SEDIMENTATION OF SAND MIXTURES in A VERTICAL CYLINDER

by

Pierre Y. Julien and Yongqiang Lan

Prepared for

M. Guy Berthault

Colorado State University

March 1990

Report CER89-90PYJ-YQL13

Engineering Research Center

Colorado State University

Fort Collins, Colorado 80523

U.S.A

SEDIMENTATION OF SAND MIXTURES
in
A VERTICAL CYLINDER

by

Pierre Y. Julien and Yongqiang Lan

Prepared for

M. Guy Berthault

Colorado State University

March 1990

Report CER89-90PYJ-YQL13

Engineering Research Center

Colorado State University

Fort Collins, Colorado 80523

U.S.A

ACKNOWLEDGEMENTS

We are very grateful to M. Guy Berthault who not only provided financial support for the experimental program but manifested great enthusiasm during the process of the experimental program.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURES

D_s	Diameter of particle
D_{10}	particle size of which 10% of mixture is finer
D_{25}	particle size of which 25% of mixture is finer
D_{50}	particle size of which 50% of mixture is finer
D_{75}	particle size of which 75% of mixture is finer
D_{90}	particle size of which 90% of mixture is finer
h	original depth of water in the cylinder
H	height of base deposit
(84cm - H)	height of fall of particles.
Particle shape	defined as the sphericity of particle.
Fall velocity	decending velocity of particle in air or water

I. INTRODUCTION

Sedimentation of heterogranular mixtures in still and running water has been studied extensively in recent years (Berthault [1986,1988], Julien and Chen [1989], Julien and Lan [1989]). Berthault's study demonstrates that in still water, continuous depositing of heterogranular sediments gives rise to laminae , due to a spontaneous periodic and continuous grading process, which takes place immediately following the deposit of the heterogranular mixture. The thickness of the laminae is found to be independent of the speed of sedimentation but increases with extreme differences in the size of particles in the mixture. This experiment was repeated under horizontal currents, thin laminated superposed layers developed laterally in the direction of the current (Berthault, 1986). The latest studies at Colorado State University by Julien and Chen (1989), and Julien and Lan (1989) in a small flume and a wide flume, respectively, also indicated that deposition of heterogranular mixtures in flume or alluvial channels leads to clear horizontal and cross stratification, or lamination. While the mechanism of sediment lamination in flume and alluvial channels is still not well-understood (Julien and Chen, 1989), it is obvious that further experiments on sediment lamination should be conducted.

This experimental study extends the early investigation conducted by Berthault in 1986 and 1988. Experiments on the sedimentation of heterogranular mixtures are conducted in a rectangular vertical cylinder. In order to investigate the importance of controlling parameters, such as particle size, density, and shape, several types of sediment sand mixtures are used for experiments. A detailed description of the experimental results and the ovservations of the mechanism of sediment lamination are given in this report.

II. EXPERIMENTS

2.1. Experimental Set Up

The experimental equipments partially designed for this study is sketched in Fig. (1) and also shown in Picture 1. The vertical cylinder is made from polyglass with a dimension of 10 cm x 10 cm x 84 cm(height). The release of heterogranular mixtures from the square cone to the cylinder is well controlled by a precisely designed gate valve at the bottom of the cone. A valve is installed at either end of the cylinder to supply or drain water during and/or after experiments. The cone at the top is removable.

2. 2. Sediment Mixtures Used in the Experiments

Ten types of sediments, varying in size, density, and shape, have been used in this study. The size distributions of these materials are showed in Fig. (2) and some characteristics of these sands are listed in Table 1 where D_{10}, D_{25}, D_{50}, D_{75} and D_{90} represent the sizes of which 10%, 25%, 50%, 75% and 90% of the materials are finer, respectively. Not listed in Table 1 is the sphericity of the particle which is difficult to define. Visual observations indicate that ERC#1, ERC#2, ERC#3, ERC#5, limestone#1, and limestone#2 are rounded, coal#1, coal #3, coal #4, B2040 and B3060 are angular, and the others are between rounded and angular.

With these many sediment samples ranging from very fine material to coarse sand size, we are able to obtain different types of mixtures for different purposes. In order to see the possible differences of lamination from differences in size, density, and shape, mixtures listed in Table 2 are proposed for this experiments. Generally, a mixture is composed of one white material and one black material for convenient observations. Also listed in Table 2 includes the conditions under which the experiments are conducted.

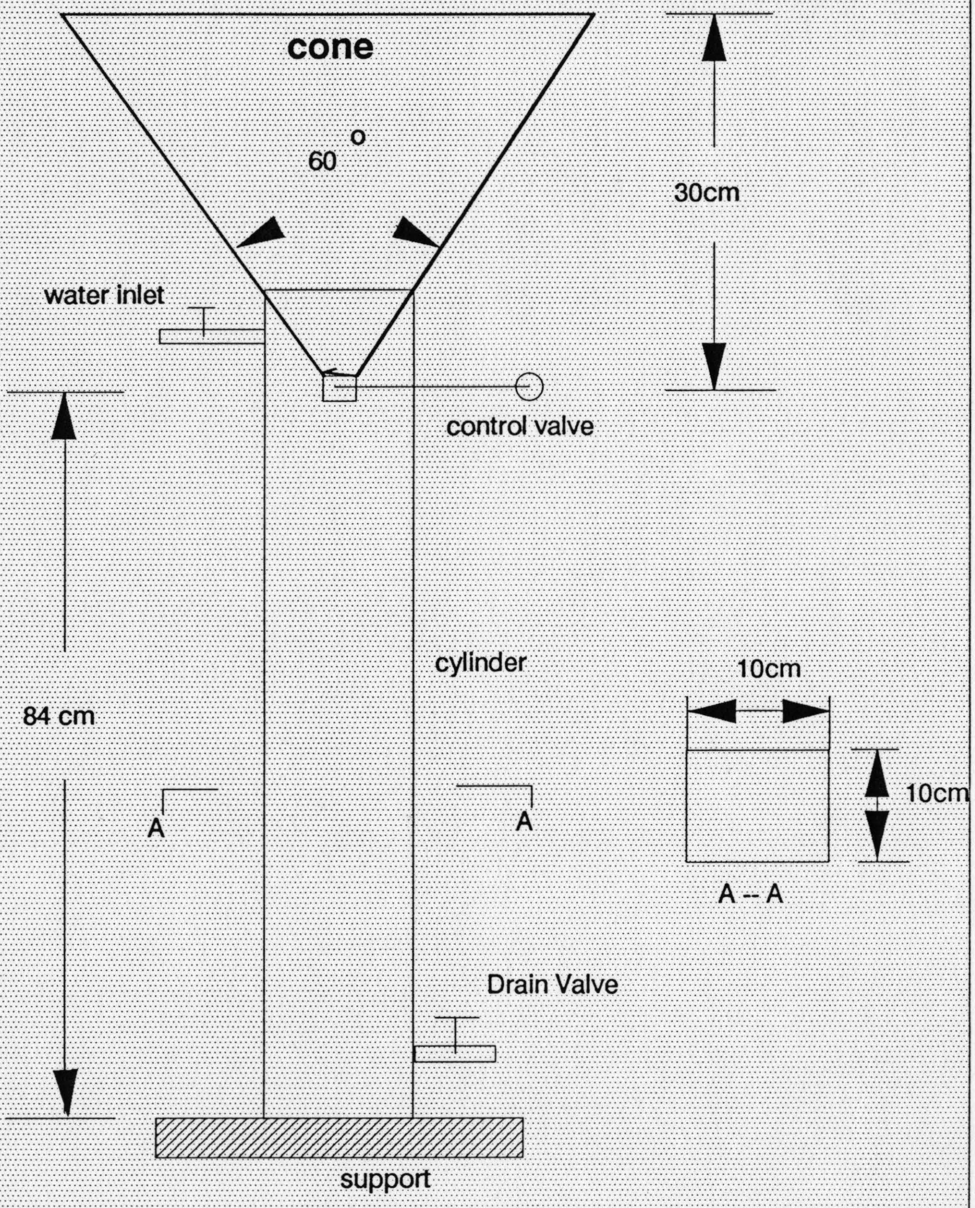
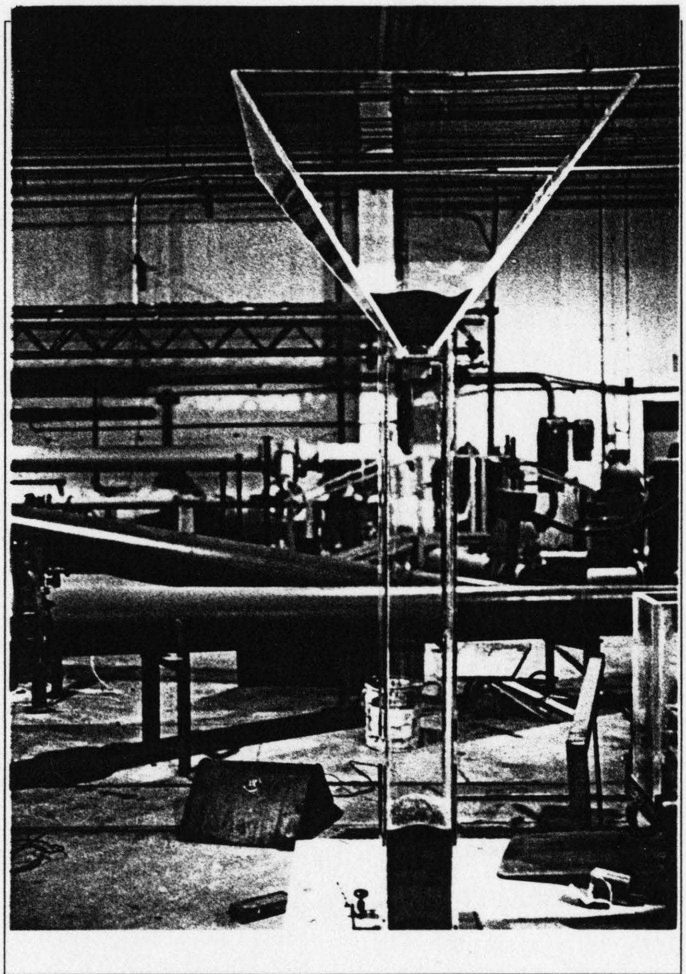


Fig. 1 Experimental Equipment Layout



Picture 1. Experimental equipments setup

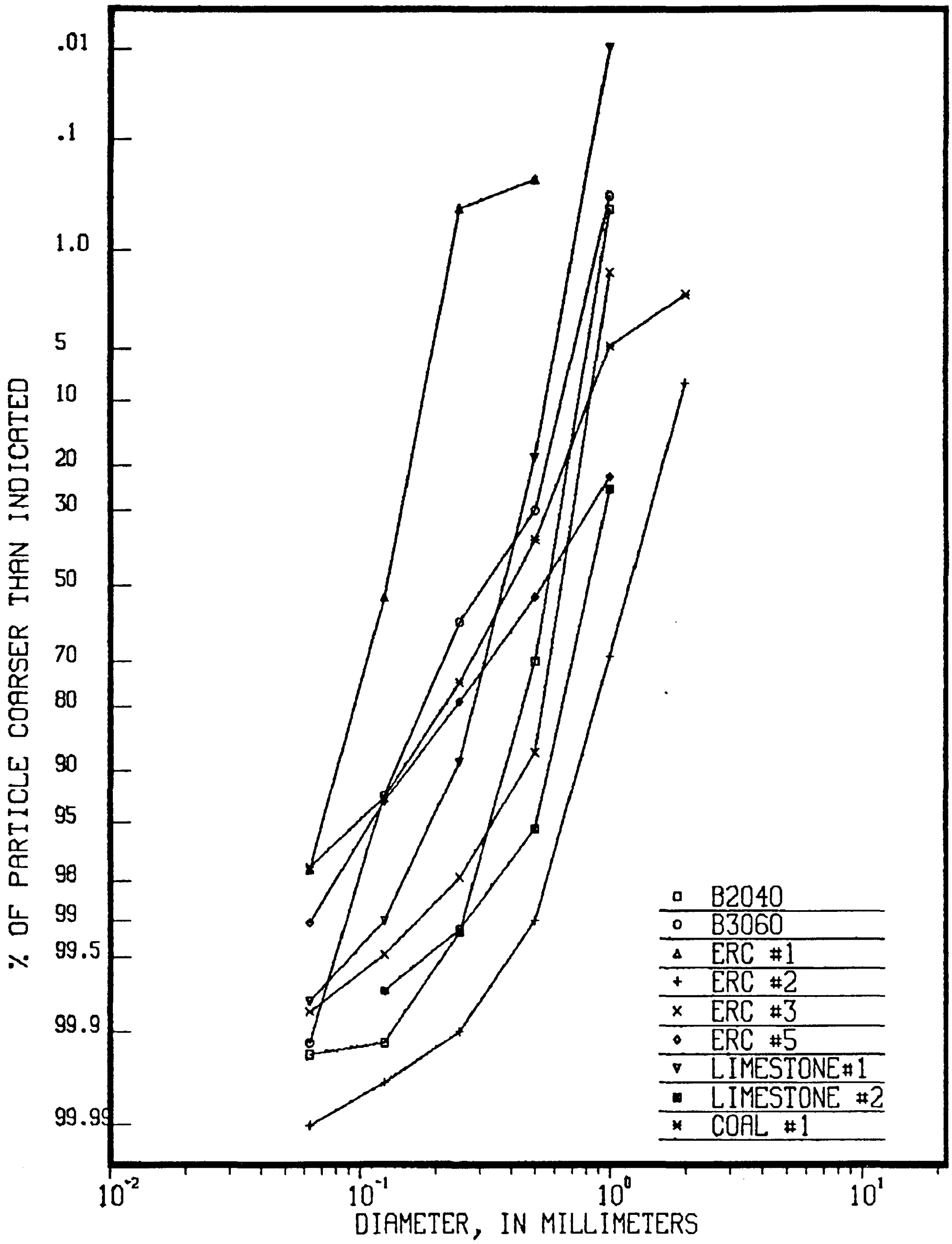


Fig. 2. Size distribution curves for tested sands

TABLE 1. Characteristics of Sands Tested

Sand	Color	Density	D_{10} (mm)	D_{25} (mm)	D_{50} (mm)	D_{75} (mm)	D_{90} (mm)
B2040	black	2.70	.380	.480	.575	.670	.760
B3060	black	2.70	.140	.205	.335	.550	.620
ERC #1	white	2.45	.084	.110	.130	.155	.180
ERC #2	white	2.65	.720	.900	1.200	1.500	1.900
ERC #3	white	2.65	.480	.550	.635	.730	.825
ERC #5	beige	2.65	.150	.290	.558	.970	
limestone #1	white	2.65		.310	.390	.470	
limestone #2	white	2.65		.760	.910	1.005	
coal #1	black	1.30		.260	.410	.575	
coal #2	black	1.30			.250		
coal #3	black	1.30			.665		
coal #4	black	1.30			1.240		

