The Center for Marine and Coastal Studies North Carolina State University

A NEW TECH
FOR BEACH EROSION CONTROL

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ABSTRACT

An experimental study of a new technique for beach erosion control was conducted in a wave channel facility in the Civil Engineering Department, North Carolina State University. The primary objective of the study was to determine the effects of a sub-sand filtering system on the stability of a beach profile. The filter system was designed, constructed and placed in the beach section 4 in. to 6 in. below the sand surface.

The effects of waves on the beach section (filtered/unfiltered) were evaluated. The sub-sand filtering system was used to control the flow conditions at the sediment boundary. In the off-shore zone, the filters had a stabilizing effect on the overlying material (measurements indicated a substantial difference between filtered and unfiltered profiles). In the breaker zone, the filters had little effect on breaker scour. The sediment eroded from the breaker zone was stored in the foreshore zone. In the fore-shore zone, the filters were a tremendous aid in speeding accretion. The filter system generated rapid and large accretion. The filter system was very effective in building/replacing a foreshore berm.

PREFACE

Research described in this report was conducted as part of both the Sea Grant Program and the Coastal Research Program at North Carolina State University.

The report is primarily written by the senior author in partial fulfillment of the requirement for the M.S. degree.

The advice and guidance of Professor J. L. Machemehl, Chairman of his M.S. Advisory Committee, have been most helpful in the completion of the study. The author would like to extend his appreciation to Professor N. E. Huang for his counsel throughout the project. Appreciation is also extended to Professor L. J. Langfelder for his review and suggestions.

The research was partially supported by NOAA's Sea Grant Program and the NCSU Coastal Research Program.

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INTRODUCTION

This study was designed to test the effectiveness of a sub-sand filtering system in stabilizing a beach profile. The sub-sand filtering system was used to modify the flow near the sediment boundary and; thereby, induce a flow of water into the beach section. The flow of water into the beach modified the normal flow pattern in the sand-water boundary layer, and increased the effective drag force exerted on the sand particles. By increasing the effective drag force acting on the sand particles, the profile of the beach section was stabilized.

Beach protection by a mechanical technique (sub-sand filtering system) allows selective protection. In other words, the system could be operated during periods of storm degradation, and shut off during periods of normal accretion. This technique has a great advantage over classical beach protection methods, in that it would not permanently modify sand movement patterns along a beach.

In nature, the sediment on a beach primarily moves in two directions; parallel to the face of the beach by littoral transport and perpendicular to the face of the beach by on-shore/off-shore transport. Since this study was conducted in a water wave channel (narrow compared to its length), it was possible to study only the effects of the sub-sand filter system on on-shore/off-shore transport. On-shore/off-shore transport is a seasonal phenomena. When the waves are long and flat (summer months) there is an on-shore transport trend. When the waves are short and steep (winter months) there is an off-shore transport trend. This study was therefore designed to include both the long, flat summer type waves and the short, steep winter type waves. By studying the effects of the sub-sand filter system in both cases, it was possible to determine if the filter was more effective in stabilizing the beach in a winter storm situation or in aiding accretion on the beach in a summer deposition situation.

The typical near shore area of a beach can be divided into three zones; the off-shore zone, the breaker zone, and the fore-shore zone. In each zone, the flow of water causing the sediment to move is different. In the off-shore zone, the water just above the bed moves back and forth along a plane parallel to the bottom. This water moves in response to the wave forms moving across the surface of the water overlying this zone. The energy of the waves decay exponentially from the surface to the bottom. This implies, that in deeper water, a water parcel directly above the bed travels a shorter distance at a slower velocity. Conversely, in the shallower water, close to the breaker zone, the distance the water travels is larger, as is its velocity. Because the movement of the sediment is a function of the velocity of the water, the greatest amount of sediment movement takes place at the on-shore edge of this zone.

In the breaker zone, the flow throughout the entire water column is completely turbulent during the breaking of a wave. In this zone of high turbulence, the lift forces acting on the sediment particles come from all directions. Since the flow in this zone is turbulent, and a great portion of the entire energy of the wave form is released, the amount of sediment lifted from the bottom and moved is highest in this zone. A large portion of the sediment lifted by the breaker is either washed off-shore or carried on-shore in the up-rush of the wave.

The fore-shore zone is either exposed or covered with a thin, wedge-shaped layer of water from the up-rush of a wave. This water proceeds from the breaking wave, decelerating up the beach, until it comes to rest; then it begins accelerating back down the beach until it meets an incoming wave. Therefore, the lowest velocities and the smallest amount of sediment movement occurs at the top of the up-rush, and the largest amount of sediment occurs at the off-shore edge of this zone.

In the fore-shore zone and in the off-shore zone, the flow is parallel to the bed; therefore, the filter induced flow of water into the beach would make two basic changes in the flow along the water-sand boundary layer. First, it would tend to reduce areas of localized turbulence, making the flow along the boundary layer more uniformly laminar and less likely to move the sediment. Secondly, the water flowing into the sand bed would tend to hold the sediment particles together, thereby increasing the effective drag on the particles. The higher effective drag would create a higher threshold of transport and lower the amount of sediment moved. The filter system would have one additional effect in the fore-shore zone. The thin wedge of water in this zone is heavily laden with sediment, and as the filters draw water into the beach, they continuously decrease the volume of water in the up-rush and the back-rush. As the volume of the water decreases, its ability to maintain the sediment in suspension decreases. The final result must be that some sediment will be deposited as the water from each wave passes over the fore-shore.

In the breaker zone, the flow is too turbulent to be controlled, by the present system. However, the filter induced flow into the beach does consolidate the sediment particles, and raise their effective drag.

The filter system was designed to be much like a typical well pumping system. The filters were designed to be similar to well points. These filters were set into the beach, parallel to the surface of the beach, and covered with four to six inches of sand.

REVIEW OF LITERATURE

In nature, the profile of a beach is continuously undergoing changes. The beach profile changes in response to the interaction with waves. Since the type waves that break on the beach are not the same from day to day or even hour to hour, the profile of the beach is not the same from day to day. There are, however, two broad classifications which are commonly used to describe most beach profiles, the summer profile and the winter profile. According to Johnson[4], summer profiles are created by gentle waves ($Ho/Lo > 0.025$). The summer profile is characterized by a low, wide berm and a relatively smooth and barless underwater profile. Winter profiles are created by steep waves ($Ho/Lo < 0.025$). The winter profile is characterized by a steep, narrow berm and an alternating series of bars and troughs on the underwater portion of the profile.

The summer beach profile is characterized by a step or an abrupt rise in elevation and a change in the beach slope right at the breaker line. The steeper slope on-shore of the breaker line cluminates in a low wide berm. According to Kemp[5], the step is created by a vortex produced by the back-wash. The back-wash is decelerated as it approaches the still water level. This deceleration results in the formation of a horizontal vortex, in which the upper layers rotate down towards the bed and thus shore-ward. The high velocities resulting from this motion produce a scoured depression forcing some of the bed material into suspension. The heavier particles are then moved on-shore by a velocity component near the bed. The high velocity, horizontal component of the orbital motion near the bed of the incoming wave, produces a reverse vortex at the edge of the scour depression, thus, deepening the depression. This double scouring creates a horizontal shelf just seaward of the breaker line. Some of this scoured material is carried on-shore in the up-rush to be deposited on the berm.

With a steeper, winter type wave ($Ho/Lo > 0.025$), the material from the fore-shore is moved off-shore to the breaker line. The fine material is then put up into suspension and moved off-shore. The coarser material is trapped in the scour depression, building the steeper fore-shore slope in the off-shore direction. A scour hole is generally formed on-shore of the breaker line. This hole is formed by the turbulence of the breaking waves, assisted by the current created by the back-rush flowing sea-ward along the bottom. After the bar profile is fully formed, the breakers become less violent, since the momentum effect of the back-wash current is reduced.

The majority of the sediment that is moved along the bed of a beach is moved by the forces generated by the waves impinging on the beach. The sediment particles begin to move when the wave forces overcome the forces holding the sediment particles in place. In order to determine how the wave forces will effect a beach, it is necessary to determine the threshold of motion point of incipient motion.

Eagleson and Dean[1] discussed the seven major forces acting on a sediment particle as shown in Figure 1.

(1) Gravity force-

$$F_G = \frac{\pi D^3}{6} \gamma \; (Ss-S) = (Ms-M)g \tag{1}$$

(2) Drag forces-

(a) Form drag-

$$F_F = C_1 \frac{\rho}{2} \frac{\pi D^2}{4} (Ue-Vs) \; |Ue-Vs| \tag{2}$$

In Equation 2, Ue is the effective velocity usually assumed at the particle crest level.

(b) Surface drag-

$$F_S = C_2 D^2 \rho \; (Ue-Vs) \; |Ue-Vs| \tag{3}$$

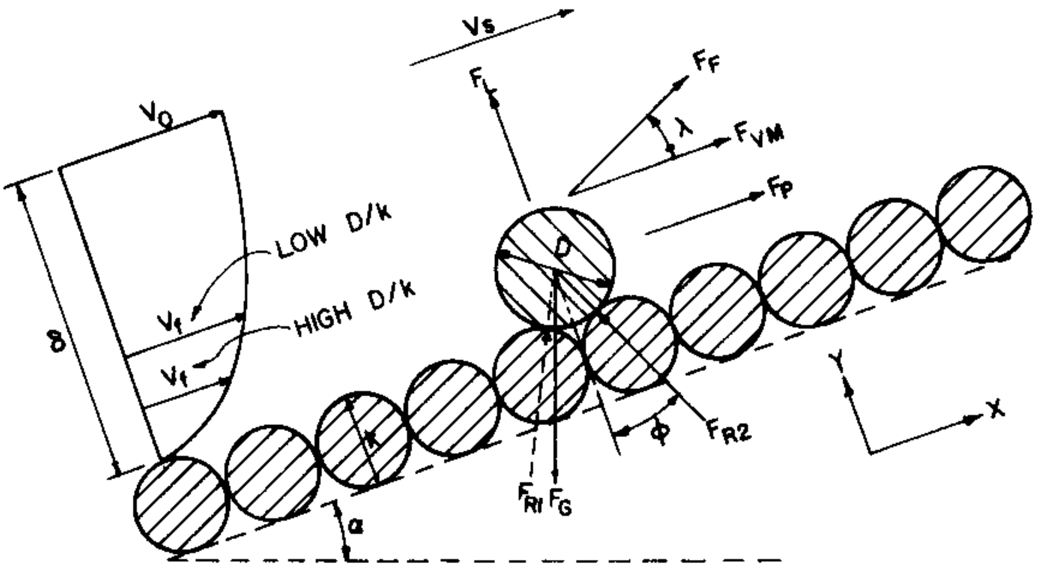


FIG. I. FORCES ACTING & IDEALIZED BED-PARTICLE GEOMETRY. (REF. I)

In a laminar boundary layer the drag coefficient over the upper surface of a sphere is:

$$C = \left[\frac{(Ue-Vs)}{V}\; D\right]^{-1/2} \quad \ldots\ldots \quad (4)$$

(3) Lift-

$$F_L = C_1\; \rho\; \frac{\pi D}{8}^{\,2} \quad (Ue-Vs)^2 \quad \ldots\ldots \quad (5)$$

This is augmented by a lift derived from the Magnus effect when the particle rolls.

(4) Virtual Mass

$$F_{VM} = C_3\; \frac{\pi D^3}{6}\; \rho \left[\frac{dUe}{dt} - \frac{dVs}{dt}\right]$$

$$= C_m\; M \left[\frac{dUe}{dt} - \frac{dUs}{dt}\right] \quad \ldots\ldots \quad (6)$$

Since the motion of the particle involves acceleration, the virtual mass has to be considered, specifically, an added inertial effect arises from accelerating some fluid along with the sediment particle. The virtual mass coefficient (C_M) will depend on the particle shape and the proximity to the boundary.

(5) Pressure force-

$$F_P = C_4\; \frac{\pi D^3}{6}\; \rho\; \frac{dUe}{dt} = M\, \frac{dUe}{dt} \quad \ldots\ldots \quad (7)$$

Pressure forces on the particle are due to the instantaneous pressure gradients under the wave. Uo refers to the potential flow velocities of the wave motion.

(6) Inertial force

$$F_I = \rho\; Ss\; \frac{\pi D^3}{6} \quad \frac{dVs}{dt} \quad \ldots\ldots \quad (8)$$

(7) Rolling friction force

$$F_{RR} = \varepsilon[F_G \cos - F_D \sin \beta - F_L]\, \frac{Vs}{[Vs]} \quad \ldots\ldots \quad (9)$$

The rolling friction force is proportional to the normal component of gravity and the fluid forces acting on the particle. Epsilon is the coefficient of rolling friction. Here beta is the angle between the resultant of the viscous resistance force (F_D) and the beach slope in radians.

The equation for incipient motion is then given to the first approximation by assuming that the viscous resistance and apparent mass forces act through the upper edge of the particle and all other forces act through the center of the particle.

$$\Sigma M = 0 = \rho \frac{\Pi D^3}{16} Ue^2 \left[C_d (1+\cos\phi+C_l \sin\phi\right]$$

Viscous resistance and lift

$$+ \rho \frac{\Pi D^4}{12} \left[C_m \frac{dUe}{dt} (1+\cos\phi) + \frac{dUo}{dt} \cos\phi\right]$$

Virtual mass and pressure

$$- \rho \frac{\Pi D^4}{12} g \left(\frac{Ss}{S} - 1\right) \sin (\alpha + \phi) \quad . . . . \quad (10)$$

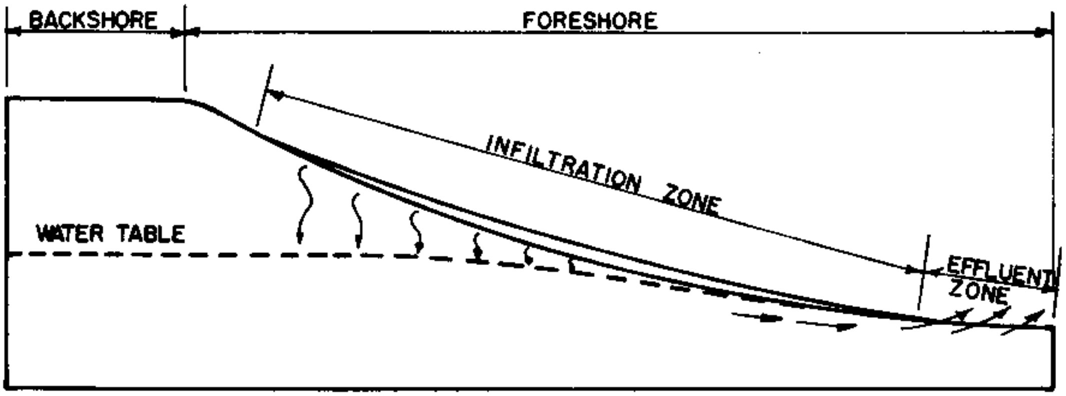
gravity

One factor which has an effect on the stability of a beach is the level of the water table. Emery and Foster[2] found that there was a definite time lag of 1 to 3 hours between the cresting of the water table beneath the beach, and the cresting of the tide. They also found that after the tide had begun to ebb, the water table beneath the beach was still relatively high. This high water table gave rise to an outflow of water at the toe of the beach. Emery and Foster observed that, as the water flowed out of the beach, it lifted the sediment from the beach and transported it down the beach face.

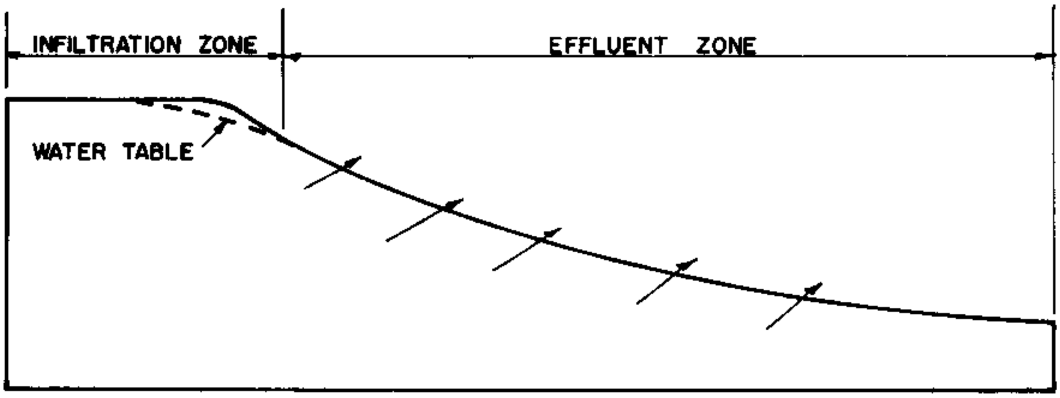
Grant[3] stated that there was a definite relationship between the height of the water under the beach and the stability of the beach. He found that a high water table accelerated erosion and a low water table retarded erosion and aided accretion on the fore-shore. Grant discussed two ways in which a low water table aided accretion on the fore-shore (See Figure 2). Grant found that when the water table was very low beneath the fore-shore; and the sand was very dry, then as the up-rush from a wave traveled up the beach, the water would soak into the beach, trapping the sediment transported up the beach face by the wave up-rush. If, however, the water table was near the beach surface and the sand was partially saturated, then only a portion of the water would soak into the beach, decreasing the depth of the back-wash. Just before the termination of the up-rush, the velocity of the water dropped below the critical Reynolds value, and the flow became laminar, the sediment would rapidly drop out of suspension. With a lower flow volume in the back-rush on a partially saturated beach, the flow would stay laminar for a greater distance down the baach face, leaving much of the sediment that came in with the up-rush on the fore-shore.

Grant also stated that during storm situations, when the entire beach became saturated, some of the water from the breaking waves would run back down through the beach. As this water flowed out of the beach, it lifted sediment up into suspension and transported it off-shore. Grant concluded that a saturated beach would erode more rapidly than one only partially saturated.

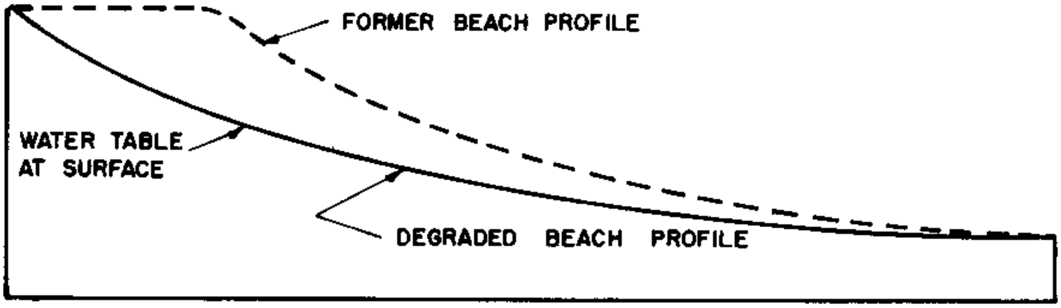
Silvester[6] stated that any factor which generated a rise in the water table beneath a beach would be in effect increasing the erosion rate of the beach. Silvester listed the three factors which tend to raise the water table beneath a beach (See Figure 3): (1) the disposal of storm water onto the beach from large catchment areas, natural or man-made, (2) the existence of a rock shelf just below the beach surface which concentrates



LOW WATER TABLE WITH EXTENSIVE INFILTRATION ZONE.



HIGH WATER TABLE WITH EXTENSIVE EFFLUENT ZONE.



DEGRADED BEACH DUE TO WATER TABLE COINCIDENT WITH SURFACE OF BEACH.

