Flume Tests Results

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Abstract: *In this paper, the 6 flume tests for the prediction event are described in detail. The flume test set up, including the flume system and measurement tools are introduced first. Then the experimental procedure is outlined. Finally, the measurements and important observations of the scour generation are presented.*

Experimental Set Up

Flume tests for the prediction event were conducted in the 1.5 m wide concrete flume in the Hydraulic Laboratory at Texas A&M University. Description of the equipment used is detailed in the following sections.

Flume and False Bottom

The in-floor concrete flume is 1.5 m wide, 30.48 m long and 3.48 m deep. Together with an upstairs flume, it forms a close system, as plotted diagrammatically in FIG 1. Water is circulated by a series of pumps and the total volume of water in the system is constant during the experiments except minor leakage and evaporation. A screen wire is placed in front of the false bottom to reduce secondary flows and turbulences created by water falling from the upper flume. The false bottom was built with plastic plates and supported by Aluminum frames, with ramps of 1:3 (vertical to horizontal) slope at both ends. The distance from the rear edge of the upstream tank to the front edge of the downstream tank is 7.6m. A trial test before the official scour tests proved that the ramp slopes were smooth enough and the soil tanks were far enough from each other, to ensure that the approaching flow to the scour areas were not modified by the existing structures. The soil tanks were 0.6 m deep, and 1.2 m long for the upstream tank and 0.6 m deep, and 1.5m long for the downstream tank.

In this flow system, the slope of the false bottom is zero, and the approaching velocity and the water depth are controlled by the pump rate. The flow cross-section area for the uniform channel is determined by the flow depth, which can be precisely justified by a mini pump (as shown in FIG 1 (4)) at the end of the tank.

Pier Model

The cylindrical piers were cut from PVC pipe with an outside diameter of 160mm. The pier was installed in the middle of the channel and a little closer to the front edge of the soil tank in the longitudinal direction.

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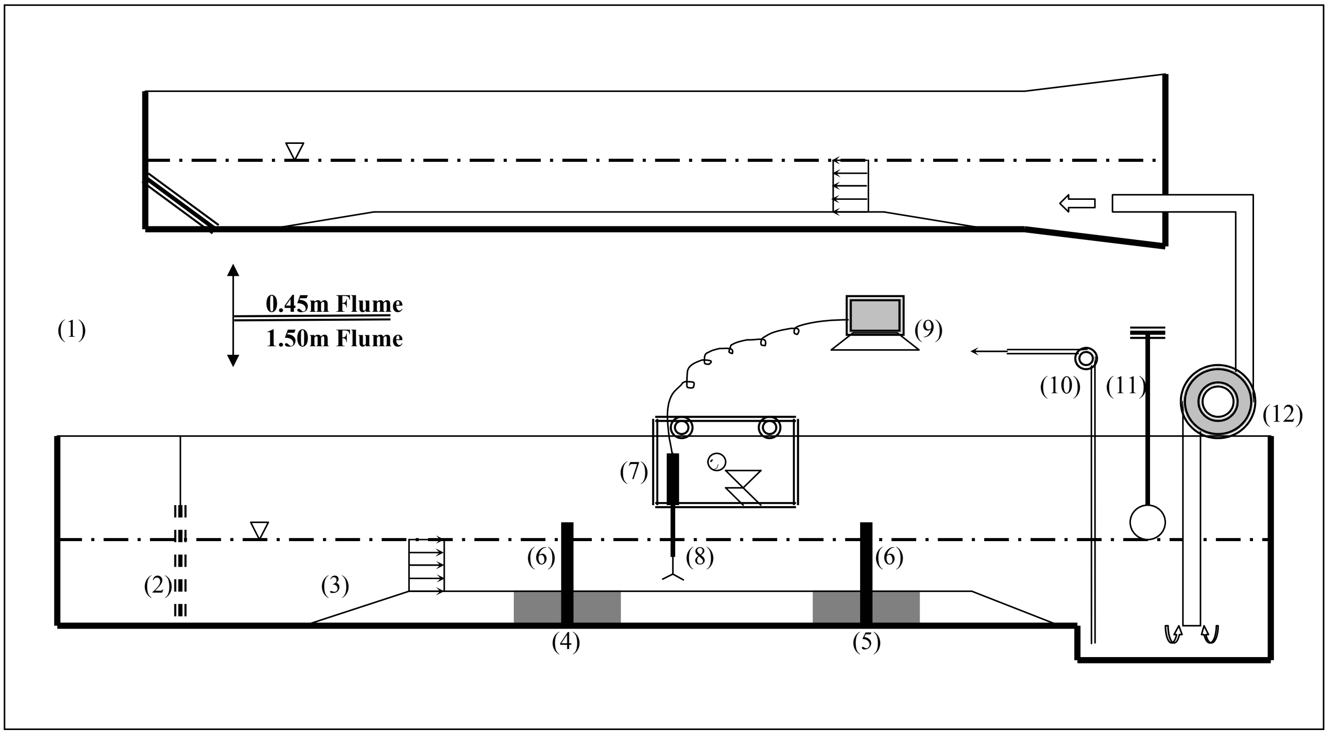


FIG 1 Diagrammatic Figure of the Flume System (not to Scale)

(1): Water Fall	(4): Soil Tank 1	(7): Movable Measurement Cage	(10): Mini Pump
(2): Screen Wire	(5): Soil Tank 2	(8): ADV and Point Gage	(11): Switch
(3): False Bottom	(6): Piers Cage	(9): Computer	(12): Pump

Equipment for Velocity Measurement

An ADV (Acoustic Doppler Velocimeter) uses acoustic sensing techniques to measure flow in a remote sensing volume so that the measured flow is undisturbed by the presence of the probe. A 2-D ADV (longitudinal direction U and vertical direction V), which is sketched in FIG 2, was used to measure the mean velocity of the flow in the tests. It had a velocity range of ±2.5m/s and a resolution of 0.1mm/s.

