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Division of New Technology, Materials and Research
Office of Geotechnical Engineering

Final Report

FIELD AND LABORATORY PULLOUT RESISTANCE TESTS FOR FOUR SOIL REINFORCEMENT SYSTEMS

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16. Abstract

This report presents the results of field and laboratory testing of several configurations of earth reinforcing elements used in retaining wall systems.

Reinforcement elements were placed in zones of sand, gravel, and clay within a specially constructed embankment in the field and tested for pullout resistance. The same elements were tested in Translab's large scale pull box under similar conditions. During testing, horizontal forces and displacements were recorded at regular time intervals under constant overburden pressures.

Pullout resistance vs. displacement curves showed that lab tests were characterized by high initial pullout resistance which decreased with continued displacement while field tests showed low initial pullout resistance which increased with continued displacement. Sand and gravel provided similar pullout resistances which were both higher than clay. "C" channels with tee configurations and corrosion resistant elements produced higher pullout resistances than other elements. No correlation was found between overburden and pullout resistance in the field tests.

Field test results were generally inconsistent making pullout behavior difficult to characterize. Lab test results were high compared to field and should not be used as an estimate of field pullout resistance within the first 2-inches of displacement.

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NOTE : KEY TO ELEMENT TYPE

EX: MSE 3B 10 S

BASIC MATERIAL TYPE — SUB TYPE — OVER-BURDEN — BACKFILL MATERIAL

BASIC ELEMENT TYPE	SUB-TYPE	OVERBURDEN HEIGHT	SOIL TYPE
MSE - MECHANICALLY STABILIZED EMBANKMENT	1B - 1 BAR 2B - 2 BARS 3B - 3 BARS	5 - 5 FEET 10 - 10 FEET 15 - 15 FEET 20 - 20 FEET	S - SAND G - GRAVEL C - CLAY
TAT - TIRE ANCHORED TIMBER WALL	WS - WITH TIRE SIDEWALL WO - WITHOUT SIDEWALL		
CRR - CORROSION RESISTANT REINFORCEMENT	1D - 1 DISK 2D - 2 DISKS		
C2- - 2 FOOT LONG C-CHANNEL	PL - PLAIN (NO BAFFLES OR TEES) 1B - 1 BAFFLE		
C4- - 4 FOOT LONG C-CHANNEL	PL - PLAIN (NO BAFFLES OR TEES) 2B - 2 BAFFLES 1T - 1 FOOT TEE 2T - 2 FOOT TEE		

1. Introduction

The California Department of Transportation (Caltrans) has developed three systems of soil reinforcement since 1973: 1) Mechanically Stabilized Embankments (MSE), 2) Tire Anchored Timber (TAT) Walls, and 3) Salvaged Material Walls. When compared to conventional rigid retaining wall systems, soil reinforcement systems have proven to be cost effective, especially when constructed with low quality backfill.

In the past, Caltrans has developed a significant pool of information on pullout resistances of various types of reinforcing elements. This information was gathered by testing pullout resistances of different elements in a large laboratory shear box (1). The only field data produced by Caltrans was for the 1983 bar mat pullout testing of a MSE wall at Baxter, California (2). For this particular test, pullout resistances proved to be much higher than those produced with the same test configuration done in the lab. No other field pullout tests have been conducted.

Up through the early 1980's, laboratory testing was thought to be useful for developing design criteria for the many different reinforcing materials and geometric shapes available to Caltrans. However, in light of the disparities noticed in the one field test Caltrans has for comparison with lab results, laboratory testing was questioned as a useful method for predicting pullout capacity. This disparity could be caused by several factors such as compaction technique and/or increased lateral confinement in the lab tests relative to field conditions.

As a result, this research project was developed to evaluate a fairly wide variety of reinforcement sizes and shapes under field conditions. Several of the elements were also lab tested under similar conditions to substantiate the above disparity. Results would then be used as an overall predictor of realistic field pullout resistances for many varying geometric shapes, such as salvaged metal beam guardrails, "C" channel sections, and potential shapes that would be amenable to fiberglass extrusion processes.

1.1 Background Information

In 1973, Caltrans developed bar mats as an alternative to the patented flat steel strip reinforcing elements introduced by the Reinforced Earth Company (RECO). This

system, referred to as MSE, uses steel bar-mats as soil reinforcement and is called a passive earth restraining system, whereas the RECO's flat strip reinforcement is referred to as an active earth restraining system.

Laboratory pullout tests with the bar-mat reinforcement indicated that pullout force is resisted by friction between the soil and the longitudinal bars, and passive resistance by the transverse bars. Studies have shown that these factors substantially increased the pullout resistance over that of flat strips (1). This increased pullout resistance qualified low grade backfill as construction material for passive systems (2). The active restraining systems, however, required high grade backfill to develop high pullout resistance.

The first "Mechanically Stabilized Embankment" project was constructed on Interstate Route 5 near Dunsmuir, California in 1974 (3). The success of this project led to the construction of a MSE with a wood facing at Santa Barbara in 1984 (4), and four MSEs at Baxter in 1982 using low quality backfill (2).

The Caltrans recycling program encouraged the re-use of discarded transportation related materials. In late autumn of 1976, Caltrans constructed a project on Route 236 in the Santa Cruz Mountains using discarded automobile tires. A slide had occurred in a hillside fill at this remote location which was subsequently reinforced by tire side walls connected with #3 rebar clips to form continuous mats. The success of this project led to the development of the Tire Anchored Timber (TAT) Wall (5). The TAT consists of tire side walls that grip steel cross bars which, in turn, are welded to a tie-back anchor bar. Like the MSE, TAT is a passive restraining system and can be constructed using low quality backfill.

This recycling program has also prompted the use of recycled guardrail materials in the construction of experimental salvaged material walls. "C" channels from recycled guardrails were used as reinforcing elements for a wall facing that was made up of W-type guardrail sections. To date, no field testing has been performed on this "C" channel system.

Several methods of evaluating the performance of soil reinforcement systems prior to their implementation have been developed. Many of these methods were reported in

the 1978 ASCE Symposium on Earth Reinforcement (6). One method of evaluating the internal stability of these passive systems is based on laboratory tests (7).

The internal stability of a soil reinforcement system depends upon the pullout resistance of its reinforcing elements. Therefore, their size, shape, surface characteristics, soil strength parameters, and in-situ soil stress conditions are important parameters for understanding pullout behavior. Although the theoretical means for computing the relative contributions of each of these factors are available, actual supporting data is very limited.

This deficiency in data for passive earth reinforcing elements has prompted this investigation. Furthermore, Caltrans designers require a reference manual for design purposes. This report aims at verifying the unconservative nature of laboratory testing and presents a comprehensive set of design specifications for various types of earth reinforcing systems in 3 different soil types useful for subsequent designs.

1.2 Research Objectives

The specific objectives of the project as submitted in the research proposal dated April 16, 1987 were as follows :

1. Determine the pullout resistance of MSE, TAT, Salvage Material and CRR wall reinforcement in three soil types (frictional, cohesive, and cohesive frictional) under controlled field conditions.
2. Determine the pullout resistance of MSE, TAT, Salvage Material and CRR wall reinforcement in the laboratory using the same soil under the same conditions as the field tests.
3. Compare and evaluate the relationships (if any) between field and laboratory test data.
4. Develop design curves for the pullout resistance of each of the four soil reinforcement systems based on:
    a. Soil strength parameters
    b. Configuration of the tested reinforcement
    c. Overburden pressures

2. Experimental Design

2.1 Project Layout

A two phase experimental approach was used to accomplish the objectives of this research. Phase one involved the testing and evaluation of the soil reinforcement elements based on controlled field conditions. The second phase involved the replication of some of the tests done in phase one using a large scale laboratory pullout testing device.

In phase one, selected soil reinforcement elements were placed in a specially constructed test embankment under 5, 10, 15, and 20-foot overburdens. Soil reinforcement elements were then pulled horizontally to failure or up to the maximum pull capacity of about 8-inches. The test embankment consisted of three different soil types: gravel, sand, and clay. The embankment materials were compacted to 95% relative compaction. Field and laboratory testing of the embankment materials established their strength parameters and material characteristics. Details of the test embankment materials, embankment construction, and the configurations of the soil reinforcement elements are discussed in the following sections. Some of the tests were replicated in order to substantiate their results.

In phase two, laboratory pullout tests simulating the field embankment tests were performed using the large scale pullout box. Soil reinforcement elements were salvaged from the field, visually inspected for damage, and reused in the laboratory. Large quantities of soil representing the three materials were obtained after completion of the field testing and used in the laboratory tests. The laboratory tests were set up to simulate field conditions: i.e. soil densities, moisture content and loading conditions. Embedded soil reinforcement elements were then pulled to failure or to the maximum pull capacity at displacement rates similar to those used in the field tests.

Laboratory procedures are discussed in detail and will be presented later. "Stage" tests were performed in order to save time and money by using the same element for two different overburden pressures. Stage testing is a procedure in which a pullout test starts at a low overburden pressure, stops at a prescribed displacement (about 2-inches), then restarts at a higher overburden pressure and proceeds until the test is terminated.

2.2 Soil Reinforcement Element Types

Various configurations of test elements representing four different "State Design" wall systems were selected for testing. These systems include:

1. Bar-mat reinforcement used in Mechanically Stabilized Embankments;
2. Steel reinforcement with tire side wall anchors used in Tire Anchor Timber walls;
3. Salvaged "C" channel reinforcement used in salvaged material walls;
4. Corrosion Resistant Reinforcement used in developing the corrosion resistant wall system. This system uses reinforcement comprised of rebar encapsulated in plastic and concrete.

Various configurations of reinforcing elements for each of the four wall systems were fabricated and tested to determine their maximum pullout forces. A total of 13 test elements were used and are described below; three MSE bar mat configurations with 1, 2, and 3 transverse bars, two TAT element configurations with and without a tire side wall attached, two CRR configurations consisting of elements with 1 passive disk and 2 passive disks, and two groups of "C" channels with 2-foot and 4-foot lengths. Among the 2-foot "C" channel configurations were elements with no baffles and one baffle. A baffle is a steel plate welded vertically within the channel groove developing passive resistance. Among the 4-foot "C" channel configurations were elements with either no baffles, two baffles, a 1-foot wide section of "C" channel welded to the end in a tee fashion, or a 2-foot wide channel section welded on its end. Figures 1 through 4 show the configurations and dimensions for each of the 13 tested reinforcement elements. Photos of selected test elements are also shown in photos 1 through 10.

2.3 Test Soil Types

Three different soil types, namely gravel, sand, and clay, were used to represent the probable extremes in soil conditions encountered in wall construction. The descriptions of these three soil types are as follows :

1. Coarse crushed river gravel, uniformly graded passing the 1 1/2" sieve and retained on the #4 sieve.
2. Clean medium to fine sand, uniformly graded, passing the 3/8" sieve and retained on a #200 sieve.
3. Brown overly consolidated highly plastic Olavia clay.

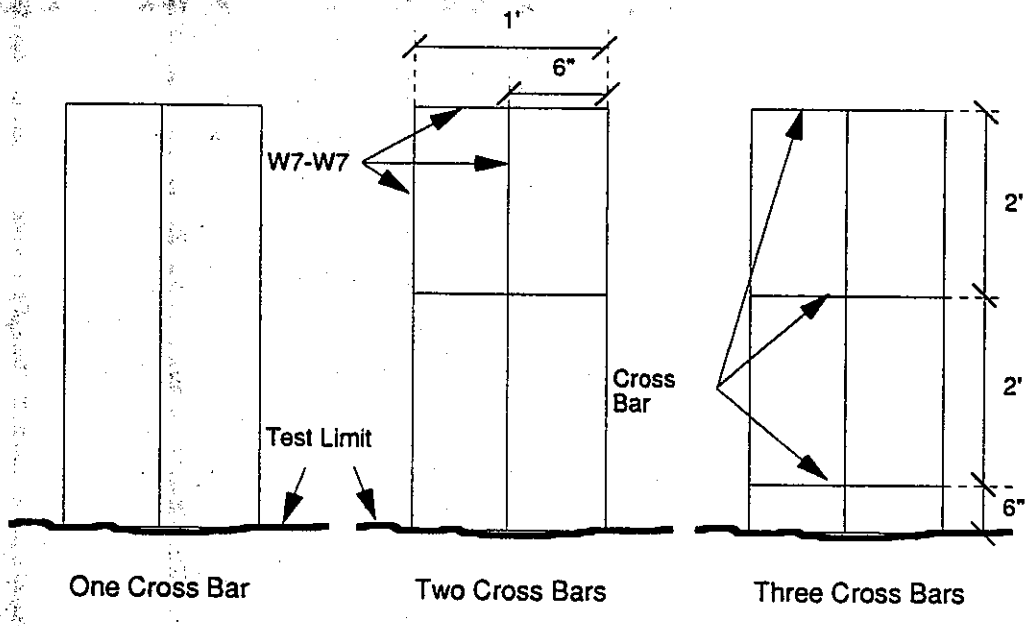


Figure 1. MSE Bar-mat configuration for field and laboratory tests.

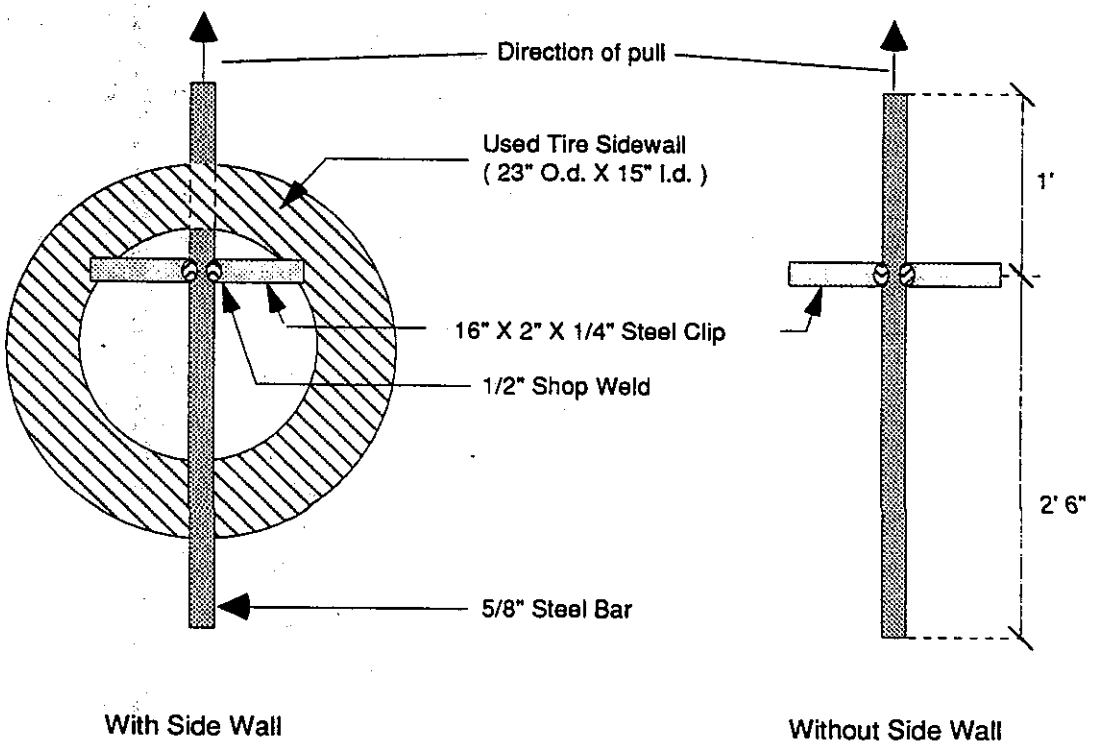


Figure 2. Tire Anchor configuration for field and laboratory tests.

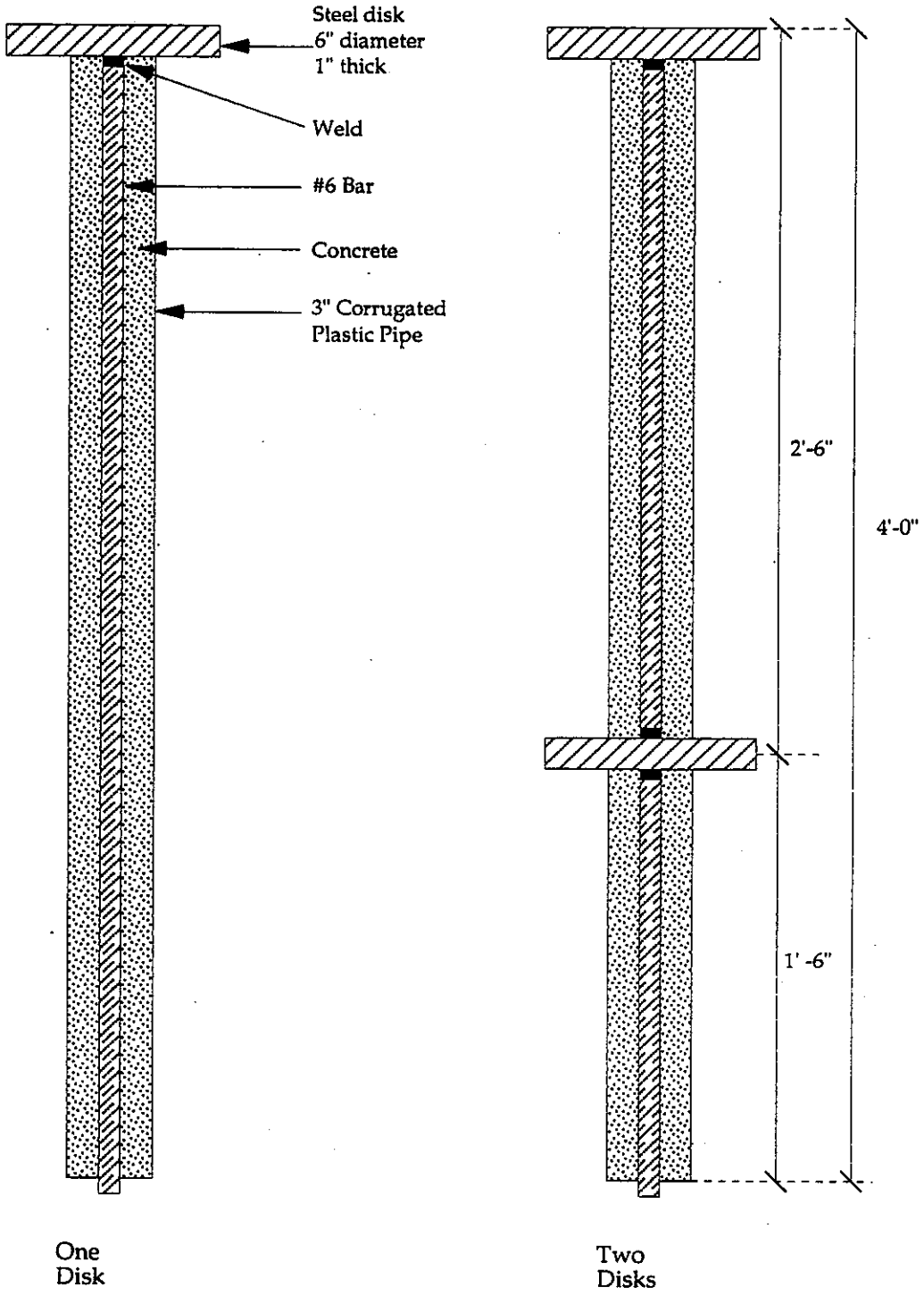
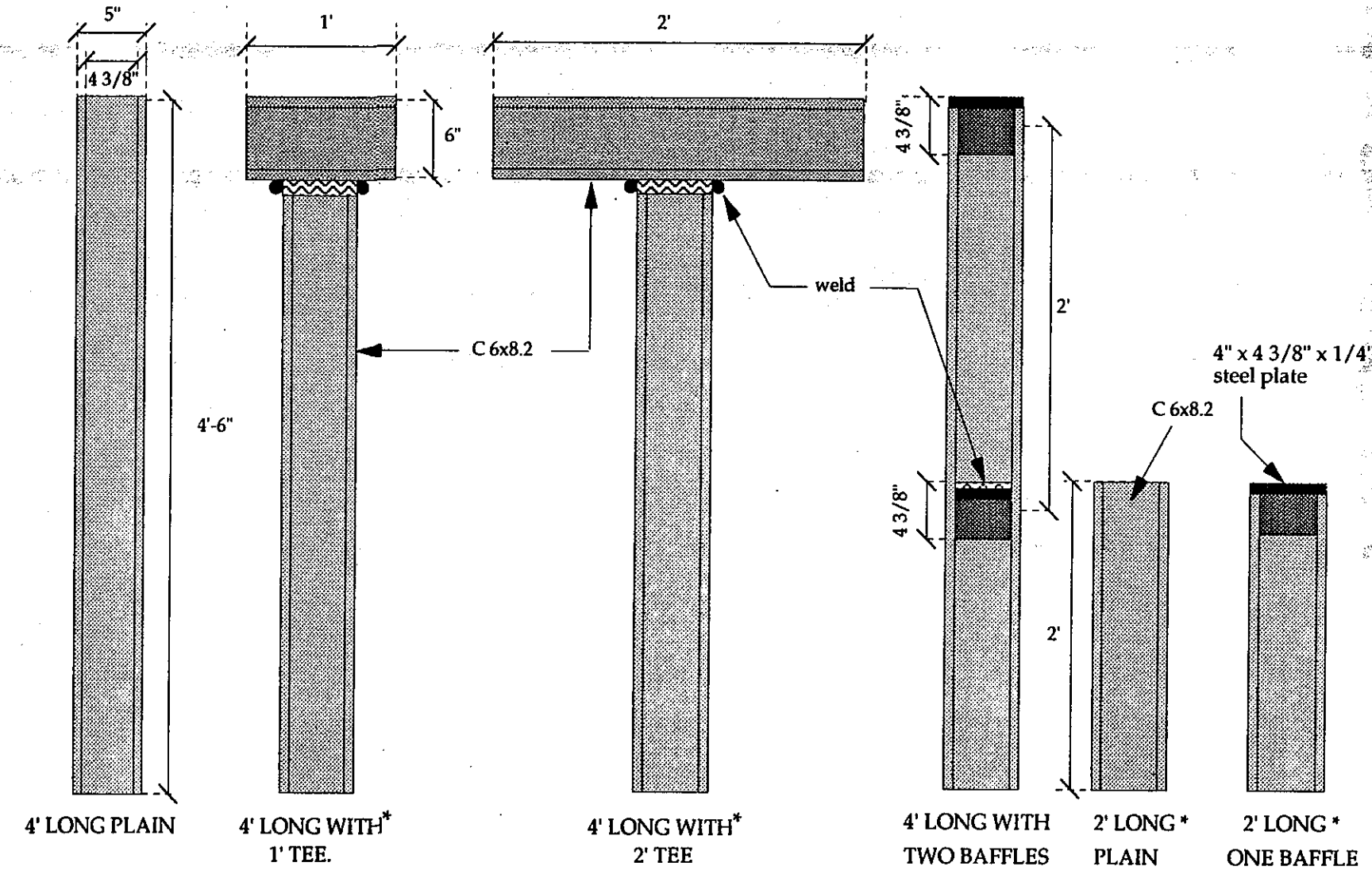


Figure 3. Corrosion resistant configuration for field and laboratory tests



* not tested in the laboratory

Figure 4. "C" channel configuration for field and laboratory tests

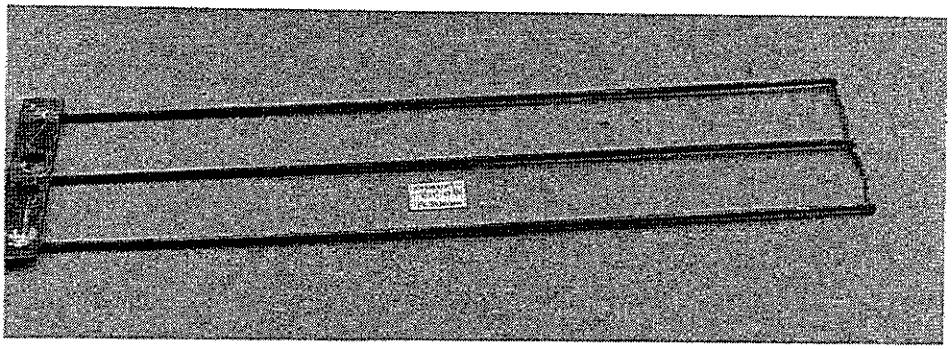


Photo 1. MSE with one transverse bar

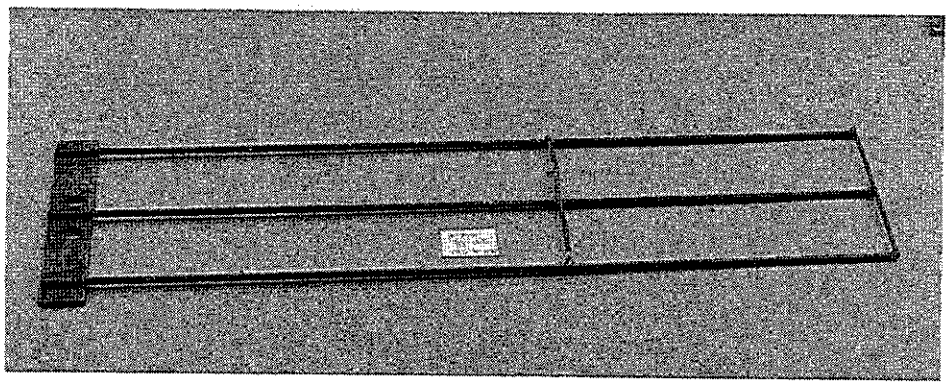


Photo 2. MSE with two transverse bars

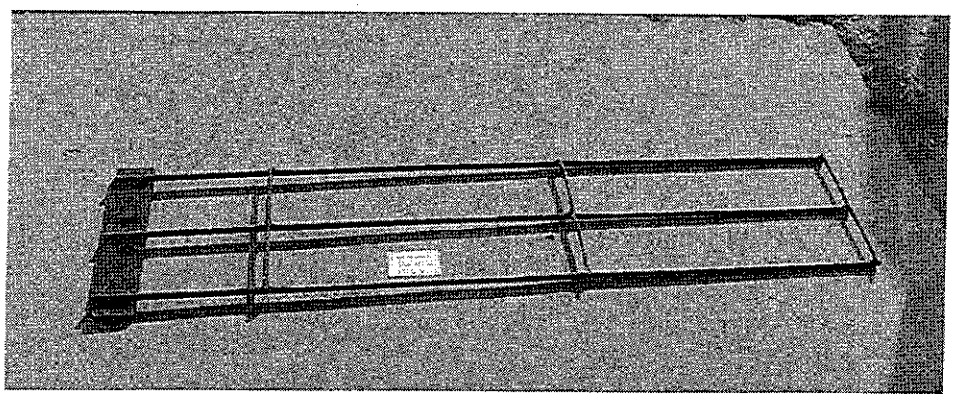


Photo 3. MSE with three transverse bars

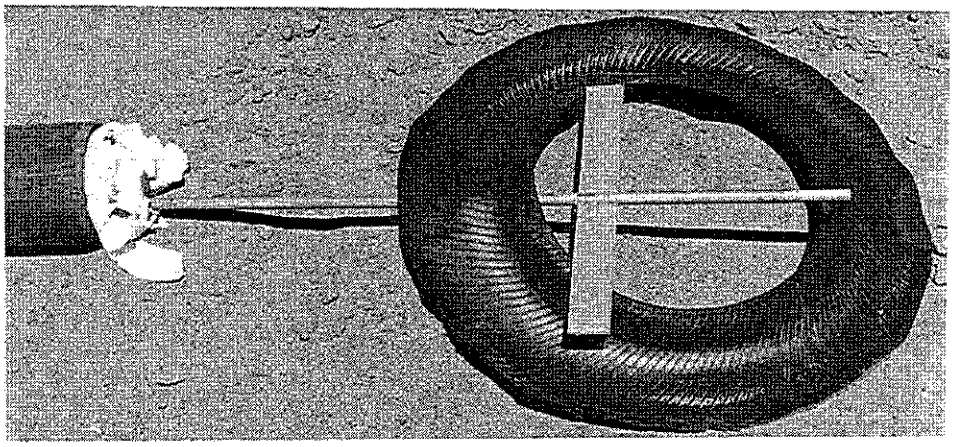


Photo 4. TAT element with tire sidewall

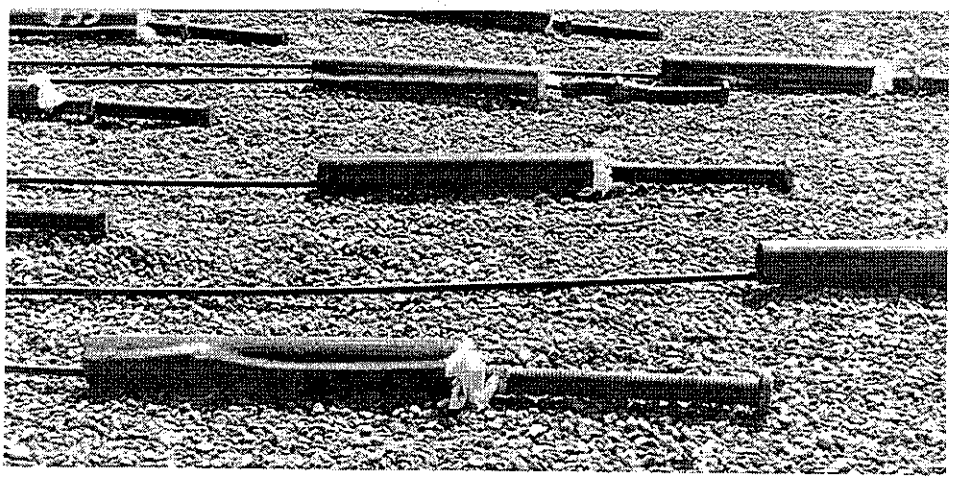


Photo 5. CRR element with one disk

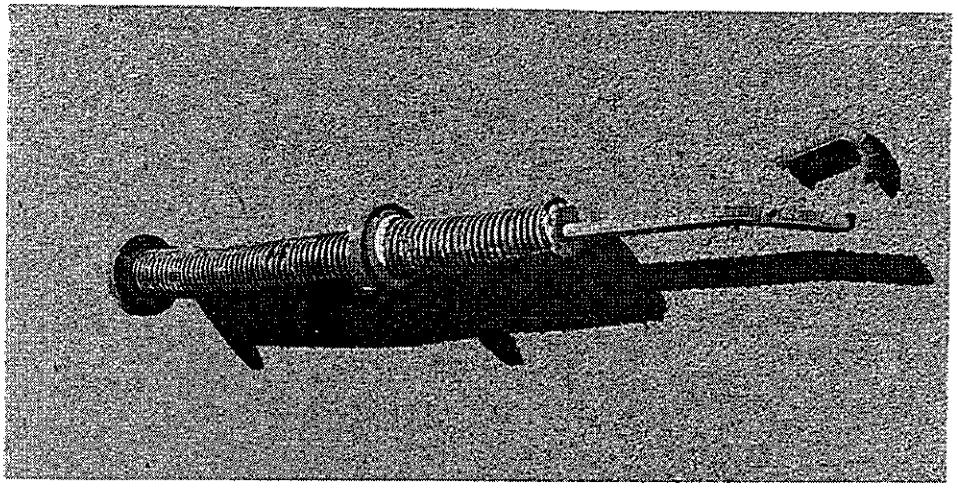


Photo 6. CRR element with two disks

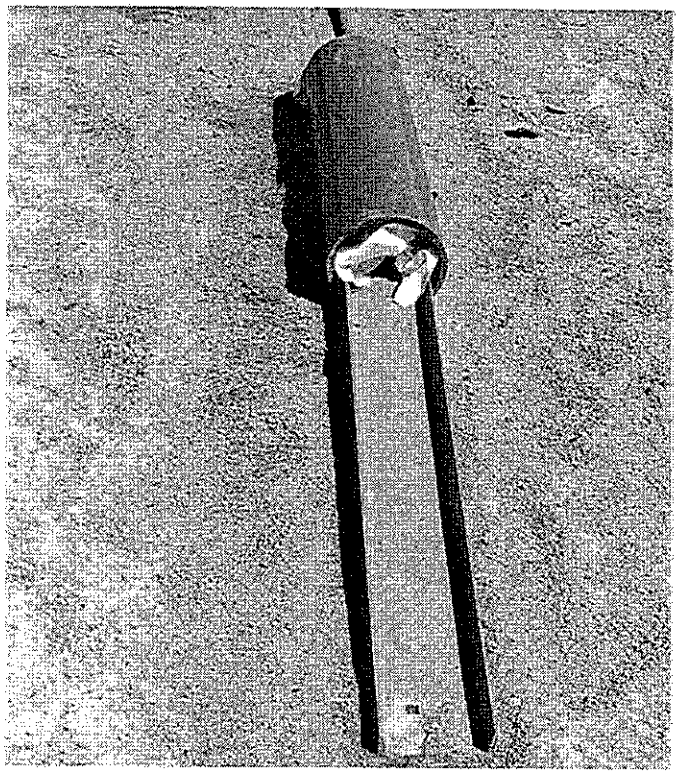


Photo 7. 4-foot plain "C" channel

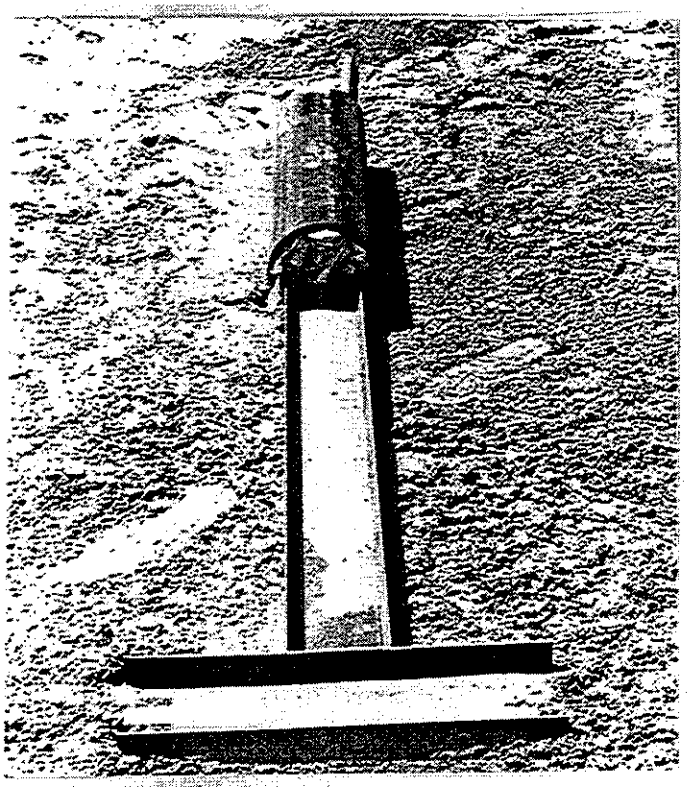


Photo 8. 4-foot "C" channel with a 2 -foot tee

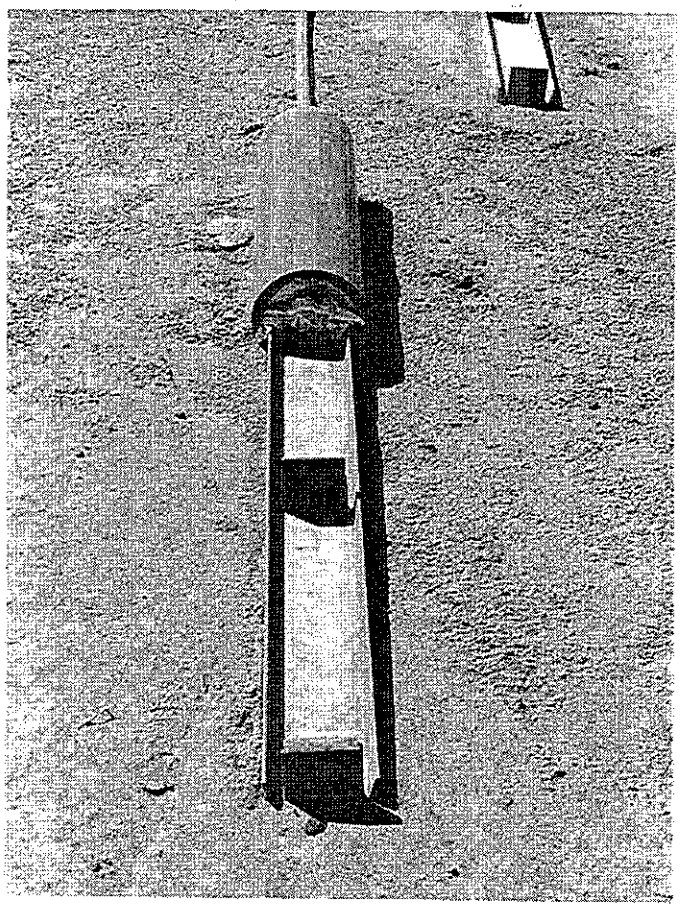


Photo 9. 4-foot "C" channel with two baffles

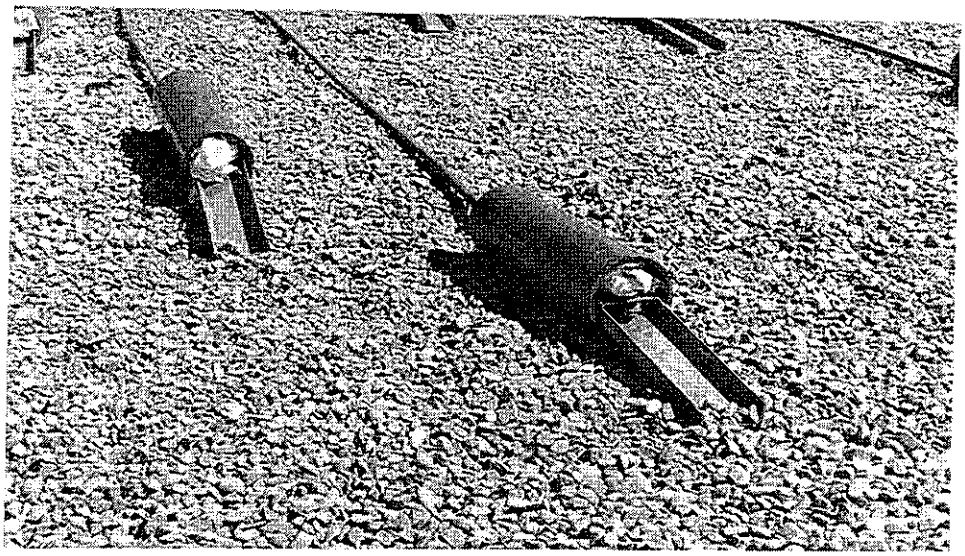


Photo 10. 2-foot plain "C" channel

The test soil properties are summarized and presented in table 1 and include the results from staged triaxial shear tests, Atterberg limit tests, in-situ density tests, moisture content tests for the clay and sand, and dry density tests. Unified soil classifications for all three types of soil are also included. The grain size distributions for the test soils are presented in figure 5.

2.4 Construction of the Test Embankment

A test embankment was constructed at the Sacramento River by-pass approximately 500-feet downstream from the Sacramento River weir. Figure 6 shows the vicinity and site map of the test embankment. The test embankment measured about 24-feet in height and about 250-feet in length with 1.5:1 side slopes and 4:1 and 2:1 end slopes. The 4:1 end slope was constructed as an equipment approach ramp. Figure 7 shows the geometry of the test embankment. The material used to construct the test embankment consisted of native silt and clay (filler). Material used for testing, sand, gravel, and clay, was placed in three zones within the embankment. The sand and clay materials were native to the site, while gravel was purchased and transported to the site. The soil reinforcing elements (SREs) were positioned within the selected zones at varying distances from the centerline of the embankment to provide the desired 5, 10, 15, and 20-foot overburden conditions (Figure 8). The SREs were placed between layers of compacted test soil in two levels. The layers containing the test elements were then covered with filler. Compaction equipment was used in such a manner that there was no contact between the SREs and the equipment (see Photo 11).

The filler material was transported from an adjacent borrow site to the embankment site with a D7 track layer dozer and a 25 yard capacity rubber tire earth mover (Photo 12). A 95% relative compaction throughout the embankment was achieved using a steel vibratory drum roller in 8-inch lifts. A water truck provided additional moisture as needed during the construction of the embankment and compaction control was maintained by using a nuclear gage. The average in-place wet densities of the clay and sand were roughly 110 pcf and 120 pcf, respectively. The dry density of the gravel was approximately 105 pcf.

Each SRE was outfitted with a cable (passed through 1-inch PVC pipe to prevent contact between the soil and the cable) which exited the embankment at the slope face. Extra

TYPE OF TEST	CLAY	SAND	GRAVEL
Triaxial			
a) Angle of Internal Friction (degree)	21.0 *	39.3 *	45.0**
b) Cohesion (psf)	1660*	0*	0.0
Atterberg Limits, PI/LL (%)	38/63	N/P	N/P
Unified Soil Classification	CH	SP	GP
Dry Density (pcf)	99.5	103.5	104.5
In situ Wet Density (pcf)	110.0	120.0	105(wet)
In situ Moisture Content(%)	23.9	10.0	N/A
Sieve Analysis			
sieve size		percent passing	
1 1/2"			100%
1"			63
3/4"			25
1/2"			3
3/8"			1
# 4		100%	
# 8	100%	99	
# 16	99	97	
# 30	98	77	
# 50	97	37	
# 100	96	13	
# 200	94	6	
5 M	93		
1 M	46		

N/A = not applicable
N/P = non-plastic
*Unsaturated drained staged
** Estimated based on gradation and angularity

Table 1. Physical properties and shear strength of test soil

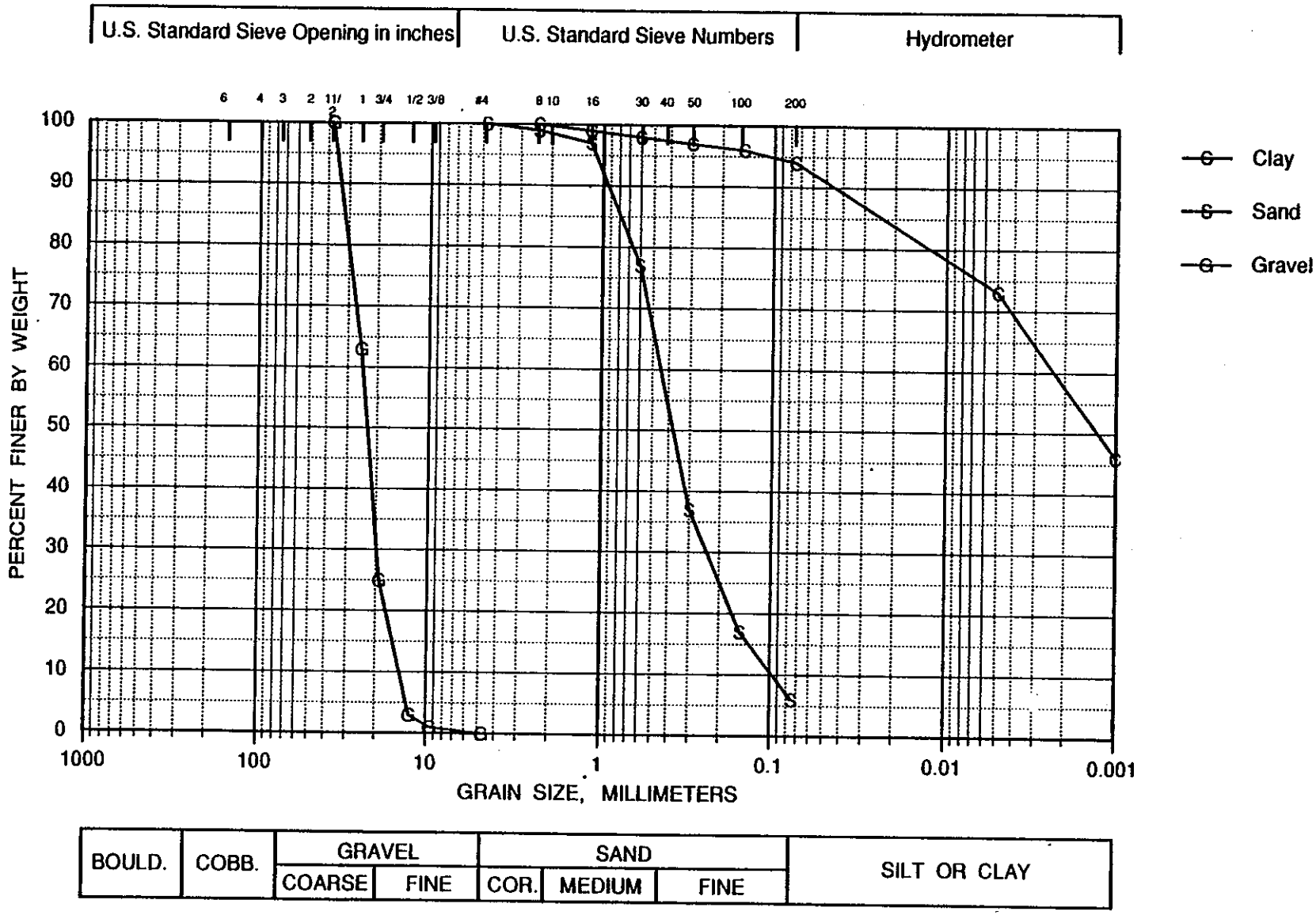


Figure 5. Grain size distribution

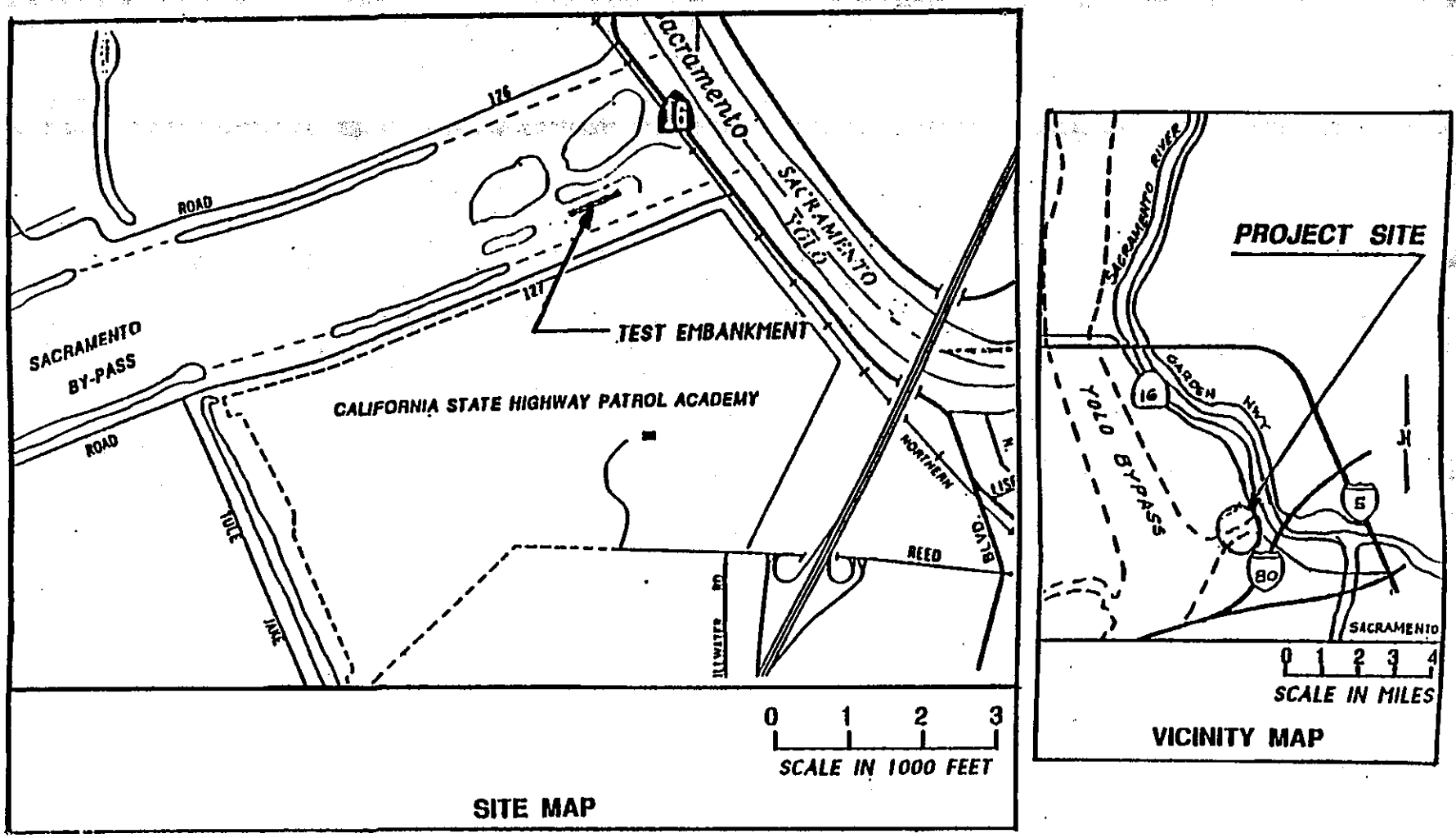
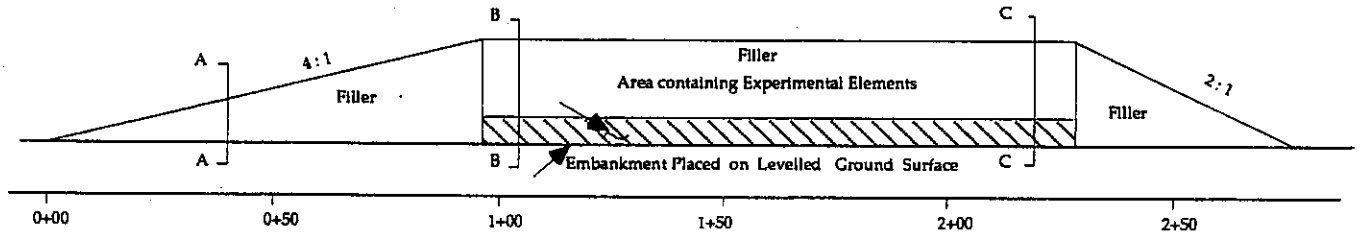
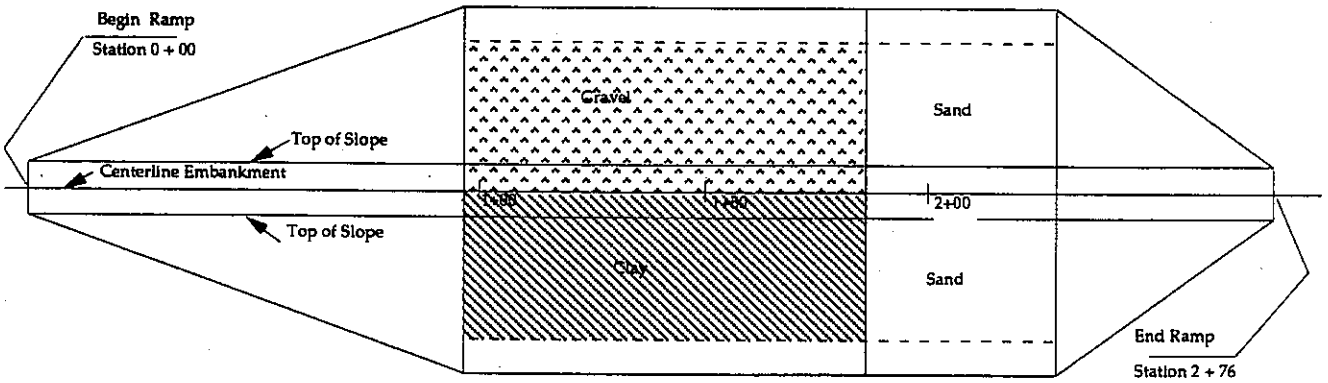


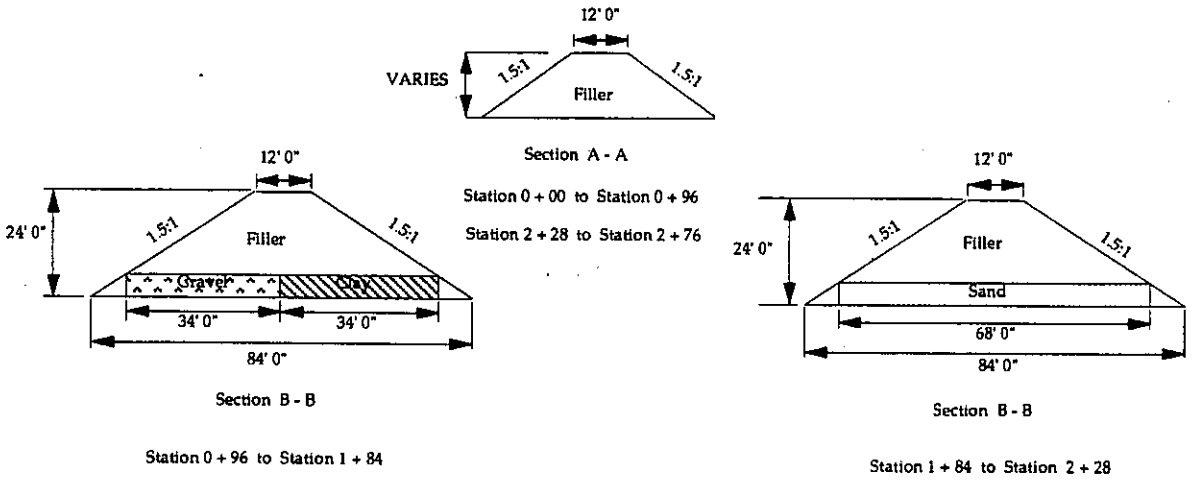
Figure 6. Location of the field test embankment



ELEVATION VIEW

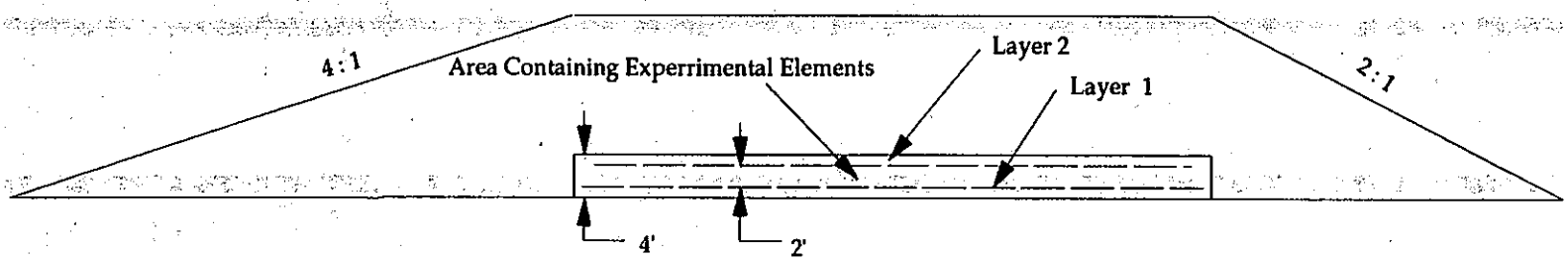


PLAN VIEW

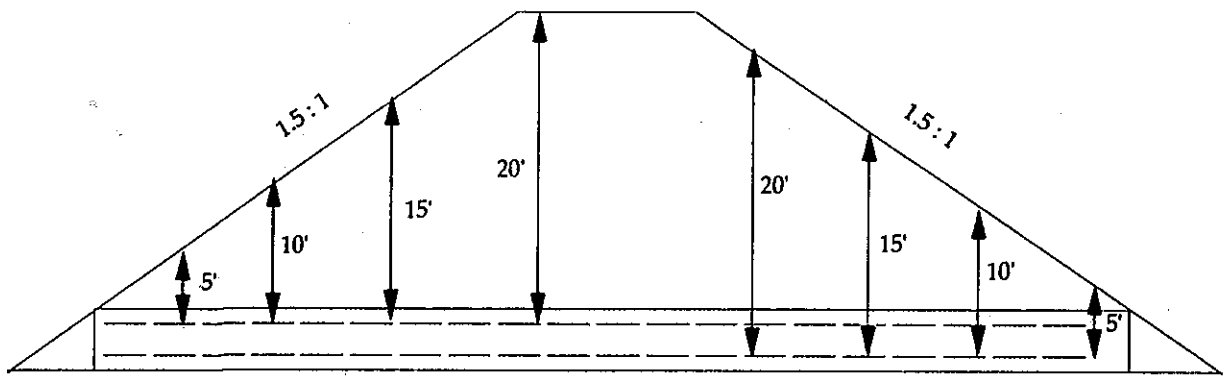


TYPICAL SECTIONS

Figure 7. Test embankment geometry



ELEVATION VIEW



SIDE VIEW

* NO SCALE

Figure 8. Test embankment showing overburden load

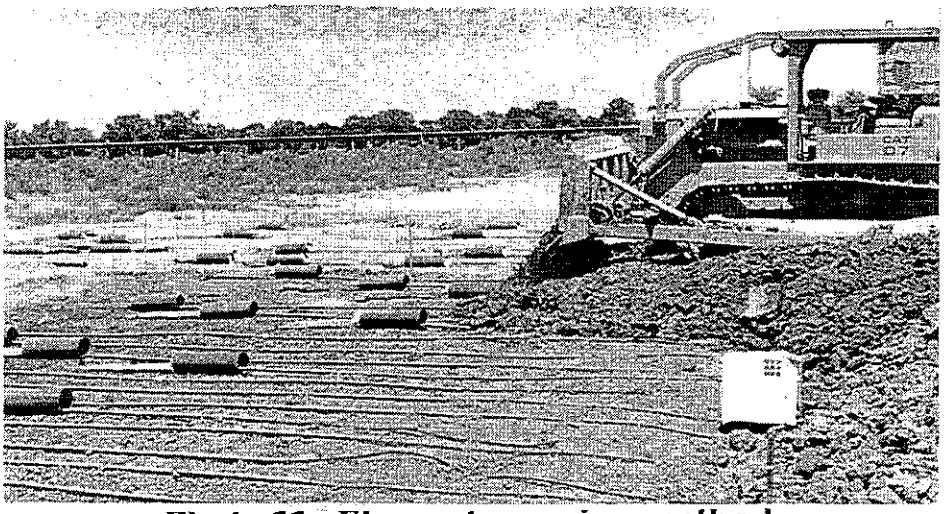


Photo 11. Element covering method

Photo 12. D-7 track layer dozer and rubber tire earth mover

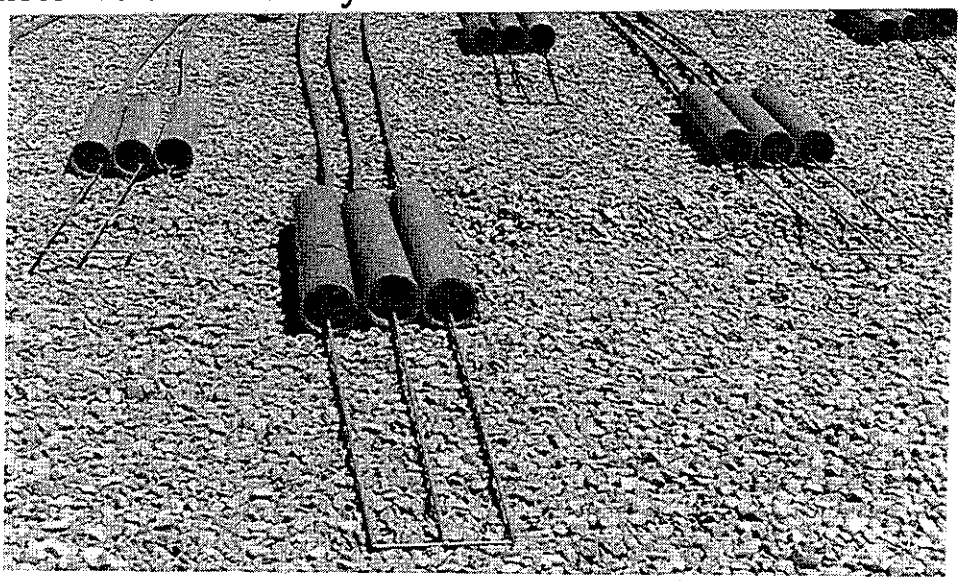


Photo 13. PVC pipe positioned around element hardware

lengths of cable were left exposed at the slope face for attachment during pullout testing. PVC pipe (6-inch diameter) was also positioned around parts of the SREs to prevent any hardware (i.e., cable clamps) from contributing to the pullout resistance force developed during testing (Photo 13).