FIG. 2. HYPOTHETICAL BEACH CROSS SECTION SHOWING WATER TABLE EFFECT. (REF. 5)

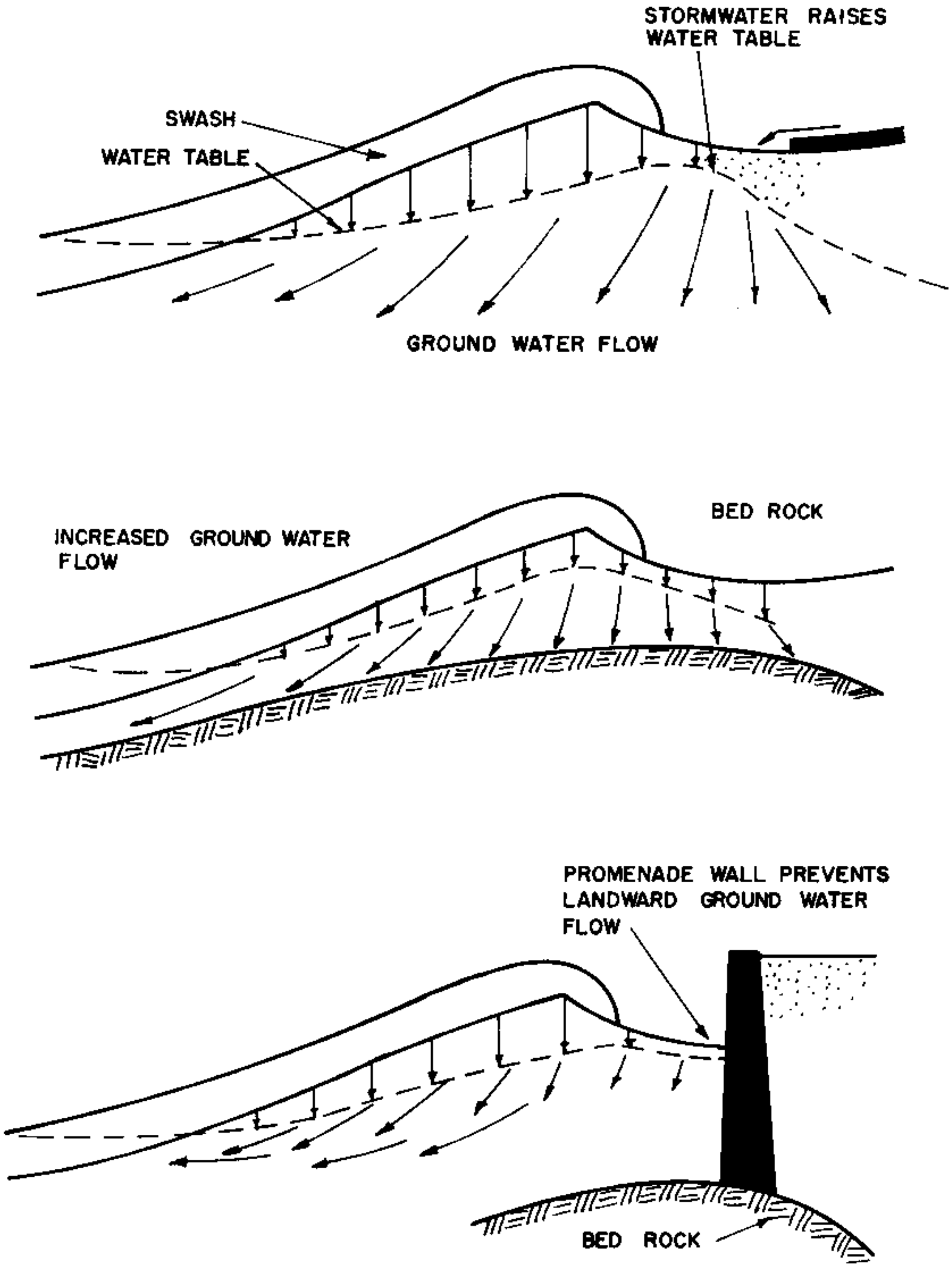


FIG. 3. HYPOTHETICAL BEACH CROSS SECTION SHOWING CONDITIONS CONDUCIVE TO BEACH EROSION. (REF. 3)

the flow of ground-water to the sea, and (3) the presence of promenade walls which prevent the temporary flow of ground-water inland when the storm sea level exceeds the normal water table level.

RESEARCH APPARATUS AND EXPERIMENTAL PROCEDURES

Research Apparatus

Wave channel. The experiments were conducted in a water wave channel facility (See Figure 4). The wave channel consisted of two basic sections: a wave generating section and a beach section. The wave channel was 50 ft. long, 3 ft. deep, and 2 ft. wide. The bottom was constructed of 3/16 in. steel plate and the walls were constructed of 1/2 in. plate glass panels.

The wave generating section provided a space for the pendulum wave generator and a reservoir and an energy absorber behind the paddle plate. The wave absorber was set in the reservoir to reduce undesirable reflection from the end of the reservoir area.

The beach section started 8 ft. from the end of the wave generating section and extended to the opposite end of the channel. This section provided a space for the beach sand and the intake end of the filter system.

Wave generator. The monochromatic wave generator shown in Figure 4 was a pendulum type, with provisions for varying the type wave produced. The pendulym generator was attached eccentrically by a push rod to a 2 ft. diameter driving disk. The driving disk was equipped with a helical screw adjustment attached to the push rod which allowed the effective diameter of the disk to be varied. The disk was attached to a Browning Worm Gear Speed Reducer (part no. 45041-GR15F model A) with a reduction ratio of 15-1. The speed reducer was driven through a V-belt by a Mark III series Eddy-Current Adjusto Spede (R) Drive model ACM9043.

The period of the waves was controlled completely by varying the speed of the driving motor. Monochromatic shallow water waves with a continuous range of periods from 1-4 sec. were generated. The height of the waves was controlled by two methods. The wave height could be changed slightly by varying the speed of the driving motor or the height could be changed to a greater extent by varying the effective diameter of the driv-

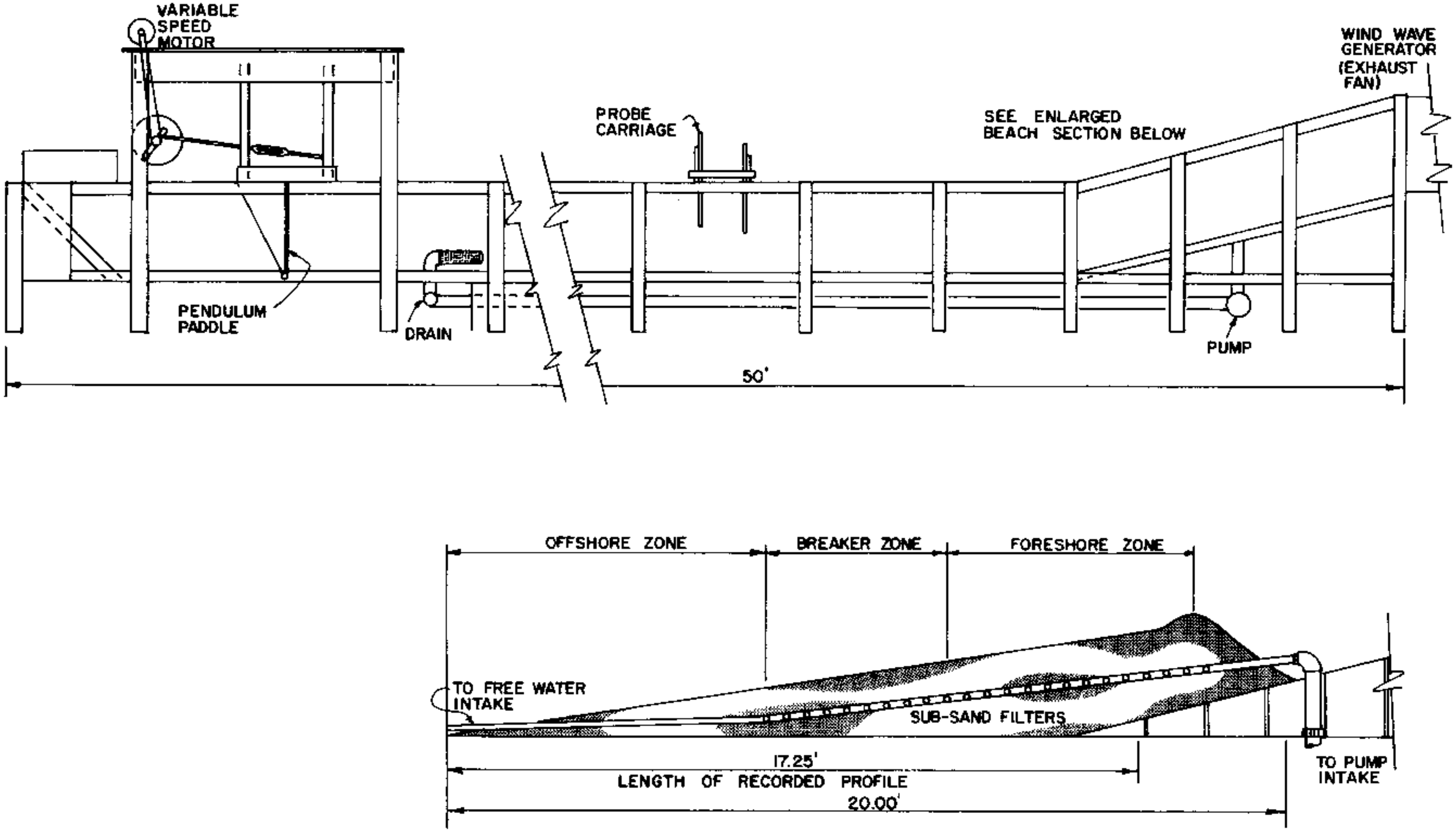


FIG.4. WATER WAVE AND BEACH CROSS SECTION.

ing disk. Once the desired period of the wave was obtained the desired wave height was obtained by adjusting the eccentricity of the driving disk.

Beach. The test beach shown in Figures 5 through 7 was 20 ft. in length and was inclined at a slope of 10.5:1. The sand used in this beach was taken from the North Carolina coast and is a typical sample of North Carolina beach sand. The sand had a D_{50} size of 0.265 mm.

Sub-sand filter system. The sub-sand filter system was composed of five sections; (1) the free water intake section, (2) the sub-sand intake section, (3) the pumping section, (4) the meter section, and (5) the discharge section as shown in Figures 8 and 9. The free water intake consisted of a 2 in. brass valve open 90 degrees to the 2 in. PVC header pipe. The intake was placed at the front edge of the wave generating section of the tank. The header pipe ran 11 ft. from the free water intake section to the sub-sand intake section. The sub-sand intake filters were constructed from slotted 2 in. PVC pipe. The filters were connected through a 2 in. brass valve to main header pipe. The slots were 0.25 mm. in width which prevented the passage of all but the finest particles. The filters were set on 6 in. centers along 11 ft. of the main header underlying the beach. At the upper end of the beach the main header was coupled to a 4 in. PVC pipe which was connected to a 90 degree vertical elbow and passed through the bottom of the tank. The pipe came out of the bottom of the tank and was coupled to the intake of the pump. The pump was a Berkley Pump (Model B62R 11 CW). The pump had a capacity of 440 gpm and was designed to operate with a flat head performance curve. This allowed the pump to be operated at various discharge rates without altering the operating head of the pump. The pump was powered by an U. S. Electric Motor (Model No F-9247-00-138) rated at 5 hp. @ 1155RPM. The discharge of the pump was connected to a flow meter by 15 ft. of pipe. The flow

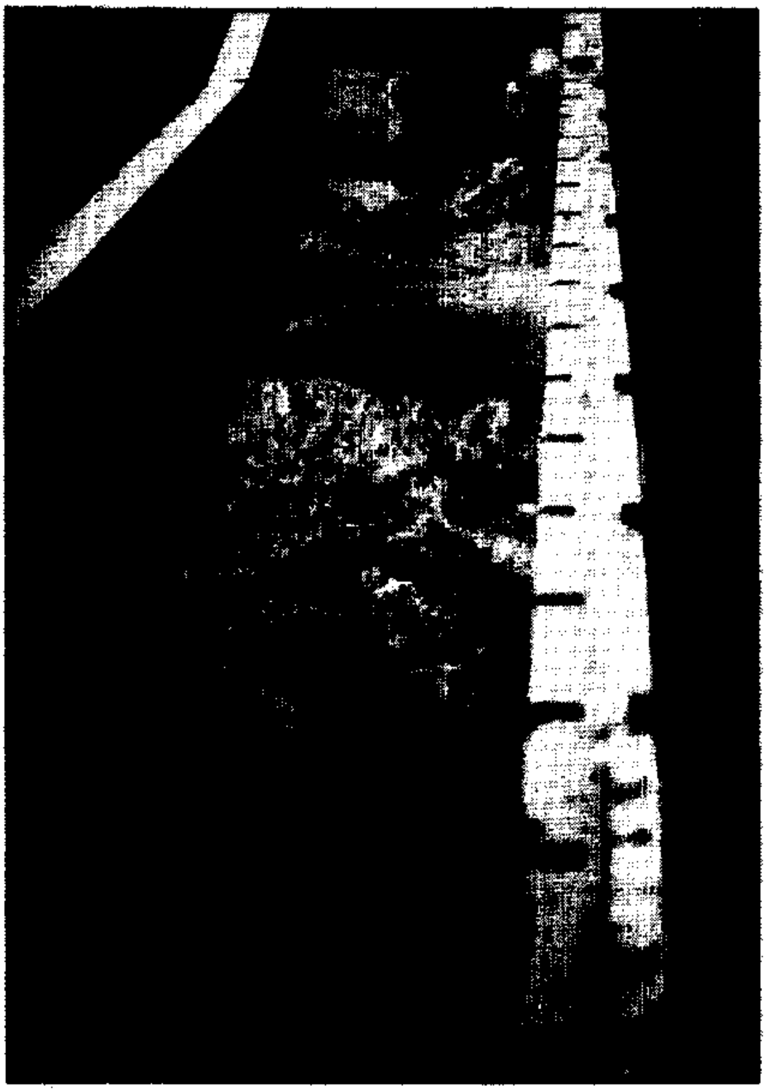


FIG. 5. TEST BEACH IN WATER WAVE CHANNEL.

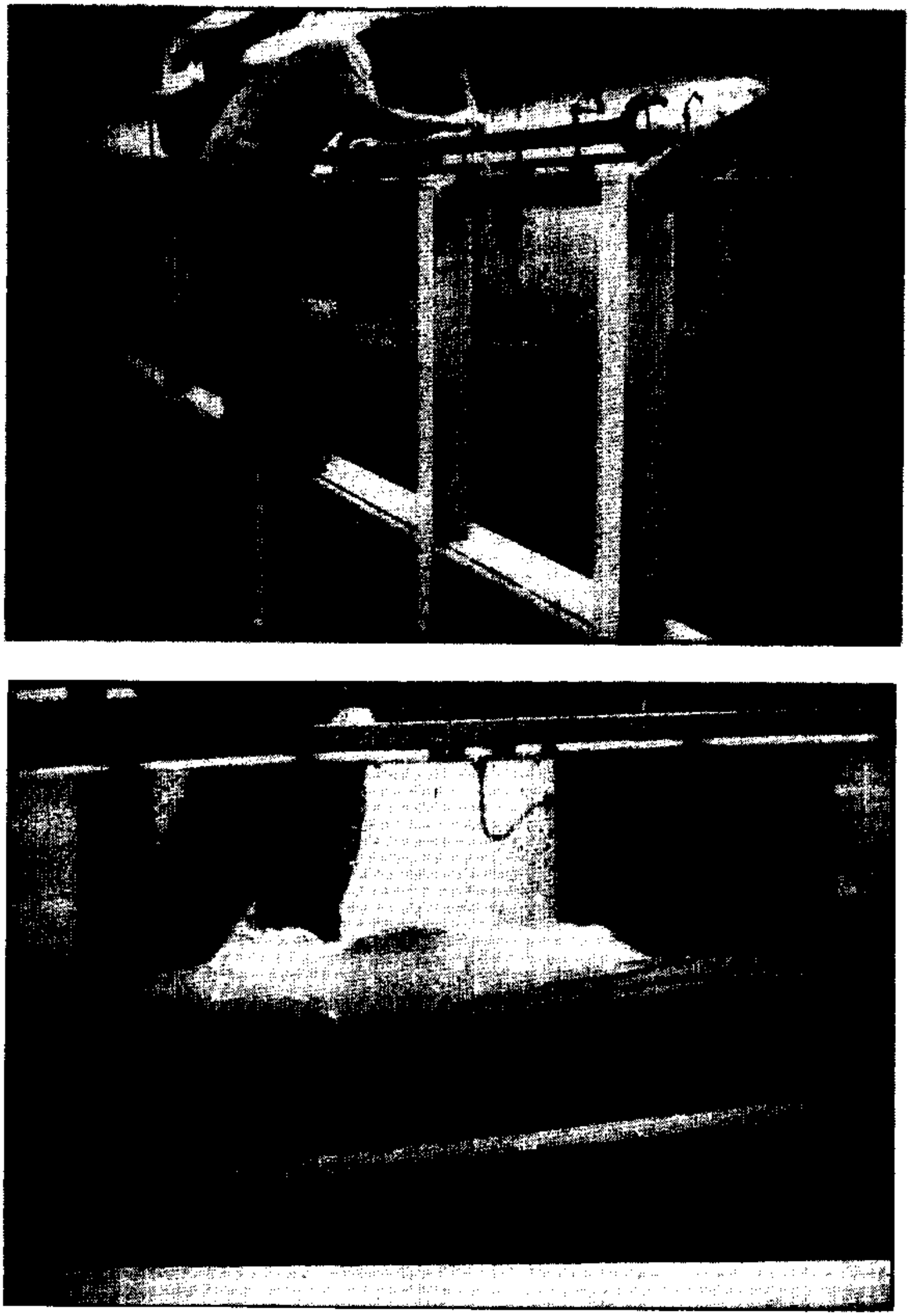


FIG. 6. TEST BEACH IN WATER WAVE CHANNEL SHOWING SCOURED SECTION.

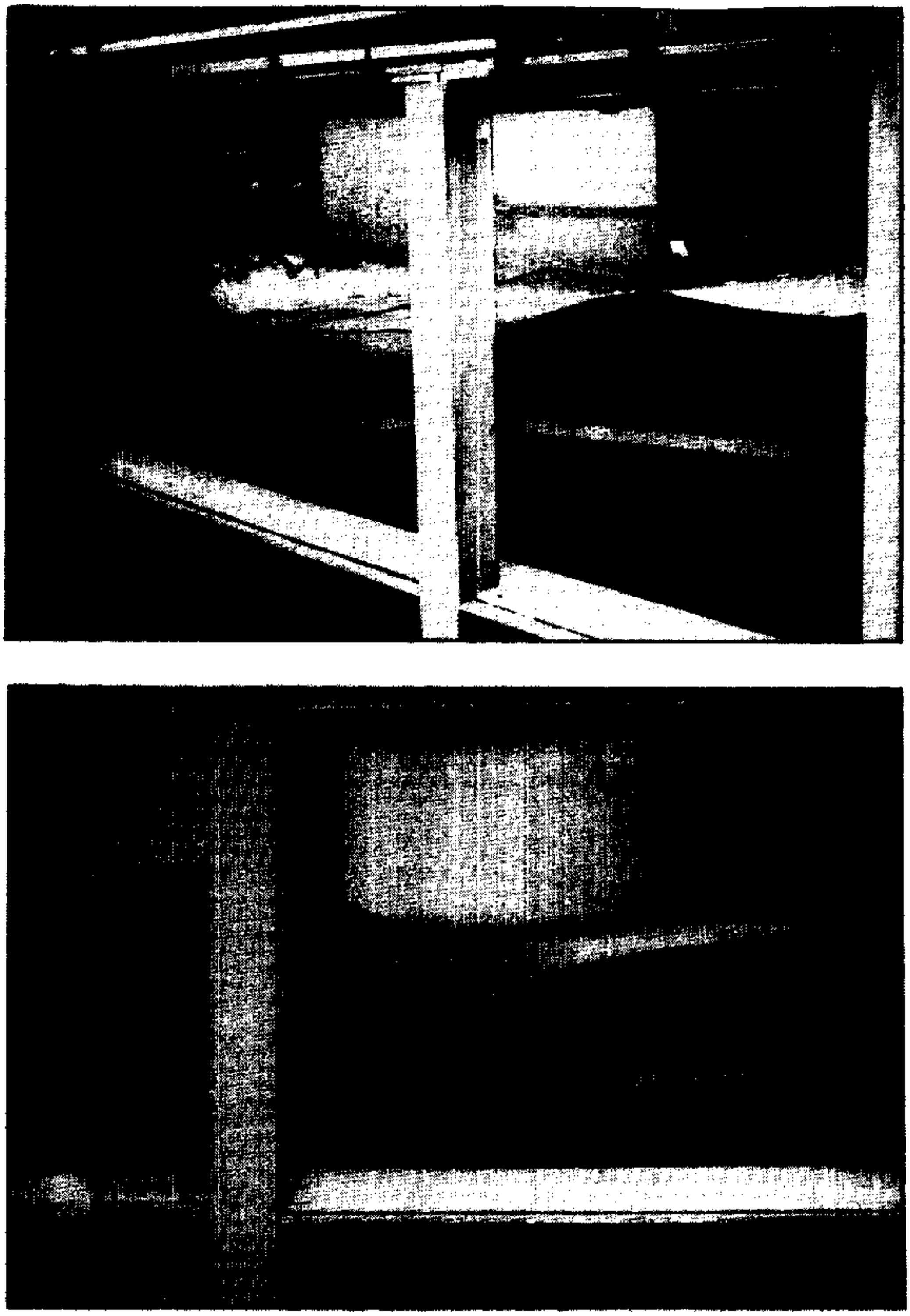


FIG. 7. TEST BEACH IN WATER WAVE CHANNEL SHOWING ACCRETTING SECTION.