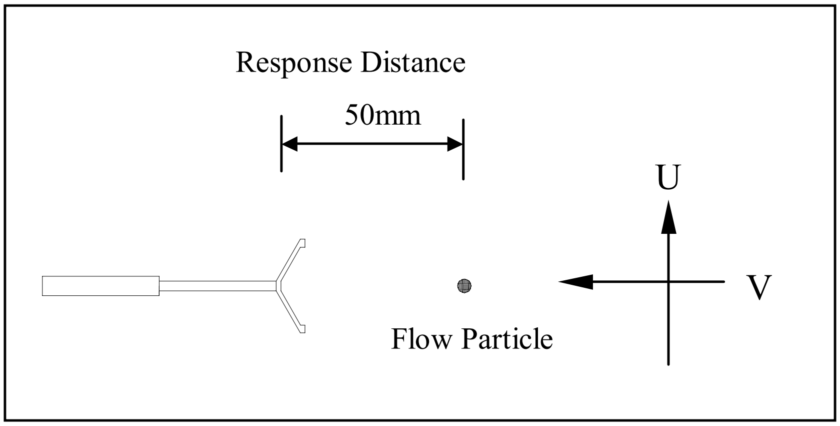


FIG 2 2-D ADV Diagram

Equipment for Elevation Measurement

An electronic point gage was designed and used to measure the increase in scour depth without interrupting the test. The point gage is designed on the principle that air, water and soil have a different electrical conductivity. In the point gage system, a close circuit is formed with a node in the soil or water and the other one in the air. Once the point gage, which is basically a needle attached to a vertical ruler, touches the surface of the scour hole (an interface between water and soil), there is a sudden change in the reading of the volt meter. The reading on the ruler marks the elevation of the scour hole at this moment. When the water is dirty and cannot be seen through, the deepest scour location needs to be searched point by point. The needle is so tiny that the damage caused by the thrust on the scour hole surface can be neglected. It takes 1 minute to take one reading and about 10 minutes to finish one set of data for a single pier scour tests. The resolution of the measurement is ±1mm.

As shown in FIG 1, the point gage and ADV are installed on a cage moving along the longitudinal direction of the flume. The hanging measurement cage is built in the 1.5m flume to decrease the distance between the reading point and the measuring point and to minimize measurement errors. In the flume tests, it was found that the presence of the piers had almost no influence on the approaching flow at a distance equal to 1 time the channel width or further, upstream of the pier. The approaching velocity and water depth are therefore measured 2.5 m upstream of the pier and in the middle of the channel. In addition, a digital camera is used to record the scour hole geometry after each test.

Soils and Soil Bed Preparation

The properties of the soil used (porcelain clay and mortar sand) are detailed in the prediction request. The porcelain clay is delivered in vacuum extruded blocks with dimensions of 250mm x 180mm x 180mm and sealed in plastic bags. The blocks are installed in the soil tank as shown in FIG 3. After one layer is finished, compaction is conducted using a 20 lbs concrete brick to minimize voids and holes between blocks. Careful compaction is performed on the clay in the vicinity of the pier where the scour hole develops. Once the soil tank is filled, the soil surface is leveled with a straightedge spatula. After each test, the scoured area is cleaned and new clay blocks are installed for the next experiments. The installation of the sand consisted of placing the sand in layers and compacting them in place. During the installation, water was added to the dry sand so that the sand could be compacted more tightly.

FIG 3 Preparation of the Clay Soil Tank

Experimental Procedure

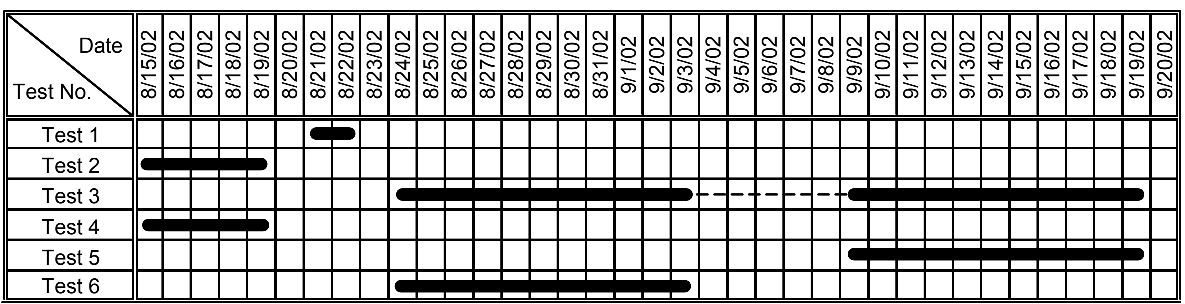
All the pier scour tests were conducted according to the following seven steps:

1. Prepare soil bed and install pier as described in the above section;
2. Measure the initial soil surface elevation around the pier with the point gage;
3. Install the ADV at the middle of the channel and 2.5m upstream of the second pier, and set the node of the ADV at a height of 0.4 times the expected water depth (0.375m in the current tests) above the false bottom; (it should be noted that the velocity measured at this point is regarded as the mean approach velocity);
4. Set the water depth and the velocity in the flume by adjusting the flow of the mini pump and of the main pump;
5. Record the scour depth at necessary intervals,
6. Set the pump rate, water depth and mean velocity according to Step 3-4 when a hydrographic flood is simulated in the flume;
7. After the scheduled time, stop the pump, empty the water in the flume, record the shape of the scour hole with a digital camera and finish the test.

In Step 5, the recorded scour depth is the deepest scour depth at the time of the measurement. The point gage is used to measure the scour depth at different locations around the pier to find the location of the deepest scour depth.

Experimental Results and Observations

Table 1 Schedule of Flume Tests



As shown in Table 1, the flume tests for the prediction event were performed in 4 groups. Most of the time, the two tanks as shown in FIG 1 were used simultaneously to save experimental time. The interval between tests represents the time to clean up the previous tests and to prepare the next ones. The duration of Test 3 was cut from 30 days as planed in the prediction request to 20 days. The measured results as shown in a later section indicate that after 20 days the maximum scour depth was close to being reached. Test 3 was conducted in two separated phases, accompanied by Test 6 in the first 10 days and Test 5 in the second 10 days.

Flume Test 1

In Flume Test 1, a 160 mm diameter circular pier was placed in a clean sand deposit and subjected to a constant velocity of 350mm/s over a period of one day. It was conducted in the upstream tank 1 in FIG 1, starting at15:35, August 21, 2002 to 15:35, August 22, 2002. The measured maximum scour depth as a function of time is given in Table 2 and plotted in FIG 4. The scour hole geometry when the test was terminated is shown in FIG 5. For pier scour in sand, the location of deepest point was in front of the pier. The sand that was eroded from the vicinity of the pier was deposited downstream.

