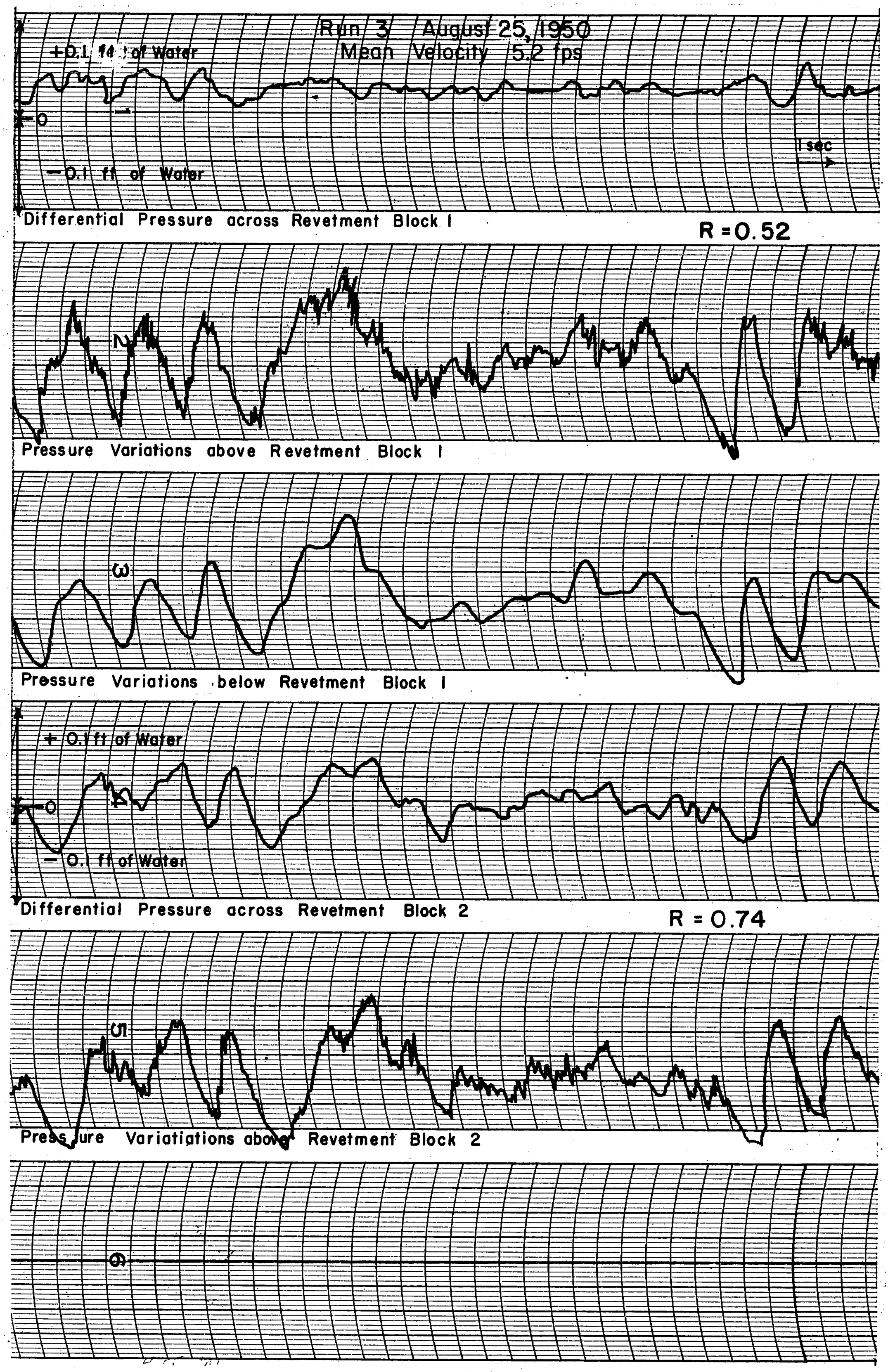


Fig. 34 — Sample Pressure Fluctuation Record

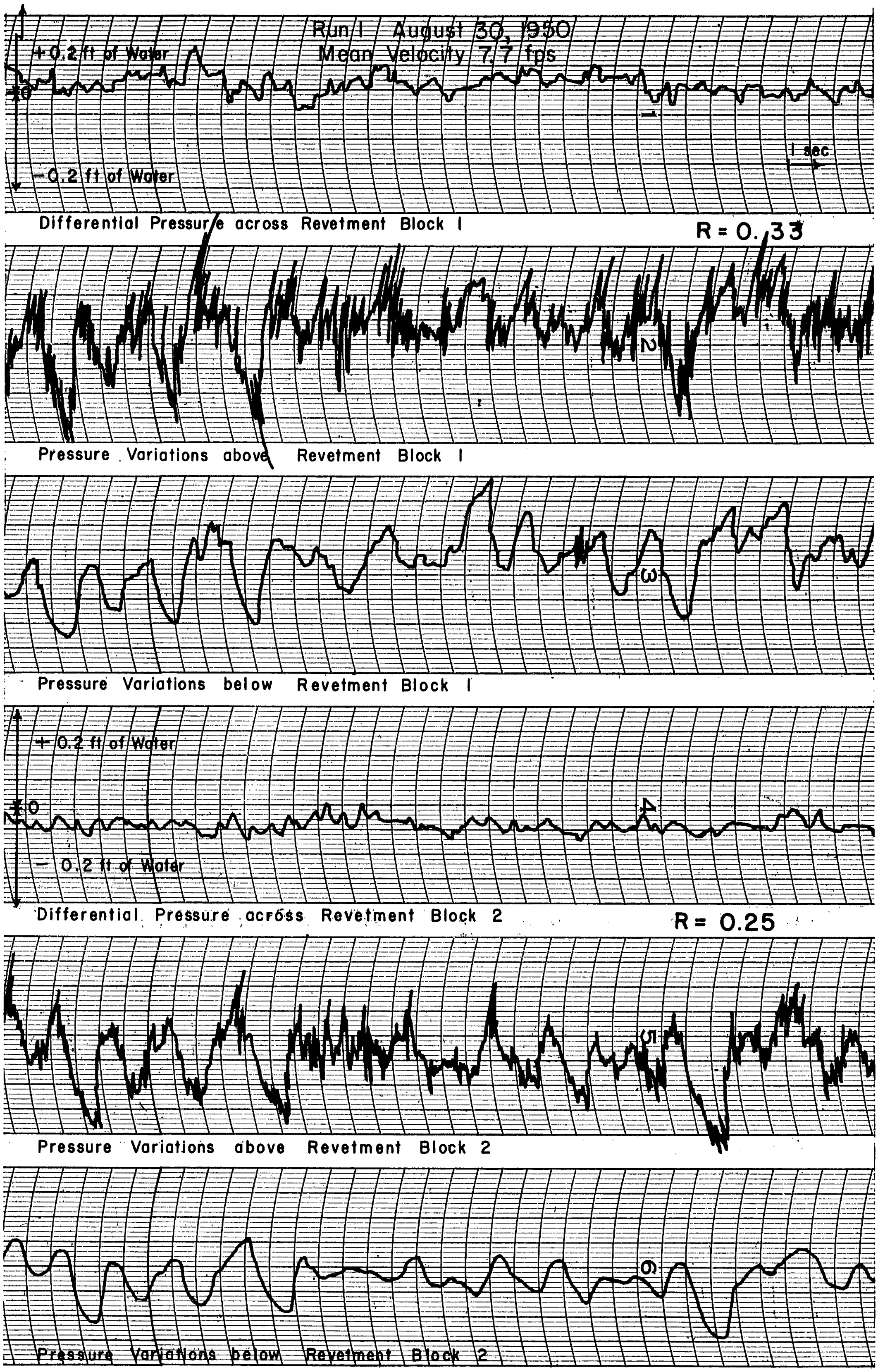