2.5 Field Test Procedure

Field pullout resistance testing was conducted by connecting the SRE's exposed cable end at the slope face to a train of pullout testing devices consisting of a computer controlled hydraulic ram, a load cell, and a track layer dozer (Photos 14, 15, and 16). A 50-kip load cell located at the cable ram connection pulled the SREs horizontally at a constant rate of 1-inch per ten minutes. Two linear measuring devices were used, one positioned on the ram to measure its piston travel, and another to measure the travel of the whole ram unit caused by the movement of the dozer anchor. Hydraulic control of the ram and data collection was provided by a portable controller and data acquisition system (Photo 17). Positioning of the ram assembly for connection to the exposed cables was provided by a truck mounted hydraulic boom (Photo 18). Displacement and pullout forces were automatically recorded at 30-second intervals throughout the testing period. Data was collected by a multi-channel data acquisition unit and recorded on floppy disk and printed hard copy. Collected data was then used to plot various graphs of pullout resistance vs. displacement as shown in appendix A.

During the field testing, varying initial pullout forces were applied to the SREs to overcome the cable sag. As a result of this varying initial pullout force, each test yielded a different initial load. In order to make the analysis simpler and to provide a common denominator for comparison, the field data was shifted to the origin. The field data was also adjusted to compensate for the elongation of the cable and cable eye connection.

2.6 Laboratory Test Procedures

Laboratory pullout tests were conducted in the large scale shear box developed by Translab in the early 1970's (Photo 19). This shear box allowed the simulation of field overburden conditions. SREs identical to those used for field pullout testing were positioned between layers of compacted backfill and pulled at a constant displacement

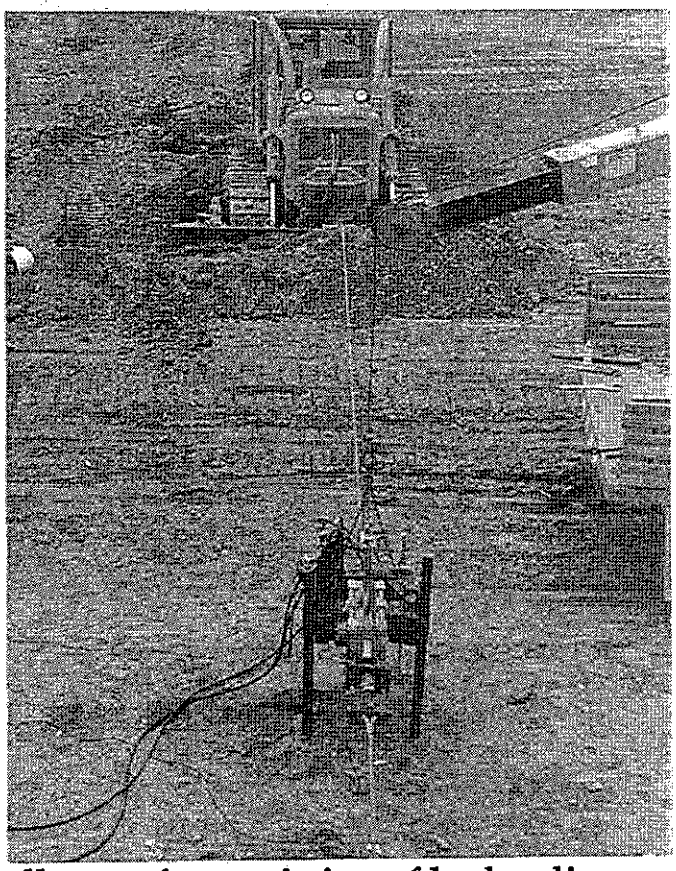


Photo 14. Pullout train consisting of hydraulic ram, load cell, track layer dozer, and truck-mounted boom

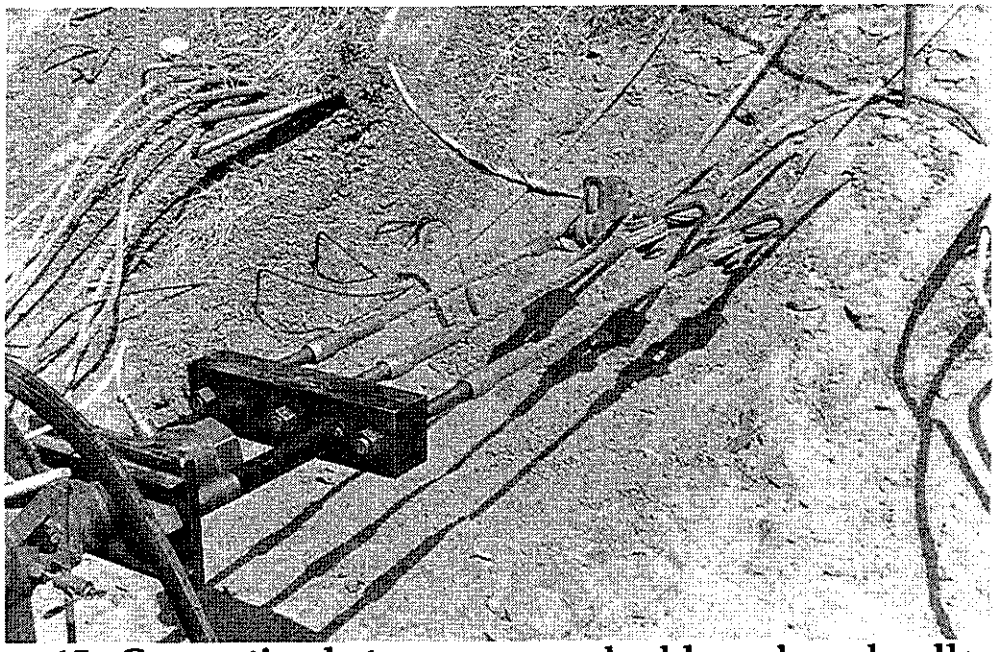


Photo 15. Connection between exposed cable ends and pullout test device

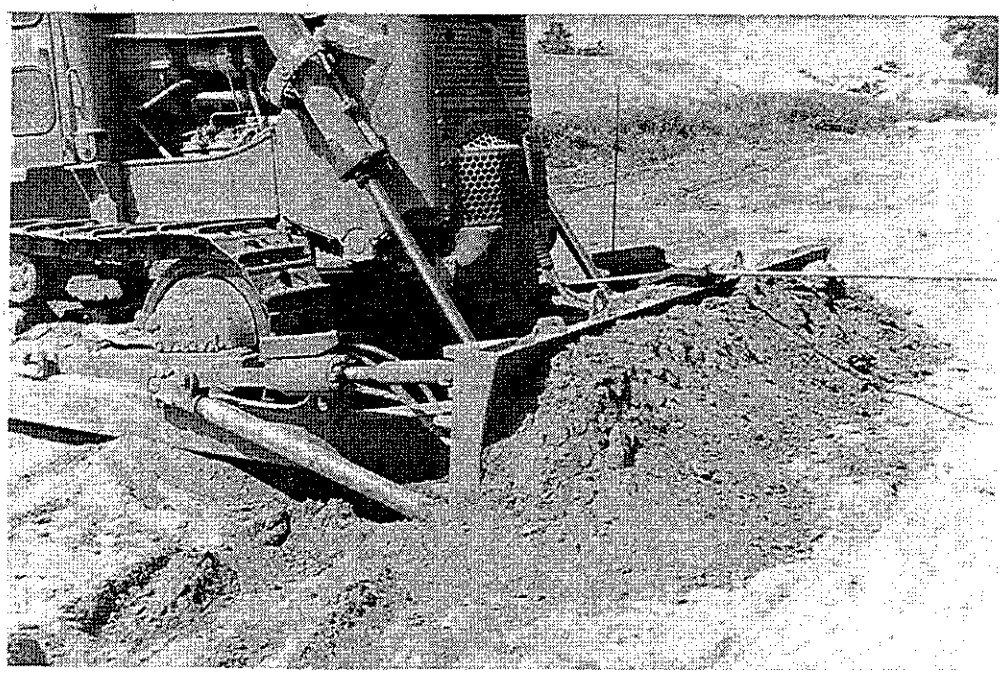


Photo 16. Track layer dozer used as an anchor for field pullout testing

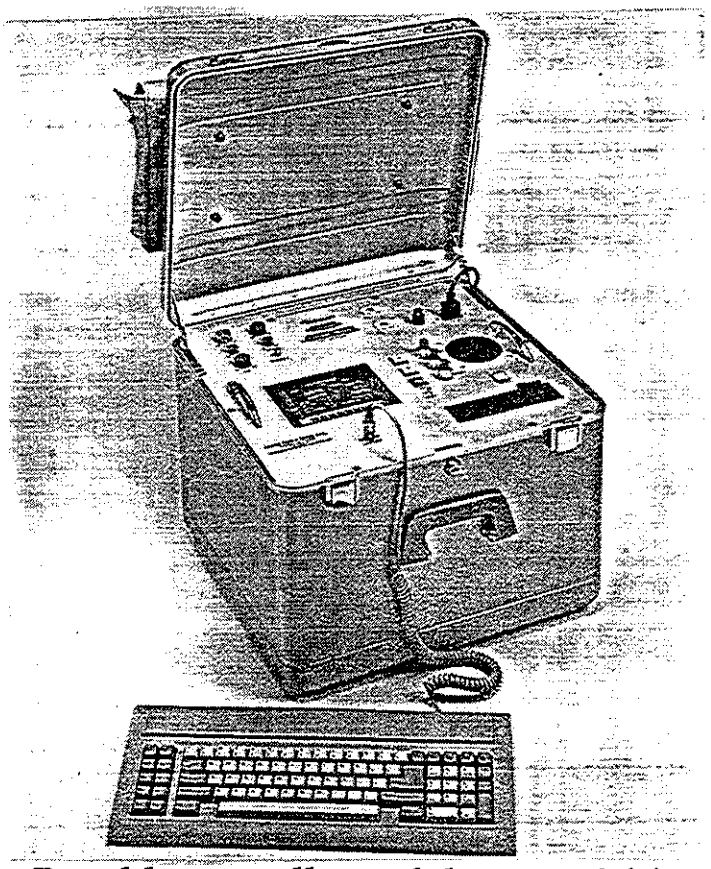


Photo 17. Portable controller and data acquisition system

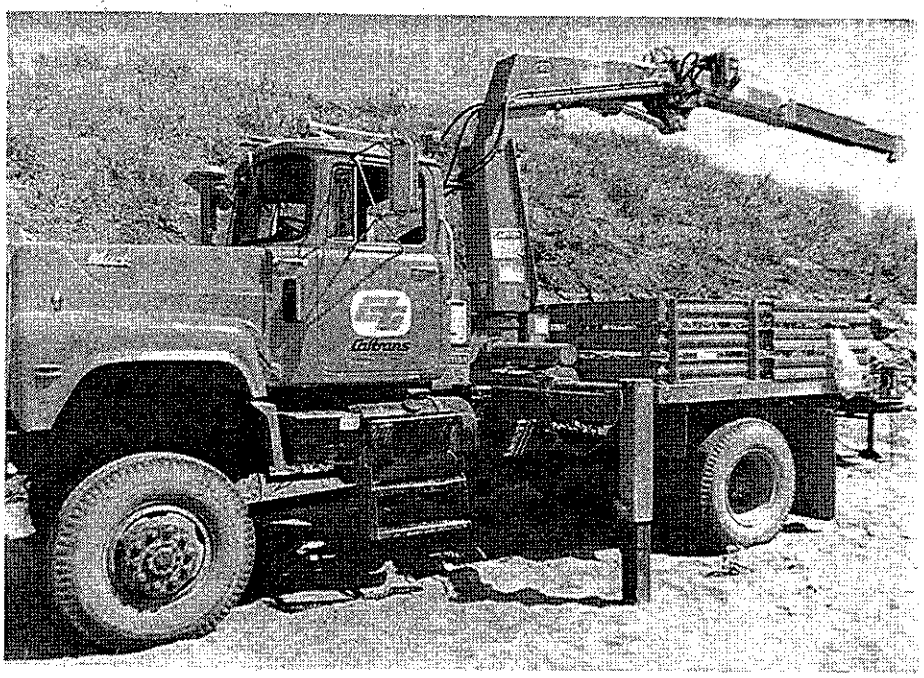


Photo 18. Truck-mounted hydraulic boom used to support hydraulic ram and load cell in field testing

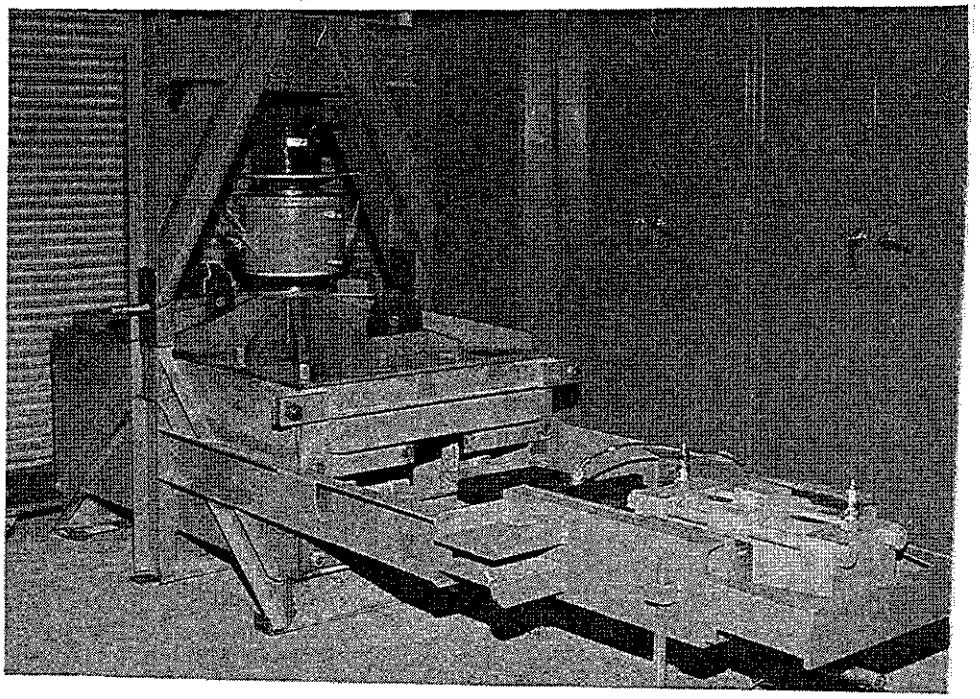


Photo 19. Large scale shear box used to perform laboratory pullout tests

rate with constant overburden pressure (with the exception of stage testing) to determine their pullout resistances.

Field conditions were simulated by reclaiming soil from the field embankment and placing it in the shear box in such a manner as to replicate the mean density and moisture content of the soil in the embankment. The soil reclaimed from the embankment was moistened, placed into the shear box, and compacted with a hand operated compactor in 6-inch layers until half of the shear box was filled. The SREs were then placed on top of the soil. Additional layers of the same soil were then added on top of the SRE and compacted until the shear box was full. A steel plate was placed on the top of the compacted soil and hydraulically loaded to simulate field overburden conditions (Photo 20). For consolidation purposes, overburden loads were applied for 12 hours prior to testing. Just before testing, the front face of the box was removed to expose the soil face. A computer controlled servo-valve hydraulic system administered the vertical loading and the horizontal pulling force.

Density measurements were taken with a nuclear gage at three locations within the shear box. Also, three soil samples at these locations were taken and oven dried to determine the moisture content.

The SREs within the compacted soil were attached to a horizontal 100-ton hydraulic ram via a universal connector and bolt arrangement. The same ram was used to provide the horizontal pulling force for both field and laboratory tests. For field testing, however, the ram was removed from the stationary shear box and retrofitted with a portable frame with adjustable legs as shown in photo 21. The SREs were then pulled at a constant rate of 1-inch per ten minutes until either the SREs failed, the maximum travel distance of the ram piston (8-inches) was reached, or the test was stopped to increase the vertical load (stage tests). Data was collected with a multi-channel data acquisition unit which recorded the displacement and pullout resistance on floppy disk and printed hard copy. Displacement and pullout resistance readings were recorded automatically at 30-second intervals throughout the testing period. The data generated was plotted on graphs relating pullout resistance to displacement. (Appendix B).

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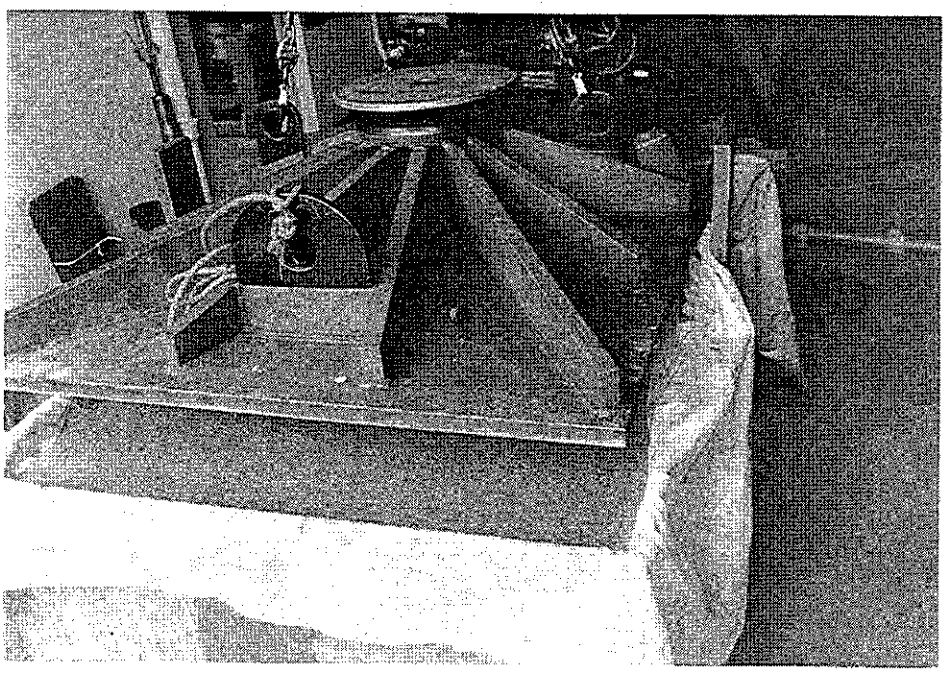


Photo 20. Steel plate used to apply simulated overburden loads in laboratory tests

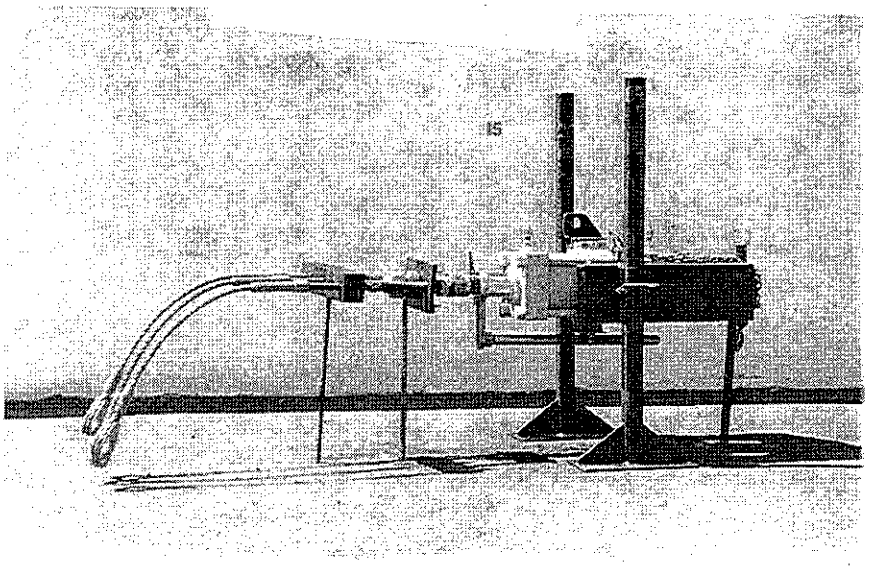


Photo 21. Computer controlled hydraulic ram and 50-kip load cell fitted with adjustable legs for field testing

3. Presentation of Results and Analysis

3.1 Introduction

A total of 228 pullout tests were performed including 182 field tests and 46 laboratory tests. Of the 182 field tests, 41 tests were replicated to substantiate their results. Field data were adjusted to compensate for cable elongation and elongation due to the eye connections. Field graphs were also shifted to the origin to account for the initial cable sag.

In the laboratory, a few replicated tests were performed prior to the actual testing to determine the consistency of the apparatus and test set-up. Good correlation was found between the replicated tests, thus replicated tests were limited to 4 duplicated tests and 4 stage tests. An inventory of laboratory and field tests is shown in table 2.

Each of the laboratory and field tests were plotted and analyzed individually. Where comparisons were made between soil or element types, the most typical replicated test was selected.

3.2 Load-Displacement Curves

For all of the 228 laboratory and field pullout tests that were performed, load vs. displacement curves were plotted and are shown in appendices A and B. Plots of replicated tests were overlaid on the same axes. The load deformation characteristics, as shown in the load displacement curves, were found to be quite different for each reinforcement and soil type. Even between the replicated field tests using identical materials and testing procedures, there were considerable differences in the peak pullout resistance. In addition, there were wide variations among displacements required to reach the maximum pullout force. However, in most cases the pullout force increased rapidly with little change in displacement to a peak value and decreased or leveled off after the peak value. For the comparison of pullout resistance, a summary sheet was prepared to include overburden height, maximum pullout force up to 1-inch of displacement (tolerable design displacement for MSE walls) and corresponding displacement, and the ultimate pullout force and its corresponding displacement for each test. In addition, the slope of the pullout vs. displacement curve

ELEMENT DESCRIPTION	BACKFILL MATERIAL	OVERBURDEN HEIGHT (ft.)						
		FIELD				LABORATORY		
		5	10	15	20	10	20	Stage
MSE 1-bar	Sand	1	1	2	2	1	1	1
1-bar	Clay	1	2	2	1	1		
1-bar	Gravel	1	1	2	1	1	1	
MSE 2-bar	Sand	1	2	2	1		1	1
2-bar	Clay	1	2	2	1	1		
2-bar	Gravel	0	1	1	1	1	1	
MSE 3-bar	Sand	1	2	2	1	1	1	
3-bar	Clay	1	2	2	1	1		
3-bar	Gravel	1	2	3	1	1	1	
TAT with side wall	Sand	1	2	2	1	1	1	
with side wall	Clay	1	2	2	1	1		
with side wall	Gravel	1	2	2	1	1	1	
TAT without side wall	Sand	1	2	2	1	1	1	
without side wall	Clay	1	2	2	1	1		
without side wall	Gravel		2	2	1	1	1	
CRR 1- Disk	Sand		2	1	1	1	1	1
1- Disk	Clay	1	2	2	1	1		
1- Disk	Gravel	1	2	2	1	1	1	
CRR 2- Disk	Sand	1	2	1		1	1	1
2- Disk	Clay	1	2	2	1	1		
2- Disk	Gravel	1	2	2		1	1	
C-Chan. 4' long,1' T	Sand	1		1				
4' long,1' T	Clay	1	1	1				
4' long,1' T	Gravel		1	2				
C-Chan. 4' long,2' T	Sand		1	1	1			
4' long,2' T	Clay	1	1	1				
4' long,2' T	Gravel	1	1					
C-Chan. 4' long,2 Baffle	Sand	1	1		1	1	1	
4' long,2 Baffle	Clay	1	1		1	2		
4' long,2 Baffle	Gravel	1	1	1	1	1	1	
C-Chan. 4' long,Plain	Sand	1	1		1	1	1	
4' long,Plain	Clay	1	1	1	1	1		
4' long,Plain	Gravel		1	1	1	1	1	
C-Chan. 2' long,1 Baffle	Sand	1	1	1	1			
2' long,1 Baffle	Clay	1	1	1	1			
2' long,1 Baffle	Gravel	1	1	1	1			
C-Chan. 2' long,Plain	Sand	2	2	1	1			
2' long,Plain	Clay	1	1	1				

Table 2. Field and laboratory test inventory

up to 1-inch displacement was calculated and shown on these summary sheets. These summary sheets are presented in appendix C.

3.3 Comparison of Replicated Tests

Some of the field and laboratory tests were replicated to substantiate their results. All of the conditions for the replicated tests were identical, including element type, soil type, overburden pressure, pullout rate, and compaction effort.

Load versus displacement curves for the replicated tests were overlaid for ease of comparison. Samples of these curves for field and laboratory testing are shown in figures 9 and 10. In addition, the results of the laboratory and field replicated tests showing the percent difference between replicated test results are summarized in tables 3 and 4. The percent difference is calculated as the difference between the maximum pullout forces up to 1-inch of displacement divided by the average of the maximum forces up to 1-inch of displacement.

For field testing, replicated test results show high percent differences regardless of element or soil type. Percent differences ranged from 3% to 155%. Some factors that may be responsible for these inconsistencies include: 1) The utilization of recycled steel cable for pulling the elements. In some cases, the cable that was used may have previously been stretched beyond its elastic limit, making compensation for cable elongation inaccurate. 2) The proximity of the PVC piping to the element hardware. In some instances, the connection hardware or even the element itself may have caught on the end of the PVC pipe, causing the pipe to contribute to the element's pullout resistance. 3) Normal construction variations in the density and moisture content within the test embankment. 4) Disruption of the soil surrounding an element caused by the testing of an adjacent element. Though this replicated field data turned out to be highly inconsistent, one must keep in mind that without other field data to compare the accuracy of these tests, this may indeed be the kind of behavior to expect.

For laboratory testing, the variation was much smaller and the difference between the replicated tests ranged from 1 to 41 percent with most variation being associated with stage testing.

3.4 Effect of Overburden

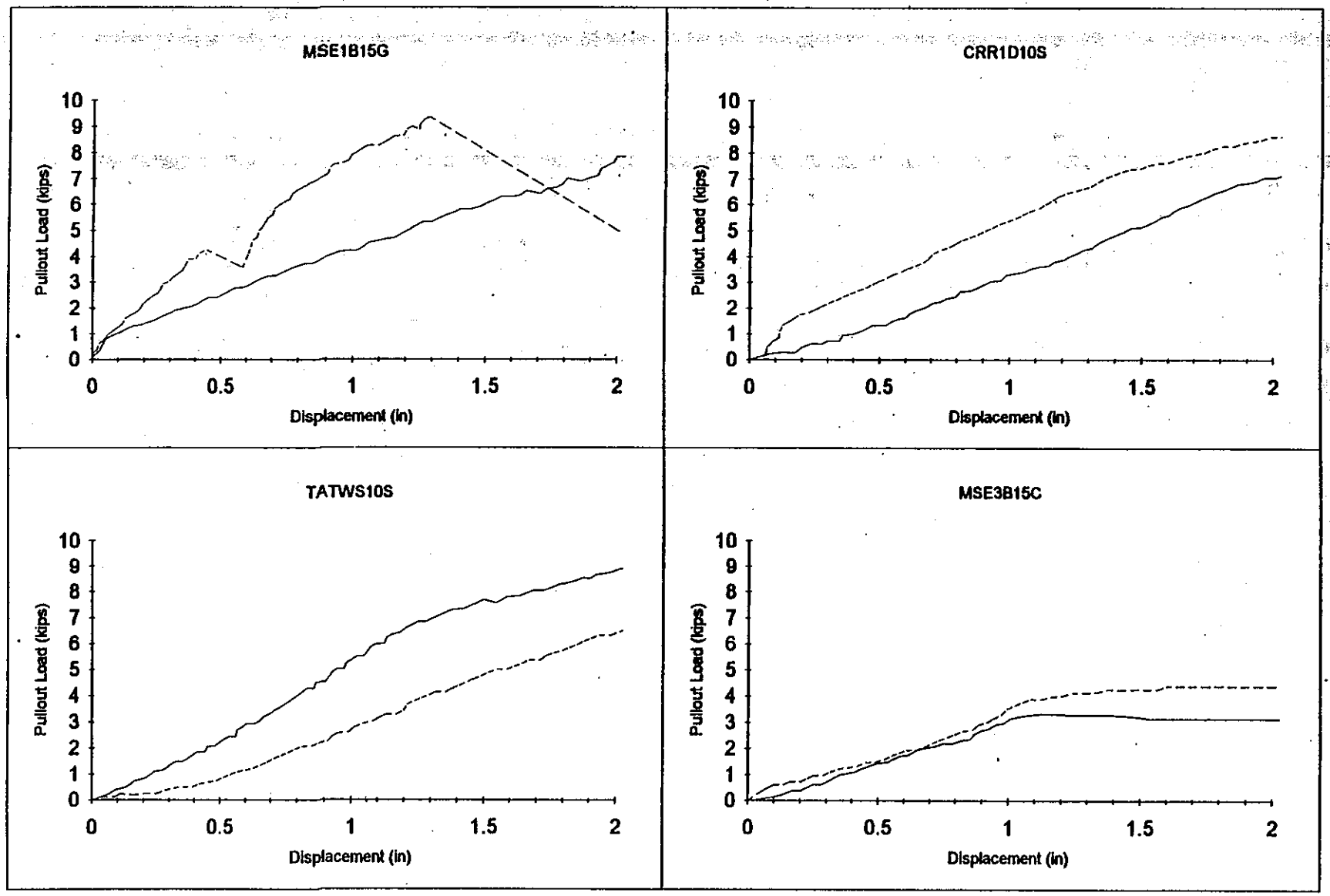


Figure 9. Comparison of replicated tests in the field

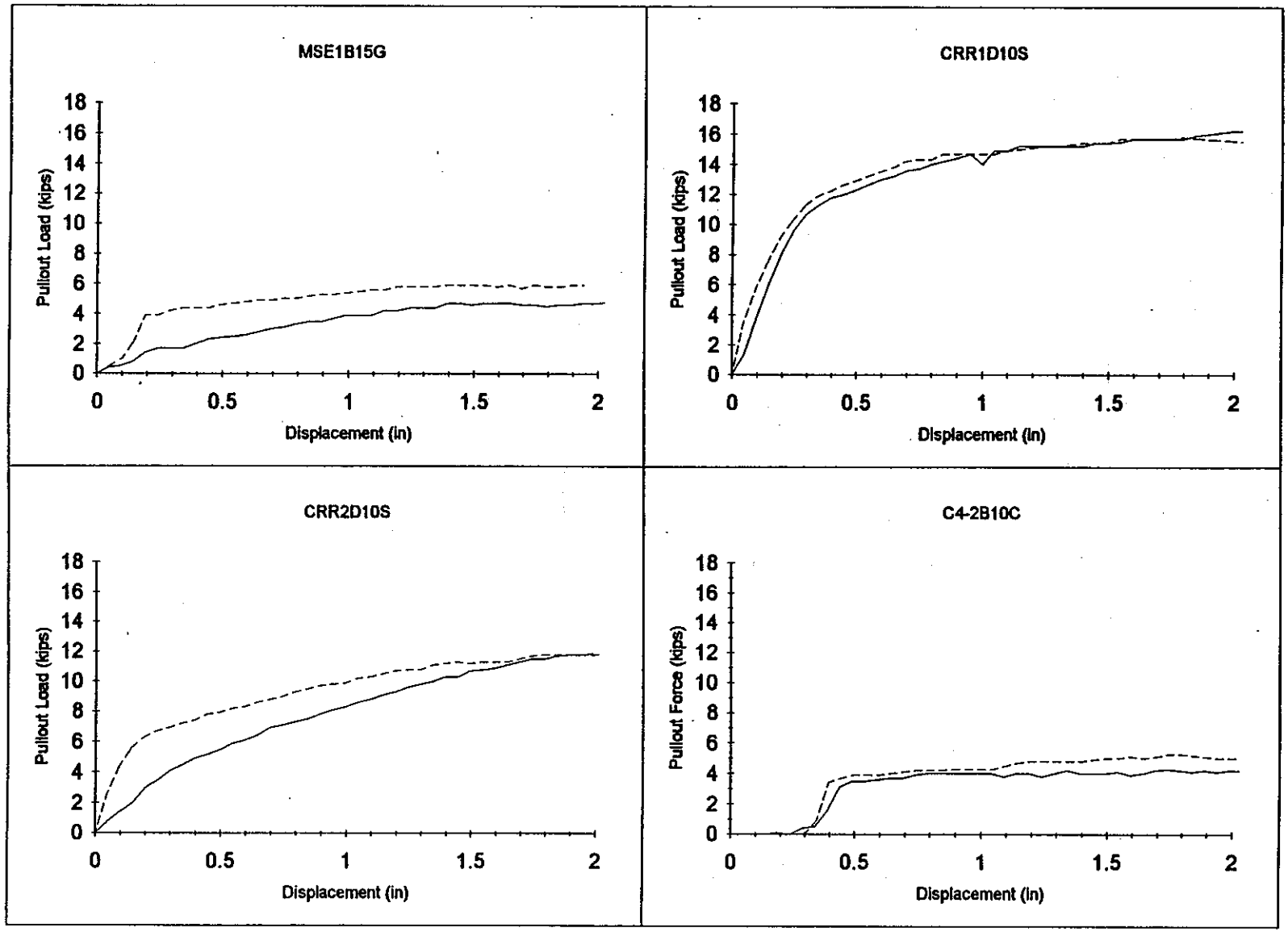


Figure 10. Comparison of replicated tests in the lab

ELEMENT TYPE	OVERBURDEN HEIGHT (ft.)	BACKFILL MATERIAL	MAX. PULLOUT UP TO 1 - INCH TEST 1 (kips)	MAX. PULLOUT UP TO 1 - INCH TEST 2 (kips)	PERCENT DIFFERENCE
TAT without side wall	10	Gravel	3.4	3.2	6.1
		Sand	4.8	3.6	28.9
		Clay	1.7	1.6	6.7
	15	Gravel	4.4	1.9	79.0
		Sand	8.3	5.7	37.5
		Clay	1.2	2.1	-56.4
TAT with side wall	10	Gravel		-	-
		Sand	4.8	3.6	28.9
		Clay	3.2	1.5	69.5
	15	Gravel	1.9	4.4	-80.8
		Sand	5.2	3.0	53.0
		Clay	2.4	3.3	-30.1
CRR single disk	10	Gravel	5.1	1.8	94.7
		Sand	3.3	5.6	-50.4
		Clay	0.4	2.3	-144.8
	15	Gravel	7.2	16.8	-80.2
		Sand	9.7	5.7	53.2
		Clay	2.3	2.1	8.3
CRR double disk	10	Gravel	1.8	6.6	-115.1
		Sand	3.0	2.2	30.6
		Clay	2.7	1.7	47.2
	15	Gravel	22.8	13.4	52.1
		Sand	-	-	-
		Clay	1.3	6.8	-134.2
MSE BAR-MAT with single transverse bar	10	Gravel	6.0	3.0	66.1
		Sand	-	-	-
		Clay	4.4	3.0	36.8
	15	Gravel	4.4	8.2	-60.2
		Sand	8.6	11.7	-30.5
		Clay	1.9	4.0	-69.8
MSE BAR-MAT with double transverse bar	10	Gravel	0.9	7.4	-155.5
		Sand	9.7	6.7	36.1
		Clay	3.2	3.1	2.9
	15	Gravel	-	-	-
		Sand	3.3	6.0	-58.7
		Clay	3.0	3.7	-22.0
MSE BAR-MAT with triple transverse bar	10	Gravel	3.4	3.3	4.2
		Sand	13.5	3.0	128.3
		Clay	2.6	1.8	35.4
	15	Gravel	20.7	12.2	51.9
		Sand	0.8	5.9	-153.8
		Clay	3.2	3.7	-12.2
C- CHANNEL 2 ft. with no baffle	10	Gravel	1.0	1.1	-14.6
		Sand	2.8	1.9	36.6

Table 3. Percent difference between field replicated tests

ELEMENT TYPE	OVERBURDEN HEIGHT (FT.)	BACKFILL MATERIAL	MAX. PULLOUT UP TO 1" or 4" TEST 1 (Kips)	MAX. PULLOUT UP TO 1" or 4" TEST 2 (Kips)	PERCENT DIFFERENCE
CRR	10	Sand	14.9	14.7	1.4
single disk	20	Sand *	27.5	28.3	2.9
CRR	10	Sand	10.2	8.6	17.0
double disk	20	Sand *	23.0	15.2	41.0
MSE with single	10	Sand	4.9	5.5	12.0
transverse bar	20	Sand *	6.3	7.9	23.0
MSE with double	20	Sand *	18.2	12.0	41.0
transverse bar					
C-CHANNEL	10	Clay	0.89	0.79	12.0
4' long, 2 baffles					

Note:

* Stage test . Maximum pullout of up to 4-inches was used for all stage tests.

Table 4. Percent difference between laboratory replicated tests

The effect of the overburden pressure on the element's pullout resistance was studied by comparing the pullout vs. displacement curves of each element in each soil type under different overburden pressures.

Tests results in the field show that overburden pressure offers no consistent effect on an element's pullout resistance. There were, however, a few cases in which the overburden pressure appeared to affect the performance of the test element. Cases where an increase in overburden pressure resulted in an increase in pullout force include: MSE2B and MSE3B in gravel, CRR2D in clay, and C4-1T and C4-2B in sand and gravel. Cases where an increase in overburden resulted in a decrease in pullout resistance include: C4-1B and C4-plain in gravel (Figure 11).

Test results in the lab, unlike the field tests, generally show an increase in an element's pullout resistance for an increasing overburden pressure. Examples of this type of behavior are shown in figure 12. Only two elements failed to follow this trend; CRR1D and MSE1B both in gravel. These two exceptions may be attributed to experimental error. Laboratory tests in clay soil were only performed at an overburden pressure of 10-feet.

3.5 Effect of Element Type

The pullout resistance of each element in each soil type was examined and an evaluation of each element's performance in each soil type was made. A linear regression analysis was performed for all data up to 1-inch of displacement. The results show that the higher the slope, the more resistance to pullout. (Note that this method of linear regression forces the regression line through the origin). For example, the plot below shows sample curves of C4-PL and MSE1B, and their corresponding linear regressions. Clearly, the C4-PL curve has a higher slope, 12.4 kips/in, than the MSE1B, 4.6 kips/in. This method was used solely for the purpose of ranking the elements and is by no means an exact indication of an element's pullout resistance as some of the curves do not display linear behavior within the first inch of displacement (as can be seen in the C4-PL curve).

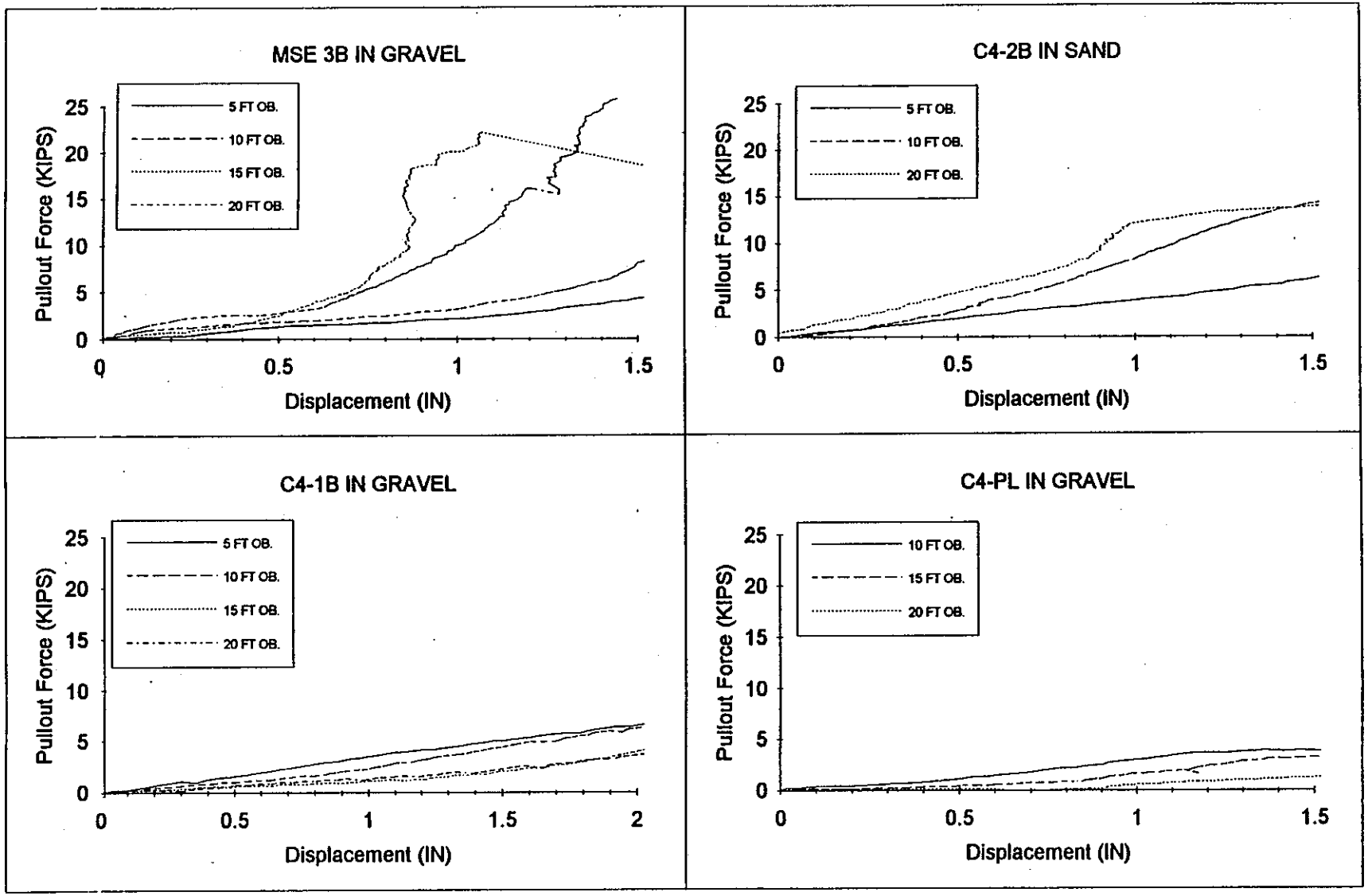


Figure 11. Typical effect of increasing overburden height on pullout force in field tests

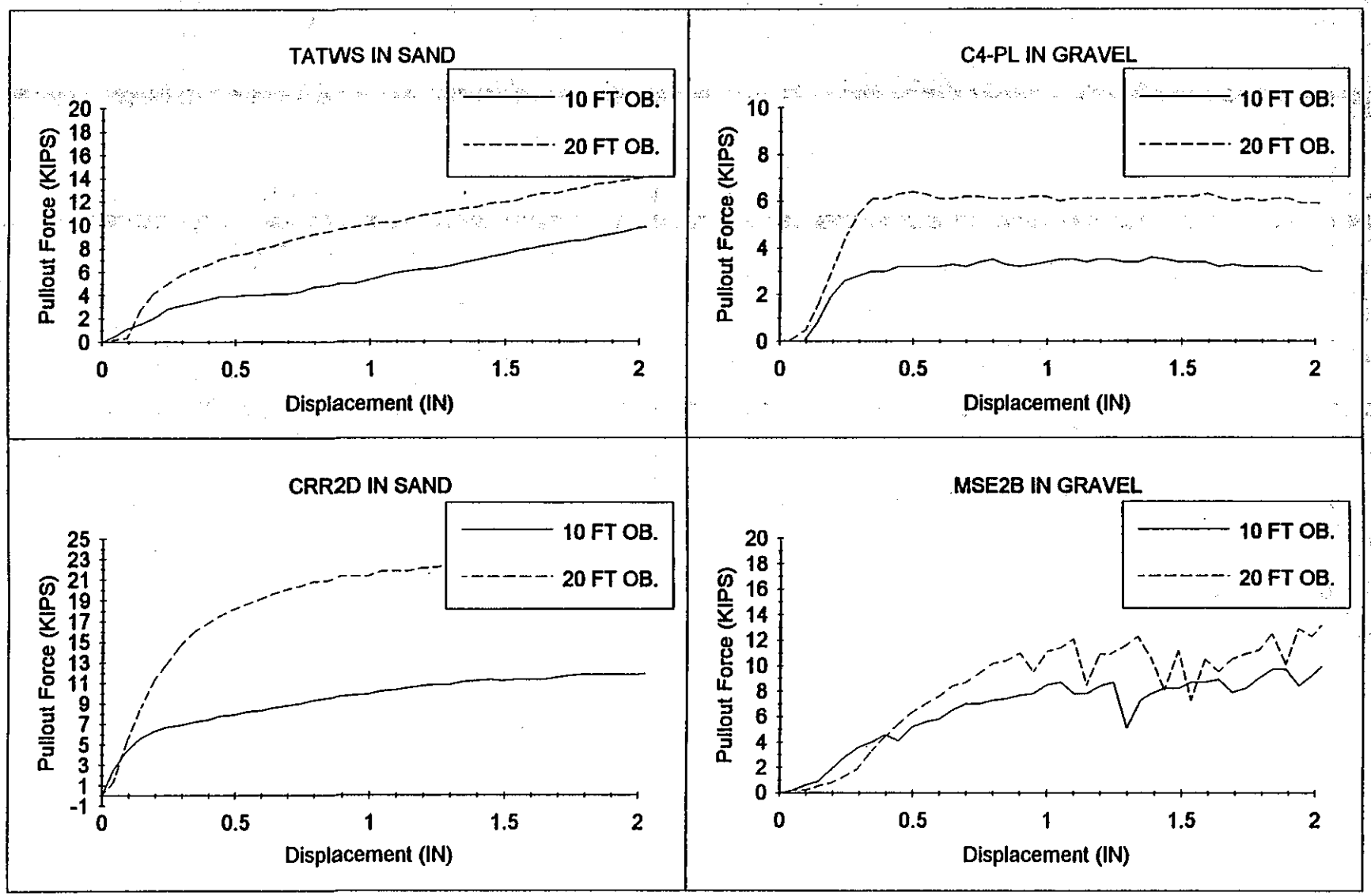
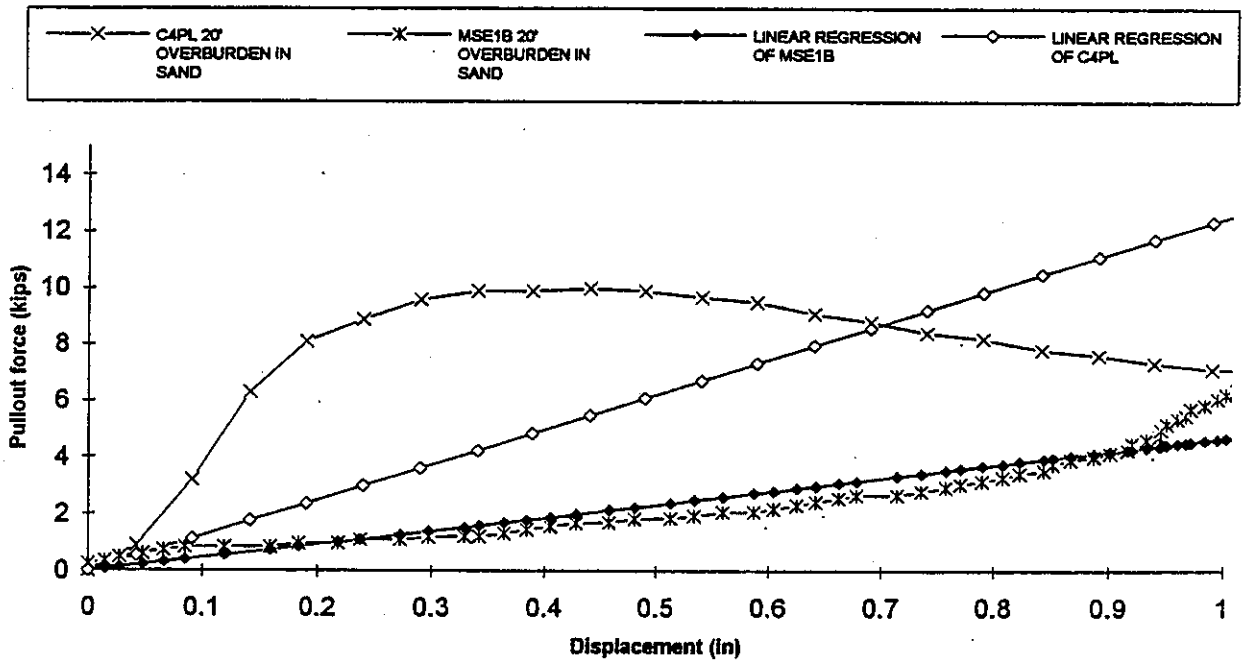


Figure 12. Typical effect of increasing overburden height on pullout force in the lab



Based on an analysis of this type, the three most effective soil reinforcing elements for each soil type are listed below.