Table 2 Measured Scour Depth as a Function of Time in Flume Test 1

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0	350
0.50	63	
1.00	110	
1.33	113	
2.00	127	
4.75	147	
7.75	160	
9.42	163	
11.33	168	
24.00	183	

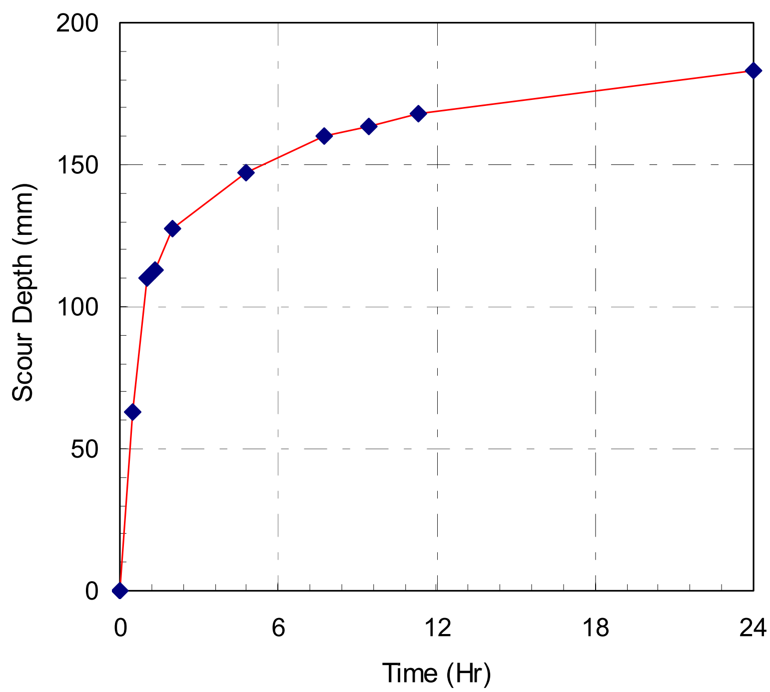


FIG 4 Measured Scour Depth as a Function of Time in Flume Test 1

FIG 5 Scour Hole Geometry for Flume Test 1

Flume Test 2

In Flume Test 2, a 160 mm diameter circular pier was placed in a clean sand deposit and subjected to a multi-velocity hydrograph as shown in FIG 6 over a period of 4 days. Test 2 was conducted in the upstream tank in FIG 1, from 21:45, August 15, 2002 to 21:45, August 19, 2002. The measured maximum scour depth as a function of time is given in Table 3 and plotted in FIG 7. It shows that scour in sand develops very fast and that the scour depth can reach a stable value in a very short time under constant flow. When the second and bigger flood comes in, there is clear jump in scour depth. After the first two days, the scour depth is already fully developed, and the next two days of flow do not bring any significant increment in scour depth.

The scour hole geometry when the test was terminated is shown in FIG 8. As shown in FIG 9, coarse particles deposit behind the pier in an armoring process.

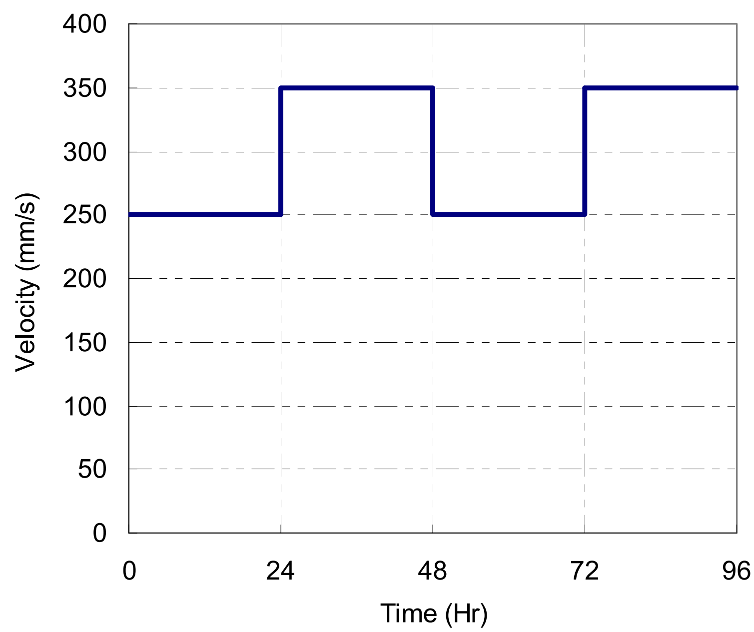


FIG 6 Multi-velocity Hydrograph for Flume Test 2 and Flume Test 4

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0.00	250
0.50	21.26	
0.83	45.72	
1.17	53.16	
1.92	69.11	
2.92	80.80	
6.17	93.56	
8.00	98.88	
9.67	104.20	
24.00	113.76	
24.33	143.53	350
24.50	145.66	
25.00	148.85	
26.50	156.29	
30.42	165.86	
35.17	171.18	
48.00	176.49	
52.00	177.56	250
58.42	178.62	
72.00	178.62	
72.50	180.75	350
82.17	180.75	
96.00	185.00	