Fig. 35 — Sample Pressure Fluctuation Record

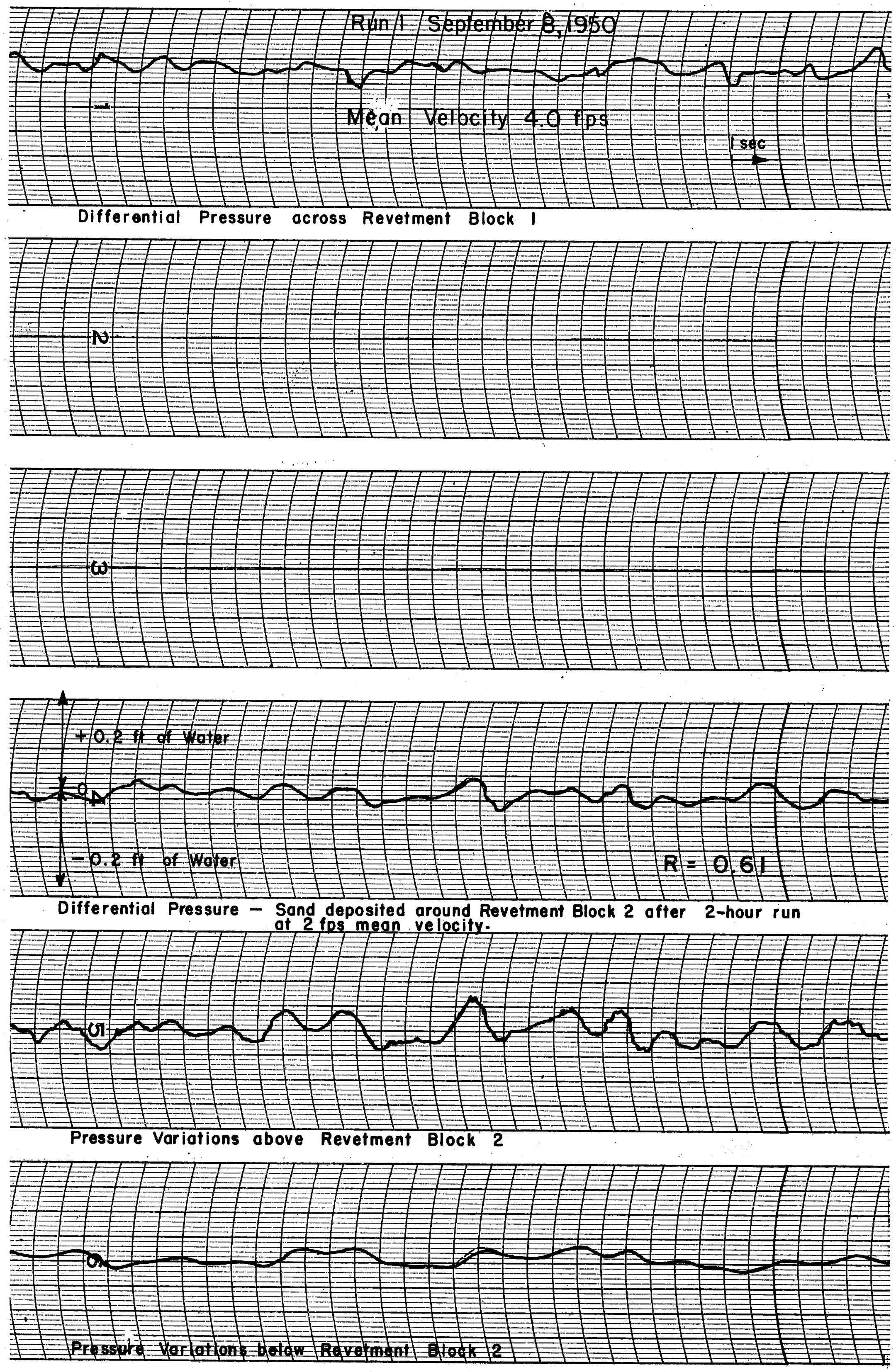


Fig. 36— Sample Pressure Fluctuation Record