Top three element types based on slope

	Sand		Gravel		Clay	
Rank	Field	Lab	Field	Lab	Field	Lab
1.	C4-2T	CRR1D	C4-2T	CRR2D	C4-2T	CRR2D
2.	C4-1T	C4-2B	C4-1T	MSE3B	C4-1T	CRR1D
3.	MSE1B	CRR2D	CRR2D	C4-2B	CRR1D	C4-2B

A complete summary of these results appears in appendix C. Due to poor correlation between overburden and pullout for field data, field pullout slopes were averaged without regard to overburden height and used as the basis for comparison between the element types (Table 5).

3.6 Effect of Soil Type

The effect of soil type on pullout resistance was studied by again looking at the slope of the pullout force versus displacement curve up to 1-inch of displacement. In general, sand and gravel offered similar pullout resistances, both of which were higher than clay. This generalized trend occurred in both the field and the lab. Some particular

	SAND		GRAVEL		CLAY	
ELEMENT	LAB	FIELD	LAB	FIELD	LAB	FIELD
TATWS	9.20	4.27	5.38	2.21	2.44	2.58
TATWO	5.33	4.98	3.61	3.28	1.21	1.54
MSE1B	5.69	7.36	6.67	5.16	1.77	3.56
MSE2B	12.44	4.29	10.49	8.63	3.83	3.39
MSE3B	13.47	6.25	13.21	6.84	4.13	2.26
C4-PL	10.13	1.55	6.67	1.36	1.36	2.54
C4-2B	18.72	7.16	11.39	2.06	5.06	2.58
C4-1T	N/A	23.23	N/A	49.96	N/A	5.57
C4-2T	N/A	23.94	N/A	281.61	N/A	10.93
C2-PL	N/A	4.42	N/A	0.69	N/A	0.97
C2-1B	N/A	2.97	N/A	1.99	1.46	1.64
CRR1D	21.83	6.71	9.72	11.04	5.12	2.93
CRR2D	16.85	5.41	18.01	13.79	6.92	3.57

N/A = element not tested in laboratory

Table 5. Average slope of pullout curves for each element up to 1-inch of displacement

exceptions to this general trend were C4PL and C21B, both in the field. (see appendices A and B for details).

3.7 Comparison of Lab and Field Test Results

A comparison of the test results obtained in the lab with those obtained in the field revealed that just over half (62%) of the reinforcing elements exerted more resistance to pullout in the lab than they did in the field, while 13% developed approximately the same pullout resistance (see Table 6). Laboratory tests in sand and gravel produced pullout resistances which were generally higher than those found in the field. Laboratory tests in clay produced pullout resistances which were generally lower than those in the field. One fundamental difference between the field and lab test results was the shape of the load vs. displacement curve in the first inch of displacement. All of the laboratory load vs. displacement curves show steep initial slopes that decreased with increased displacement (concave down), however, the field curves in sand and gravel tend to have low initial slopes which would gradually increase with increasing displacement (concave up). This difference may be due to the physical restrictions imposed by the laboratory pullout testing device wherein increased shear resistance between the passive elements and the walls of the shear box will occur relative to field conditions. It is also likely that in pulling the field elements, the soil immediately surrounding them was free to dilate, whereas in the laboratory, dilation was restricted and resulted in much greater soil resistance.

3.8 Summary

This research project, as a whole, succeeded in producing a quantitative set of pullout resistance values for 13 different types of earth reinforcing elements. Though the data were largely inconsistent and uncorrelated, a few useful conclusions have been drawn.

1) Laboratory curves were characterized by decreasing slopes. Field curves were characterized by increasing slopes for most elements (primarily MSE's) and are otherwise constant. These differing curve shapes suggest that laboratory pullout resistance values are inappropriate for use in design.

2) The field tests indicate that overburden height is not a useful predictor of pullout resistance. In the lab, an increase in the overburden pressure generally produced an increase in pullout resistance.

ELEMENT TYPE	LABORATORY			FIELD			% DIFF. BETWEEN SLOPES UP TO 1-INCH
	PULL UP TO 1-INCH (KIPS)	SLOPE UP TO 1 INCH (KIPS/INCH)	ULTIMATE PULL (KIPS)	PULL UP TO 1-INCH (KIPS)	SLOPE UP TO 1 INCH (KIPS/INCH)	ULTIMATE PULL (KIPS)	
C4-2B10C	4	4.83	5.2	4.97	4.41	4.97	9%
C4-2B10G	7.6	8.21	13	1.22	0.90	19.59	160%
C4-2B10S	14.4	17.93	14.7	8.29	7.13	15.82	86%
C4-2B20G	13.4	14.58	24.9	3.73	3.37	26.00	125%
C4-2B20S	23	19.52	23.8	12.29	10.43	14.00	61%
C4-PL10C	1.1	1.36	1.1	3.78	4.43	3.78	106%
C4-PL10G	3.5	4.61	3.6	3.03	2.65	4.37	54%
C4-PL10S	6.9	7.81	6.9	1.22	1.12	7.80	150%
C4-PL20G	6.4	8.74	6.4	0.61	0.25	7.79	189%
C4-PL20S	10	12.46	10	2.31	2.20	14.37	140%
CRR1D10C	3.6	5.12	3.8	2.31	3.22	3.41	46%
CRR1D10G	9.8	10.57	19.8	5.09	3.79	19.09	94%
CRR1D10S	14.9	19.07	18.6	3.34	3.04	11.86	145%
CRR1D10S	14.7	19.97	15.8	5.59	5.79	18.14	110%
CRR1D20G	7.9	8.86	26.9	5.35	7.73	5.35	14%
CRR1D20S	19.9	26.45	31.9	9.00	11.84	15.08	76%
CRR2D10C	5.2	6.92	7.6	2.67	3.46	7.88	67%
CRR2D10G	14.4	14.68	25.2	6.57	5.60	24.70	90%
CRR2D10S	10.2	12.76	11.9	2.19	1.95	16.43	147%
CRR2D20G	20.1	21.34	36.5	7.80	12.10	7.80	55%
MSE1B10C	1.3	1.77	1.3	3.02	3.91	3.76	76%
MSE1B10G	7.3	8.32	10.4	5.96	4.95	14.09	51%
MSE1B10S	4.9	4.28	6.3	7.58	5.51	18.61	25%
MSE1B20G	4.4	5.02	8.8	3.41	2.64	10.35	62%
MSE1B20S	4.7	5.71	8.1	7.29	4.65	14.24	21%
MSE2B10C	2.7	3.83	3	3.17	3.64	3.78	5%
MSE2B10G	8.7	9.24	14.6	7.43	6.80	26.59	30%
MSE2B10S	6.8	8.38	8.1	9.65	7.12	23.40	16%
MSE2B20G	11.4	11.74	17.9	16.19	12.95	23.98	10%
MSE2B20S	13.8	16.51	19.3	4.86	3.84	23.00	124%
MSE3B10C	3.1	4.13	3.4	2.56	2.19	7.43	62%
MSE3B10G	10.4	10.92	14.6	3.27	2.65	27.85	122%
MSE3B10S	7.5	10.10	11.7	13.51	11.96	18.25	17%
MSE3B20G	13	15.51	15.6	10.82	8.01	30.76	64%
MSE3B20S	13.3	16.84	16.7	11.00	8.60	23.49	65%
TATWO10C	0.9	1.21	1.7	1.70	1.84	2.07	41%
TATWO10G	2.7	2.71	7.9	3.16	2.98	12.66	9%
TATWO10S	1.6	2.28	3.7	3.55	2.77	12.13	19%
TATWO20G	3.9	4.50	9.3	6.07	4.90	19.18	8%
TATWO20S	7.2	8.37	9.6	6.32	5.25	11.08	46%
TATWS10C	2.2	2.44	6.9	3.16	3.79	9.37	43%
TATWS10G	3.1	3.61	13.3	2.43	1.51	15.42	82%
TATWS10S	5.6	6.24	14.8	5.49	4.91	16.20	24%
TATWS20G	7.2	7.15	17.7	2.59	2.54	15.82	95%
TATWS20S	10.2	12.16	24.5	3.17	2.49	18.62	132%

Table 6. Comparison of lab and field data

3) Sand and gravel generally provided similar pullout resistance, both of which were higher than clay.

4) "C"-channels with one and two-foot tees, corrosion resistant reinforcement with 1 or 2 disks, and to a lesser extent, MSE elements with 1 or 3 cross bars yielded the greatest pullout resistances.

3.9 Design Recommendations

Figures 13 through 18 illustrate the design pullout resistance of the 13 tested elements in sand, gravel, and clay. The pullout resistance values are based on 2 or 4-foot element lengths. For the design of longer lengths of MSE bar mats, the pullout resistance is proportional to the increased length, therefore multiply the pullout resistance by the ratio of the longer length (ft) by that noted. Pullout resistances may not be proportional to the increase in length for configurations with passive elements spaced at intervals other than the optimum spacing.

Design curves for the tested elements are drawn in such a way as to reflect field test pullout behavior. This bias is justified because, as stated previously, 1) field test data is more useful as a design tool because the installation techniques used for these tests are very similar to the kind of installation actual pullout resistance elements will see; 2) lab test data proved to be consistently higher than field test data, and 3) no other studies have been made to date on field pullout behavior, meaning that though this data is inconsistent, no evidence exists to disprove this type of field behavior.

A complete set of design envelopes with their corresponding data sets can be found in appendix D. These suggested design curves are based on the kind of pullout resistance one might expect given similar conditions. The actual design of reinforced earth wall systems should take into account any factors that vary from those tested in this project.

4. Implementation

This report will be used to identify general trends in the pullout behavior of various soil reinforcement elements. The effectiveness of certain salvaged or other reinforcement materials will be determined and their pullout characteristics used to develop design standards.

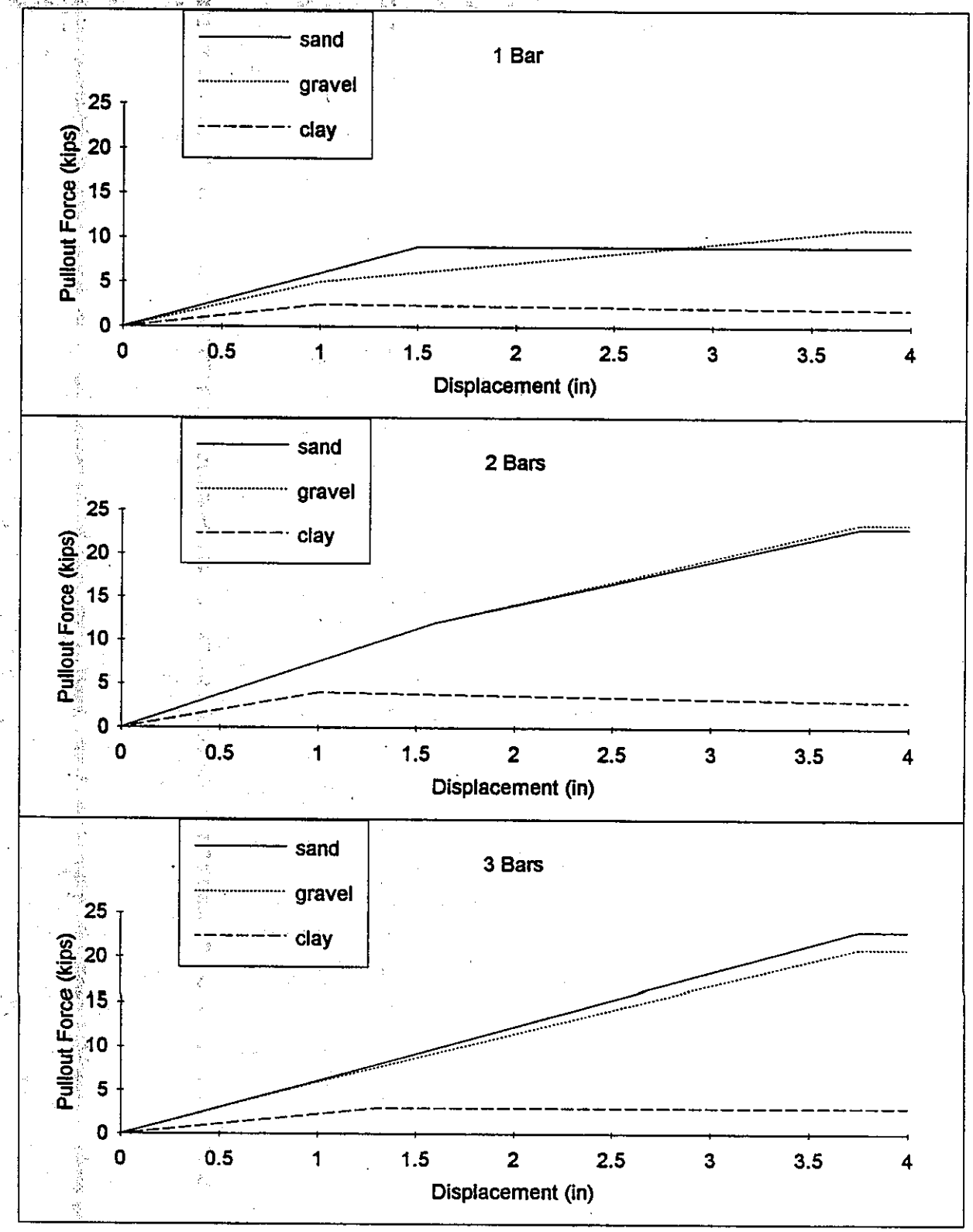


Figure 13. Design envelopes for 4-foot long by 1-foot wide MSE bar mats

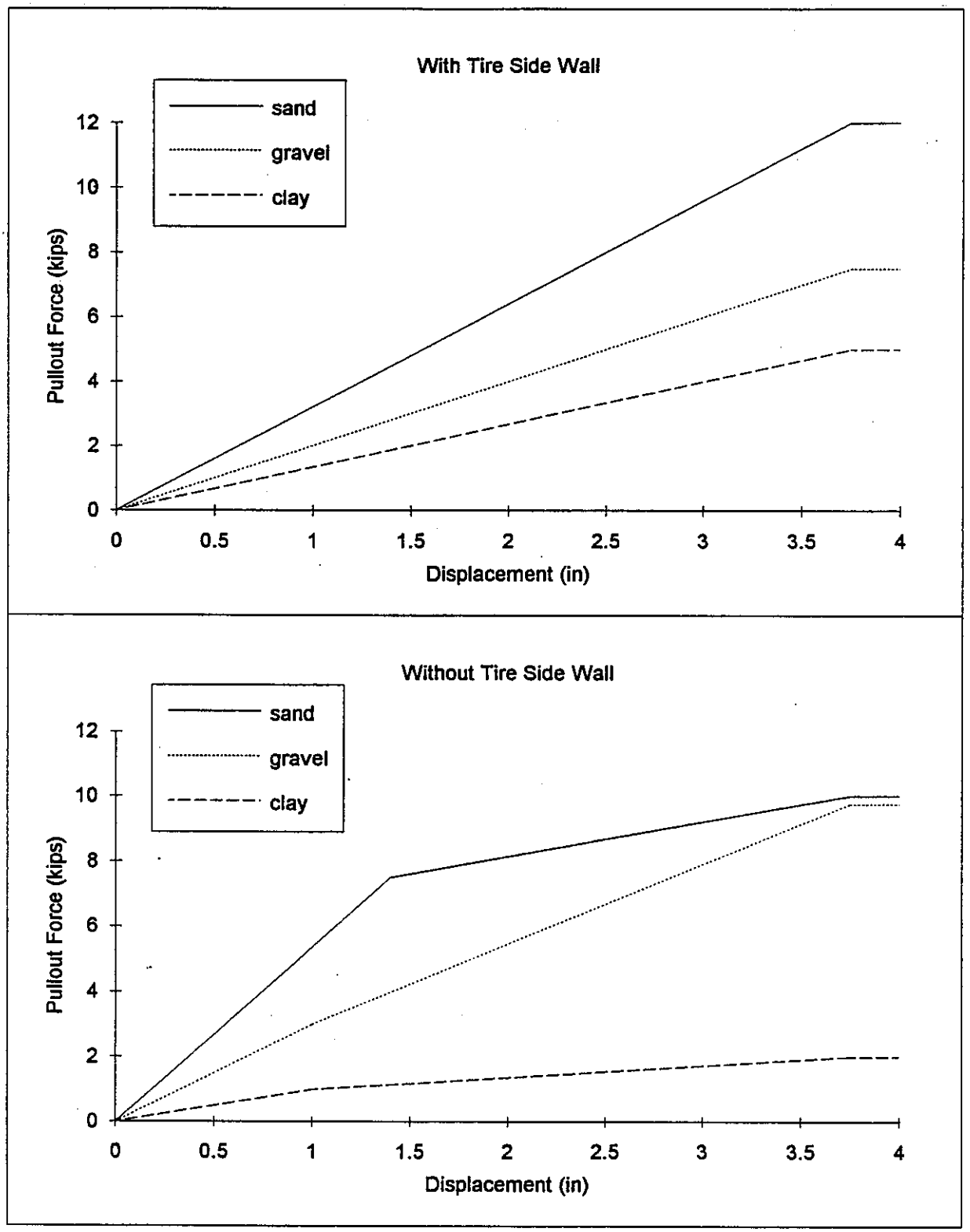


Figure 14. Design envelopes for 4-foot long TATs

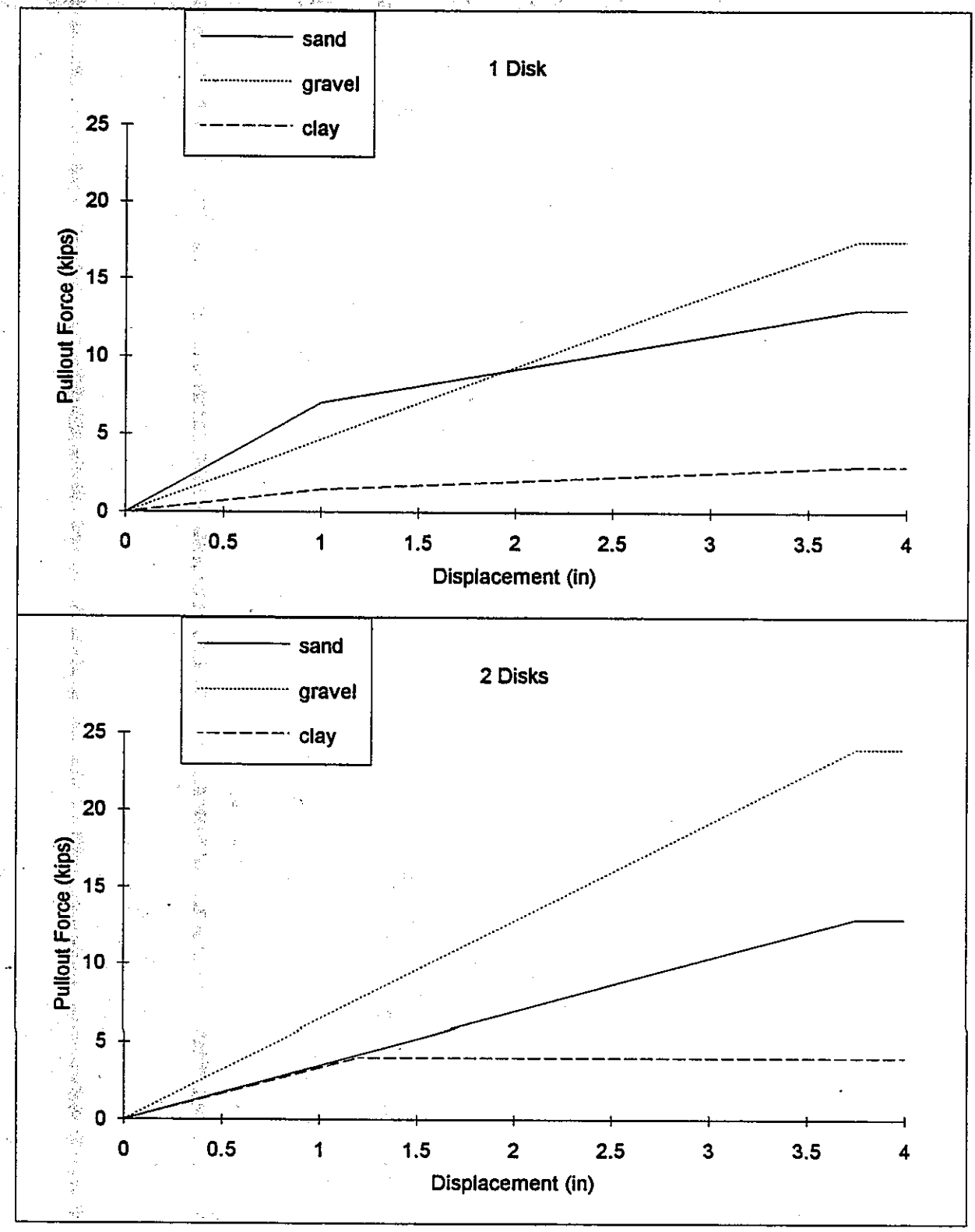


Figure 15. Design envelopes for 4-foot long CRRs

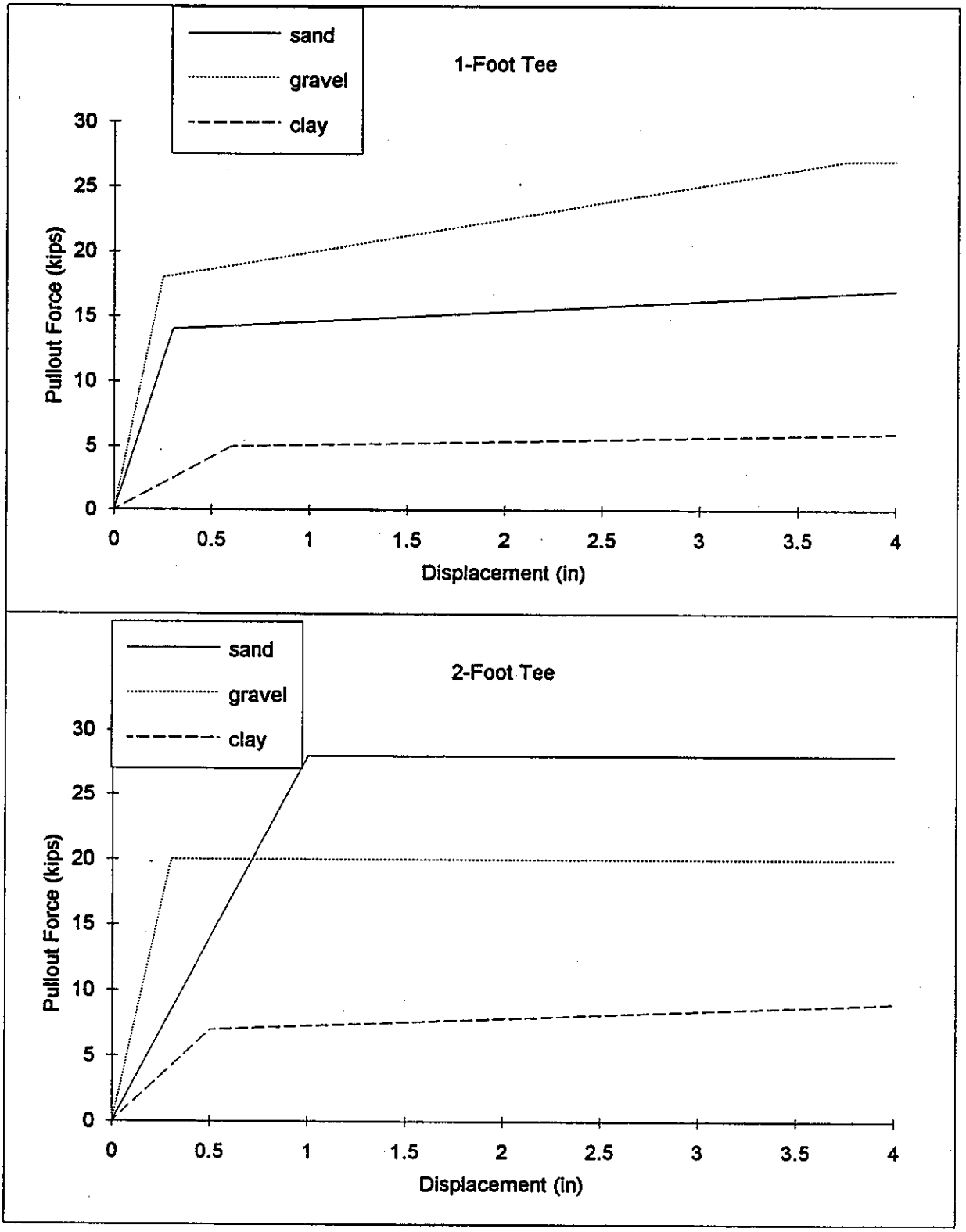


Figure 16. Design envelopes for 4-foot long "C" channels with tees

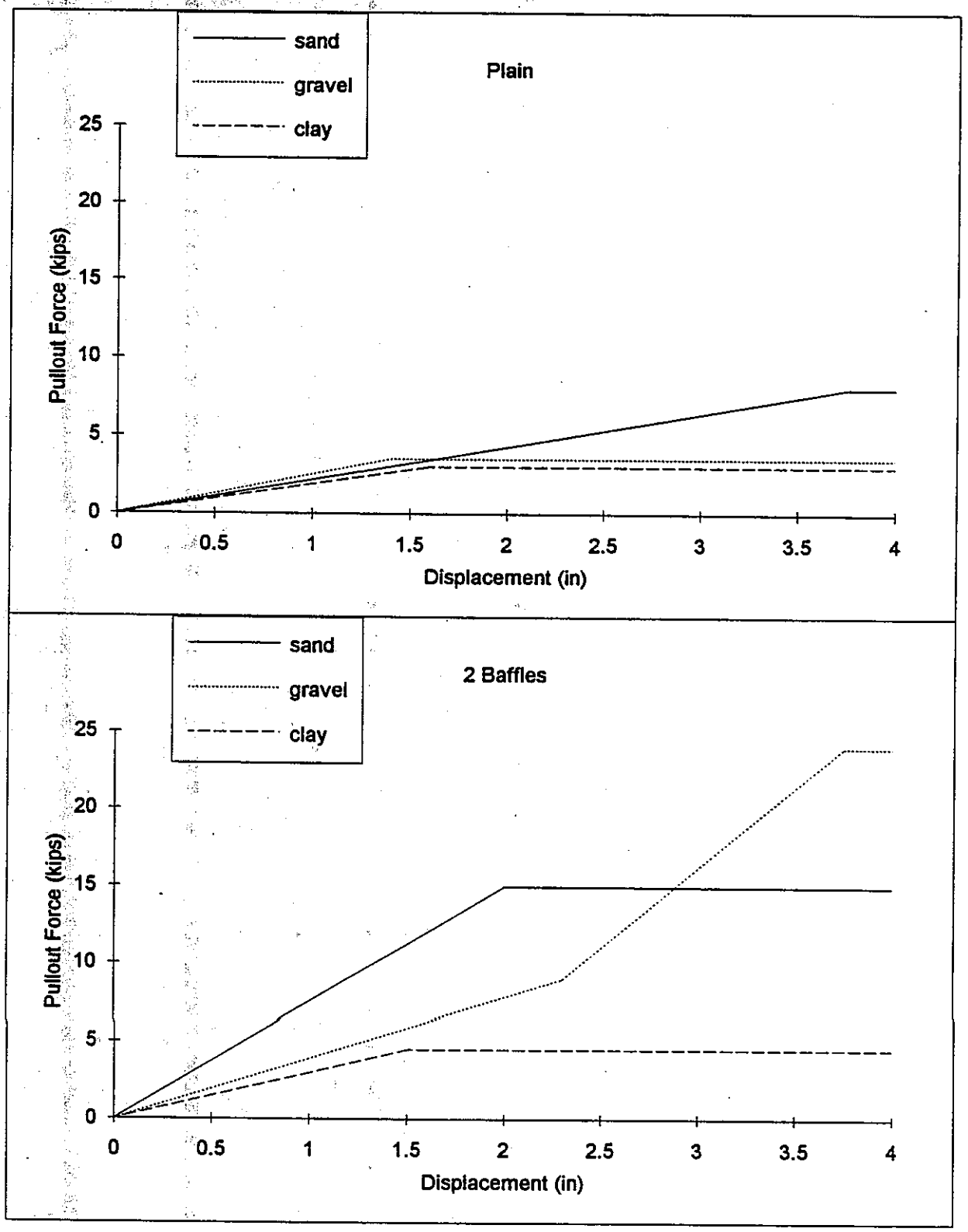


Figure 17. Design envelopes for 4-foot long "C" channels

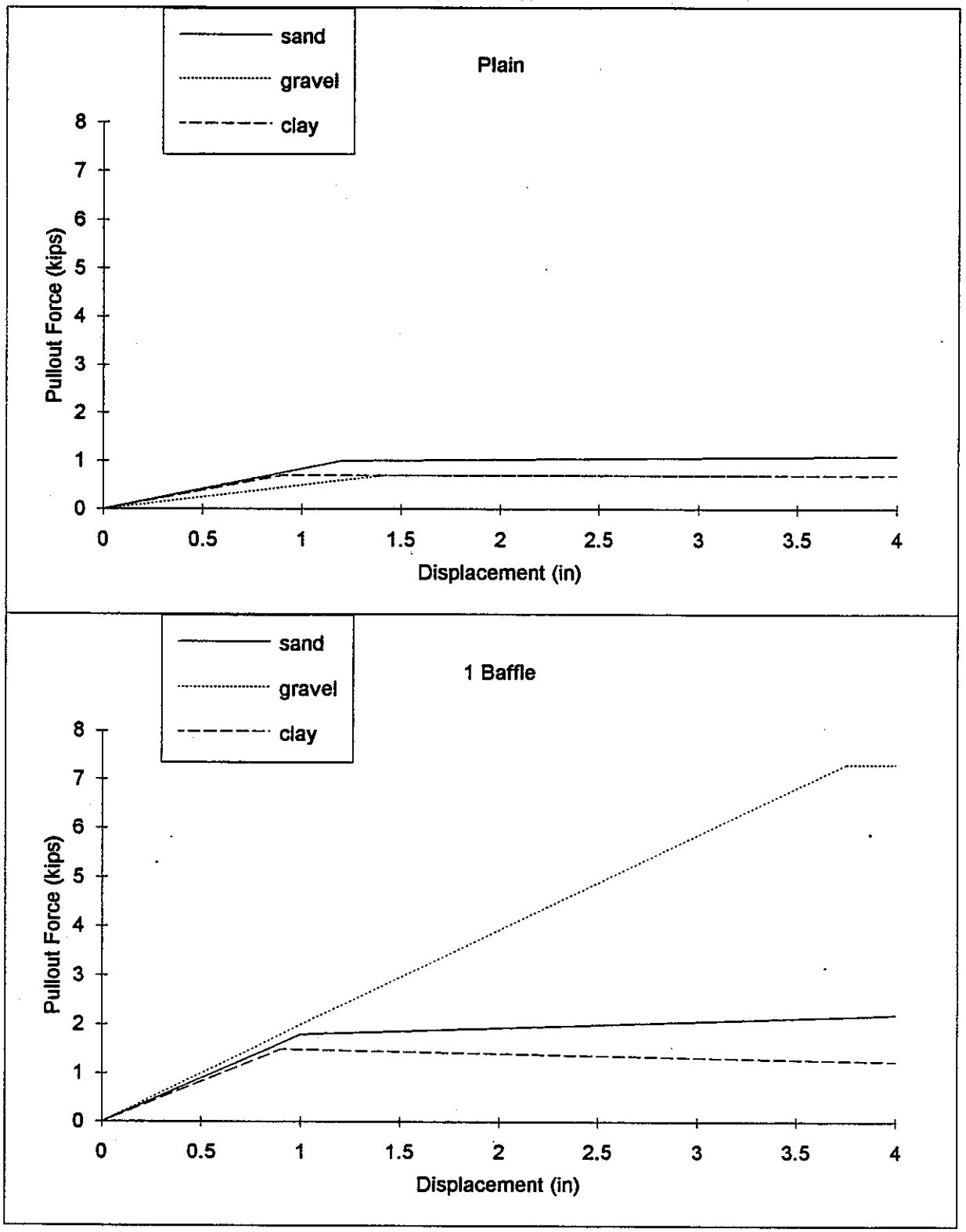
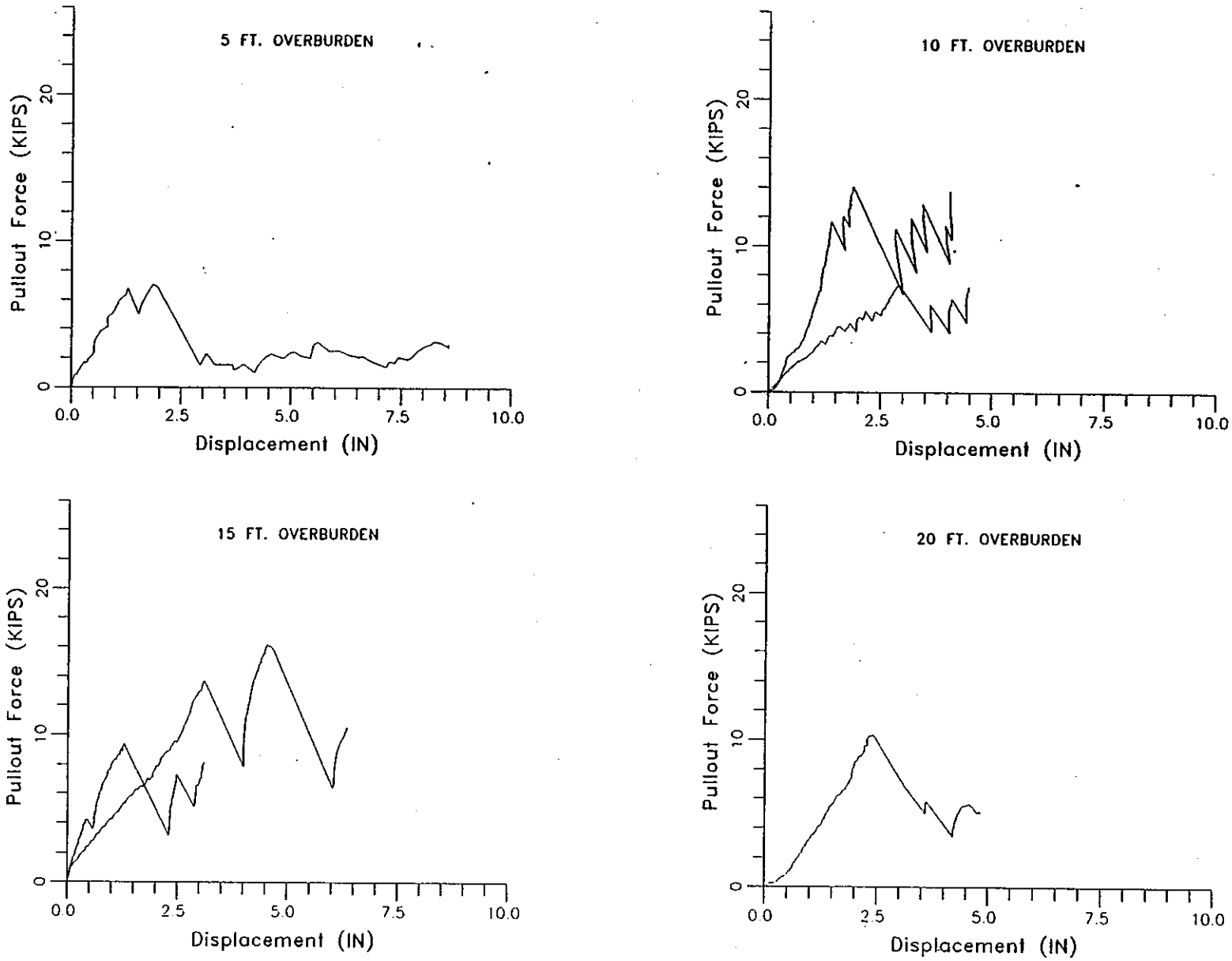


Figure 18. Design envelopes for 2-foot long "C" channels

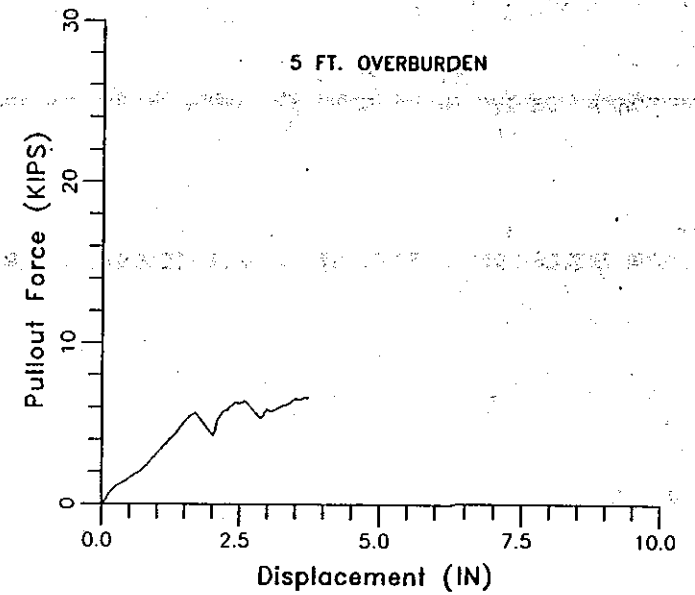
REFERENCES

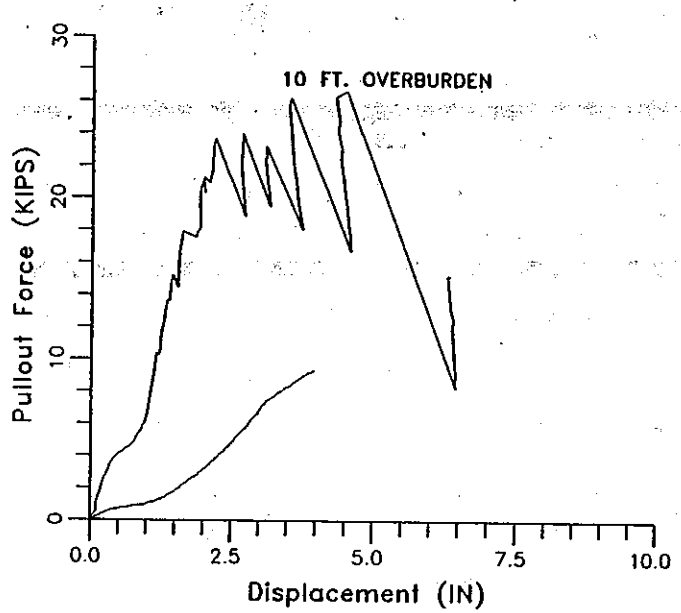
1. Chang, J. C., Hannon, J. B., and Forsyth, R. A. ""Pull Resistance and Interaction of Earthwork Reinforcement and Soil." California Department of Transportation Laboratory. Sacramento, California. January 1977.
2. Bressette, T., Chang, H. G. "Mechanically Stabilized Embankment Constructed With Low Quality Backfill." California Department of Transportation Laboratory. Sacramento, California. June 1986.
3. Hannon, J. B., Forsyth, R. A., and Chang, J. C. "Field Performance Comparison of Two Earthwork Reinforcement Systems." TRB. Transportation Research Record 872. pp. 24-32. 1983.
4. Richman, R. L. and Jackura, K. A. "Field Performance of Tire Anchored Timber Wall." California Department of Transportation Laboratory. Sacramento, California. July, 1984.
5. Hannon, J. B., Chang, J. C. and Cornelius, R. "Soil Pressure and Stresses Transportation Laboratory. Sacramento, California. August, 1984.
6. Forsyth, R. A. Alternative Earthwork reinforcement." Symposium on Earth Reinforcement. American Society of Civil Engineers. pp. 358-370. April, 1978.
7. Schlosser, F. and Ellas, V. "Friction in Reinforced Earth." American Society of Civil Engineers Symposium on Earth reinforcement. Pittsburg. 1978.

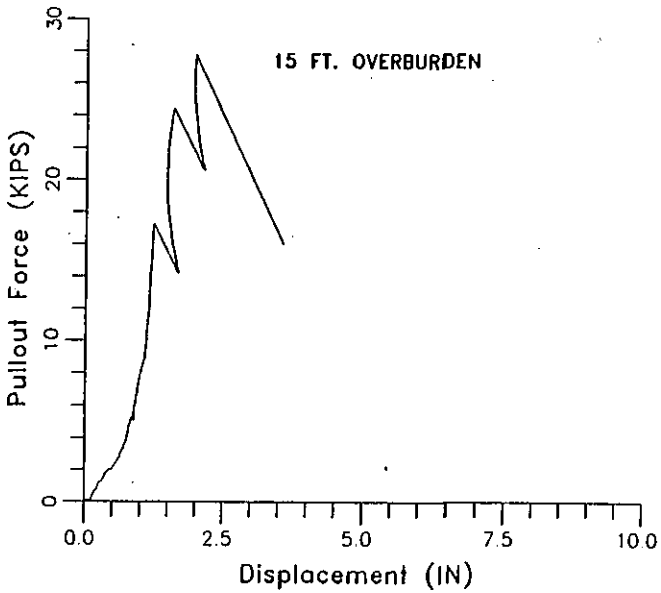
APPENDIX A

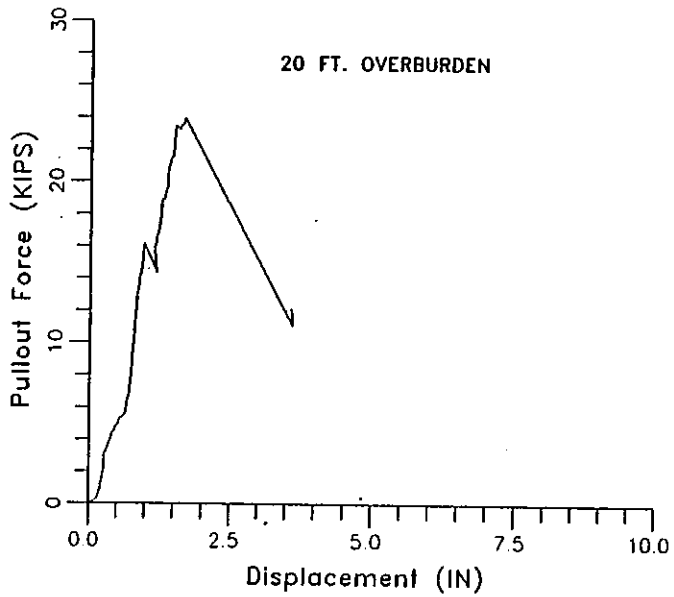


Field: Force–Displacement curves for MSE Bar–mat with Single Transverse bar in gravel. Double curves represent replicated tests.

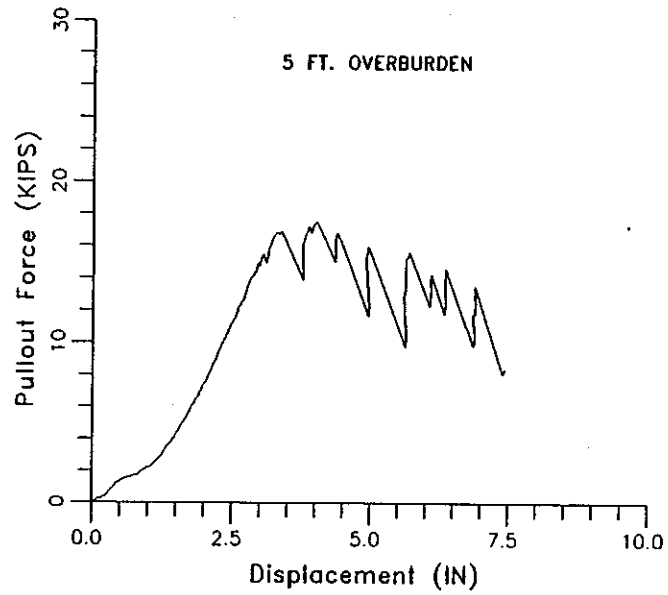


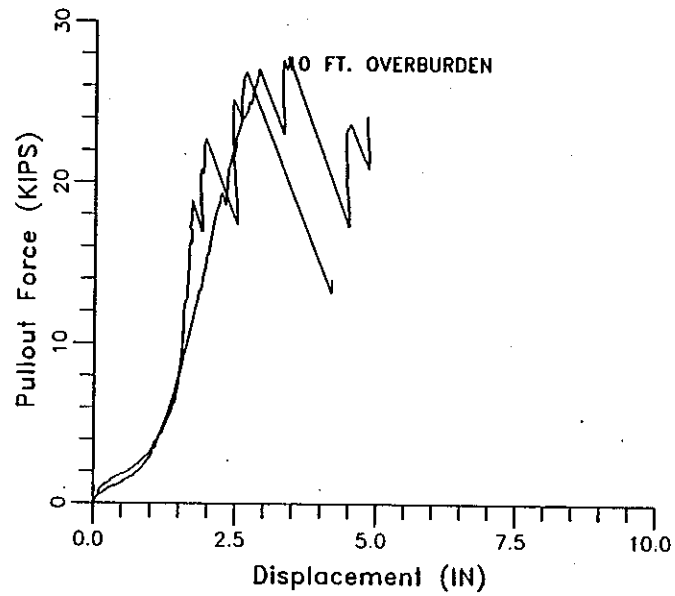


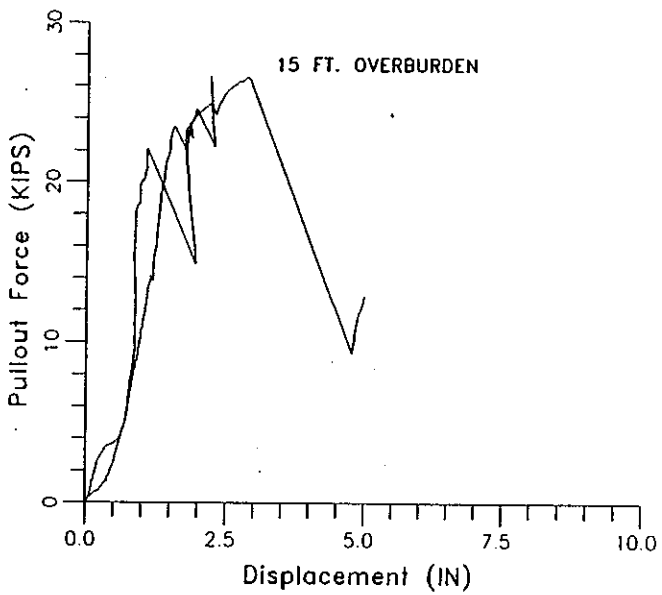


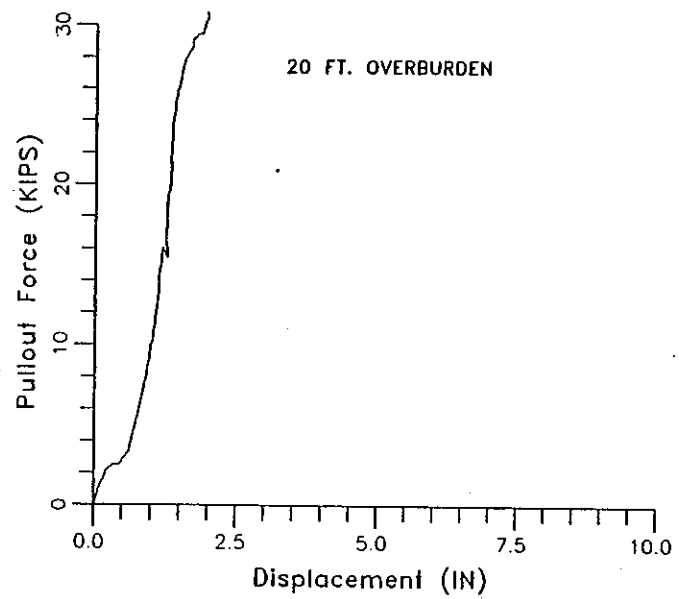


Field: Force-Displacement curves for MSE Bar-mat with Double Transverse bar in gravel. Double curves represent replicated tests.

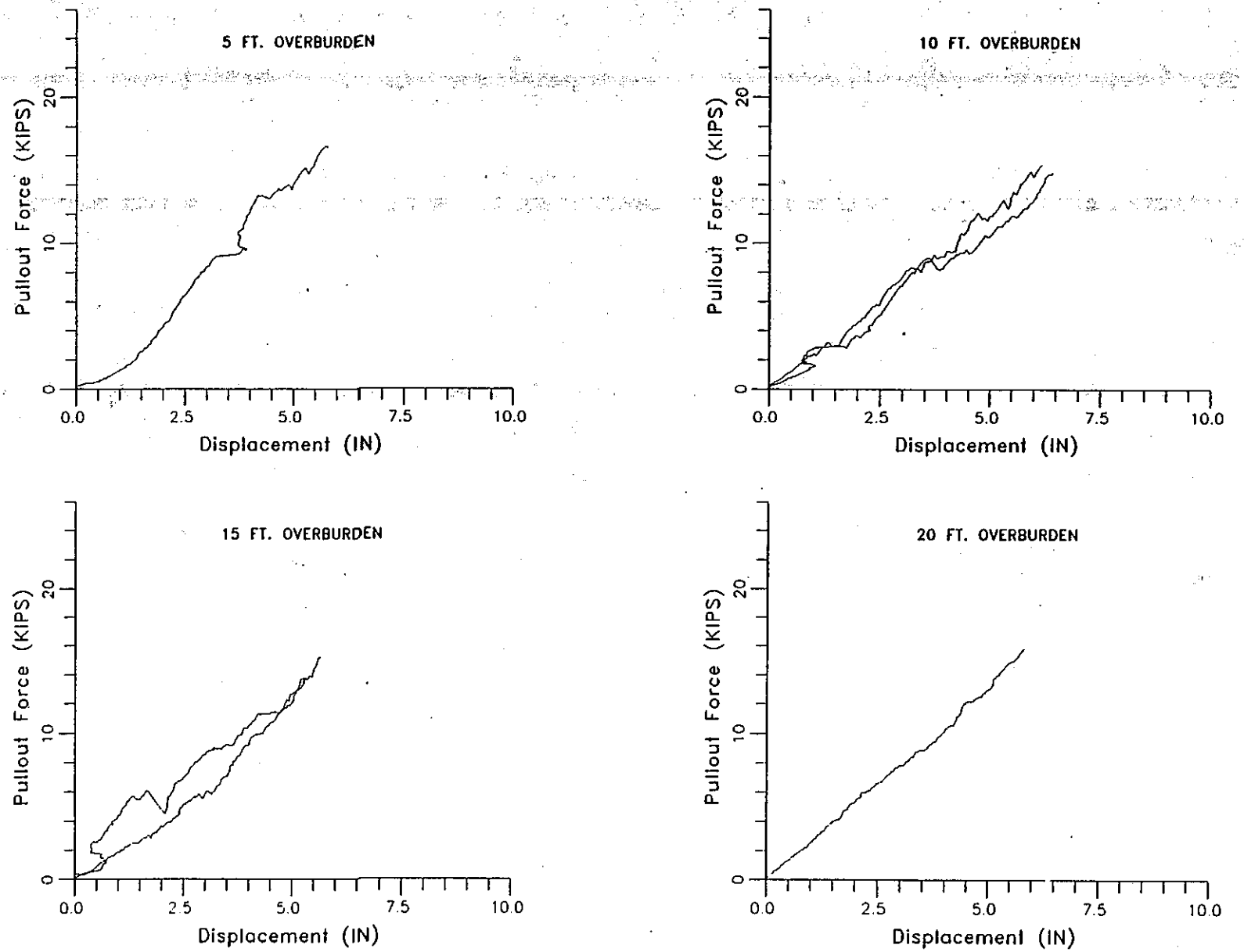




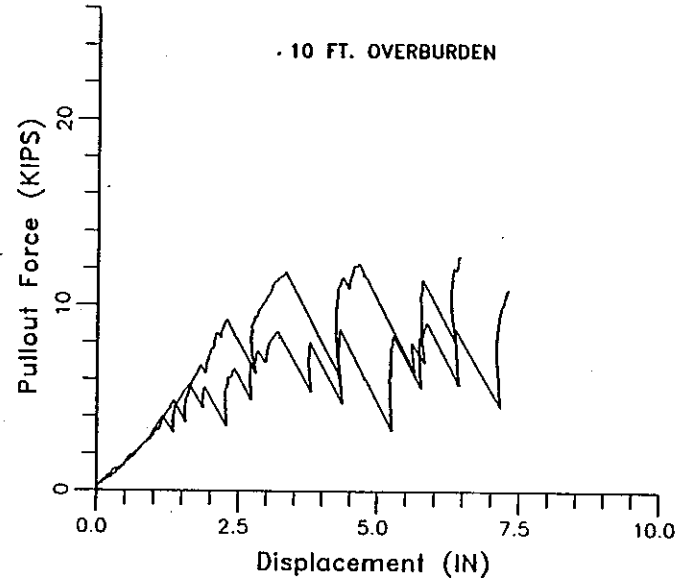


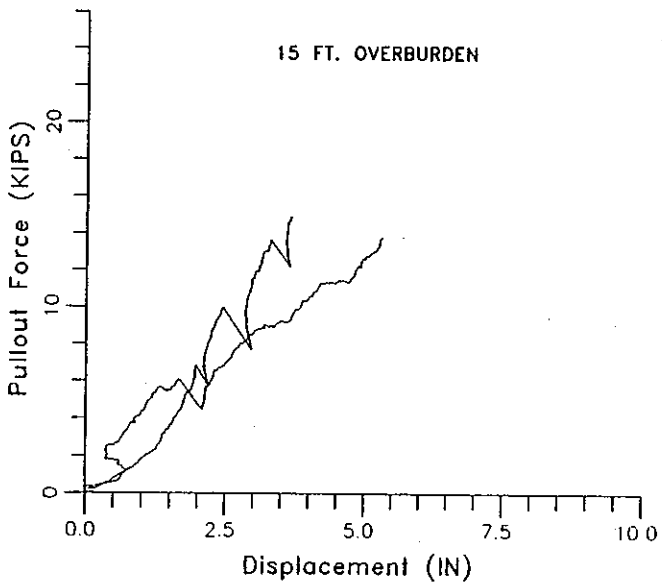


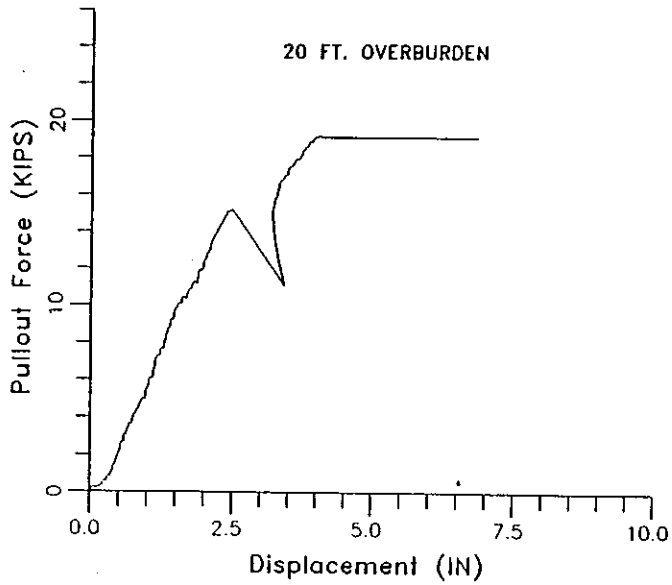
Field: Force–Displacement curves for MSE Bar–mat with Triple Transverse bar in gravel. Double curves represent replicated tests.



