EARTH FORCE REDUCTION BY A SYNTHETIC COMPRESSIBLE INCLUSION

A Report of Research Conducted under the Sponsorship of

GeoTech Systems Corporation
And
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EXECUTIVE SUMMARY

Compaction of backfill adjacent to basement walls increases the lateral earth pressures that these walls must withstand. One possible method of reducing compaction-induced earth pressures is by the use of a compressible inclusion between the wall and the soil backfill. In this research, several instrumented retaining wall tests were performed using a synthetic compressible inclusion known as TerraFlex™ to quantify its effect on reducing compaction-induced earth pressures. TerraFlex is manufactured by GeoTech Systems Corporation of Winchester, Virginia.

The scope of this research was to perform 1) laboratory tests on specimens of TerraFlex, 2) instrumented retaining wall tests using TerraFlex, and 3) an engineering economic analysis on the impact of TerraFlex on retaining wall costs.

Laboratory testing on TerraFlex consisted of creep and cyclic testing. The creep tests show that the compressibility of TerraFlex increases with compressive stress up to about 400 psf. Between 400 psf and 500 psf, the compressibility of TerraFlex begins to decrease. The cyclic tests show that there is a significant amount of permanent deformation of the TerraFlex associated with loading/unloading cycles.

Several instrumented retaining wall tests were performed in which TerraFlex was placed on the backfill side of a 6.5-foot high instrumented retaining wall. TerraFlex thicknesses of 2, 4, 6, and 10 inches were used in the tests. The soil backfill was placed in lifts and compacted with either a rammer compactor or a vibrating plate compactor. Each instrumented retaining wall test consisted of a stationary wall test to simulate a basement wall condition, and then the wall was moved in a cyclic manner to investigate potential benefits of using TerraFlex in integral bridge abutment applications. The results of stationary wall tests show that the lateral earth pressures can be reduced over 50 percent when 10 inches of TerraFlex is used with backfill compacted by the rammer compactor. The lateral earth pressures were also reduced over 50 percent when 6 inches of TerraFlex was used with backfill compacted by a vibrating plate compactor. The cyclic wall tests show that there is a progressive increase in lateral earth pressures with increasing wall cycles. However, the increase in lateral earth pressure is much less pronounced when larger TerraFlex thicknesses are placed against the retaining wall.

The economic analysis was performed to study the potential economic benefit of using TerraFlex in reinforced-concrete basement wall applications and in mass-concrete gravity retaining wall applications. For each of these analyses, the economic benefit of using 4 inches of TerraFlex was evaluated. For reinforced-concrete basement wall applications, it was found that the use of TerraFlex may produce cost savings of about 13 to 27 percent for walls that are 20 to 26 feet high, with the percent cost savings increasing as the wall height increases. For mass-concrete gravity wall applications, it was found that cost savings of about 28 percent could be obtained by the use of TerraFlex, with the percent cost savings remaining approximately constant for wall heights ranging from 10 to 40 feet.

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CHAPTER 1 – INTRODUCTION

1.1 Background

Basement walls retain soil to create useable spaces below adjacent ground surfaces. The retained soil exerts lateral pressures on these walls, which must be designed to withstand the soil pressures. Backfill soil next to these walls is typically compacted to minimize settlement of the ground surface. Compaction increases the lateral earth pressures that these walls must be able to withstand (Broms 1971, Duncan and Seed 1986).

One possible method to reduce compaction-induced earth pressures is by the use of a synthetic compressible inclusion between the wall and the retained soil backfill (Horvath 1995, 1997). If a compressible inclusion is placed against a basement wall prior to placing and compacting the soil, the magnitude of lateral earth pressures may be decreased. As the inclusion compresses under the lateral pressures, the backfill expands laterally, and the strength of the backfill becomes more fully mobilized. Lateral earth pressures are smaller when the soil strength is mobilized by lateral expansion than when it is not.

Controlled experimental data is needed to demonstrate that synthetic compressible inclusions significantly and reliably reduce compaction-induced earth pressures. If such data were available, then basement walls could be constructed more economically because they could be designed to resist smaller pressures.

