EXPERIMENTAL STUDY OF HORIZONTAL LAMINATION IN A RECIRCULATING FLUME

by
Pierre Y. Julien
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prepared for
M. Guy Berthault

Colorado State University

Report CER88-89PYJ-YCC14
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LIST OF SYMBOLS

Cross-lam.	-	Cross-lamination
D_{10}	-	The particle-size for which 10% of the sand mixture is finer
D_{25}	-	The particle-size for which 25% of the sand mixture is finer
D_{50}	-	The particle-size for which 50% of the sand mixture is finer
D_{75}	-	The particle-size for which 75% of the sand mixture is finer
D_{90}	-	The particle-size for which 90% of the sand mixture is finer
f	-	friction coefficient
Fr	-	Froude number
h	-	Depth of flow (cm)
H.Lam	-	Horizontal lamination
H.L.	-	Horizontal lamination
Q	-	Discharge (cm^3/sec)
Shear	-	Bed shear stress (dyne/cm^2)
Sw	-	Water surface slope
U_*	-	Friction velocity (cm/sec)
Vm	-	Mean velocity (cm/sec)
Vs	-	Water surface velocity (cm/sec)

I. INTRODUCTION

Several researchers have carried field and laboratory investigations on the formation of cross-laminae under lower regime conditions where bed forms of various sizes and shapes migrate in the downstream direction. Few studies, however, examined the internal structure of horizontal laminae seen in plane bed configurations with motion of sediment. Upper regime conditions are difficult to control because of the hydraulic instability of open channel flows near critical flow conditions.

The proposed laboratory experiments of horizontal lamination in a recirculating flume extends the recent investigations of Berthault (1986 and 1988). The primary objective of this experimental study is to examine the formation of horizontal laminae under fluvial conditions of plane bed with sediment transport.

A recirculating plexiglass flume has been particularly designed at the Engineering Research Center of Colorado State University to permit the analysis of lamination processes under a wide variety of flow conditions. The flume recirculates both water and sediment in order to provide a constant supply of sediments under steady flow conditions during the course of each experiment. The slope of the channel could be determined prior to each run in order to study the thickness of laminae and the angle of laminated deposits with the slope of the flume bed.

A key feature in this investigation is the use of sand mixtures with grains of different colors in a similar fashion as suggested in earlier experiments by Berthault (1986). Mixtures of natural black and white sediment particles with the same specific gravity ensure a better visualization of the laminae besides providing an assessment of the distribution of sediment particles with different sizes.

This study is limited to horizontal lamination without bedforms under various conditions of discharge and slope for two different sediment mixtures. The superposition of deposits is induced by controlling the tailwater elevation which does not affect the lamination process and maintains a constant supply of sediment during the entire investigation.

2. ABRIDGED LITERATURE REVIEW ON HORIZONTAL LAMINATION

Horizontal lamination in mixtures of sand particles is very common in many aqueous environments. Horizontal laminae are composed of many thin layers of slightly different grain sizes. Their dimensions range from fractions of a millimeter to several millimeters. Those thin laminae are always in different thicknesses and the finer laminae are often darker than coarser ones, due to relatively larger proportions of clay, mica, and heavy minerals (Bridge, 1978; McBride et al., 1975).

Berthault (1986 and 1988) conducted series of experiments on the lamination characteristics in still water and running water conditions. These laminae resulted from spontaneous periodic and continuous grading process, which took place immediately following the deposit of the heterogranular mixture. From his experiments some lamination characteristics could be found. The thickness of laminae increased as the difference between the size of particles became greater in still water, and the laminae thickness also increased with flow velocity of running water. Also, the slope of the surface has little influence on lamination and seems to favor it.

Few laboratory experiments of horizontal lamination have been obtained for unidirectional, upper flow regime flow conditions. However, from some observations, the horizontal laminae were formed under lower flow regime near critical flow condition. Paola et al. (1989), along with Bridge and Best's (1988) experiment, explained that lamination results from the superposition of two processes: high-frequency erosion and deposition due to turbulence, and migration of low-amplitude bed forms that is neither upper-regime nor lower-regime solely.

About the upper-regime bed, some researchers invoke the interaction of sediment transport and turbulence to interpret the formation of horizontal lamination. Bridge (1978) firstly submitted the "burst-sweep cycle" in the turbulent boundary layers to explain the vertical sorting that defines laminae. The bursting process, a quasi-cyclic sequence of fluid motion, caused temporal and spatial variation in bed shear and lift forces acting on sediment particles in motion over plane beds. It was an average deterministic sequence of ejection (burst) and sweep events repeated in space and time. Bursts will cause upward dispersion of the suspended load throughout the flow, also some of the saltating load will carry coarser grains due to higher shear stress. As bed shear stress decreases, the dispersed particles settle down by a "like-seeks-like" mechanism (Moss, 1963; and Kuenen, 1966) to deposit together and to form a laminated layer. According to this possible explanation, the repeated burst-sweep cycle forms laminae. In the report of investigation in horizontal laminae formed under upper-regime plane bed by Cheel and Middleton (1986b) the probable mechanism for the formation of FU (fining-upward) and CU (coarsening-upward) laminae was the burst-sweep process: (1) FU laminae formed by fallout of progressively finer sand bursted upward temporarily, and (2) CU laminae formed of sorting by dispersive pressure in a layer of high grain concentration produced by locally high shear stress developed beneath a sweep of high speed fluid approaching the bed.

Allen (1984) created a model based on the larger coherent structures of the turbulent boundary layers to explain the formation of horizontal laminae from upper-regime plane bed. He assumed that the upper-regime plane bed occurred in a long bed wave of little height which was driven rapidly downstream and forced by the larger coherent turbulence structure to which they were coupled through a pattern of bed shear stress. Under the uniform steady conditions each bed wave generated a normally graded lamina. This model provided one possible explanation for the origin of horizontal lamination at high sediment transport stages but is inadequate in describing the formation from flat bed in slow-moving bed forms (e.g. Smith 1971; McBride et al., 1975). Also, the larger coherent turbulent structure within outer region of boundary layers was different than Bridge's model (1978) within inner region of turbulent boundary layers.

In the experiments of Paola et al. (1989), the deposition of a lamina was usually initiated by a surge of high-concentration of coarser grains near the bed, which decelerated and rapidly stopped during a few tenths of a second. Subsequently, the fine grains were sieved from the flow as their saltation or rolling paths direct them into pockets in the pores created by the larger stationary grains. This process of selective removal of fine grains by smoothing the top of the bed: the effective friction angle between the bed surface and the larger grains was reduced while that of the fine grains trapped in the bed was increased. This "glazing" process took over several seconds and was not directly related to turbulent fluctuations. It differed with Bridge's model (1988).

Through the investigation of bedforms in the Platte River, Nebraska, Smith (1971) observed that horizontal laminae were produced by migration of thin sand sheets, i.e. low amplitude sand waves, with downstream foresets. They had very shallow to nearly horizontal stoss sides, steep foresets at the angle of repose. In cross section the thinnest waves appeared as horizontal laminae, whereas the thicker waves showed readily discerned planar or cross-lamination. The most important factor controlling production of the thin flat-topped waves was the very shallow depths in which they formed. The Froude numbers ranges from 0.46 to 0.73 which were below unity. They produced internal horizontal stratification which was similar to upper-regime plane bed deposition except that the grains were differentiated into alternating coarse and fine lamination by sorting processes at the foreset. Moreover, McBride et al. (1975) proposed a series of experiments to reproduce horizontal laminae under lower-regime bed. They found that lamination had been observed as the result of the migration of very low-relief ripple and in-phase waves which produced thin laminae when coarser grains in the lee side of the bedforms buried finer grains in the stoss side of the bedforms; the lack of avalanche face prevented cross-laminae from developing. Shallow depths also were essential to form the near horizontal laminae, because at greater flow depths, ripples developed avalanche faces and produced micro cross-laminae.

Bridge (1978) had listed some authors' hypotheses in the origin of near-horizontal lamination in unidirectional aqueous flow; and Cheel & Middleton (1986) had summarized some researches about the horizontal laminae formation under upper-regime bed conditions. Table 1 summarizes the various hypotheses attempting to explain horizontal lamination.

Table 1. Summary of hypotheses explaining the origin of horizontal lamination

	REFERENCE	SUMMARY HYPOTHESIS
1.	Kuenen and Menard (1952) Kuenen (1953, 1957)	*Velocity pulsations in turbidity current, perhaps with some sorting by traction.
2.	Ksiazkiewicz (1952)	*Diluted secondary turbidity currents suspended above bed.
3.	Ten Haaf (1956)	*Sorting action of vortices produced by produced by turbulence in turbidity currents.
4.	Hsu (1959)	*Settling and laminar flow of fluidized sediment along bed.
5.	Unrug (1959) Wood & Smith (1959)	*Settling from tail of turbidity current with a non-uniform concentration.
6.	Bouma (1962) Lombard (1963)	*Small turbulence eddies. Current velocity pulses with settling or traction.
7.	Moss (1963) Kuenen (1966)	*Grains of similar susceptibility to transport tend to deposit together, i.e. spatial and temporal selection similar grains due to grain interaction under quasi-steady flow condition: the "like-seek-like" principle.
8.	Allen (1964)	*Pulsating sediment supply due to separate large scale eddies. Upper regime plane bed.
9.	Walker (1965)	*Intermittent supply of mixed sediment to top of viscous sublayer followed by differential settling through; for finer grained laminae. Coarser grained laminae under upper regime plane bed.
10.	Sanders (1965)	*Settling and traction during current velocity fluctuation. Not upper regime plane bed.

11. Jopling (1967)	*Attributed laminae to the superposition of longitudinal segregations of bedload grains under aggradation of a upper regime plane bed.
12. Pettijohn (1957, 1975)	*Transitory phases or minor chance fluctuations in velocity of depositing current.
13. Smith (1971) McBride et al. (1975)	*Migration of very low relief bedforms (diminished ripples & dunes).
14. Frostick and Reid (1977)	*Combine the ideas of Pettijohn, Moss and Kuenen.
15. Bridge (1978)	*Described possible lamination formation due to the effect of single burst-sweep cycle on a plane bed.
16. Hesse and Chough (1980)	*Suggested that a horizontal lamination formed with multiple burst and sweep events on plane bed.
17. Allen (1984)	*Laminae form due to the shifting distribution of boundary shear stress as large eddies move down-stream over a plane bed.

3. EXPERIMENTS:

3.1 Equipment

All the experiments are carried out in a tilting, recirculating flume: 0.15m wide, 0.15m deep, and 2.40m long, as sketched in Fig. 1. The flow rate is controlled by a gate valve and measured by a Venturi orifice. The deposition of sand in the flume is controlled by small tailgates 0.15m wide and 0.02m high. In one experiment, a 0.04m high tailgate is also used. The depth of water and deposition is measured by an affixed ruler on the sidewall of flume. The slope of flume can be adjusted by a screw jack. The details of the experiment facilities are shown as Fig. 1 and a photograph of the flume is also presented in Picture 1.

Particular consideration in the design procedure has been given to the entrance condition of the flume. The return of water and sediment in the head water box needs to be carefully designed in order to ensure complete mixing of the sediment particles and constant inflow of sediment under steady flow conditions. The rounded entrance profile and the use of a movable plate shown on Picture 2 provided excellent feeding conditions into the plexiglass flume.

THE FACILITIES FOR LAMINATION EXPERIMENT IN A SMALL FLUME

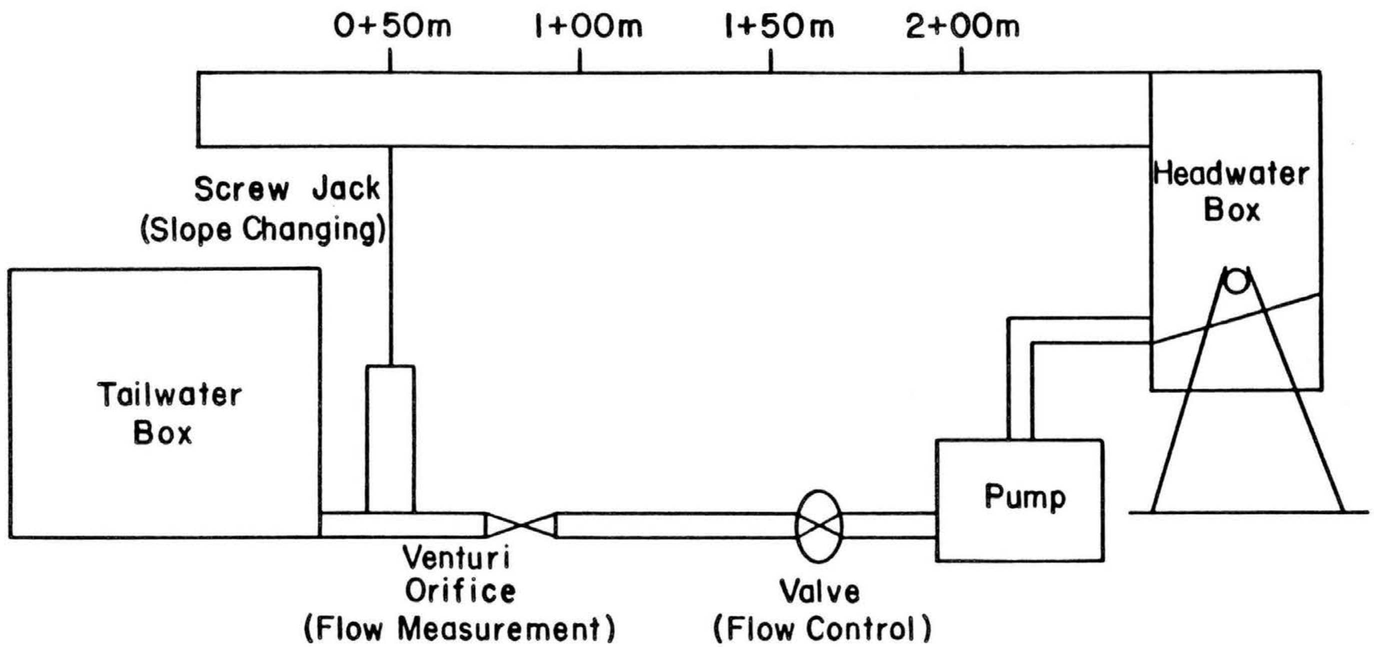
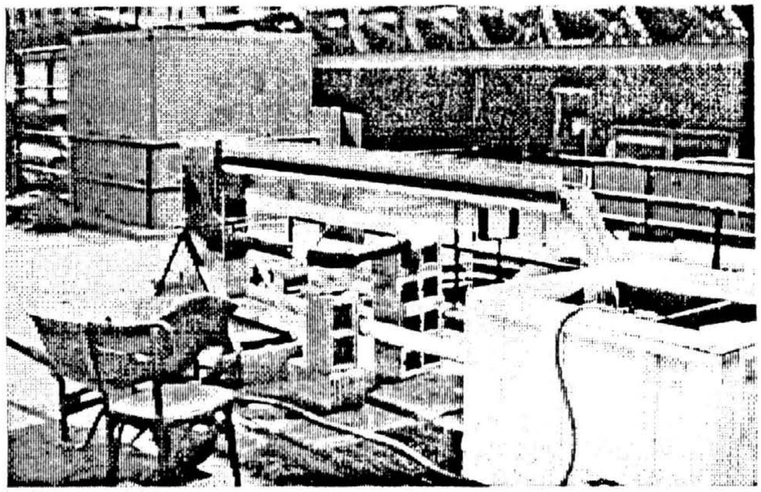
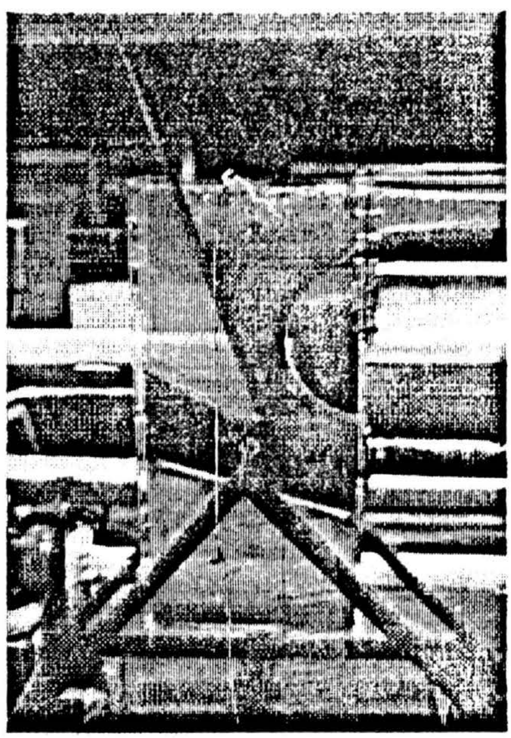


Fig. 1. Recirculating flume.



Picture 1. Experimental facilities (whole view)



Picture 2. Headwater box

3.2 Sand Material

Four types of sands are readily available at ERC, out of which two white sands identified as ERC#2 and ERC#4 have been selected for this analysis. In order to clearly visualize the lamination process, two black sands with a specific gravity of 2.65 identified as B3060 and B2040 were obtained to prepare several mixtures. The characteristics of the original sands are summarized in Table 2.

Table 2. The original sand size distributions

Type	Color	D_{10}	D_{25}	D_{50}	D_{75}	D_{90}
B3060	black	0.14mm	0.205mm	0.335mm	0.55mm	0.62mm
B2040	black	0.38mm	0.48mm	0.575mm	0.67mm	0.76mm
ERC#2	white	0.72mm	0.90mm	1.20mm	1.50mm	1.90mm
ERC#4	white	0.094mm	0.13mm	0.16mm	0.19mm	0.24mm

From these original sands, four sand mixtures were prepared after sieving out the coarser fraction of one sand and the finer fraction of the second one. The four mixtures identified as SM-1, SM-2, SM-3, and SM-4 were analyzed in a preliminary study by Julien and Chen (1989), and the best two mixtures (SM-2 and SM-3) were considered in the following analysis. The characteristics of these two black and white mixtures are summarized in Table 3. Note that in the mixture SM-2, the coarse material is black and the fines are white. Conversely, the mixture SM-3 is comprised of coarse white particles mixed with fine black particles. The particle-size distributions of the original sands and the mixtures are shown on Fig. 2 and 3.