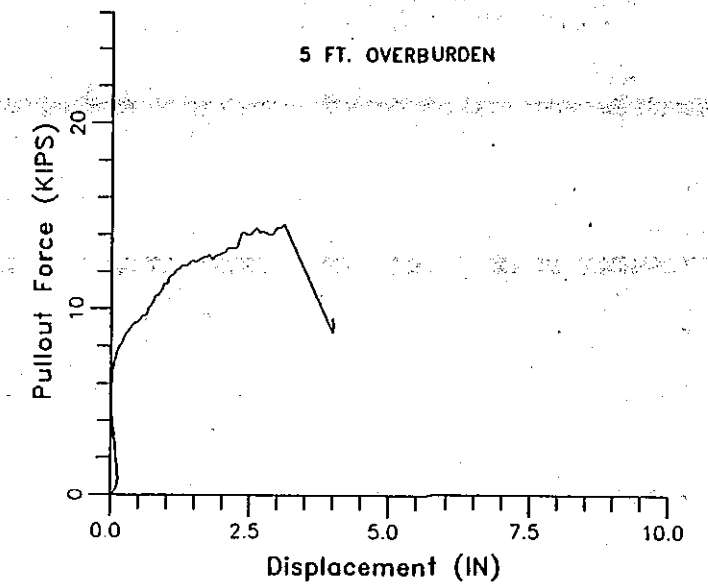
Field: Force–Displacement curves for TAT with sidewall in gravel. Double curves represent replicated tests.

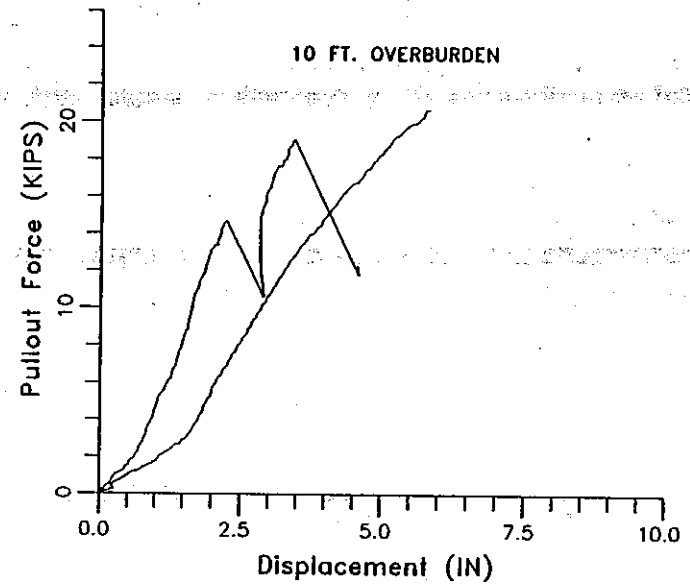


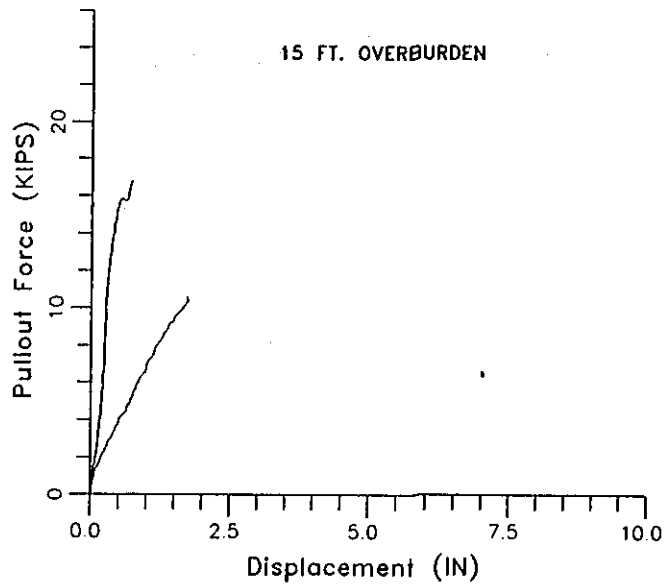


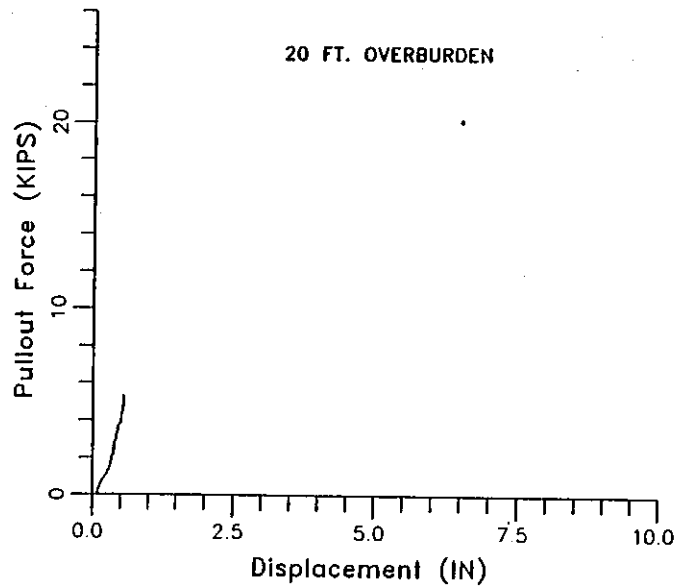


Field: Force–Displacement curves for TAT without sidewall in gravel. Double curves represent replicated tests.

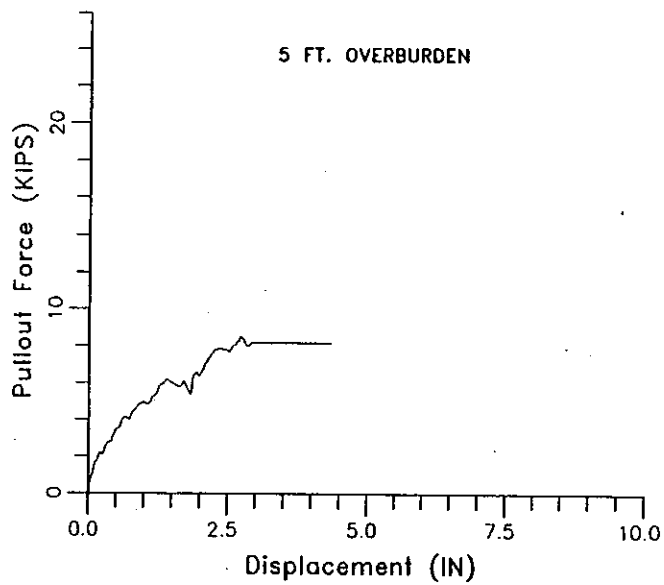


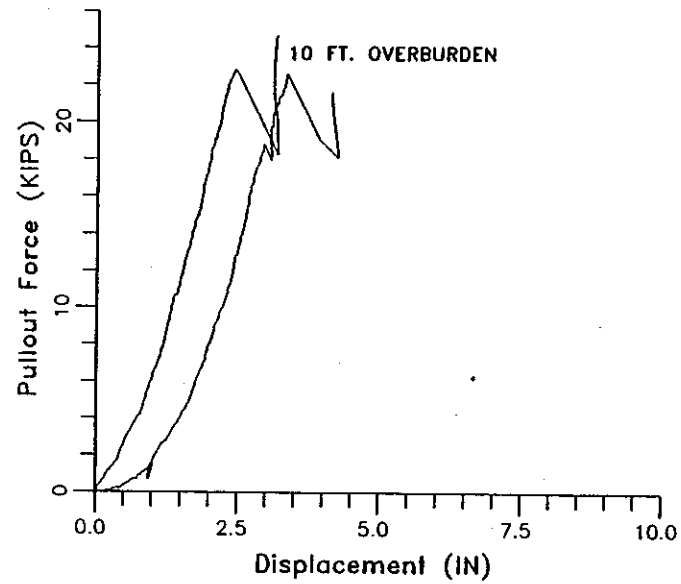


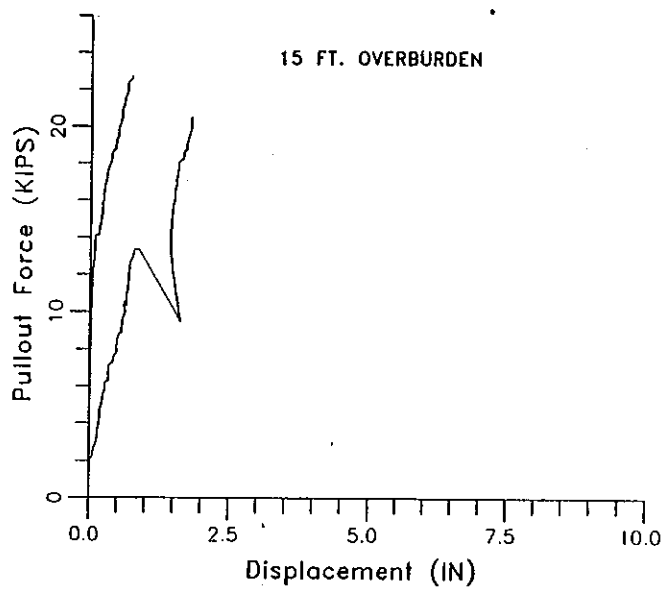


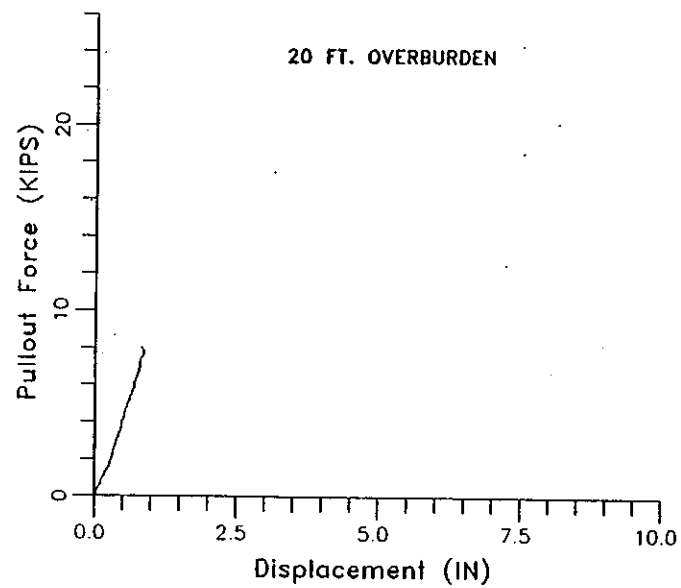


Field: Force–Displacement curves for CRR with one–disk in gravel.Double curves represent replicated tests.

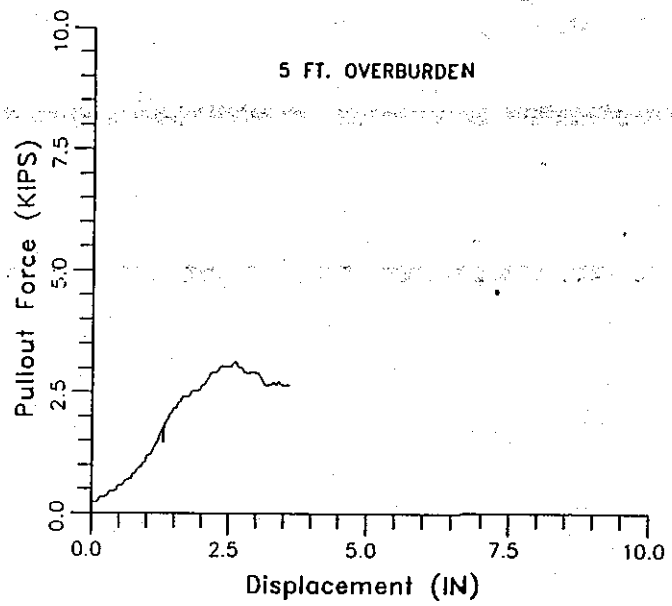


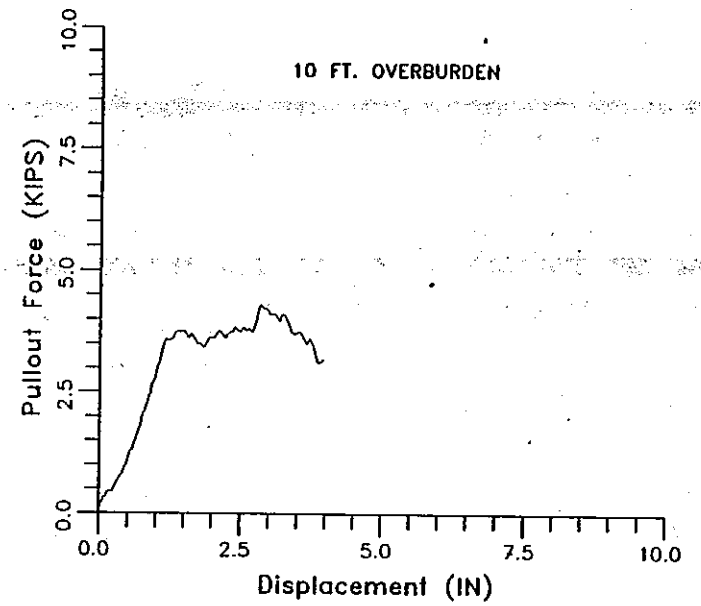


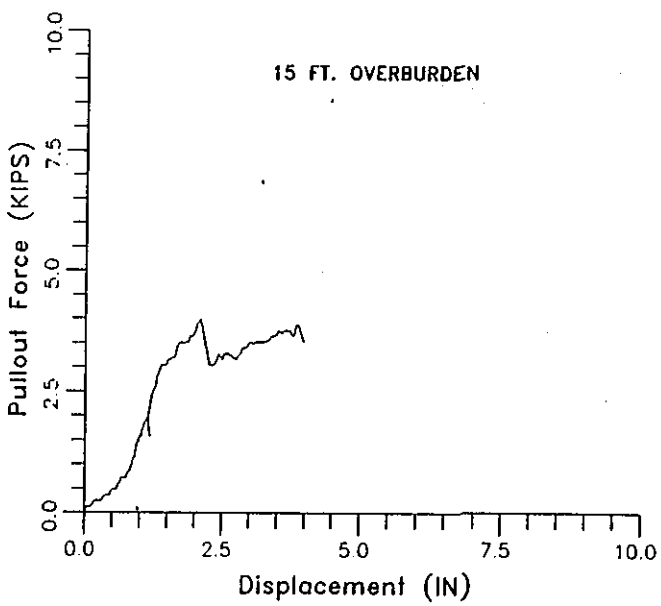


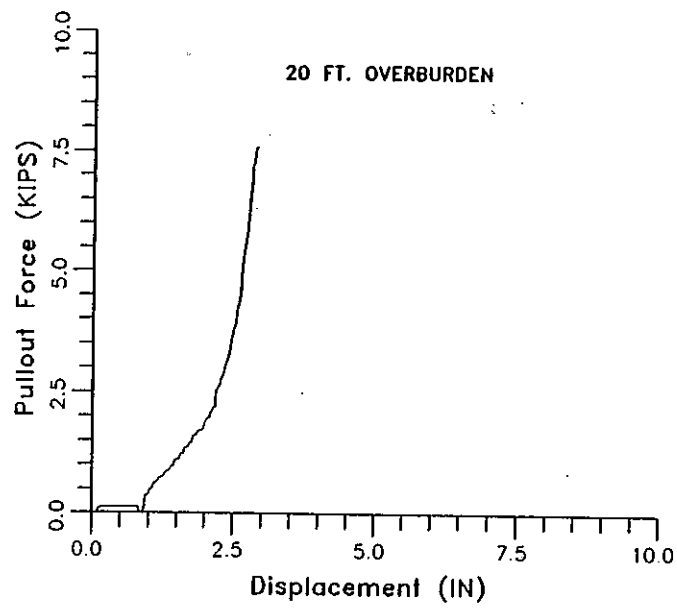


Field: Force–Displacement curves for CRR with two-disk in gravel. Double curves represent replicated tests.

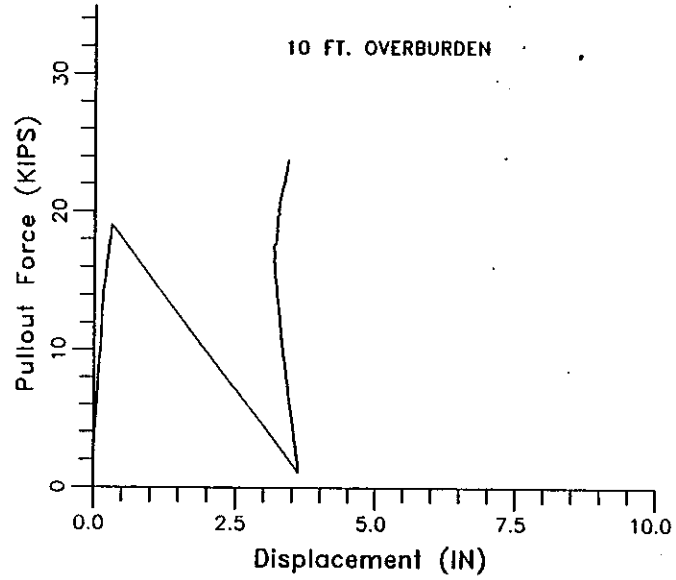


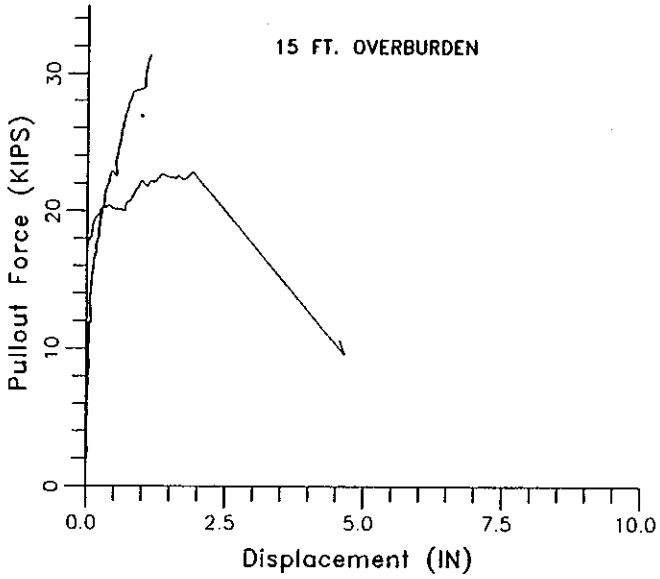


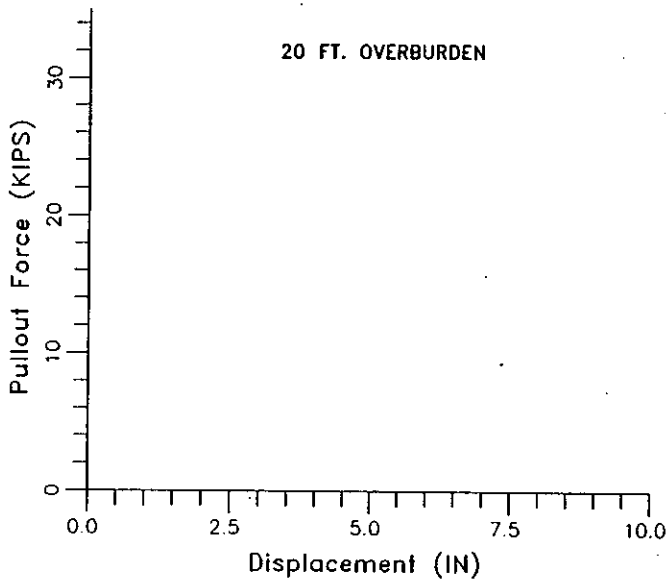




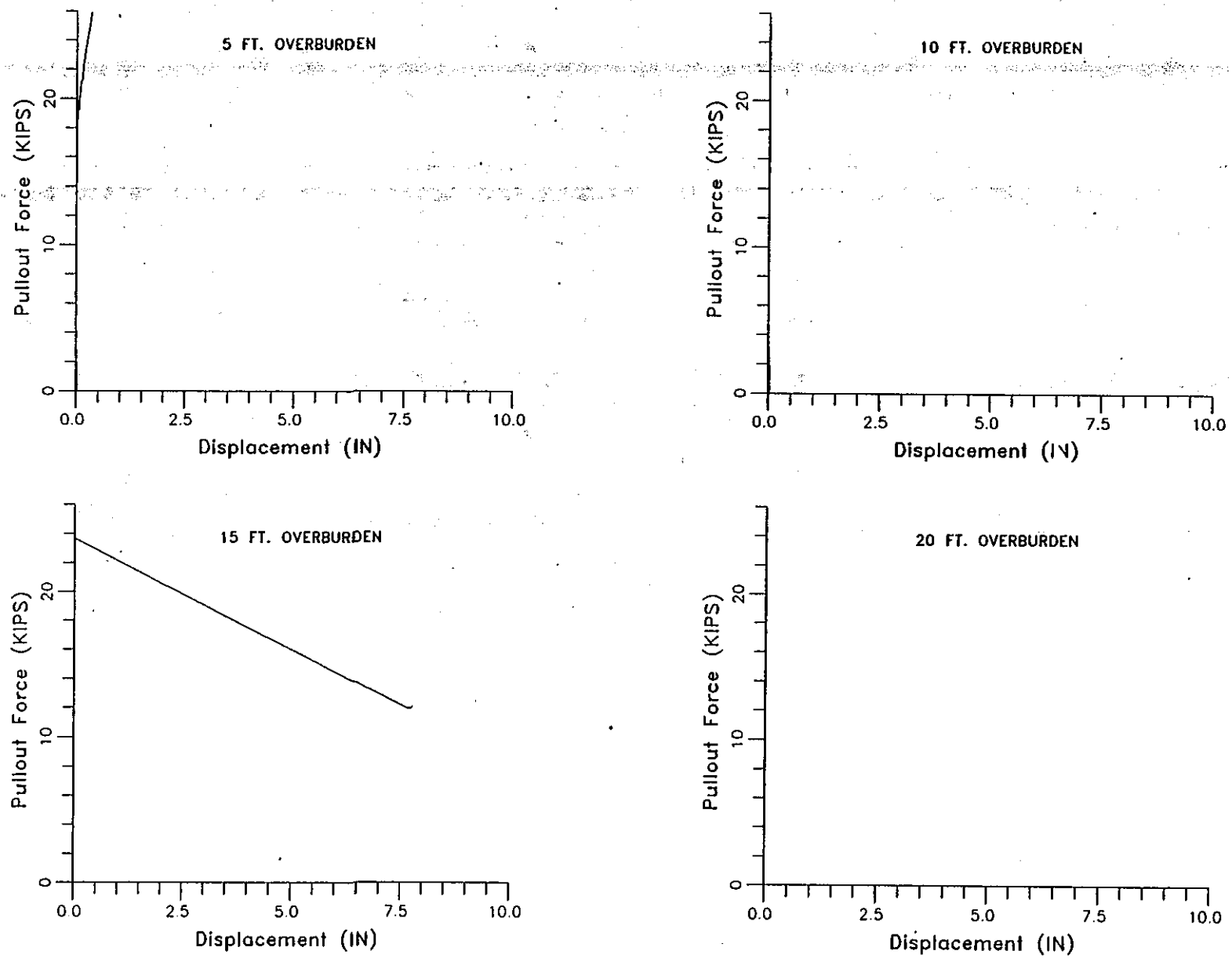
Field: Force-Displacement curves for C-channel 4-feet long, plain in gravel.



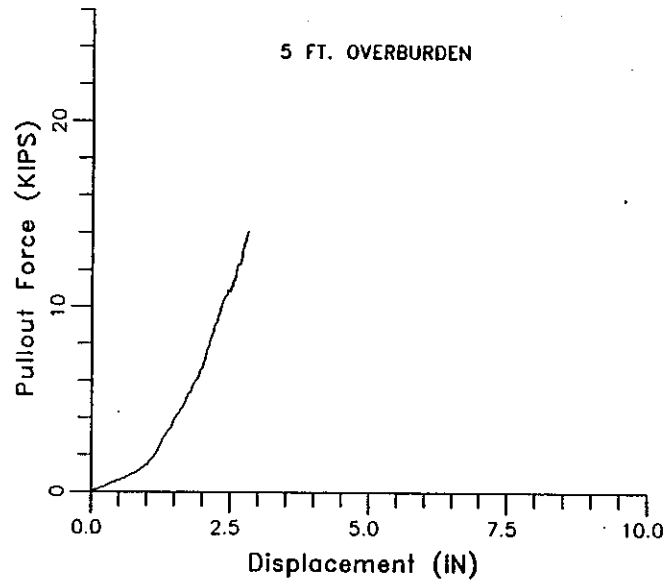


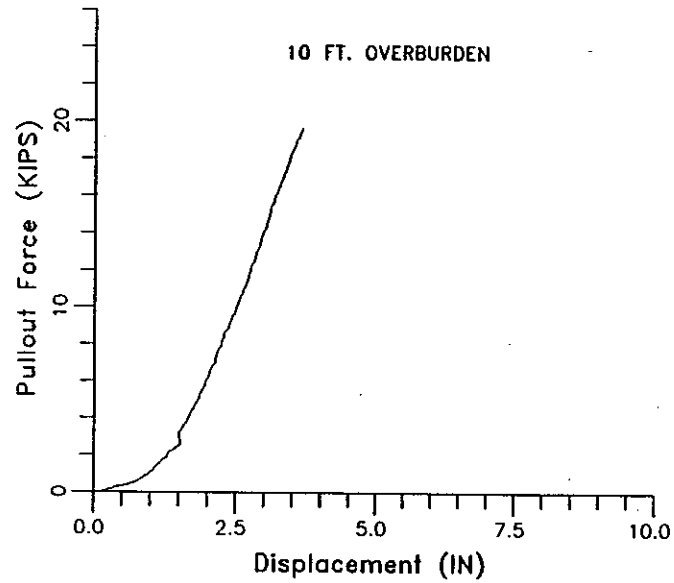


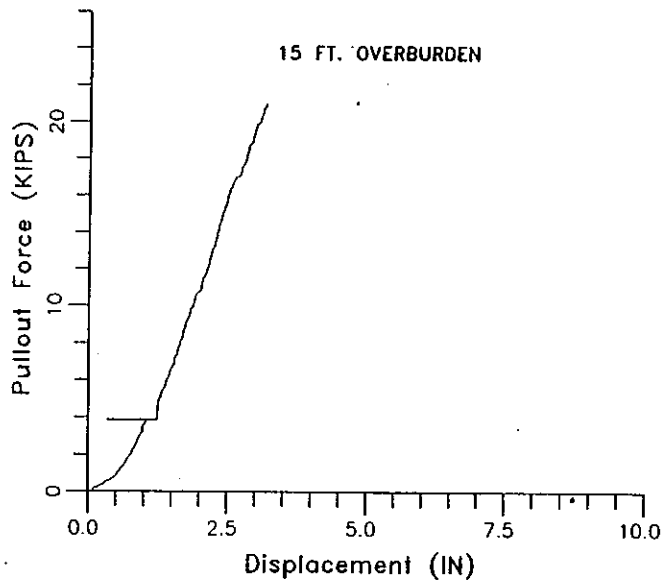
Field: Force–Displacement curves for C–channel 4–feet long, one foot Tee in gravel. Double curves represent replicated tests.

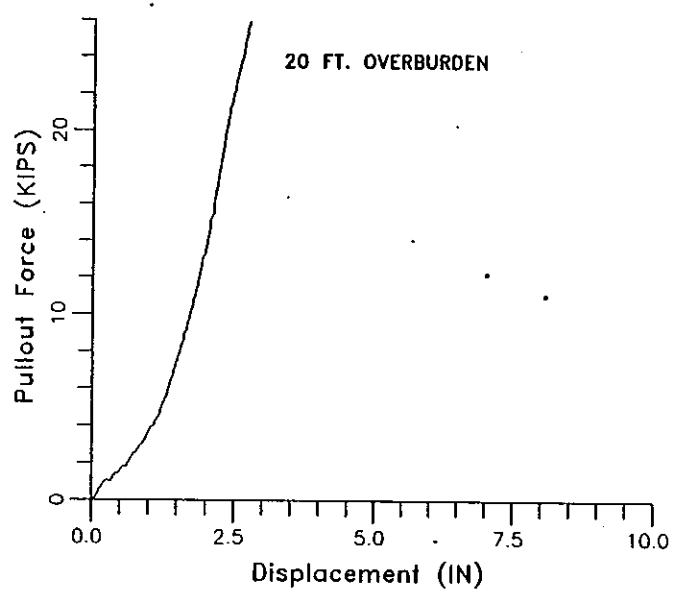


Field: Force–Displacement curves for C–channel 4–feet long, two feet Tee in gravel.

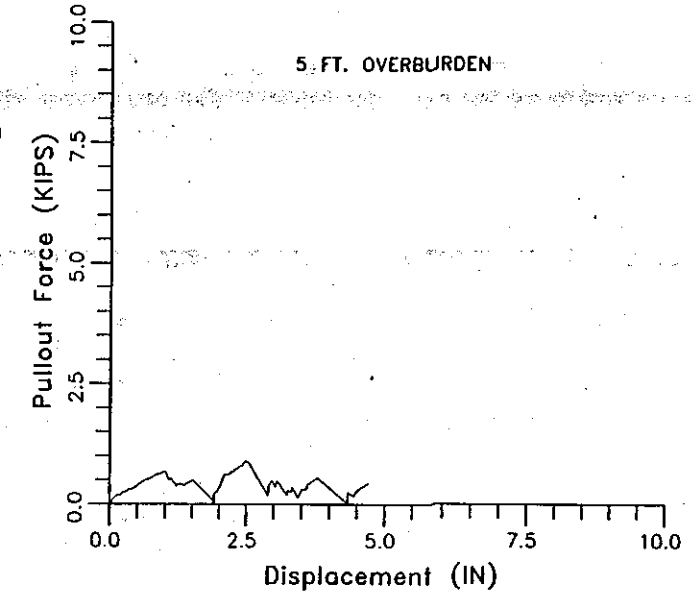


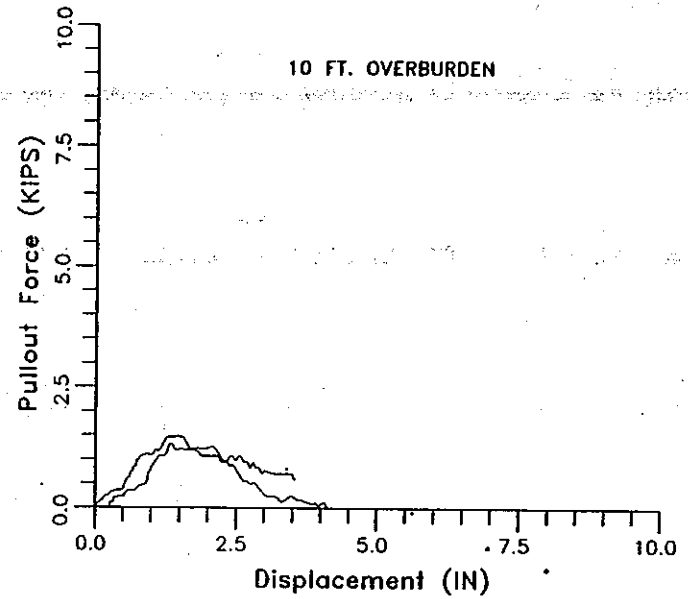


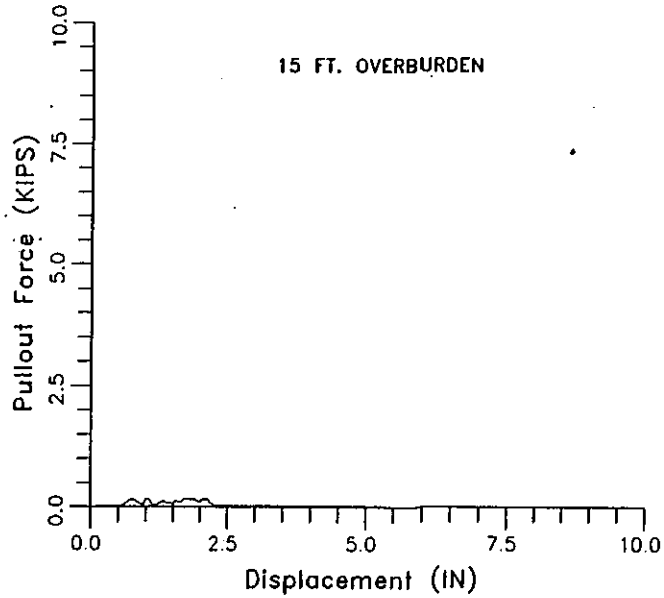


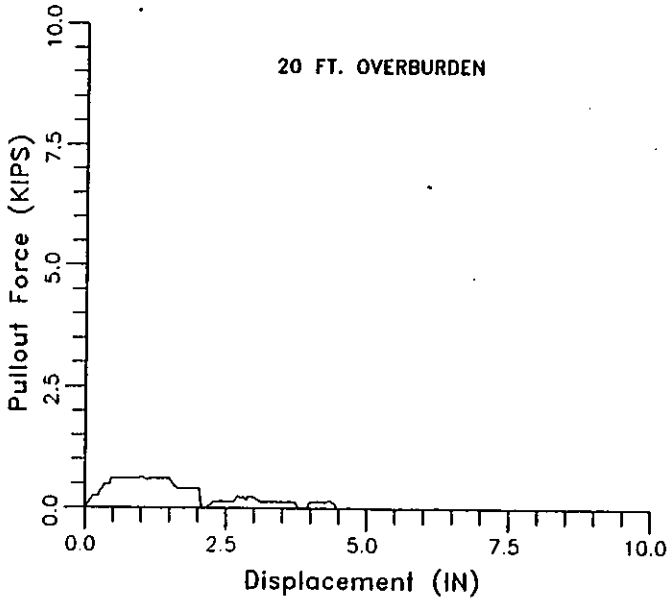


Field: Force–Displacement curves for C–channel 4–feet long, two Baffels in gravel.

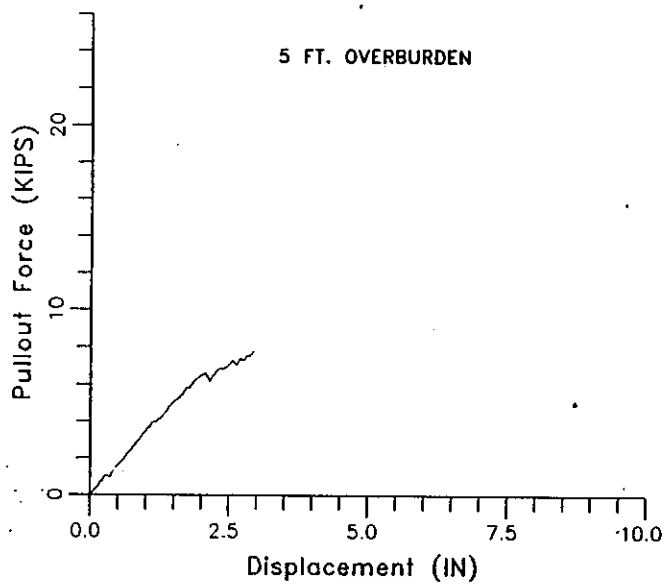


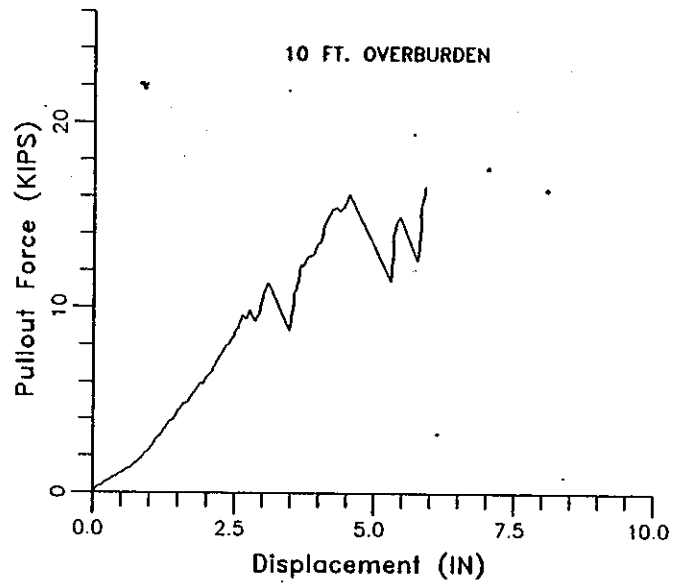


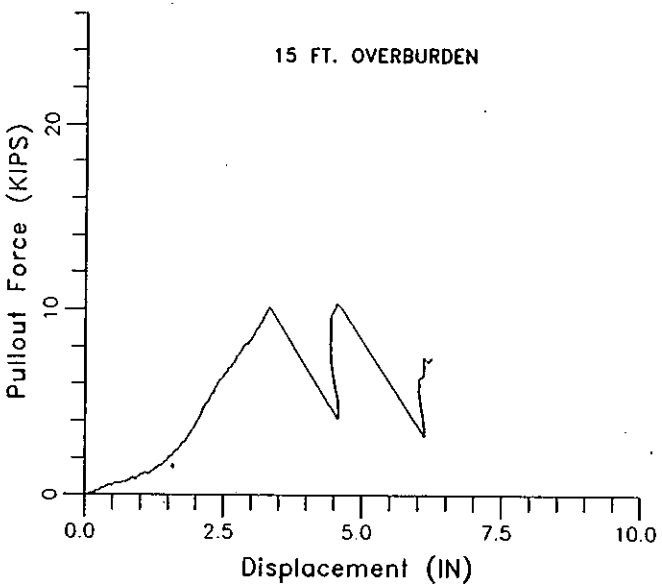


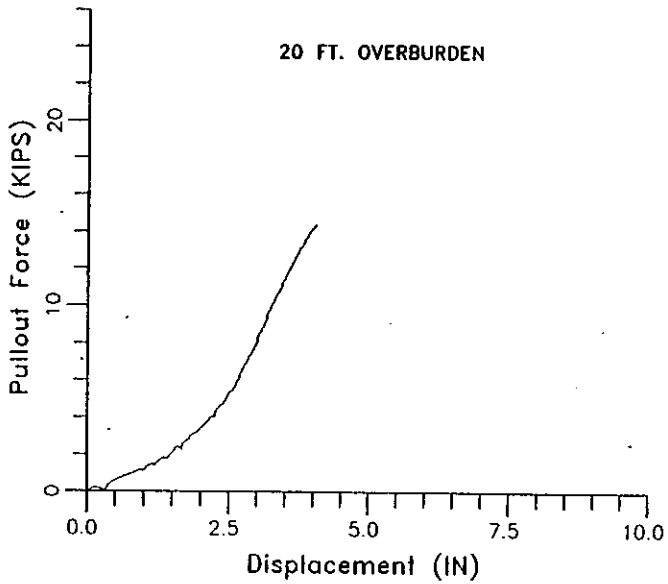


Field: Force–Displacement curves for C–channel 2–feet long, plain in gravel. Double curves represent replicated tests.

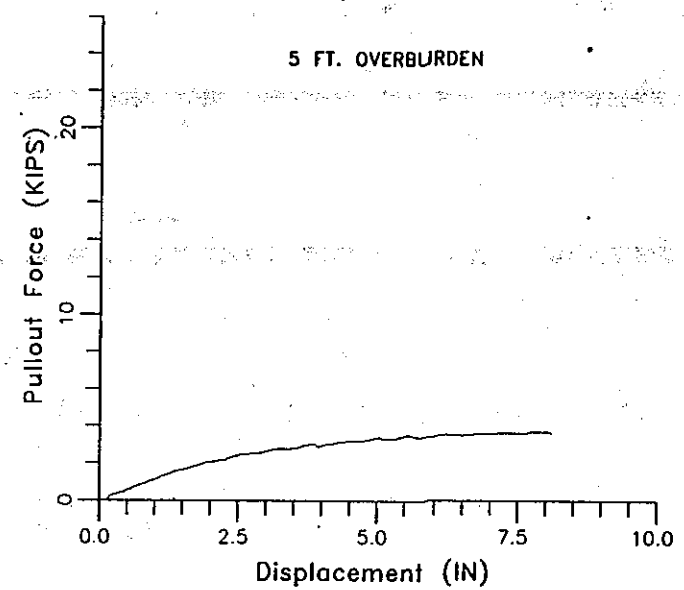


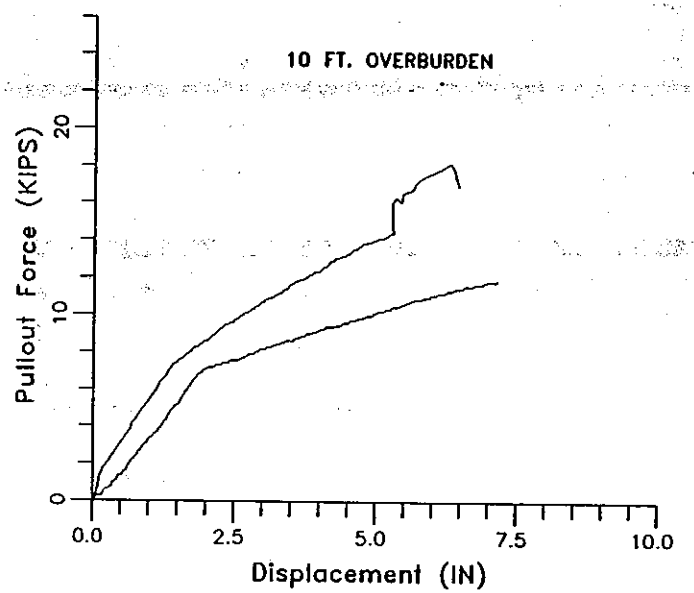


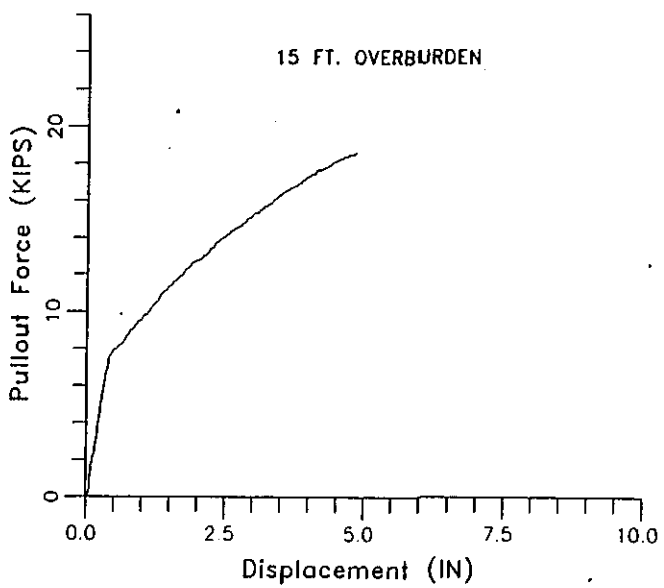


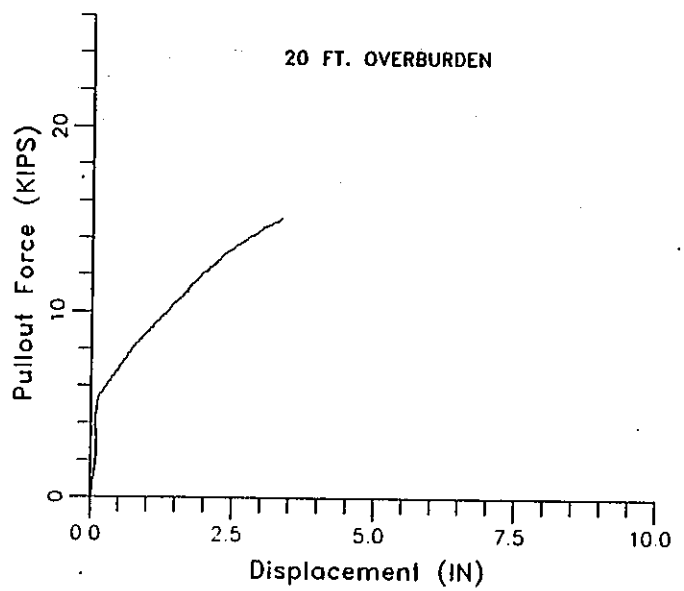


Field: Force–Displacement curves for C–channel 2–feet long, one Baffel in gravel.

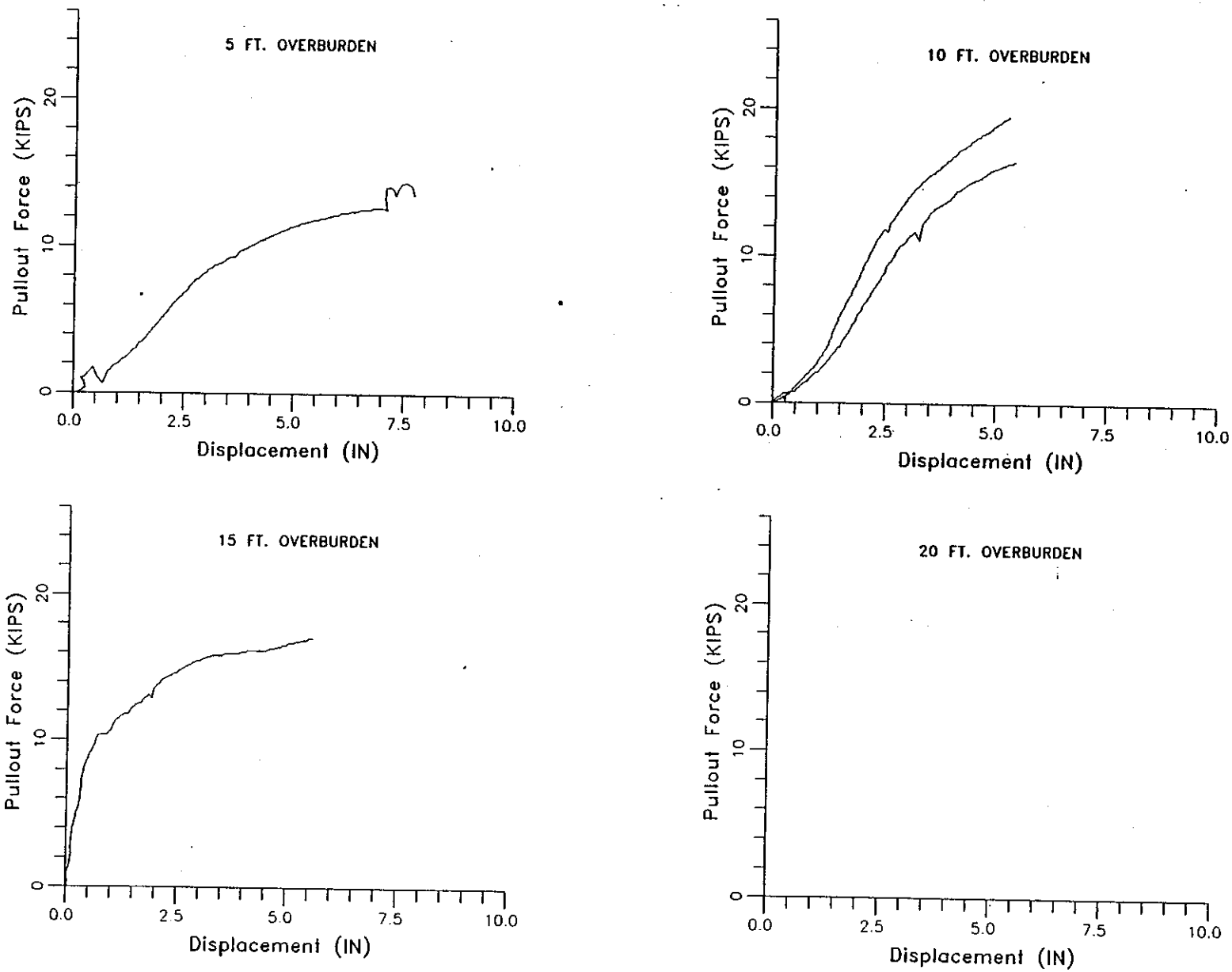




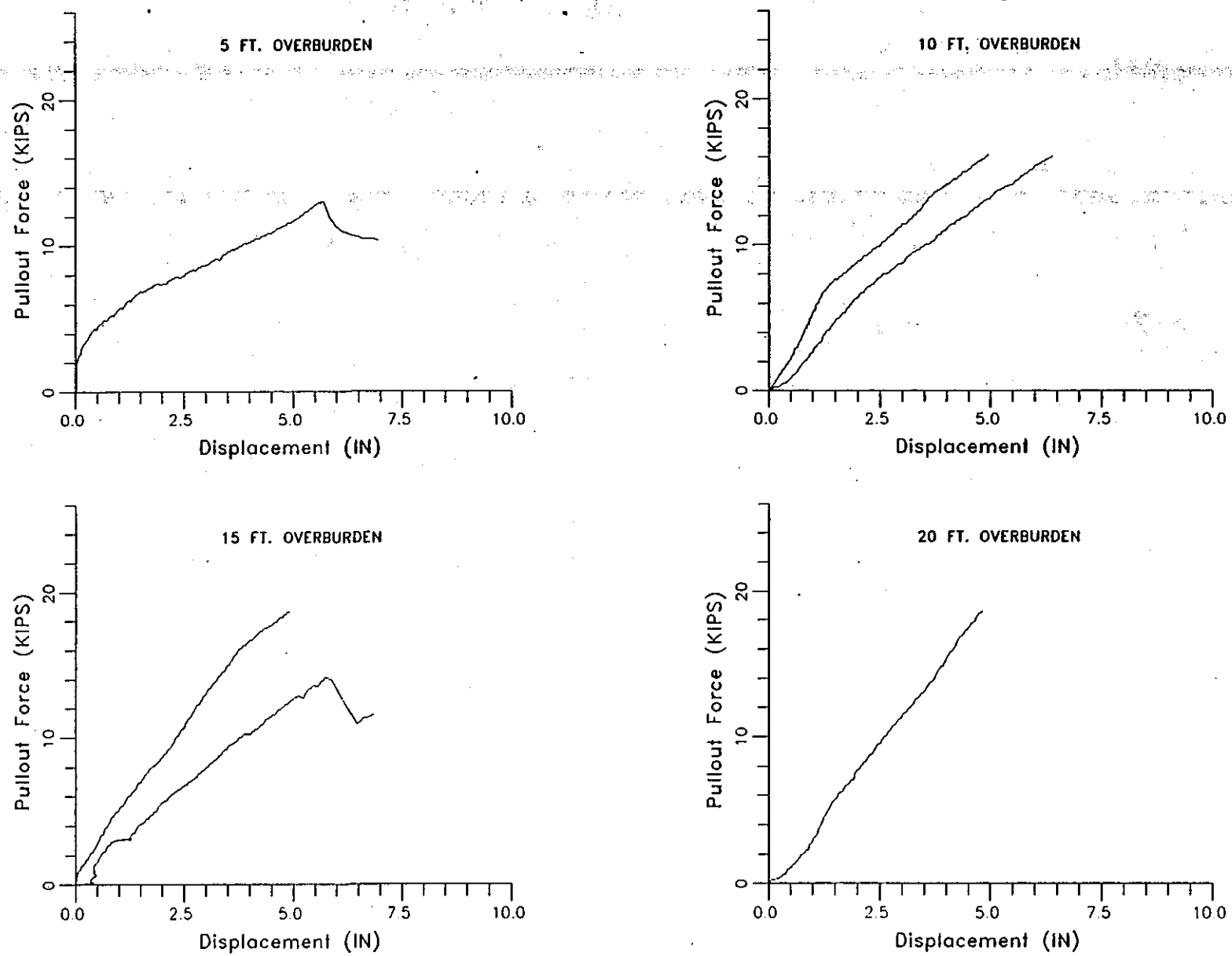




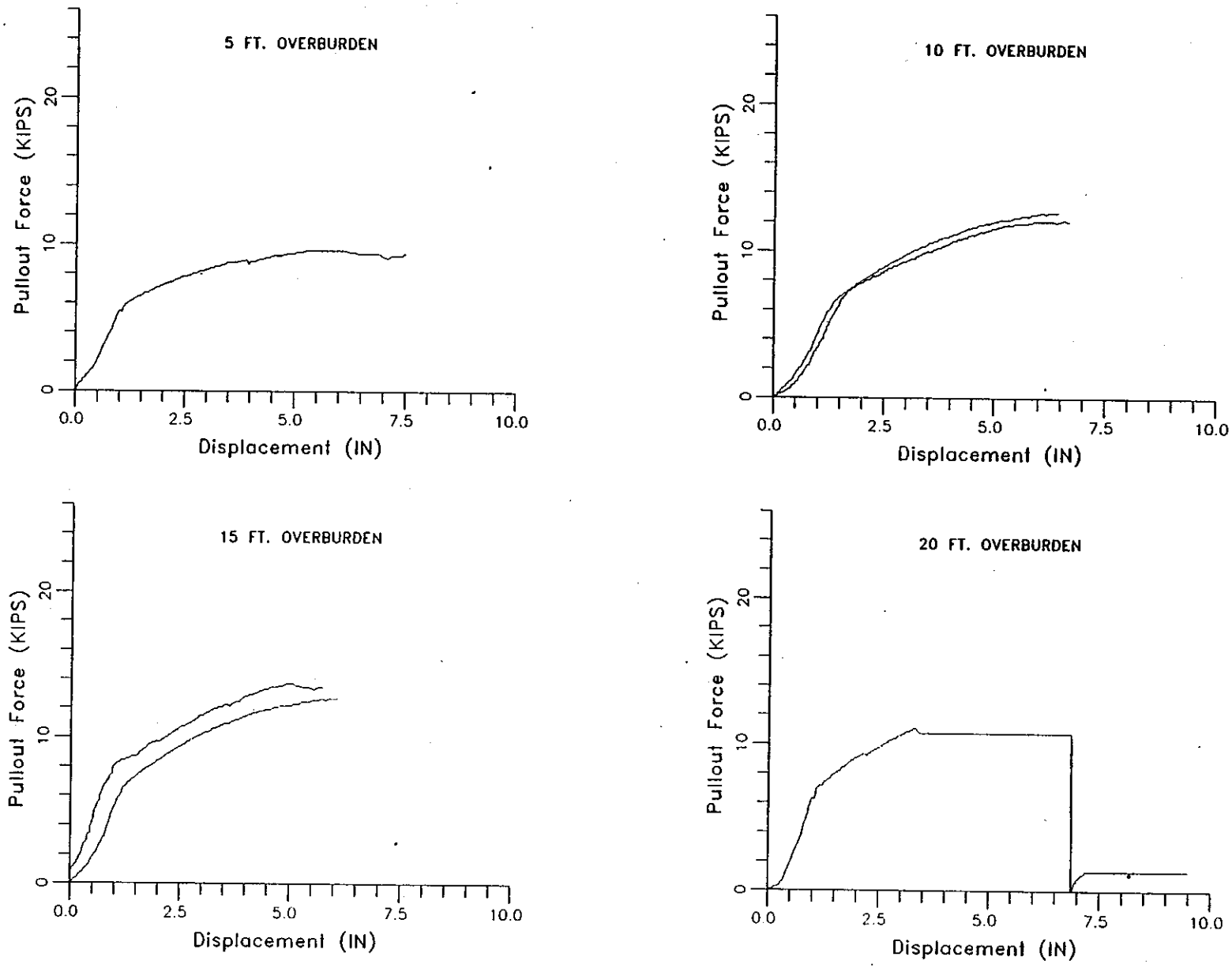
Field: Force–Displacement curves for CRR with one–disk in sand. Double curves represent replicated tests.