Table 3 Measured Scour Depth as a Function of Time in Test 2

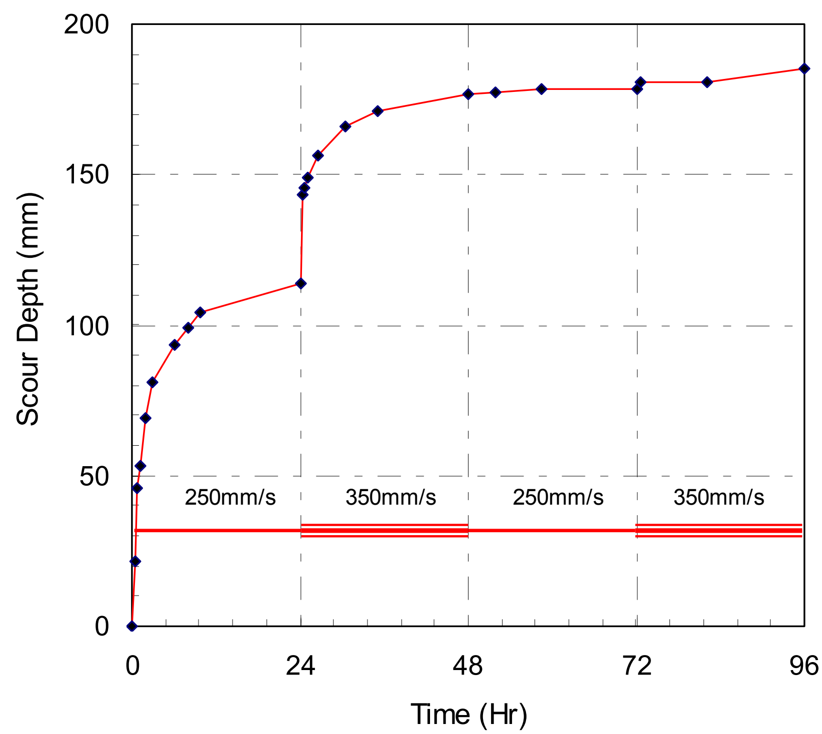


FIG 7 Measured Scour Depth as a Function of Time in Test 2

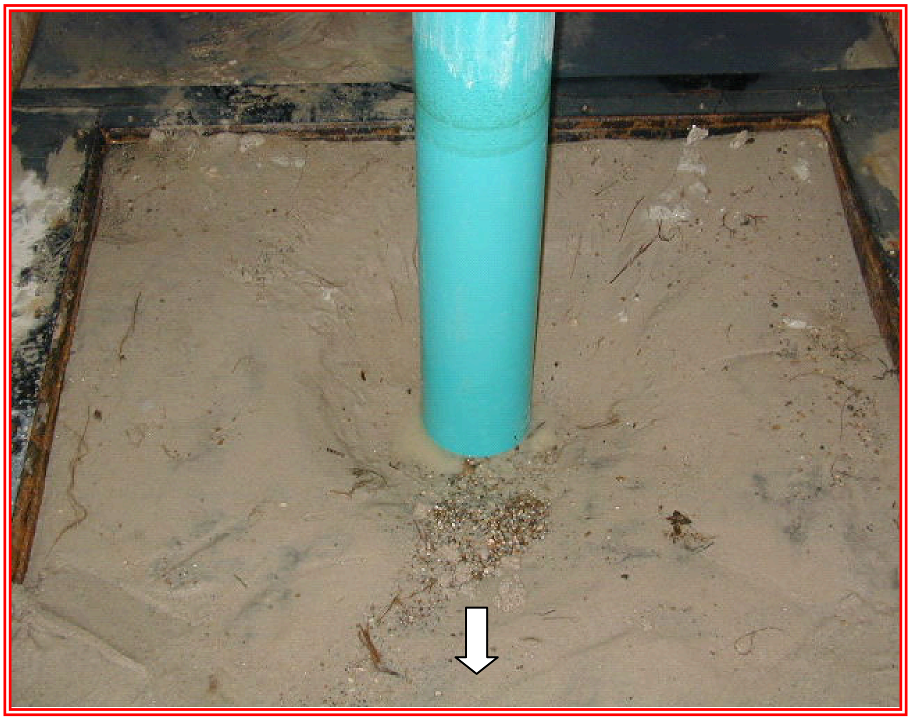


FIG 8 Back View of Scour Hole for Test 2

FIG 9 Coarse Particle Deposition in Test 2

Flume Test 3

In Flume Test 3, a 160 mm diameter circular pier was placed in a clay deposit and subjected to a constant velocity of 350mm/s over a period of 20 days. The test is conducted in the downstream tank in FIG 1, with Test 5 and 6 conducted in the upstream tank consecutively. As shown in Table 1, the duration of Test 3 is broken into two periods, accompanied by Test 6 from 14:40, August 24, 2002 to 14:40, September 3, 2002 and accompanied by Test 5 from 12:45, September 9, 2002 to 12:45, September 19, 2002. During the interval, the scour hole was kept under water to void soil desiccation. The measured maximum scour depth as a function of time is presented in Table 4 and FIG 10. It can be seen on FIG 10 that within 144 hours (about 6 days or 30% of the total scour duration) the scour depth in the clay has reached 150mm, or 93% of the final scour depth of 161mm. FIG 11 shows the scour hole geometry when the test was terminated. The deepest scour hole in this clay is generated on the side of the pier, instead of the front of the pier as in sand.

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0	
6.17	12	
9.67	26	
23.92	56	
34.33	70	
47.08	98	
71.50	115	
82.50	130	
98.67	130	350
105.33	138	
128.50	145	
152.33	150	
200.92	154	
240.00	156	
336.42	156	
387.25	160	
480.00	161	

Table 4 Measured Scour Depth as a Function of Time in Test 3

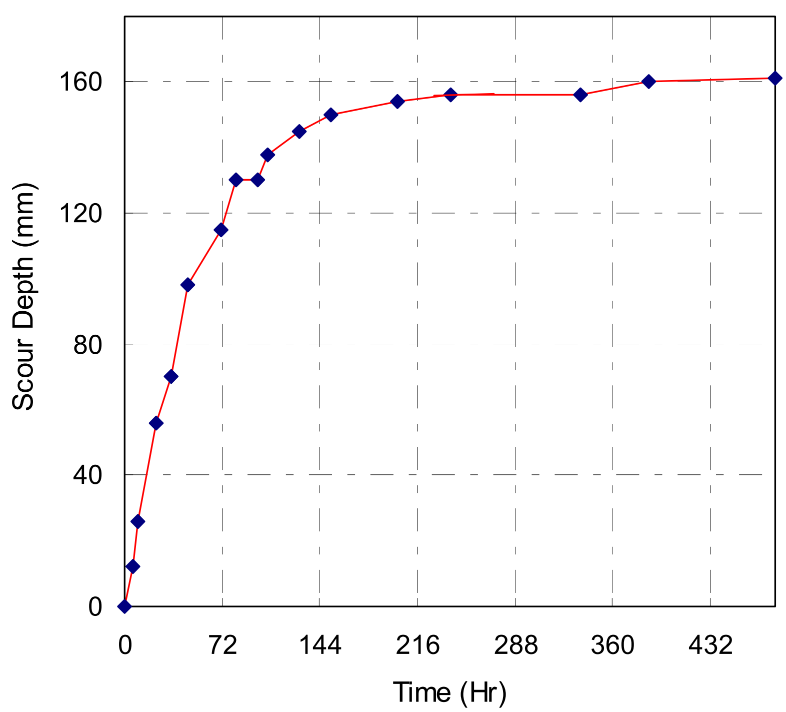


FIG 10 Measured Scour Depth as a Function of Time in Test 3

FIG 11 Scour Hole Geometry for Test 3

Flume Test 4

In Flume Test 4, a 160 mm diameter circular pier was placed in a uniform clay deposit and subjected to a multi-velocity hydrograph as shown in FIG 4 over a period of 4 days. Test 4 was conducted in the downstream tank in FIG 1, with Test 2 conducted in the upstream tank simultaneously. Test 4 is same as Test 2 except that the soil is clay instead of sand. Their comparison can be used to illustrate the difference between scour in sand and in clay. The measured maximum scour depth as a function of time is presented in Table 5 and FIG 12. It shows that there is a change in scour rate associated with the change in velocity. However, this change is not as drastic as in sand (compare FIG 12 and FIG 7).