Table 3. The composition of sand mixtures

Sand mixture	Composition	Total Weight	D_{50}
* SM-2	B2040 & ERC#4 2.0mm-0.425mm : 0.425mm-0.063mm 80kg : 80kg	160kg	0.28mm
* SM-3	B3060 & ERC#2 0.6mm-0.063mm : 2.0mm-0.6mm 62kg : 82kg	144kg	0.62mm

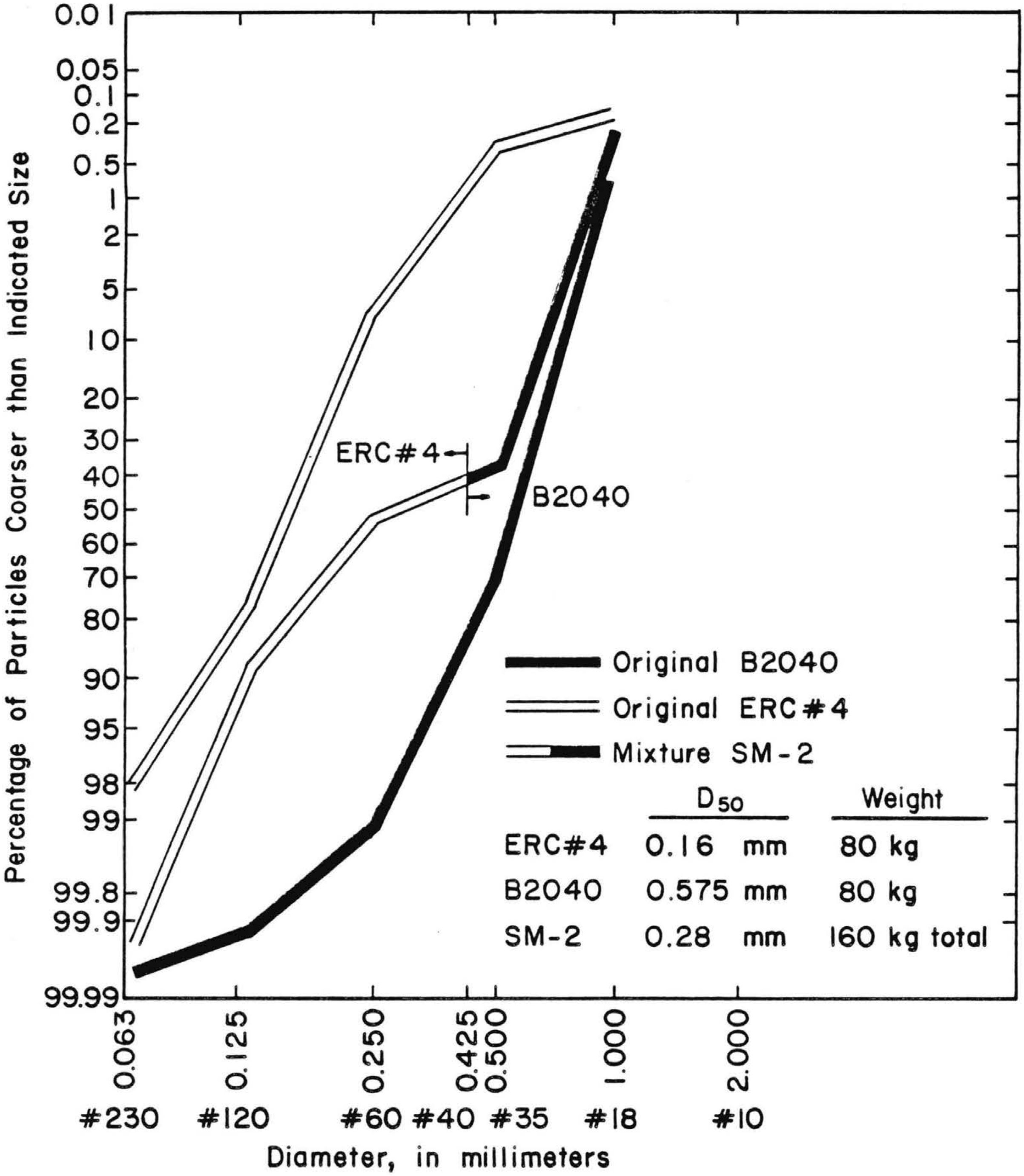


Fig. 2. Particle-size distribution for sand mixture No. 2 (mixing B2040 sieve #10-#40 & ERC #4 sieve #40-#230)

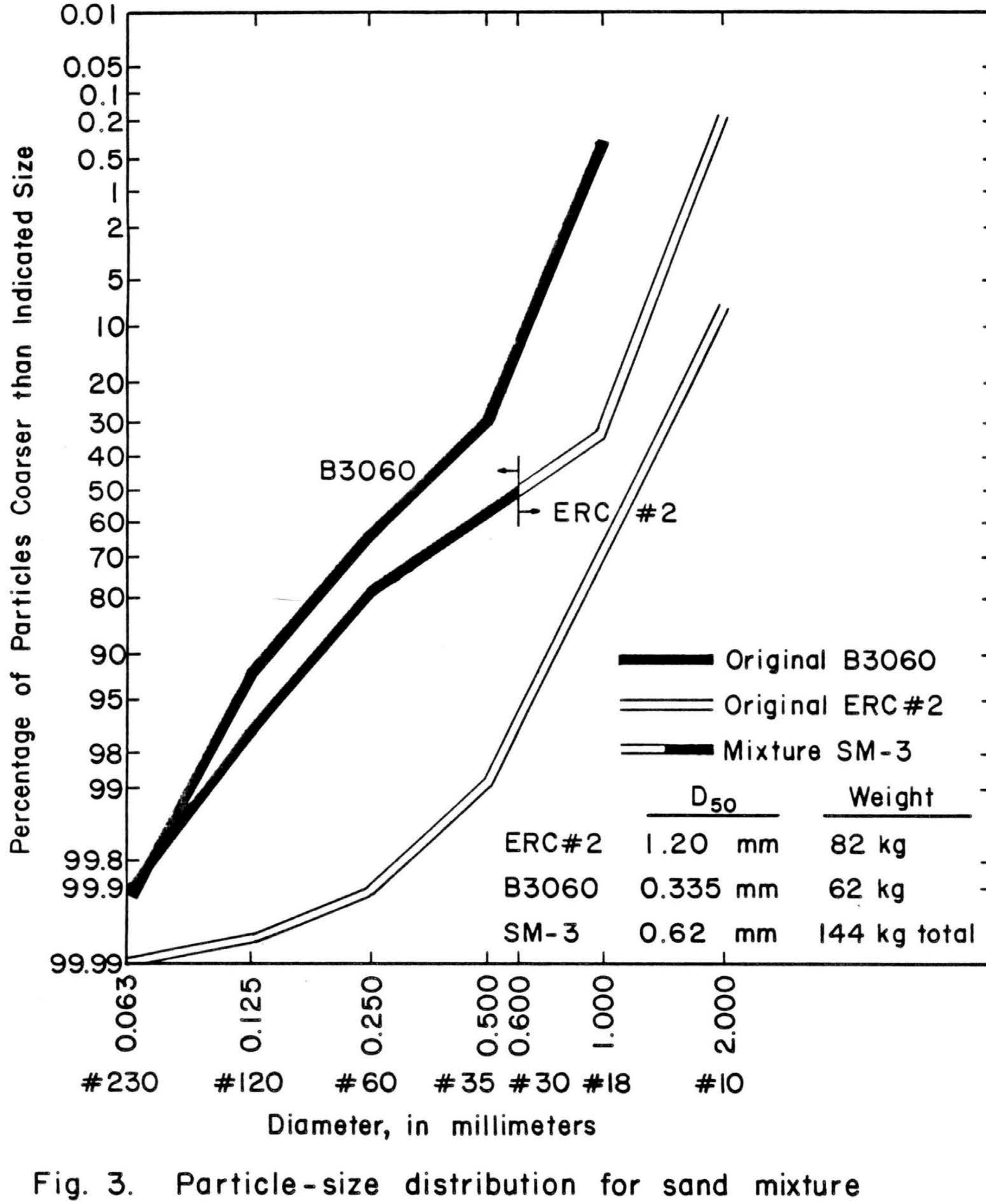


Fig. 3. Particle-size distribution for sand mixture No. 3 (mixing B3060 sieve #30-#230 & ERC#2 sieve #10-#30)

3.3 Procedure

In this experimental program, five runs are detailed in Table 4 for two sand mixtures, i.e. four runs for SM-2 and one run for SM-3. In each run the flume slope is fixed and four constant values of flow discharge are selected for each of the four steps. Therefore, for each step we specify flume slope and flow discharge. The discharge increases slightly at each subsequent step. Two tailgates (2cm high) are used to control tailwater depth and sand deposition under three conditions, i.e. without tailgate, one tailgate, and two tailgates; but for RUN SM-2D, we propose two different gate sizes (2cm & 4cm high) to study the effect of gate size.

Before each experiment, we set the flume slope (horizontal, positive, or adverse slope). For each step we adjust the valve to control the flow rate and fix the discharge. Firstly, the flow runs freely without gate control until the first deposition layer is formed. Sequentially, the first tailgate is inserted at the downstream end of the flume. We wait until the deposit layer is completely formed and equilibrium conditions are reached (about 20 to 30 minutes). Then, we measure the discharge, surface velocity, depth and record the configuration of laminae deposition. After the measurements are completed, the second gate is inserted to form the second layer of deposits and the procedure similar to the first gate is repeated. For the other steps and runs the whole procedure is repeated. The detailed procedure is listed on a flow chart in Fig. 4. The cross section SEC1+00 has been selected for the comparison of the various sedimentation profiles.

Table 4. The runs and steps in the horizontal lamination experiment

	RUN	Step	Flume Slope	Tailgate Condition
1.	SM-2A	1,2,3,4	horizontal	without gate add first gate add second gate
2.	SM-2B	1,2,3,4	adverse slope (S=-0.005)	without gate add first gate add second gate
3.	SM-2C	1,2,3,4	positive slope (S=+0.005)	without gate add first gate add second gate
4.	SM-2D	1,2*	horizontal	without gate add 1st small gate (2cm high) add 2nd large gate (4cm high)
5.	SM-3A	1,2,3,4	horizontal	without gate add first gate add second gate

*Note: The SM-2D experiment involves a larger tailgate which increases the water depth and causes overflow at larger discharges. Therefore, two steps were used to avoid excessive flow discharges.

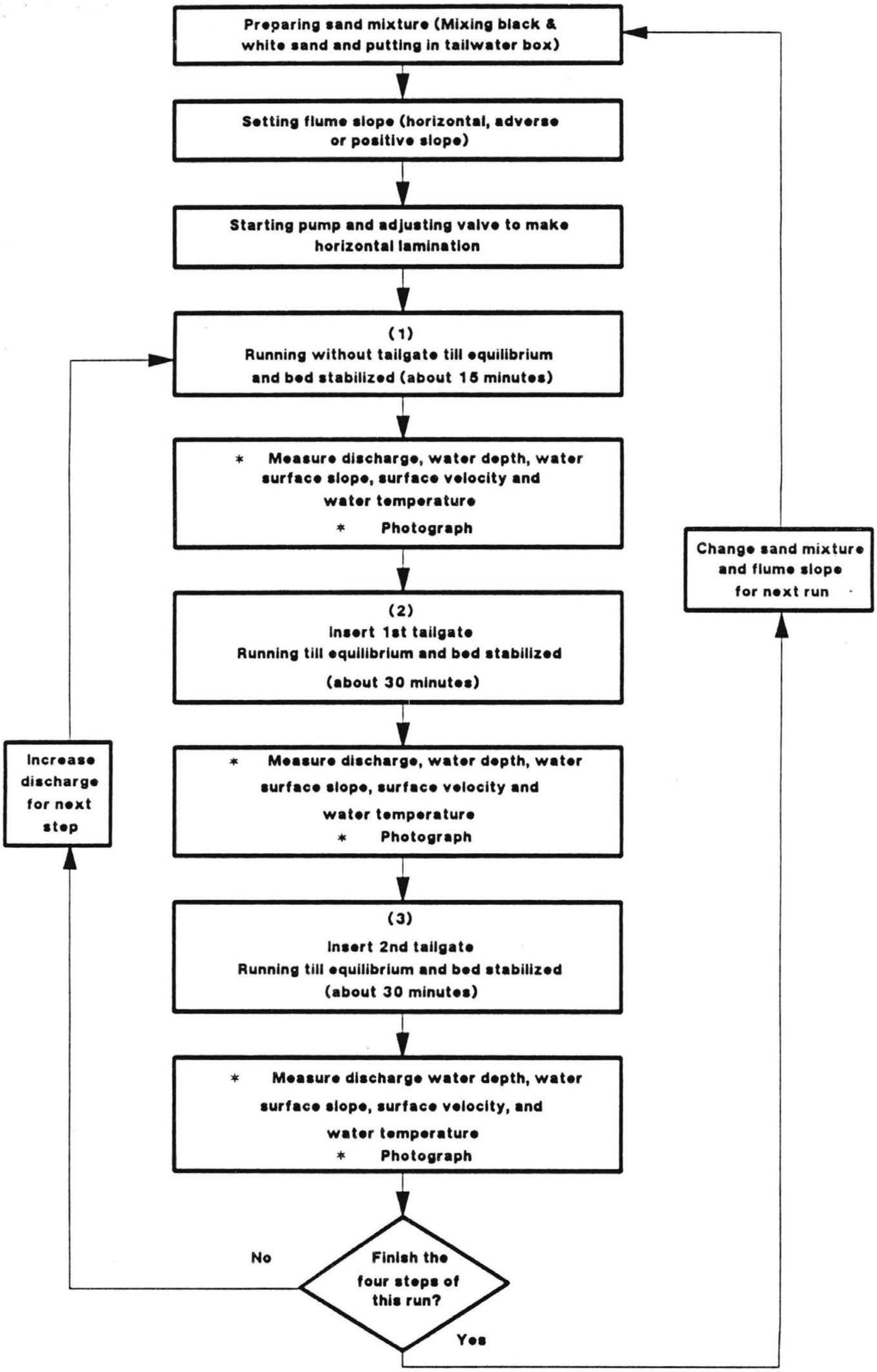


Fig. 4 Flow chart for experimental procedure in each run.

3.4 Data Measurement

During each step, several types of measurements are repeated to generate a data base of hydraulic conditions associated with the observed formations of laminae and stratified deposits.

The flow discharge is measured by a Venturi orifice shown in Fig. 1. The manometer readings are transformed into discharge values through a calibrated chart. The water temperature is measured with a mercury thermometer.

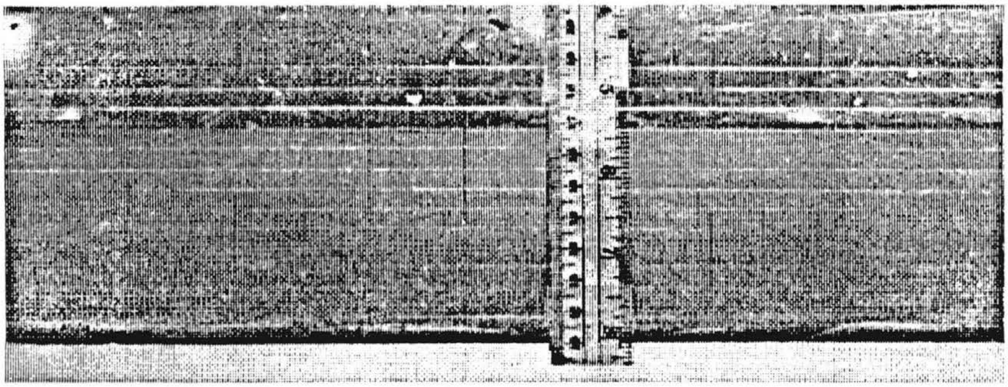
The hydraulic characteristics of flow depth and flow velocity were measured with the water surface slope. The water depth is measured with a ruler affixed on the flume sidewall at several sections including SEC1+00 and others. The water surface slope is determined from the difference in water surface elevation between two points. The surface velocity is determined from average measurements of the travel time of a floating paper ball between two points. Average flow velocities are calculated from the discharge measurements and the cross-section area.

The thickness of horizontal laminae deposits are measured from the ruler affixed on the flume sidewall at SEC1+00.

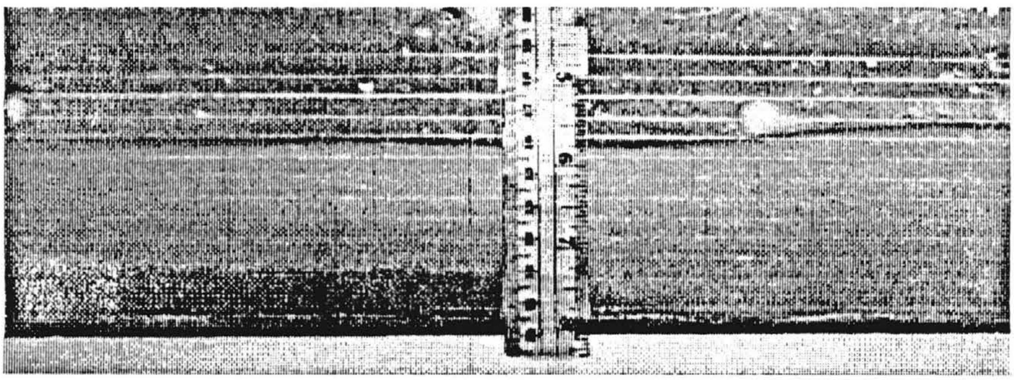
4. EXPERIMENTAL RESULTS

This section presents the results of all the measured and calculated parameters for each run of the experimental program detailed in the previous section. One of the most interesting features of the experimental program is illustrated in Pictures 3 to 8 in the next pages. From the equilibrium conditions of mostly fine white sand particles on the bed, shown in Picture 3, the insertion of a tailgate induces a deltaic formation of coarse black particles which is shown to propagate downstream on Pictures 4 and 5. As the delta reaches the downstream and of the flume, finer white particles are seen to segregate and deposit in the form of laminae on top of the coarse black particles as shown on Picture 6.

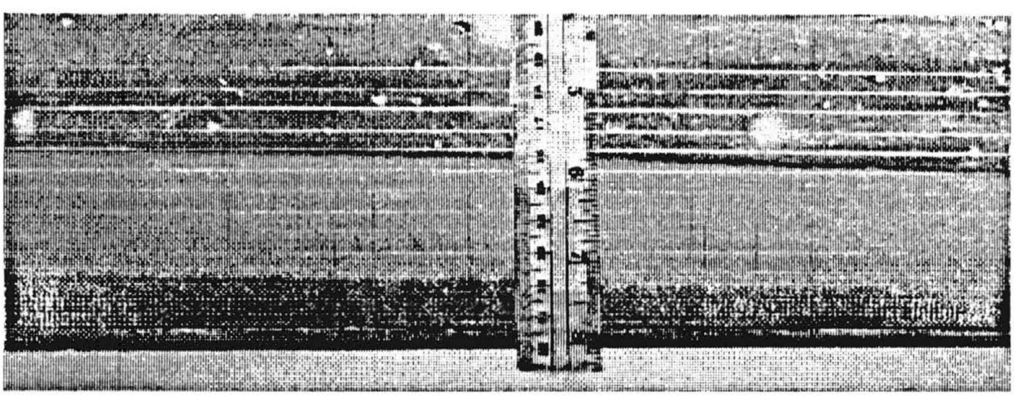
The lamination process continues in time and the thickness of the overlying laminated white deposit increases gradually until equilibrium conditions are reached. The following sub-section document each of the five runs separately.



Picture 3

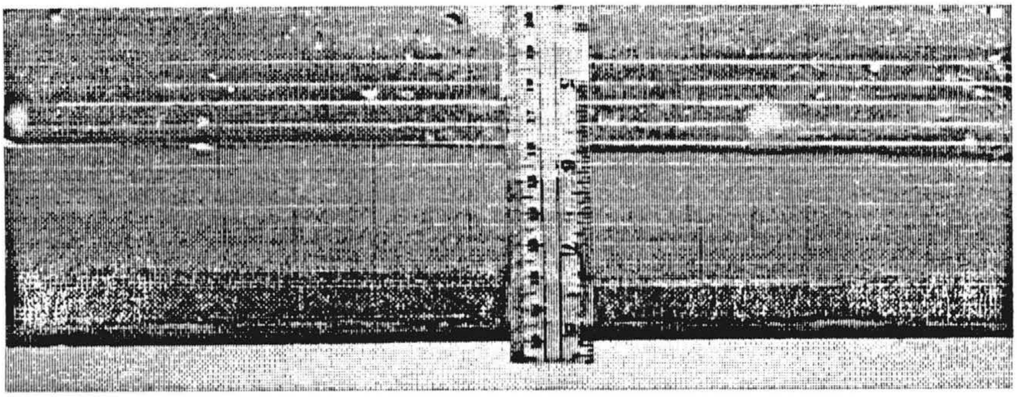


Picture 4

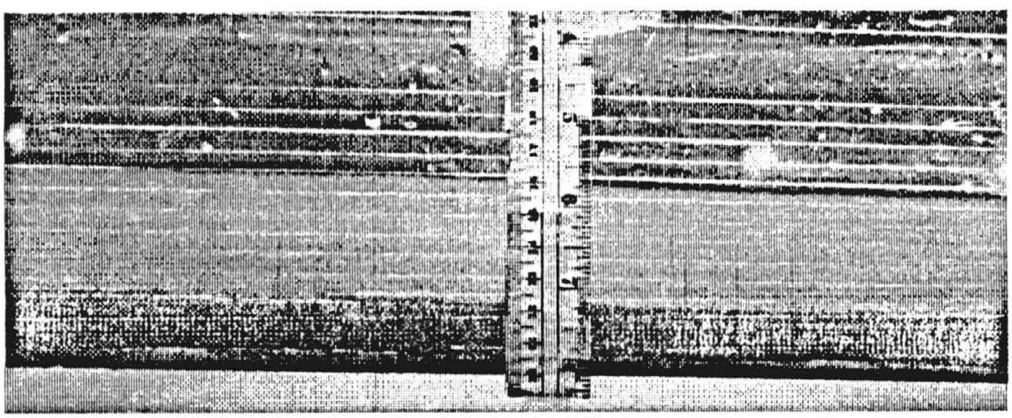


Picture 5

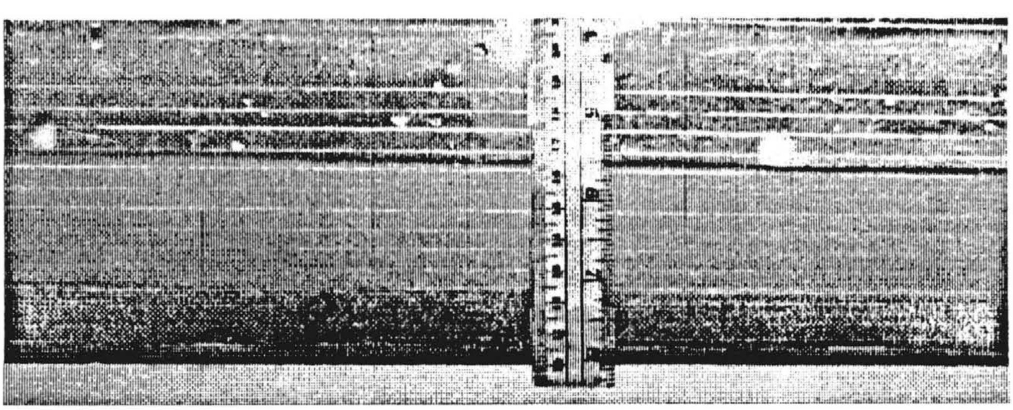
Laminae formation - Delta propagation



Picture 6



Picture 7



Picture 8

Laminae formation - Laminae thickness increasing superposed on delta

4.1 Run SM-2A

(1) Objective of this run: Examine the relationship between velocity and lamination thickness.