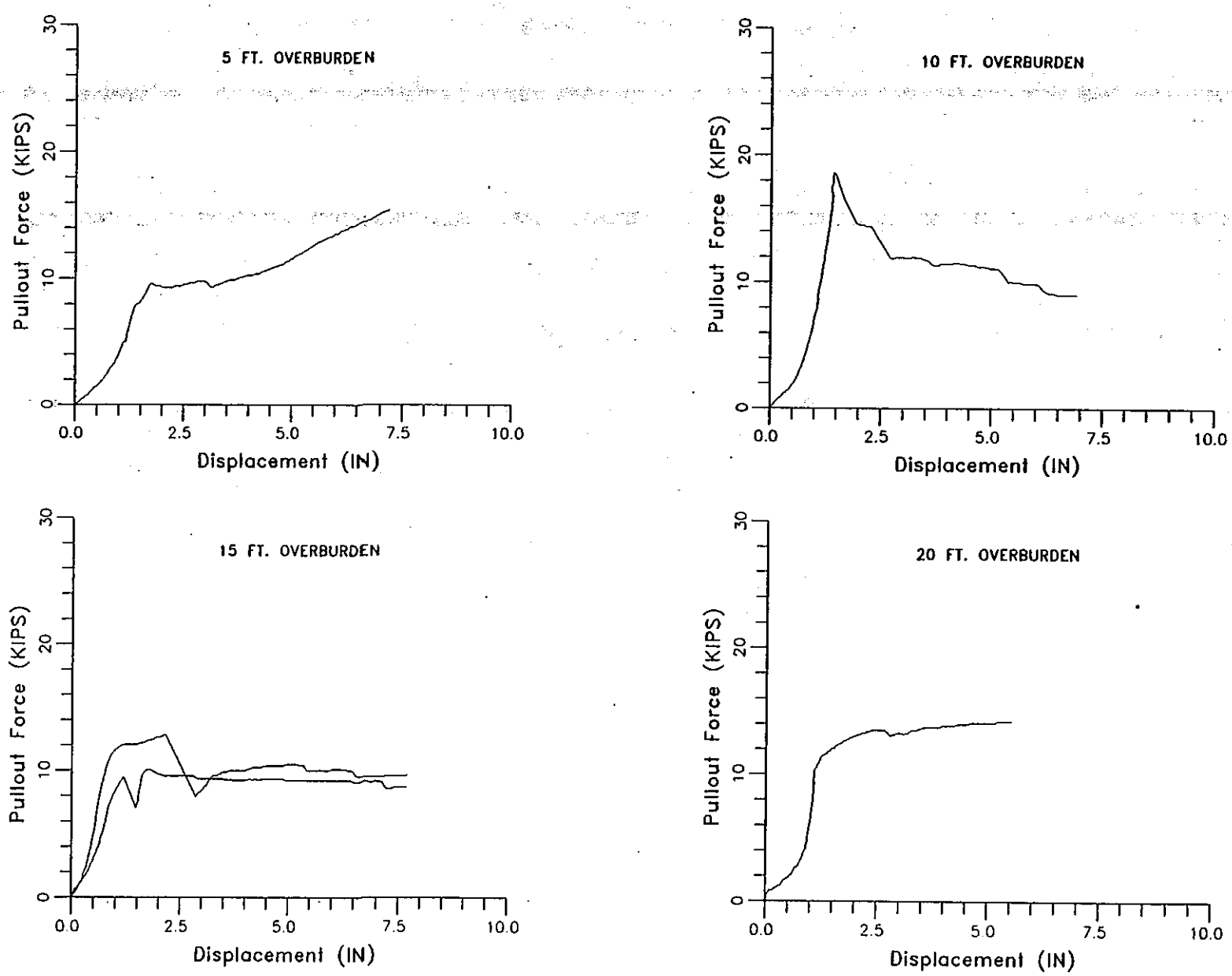
Field: Force–Displacement curves for CRR with two–disk in sand. Double curves represent replicated tests.



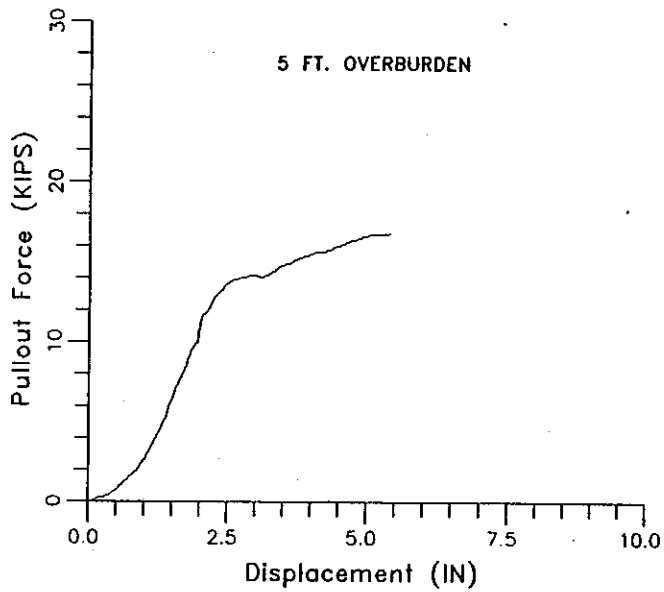
Field: Force–Displacement curves for TAT with sidewall in sand. Double curves represent replicated tests.

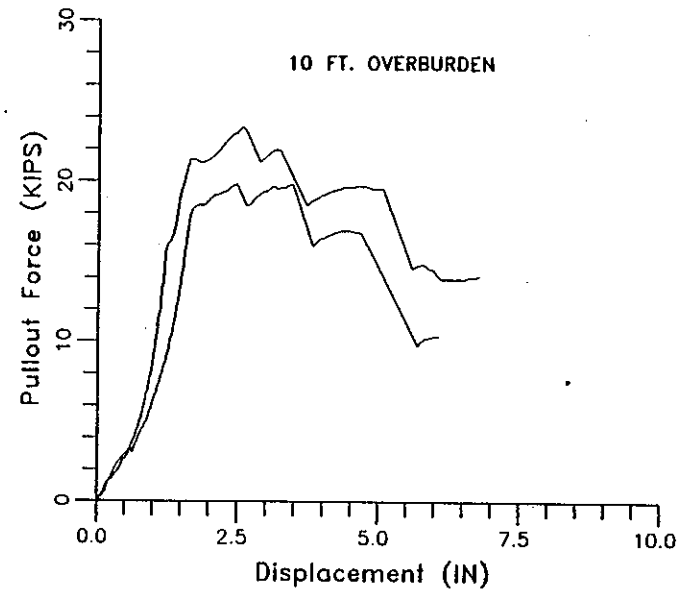


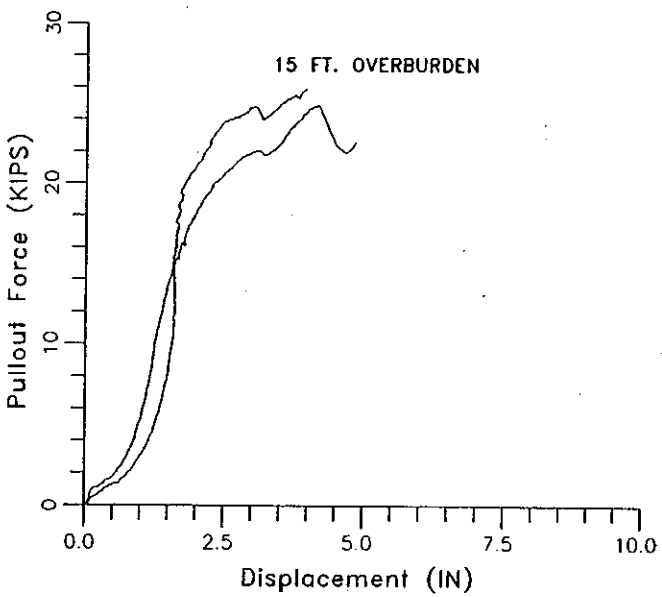
Field: Force–Displacement curves for TAT without sidewall in sand. Double curves represent replicated tests.

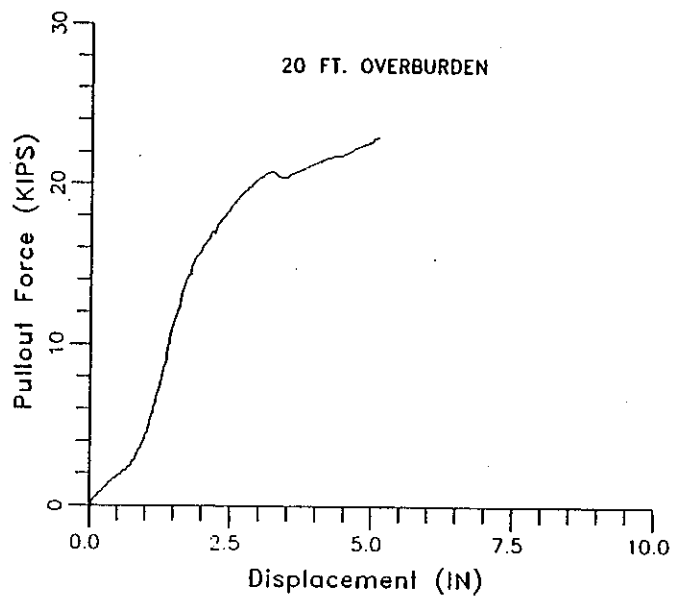


Field: Force–Displacement curves for MSE Bar–mat with Single Transverse bar in Sand. Double curves represent replicated tests.

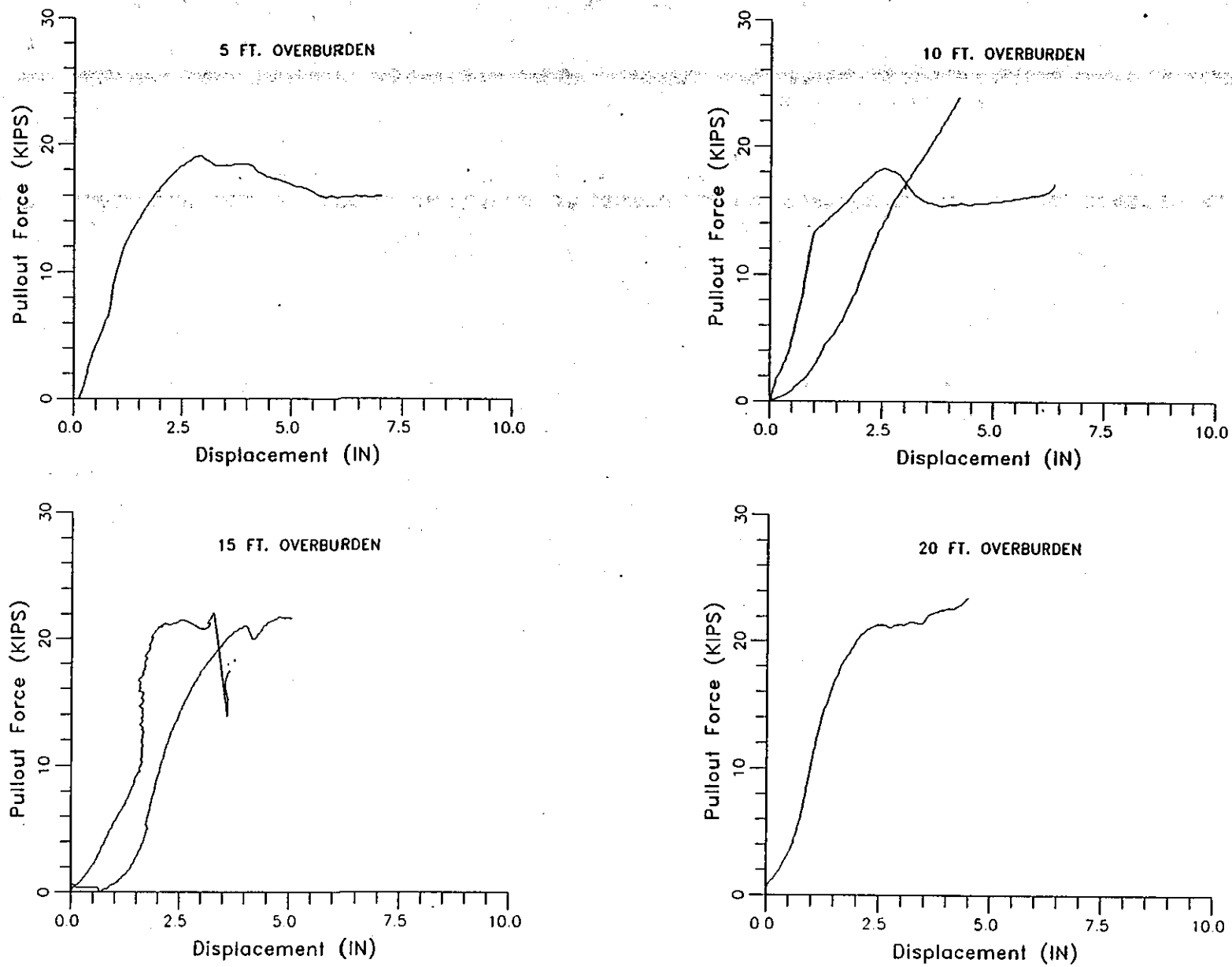




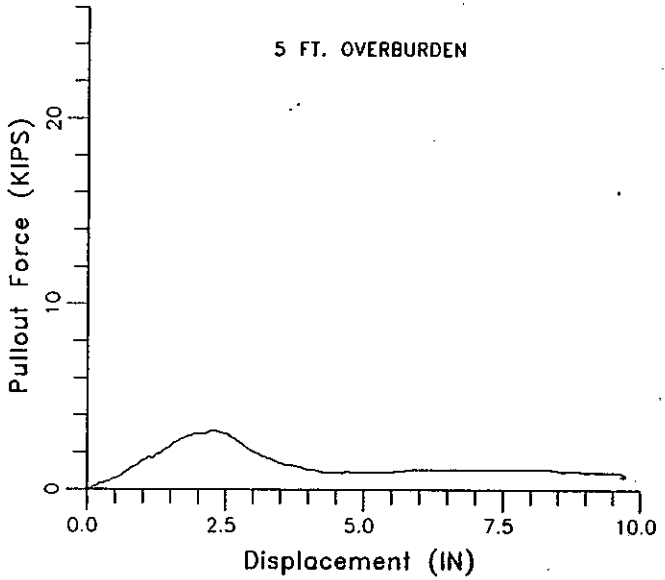


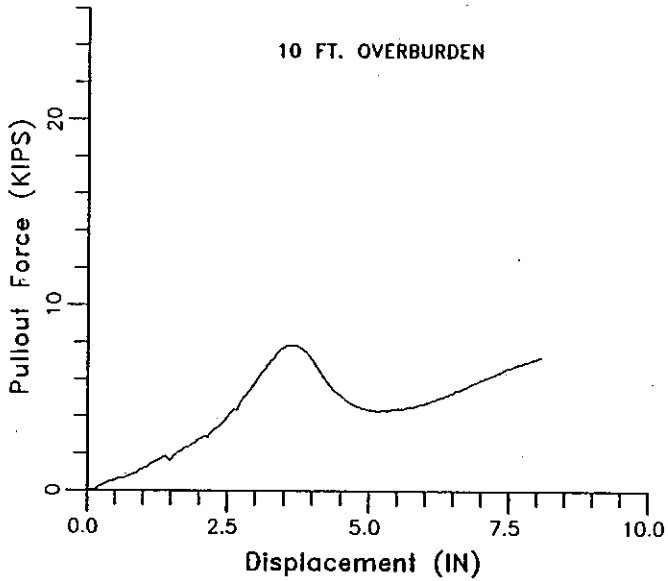


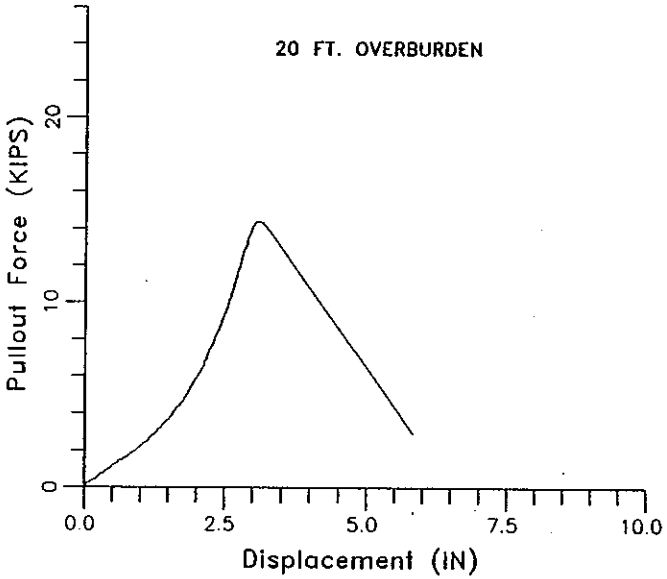
Field: Force–Displacement curves for MSE Bar–mat with Double Transverse bar in Sand. Double curves represent replicated tests.



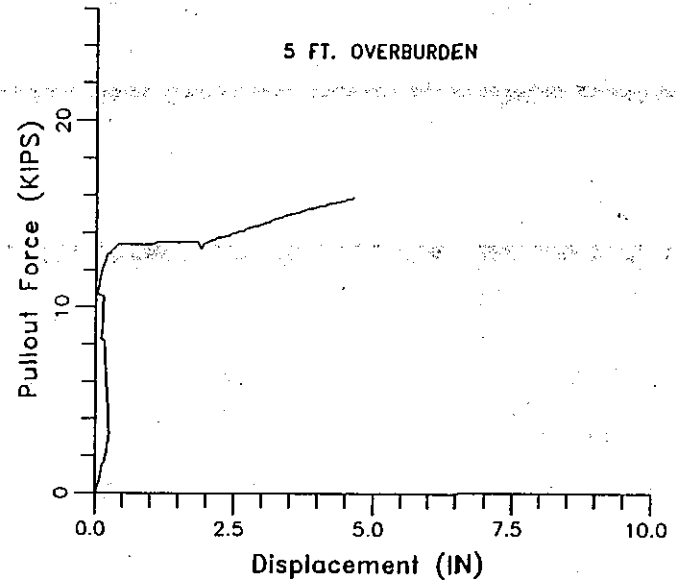
Field: Force-Displacement curves for MSE Bar-mat with Triple Transverse bar in Sand. Double curves represent replicated tests.

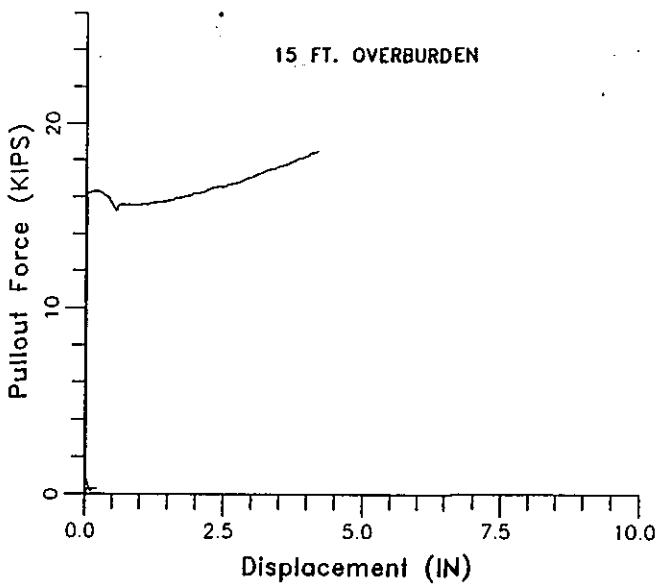


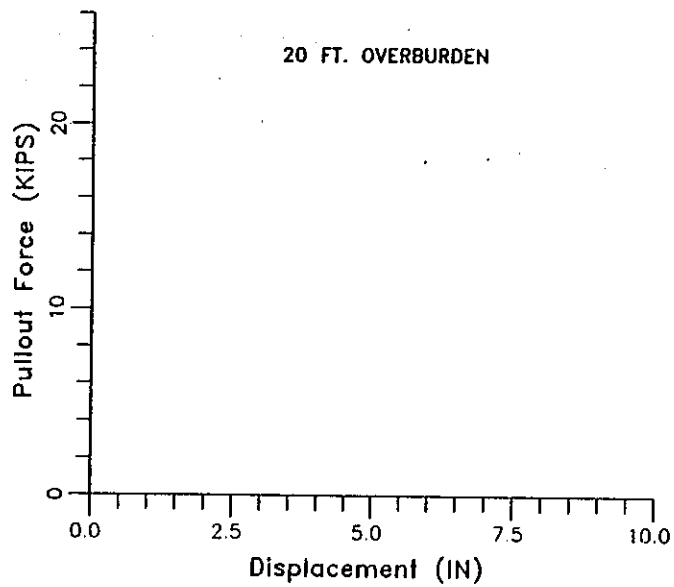




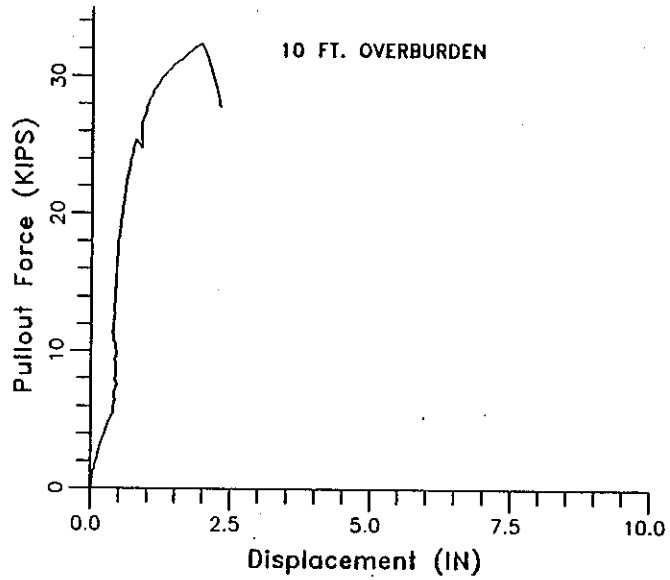
Field: Force–Displacement curves for C–channel 4–feet long, plain in sand.

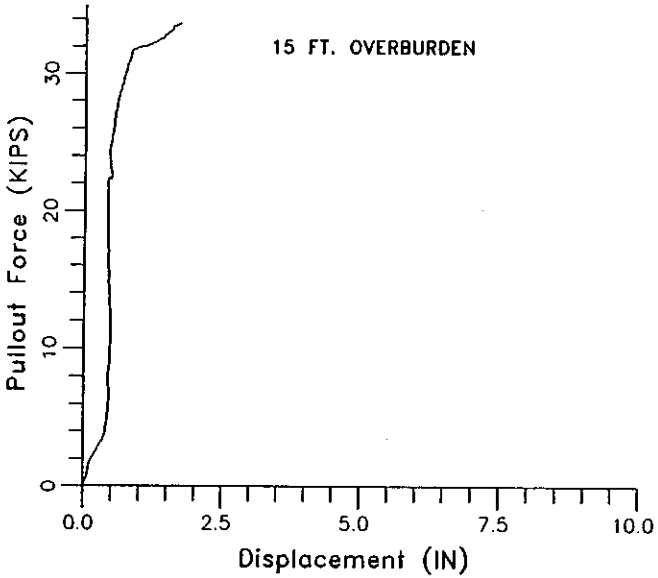


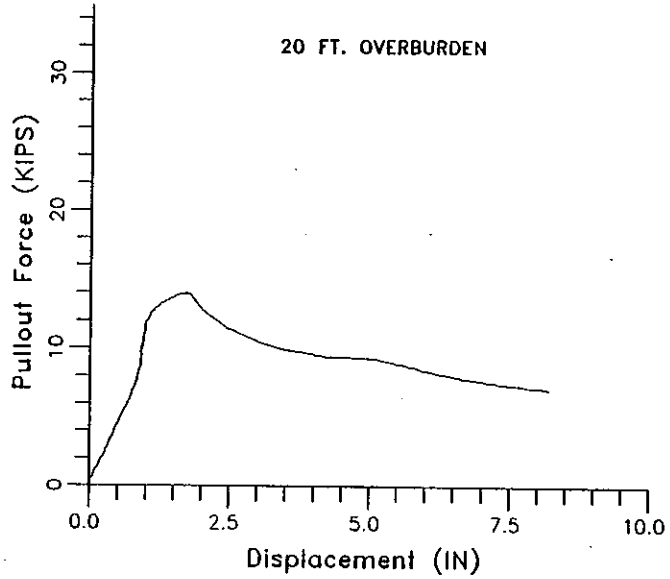




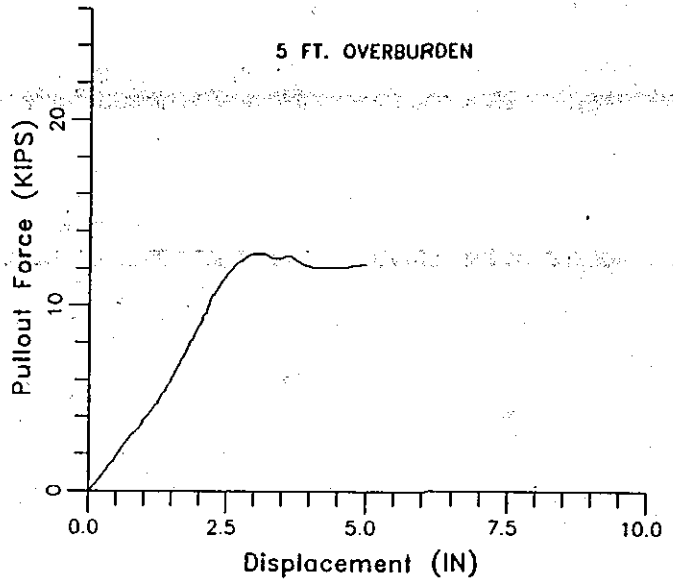
Field: Force-Displacement curves for C-channel 4-feet long, one foot Tee in sand.

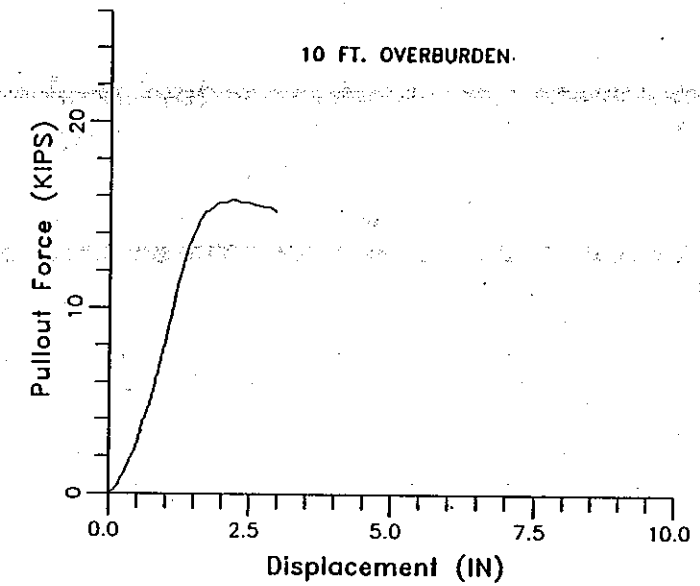


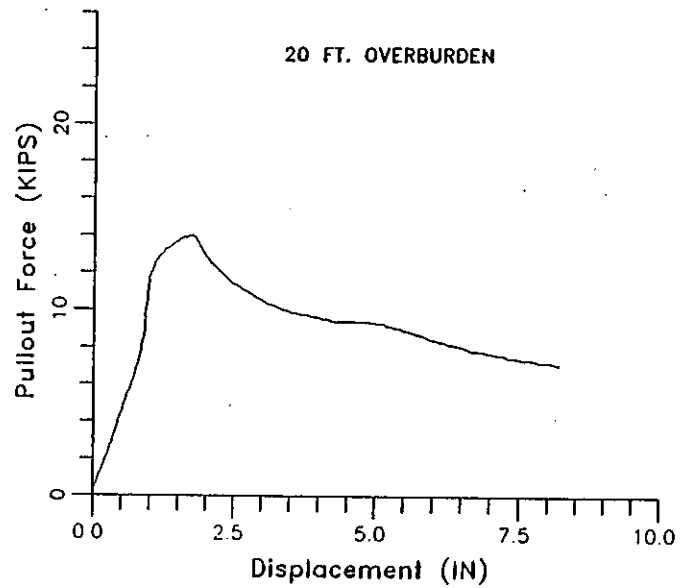




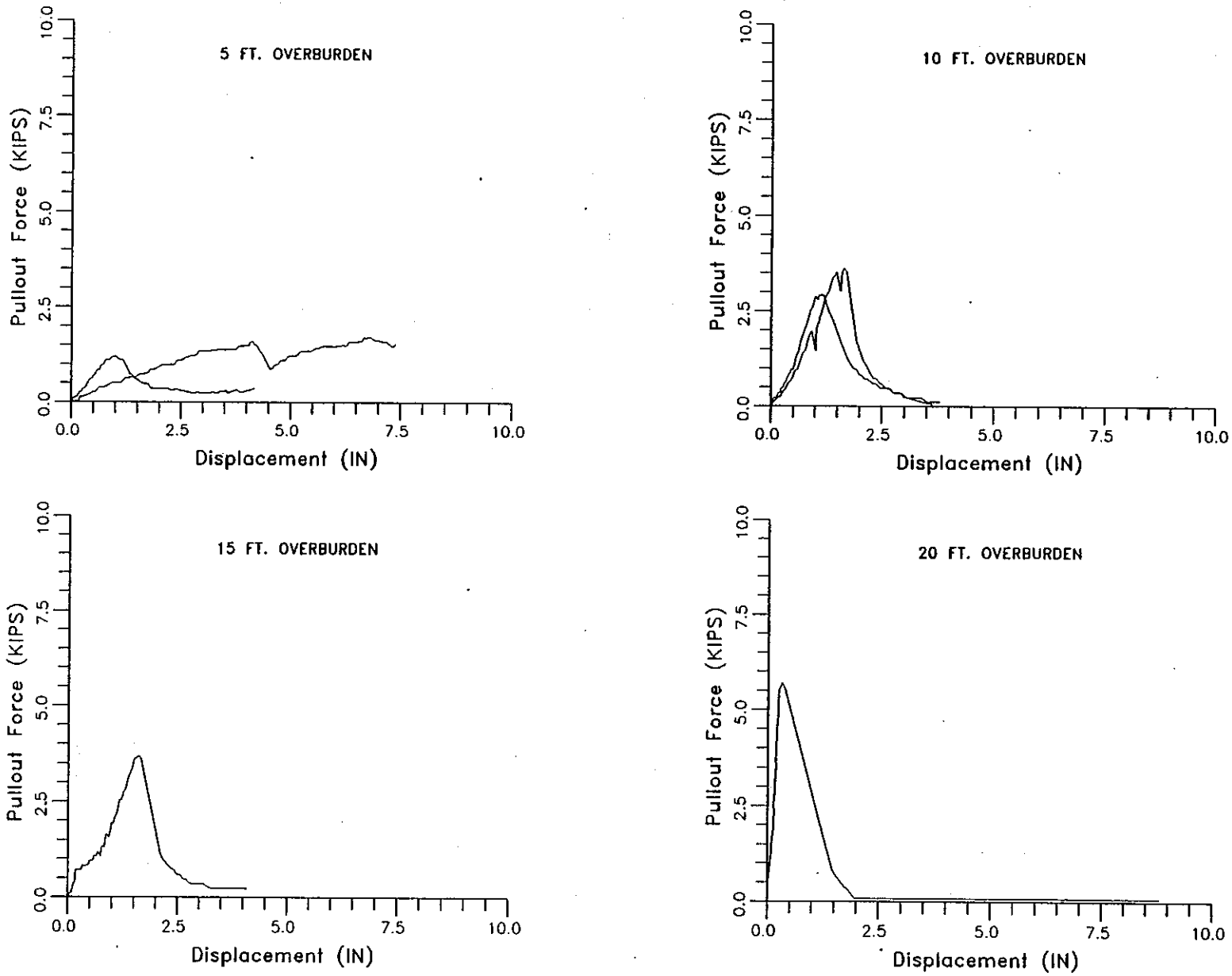
Field: Force–Displacement curves for C–channel 4–feet long, two feet Tee in sand.



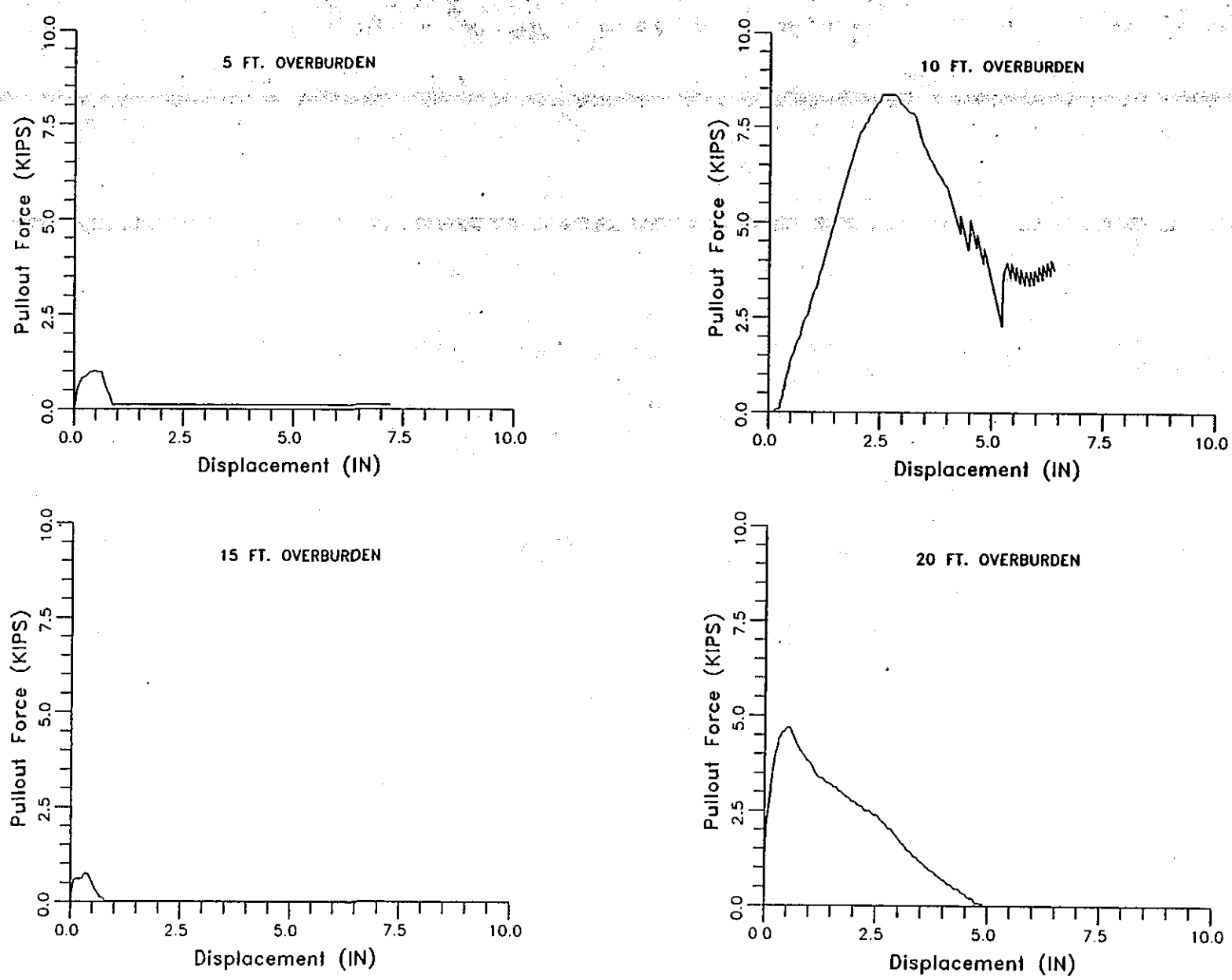




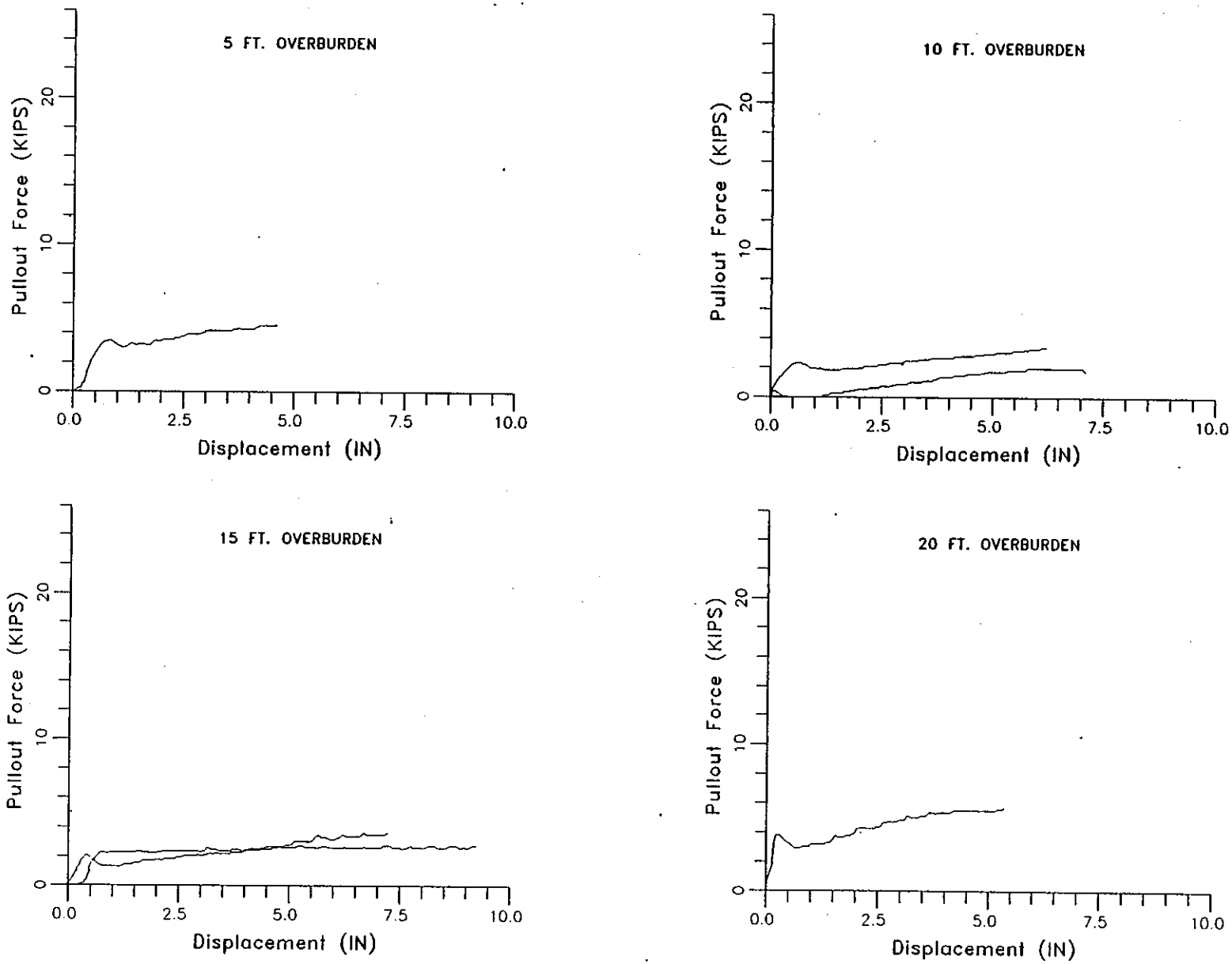
Field: Force-Displacement curves for C-channel 4-feet long, two Baffels in sand.



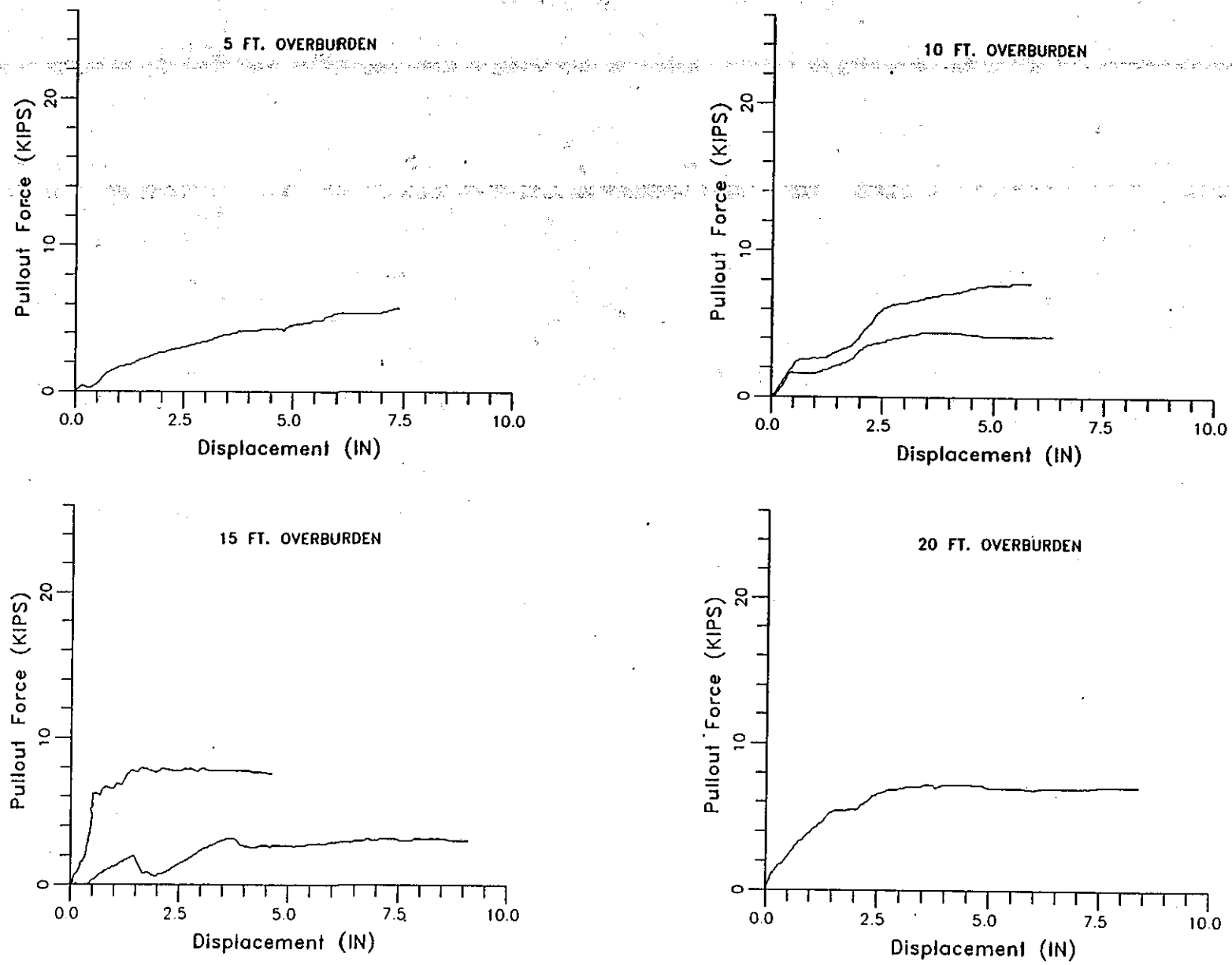
Field: Force–Displacement curves for C–channel 2–feet long, plain in sand. Double curves represent replicated tests.



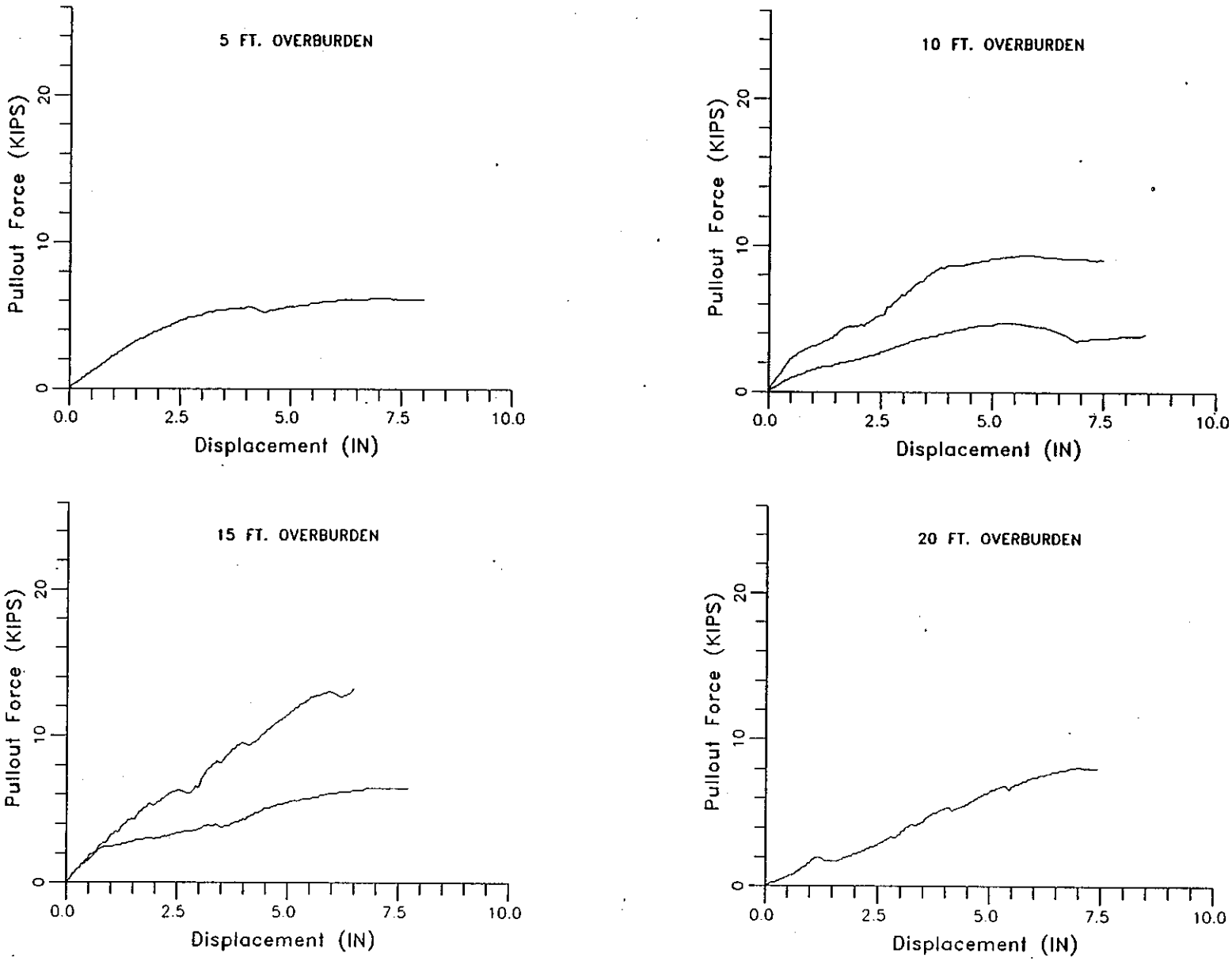
Field: Force–Displacement curves for C–channel 2–feet long, one Baffel in sand.



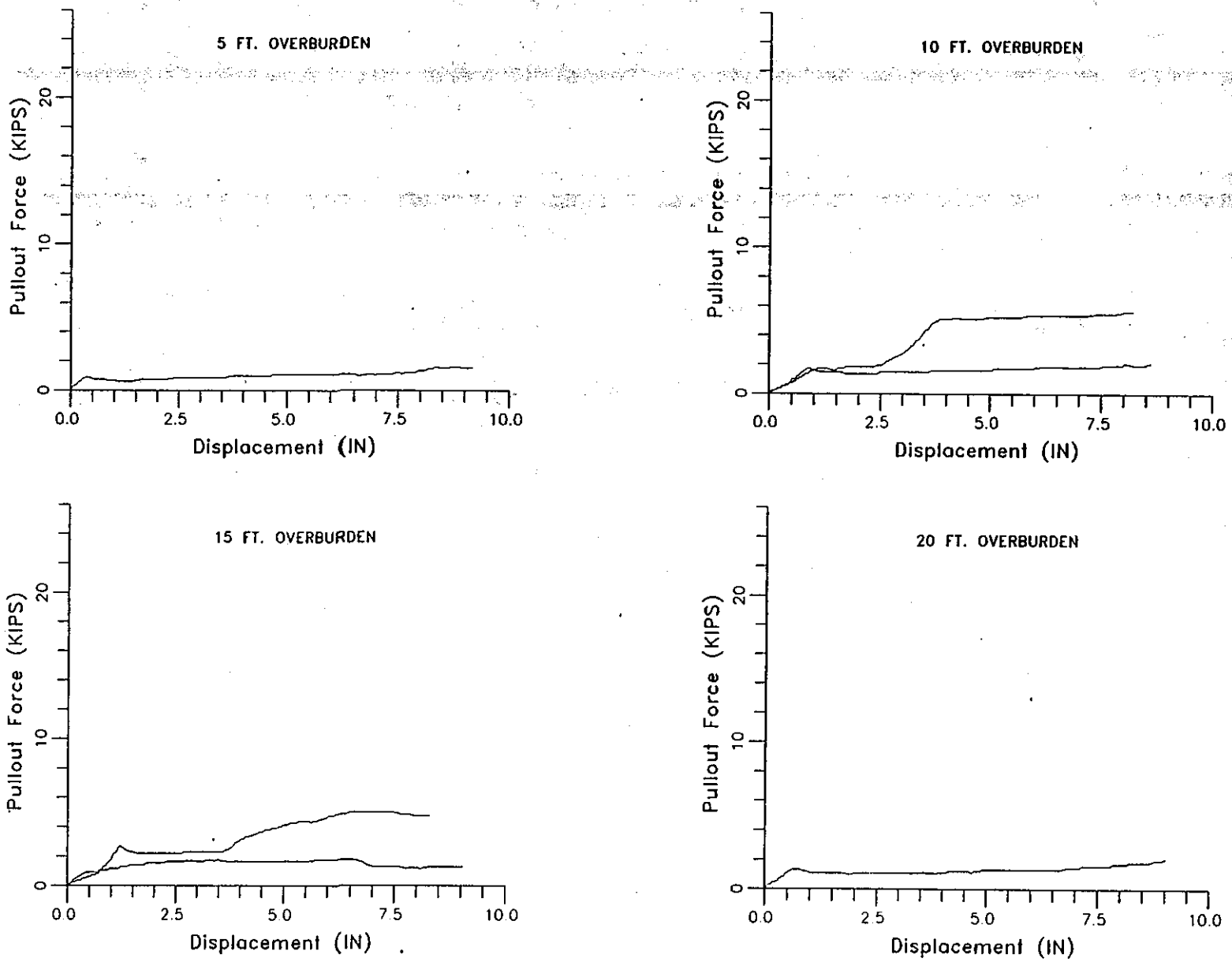
Field: Force–Displacement curves for CRR with one–disk in clay. Double curves represent replicated tests.