The scour hole geometry when the test was terminated is shown in FIG 13. As shown in the figure, there is no erosion on the soil in the soil tank except the vicinity around the pier. The scour hole is relatively localized compared to the scour hole in sand. The deepest scour depth is formed at the side of the pier as marked in FIG 14.

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0.00	250
6.08	21.26	
11.67	45.72	
24.00	53.16	
25.00	69.11	350
26.50	80.80	
30.42	93.56	
35.17	98.88	
48.00	104.20	
52.00	113.76	250
58.42	143.53	
72.00	145.66	
96.00	148.85	350

Table 5 Measured Scour Depth as a Function of Time in Test 4

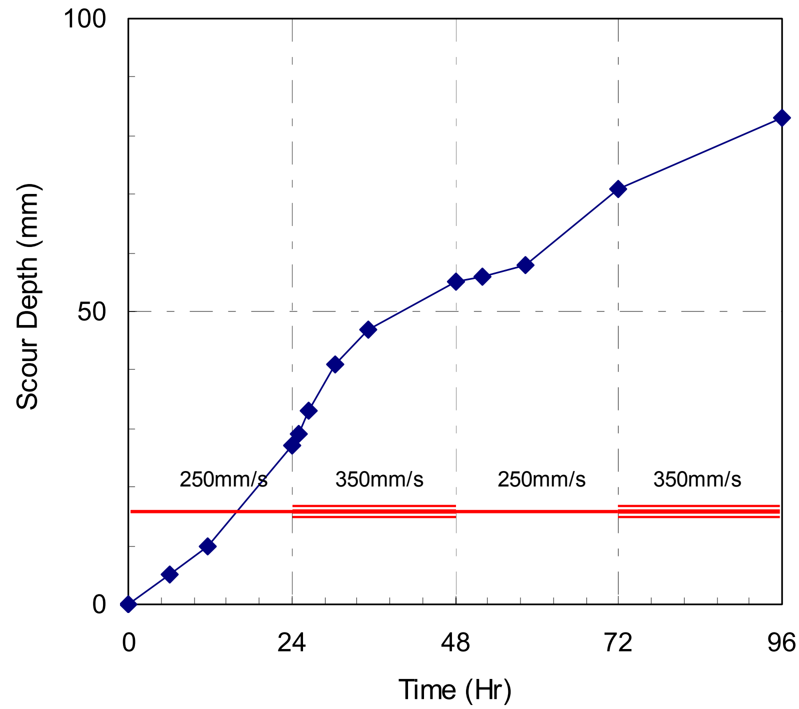


FIG 12 Measured Scour Depth as a Function of Time in Test 4

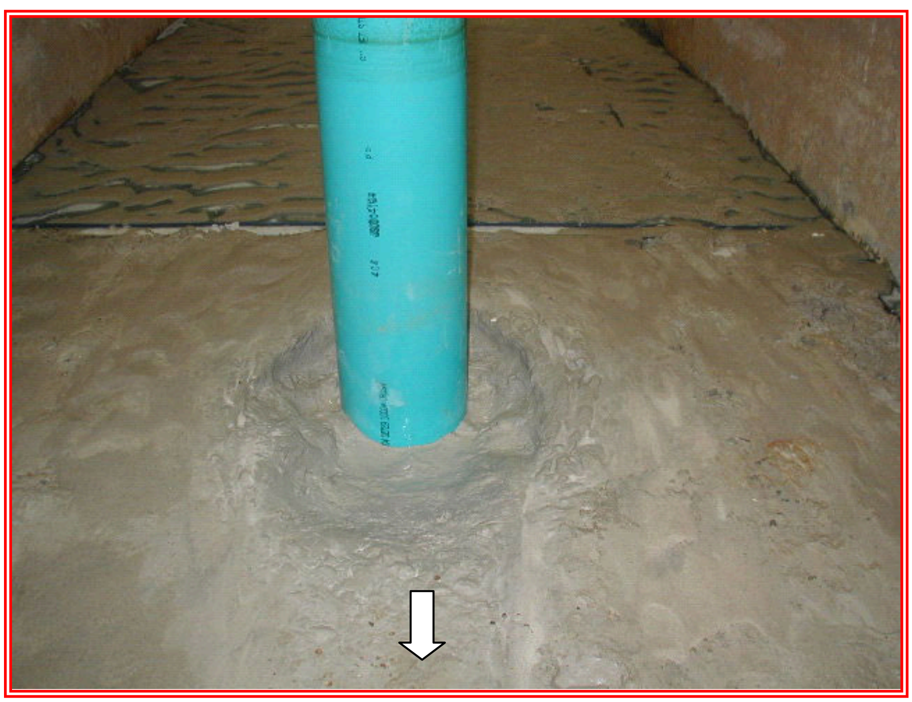


FIG 13 Back View of Scour Hole for Test 4

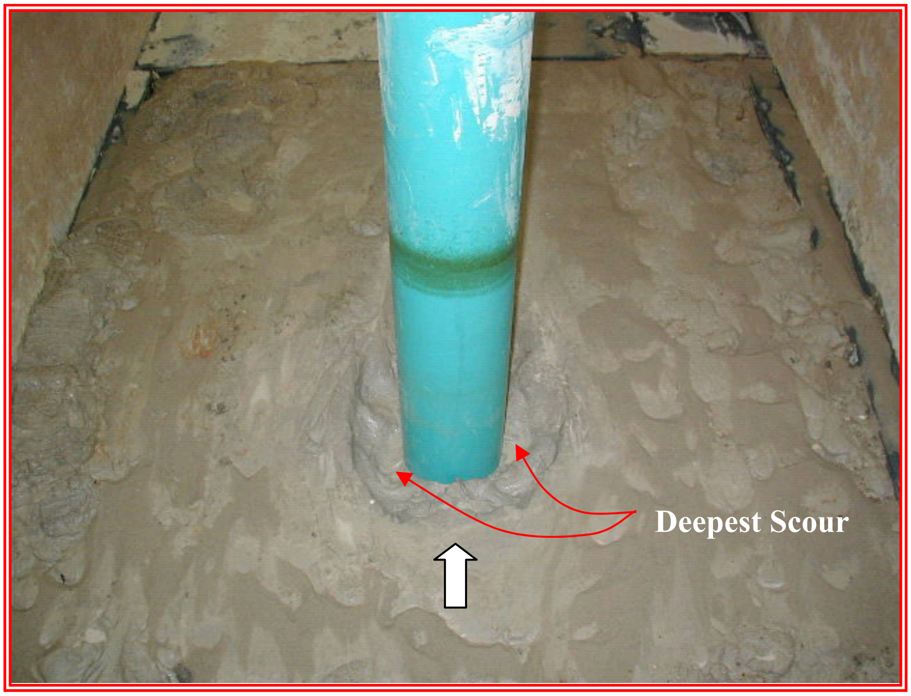


FIG 14 Front View of Scour Hole for Test 4

Flume Test 5

In Flume Test 5, a 160 mm diameter circular pier was placed in a sand over clay layered soil and subjected to a constant velocity flow of 350mm/s over a period of 10 days. The thickness of the top sand layer was 80mm. The measured maximum scour depth as a function of time is presented in Table 6 and FIG 15. FIG 16 shows the scour hole geometry when the test was terminated. It indicates that when the scour penetrates the top sand layer and touches the bottom clay layer, the scour rate drops suddenly, but there is still further scour developing in the clay layer over a long duration. The sand around the scour hole is swept into the scour hole and eroded way. As shown in FIG 16, only a relatively small scour hole exists in the clay layer. As the scour hole develops from the sand layer to the clay layer, the deepest scour location moves from the front of the pier to the side of the pier.

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0	350
0.50	30	
1.00	60	
1.50	76	
2.00	80	
3.00	80	
5.92	81	
8.83	83	
20.00	106	
31.92	118	
35.92	120	
48.42	128	
71.67	144	
96.42	146	
123.25	147	
147.25	147	
169.25	150	
191.25	150	
240.00	152	

Table 6 Measured Scour Depth as a Function of Time in Test 5

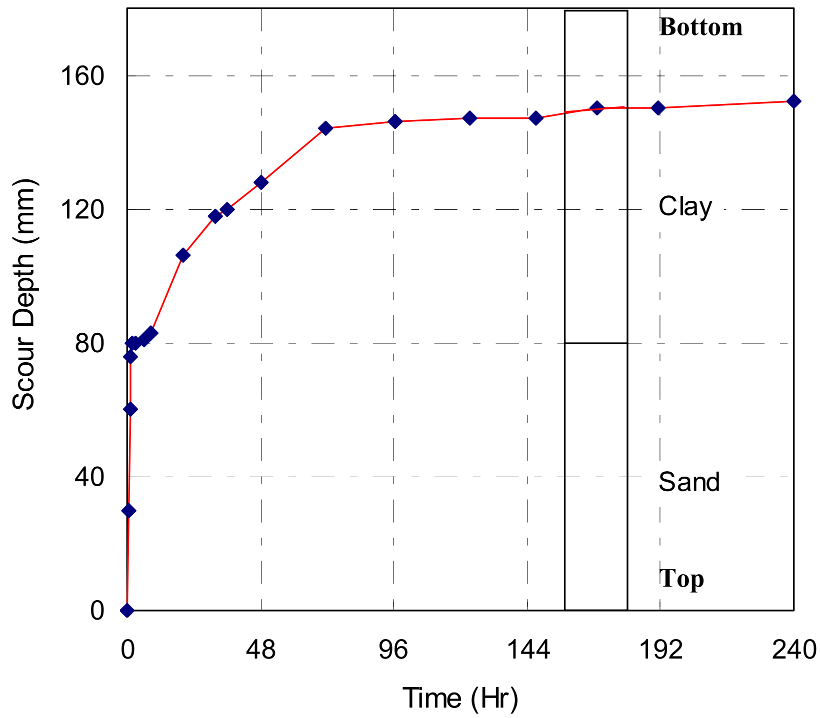


FIG 15 Measured Scour Depth as a Function of Time in Test 5

