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DATA REPORT #1

Full-Scale Pipe/Soil Interaction

Test MMS 01

Contract Report

Prepared for:

Minerals Management Service

Prepared by:

C-CORE
St. John's, Newfoundland

C-CORE Publication No. 99-C12
April, 1999

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Quality Control Report

Client/Project: Minerals Management Service, U.S. Dept. of the Interior

Contract Ref.:

C-CORE Project No. 340480

Document Title: Full-Scale Pipe/Soil Interaction – Test MMS 01

C-CORE Publication No. 99-C12

Prepared By: Shawn Hurley

Date: April, 1999

Checked by Reviewers	Document Accepted	
	Date	Sign
Technical Accuracy		
	April 8, 1999	[illegible]
	April 8, 1999	[illegible]
Syntax	April 8/99	[illegible]
Layout & Presentation	April 8/99	[illegible]

Approval for Release [illegible]

Date: Apr. 10/99

The correct citation for this report is:

Hurley, S. and Phillips, R. (1999). "Full-Scale Pipe-Soil Interaction Study - Test MMS 01 Data Report". Contract Report for Minerals Management Service, U.S. Department of the Interior, C-CORE Publication 99-C12.

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1.0 GENERAL

1.1 Program Summary

This is the first data report associated with the "Large Scale Modelling of Soil/Pipe Interaction Under Lateral Loading" project for the Minerals Management Service (MMS).

The research program for the MMS is composed of fundamental research on offshore lateral pipeline/soil interaction and provides a study of the influence of selected ground conditions on load transfer behaviour. The results of this program are directly applicable to problems of offshore pipeline/soil interaction resulting from offshore mudslides or as the result of offshore seismic activity (i.e. faulting or lateral spreading). However, conditions to be modelled will yield results applicable to the Geological Survey of Canada (GSC) tests (Hurley et al, 1998a,b) in that the soil, pipe, and loading conditions will be similar.

The MMS tests provide the two-dimensional force-displacement or p-y response of the pipe. These data will then be used to back-analyse the observed behaviour of the GSC pipe bending tests using discrete pipeline finite element analyses (soil springs).

2.0 WORK ACTIVITY PROGRESS

2.1 Procurement and Modifications

The pipe used for the first MMS test was constructed from sections of the pipe that had been used previously during test GSC 02. Test GSC 02 was carried out using a 6 m long pipe buried in dense sand loaded laterally approximately 0.1 m from each end. To fabricate the MMS 01 pipe, a 300 mm long steel insert with a thickness of about 6 mm was fabricated. The outside diameter of the steel insert was approximately equal to the inside diameter of the GSC 02 pipe. Two straight pipe sections, each about 1.5 m long, were then cut from the GSC 02 pipe. Approximately one-half the length of the steel insert was then positioned inside one of the straight sections and welded in place. The second straight section was then positioned over the steel insert so that the distance between the two straight sections was about 3 mm. The two straight pipe sections were then welded together and the surface of the pipe in the vicinity of the weld was machined to produce a smooth surface.

To create a rigid pipe and prevent buckling, it was necessary to increase the pipe stiffness. The pipe stiffness was evaluated using a pile flexibility factor as outlined by Poulos and Davis (1980):

$$K_R = (E_p I_p) / (E_s L^4)$$

where:
- K_R = Pile flexibility factor
- E_p = Young's modulus for pipe (pile)
- I_p = Moment of inertia for pipe (pile)
- E_s = Young's modulus for sand
- L = Length of pipe (pile)

A relatively rigid pile is defined by Poulos and Davis (1980) as one for which $K_R > 10^{-2}$ (0.01). Bowles (1988) gives a range of values for Young's modulus of dense sand from 50 to 81 MPa. The average value of 65 MPa was used in the stiffness analysis of the MMS 01 pipe. For a 3 m long pipe with E_p = 194 GPa (Hurley et al., 1998c), an outside diameter of 203.2 mm and a wall thickness of 4.7 mm, the resulting flexibility factor was ~ 0.00053 which is lower than the recommended value.

The flexibility factor of a previous rigid pipe (328 mm O.D., 3 m length, t = 12.7 mm) (Paulin and Hurley, 1996) is evaluated with the same value of E_p and E_s, the result is a flexibility factor of approximately 0.0057. This value is about 10 times higher than the unreinforced MMS pipe factor and about one-half of the recommended value.

To minimise ovalisation and marginally increase the stiffness of the MMS 01 pipe, it was decided to completely fill the interior area of the pipe between the loading points with a locally obtained non-shrink construction grout. The flexibility factor of the reinforced pipe was then increased to about 0.00089, which represents an increase of about 69%. It was thought that the combination of the 300 mm long steel insert at the centre of the pipe and the addition of the grout would provide enough pipe stiffness to conduct the test. The load was applied to the Master and Slave ends of the pipe using 50 mm diameter steel loading arms. One end of each arm was connected to an actuator and 35 tonne in-line load cell while the other end was connected to "knuckles" located about 300 mm from each end of the pipe.

2.2 Sand Properties

As part of the GSC project, a series of soil tests were conducted on samples of the testbed sand. The properties determined from these tests are summarised in Table 1. Due to the large quantity of sand required to fill the tank, three different sand shipments were obtained from a local supplier.

2.3 Test MMS 01

2.3.1 Pipeline Placement

Figure 1 and 2 present plan and profile views of the test setup. The pipeline was removed during placement of a dense bedding layer approximately 240 mm thick. Upon completion of this layer, the pipeline was lowered inside the tank and connected to the two loading arms. Measurements taken after pipeline placement indicated that the base of the pipeline was at an average elevation of 238 mm above the base of the tank. Figure 3 shows the pipe in final position.

2.3.2 Testbed Preparation

During testbed preparation, plywood sheets were placed on the prepared soil layers to minimize disturbance of the layers and to provide a platform from which to work. Sand was placed in the tank from large one tonne bags, as shown in Figure 4, which were positioned about 150 mm over the testbed surface and then opened from the bottom. The sand was initially levelled using a rake and shovel to the appropriate layer thickness of 100 mm. A manual tamper with a mass of 5 kg and a footprint of 127 x 300 mm was then used to compact the sand. After at least two passes with the manual tamper, two passes over the soil surface were made with a vibratory tamper, as shown in Figure 5. This process was repeated for each layer until the soil reached the final elevation of about 850 mm from the floor of the tank. The final elevation of the prepared surface was approximately ± 30 mm with respect to the final grade. After preparing the surface of the testbed, a chalk line was used to place a grid on the soil surface as depicted in Figure 6. Grid point and grid square designations are indicated on the figure as is an outline of the pipeline position. The grid cell designation was made from the lower right corner as shown in the figure.

A number of density checks were carried out during the preparation of the testbed to characterize the soil. Density pans (approximate inside diameter = 243 mm, approximate height = 50 mm) were placed at different positions within the testbed (Method #1) and removed after the test during testbed excavation. The results of these tests are summarized in Table 2. Another type of test (Method #2) was conducted during testbed preparation in which one of the pans was lowered by a harness, filled with compacted material, retrieved and weighed. Results are also presented in Table 2. The test locations are presented using the approximate elevation and grid square in which the tests were conducted. The Type #1 tests yielded densities ranging from 1919 kg/m^3 to 2059 kg/m^3 with an average density of 1982 kg/m^3. The Type #2 tests yielded an average density of 1986 kg/m^3 with values ranging from 1809 to 2055 kg/m^3. Overall, the average density was 1984 kg/m^3. Table 2 also presents moisture content data determined from the density pan tests.

Following completion of the testbed, vertical deformation tubes (VDT's) and internal deformation markers (IDM's) were inserted into the testbed and the pre-test surface elevation was measured using a surveyors level and rod. Surface elevation data are presented in Table 3 where the pre-test surface position has been established at an elevation of 850 mm (rod reading = 949 mm). An acoustic surface profiler was then positioned over the testbed. These instrumentation are described further below.

2.3.3 Vertical Deformation Tubes

The vertical deformation tubes, initially developed to measure soil deformation profiles during the NOVA full-scale pipeline/soil interaction project (Paulin and Hurley, 1996), consist of flexible tygon tubing connected to a metal tip. The overall length of the vertical deformation tubes used for test MMS 01 was approximately 900 mm. The tubes and attached tips were driven the complete depth of the testbed using a 0.25 inch metal rod which was inserted down the tubing and rested in a recess in the anchor. Prior to removal of the rod, the entry angle of the tube both parallel and perpendicular to the pipeline were measured and recorded (Table 4). The coordinates of the location where the tubing intersected the soil surface were then measured and recorded (Table 4).

Following the test, the position of the tubing/testbed intersection was again recorded. The tubes were then filled with a fibreglass resin and allowed to cure overnight prior to beginning excavation. The excavation was conducted in stages and periodically the vertical tube above the excavation was fixed in position to a string suspended to the sides of the tank. Care was taken during the excavation process not to disturb the tubing and positions of the tubes were measured at 50 mm increments (Table 6).

Figure 7 shows a profile view of the vertical deformation tubes used in Test MMS 01. Shown on the figure are the inferred pre-test centreline positions of the deformation tubes based on the entry angle measurement of the rod. As well, the pre-test centreline positions of the deformation tubes based on pre-test surface positions of the tubes and post-test locations (Table 6) of the tubes at an elevation of 50 mm are presented (it has been assumed that no deformation of the tubes occurred at that elevation during pipeline movement).

2.3.4 Acoustic Surface Profiler

Prior to testing, the acoustic surface profiler was set up over the testbed. The set up was such that the profile would be taken along the X = 1460 mm transect perpendicular to the central axis of the pipe. A complete description of the profiler system, its calibration, and proofing tests is available as an engineering student work term report (Bungay, 1996) on request. During some of the initial profiles, a wooden block was placed on the testbed surface to check the profiler calibration.

2.3.5 Internal Displacement Markers

The internal displacement markers used in test MMS 01 were essentially identical in construction to the VDT tubes. However, instead of being inserted to the bottom of the testbed, the IDM's were inserted to varying depths within the testbed and were connected to linear potentiometers to monitor internal soil deformations during pipeline displacement. The pre-test IDM positions are shown in Figure 8 and given in Table 5. Following the test, these tubes were excavated in a manner similar to the VDT's. Post-test IDM locations are given in Table 7.

Figure 9 is a plan view of the tank showing the positions of the VDT's and IDM's with respect to the tank outline. Figure 10 is a photograph showing the general appearance of the testbed just prior to beginning the test.

2.3.6 Test Conduct and Results

Testbed preparation took place from March 8 to March 15/1999. The surface profiler system was installed on March 16 and on the same day, the electrical instrumentation and data acquisition systems were powered up. The pipeline pull was started at 9:00 am on March 17 and pipeline displacement was completed by approximately 7:00 pm on the same day.

Three displacement transducers were incorporated into the test to monitor pipeline movement; one was located to monitor the master pipeline end displacement; one was located to monitor the slave pipeline end displacement and the third was located to monitor movement at the center of the pipeline. Output from the three separate displacement transducers is presented in Figure 11 while Figure 12 presents a comparison of all three displacement transducers.

There was a delayed response in the displacement transducer at the center of the pipe. This lag can be attributed to some initial flexing of the pipe at the beginning of the test. Shortly after beginning the test however, the displacement rate measured at the center of the pipe compared favourably with the rate measured at the pipe ends. A displacement rate of 10.10 mm/hour was calculated at the Master end of the pipe, a rate of 10.30 mm/hour at the center and a rate of 10.14 mm/hour was calculated at the Slave end of the pipe. Overall, the average displacement rate during test MMS 01 was 10.20 mm/hour.

Filtered processed data from the Master Load Cell (MLC) and Slave Load Cell (SLC) are presented in Figure 13 and Figure 14 as load-displacement curves. Data from the Slave Load Cell is plotted up to a displacement of 65 mm only because the load cell behaviour became erratic at this stage. Figures 13(b) and 14(b) show load-displacement for the first 25 mm of pipe displacement. Measured response of the two actuators are compared in Figure 15 and total load to displace the pipe is presented in Figure 16. During conduct of the test, significant heave and cracking of the testbed surface was observed. Subsequent observations and measurements are discussed in the following sections.

Data obtained using the acoustic surface profiler prior to the start of pipeline displacement are presented in Figure 17. Profiles taken during the test are presented in Appendix B. Figure 18 presents an average post-test profile after the release of pipeline load. The data suggest a maximum of approximately 35 mm of testbed surface heave along the transect of the surface profiler during testing. The post-test survey data from the same area of the testbed (Gridline 5) indicates maximum testbed heave on the order of 50 mm. Surface profiles from t = 540 minutes (90 mm pipeline displacement) until the end of the test indicate a relatively flat surface between tank positions of about 1200 - 2000 mm. It therefore seems that at about 90 mm of pipeline displacement, the distance from the surface profiler to the testbed surface reached a minimum limit.

Processed data from the internal displacement marker are presented in Figure 19 as a function of pipeline displacement. Extension of the linear potentiometer is positive and conversely retraction is negative. The response of each linear potentiometer is the result of both horizontal and vertical movement of the soil surface.

2.3.7 Post-Test Observations and Excavation

The post-test elevation of the testbed surface was measured using a surveyors level and rod. Post-test surface elevation data are presented in Table 3 where the datum has been established as an elevation of 850 mm (rod reading = 833 mm). Significant heave (maximum 50 mm) of the testbed surface occurred as the pipe translated through the soil.

Pre-test positions of the vertical deformation tubes that were used during this test were presented in Figure 7. Figure 20 shows the pre-test positions of the vertical deformation tubes taken as the average of the two measurement methods presented in Figure 7. The initial position of the deformation tubes has been taken as the average position of the tubes based on the entry angle measurements as well as the post-test location of the tube tip assuming no deformation of the tubes occurred at that elevation during pipeline movement. Also shown on Figure 20 are the post-test positions of the vertical deformation tubes based on the excavation measurements at 50 mm increments. It was discovered upon excavation of the tubes that they did not extend to the bottom of the testbed. However, each tube did extend to at least the elevation of the bottom of the pipe. Figure 21 contains photographs which show the vertical deformation tubes after excavation.

Figure 22 shows the post-test positions of the internal displacement markers. It can be seen that the extent of horizontal movement recorded by these markers was limited. Figure 23 is a plan view of the tank showing the general position and extent of cracks that developed in the testbed surface.

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Appendix A

Data Presentation, Tables and Figures

List of Tables

Table 1 Geotechnical Properties of GSC Sand

Property	Shipment #1	Shipment #2	Shipment #3	Average
Friction Angle (Degrees)	53.1	53.3	52.0	52.7
Maximum Dry Unit Weight, $\gamma_{d\,max}$ (kN/m^3)	19.9	19.8	19.3	19.7
Minimum Dry Unit Weight, $\gamma_{d\,min}$ (kN/m^3)	16.3	16.2	15.5	16.0
Maximum Void Ratio, e_{max}	N/A	N/A	N/A	0.62[1]
Minimum Void Ratio, e_{min}	N/A	N/A	N/A	0.32[1]
Effective Grain Size, d_{10} (mm)	0.15	0.13	0.17	0.15
Mean Grain Size, d_{50} (mm)	0.60	0.65	0.65	0.63
Constrained Grain Size, d_{60} (mm)	0.84	0.94	0.89	0.89
Uniformity Coefficient, C_u	5.6	7.2	5.2	5.9
Fines Content (%)	2.5	3.1	1.3	2.3

Table 2 - Density and Moisture Content Measurements - Test MMS01

Pan Type	Elevation (mm)	Grid	Pan Mass (kg)	Pan + Sand (kg)	Mass of Sand (kg)	Pan Volume (m^3)	Density (kg/m^3)	Water Content (%)
1	0	H-7	7.24	11.98	4.74	0.00235	2017.0	2.7
1	100	C-8	7.24	12.02	4.78	0.00236	2025.4	2.3
1	200	A-2	7.18	11.76	4.58	0.00236	1940.7	2.6
1	500	B-3	7.22	12.08	4.86	0.00236	2059.3	1.9
1	600	H-6	7.19	11.74	4.55	0.00236	1928.0	2.4
1	700	B-7	7.20	11.69	4.49	0.00234	1918.8	1.3
						Average:	1981.5	2.2
2	0	B-1	7.67	12.41	4.74	0.00236	2008.5	---
2	100	A-4	7.67	12.47	4.80	0.00236	2033.9	0.2
2	200	J-4	7.67	12.52	4.85	0.00236	2055.1	0.2
2	300	A-10	7.67	12.44	4.77	0.00236	2021.2	0.8
2	400	A-7	7.67	12.32	4.65	0.00236	1970.3	0.2
2	500	F-10	7.67	12.39	4.72	0.00236	2000.0	0.6
2	600	G-1	7.67	12.37	4.70	0.00236	1991.5	1.3
2	700	J-10	7.67	11.94	4.27	0.00236	1809.3	0.7
						Average:	1986.2	0.6

Table 3 - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
A0	0	0	960	-11	844	-11	0
A1	300	0	964	-15	850	-17	-2
A2	600	0	959	-10	842	-9	1
A3	900	0	958	-9	842	-9	0
A4	1200	0	950	-1	836	-3	-2
A5	1500	0	951	-2	836	-3	-1
A6	1800	0	954	-5	841	-8	-3
A7	2100	0	965	-16	848	-15	1
A8	2400	0	951	-2	835	-2	0
A9	2700	0	945	4	828	5	1
A10	3000	0	945	4	828	5	1
B0	0	300	948	1	835	-2	-3
B1	300	300	953	-4	837	-4	0
B2	600	300	952	-3	838	-5	-2
B3	900	300	956	-7	841	-8	-1
B4	1200	300	960	-11	845	-12	-1
B5	1500	300	961	-12	845	-12	0
B6	1800	300	960	-11	847	-14	-3
B7	2100	300	962	-13	848	-15	-2
B8	2400	300	954	-5	839	-6	-1
B9	2700	300	945	4	831	2	-2
B10	3000	300	946	3	831	2	-1

Table 3 (Cont'd) - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
C0	0	600	952	-3	836	-3	0
C1	300	600	953	-4	837	-4	0
C2	600	600	955	-6	839	-6	0
C3	900	600	959	-10	843	-10	0
C4	1200	600	965	-16	846	-13	3
C5	1500	600	965	-16	845	-12	4
C6	1800	600	963	-14	848	-15	-1
C7	2100	600	962	-13	842	-9	4
C8	2400	600	949	0	830	3	3
C9	2700	600	952	-3	835	-2	1
C10	3000	600	957	-8	843	-10	-2
D0	0	900	950	-1	810	23	24
D1	300	900	943	6	792	41	35
D2	600	900	950	-1	801	32	33
D3	900	900	964	-15	821	12	27
D4	1200	900	971	-22	832	1	23
D5	1500	900	960	-11	821	12	23
D6	1800	900	952	-3	816	17	20
D7	2100	900	945	4	807	26	22
D8	2400	900	942	7	804	29	22
D9	2700	900	940	9	800	33	24
D10	3000	900	946	3	806	27	24

Table 3 (Cont'd) - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
E0	0	1200	952	-3	788	45	48
E1	300	1200	942	7	771	62	55
E2	600	1200	950	-1	784	49	50
E3	900	1200	955	-6	789	44	50
E4	1200	1200	955	-6	788	45	51
E5	1500	1200	949	0	785	48	48
E6	1800	1200	942	7	781	52	45
E7	2100	1200	937	12	774	59	47
E8	2400	1200	940	9	780	53	44
E9	2700	1200	940	9	775	58	49
E10	3000	1200	942	7	771	62	55
F0	0	1500	950	-1	800	33	34
F1	300	1500	948	1	788	45	44
F2	600	1500	940	9	778	55	46
F3	900	1500	948	1	780	53	52
F4	1200	1500	942	7	776	57	50
F5	1500	1500	954	-5	786	47	52
F6	1800	1500	936	13	776	57	44
F7	2100	1500	928	21	767	66	45
F8	2400	1500	929	20	764	69	49
F9	2700	1500	951	-2	780	53	55
F10	3000	1500	953	-4	785	48	52

Table 3 (Cont'd) - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
G0	0	1800	934	15	813	20	5
G1	300	1800	941	8	810	23	15
G2	600	1800	935	14	800	33	19
G3	900	1800	940	9	796	37	28
G4	1200	1800	936	13	793	40	27
G5	1500	1800	938	11	791	42	31
G6	1800	1800	913	36	775	58	22
G7	2100	1800	922	27	778	55	28
G8	2400	1800	934	15	785	48	33
G9	2700	1800	949	0	805	28	28
G10	3000	1800	938	11	810	23	12
H0	0	2100	935	14	817	16	2
H1	300	2100	933	16	813	20	4
H2	600	2100	925	24	801	32	8
H3	900	2100	911	38	789	44	6
H4	1200	2100	910	39	788	45	6
H5	1500	2100	915	34	792	41	7
H6	1800	2100	915	34	790	43	9
H7	2100	2100	920	29	798	35	6
H8	2400	2100	944	5	818	15	10
H9	200	2100	960	-11	835	-2	9
H10	3000	2100	940	9	822	11	2

Table 3 (Cont'd) - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
I0	0	2400	922	27	806	27	0
I1	300	2400	920	29	802	31	2
I2	600	2400	922	27	805	28	1
I3	900	2400	914	35	798	35	0
I4	1200	2400	902	47	786	47	0
I5	1500	2400	904	45	786	47	2
I6	1800	2400	911	38	796	37	-1
I7	2100	2400	922	27	810	23	-4
I8	2400	2400	941	8	822	11	3
I9	2700	2400	945	4	829	4	0
I10	3000	2400	948	1	831	2	1
J0	0	2700	925	24	810	23	-1
J1	300	2700	917	32	802	31	-1
J2	600	2700	920	29	806	27	-2
J3	900	2700	915	34	801	32	-2
J4	1200	2700	916	33	800	33	0
J5	1500	2700	920	29	802	31	2
J6	1800	2700	916	33	804	29	-4
J7	2100	2700	927	22	814	19	-3
J8	2400	2700	947	2	832	1	-1
J9	2700	2700	945	4	830	3	-1
J10	3000	2700	952	-3	838	-5	-2

Table 3 (Cont'd) - Surface Elevation Measurements - Test MMS01

Grid Point	X (mm)	Y (mm)	Pre Test Reading (mm)	Pre Test Elevation (mm)	Post Test Reading (mm)	Post Test Elevation (mm)	Elevation Difference (mm)
K0	0	3000	929	20	814	19	-1
K1	300	3000	924	25	809	24	-1
K2	600	3000	920	29	804	29	0
K3	900	3000	920	29	804	29	0
K4	1200	3000	923	26	807	26	0
K5	1500	3000	920	29	812	21	-8
K6	1800	3000	918	31	804	29	-2
K7	2100	3000	928	21	811	22	1
K8	2400	3000	933	16	819	14	-2
K9	2700	3000	954	-5	836	-3	2
K10	3000	3000	957	-8	841	-8	0

Table 4 - Pre-Test Vertical Deformation Tube Positions - Test MMS01

Vertical Deformation Tube	Approximate Z (mm)	X (mm)	Y (mm)	Angle[1] Perpendicular to Pipe (Deg.)	Angle[2] Parallel to Pipe (Deg.)
1	850	566	1207	1.05	2.55
1[3]	225	585	1226	---	---
2	850	566	1510	1.72	-1.61
2[3]	150	546	1497	---	---
3	850	548	1812	2.51	4.92
3[3]	150	620	1793	---	---
4	850	556	2110	1.63	1.42
4[3]	200	581	2116	---	---
5	850	551	2411	-1.31	2.15
5[3]	275	593	2406	---	---

Notes: 1. Top of rod inclined towards increasing X-direction, angle is negative.
2. Top of rod inclined towards increasing Y-direction, angle is negative.
3. Inferred from post-test tip position

Table 5 - Pre-Test Internal Displacement Marker Tube Positions - Test MMS01

Internal Displacement Marker	**X (mm)**	**Y (mm)**	**Approximate Z (mm)**
1	2519	910	850
2	2535	1614	850
3	2505	2310	850

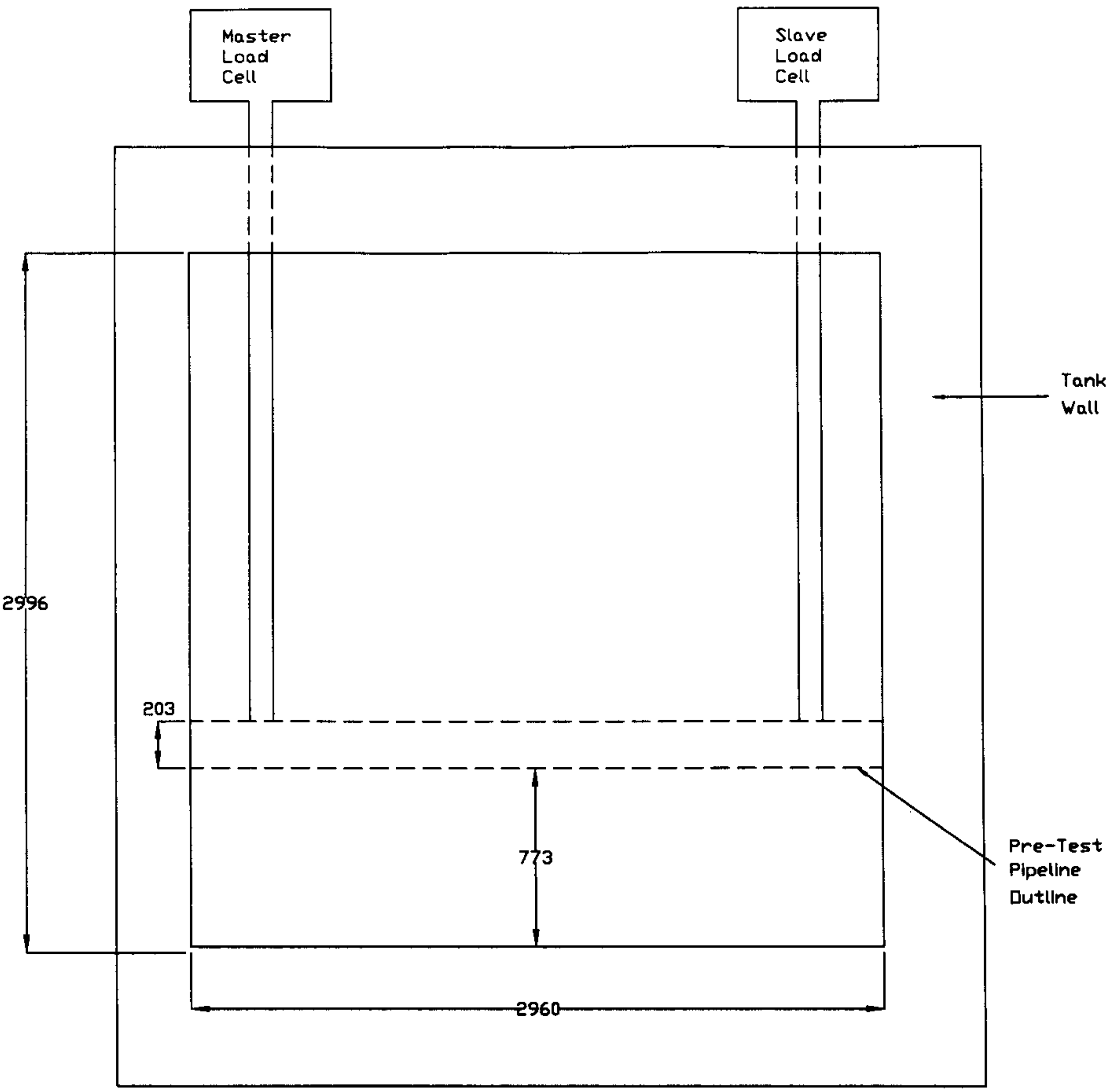
Table 6 - Post-Test Vertical Deformation Tube Positions - Test MMS01