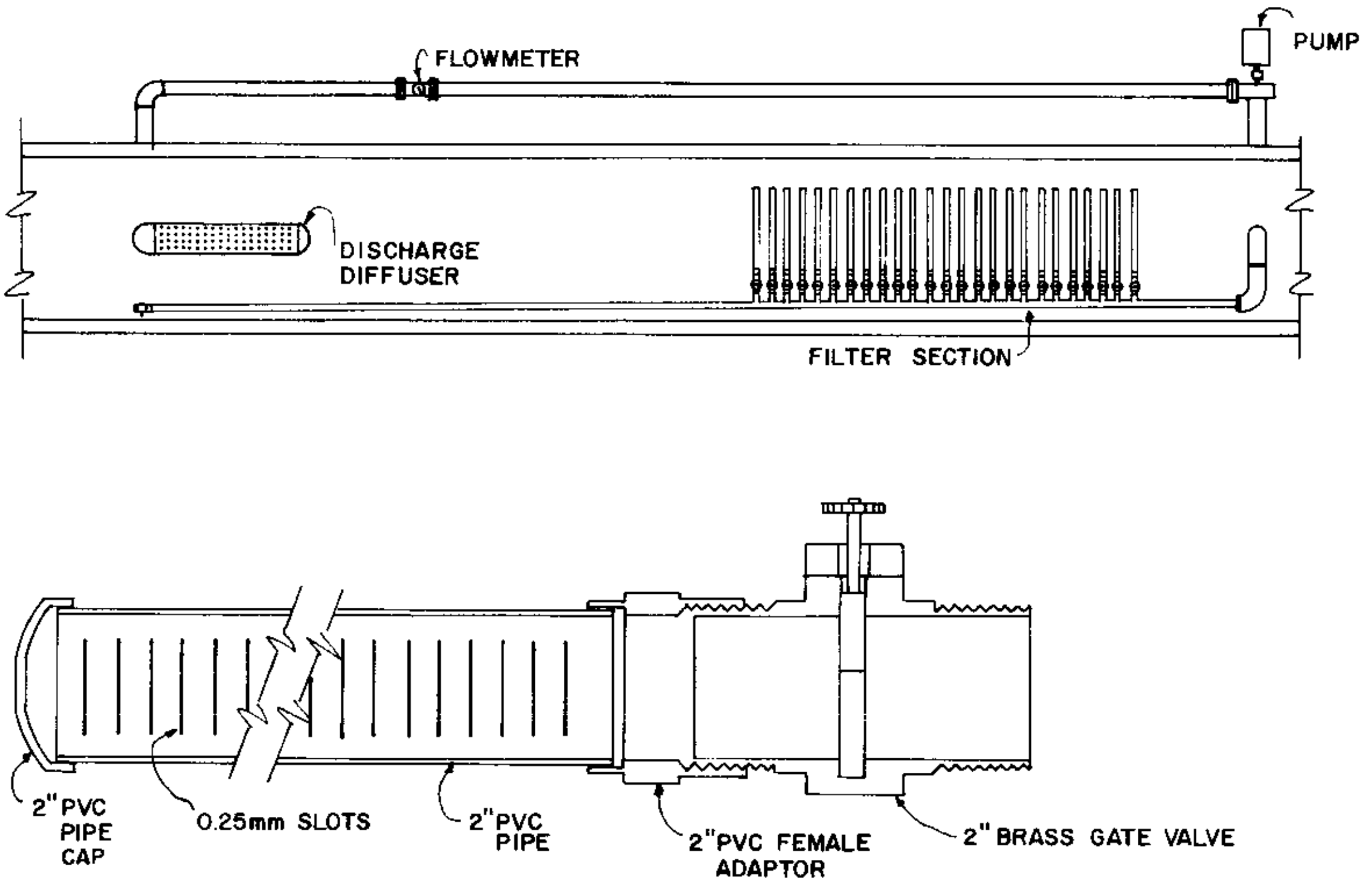


FIG. 8. PIPING DIAGRAM OF FILTER SYSTEM.

FIG. 9. FILTER SYSTEM

meter was a Rockwell Register type (serial no. 8197). This meter was the continuous read type that could be timed for one hour periods to give an accuracy of ± 1 gpm. The flow meter was connected to the discharge diffuser by 15 ft. of pipe. This pipe passed up through the tank bottom at the edge of the wave generator section and was connected to the discharge diffuser. The diffuser was constructed from a 3 ft. section of 4 in. PVC pipe. One end of the pipe was capped and 1/2 in. holes were drilled around the circumference of the pipe down the entire length of the pipe. The diffuser was set in the tank parallel to the walls. The bottom edge of the diffuser was set 4 in. above the center of the tank bottom.

Research Instruments

Rail system. A level rail system was mounted to the top of the wave channel. The rails were constructed from 1in.-1in. steel bar stock and mounted on 1/4 in. posts on 6 in. centers. The posts were attached to the top of the channel through a set of hemispherical washers which enabled the track to be leveled accurately. Two three wheel cars were constructed to fit the rail system. The cars were free rolling on the rails and were equipped with a locking system which allowed the cars to be used either as moving or fixed probe mounts. The rail system furnished a level reference plane from which measurements could be made anywhere in the channel.

Depth gauges. Two different depth gauges were used to obtain a complete profile of the beach. An Ultrasonic Distance Meter (Model 1054) was used to profile from the toe of the beach to 7 1/2 ft. along the profile. The Ultrasonic Distance Meter was produced by Automation Industries, Inc. and had a range of 0-15 ft. and an error of ± 1% full scale. Since the Ultrasonic Distance Meter had to be completely submerged, the profile from 7 1/4 ft. to 17 1/4 ft. along the length of the beach was obtained by using a calibrated point gauge. The point gauge was attached to one of the rail cars and could be read to ± 0.005 ft.

Wave gauge. A capacitance type wave gauge was used to obtain a wave record. The gauge was constructed from a no. 15 bare copper wire and a no. 17 standard insulated wire coated with Micro Measurement's M-coat B. Both wires were strung on an acrylic U frame, with a 12 in. span. The insulated wire was attached to an eyebolt which allowed the wire to be strung with variable tension. The two leads were connected to a bridge circuit which was connected to a Hewlett Packard Carrier Amplifier (Model 8805).

The capacitance wave gauge measured the capacitance between two conductors separated by a dielectric medium. Because of the exposed lead, the water acted as one conductor and the insulated wire was the other. The insulation on the wire served as the diaelectric medium; therefore, the apparent capacitance of the gauge varied linearly with the wetted length of the insulated wire. If a wave passed the gauge frame, the bridge output would show a fluctuation in the apparent capacitance of the system.

This type of gauge was chosen because it was sensitive and gave a repeatable linear output. The gauge also was small enough not to disturb the flow, while being durable.

Recorder. The recorder that was used to record the output from the wave gauge and the Ultrasonic Distance Meter was a Hewlett Packard 4 channel Sanborn Recorder (Model 7414A). The recorder was equipped with three carrier amplifiers model 8805B and one medium gain amplifier model 8802A. The wave gauge was connected to one of the carrier amplifiers and the Ultrasonic Distance Meter was connected to the medium gain amplifier. All the amplifiers were internally connected to the strip chart recorder which allowed all data to be read out directly.

Measurements

Measurement of sand characteristics. A sieve analysis was used to determine the grain size (See Figure 10) of the sand that made up the beach. The sand samples were air dried and then sieved. Two samples in the pans were hand shaken for 15 min. and the results from these tests were compared to one sample shaken on a rotap for 10 min. (sieve sizes that were used were #20, #48, #60, #140, and #200).

The permeability of the sand was determined with a constant head permeameter. To determine the permeabilities of the sand at a low density and a high density, two tests were conducted. The permeameter was weighed empty and then weighed with an air dried sand sample. Then a permeability test was conducted with a constant head. Next the sand was compacted as much as possible and the test was repeated. By noting the volume the sand occupied during each test the density of the sand was determined for each test. The sand samples were found to have a range of permeabilities from 0.030 cm./sec. to 0.025 cm./sec.

Wave measurements. Wave measurements were made with a capacitance type wave gauge. The gauge was connected to a 4-channel Sanborn Recorder. Static calibration of the wave gauge was accomplished by raising and lowering the gauge in still water. The wave gauge was calibrated before each experimental run. Since the strip chart recorder recorded at a known rate, the wave height and the wave period could be read directly from the strip chart. The wave record was kept to insure that the operation of the monochromatic wave generator was consistent.

Profile measurements. The complete profile was measured using two instruments. The lower portion of the profile (from the toe to 7 1/4 ft. along the profile) was measured using an Ultrasonic Distance Meter. The transducer for the Ultrasonic Distance Meter was mounted to the top of one

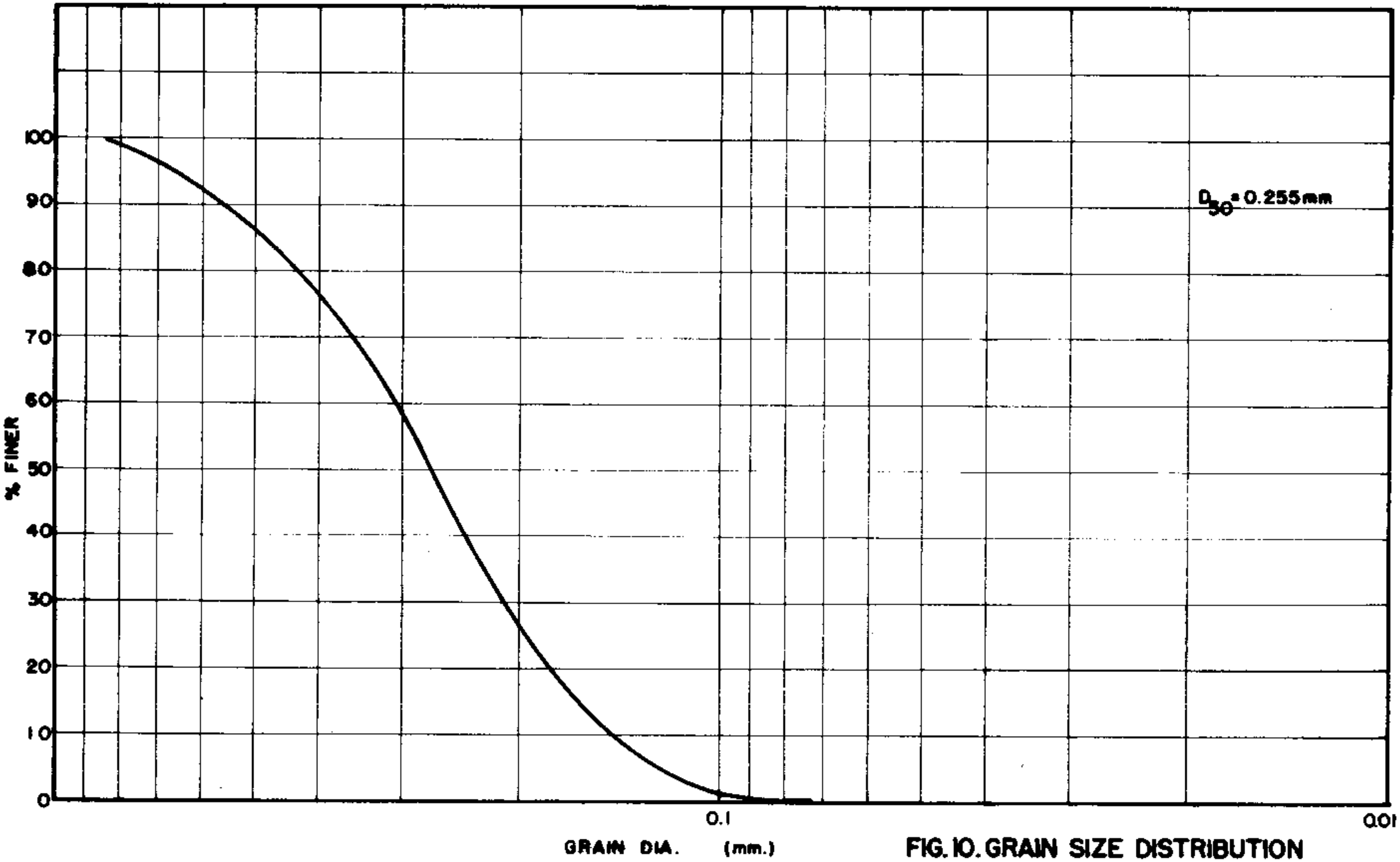


FIG. 10. GRAIN SIZE DISTRIBUTION

of the rail cars. The head of the transducer was set 5 in. below the still water level. Measurements were made every six inches and recorded on the strip chart. Measurements were made while the experiments were in progress so this portion of the profile was recorded on the same paper as the wave record. Because there was a limiting depth for the Ultrasonic Distance Meter, the upper end of the profile (7 1/4 - 17 1/4 ft.) was measured with a point gauge. The point gauge was equipped with a 1 in. x 1 in. acrylic foot, and all distance measurements were made from the foot of the gauge to a zero point set at the lower edge of the rail car.

Both probes were moved along the rails by hand. All measurements were made 6 inches apart except where the upper and lower region overlapped, where measurements were made every 3 inches. After the initial profile had been measured for each run, profile measurements were made every 20 min. for the first 60 min, every 30 min. for the next 60 min., and every 60 min. for the remainder of the test.

Test program. To determine the effect that the sub-sand filter system on the stability of the experimental beach profile, it was necessary to compare the changes that took place on the profile of the unfiltered beach to those changes which took place on the profile of the filtered beach. The study was divided into four separate tests. Each test was numbered according to the monochromatic wave used throughout that particular test. Wave characteristics are shown in Table 1.

Table 1 - Test Numbers and Wave Characteristics.

Test Number	Wave Period T (Sec.)	Wave Height H (Ft.)	Wave Slope H/T^2 (Ft/Sec^2)
1	3	0.16	0.017
2	2	0.32	0.080
3	3	0.24	0.026
4	2	0.46	0.115

Each test was further divided into two parts; an unfiltered part (here after denoted as Part A), and a filtered part (here after denoted as Part B).

Each test was conducted in the following manner. First, the desired wave characteristics were set. The beach was raked into its initial profile (1:10.5 slope) and a profile was recorded. The wave generator was then turned on and run for 180 min. (profiles were recorded at 20 min., 40 min., 60 min., 90 min., 120 min., and 180 min). At the end of 180 min. the paddle was stopped. Part A of the test served as a control comparison since the sub-sand filter system was not in operation. The B part of each test was conducted in exactly the same method as the A part except that the filter system was turned on. The pump for the filter system was operated at as constant a flow rate as possible during all four tests.

ANALYSIS OF DATA AND DISCUSSION OF RESULTS

The profiles for the four tests were plotted and normalized. The profile plots contain all the profiles that were recorded during the test series. These plots show the changes that took place on the experimental beach profile with respect to time. The normalized profile plots contain the profiles that were recorded at 60 min. intervals. These plots were normalized by setting the initial profile equal to a zero line and then indicating the deviation the hourly profiles made from the initial profile. Since these profiles were normalized, it was possible to compare the magnitude of the changes that took place on the experimental beach profiles.

The following discussion, therefore, is broken up into sections. The first section is a comparison of the profile plots of the A part and the B part of each test. The second section is a comparison of the normalized profile plots of the A part and the B part of each test.

In the following discussion, a point on the profile was defined by a single distance along the base line, and a zone was defined by giving the two distances along the base line which defined the two edges of the zone.

Analysis of Profiles for Test No. 1-A

No major changes occurred from 0.00 ft. to 9.00 ft. and from 16.20 ft. to 18.25 ft. during this 180 min. part of the test, as shown in Figure 11 (Appendix A). Major changes did occur in the zone from 9.00 ft. to 16.20 ft. In the off-shore portion of this zone a large scour hole developed in the first 20 min. From 20 min. to 60 min., the scour hole moved off-shore and deepened. Then from 60 min. to 180 min. the bottom of the scour hole flattened and the on-shore side of the hole steepened. In the on-shore portion of this zone, a large accreted mound developed in the first 20 min. of the run. For the remaining 160 min., the off-shore side of the mound grew toward the breaker zone and the slope became flatter.

Analysis of Profiles for Test No. 1-B

No major changes occurred from 0.00 ft. to 10.20 ft. during 180 min. of the test, as shown in Figure 11 (Appendix A). Major changes took place from 10.20 ft. to 17.25 ft. In the zone from 12.00 ft. to 14.20 ft. a breaker scour hole developed and was evident at 20 min. The scour hole was narrow with steep sides. At 40 min., there were two scour holes covering a zone from 10.20 ft. to 14.20 ft. Both scour holes had horizontal off-shore walls with steep on-shore walls. At 60 min., the on-shore hole had become shallower and wider and the off-shore hole had become deeper and wider. After 90 min. the on-shore hole had deepened and established a V-shaped in cross section. In the zone from 14.20 ft. to 17.25 ft. an accreted mound had formed in the first 20 min. of the test. The off-shore side of the mound had a steep slope while the top of the mound was almost horizontal. At 40 min., the off-shore side of the mound stayed the same while the top of the mound had risen in elevation and had become rounded in cross section. From 40 min. to 120 min., the slope of the off-shore side of the mound stayed the same while the top of the mound continued to rise and become more pointed in cross section. During the last 60 min. of the test very little change took place in the accreted mound.

There are three basic differences between the two final profiles for the two parts of this tests, (1) the scour hole was farther in-shore and it was wider and shallower in Part B., (2) the accreted mound was located farther in-shore with a steeper off-shore face and a higher elevation in Part B., and (3) the zone from 9.00 ft. to 10.20 ft. experienced no major changes in Part B.

Analysis of Profiles for Test No. 2-A

No major changes took place on the profile until after 90 min. of the test had elapsed, as shown in Figure 12 (Appendix A). These changes took place in the zone from 11.35 ft. to 16.00 ft. During this period, a breaker zone scour hole appeared as did a mound of a accreted material on the foreshore. The scour hole had steep sides and remained narrow throughout the remaining 90 min. The accreted mound had a low slope and was rounded in cross section. The only other zone on the profile which changed to any extent occurred from 7.50 ft. to 10.80 ft. This portion of the profile was steadily degraded for the entire 180 min.

Analysis of Profiles for Test No. 2-B.

During 180 min. of Part B major changes took place on the profile from 10.80 ft. to 17.25 ft., as shown in Figure 12 (Appendix A). From 10.80 ft. to 15.00 ft. scour was evident during the entire 180 min. During the first 60 min., there was one scour hole migrating in the on-shore direction. This hole was steep sided and narrow. From 60 min. to 120 min., the scour hole had become shallower and wider. By the end of the 180 min., there were three separate scour holes on the profile. Two of the holes were separated from the third hole by a small accreted mound which was located from 12.00 ft. to 12.80 ft.

From 15.00 ft. to 17.25 ft. accretion took place during the entire 180 min. period. The largest portion of the accretion took place during the first 60 min. During this period, the accreted mound grew in the offshore direction and stayed rounded in cross section. From 60 min. to 180 min. the mound moved on-shore and the cross section became more elongated.

There are three basic differences in the final profiles for Part A and those for Part B of Test No. 2, (1) the region from 8.20 ft. to 10.80 ft. was stable in the B part of the test, (2) the scoured area was flatter and shallower in Part B., and (3) the accreted portion of the profile had a higher elevation and was located farther in-shore in Part B.