FIG 16 Scour Hole Geometry for Test 5

Flume Test 6

In Flume Test 6, a 160 mm diameter circular pier was placed in a clay over sand layered soil and subjected to a constant velocity flow of 350mm/s over a period of 10 days. The top clay layer is 80mm thick. The measured maximum scour depth as a function of time is presented in Table 7 and FIG 17. FIG 18 to FIG 21 show the scour hole geometry when the test was terminated.

Several interesting phenomena are observed in this test. First, the scour development curve (FIG 17) indicates that the scour rate does not suddenly increase as expected when the scour touches the bottom sand layer. Instead, the scour rate remains approximately equal to the rate in the clay. This rate continues until the scour depth reaches 100mm and then the scour rate begins to increase compared to the scour rate in uniform clay at the same depth. It was found that when the scour depth first touches the sand layer, the deepest part of the scour hole in clay is so concentrated that only a very tiny area touches the sand layer. Under this condition, the sand cannot be effectively eroded away and the scour process consumes most of its energy to enlarge the scour hole horizontally but not to increase the scour depth. At this stage, the scour generation is mostly dominated by the characteristics of a scour hole in clay. After finishing the enlargement of the scour hole, the scour hole works like a scour hole in uniform sand and the scour begins to show a larger scour rate. Meanwhile, the deepest scour location moves from the side of the pier to the front of the pier just where it usually is in uniform sand.

FIG 18 and 19 demonstrate that the scour hole for a clay over sand layered soil is wider and larger than the scour hole developed in uniform clay but smaller than that scour in uniform sand. Another important aspect of the scour hole is its edge slope. FIG 20 indicates that slopes with angles larger than 90º exist in the top clay layer. FIG 21 clearly illustrates that during the scour development in the bottom sand layer, the flow will dig underneath the top clay layer, which will fail in blocks into the scour hole; this is another mechanism in the scour hole development.

