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Simulation of 12 High Geosynthetic Reinforced Retaining Walls Under Surcharge Loading by Centrifuge Testing

James M. Klamerus
Hon-Yim Ko
University of Colorado
Department of Civil, Environmental
and Architectural Engineering
Boulder, Colorado 80309

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U.S. Department of Transportation
Federal Highway Administration

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13. ABSTRACT (Maximum 200 words)

Total of 13 centrifuge model tests on geosynthetic reinforced retaining walls were conducted. These tests were designed to determine the effects of backfill type, reinforcement shape (length), and degree of saturation on displacement and mode of failure under surcharge loading. The backfill types are sand, silty clay, recycled asphalt, and sand-clay materials. Material analysis for the sand and clay soils is obtained.

Only one centrifuge test showed signs of a catastrophic failure so it was hard to draw general conclusions on the failure performance of other tests. It was found that drained backfill reinforced with trapezoidal shaped reinforcement (truncated base) functions equally as well as the rectangle shaped. The use of sand as a backfill material increases the stability of the wall. Yet if 5 psi is the anticipated surcharge pressure for field walls, the results for other types of backfill showed adequate factor of safety. The adverse effect of increasing saturation is more significant in the silty-clay backfill than in the sandy backfill.

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Report Review and Comments

The review revealed that the basic modeling methodology utilized in this study was valid, but lacked sufficient successful tests to draw general conclusion. The predicted surcharge pressure at failure for the model built at UCD was between 55-60 psi, while the actual model failed at 29 psi under different failure mode than predicted. Therefore, IT IS CONCLUDED THAT THE OUTCOME OF THIS RESEARCH STUDY IS BASED ON VERY LIMITED AND NOT VERIFIED TESTS.

The report affirms other studies findings that truncated base are stable in MSB constructions and that the performance of granular backfills is superior to finer backfills.

Centrifuge modeling of GRS retaining walls is a cost-effective method for establishing safe and economical design guidelines. However, there remains a need for performance data of full-scale walls tested to destruction for confirmation or calibration of the centrifuge tests.

This study attempted to evaluate three very important variables for the performance of MSE walls: backfill type, truncated base concept, and the backfill degree of saturation. Future studies on centrifuge model tests for studying these variables and other MSE relevant issues should be considered.

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Appendices

1) Introduction

The primary objective of this project was to perform a minimum of ten model tests on geosynthetic reinforced retaining walls in the 440 G-Ton centrifuge at the University of Colorado. These tests were designed to determine the effects of backfill type, reinforcement shapes and degree of saturation on displacement and mode of failure under surcharge loading. All of the tests were performed under 11 G's in the 440 G-ton centrifuge located at the University of Colorado at Boulder.

2) Theory

Due to the complex behavior of reinforced-earth structures the design is often based on empirical rules or unproven theories and are extremely conservative. The primary obstacle to development of a rational theory of safe and economical designs for the behavior of reinforced earth is the lack of instrumentation data on the performance of full-scale structures tested to destruction. Small scale models tested under normal gravity conditions cannot replicate the in-situ stress conditions which play a prominent role in influencing deformation and failure of reinforced earth works. Thus, if model test are to produce meaningful results, they must be conducted in the increased gravity environment produced by a centrifuge.

Research on geosynthetic reinforced retaining walls, by centrifuge testing, was performed by Deborah J. Goodings at the University of Maryland in 1990. In this research the models were constructed with between 2 and 20 layers of reinforcement, and the lengths or reinforcement varied between 33 and 150 percent of the wall height. On all of the models the G level of the centrifuge was increased until catastrophic failure occurred. The following is a list of significant findings of this research: 1) Use of sand backfill had much superior stability as compared to cohesive backfill. 2) Lightly reinforced walls tended to fail by overturning. 3) The optimum length, beyond which improvement in stability was small, was equal to the wall height.

Prediction of the performance of geosynthetic-reinforced wall by centrifuge experiments was performed by Tohda, et al, at the University of Colorado, Boulder, in 1991. In this perdition a series 1/5th scale models of the prototype wall tested to catastrophic failure at the University of Colorado, Denver, were prepared and tested to failure in the 440 G-Ton centrifuge at CU, Boulder. Since it was impossible to come up with a geosynthetic that was exactly 1/5th the thickness of prototype, test were performed with a single sheet of geosynthetic having 1/9 to 1/10 the thickness of the prototype and a double layer of that geosynthetic having a thickness of 1/4 to 1/5 that of the prototype. The predicted surcharge pressure at failure for the model was between 55 and 59 psi., but the authors gave explanations as to why the model surcharge pressure at failure might be higher than that of the prototype. The actual surcharge at failure of the prototype wall was 29 psi. The conclusion was that if the model wall backfill would have had a relative density of 95% 45%, the model wall would have failed much nearer the 29 psi. The container used for Tohda's experiments was modified slightly to accommodate the 1/11th scale tests in the current study.

Table No. 1 shows the scaling relations of centrifuge modeling. Application of these relations show that a 1/N scale model constructed of the same soil as the prototype, with thickness of the reinforcement and wall facing scaled at 1/N, can be tested to N G's in the centrifuge to produce the same surcharge load-wall deformation characteristics as in the prototype.

Quantity	**Prototype**	**Model**
Length	n	1
Area	n^2	1
Volume	n^3	1
Force	n^2	1
Stress	1	1
Strain	1	1

TABLE No. 1 Scaling relations for centrifuge modeling.

3) Centrifuge Testing

It was decided to run all test at one eleventh scale. This was decided due to the fact that rupture strength of the reinforcement used was one eleventh that of the prototype reinforcement. The scale factor of the initial modules of elasticity of the model geosynthetic versus that of the prototype is one to twelve. Their load-deformation characteristics are shown in figure 2. Increasing the scale factor from one fifth to one eleventh scale also increased the relative maximum prototype displacement from 6.4 inches to 14 inches. It was determined to be impractical to use strain gauges to measure the strain in the reinforcement layers due to the fact that the strain gauges, being stiffer than the reinforcement, would cause stress concentrations in the reinforcement.

The type of reinforcement used is a nonwoven heat-bonded polypropylene geotextile (the prototype geotextile has a unit weight of 3 oz/sy) the model reinforcement has a unit weight of 0.6 oz/sy. Both weights of reinforcements are produced by Reemay Inc..

Figure 1. show the container used in the experiments. Five LVDT's were used in all but tests 10 and 12. The LVDT's were located 3, 5.8, 8, 10.2, & 12 inches from the bottom of the wall. LVDT 5 was placed at the bottom of the wall and LVDT 1 was placed at the top of the wall. The calibration factors for the LVDT's in volts/inch are as follows: LVDT 1 = 7.807, LVDT 2 = 8.053, LVDT 3 = 8.462, LVDT 4 = 7.231, and LVDT 5 = 8.133.

Test 10 and test 12 were performed with a foundation of soft clay. The top of the one-eleventh scale model was raised to the level of the one-fifth scale model. Only three LVDT's were used due to the time constraints required to modify the container. They were placed 2.25, 4, & 8 inches from the bottom of the wall.

4) Model Preparation

The model was prepared in the container shown in figure 1. Silicone grease was applied to all interior surfaces of the container to reduce the edge effects of the container. A 0.2 mm latex membrane was attached to the plexiglass panel with a one inch square grid pre-drawn on the latex for visual enhancement of the displacement. A sheet of sand paper was glued to the

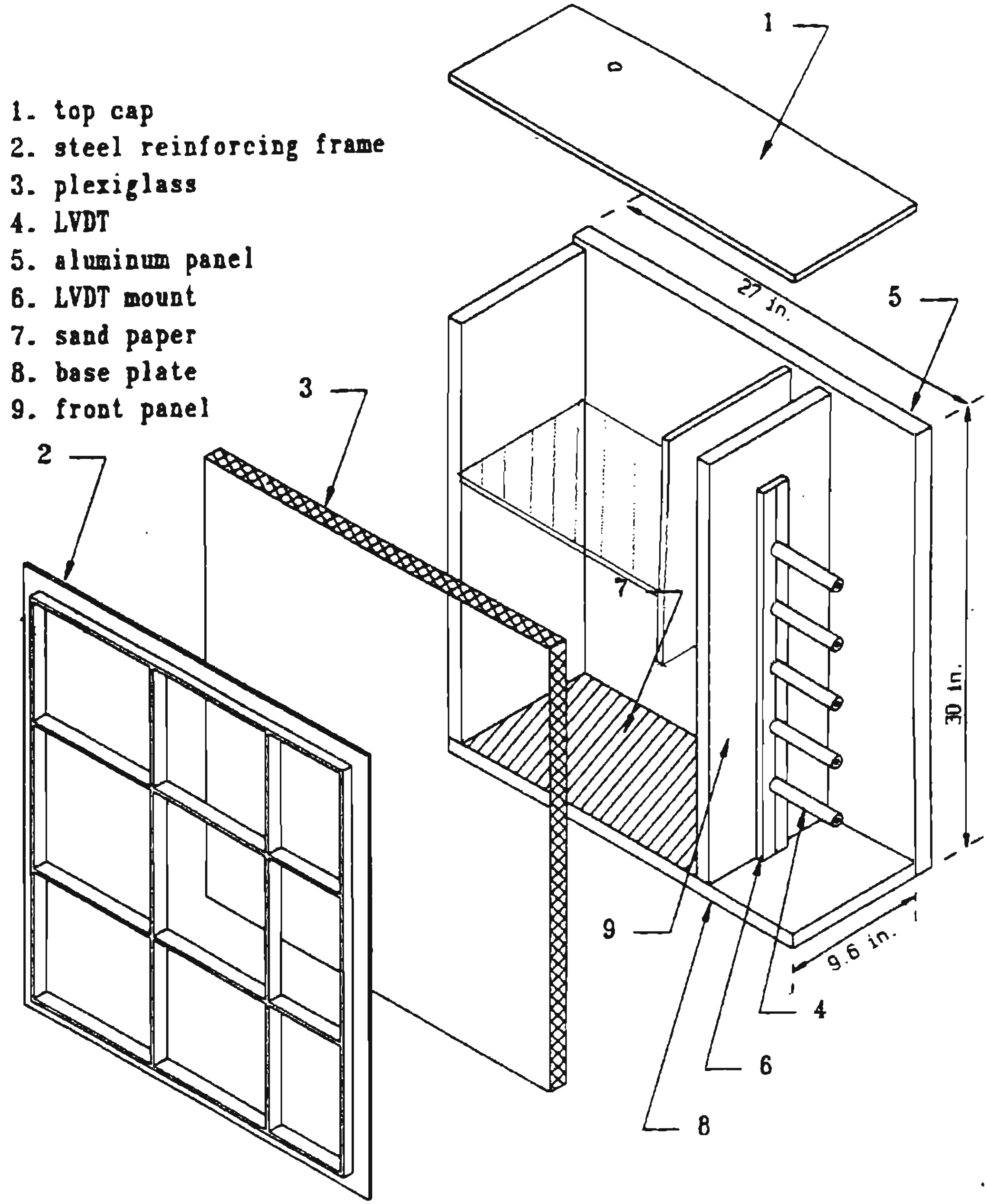


Figure 1. The schematic view of the container

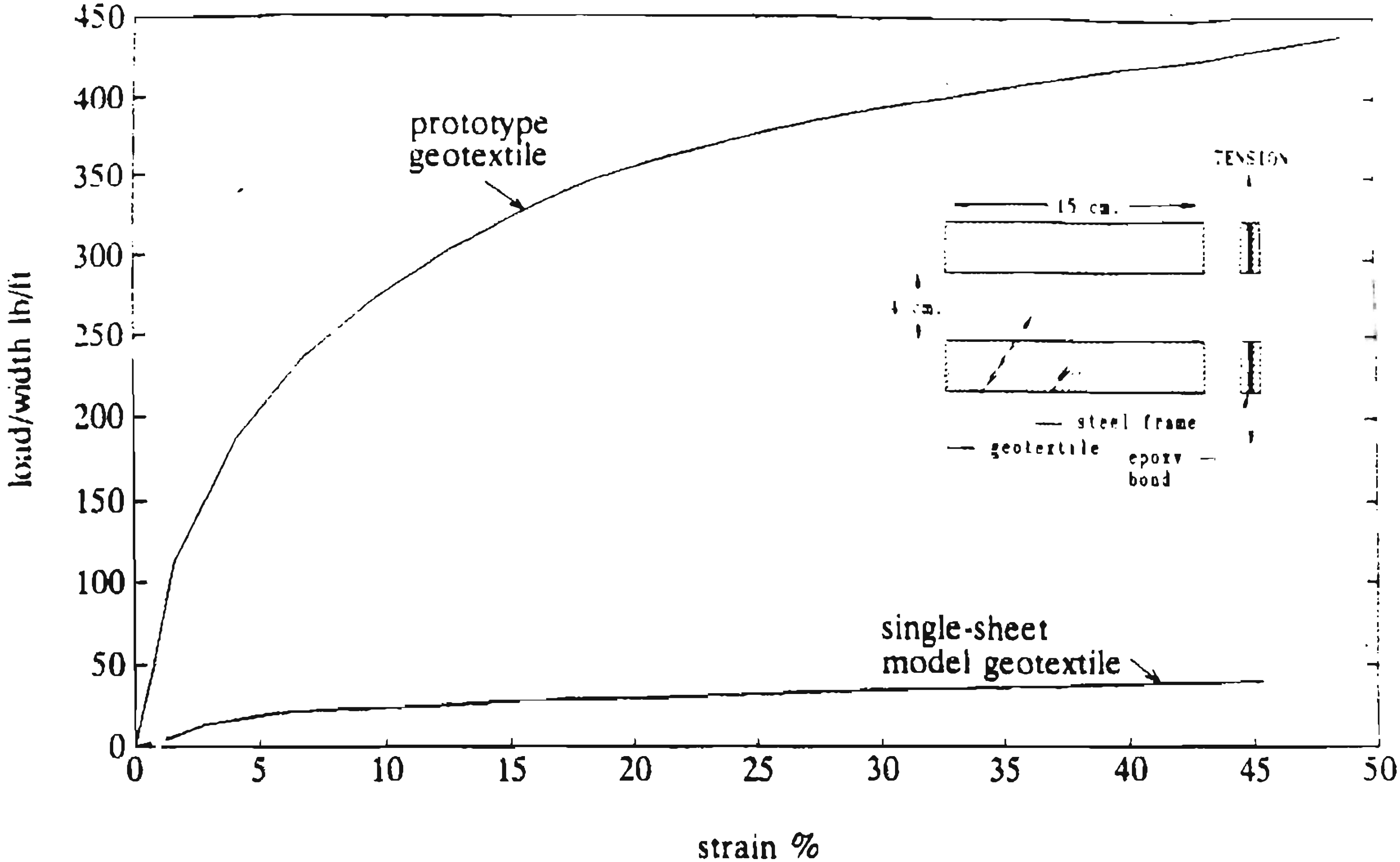


Figure 2. Load-deformation behavior of the geotextile and the configuration of the test setup

bottom of the box in order to limit movement of the bottom of the model. The wall consisting of wooden blocks , hard boards, and geosynthetic layers was assembled beforehand. The bonding of the different materials was obtained with five minute epoxy.

Control of the density of the backfill for clay and sand was obtained by weighing out the proper amount of material to obtain the required compaction for a given layer then placing the material in the container and compacting it with a 4*4 block to the desired height. Since there was no proctor compaction test run on the recycled asphalt this material was placed in the container with no moisture and compacted to the proper height. By knowing the total volume of material in the container and keeping track of the total weight of material placed in the container the density of the recycled asphalt was calculated.

After the wall was erected and backfilled, 3 inches of sand was placed on top of the backfill to serve as a cushion for the surcharge tube. Due to having many tubes blown during testing a heavy duty tube designed for a skid-steer tire was obtained and an inch of clay was place against the front face of the tube restraint. After these modifications were enacted there was no more blown tubes. The tube was placed on top of the cushion and the top cap secured. After running two tests on the clay it was observed that compacting the clay with the latex membrane in place caused the latex membrane to deform during compaction and therefore the grid was no longer square. It was then determined that in order to have the grid square, after the clay was compacted the plexiglass face should be removed and the latex membrane would then be attached to the plexiglass and the container resecured. The LVDT's were then adjusted against the front face of the container to maximize their range of motion.

There were three types of material used for the back fill of the walls sand, clay, and recycled asphalt. The sand was a washed, fine graded, concrete sand obtained from the bins in the south basement of the civil engineering lab. See Appendix No. I for the analysis of the sand's material properties. The clay material was obtained from a conglomeration of samples of minus number 40 material supplied by the Colorado Department of Transportation Denver Materials Laboratory. The conglomeration of samples were homogenized prior to testing. See Appendix No. II for the analysis of the clay's material properties. Appendix No. III contains the results of an undrained triaxial test performed on the clay material. The recycled asphalt was obtained from wall backfill on a Colorado Department of Transportation highway project on I-25 near 58th Avenue in Denver. There was no analysis of material properties performed on the recycled asphalt. It is recommended that percent asphalt, gradation and proctor be performed on this material.

Starting with Test No. 8 moisture samples were taken from the middle of the model at the end of the test to verify the actual percent moisture. For the rectangular shaped reinforcement all of the layers of the reinforcement extended 0.75 times the height of the wall horizontally into the backfill. The prototype dimensions for the trapezoidal shaped reinforcement has the bottom reinforcement as 4 foot long and the top reinforcement equal to the height of the wall. The lengths of intermediate layers are such that they intersect the line between the end of the top and bottom reinforcements. The vertical distance between reinforcement layers is one foot.

After the model was secured in the centrifuge it was spun up to 11 G's and the displacement was measured by the LVDT's. When the displacement stabilized the surcharge pressure was applied in increments of 5 psi. and the displacement was allowed to stabilize prior to application of more surcharge pressure. The accuracy of the pressure gauge was plus or minus 2 psi. up to 20 psi. and then plus or minus 1 psi. from 20 psi. to 100 psi.. The maximum in house air pressure is 100 psi.

For each test performed there is a set of figures produced showing the displacement of the wall at each LVDT versus surcharge pressure. There is another figure showing the shape of the wall at different surcharge pressures for each test. The photographs included show the final shape of the wall and where the photograph is clear enough to see, the original grid, show the relative displacement of the soil behind the wall face. (If greater clarification is needed there is a set of slides in which the original alignment of the grid is shown more clearly.)

5) Description of visual aids and computer files attached

Video Tape No. 1 contains pictures of tests 3, 4, 5, & 7. Video tape No. 2 contains pictures of tests 8, 9, 10, & 12. Video tape No. 3 contains pictures of test 13. There is no video tapes of tests 1, 2, 6, & 11. Copies of relevant slides of test are included. The number on the slide represents the test number the slide was taken of. There is no photographs of test No. 4. Nelson Chow should have the only photographs of test No. 5. On computer disk No. 1 is the copies of the raw data from the LVDT's, stored under file names TEST(No.x).PRN. On computer disk No. 2 are copies of the work sheets in Quattro stored under file names TEST(No.x).WQ1 and a copy of the text in Word Perfect stored under file name TEXT.1

Test No. 1

Backfill type: Sand
Density: 95% standard proctor = 101.2 Lbs./cubic foot
Reinforcement shape: Rectangular
Target moisture content: 1% dry of optimum = 15.2%
Moisture content at end of test: Unknown
Date: March 16, 1992

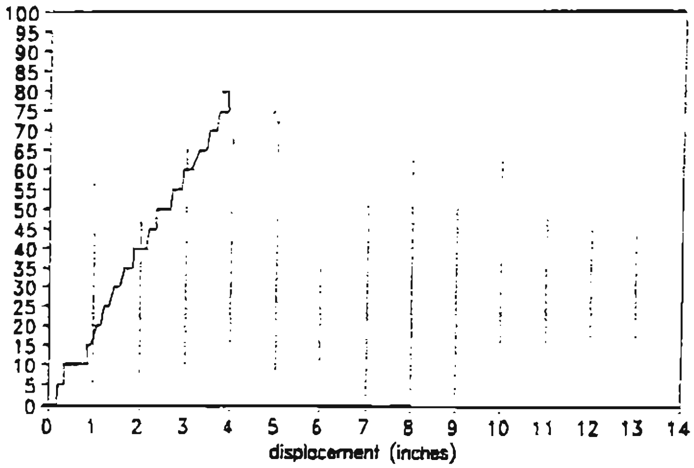
The data from test one was determined to be of no value, so the model was tested to failure under one G. The model failed at 60 psi of surcharge pressure. The failure plane was the standard semi circular failure plane observed in previous testing. All of the reinforcement strips except the lower two ruptured. The failure plane intersected 6 inches back from the top of the wall face and three inches from the bottom of the wall face.

Test No. 2

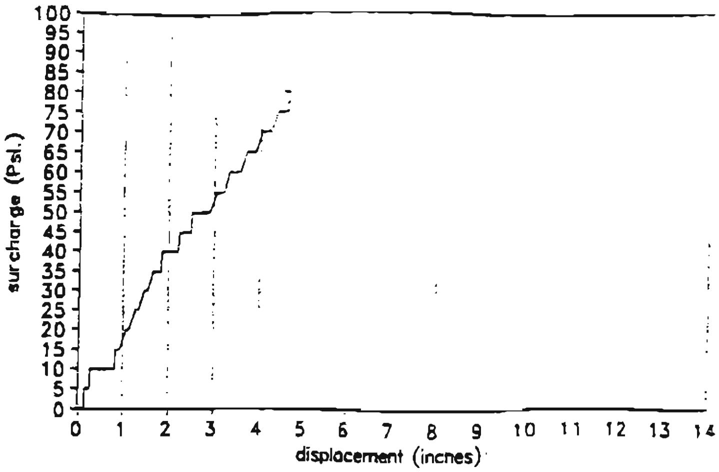
Backfill type: Sand
Density: 95% standard proctor = 101.2 Lbs./cubic foot
Reinforcement shape: Rectangular
Target moisture content: 1% dry of optimum = 15.2%
Moisture content at end of test: Unknown
Date: March 23, 1992

The surcharge tire blew at 80 psi. and the test was discontinued.

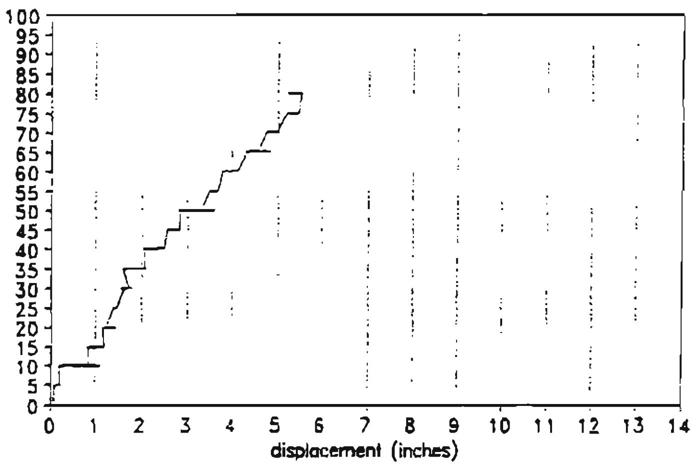
TEST 2
LVDT 1



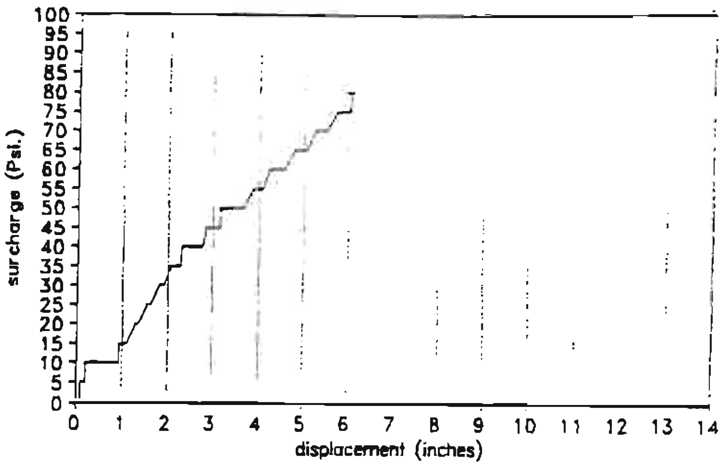
TEST 2
LVDT 2



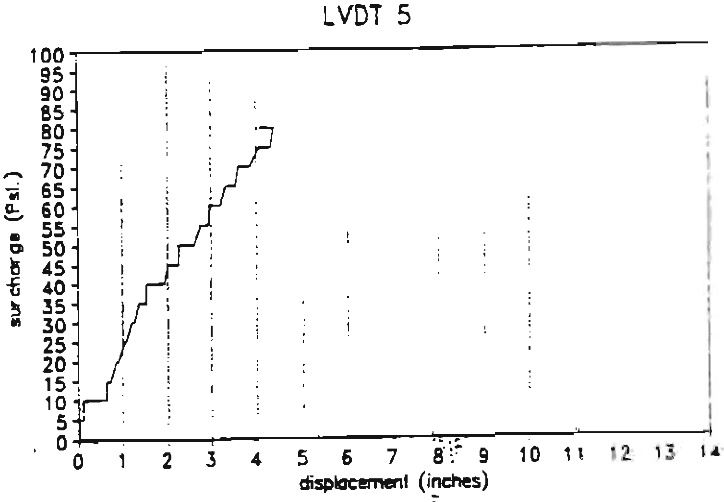
TEST 2
LVDT 3



TEST 2
LVDT 4

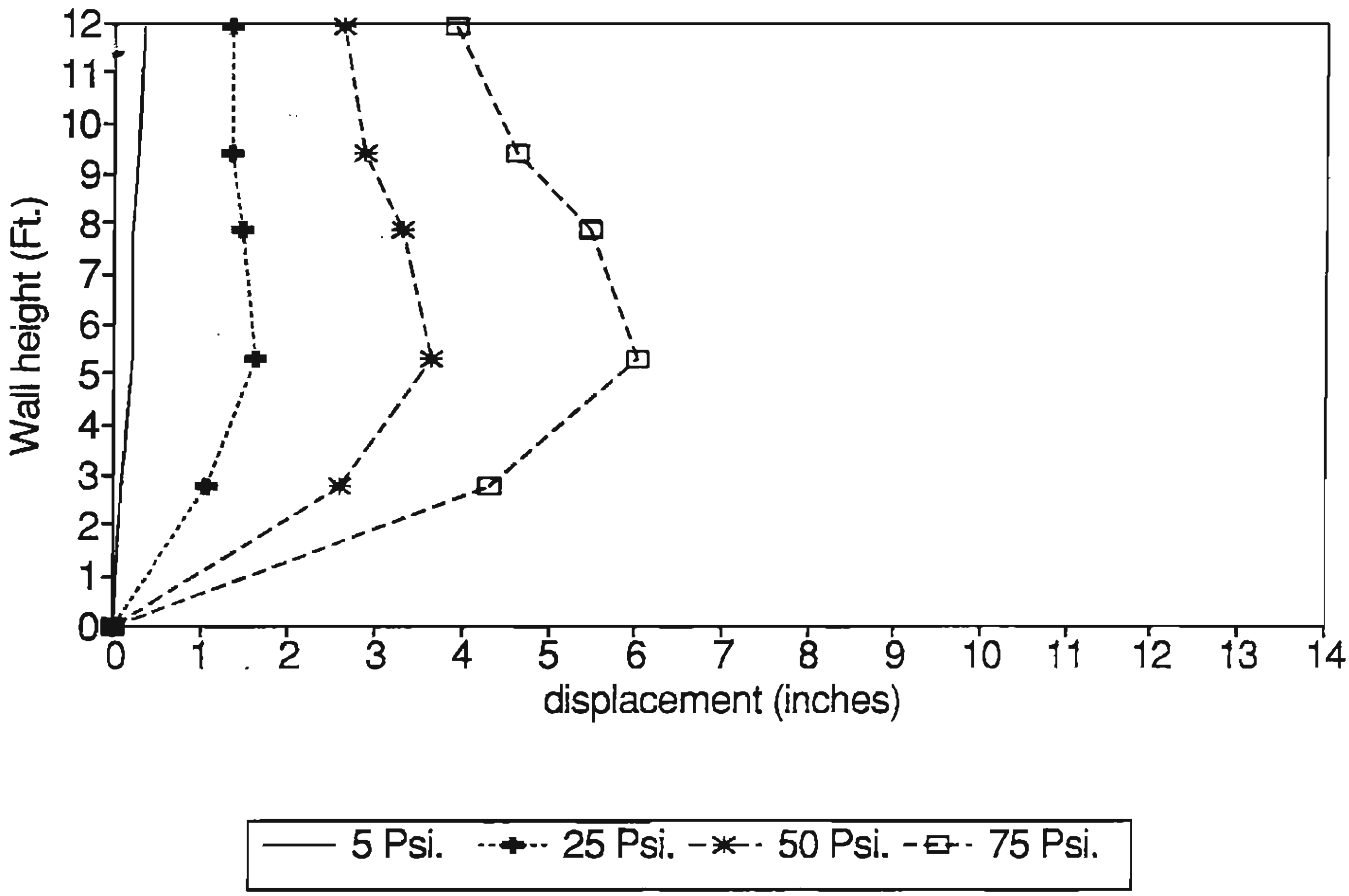


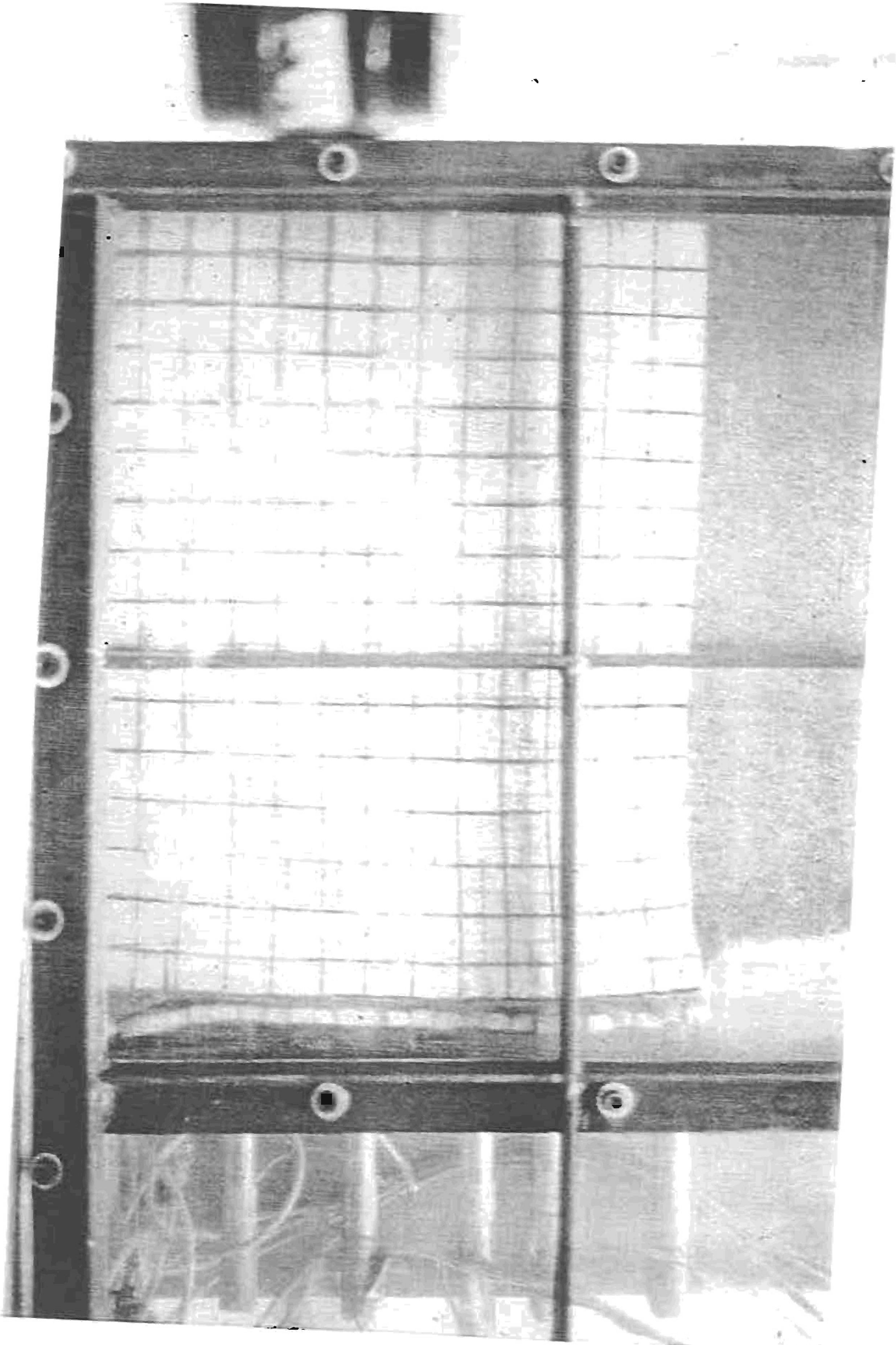
TEST 2
LVDT 5



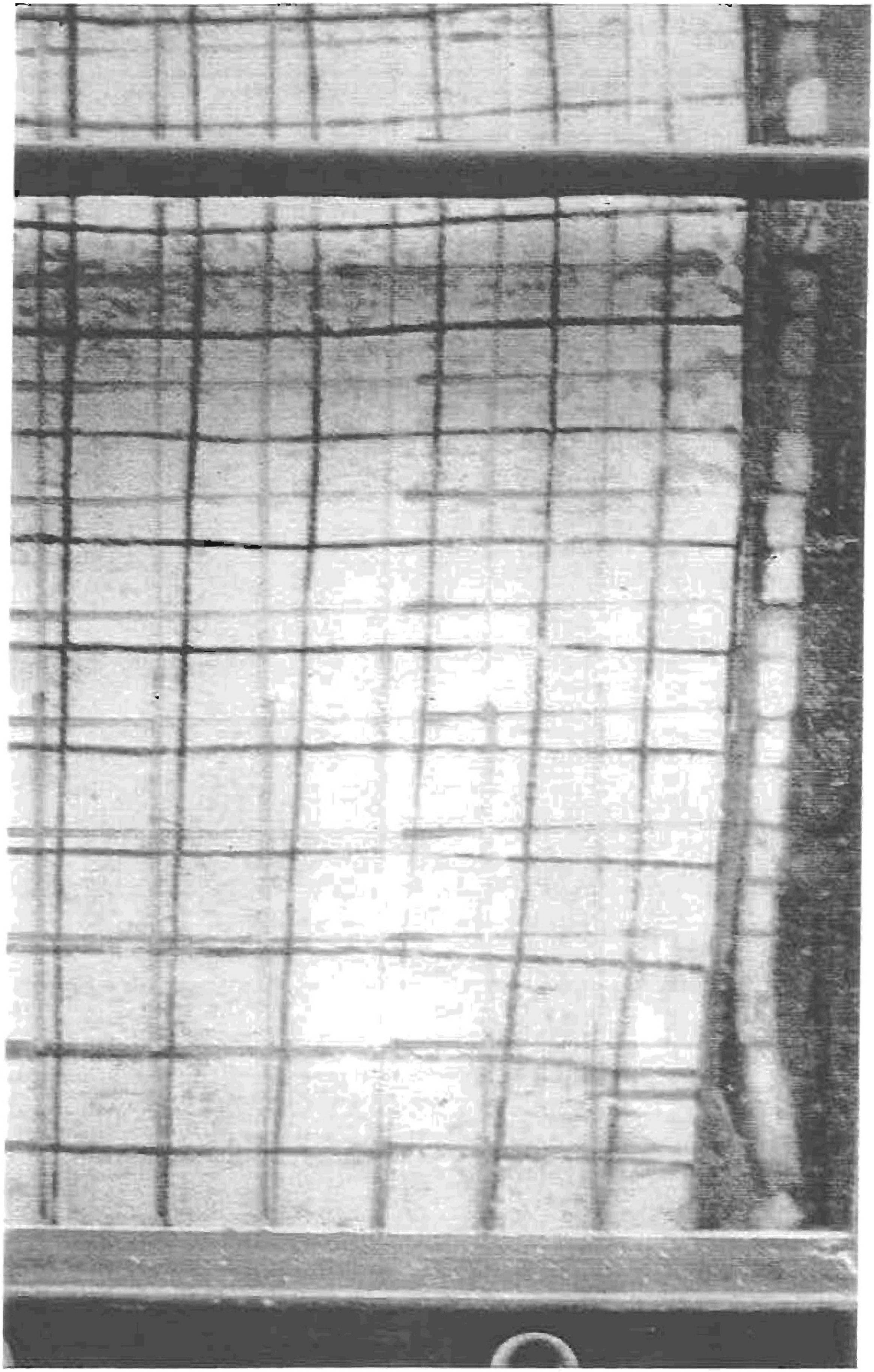
TEST 2

Wall face





Photograph No.2-1



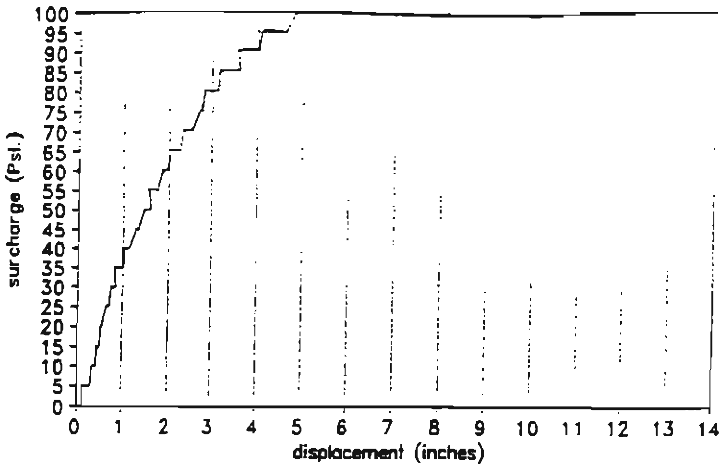
Photograph No. 2-2

Test No. 3

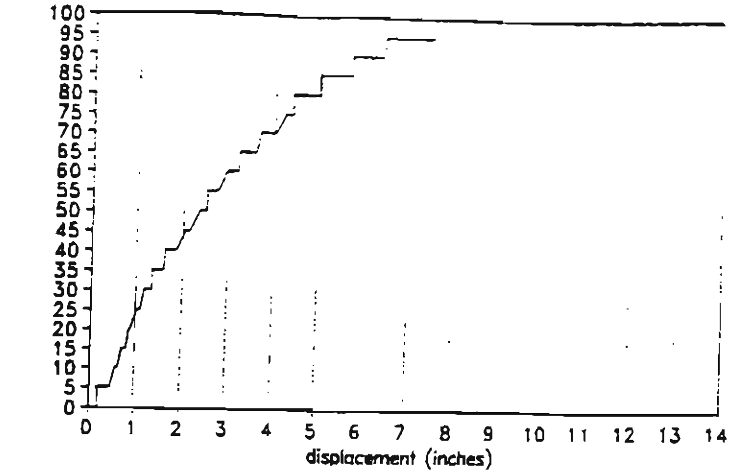
Backfill type: Sand
Density: 95% standard proctor = 101.2 Lbs./cubic foot
Reinforcement shape: Trapezoidal
Target moisture content: 1% dry of optimum = 15.2%
Moisture content at end of test: Unknown
Date: March 24, 1992

This is the first test that was video taped. The in house air pressure of 100 psi. was reached so the test was discontinued. Layer's 5, 6, 7 & 8 showed sign's of significant strain, but none of the reinforcements ruptured.