TABLE 2. Sand Mixtures and Testing Conditions

Mixture	Combination	Characteristics	in air	in water
1	B2040 & ERC #3	similar size & density	yes	yes
2	ERC #1 & B3060	different size & similar density (fine sands)	yes	yes
3	ERC #1 &coal#1	different density, size & shape	yes	yes
4	ERC#3 & coal#3	similar size & different density, shape	yes	yes
5	limestone #1 & B3060	similar size, density & different shape	yes	yes
6	limestone #2 & coal#1	different size and shape. similar density	yes	no
7	Limestone#2 & B3060	different size and shape, same density. limestone much coarser	yes	no
8	ERC #2 & coal#1	different size, shape and density. lighter material finer	yes	no
9	Limestone#1 & coal#2	different density, size & similar shape	yes	yes
10	Limestone#1 & B2040	same density, different shape and size	yes	yes

2.3. Experimental Procedure

After a designed mixture is well prepared in a certain container, the mixture is poured into the cone at the top of the cylinder. The control valve is then opened to let the mixture settle directly to the center of the cylinder. The rate of settling is controlled by the control valve. During the process of sedimentation, the cylinder is held stationary without vibration. Time spent in each run is recorded in order to determine the rate of deposition by dividing the volume of mixture by time. The process of sedimentation of different mixtures is also documented. At the end of each run, a few pictures in different directions are taken to illustrate the lamination phenomenon.

The experiments are conducted under two conditions, with or without water in the cylinder. Under both conditions, the fall (or settling) velocity of the particles influences the formation of laminae. To achieve this, a base, defined as the original height of sediment at the bottom of the cylinder before the start of each run is set before starting the run. This base can be replaced by several short wood logs in square shape (approximately 10 cm x 10 cm x 10 cm). Obviously, higher base reduces the fall velocity of particle when it impacts with the particles on the base and surely weakens the splashing of particles.

III. EXPERIMENTAL RESULTS

3.1. General.

A summary of experimental results from the present experiments is given in Tables 3 and 4 for those in air and in water, respectively. In these tables, 'proportion' means the volumetric ratio of one type of material over the other in the mixture, and 'rate of dep'denote the rate of sedimentation of the mixture. Tables 3 and 4 give a general idea how different type of mixtures affect the formation of laminae. Detailed explanations of these two tables are given in the next two sections.

TABLE 3. Results of Tests in air

Run #	Mixture	Proportion	Rate of dep. (cm^3/s)	Observation	Pictures
1	1	1:1	2.05 and 5.76	no clear lamination	2, 3
2	2	1:1	9.14	clear lamination	4, 5, 6
3	2	1:1	9.14	clear lamination	7, 8, 9
4	3	1:1	7.00	clear lamination	10
5	4	1:1	4.01	no clear lamination	11
6	5	1:1	9.0	no lamination	12
7	6	1:1	5.20	no lamination	
8	7	1:1	9.0	no lamination	13
9	8	1:1	9.0	no lamination	14
10	9	1:1	3.44	no clear lamination	15
11	10	1:1	1.619	no clear lamination	16

TABLE 4. Results from Tests in Water

Run #	Mixture	Proportion	Rate of dep. (cm^3/s)	Observation	Pictures
12, 13, 14, 15	2	1:1	9.14	no clear lamination	17, 18, 19, 20
16	2	1:1	0.384	no clear lamination	21, 22, 23
17	3	1:1	9.0	no lamination	'24
18	4	1:1	0.797	clear lamination	25, 26, 27, 28
19	5	1:1	0.837	no clear lamination	29, 30, 31
20	10	1:1	0.759	clear lamination	32, 33, 34
21	1	1:1	1.02	no lamination	no picture

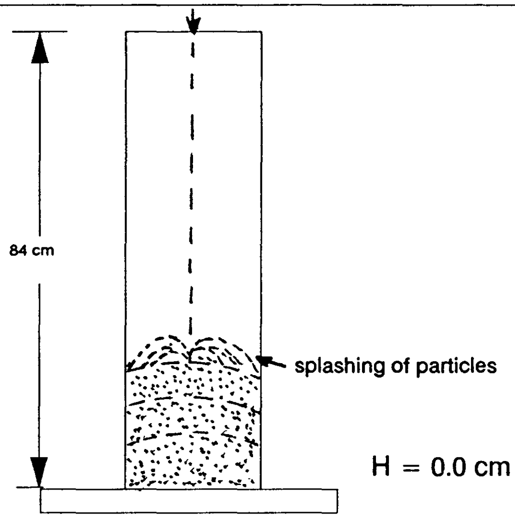
3.2. Sedimentation in Air

Detailed results from sedimentation experiments in air are presented in the following including observations of the sedimentation process and pictures.

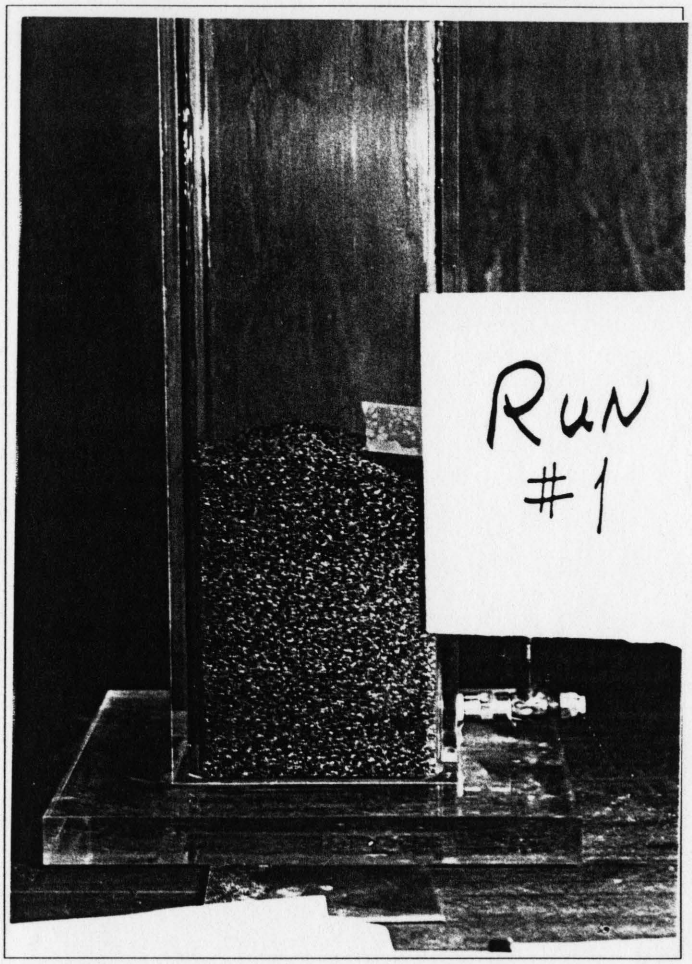
Run #1

This run actually includes two tests, one at a higher rate of sedimentation with no base and the other at a lower rate with high base.

In the first test, the base height, denoted as H, is zero. The rate of sedimentation is 2.05 cm^3/sec. During the experiment, splashing of falling particles, when they impact with surface of deposit on the bottom, dominates the process due to high fall velocities of the particles. The jumping distance of particles can vary from zero to 5 centimeter, that is, from the center to the wall of the cylinder (see Sketch 1 below). Rolling of one type of particles on the other is not obvious. And eventually, no lamina is formed (see Picture 2).



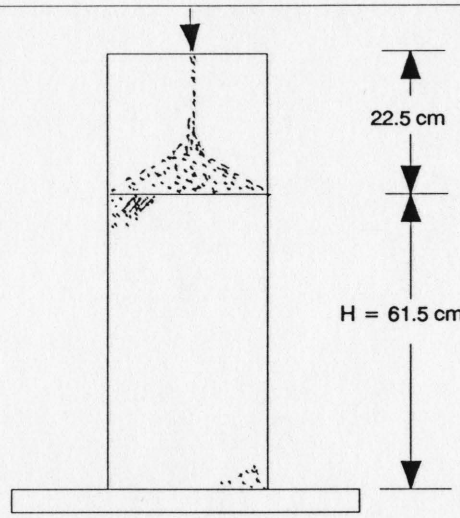
Sketch 1. Positioning of cylinder for run #1



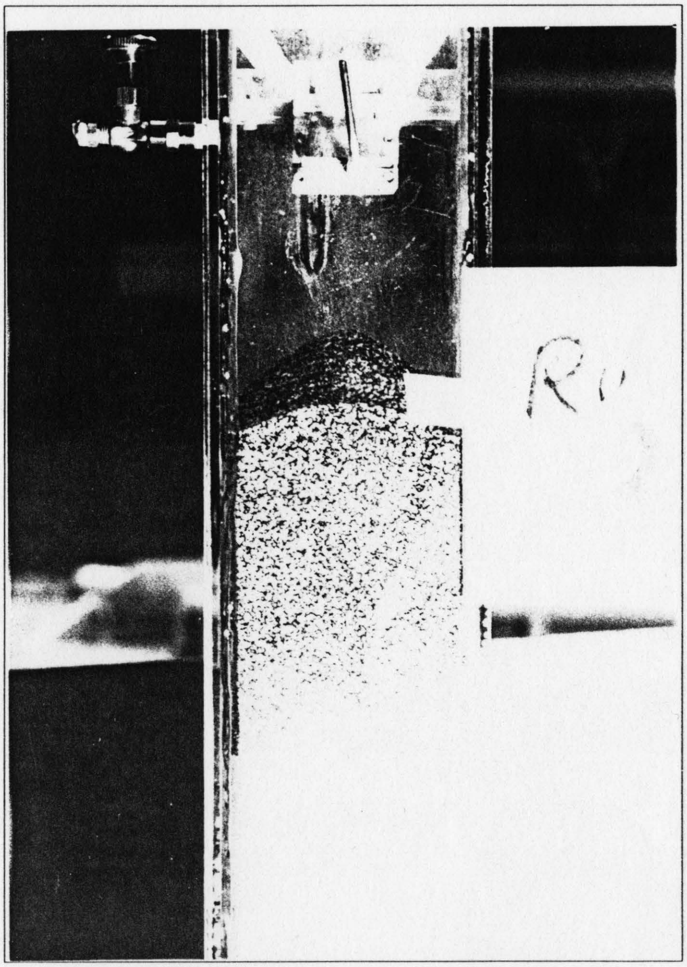
Picture 2. No clear laminae from run #1

Mixture #1: white ERC#3 D_{50} = 0.635 mm
and black B2040 D_{50} = 0.575 mm

In the second test, the height of the base is no longer zero but 61.5 cm. And the rate is 5.76 cm^3/sec. Consequently, the fall velocities of particles are dramatically reduced. The splashing of particles is much weakened. Meanwhile, a cone is well formed and landsliding occurs (see Sketch 2). Again, no lamina is observed (see Picture 3).