(2) Experimental conditions and data summary:

- Horizontal flume
- SM-2 sand mixture (B2040 & ERC#4), D_{50} = 0.28mm
- Two small tailgates (2 cm high each).
- Two deposition for each step is shown on pictures as:

  Step 1 - Picture 9 and 10

  Step 2 - Picture 11 and 12

  Step 3 - Picture 13 and 14

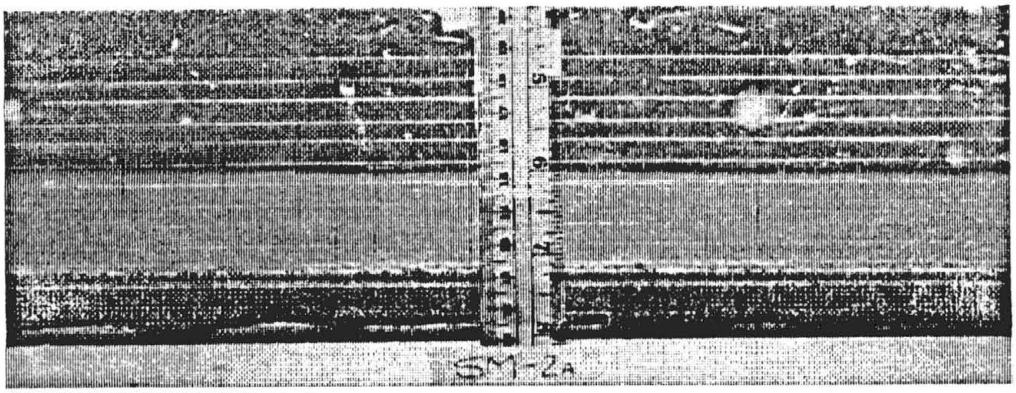
  Step 4 - Picture 15 and 16
- The data for this run is summarized in Table 5 below.

Table 5. Data Summary for Run SM-2A

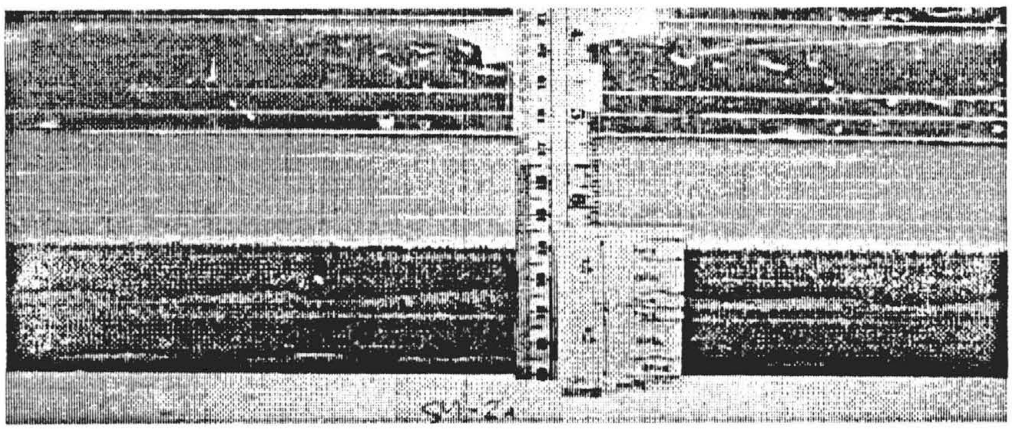
RUN: SM2A (Horizontal) D_{50} = 0.28mm

Step	Gate	Q cm^3/s	h cm	Vm cm/s	Vs cm/s	Sw	Shear $dyne/cm^2$	Fr	U*	f	thickness H.Lam mm	thickness Delta mm
SM2A-1	1st	2606	3.1	54.23	62.14	0.010	23.54	0.983	4.852	0.064	4	12
	2nd	2546	3.4	48.31	55.02	0.010	23.57	0.836	4.855	0.080	5	10
SM2A-2	1st	3536	3.7	61.65	73.54	0.011	29.08	1.023	5.392	0.061	9	7
	2nd	3470	3.9	57.40	64.96	0.011	30.12	0.928	5.488	0.073	8	8
SM2A-3	1st	4026	3.9	66.60	76.78	0.014	37.75	1.077	6.144	0.068	14	5
	2nd	3949	4.0	63.69	69.30	0.011	30.63	1.017	5.534	0.060	11	4
SM2A-4	1st	4548	3.9	75.23	82.83	0.015	40.29	1.216	6.348	0.056	16	5
	2nd	4480	4.1	70.49	76.54	0.012	33.76	1.112	5.810	0.054	12	2

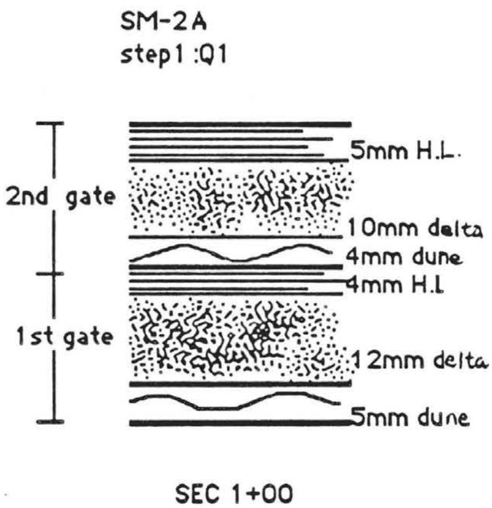
Q = flow discharge; h = water depth SEC1+00; Vm = mean velocity; Vs = surface velocity Sw = water surface slope; shear = bed shear stress; Fr = Froude number; U* = friction velocity; f = friction force coefficient; H.Lam = horizontal lamination.



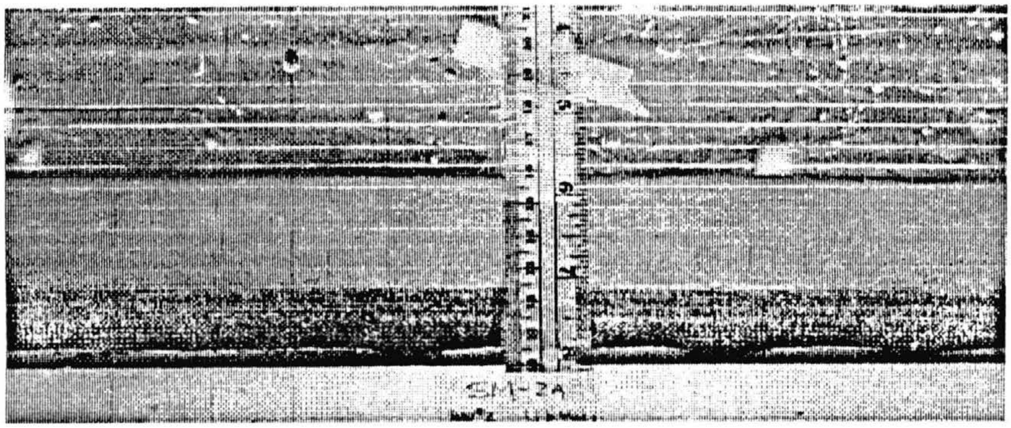
Picture 9



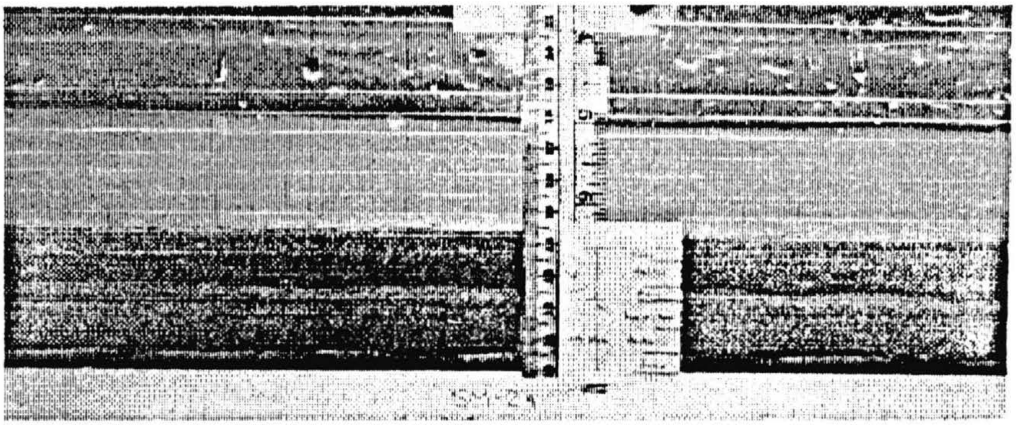
Picture 10



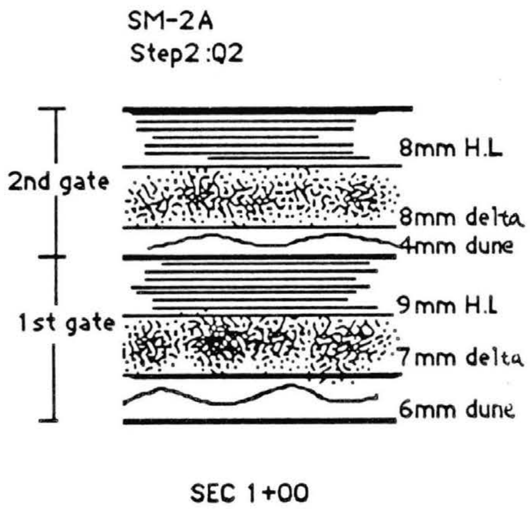
Run SM-2A, Step 1 (horizontal)



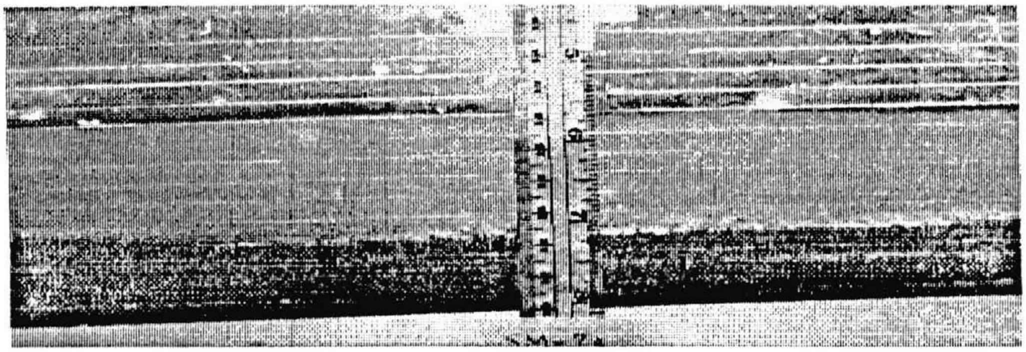
Picture 11



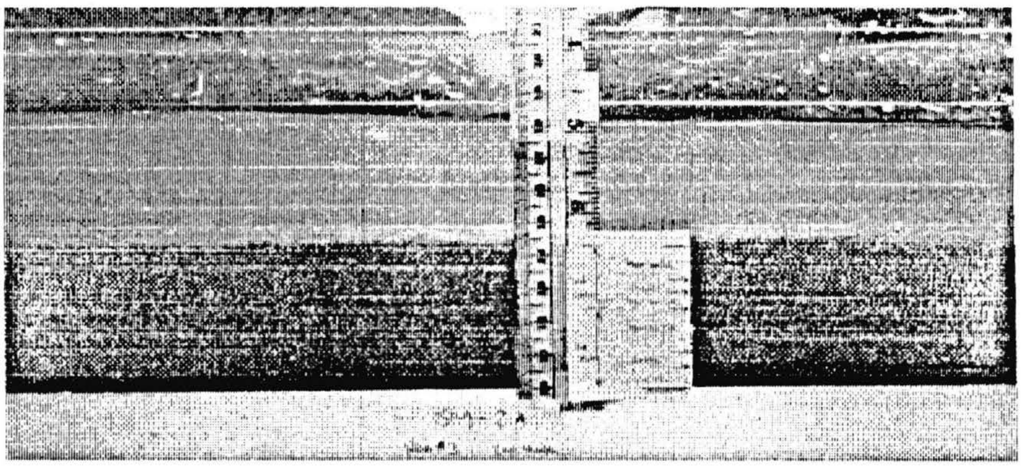
Picture 12



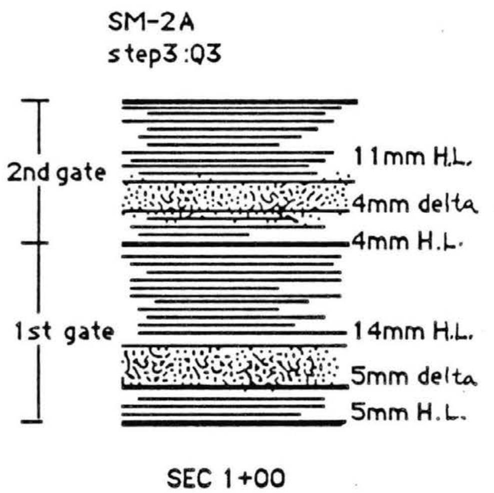
Run SM-2A, Step 2 (horizontal)



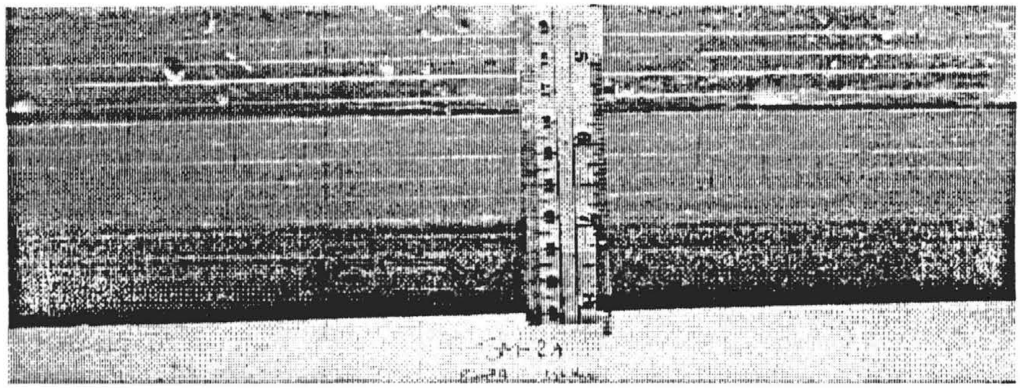
Picture 13



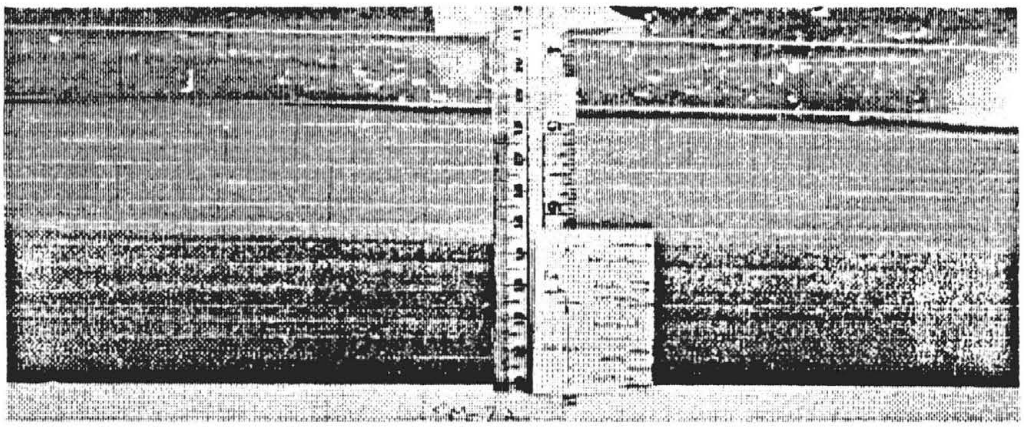
Picture 14



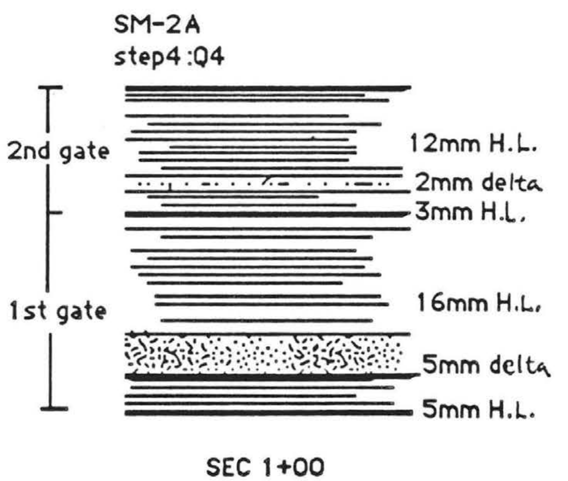
Run SM-2A, Step 3 (horizontal)



Picture 15



Picture 16



Run SM2-A, Step 4 (horizontal)

(3) Results and Conclusions of Run SM-2A:

(a) Comparing the horizontal lamination thickness under 1st gate condition from step 1 to 4 as shown in Figure 5, the thickness increased in 4mm, 9mm, 14mm, and 16mm by increasing velocity and delta thickness decreased from 12mm, 7mm , 5mm and 5mm. For the 2nd gate condition, the tendency was the same. The horizontal lamination thickness is therefore dependent to the flow velocity (or discharge). This phenomenon is similar to Berthault's experiment (1988).

(b) From the observation of horizontal lamination we found that coarser particles (black) were rolling on the bed and also moving in saltation, but finer particles (white) deposited. This phenomenon is beyond the explanation of the Shield's diagram.