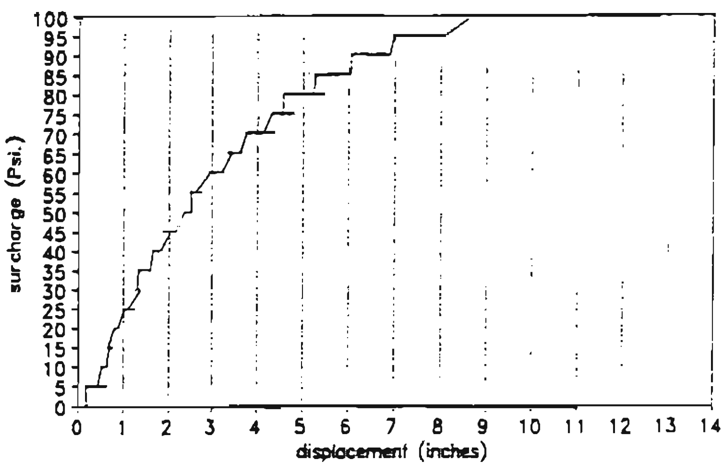
TEST 3
LVDT 1



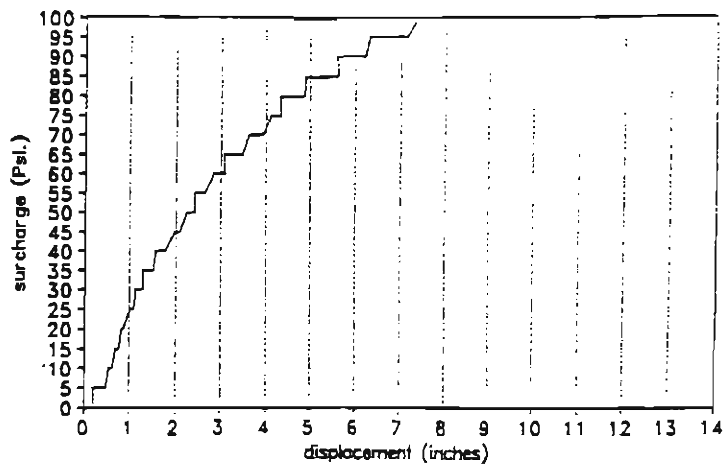
TEST 3
LVDT 2



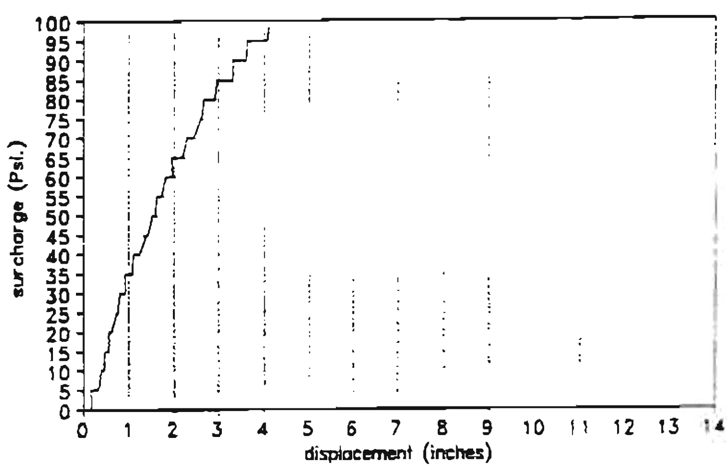
TEST 3
LVDT 3

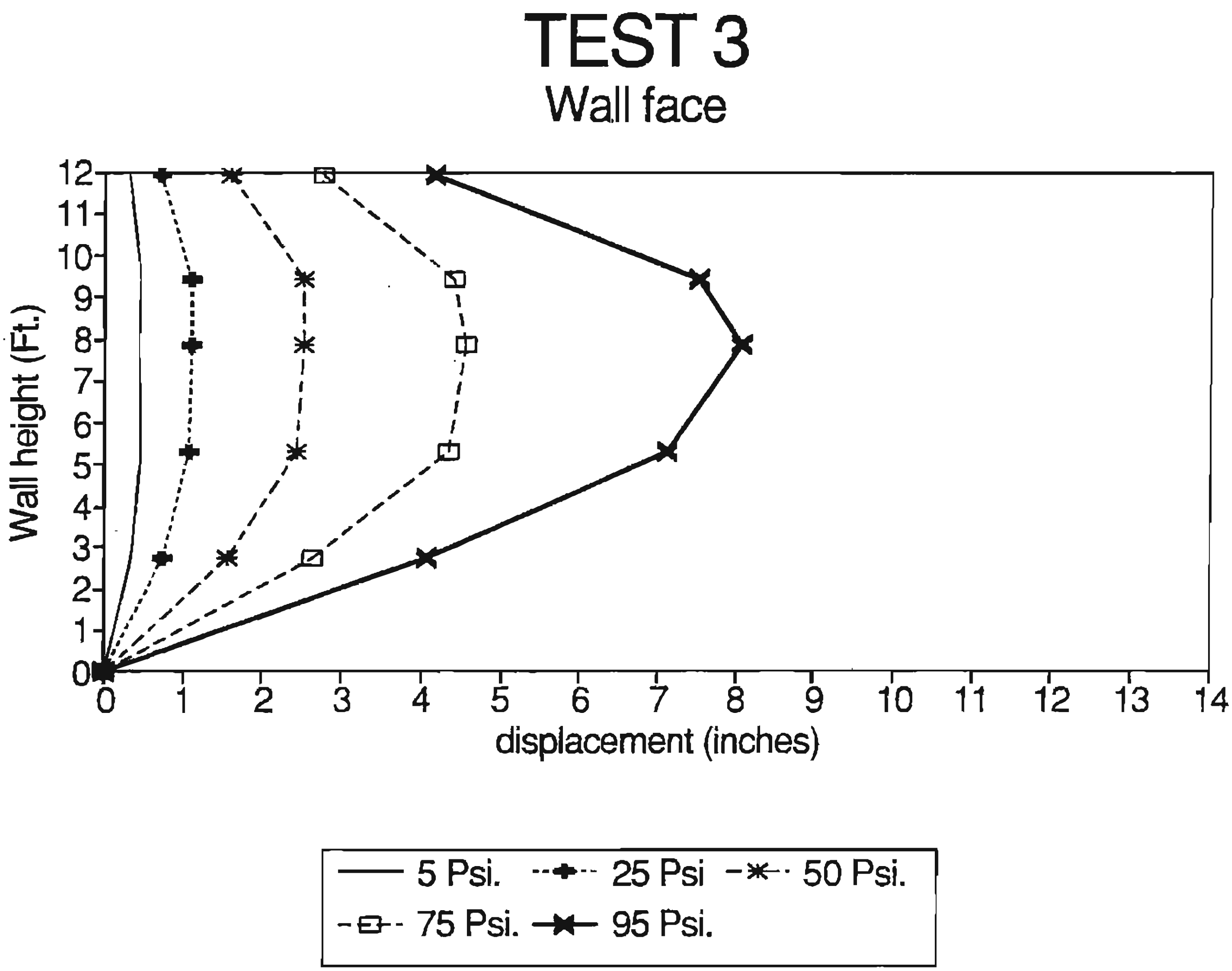


TEST 3
LVDT 4

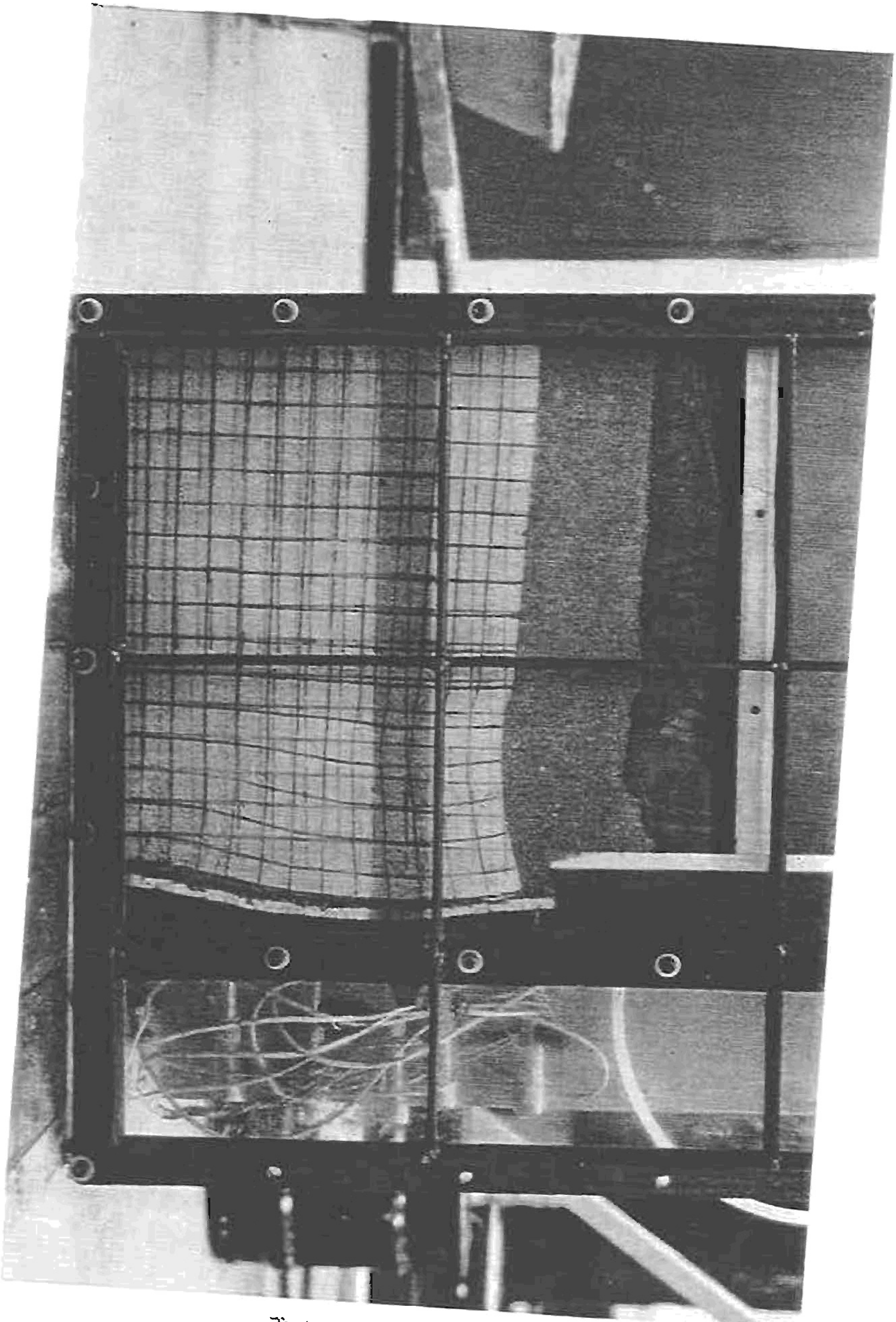


TEST 3
LVDT 5





TEST 3
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
displacement (inches)
5 Psi.
25 Psi
50 Psi.
75 Psi.
95 Psi.



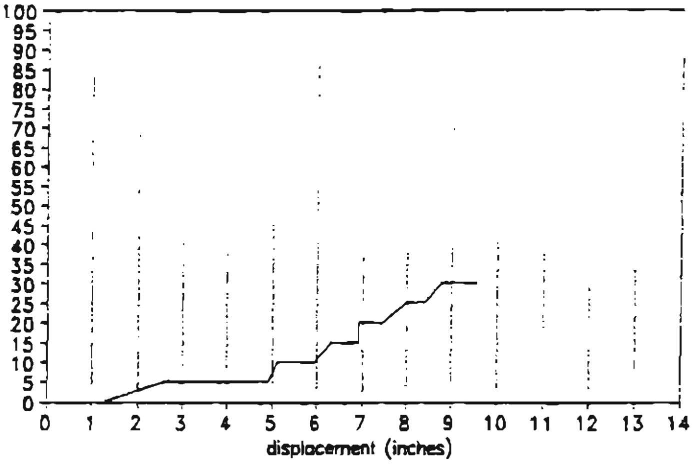
Photograph No. 3-1

Test No. 4

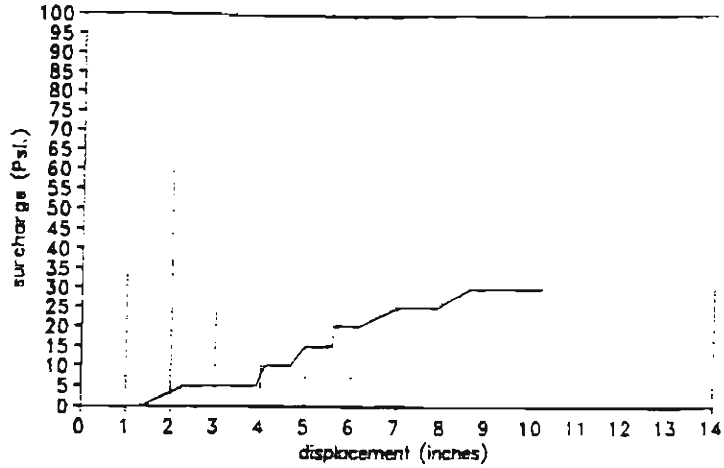
Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: rectangular
Target moisture content: 1% dry of optimum = 14.2%
Moisture content at end of test: 18.8%
Date: April 27, 1992

The model was compacted at one percent dry of optimum moisture content. One inch of sand and weep holes were placed at the back of the container in order to increase the rate of saturation. The container was sealed and filled with water and allowed to stand for ten days. The water was drained from the container immediately prior to placement in the centrifuge. The 18.8% moisture content is equivalent to 95% saturation. The test was discontinued due to the wall deformation being constrained by the silicone sealant used on the front face of the container. After this test the front face was sealed with rubber stoppers through the LVDT holes. There were no pictures taken of test 4, since the camera broke.

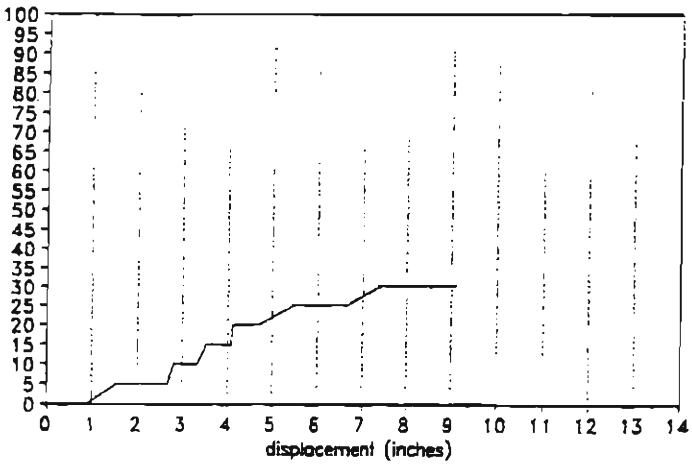
TEST 4
LVDT 1



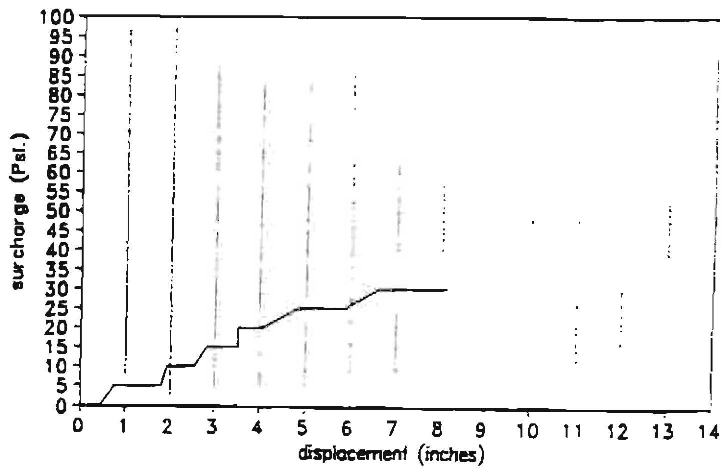
TEST 4
LVDT 2



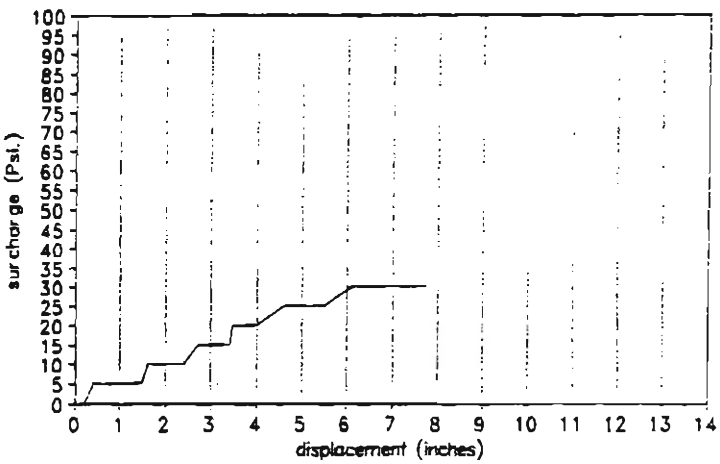
TEST 4
LVDT 3

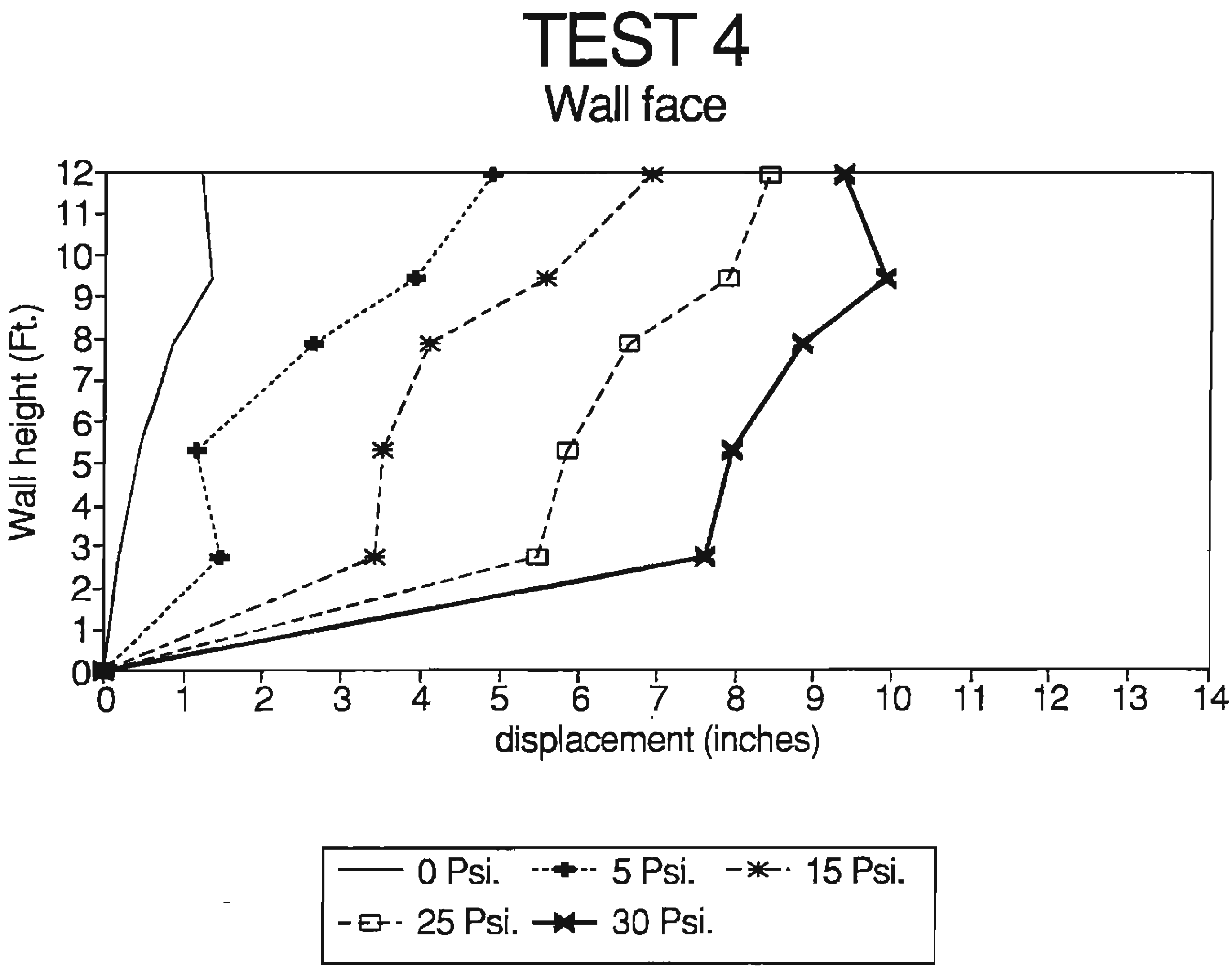


TEST 4
LVDT 4



TEST 4
LVDT 5



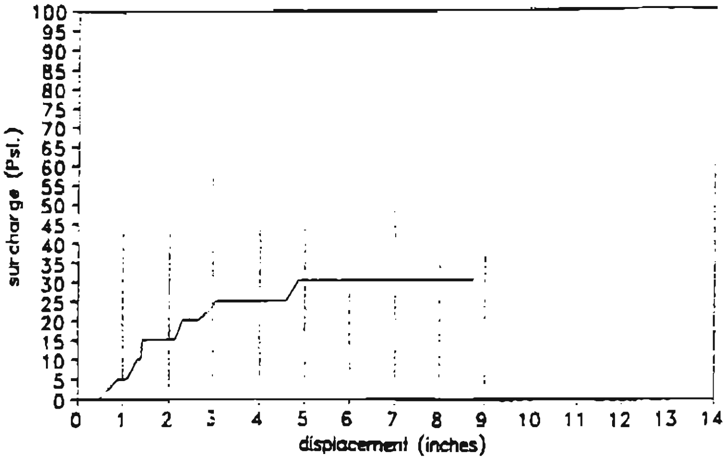

TEST 4
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
displacement (inches)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0 Psi.
5 Psi.
15 Psi.
25 Psi.
30 Psi.

Test No. 5

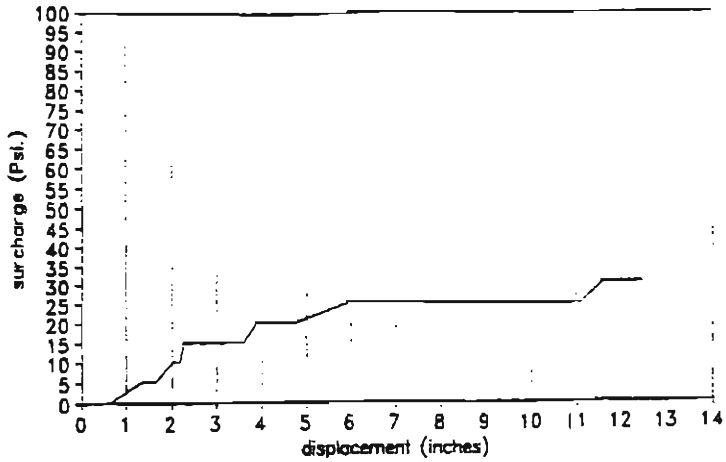
Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: rectangular
Target moisture content: 1% dry of optimum = 14.2%
Moisture content at end of test: Unknown
Date: April 28, 1992

Nelson Chow, Trever Wayne, and Jeff Smith were present for this test. Nelson Chow took a series of photographs of this test, since the CU camera was still broken. The tube blew at 30 psi., so the test was discontinued.

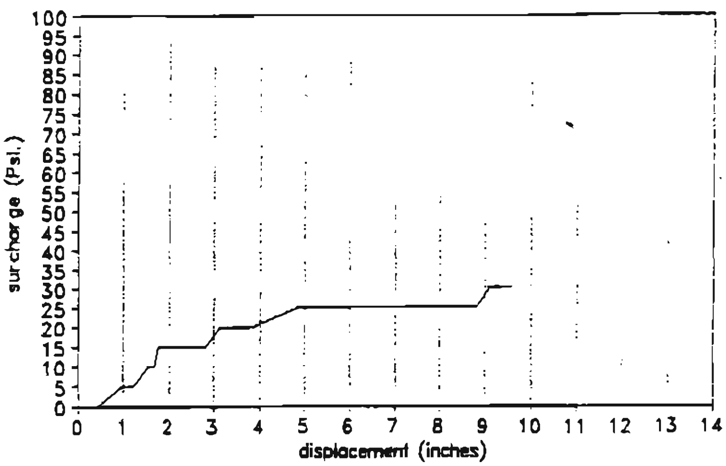
TEST 5
LVDT 1



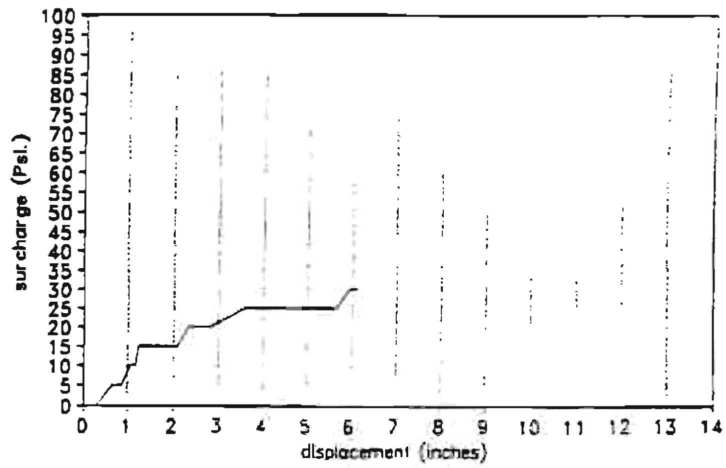
TEST 5
LVDT 2



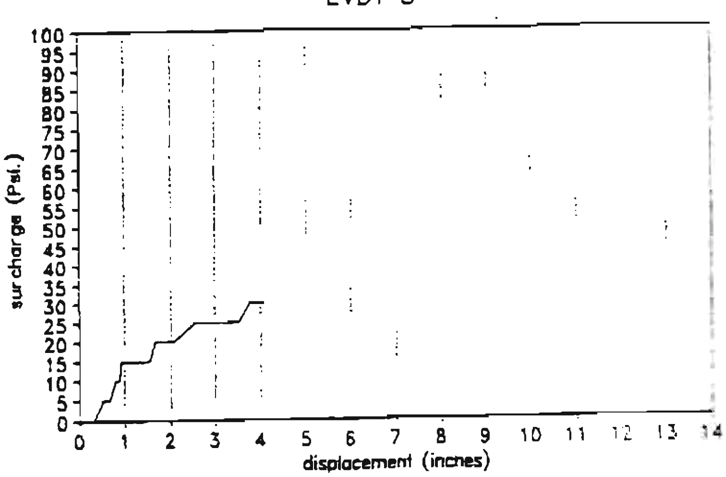
TEST 5
LVDT 3

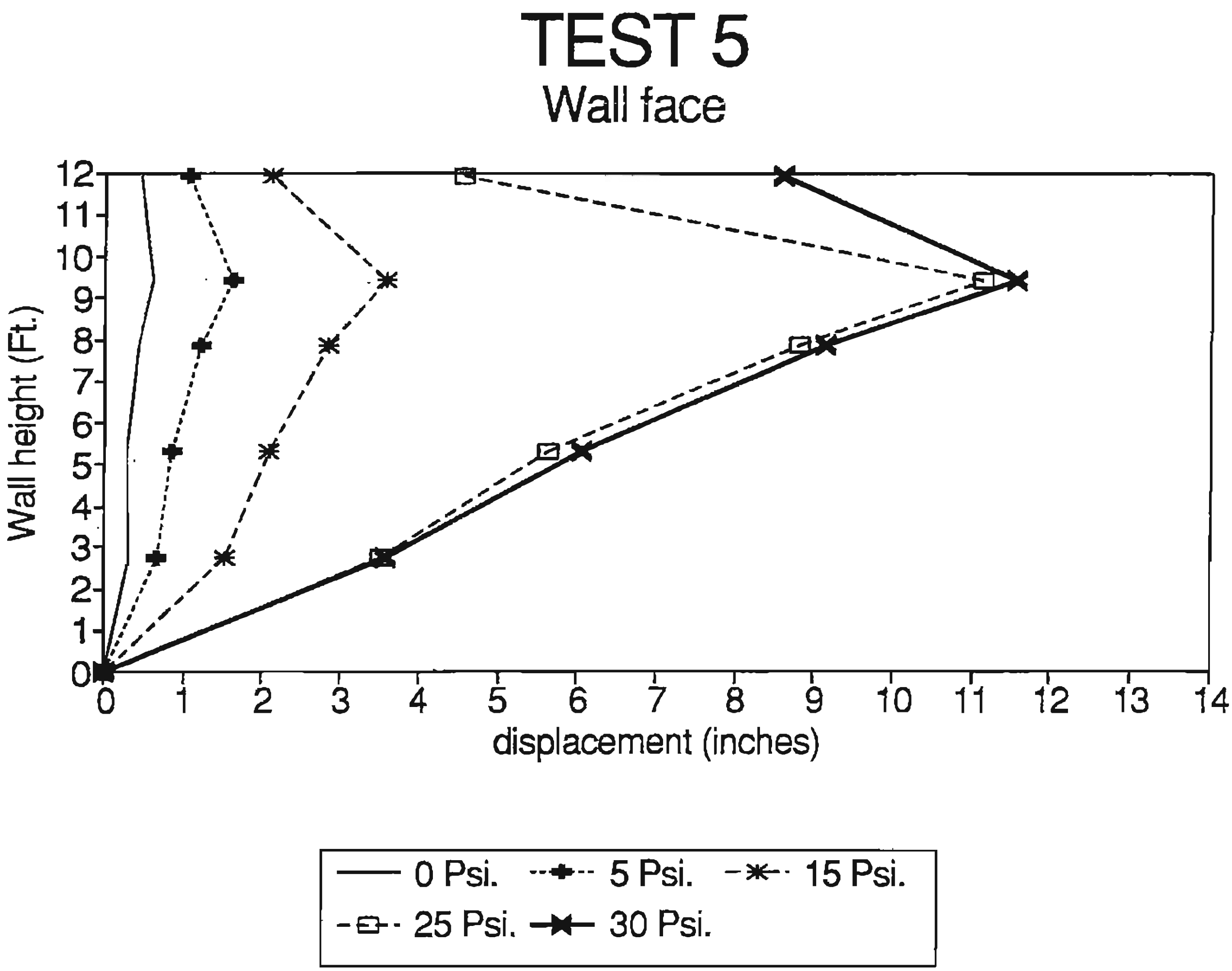


TEST 5
LVDT 4



TEST 5
LVDT 5

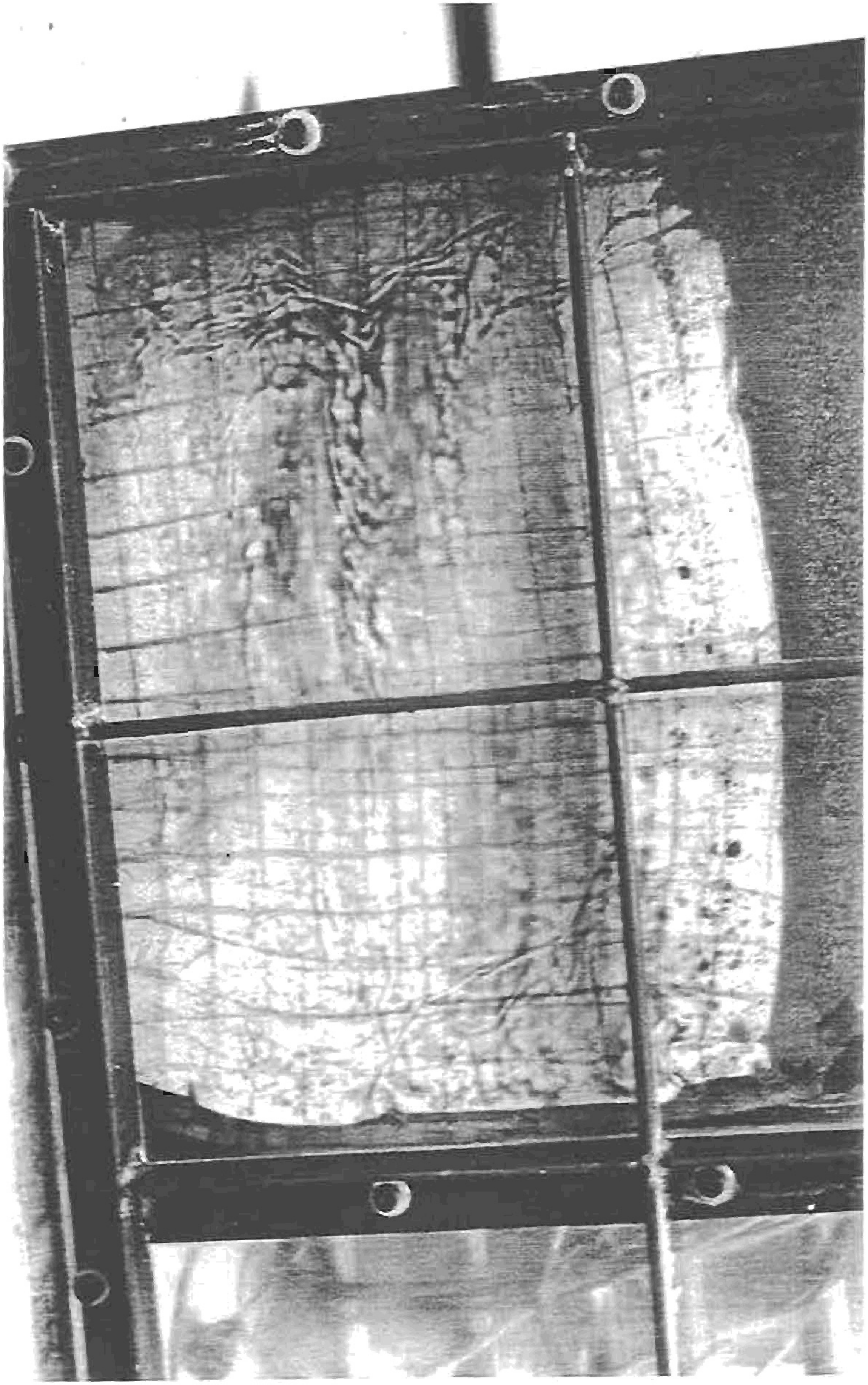



TEST 5
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
displacement (inches)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0 Psi.
5 Psi.
15 Psi.
25 Psi.
30 Psi.