Sketch 2. Positioning of cylinder for run #1 (2)

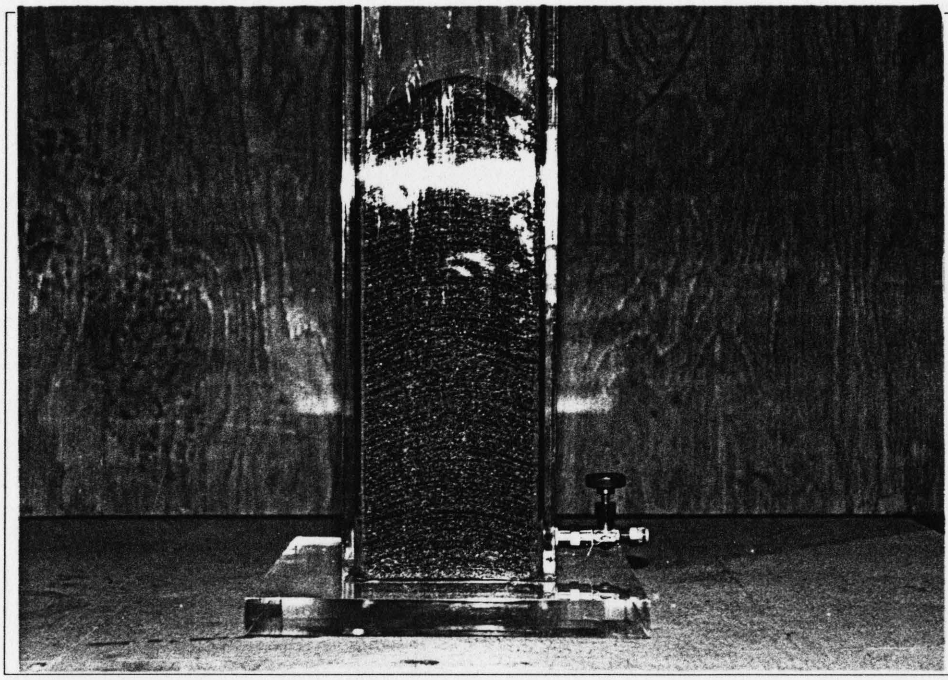


Picture 3. No clear laminae from run #1 (2)

Mixture #1: white ERC#3 $D_{50} = 0.635$ *mm*
and black B2040 $D_{50} = 0.575$ *mm*

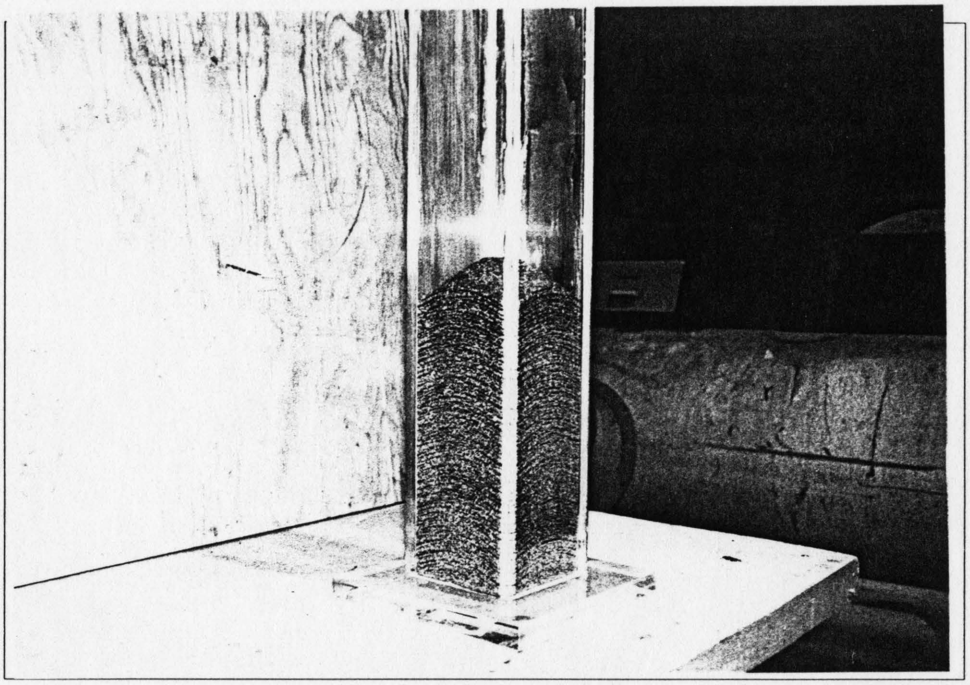
Run #2

In this run, the height of the base is zero. And the rate is 9.14 cm^3/sec. Splashing of particles does not occur while landsliding is dominant. Rolling of black particles on the white particles before landsliding is observed. Consequently, clear laminae with thickness less than 0.5 cm are observed (see Picture 4, 5, 6).



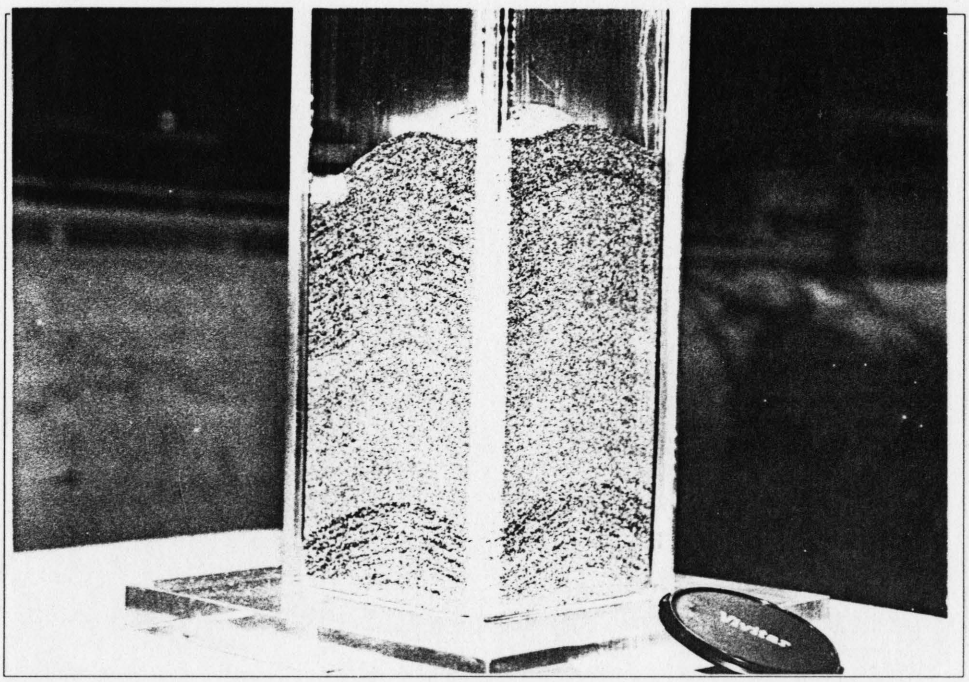
Picture 4. Clear laminae from run #2

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm



Picture 5. Clear laminae from run #2

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm

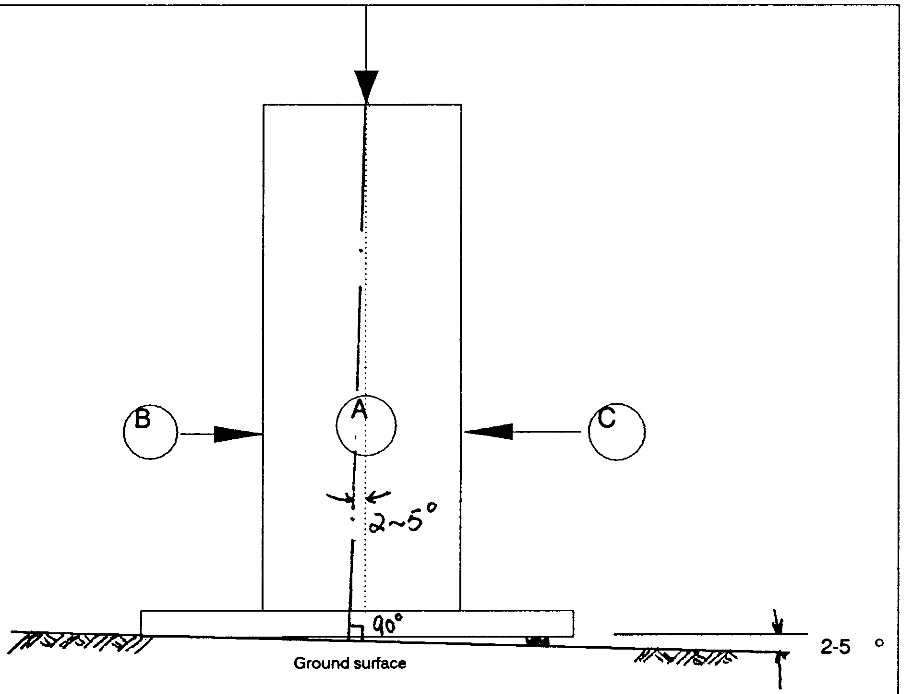


Picture 6. Clear laminae from run #2

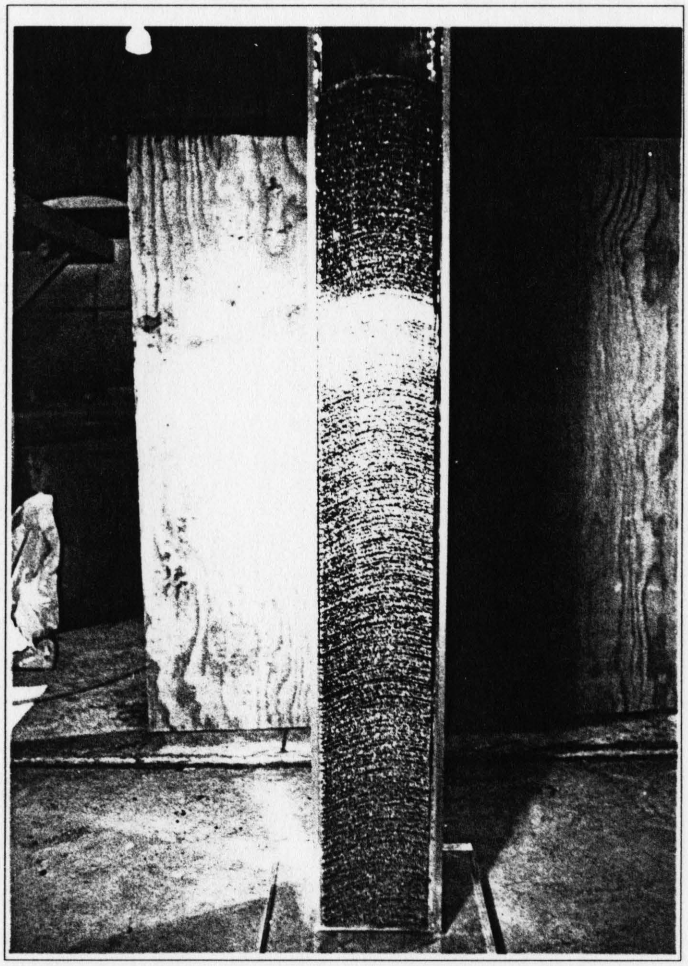
Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm

Run #3

This run is under the same condition as in Run #2 except that the cylinder is not straight up but a little inclined with an angle of approximately 5 degree (see Sketch 3). The purpose of this setup is to see the importance of rolling distance of the particles. Pictures 7, 8, and 9 are taken in directions of A, B, and C shown in Sketch 3. From these pictures, it can be see easily that longer rolling distance produces clearer lamination.