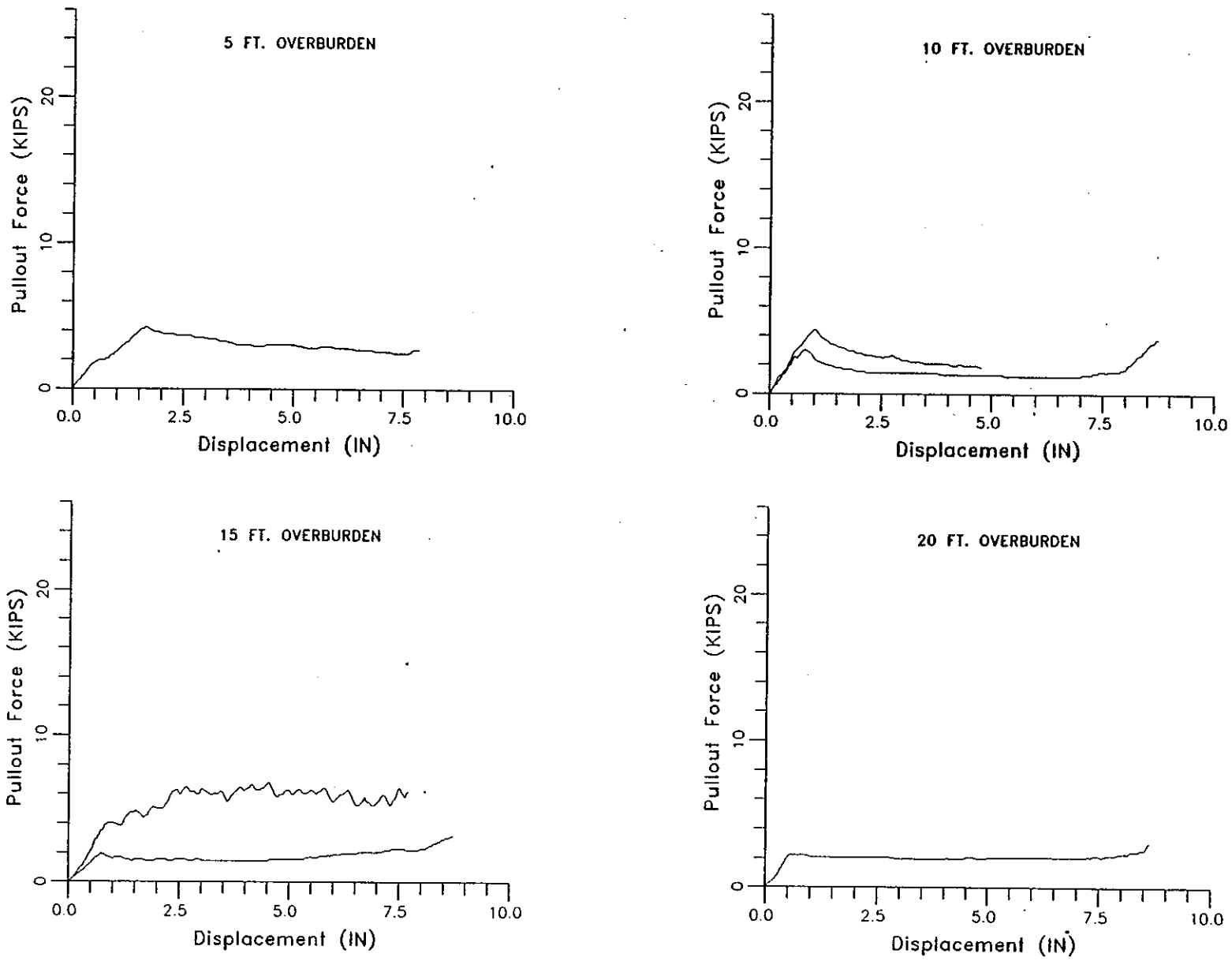
Field: Force–Displacement curves for CRR with two–disk in clay. Double curves represent replicated tests.



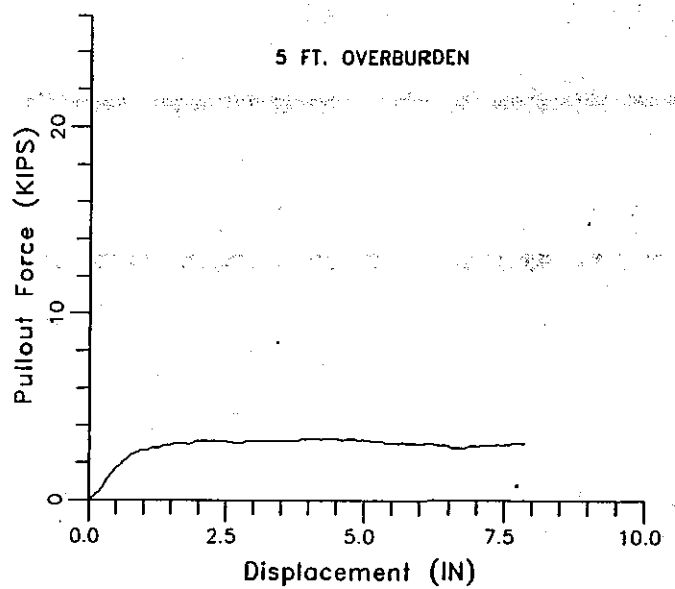
Field: Force–Displacement curves for TAT with sidewall in clay. Double curves represent replicated tests.

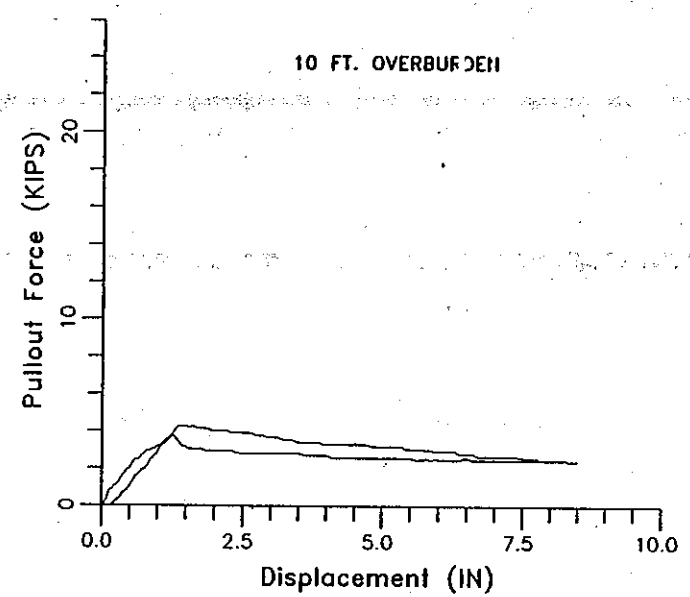


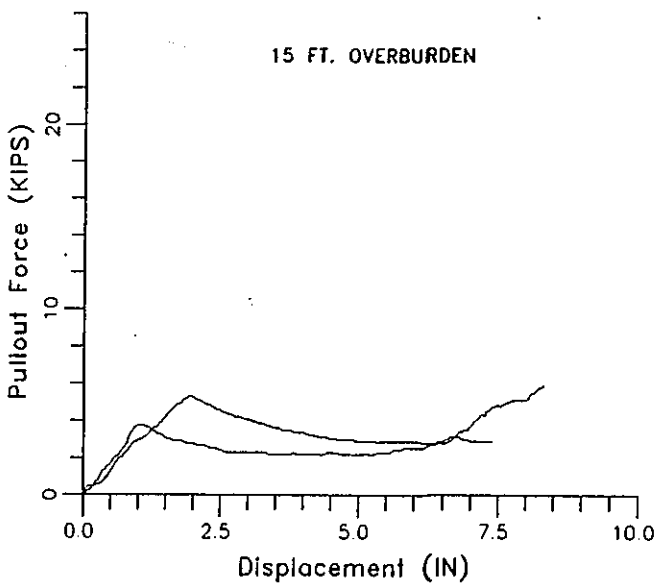
Field: Force–Displacement curves for TAT without sidewall in clay. Double curves represent replicated tests.

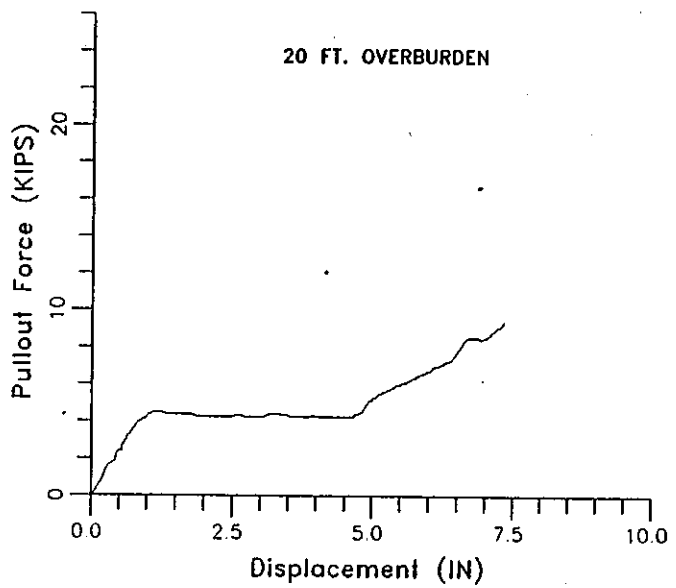


Field: Force–Displacement curves for MSE Bar–mat with Single Transverse bar in Clay. Double curves represent replicated tests.

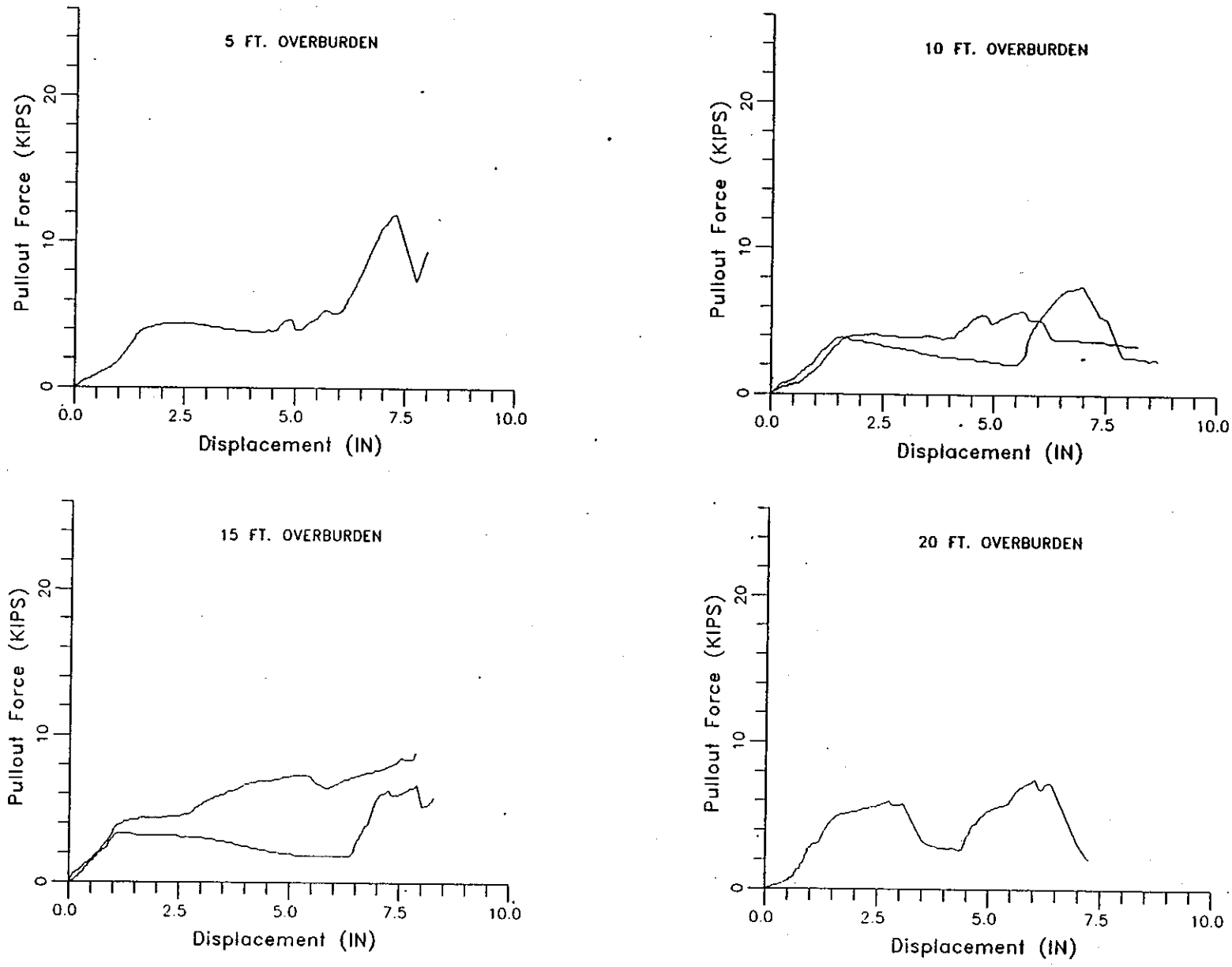




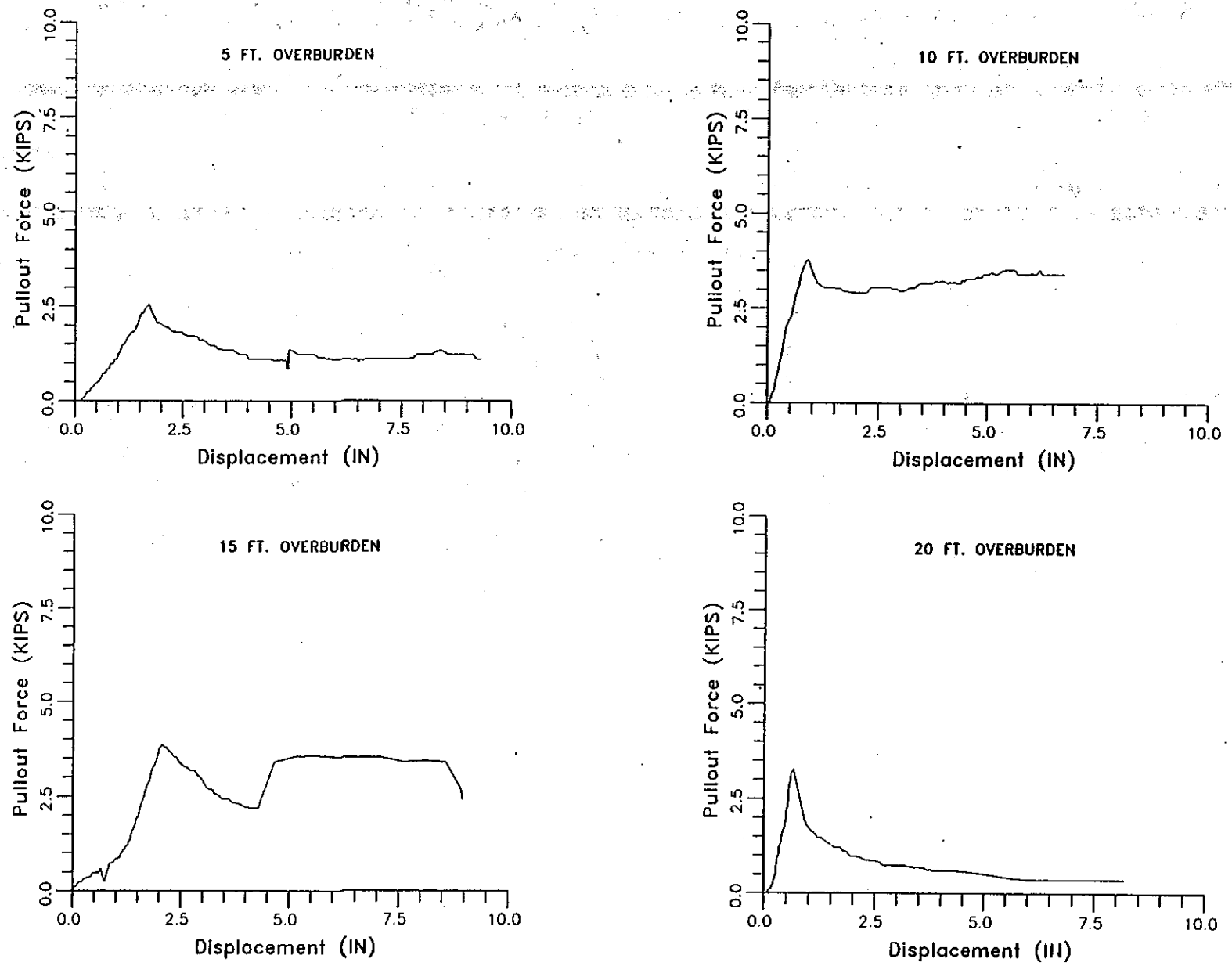




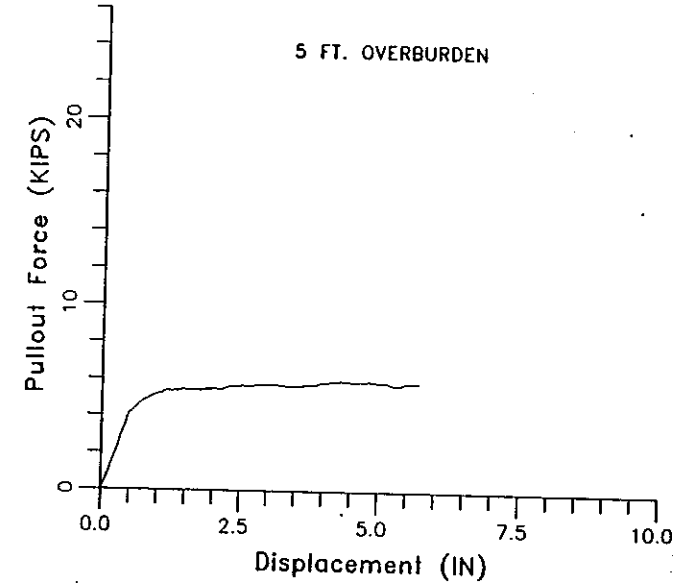
Field: Force-Displacement curves for MSE Bar-mat with Double Transverse bar in Clay. Double curves represent replicated tests.

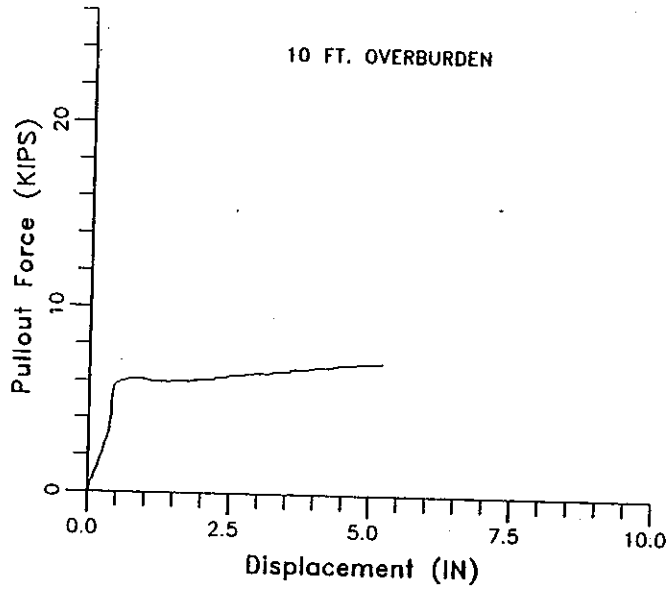


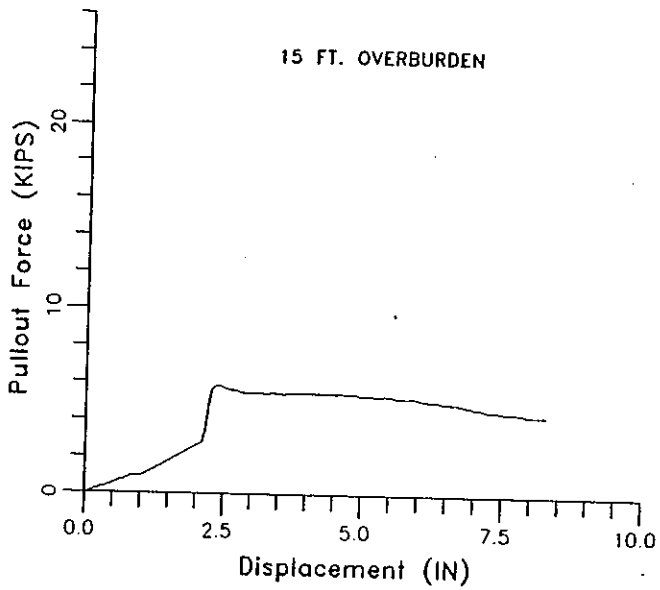
Field: Force–Displacement curves for MSE Bar–mat with Triple Transverse bar in Clay. Double curves represent replicated tests.

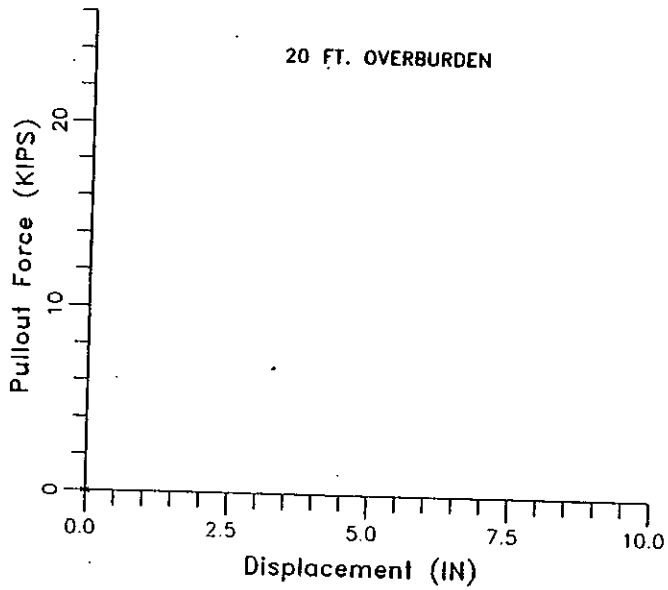


Field: Force-Displacement curves for C-channel 4-feet long, plain in clay.

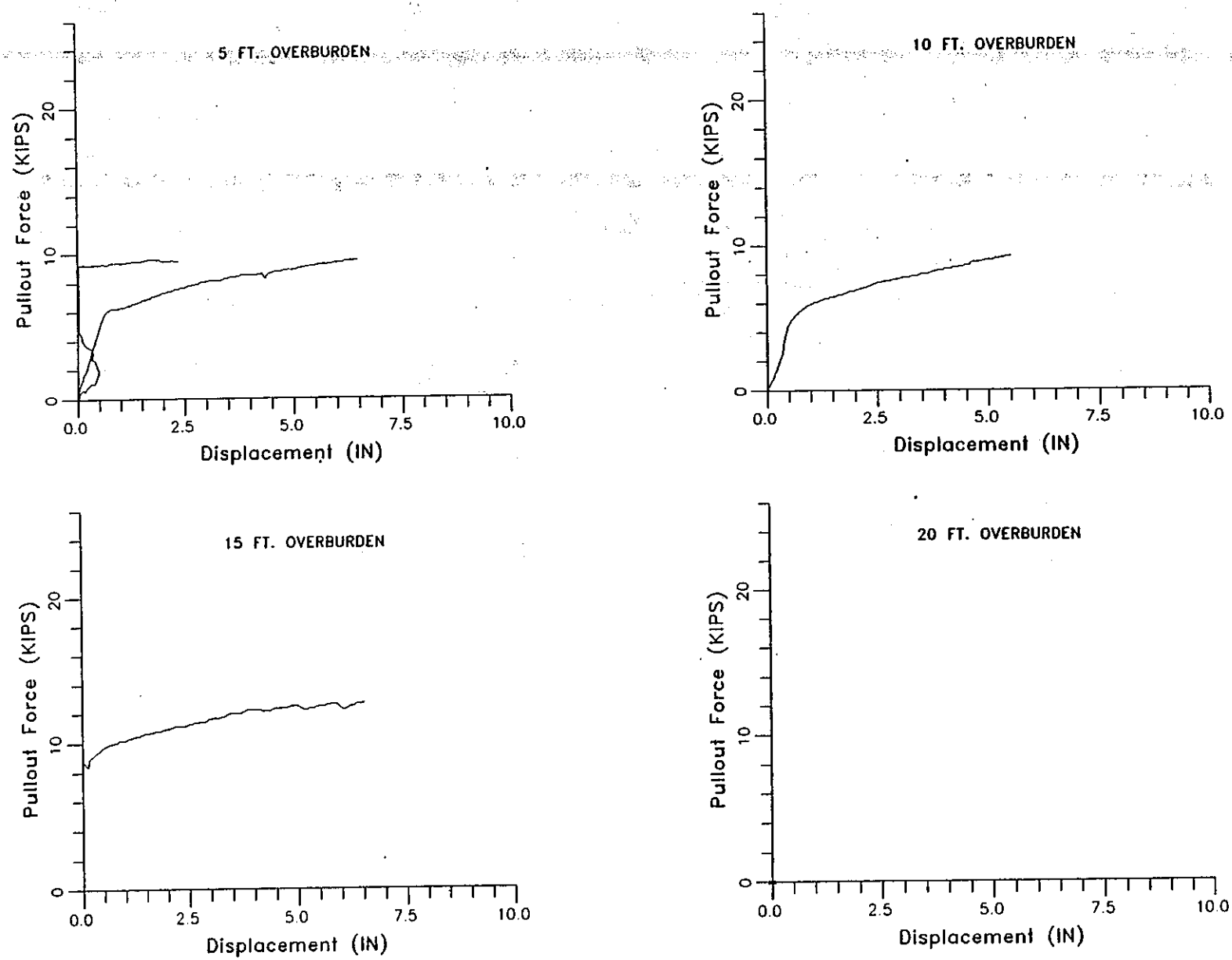




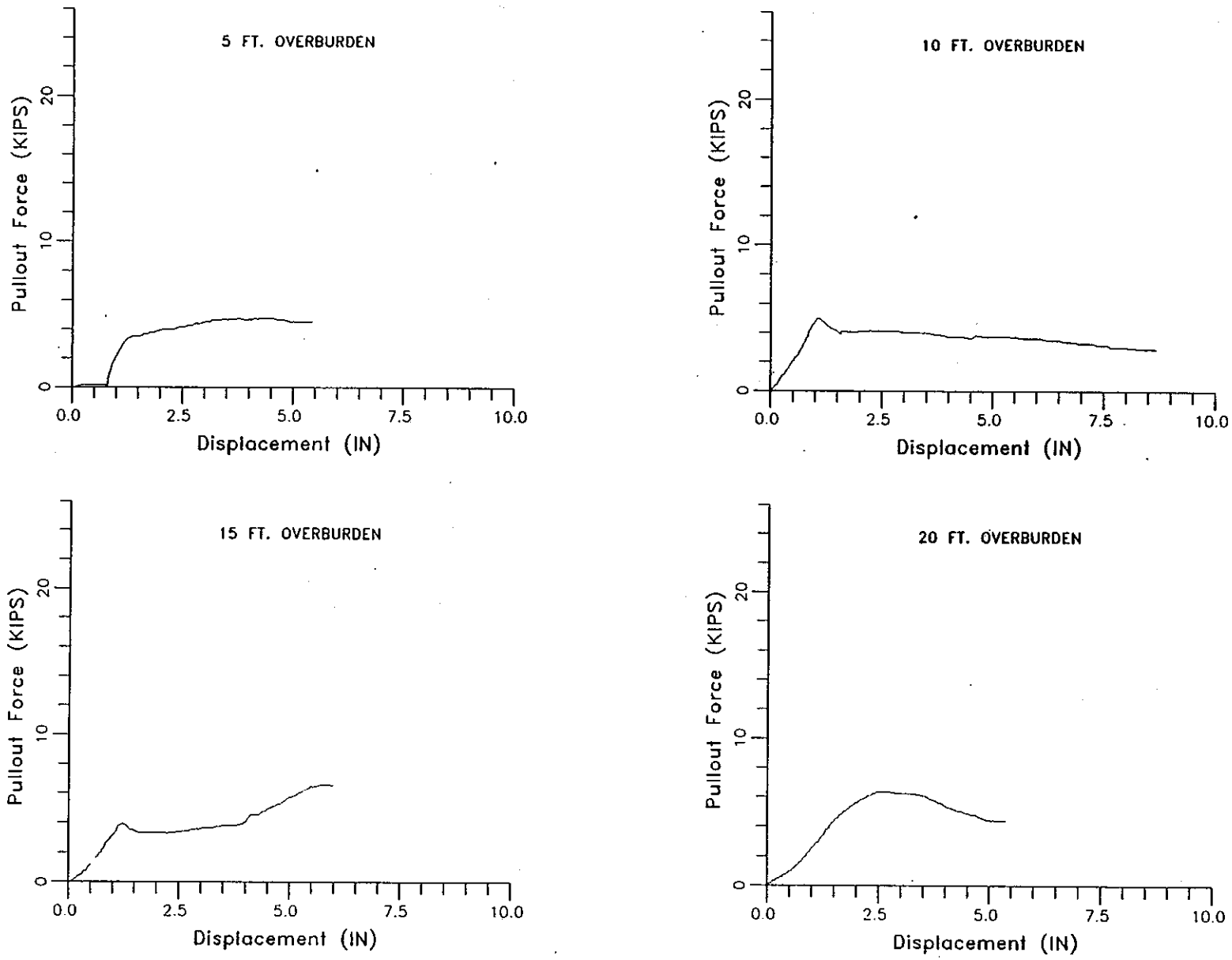




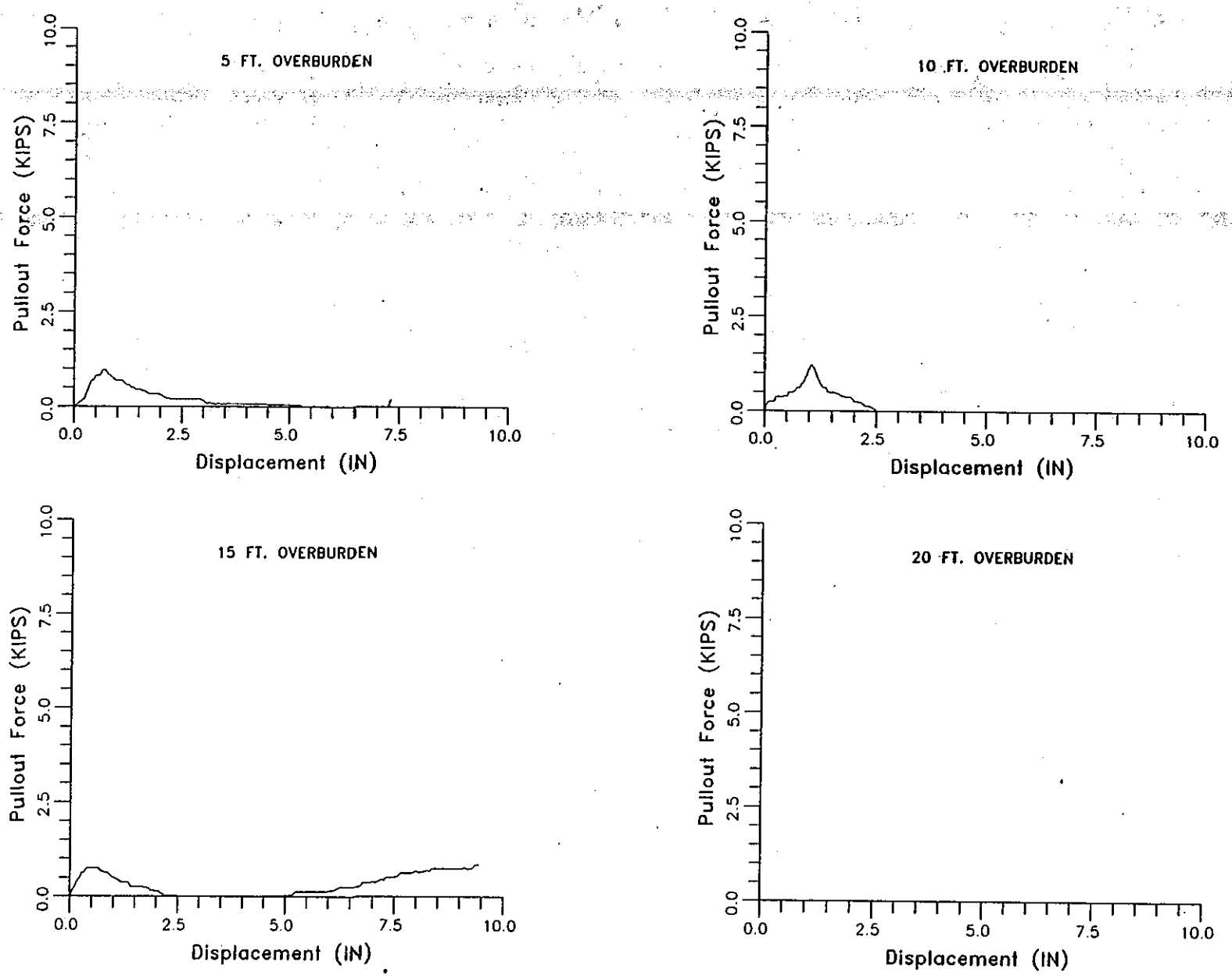
Field: Force–Displacement curves for C–channel 4–feet long, one foot Tee in clay.



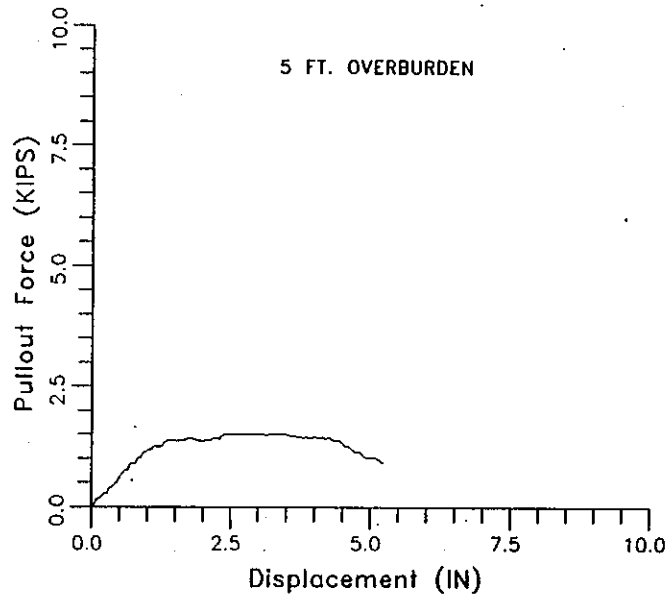
Field: Force-Displacement curves for C-channel 4-feet long, two feet Tee in clay. Double curves represent replicated tests.

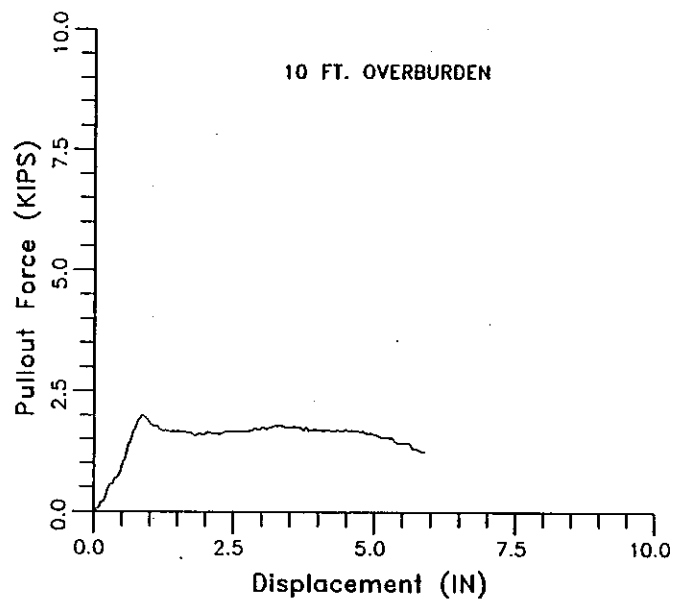


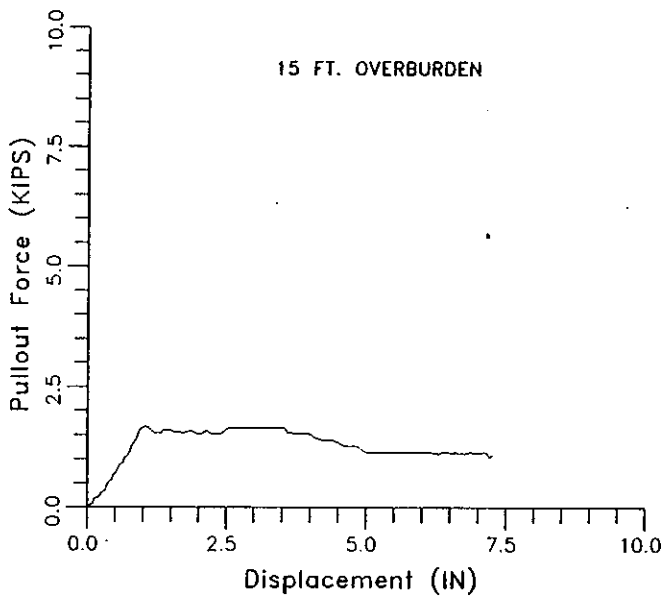
Field: Force–Displacement curves for C–channel 4–feet long, two baffels in clay.

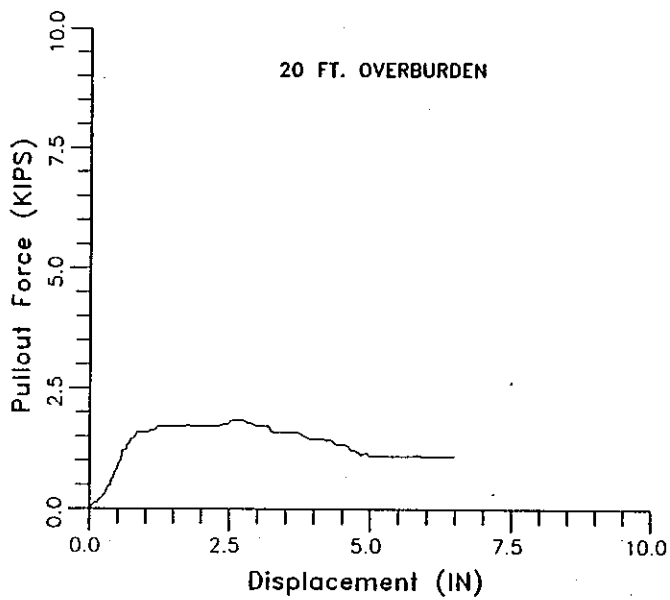


Field: Force–Displacement curves for C–channel 2–feet long, plain in clay.



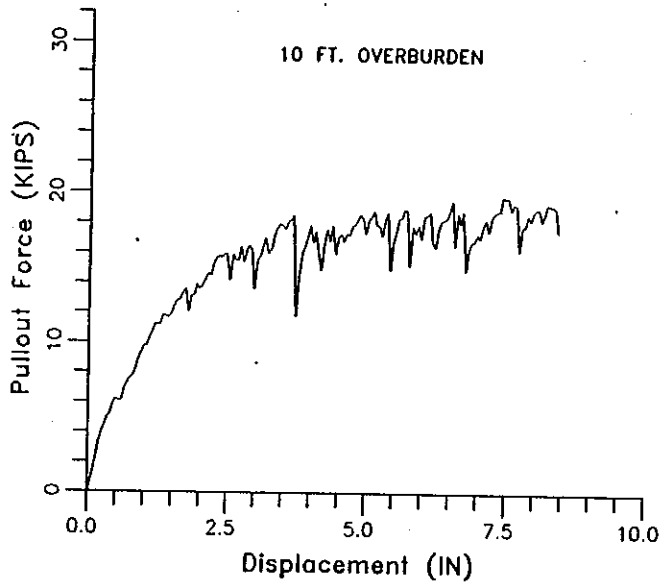






Field: Force-Displacement curves for C-channel 2-feet long, one Baffel in clay.

APPENDIX B



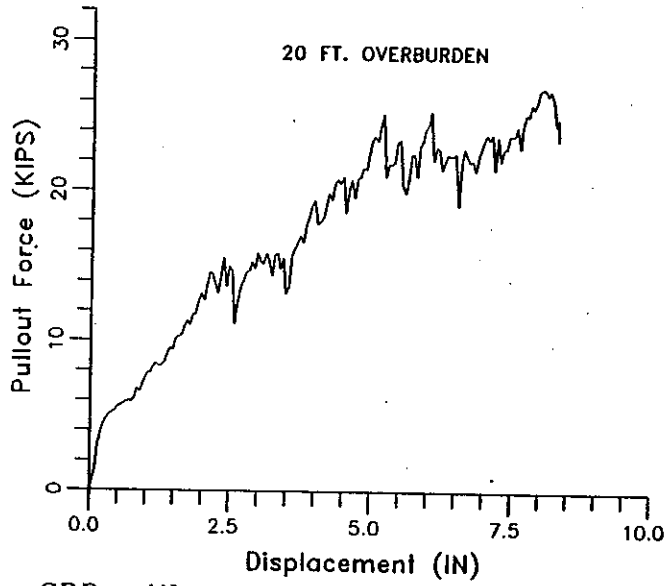
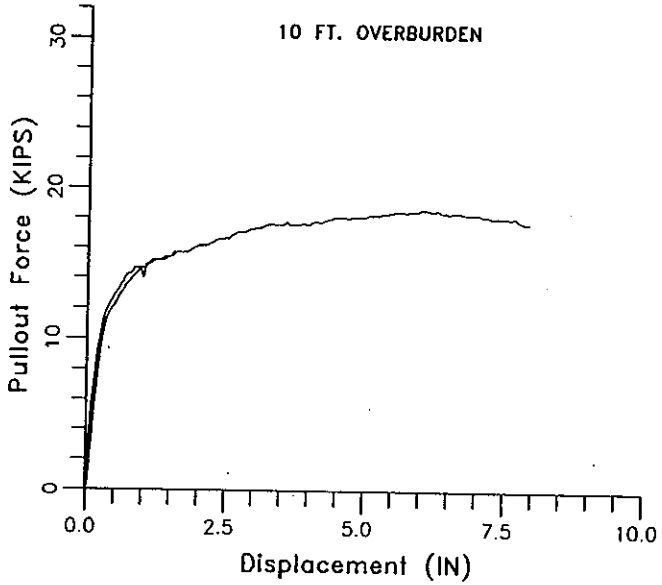
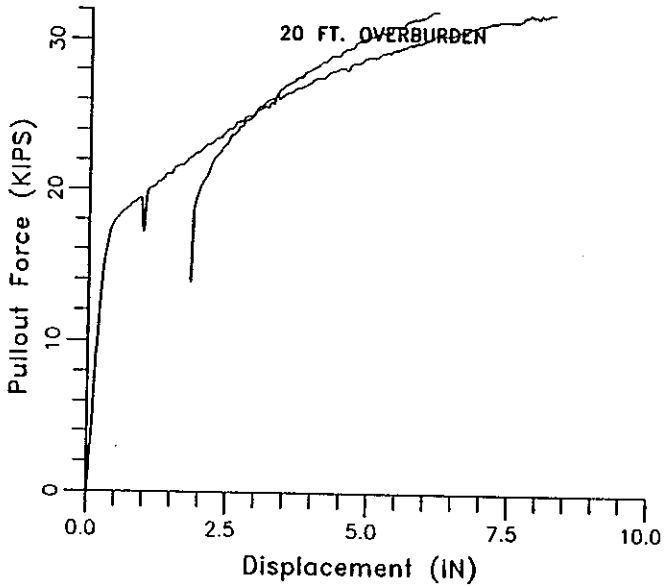
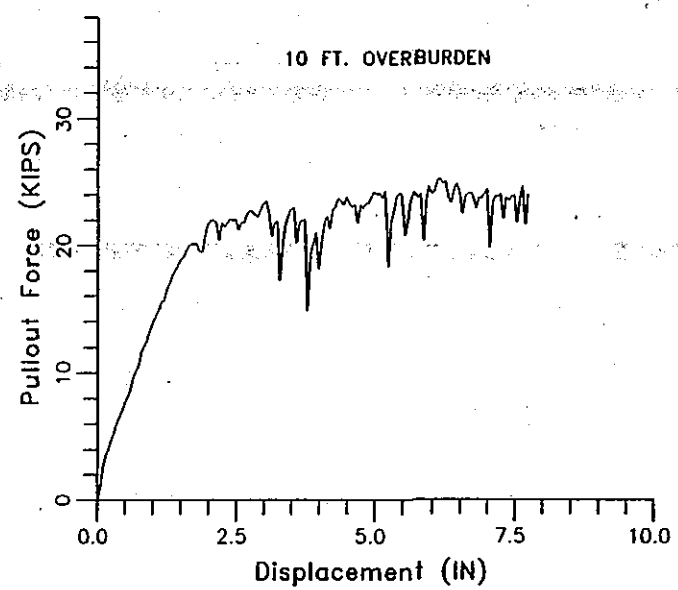


Fig: – Lab: Force–Displacement curves for CRR with one–disk in gravel.





Lab: Force–Displacement curves for CRR with one–disk in sand.



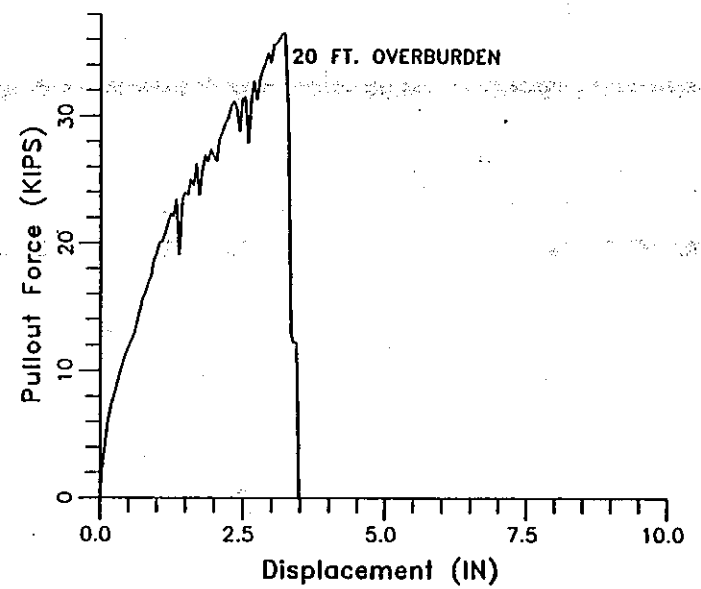
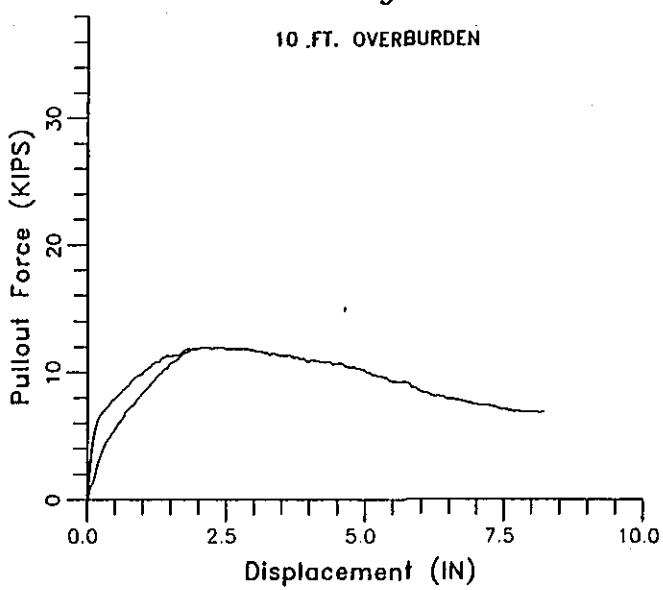
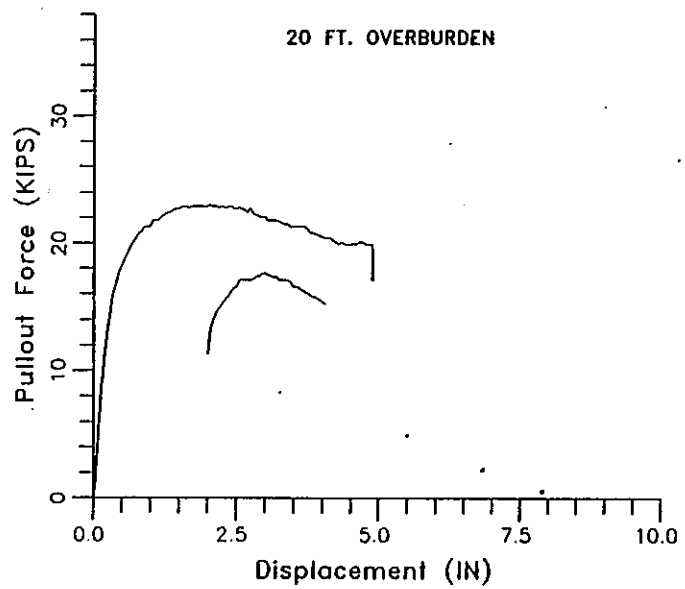
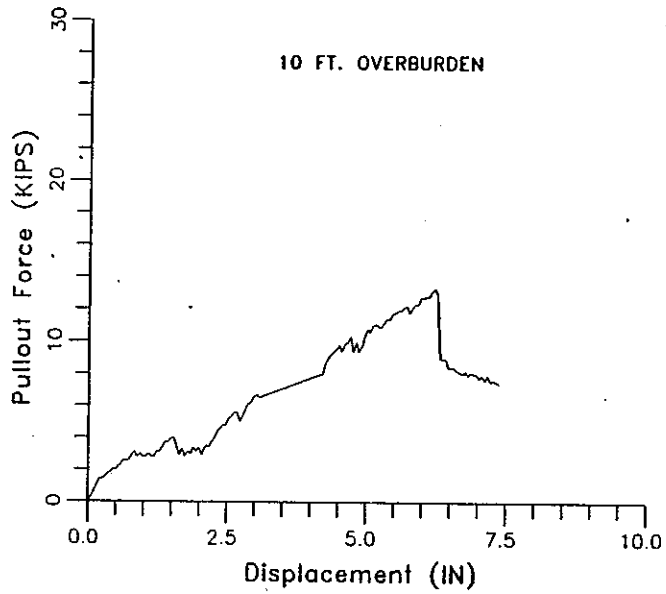


Fig: – Lab: Force–Displacement curves for CRR with two–disk in gravel.





Lab: Force–Displacement curves for CRR with two–disk in sand.



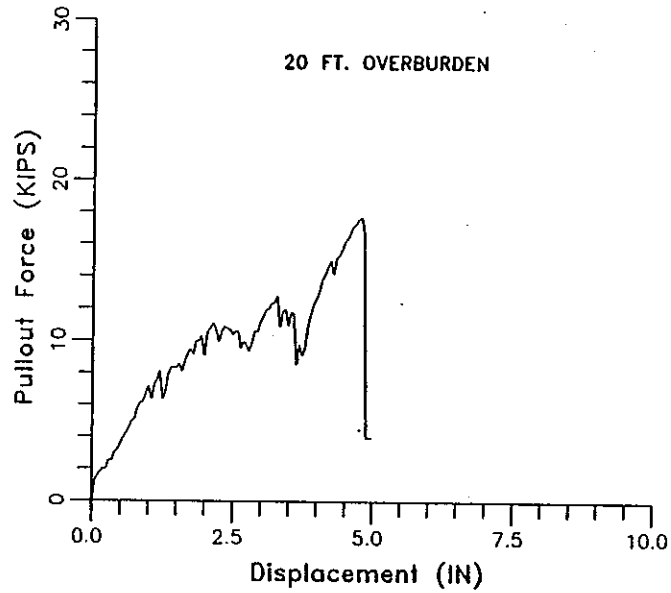
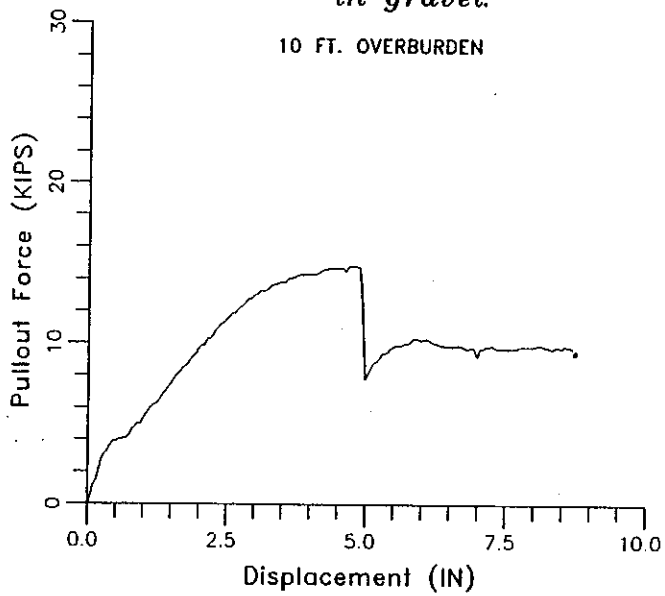
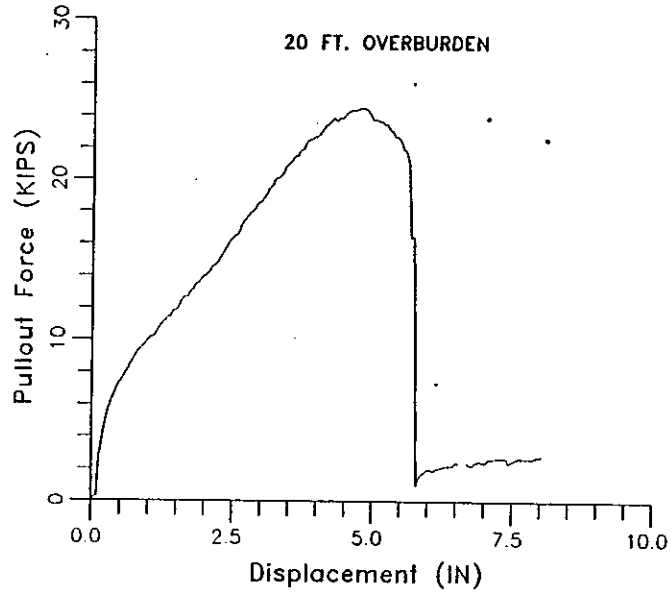
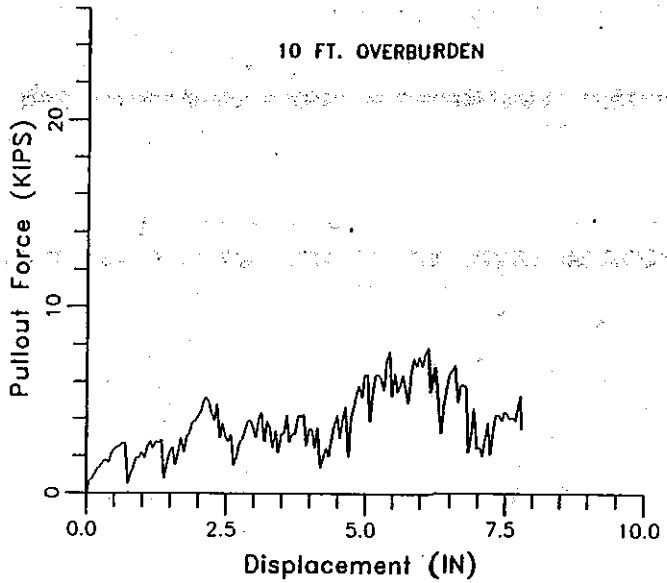


Fig: – Lab: Force–Displacement curves for TAT with sidewall in gravel.





Lab: Force–Displacement curves for TAT with sidewall in sand.