Test No. 6

Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: Trapezoidal
Target moisture content: 2% wet of optimum = 17.2%
Moisture content at end of test: 22.1%
Date: May 22, 1992

The model was compacted at two percent over optimum moisture content. One inch of sand and weep holes were placed at the back of the container in order to increase the rate of saturation. The container was then sealed and filled with water and allowed to stand for 14 days. During the compaction there were large amounts of water pumping observed. The data acquisition system of the centrifuge went bad just as the centrifuge reached 11 G's, so no LVDT data was acquired. On the video tape one will see a plexiglass container being spun for consolidation in this test. When the model was examined after the test the wall was observed to have displaced to the end of the LVDT's, so the wall failed with no surcharge pressure. The 22.1% moisture at the end of the test is comparable to 111% saturation, or 100% saturation at 90% compaction. Due to the large amount of pumping observed during compaction it is possible that a compaction of only 90% was obtained.



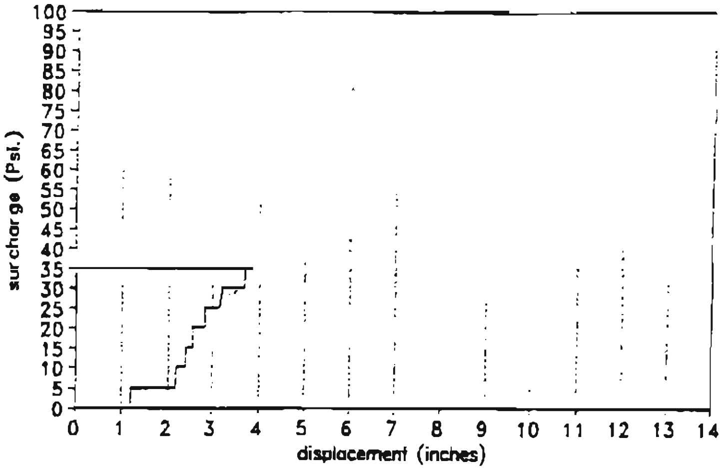
Photograph No. 6-1

Test No. 7

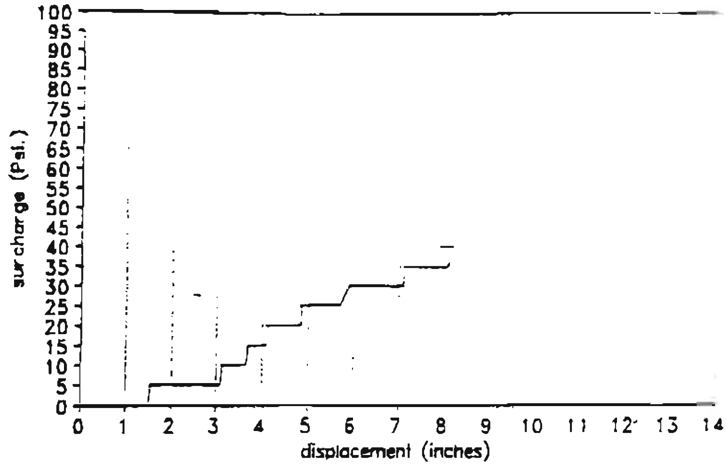
Backfill type: Recycled Asphalt
Density: 96.2 Lbs./cubic foot
Reinforcement shape: rectangular
Target moisture content: dry = 0.0%
Moisture content at end of test: 0.0%
Date: June 5, 1992

The material was a fine graded material with a few large chunks of asphalt. All material larger than 3/8th of an inch was discarded prior to compaction. Test 7 is the last test on video tape No. 1. Since the material had no moisture content and no cohesion it compacted to the density that was achieved relativity easily. The tube blew at 40 psi..

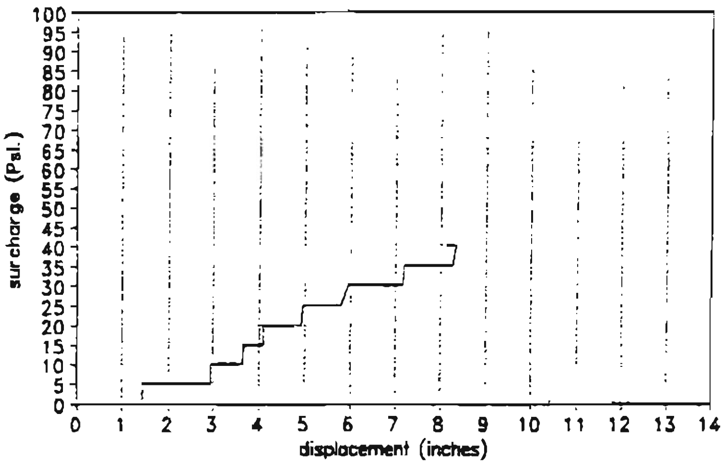
TEST 7
LVDT 1



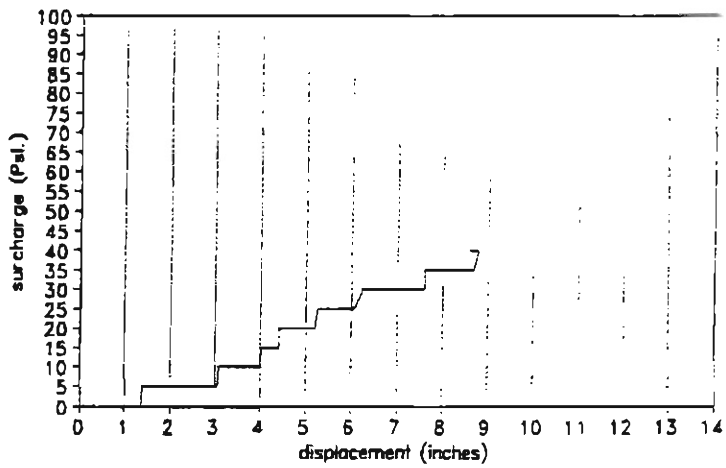
TEST 7
LVDT 2



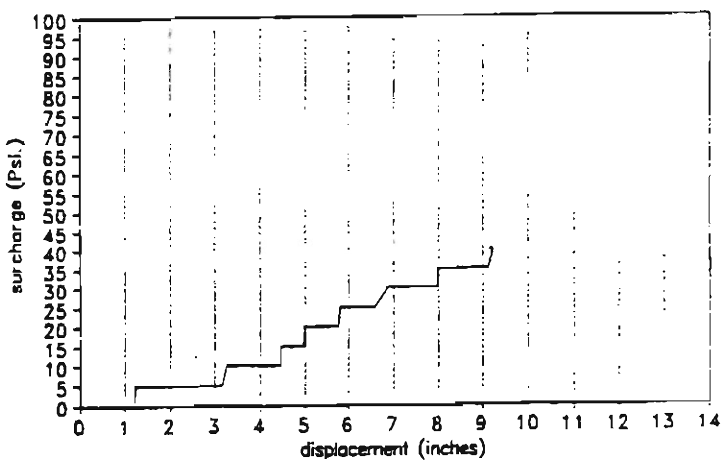
TEST 7
LVDT 3

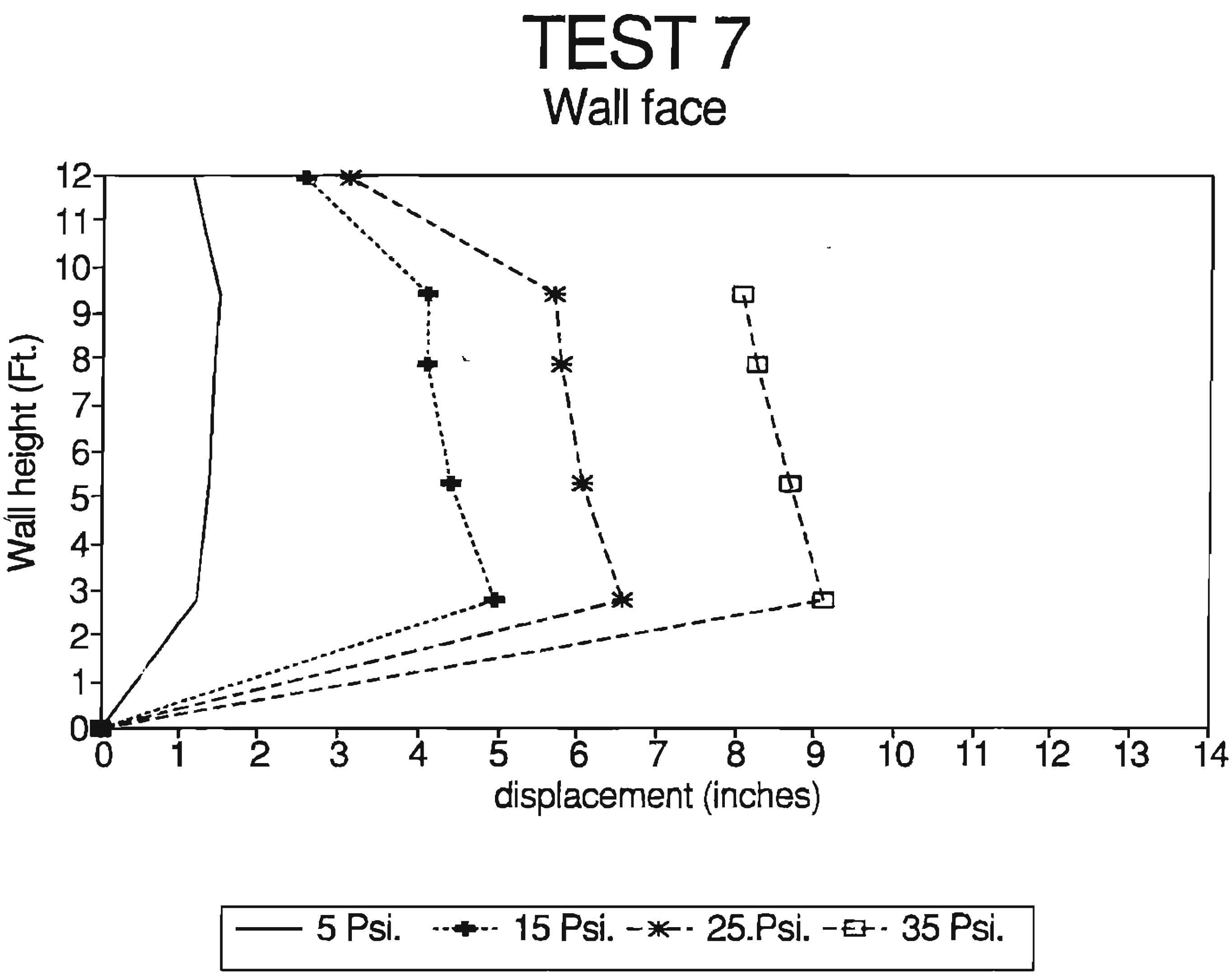


TEST 7
LVDT 4

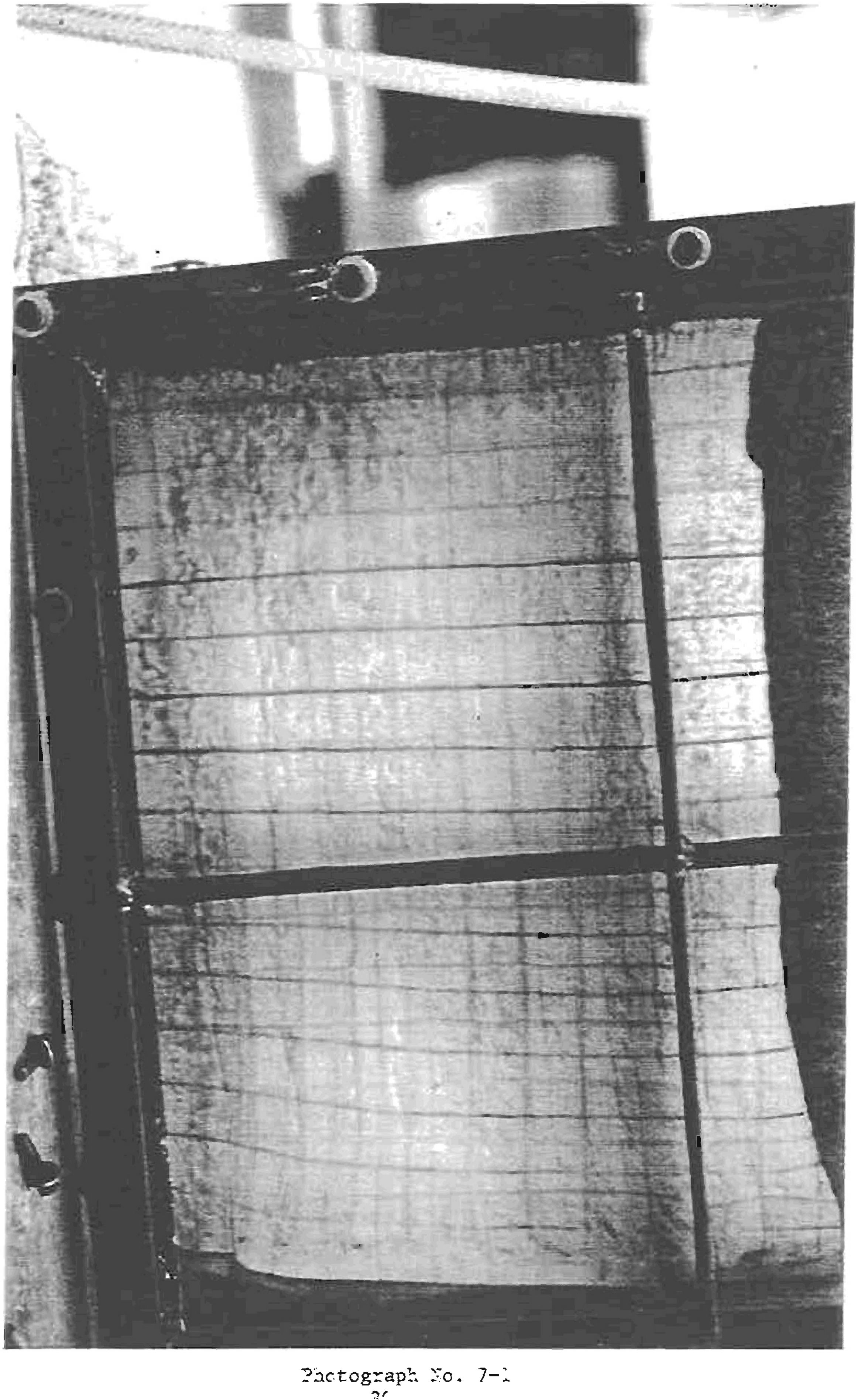


TEST 7
LVDT 5





TEST 7
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
displacement (inches)
5 Psi.
15 Psi.
25.Psi.
35 Psi.

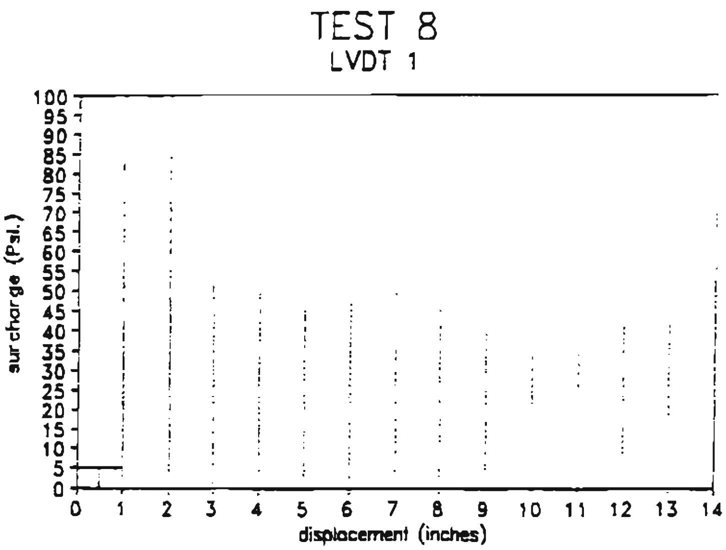


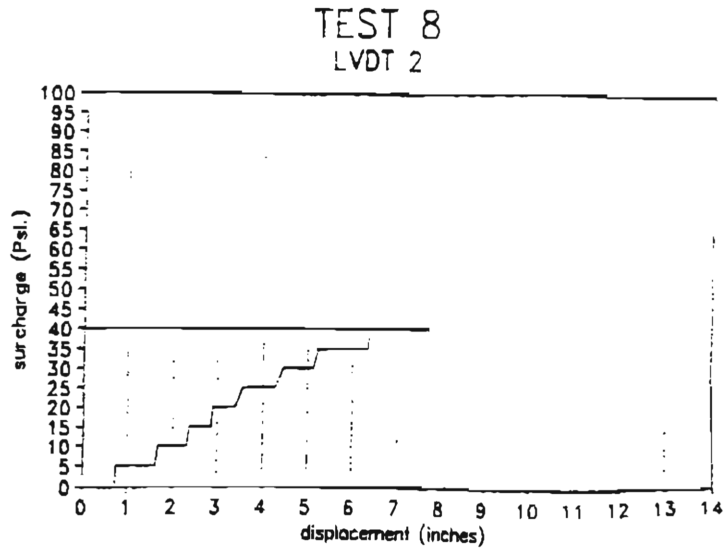
Photograph No. 7-1

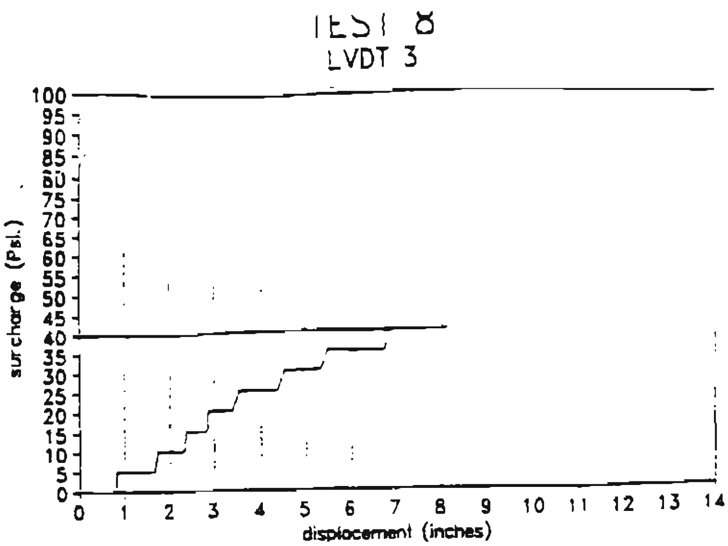
Test No. 8

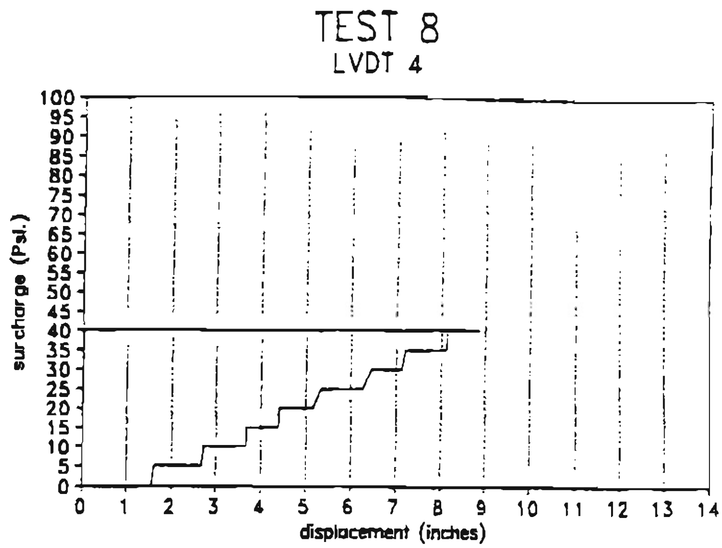
Backfill type: Recycled Asphalt
Density: 98.8 Lbs./cubic foot
Reinforcement shape: Trapezoidal
Target moisture content: dry
Moisture content at end of test: 0.0%
Date: June 8, 1992

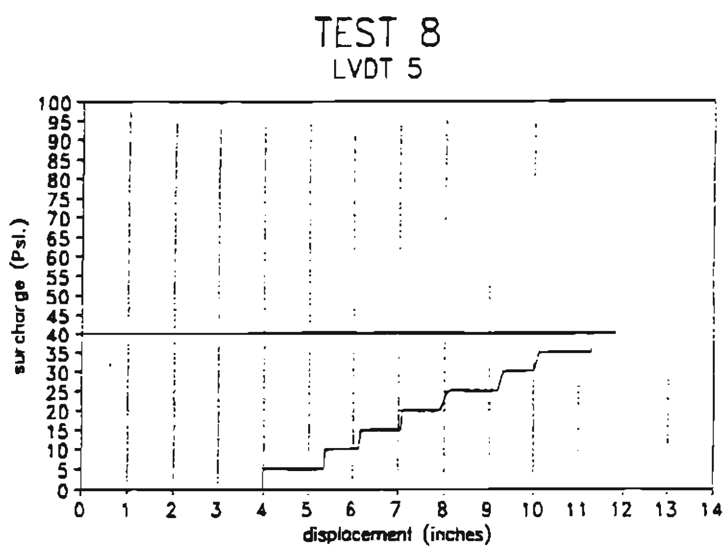
This is the first test in which a one inch thick layer of clay was placed next to the front constraint for the sand cushion, so the sand would not slide down under the restraint allowing the tube to contact the front edge of the restraint and blow. LVDT No. 1 went over the top of the wall at 5 psi., so the data from LVDT No. 1 was discarded. This is the first test shown on video tape No. 2. The data acquisition system on the centrifuge went down at 40 psi. so the test was discontinued.

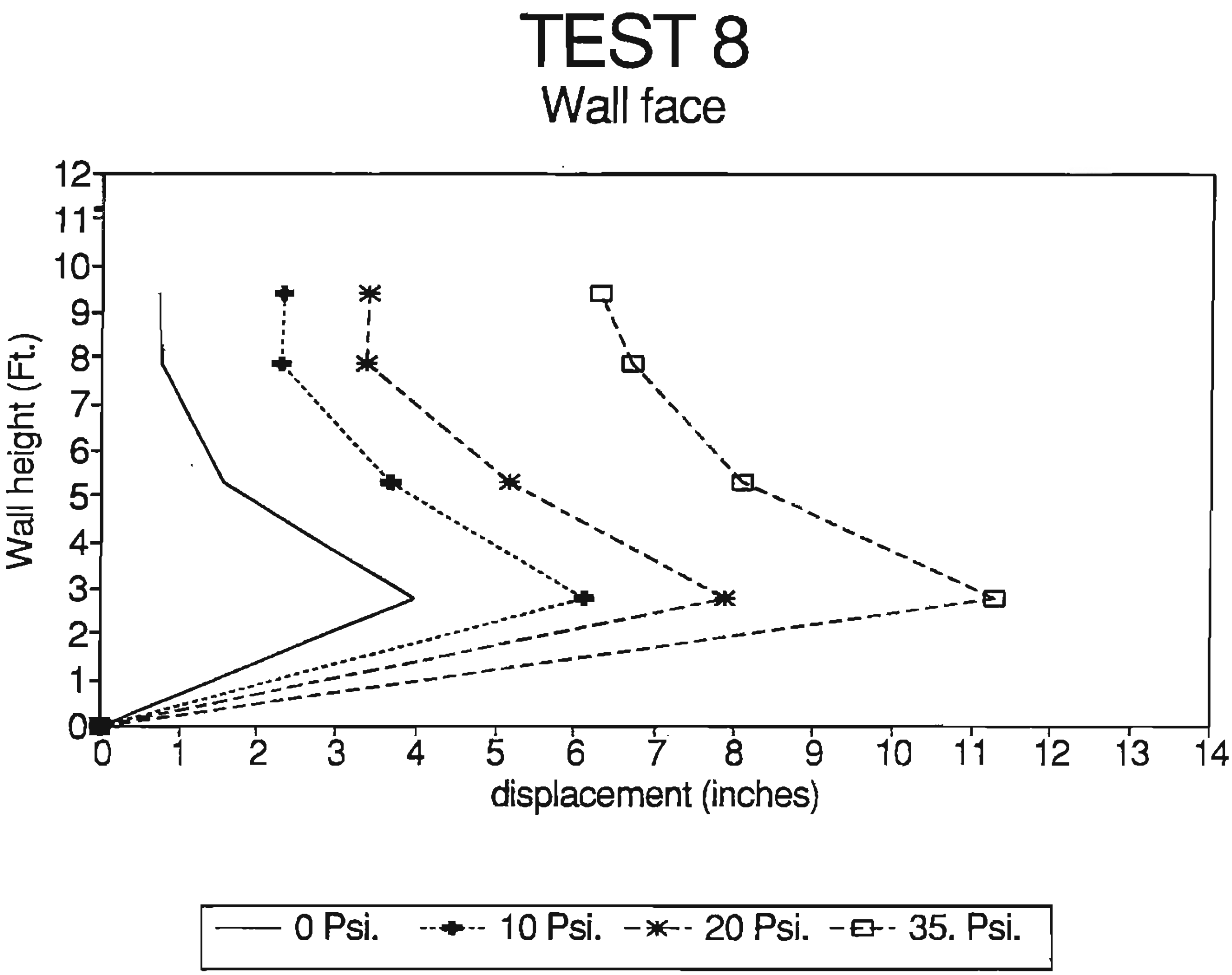

TEST 8
LVDT 1
surcharge (Psi.)
displacement (inches)

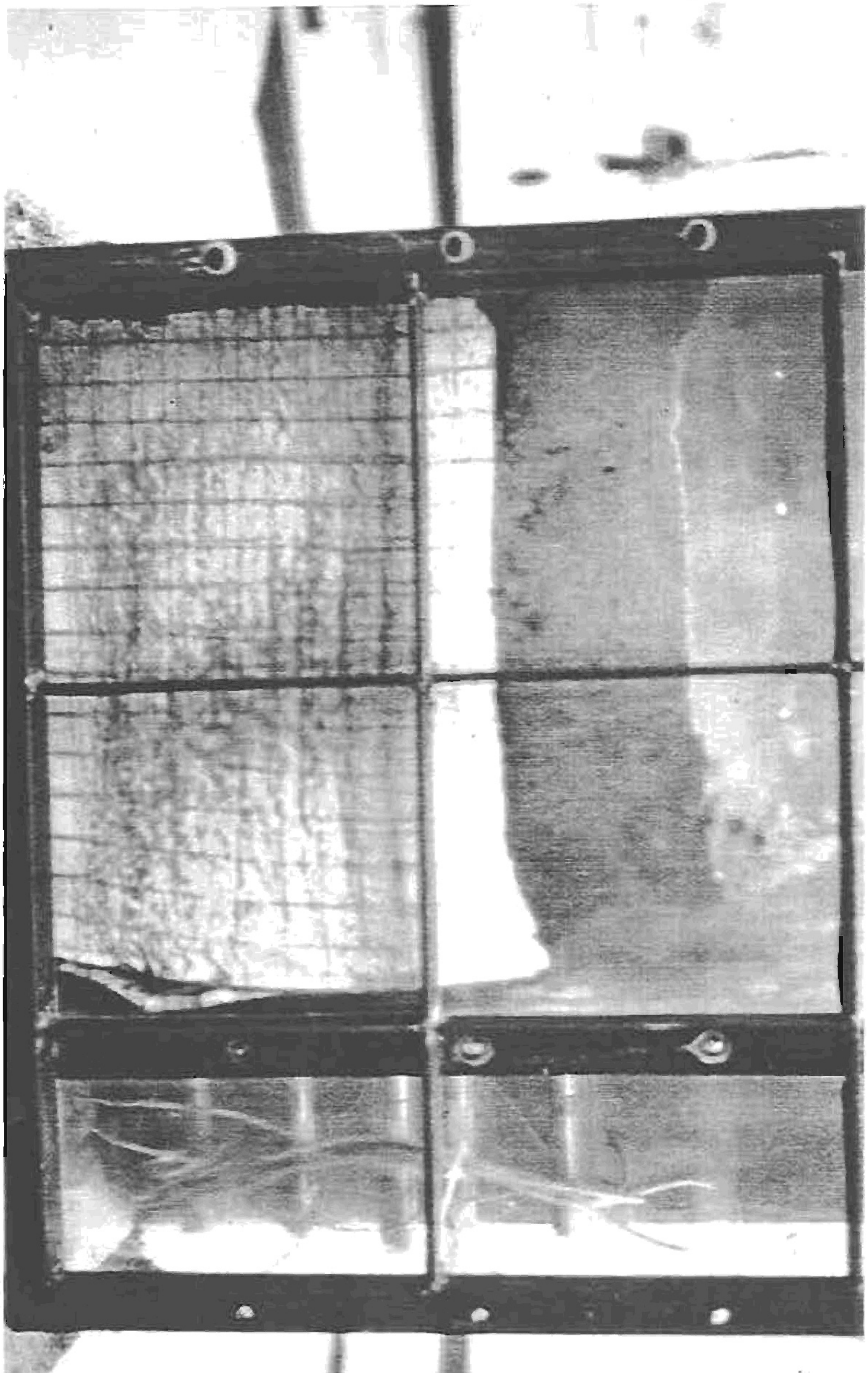

TEST 8
LVDT 2
surcharge (Psi.)
displacement (inches)


TEST 8
LVDT 3
surcharge (Psi.)
displacement (inches)

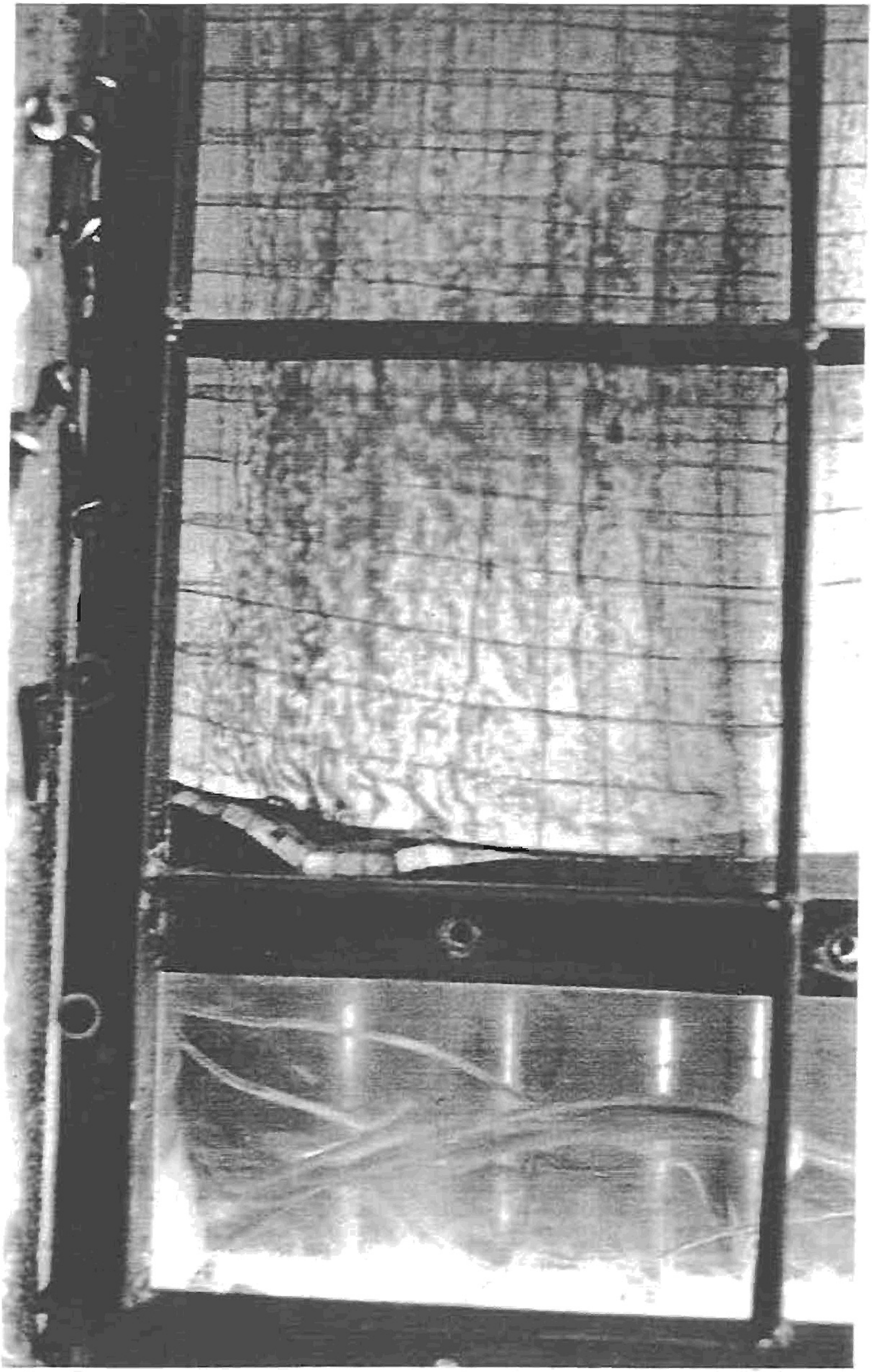

TEST 8
LVDT 4
surcharge (Psi.)
displacement (inches)


TEST 8
LVDT 5
surcharge (Psi.)
displacement (inches)


TEST 8
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
0 Psi.
10 Psi.
20 Psi.
35. Psi.