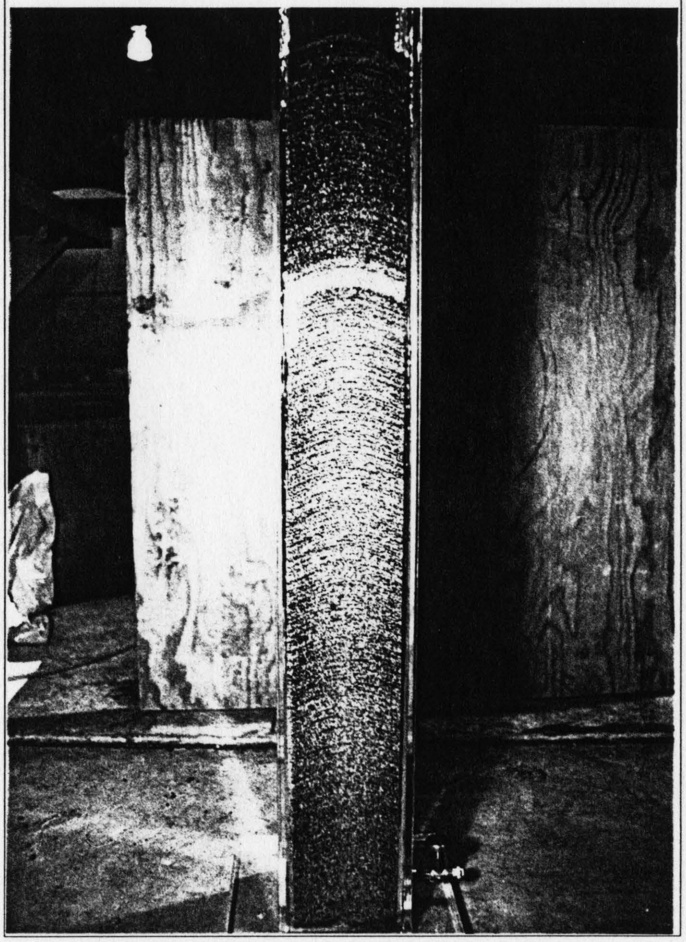


Sketch 3. Positioning of cylinder in run #3



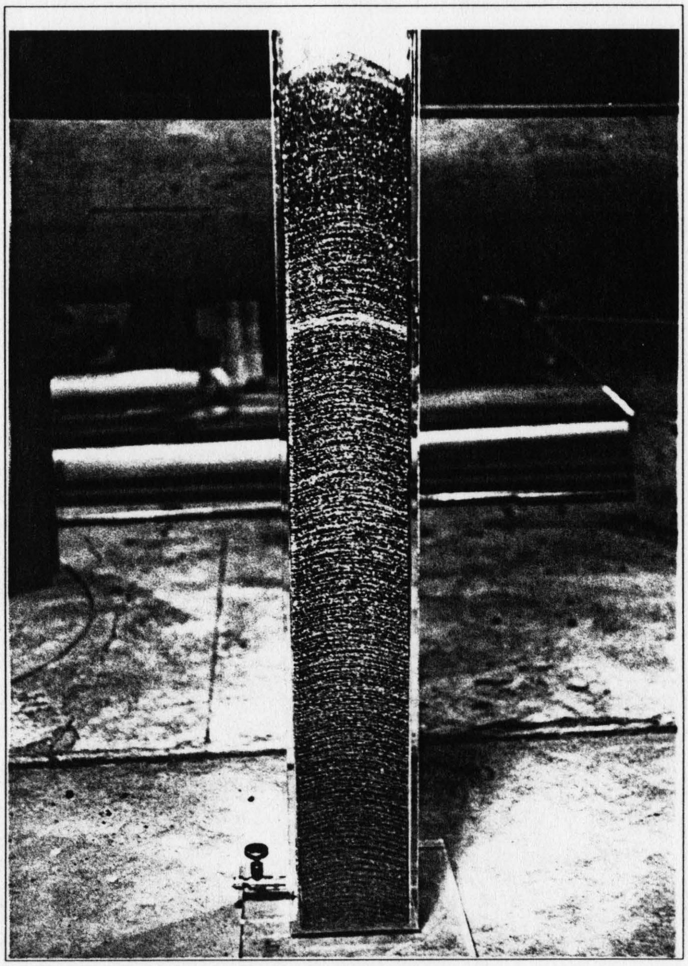
Picture 7. Clear laminae from run #3

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm



Picture 8. Laminae become clearer as deposit gets higher

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm

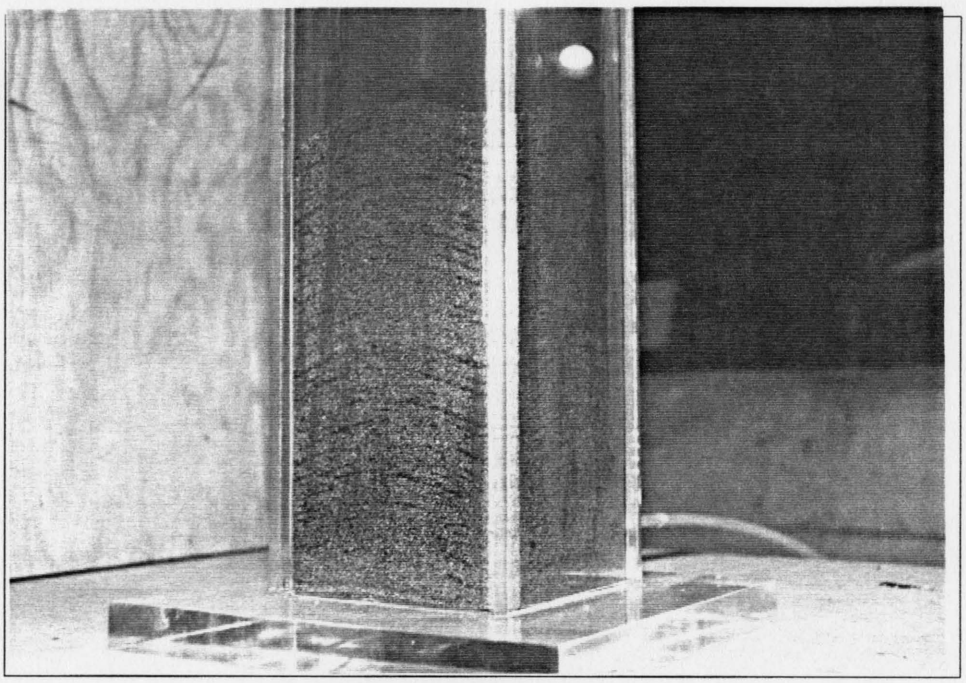


Picture 9. Clearer laminae from side far from the center

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm

Run #4

In this run, the height of the base is zero. And the rate is 7.00 cm^3/sec. Splashing of particles does not occur while landsliding is dominant. Rolling of black particles on the white particles before landsliding is observed. Consequently, clear laminae with thickness less than 0.5 cm are observed (see Picture 10).

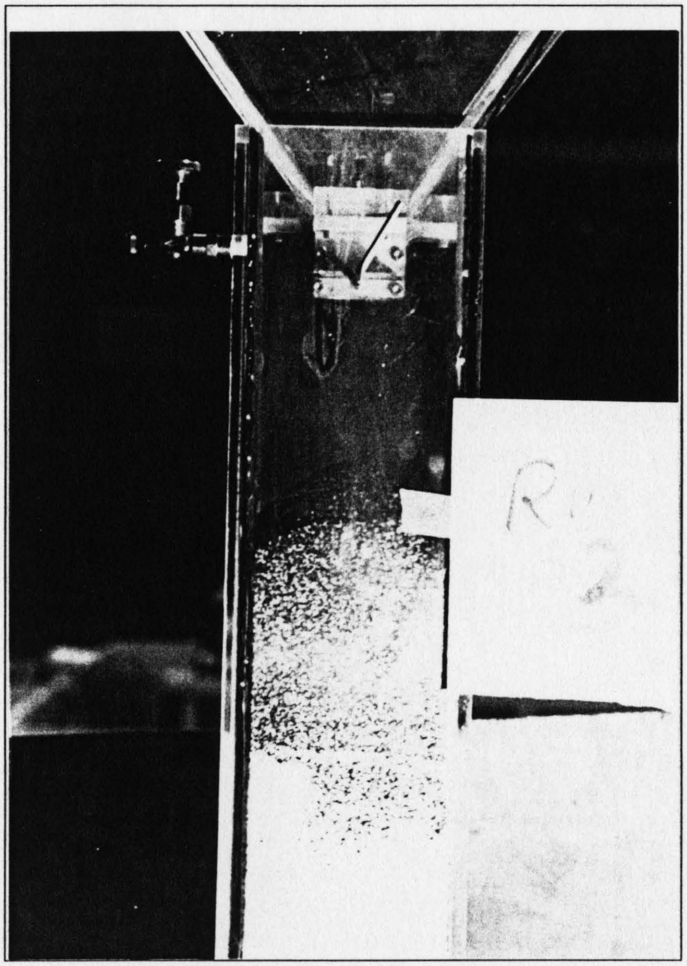


Picture 10. Clear laminae from run #4

Mixture #3: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm

Run #5

In this run, the height of the base is 63.5 cm. And the rate is 4.01 cm^3/sec. Consequently, the fall velocities of particles are dramatically reduced. The splashing of particles is weak. Meanwhile, a cone is well formed and landsliding occurs . No clear lamina is observed (see Picture 11).

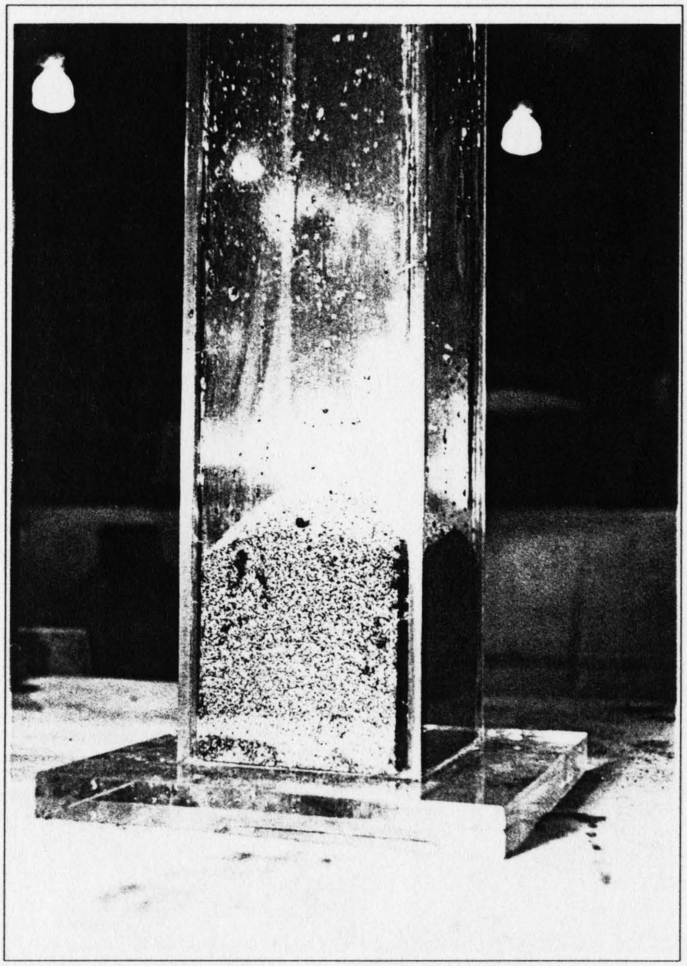


Picture 11. No clear laminae from run #5

Mixture #4: white ERC#3 D_{50} = 0.635 mm
and black coal#3 D_{50} = 0.665 mm

Run #6

In this run, the height of the base is zero. the rate of sedimentation is 9.0 cm^3/sec. The splashing of particles is weak because both types of particles are fine materials. Meanwhile, a cone is well formed and landsliding occurs occasionally. Laminae is observed but not distinct(see Picture 12).



Picture 12. No laminae from run #6

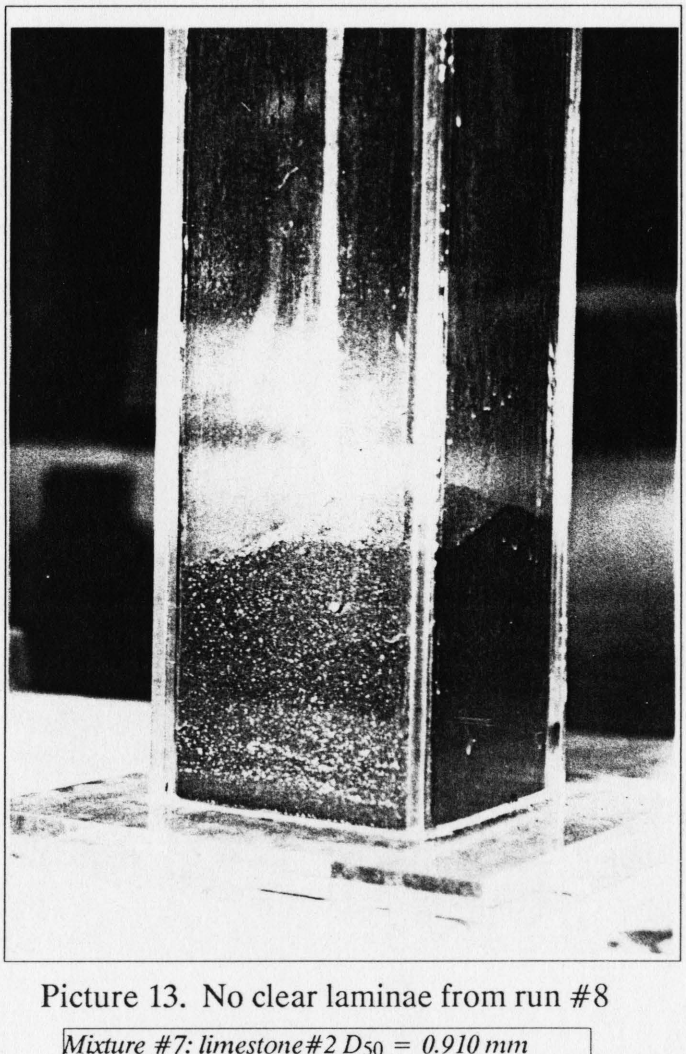
Mixture #5: limestone#1 D_{50} = 0.390 mm
and black B3060 D_{50} = 0.335 mm

Run #7

Compared with run #6, the limestone used in this run is much coarser. Consequently, splashing of particles is dominant in the sedimentation process. Lighter material, coal, is pushed to the wall of the cylinder. No lamina is observed.

Run #8

The conditions in this run are the same as in run #6, except that the limestone is much coarser. The height of the base is zero. The rate of sedimentation is 9.0 cm^3/sec. The splashing of limestone particles is strong and the cone is not well formed. Meanwhile, the black sand is pushed to the wall of the cylinder. Landsliding does not occur. Laminae are not observed (see Picture 13).

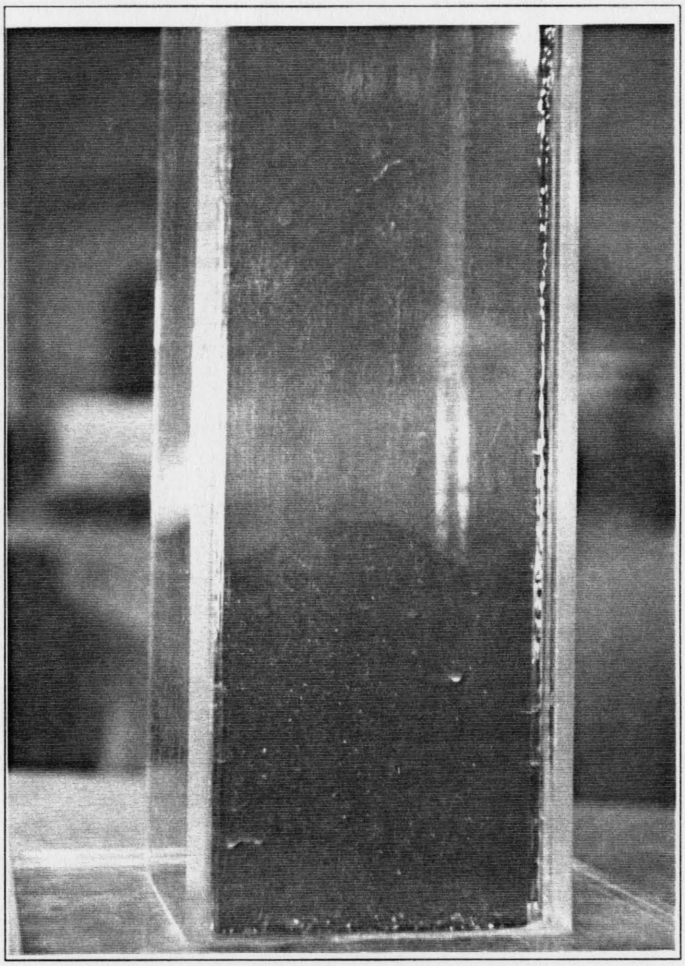


Picture 13. No clear laminae from run #8

Mixture #7: limestone#2 D_{50} = 0.910 mm
and black B3060 D_{50} = 0.335 mm

Run #9

In this run, the lighter material, namely coal, is much finer than the other material, ERC#2. The height of the base is zero. The rate of sedimentation is 9.0 cm^3/sec. Splashing of particles is weak but no landsliding is observed. The cone is not well formed then. Meanwhile, the black coal is pushed to the wall of the cylinder. Laminae are not observed (see Picture 14).