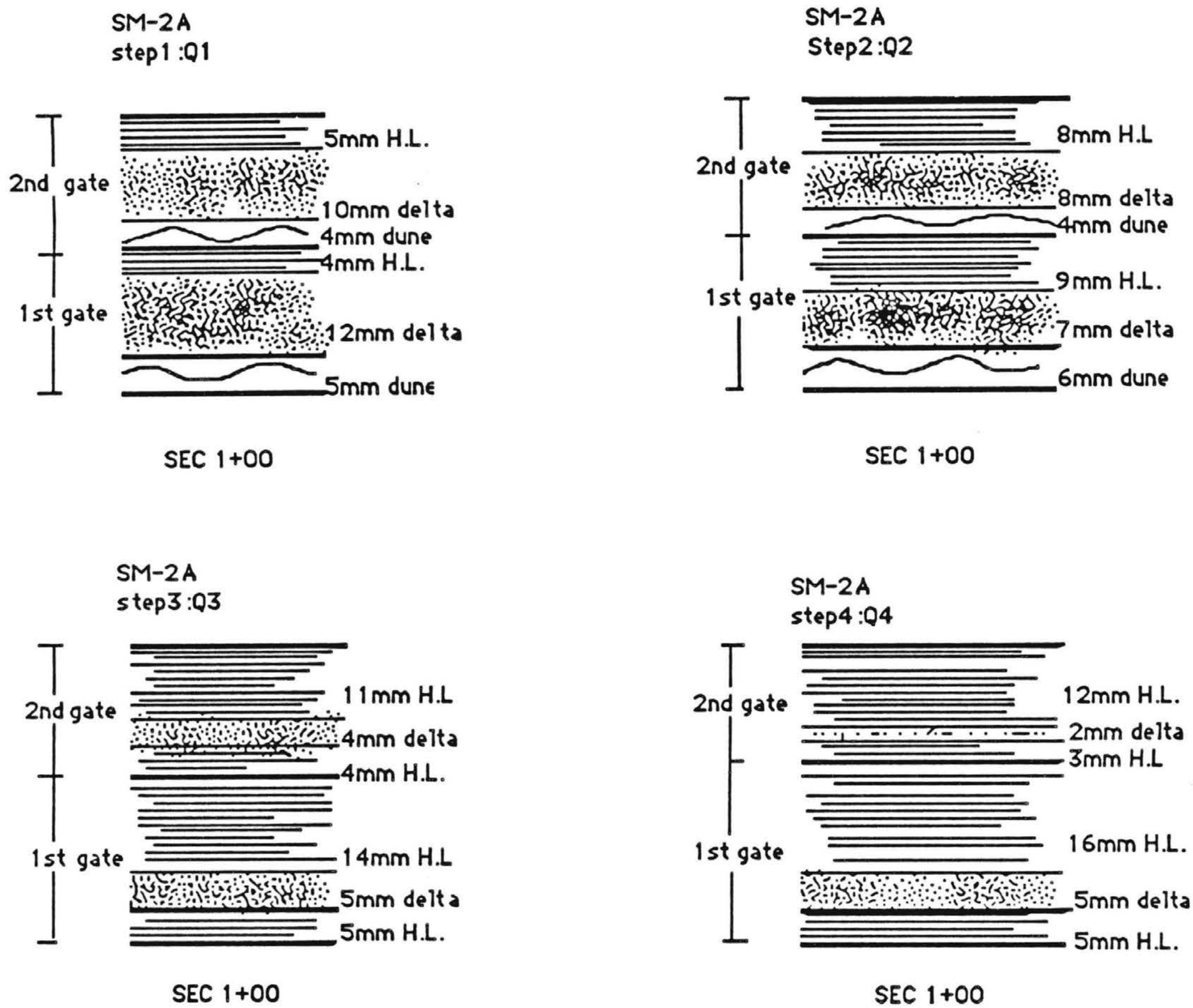


Fig. 5. Deposition sketches for SM-2A (horizontal)

4.2 Run SM-2B

(1) Objective of this run: Examine the lamination slope referring to flume bed under the adverse flume slope condition.

(2) Experimental conditions and data summary:

- Adverse flume slope (S = -0.005)
- SM-2 sand mixture (B2040 & ERC#4), D_{50} = 0.28mm
- Two small tailgates (2cm high each)
- The deposition for each step is shown on pictures as:

  Step 1 - Picture 17, 18 and 19;

  Step 2 - Picture 20 and 21;

  Step 3 - Picture 22, 23 and 24;

  Step 4 - Picture 25 and 26.

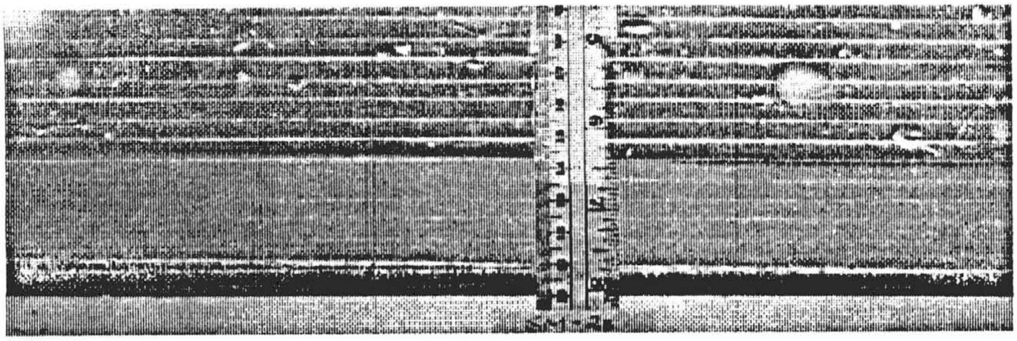
- The data for this run is summarized in Table 6 below.

Table 6. Data Summary for Run SM-2B

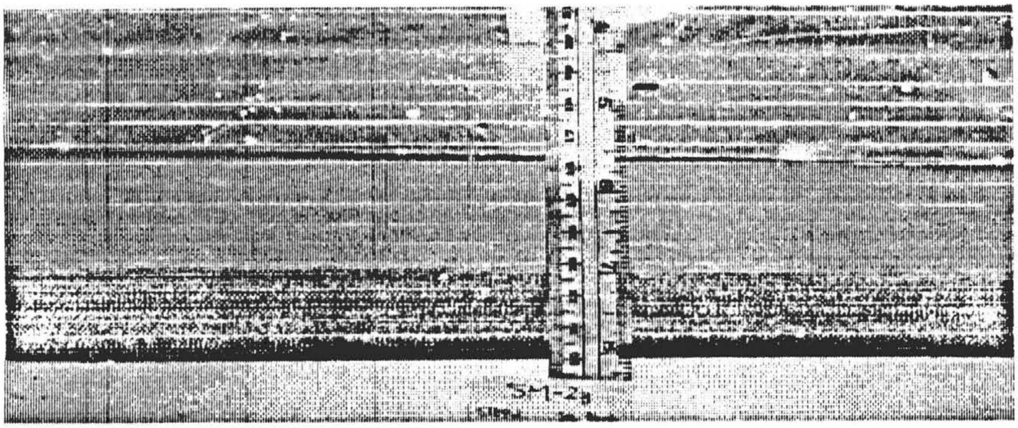
RUN: SM2B (Adverse slope S=-0.005) D_{50} = 0.28mm

STEP	Gate	Q cm^3/s	h cm	Vm cm/s	Vs cm/s	Sw	Shear $dyne/cm^2$	Fr	U*	f	thickness H. Lam mm	thickness Delta mm
SM2B-1	no	3425	3.4	64.99	76.43	0.016	38.39	1.124	6.196	0.072	4	4
	1st	3380	4.0	54.51	67.25	0.013	35.96	0.870	5.997	0.096	8	6
	2nd	3334	4.0	53.77	66.24	0.011	30.76	0.858	5.546	0.085	7	12
SM2B-2	1st	3728	3.3	72.88	75.63	0.016	36.29	1.281	6.024	0.054	11	11
	2nd	3601	4.1	56.66	65.93	0.011	28.90	0.893	5.376	0.072	6	9
SM2B-3	no	3789	3.4	71.89	73.94	0.016	38.39	1.245	6.196	0.059	4	5
	1st	3665	3.8	62.22	71.69	0.012	31.48	1.019	5.611	0.065	8	6
	2nd	3644	4.0	58.77	66.40	0.012	32.52	0.938	5.703	0.075	7	8
SM2B-4	1st	4121	4.0	66.46	71.82	0.019	49.12	1.061	7.008	0.088	10	11
	2nd	3988	4.1	62.75	69.01	0.013	34.68	0.989	5.889	0.070	8	12

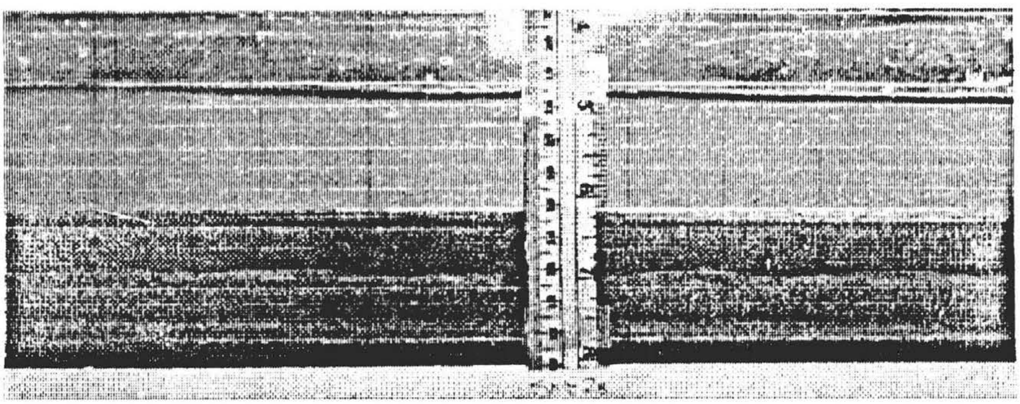
Q = flow discharge; h = water depth SEC1+00; Vm = mean velocity; Vs = surface velocity Sw = water surface slope; shear = bed shear stress; Fr = Froude number; U* = friction velocity; f = friction force coefficient; H.Lam = horizontal lamination.



Picture 17

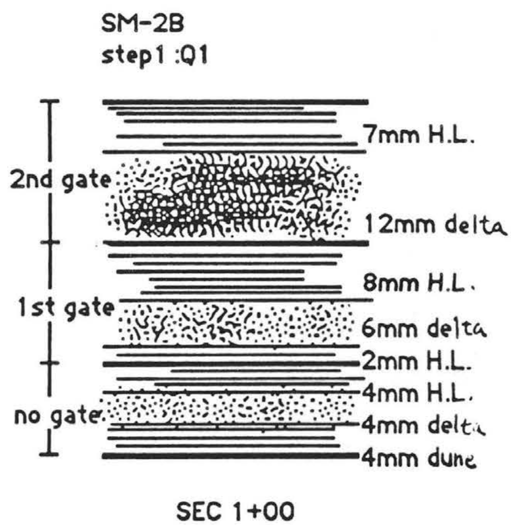


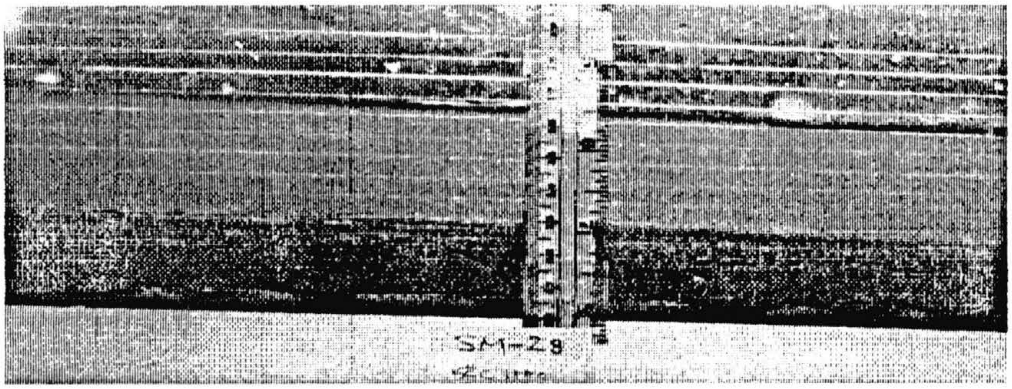
Picture 18



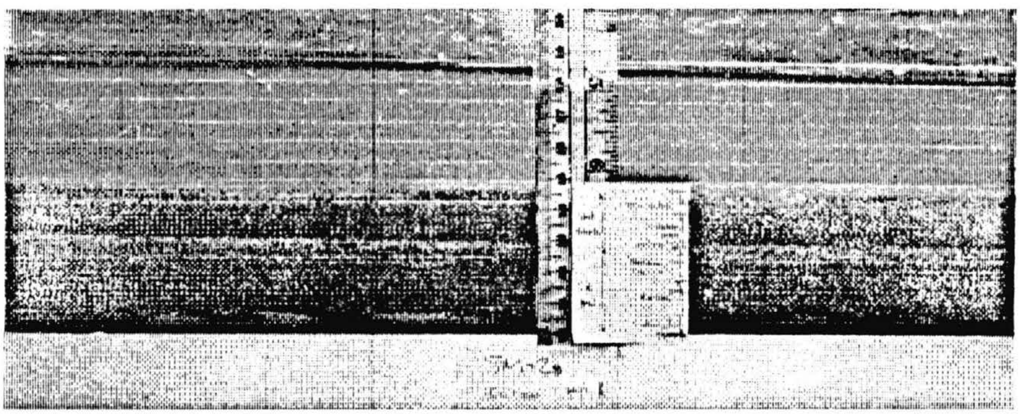
Picture 19

Run SM2-B, Step 1 (adverse slope)

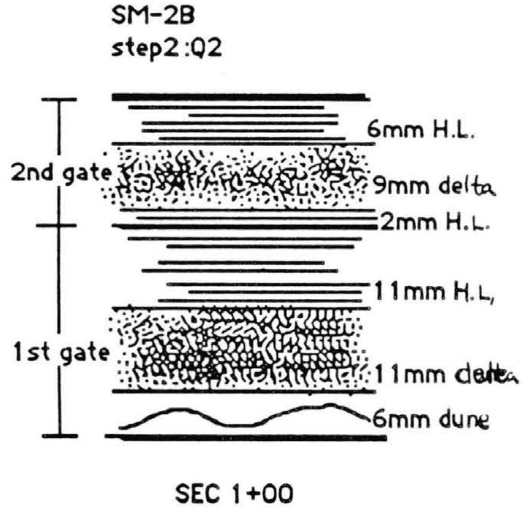




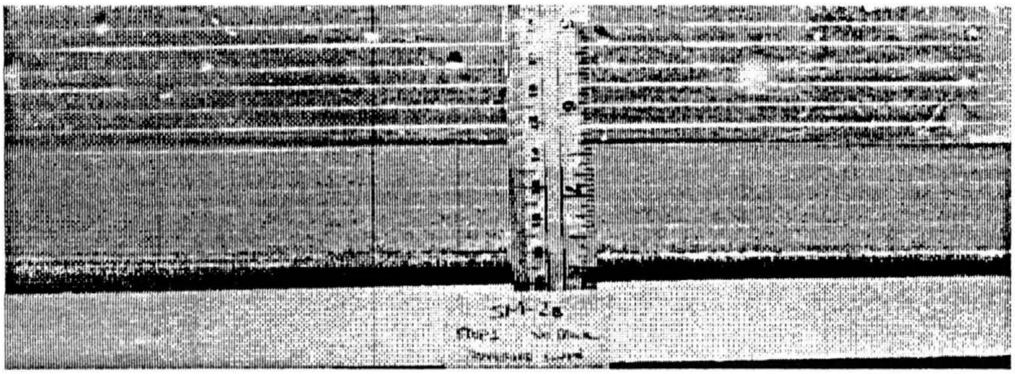
Picture 20



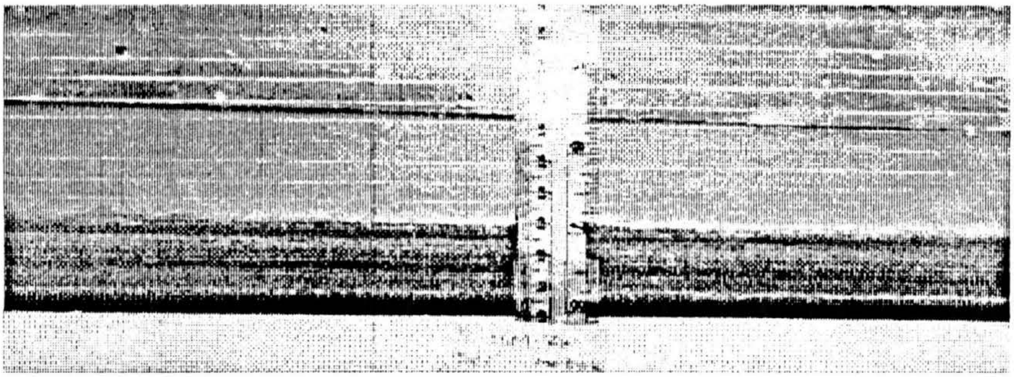
Picture 21



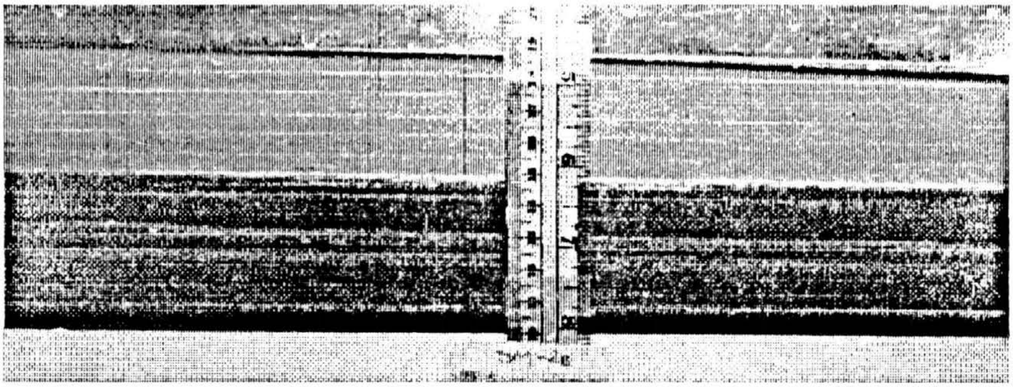
Run SM-2B, Step 2 (adverse slope)



Picture 22



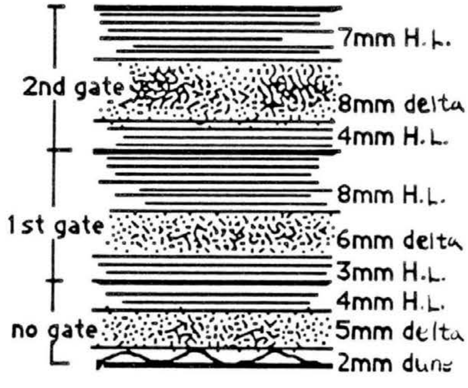
Picture 23



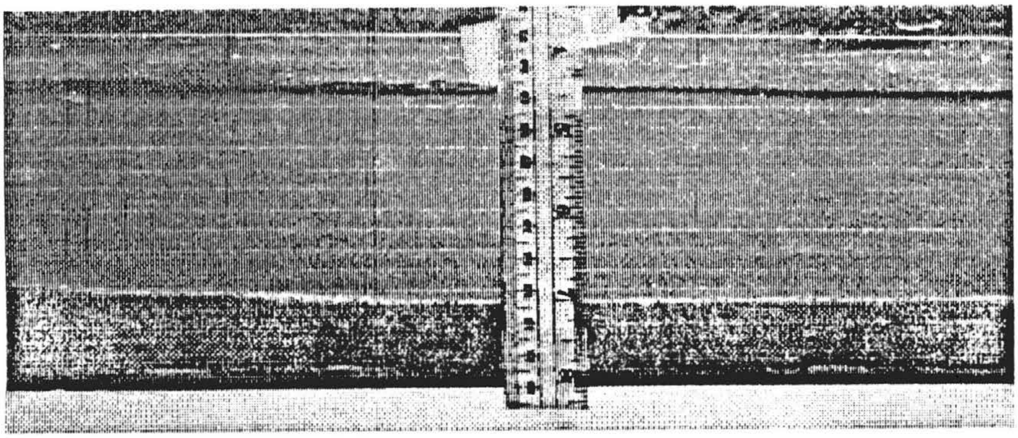
Picture 24

Run SM-2B, Step 3 (adverse slope)