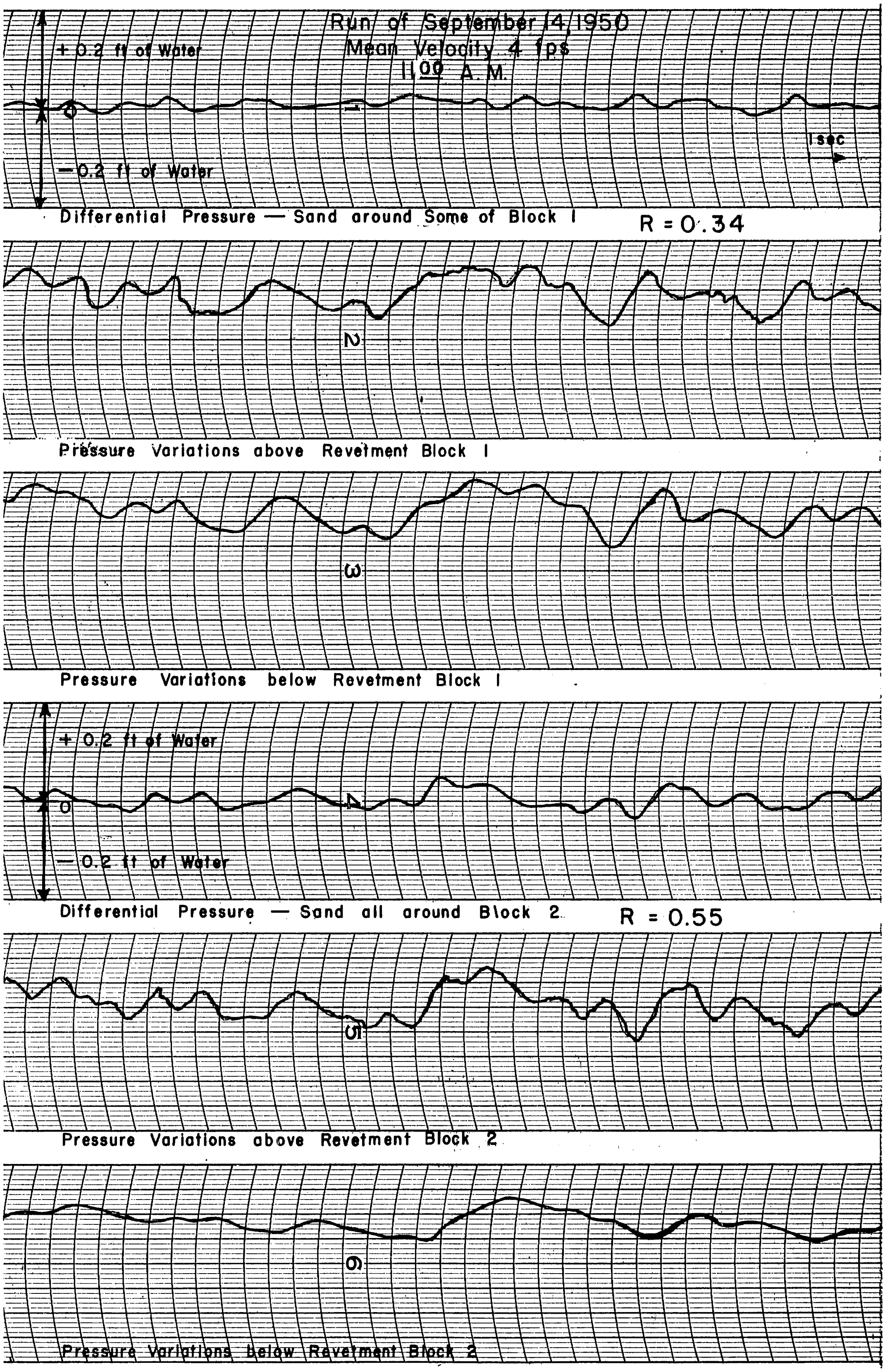
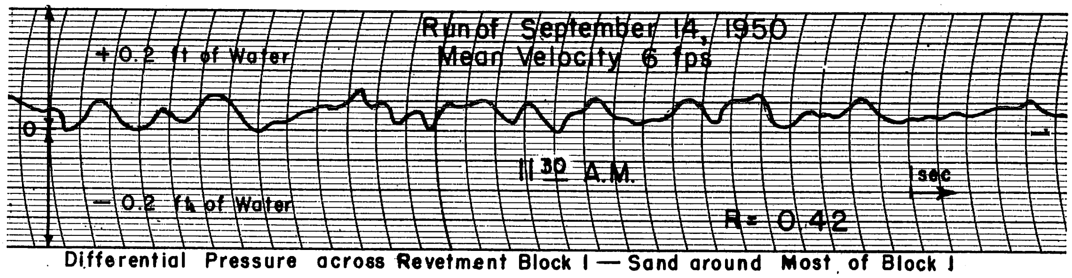
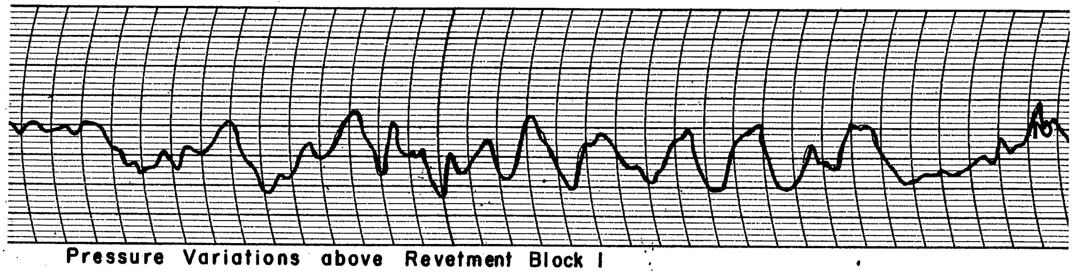