	Tube 1		Tube 2		Tube 3		Tube 4		Tube 5	
Approximate Elevation, Z (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
Surface	557	1206	583	1505	574	1803	564	2105	560	2383
800	566	1203	583	1496	573	1801	569	2104	568	2395
750	575	1205	583	1496	573	1800	570	2103	570	2396
700	579	1206	580	1499	574	1798	569	2102	572	2395
650	580	1211	579	1500	578	1801	568	2103	571	2395
600	586	1211	577	1503	580	1800	567	2104	577	2396
550	587	1231	578	1518	586	1801	569	2106	584	2396
500	586	1236	572	1520	589	1799	568	2106	583	2397
450	586	1241	570	1520	594	1797	569	2109	588	2396
425	587	1251	566	1517	597	1798	568	2109	590	2396
400	590	1281	566	1516	598	1797	568	2109	587	2397
375	586	1298	565	1502	603	1796	569	2108	594	2397
350	588	1304	562	1500	607	1795	568	2110	595	2397
325	581	1291	558	1498	617	1793	570	2111	595	2398
300	580	1281	556	1498	619	1793	572	2113	594	2399
275	583	1234	556	1496	620	1795	573	2118	593	2406
250	580	1231	555	1496	621	1794	579	2119	---	---
225	585	1226	553	1495	622	1794	581	2119	---	---
200	---	---	551	1494	621	1795	581	2116	---	---
175	---	---	552	1497	620	1793	---	---	---	---
150	---	---	546	1496	620	1793	---	---	---	---

Table 7 - Post-Test Internal Displacement Marker Tube Positions - Test MMS01

	Internal Displacement Marker 1		Internal Displacement Marker 2		Internal Displacement Marker 3	
Approximate Elevation, Z (mm)	**X (mm)**	**Y (mm)**	**X (mm)**	**Y (mm)**	**X (mm)**	**Y (mm)**
Surface	---	---	2535	1629	---	---
850	2513	902	2534	1615	2506	2328
800	2530	908	2535	1620	2504	2324
750	2520	925	2535	1615	2503	2326
700	2515	940	2533	1617	2506	2321
650	2505	942	---	---	---	---
600	2515	945	---	---	---	---

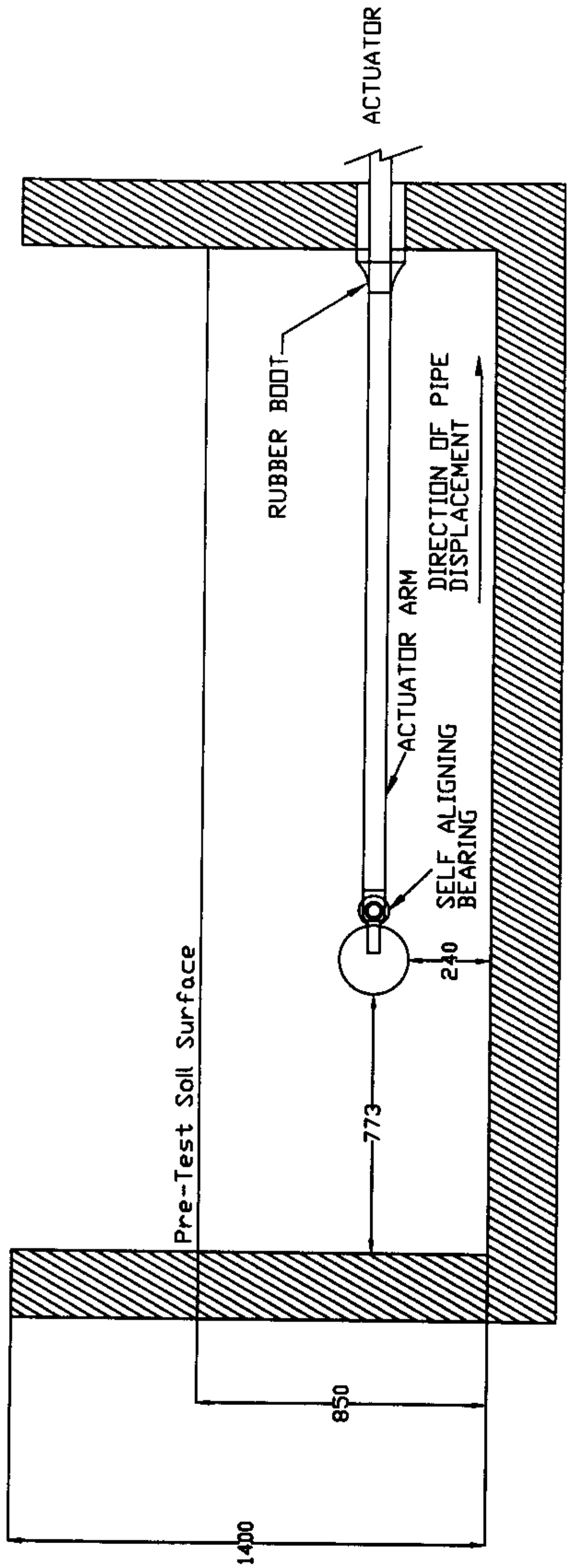
List of Figures



C-CORE

Experimental Setup - Plan View

1

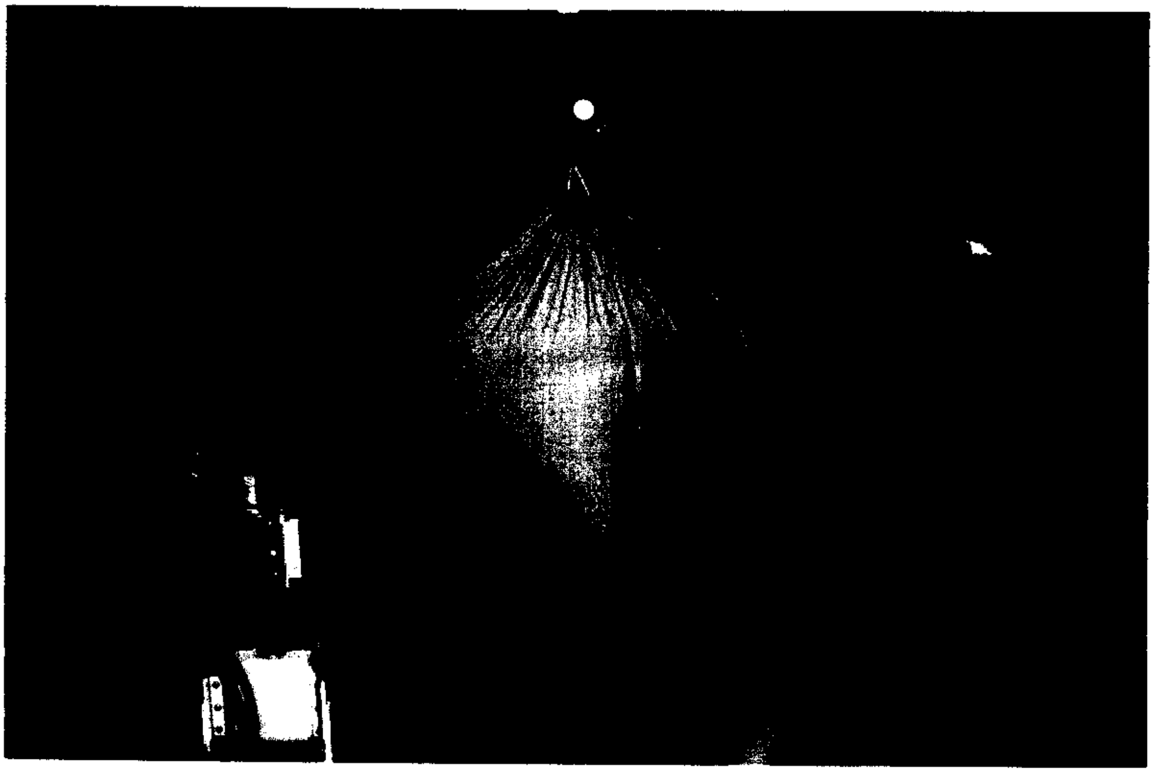


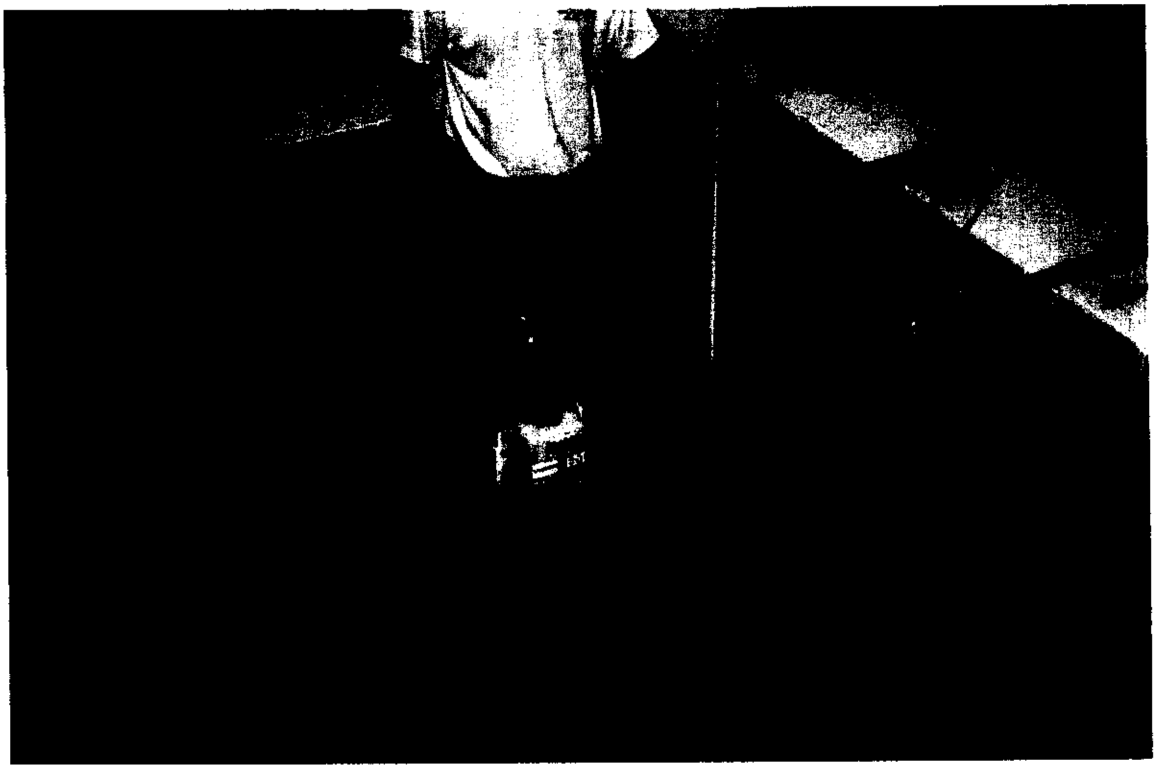
C-CORE

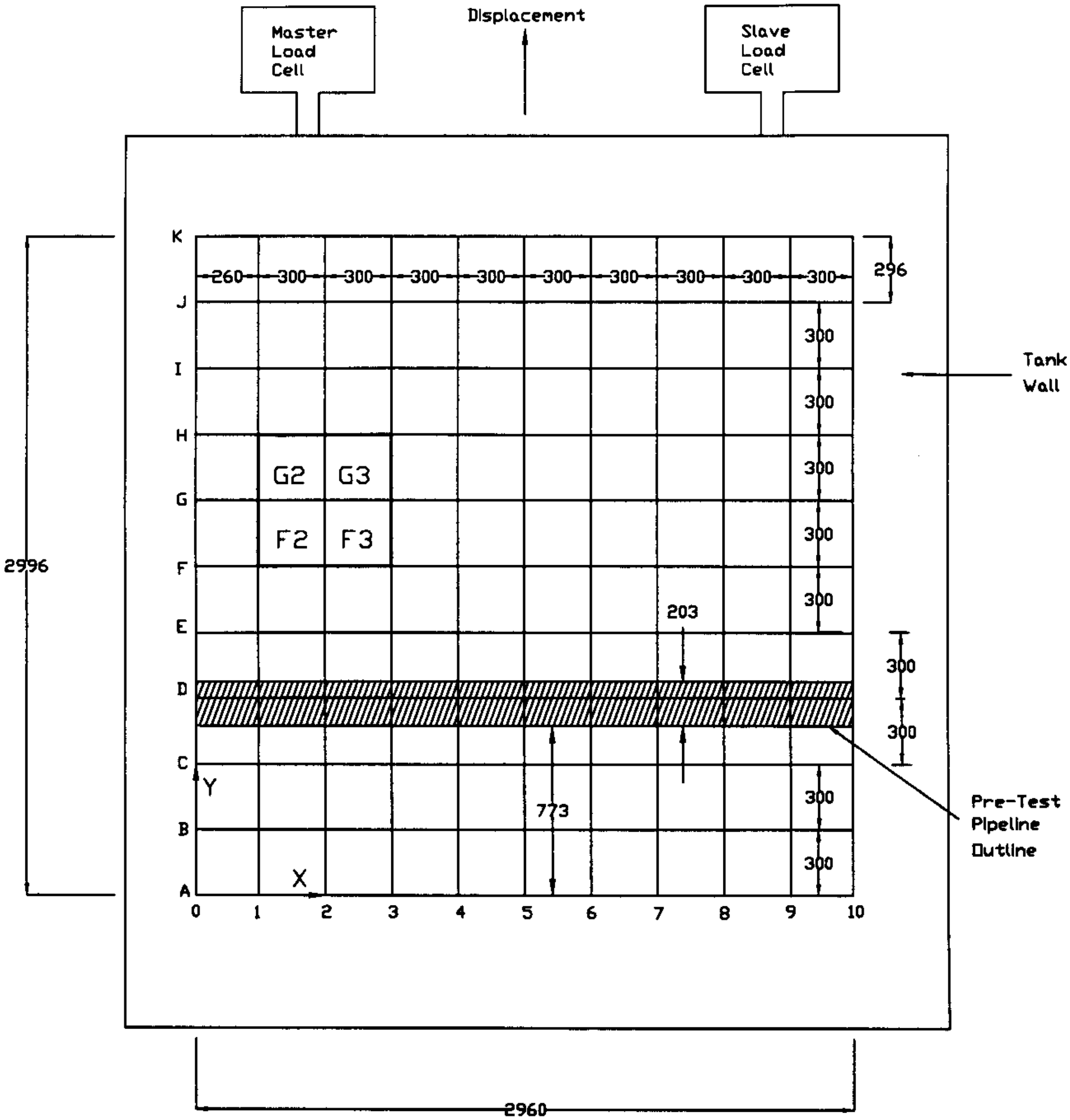
Experimental Setup - Profile View

2

Pipe in Position

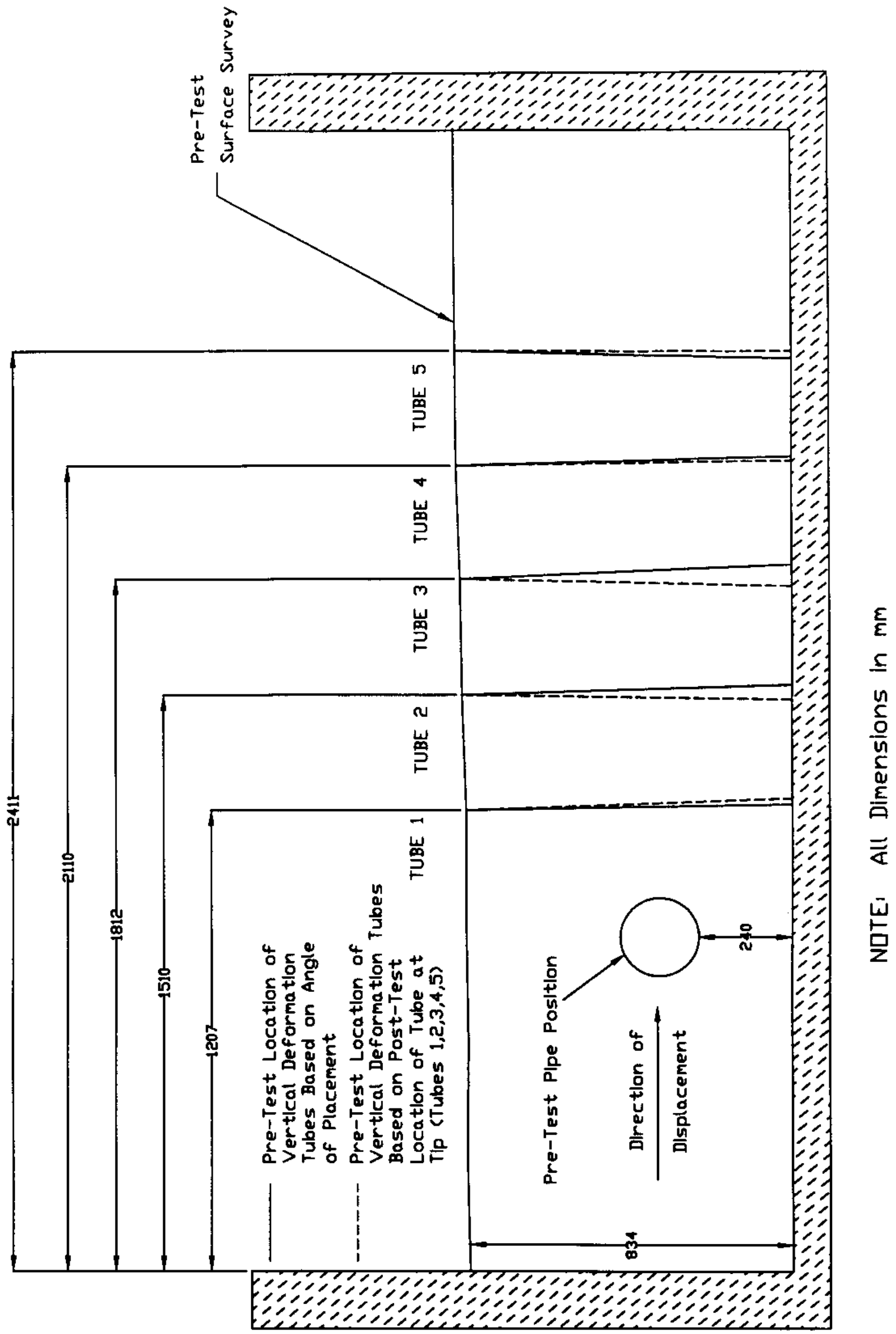






Note: All Dimensions in mm.