Analysis of Profiles for Test No. 3-A

Major changes took place on the profile in the zone from 7.00 ft. to 17.25 ft., as shown in Figure 13 (Appendix A). In the first 20 min., a scour hole had developed in the zone from 8.50 ft. to 13.40 ft. This scour had two broad, shallow troughs separated by a low ridge. At 40 min. the on-shore trough was shallower and the ridge had disappeared. The off-shore trough was deeper and wider. At 60 min. the on-shore trough had become the on-shore side of an enlarged off-shore trough. The off-shore trough then completely covered the zone from 8.50 ft. to 13.40 ft. At 90 min. the large trough had continued to enlarge while its on-shore side had moved in the off-shore direction. The trend apparent at 90 min. continued for the remaining 90 min. of the run.

In the zone from 13.40 ft. to 17.25 ft. an accreted mound appeared in the first 20 min. The sides of the mound had low slopes and the mound itself had an elliptical cross section. At 40 min. the elevation of the mound was higher while the cross section remained similar to what it had been at 20 min. At 60 min., the off-shore side of the mound was steeper. The top of the mound had a higher elevation and had a more rounded cross section. From 60 min. to 180 min. the mound continued to gain elevation while the slope of the off-shore side remained almost constant. Some changes did occur in the profile in the zone from 0.00 feet to 6.00 feet. These changes indicated significant sediment movement was taking place although there was no definite trend in the movement.

Analysis of Profiles for Test No. 3-B

Major changes took place on the profile from 9.25 ft. to 17.25 ft. In the first 20 min., a shallow and wide scour hole developed in zone from 9.25 ft. to 14.00 ft., as shown in Figure 13 (Appendix A). It was composed of two shallow troughs separated by a low ridge. At 40 min., the on-shore trough had become part of the deepened off-shore trough. From 40 min. to 120 min. the scour hole remained the same. At the end of 180 min., however, the bottom of the scour hole had widened and the slope of the on-shore side had gotten much steeper.

In the zone from 14.00 ft. to 17.25 ft. an accreted mound appeared in the first 20 min. The off-shore side of the mound had a steep slope and the top of the mound was horizontal. From 20 min. to 120 min., the off-shore side of the mound maintained the same slope while the top of the mound continued to gain elevation. During this period the top of the mound became more rounded in cross section. At the end of 180 min.; however, the slope of the off-shore side had decreased and the top of the mound had been moved farther in-shore. Some other significant changes did take place on the profile in the zone from 2.40 ft. to 7.96 ft. In the zone from 2.40 ft. to 4.80 ft. a secondary scour hole formed. This scour hole was narrow and shallow. An accreted mound formed in the zone 4.80 ft. to 7.95 ft. The sides of the mound had low slopes and the top of the mound had a low elevation.

There are four basic differences between Part A and Part B of this test, (1) the scour hole was narrower with steeper sides in Part B., (2) the accreted mound had steeper sides and was set farther in-shore. (Also, the accreted mound initially built up more rapidly in Part B), (3) the zone from 8.20 ft. to 9.25 ft. was stabilized in Part B., and (4) there was the formation of a secondary off-shore scour hole and accretion mound in Part B.

Analysis of Profiles for Test No. 4-A

Major changes took place on the profile from 0.90 ft. to 17.25 ft., as shown in Figure 14 (Appendix A). Three scour holes appeared in the first 20 min. in the zone from 0.90 ft. to 7.40 ft. The scour hole in the zone from 0.90 ft. to 2.00 ft. was very shallow compared to its width. It was separated from the nearest on-shore scour hole by a narrow sharp ridge. This next scour hole was narrow with steep sides. The fartherest on-shore scour hole was the widest of the three holes. This hole was shallow with low sloping sides. At 40 min. all three holes were enlarged. The center hole, (the only hole to change its general shape), was a much wider bottom with more gently sloping sides. At 60 min., the three scour holes had merged to form two larger holes, covering a zone from 1.20 ft. to 7.10 ft. These two holes were deeper and wider than any of the preceeding holes. At 90 min. the two holes had merged to form one wide slightly deeper hole. At 120 min. two scour holes, were in the same zone as the two holes evident on the 60 min. profile. These two holes had very flat bottoms and were deeper than any of the previous holes . At 180 min. only one large scour hole was evident in the zone from 1.00 ft. to 7.00 ft. This hole was deeper than all preceeding holes.

After 20 min. an accreted mound appeared in the zone from 7.40 ft. to 8.40 ft. The mound had a flat top, while the slope of the on-shore side of the mound was much steeper than the slope of the off-shore side. At 180 min. this mound had the same general shape but it was taller and both sides had expanded covering a zone from 7.00 ft. to 8.60 ft. After 20 min. a scour hole appeared in the zone from 8.40 ft. to 9.60 ft. This hole was narrow and deep with steep sides. At 40 min., the hole was shallower and narrower with a flat bottom. At 60 min., the hole had been deepened and widened. The sides at this point were very steep. This hole stayed the same for the next 60 min. At 180 min. the scour hole was much shallower. The sides of the hole had the same slope that they did in the 60 min. profile but the bottom had gotten wider and flatter.

In the first 20 min., and accreted mound formed in the zone from 9.60 ft. to 13.75 ft. The general shape of the mound stayed the same but the elevation of the top of the mound flucturated up and down for the next 100 min. At 180 min. there were two distinct mounds in this zone. One very narrow mound which extended from 9.50 to 10.25 ft. and one much larger mound which extended form 10.25 ft. to 13.00 ft.

During the first 20 min. a small scour hole appeared in the zone from 13.75 ft. to 15.00 ft. This hole maintained about the same shape but during the 180 min. it shifted in the off-shore direction. At 180 min., the scour hole was located in a zone from 13.00 ft. to 14.40 ft. During the first twenty min. a small accreted mound appeared in the zone from 15.00 ft. to 16.70 ft. The mound kept its general shape but continued to grow taller and wider so that at 180 min. the mound covered a zone from 14.40 ft. to 17.25 ft.

Analysis of Profiles for Test No. 4-B

Major changes took place over the entire length of the profile during this part of this test, as shown in Figure 14 (Appendix A). In the first 20 minutes of the test, an accretion mound formed in the zone from 0.00 ft. to 1.40 ft. At 40 min., the mound had risen to a higher elevation and expanded to cover the zone from 0.00 ft. to 2.00 ft. From 40 min. to 180 min., the on-shore side of the mound gained elevation and the off-shore side moved off-shore. At 180 min. the mound covered the zone from 0.00 ft. to 1.30 ft.

In the first 20 min., of the test two adjacent scour holes formed covering the zone from 3.80 ft. to 8.60 ft. The smaller scour hole covered a zone from 3.80 feet to 5.40 feet. This scour hole was narrow and shallow and had gently sloping sides. The larger scour hole covered a zone from 5.40 ft. to 8.60 ft. This hole was wide and deep with gently sloping sides. At 40 min., the smaller hole was smaller and farther off-shore covering a zone from 3.50 ft. to 4.50 ft. The larger hole deepened and expanded covering a zone from 4.50 ft. to 8.95 ft. At 60 min., the large hole and the small hole had merged to form one very large scour hole covering a zone from 3.20 ft. to 8.90 ft. For the remaining 120 min., this large hole expanded and deepened, so that at 180 min. the hole covered a zone from 1.3 ft. to 9.7 ft.

After 40 min., a scour hole had developed covering a zone from 9.95 feet to 11.50 feet. The hole was narrow with steep sides. At 60 min., the scour hole had the same shape but had deepened and widened covering a zone from 9.80 ft. to 12.00 ft. At 90 min., the hole had become shallower and looked much the same as the scour hole that appeared on the 40 min. profile except that the on-shore side of the hole had a more gentle slope. At 120 min., the hole had deepened or shifted in the on-shore direction covering a zone from 10.30 ft. to 11.6 ft. The sides of the hole were very steep.

At 20 min., two accreted mounds appeared in the zone from 11.3 ft. to 17.75 ft. The larger of the two mounds had very gently sloping sides while the smaller of the two mounds had steep sides with a pointed top. The two mounds were separated by a small scour hole covering a zone from 15.05 ft. to 15.85 ft. At 40 min., the two mounds had expanded and merged together to form one large mound with a slight dip in the middle. Both sides of this new large mound had low slopes. At 60 min., the off-shore half of the mound was lower while the upper portion was higher with a rounded top. For the remaining 120 min. of the off-shore half continued to get lower while the back side of the on-shore half of the zone continued to get higher.

There were five basic differences between the two parts of this test, (1) an accreted mound formed in the zone from 0.00 ft. to 1.30 ft. in Part B., (2) the scour hole was wider in Part B., (3) the accreted mound which formed in Part A in the zone from 7.00 ft. to 8.60 ft. had a much lower elevation in Part B., (4) the scour hole which covered a zone from 8.60 ft. to 9.50 ft. in Part A, was larger in Part B., and (5) the accreted berm on the foreshore was much larger and farther in-shore in Part B. (The sides of the mound in Part B were also much steeper),

Analysis of Normalized Profiles for Test No. 1-A

In this part of the test there were two large deviations from the initial profiles, as shown in Figure 15 (Appendix B). There was a scour hole which covered a zone from 7.75 ft. to 12.20 ft. and an accreted mound which covered a zone from 12.20 ft. to 16.75 ft. The scour hole had a maximum negative deviation from the initial profile of 0.21 feet. The accretion mound had a positive maximum deviation from the initial profile of 0.29 ft. There were some changes taking place in the zone from 3.00 ft. to 7.75 ft., but these changes were temporary and did not develop into a trend.

Analysis of Normalized Profiles for Test No. 1-B

In this part of the test there were two large deviations and two smaller deviations from the initial profile, as shown in Figure 16 (Appendix B). There was a large scour hole which covered the zone from 10.00 ft. to 14.00 ft. This scour hole had a maximum negative deviation of 0.17 ft. There was a large accreted mound which covered a zone from 14.00 ft. to 17.25 ft. This mound had a maximum positive deviation of 0.48 feet. There was a small accreted mound which formed in the zone from 5.00 ft. to 6.70 ft. This mound had a maximum positive deviation of 0.10 ft. A small scour hole appeared in the zone from 3.20 ft. to 5.00 ft. This scour hole had a maximum negative deviation of 0.05 ft. This hole became shallower at the end of 180 min. and had only a maximum negative deviation of 0.03 feet.

There were four basic differences between Part A and Part B of this test, (1) the large accreted mound had a higher maximum deviation by 0.19 ft. in Part B, (2) the large scour hole had a lower maximum deviation by 0.04 ft. in Part B, (3) the zone from 9.50 ft. to 10.00 ft. was not scoured in Part B, and (4) the point at 9.70 ft. was 0.14 ft. higher in Part B.

Analysis of Normalized Profiles for Test No. 2-A

In this part of the test there were two major scour holes and one major accreted mound formed on the beach profile, as shown in Figure 17

(Appendix B). The largest scour hole covered the zone from 5.70 ft. to 10.30 ft. This hole had a maximum negative deviation of 0.14 ft. The smaller scour hole covered the zone from 11.60 ft. to 13.00 ft. It had a maximum negative deviation of 0.17 ft. The accreted mound covered a zone from 13.00 ft. to 16.60 ft. This mound had a maximum positive deviation of 0.18 ft. One small accreted mound formed in the zone from 10.30 ft. to 11.60 ft. This mound had a maximum positive deviation of 0.07 ft.

Analysis of Normalized Profiles for Test No. 2-B

In this part of the test two major scour holes and one major accreted mound formed on the beach profile as shown in Figure 18 (Appendix B). The largest scour hole covered the zone from 5.10 ft. to 10.00 ft. This hole had a maximum negative deviation of 0.08 ft. which had occurred by the end of 120 min. The maximum negative at the end of 180 min., however, was 0.07 ft. The smaller scour hole covered the zone from 12.80 ft. to 15.00 ft. It had a maximum negative deviation of 0.12 ft. which occurred at the end of 60 min. The maximum negative deviation at the end of 180 min. was 0.09 ft.

The accreted mound covered the zone from 15.00 ft. to 17.25 ft. This mound had a maximum positive deviation of 0.25 ft. which had occurred by the end of 120 min. The maximum positive deviation at the end of 180 min. was 0.24 ft.

There are four basic differences between Part A and Part B of this test, (1) the accreted mound had a greater maximum positive deviation of 0.07 ft. in Part B., (2) the large scour hole had a smaller maximum negative of 0.07 ft. in Part B., (3) the smaller scour hole had a smaller maximum negative deviation of 0.08 ft. in Part B and (4) the point of maximum negative deviation for the large scour hole occurred at 8.75 ft. in Part A but in Part B the point of maximum negative deviation for this hole fell outside the filtered zone at 7.75 ft. This means the changes in depth of the point at 8.75 ft. in Part B was from 0.04 ft. to 0.14 ft., a difference of 0.10 ft.

Analysis of Normalized Profiles for Test No. 3-A

In this part of the test there were two large deviations from the initial profile, as shown in Figure 19 (Appendix B). There was a large scour hole which covered the zone from 6.40 ft. to 12.00 ft. and a large accreted mound which covered the zone 12.00 ft. to 17.25 ft. The scour hole had a maximum negative deviation of 0.03 ft. The accreted mound had a maximum positive deviation of 0.43 ft. There were some small deviations in the zone from 0.00 ft. to 6.40 ft. but these deviations were all under 0.07 ft. except the point at 4.50 ft. at 120 min., which had an elevation of 0.075 ft.

Analysis of Normalized Profiles for Test No. 3-B

In this part of the test two accreted mounds and two scour holes were formed on the profile of the beach, as shown in Figure 20 (Appendix B). The largest scour hole covered a zone from 9.25 ft. to 13.90 ft. and had a maximum negative deviation of 0.30 ft. The smaller scour hole covered the zone from 2.40 ft. to 4.80 ft. and had a maximum negative deviation of 0.23 ft. which had occurred by the end of 120 min. By the end of 180 min., the maximum negative deviation had decreased to 0.12 ft. The largest accreted mound covered the zone from 13.90 ft. to 17.25 ft. and had a maximum positive deviation of 0.52 ft. which had occurred by the end of 120 min. By the end of the 180 min., the maximum positive deviation had decreased to 0.43 ft. The smaller accreted mound covered the zone from 4.80 ft. to 7.90 ft. and had a maximum positive deviation of 0.12 ft.

There are three basic differences between Part A and Part B of this test, (1) the scour hole was smaller in Part B. The maximum depth was the same in both parts but the maximum deviation occurred 1.50 ft. further on-shore in Part B. The four points off-shore of the maximum deviation Part A have a much larger deviation than the comparable same four points in Part B. For instance the point at 9.75 ft. in Part A was 0.13 ft. farther from the original profile than the point at 11.25 ft. in Part B., (2) the point of maximum positive deviation on the large accreted mound was farther on-shore in Part B. The point was at 16.25 ft. in Part A and 17.25 ft. in Part B. This point, however, does have the same maximum deviation from the initial profile, (3) the smaller scour hole and the smaller accreted mound are appreciably bigger in Part B., than the small oscillating deviations that took place in the same zone in Part A.

Analysis of Normalized Profiles for Test No. 4-A

In this part of the test two major scour holes and three major accretion mounds formed on the profile of the beach, as shown in Figure 21 (Appendix B). The larger scour hole covered the zone from 1.00 ft. to 7.00 ft. and had a maximum negative deviation of 0.24 ft. The smaller scour hole covered the zone from 8.60 ft. to 9.50 ft. and had a maximum negative deviation of 0.14 ft., which had occurred by the end of 60 min. At the end of 180 min. the maximum negative deviation had decreased to 0.05 ft. The large accretion mound covered the zone from 9.50 ft. to 13.00 ft. and had a maximum positive deviation of 0.12 ft. which had occurred by the end of 120 min. At the end of 180 min., the maximum deviation had decreased to 0.09 ft. The next largest scour hole covered the zone from 14.40 ft. to 17.25 ft. and had a maximum positive deviation of 0.08 ft. The smallest accreted mound covered the zone from 7.00 ft. to 18.60 ft. and had a maximum positive deviation of 0.12 ft.

Analysis of Normalized Profiles for Test No. 4-B

In this part of the test two major scour holes and two major accretion mounds formed on the profile as shown in Figure 22 (Appendix B). The largest scour hole covered the zone from 1.30 ft. to 9.60 ft. and had a maximum negative deviation of 0.16 ft. which occurred by the end of 120 min. At the end of 180 min., the maximum deviation had decreased to 0.12 ft. The large accreted mound covered the zone from 11.90 ft. to 17.25 ft. and had a maximum positive deviation of 0.29 ft. The smaller accreted mound covered the zone from 0.00 ft. to 1.30 ft. and had a maximum positive deviation of 0.24 ft.

There are three basic differences between the profiles in Part A and the profiles in Part B., (1) the large scour hole in Part B had a larger negative deviation by 0.12 ft. (2) the accreted mounds evident on the foreshore in Part A appeared as one large mound in Part B. This large mound in Part B had a higher positive deviation by 0.15 feet. (3) The accreted mound which appeared on the toe of the beach in Part B had a higher positive deviation by 0.23 ft. than the small mound which appeared on the toe of the beach in Part A.

Analysis of the Plots of the Sediment Movement Trends

Sediment movement trends were determined by taking the profile deviations, squaring the deviations, and then summing the deviations over the length of the zone of interest on the profile. The filters covered the zone from 8.20 ft. to 17.25 ft. This zone covered a section of saturated sand from 8.20 ft. to 13.25 ft. and a section of partially saturated sand from 13.75 ft. to 17.25 ft. Therefore, to determine the effect the filters had on the trends of sediment movement in each of these two sections, the sum of the squared deviations for each section was plotted versus the length of time into the test, as shown in Figure 23 through 30 (Appendix C).

Analysis of the plots of the sediment movement trends in the saturated section. Test Nos. 1 and 2 the sums of the squared deviations were small throughout Part B., as shown in Figures 23 and 24 (Appendix C). The smaller squared deviations indicated that, during filter operation, the saturated section of the beach was move stable. In Test No. 3, the sums of the squared deviations were smaller for the last 130 min. of Part B., as shown in Figure 25 (Appendix C). This indicated that, when the filters were operating, the saturated section of the beach, was more stable, (even though initially the unfiltered beach section was slightly more stable). In Test No. 4, the sums of the squared deviations were smaller for the first 60 min. of Part B., as shown in Figure 26 (Appendix C). This indicated that, when the filters were operating, the saturated section of the beach was less stable than the unfiltered beach section.

These plots show that the saturated section of the beach was more stable with the filters operating in all the tests except Test No. 4, where the breaker scour occurred outside of the filtered section.

Analysis of the plots of the sediment movement trends in the partially saturated section. In Test Nos. 1, 2, and 4, the sums of the squared deviations were larger throughout Part B, as shown in Figures 27, 28, and 30 (Appendix C) also refer to Figures 15 through 22 (Appendix B). This indicated that the amount of accretion on the partially saturated fore-shore zone was much larger when the filters were operating. The initial slopes of curves were steeper in Part B of these three tests which indicated that the rate at which the accretion took place was much faster when the filters were operating. In Test No. 3., the sumes of the squared deviations were larger for the first 160 min., of Part B., as shown in Figure 29 (Appendix C). This indicated that the amount of accretion on the fore-shore was larger when the filters were operating until the last 20 min. of the test when the accreted berm began to be degraded. The initial slope of the curve for Part B was steeper than the initial slope of the curve for Part A. This indicated that rate at which the accretion was taking place in this section was greatest in Part B.

These plots show that accretion took place on the partially saturated section at a greater rate and in larger amounts when the filters were operating.

RESULTS OF TESTS

Since the filters covered only the zone from 8.20 ft. to 17.25 ft., it is necessary to compare the changes which took place on the profiles in the A part and the B part of each test in this zone.

Test No. 1

The scour hole and the accreted mound were both situated further onshore in Part B. The accreted mound had a higher elevation of 0.19 ft. and the scour hole was shallower by 0.04 ft. in Part B. The zone from 9.00 ft. to 10.20 ft. which was scoured in Part A, was stabilized in Part B. The zone from 9.00 ft. to 10.20 ft. lay at the off-shore edge of breaker zone and formed part of the large breaker scour hole in Part A (See Figure 11).