Photograph No. 8-1



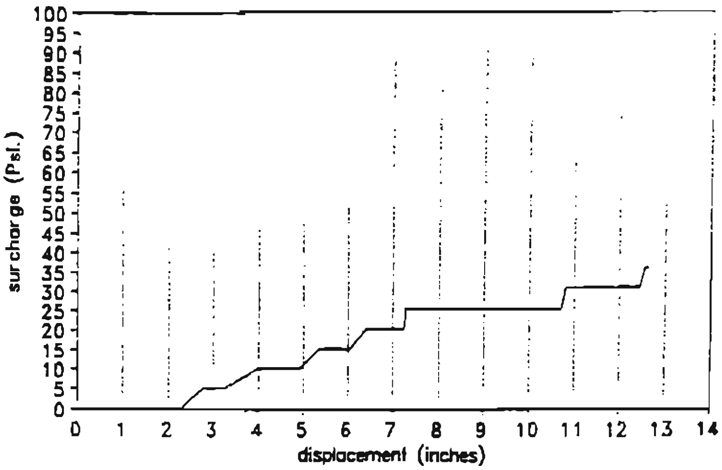
Photograph No. 8-2

Test No. 9

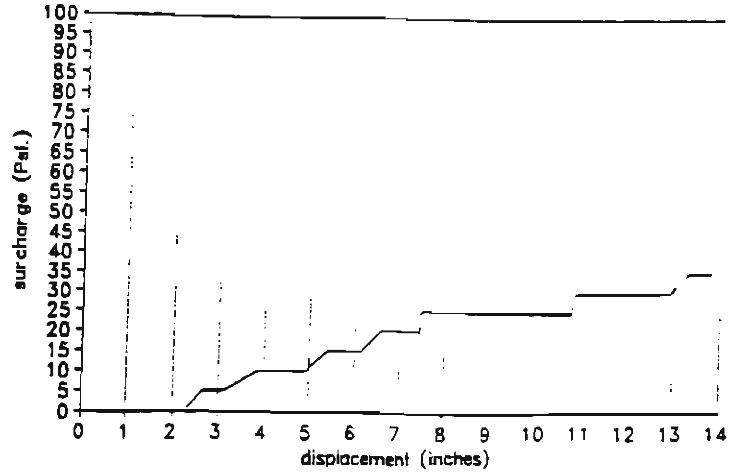
Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: Trapezoidal
Target moisture content: 2% wet of optimum = 17.2%
Moisture content at end of test: 17.7%
Date: June 9, 1992

The data from test No. 9 was cut and pasted from two test. The data acquisition system went down after the centrifuge achieved 11 G's and no surcharge pressure was applied. The system was checked out and spun up to 11 G's again and then a surcharge load was applied. Therefore, there is two test 9 & 9A in the raw data disk of this test. The data was blended together in order to account for the original displacement of the 11 G' spin up with no surcharge load. The test was discontinued due to the fact that the wall had displaced to the end of the LVDT's.

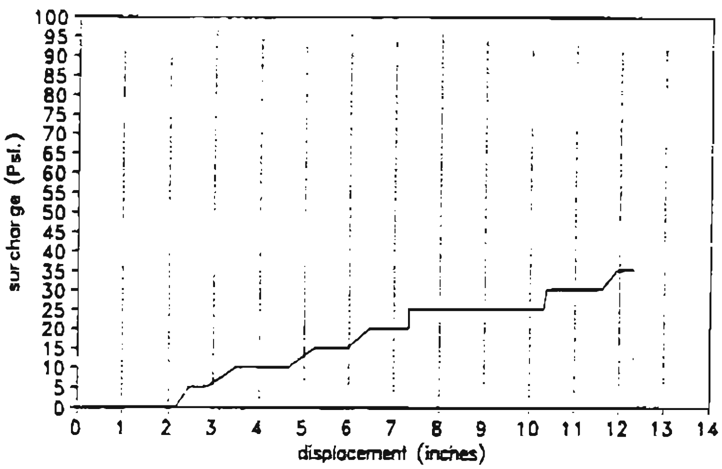
TEST 9
LVDT 2



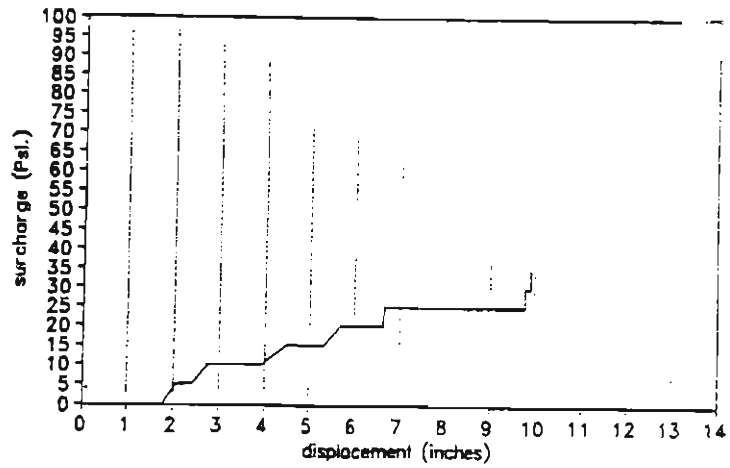
TEST 9
LVDT 3

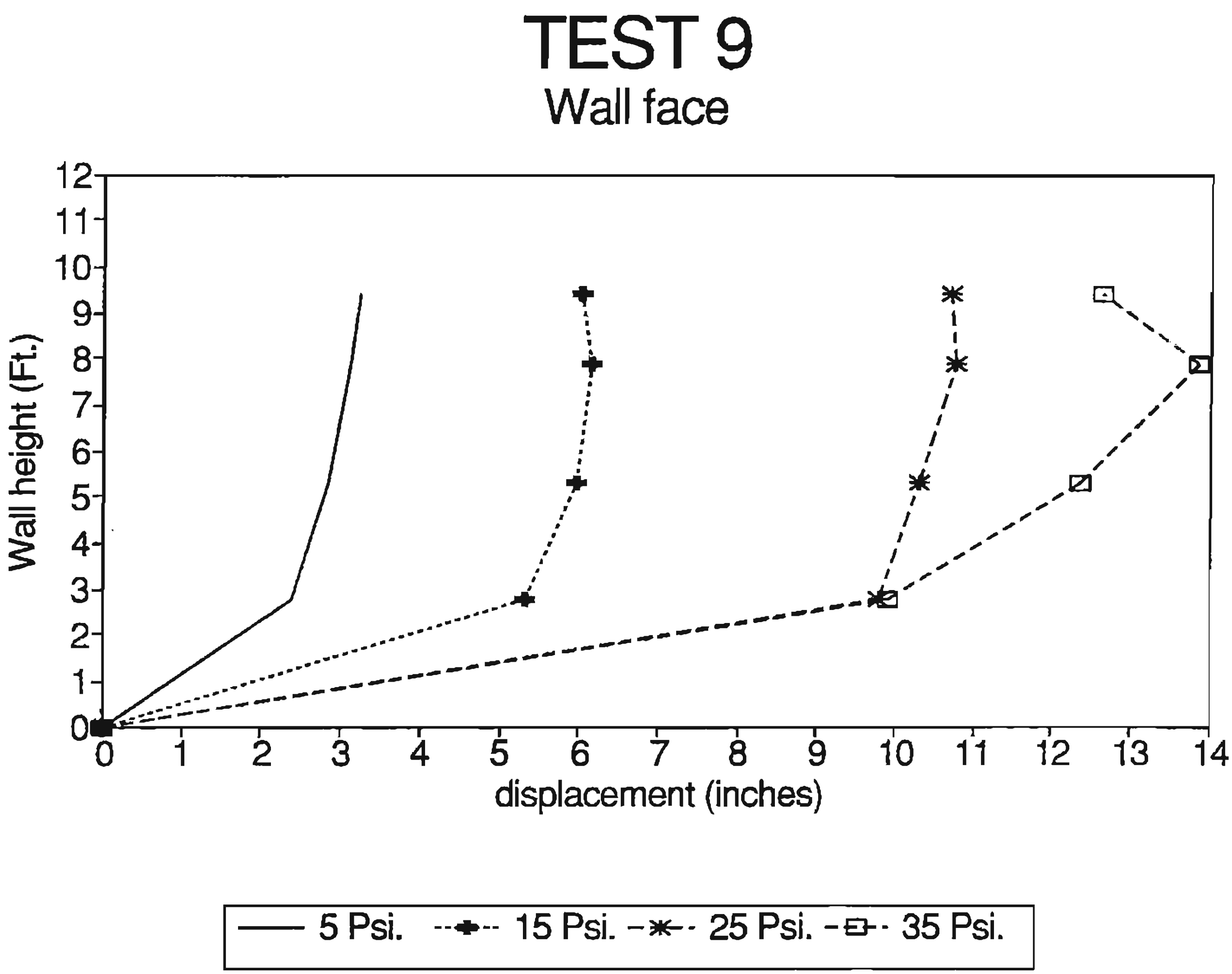


TEST 9
LVDT 4

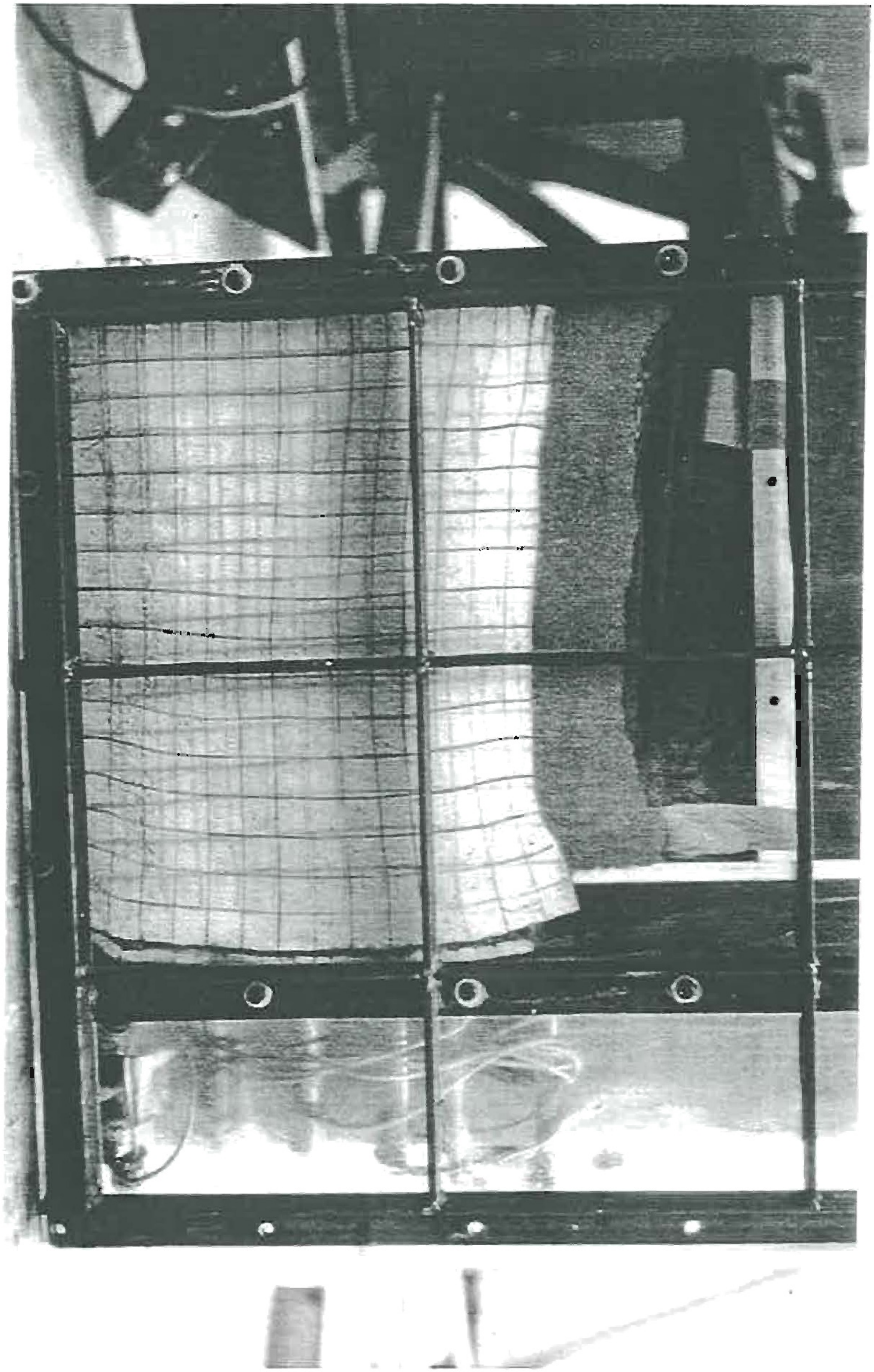


TEST 9
LVDT 5

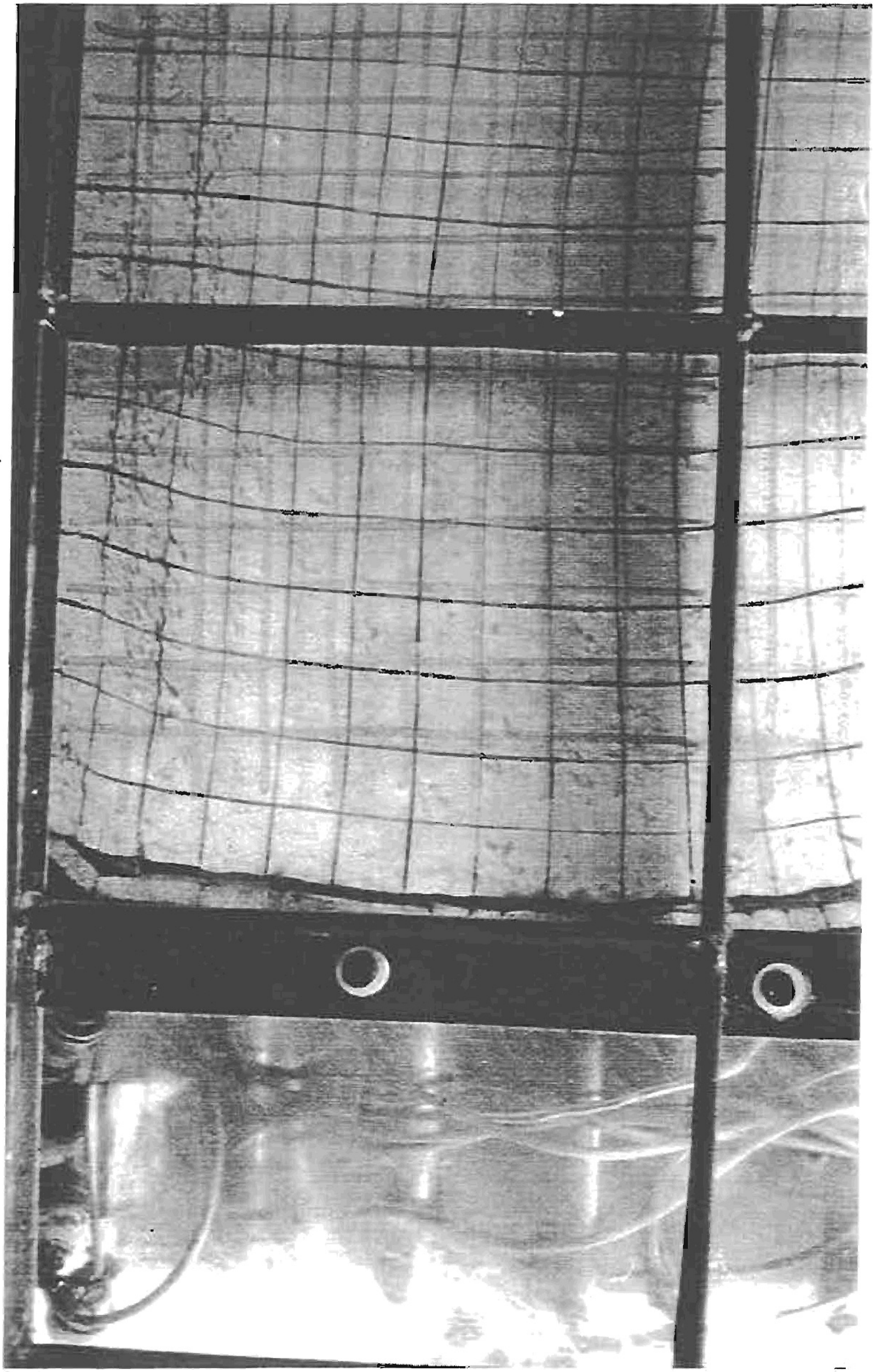




TEST 9
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
5 Psi.
15 Psi.
25 Psi.
35 Psi.



Photograph No. 9-1



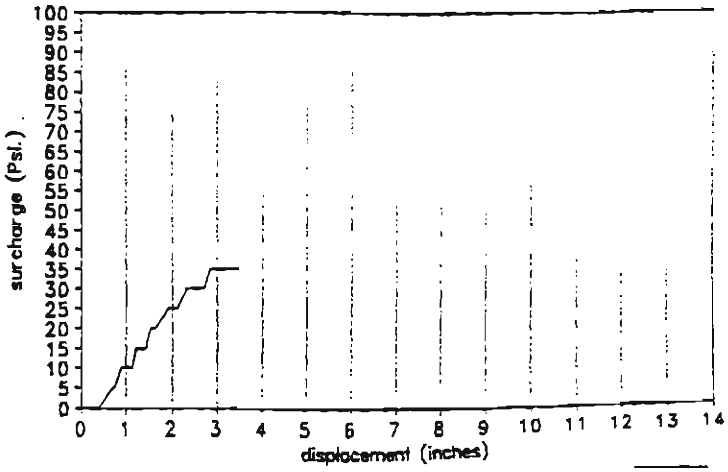
Photograph No. 9-2

Test No. 10

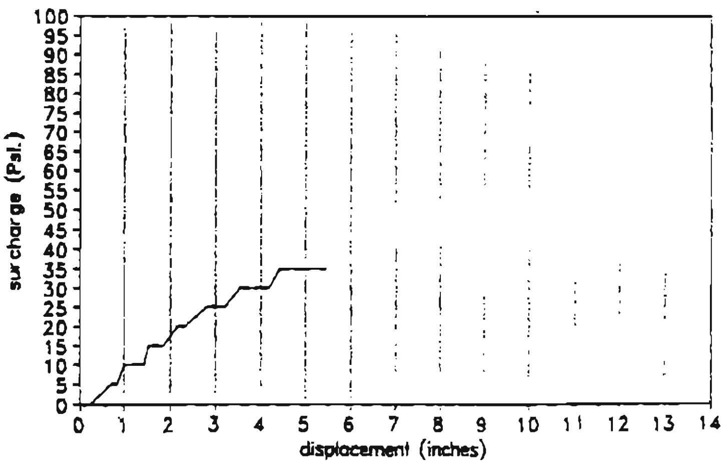
Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: rectangular on a soft foundation
Target moisture content: 2% wet of optimum = 17.2%
Moisture content at end of test: 16.1%
Date: June 11, 1992

This test was run with 9.75 inches of compacted clay below the bottom of the wall. The wall face was constructed with a ten to one batter. There was only 3 LVDT's used at 2.25, 4, & 8 inches from the bottom of the wall. It is hard to compare data produced from this test to other test, since too many variables were changed for this test.

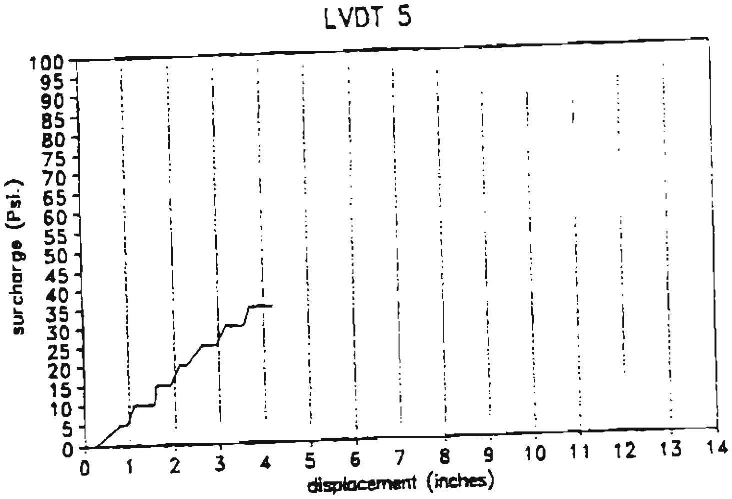
TEST 10
LVDT 2

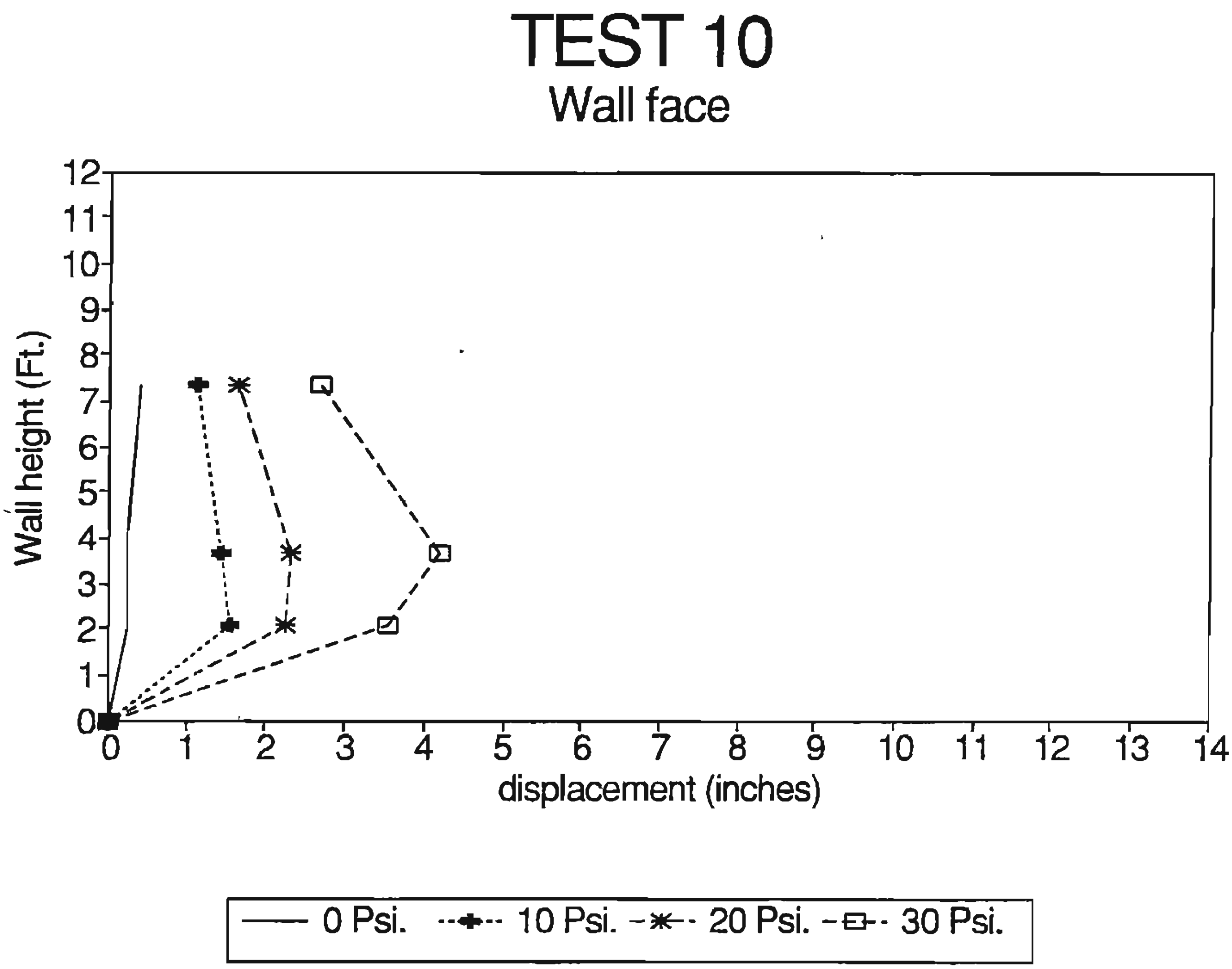


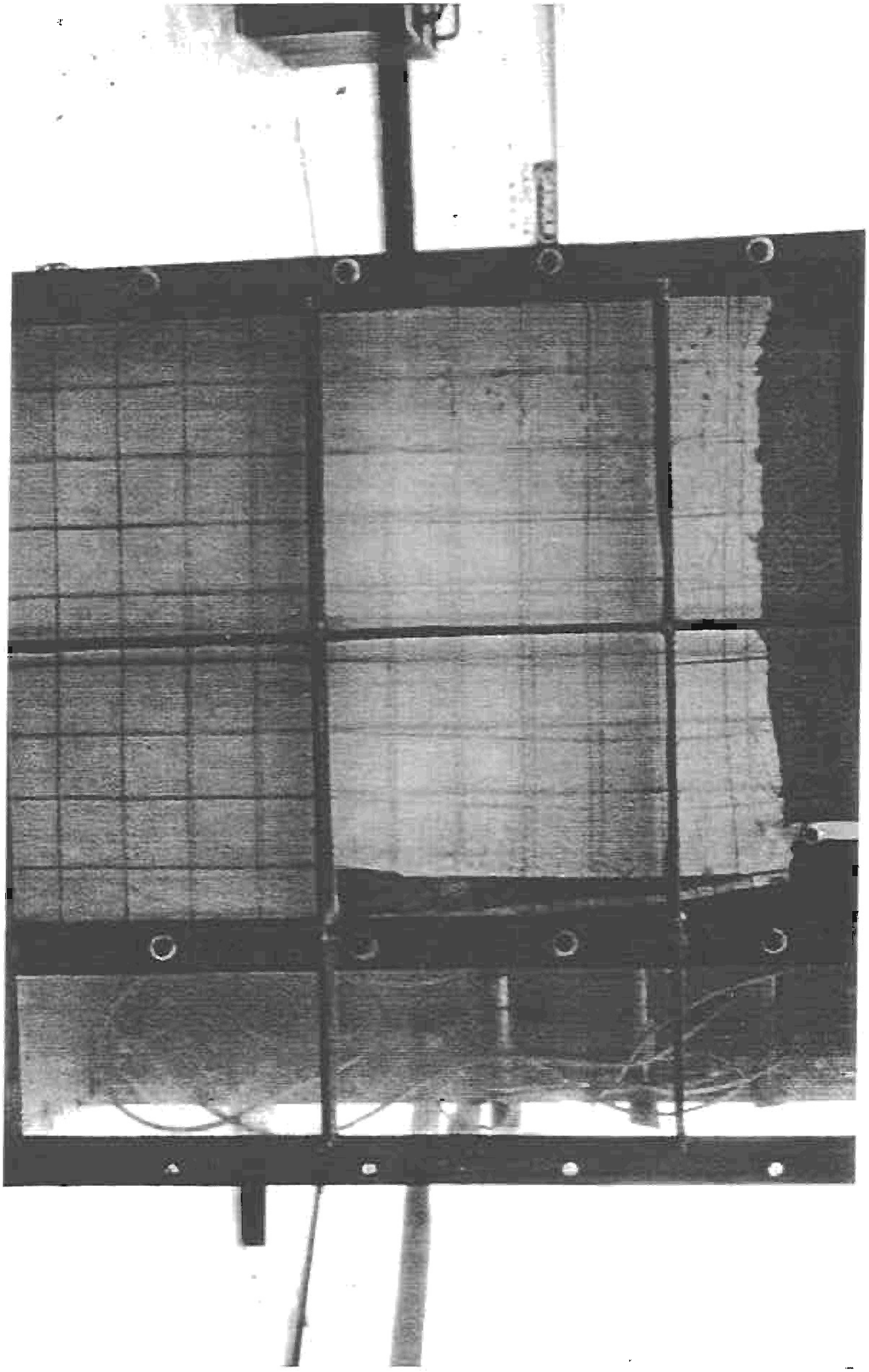
TEST 10
LVDT 4



TEST 10
LVDT 5




TEST 10
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
0 Psi.
10 Psi.
20 Psi.
30 Psi.

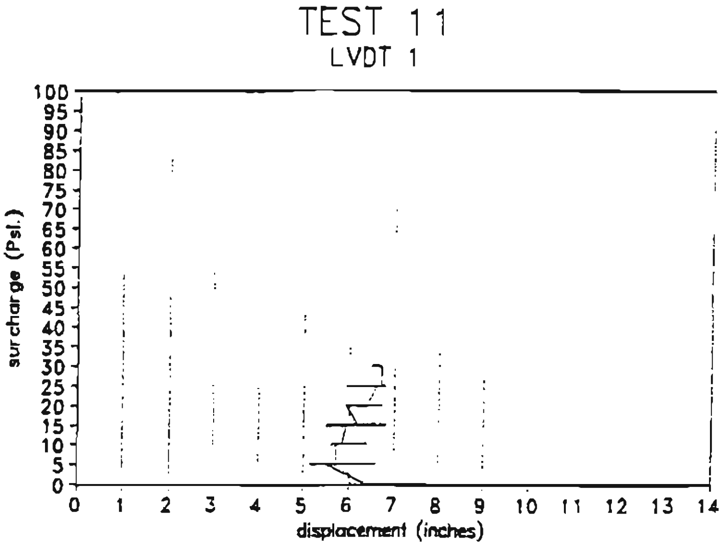


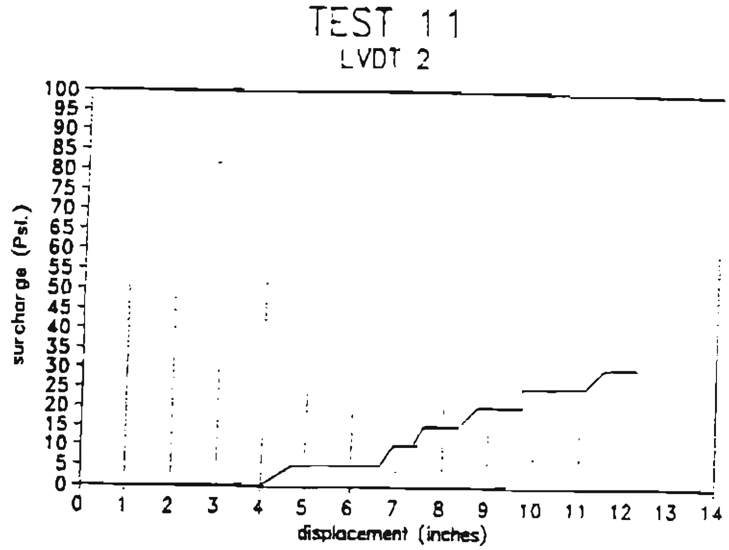
Photograph No. 10-1

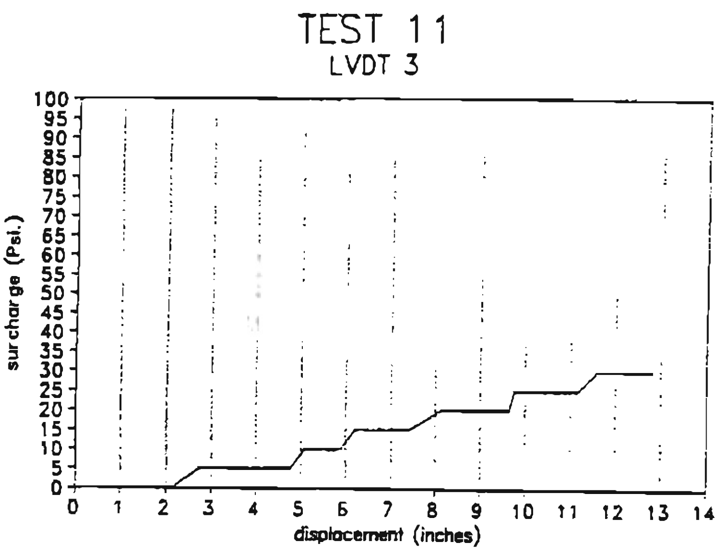
Test No. 11

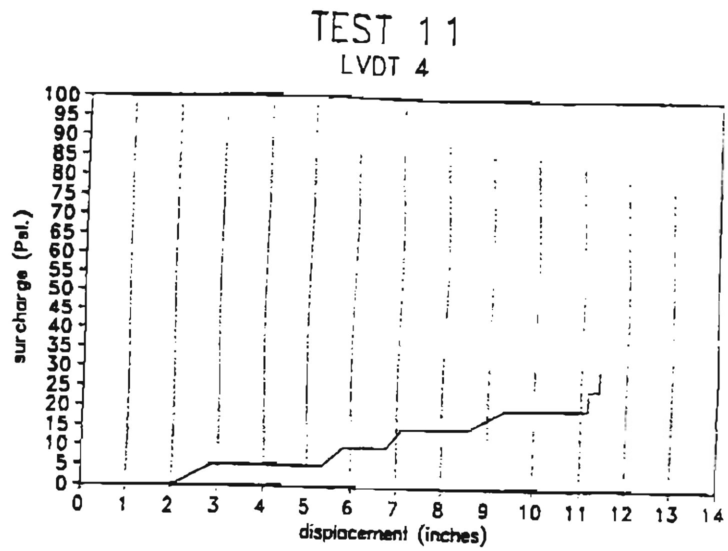
Backfill type: Alternating layers of sand and clay the sand is on the bottom
Density: 95% standard proctor = 101.2 #/CF. Sand & 109.3 #/CF. Clay
Reinforcement shape: Trapezoidal
Target moisture content: 15.2% Sand & 17.2% Clay
Moisture content at end of test: 9.8% Sand & 20.1 Clay
Date: July 1, 1992

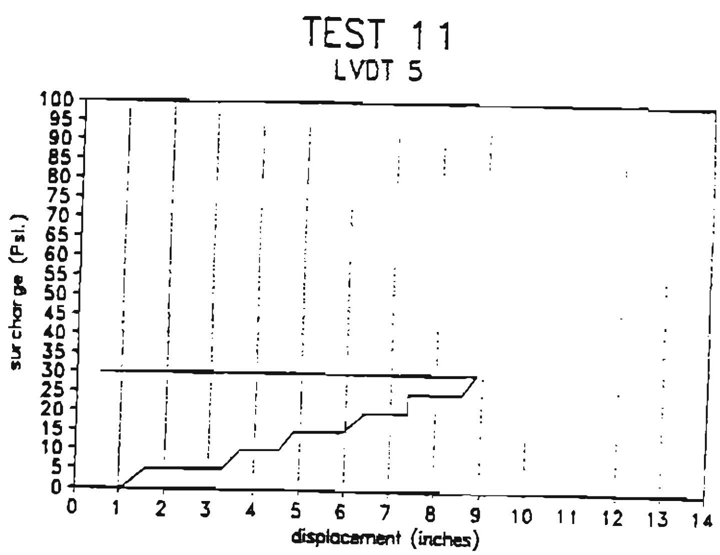
The back fill material was compacted in alternating layers of sand and clay. Sand was placed on the bottom layer. The sand was compacted at 15.2% moisture and the clay was compacted at 17.2% moisture. The container was sealed and filled with water and allowed to stand for 9 days. The low moisture content of the sand at the end of the test is probably due to water being spun out of the sand by the centrifuge during the test. LVDT No. 1 rode over the top of the wall at less than 11 G's so this data was not used. This is the first test with the new data acquisition system in the centrifuge. Test 11 did not get recorded on video tape. The shear surface of the failure plane was observed behind the end of the trapezoidal shaped reinforcements as can be seen in pictures 11-1 & 11-2.