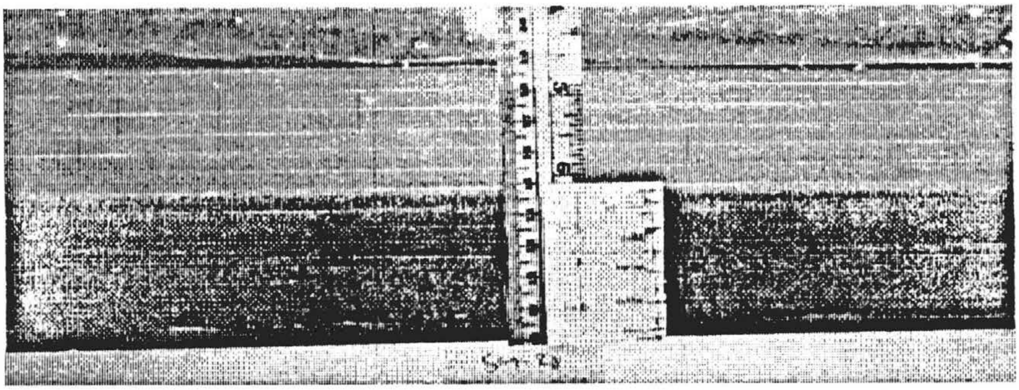
SM-2B
step3 :Q3



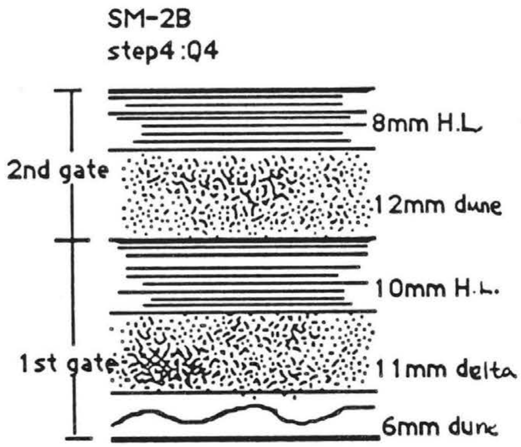
SEC 1+00



Picture 25



Picture 26



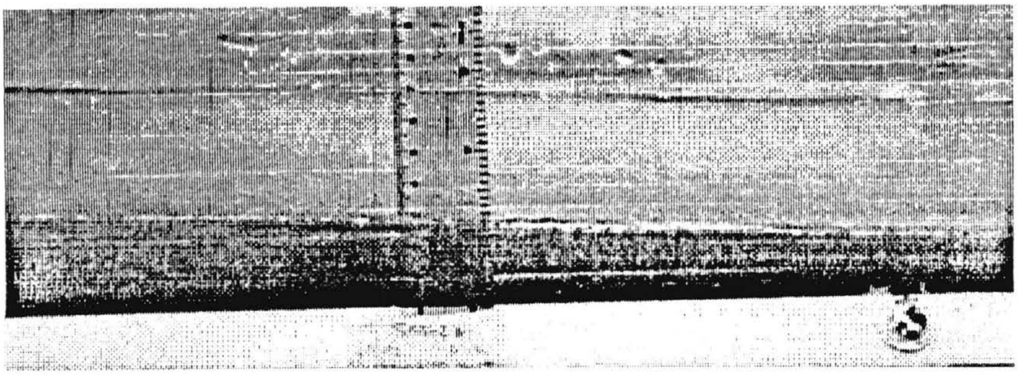
Run SM-2B, Step 4 (adverse slope)

(3) Results and Conclusions of Run SM-2B:

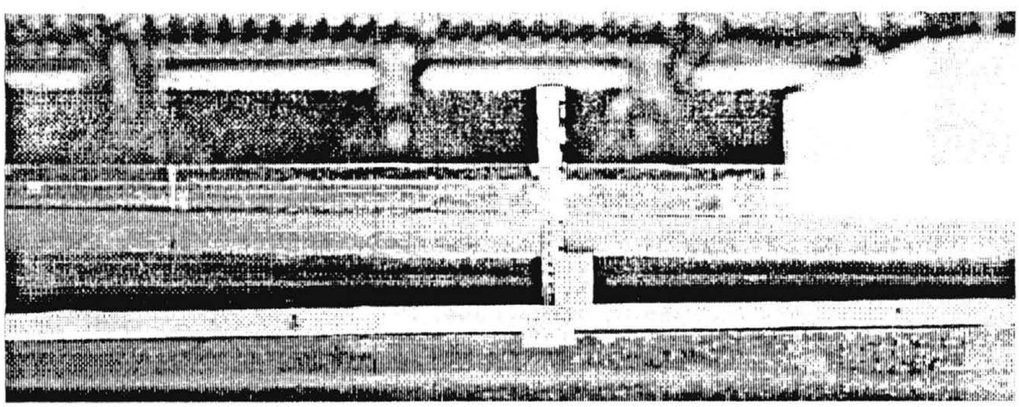
(a) From the observation of laminae deposition we can find that the horizontal lamination is subparallel to its boundary of previous deposition instead of flume bed (as shown on Picture 27). It is similar to the results of Berthault's experiment (1988) in calm water-the slope of the bed surface has little influence on lamination and seems to favor it.

(b) In the observation of step 4 we could find a series of extremely low-relief sandwaves migrating as shown on Picture 28. The Froude number for this step is 0.989 which is nearly unity. This phenomenon is similar to the observation in Smith's report (1971) and the experiment of McBride et al. (1975). The extremely low-relief sandwave should be an important factor in the formation of horizontal lamination.

(c) The deposition for each run is sketched as shown in Figure 6.



Picture 27
Horizontal laminae slope referring to flume bed
Run SM-2B (adverse slope)



Picture 28
Very low-relief sand waves migration in the formation of horizontal lamination
Run SM-2B (adverse slope)

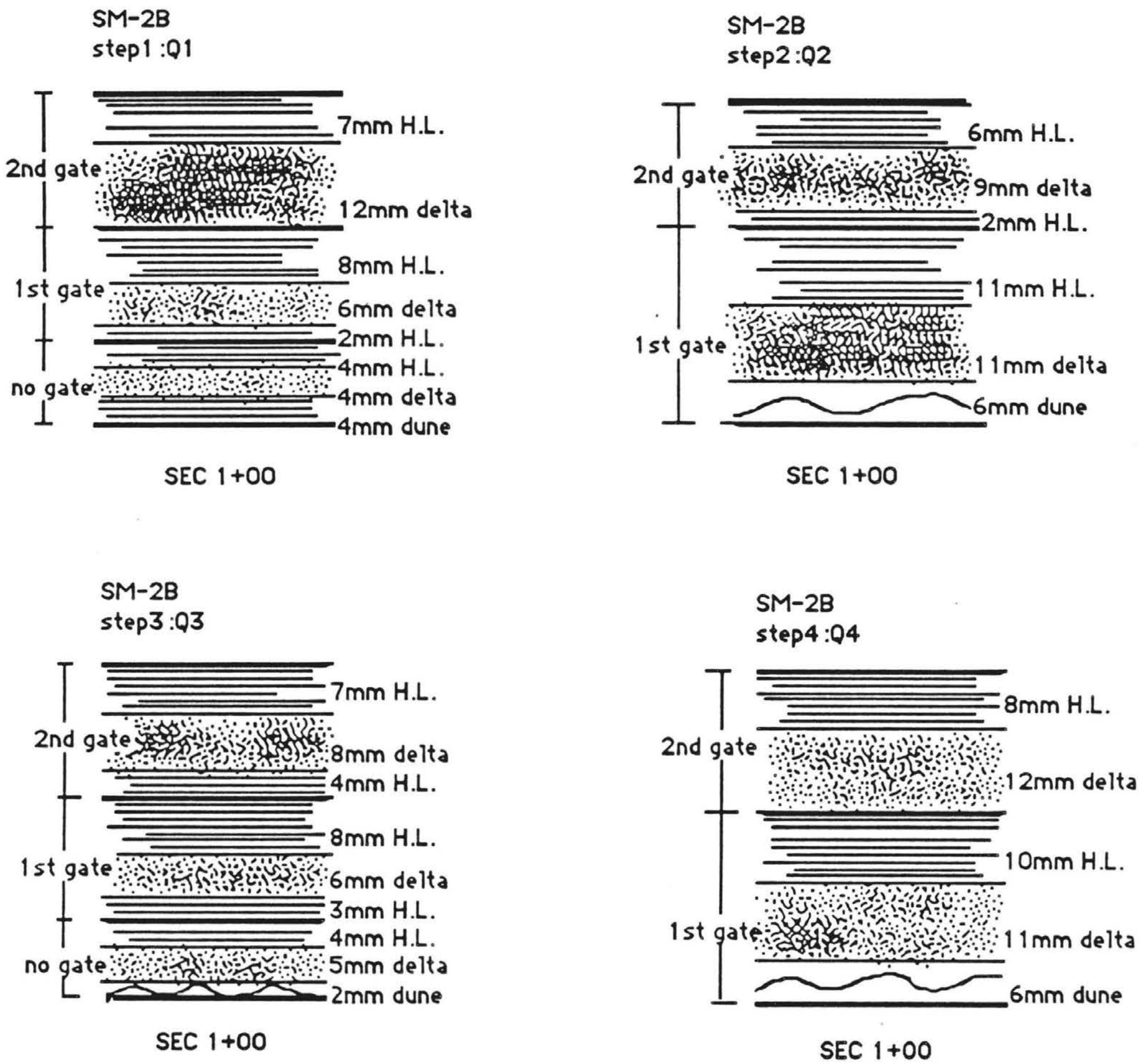


Fig. 6. The deposition of SM-2B (adverse slope)

4.3 Run SM-2C

(1) Objective of this run: Examine the lamination slope referring to flume bed under the positive flume slope condition.

(2) Experimental conditions and data summary

- Positive flume slope (S = + 0.005)
- SM-2 Sand Mixture (B2040 & ERC #4), D_{50} = 0.28mm
- Two small tailgates (2cm high each)
- The deposition for each step is shown on picture as:

  Step 1 - Picture 29, 30 and 31

  Step 2 - Picture 32, 33 and 34

  Step 3 - Picture 35, 36 and 37

  Step 4 - Picture 38, 39 and 40

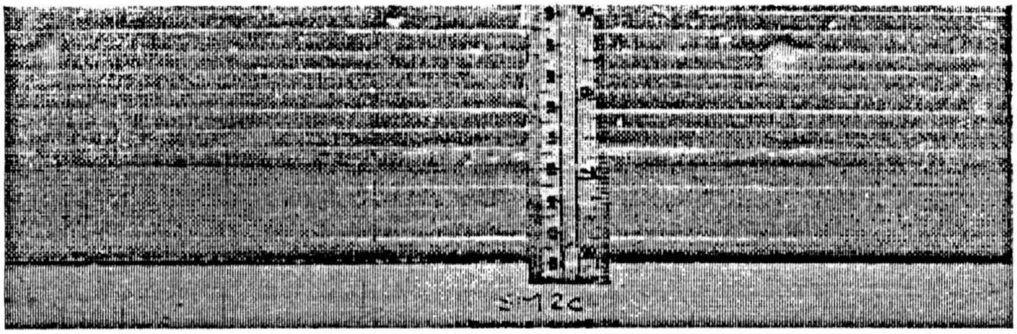
- The data for this run is summarized in Table 7 below.

Table 7. Data Summary for Run SM2C

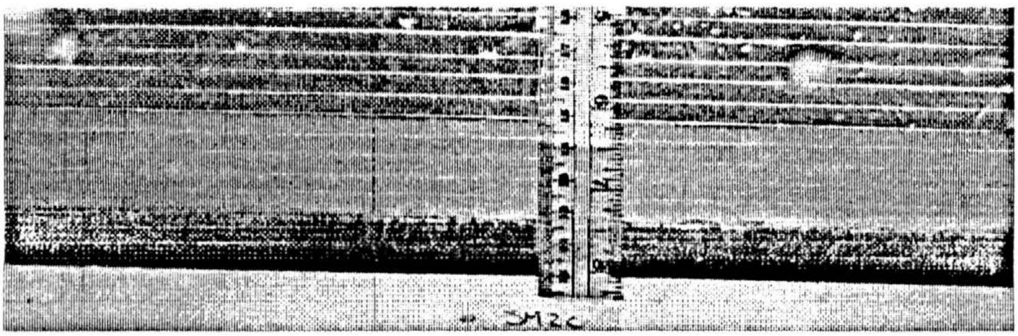
RUN: SM2C (Positive slope S=+0.005) D_{50} = 0.28mm

STEP	GATE	Q cm^3/s	h cm	Vm cm/s	Vs cm/s	Sw	Shear dyne/cm^2	Fr	U* cm/s	f	thickness H. Lam mm	thickness Delta mm
SM2C-1	no	3019	3.0	64.92	70.31	0.012	25.60	1.197	5.060	0.048	2	0
	1st	2887	3.5	53.21	65.90	0.009	21.45	0.908	4.631	0.060	9	6
	2nd	2778	3.7	48.43	56.45	0.007	17.37	0.804	4.168	0.059	6	8
SM2C-2	no	3558	3.2	71.73	79.88	0.013	29.03	1.280	5.388	0.045	2	0
	1st	3470	3.5	63.96	69.33	0.018	42.72	1.092	6.536	0.083	10	5
	2nd	3470	3.8	58.91	61.98	0.009	22.68	0.965	4.763	0.052	7	9
SM2C-3	no	4102	3.5	75.61	79.25	0.017	40.35	1.291	6.352	0.056	3	0
	1st	4121	4.0	66.46	74.81	0.013	33.81	1.061	5.815	0.061	12	5
	2nd	4007	4.5	57.44	62.90	0.009	25.33	0.865	5.033	0.061	7	5
SM2C-4	no	4514	3.8	76.63	83.84	0.016	40.18	1.255	6.338	0.054	3	0
	1st	4497	4.1	70.76	78.75	0.016	42.25	1.116	6.500	0.067	10	6
	2nd	4428	4.4	64.92	70.76	0.011	30.47	0.988	5.520	0.057	9	4

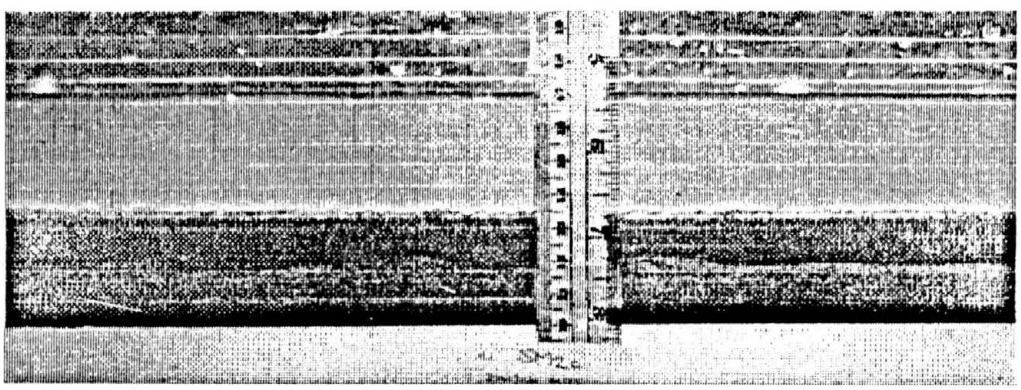
Q = flow discharge; h = water depth SEC1+00; Vm = mean velocity; Vs = surface velocity Sw = water surface slope; shear = bed shear stress; Fr = Froude number; U* = friction velocity; f = friction force coefficient; H.Lam = horizontal lamination.



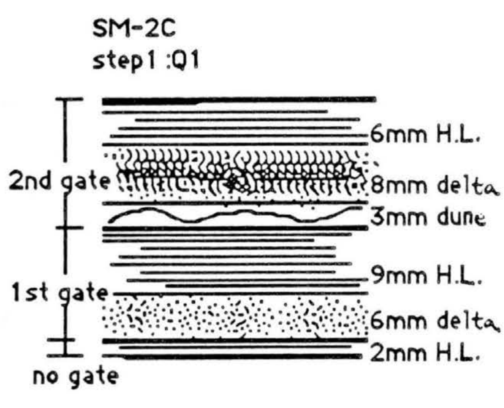
Picture 29



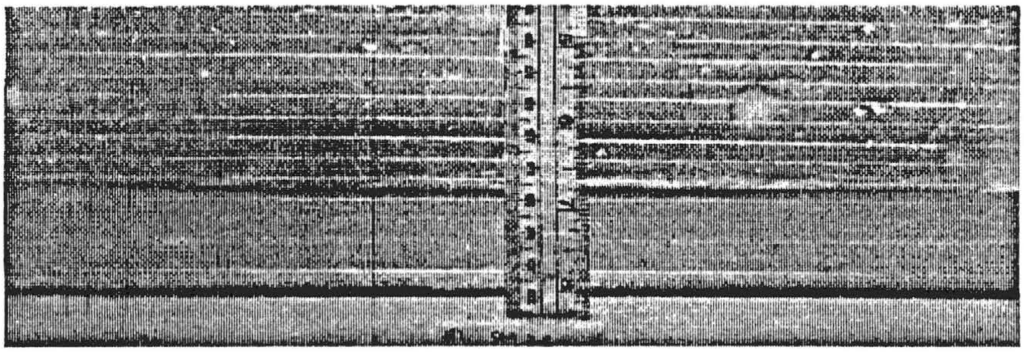
Picture 30



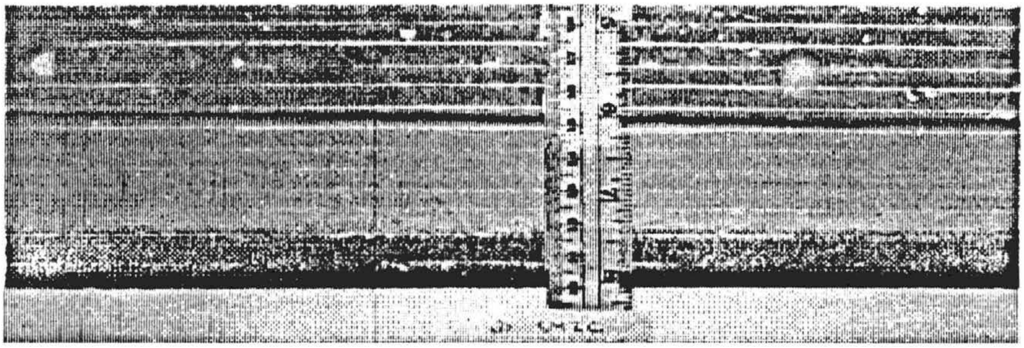
Picture 31



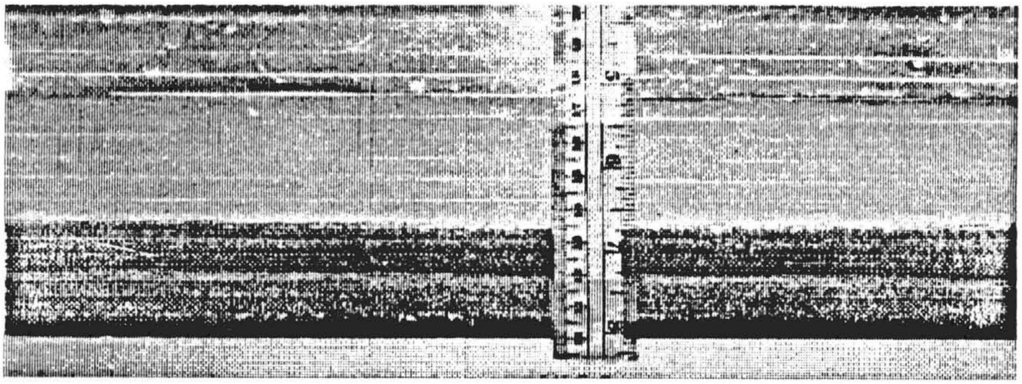
Run Sm-2C, Step 1 (positive slope)