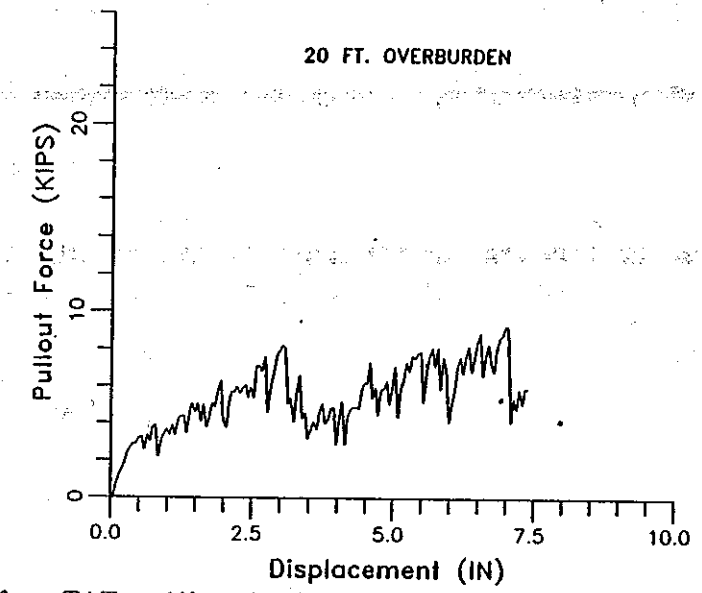
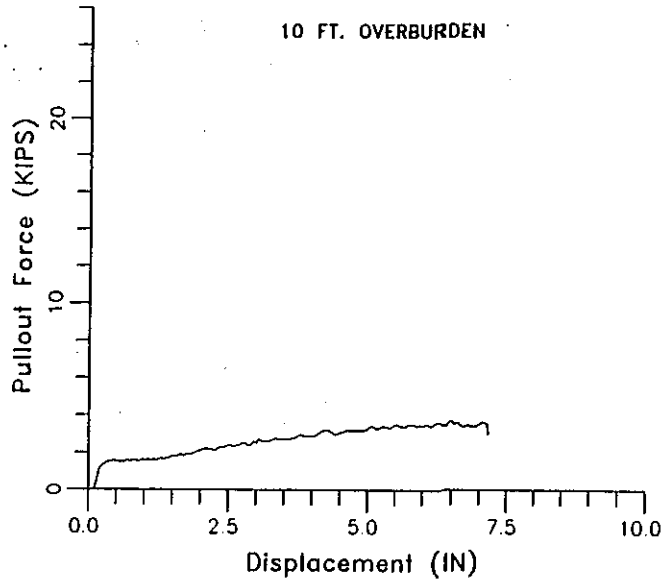
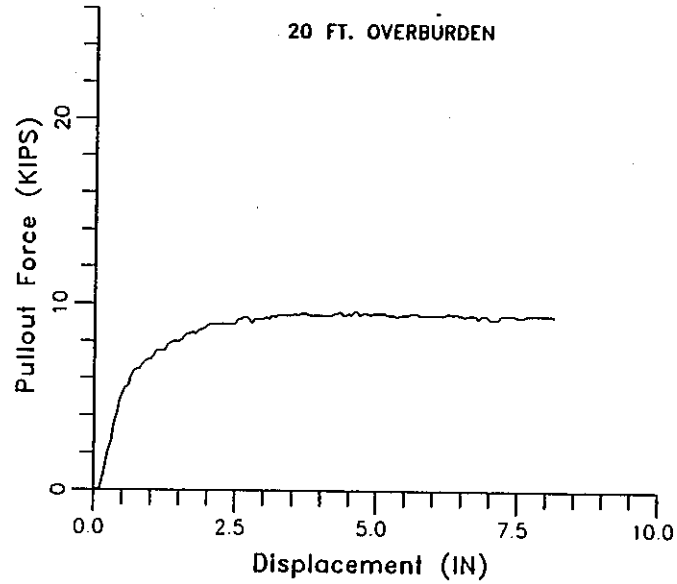
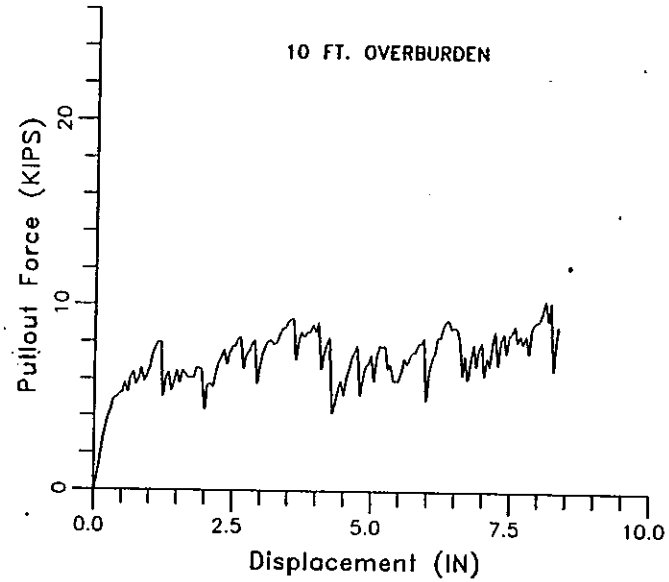


Fig: – Lab: Force–Displacement curves for TAT without sidewall in gravel.





Lab: Force–Displacement curves for TAT without sidewall in sand.



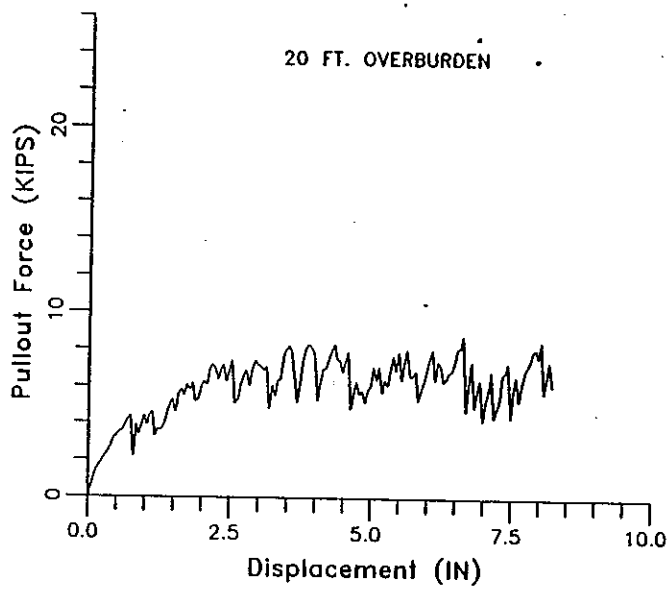
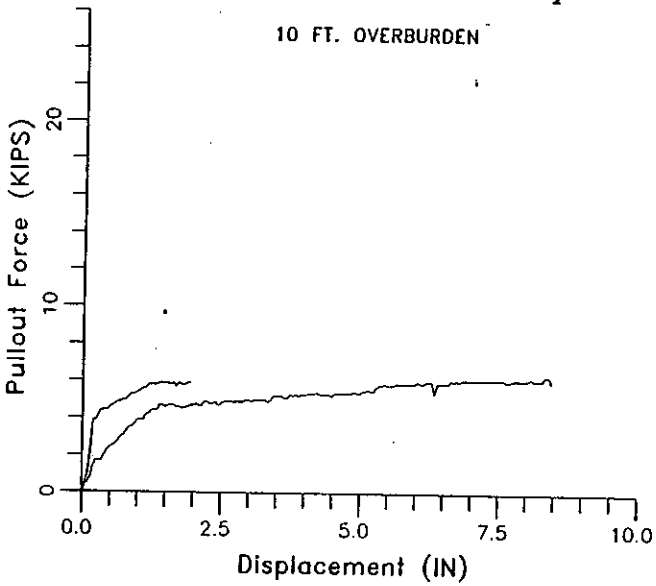
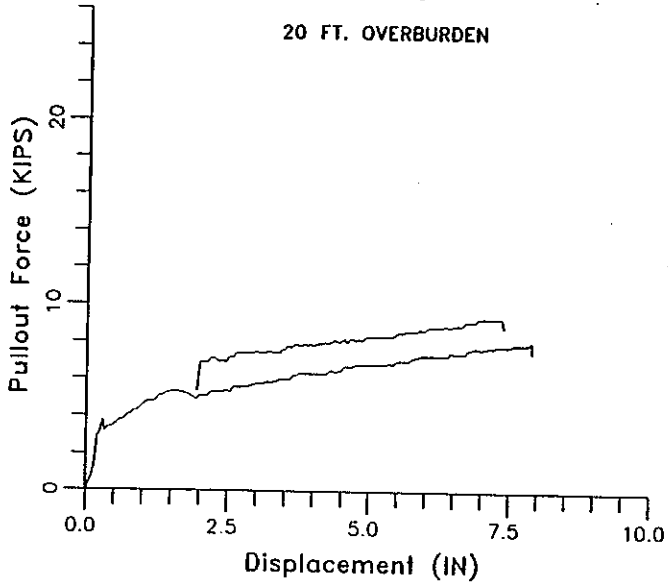
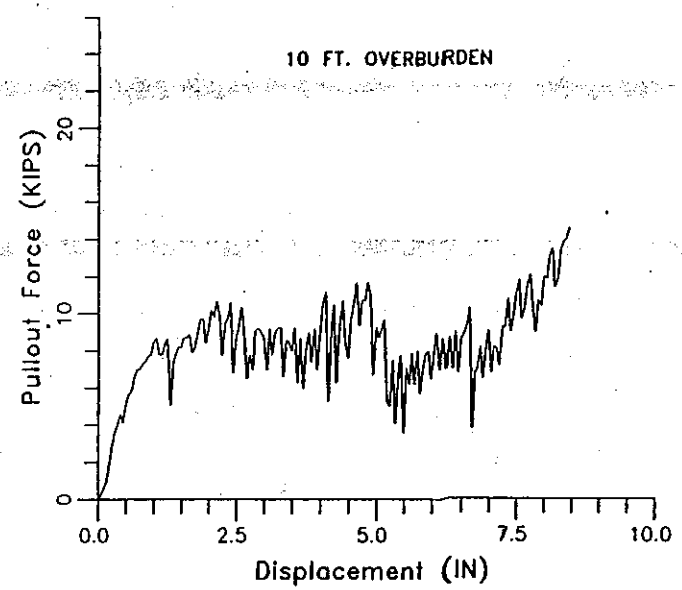


Fig: – Lab: Force–Displacement curves for MSE with one bar in gravel.





Lab: Force–Displacement curves for MSE with one bar in sand.



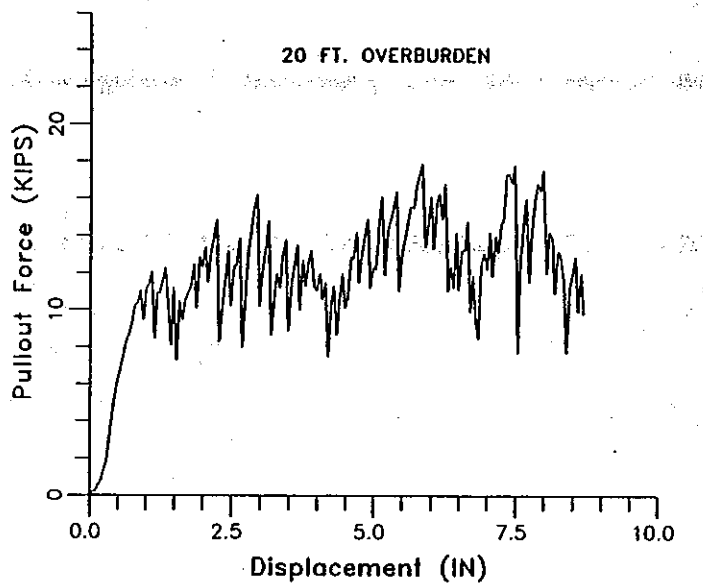
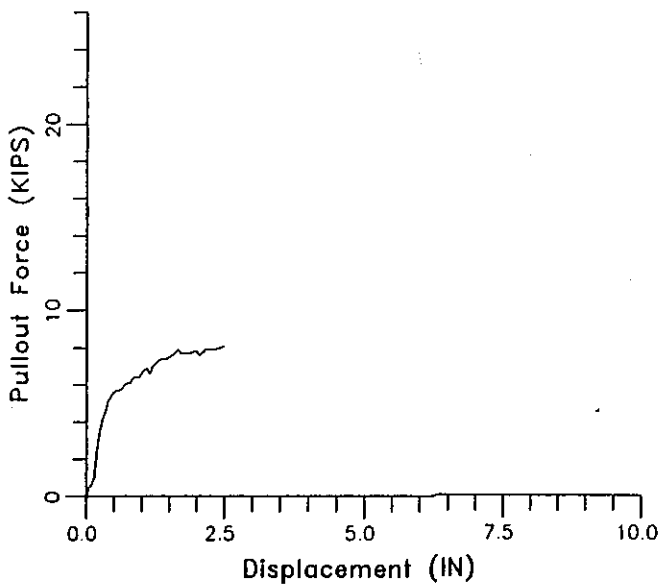
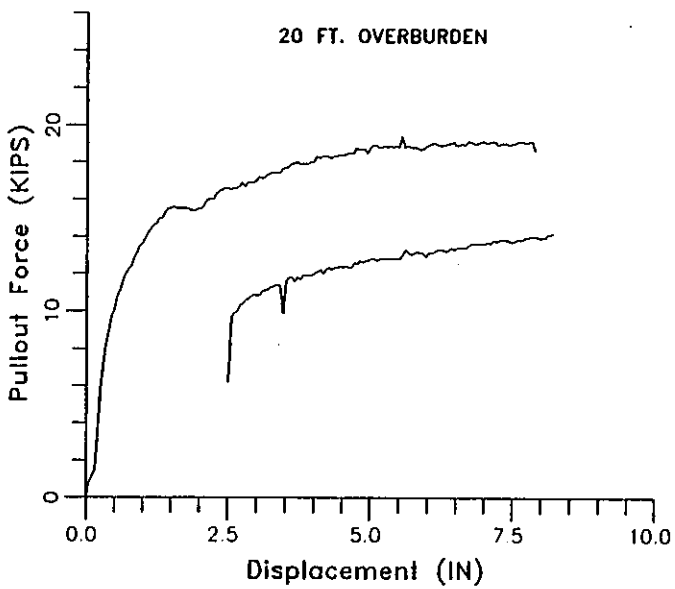
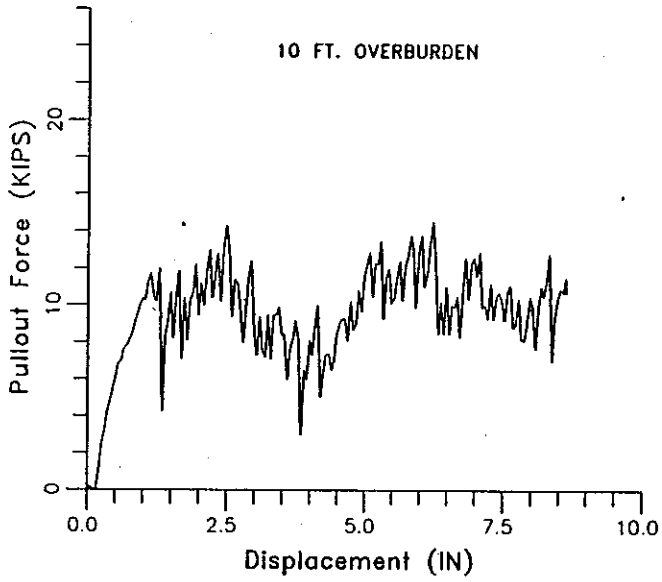


Fig: – Lab: Force–Displacement curves for MSE Bar–mat with Double Transverse bar in gravel





Lab: Force–Displacement curves for MSE Bar–mat with Double Transverse bar in sand.



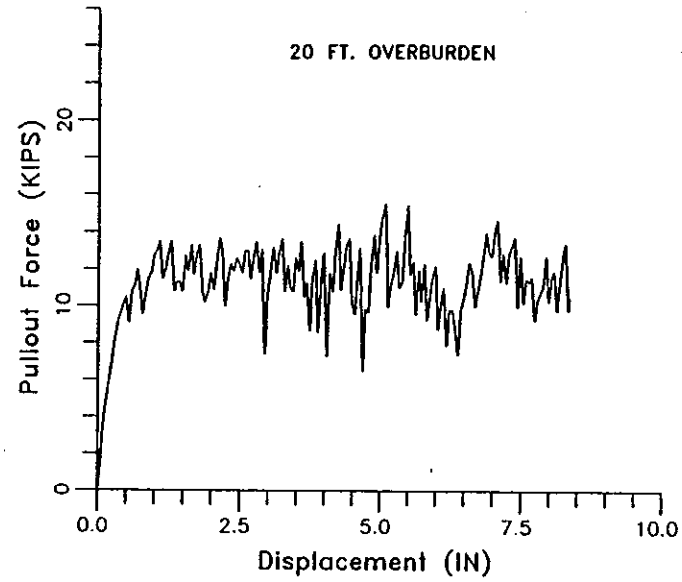
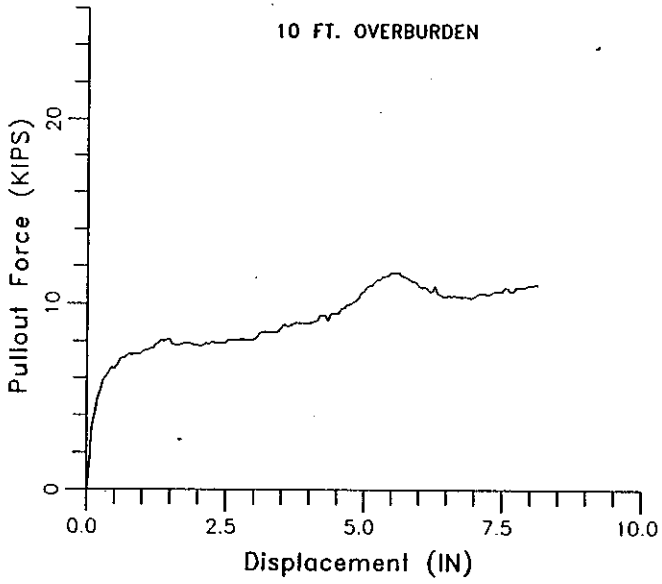
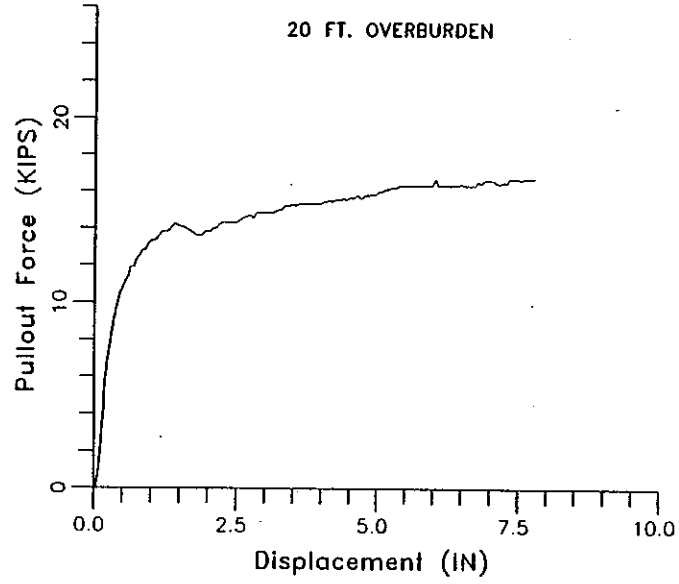
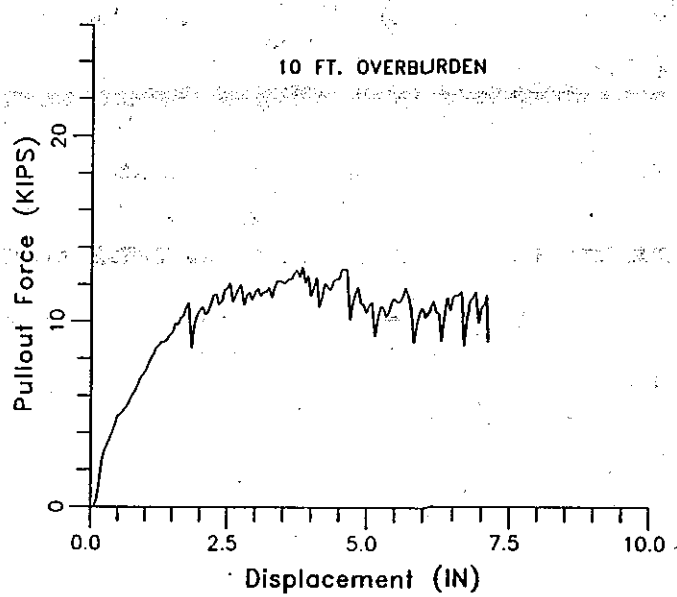


Fig: – Lab: Force–Displacement curves for MSE Bar–mat with Triple Transverse bar in gravel





Lab: Force–Displacement curves for MSE Bar–mat with Triple Transverse bar in sand.



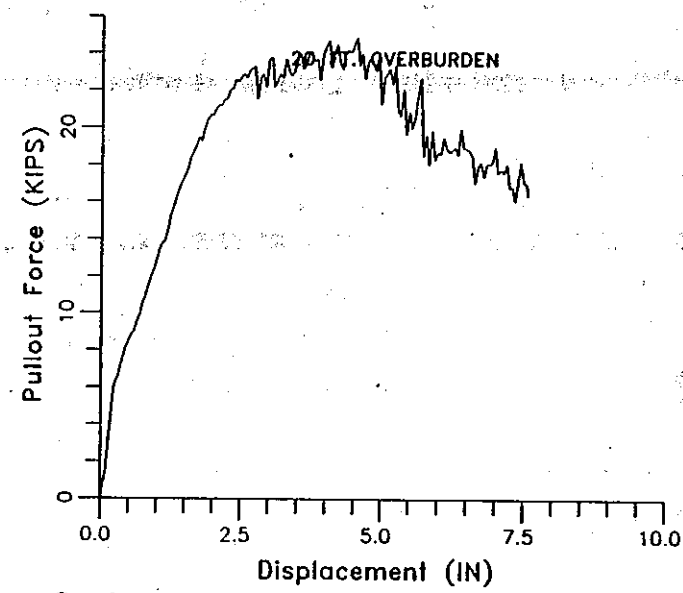
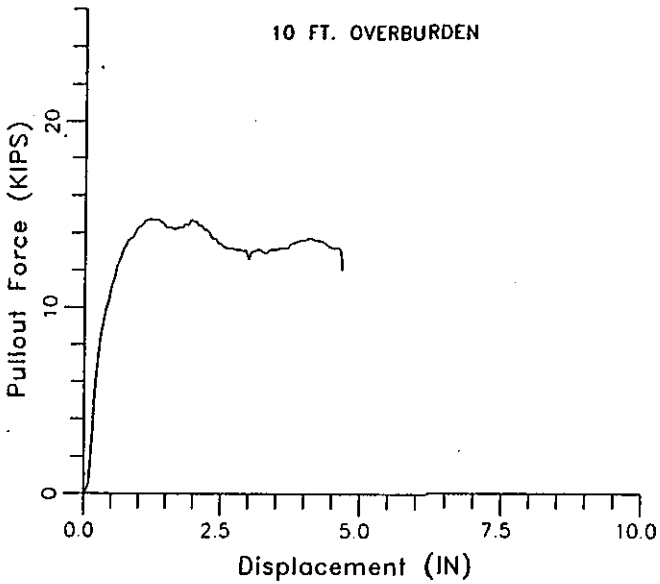
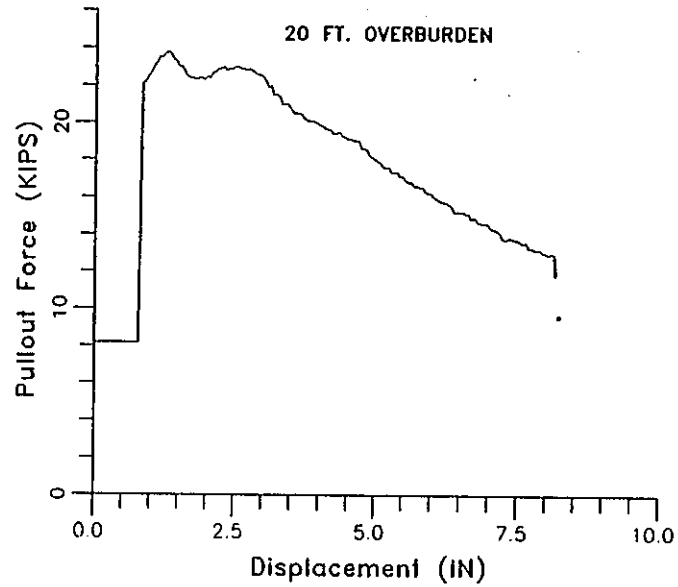
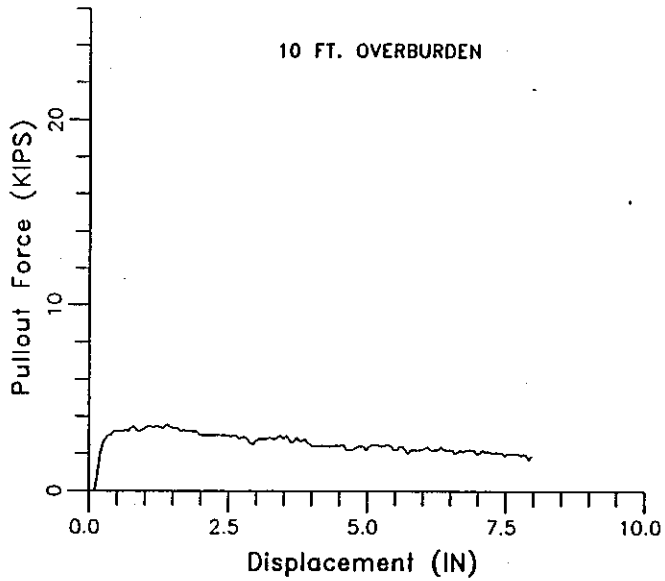


Fig: – Lab: Force–Displacement curves for C–channel 4–feet long, two Baffels in gravel.





Lab: Force–Displacement curves for C–channel 4–feet long, two Baffels in sand.



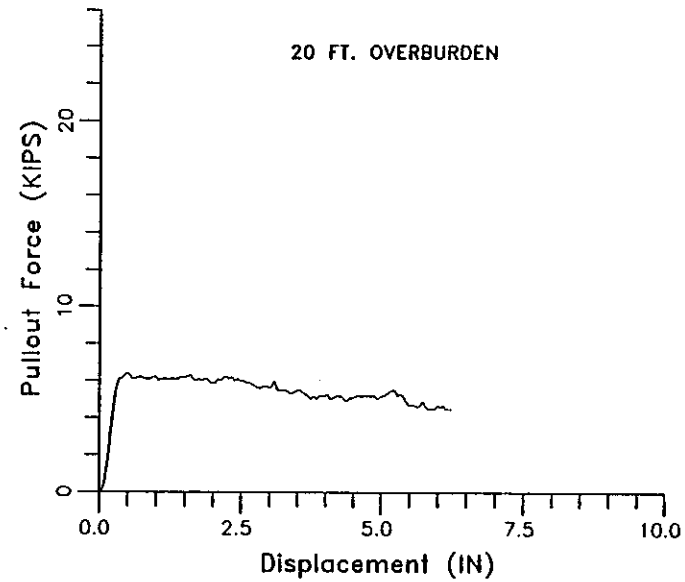
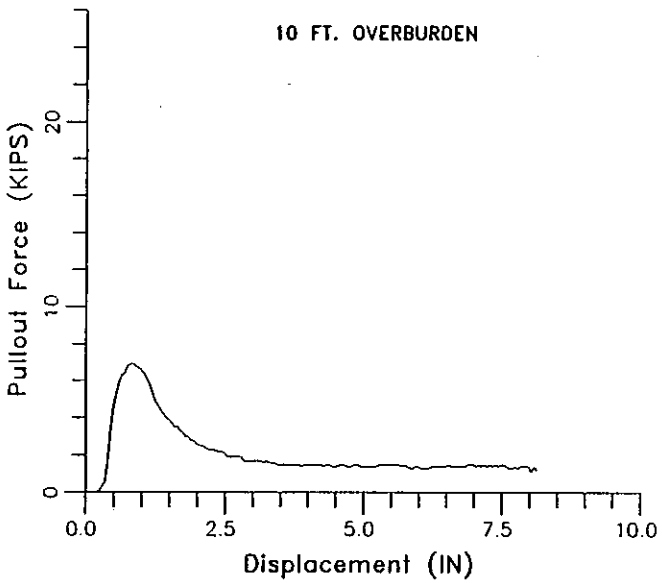
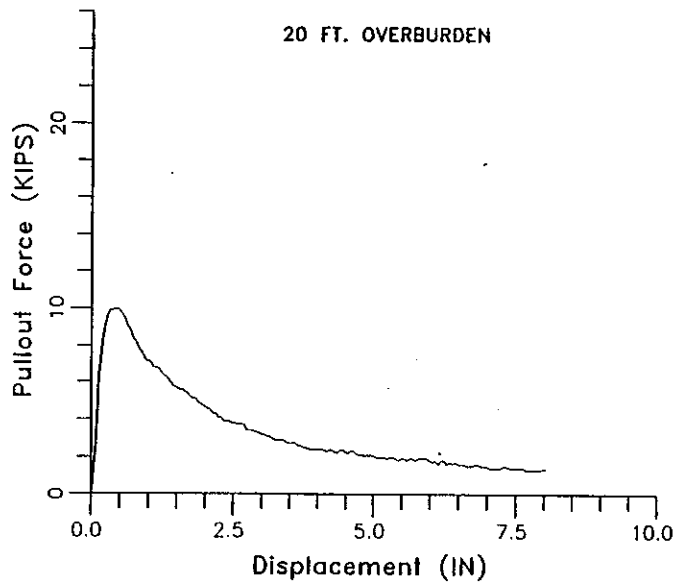


Fig: – Lab: Force–Displacement curves for C–channel 4–feet long, plain in gravel.





Lab: Force–Displacement curves for C–channel 4–feet long, plain in sand.

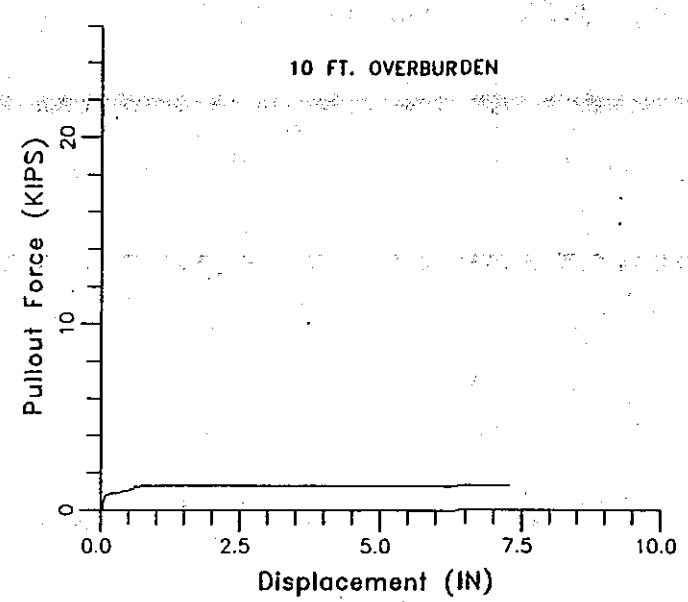
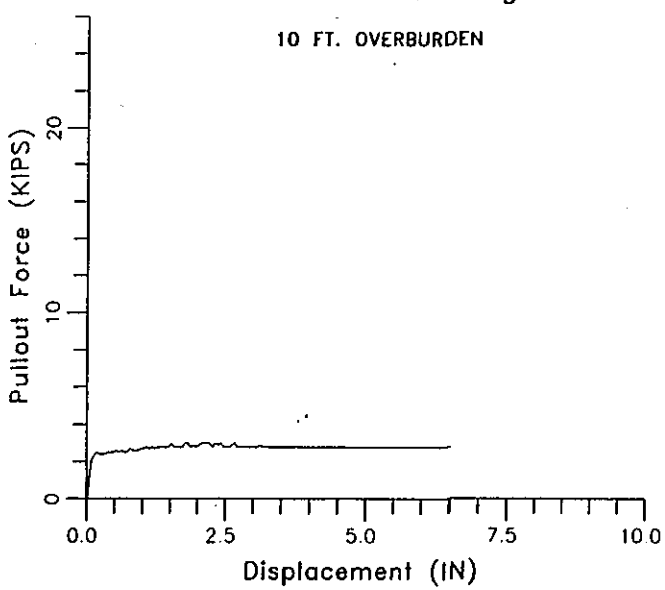
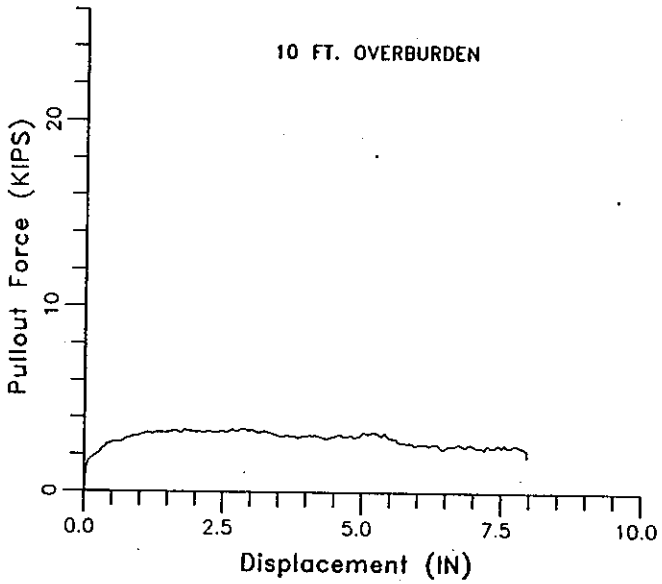


Fig: – Lab: Force–Displacement curves for MSE Bar–mat with Single Transverse bar in clay.



Lab: Force–Displacement curves for MSE Bar–mat with Double Transverse bar in clay.



Lab: Force–Displacement curves for MSE Bar–mat with Triple Transverse bar in clay.

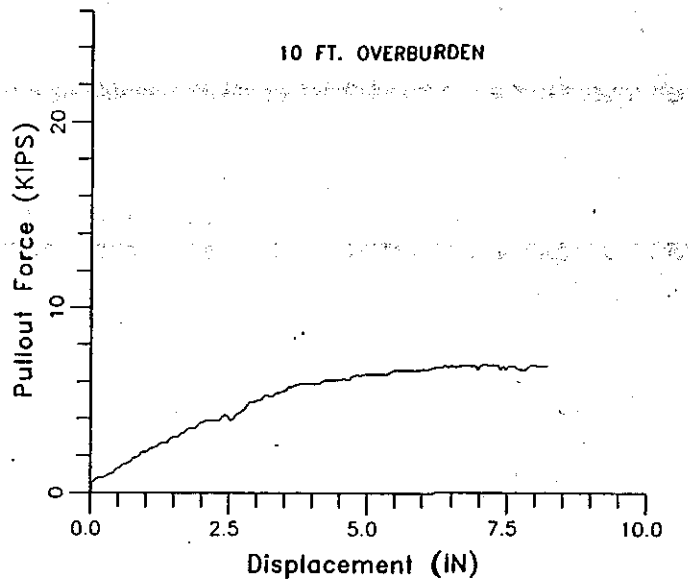
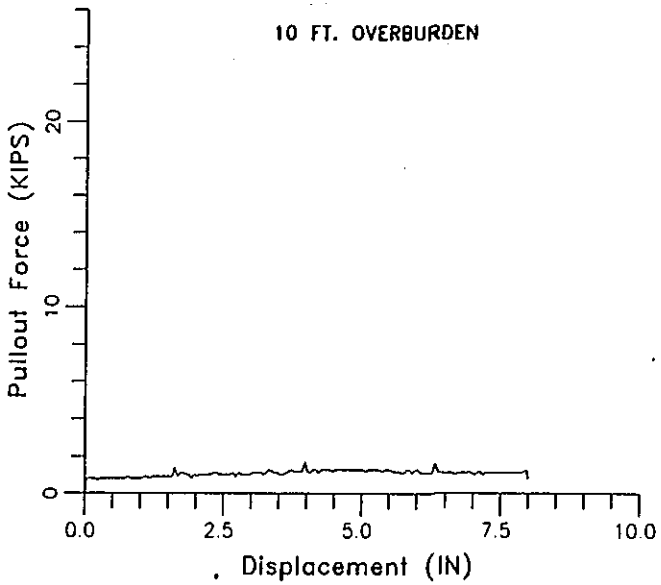


Fig: – Lab: Force–Displacement curves for TAT with sidewall in clay.



Lab: Force–Displacement curves for TAT without sidewall in clay.

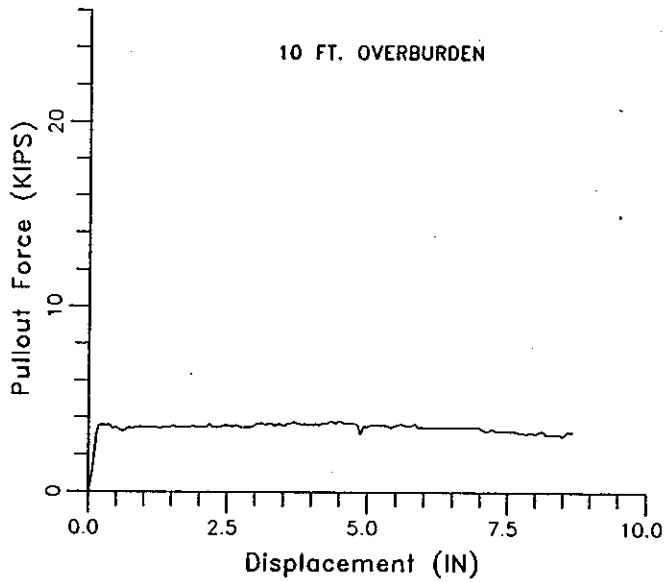
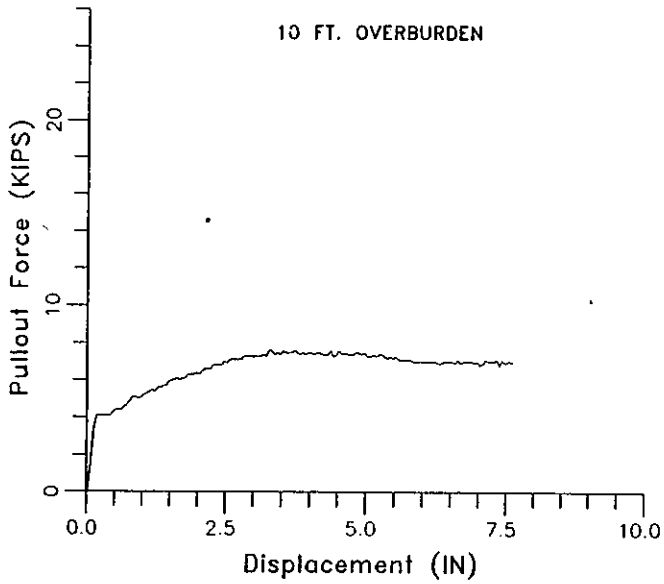


Fig: – Lab: Force–Displacement curves for CRR with one–disk in clay.



Lab: Force–Displacement curves for CRR with two–disk in clay.

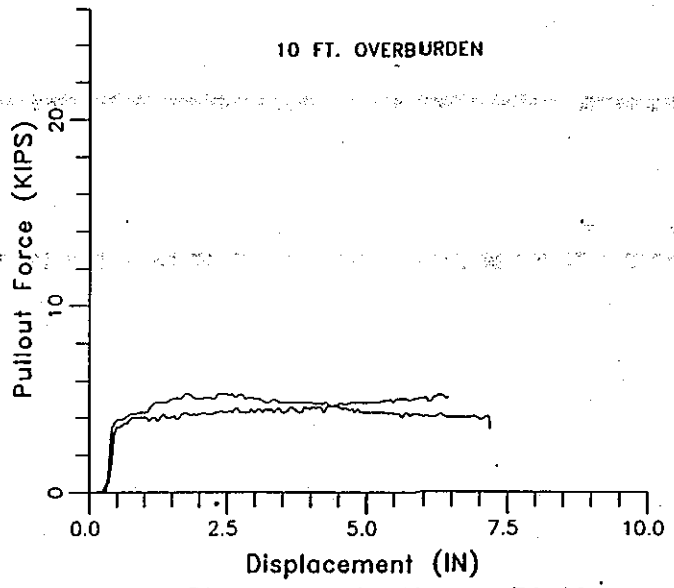
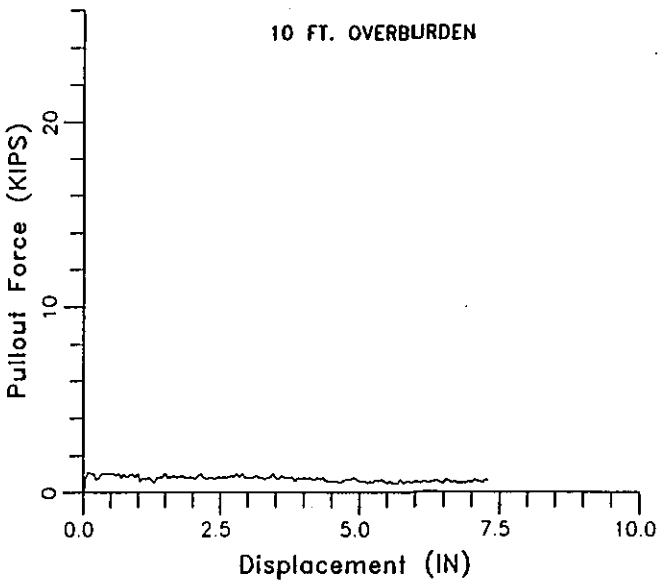


Fig: – Lab: Force–Displacement curves for C–channel 4–feet long, two Baffels in clay.



Lab: Force–Displacement curves for C–channel 4–feet long, plain in clay.

APPENDIX C

ELEMEMT TYPE	O.B HE1GHT (FT.)	MAX. PULL UP TO 1 1NCH (K1PS)	CORRES. D1SPL. (1N.)	SLOPE UP TO 1 IN (KIPS/INCH)	ULT1MATE PULL (K1PS)	D1SP. AT ULT1MATE PULL (1N.)
C2-1B10C	10	1.95	0.83	2.11	1.95	0.83
C2-1B10G	10	2.44	1.03	2.14	16.54	5.89
C2-1B10S	10	3.16	1.05	2.67	8.30	2.58
C2-1B15C	15	1.64	0.99	1.54	1.76	3.18
C2-1B15G	15	1.15	1.01	1.12	10.27	4.55
C2-1B15S	15	0.81	0.34	0.58	0.81	0.34
C2-1B20C	20	1.59	0.90	1.73	1.82	2.67
C2-1B20G	20	1.47	1.05	1.35	14.48	4.03
C2-1B20S	20	4.64	0.49	7.23	4.64	0.49
C2-1B5C	5	1.15	0.97	1.19	1.51	2.39
C2-1B5G	5	3.60	1.04	3.37	7.67	2.95
C2-1B5S	5	1.10	0.37	1.41	1.10	0.37
C2-PL10C	10	1.10	1.02	0.77	1.10	1.02
C2-PL10G	10	1.10	0.90	1.15	1.47	1.38
C2-PL10G	10	1.07	1.00	-	1.49	1.47
C2-PL10S	10	2.81	1.02	2.49	2.90	1.14
C2-PL10S	10	1.94	0.92	1.86	3.53	1.48
C2-PL15C	15	0.75	0.40	0.95	0.87	8.96
C2-PL15G	15	0.13	0.64	0.09	0.13	0.64
C2-PL15S	15	1.95	0.99	1.76	3.65	1.55
C2-PL20G	20	0.67	1.00	0.84	0.67	1.00
C2-PL20S	20	5.61	0.28	18.46	5.61	0.28
C2-PL5C	5	0.97	0.69	1.18	0.97	0.69
C2-PL5G	5	0.67	0.97	-	0.89	2.49
C2-PL5S	5	0.67	1.02	0.67	1.93	6.66
C2-PL5S	5	1.16	0.97	1.30	1.16	0.97
C4-1T10C	10	6.21	0.75	9.07	7.19	4.96
C4-1T10G	10	19.07	0.31	74.16	23.82	3.42
C4-1T15C	15	0.96	0.92	1.01	5.96	2.33

Field test results summary

C4-1T15G	15	30.78	1.05	45.95	31.51	1.13
C4-1T15G	15	22.17	0.98	29.77	22.87	1.90
C4-1T15S	15	16.36	0.17	24.40	18.50	4.13
C4-1T5C	5	5.25	1.03	6.64	5.98	4.81
C4-1T5S	5	13.51	0.45	22.06	15.94	4.64
C4-2B10C	10	4.97	1.05	4.41	4.97	1.05
C4-2B10G	10	1.22	1.03	0.90	19.59	3.66
C4-2B10S	10	8.29	1.00	7.13	15.82	2.16
C4-2B15C	15	3.33	1.04	-	6.67	5.82
C4-2B15G	15	3.90	0.33	2.71	20.93	3.17
C4-2B20C	20	2.80	1.05	2.33	6.39	2.72
C4-2B20G	20	3.73	1.03	3.37	26.00	2.75
C4-2B20S	20	12.29	1.04	10.43	14.00	1.62
C4-2B5C	5	2.31	1.03	0.99	4.75	4.25
C4-2B5G	5	1.53	1.04	1.27	14.02	2.82
C4-2B5S	5	4.02	1.03	3.93	12.90	3.09
C4-2T10C	10	5.96	1.01	7.37	9.24	5.37
C4-2T10G	10	22.88	0.01	505.68	22.88	0.01
C4-2T10S	10	28.59	1.03	31.30	32.49	1.92
C4-2T15C	15	10.35	0.92	15.72	12.90	6.45
C4-2T15G	15	-	-	-	23.64	0.00
C4-2T15S	15	32.07	1.03	37.46	33.83	1.70
C4-2T20S	20	12.29	1.04	10.43	14.00	1.62
C4-2T5C	5	9.37	0.02	12.38	9.61	1.66
C4-2T5C	5	6.22	0.91	8.25	9.51	6.42
C4-2T5G	5	30.42	0.71	57.54	30.42	0.71
C4-PL10C	10	3.78	0.82	4.43	3.78	0.82
C4-PL10G	10	3.03	1.03	2.65	4.37	2.85
C4-PL10S	10	1.22	1.03	1.12	7.80	3.54
C4-PL15C	15	0.86	0.98	0.78	3.81	2.07
C4-PL15G	15	1.70	1.03	1.17	4.14	2.08

Field test results summary (continued)

C4-PL20C	20	3.29	0.65	3.74	3.29	0.65
C4-PL20G	20	0.61	1.00	0.25	7.79	2.87
C4-PL20S	20	2.31	1.04	2.20	14.37	3.06
C4-PL5C	5	1.46	1.04	1.21	2.67	1.71
C4-PL5G	5	1.19	0.99	-	3.14	2.62
C4-PL5S	5	1.54	1.03	1.34	3.07	2.17
CRR1D10C	10	0.37	0.06	0.02	1.95	5.79
CRR1D10C	10	2.31	0.57	3.22	3.41	6.11
CRR1D10G	10	5.09	1.05	3.79	19.09	3.44
CRR1D10G	10	1.82	1.04	1.79	20.69	5.76
CRR1D10S	10	3.34	1.02	3.04	11.86	7.15
CRR1D10S	10	5.59	1.05	5.79	18.14	6.30
CRR1D15C	15	2.25	0.71	2.59	2.74	5.23
CRR1D15C	15	2.07	0.44	2.30	3.65	6.69
CRR1D15G	15	7.18	1.05	7.29	15.46	1.10
CRR1D15G	15	16.80	0.71	30.22	16.80	0.71
CRR1D15S	15	9.74	1.02	12.90	18.62	4.85
CRR1D20C	20	3.78	0.22	5.01	5.72	5.37
CRR1D20G	20	5.35	0.56	7.73	5.35	0.56
CRR1D20S	20	9.00	1.04	11.84	15.08	3.37
CRR1D5C	5	3.50	0.83	4.44	4.51	4.24
CRR1D5G	5	11.65	1.02	15.43	14.60	3.11
CRR1D5S	5	0.00	0.00	0.00	0.00	0.00
CRR2D10C	10	2.67	1.00	3.46	7.88	5.79
CRR2D10C	10	1.65	0.47	2.26	4.38	3.37
CRR2D10G	10	1.77	1.03	1.10	22.59	3.35
CRR2D10G	10	6.57	1.04	5.60	24.70	3.17
CRR2D10S	10	2.98	1.04	2.37	19.53	5.27
CRR2D10S	10	2.19	1.04	1.95	16.43	5.35
CRR2D15C	15	1.34	1.03	1.03	3.16	3.61
CRR2D15C	15	6.81	1.03	8.68	7.96	1.64
CRR2D15G	15	22.76	0.75	40.97	22.76	0.75

Field test results summary (continued)

CRR2D15G	15	13.36	0.80	17.03	20.54	1.81
CRR2D15S	15	11.06	1.05	15.29	17.04	5.47
CRR2D20C	20	4.02	1.03	4.41	7.19	3.52
CRR2D20G	20	7.80	0.87	12.10	7.80	0.87
CRR2D5C	5	1.70	1.02	1.56	5.72	7.31
CRR2D5G	5	4.98	0.98	5.94	8.51	2.73
CRR2D5S	5	2.07	1.04	2.02	14.37	7.55
MSE1B10C	10	4.38	0.99	4.60	4.38	0.99
MSE1B10C	10	3.02	0.77	3.91	3.76	8.69
MSE1B10G	10	5.96	1.03	4.95	14.09	1.87
MSE1B10G	10	2.80	1.00	-	7.34	2.91
MSE1B10S	10	7.58	1.04	5.51	18.61	1.42
MSE1B15C	15	1.94	0.73	2.38	3.16	8.68
MSE1B15C	15	4.02	0.89	4.46	6.82	4.54
MSE1B15G	15	4.38	1.04	4.69	16.15	4.53
MSE1B15G	15	8.15	1.03	8.14	9.37	1.28
MSE1B15S	15	8.60	1.02	7.65	10.07	1.71
MSE1B15S	15	11.70	1.01	11.83	12.80	2.11
MSE1B20C	20	2.19	0.52	3.11	3.04	8.63
MSE1B20G	20	3.41	1.04	2.64	10.35	2.40
MSE1B20S	20	13.52	0.96	11.00	14.49	1.49
MSE1B20S	20	7.29	1.04	4.65	14.24	5.25
MSE1B5C	5	2.68	1.03	2.91	4.27	1.65
MSE1B5G	5	5.56	1.03	5.38	7.04	1.84
MSE1B5S	5	4.49	1.04	3.53	15.45	7.20
MSE2B10C	10	3.17	1.00	3.64	3.78	1.26
MSE2B10C	10	3.08	1.04	2.48	4.26	1.37
MSE2B10G	10	7.43	1.05	6.80	26.59	4.50
MSE2B10S	10	9.65	1.04	7.12	23.40	2.57
MSE2B10S	10	6.70	1.05	5.60	19.84	2.48
MSE2B15C	15	3.00	1.01	2.87	5.31	1.93
MSE2B15C	15	3.74	1.03	3.61	5.96	8.33

Field test results summary (continued)

MSE2B15G	15	8.64	1.04	6.14	27.80	1.97
MSE2B15S	15	3.29	1.05	2.65	25.89	3.96
MSE2B15S	15	6.02	1.04	4.41	24.94	4.18
MSE2B20C	20	4.38	1.03	4.64	9.37	7.34
MSE2B20G	20	16.19	0.97	12.95	23.98	1.67
MSE2B20S	20	4.86	1.04	3.84	23.00	5.12
MSE2B5C	5	2.67	0.93	3.09	3.28	3.98
MSE2B5S	5	2.95	1.05	2.11	16.82	5.41
MSE3B10C	10	2.56	1.05	2.19	7.43	6.92
MSE3B10C	10	1.79	1.04	1.44	5.71	5.61
MSE3B10G	10	3.41	1.03	3.33	26.90	2.66
MSE3B10G	10	3.27	1.04	2.65	27.85	3.41
MSE3B10S	10	13.51	1.04	11.96	18.25	2.51
MSE3B10S	10	2.95	1.03	2.26	23.89	4.22
MSE3B15C	15	3.23	1.04	2.88	6.69	7.89
MSE3B15C	15	3.65	1.02	3.25	8.88	7.87
MSE3B15G	15	20.68	1.05	14.26	26.53	2.84
MSE3B15G	15	12.16	1.04	9.24	26.65	2.20
MSE3B15S	15	0.77	1.05	0.48	21.76	4.77
MSE3B15S	15	5.89	1.04	5.18	22.12	3.29
MSE3B20C	20	2.92	1.03	2.04	7.54	6.02
MSE3B20G	20	10.82	1.04	8.01	30.76	1.96
MSE3B20S	20	11.00	1.04	8.60	23.49	4.49
MSE3B5C	5	1.96	1.03	1.75	11.86	7.29
MSE3B5G	5	2.18	0.98	2.27	17.52	4.01
MSE3B5S	5	10.71	1.03	9.00	19.10	2.94
MSE3BA5G	5	7.95	1.03	8.15	21.78	2.75
TATWO10C	10	1.70	0.86	1.84	2.07	7.99
TATWO10C	10	1.59	0.96	1.56	5.59	8.00
TATWO10G	10	3.36	1.04	3.09	10.91	7.31
TATWO10G	10	3.16	1.03	2.98	12.66	6.40
TATWO10S	10	4.75	1.05	3.73	12.68	6.43

Field test results summary (continued)

TATWO10S	10	3.55	1.04	2.77	12.13	6.57
TATWO15C	15	1.16	0.96	1.44	1.76	3.50
TATWO15C	15	2.07	1.05	1.48	4.99	6.52
TATWO15G	15	4.38	1.00	3.80	13.81	5.31
TATWO15G	15	1.90	1.04	1.65	14.85	3.66
TATWO15S	15	8.26	1.03	8.60	13.66	4.91
TATWO15S	15	5.65	1.04	4.48	12.68	6.08
TATWO20C	20	1.35	0.59	1.79	2.07	8.97
TATWO20G	20	6.07	1.05	4.90	19.18	4.05
TATWO20S	20	6.32	0.99	5.25	11.08	3.28
TATWO5C	5	0.93	0.36	1.12	1.59	8.32
TATWO5S	5	5.47	1.00	5.01	9.61	5.26
TATWS10C	10	3.16	0.98	3.79	9.37	5.59
TATWS10G	10	2.82	1.03	2.43	14.88	6.42
TATWS10G	10	2.43	1.02	1.51	15.42	6.17
TATWS10S	10	2.92	1.04	2.27	16.07	6.40
TATWS10S	10	5.49	1.02	4.91	16.20	4.95
TATWS15C	15	2.43	0.83	2.99	6.45	6.76
TATWS15C	15	3.29	1.01	3.29	13.27	6.48
TATWS15G	15	1.86	1.00	1.82	15.24	5.67
TATWS15G	15	4.38	1.00	3.80	13.81	5.31
TATWS15S	15	5.23	1.03	5.52	18.62	4.86
TATWS15S	15	3.04	0.91	3.09	14.12	5.73
TATWS20C	20	1.82	1.04	1.45	8.14	6.96
TATWS20G	20	2.59	1.03	2.54	15.82	5.83
TATWS20S	20	3.17	1.04	2.49	18.62	4.82
TATWS5C	5	2.31	1.02	2.27	6.21	6.81
TATWS5G	5	1.34	1.02	1.16	16.64	5.74
TATWS5S	5	5.82	1.03	7.34	13.02	5.66