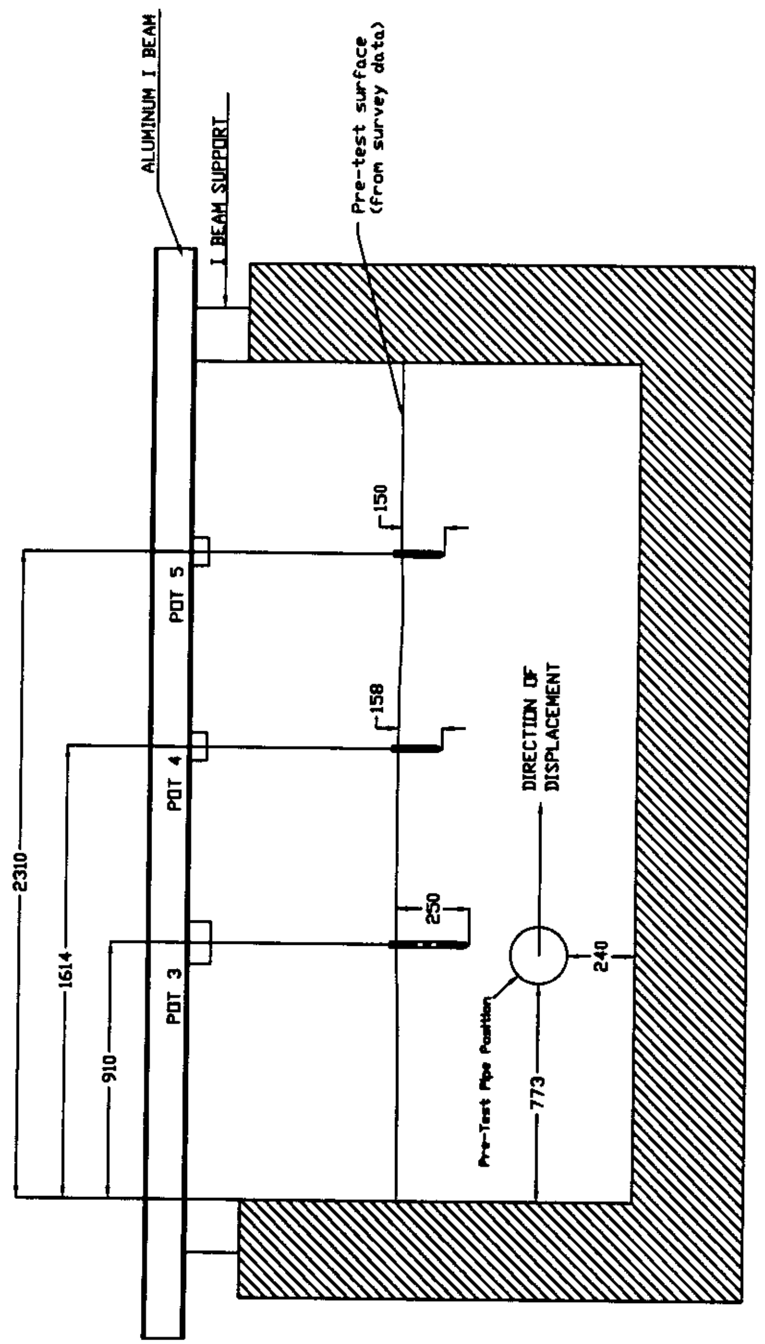
Grid Measurement System



C-CORE

Pre-Test Vertical Deformation Tube Positions

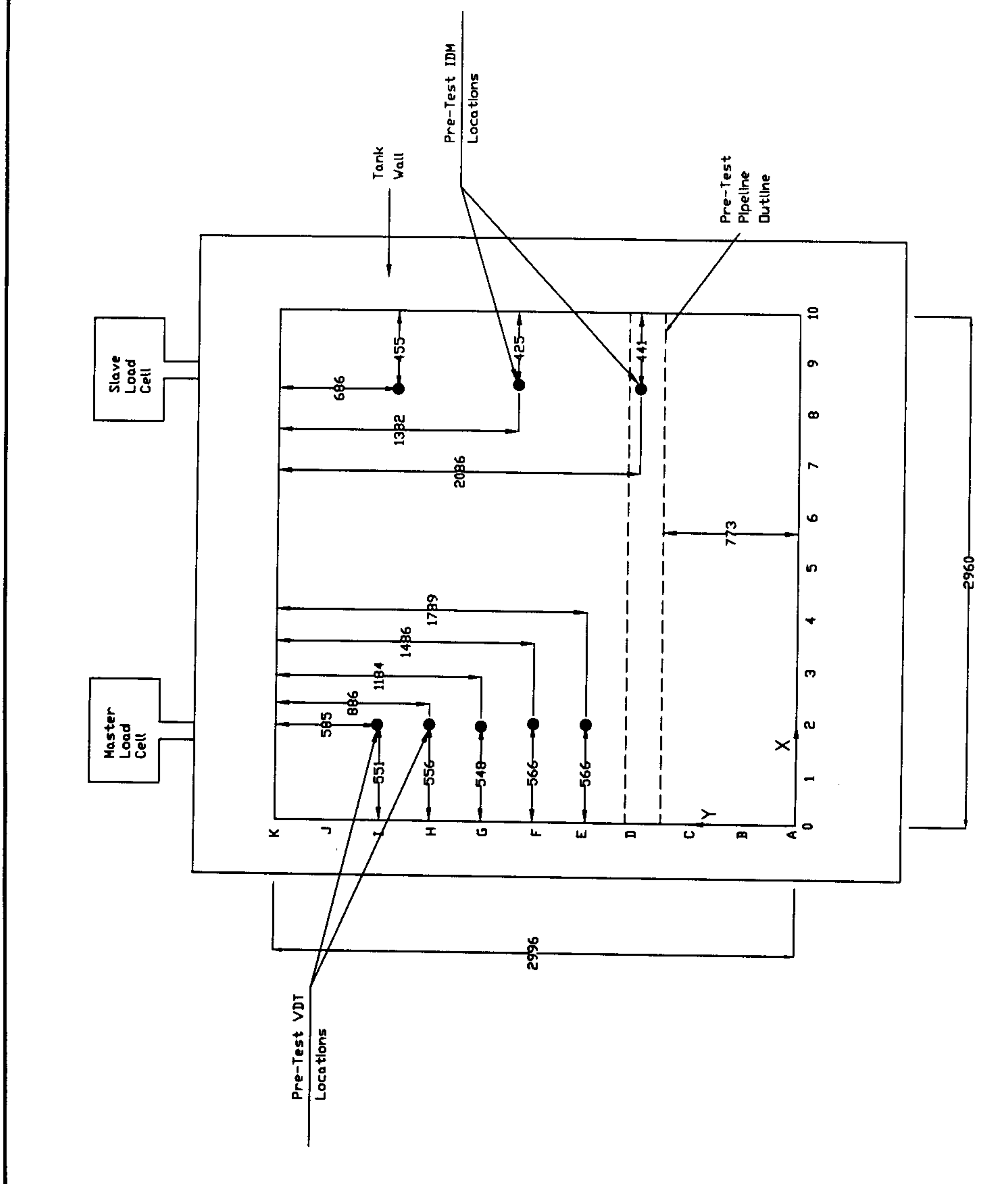
7



NOTES:
(1) SHOWS PRE-TEST POSITIONS ONLY
(2) ALL DIMENSIONS IN mm
(3) TUBE MEASUREMENTS ARE FROM CENTER
OF TUBE TO WALL

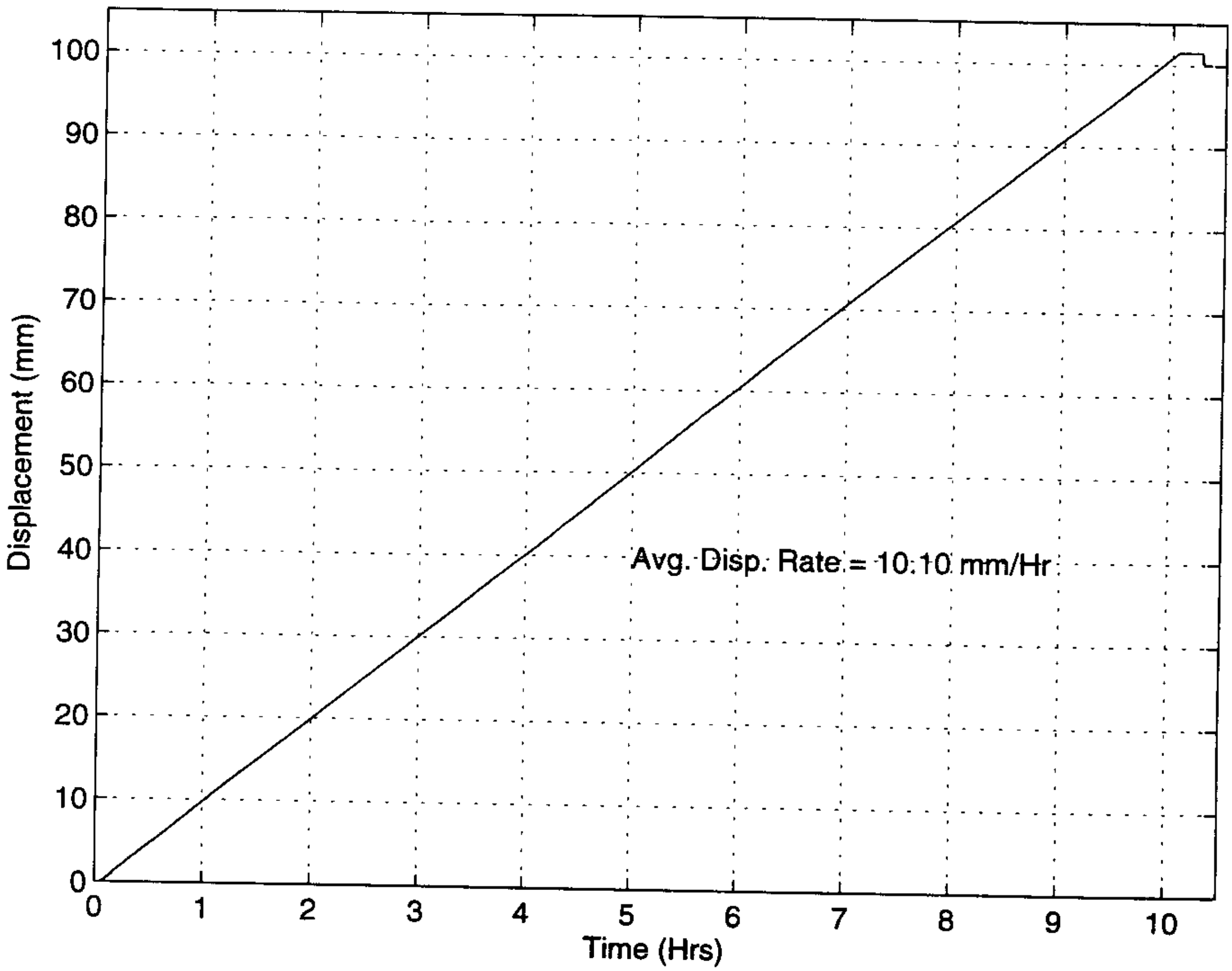
C-CORE

Pre-Test Internal Displacement Marker Positions



Plan View of Tank Showing Passive Instrumentation Positions

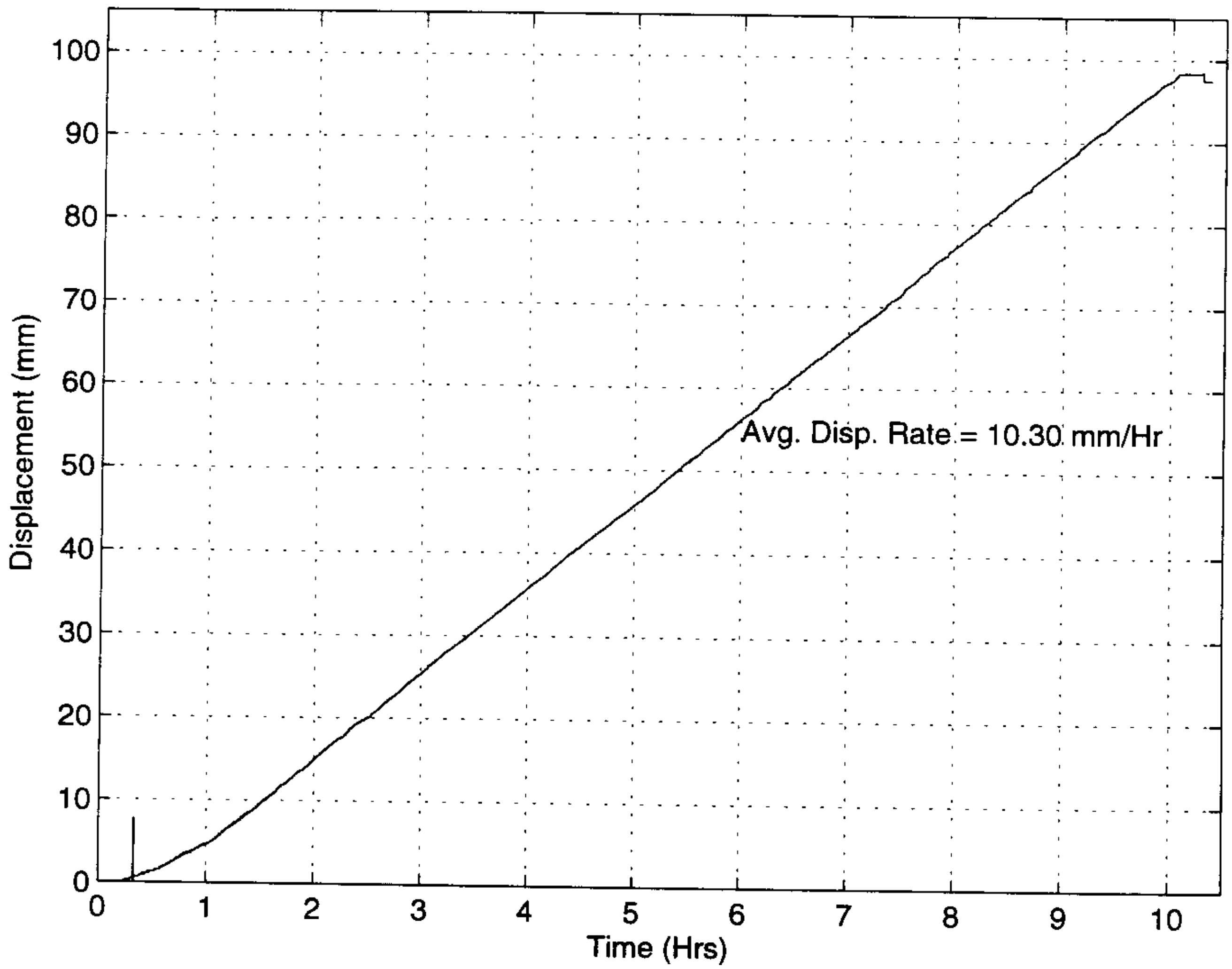
Photograph of Pre-Test Testbed Surface



C-CORE

Master Displacement Transducer Output vs. Time

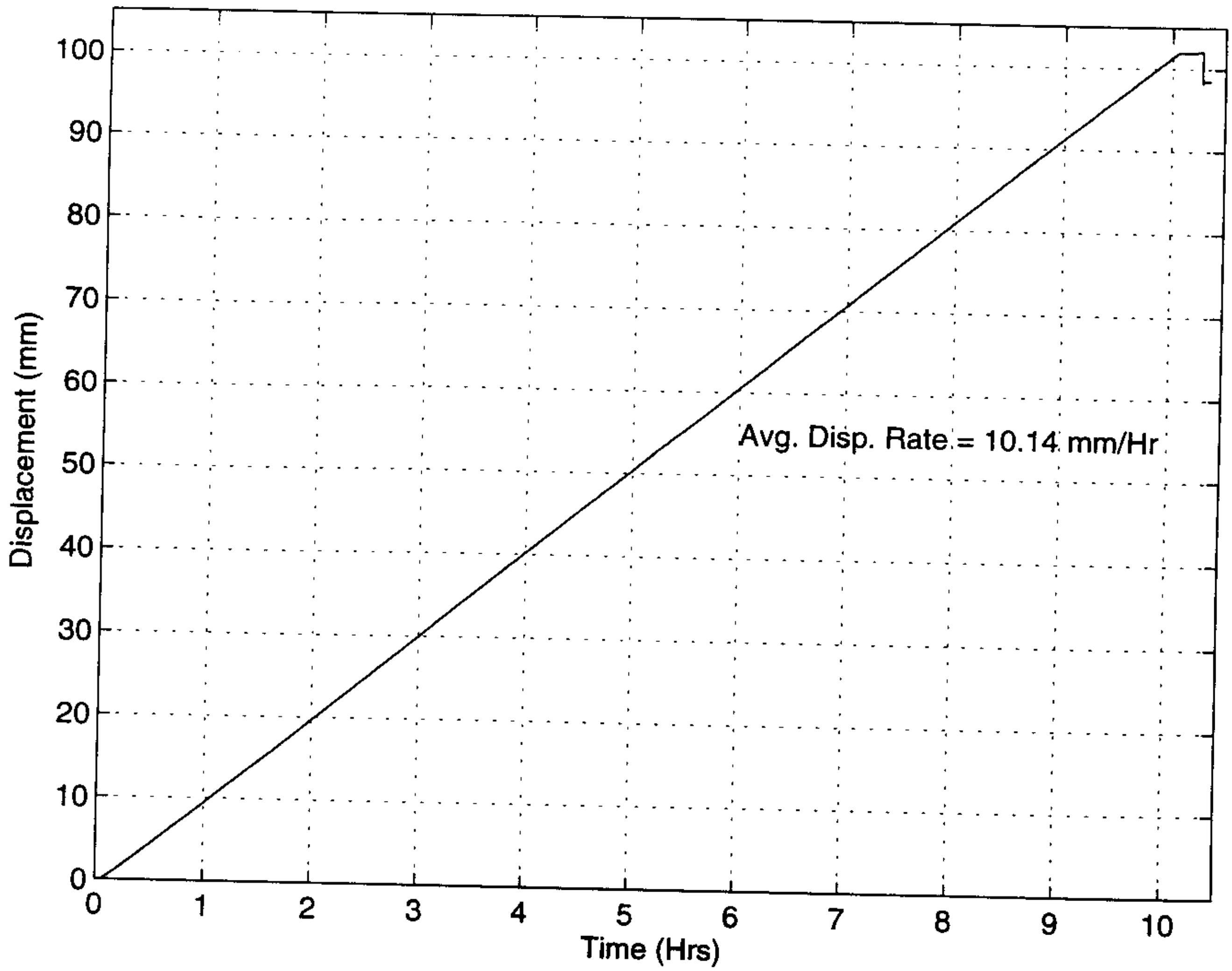
11(a)



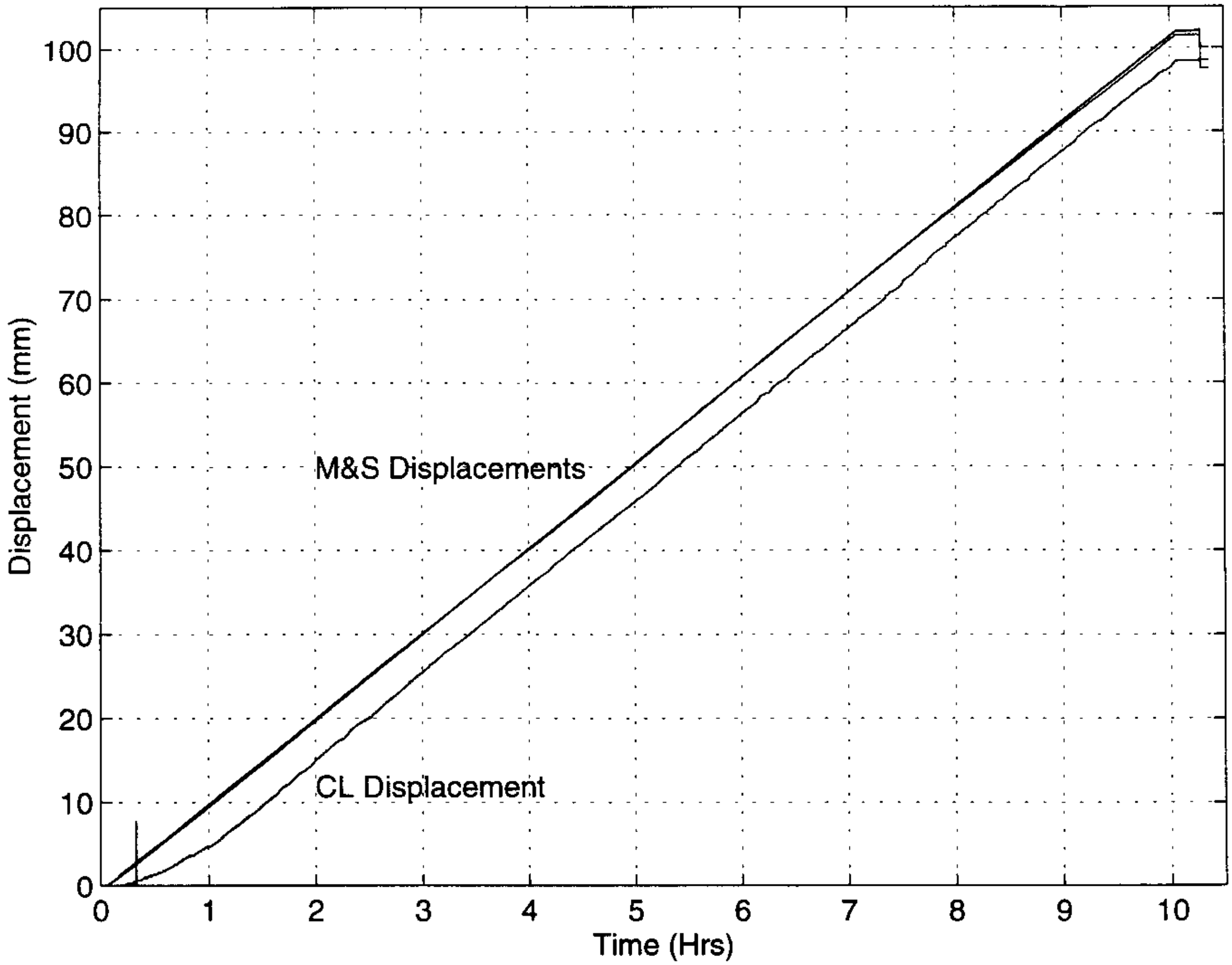
C-CORE

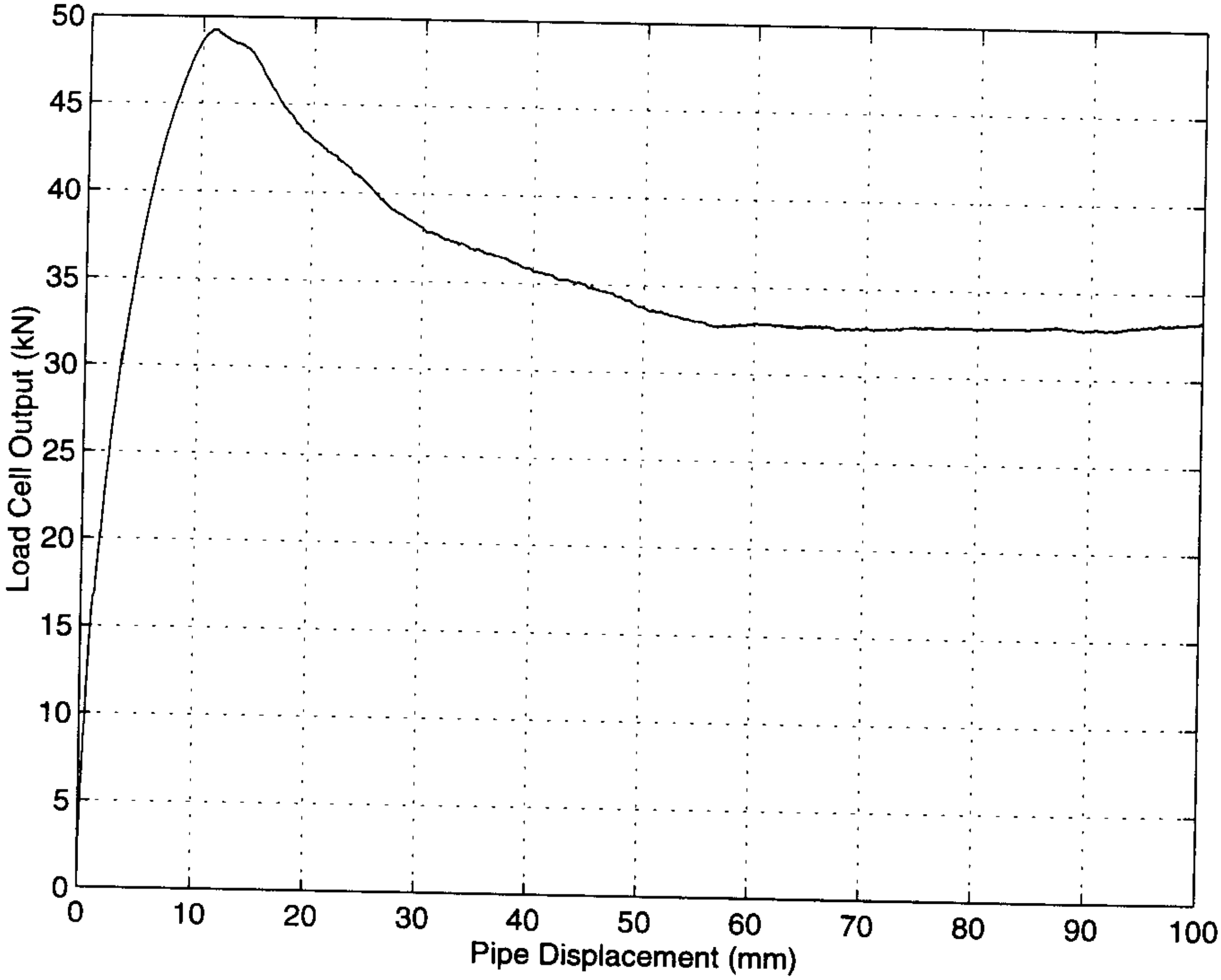
Mid-Pipe Displacement Transducer Output vs. Time

11(b)

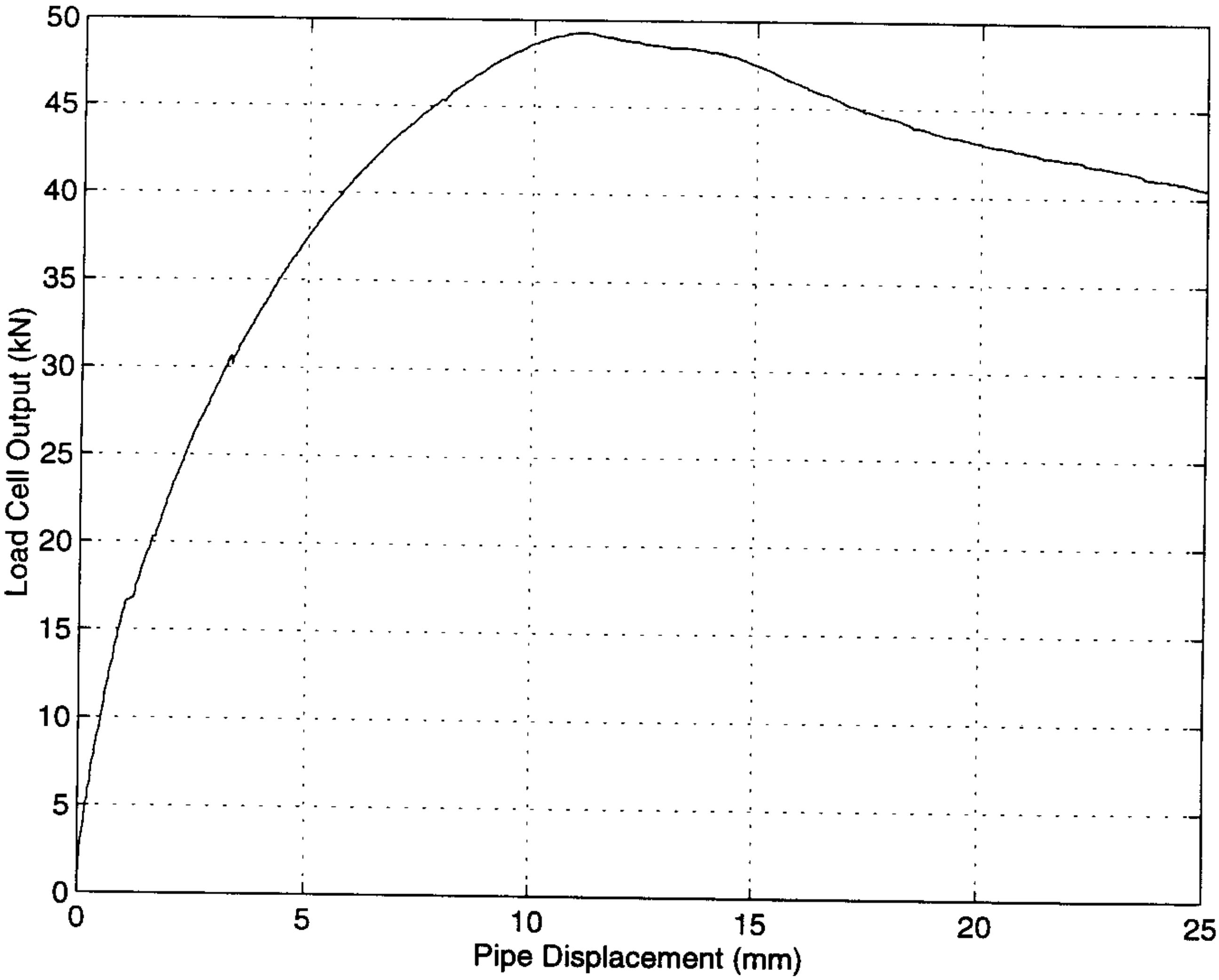


C-CORE	Slave Displacement Transducer Output vs. Time	11(c)


M&S Displacements
CL Displacement
Displacement (mm)
Time (Hrs)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10



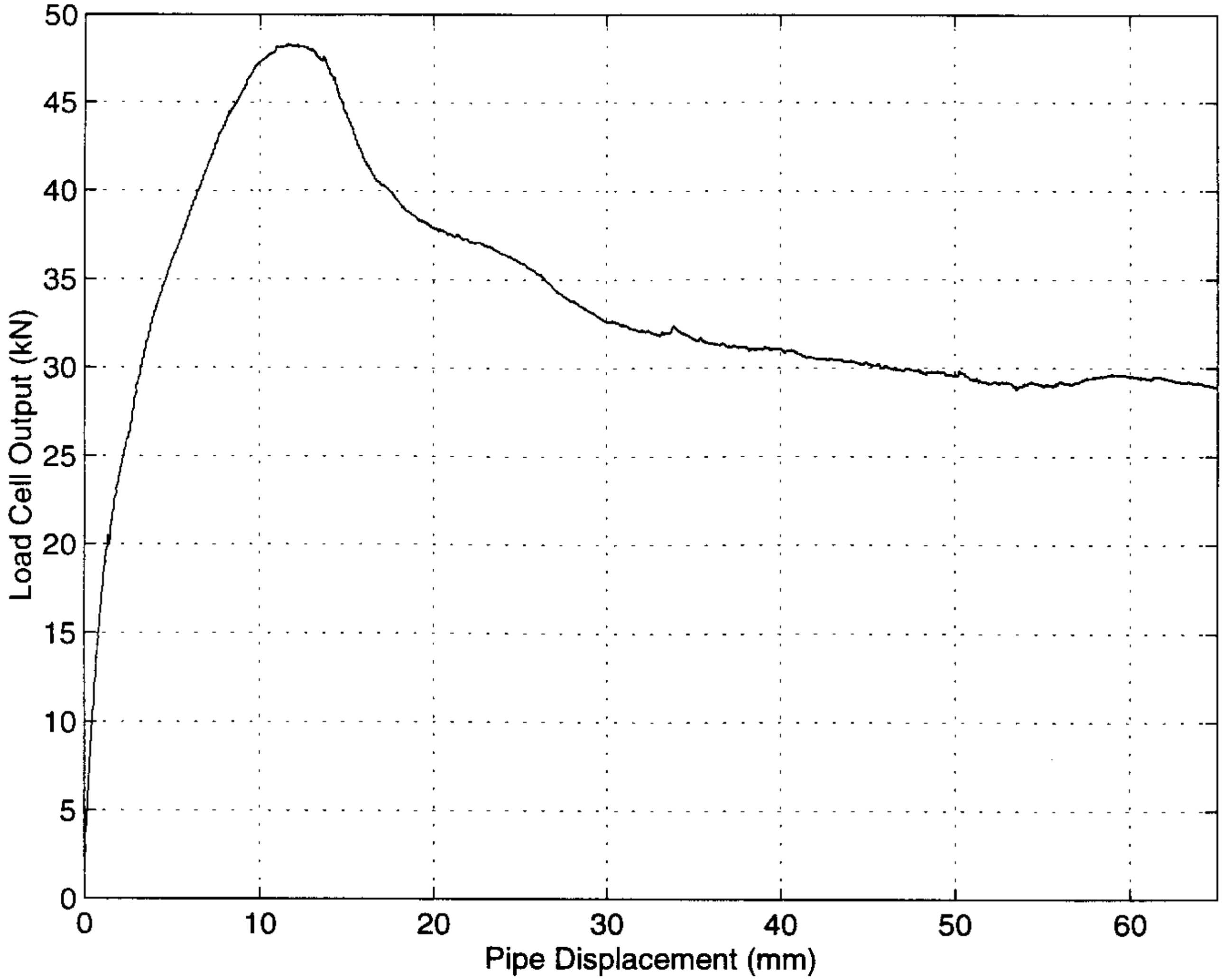
C-CORE	Load vs. Displacement - Master Load Cell	13(a)



C-CORE

Load vs. Displacement - Master Load Cell

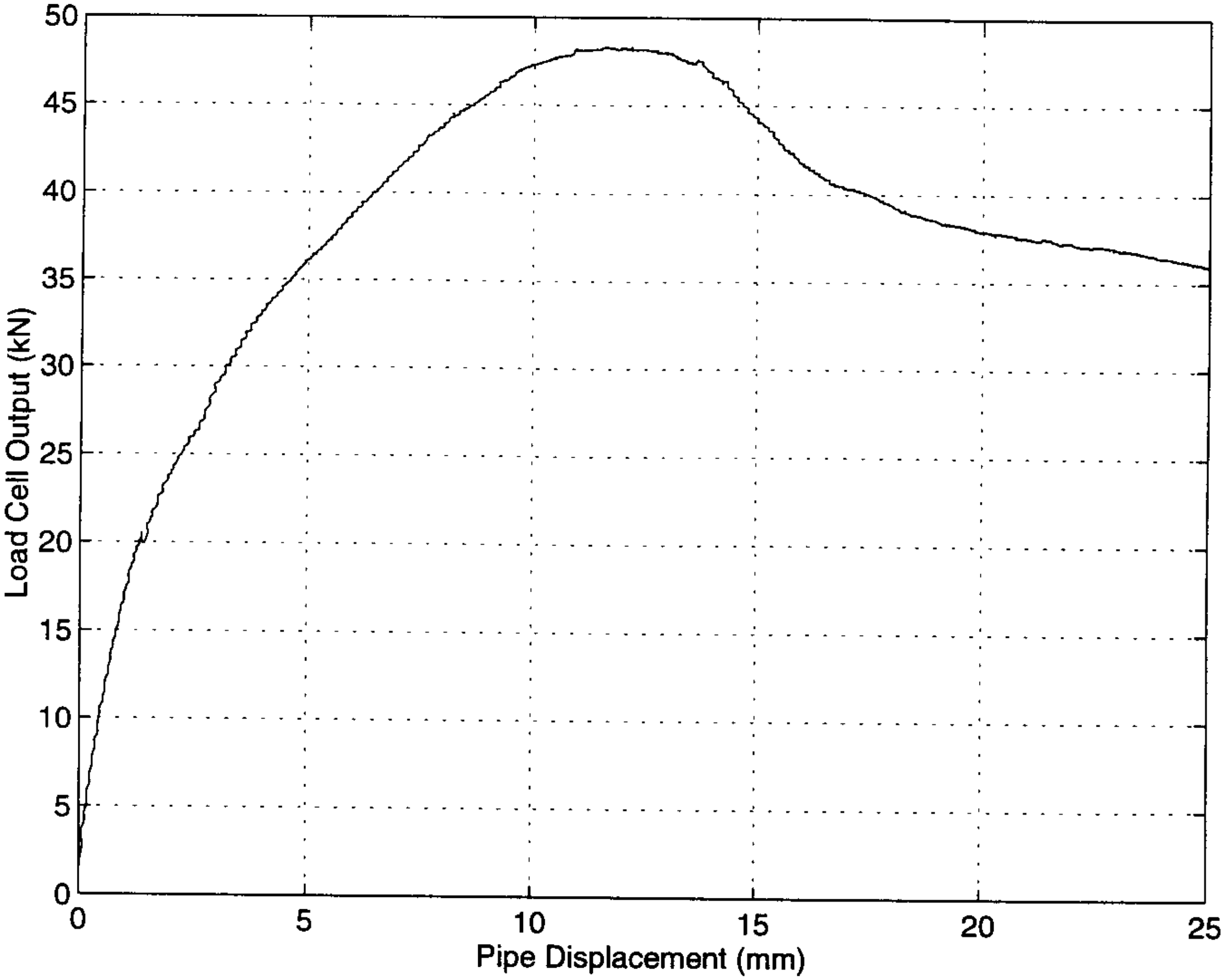
13(b)