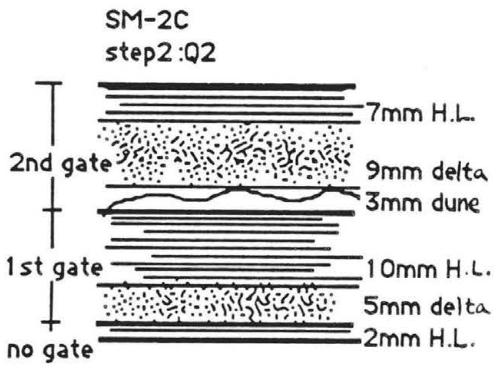
Picture 32



Picture 33

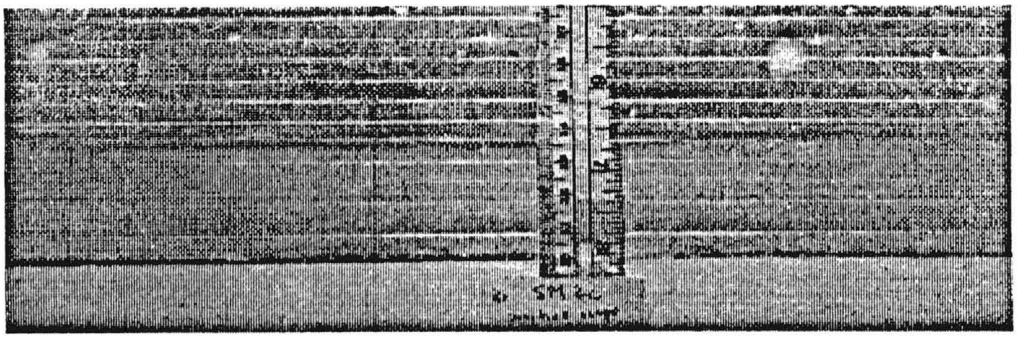


Picture 34

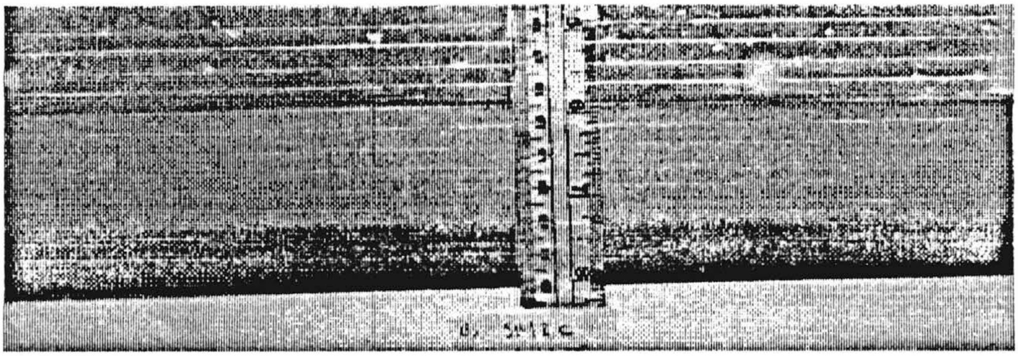


SEC 1+00

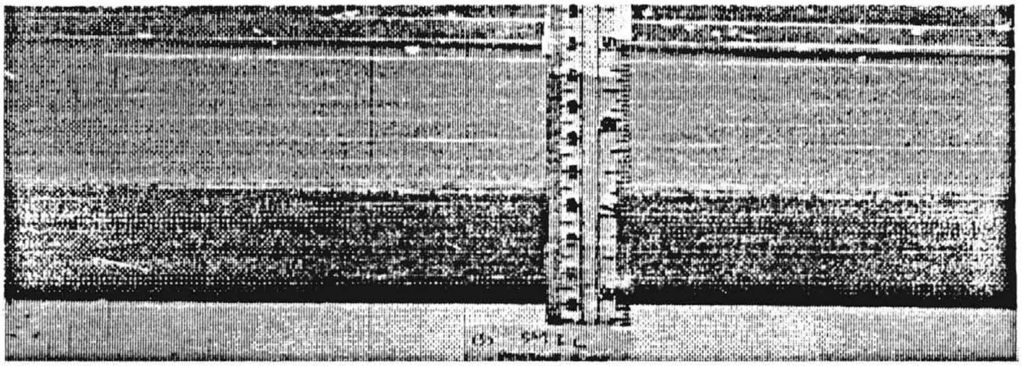
Run SM-2C, Step 2 (positive slope)



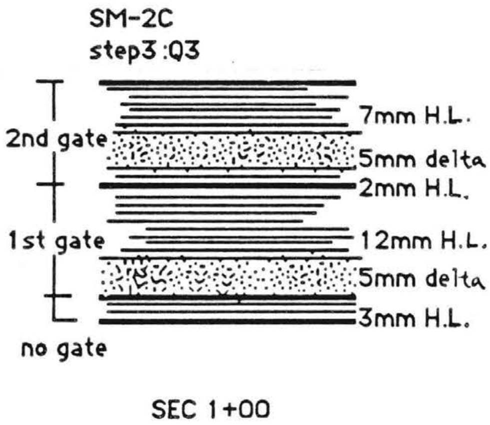
Picture 35



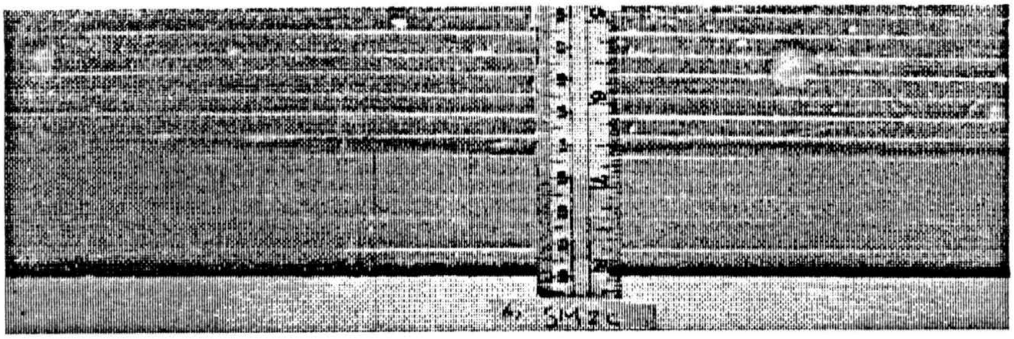
Picture 36



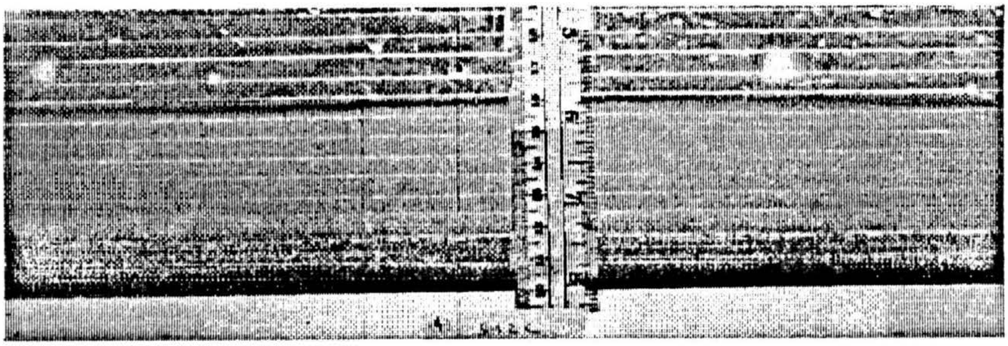
Picture 37



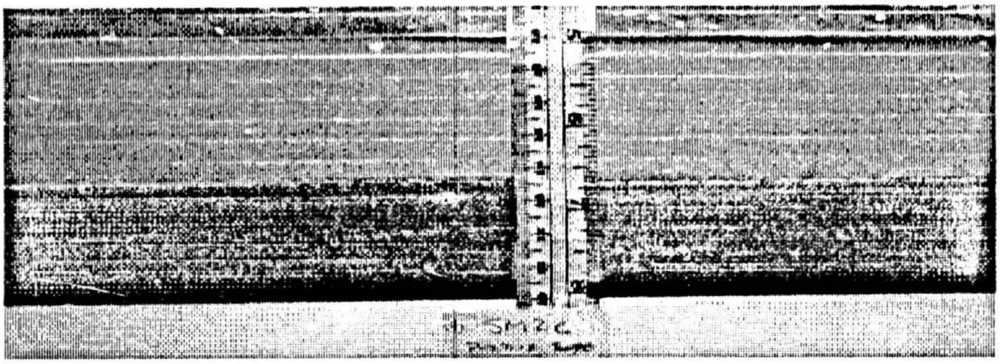
Run SM-2C, Step 3 (positive slope)



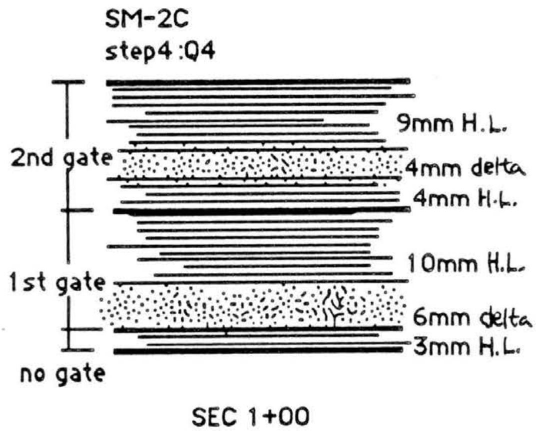
Picture 38



Picture 39



Picture 40



Run SM-2C, Step 4 (positive slope)

(3) Results and Conclusions for Run SM-2C:

(a) The horizontal lamination is subparallel to the underlying laminae and not parallel to the flume bed. These results are in agreement with those of Berthault (1988).

(b) The thickness of horizontal lamination is also dependent on flow velocity (comparing 2nd gate condition, thickness increased from 6mm, 7mm, 7mm to 9mm as velocity increased). The deposition for each step is sketched on Figure 7.

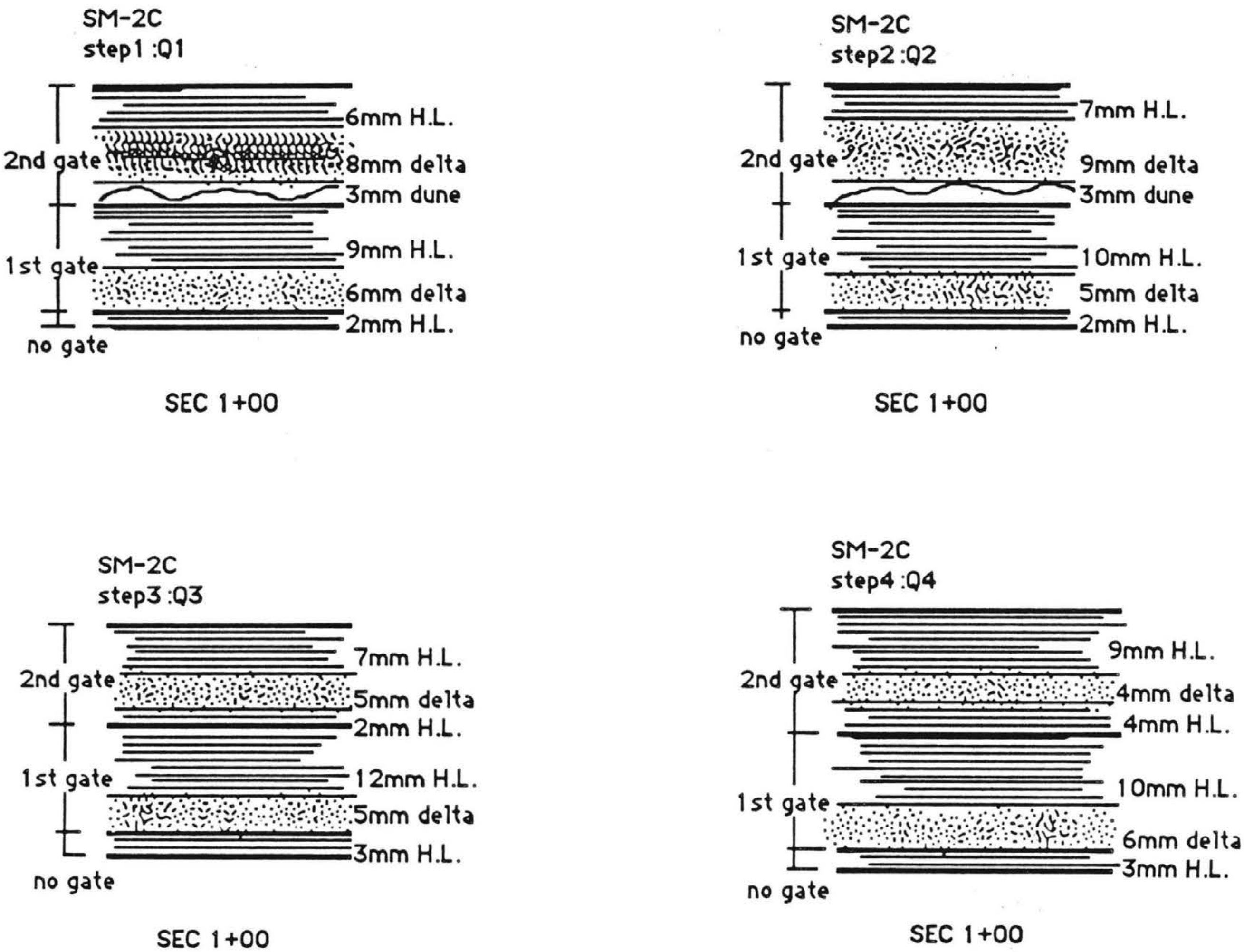


Fig. 7. The deposition of SM-2C (positive slope)

4.4 Run SM-2D

(1) Objective of this run: **Examine** the influence of larger tailgate conditions on the thickness of horizontal lamination.

(2) Experimental conditions and data summary

- Horizontal flume slope
- SM2 sand mixture (B2040 & ERC #4), D_{50} = 0.28mm
- First small gate (2cm high) and second larger gate (4cm high)
- The deposition for each step is shown:

  Step 1 - Picture 41, 42 and 43

  Picture 44,45 and 46 (Infrared pictures)*

  Step 2 - Picture 47, 48 and 49

*Note: We took infrared pictures for this run only. The results did not justify taking infraed photographs for the other runs and therefore color prints were shown for every run.

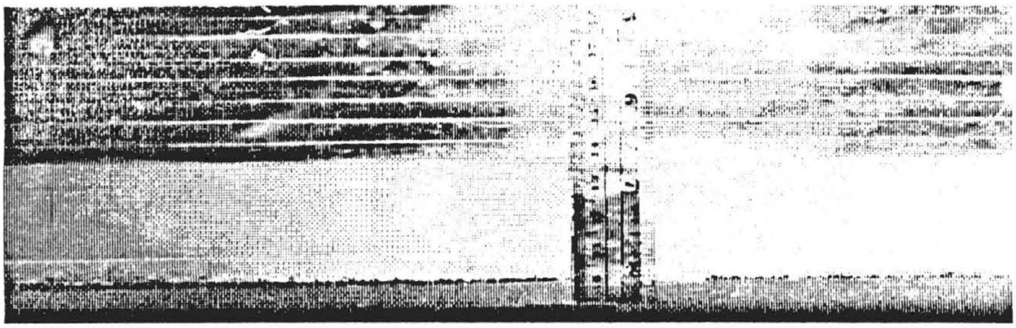
- The data for this run is summarized on Table 8 below.

Table 8. Data Summary for SM2D

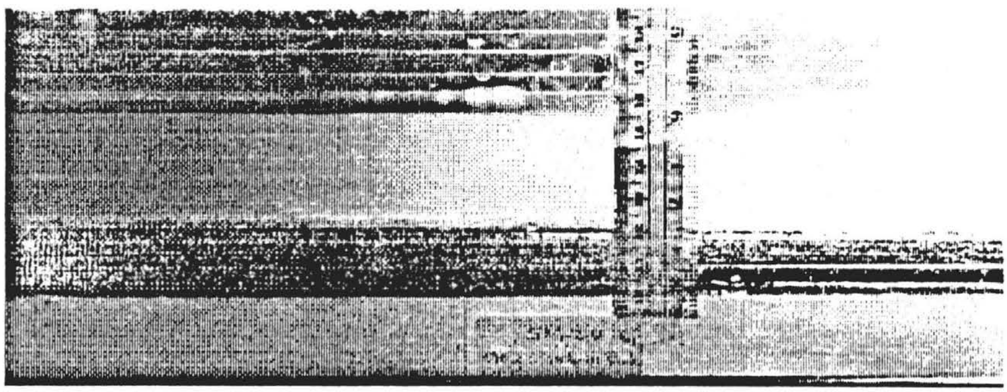
Run: SM2D (Horizontal) D_{50} = 0.28mm

STEP	Gate	Q cm^3/s	h cm	Vm cm/S	Vs cm/s	Sw	Shear $dyne/cm^2$	Fr	U*	f	thickness H.Lam mm	thickness Delta mm
SM2D-1	no	3404	3.4	64.57	71.80	0.010	24.78	1.118	4.978	0.047	2	0
	1st	3334	3.5	61.45	67.26	0.01	23.62	1.049	4.860	0.050	10	5
	2nd(L)	2750	3.4	52.18	62.65	0.004	9.263	0.904	3.043	0.027	4	29
SM2D-2	no	4480	3.3	87.58	99.01	0.027	61.92	1.540	7.869	0.064	7	0
	1st	4428	3.5	81.62	91.52	0.02	47.25	1.393	6.874	0.056	21	0
	2nd(L)	4026	4.0	64.93	66.10	0.010	27.66	1.037	5.259	0.052	5	23

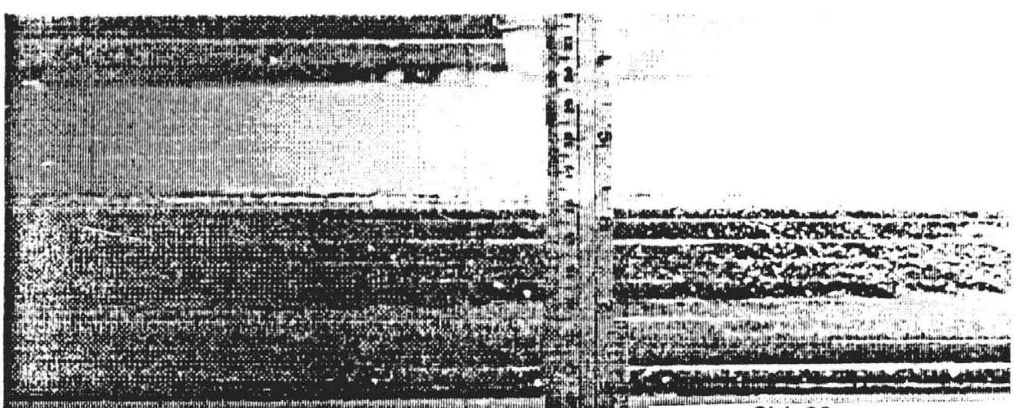
Q = flow discharge; h = water depth SEC1+00; Vm = mean velocity; Vs = surface velocity Sw = water surface slope; shear = bed shear stress; Fr = Froude number; U* = friction velocity; f = friction force coefficient; H.Lam = horizontal lamination.