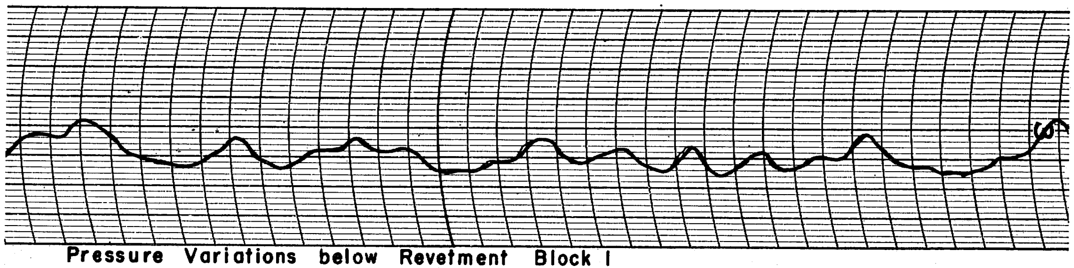
Fig. 37 — Sample Pressure Fluctuation Record



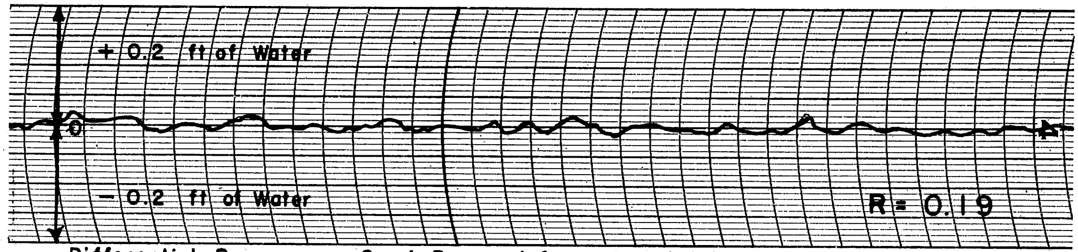
Differential Pressure across Revetment Block 1 — Sand around Most of Block 1