C-CORE

Load vs. Displacement - Slave Load Cell

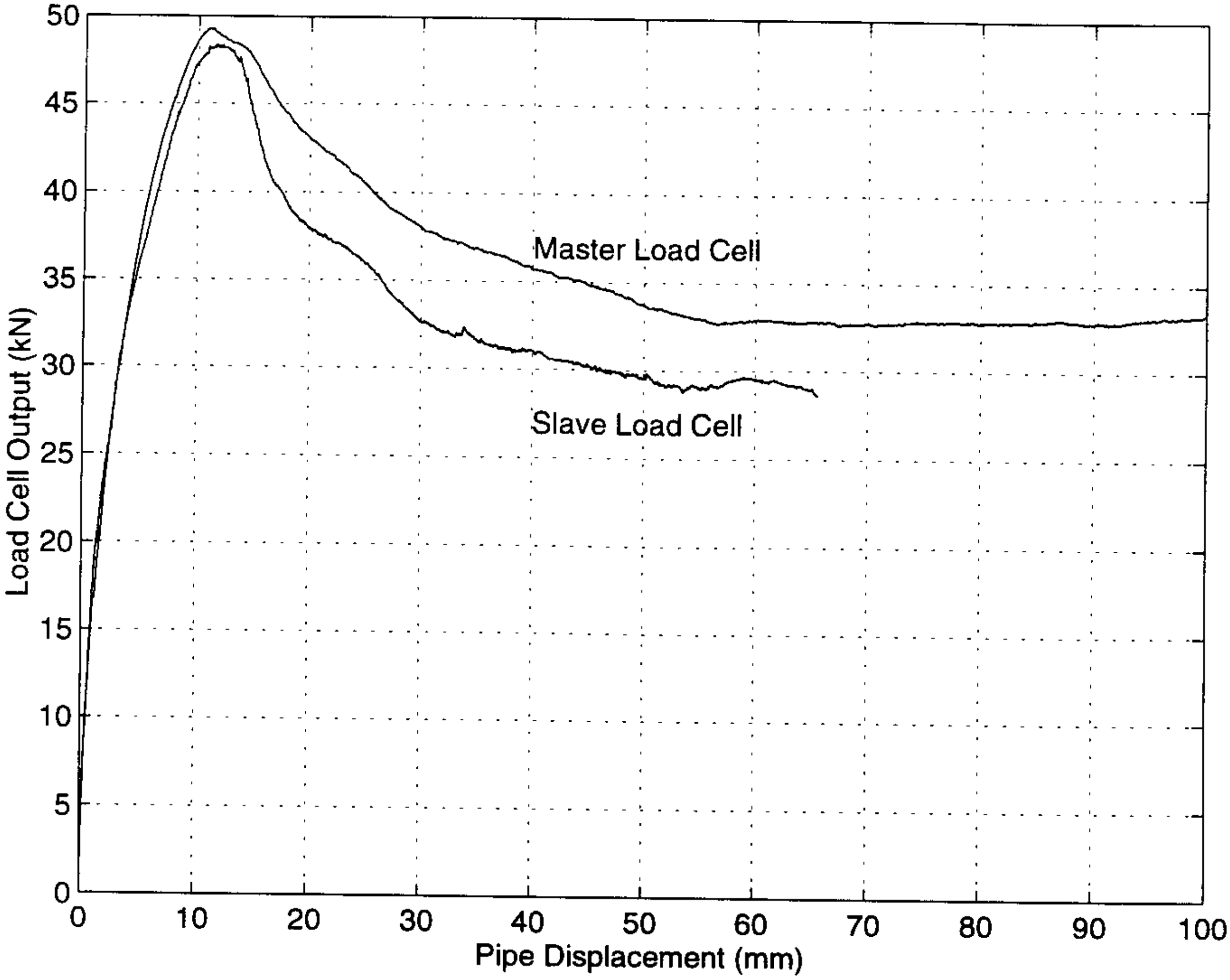
14(a)



C-CORE

Load vs. Displacement - Slave Load Cell

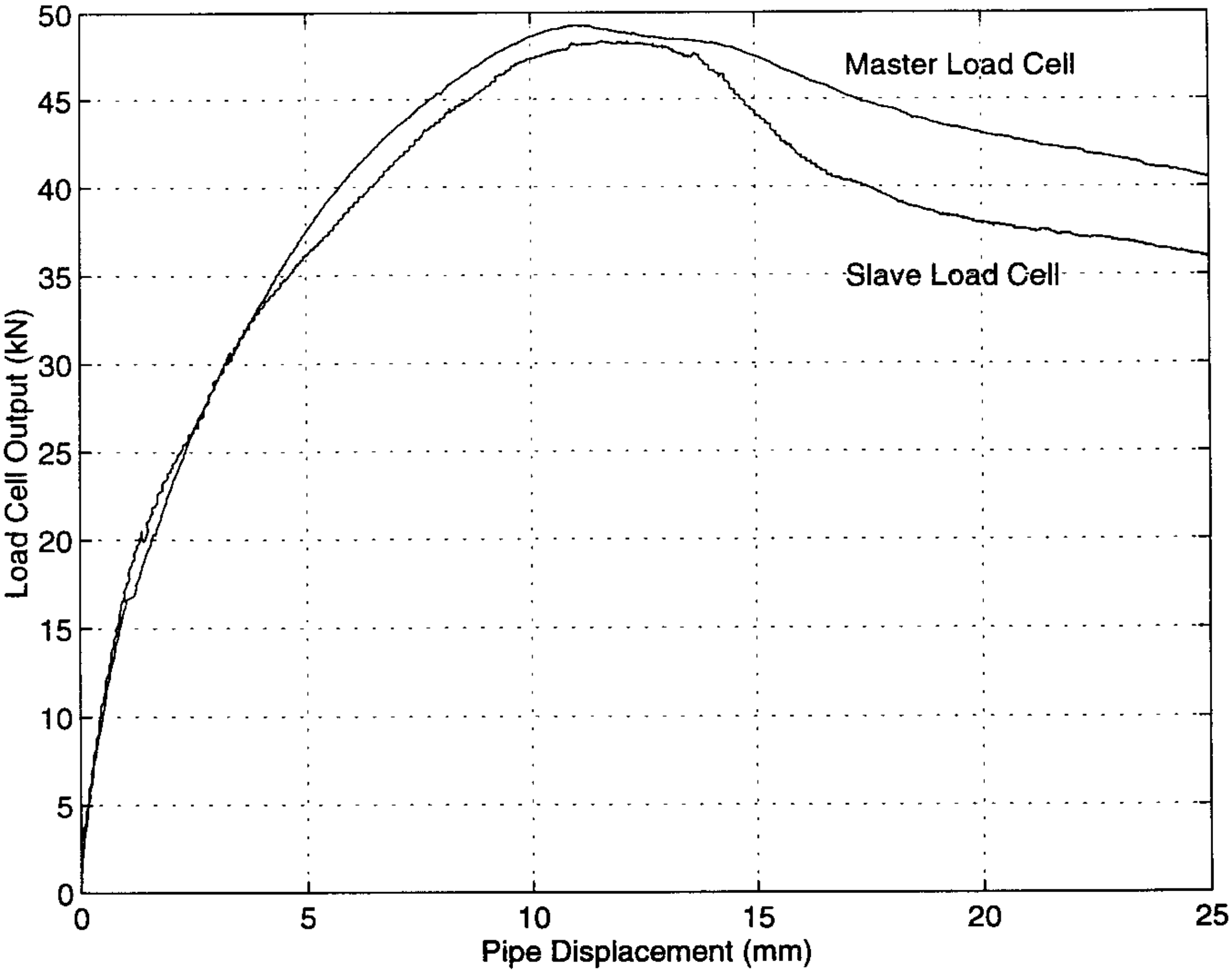
14(b)



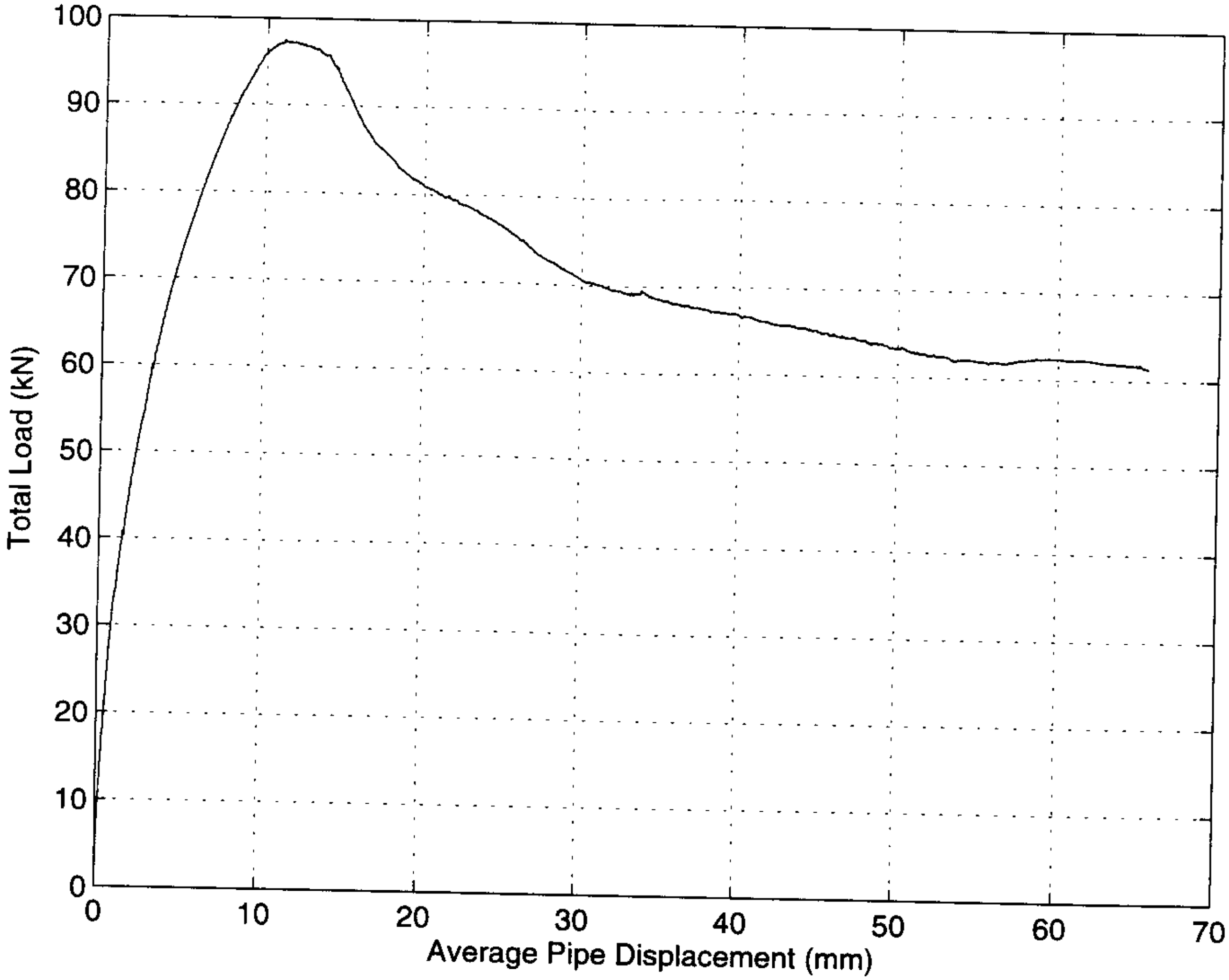
C-CORE

Comparison of Load Displacement Curves

15(a)



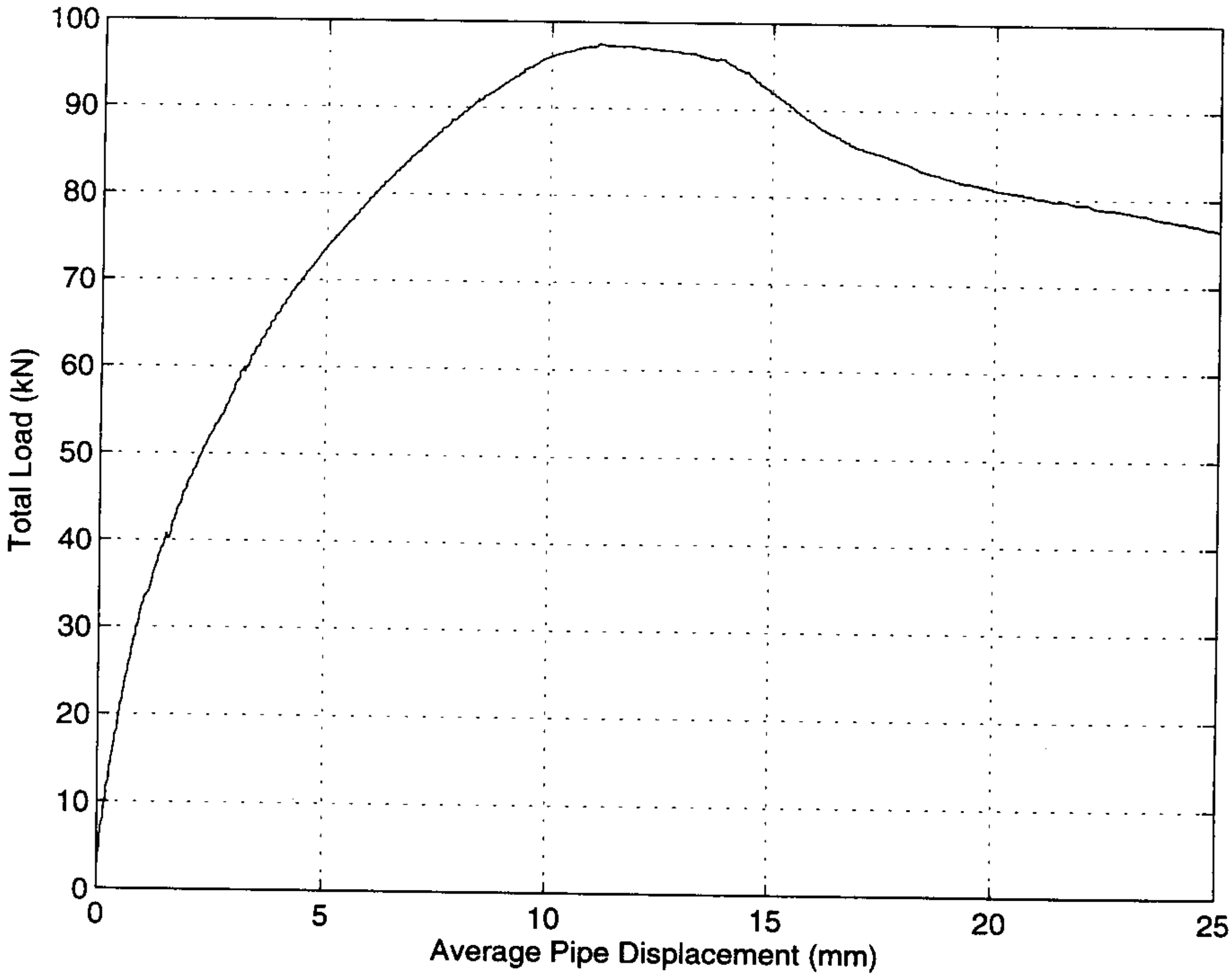
C-CORE	Comparison of Load Displacement Curves	15(b)



C-CORE

Total Load vs. Displacement Curve

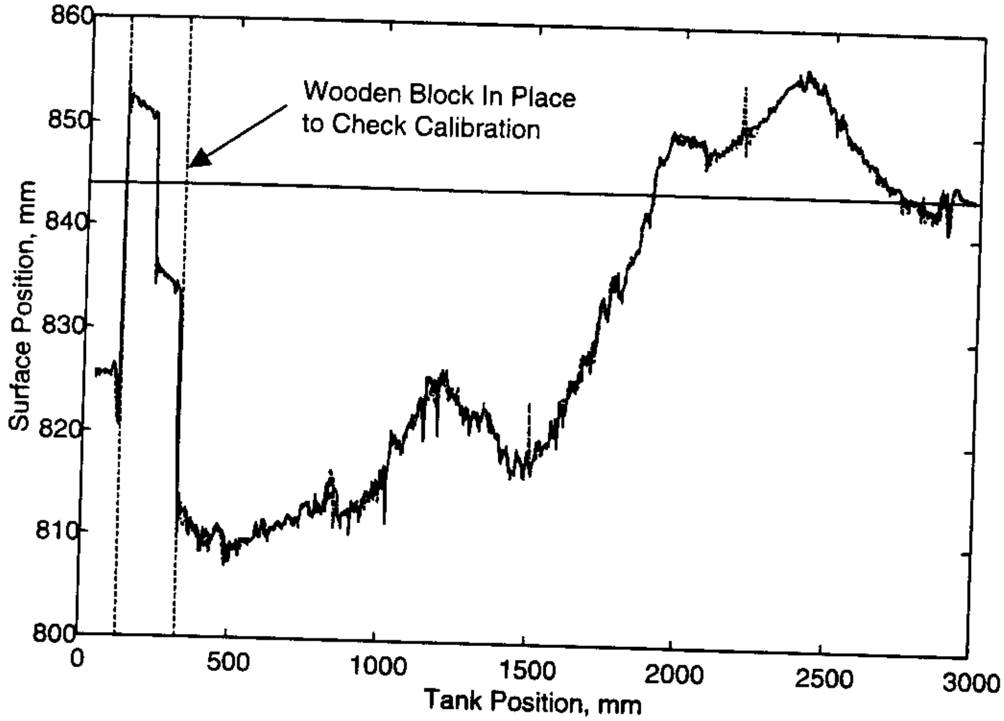
16(a)

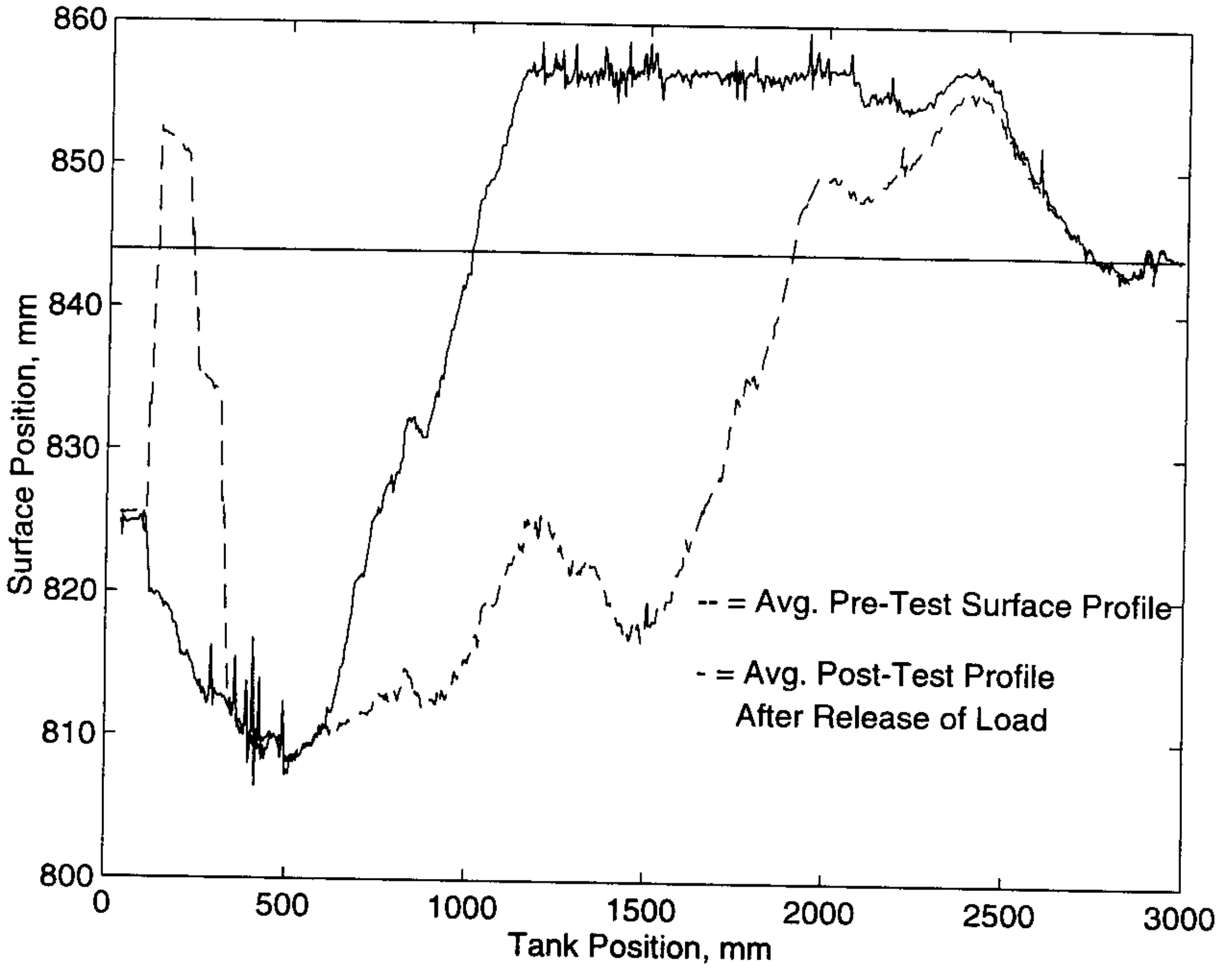


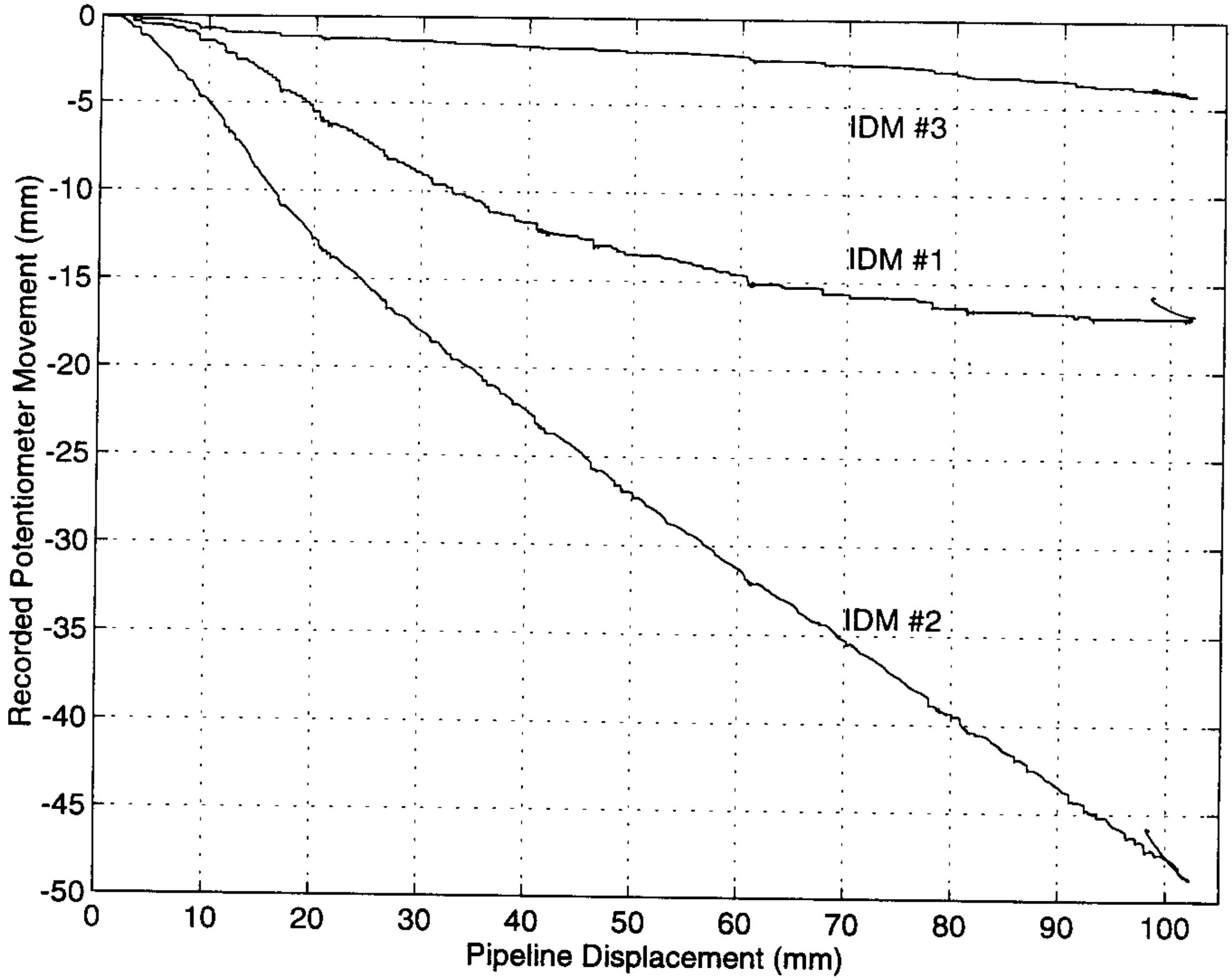
C-CORE

Total Load vs. Displacement Curve

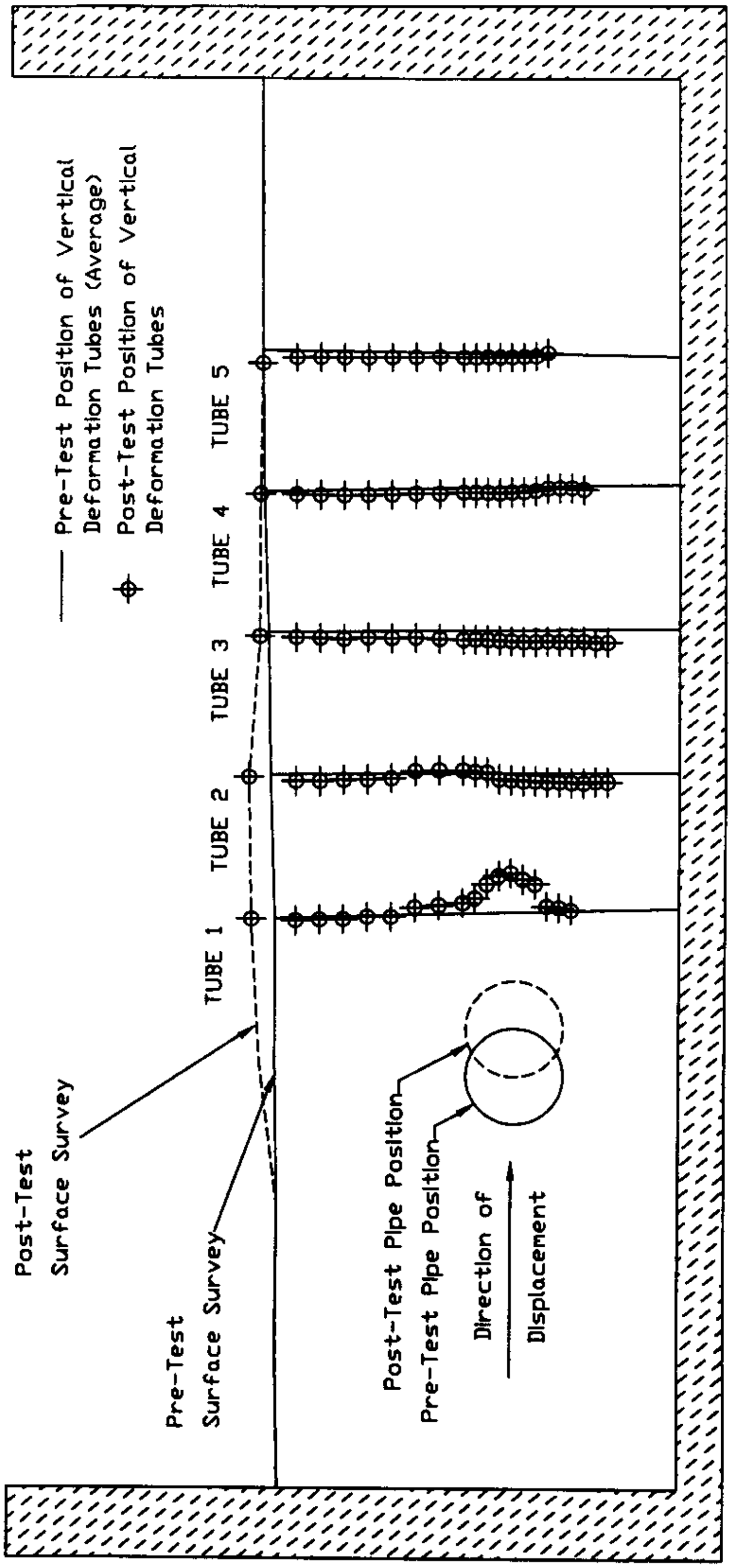
16(b)