Virginia Tech was contacted by Mr. David Van Wagoner of GeoTech Systems Corporation of Winchester, Virginia, to study the effects that a synthetic compressible inclusion known as TerraFlex™ has on reducing lateral earth pressures on basement walls. TerraFlex is an elasticized geofoam product manufactured by GeoTech Systems Corporation. A research project was completed with funding provided by GeoTech Systems Corporation and Virginia's Center for Innovative Technology. This report presents the findings of the research.

1.2 Purpose and Scope

The purpose of this research project is to quantify the influence that TerraFlex has on the magnitude of lateral pressure applied to basement walls by soil compacted with hand-operated compactors. The original scope of work for this research project consisted of four instrumented retaining wall tests, a limited series of laboratory tests on TerraFlex, and engineering economic analyses of the impact of TerraFlex on retaining wall costs. During the course of the work, we expanded the scope by performing one additional instrumented retaining wall test, by cyclically moving the instrumented wall, and by performing a series of cyclic load tests on specimens of TerraFlex in the laboratory. The purpose of these additional cyclic tests was to investigate potential benefits of using TerraFlex in integral bridge abutment applications. Integral bridge abutments experience cyclic movements due to seasonal expansion/contraction cycles of the bridge deck.

The instrumented retaining wall tests were performed in Virginia Tech's Instrumented Retaining Wall Facility. This facility is a 7-foot high by 10-foot long wall that is instrumented with load and pressure transducers so the lateral pressures on the wall can be measured.

1.3 Contents of Report

This report is divided into 6 chapters. A brief description of the retaining wall test facility is presented in Chapter 2. Chapter 3 provides a description of the laboratory tests performed and the test results. A description of the instrumented retaining wall tests and a summary of the results of these tests are provided in Chapter 4. Chapter 5 presents a study of the engineering economic impact of TerraFlex on the design and cost of basement walls and gravity retaining walls. Chapter 6 provides a summary, conclusions, and recommendations for further research.

CHAPTER 2 – DESCRIPTION OF TEST FACILITY

2.1 Introduction

This chapter provides a summary description of the instrumented retaining wall facility. More complete details of the facility are provided by Sehn and Duncan (1990).

2.2 Wall Configuration

The instrumented retaining wall consists of four, 8-inch thick concrete panels located within a very stiff reinforced concrete structure, as shown in the oblique view in Figure 2.1. Each of the panels is 2.5 feet wide by 7 feet tall, so the overall wall size is 10 feet long by 7 feet high. The backfill area is 6 feet wide, 7 feet high, and 10 feet long. An access ramp leads to the bottom of the backfill area and is 6 feet wide by 12 feet long. During backfill operations, the backfill area and ramp are both filled with compacted soil.

Lateral support for the instrumented wall is provided by the 15-inch thick concrete reaction wall shown in Figure 2.1. A cross-section through the reaction wall and lateral support system for the instrumented wall is shown in Figure 2.2. The lateral support system includes load cells, a steel frame, and screw jacks. Each panel is supported by three load cells (not shown in Figure 2.2) that react against a steel frame. The steel frame is, in turn, supported by four screw jacks, two located toward the bottom of the wall and two located near the top. The screw jacks bear on the 15-inch thick concrete wall. The reaction wall is part of a massive U-frame structure that contains the backfill area and instrumented wall, as shown in Figure 2.2. The base of the U-frame structure is 21 inches thick. The U-frame structure is essentially non-deflecting under lateral loads from the backfill.