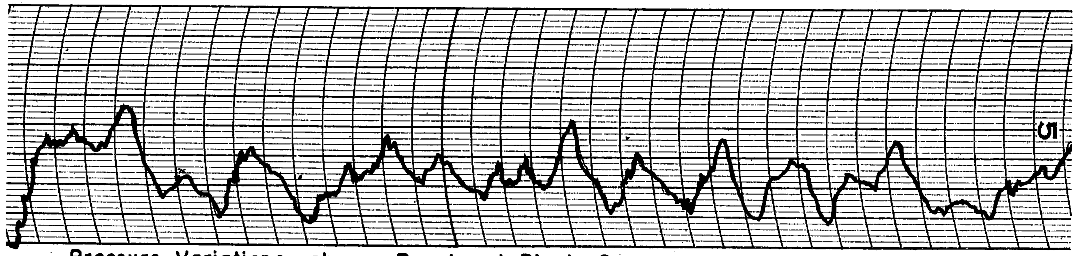
Pressure Variations above Revetment Block 1



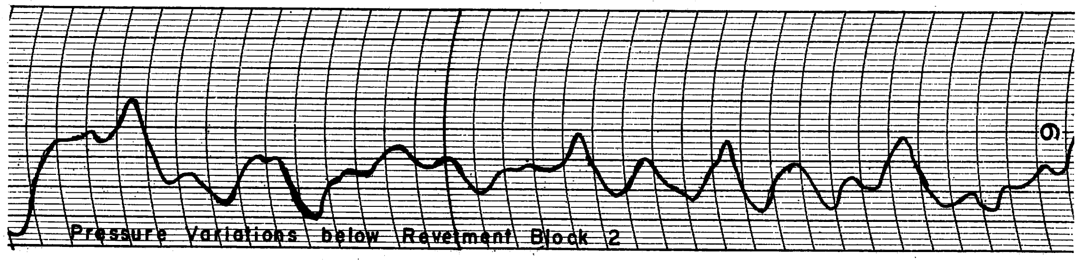
Pressure Variations below Revetment Block 1