Time (Hr)	Scour (mm)	Velocity (mm/s)
0.00	0	
6.17	16	
9.67	19	
23.92	52	
34.33	72	
47.08	94	
57.58	100	
71.50	120	350
82.50	120	
98.67	135	
105.33	151	
128.50	162	
152.33	164	
200.92	170	
240.00	177	

Table 7 Measured Scour Depth as a Function of Time in Test 6

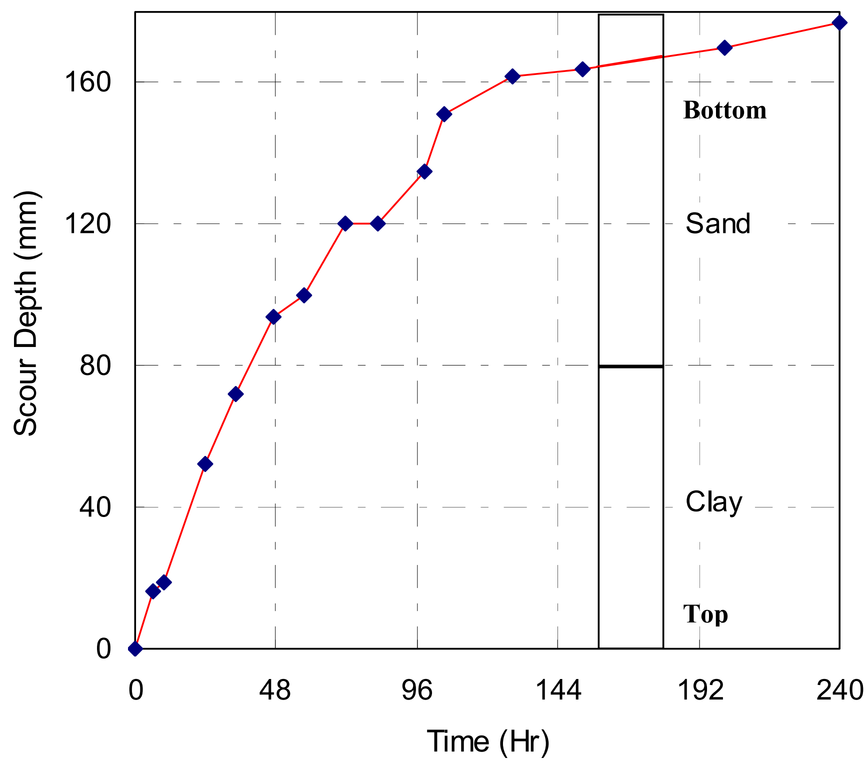


FIG 17 Measured Scour Depth as a Function of Time in Test 6

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FIG 18 Back View: Scour Hole Geometry for Test 6

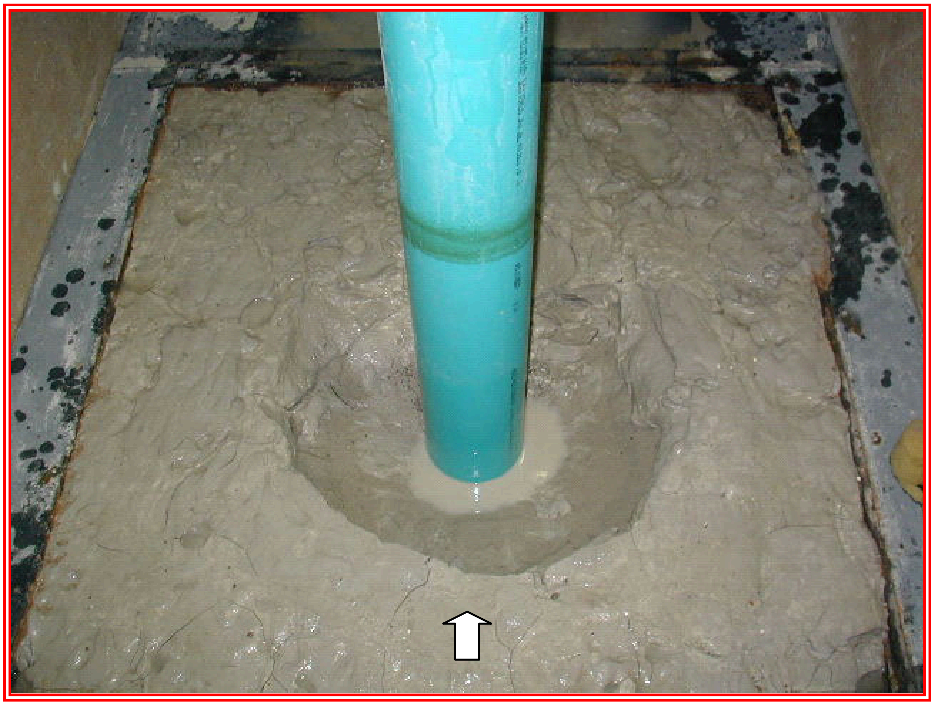

FIG 19 Front View: Scour Hole Geometry for Test 6

FIG 20 Steep Slope of the Scour Hole in Test 6

FIG 21 Falling Clay Block in the Scour Hole for Test 6

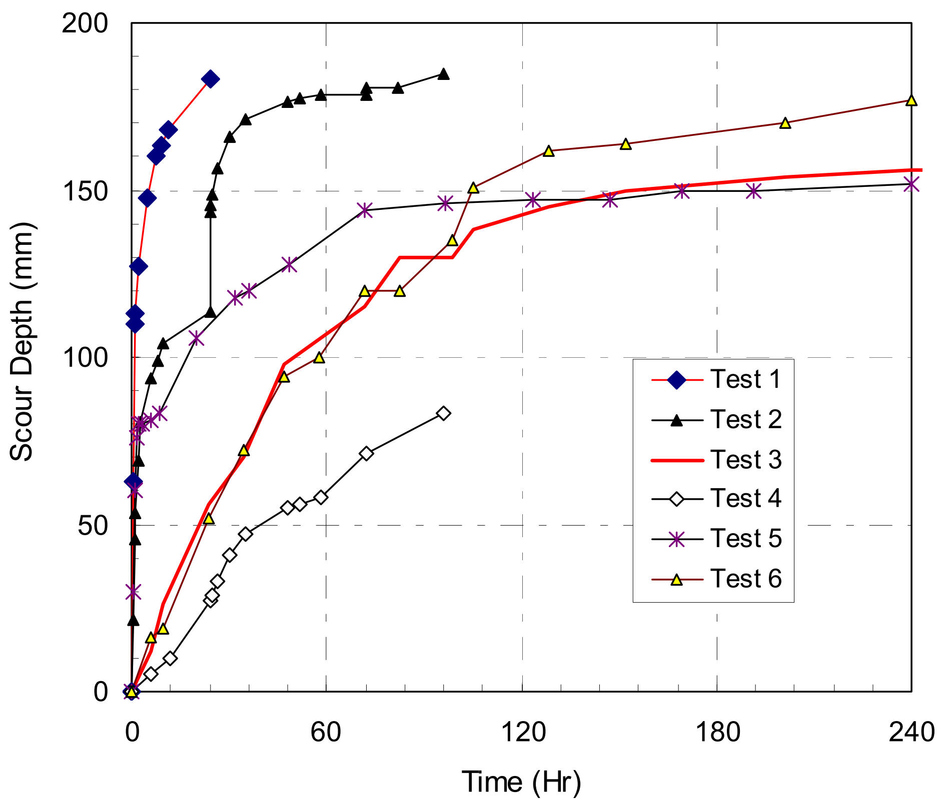

FIG 22 Comparison between Flume Test Results

Evaluation of Flume Test Results

The scour development curves are plotted in FIG 22 for all the 6 flume tests. Similarities exist among the flume tests, which can be used to check the validity of the flume tests.