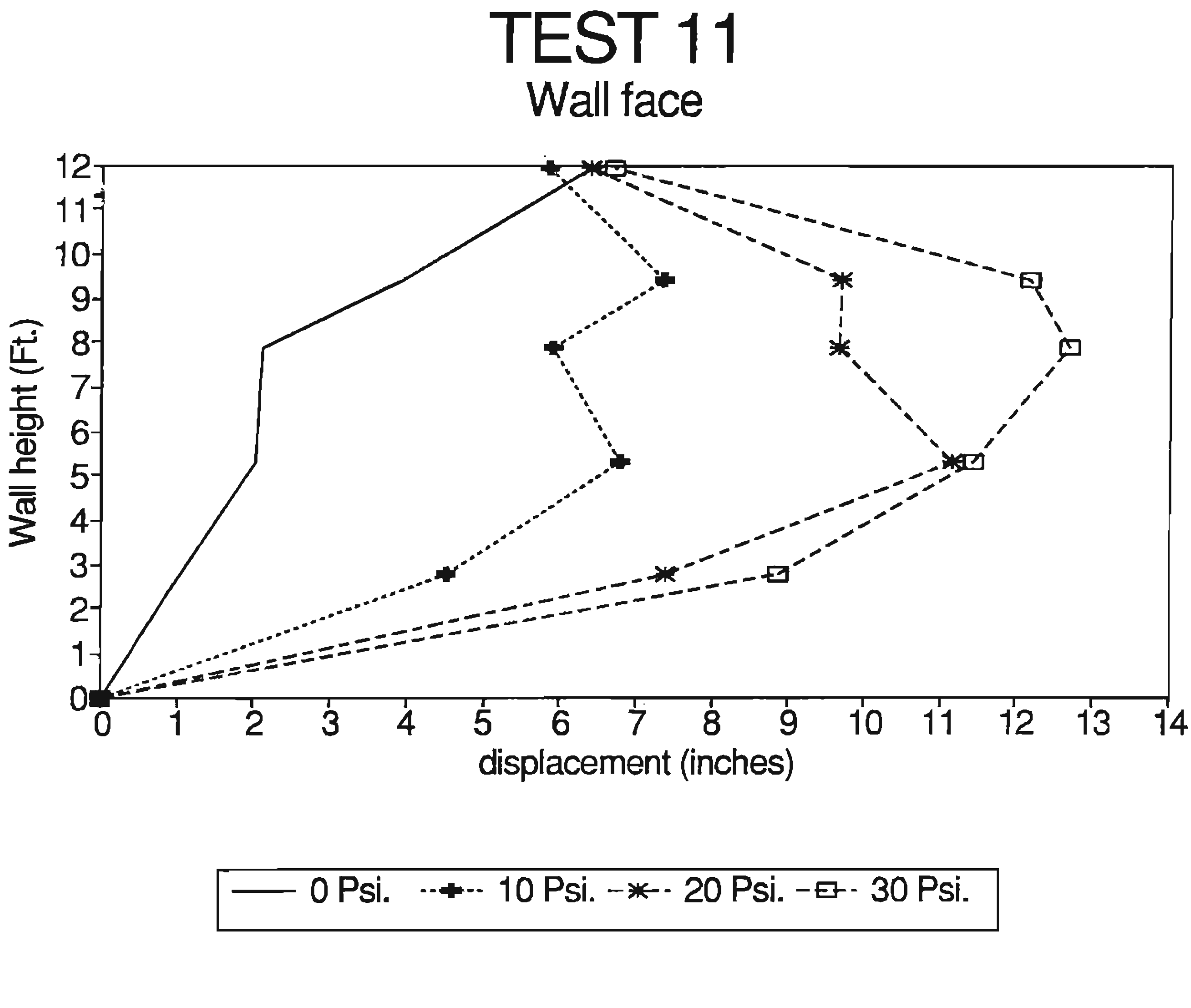

TEST 11
LVDT 1
surcharge (Psi.)
displacement (inches)


TEST 11
LVDT 2
surcharge (Psi.)
displacement (inches)

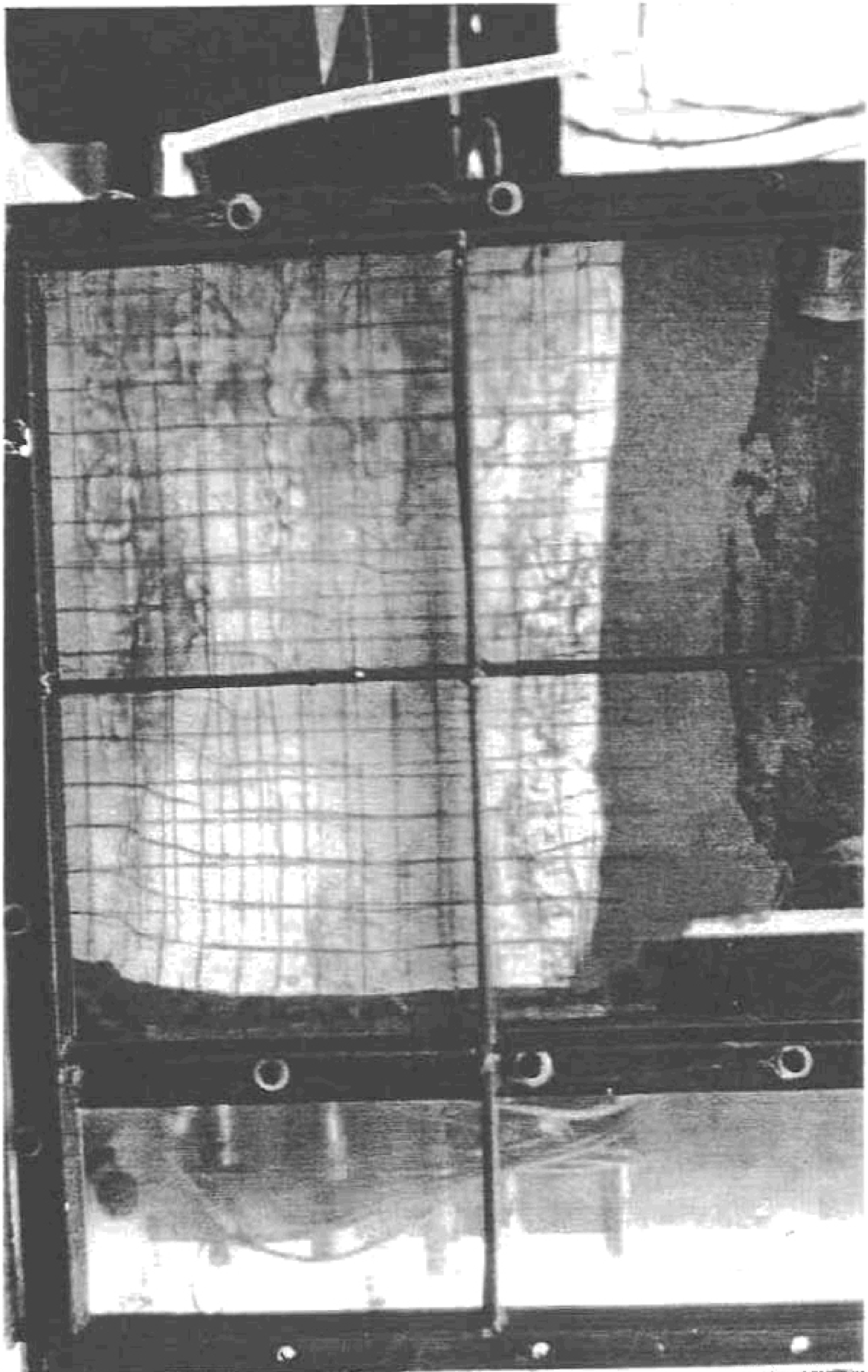

TEST 11
LVDT 3
surcharge (Psi.)
displacement (inches)


TEST 11
LVDT 4
surcharge (Psi.)
displacement (inches)

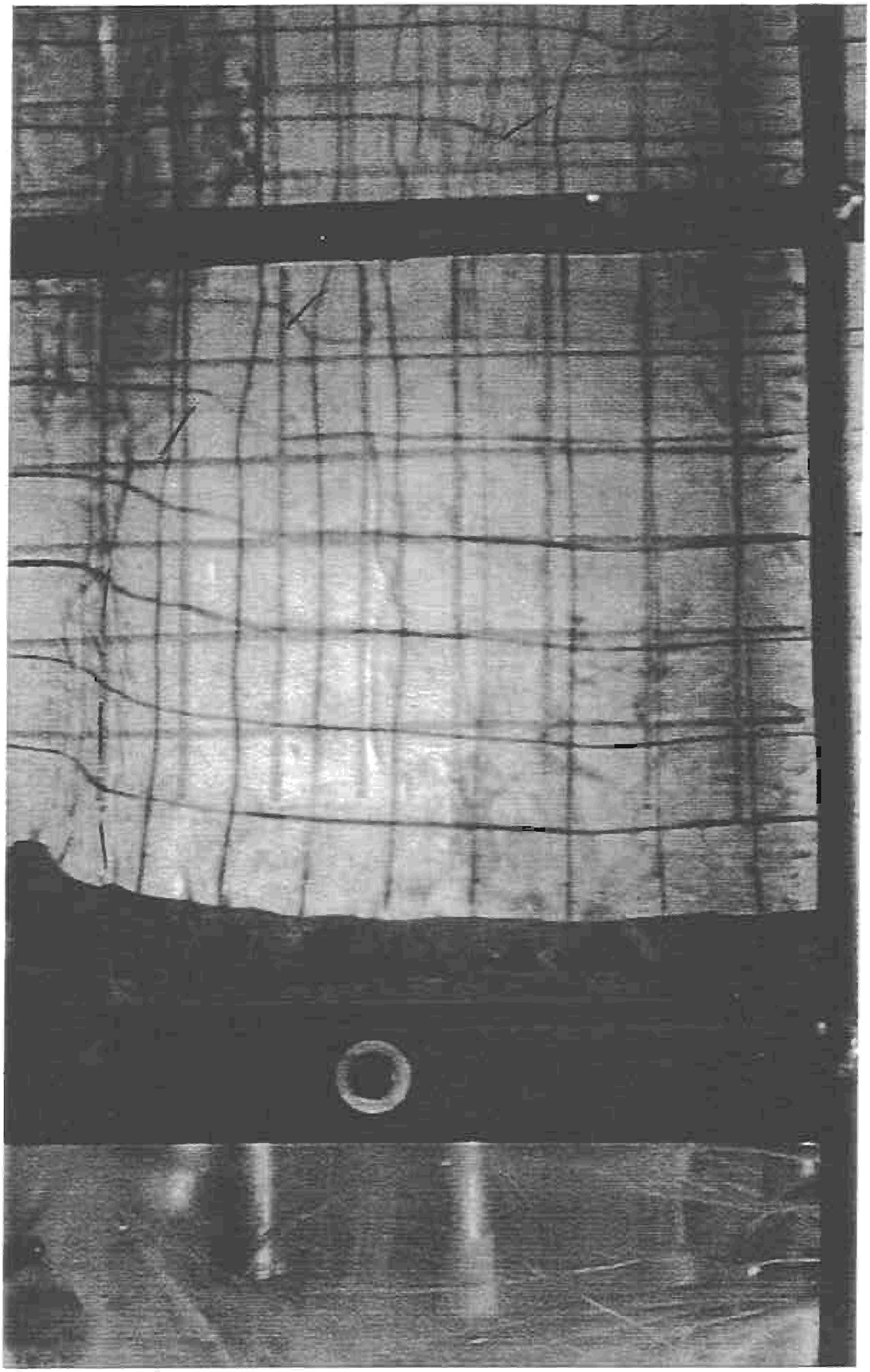

TEST 11
LVDT 5
surcharge (Psi.)
displacement (inches)



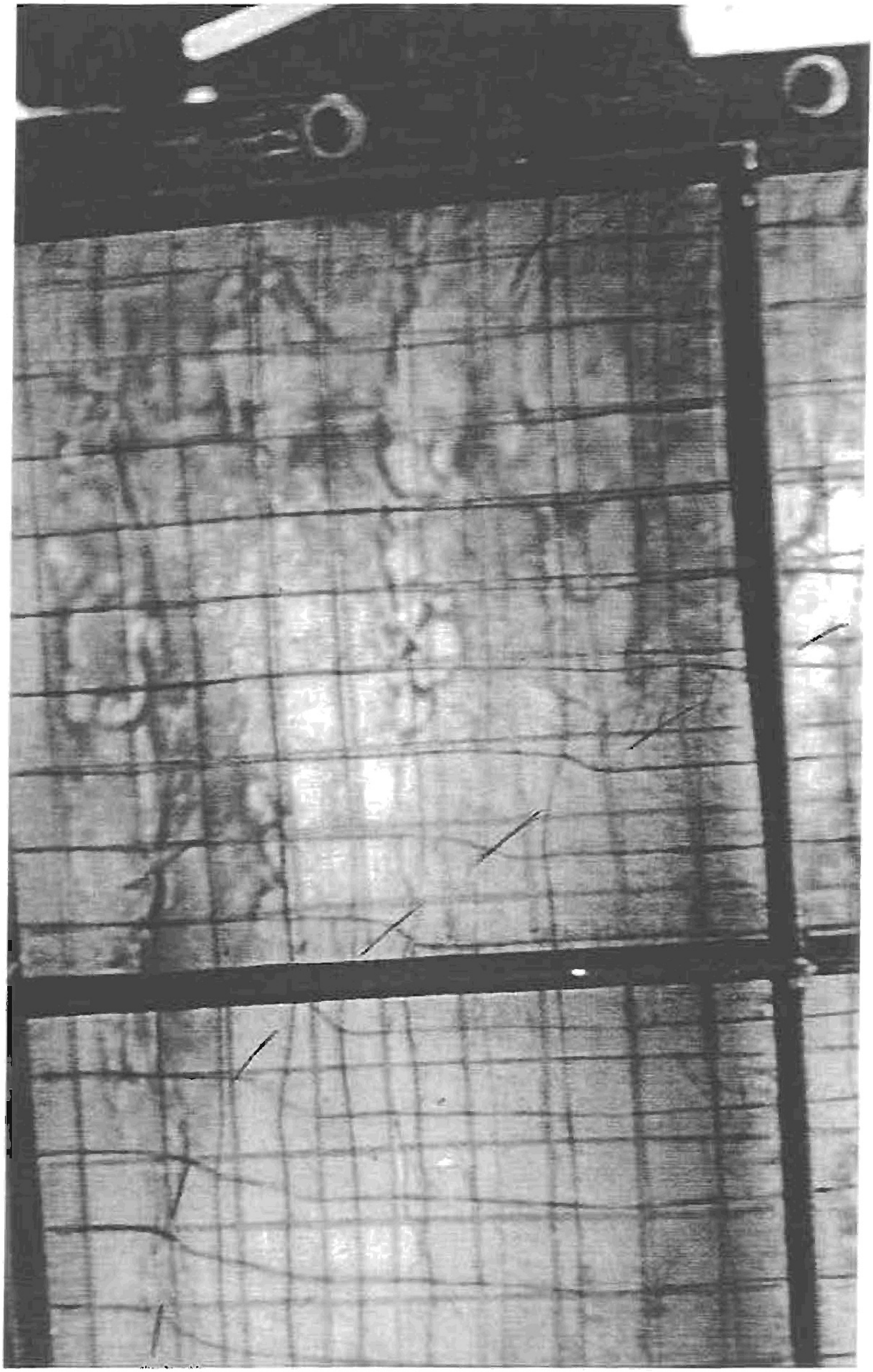
TEST 11
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
0 Psi.
10 Psi.
20 Psi.
30 Psi.



Photograph No. 11-1



Photograph No. 11-2



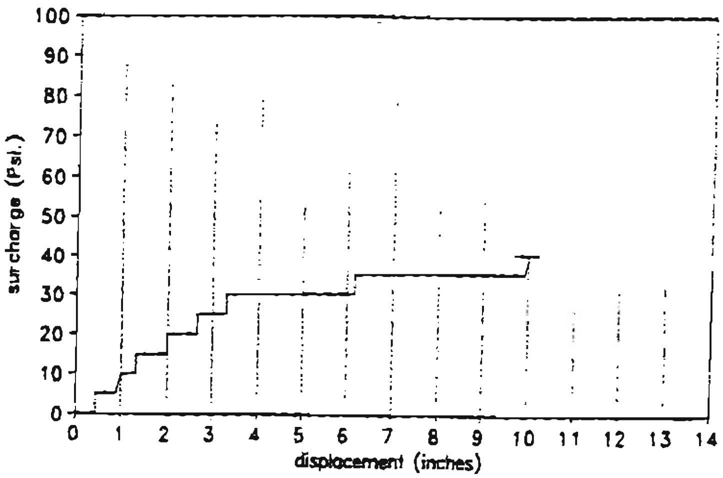
Photograph No. 11-3

Test No. 12

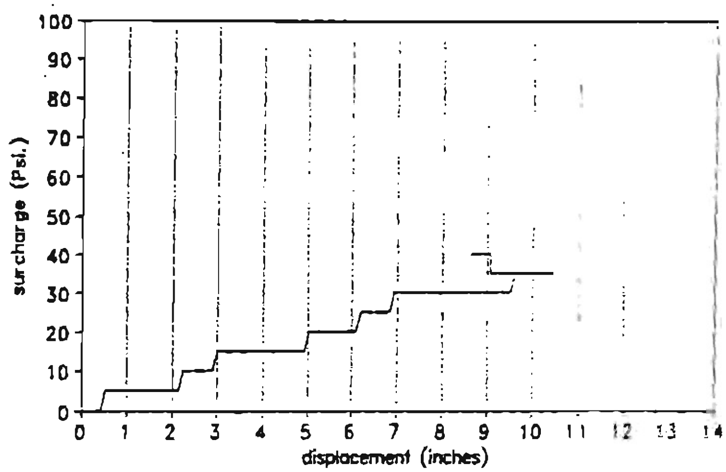
Backfill type: Clay
Density: 95% standard proctor = 109.3 Lbs./cubic foot
Reinforcement shape: Trapezoidal
Target moisture content: 2% wet of optimum = 17.2%
Moisture content at end of test: Reinforced = 17.6, Foundation = 25.0%
Date: July 2, 1992

This test was performed on 9.75 inches of clay at 25% moisture content. the material was placed in 4 lifts of 2 inches and lightly compacted. The last 1.75 inches of material was compacted at 17.2% moisture to bridge the lower foundation material and to allow the lifts inside the wall to be compacted without excessive pumping. The wall face was vertical for this test. The plexiglass broke at 40 psi., so the test was discontinued. LVDT No. 2 had bottomed out at 35 psi., so the model was at the end of its test.

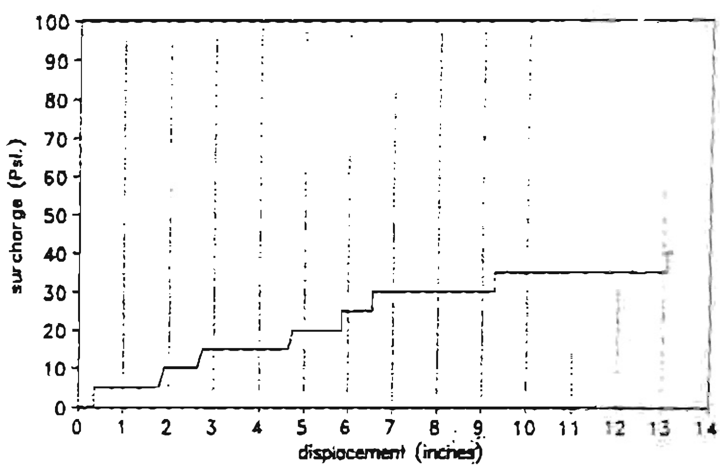
TEST 12
LVDT 1

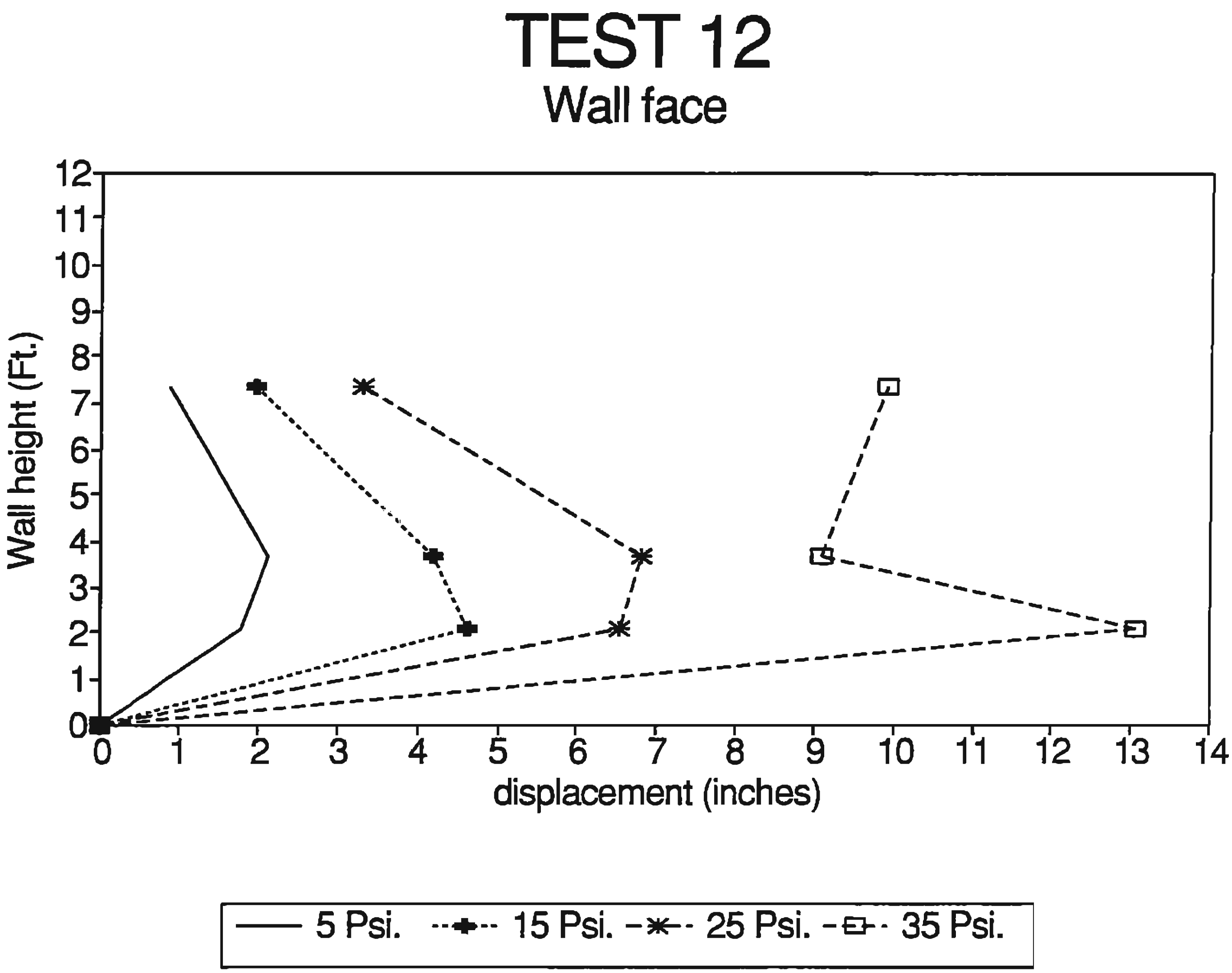


TEST 12
LVDT 2



TEST 12
LVDT 4



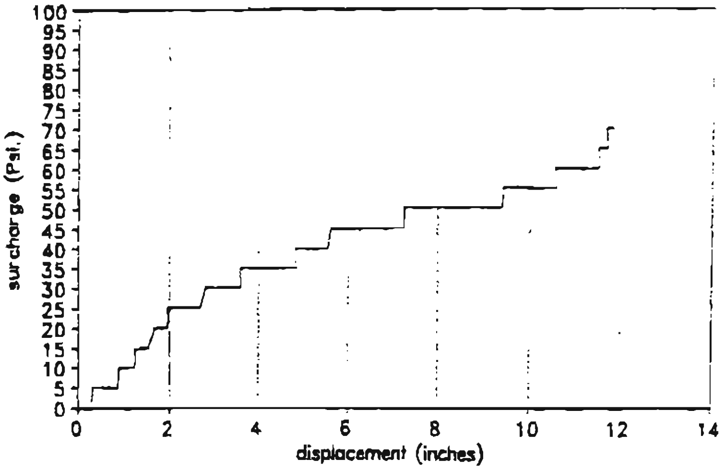

TEST 12
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
5 Psi.
15 Psi.
25 Psi.
35 Psi.

Test No. 13

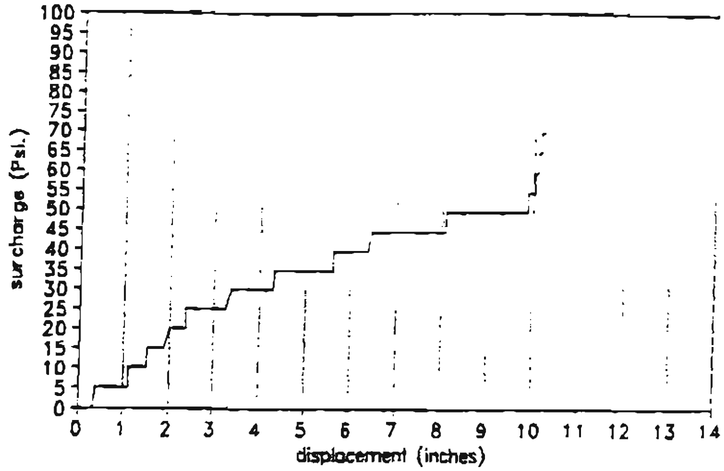
Backfill type: Alternating layers of sand and clay the sand is on the bottom
Density: 95% standard proctor = 101.2 #/CF. Sand & 109.3 #/CF. Clay
Reinforcement shape: Trapezoidal
Target moisture content: 15.2% Sand & 17.2% Clay
Moisture content at end of test: 7.2% Sand & 18.4% Clay
Date: July 1, 1992

The backfill material was compacted in alternating layers of sand and clay. Sand was placed on the bottom layer. The sand was compacted at 15.2% moisture and the clay was compacted at 17.2% moisture. The low moisture content of the sand at the end of the test is probably due to water being spun out of the sand by the centrifuge during the test. Picture 13-2 was trying to show the large amount of consolidation of the clay layers near the front face of the wall. There is a slide that shows this fairly clear. This is the only test taped on video tape No. 3.