Differential Pressure — Sand Removed from around Most of Block 2



Pressure Variations above Revetment Block 2



Pressure Variations below Revetment Block 2

Fig. 38 — Sample Pressure Fluctuation Record

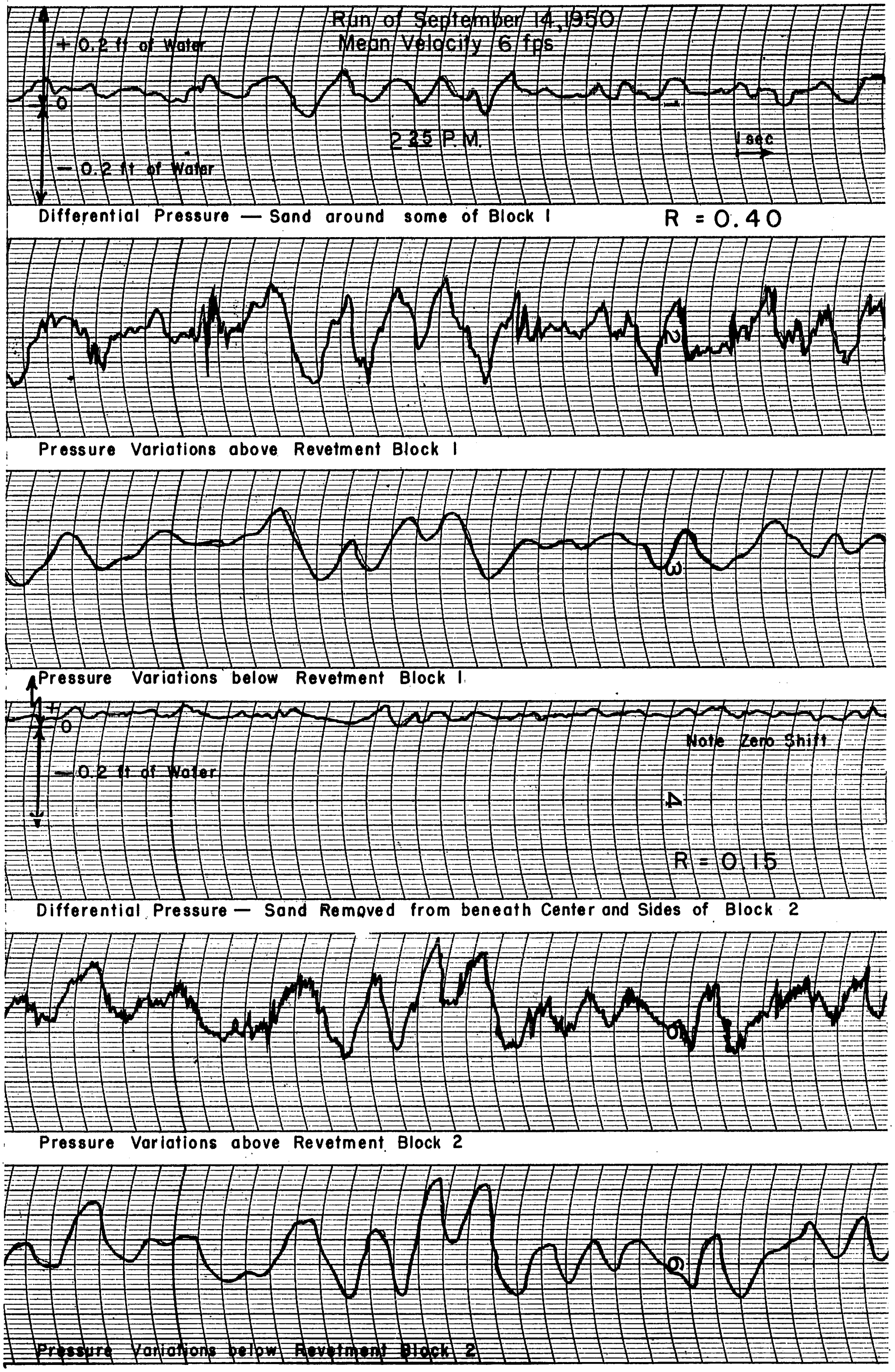


Fig. 39 — Sample Pressure Fluctuation Record

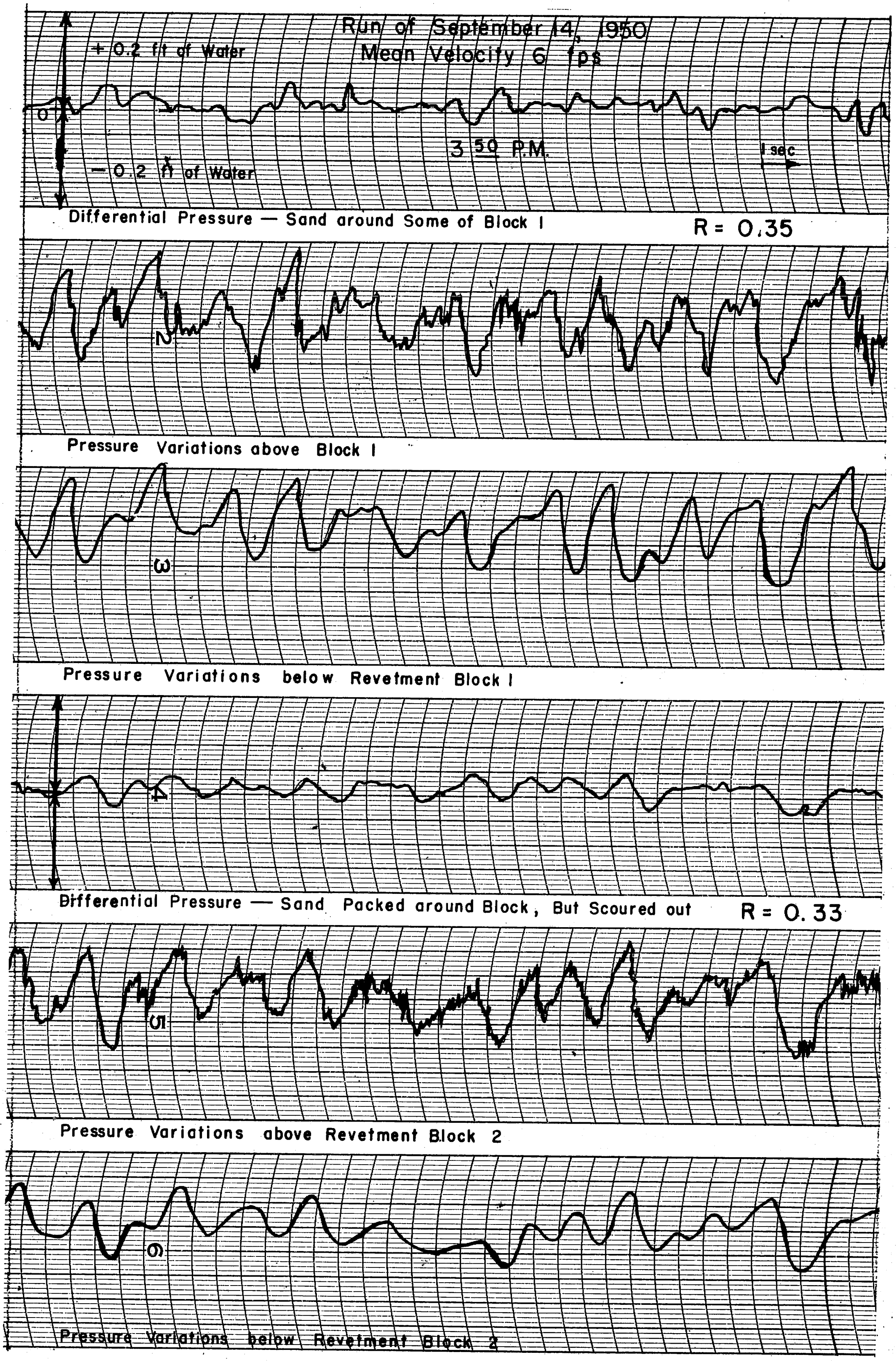
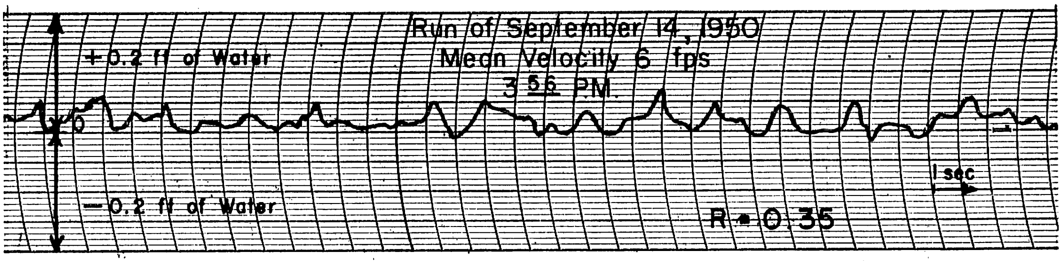
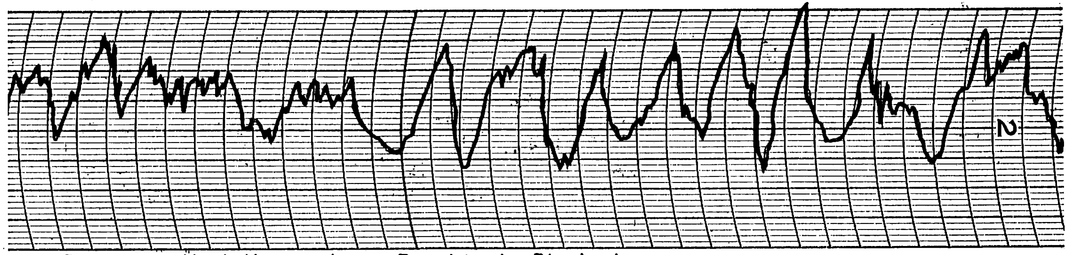