Because the scour depth is a function of time, the final scour depth measured in the flume tests only represents the instantaneous scour depth when the test is stopped. A hyperbolic extrapolation model (Briaud et al, 1999) is used to predict the ultimate scour depth $Z_{max.}$ Examples of the hyperbolic regression fit are shown in FIG 23 and FIG 24 and the predicted ultimate scour depths are listed in Table 8. It can be seen that the order of the magnitude of the ultimate scour depth is: clay over sand > sand> clay >sand over clay.

Table 8 Instant scour depth Z and ultimate scour depth Z_{max} for the Flume Tests

Test No.	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Z(mm)	183	185	161	83	152	177
Z_{max} (mm)	189	---	172	---	159	238

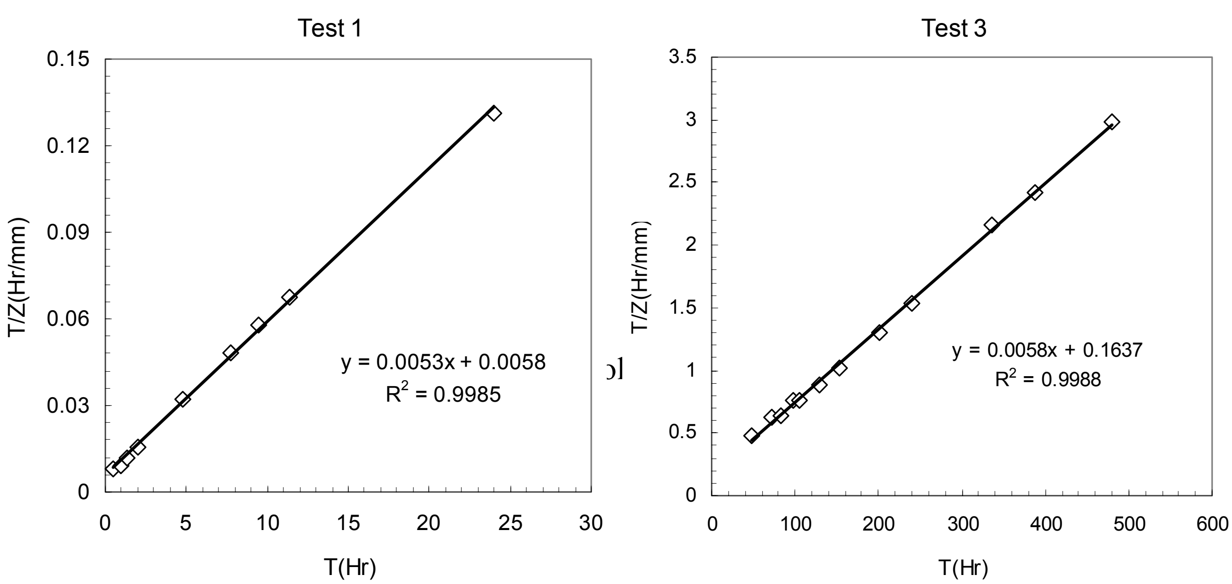

FIG 23 Linear Regression for Flume Test 1 3 by Hyperbola Model

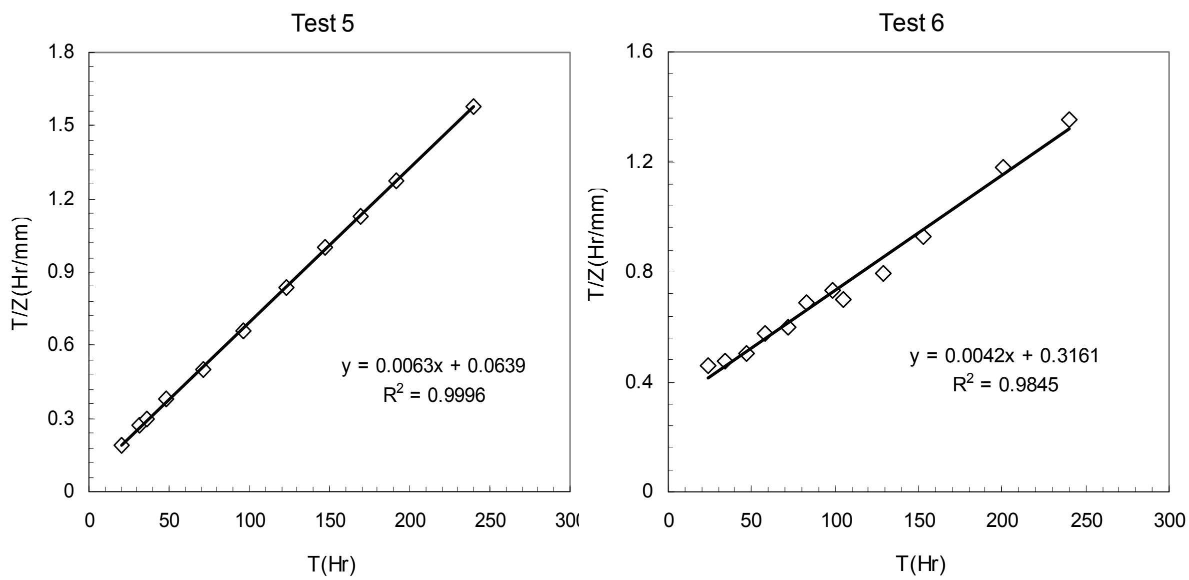

FIG 24 Linear Regression for Flume Test 5 6 by Hyperbola Model

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1. Briaud, J.-L., Ting, F., Chen, H.C., Gudavalli, R., Perugu, S., Wei, G.S., "SRICOS: Prediction of Scour Rate in Cohesive Soils at Bridge Piers", ASCE Journal of Geotechnical Engineering, Vol 125, No.41999, pp.237-246.