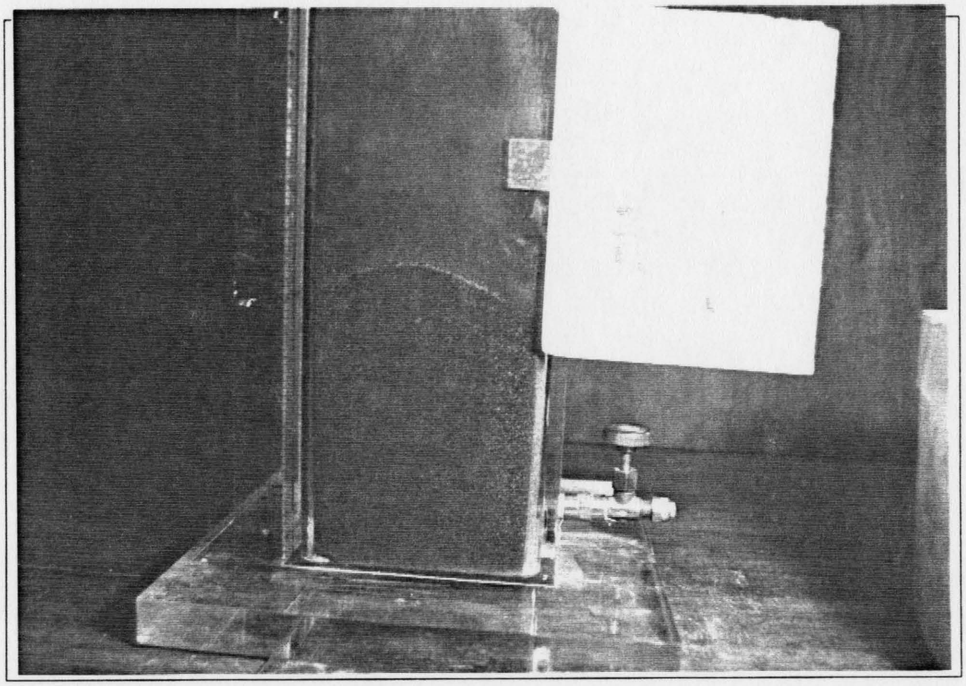


Picture 14. No laminae from run #9

Mixture #8: white ERC#2 D_{50} = 1.200 mm
and black coal#1 D_{50} = 0.410 mm

Run #10

In this run, the lighter material, namely coal, is coarser than the other material, limestone #1. The height of the base is zero. The rate of sedimentation is 3.44 cm^3/sec. Splashing of particles is weak. Landsliding occurs but no distinct separation of black and white particles is observed. Rolling of one particle over the other is observed but no clear lamina is formed (Picture 15).

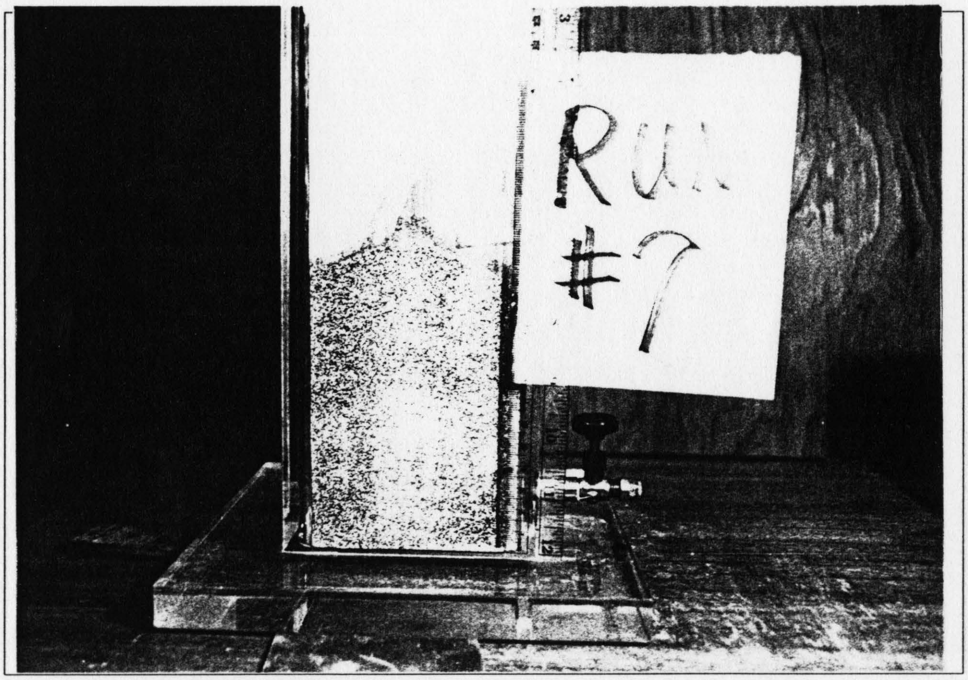


Picture 15. No clear laminae from run #10

Mixture #9: limestone#1 D_{50} = 0.390 mm
and black coal#2 D_{50} = 0.250 mm

Run #11

The height of the base is zero. The rate of sedimentation is 1.619 cm^3/sec. Splashing of particles is moderate. Landsliding occurs occasionally but no distinct separation of black and white particles is observed. Rolling of one particle over the other is observed but no clear lamina is formed (Picture 16).



Picture 16. No clear laminae from run #11

Mixture #10: limestone#1 D_{50} = 0.390 mm
and black B2040 D_{50} = 0.575 mm

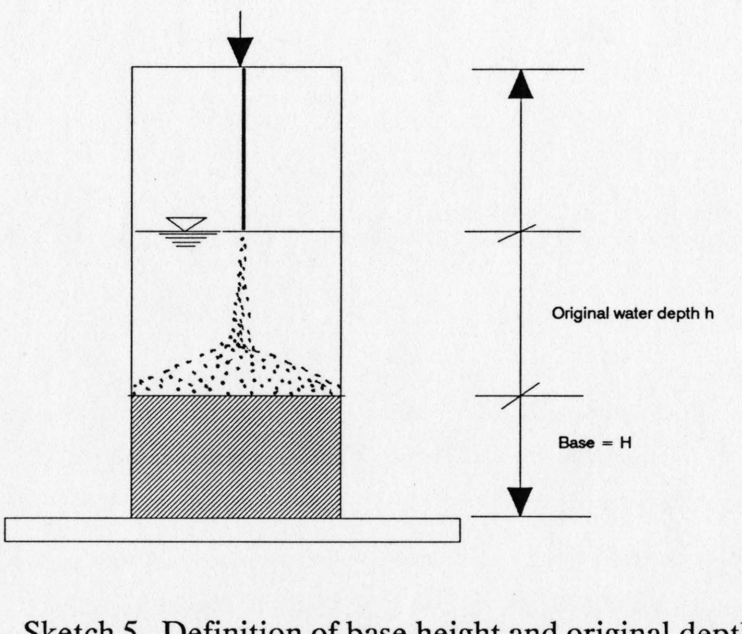
3.3. Sedimentation in Water

Run #12, 13, 14, and 15.

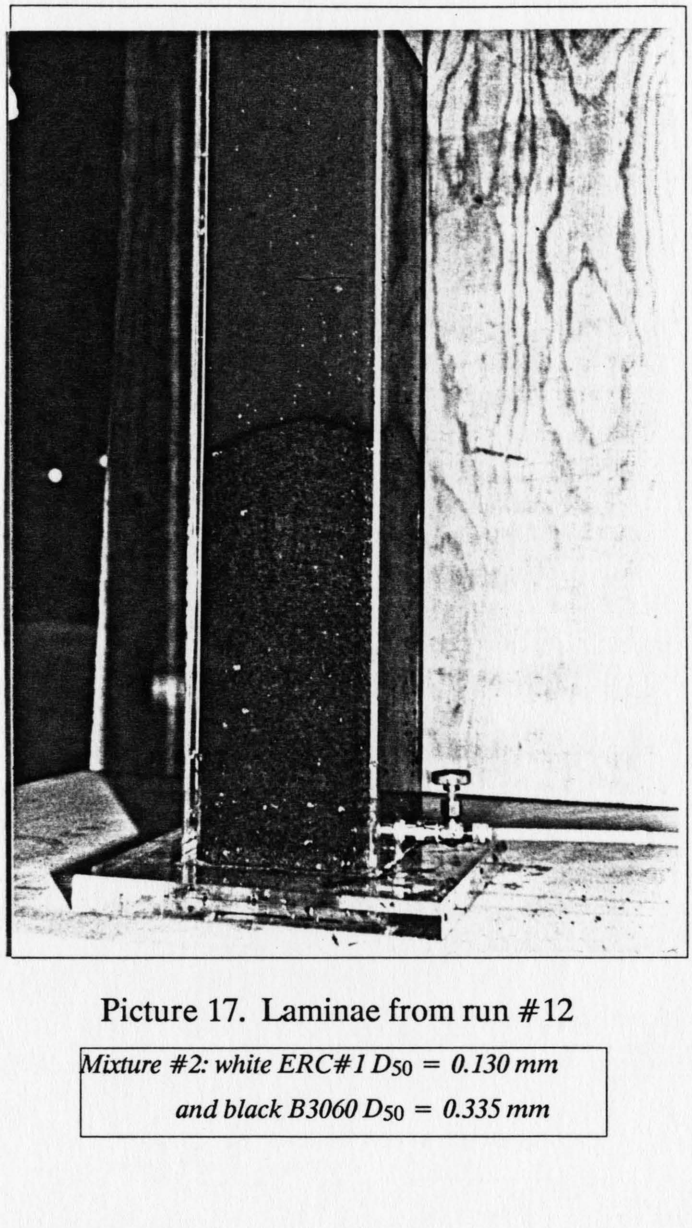
The rate of sedimentation in these three runs is the same, 9.14 cm^3/sec. The only difference among these runs is the height of base and the original water depth. These conditions are summarized in Table 5. Laminae can be seen although not distinctly when the original water depth, h, is low (Pictures 17, 19, 20). When the original water depth is too high, no lamina is formed due to the uniform settling at the bottom of the cylinder.

TABLE 5. Experimental Conditions for Run #12, 13, 14, and 15 (height in cm)

Run #	Height of Base	Original Water Depth, h	Picture #
12	0.0	35.0	17
13	0.0	68.5	18
14	65.0	6.5	19
15	10.0	5.0	20