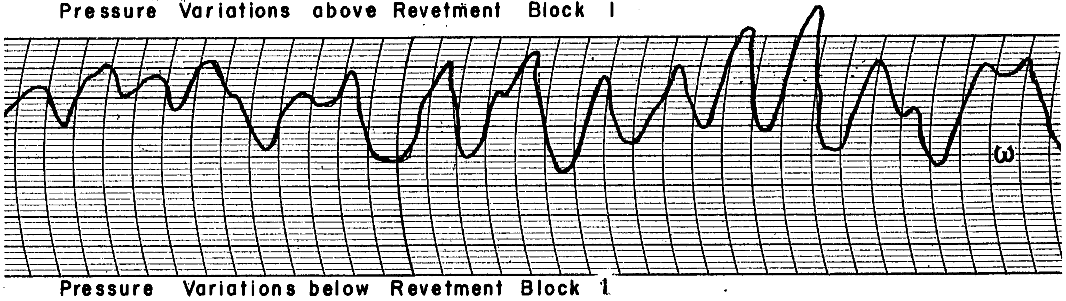
Fig. 40 — Sample Pressure Fluctuation Record



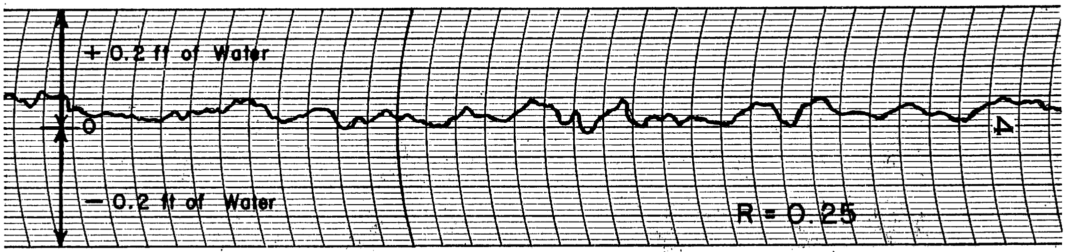
Differential Pressure across Revetment Block 1 — Sand around Some of Block 1



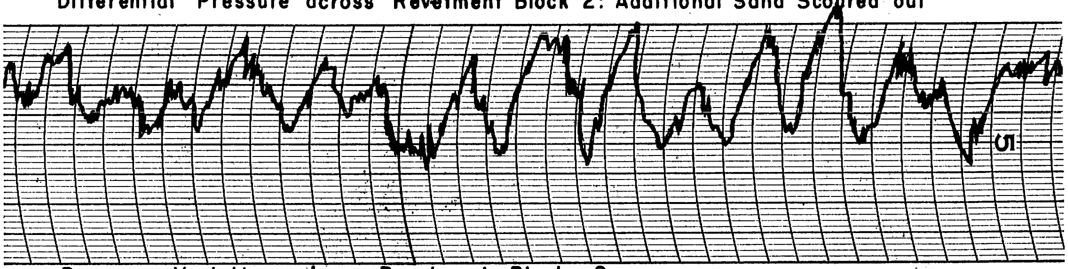
Pressure Variations above Revetment Block 1