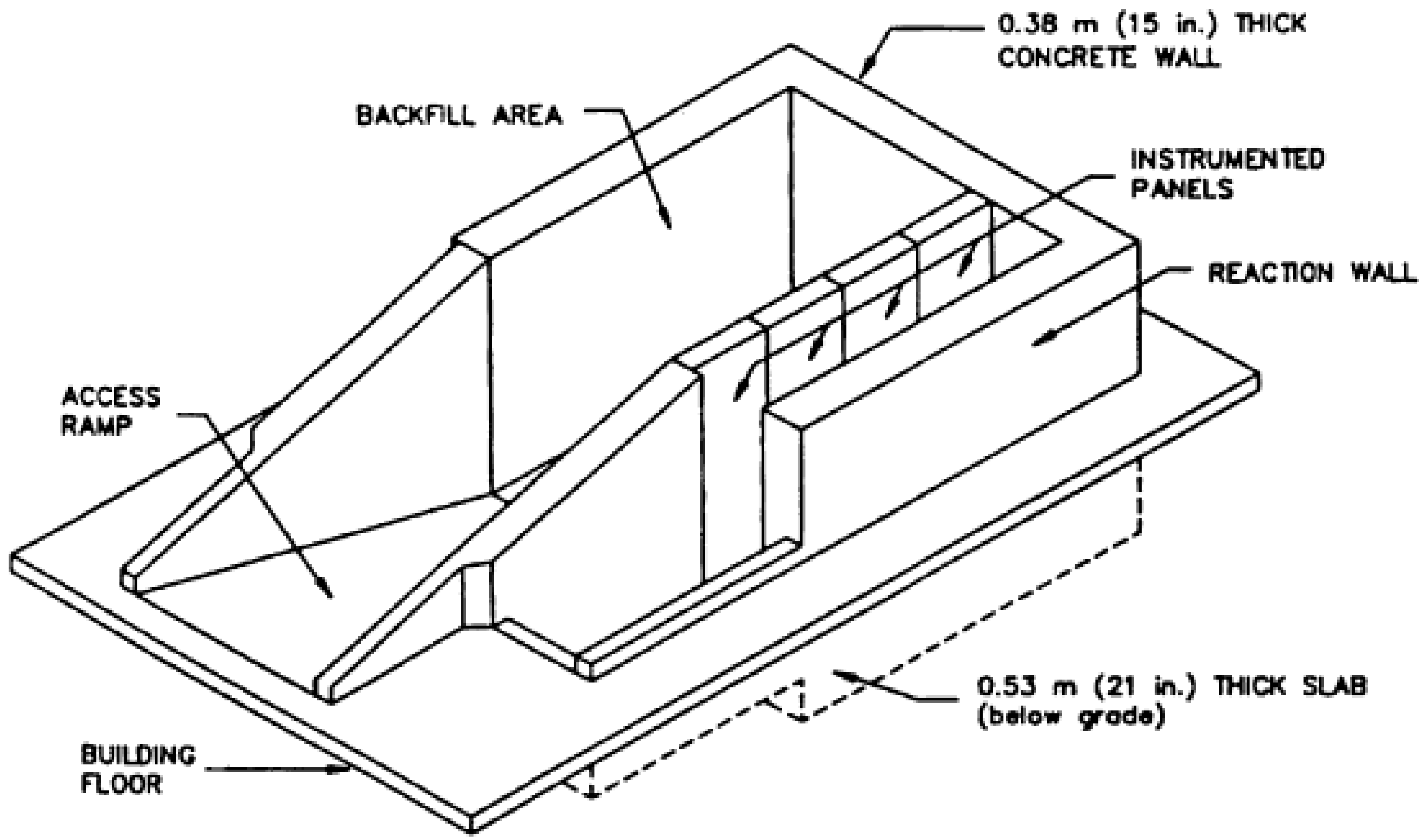


Figure 2.1: Instrumented Retaining Wall Facility (After Sehn and Duncan 1990)