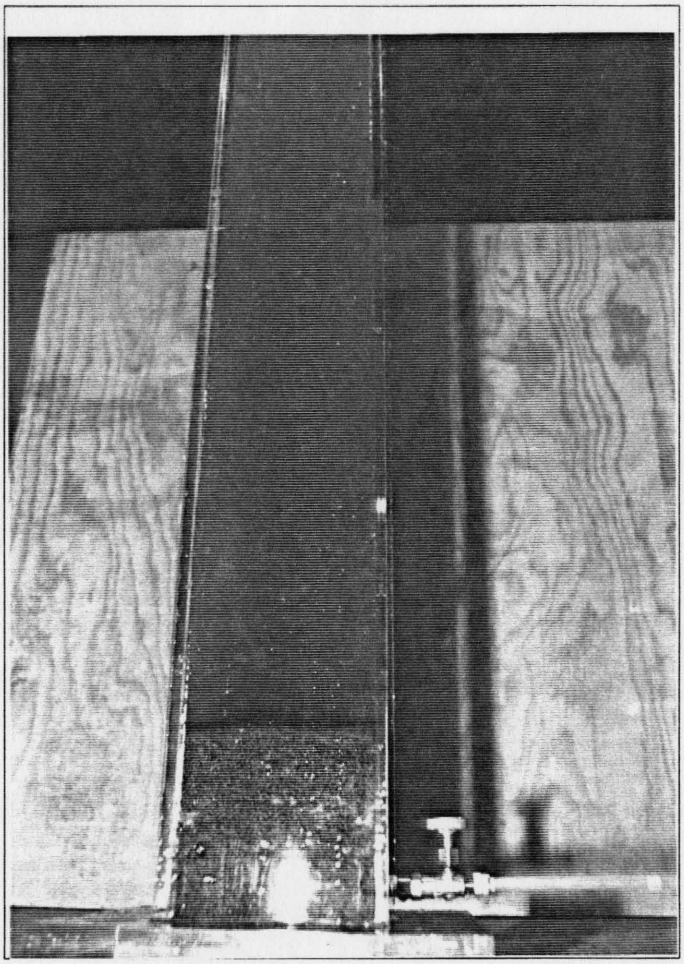


Sketch 5. Definition of base height and original depth



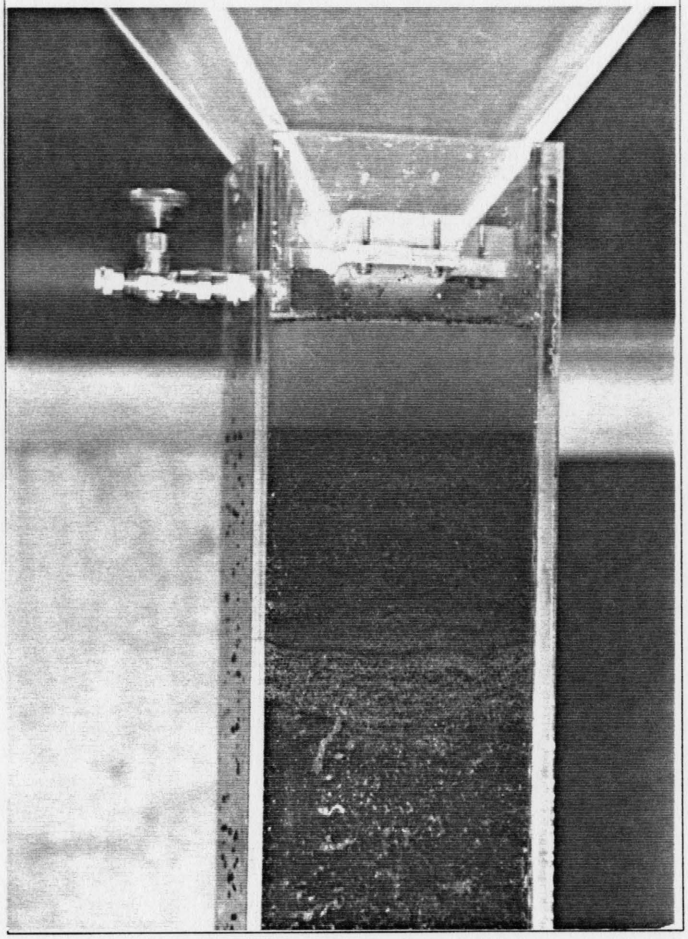
Picture 17. Laminae from run #12

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm



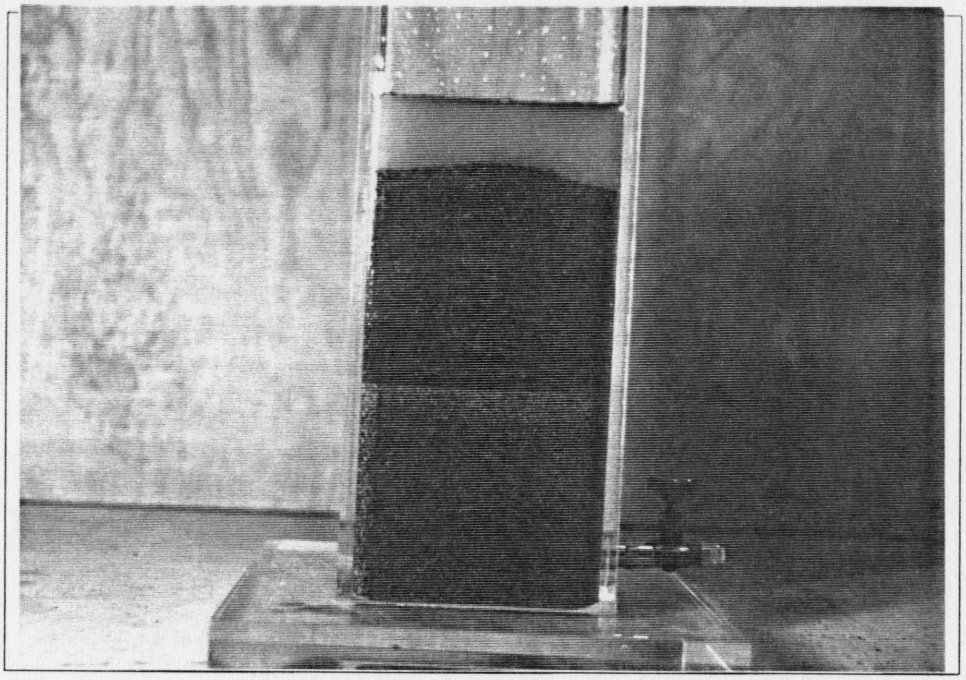
Picture 18. No laminae from run #13

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm.
$H = 0.0$, $h = 35$ cm



Picture 19. Laminae from run #14

Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm.
H = 65.0 cm, h = 6.5 cm

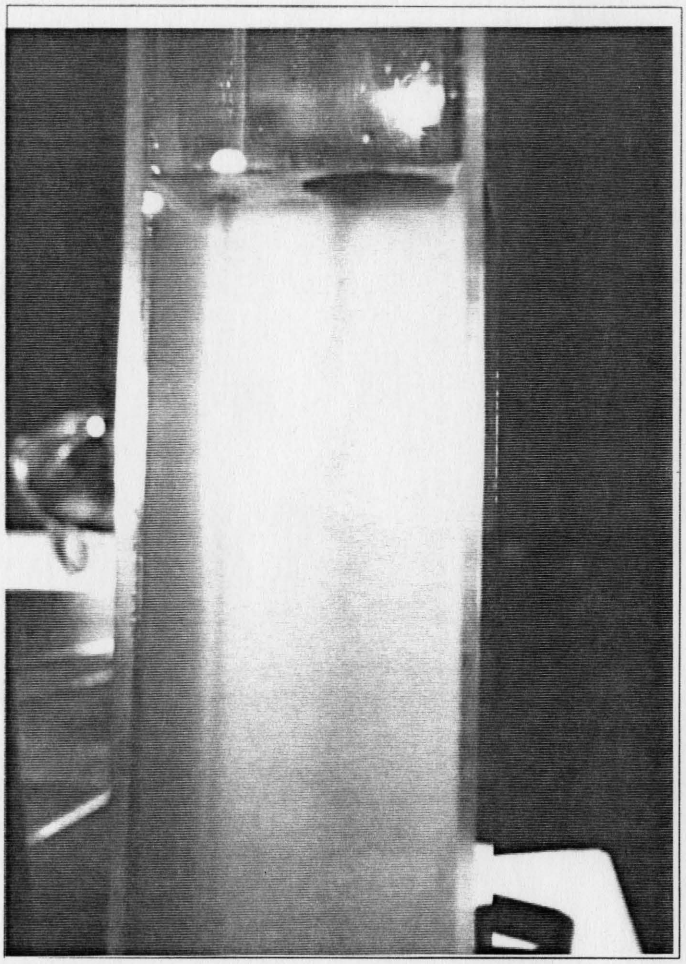


Picture 20. Laminae from run #15

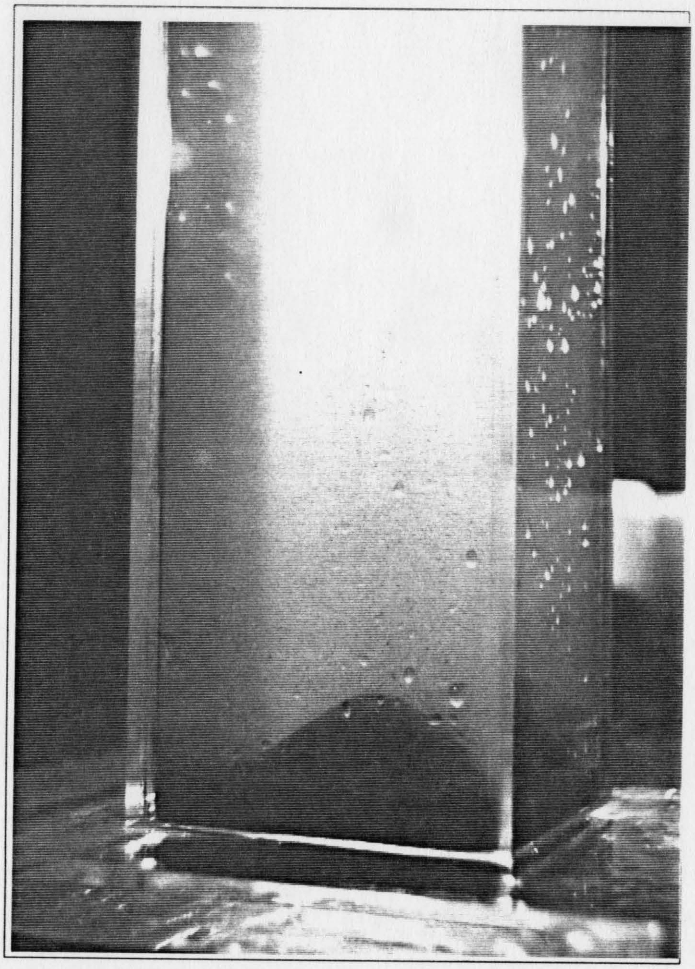
Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm.
H = 10.0 cm, h = 5.0 cm

Run #16

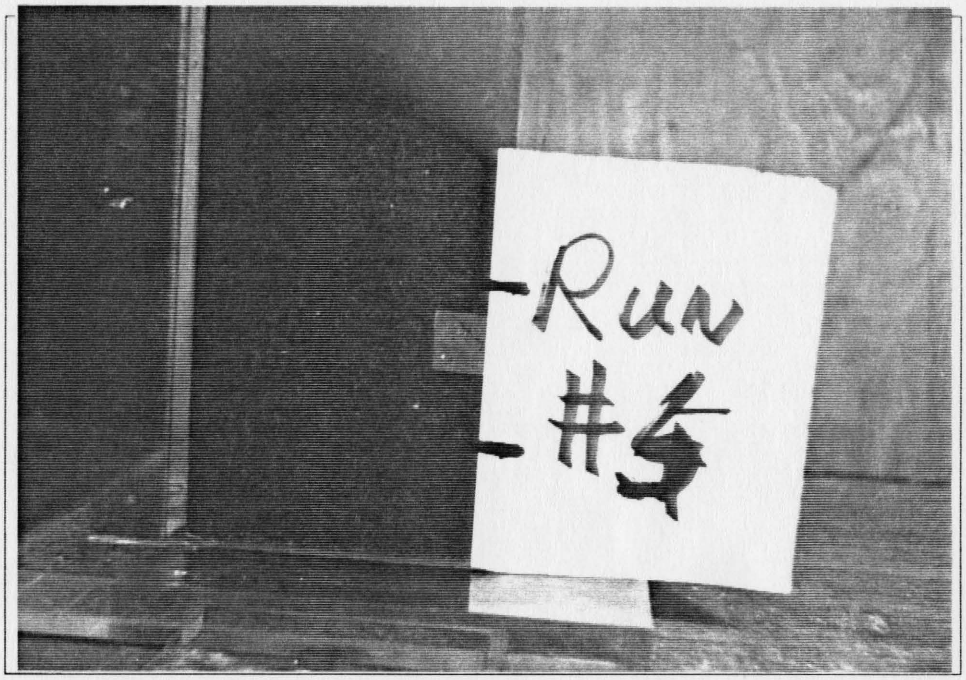
The mixture used in this run is the same as in runs #12-15. However, the rates of sedimentation is much lower, 0.384 cm^3/sec, 1.24 cm^3/sec, and 2.00 cm^3/sec, respectively. The original water depth is 62 cm and base height is zero. The process of sedimentation can be seen in Pictures 21and 22, taken at the water surface and bottom of cylinder, respectively. Laminae, although not clear, can be seen from Picture 23.



Picture 21. Sedimentation Process at the water surface

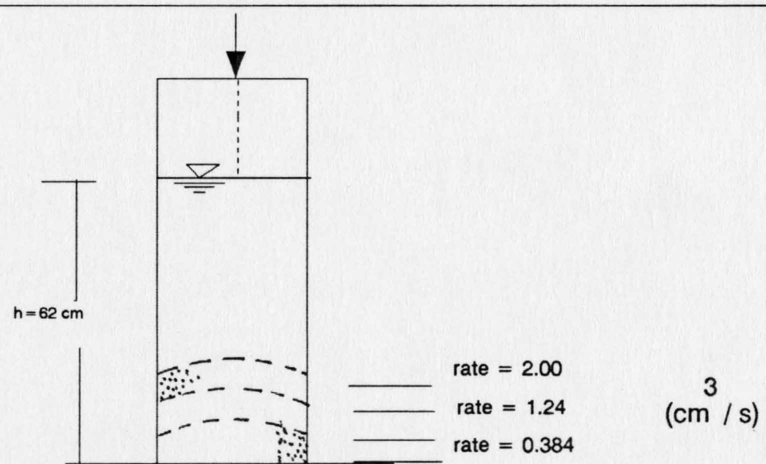


Picture 22. Sedimentation process at bottom in run #16



Picture 23. Laminae (not clear) from run #16

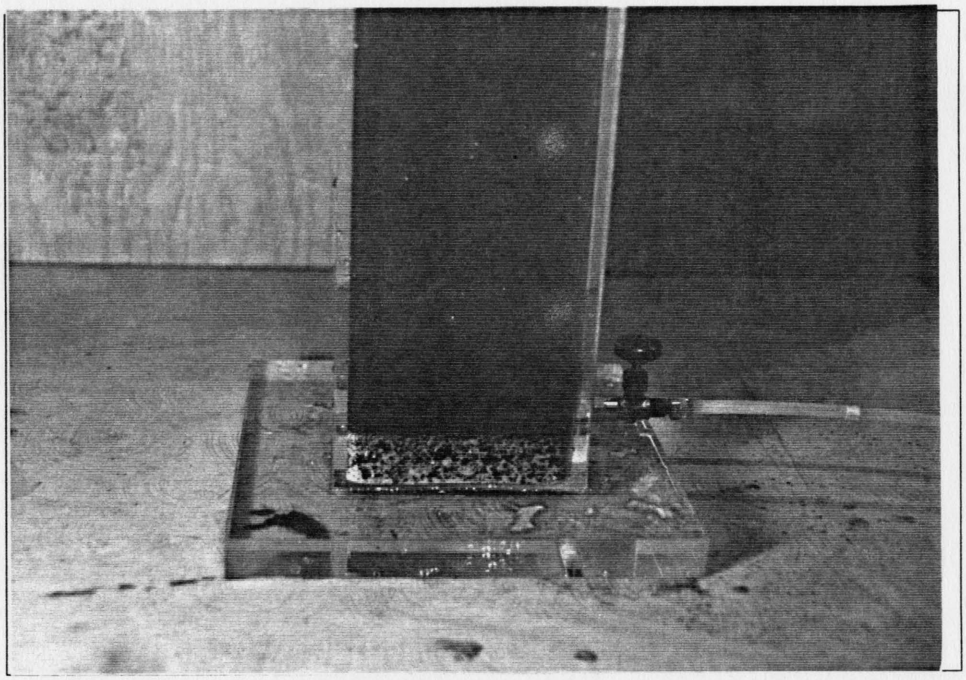
Mixture #2: white ERC#1 D_{50} = 0.130 mm
and black B3060 D_{50} = 0.335 mm.
H = 0.0, h = 62 cm



Sketch 6. Explanation of Picture 23

Run #17

In this run, the base height is zero and the original water depth is 79.2 cm. Since the settling velocity of coal is much smaller than that of the white sand, heavier materials deposited on the bottom of the cylinder first, and then both materials together. If there is a discontinuity during the process, a layer of coal with thickness depending on the interval of discontinuity, would form. Otherwise, no lamina is observed (Picture 24).