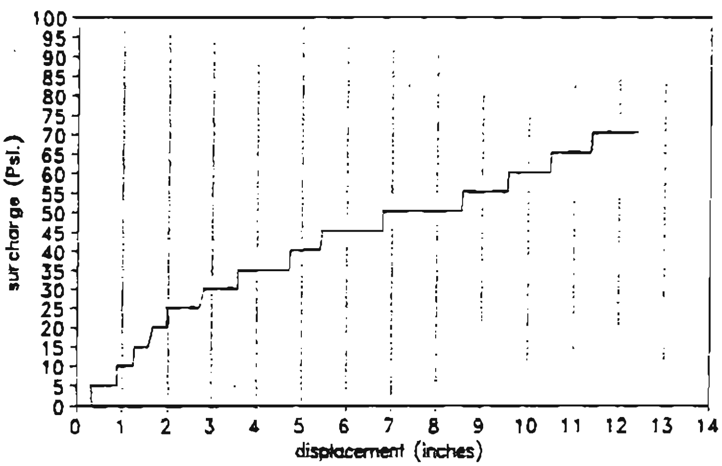
TEST 13
LVDT 1



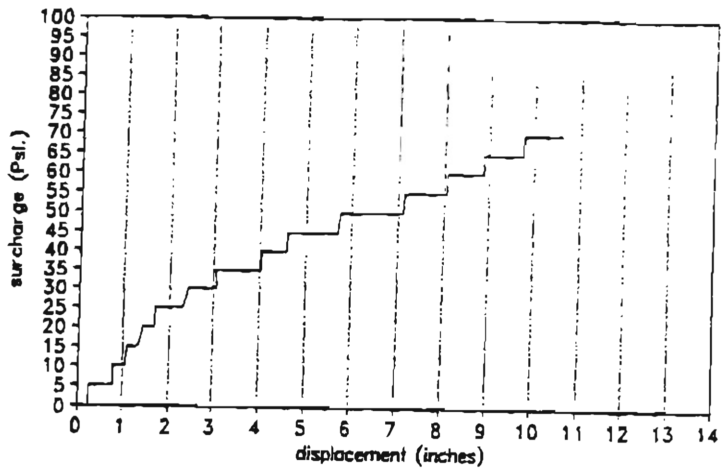
TEST 13
LVDT 2



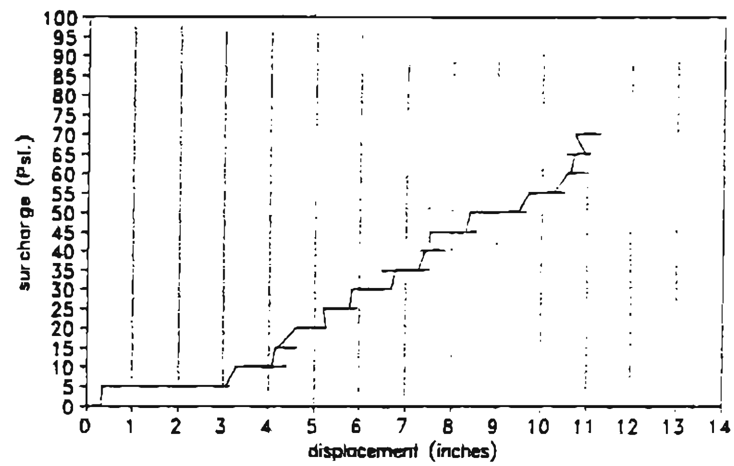
TEST 13
LVDT 3

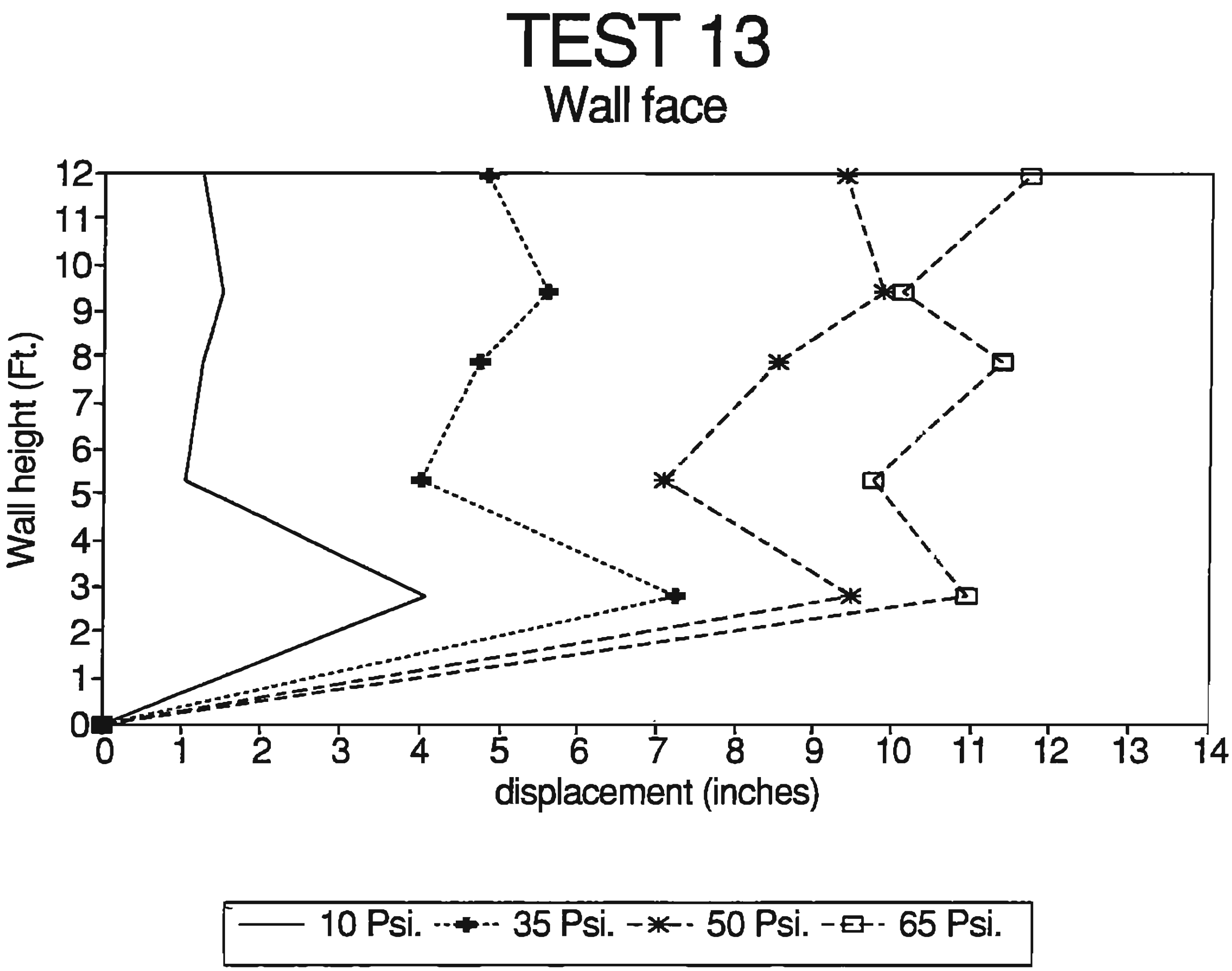


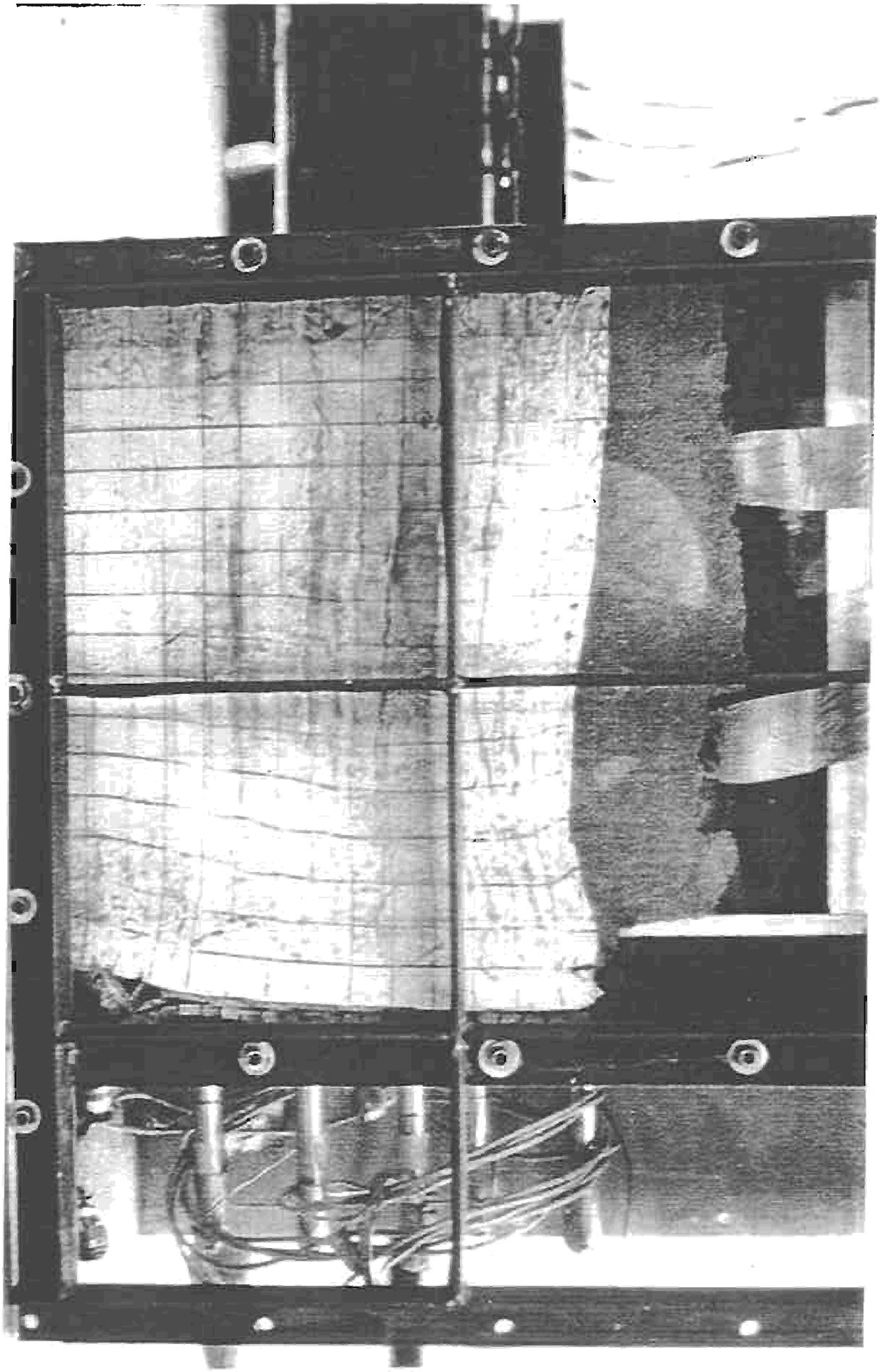
TEST 13
LVDT 4



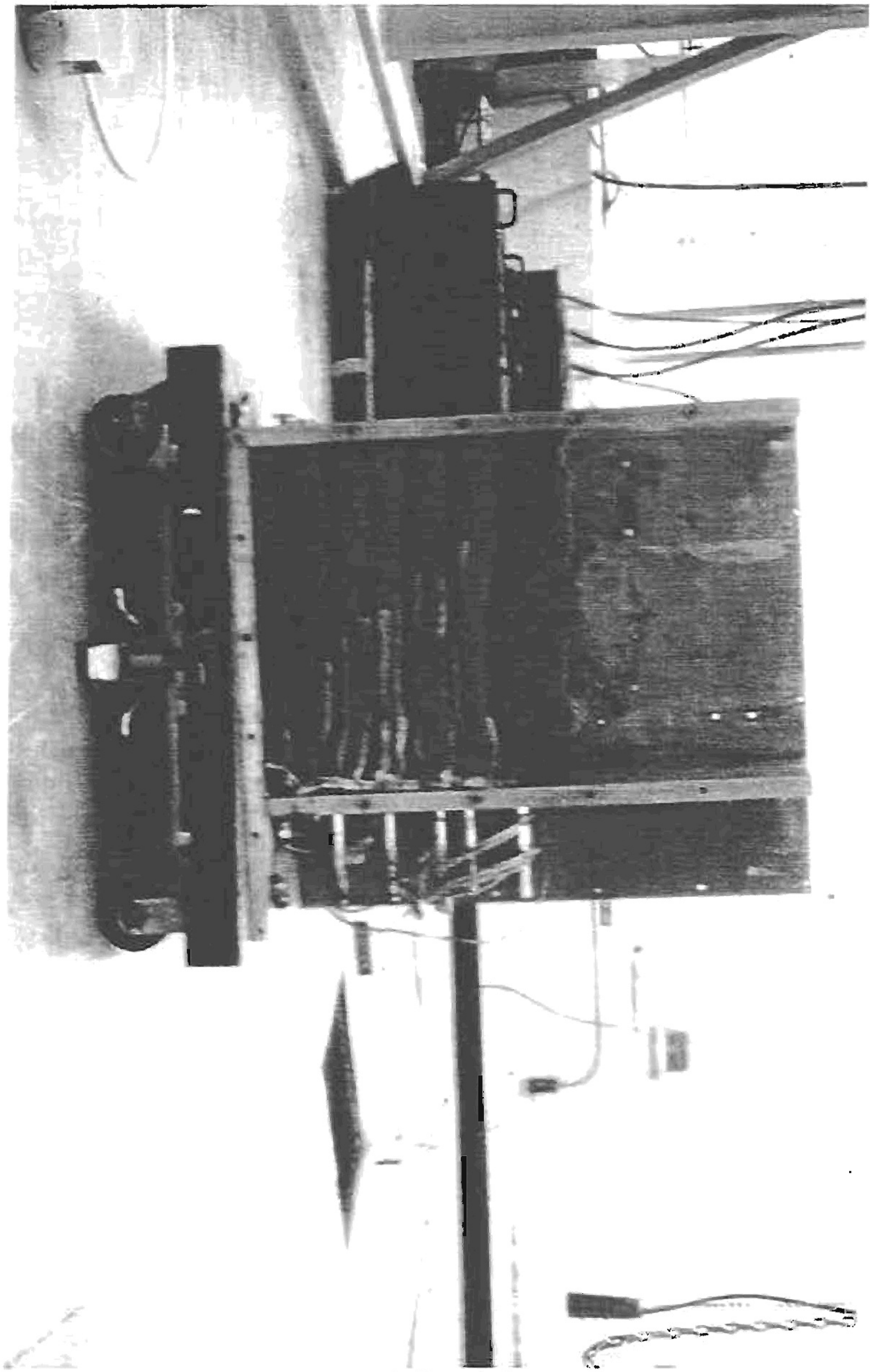
TEST 13
LVDT 5




TEST 13
Wall face
Wall height (Ft.)
0
1
2
3
4
5
6
7
8
9
10
11
12
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
displacement (inches)
10 Psi.
35 Psi.
50 Psi.
65 Psi.



Photograph No. 13-1



Photograph No. 13-2

7) <u>Analysis of Data</u>

The surcharge pressure analysis does not include the 2.5 psi. of surcharge due to the 3 inches of sand on top of the wall. The displacement of the wall was analyzed at a displacement of 5.0% which is equivalent to 7.2 inches. This is equivalent to the maximum allowable displacement under the Colorado Department of Transportation's standard design recommendation.

Test No.	Reinforcement Shape	Backfill Type	Percent Moisture	LVDT No. @ 5% Def.	psi. at @ 5% Def.	Remarks
1	R	S	15.2	--	--	no test
2	R	S	15.2	--	--	5% not reached
3	Tr	S	15.2	3	95	
4	R	C	18.8	1	20	Saturated
5	R	C	14.2	2	25	
6	Tr	C	22.1	--	0	Saturated
7	R	Re	0.0	5	30	
8	Tr	Re	0.0	5	20	
9	Tr	C	17.7	3	20	
10	R	C	16.1	--	--	Soft Found. 10:1
11	Tr	S&C	S=9.8 C=20.1	2	10	Saturated
12	Tr	C	17.6	2	30	Soft Found.
13	Tr	S&C	S=7.2 C=18.4	2	45	

TABLE No. 2

R = Rectangular
Tr = Trapezoidal
S = Sand
C = Clay
Re = Recycled Asphalt

Test No. 2 was used to simulate the existing standard design of Geosynthetic retaining walls. When comparing the graphs of the surcharge versus displacement of test No. 2 with that of test No. 3 one will see that the slopes of the curves are only slightly flatter for test No. 2 than for test No. 3. This would indicate that for a material with a relatively high angle of internal friction the trapezoidal shaped reinforcement performs equally as the rectangular shaped reinforcement. By comparing the results of test No. 5 with those of test No. 9 the same conclusion can be drawn for walls with a clay backfill. A similar comparison could be made between test No. 4 and test No. 6, but due to the fact that there was no surcharge pressure required for failure of test No. 6 and these results are not consistent with any of the other test results it is recommended that the results of test No. 6 be discarded. Test No. 11 was a model containing trapezoidal shaped reinforcement with alternating layer of sand and clay that was allowed to saturate. Test No. 11 achieved 5% displacement at a relatively low 10 psi. of surcharge pressure, but the one result of this test that is of concern is that the observed failure plane as shown in photograph No. 11-1 is behind the end of the reinforcement layers. It is therefore concluded that as the angle of internal friction for the backfill material is reduced past some level, the lengths of reinforcement for the trapezoidal shaped reinforcement are not long enough for the wall to be considered stable.

The comparison of test No. 7 and test No. 8 shows relatively low surcharge pressures of 30 psi. and 20 psi. required for 5% displacement. Without the material properties of the recycled asphalt one can not come up with a very logical explanation for this, but it may be due to the fact that, without any moisture and therefore no apparent cohesion and possibly low percent compaction, the appropriate strength of the walls were not achieved. The results, however show that recycled asphalt could be a viable backfill material for the type of reinforced wall construction. However, further investigation is required to arrive at affirm recommendation. It may be determined from these results though, that the rectangular and trapezoidal reinforcement shapes have similar structural integrity.

The effects of saturation can be analyzed by comparing the results of test No. 11 with that of test No. 13 and test No. 4 with that of test No. 5. The differences in surcharge pressure required for failure between test No. 4 and test No. 5 (20 psi. to 25 psi.) is minimal. The differences in surcharge pressure required for failure between test No. 11 and test No. 13 (10 psi. to 45 psi.) are fairly large as one would expect due to increased pore water pressure.

Table No. 3 summarizes the effects of the different backfill types on stability of the wall.

Test No.	Backfill type	psi. at 5% Def.	
2	sand	100+	Rectangular shaped reinforcement unsaturated
5	clay	25	
7	recycled asphalt	30	
3	sand	95	Trapezoidal shaped reinforcement unsaturated
8	recycled asphalt	20	
9	clay	20	
13	sand & clay	45	

Table No. 3

As can be seen by Table No. 3 the use of sand as a backfill material greatly increases the stability of the wall. Yet if 5 psi is the anticipated surcharge pressure for field walls the results for the other types of backfills show adequate factors of safety.

As can be seen in the figures showing the shapes of the wall at different surcharge pressures there is quit often a buckling of the wall face due to the vertical forces applied to the top of the wall facing. Test No. 13 shows this phenomenon most dramatically. It can be seen in photograph No. 13-1 that at the height of LVDT No. 5 the wall is not in contact with the soil due to this buckling.

While running the test and by analysis of the surcharge load versus displacement curves, it can be seen that in the tests with backfill other than sand, the wall face displaces a relatively large amount at 0 or 5 psi. of surcharge and then stiffens up. These initial displacements are probably due to the displacement required to take up the slack in the reinforcements left from construction of the wall. In the construction of the prototype wall these initial stresses are compensated for during construction and these initial displacements would probably not be observed.

8) <u>Recommendations for further research</u>

For the results of scientific research to be considered meaningful it must pass two criteria. First the research must pass the scrutiny of one's peers and secondly the results must be repeatable. This research probably pass the first criterion, but the repeatability of the results is questionable for the following reasons: 1) It will be very difficult to reproduce the material properties of the clay or the recycled asphalt and there is only enough of these materials left for one or two more tests. 2) None of these tests were repeated for verification of accuracy. It is therefore recommended that a stockpile, capable of supplying material for these tests indefinitely and of consistent material properties, be acquired. It is recommended that a minimum of two tests be performed on any given model. More tests may be required if the results of the two tests are not consistent. When determining the next series of tests not more than one variable should be changed from the last series of tests. It is recommended that tests for Atterberg limits, Proctor compaction, permeability, grain size distribution, triaxial and percent asphalt, for recycled asphalt, be performed on all future materials. It is very difficult to run tests on soft foundations due to the need to get compaction on top of the soft foundation. The 10:1 batter employed in test No. 10 is too constrained in this container and no further testing of this wall shape, with this container, is recommended.

9) Conclusion

Centrifuge modeling of geosynthetic reinforced retaining walls is considered to be a cost effective method of producing meaningful results for developing a rational theory of safe and economical design guidelines. There remains a need for acquisition of data on performance of full-scale walls tested to destruction for confirmation or calibration of the centrifuge test results. There needs to be a long range program for the sequence of future testing in order to make the testing program as efficient as possible.

The only test that showed signs of a catastrophic failure was test No. 11, yet both previous sets of research on geosynthetic reinforced retaining walls by centrifuge modeling were aimed at testing walls to catastrophic failure. By defining 5% displacement as failure the results of this test should not be compared with the data from the other two sets of research.

It would be desirable to repeat test No. 6 for adequate comparison to other test results. For drained backfills the trapezoidal shaped reinforcement functions equally as well as the rectangular shaped reinforcement. The use of sand as a backfill material greatly increases the stability of the wall.

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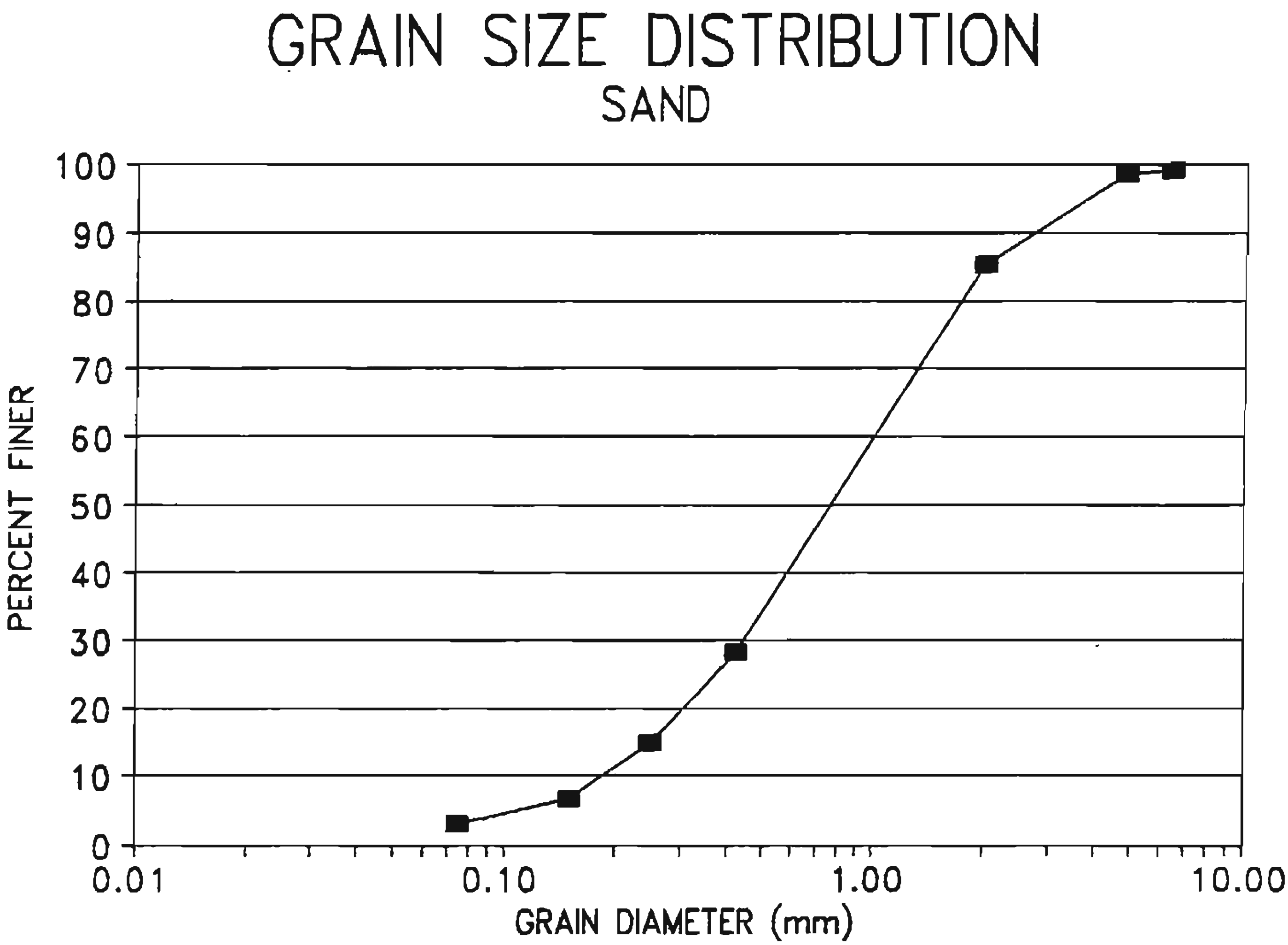
APPENDIX I

Material Analysis of Sand Backfill

PROJECT: CDOT - GRAIN SIZE DISTRIBUTION - SAND

TOTAL WT OF SOIL FOR TEST = 800.5g
WT WASHED THRU 200 SIEVE = 19.3g
WT DRY SOIL = 781.2g

SIEVE NO.	SIEVE DIA.	WT RET.	%FINER
1/4 IN.	6.350 mm	7.6 g	99.1
#4	4.750 mm	4.7 g	98.5
#10	2.000 mm	105.2 g	85.4
#40	0.425 mm	456.6 g	28.4
#60	0.250 mm	108.6 g	14.8
#100	0.150 mm	65.1 g	6.7
#200	0.075 mm	29.2 g	3.1
PAN		4.7 g	



GRAIN SIZE DISTRIBUTION
SAND
PERCENT FINER
100
90
80
70
60
50
40
30
20
10
0
0.01
0.10
1.00
10.00
GRAIN DIAMETER (mm)

Rev. 7/85 WORKSHEET FOR MOISTURE-DENSITY RELATIONSHIP

(COMPACTION TEST)

Project: CDOT-MSE Walls-Centrifuge Lot: sand Sublot:

Lab. No.: Date: 8-5-92 Tested by: JMK Method: T-99

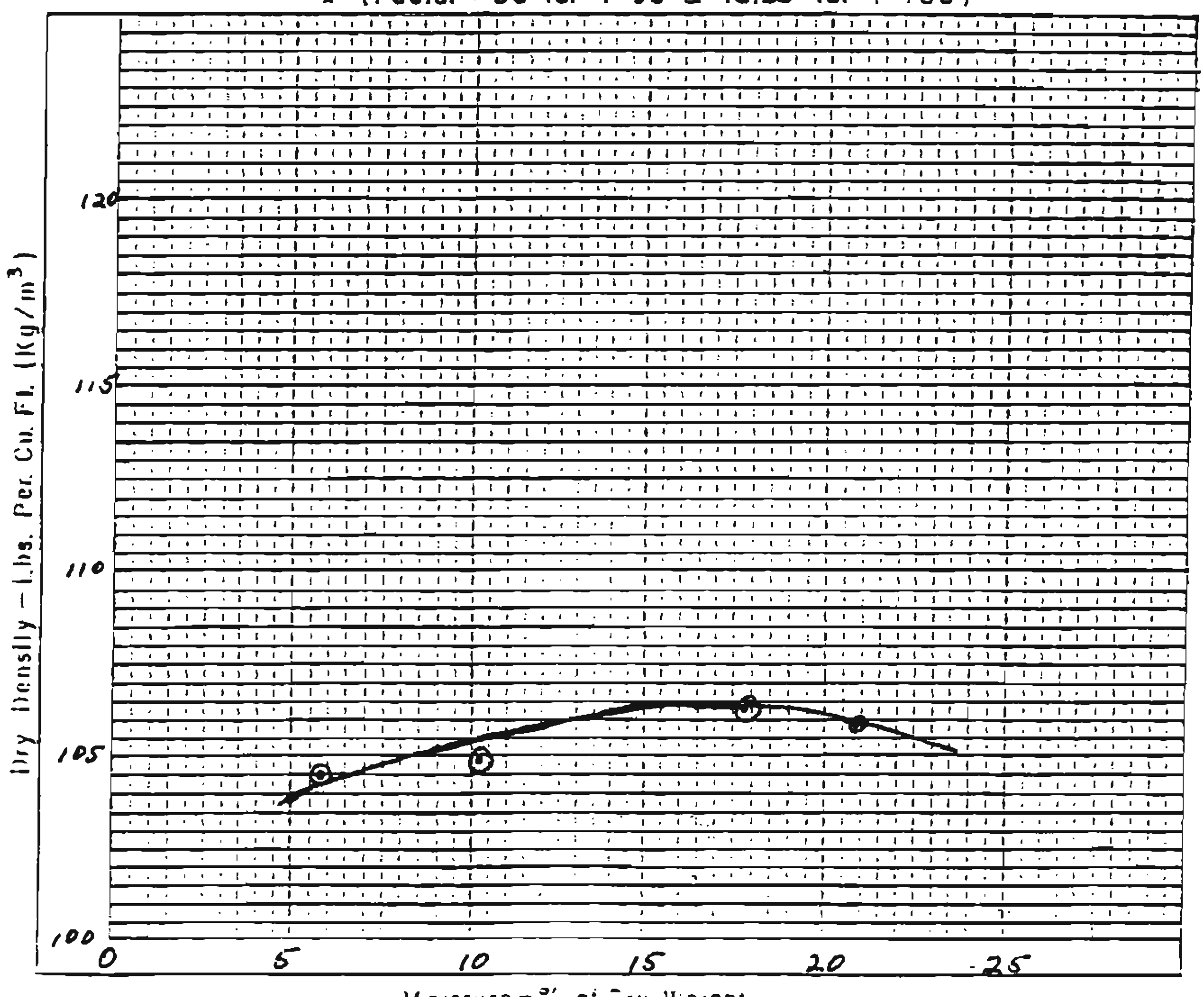
Max. Dry Dens.: 106.5 Optimum Moist.: 16.2 Spec. Gravity:

Density Determination	Test No.	1	2	3	4			
	Wet Soil + Tare (a)	5962.5	6030.5	6175	6219			
	Mold Tare (b)	4283	4283	4283	4283			
	Wet Wt. (c) = a − b	1679.5	1747.5	1892	1936			
	Remarks							
	Wet Dens. (d) = c x factor*	50.385	52.425	56.760	58.080			
	Dry Dens. (e) = d/(1 + k/100)	104.5	104.9	106.3	105.9			
Moisture Determination	Pan No. 453.6	24A	18B	3	10			
	Wet Soil Wt. + Tare (f)	166.52	161.44	173.9	282.7			
	Dry Soil Wt. + Tare (g)	159.1	149.2	152.1	238.8			
	Container Tare (h)	28.64	29.0	29.1	28.73			
	Dry Soil Wt. (i) = g − h	130.5	120.2	123.0	210.1			
	Water Wt. (j) = f − g	7.42	12.24	21.81	43.9			
	% Moisture (k) = (j/i) x 100	5.7	10.2	17.7	20.9			

#/ft³

Figure 2

* (Factor = 30 for T-99 & 13.33 for T-180)



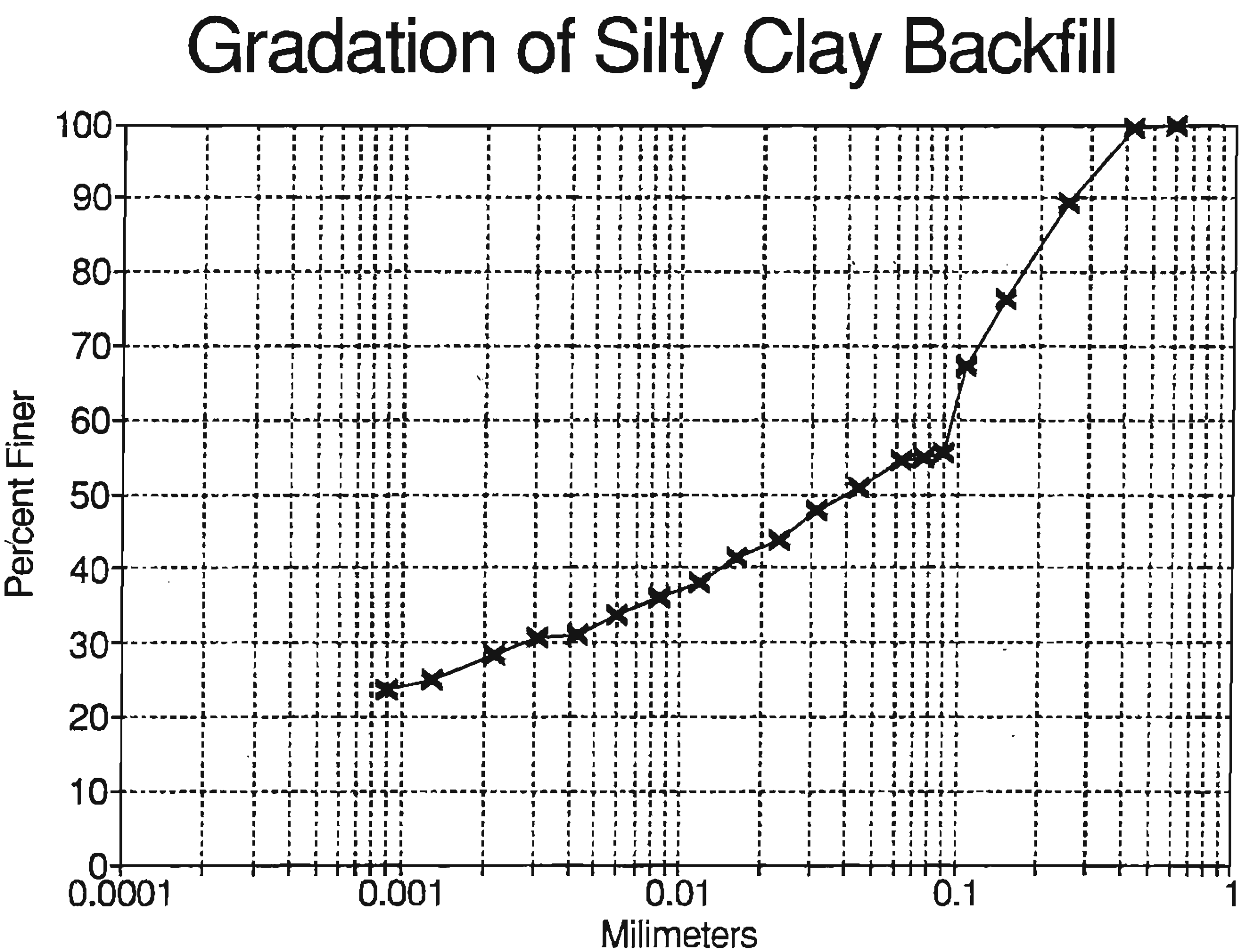
APPENDIX II

Material Analysis of Clay Backfill

Analysis of Silty Clay Backfill
Tests' performed by: Mr. Perter C. Glashagel
Liquid limit=29, Plastic limit=20
Plasticity index=9, Specific gravity=2.68
Siol Clasification, A-4, ML, Silty Clay

Neg. No. 200 sieve portion obtained from a hydrometer test

Sieve No.	Partical Diam. mm	Percent Finer
4	4.75	100
10	2	100
30	0.6	100
40	0.425	99.6
60	0.25	89.4
100	0.15	76.5
140	0.106	67.1
	0.0884	55.3
200	0.075	54.8
	0.0628	54.4
	0.0443	50.9
	0.0316	47.7
	0.0227	43.9
	0.0162	41.6
	0.0119	38.2
	0.0085	35.9
	0.006	33.7
	0.0043	31.2
	0.0031	30.5
	0.0022	28.3
	0.0013	25.1
	0.0009	23.8



Gradation of Silty Clay Backfill
Percent Finer
100
90
80
70
60
50
40
30
20
10
0
0.0001
0.001
0.01
0.1
1
Milimeters

Rev. 7/95

WORKSHEET FOR MOISTURE-DENSITY RELATIONSHIP
(COMPACTION TEST)

Clay

Project: CDOT - MSE Walls - Centrifuge Lot: ______ Sublot: ______

Lab. No.: ______ Date: Feb, 1992 Tested by: Jim Klamerus Method: T-99

Max. Dry Dens.: 113 Optimum Moist.: 15.2 Spec. Gravity: ______

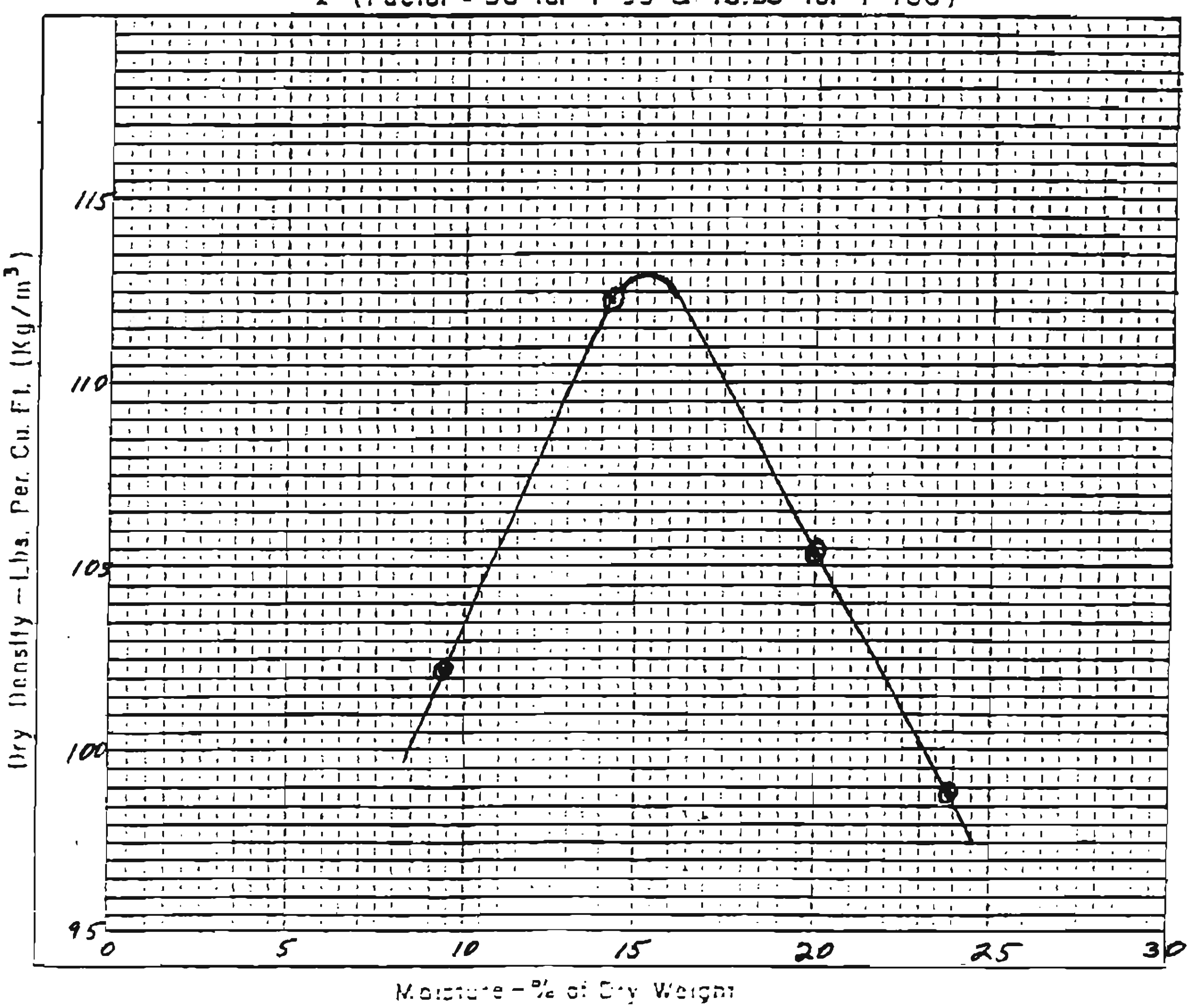
Density Determination							
Test No.	1	2	3	4			
Wet Soil + Tare (a)	5975	6228	6196	6137			
Mold Tare (b)	4283	4283	4283	4283			
Wet Wt. (c) = a−b	1692	1945	1913	1854			
Remarks							
Wet Dens. (d) = c x factor*	50,760	58,350	57,390	55,620			
Dry Dens. (e) = d/(1 + k/100)	102.2	112.4	105.4	98.9			

#/ft³

Moisture Determination							
Pan No. 453.6	1	2	3	4			
Wet Soil Wt. + Tare (f)	110.5	129.9	153.6	180.0			
Dry Soil Wt. + Tare (g)	102.9	116.4	131.6	150.4			
Container Tare (h)	21.9	22.1	21.4	26.7			
Dry Soil Wt (i) = g − h	81.0	94.3	110.2	123.7			
Water Wt. (j) = f−g	7.6	13.5	22.0	29.6			
% Moisture (k) = (j/i) x 100	9.4	14.3	20.0	23.9			

* (Factor = 30 for T-99 & 13.33 for T-180)

igure 2



APPENDIX III

Undrained Triaxial Test Performed on Clay Backfill

Triaxial Test on Clay for CDOT MSE Wall Model

Test performed by Jim Klamerus May 1992

Purpose:

The purpose of this test was determine the effective cohesion and angle of internal friction, and M parameter from the Cam Clay model on a remolded sample AASHTO-classification A-4 soil. If other Cam Clay parameters were desired a set of odometer test need to be run.

Procedure:

Three samples were compacted in a standard proctor mold at 14.2% moisture, 1% dry of optimum. The samples were then trimmed to 2 inch diameter approximately 4 inches long. The samples were then placed in a triaxial cell and allowed to consolidate for approximately 24 hours at 50,65,75, & 70 psi. of cell pressure and 35 psi of back pressure.

B parameter test were the then run by closing of the back pressure line and increasing the cell pressure in two increments of 10 psi. and measuring the increase in back pressure. The increase in back pressure divided by the increase in cell pressure yields the B parameter value.

The samples were then loaded at a constant rate of .05 mm/min. and increase in axial loads and pore preasures were measured.

	Sample No.1	Sample No.2	Sample No.3	Sample No.4
Cell pressure (Psi.)	50	65	75	70
Back pressure (Psi.)	35	35	35	35
Shear stress (Psi.)	15	30	40	35
B parameter 10 Psi.	84%	71%	60%	48%
B parameter 20 Psi.	87%	74%	68%	61%
%Moisture at end of test	20.6%	18.3%	16.2%	

Effective cohesion	3 Psi.
Angle of internal friction	24 degrees
Liquid limit	29.2%
Plastic limit	18.6%
Plasticity index	10.6
Cam Clay M value	1.27

Sources of Error:

The low B parameter values indicate air was present in the samples, which if time was available to de-air the samples the accuracy of the results would have increased. It is unsure whether the samples were allowed to fully consolidate. Compaction of the specimens in a standard proctor probably yielded different degrees of initial consolidation.

Conclusions:

The samples should have been given a much greater time to become saturated as can be seen by the low B parameter values. Failure was chosen at the stress where the pore pressures started to decrease. It would be nice to run a set of odometer test in order to complete the Cam Clay model. The values of Cohesion and angle of internal friction of 3 Psi. and 24 degrees seems reasonable for this type of material.