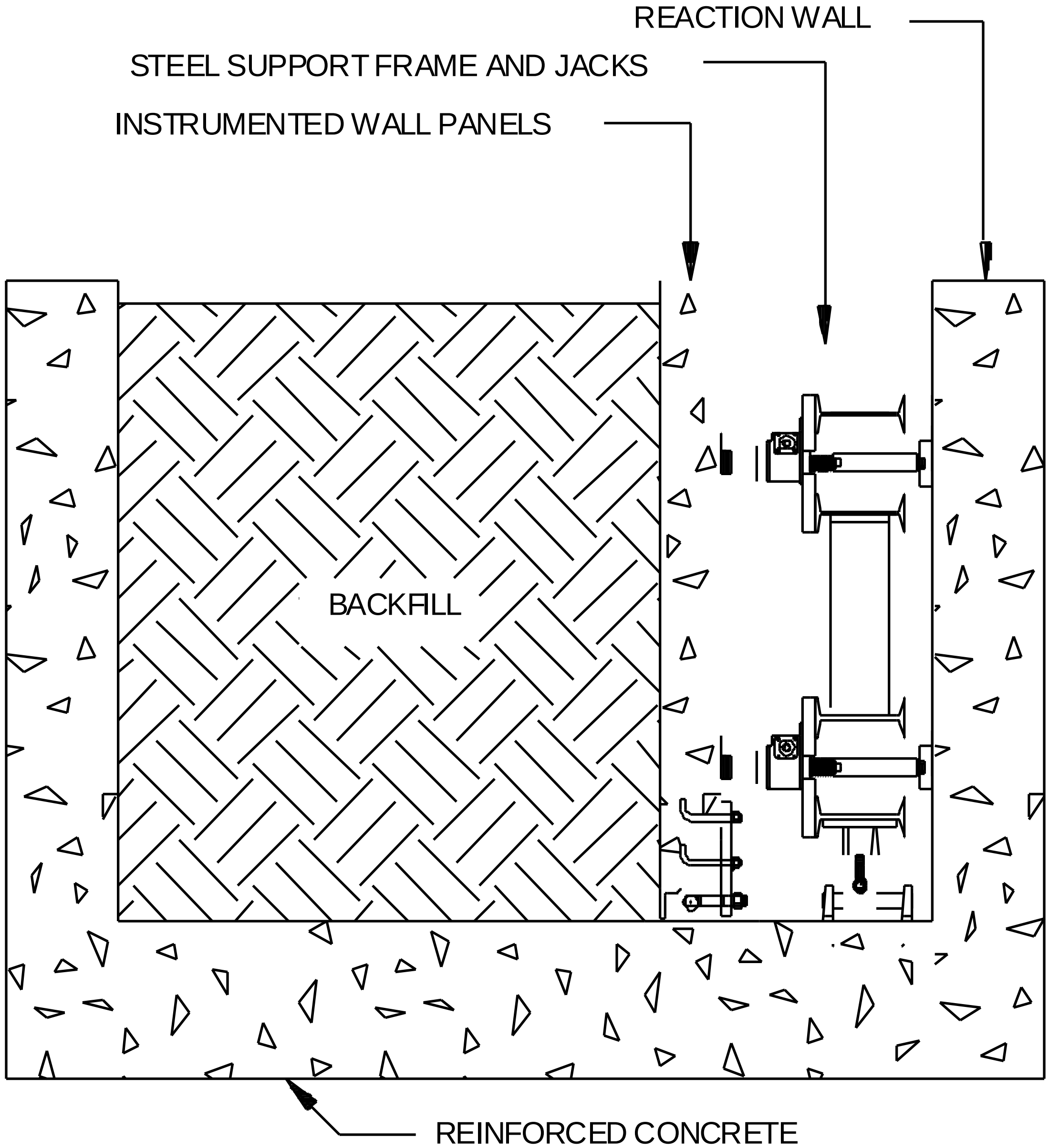


Figure 2.2: Cross-section through the Instrumented Retaining Wall Facility (After Sehn and Duncan 1990)

Each panel is supported vertically by two steel rollers located at the base of the panels. Each roller bears against a hardened steel plate mounted to the base of the U-frame structure. The rollers allow the wall to be moved laterally.

The screw jacks permit the instrumented wall to be moved toward or away from the backfill. The upper jacks can be moved independently of the lower jacks so that the instrumented wall can be rotated as well as translated. However, the panels cannot be moved independently; the steel frame moves all four panels the same distance and in the same mode.

<u>2.3 Tranducers</u>

The instrumented wall is equipped with 20 load cells, 17 pressure cells, 8 linear variable differential tranducers (LVDTs), and 12 thermocouples. Figure 2.3 provides an elevation view of the instrumented panels showing the locations of load cells and pressures cells. The view in Figure 2.3 is from the backfill area of the facility. Thus, Panel 4 is closest to the access ramp.

The load cells provide both lateral and vertical support for the instrumented panels. Each panel has three horizontal load cells and two vertical load cells.