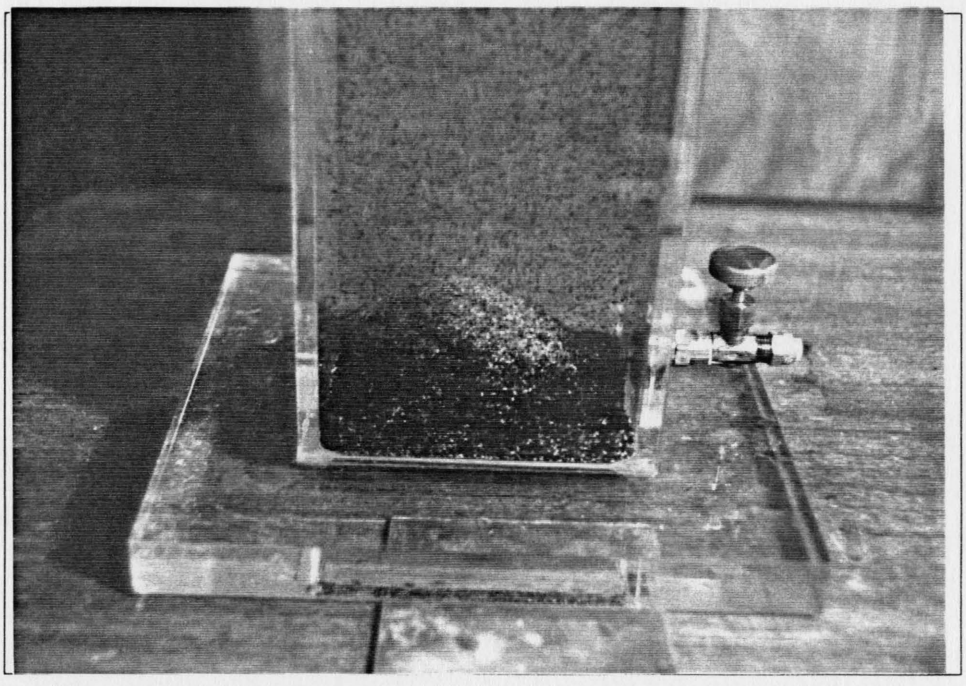


Picture 24. No laminae from run #17

Mixture #3: white ERC#1 D_{50} = 0.130 mm
and black coal#1 D_{50} = 0.410 mm.
H = 0.0, h = 79.2 cm

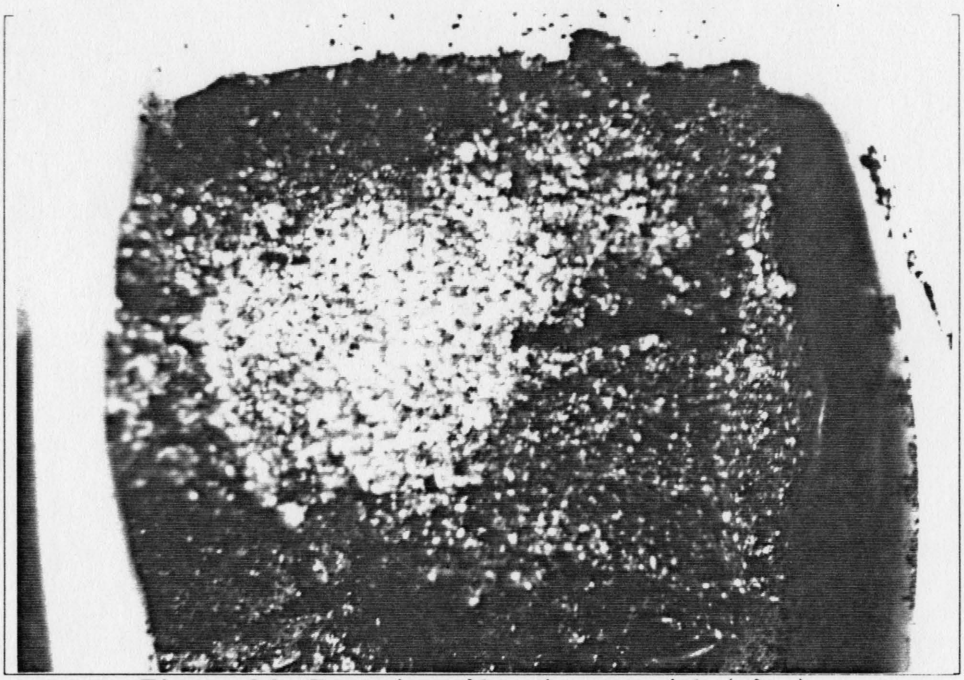
Run #18

The base height is zero and original water depth is 60 cm in this run. Since the settling velocity of the white sand is much larger than that of coal, the settling of the white materials is straight down to the bottom while coal particles suspend in water up and down for a while and then settle down. The white sand therefore deposits at the center of the cylinder while the coal deposits around the cone form by white particles. This can be demonstrated from Pictures 25 (taken during the process) and 26 (taken after the water is drained). Landsliding is observed during the process. And eventually, laminae are formed (Pictures 27 and 28).

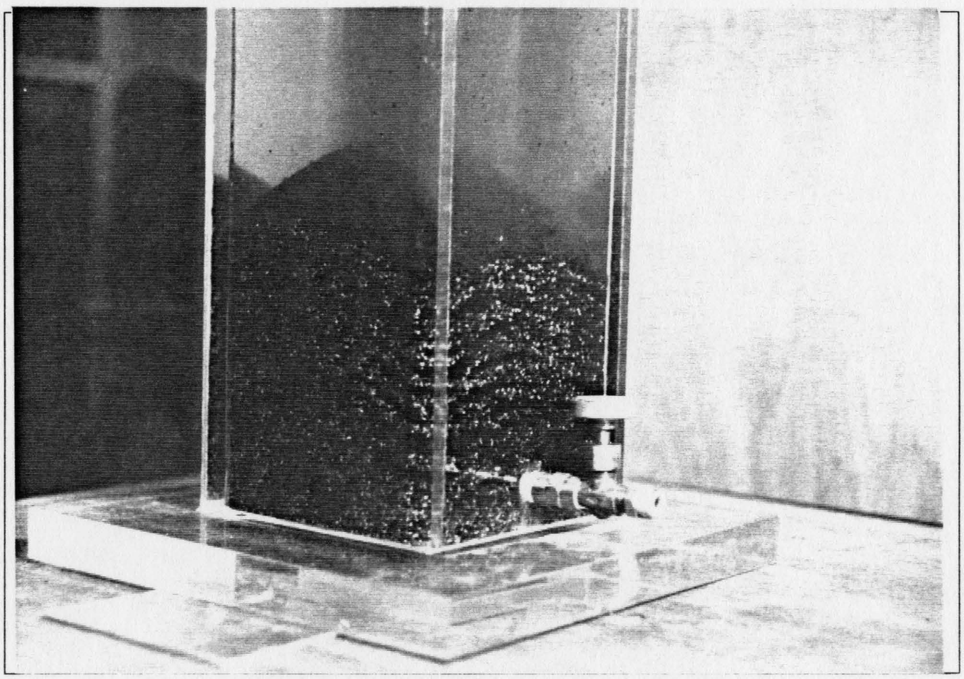


Picture 25. Sedimentation process in run #18

Mixture #4: white ERC#3 D_{50} = 0.635 mm
and black coal#3 D_{50} = 0.665 mm.
$H = 0.0,\ h = 60$ cm

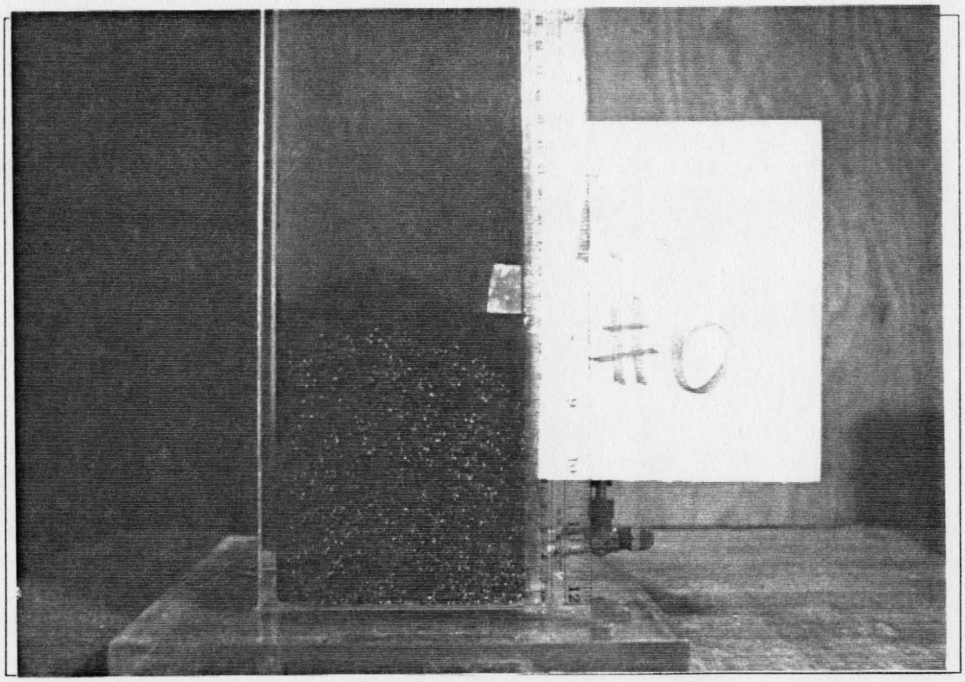


Picture 26. Centering of heavier materials (after)



Picture 27. Clear laminae from run #18

Mixture #4: white ERC#3 D_{50} = 0.635 mm
and black coal#3 D_{50} = 0.665 mm.
H = 0.0, h = 60 cm

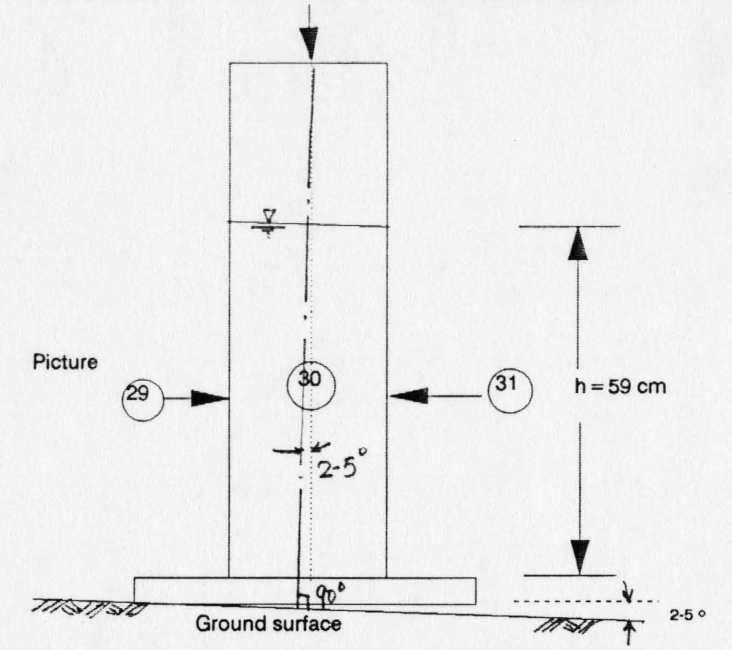


Picture 28. Clear laminae from run #18

Mixture #4: white ERC#3 D_{50} = 0.635 mm
and black coal#3 D_{50} = 0.665 mm.
H = 0.0, h = 60 cm

Run #19

The base height is zero and original water depth is 59 cm in this run. Since particle settling velocities are small, particles suspend all over the cross-section. Landsliding occurs but is not as dominant as in run #18. Laminae are much clearer from the side wall farther from the center of cylinder (The cylinder stands a little inclined). This can be demonstrated from Pictures 29, 30, 31 with reference from Sketch 7.