Wooden Block In Place
to Check Calibration
Surface Position, mm
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Tank Position, mm


860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Avg. Pre-Test Surface Profile
- = Avg. Post-Test Profile
After Release of Load

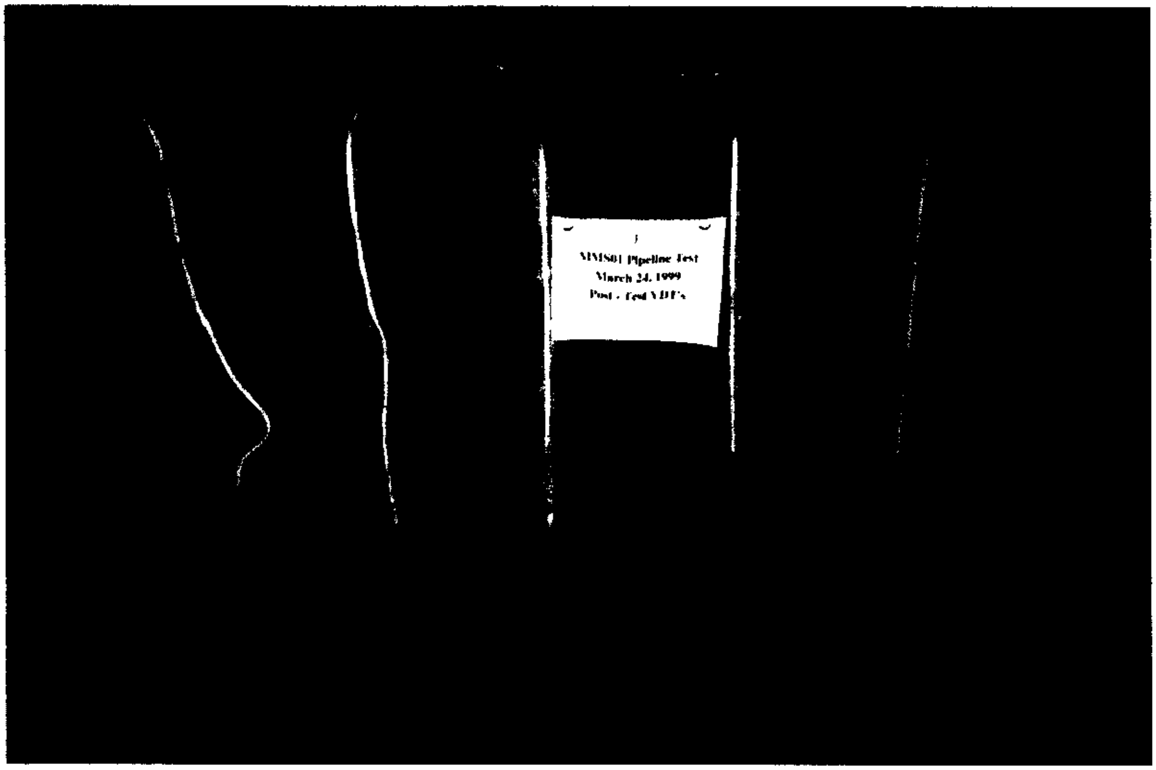


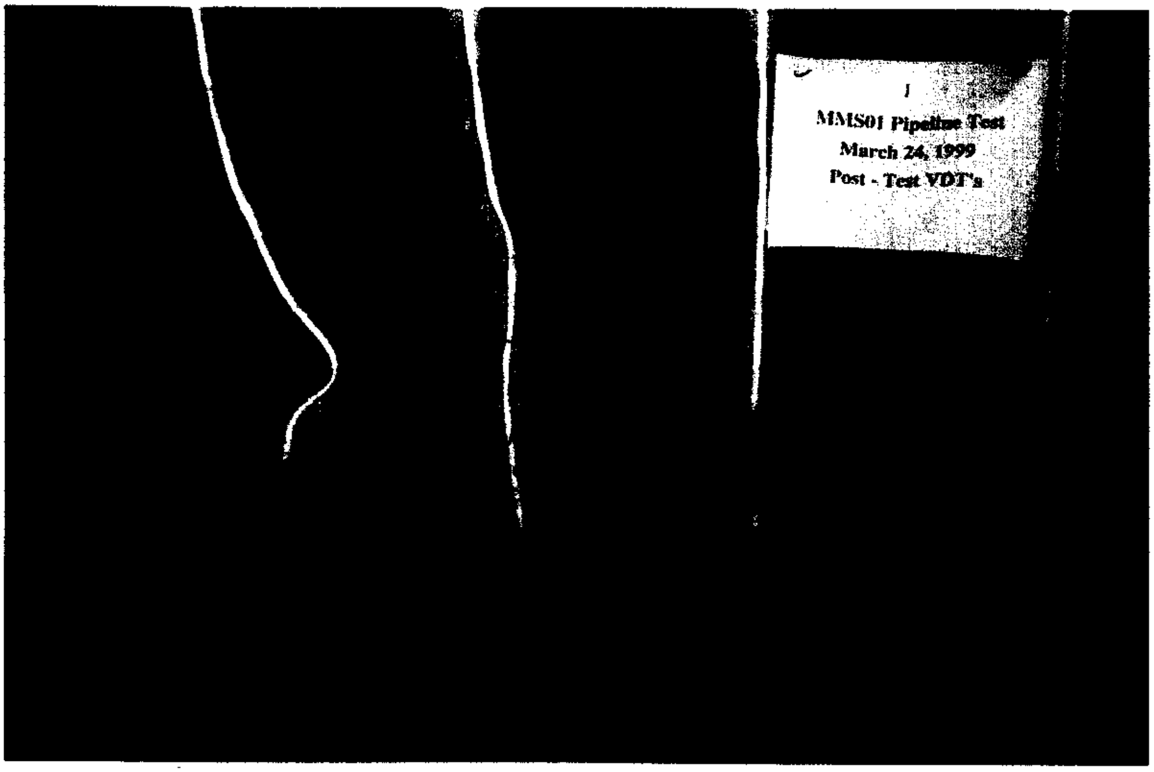
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
0
10
20
30
40
50
60
70
80
90
100
Recorded Potentiometer Movement (mm)
Pipeline Displacement (mm)
IDM #3
IDM #1
IDM #2

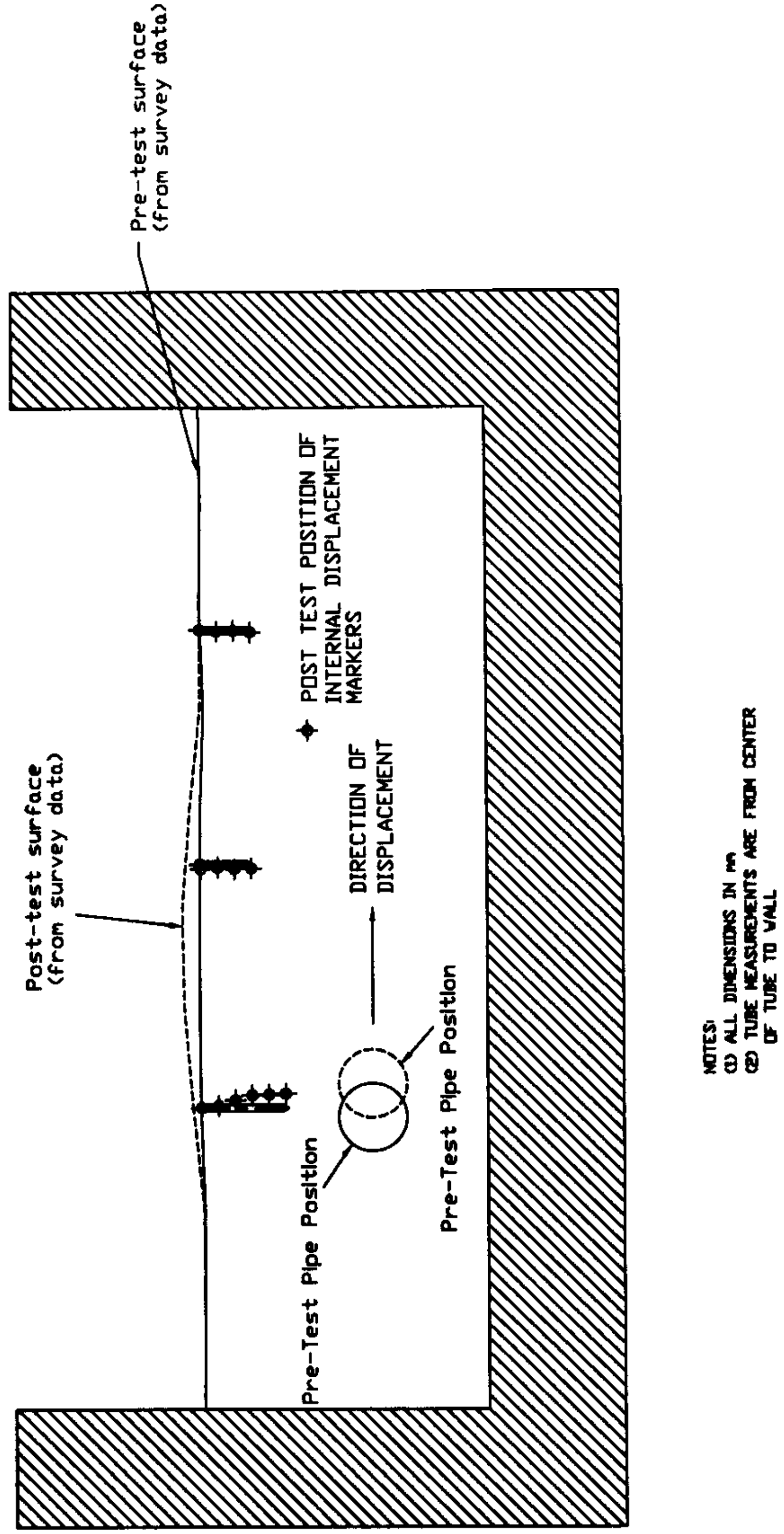


C-CORE

Post-Test Vertical Deformation Tube Positions


MMS01 Pipeline Test
March 24, 1999
Post - Test VDT's

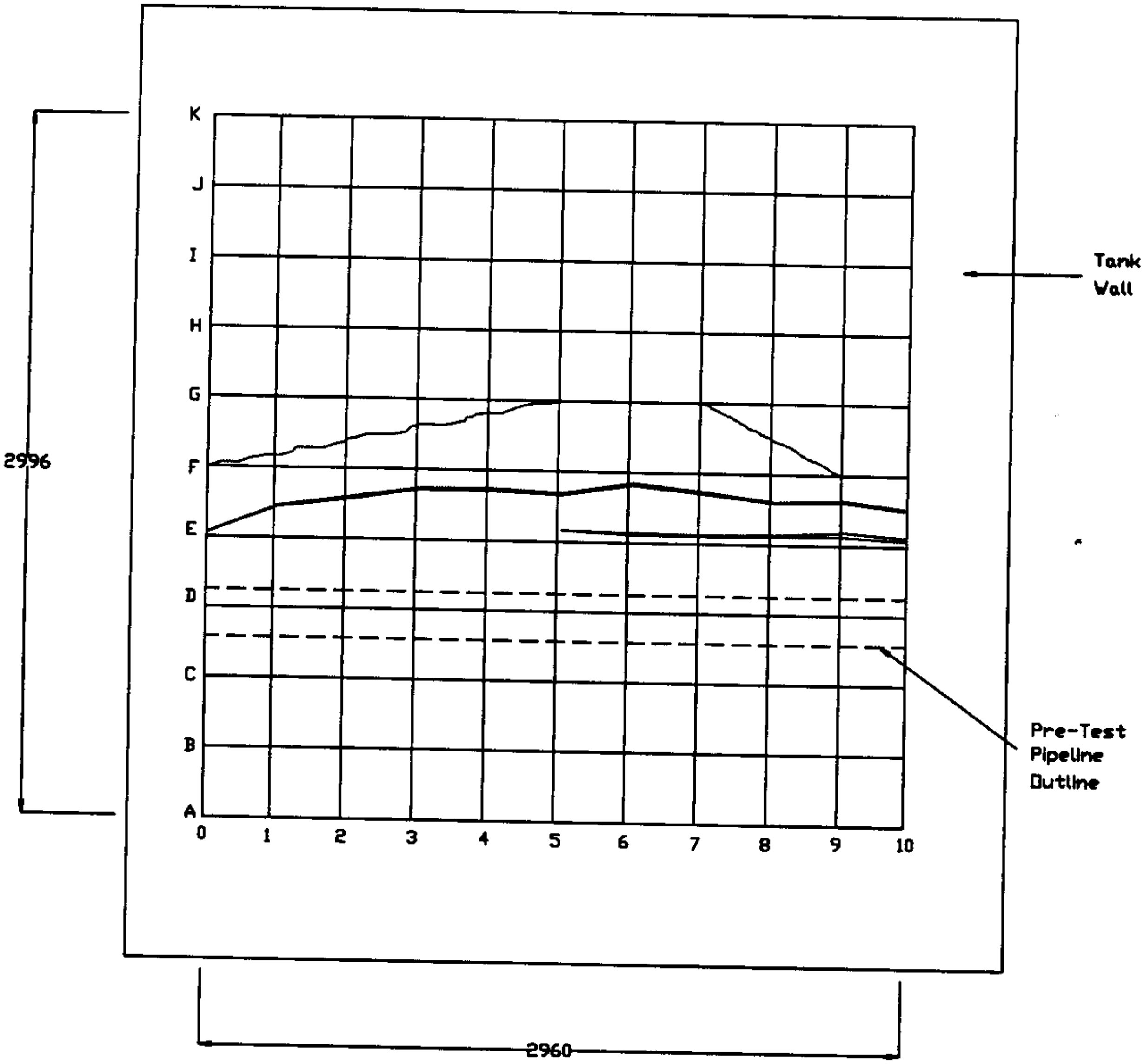

1
MMS01 Pipeline Test
March 24, 1999
Post - Test VDT's



C-CORE

Post-Test Internal Displacement Markers

22



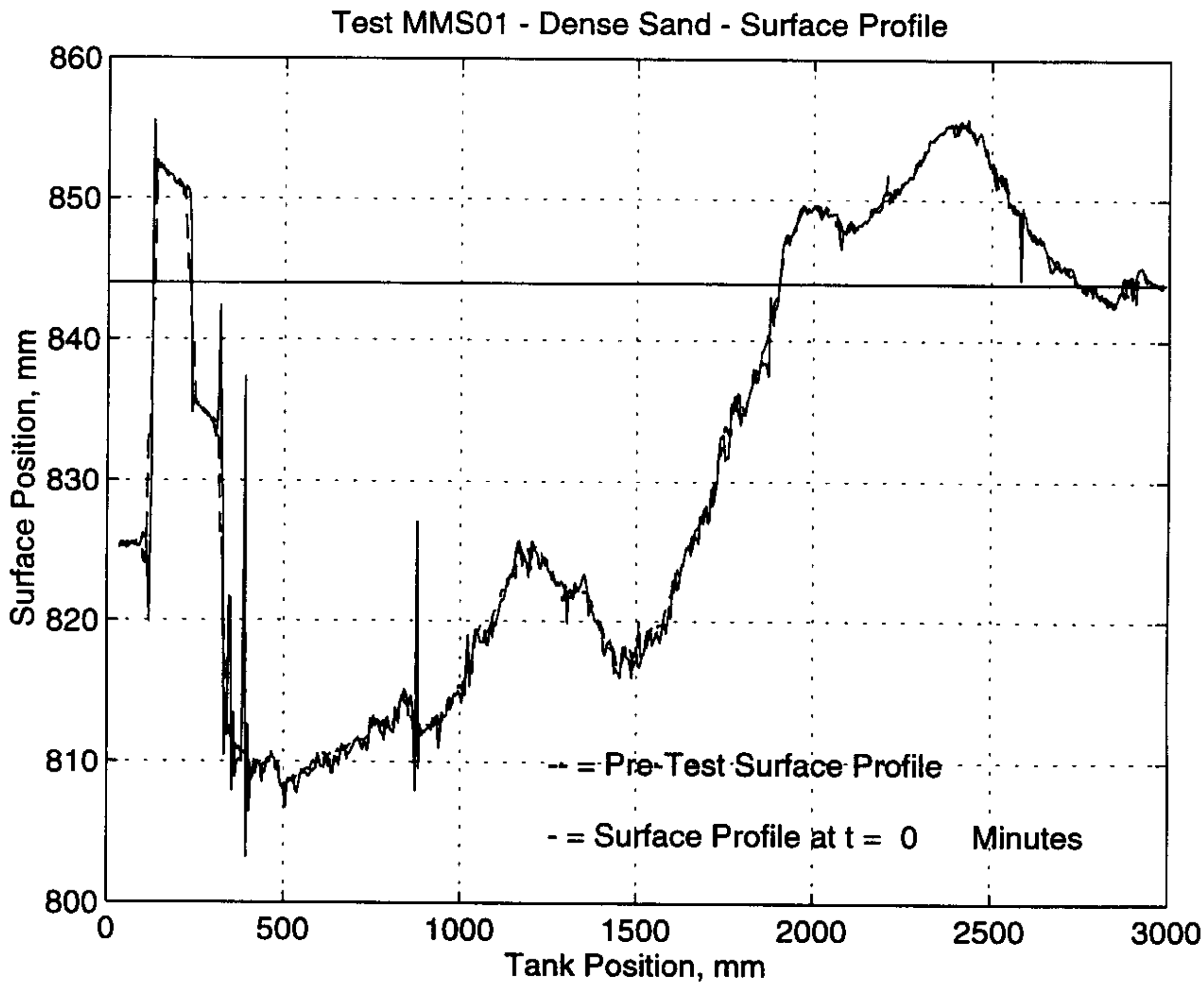
NOTES:
(1) ALL DIMENSIONS IN mm
(2) AVERAGE CRACK THICKNESS t = 8 mm

C-CORE

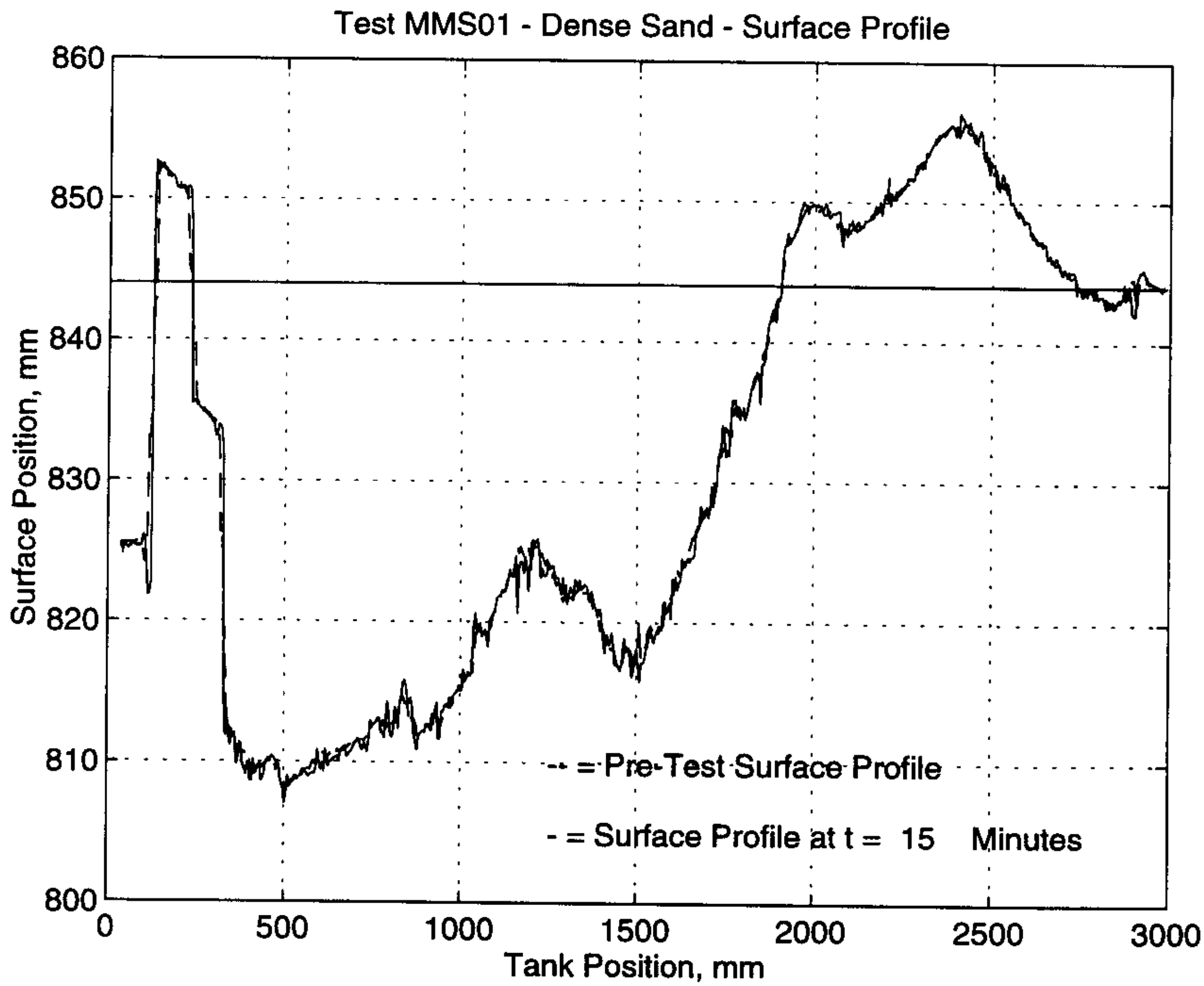
Post-Test Surface Cracks

Appendix B

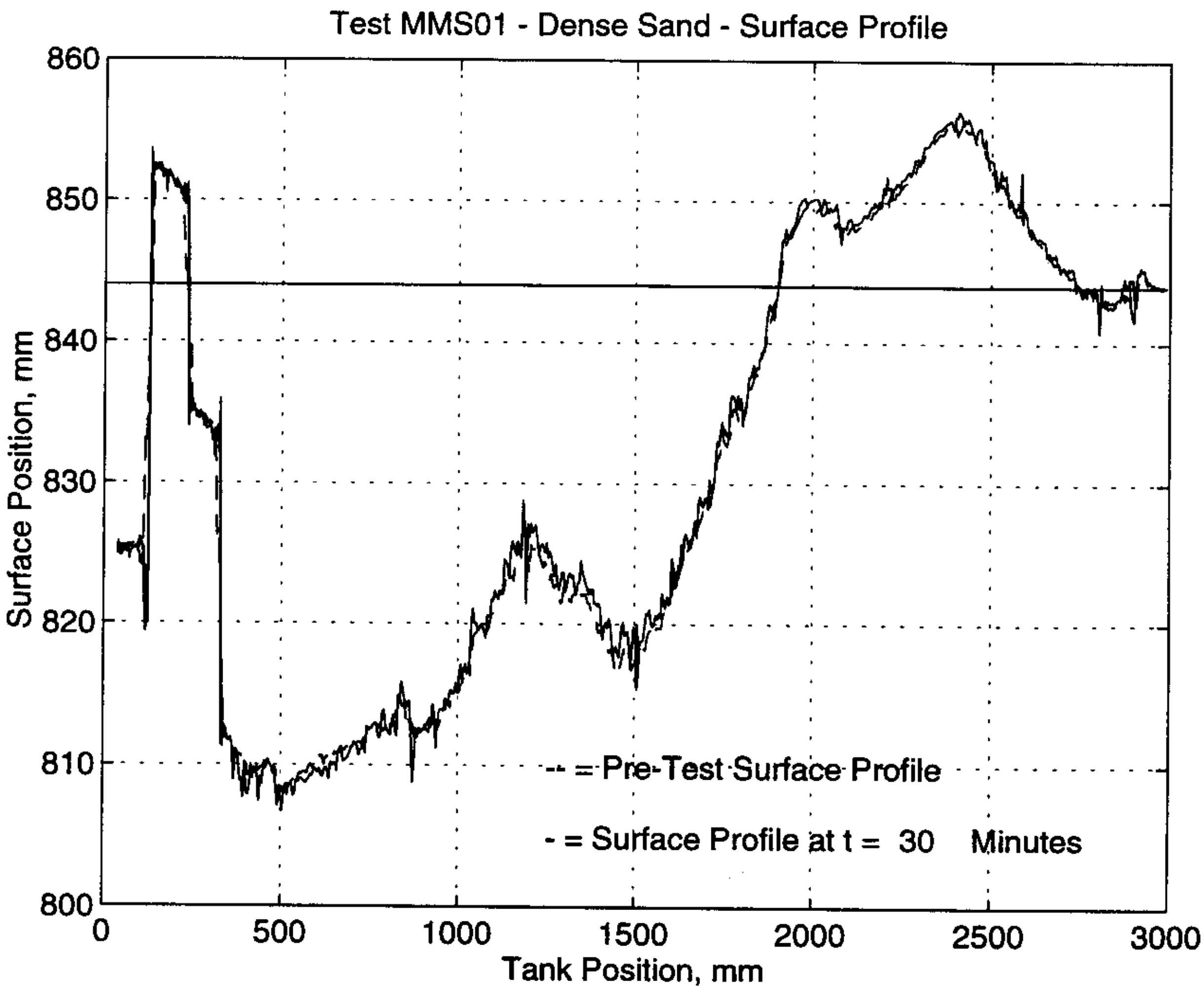
Acoustic Surface Profiles



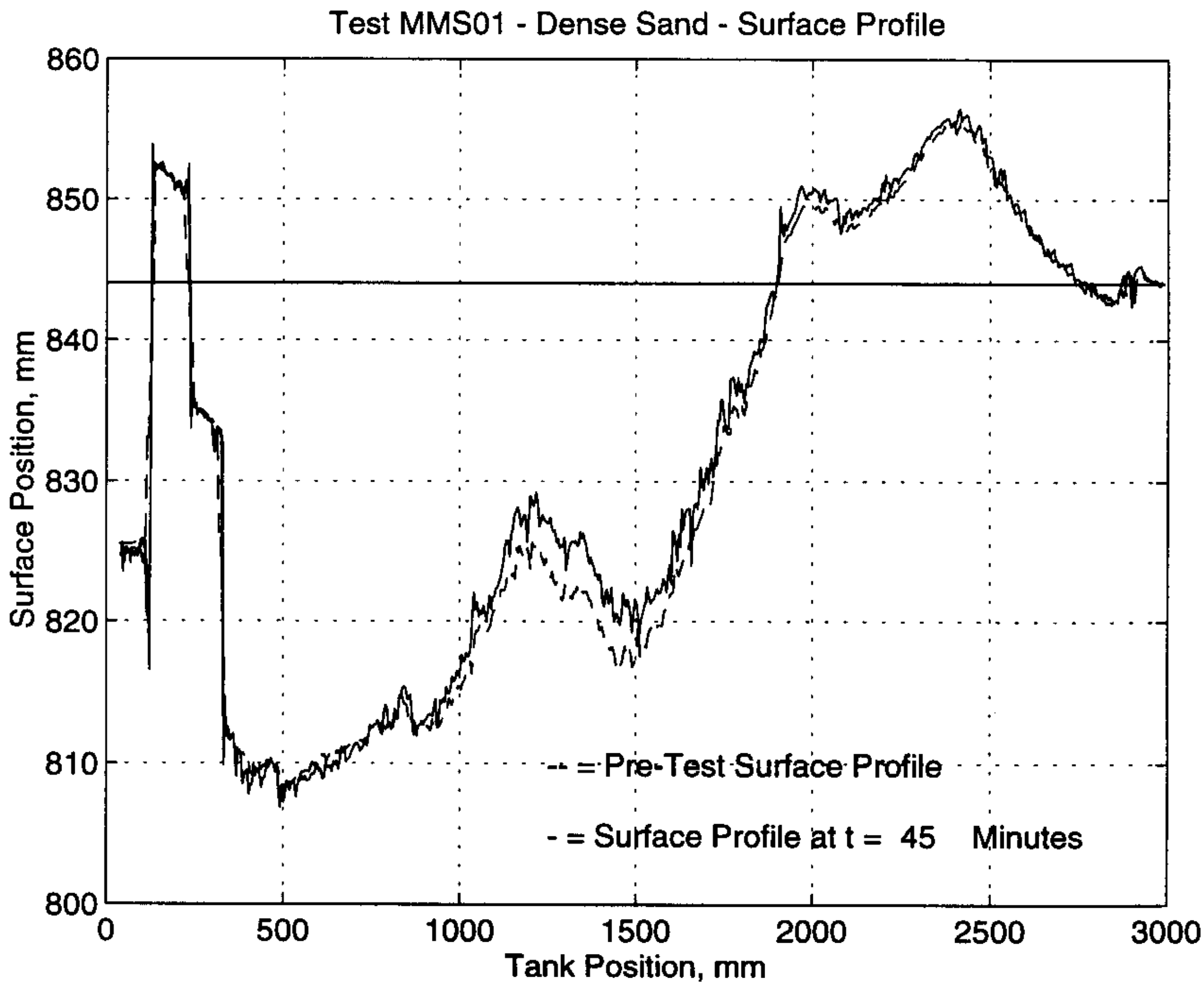
Test MMS01 - Dense Sand - Surface Profile
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 0 Minutes
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000