Sample Calculations

Spread Sheet

Elapsed Time	ΔL	Σ	A'	Load Volts	Δ Load (lbs.)	q	p	p'	PWP Volts	Δu (psi)
From swd				From swd					From swd	

ΔL = Elapsed Time * Loading rate

$\Delta L = 1.0 \times 0.01181102$ in/hr

$$\Sigma = \frac{\Delta L}{L_o} = \frac{.010}{4.0} = .0025$$

A' = Adjusted Area = $A_o / (1 - \Sigma)$

ΔLoad lbs. = ΔVolts * 23.1093

23.1093 = Transducer Calibration Factor lbs/volt

q = Deviator Stress = ΔLoad lbs / A'

p = (cell pressure − Back pressure) + (q/3)

p effective = $p' = p - \Delta u$

$\Delta u = \Delta$PWP(volts) * 2.08

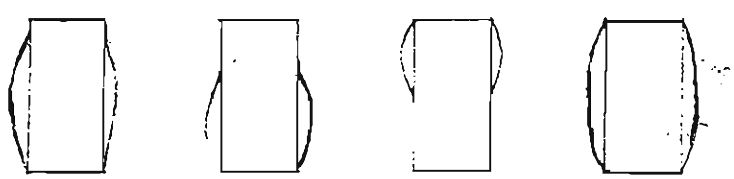
2.08 = PWP Transducer calibration Factor (psi/volt)

M =

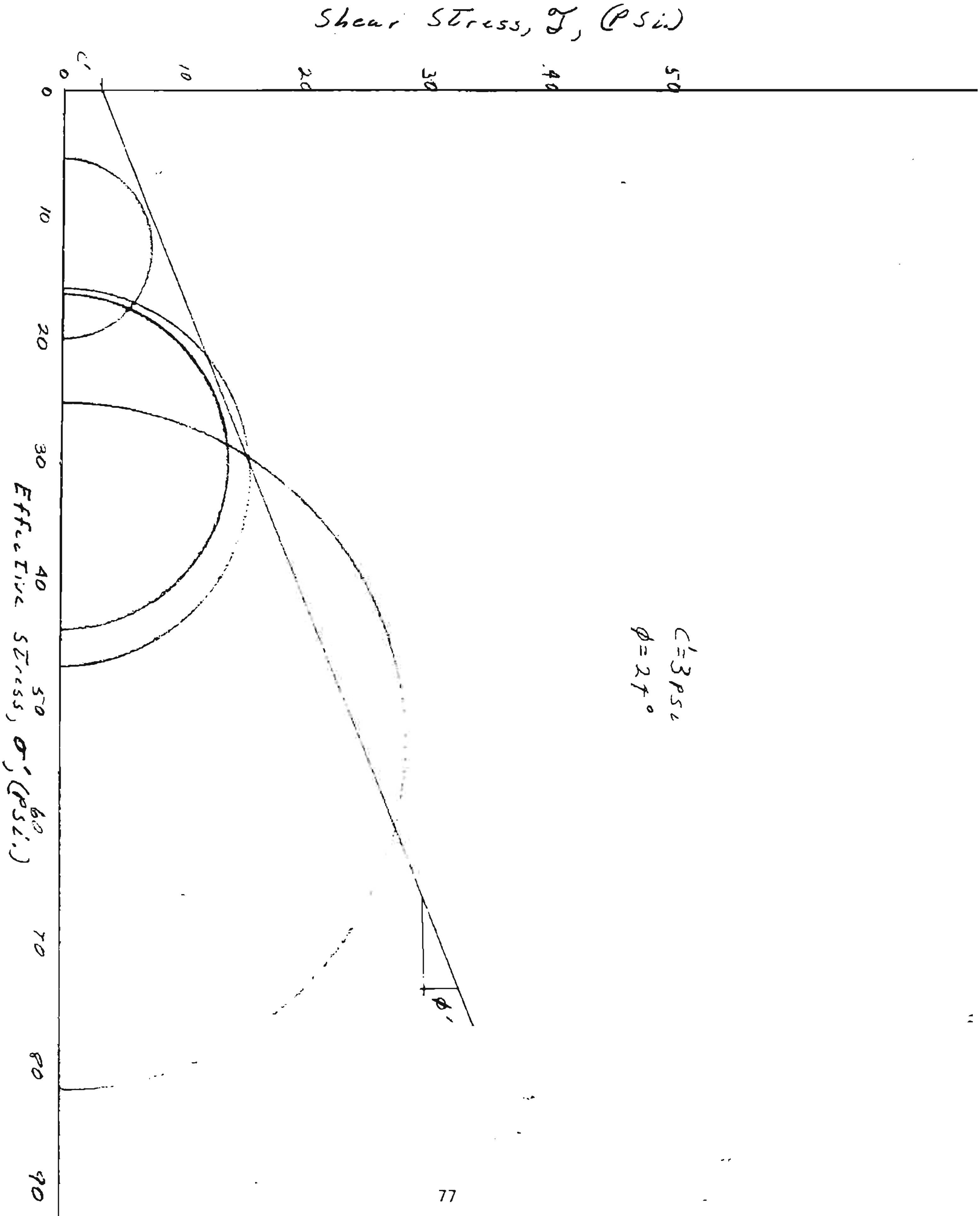
σ_1' = (cell pressure + Load at Failure) − (Back pressure + u at Failure)

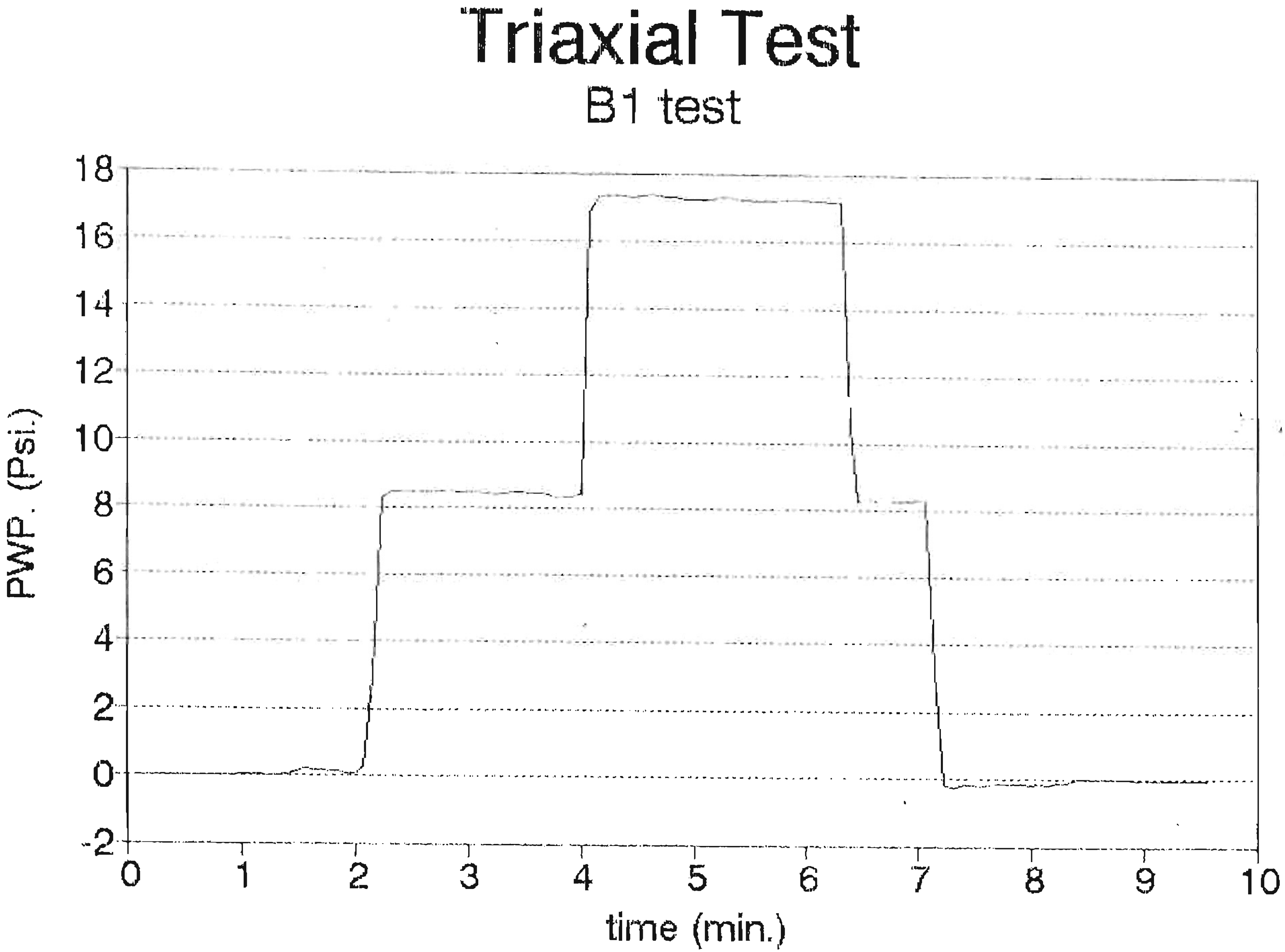
σ_3' = (cell pressure) − (Back pressure + u at failure)

Sketch of Samples at Failure



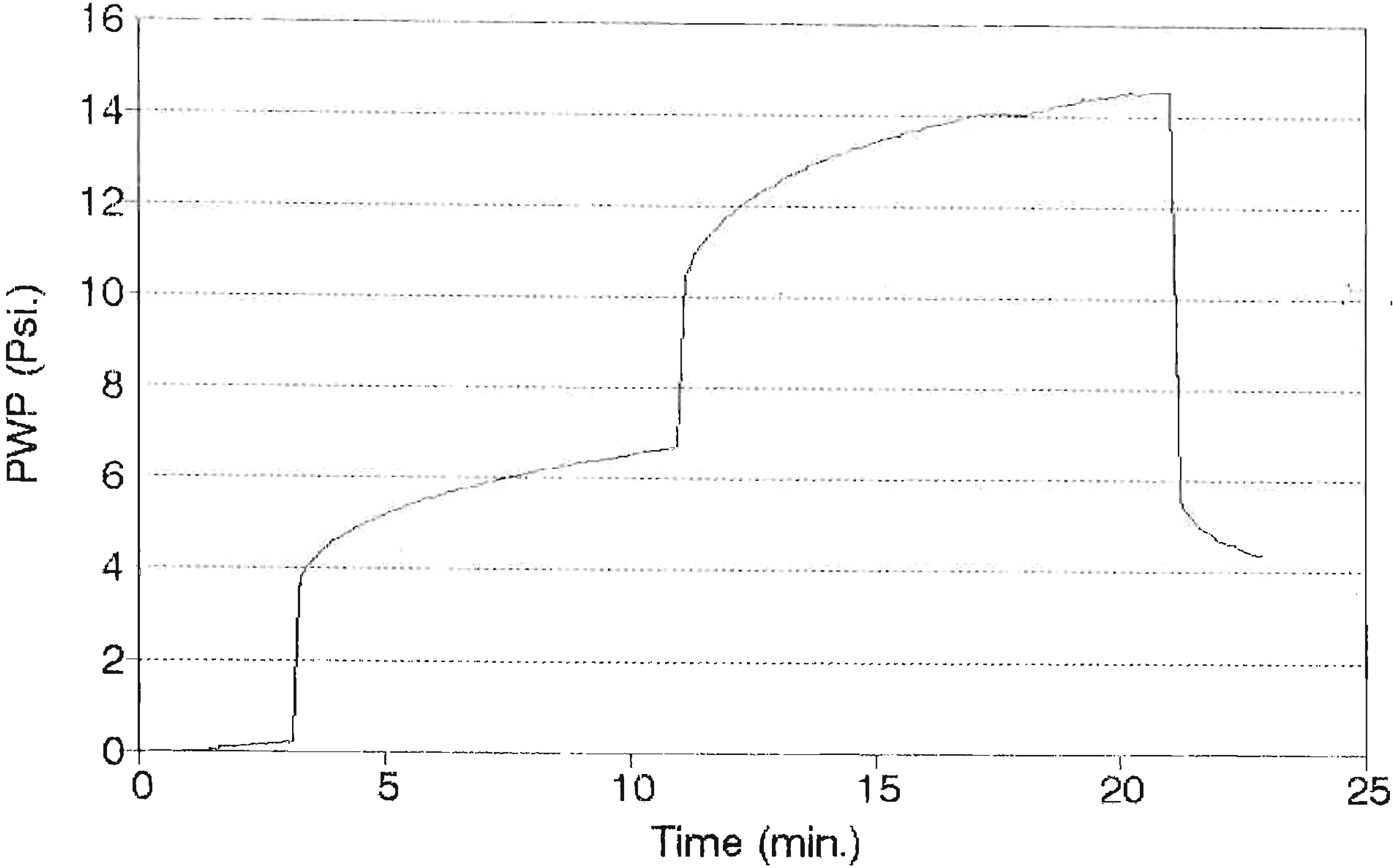
1 2 3 4

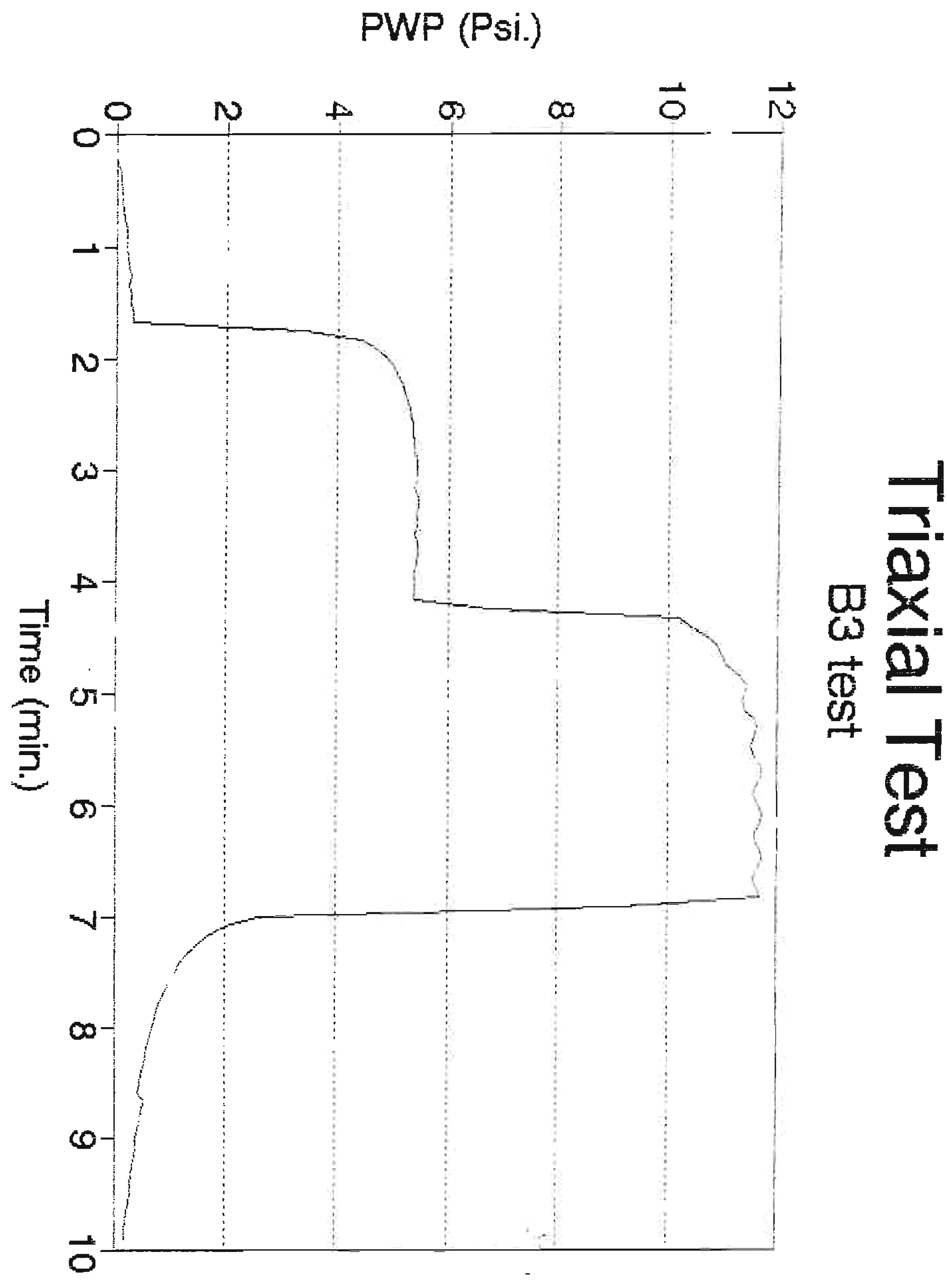

Shear Stress, τ, (Psi)
Effective Stress, σ', (Psi)
c' = 3 psi
φ = 27°
φ'


Triaxial Test
B1 test
PWP. (Psi.)
time (min.)
18
16
14
12
10
8
6
4
2
0
-2
0
1
2
3
4
5
6
7
8
9
10

Triaxial Test

B2 test

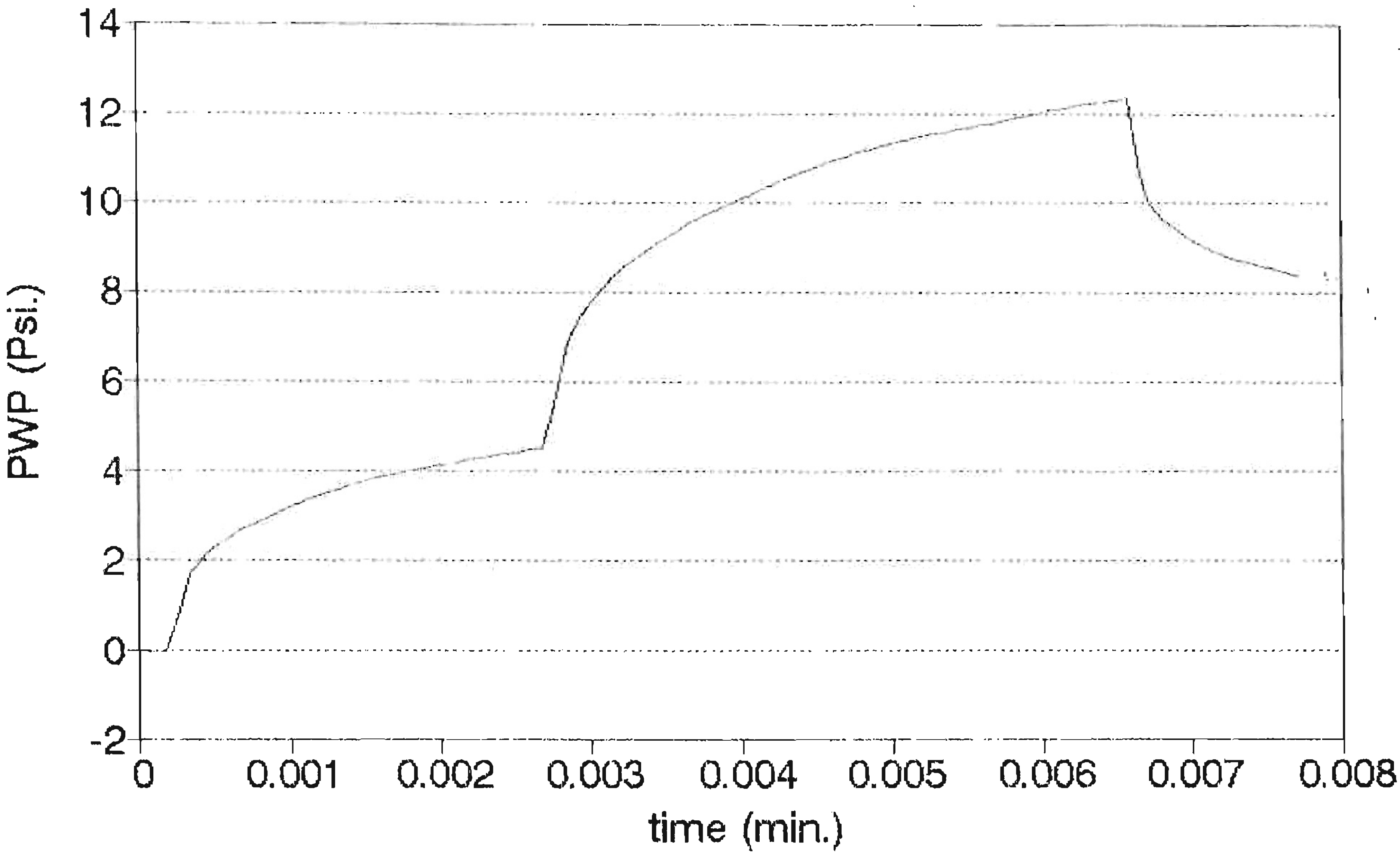


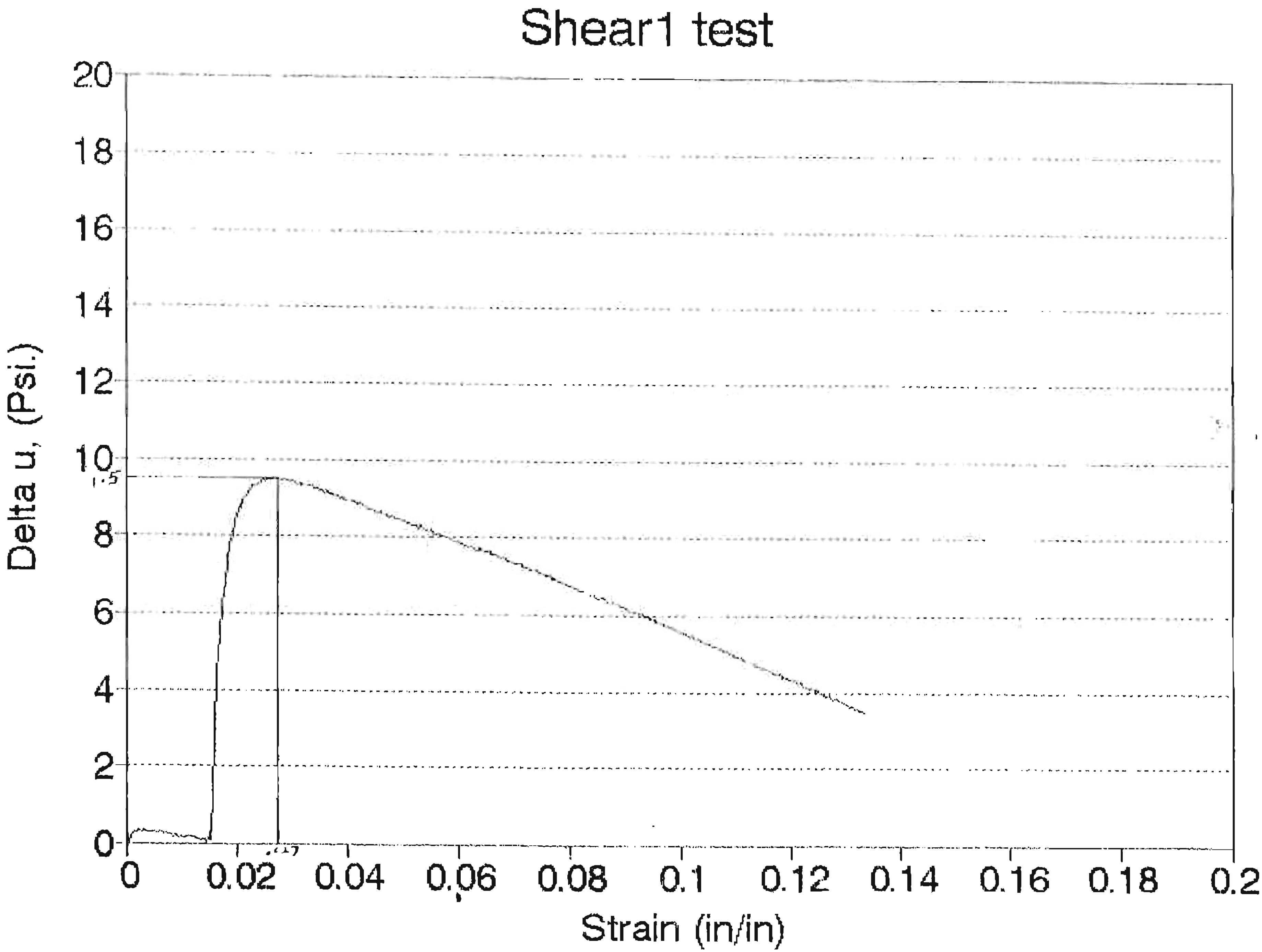


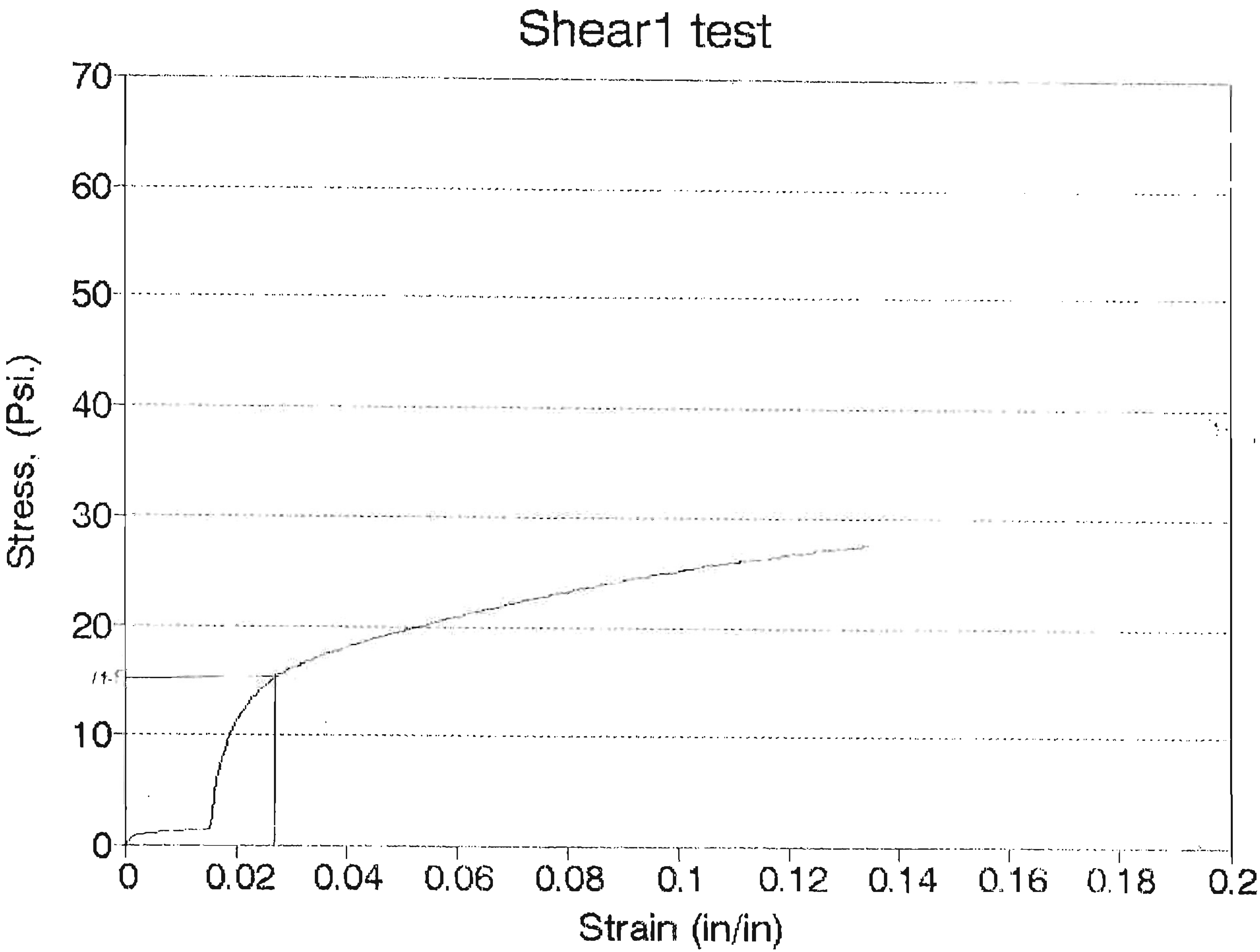
Triaxial Test
B3 test
PWP (Psi.)
Time (min.)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
9
10

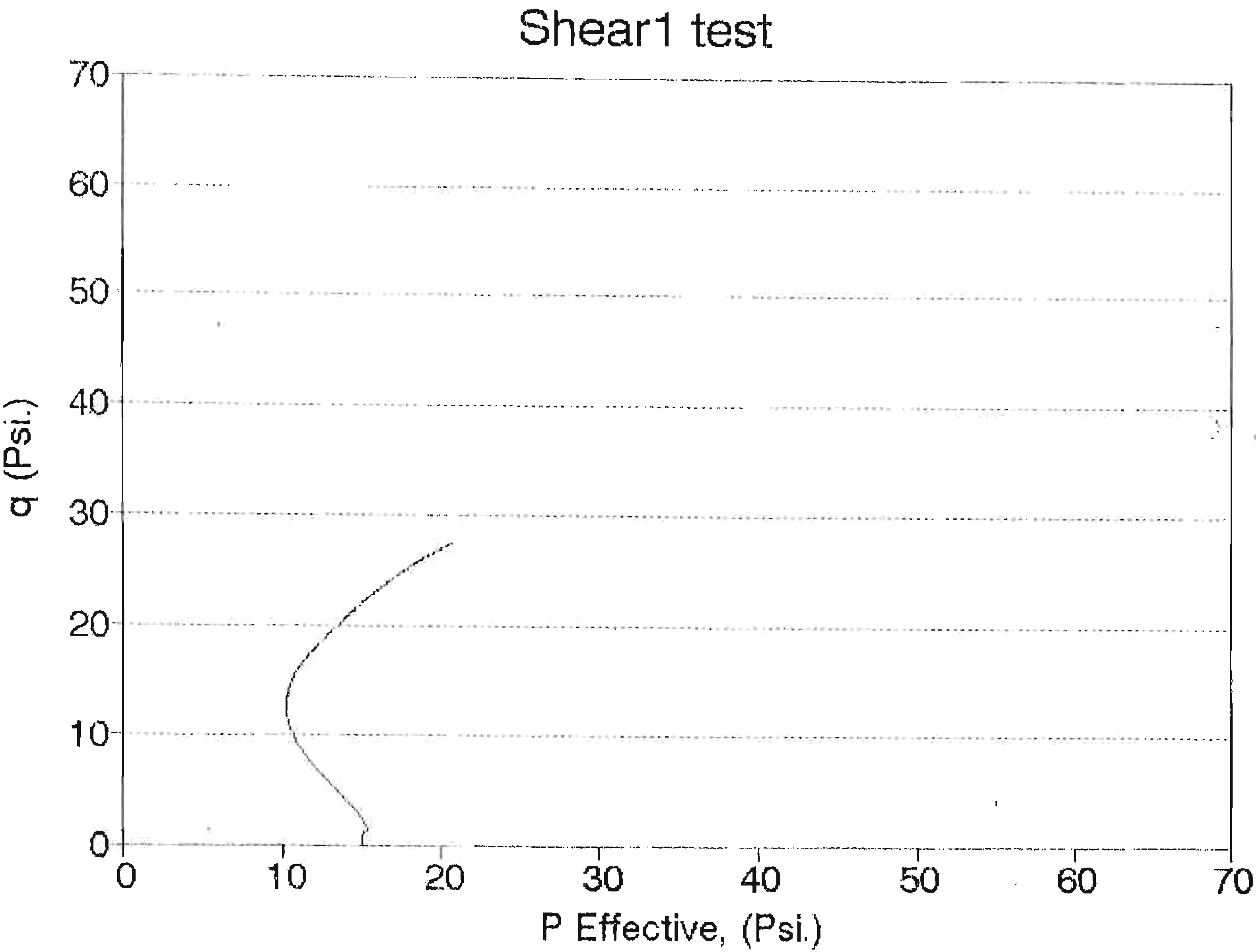
Triaxial Test

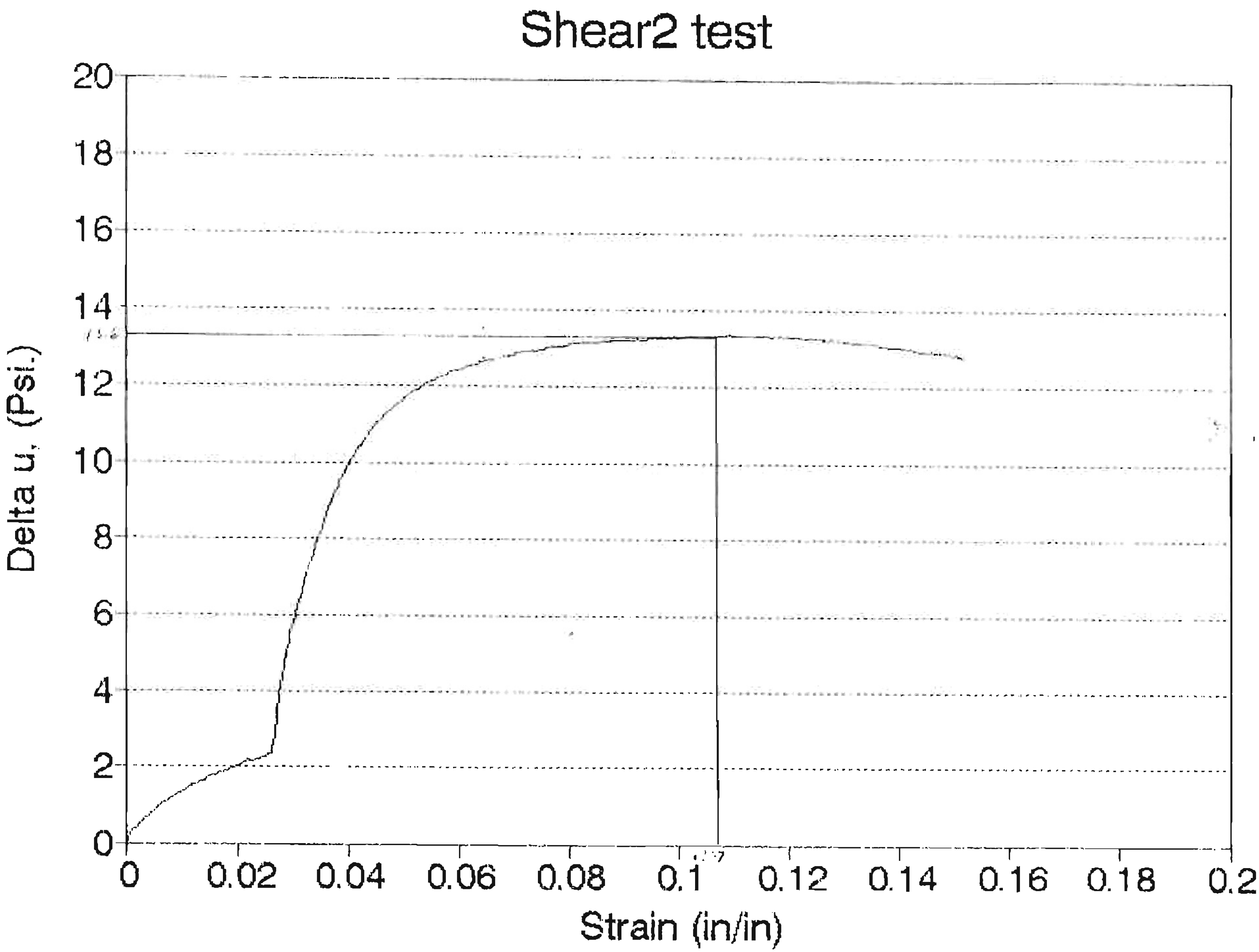
B4 test



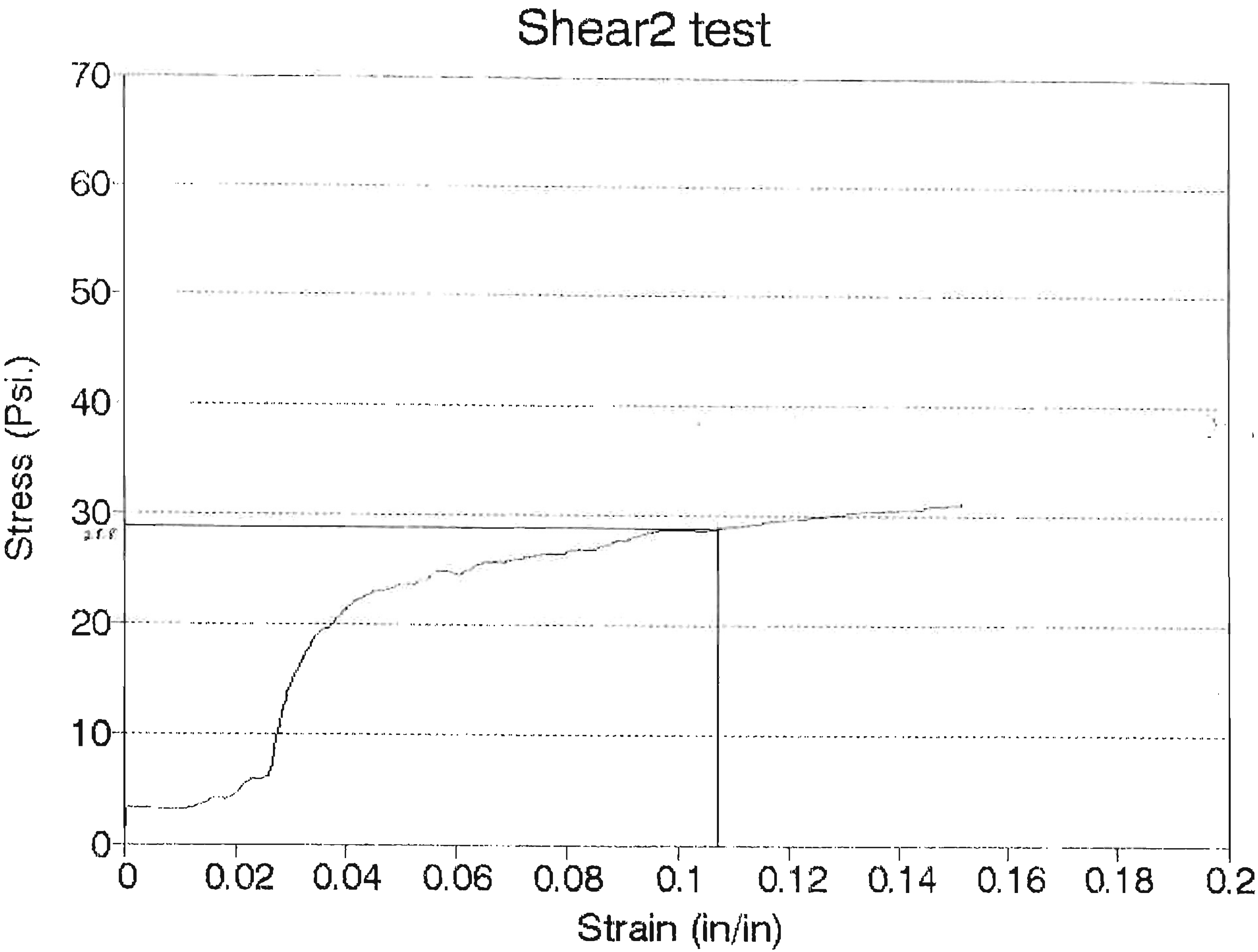

Shear1 test
Delta u, (Psi.)
Strain (in/in)
0
2
4
6
8
10
12
14
16
18
20
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2