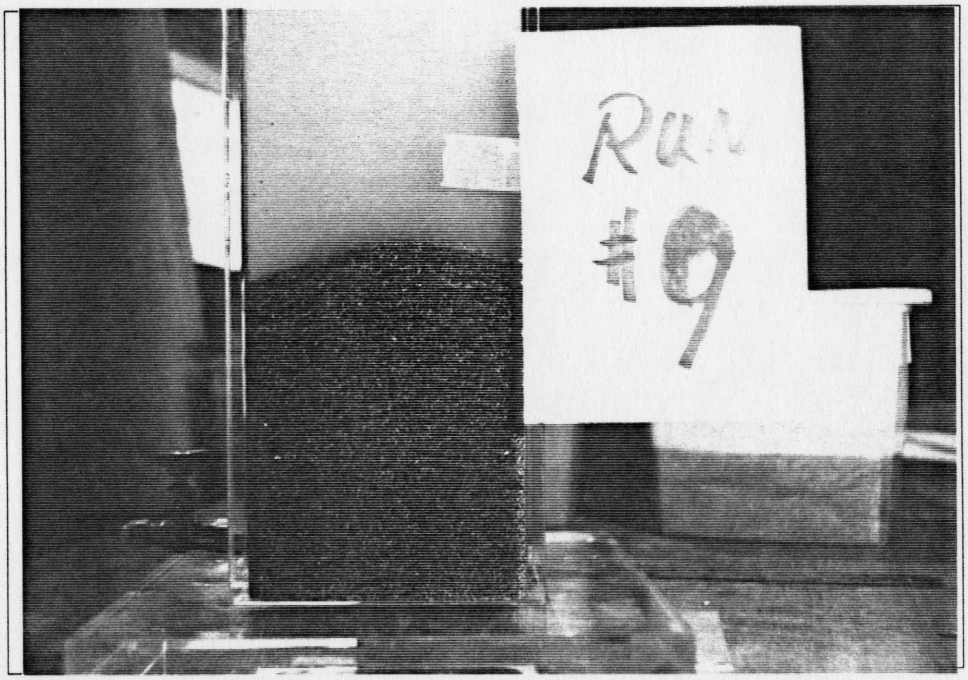
Sketch 7. Positioning of cylinder in run #19

Picture 29. No clear laminae closest to the center (run#19)

Mixture #4: white ERC#3 D_{50} *= 0.635 mm*
and black coal#3 D_{50} *= 0.665 mm.*
H = 0.0, h = 60 cm

Picture 30. Better laminae in frontal view (run #19)

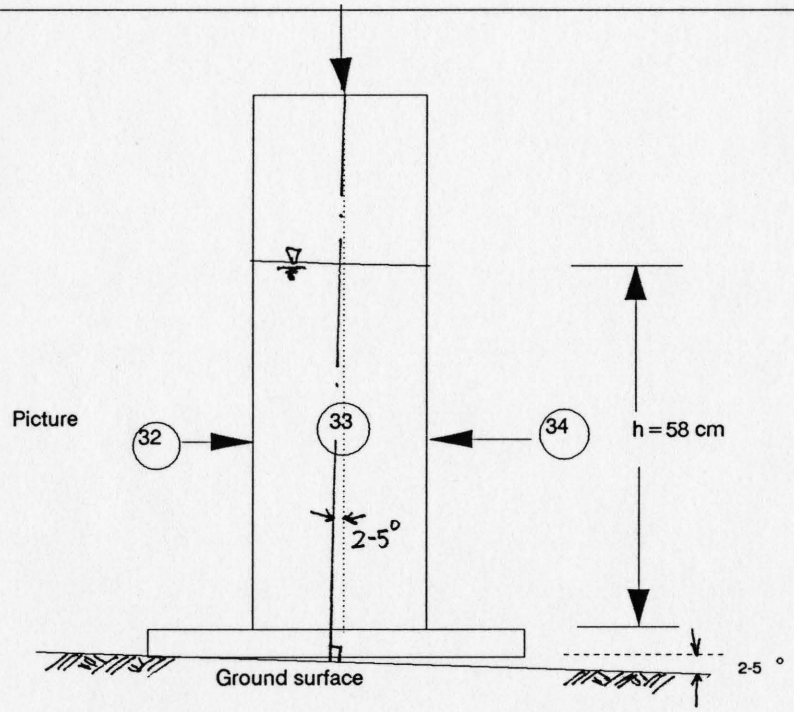
Mixture #4: white ERC#3 D_{50} = 0.635 mm *and black coal#3 D_{50} = 0.665 mm.* *H = 0.0, h = 60 cm*



Picture 31. Clearer laminae far from the center (run #19)

Run #20

The base height is zero and original water depth is 58 cm in this run. The rate of sedimentation is 0.759 cm^3/sec. A cone in water is well created. Landsliding appears to be stronger than that in the air because splashing of particles couldn't happen in water. The obvious segregation of black particles from the whites really causes the clear formation of laminae. Again, it is indicated from Pictures 32-34 that longer distances from the crest produce clearer lamination.

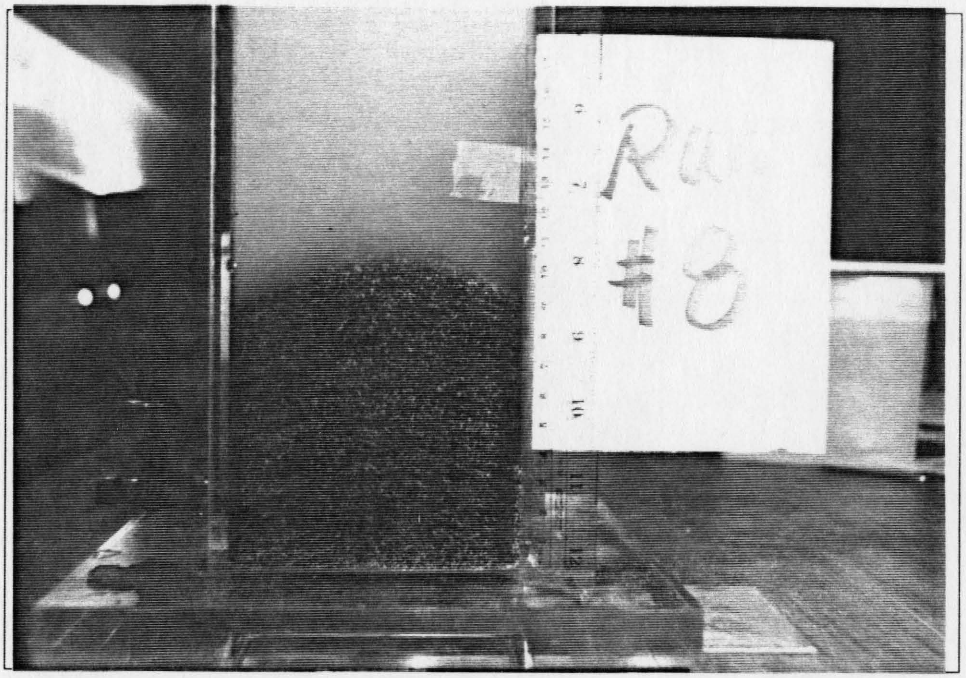


Sketch 8. Positioning of cylinder for run #20

Picture 32. Laminae from side nearest to the center (run#20)

Mixture #10: limestone#1 D_{50} = 0.390 mm
and black B2040 D_{50} = 0.575 mm.
$H = 0.0$, $h = 58$ cm

Picture 33. Good lamination in frontal view (run#20)



Picture 34. Clearer lamination from the far side (run #20)

Mixture #10: limestone#1 D_{50} = 0.390 mm

and black B2040 D_{50} = 0.575 mm.

$H = 0.0$, $h = 58$ cm

Run #21

In this run, the base height is zero and water depth is 55 cm. The rate of sedimentation is small, 1.02 cm^3/s. Landsliding is dominant during the process, which is in contrast to the experiment in the air where splashing is dominant (run #1). Although the sizes of ERC#3 and B2040 are different, segregation of black and white particles during the landsliding is not observed. Obviously, no lamina is observed.

IV. OBSERVATIONS ON THE MECHANISM OF SEDIMENT LAMINATION

In flume experiments with running water, the horizontal lamination of heterogranular mixtures has been explained by many theories, such as that by Paola et al. (1989). They explained that lamination resulted 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. From experiments in still and running water in vertical cylinder, Berthault (1986, 1988) concluded that a clear segregation of particles of the same size within the deposited mixture is the genesis of the lamination, and this segregation resulted from spontaneous periodic and continuous grading process, which took place immediately following the deposit of the heterogranular mixture. The thickness of formed laminae increased as the difference between the size of particles becomes greater in still water, and increased with flow velocity of running water.

The present experiments surely have support to this hypothesis. From these experiments, either in air or in still water, laminae formed only under the circumstance that landsliding occurs as sedimentation progresses. Needless to say, this landsliding creates an ideal condition for grading or sorting of sediment particles of different size, density, and shape.

Landsliding (grading or sorting of mixture) is related to the cone formed by the deposit which is in turn apparently affected by the size of particles in the mixture. For fine particle, the fall velocity in air or in water is small and no or weak splashing of particles occurs when they impact the surface of deposit. And this type of sedimentation really created a well-formed cone at the center of the cylinder. As the particle size increases, the size of the cylinder probably should increase to compensate for the increase of splashing distance of coarser particles if landsliding is to occur.

Density differences between mixing particles also play an important role in the formation of laminae. Generally, the lighter particles in the mixture are pushed away from the point of impact towards the wall of the cylinder while heavier particles stay in the center. Again, the formation of laminae depends on whether landsliding occurs or not. In cases where landsliding and segregation of particles occurs, lamination are observed. The lamination of this type of mixture is still quite uniform, although the layers are apparently thicker (See Pictures 27 and 28). Since the fall velocity of lighter particles is much smaller than that of heavier particles in water, any discontinuity of sediment supply during the process will cause the formation of a layer of lighter material on top of the heavier materials, due to the longer suspension of lighter particles in the water. The thickness of this layer depends on the settling rate.

The shape of particles is assumed to influence the process of lamination, since the internal friction coefficients of different shaped particles are different. This is demonstrated by comparing mixtures 2 and 5 (run #2 and #6) where ERC#1 and limestone#1 have different shapes while the other type of material is the same (B3060). Unfortunately, this hypothesis cannot be confirmed because the shape of particle in this experiment is not carefully measured. Further experiments should take this parameter under further consideration.

V. CONCLUSIONS

Sedimentation experiments of heterogranular sand mixtures in air and still water have been conducted in a vertical square cylinder. With these experiments, the lamination of heterogranular mixtures composed of sediments of different size, density, and shape is investigated and documented. The following conclusions can be obtained from this study.

1. Laminae can be observed under the following conditions: (1) sand mixtures of the same density but different sedinent size; (2) sand mixtures of the same size but different density; or (3) sand mixtures of different density and different sediment size.

2. Laminae can be obtained both in air and water. Segregation of sediment sand mixtures is the primary cause to lamination. In air, splashing of particles when they impact the surface of deposit becomes stronger as the mixture gets coarser due to higher fall velocity. However, splashing does not occur in water. In water, the least fluid turbulence created by settling of particles should be maintained, such as in runs # 12, 14, 15, 18, 19, and 20. As the fall velocity of coarser particles increases such that turbulence created by the settling causes suspension of finer particles, the deposition of the mixtures becomes more uniform and no laminae in the deposit can be found. Under this circumstance, landsliding and rolling of one type of particles over the other are generally not observed.

3. Lamination is mainly caused by landsliding and the rolling of one particle over the other during sedimentation process. While the occurrence of landsliding and segregation of particles requires sufficient space, lamination would not be obtained if insufficient distance exists between the center and the walls of the cylinder. This phenomenon is shown in runs #3 and 20. In these runs, the cylinder does not stand straight up but is inclined at about 2-5 degree. This means that the impact point of sediment at the bottom is decentralized. In run #3, picture 9 is taken against the wall with longer distance from the impact point while picture 7 is taken against the wall with shorter distance from the impact point. These two pictures

clearly show that clearer laminae are obtained at the section farther from the impact point. Picture 7 also indicates that as the section gets farther from the impact point, the laminae gets clearer. Similar results are obtained in run #20. On the other hand, for those runs (#1, 7, 8, for instance) without enough spacing, no laminae is observed. Coarser mixtures generally create splashing of particles when they impact the surface of deposit on the bottom of the cylinder, due to the high fall velocity of the particles. And this splashing of particles causes the mixing of particles around the center of the cylinder, lamination is not clearly observed within a short distance. Perhaps a bigger cylinder is required to provide sufficient sliding distance for coarse particles to form laminae.

4. The shape of the particles in the mixture affects the lamination process. The densities of ERC #1 and the limestone#1 are about the same, but their mixing with black sand (B3060) and coal#1 gives different results. Mixtures 2 and 3 in runs 3 and 4, respectively, produces clear lamination, while mixtures 5 and 6 in runs 6 and 7, respectively, produce no lamina. Another example is from comparing mixture #1 and #10. The densities of limestone#1, B2040, and ERC#3 are about the same in these two mixtures. The size difference of B2040 and ERC#3 in mixture #1 cannot produce lamination in either air or water, however mixture #10 can produce lamination in the water (Pictures 32-34) although not in the air. These two mixtures both produce splashing in the air and landsliding in the water. But as we mentioned before (pages 39 and 42), these is an obvious segregation of limestone#1 from B2040 during the landsliding in run #20 while such phenomena is not observed in Run #21. This could be caused by the difference in density rather than the size. From laboratory observations, it is found that the shape of ERC#3 is more angular while the shape of limestone#1 is more rounded. However, this conclusion can only be confirmed from further experiments.

5. Heavier and coarser materials have the tendency to push lighter and finer sediment particles away from the center of the deposit. This makes it more difficult for the mixtures to form laminae. However, this type of mixture tends to produce

clearer laminae in water if the sedimentation is not continuous (see mixture 4 in run #18).

REFERENCES

Berthault, G., 1986. "Sedimentology-experiments on lamination of sediments", C.R. Acad. Sci. Paris, t303, Serie II, No.17, pp.1569-1574.

Berthault, G., 1988. "Sedimentation of heterogranular mixture experimental lamination in still and running water", C.R. Acad. Sci. Paris, t306, Serie II, pp.717-724.

Julien P.Y. and Y.C. Chen, 1989. Experimental study of horizontal lamination in a recirculating flume, Civil Engineering Report CER88-89PYJ-YCC14, Dept. of Civil Engineering, Colo. State University, Fort Collins, Co., 63p.

Julien P.Y. and Y.Q. Lan, 1989. Experimental Formation of Alluvial Channel in Wide Rectangular Flume. Civil Engineering Report CER89-90PYJ-YQL2, Dept. of Civil Engineering, Colo. State University, Fort Collins, CO., 29p.