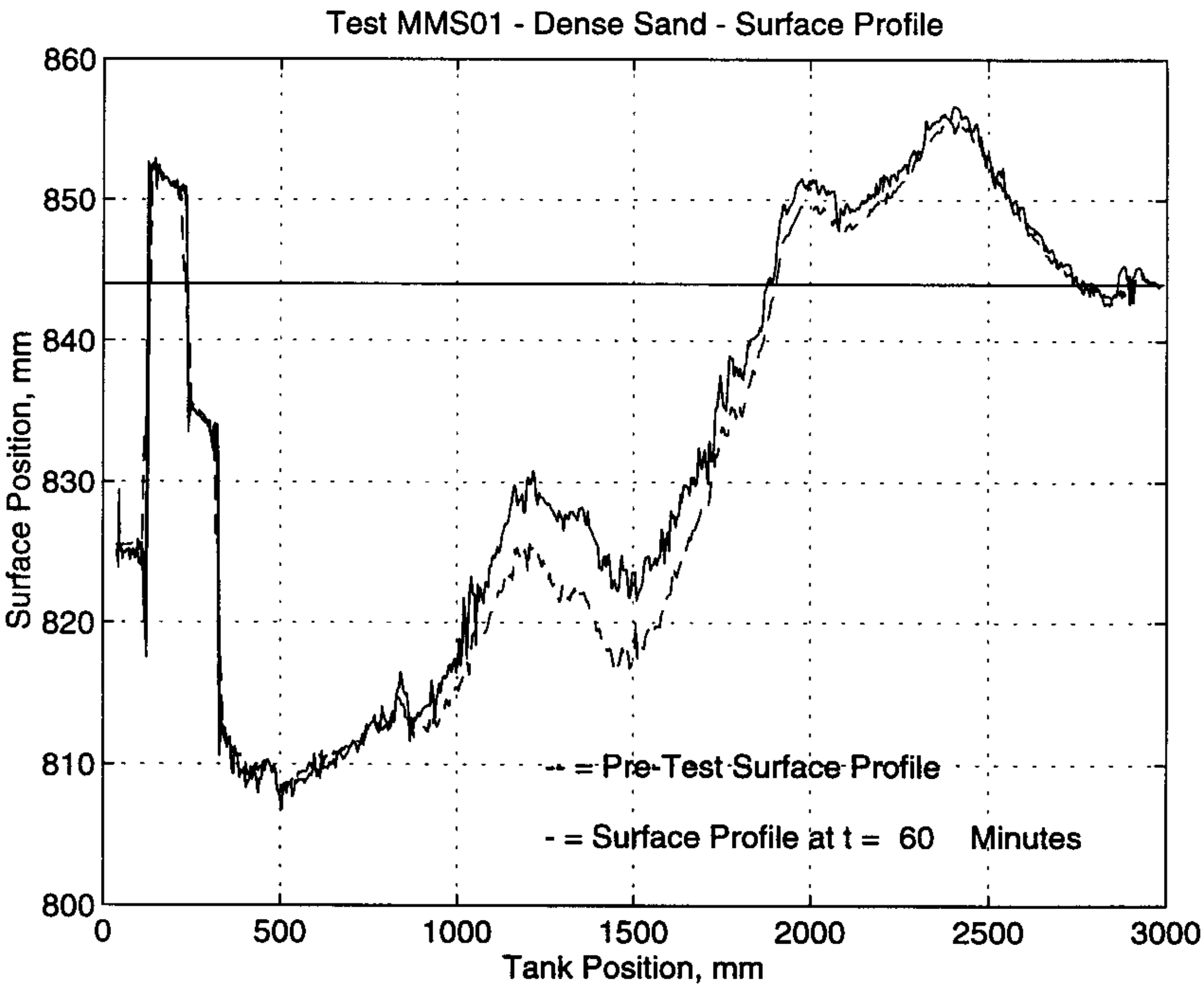
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 15 Minutes



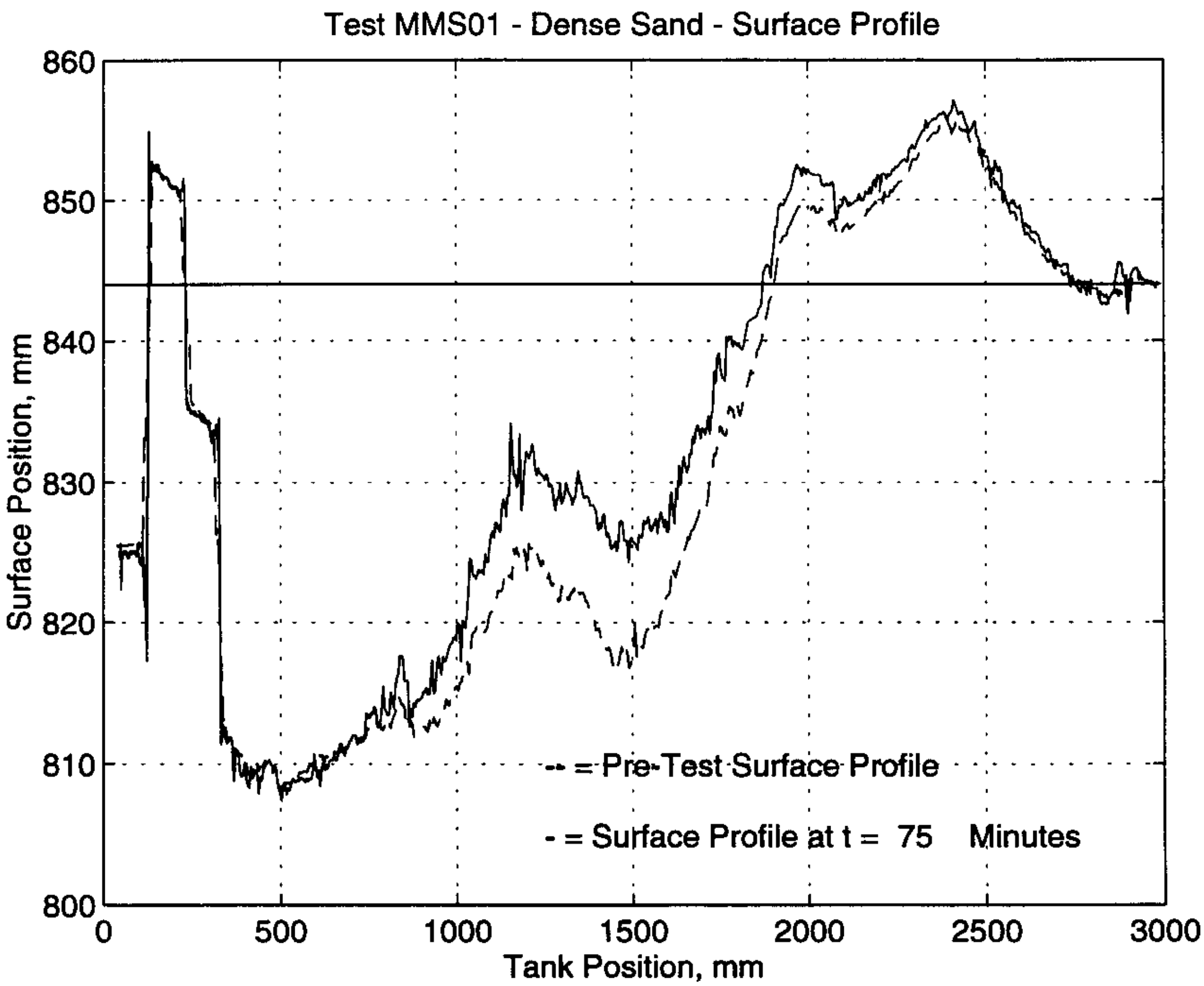
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 30 Minutes



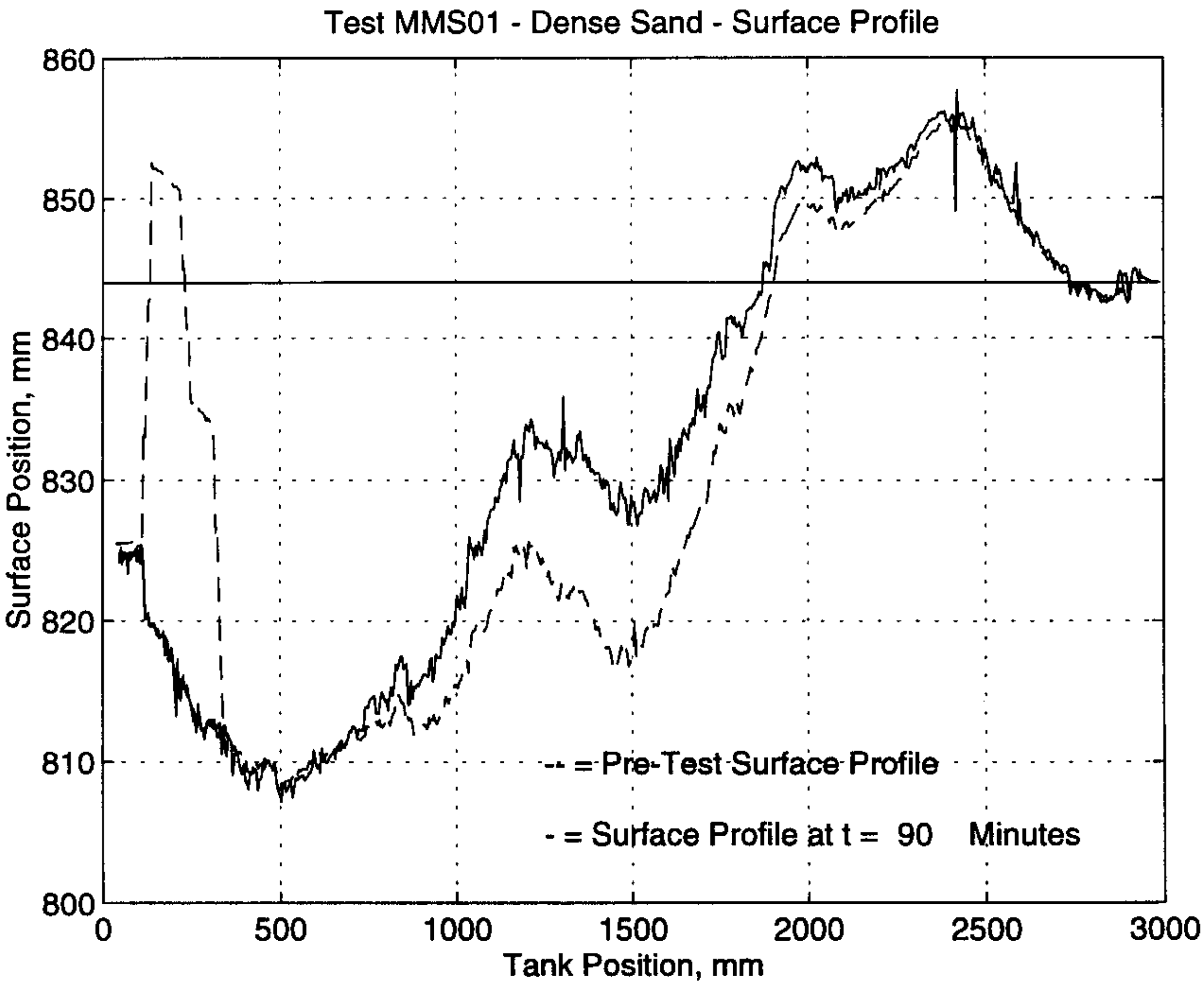
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 45 Minutes



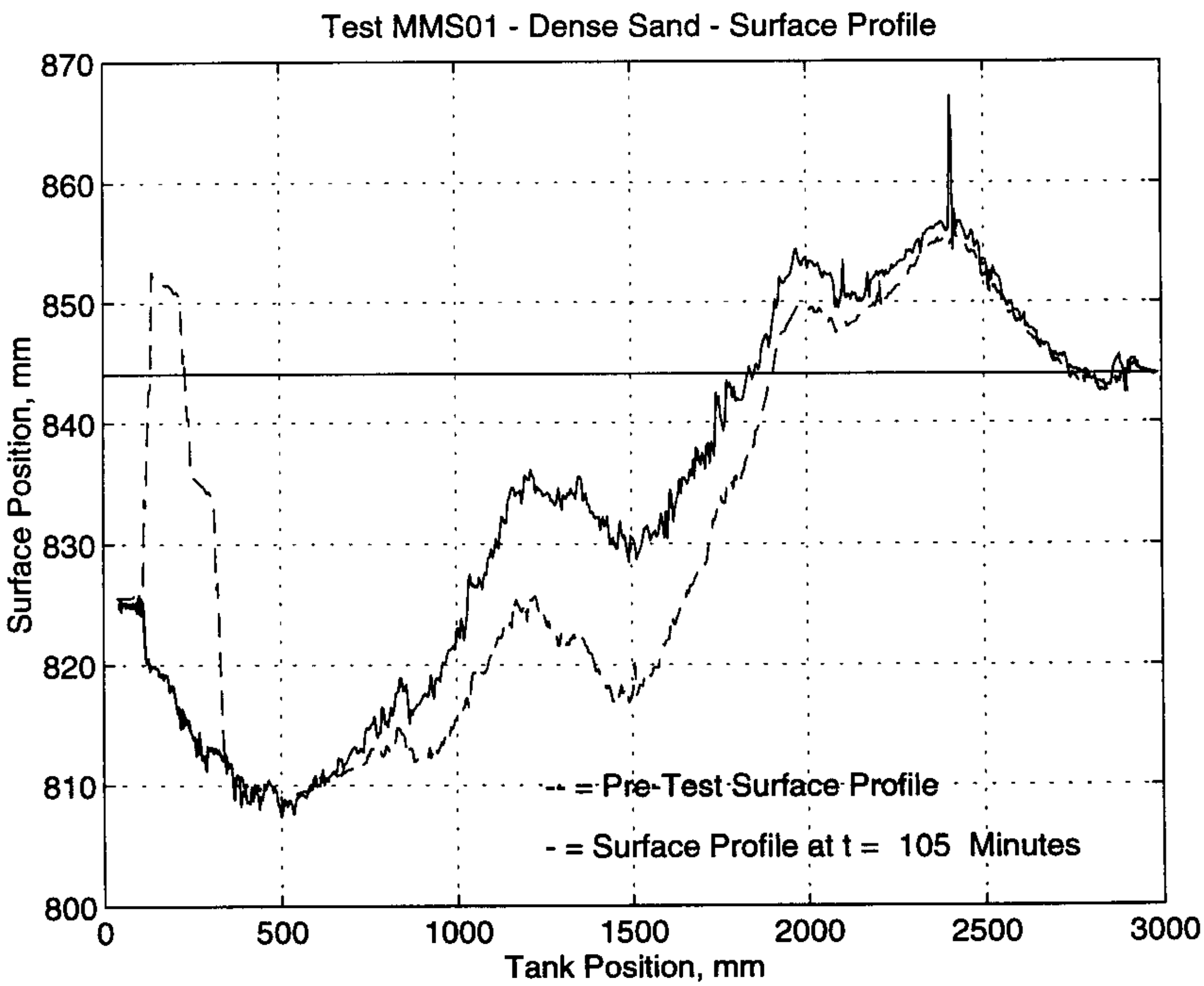
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 60 Minutes



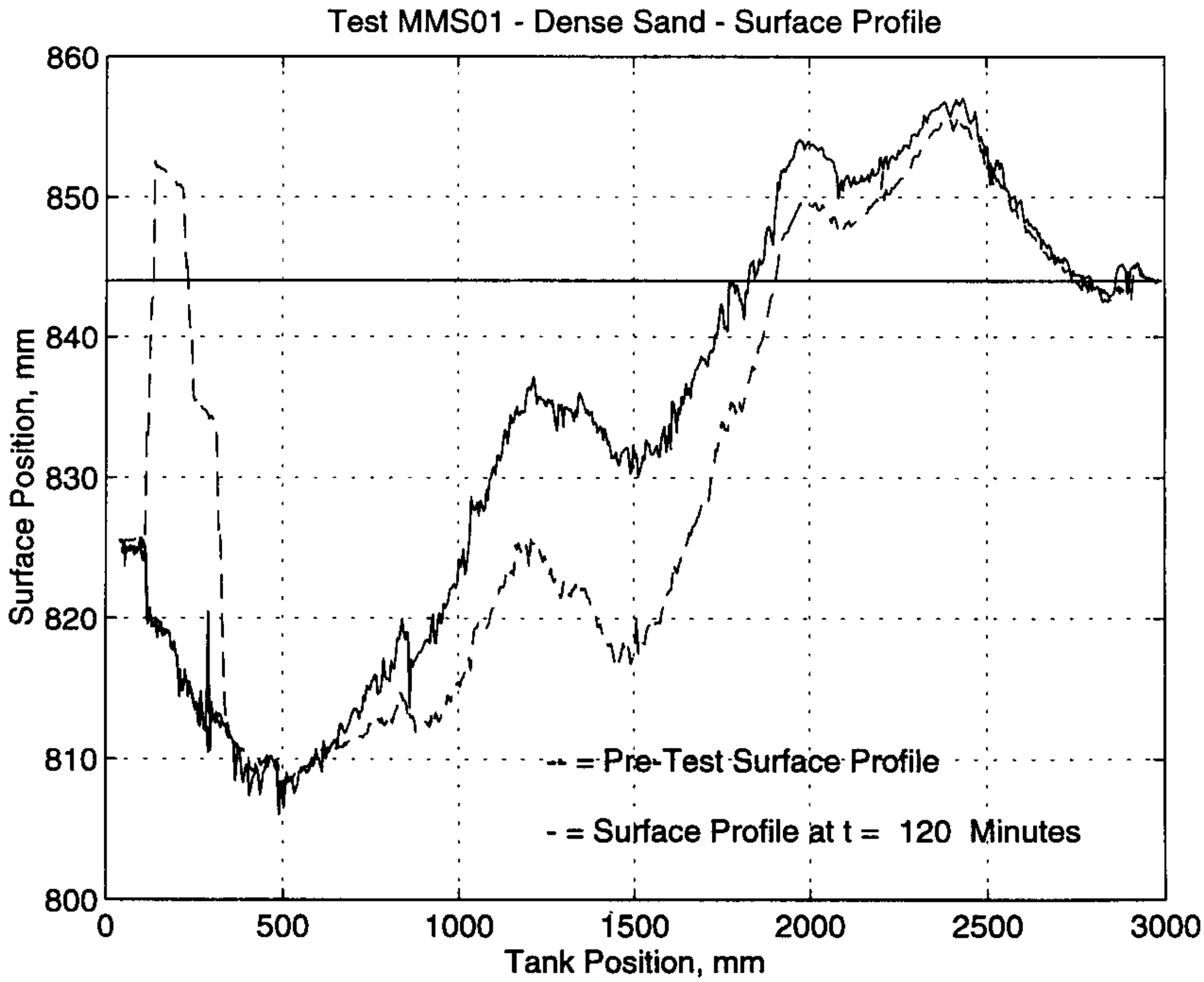
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 75 Minutes



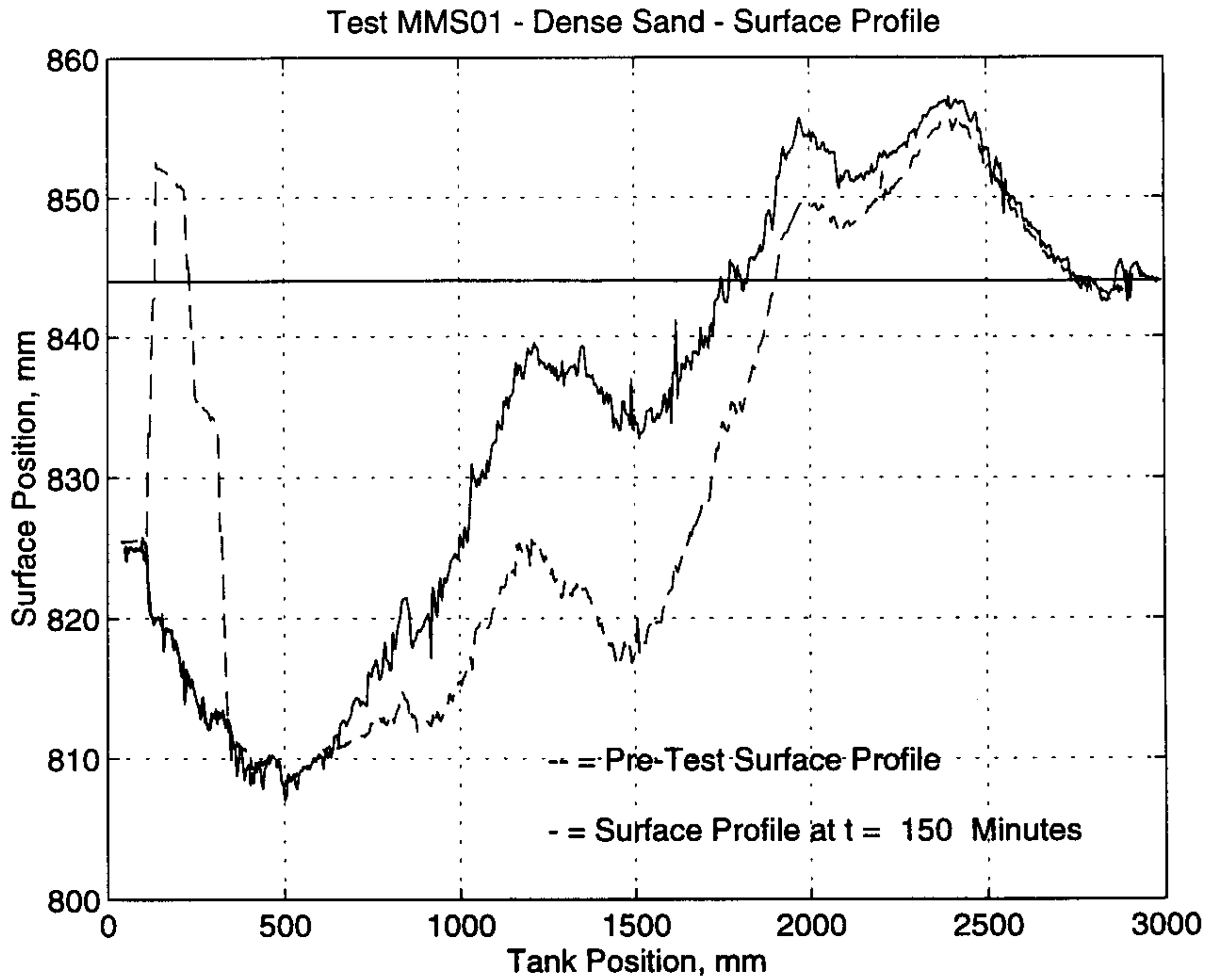
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 90 Minutes