Shear1 test
Stress, (Psi.)
Strain (in/in)
0
10
20
30
40
50
60
70
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

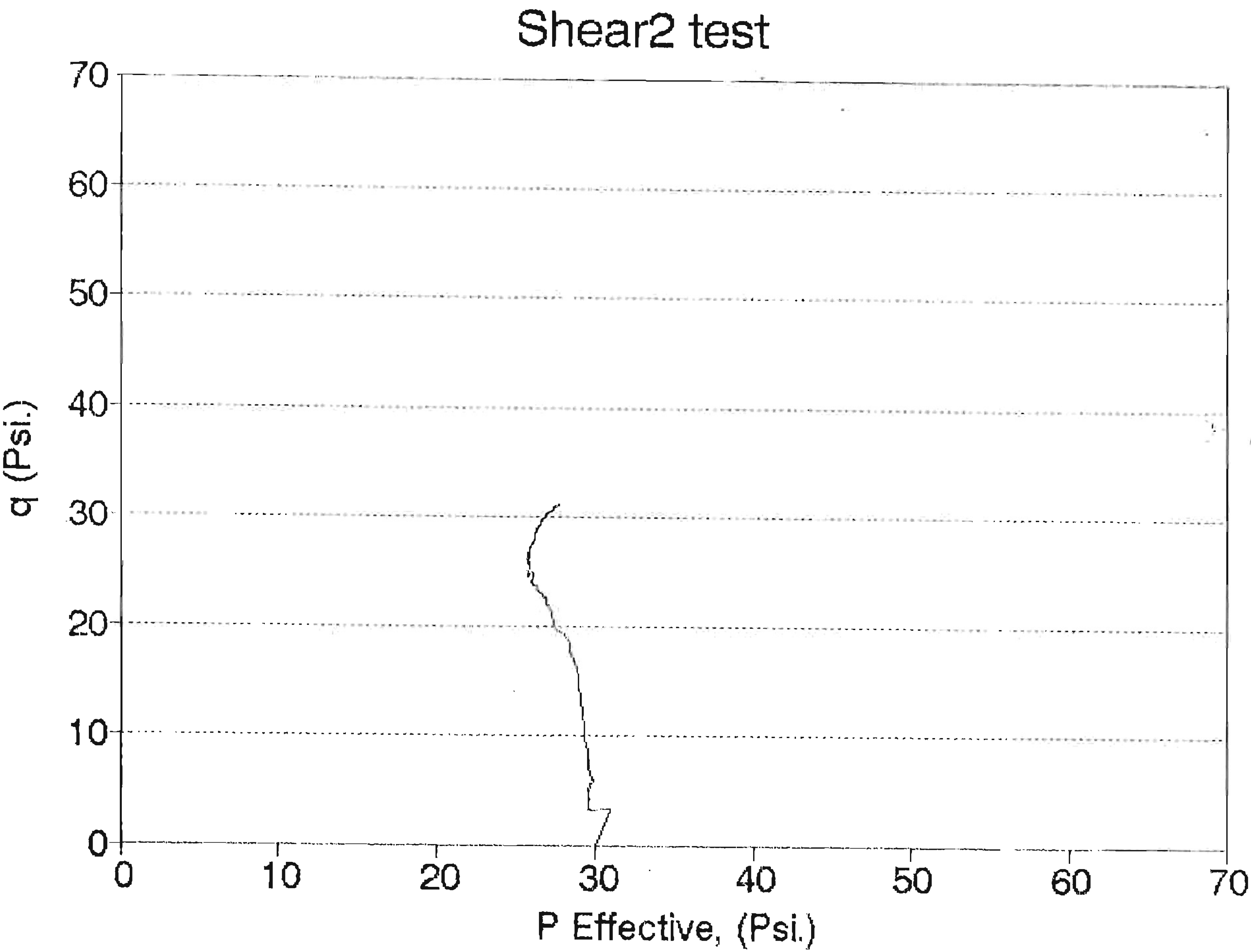

Shear1 test
q (Psi.)
P Effective, (Psi.)
0
10
20
30
40
50
60
70

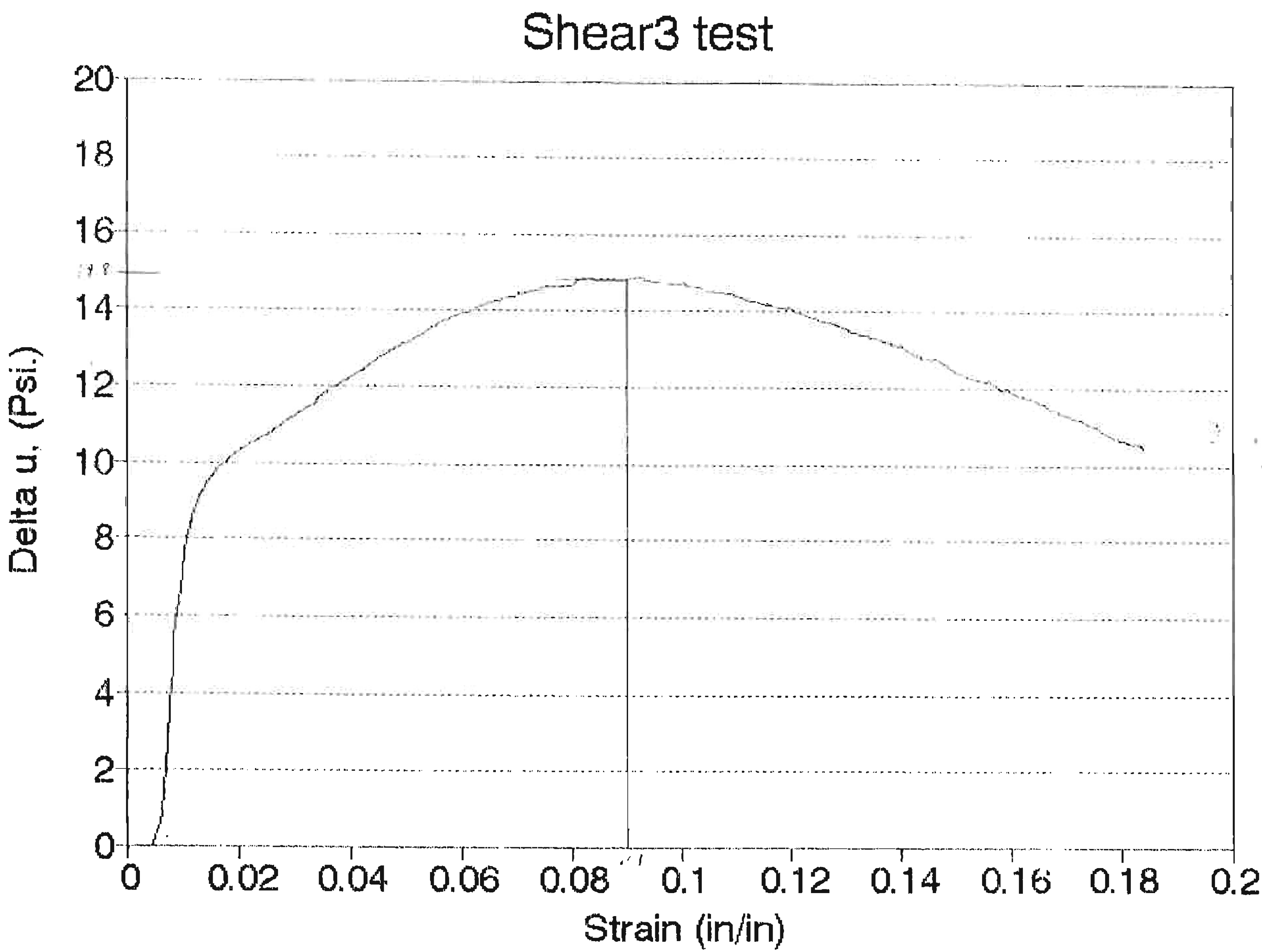


Shear2 test
Delta u, (Psi.)
20
18
16
14
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Strain (in/in)

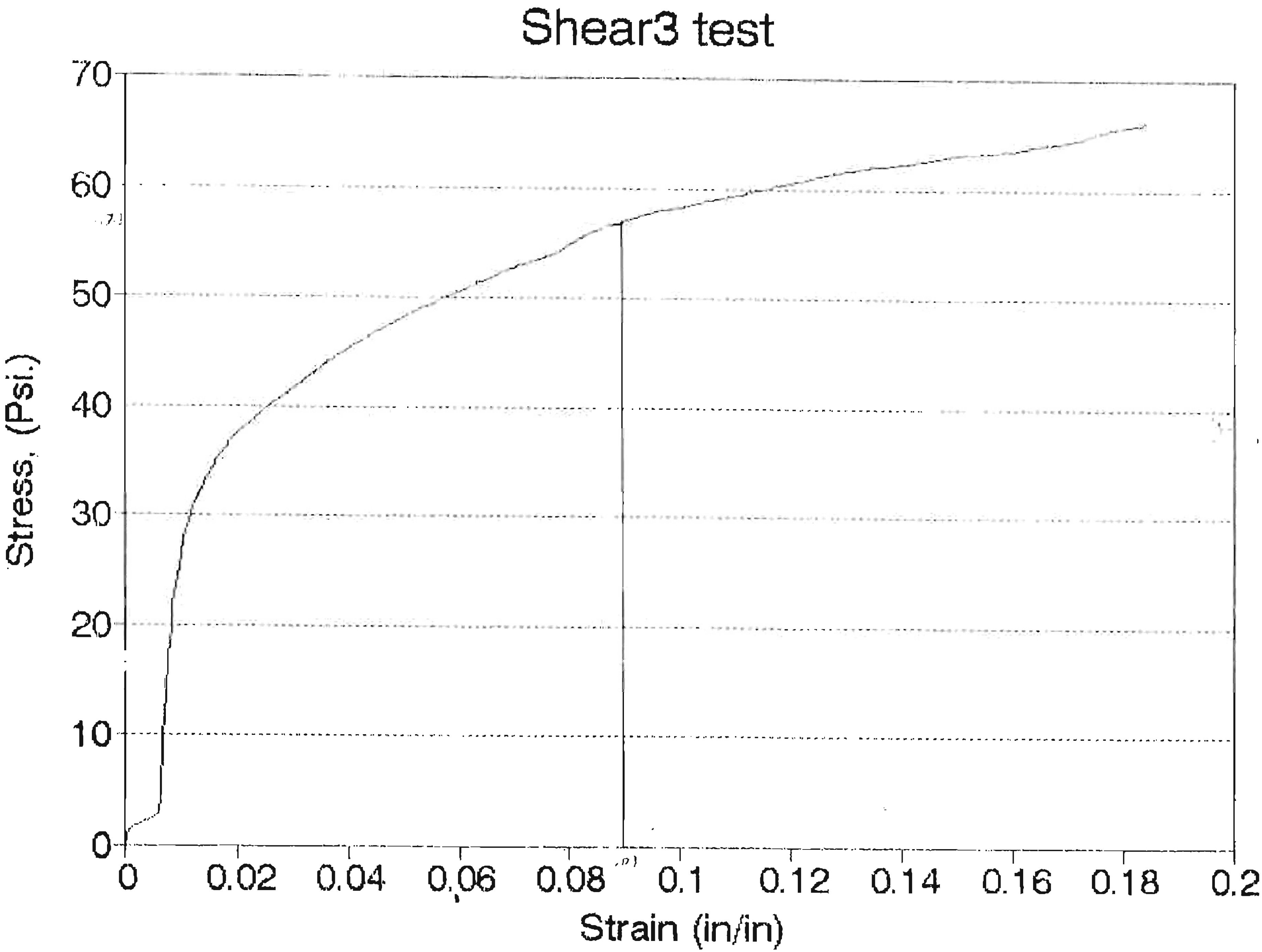


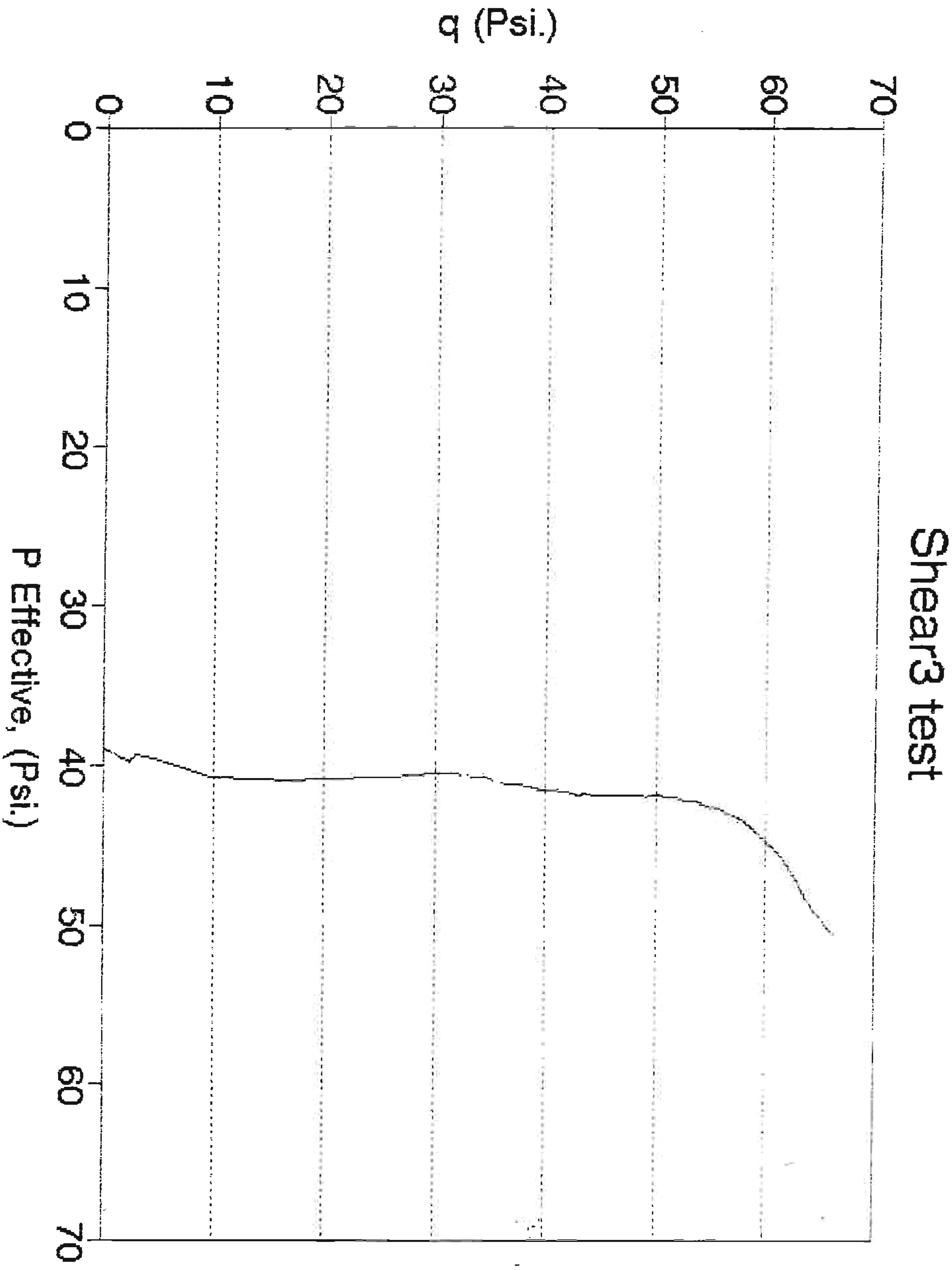
Shear2 test
Stress (Psi.)
Strain (in/in)
0
10
20
30
40
50
60
70
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

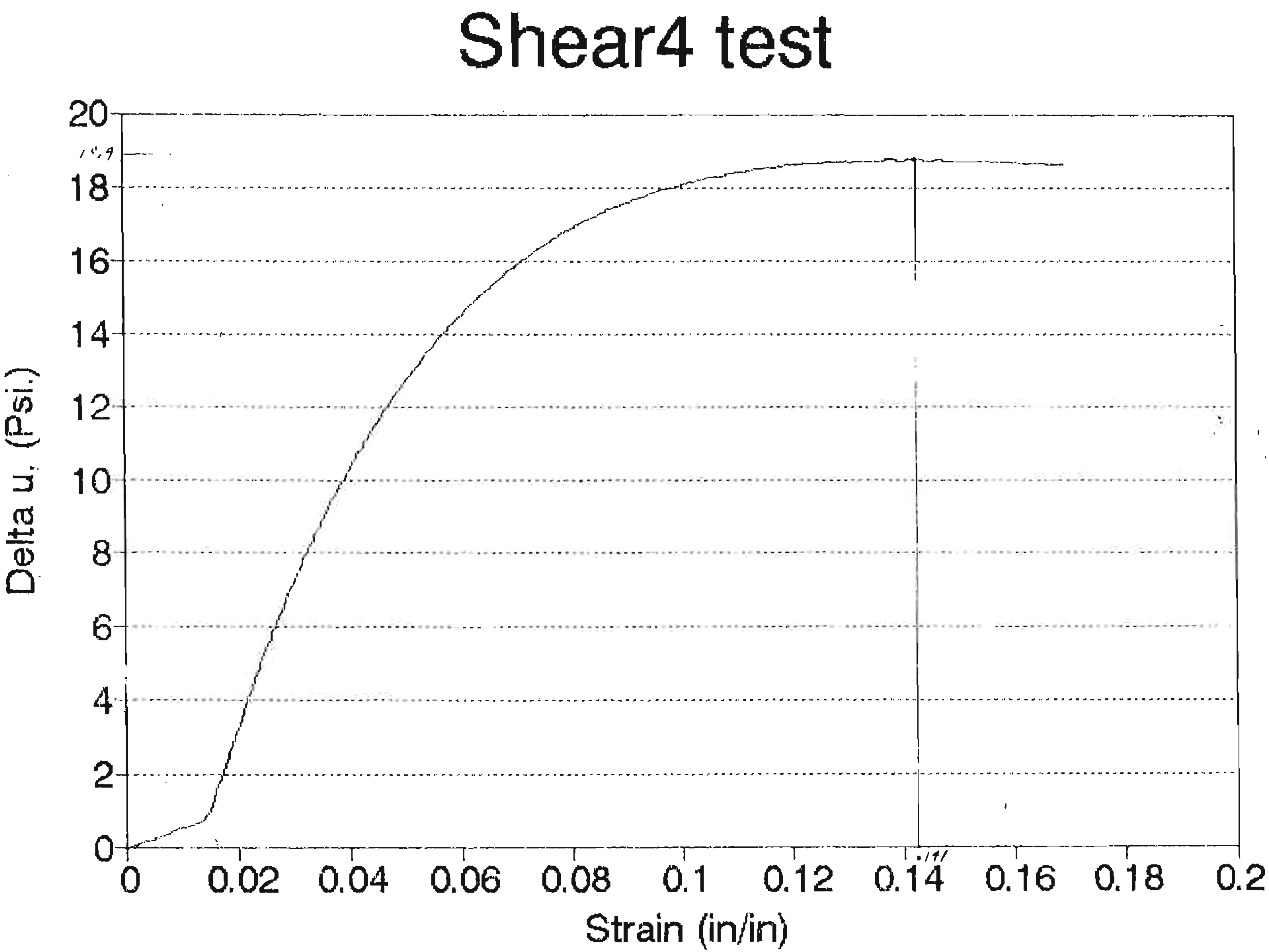

Shear2 test
q (Psi.)
P Effective, (Psi.)
0
10
20
30
40
50
60
70

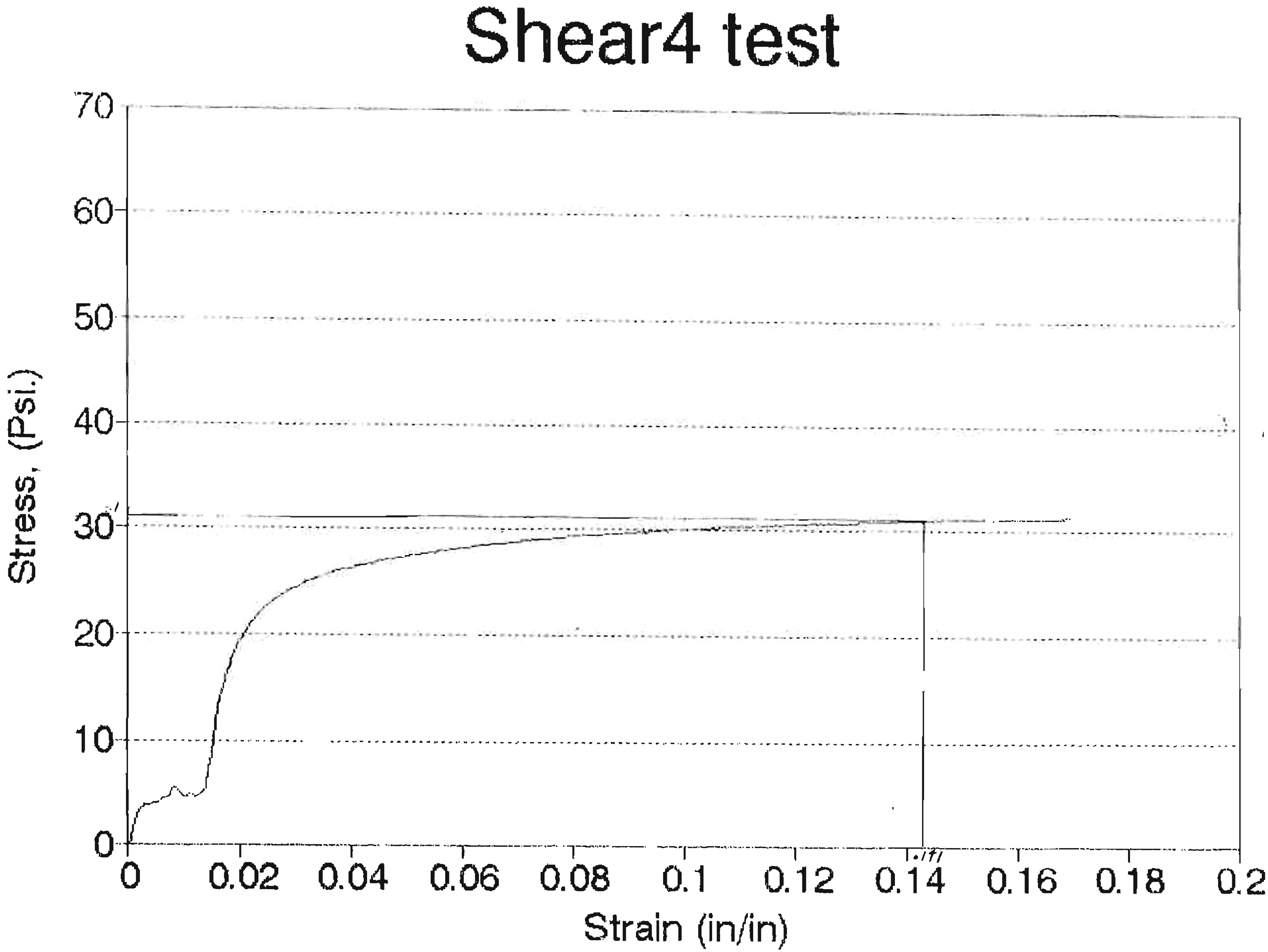


Shear3 test
Delta u, (Psi.)
20
18
16
14
12
10
8
6
4
2
0
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Strain (in/in)

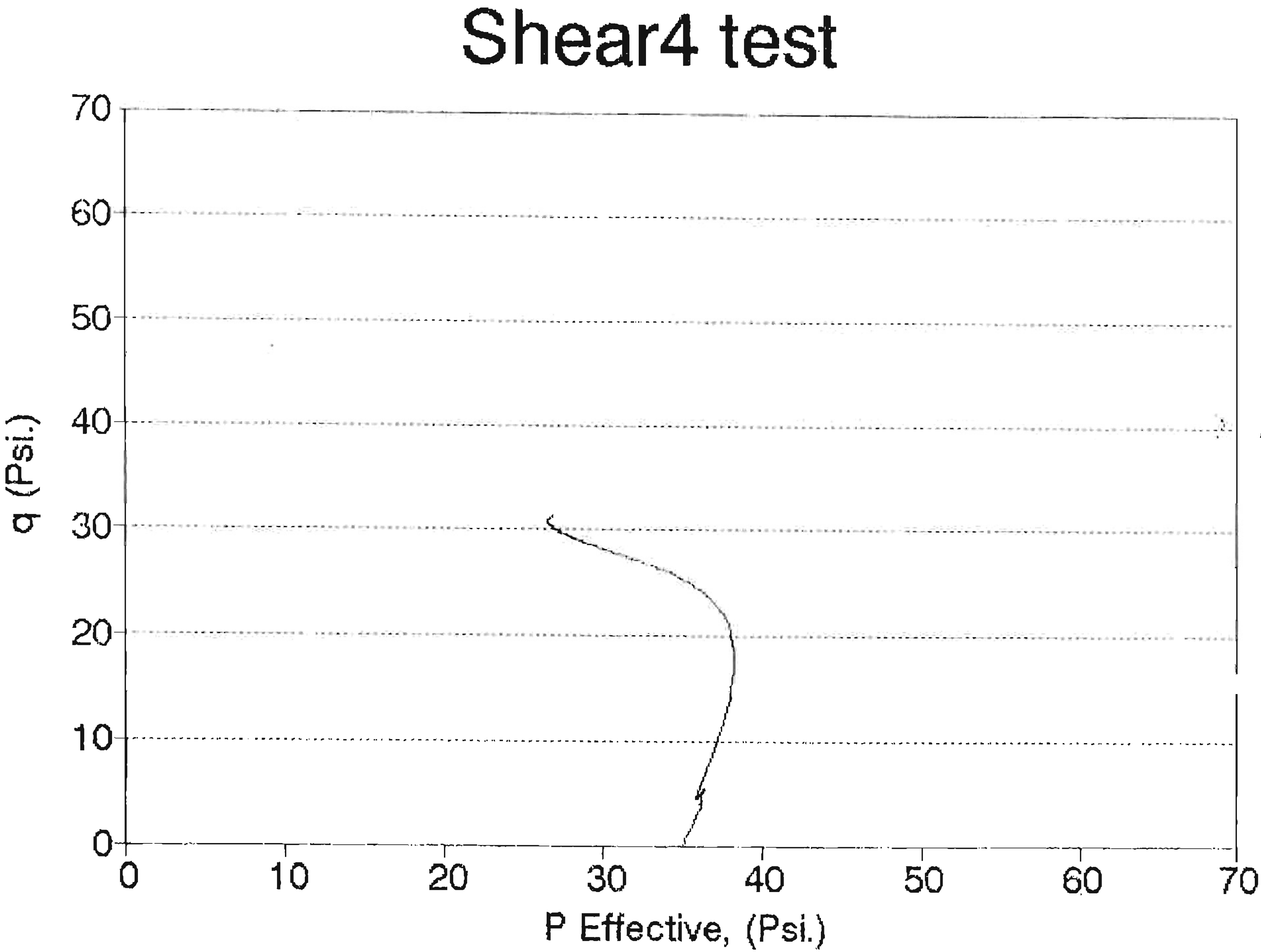

Shear3 test
Stress, (Psi.)
0
10
20
30
40
50
60
70
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
Strain (in/in)

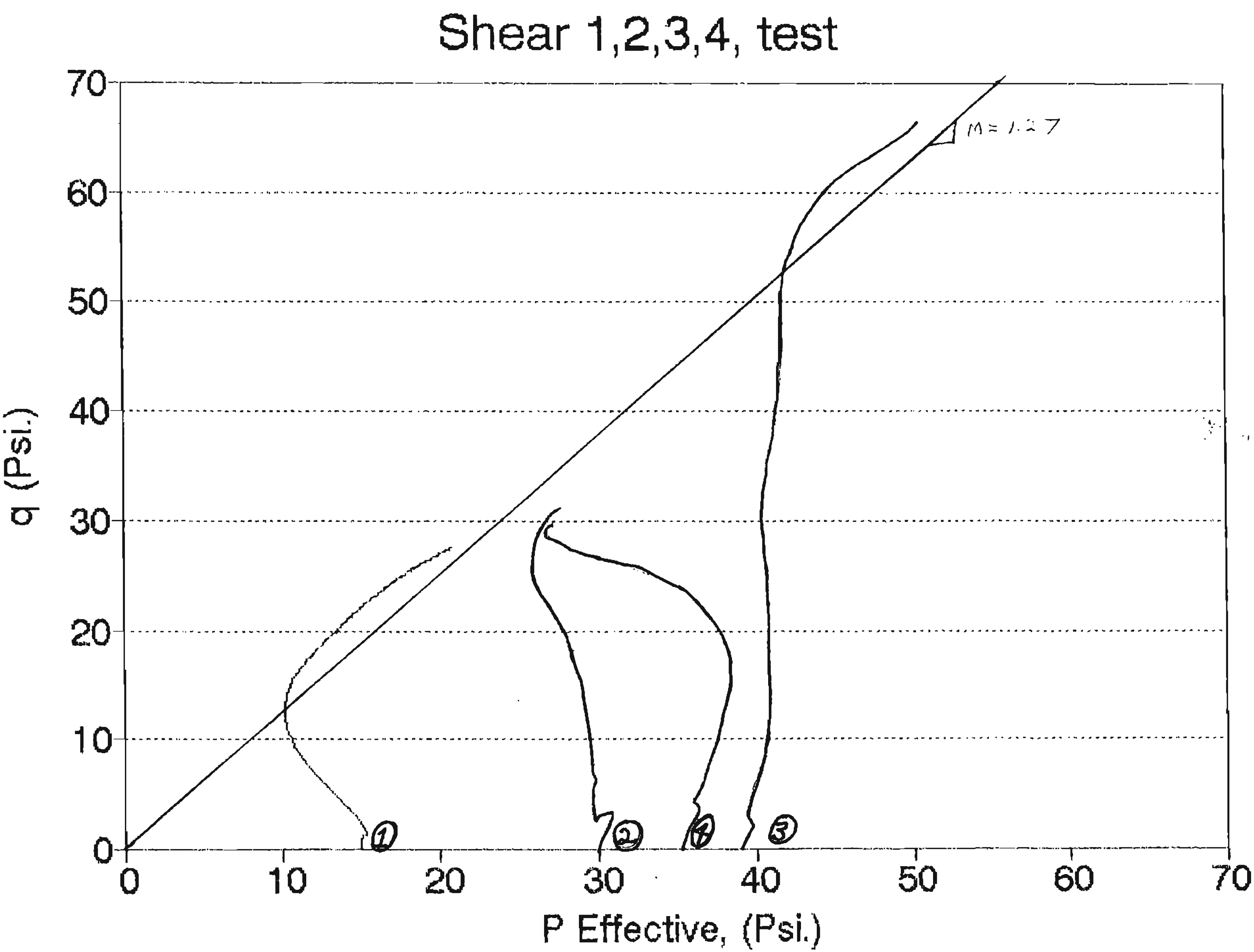

Shear3 test
q (Psi.)
0
10
20
30
40
50
60
70
P Effective, (Psi.)
0
10
20
30
40
50
60
70


Shear4 test
Delta u, (Psi.)
Strain (in/in)
0
2
4
6
8
10
12
14
16
18
20
18.9
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
.141


Shear4 test
Stress, (Psi.)
Strain (in/in)
0
10
20
30
40
50
60
70
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2

92


Shear4 test
q (Psi.)
P Effective, (Psi.)
0
10
20
30
40
50
60
70



Shear 1,2,3,4, test
q (Psi.)
P Effective, (Psi.)
0
10
20
30
40
50
60
70
1
2
3
4
M = 1.27