Field test results summary (continued)

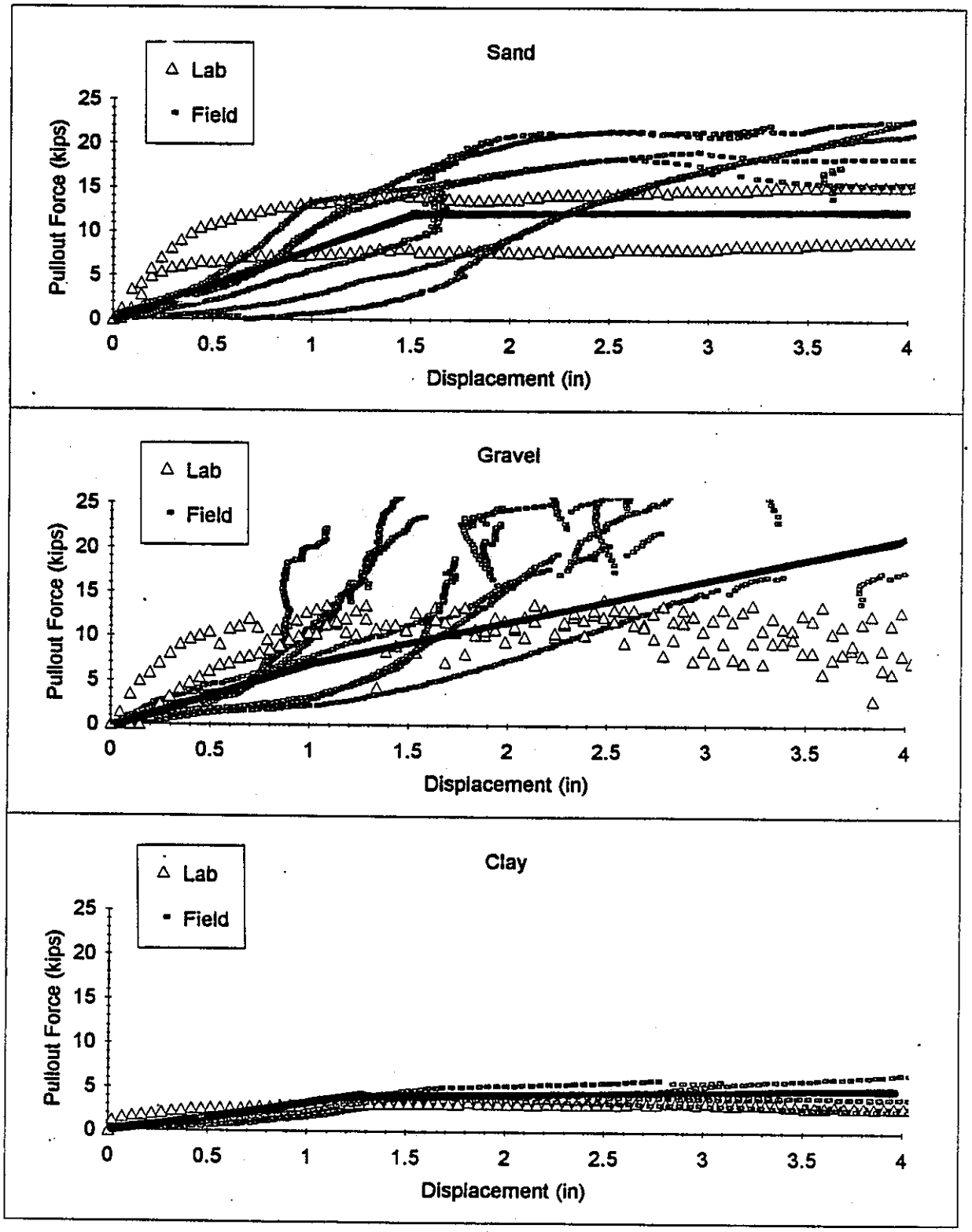
ELEMENT TYPE	OVERBURDEN HEIGHT (FT.)	MAX. PULL UP TO 1 INCH (KIPS)	CORRESPONDING DISPLACEMENT (IN.)	SLOPE UP TO 1 INCH (KIPS/INCH)	ULTIMATE PULL (KIPS)	DISPLACEMENT AT ULTIMATE PULL (IN.)
C4-2B10C	10	4	0.79	4.83	5.2	6.24
C4-2B10C	10	4.3	0.89	5.28	5.3	1.74
C4-2B10G	10	7.6	1.04	8.21	13	3.84
C4-2B10S	10	14.4	1.04	17.93	14.7	1.14
C4-2B20G	20	13.4	1.04	14.58	24.9	4.53
C4-2B20S	20	23	1.04	19.52	23.8	1.29
C4-PL10C	10	1.1	0.09	1.36	1.1	0.09
C4-PL10G	10	3.5	0.8	4.61	3.6	1.38
C4-PL10S	10	6.9	0.79	7.81	6.9	0.79
C4-PL20G	20	6.4	0.49	8.74	6.4	0.49
C4-PL20S	20	10	0.44	12.46	10	0.44
CRR1D10C	10	3.6	0.18	5.12	3.8	3.68
CRR1D10G	10	9.8	1	10.57	19.8	7.43
CRR1D10S	10	14.9	1.04	19.07	18.6	5.99
CRR1D10S	10	14.7	0.84	19.97	15.8	1.79
CRR1D20G	20	7.9	1.03	8.86	26.9	8.02
CRR1D20S	20	19.9	1.04	26.45	31.9	7.83
CRR1D20S	Stage 20	0	0	-	34.5	8.38
CRR2D10C	10	5.2	1.03	6.92	7.6	3.28
CRR2D10G	10	14.4	1.04	14.68	25.2	6.13
CRR2D10S	10	10.2	1.04	12.76	11.9	2.04
CRR2D10S	10	8.6	1.04	9.59	11.9	1.99
CRR2D20G	20	20.1	1.04	21.34	36.5	3.18
CRR2D20S	20	21.8	1.04	28.22	23	2.04
CRR2D20S	Stage 20	0	0	-	17.6	2.95

Laboratory test results summary

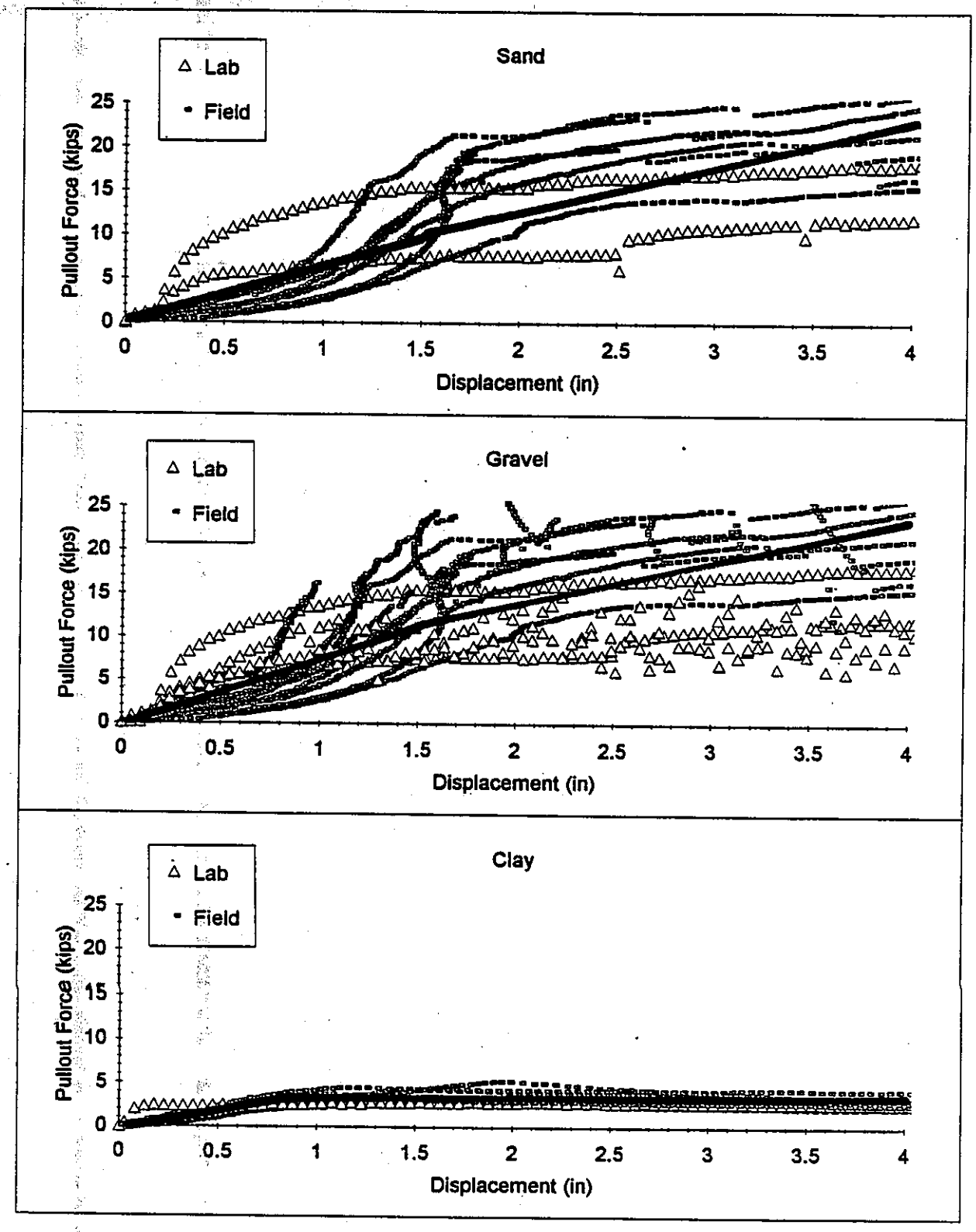
MSE1B10C	10	1.3	0.63	1.77	1.3	0.63
MSE1B10G	10	7.3	1.05	8.32	10.4	8.13
MSE1B10S	10	4.9	0.99	4.28	6.3	8.34
MSE1B10S	10	5.5	1.04	7.09	5.9	1.39
MSE1B20G	20	4.4	0.75	5.02	8.8	6.63
MSE1B20S	20	4.7	1.04	5.71	8.1	7.89
MSE1B20S	Stage 20	0	0	-	8.8	7.4
MSE2B10C	10	2.7	0.77	3.83	3	1.53
MSE2B10G	10	8.7	1.05	9.24	14.6	8.43
MSE2B10S	10	6.8	1.04	8.38	8.1	2.49
MSE2B20G	20	11.4	1.05	11.74	17.9	5.83
MSE2B20S	20	13.8	1.04	16.51	19.3	5.54
MSE2B20S	Stage 20	0	0	-	14.2	8.21
MSE3B10C	10	3.1	1.02	4.13	3.4	1.82
MSE3B10G	10	10.4	1	10.92	14.6	6.23
MSE3B10S	10	7.5	1.04	10.10	11.7	5.49
MSE3B20G	20	13	1.03	15.51	15.6	5.08
MSE3B20S	20	13.3	0.99	16.84	16.7	6.04
TATWO10C	10	0.9	0.78	1.21	1.7	3.97
TATWO10G	10	2.7	0.64	2.71	7.9	6.13
TATWO10S	10	1.6	0.45	2.28	3.7	6.5
TATWO20G	20	3.9	0.79	4.50	9.3	6.98
TATWO20S	20	7.2	1.04	8.37	9.6	4.34
TATWS10C	10	2.2	0.93	2.44	6.9	6.37
TATWS10G	10	3.1	0.84	3.61	13.3	6.22
TATWS10S	10	5.6	1.04	6.24	14.8	4.69
TATWS20G	20	7.2	1	7.15	17.7	4.78
TATWS20S	20	10.2	1.04	12.16	24.5	4.74

Laboratory test results summary (continued)

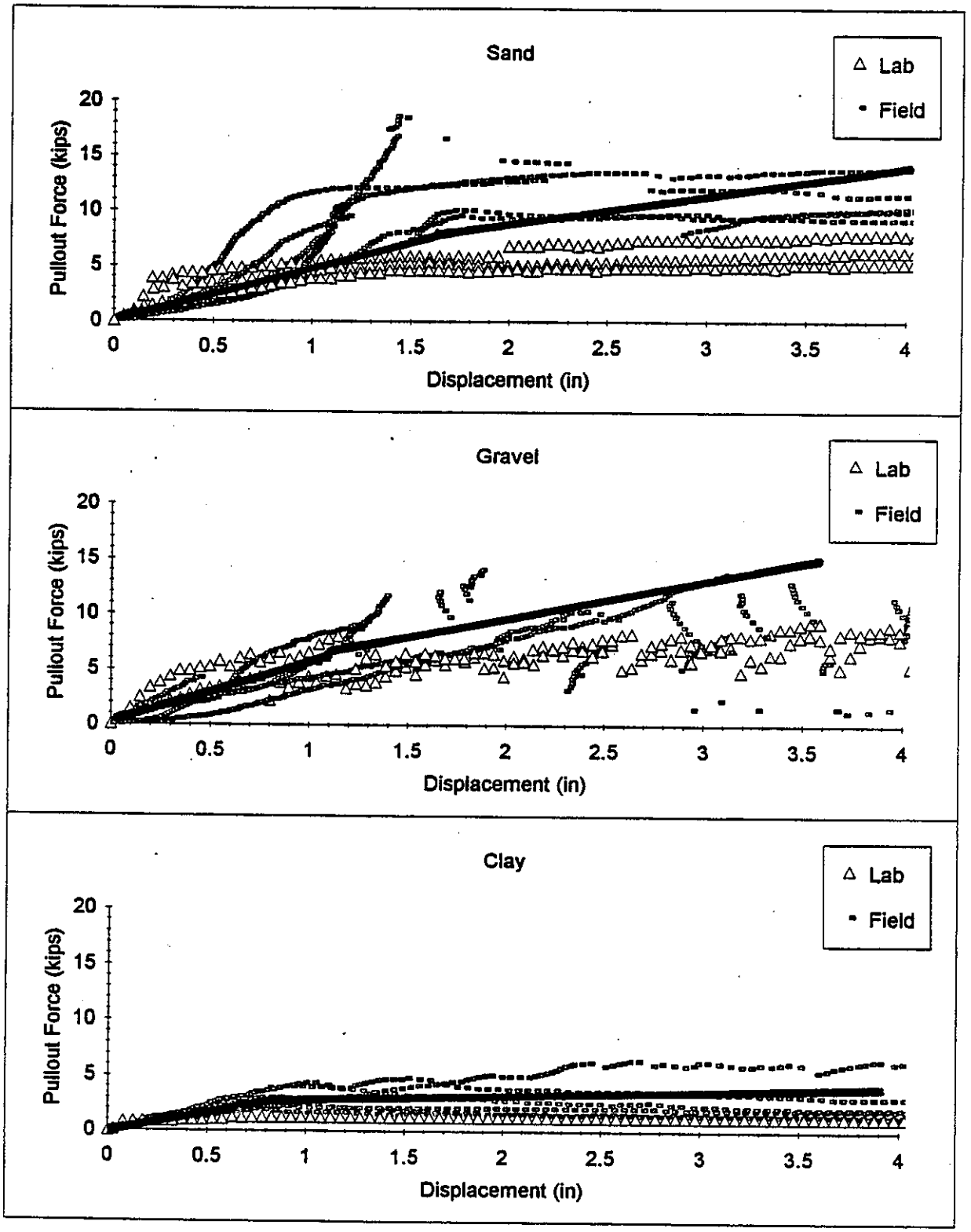
APPENDIX D



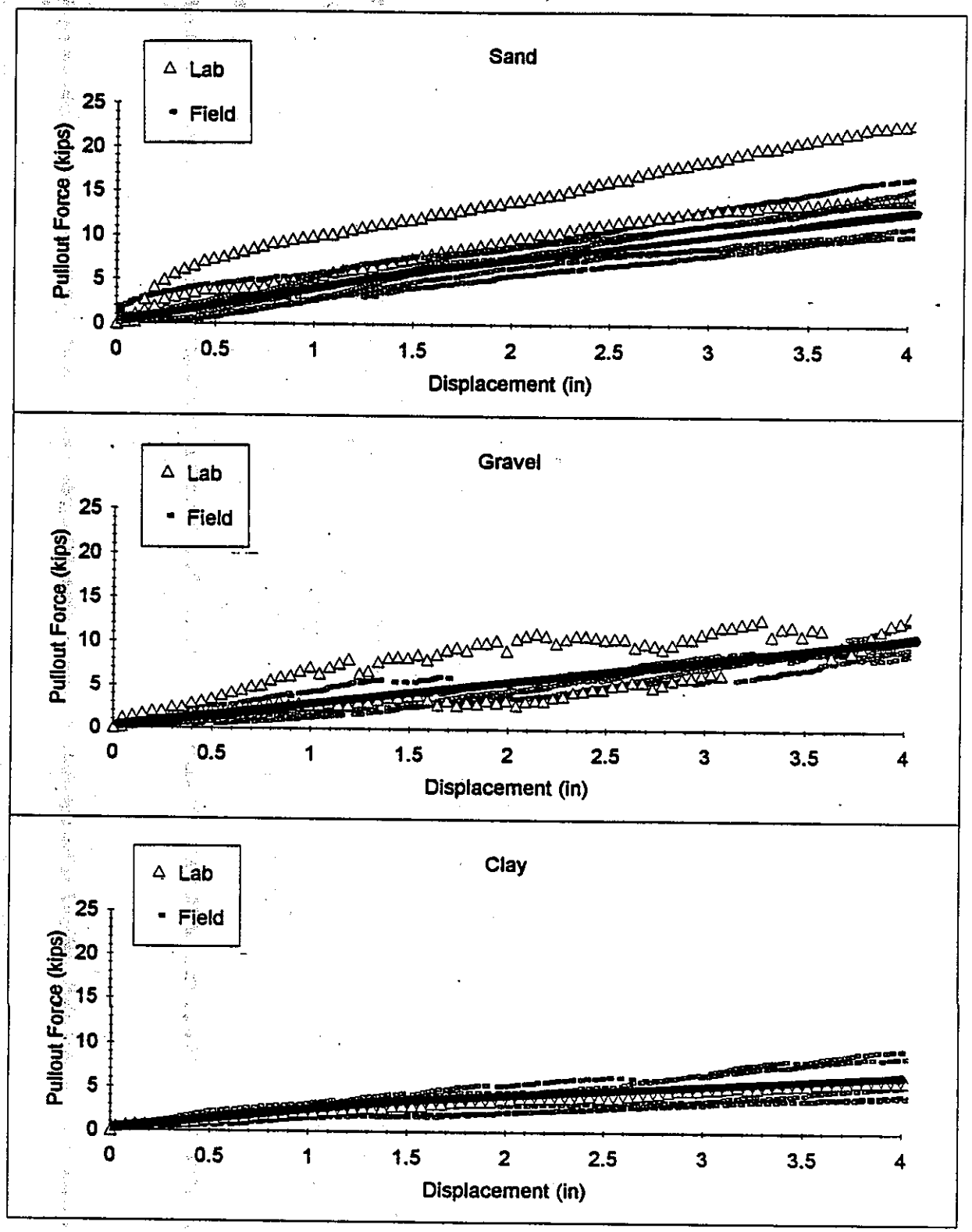
Design envelopes for 4-foot long by 1-foot wide MSE bar mats with three transverse bars (displacement shown up to 4-inches)



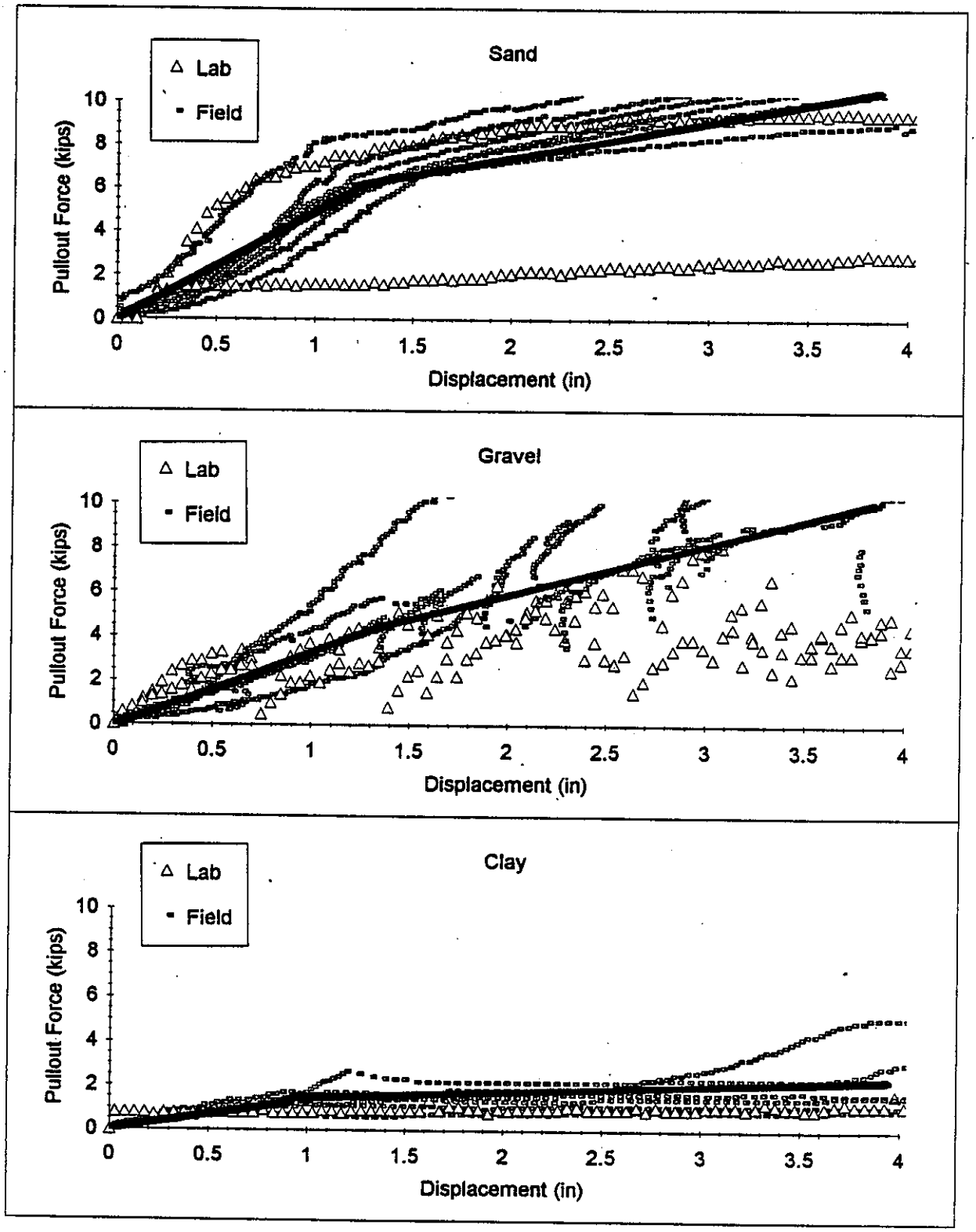
Design envelopes for 4-foot long by 1-foot wide MSE bar mats with two transverse bars (displacement shown up to 4-inches)



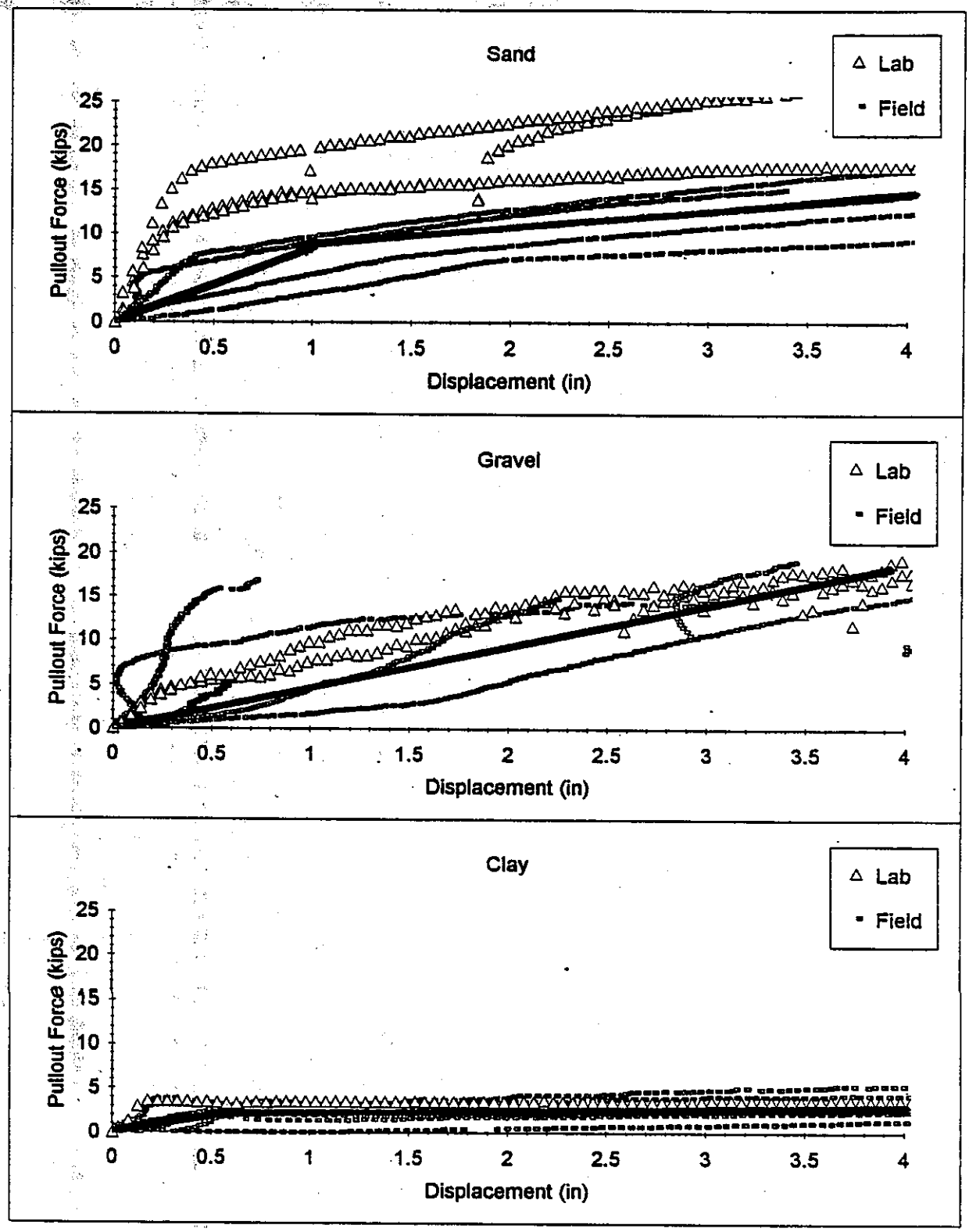
Design envelopes for 4-foot long by 1-foot wide MSE bar mats with one transverse bar (displacement shown up to 4-inches)



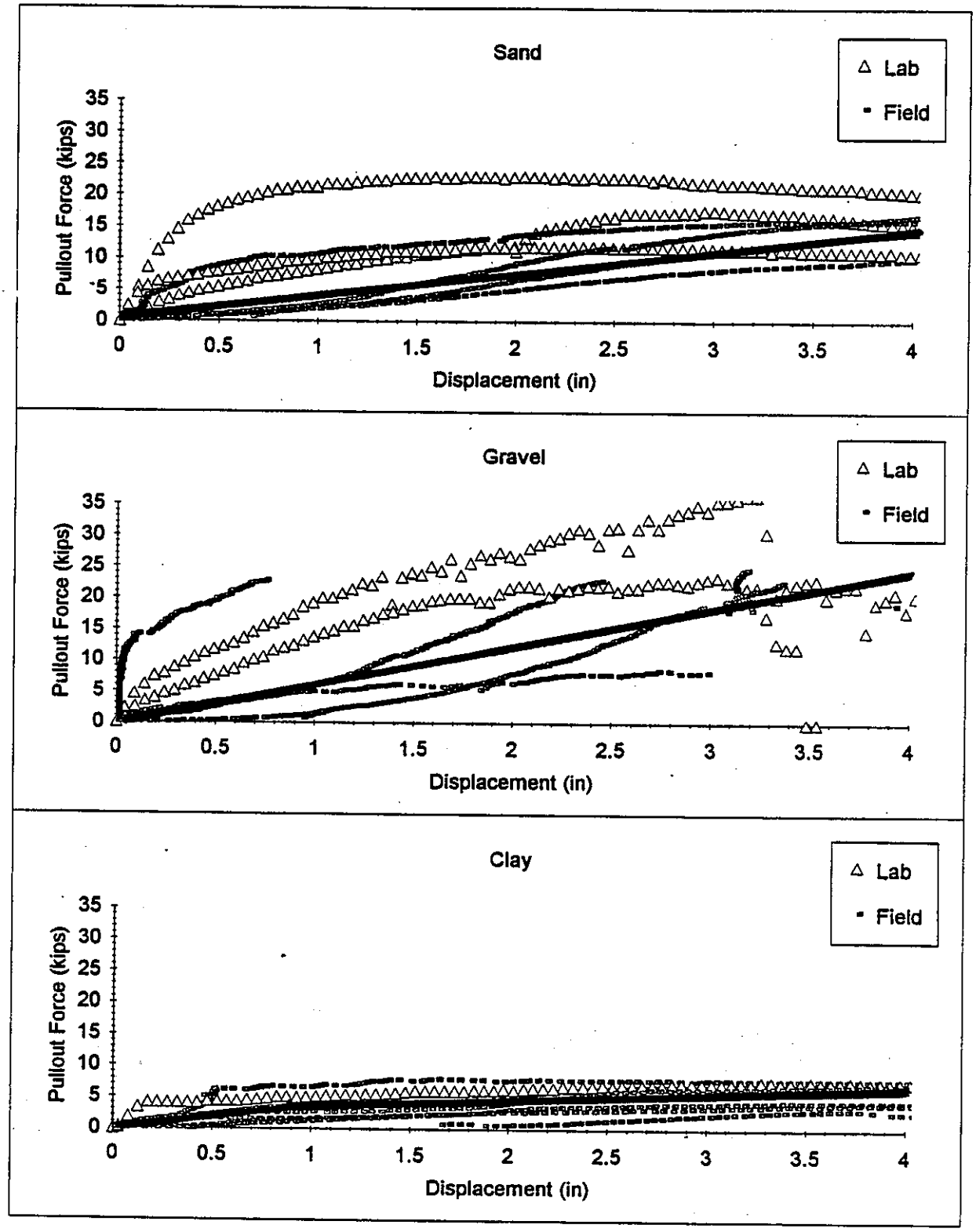
Design envelopes for 4-foot long TATs with a tire side wall (displacement shown up to 4-inches)



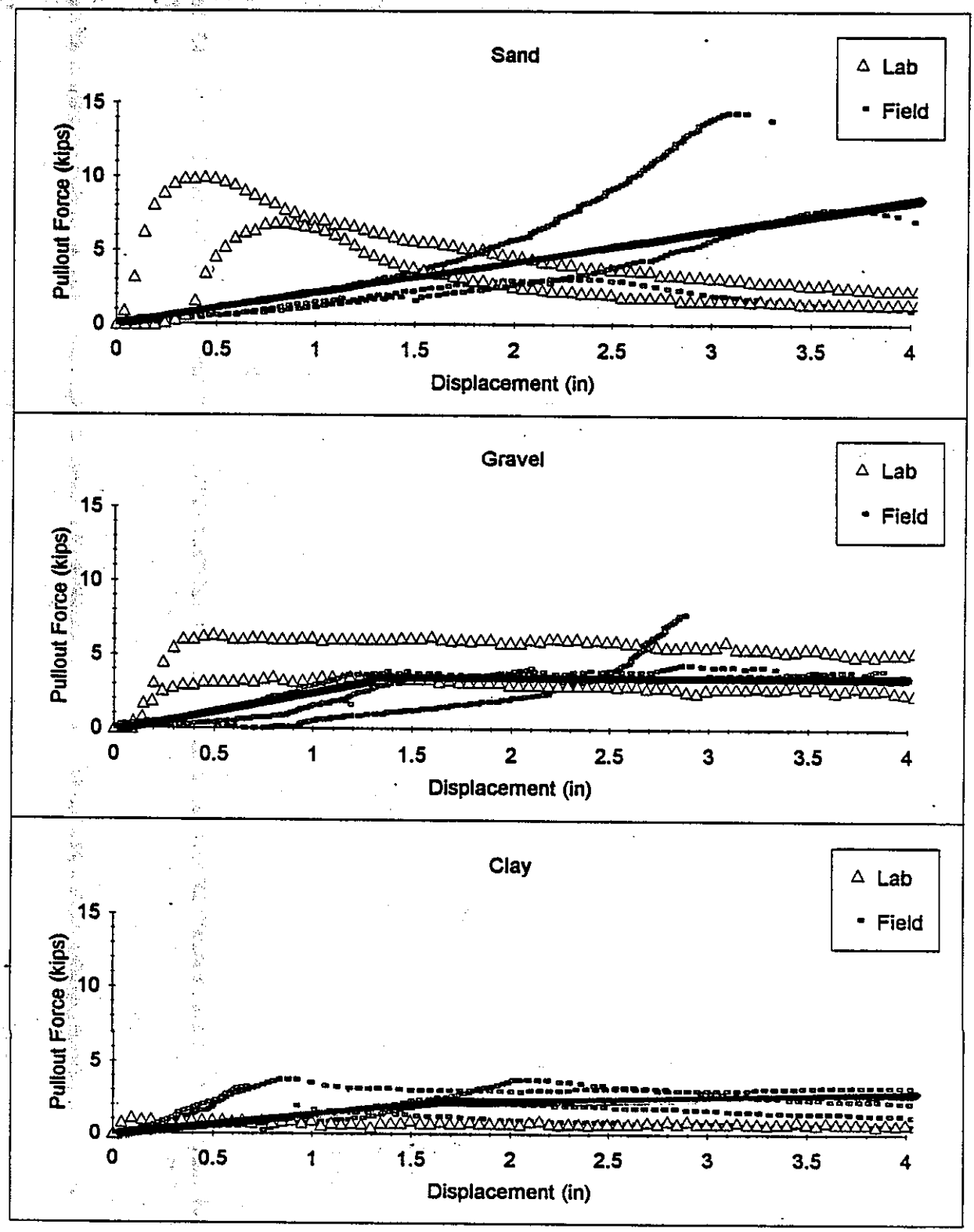
Design envelopes for 4-foot long TATs without a tire side wall (displacement shown up to 4-inches)



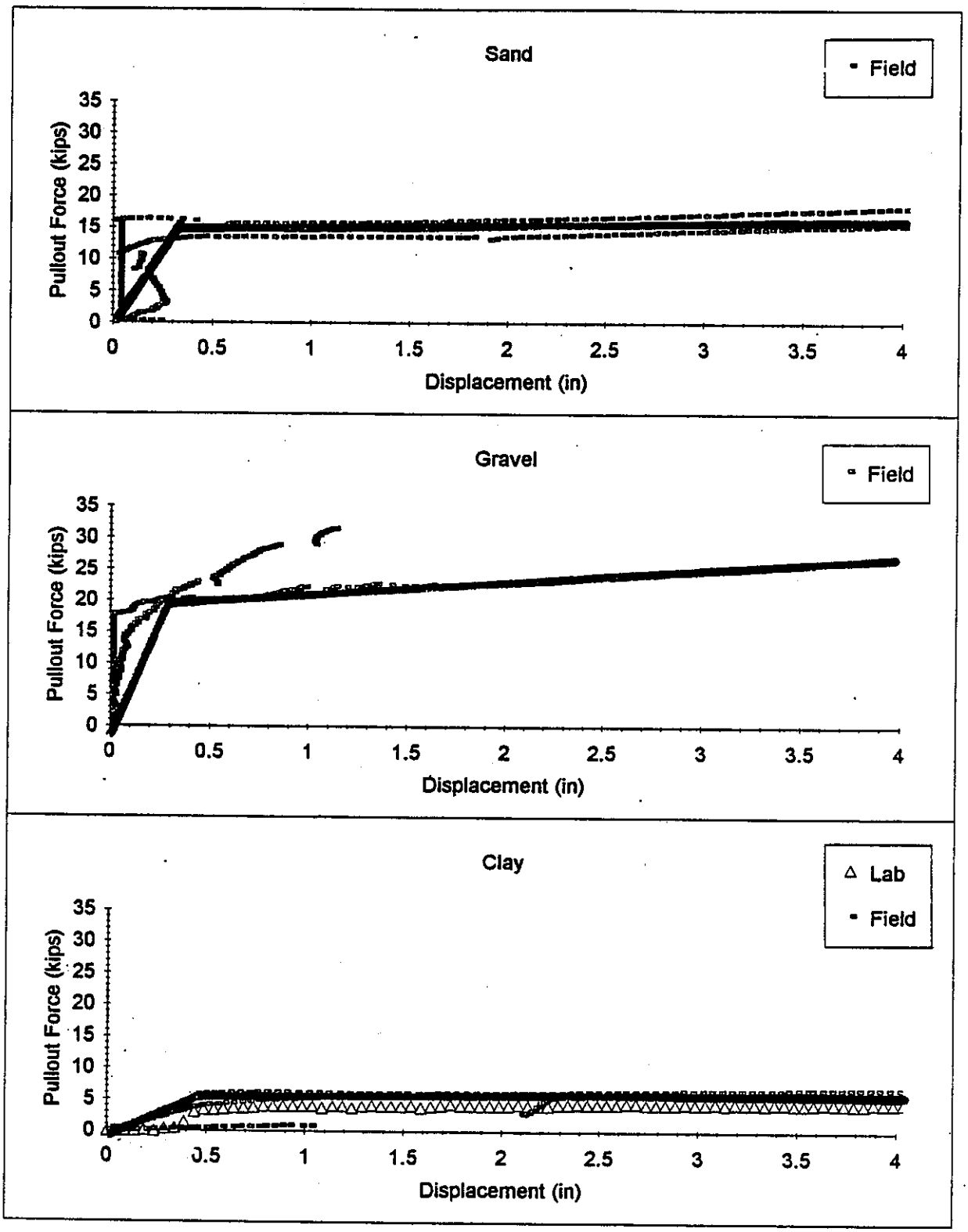
Design envelopes for 4-foot long CRRs with one disk (displacement shown up to 4-inches)



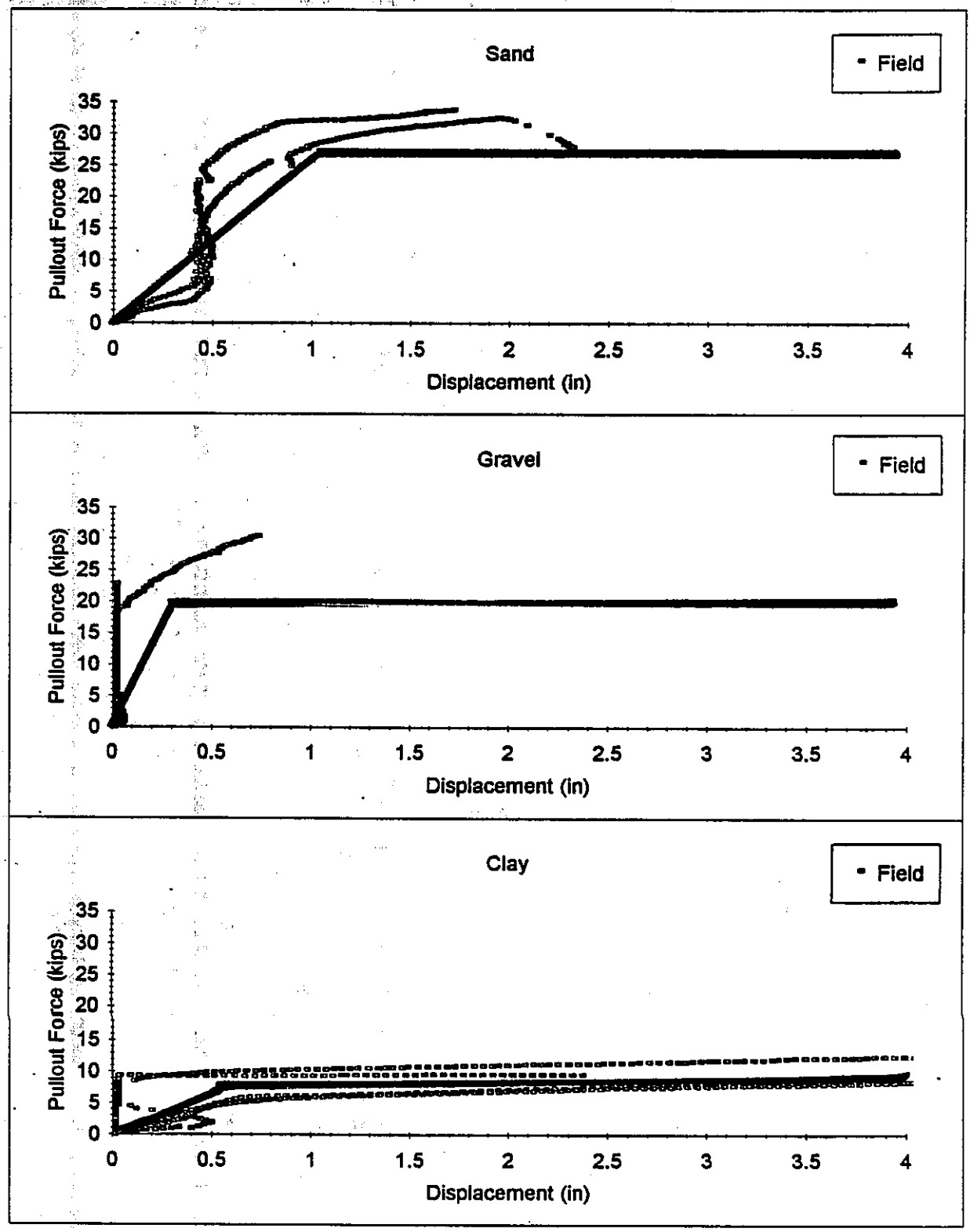
Design envelopes for 4-foot long CRRs with two disks (displacement shown up to 4-inches)



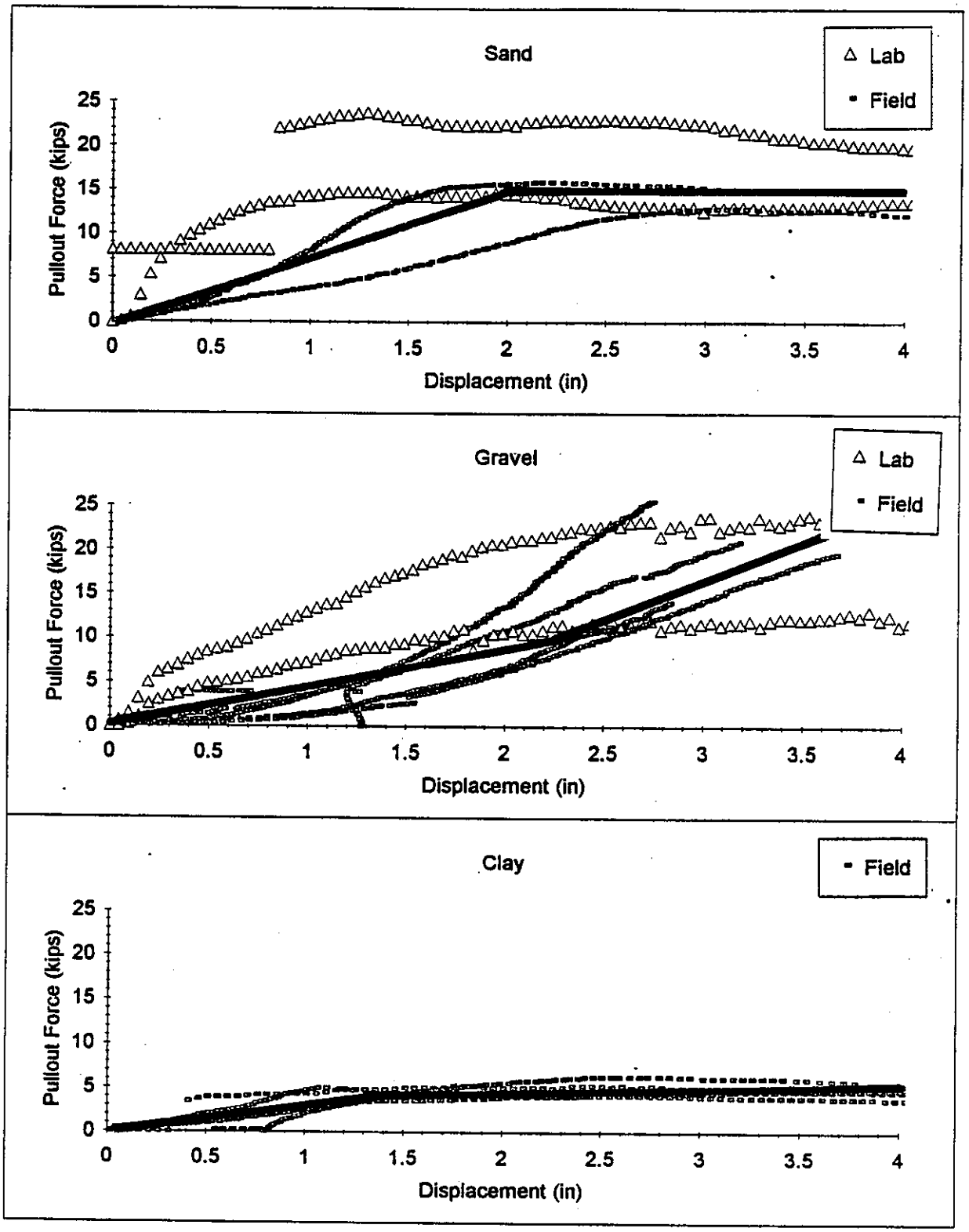
Design envelopes for 4-foot long "C" channels (displacement shown up to 4-inches)



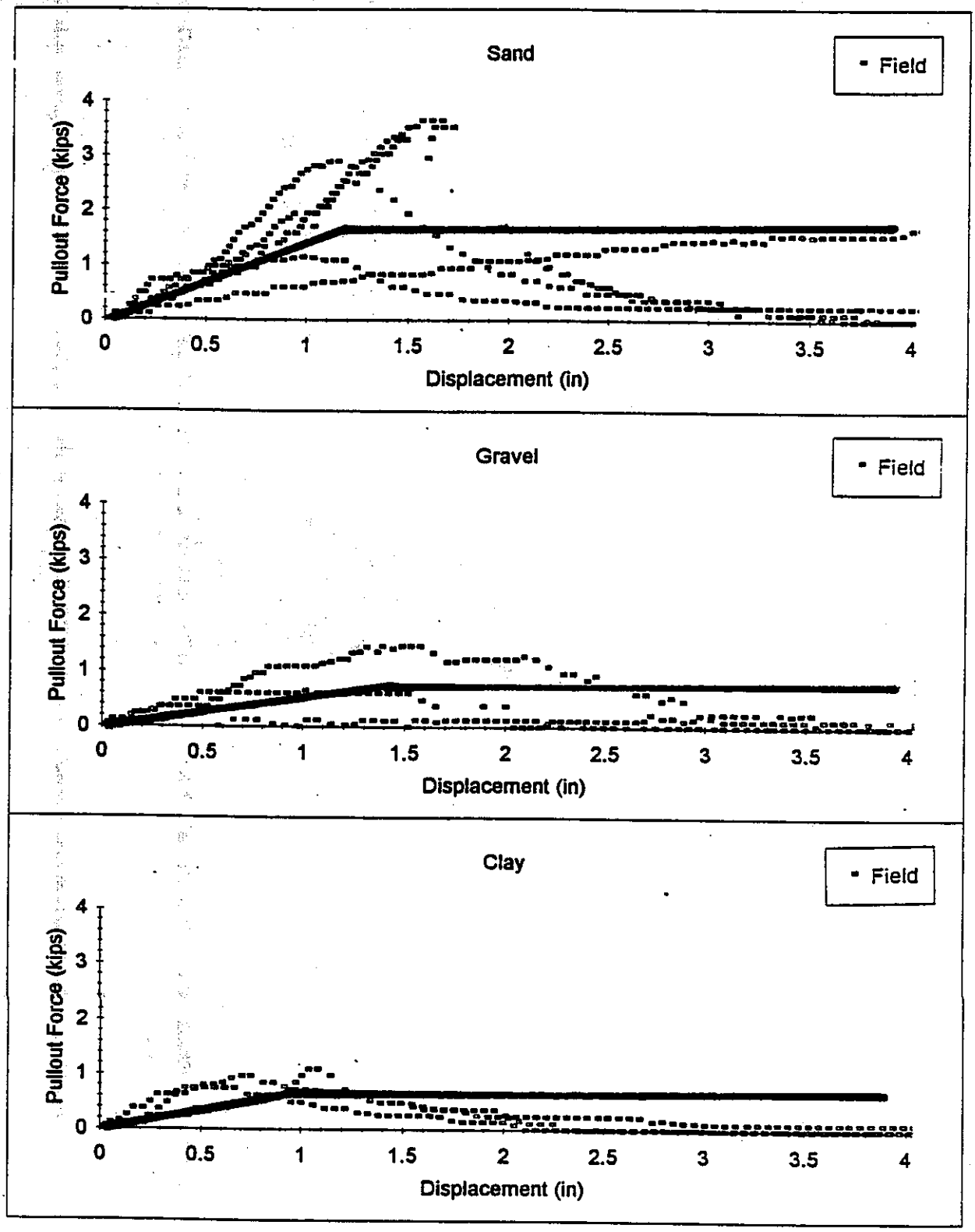
Design envelopes for 4-foot long "C" channels with 1-foot tees (displacement shown up to 4-inches)



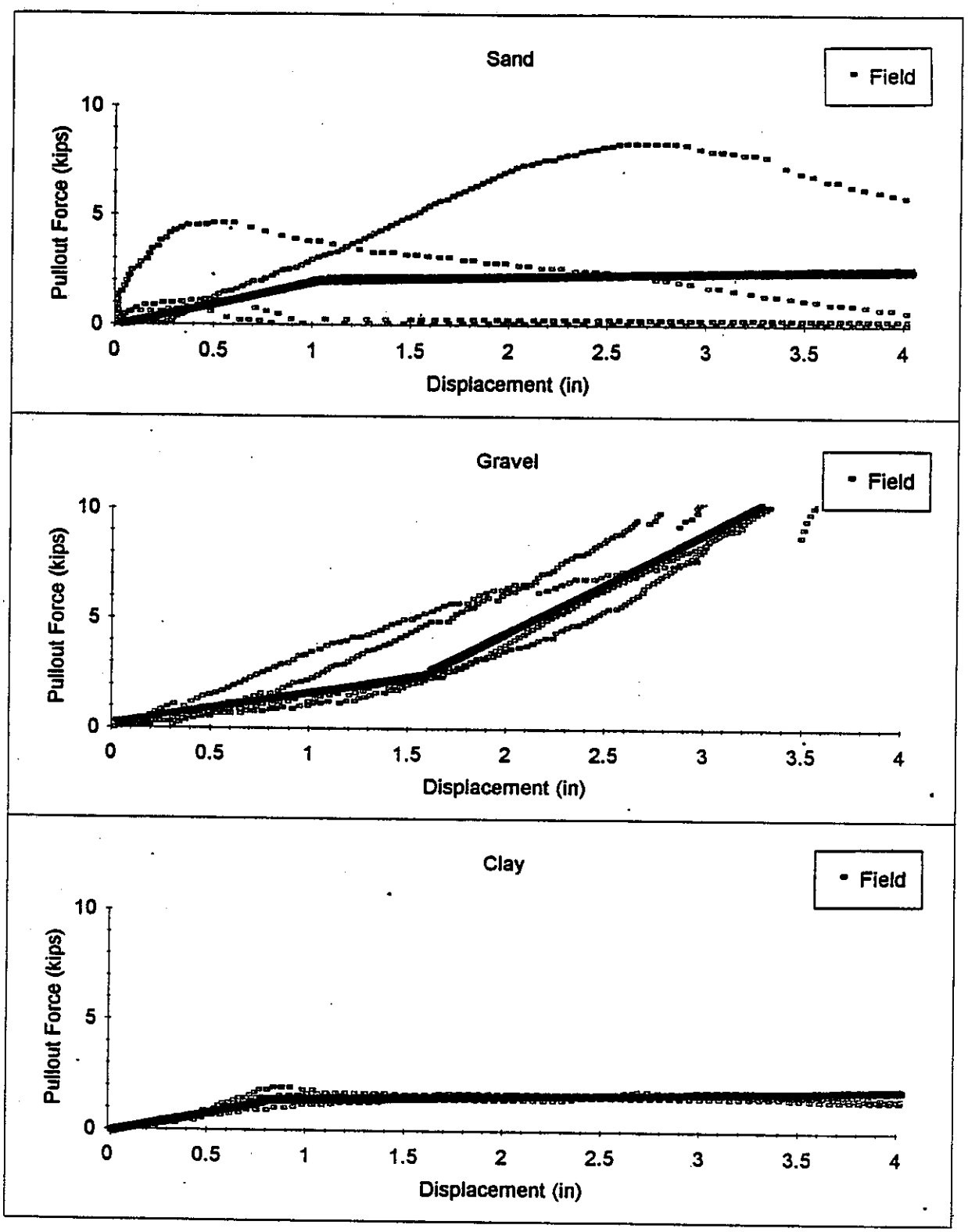
Design envelopes for 4-foot long "C" channels with 2-foot tees (displacement shown up to 4-inches)



Design envelopes for 4-foot long "C" channels with two baffles (displacement shown up to 4-inches)



Design envelopes for 2-foot long "C" channels (displacement shown up to 4-inches)



Design envelopes for 2-foot long "C" channels with one baffle (displacement shown up to 4-inches)