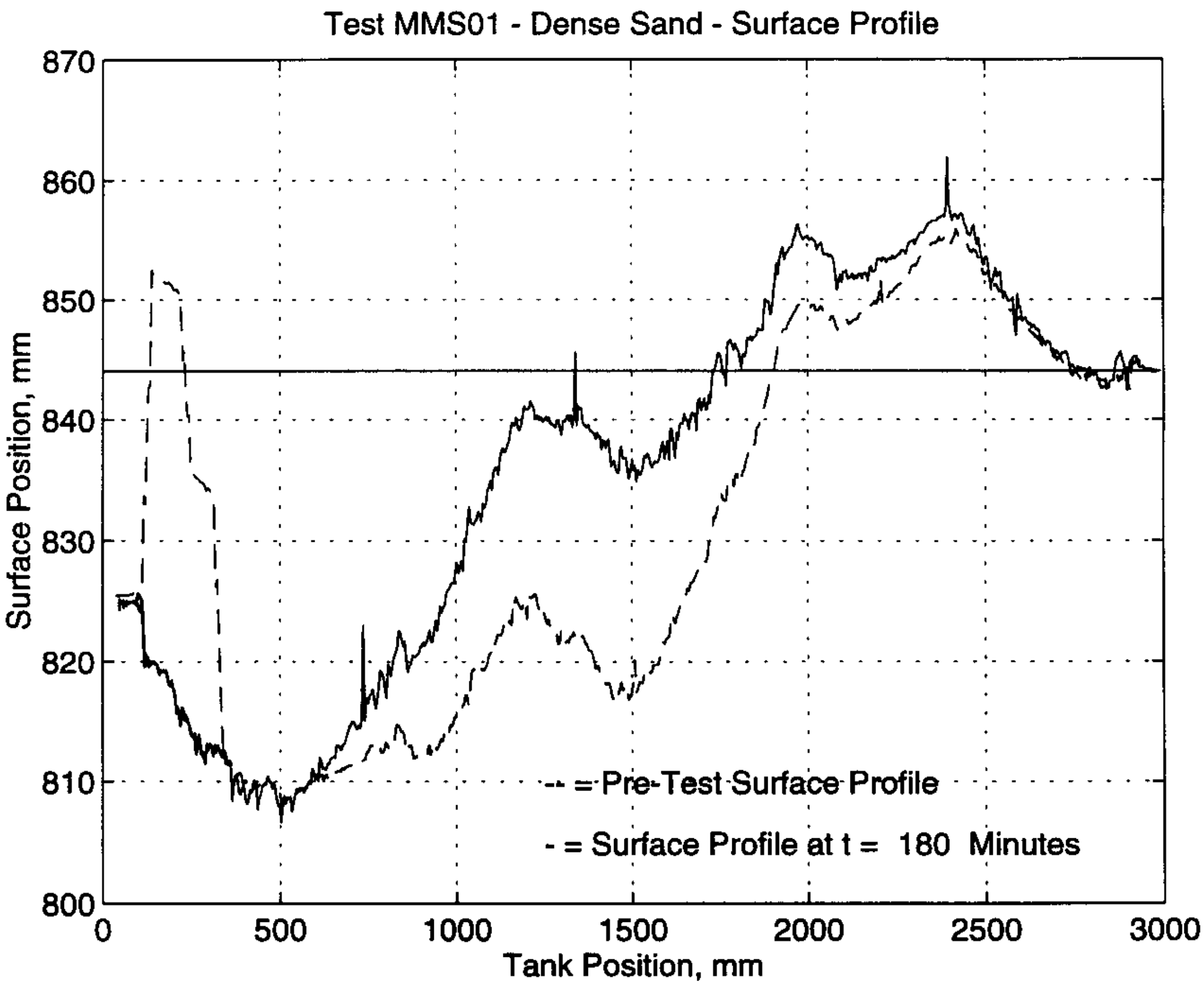


Test MMS01 - Dense Sand - Surface Profile
Surface Position, mm
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 105 Minutes

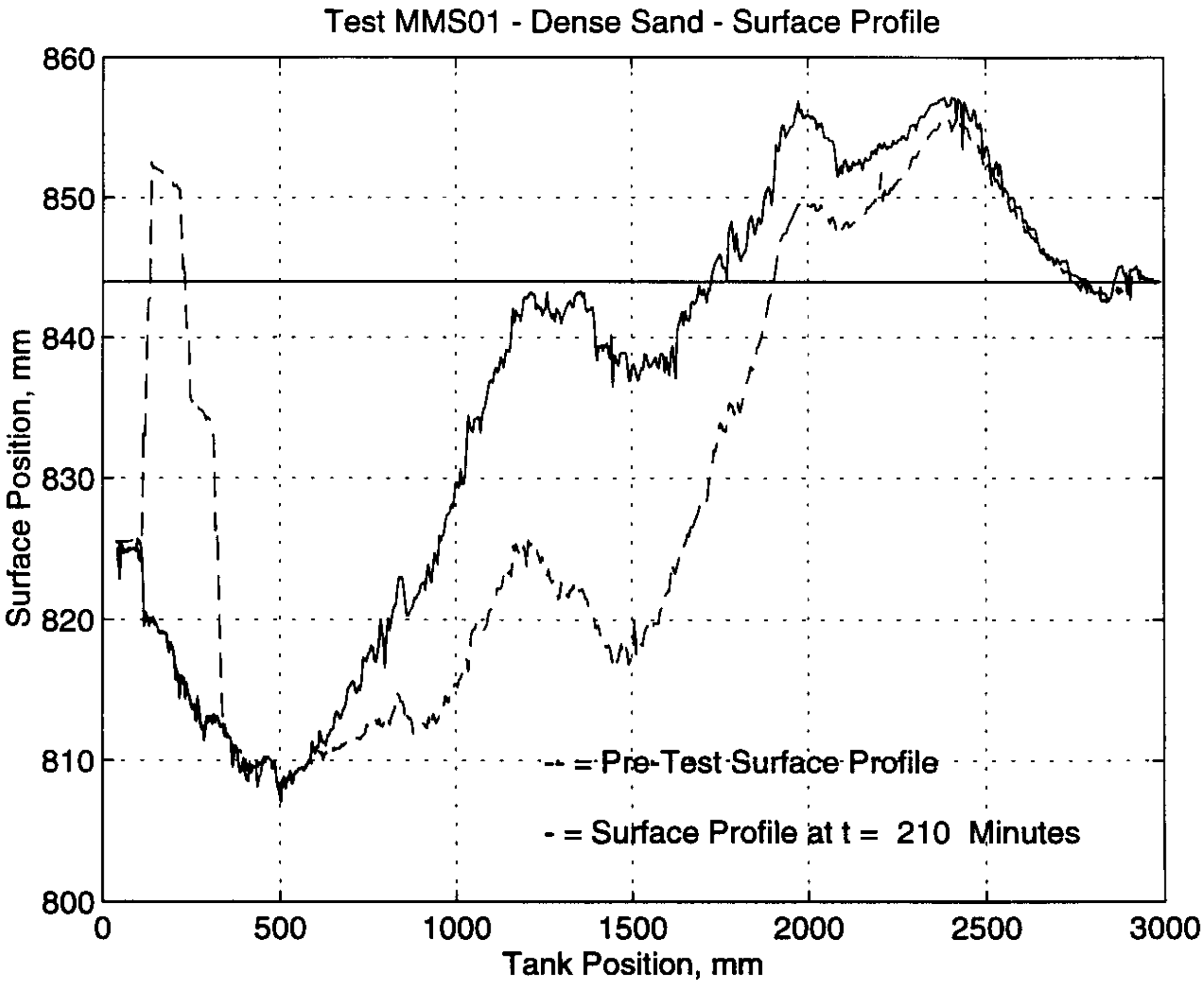


Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 120 Minutes

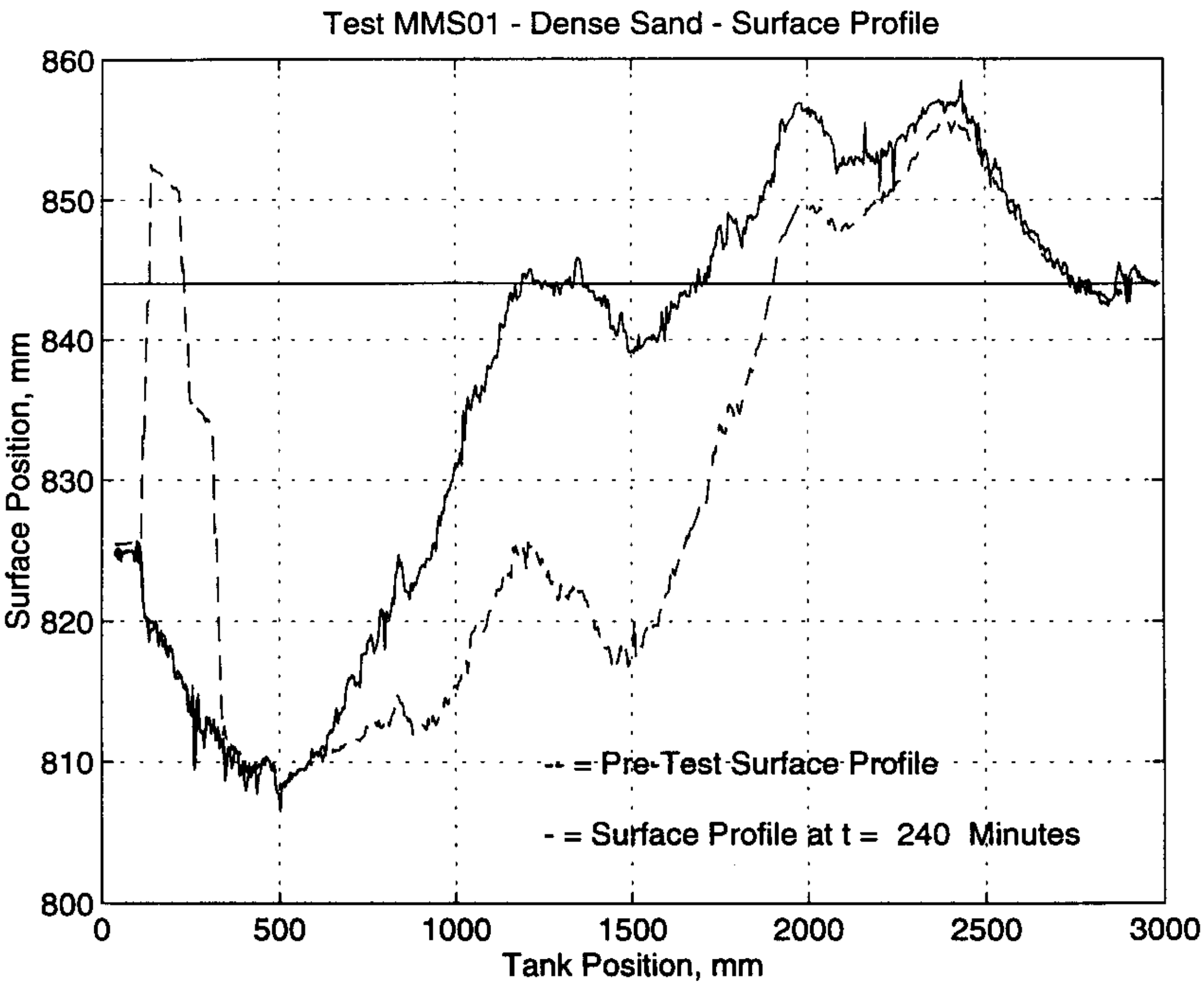

Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 150 Minutes

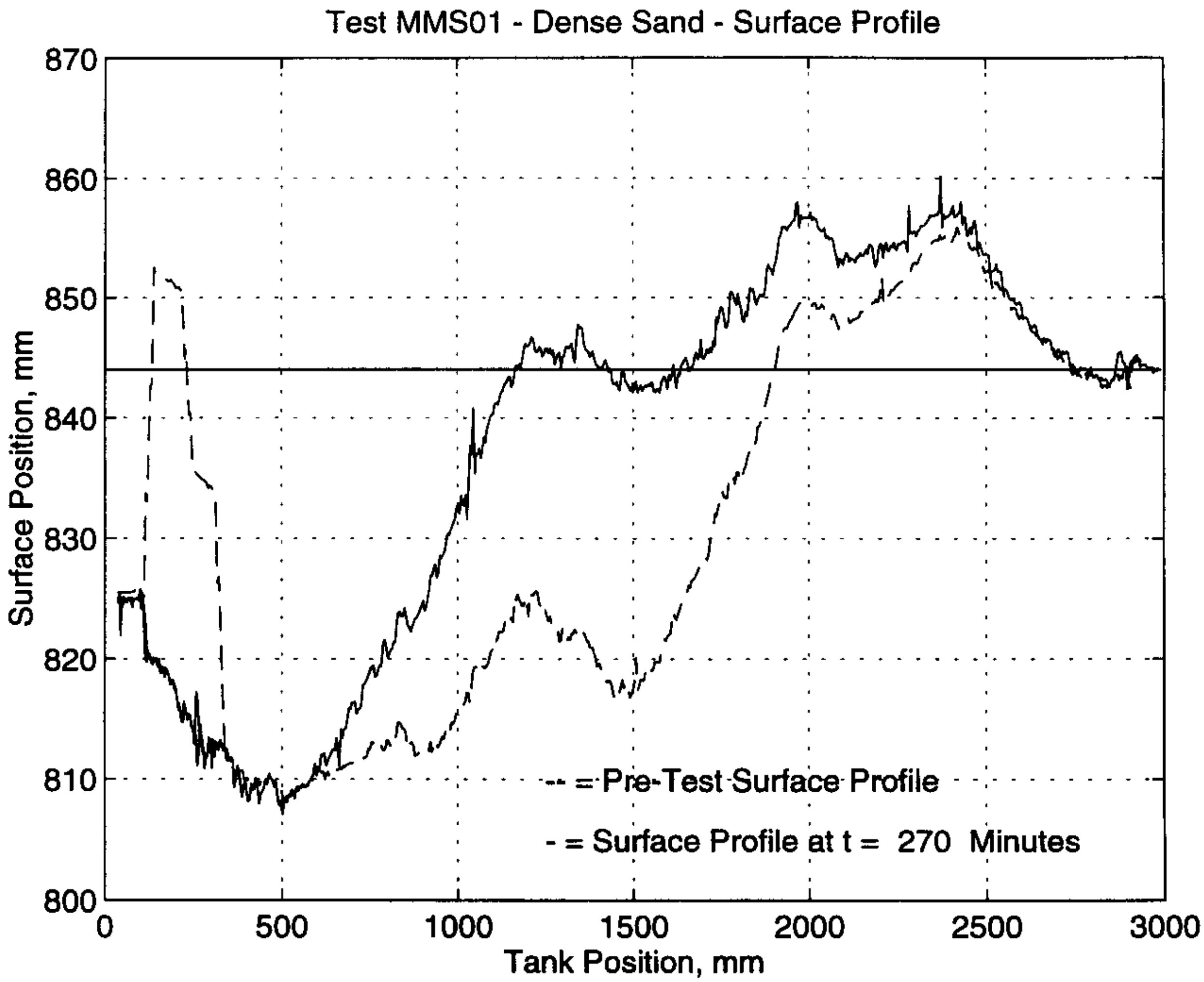


Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 180 Minutes

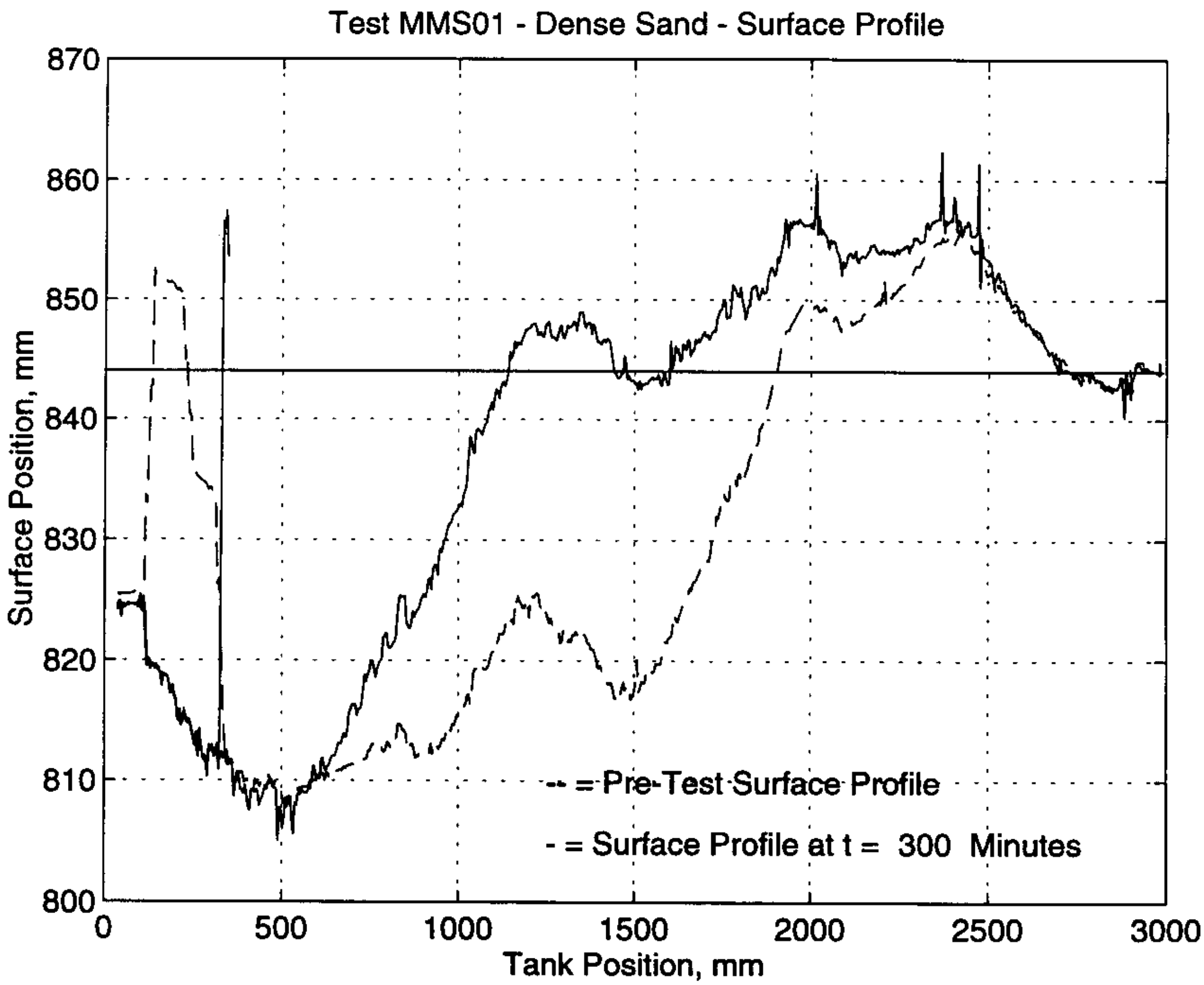


Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 210 Minutes

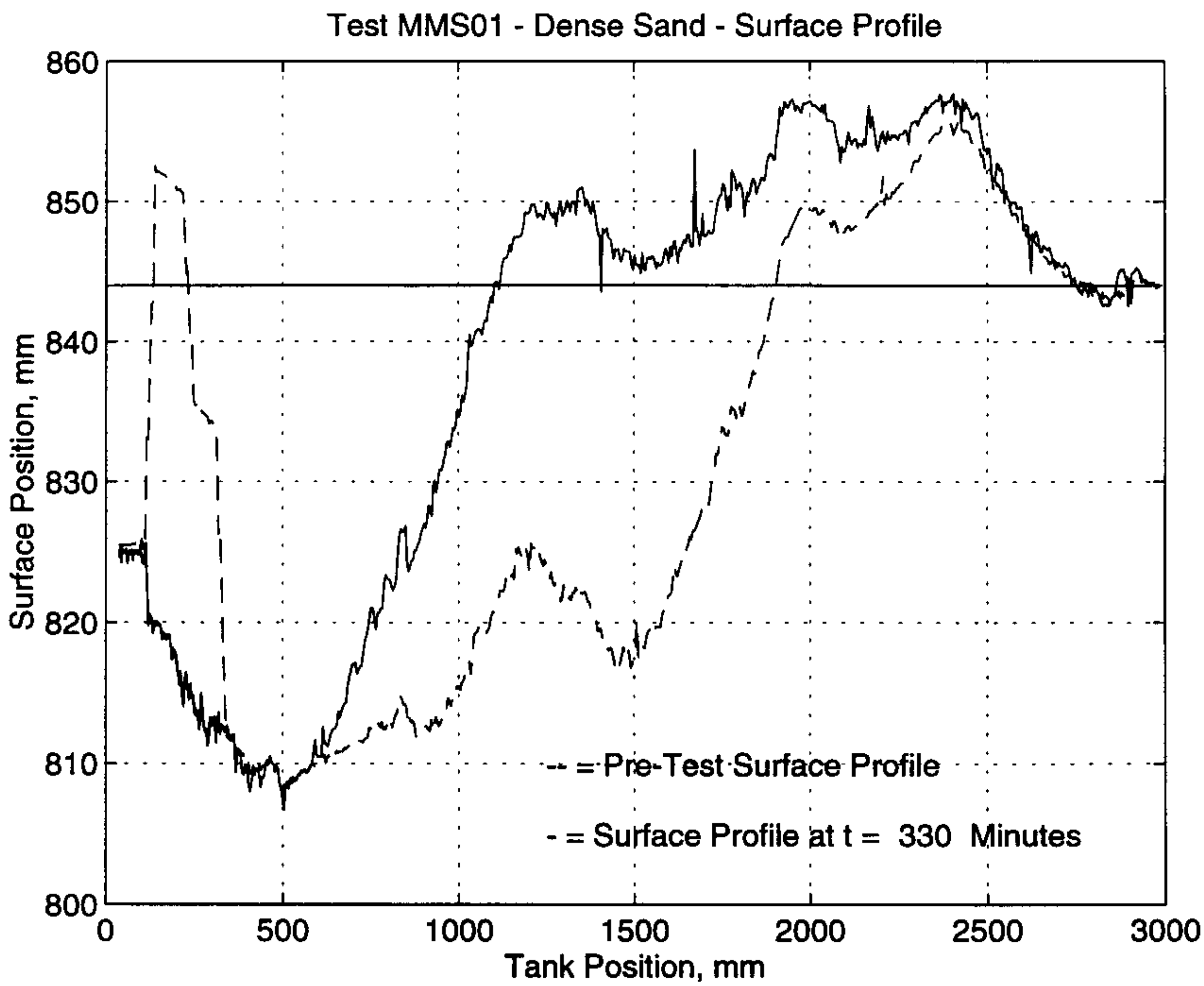

Test MMS01 - Dense Sand - Surface Profile
Surface Position, mm
Tank Position, mm
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
-- = Pre-Test Surface Profile
- = Surface Profile at t = 240 Minutes