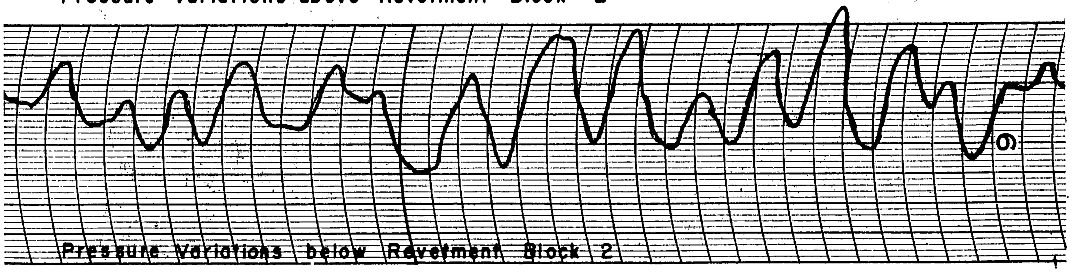
Pressure Variations below Revetment Block 1



Differential Pressure across Revetment Block 2: Additional Sand Scoured out



Pressure Variations above Revetment Block 2



Pressure Variations below Revetment Block 2

Fig. 41 — Sample Pressure Fluctuation Record

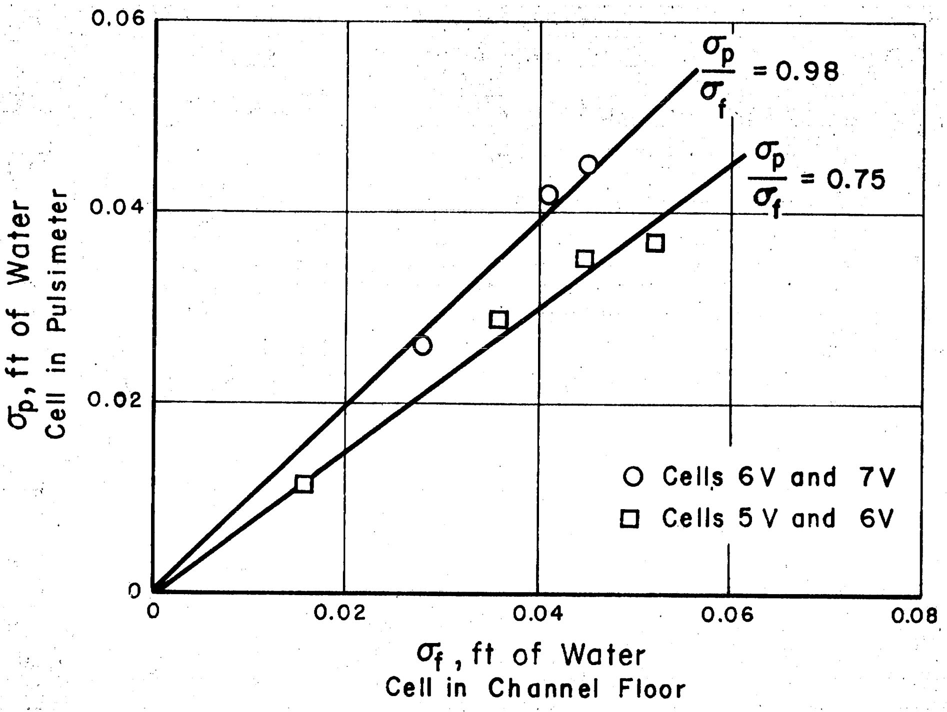


Fig. 42— Tests of Hydrodynamic Pulsimeter

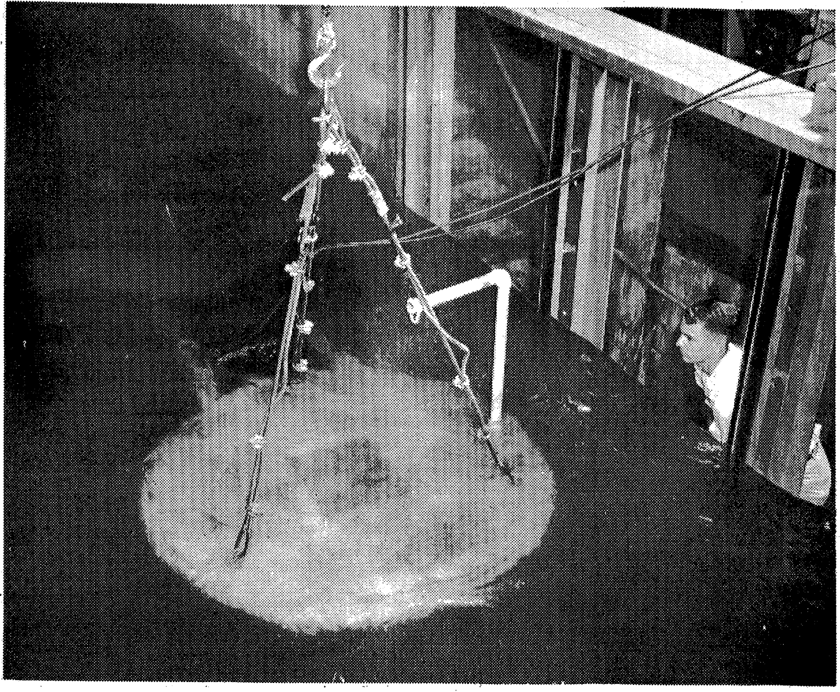


Fig. 43— Hydrodynamic Pulsimeter in Main Testing Channel