Test No. 2

The large accreted mound and the smaller scour hole were farther inshore in Part B. The large accreted mound had a higher elevation of 0.07 ft. and the smaller scour hole was shallower by 0.08 ft. in Part B. The larger scour hole was situated farther off-shore and was shallower by 0.07 feet in Part B. The zone from 8.20 ft. to 10.20 ft., which was part of the large scour hole in Part A, was stabilized in Part B. This zone lay at the off-shore edge of the breaker zone. (See Figure 12).

Test No. 3

The accreted mound had the same final elevation in Part A and B, but the slope of sides of the mound were steeper in Part B. After 90 min., however, the accreted mound in Part B had a higher than the final mound by 0.09 ft. The scour hole had the same maximum depth in Part A and B, but the bottom of the hole was narrower and farther on-shore in Part B. The zone from 8.20 ft. to 9.25 ft. was stabilized in Part B. This zone was at the off-shore edge of the breaker zone. (See Figure 13).

Test No. 4

The large accreted mound in Part B took the place of the three smaller accreted mounds in Part A. The single large mound had a higher elevation than the three smaller accreted mounds in Part A. The single large mound had a higher elevation than the three small mounds by 0.015 ft. The large scour hole, which was on the toe of the beach in Part A, was situated farther up on the beach in Part B. The scour hole had its on-shore edge protruding into the filtered zone and was deeper by 0.12 feet in Part B. The breaker scour hole was deeper in Part B by 0.07 ft. (See Figure 14).

Physical Observations

Several common events took place in the wave tank during the filtered portion of all four tests which did not show up in the data, and are reviewed in the following discussion.

Severe scour took place on the valve side of the header in the zone off-shore of the breaker zone. During the filtered portion of the tests the filters were never exposed even under the steepest wave, but the valve side of the header was scoured so severely at times that the top half of the main header pipe was exposed. If a profile were taken across the width of the tank, it would have shown an almost vertical rise when passing from the valve side of the header, over the edge of the filtered section. As soon as the pump was turned off at the end of the test this vertical wall collapsed, and the sand from the filtered side slid down into the scoured section. This indicated that the filters had an effect on the sand directly above them but no lateral effect on the sand surrounding them. During the non-filtered portion of all the tests the scour was never as deep as it was on the header side during the filtered part. The scouring was uniform across the width of the tank during the unfiltered portion of the tests.

There were not any scour pockets formed between the filters along the length of the header system. This indicated an overlapping of the effect of the filters on 6 in. centers.

During the filtered portion of all the tests there was almost no back-rush from the waves. The wave would break and rush up the beach, but by the time the back-rush started almost all of the thin wedge of up-rush water had been absorbed into the beach. This elimination of the back-rush very effectively trapped the sediment that came up the beach with the up-rush. The filter system kept this portion of the beach partially saturated except when it was completely covered with wave up-rush. Since the entire width of the beach was partially saturated, the water from the wave up-rush flowed evenly into the beach. This effectively trapped the sediment across the width of the beach without giving the localized filter effect that the off-shore zone experienced. One problem which did result from pumping through a partially saturated sand medium was a large intake of air through the beach, which tended to air lock the pump. The air locking was partially eliminated by the inclusion of the free water intake at off-shore end of the header. This free water intake, however, lowered the pumping head in the filters and thus their effectiveness.

Filter Effect on Three Beach Zones

Since the effect of the filters was not uniform over the entire length of the beach, it is necessary in the following discussion to look at the three basic zones of the beach and discuss the effect the filters had on each zone. The three zones are the off-shore zone, the breaker zone, and the fore-shore zone, as shown in Figure 4.

Off-Shore Zone

In the off-shore zone, the filters tended to stabilize the sand directly above them in Tests Nos. 1-3. They did not completely stop the sand from moving but they did minimize the amount that moved out of the filtered portion of this zone. By stabilizing the filtered portion of the off-shore zone, the filters moved the formation of the breaker scour in the on-shore direction. In these three tests the sand over the valve system and main header pipe was scoured very severly in this zone. This indicated that the filters have effect only on the sand around the diameter of the filter section; therefore, the filters actually encouraged scour in lateral unfiltered areas. In Test No. 4., the filters had no effect in stabilizing the off-shore zone, where the breaker scour occured out of the filtered section. In Part B of Test No. 4, the off-shore scour hole was much deeper, wider, and farther on-shore than in Part A.

There is a very good reason for the limited effect of the filters in this zone. The sand during all tests was completely saturated; thus enabling the filter to draw water from the sand around the entire circumference of the pipe. The water that flowed toward the filter came from all directions in the sand bed, thus the vertical influx of water from the sand water interface was only a part of the total volume pumped in this area.

Breaker Zone

In the breaker zone the filters had some stabilizing effect in Test No. 1 and No. 2 The filter sections did not stop the breaker scour, but tended to decrease the depth of the scour. In Test No. 3., the filters had no effect in decreasing the depth of the scour hole, but they did make the bottom of the hole narrower. In Test No. 4., the filters had an adverse effect on the stability of the scour hole. The hole was deeper and wider under the influence of the filter system.

Fore-shore Zone

On the fore-shore the filters caused accretion in Tests No. 1-No. 4. This accretion was uniform across the width of the beach and was very rapid during the first hour of all four tests. The filters in this zone all lay above the still water level so the water entering the beach from this zone came from the sand surface from the wave up-rush. The filters were able to keep the sand in this area only partially saturated. This kept the sand absorbent enough to soak up the water from the wave up-rush. Since there was initially no back-rush from the wave, the sediment that came in with the up-rush stayed on the fore-shore. The accreted mound grew very rapidly initially, in Part B of all four tests, but as the mound gained higher elevation the filters were not as effective so some back-rush did occur toward the end of all four tests. The largest accretion took place in the first 60 min. in Part B of all four tests. After 60 min., the accretion rate on the fore-shore varied in the four tests. In Test No. 1-B, the accreted mound continued to grow for 120 min., but remained stable from 120 min. to 180 min. In Test No. 2-B, the accreted mound grew very little from 60 min. to 120 min., and from 120 min. to 180 min. It was degraded slightly. In Test No. 3-B, the mound grew slightly from 60 min. to 120 min., but was degraded rather heavily from 120 min. to 180 min. In Test No. 4., the mound grew steadily during 180 min. of the B part of the Test.

Instrument Error

Wave height measurement. Wave heights were determined by measuring the change in capacitance between an exposed ground lead and a thin insulated wire. Errors were introduced into the wave measurement by surface film on the insulated wire, miniscus effect, the disturbance of the wave form by the wave gauge, and wave reflection. Errors were also caused by thermal changes in the wiring, inertial effects of the mechanical plotter and pen drag. The total estimated error is ±0.02 ft. for the wave measurement.

Wave generation. It is extremely difficult to generate a uniform monochromatic wave. In this experiment certain errors were introduced into the wave generating mechanism which tended to introduce slight changes into the wave form. First, there was the variation of line voltage and the coarseness of the motor controls. Secondly, the discharge from the filter system, created a disturbance on the water's surface at the front edge of the wave generating section. Lastly, the wave reflection from the beach tended to vary the operating depth of the paddle.

Depth measurement. Depth measurements were made with two different instruments; an ultrasonic distance meter and a point gauge. Error was introduced into the reading of the ultrasonic distance meter primarily by suspended material. Error was introduced into the reading of the point gauge primarily by momentary scour around the foot of the gauge during the reading. The error for the combined system was ±0.01 ft.

Pumping rate. Teh pumping rate of the system was regulated by a large butter fly valve on the discharge side of the pump and by a gate valve at discharge end of each filter. Error were introduced into the control of this system by variations in sand depth and variations in the period of the wave. The pumping rate, while staying stable within ± 2 gpm for a given test would vary as much as 45 gpm from one test to the next with all valves completely open. (See Table 2).

Table-2 Pumping Rates.

Test No.	Pumping Rates in GPM
1	99
2	133
3	143
4	134

The pumping rates in Table 2 are the total volume flow rates of water which were pumped through the system. This pumping rate included the water that was taken in through the filters as well as through the free water intake. These pumping rates are, therefore, not indicative of the volume flow rate into the filter section.

SUMMARY AND CONCLUSIONS

Summary

A study of a sub-sand filtering system was conducted, (1) to determine the effectiveness of the system on stabilizing the off-shore profile, (2) to determine the effectiveness of the system on stabilizing the fore-shore profile and speeding accretion on the fore-shore during periods of natural accretion, and (3) to determine the effectiveness of the system on decreasing breaker scour.

Conclusions

The following conclusions were drawn from the research to determine the effectiveness of the sub-sand filtering system.

1. In the off-shore zone, the filters had a stabilizing effect on the material directly above them.
2. In the breaker zone, the filters had little effect on breaker scour except on the smallest waves under the present system.
3. In the fore-shore zone, the filters were a tremendous aid in speeding accretion. The filter system generated rapid and large accretion on the fore-shore. Therefore, the filter system was very effective for berm building or berm replacement.

Recommendations for Further Research

1. Develop a water removal system for sub-sand filters that is not subject to air locking.
2. Investigate the various designs of sub-sand filters to determine the most efficient design.
3. Develop an effective means of determining sub-sand fluid velocities, and or pressure measurement.
4. Investigate the effects of a simulated storm on a filter built berm.