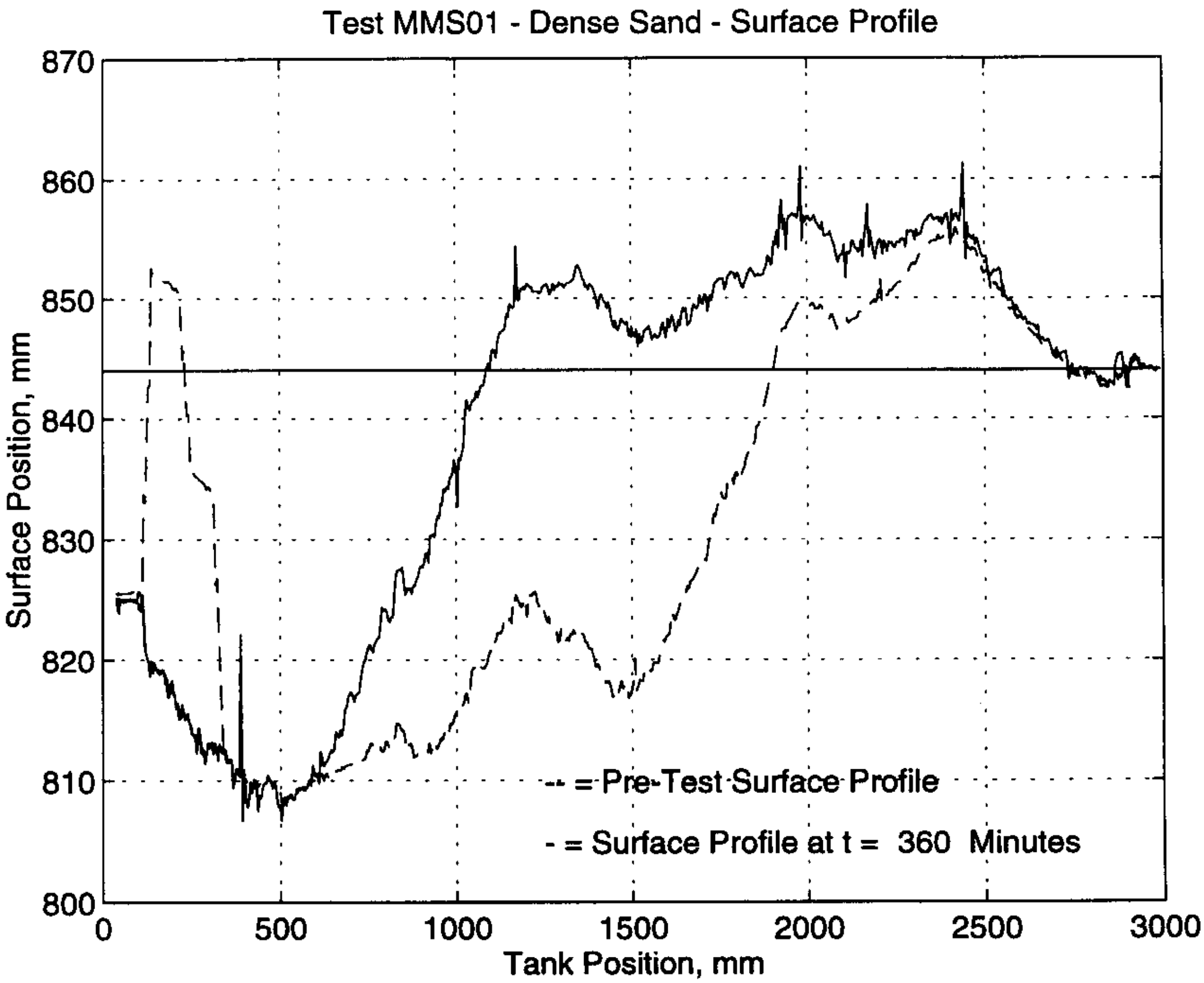


Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 270 Minutes

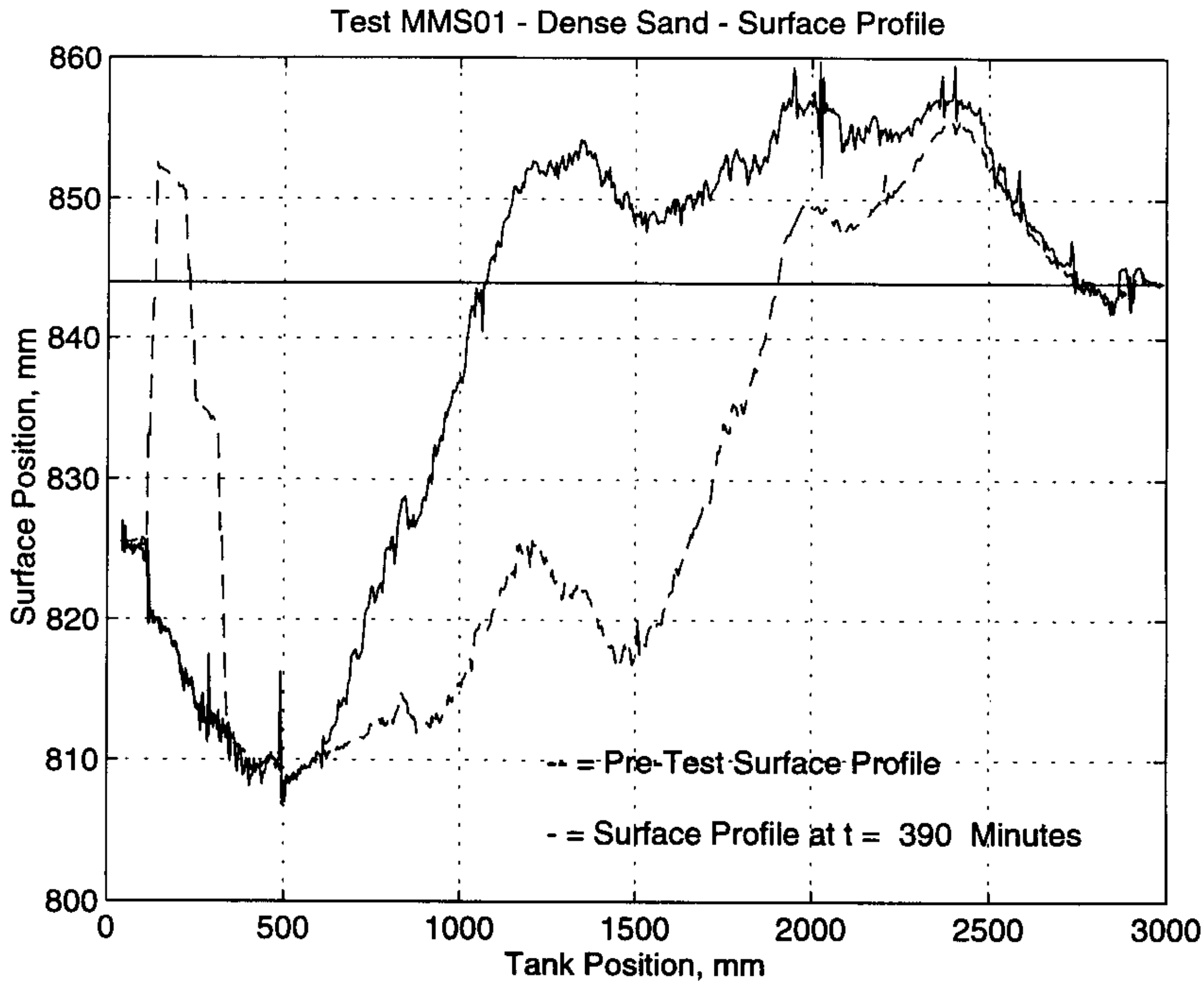


Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 300 Minutes

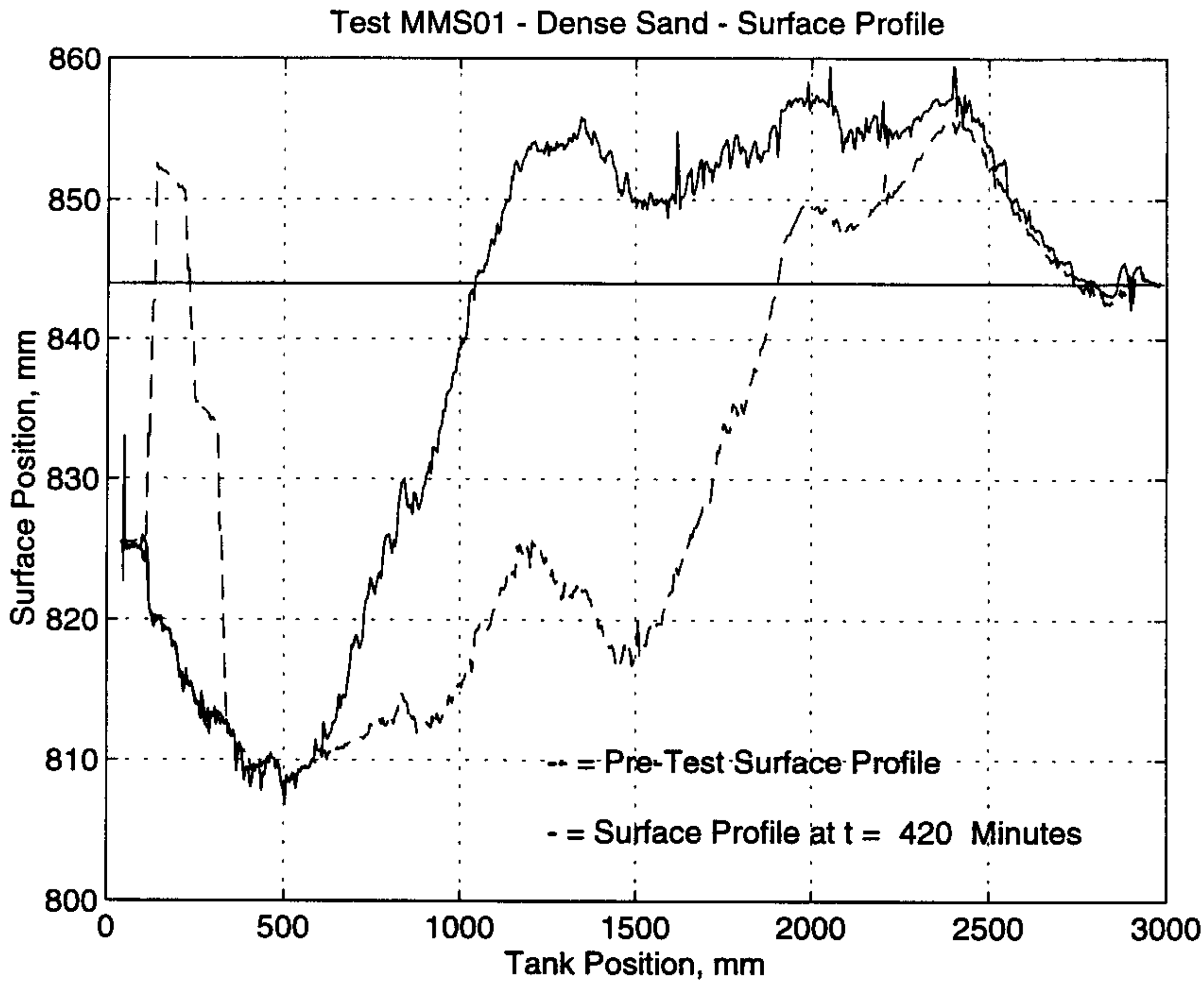

Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 330 Minutes

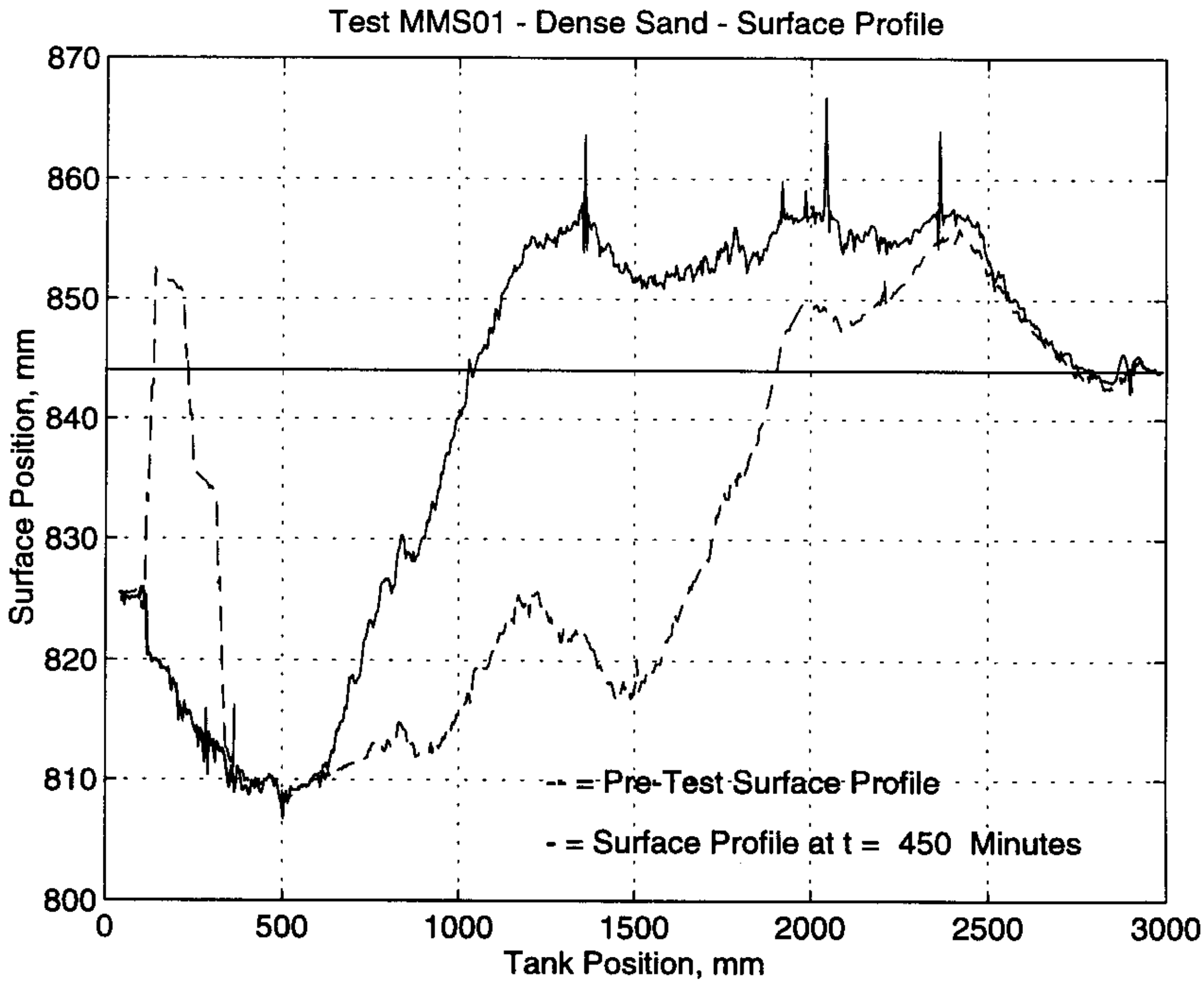


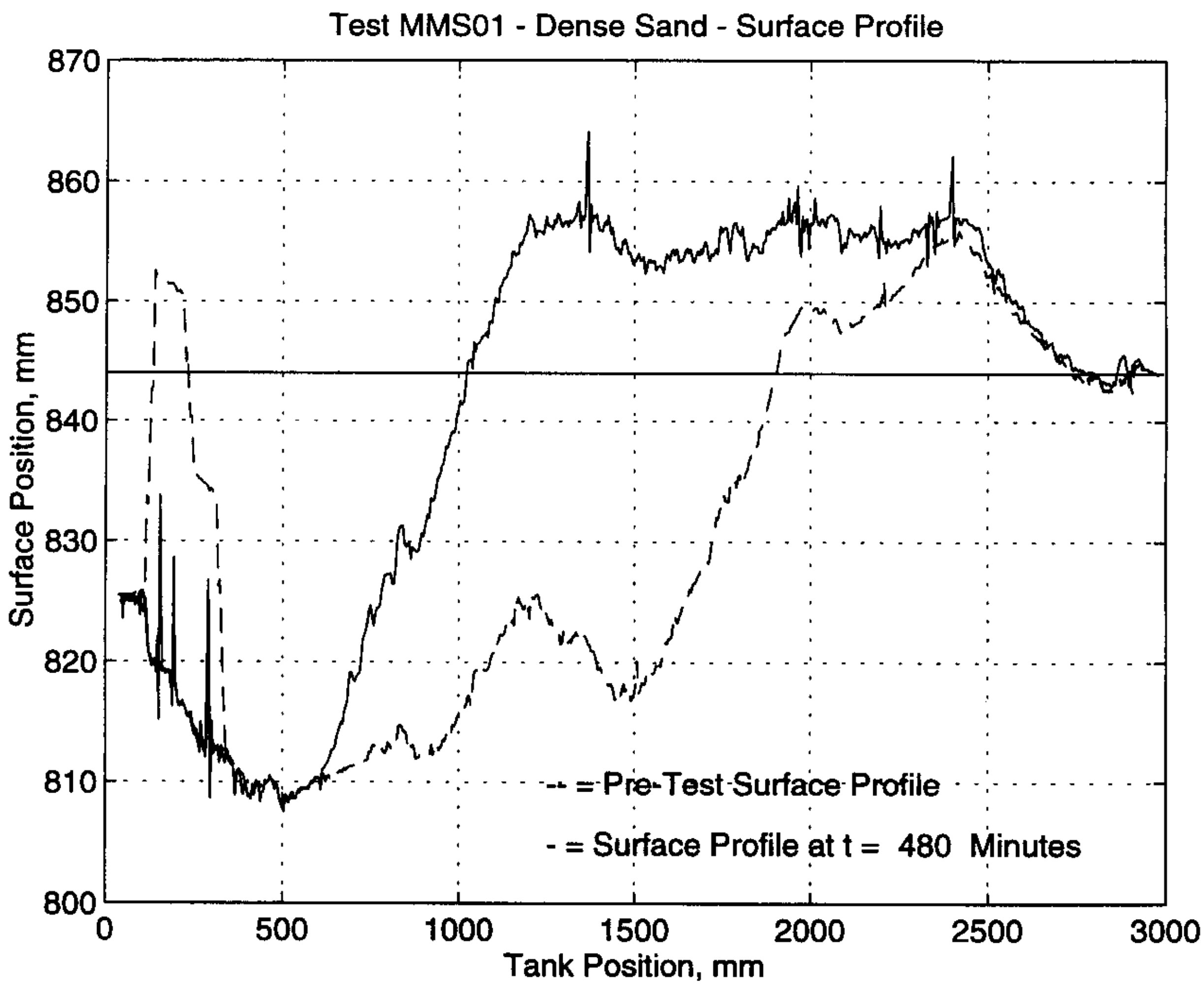
Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 360 Minutes



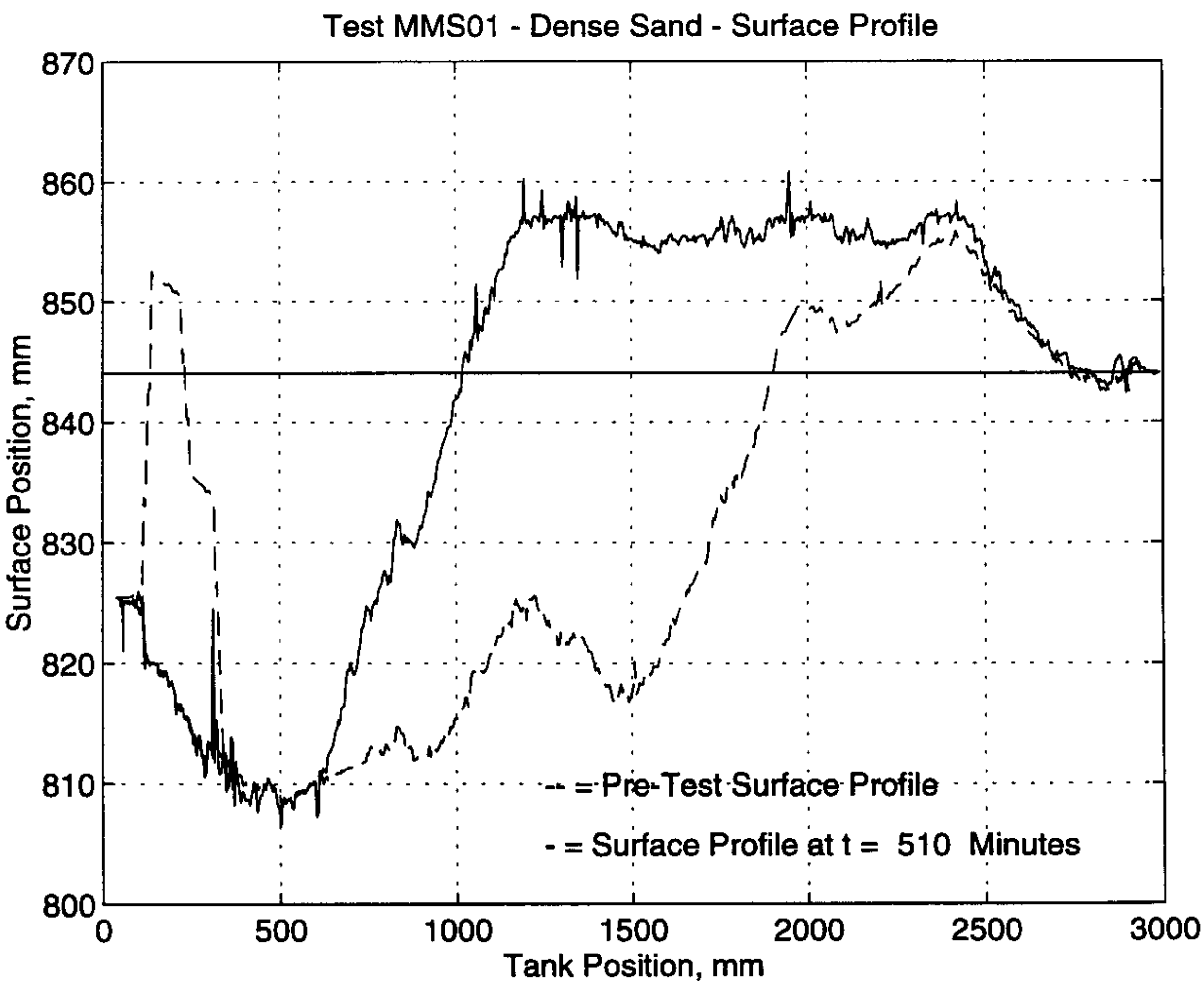
Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
= Pre-Test Surface Profile
- = Surface Profile at t = 390 Minutes

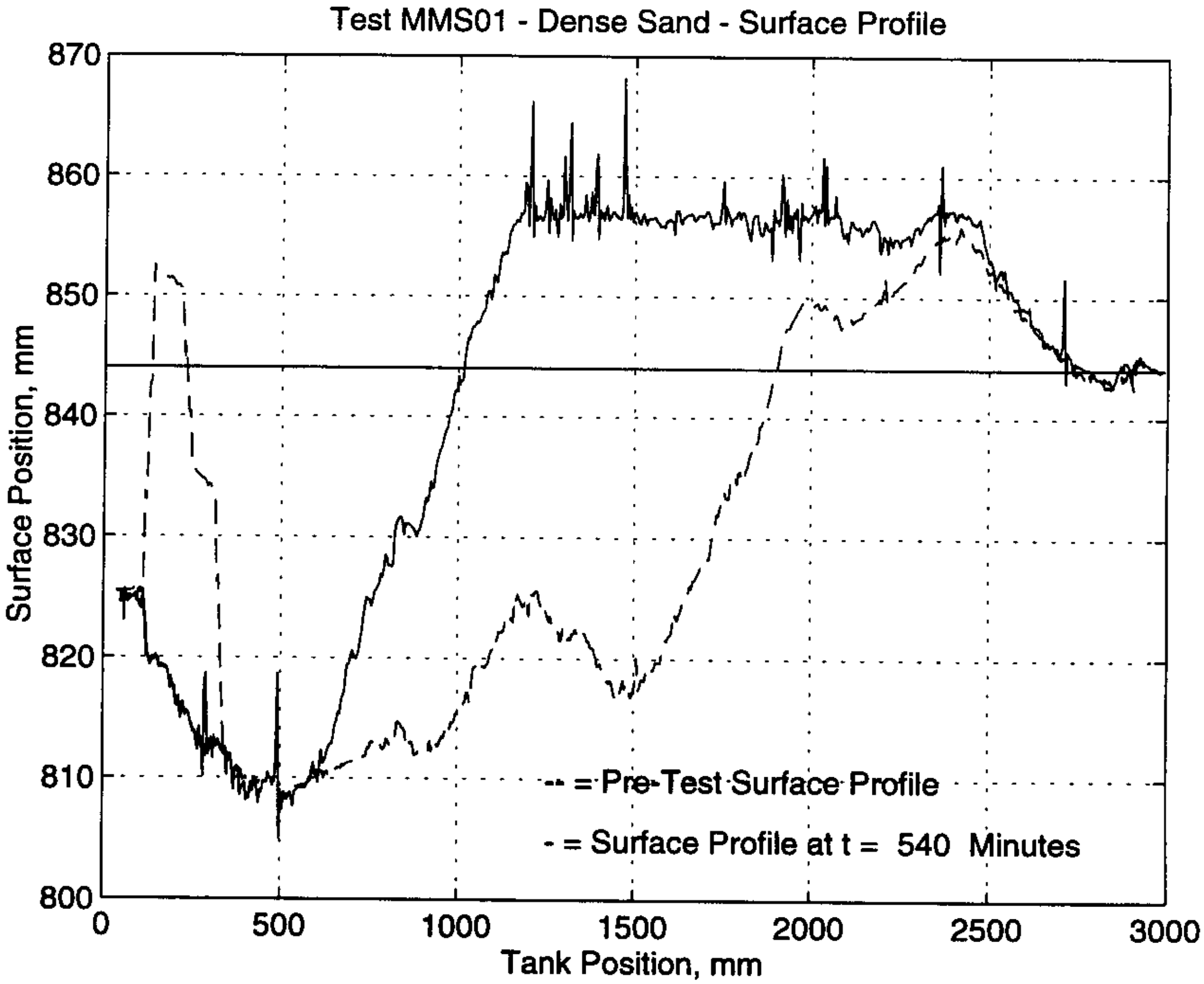

Test MMS01 - Dense Sand - Surface Profile
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
= Pre-Test Surface Profile
- = Surface Profile at t = 420 Minutes


Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 450 Minutes

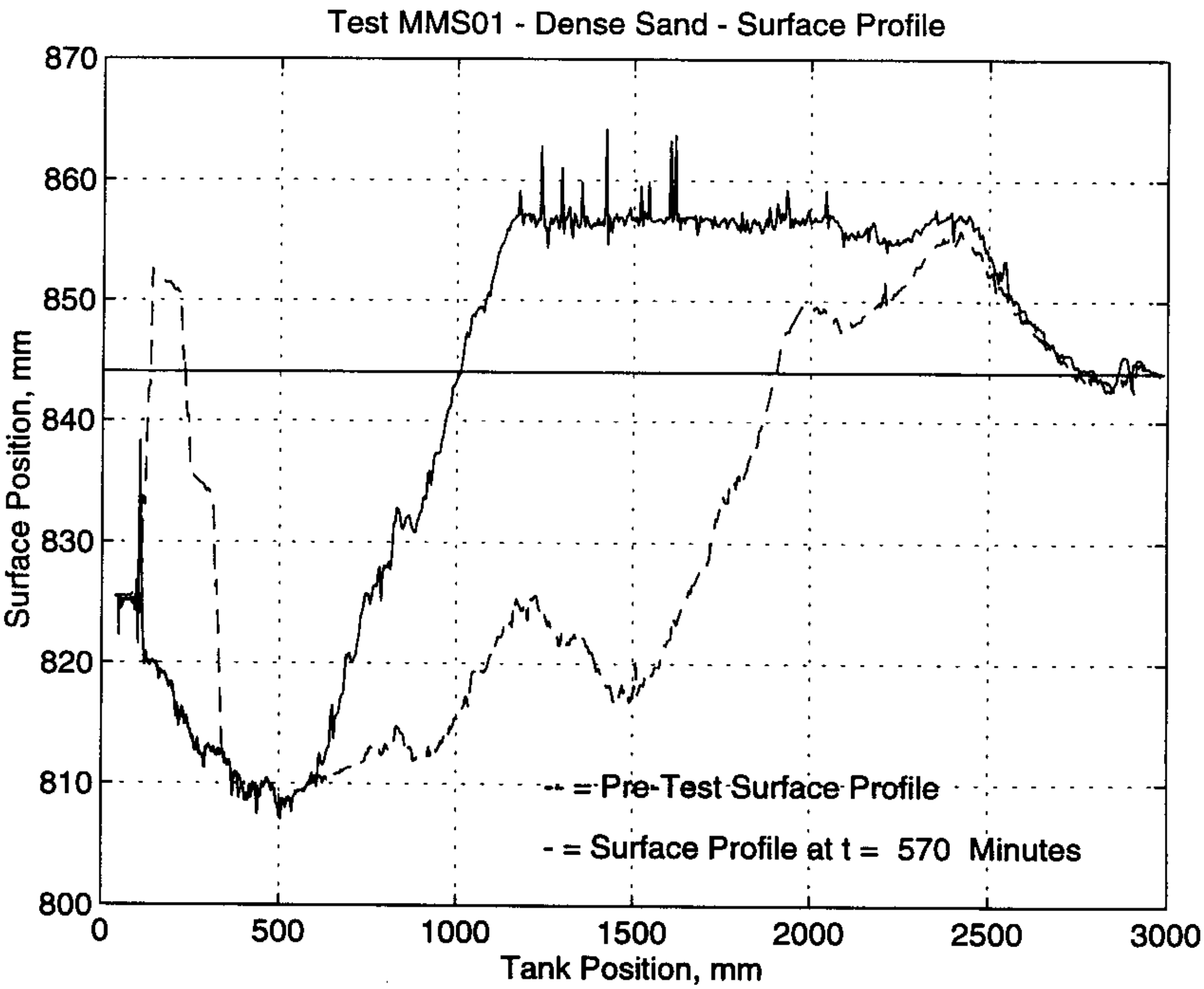


Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 480 Minutes

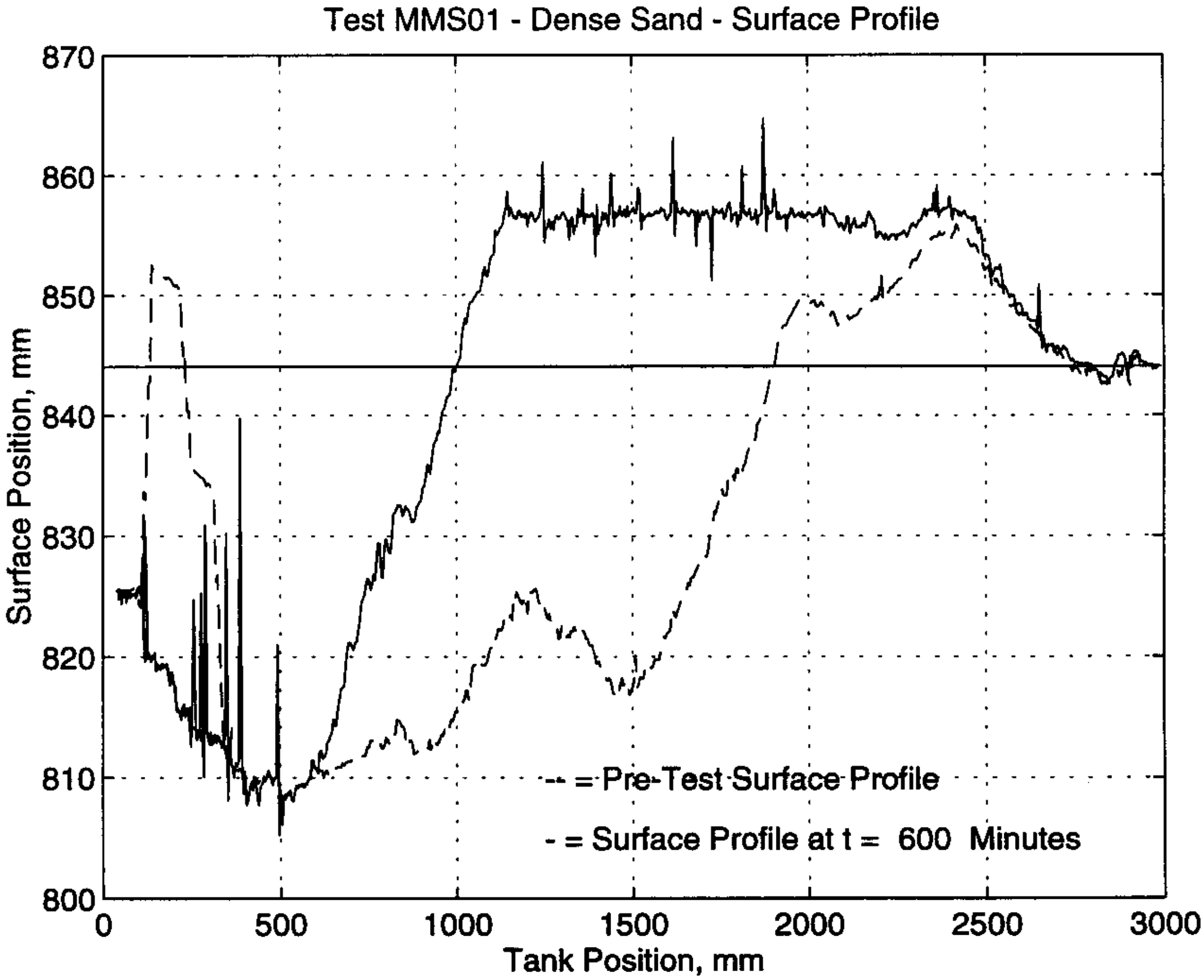

Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 510 Minutes



Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 540 Minutes



Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
0
500
1000
1500
2000
2500
3000
Surface Position, mm
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 570 Minutes



Test MMS01 - Dense Sand - Surface Profile
870
860
850
840
830
820
810
800
Surface Position, mm
0
500
1000
1500
2000
2500
3000
Tank Position, mm
-- = Pre-Test Surface Profile
- = Surface Profile at t = 600 Minutes