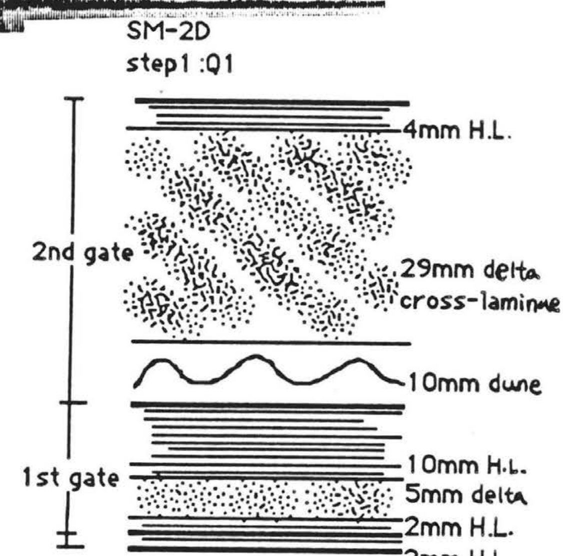
Picture 41



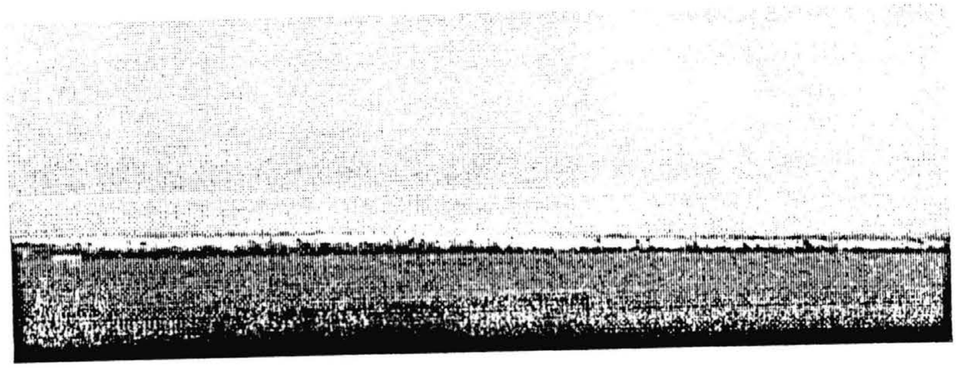
Picture 42



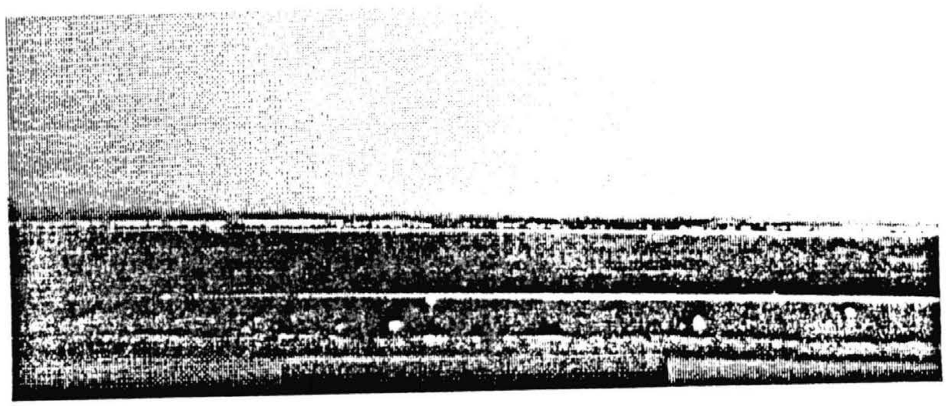
Picture 43



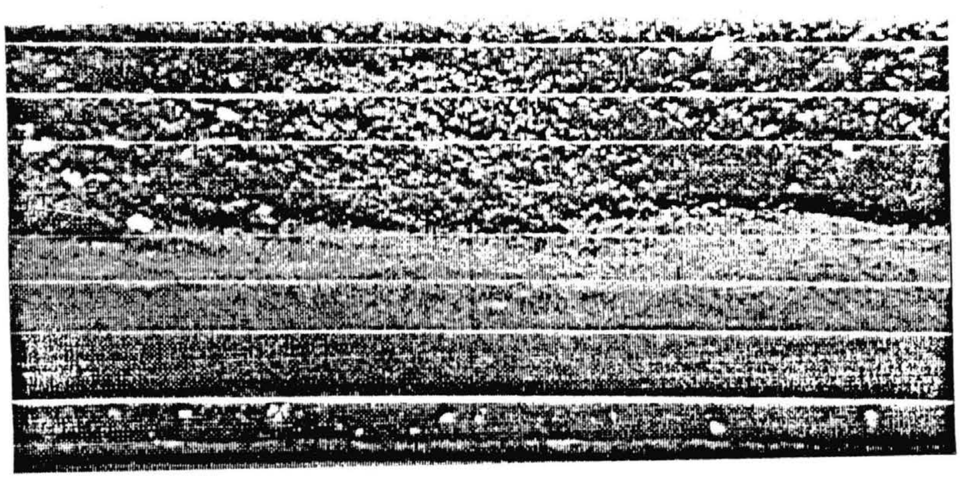
Run SM-2D, Step 1 (horizontal)



Picture 44



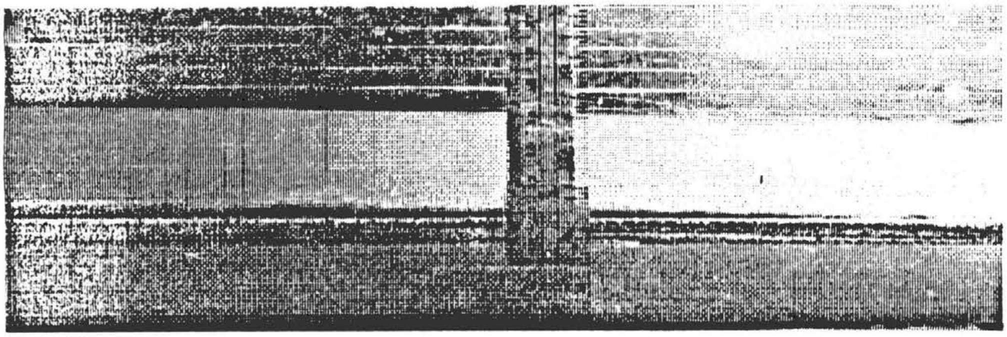
Picture 45



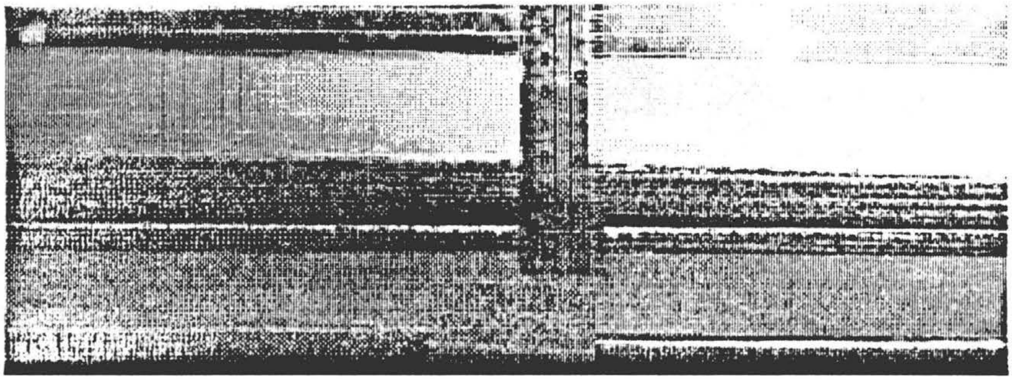
Picture 46

Run SM-2D, Step 1 (horizontal)

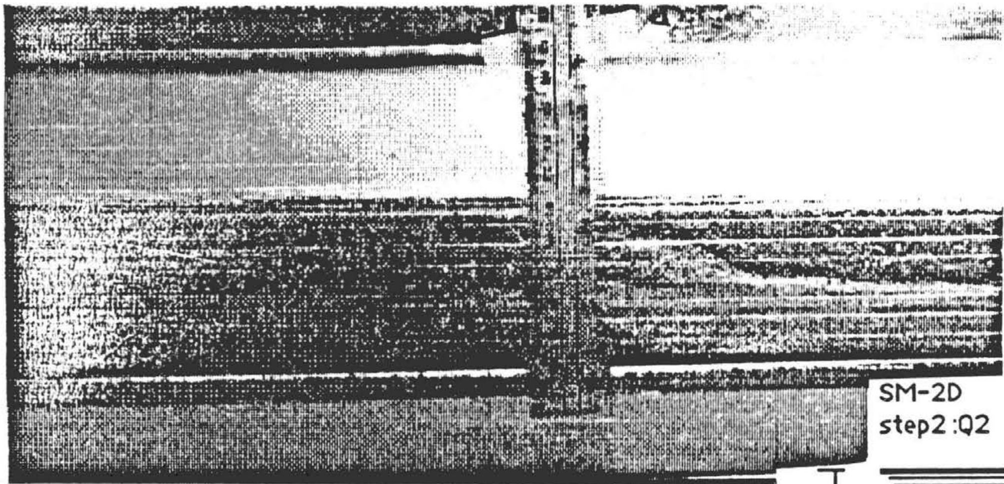
- Infrared picture



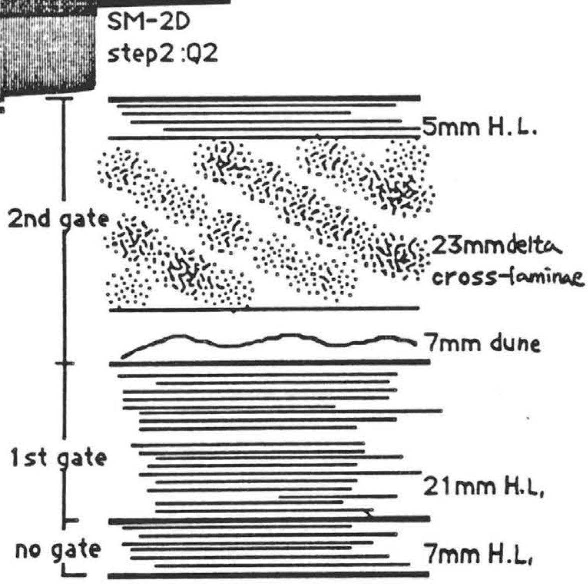
Picture 47



Picture 48



Picture 49



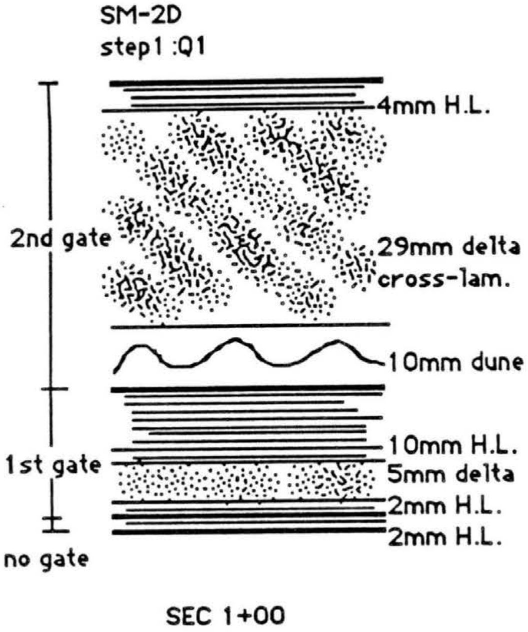
Run SM-2D, Step 2 (horizontal)

(3) Results and Conclusions of Run SM-2D:

(a) The larger second tailgate reduces a thicker delta deposit. On the other hand it does not increase the thickness of horizontal lamination but decrease it.

(b) The thickness of horizontal lamination is dependent on flow velocity (comparing 1st gate condition, it increased from 10mm to 21mm). The deposition for each run is sketched on Figure 8.

(c) Under larger flow velocity condition delta may not occur as in the 1st gate of step 2 (SM-2D-2).



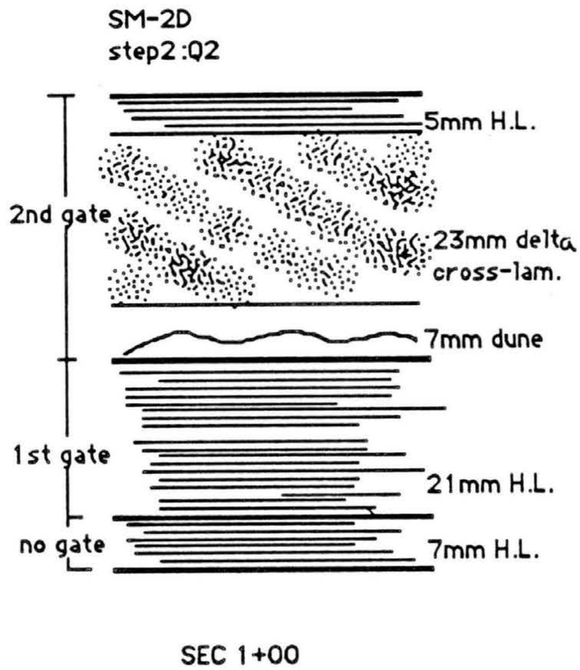


Fig. 8. The deposition of SM-2D (horizontal)

4.5 Run SM-3A

(1) Objective of this run: Examine the thickness of horizontal lamination in a coarser sand mixture.

(2) Experimental conditions and data summary

- Horizontal flume
- SM-3 sand mixture (B3060 & ERC #2), D_{50} = 0.62mm
- Two small tailgates (2cm high each)
- The deposition for each step is shown on pictures as

  Step 1 - Picture 50, 51 and 52

  Step 2 - Picture 53, 54 and 55

  Step 3 - Picture 56, 57 and 58

  Step 4 - Picture 59, 60 and 61

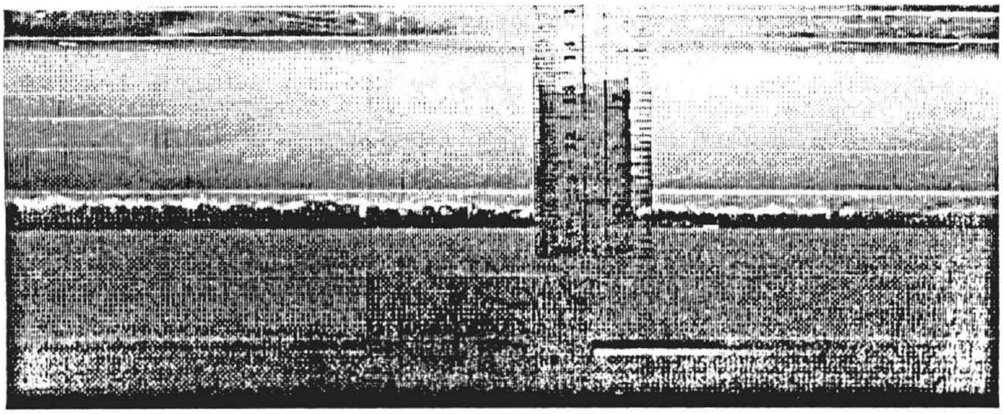
- The data for this run is summarized in Table 9 below.

Table 9. Data Summary for SM-3A

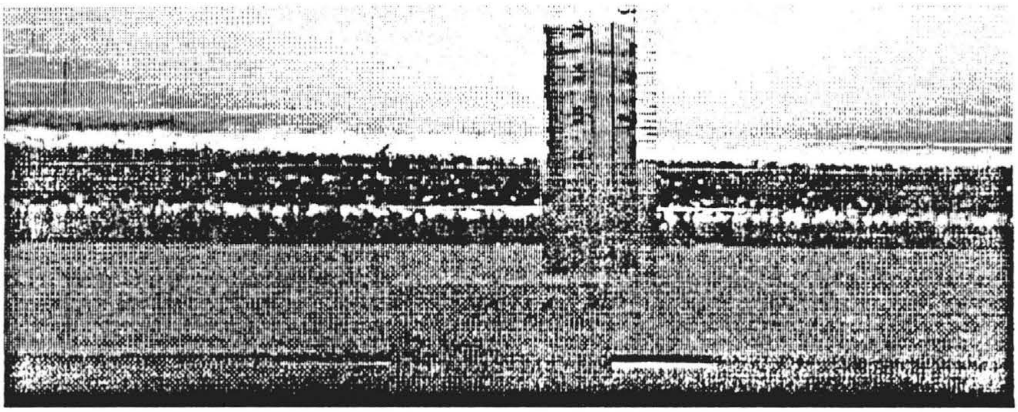
RUN: SM3A (Horizontal) D_{50} = 0.62mm

Step	Gate	Q cm^3/s	h cm	Vm cm/s	Vs cm/s	Sw	Shear $dyne/cm^2$	Fr	U* cm/s	f	thickness H.Lam mm	thickness Delta mm
SM3A-1	no	3727	3.5	68.70	81.53	0.014	33.08	1.173	5.751	0.056	?	0
	1st	3665	3.7	63.90	69.22	0.009	22.08	1.061	4.699	0.043	14	4
	2nd	3558	3.9	58.85	64.80	0.008	20.34	0.952	4.510	0.046	7	6
SM3A-2	no	3948	3.4	74.91	79.40	0.014	32.42	1.297	5.694	0.046	?	0
	1st	3909	3.9	64.66	71.10	0.012	30.51	1.045	5.523	0.058	11	5
	2nd	3850	3.9	63.68	63.96	0.01	25.42	1.030	5.042	0.050	11	5
SM3A-3	no	4195	3.8	71.22	83.88	0.016	39.98	1.167	6.323	0.063	8	0
	1st	4304	4.0	69.41	80.46	0.011	28.44	1.108	5.332	0.047	14	0
	2nd	4304	4.4	63.10	70.43	0.01	27.50	0.961	5.244	0.055	12	10
SM3A-4	no	5032	3.9	83.24	81.16	0.018	45.76	1.346	6.765	0.052	8	0
	1st	4764	4.2	73.17	74.42	0.015	40.04	1.140	6.327	0.059	16	3
	2nd	4939	4.5	70.81	77.52	0.01	27.9	1.066	5.282	0.044	13	4

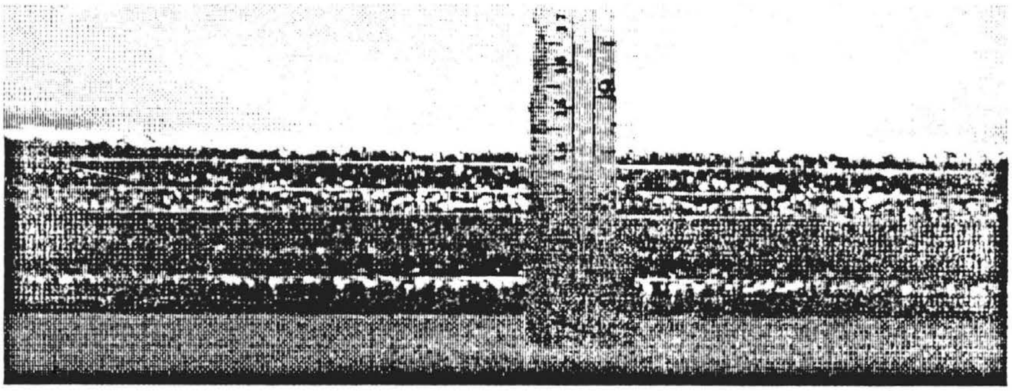
Note: ? = lamination type not clear
Q = flow discharge; h = water depth SEC1+00; Vm = mean velocity; Vs = surface velocity Sw = water surface slope; shear = bed shear stress; Fr = Froude number; U* = friction velocity; f = friction force coefficient; H.Lam = horizontal lamination.



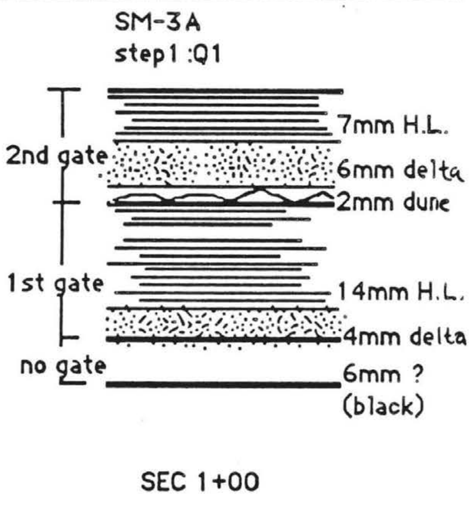
Picture 50



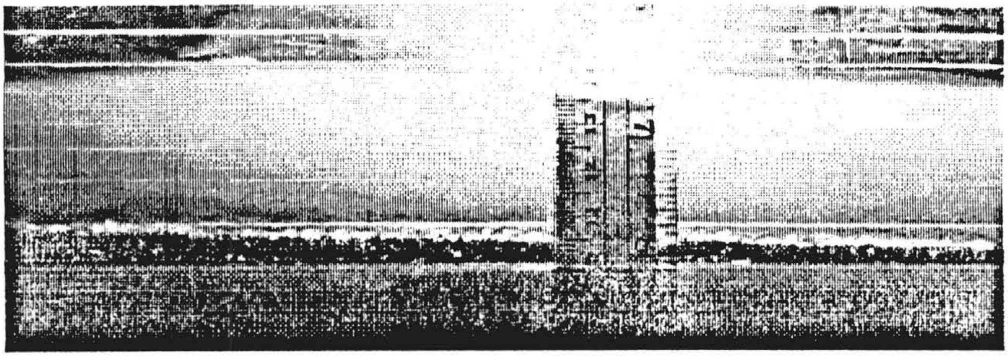
Picture 51



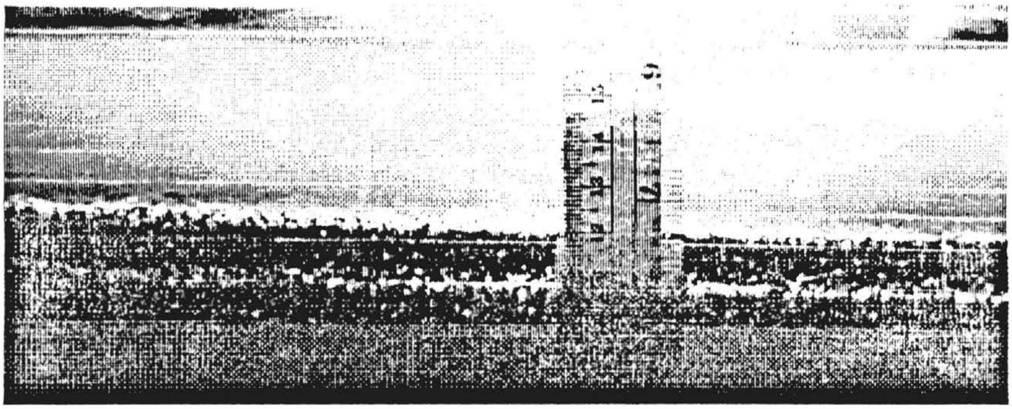
Picture 52



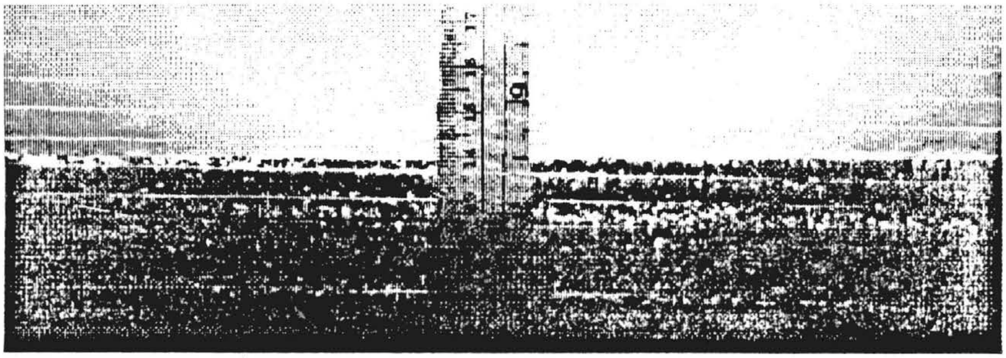
Run SM-3A, Step 1 (horizontal)