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LIST OF SYMBOLS USED

Ss = specific gravity of solids

S = specific gravity of sea water

Ms = mass of solids

M = mass of displaced water

Ue = effective velocity at particle crest

Vs = velocity of sediment particle

Uo = potential flow velocities

C_1 = drag coefficient for form drag

C_2 = drag coefficient for surface drag

C_m&C_3 = drag coefficient for virtual mass

C_4 = drag coefficient for lift

F_L = lift force

F_R = reaction force

F_F = drag force

F_{VM} = virtual mass force

F_G = gravity force

F_s = surface drag force

F_P = pressure force

F_I = inertial force

F_{RR} = rolling friction force

F_D = viscous resistance force

D = particle diameter

g = gravitational acceleration

α = angle of bed slope

β = angle between viscous resistance force and beach slope

δ = thickness of the boundary layer

ε = coefficient of rolling friction

ϕ = angle of action of the reaction force

ρ = density of the fluid

APPENDICES

APPENDIX A--Profile Plots for Tests No. 1 through 4

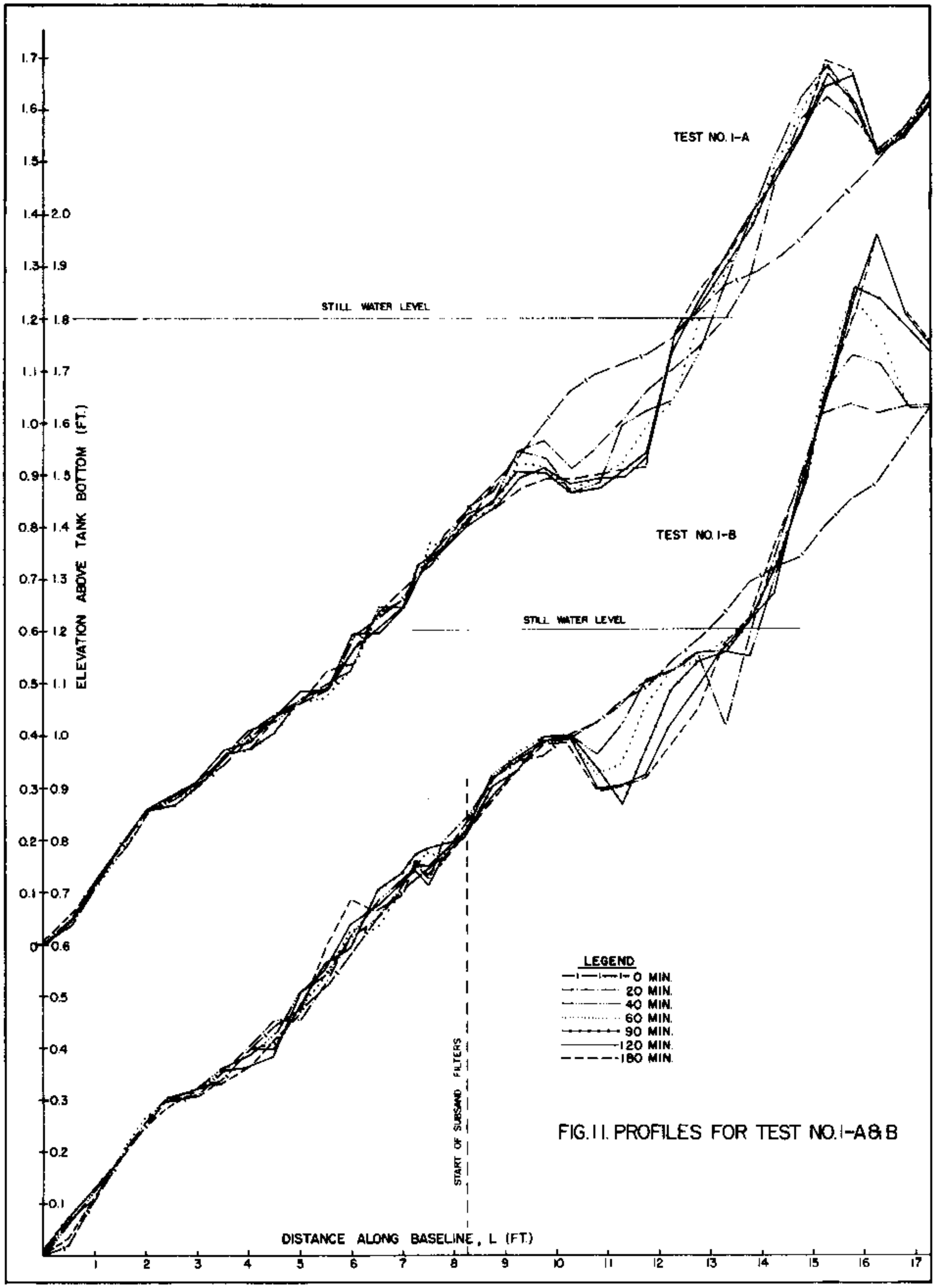

FIG. 11. PROFILES FOR TEST NO. 1-A & B

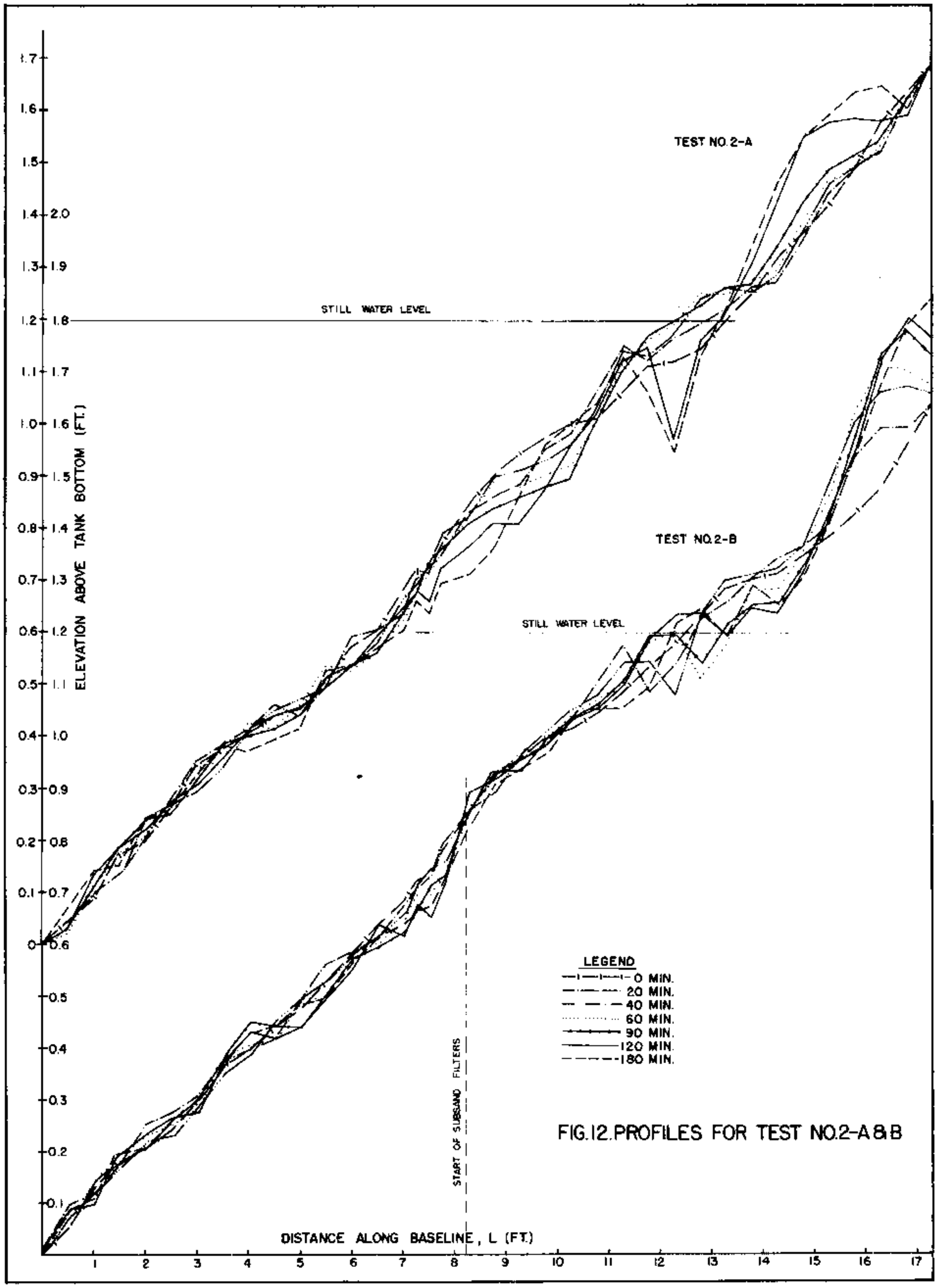

FIG.12. PROFILES FOR TEST NO.2-A & B

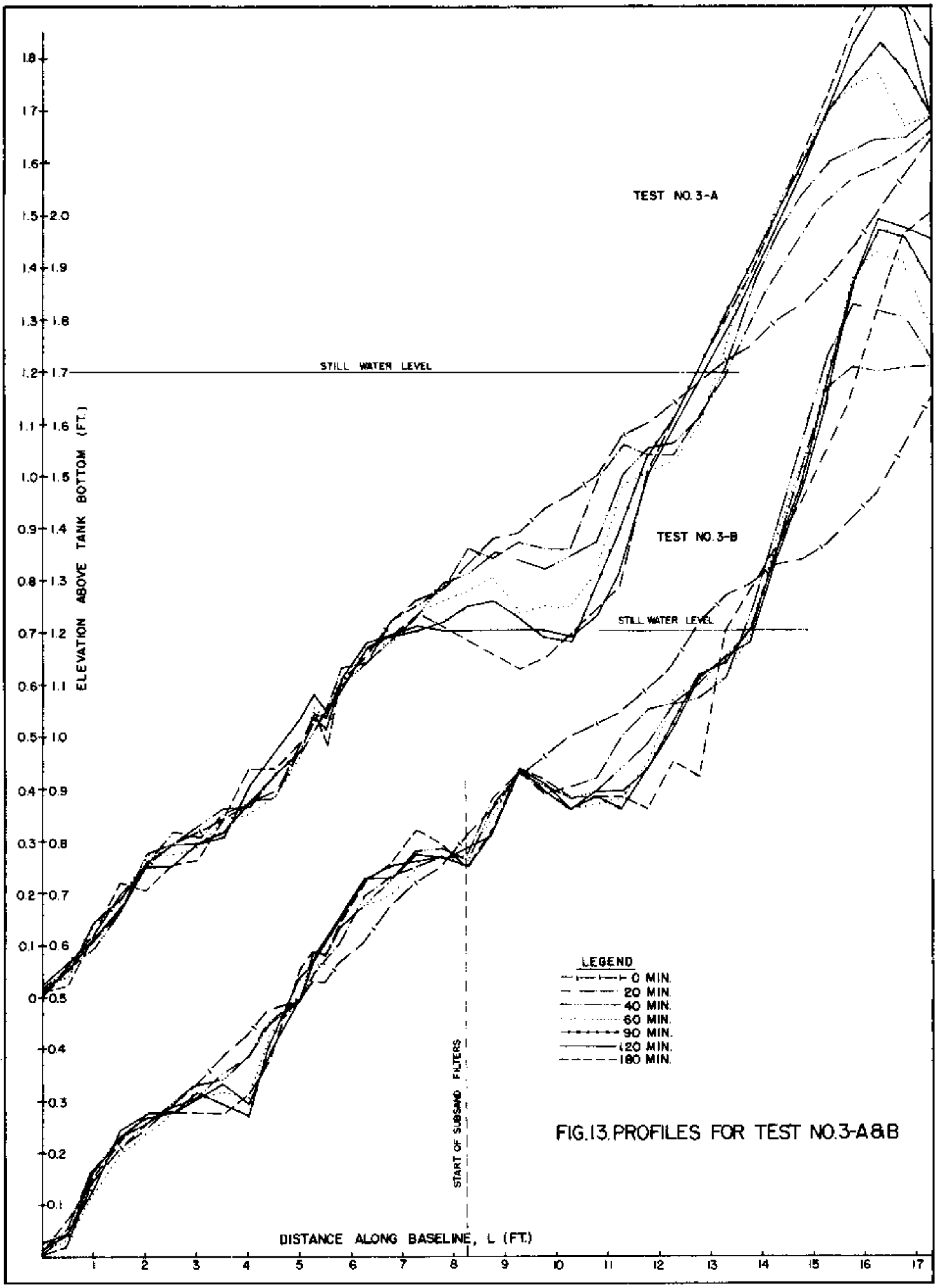

FIG. 13. PROFILES FOR TEST NO. 3-A & B

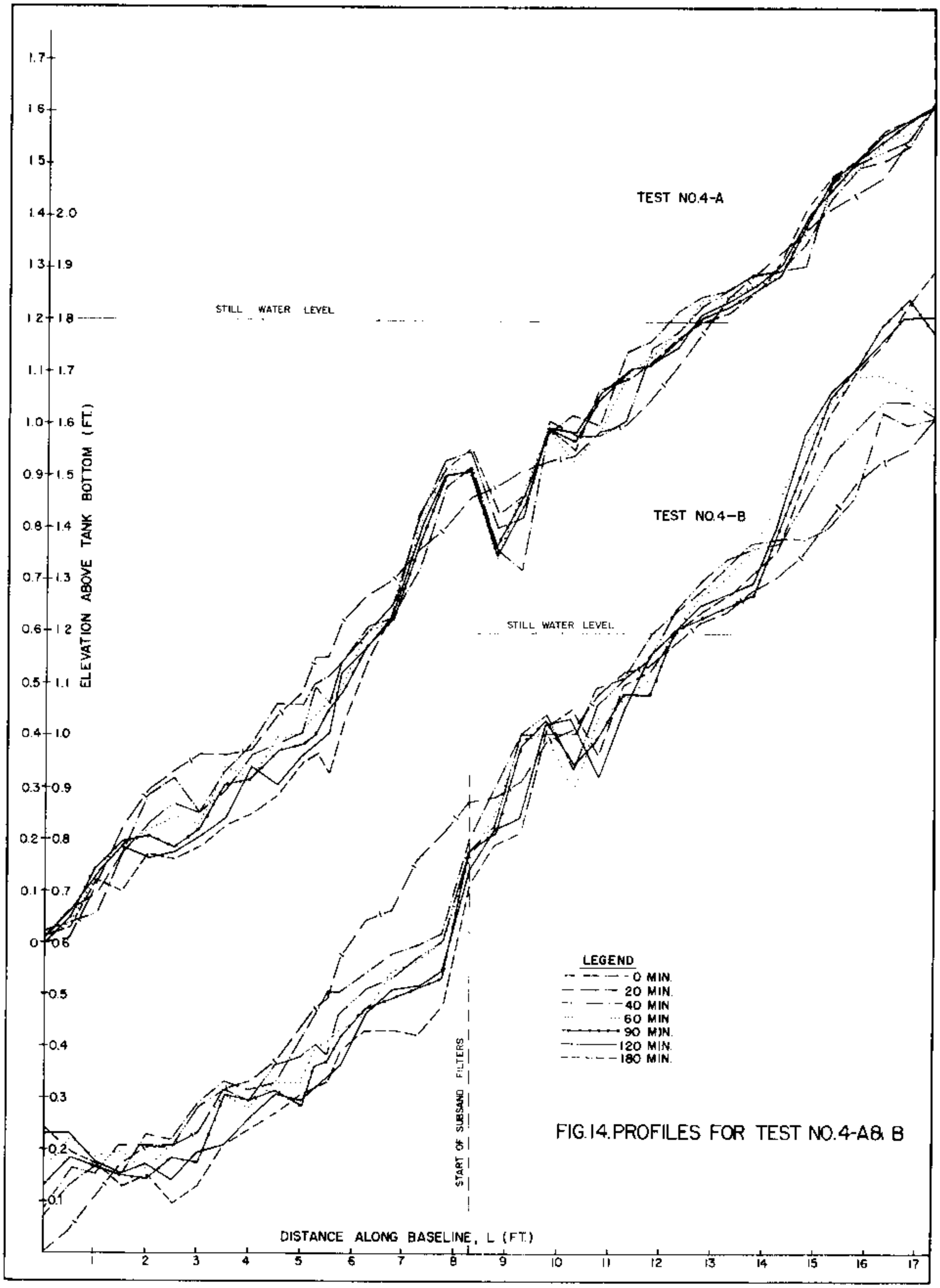

FIG.14.PROFILES FOR TEST NO.4-A& B

APPENDIX B--Normalized Profile Plots for Tests No. 1 through 4.