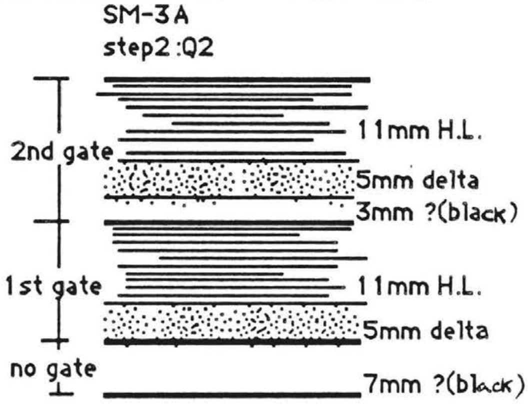
Picture 53



Picture 54

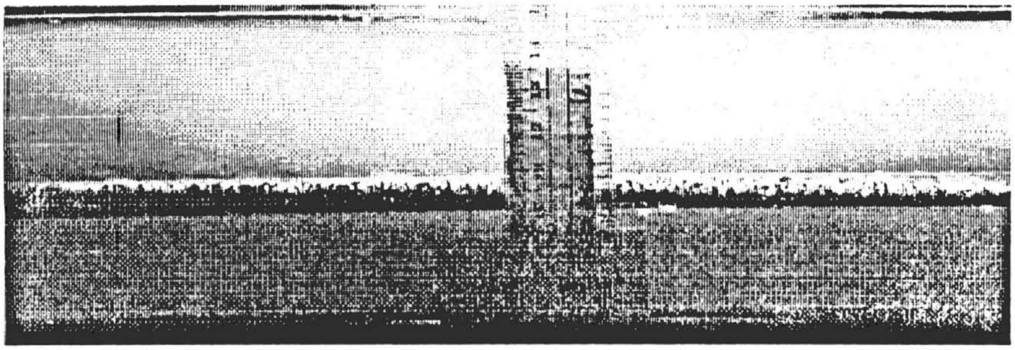


Picture 55

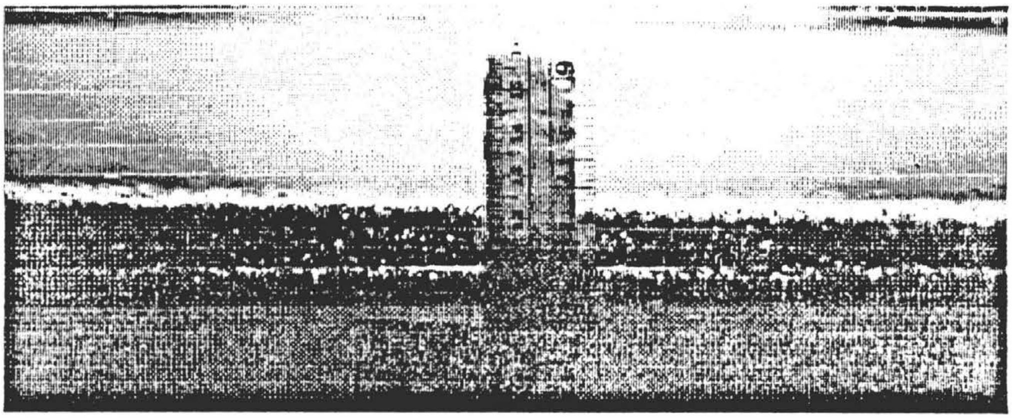


Run SM-3A, Step 2 (horizontal)

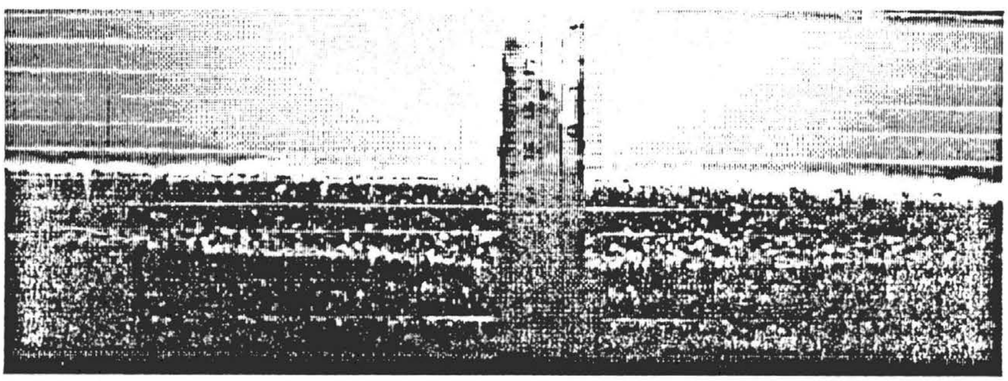
SEC 1+00



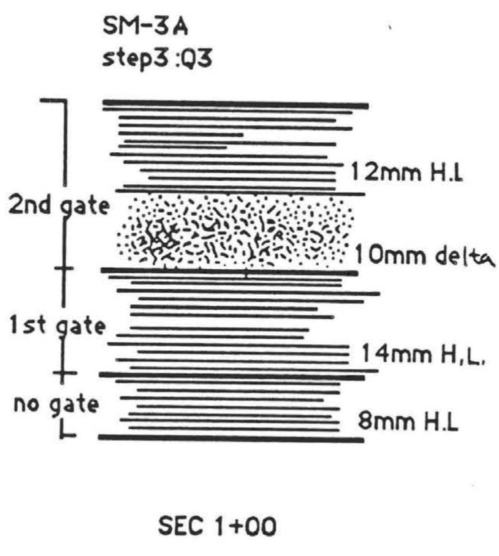
Picture 56



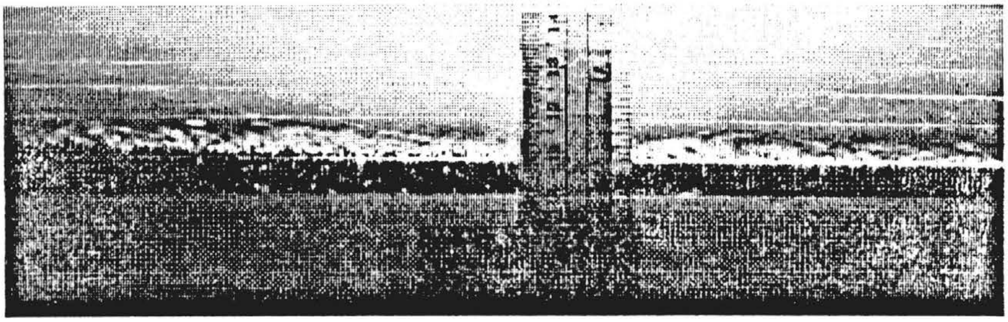
Picture 57



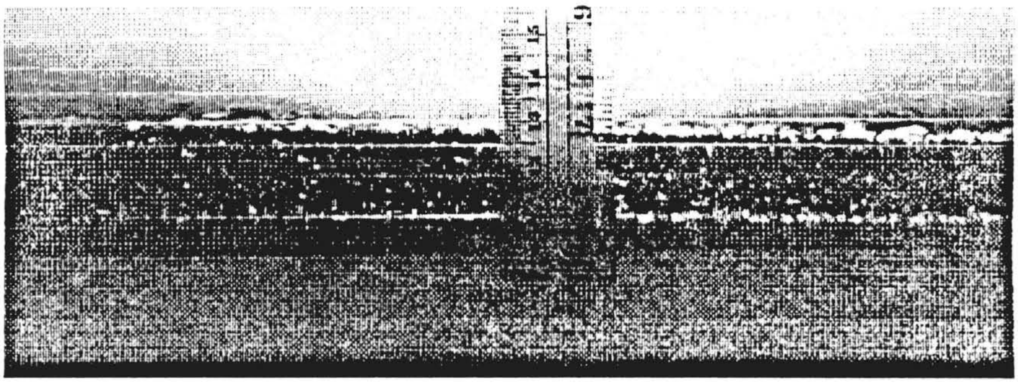
Picture 58



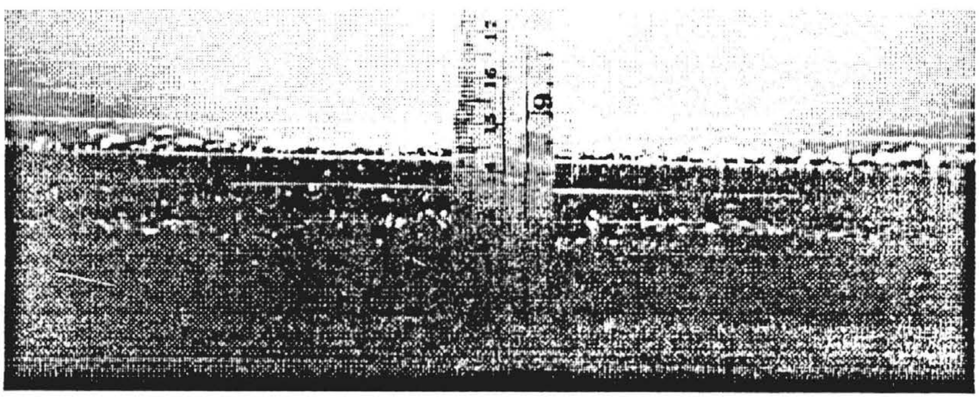
Run SM-3A, Step 3 (horizontal)



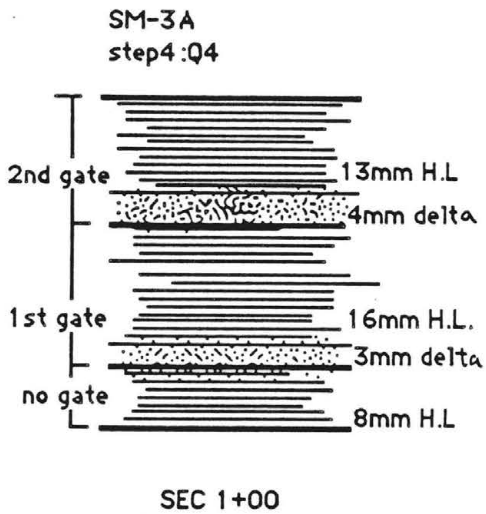
Picture 59



Picture 60



Picture 61



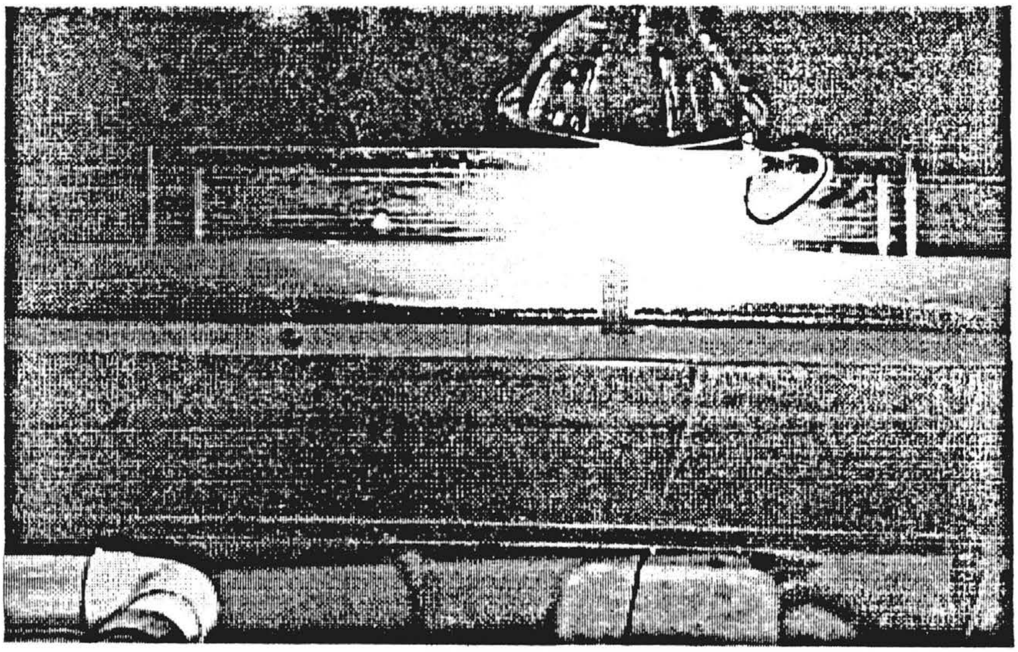
Run SM-3A, Step 4 (horizontal)

(3) Results and Conclusions of Run SM-3A:

(a) Under similar flow discharge as in the 1st gate between SM-3A-1 and SM-2B-2, the thickness of horizontal lamination in SM-3A-1 is larger than it is in SM-2B-3 (14mm in SM-3A-1 and 8mm in SM-2B-3). Overall, the thickness of horizontal lamination in SM-3A is larger than others in SM-2 at a similar range of flow discharge. This may be caused by the larger difference of particle size distribution in SM-3 (D_{50} in B3060: D_{50} in ERC #2 = 0.355mm: 1.20mm than SM-2 (D_{50} in ERC #4: D_{50} in B2040 = 0.16mm: 0.575mm). These results are similar to those of Berthault's experiment in still water (1986).

(b) We also observed a series of low-relief sandwaves migration during the formation of horizontal lamination (as shown in Picture 62). It is similar to the result of SM-2B and the observation of Smith's (1971) and McBride et al. (1975).

(c) The deposition for each step is sketched on Figure 9.



Picture 62
Low-relief sandwaves migration in the formation of horizontal lamination (SM-3A, horizontal)

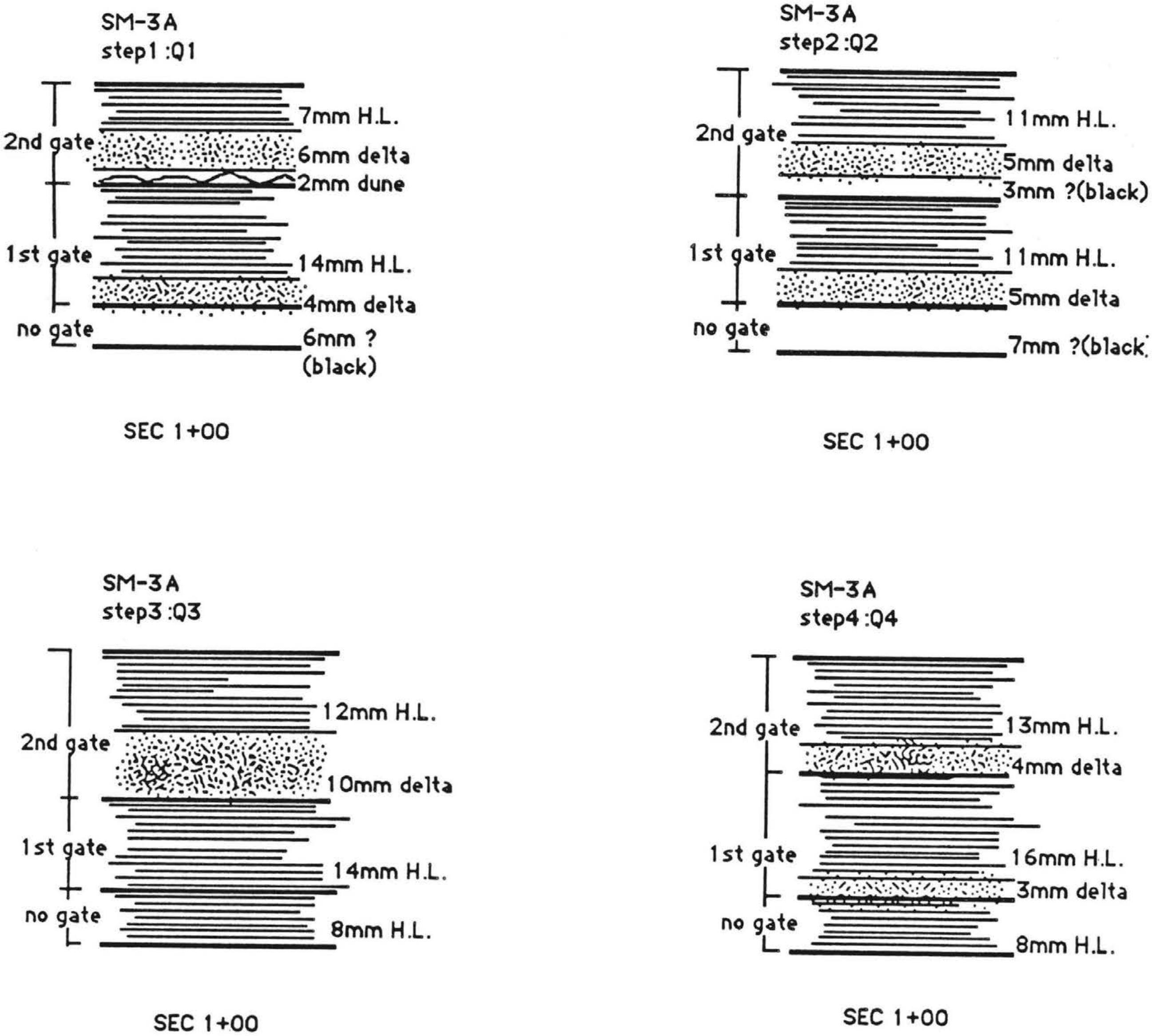


Fig. 9. The deposition of SM-3A (horizontal)

SUMMARY AND CONCLUSIONS

Laboratory experiments have been conducted on the process of horizontal lamination under flat bed conditions in a recirculating flume. A primary feature of the experimental program is the use of two different colors to separate the fines from the coarse sand particles. With these black and white sand mixtures, the laminae can be easily observed and documented. The horizontal lamination process has been scrutinized by analyzing four conditions of discharge for each plane bed condition. Two different mixtures are considered and the influence of tailgate size can also be determined from one run. Experiments were also conducted under various slopes including horizontal, adverse and positive slopes. A total of 5 runs and 18 steps is documented with measurements of discharge, flow depth, average velocity, surface velocity, water surface slope, bed shear stress, Froude number, shear velocity, resistance parameter and thickness of the delta and horizontal laminae deposits.

The results of the experimental program have been detailed in Section 4 and the primary conclusions can be summarized as:

1. The thickness of the deposit of horizontal laminae increases with flow velocity. These results confirm those of Berthault (1988) taken at much lower velocity.

2. The thickness of the deposit of horizontal laminae increases with the gradation of the sediment mixtures. This result also corroborates the previous findings of Berthault under tranquil flow conditions.

3. The thickness of the delta increases with he size of the tailgate and for downstream control. The thickness of the layer of horizontal laminae remains unchanged regardless of tailwater conditions.

4. The observations of the SM-2 experiments showed that the coarser particles kept rolling on a deposit of finer particles. The most intriguing phenomenon relates to the gradual thickening of the deposits of finer particles while the coarser particles keep rolling on the surface. This phenomenon certainly contradicts any prediction from either the Shields Diagram or the critical velocity criterion.

5. The experiments with adverse slope SM-2B indicates that the laminae do not necessarily remain parallel to the flume bed slope. Experiment SM-2C also demonstrates that they are not necessarily horizontal either.

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