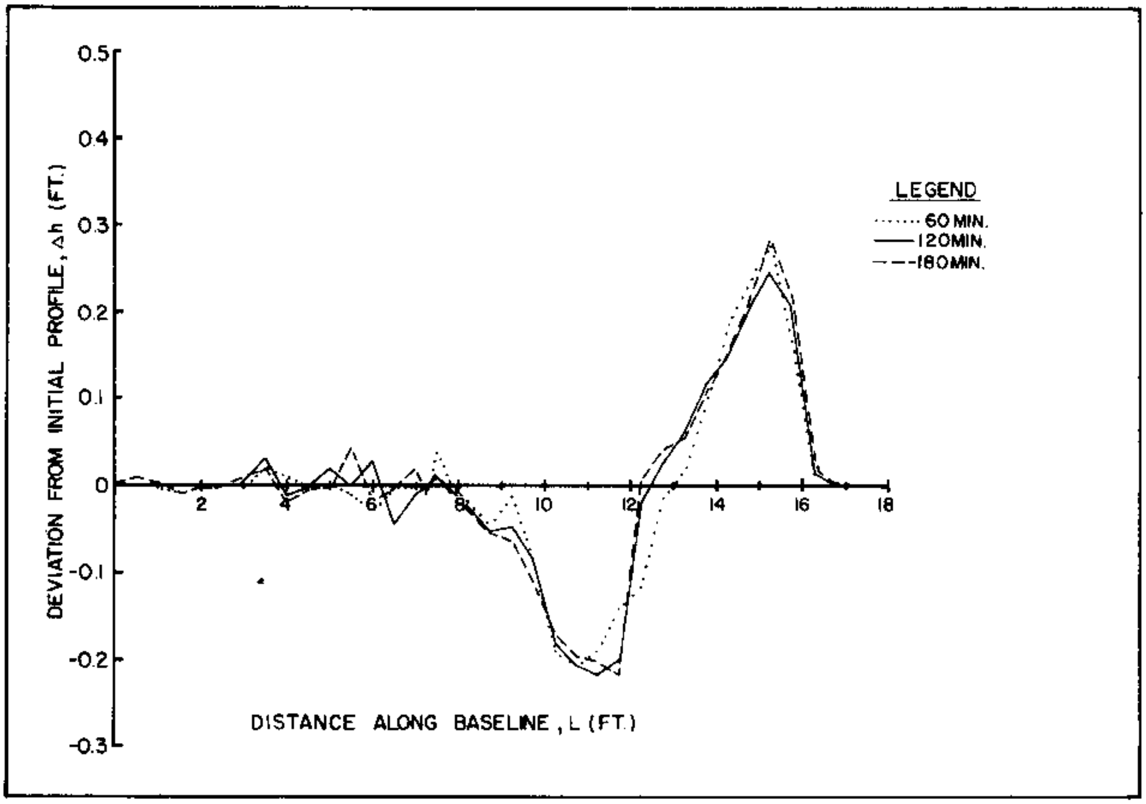

FIG. 15. NORMALIZED PROFILES FOR TEST NO. 1-A

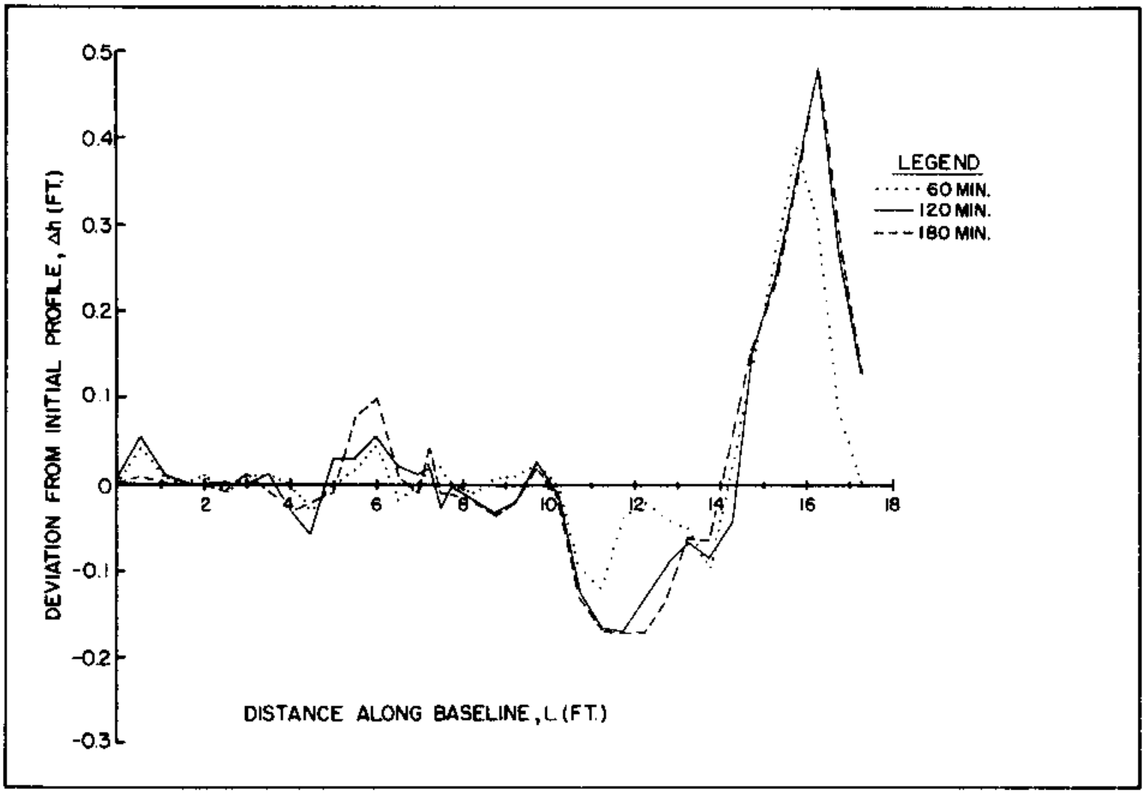

FIG. 16. NORMALIZED PROFILES FOR TEST NO. 1-B

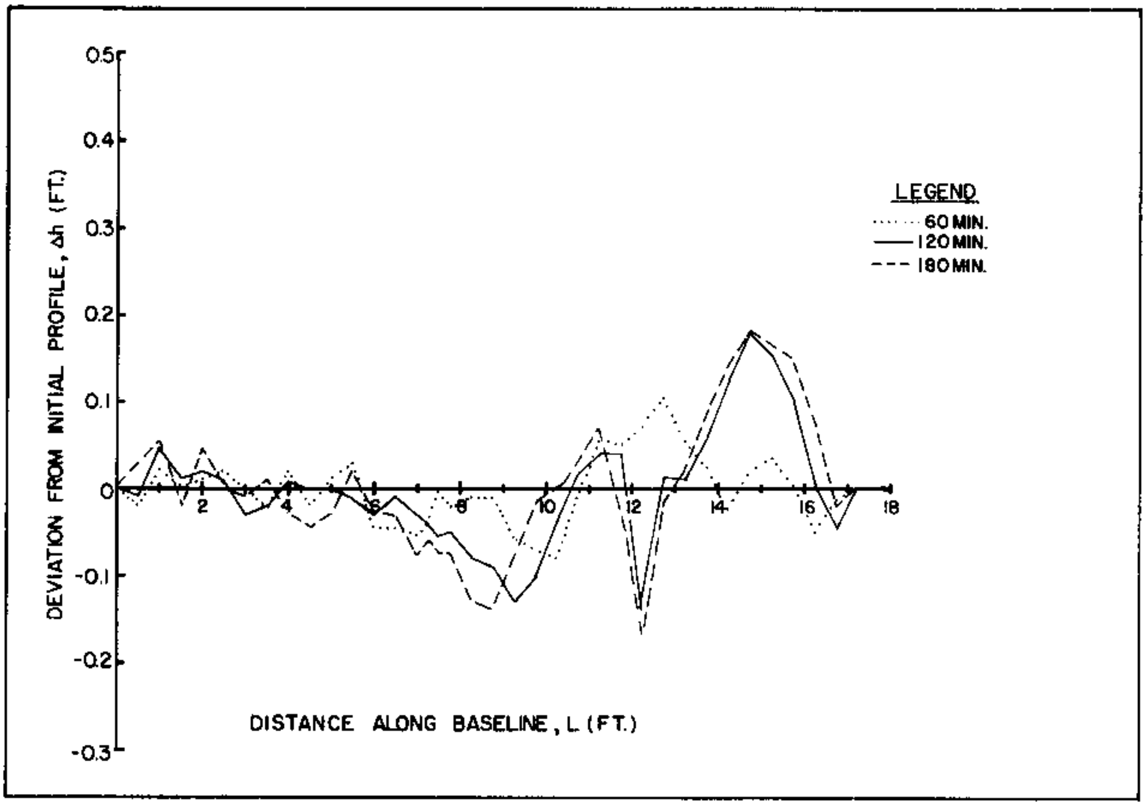

FIG. 17 NORMALIZED PROFILES FOR TEST NO. 2-A

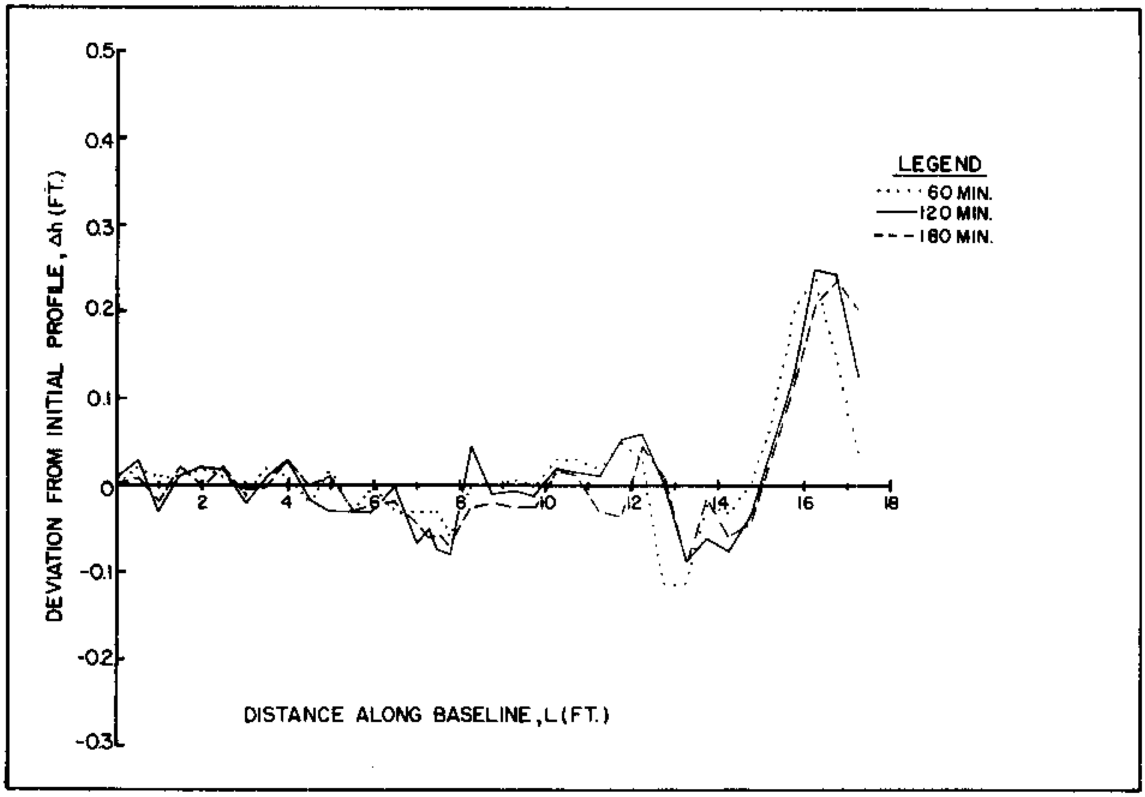

FIG. 18. NORMALIZED PROFILES FOR TEST NO. 2-B

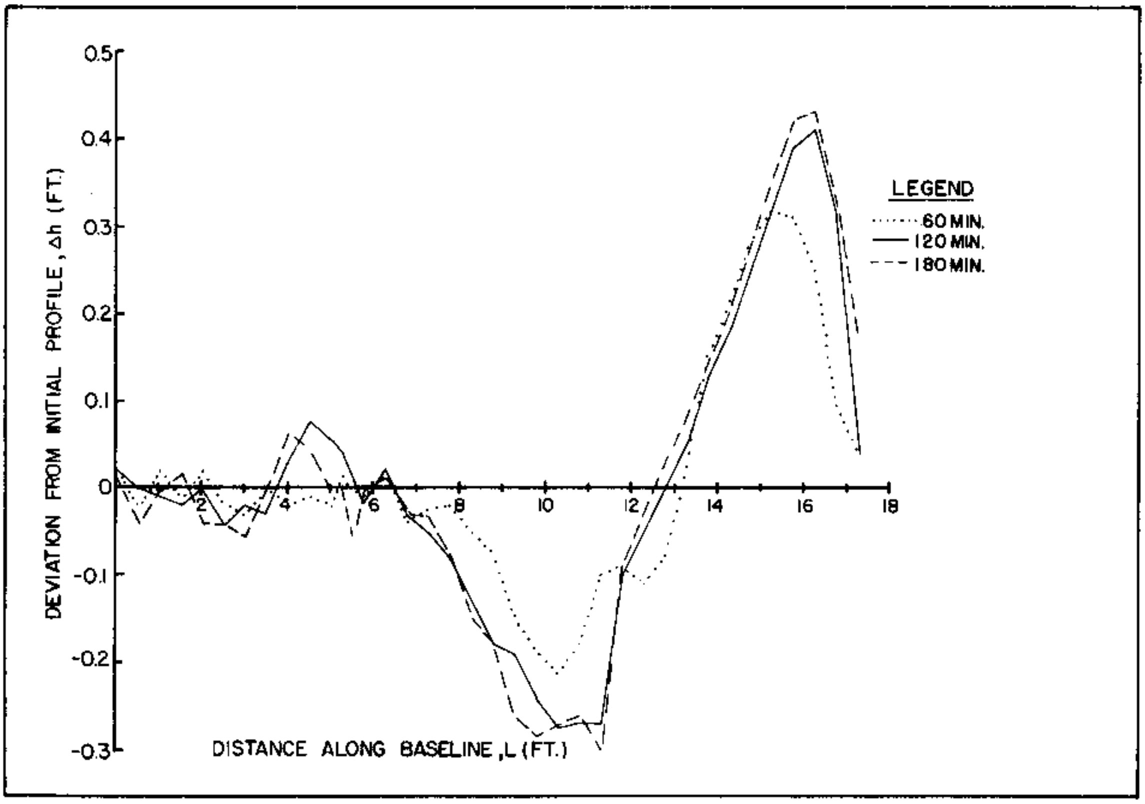

FIG. 19. NORMALIZED PROFILES FOR TEST NO.3-A

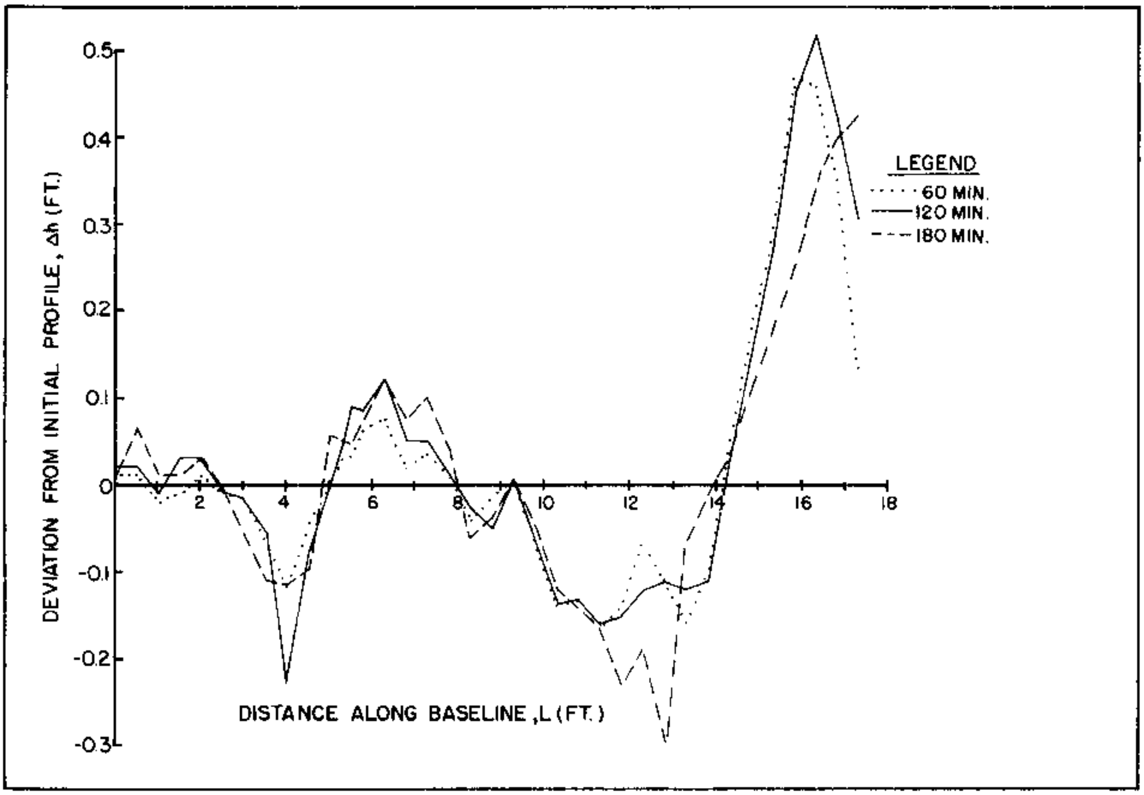

FIG. 20. NORMALIZED PROFILES FOR TEST NO. 3-B

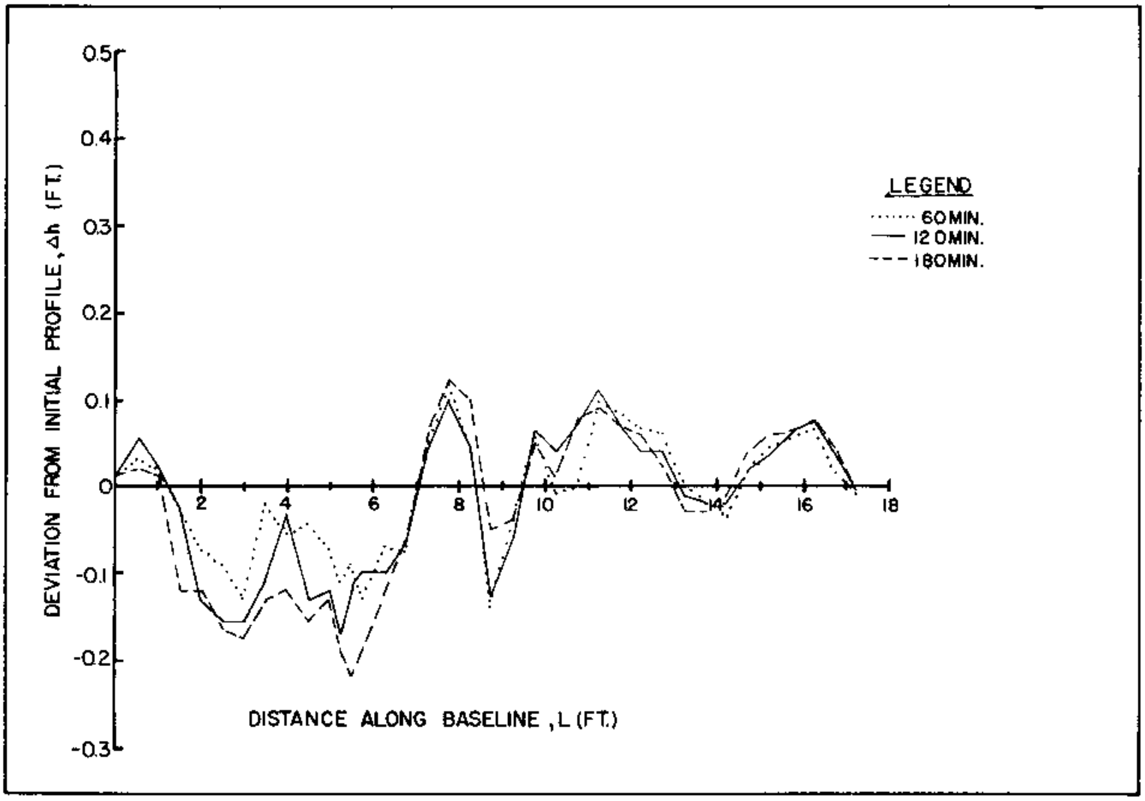

FIG. 21. NORMALIZED PROFILES FOR TEST NO. 4-A

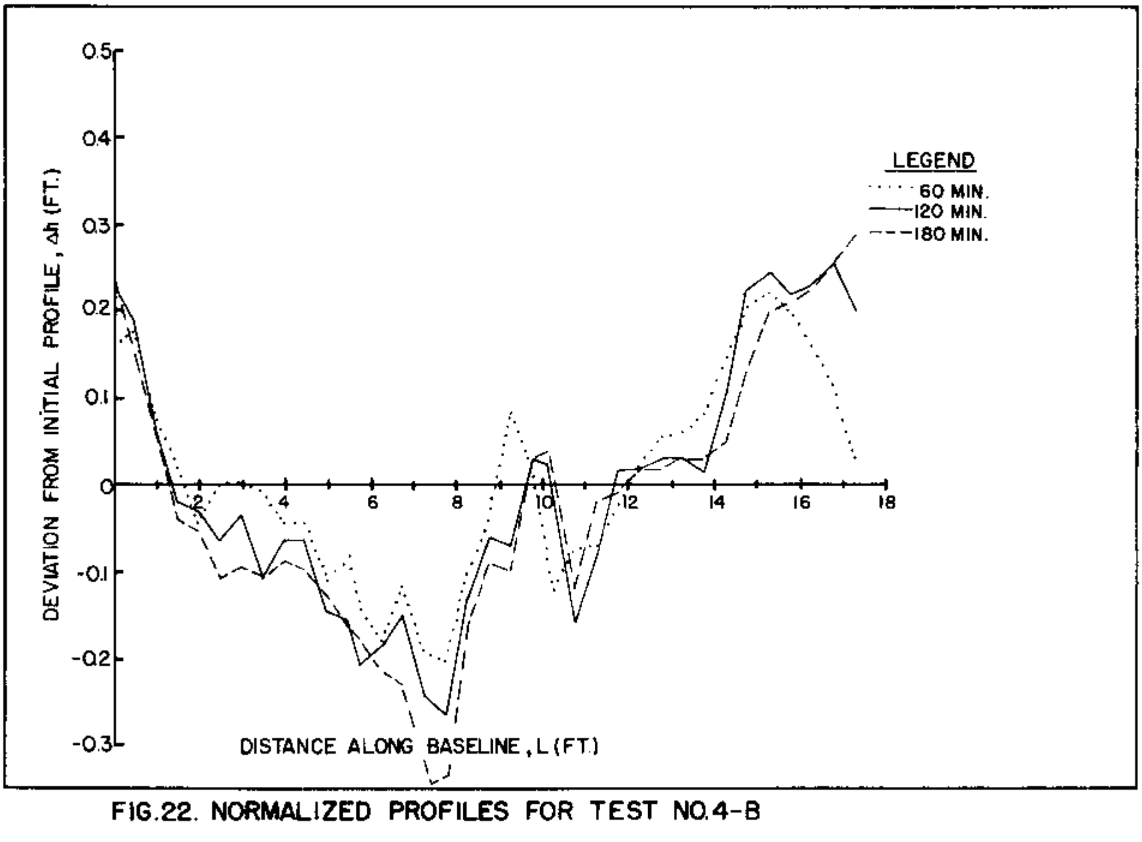

FIG. 22. NORMALIZED PROFILES FOR TEST NO. 4-B

APPENDIX C--Sediment Movement Trend Plots for Tests No. 1 through 4.

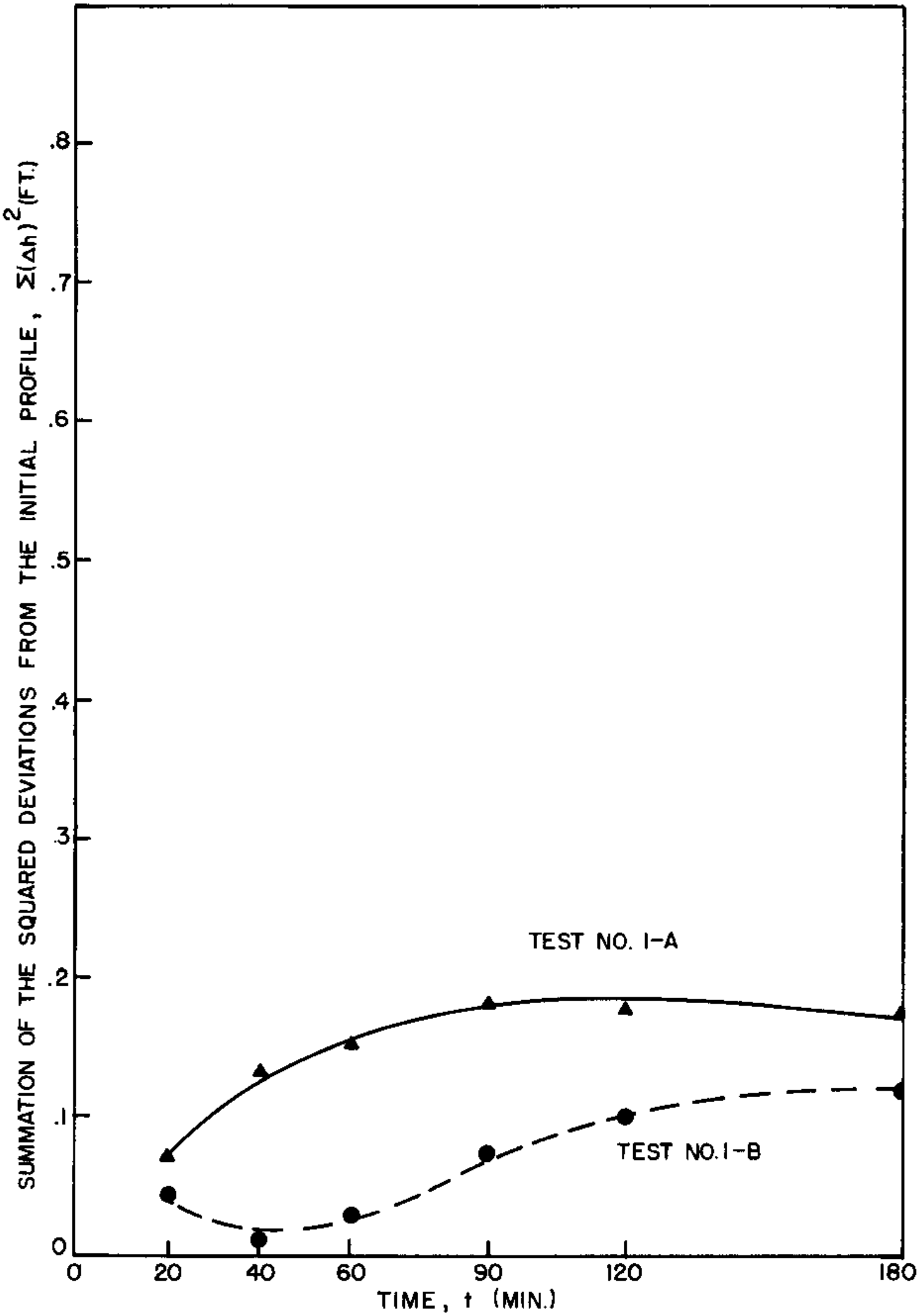

FIG. 23. SEDIMENT MOVEMENT TRENDS FOR THE SATURATED ZONE OF TEST NO. 1.

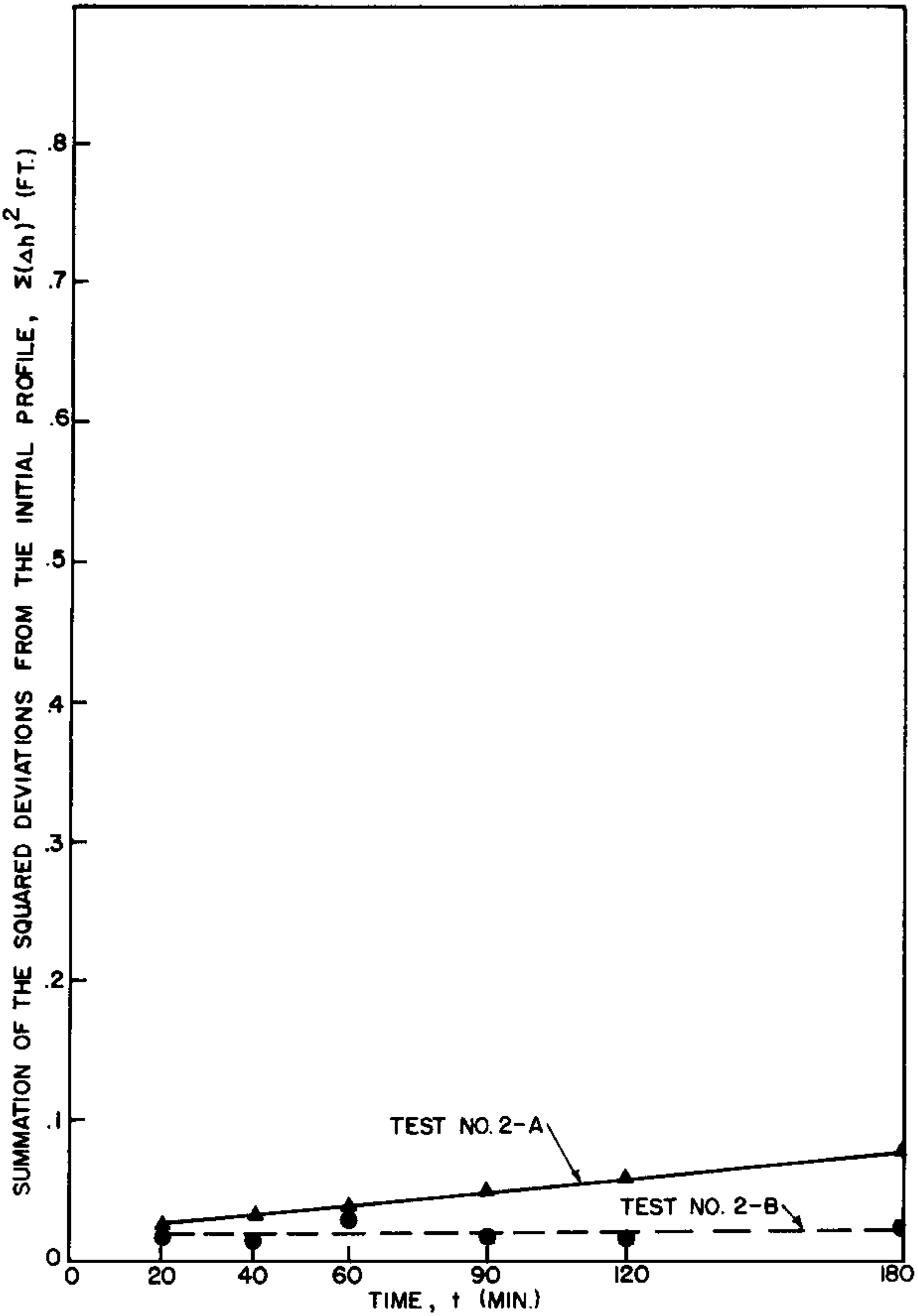

FIG. 24. SEDIMENT MOVEMENT TRENDS FOR THE SATURATED ZONE OF TEST NO. 2.

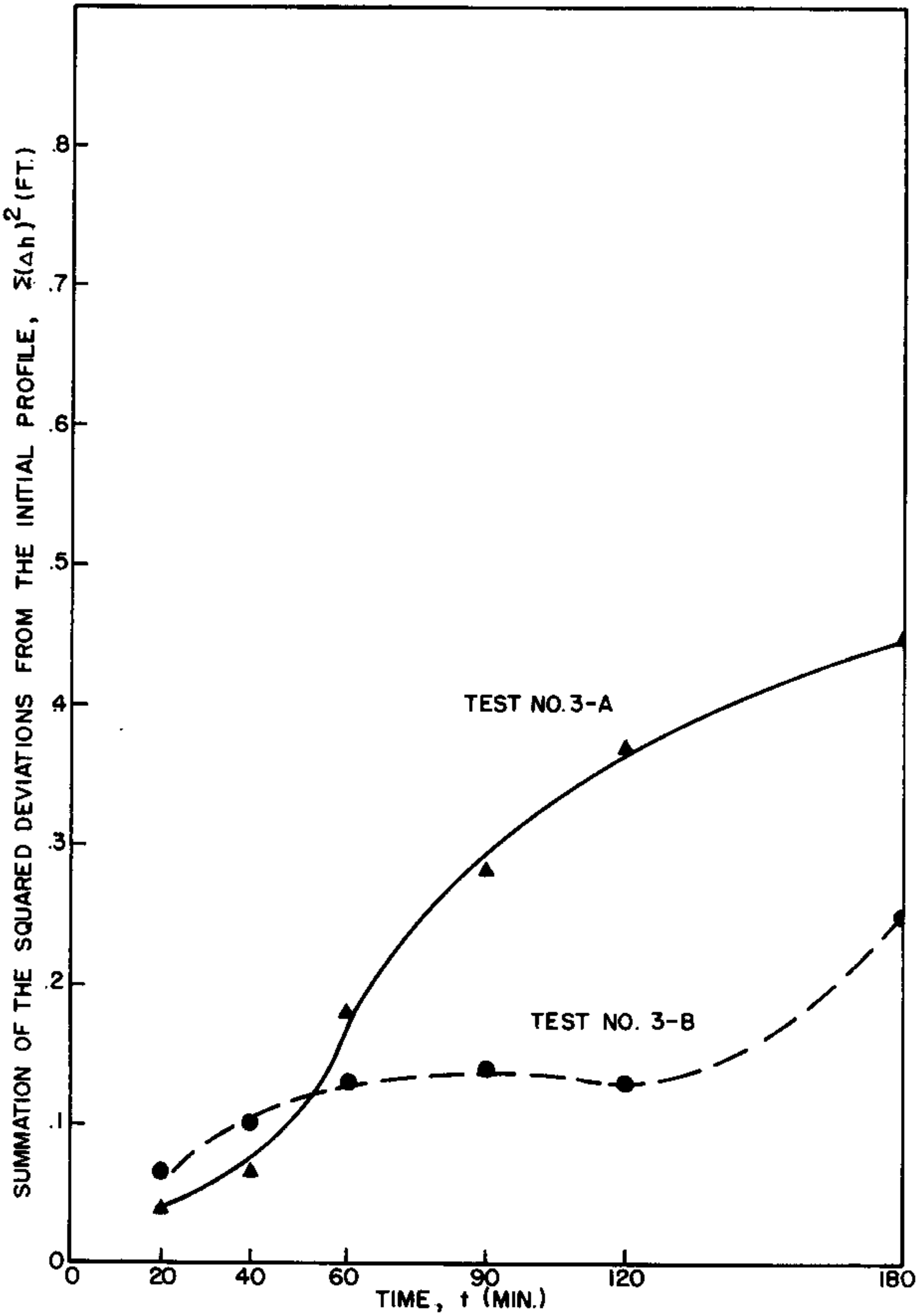

FIG. 25. SEDIMENT MOVEMENT TRENDS FOR THE SATURATED ZONE OF TEST NO. 3.

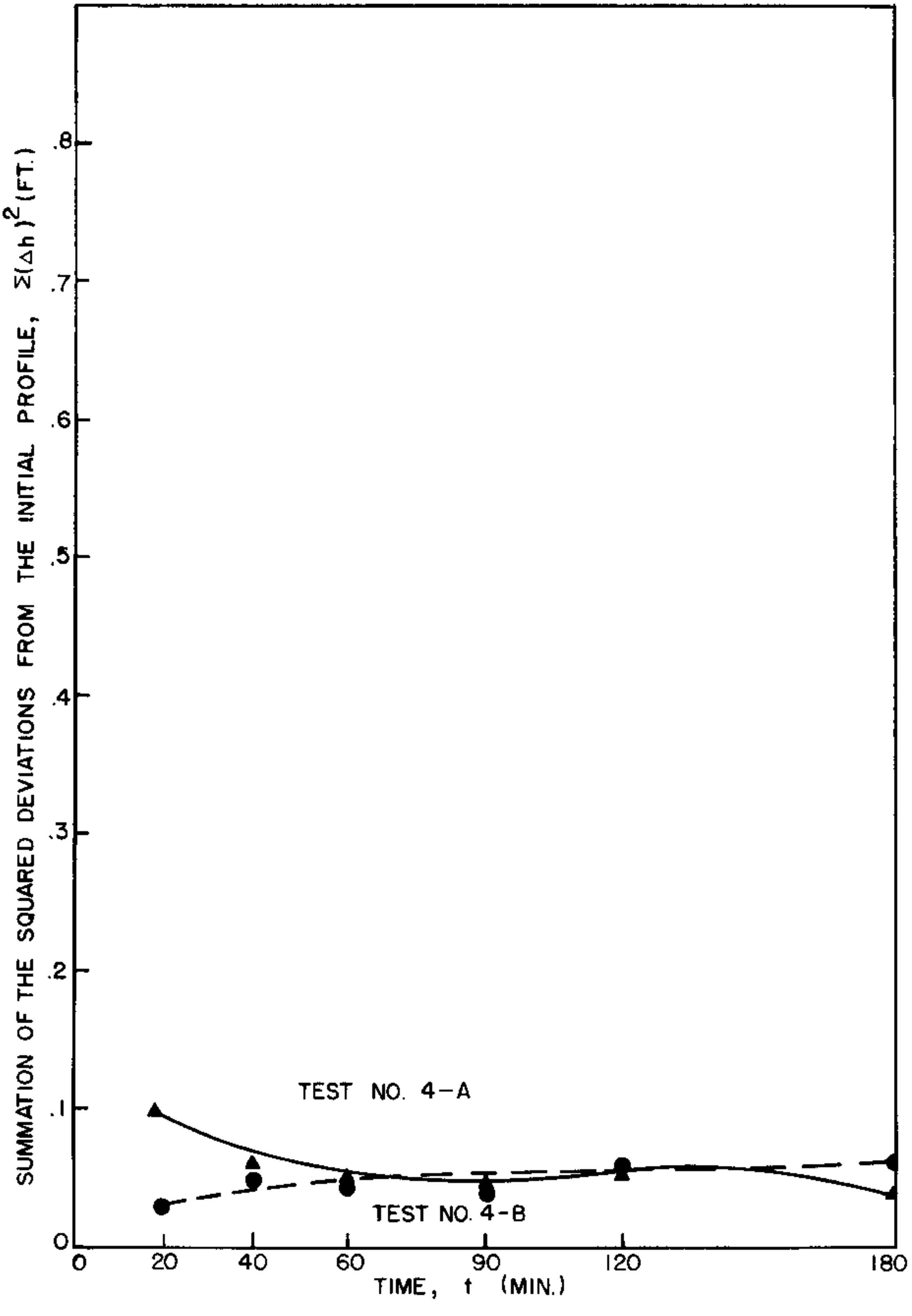

FIG. 26. SEDIMENT MOVEMENT TRENDS FOR THE SATURATED ZONE OF TEST NO. 4.

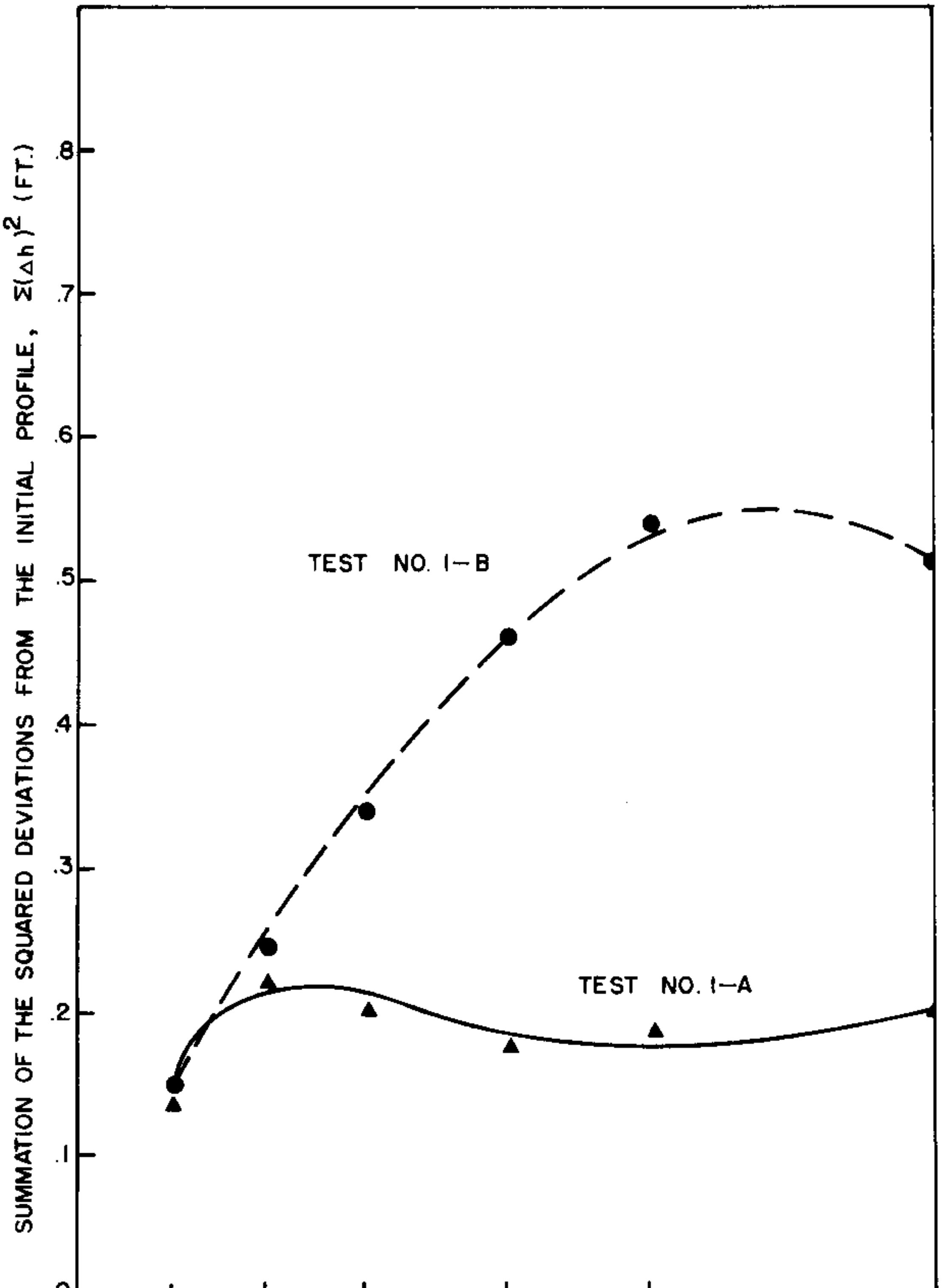

FIG. 27. SEDIMENT MOVEMENT TRENDS FOR THE PARTIALLY SATURATED ZONE OF TEST NO. 1.

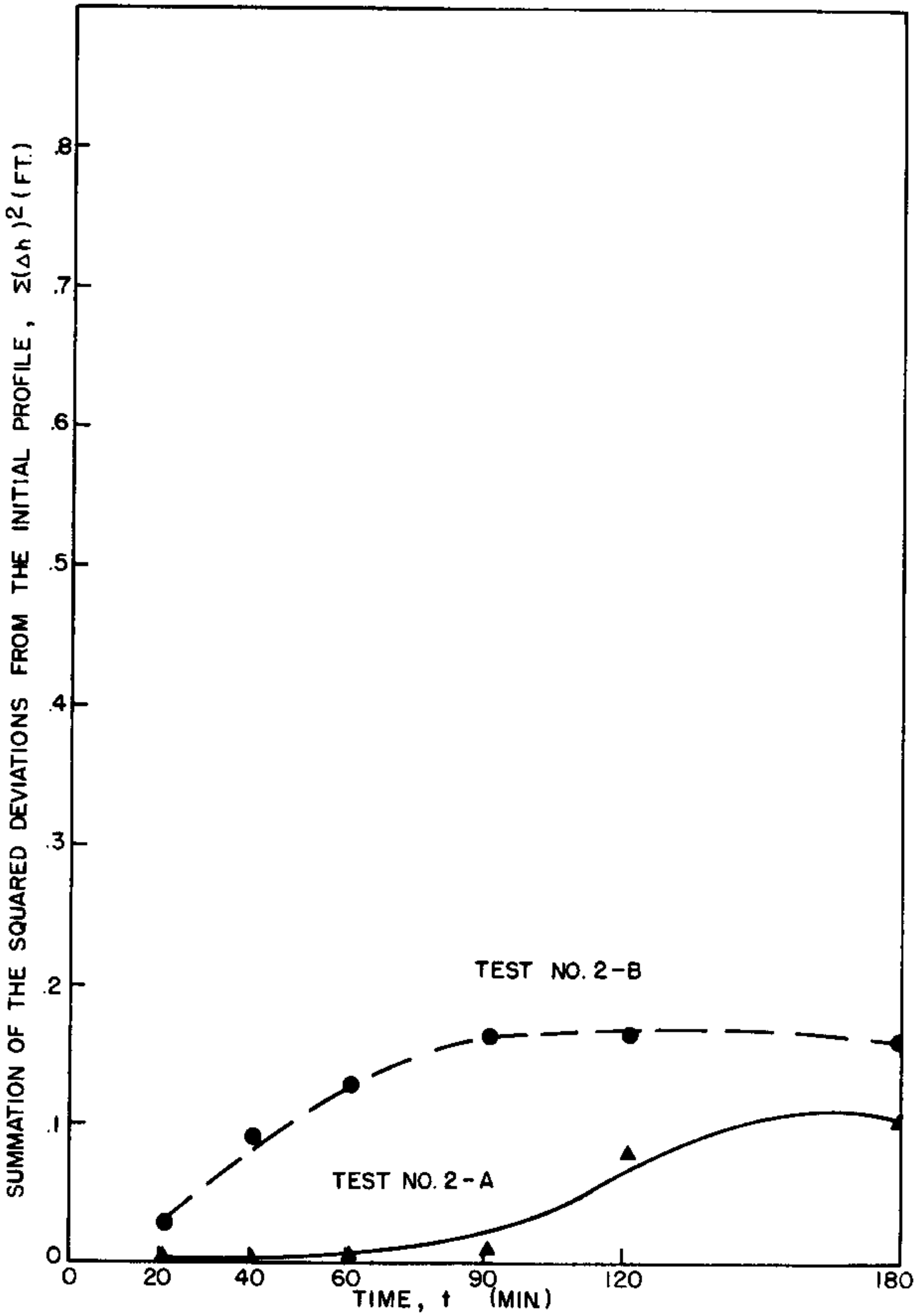

FIG. 28. SEDIMENT MOVEMENT TRENDS FOR THE PARTIALLY SATURATED ZONE OF TEST NO. 2.

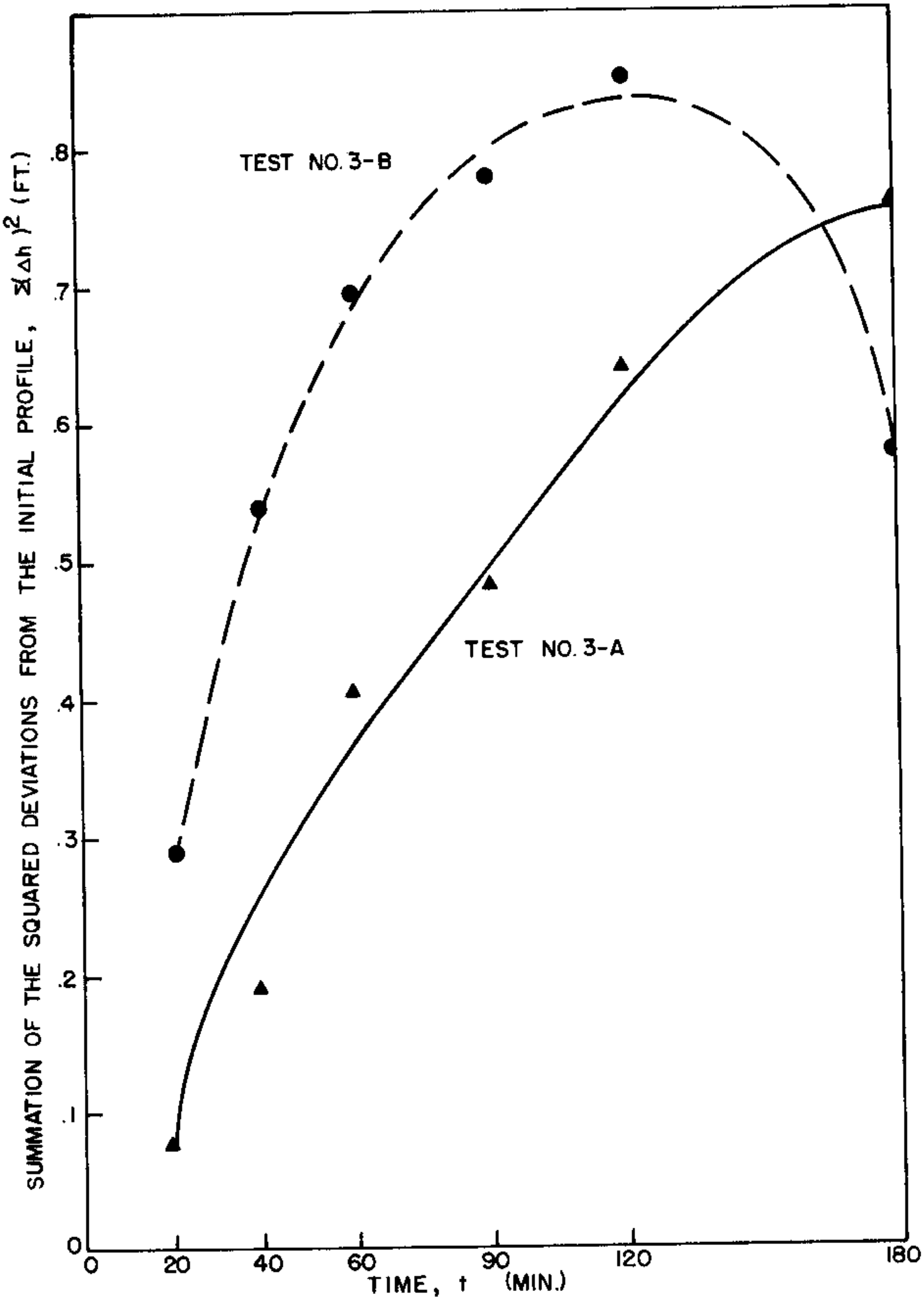

FIG. 29. SEDIMENT MOVEMENT TRENDS FOR THE PARTIALLY SATURATED ZONE OF TEST NO. 3.

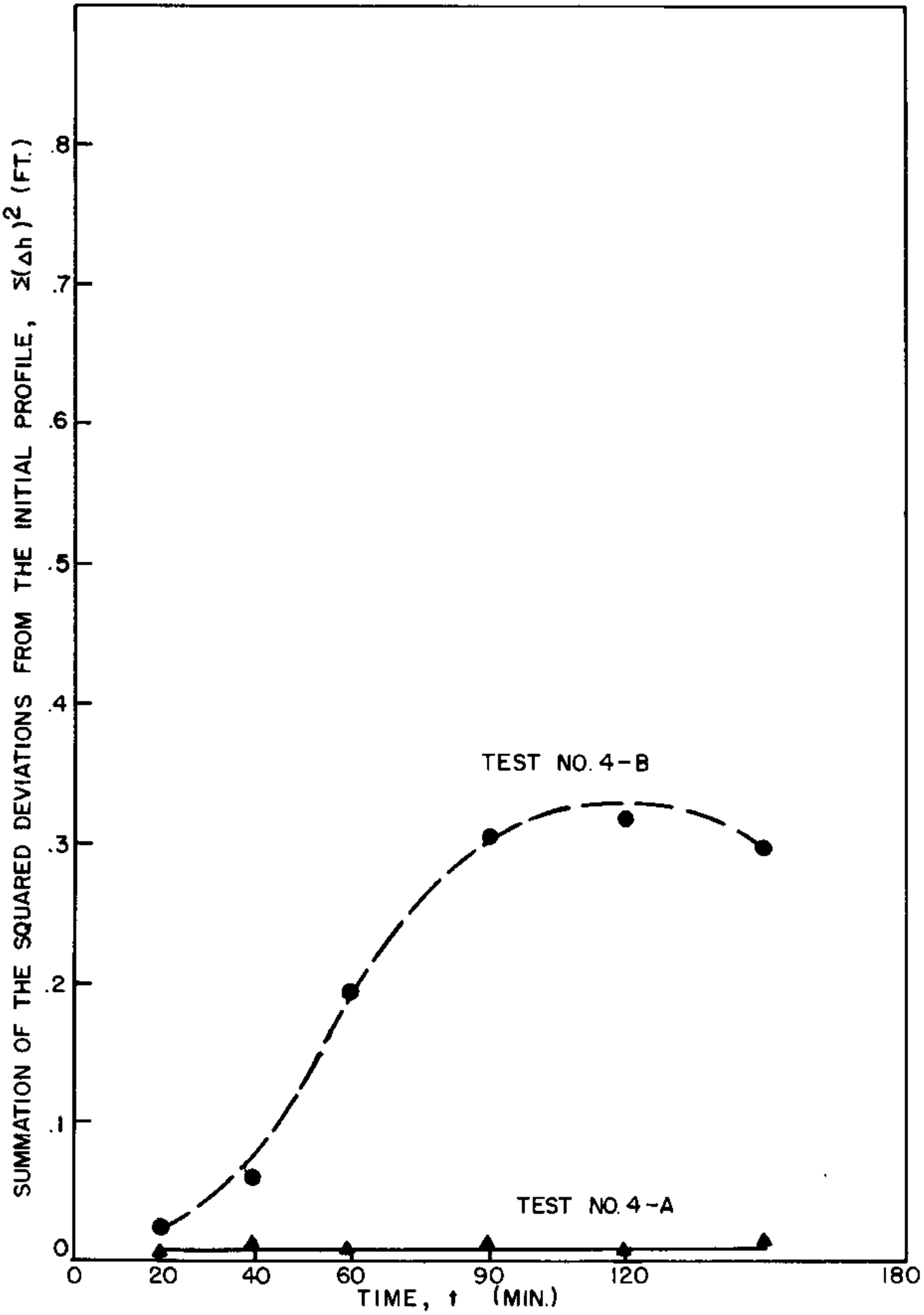

FIG. 30. SEDIMENT MOVEMENT TRENDS FOR THE PARTIALLY SATURATED ZONE OF TEST NO. 4.

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