The 17 pressure cells are flush mounted in panels 2 and 3 and consist of three different types: 11 Gloetzl cells, 4 Carlson cells, and 2 Geonor cells. At the beginning of this research project, calibration studies showed that the Carlson and Geonor cells were not reliable. Thus, the Gloetzl cells were the only pressure cells used in this research.

Lateral wall movement is recorded by 8 LVDTs, one at the top and one at the bottom of each panel. These instruments are located on the panel side opposite the backfill.

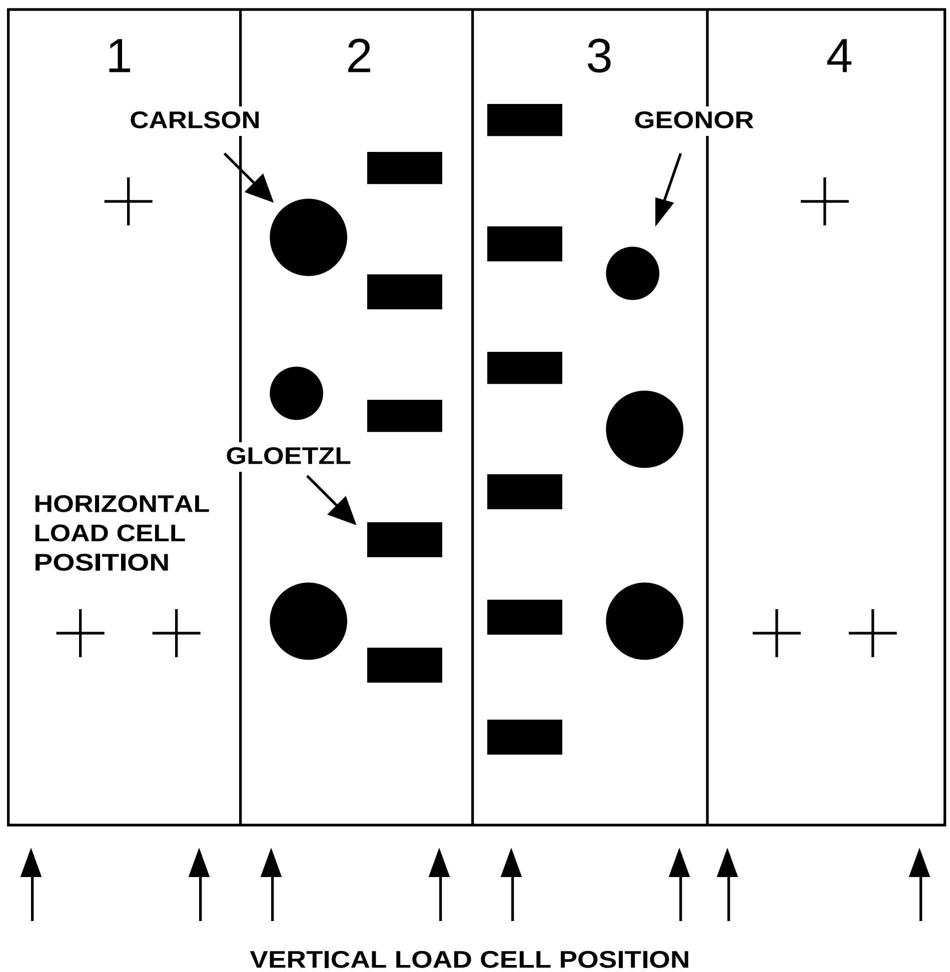


Figure 2.3: Instrumented Retaining Wall Panels (After Sehn and Duncan 1990)

Twelve thermocouples are used to measure temperature at various locations on and near the instrumented wall. These thermocouples can measure temperatures at the backfill side of the panel and within the support system area.

2.4 Data Acquisition

Data acquisition is automated. Software running on a personal computer controls analog-to-digital converters to read each transducer. Several readings are taken for each transducer. The average of the readings is then converted to engineering units (e.g., load, pressure, deflection, or temperature) by multiplying by a calibration factor specific to each transducer.

CHAPTER 3 – LABORATORY TESTING

3.1 Introduction

Laboratory testing was performed on 2-inch cubes of TerraFlex in an unconfined condition, consistent with testing procedures found in published literature (Horvath 1995). All TerraFlex samples were loaded in a direction perpendicular to the TerraFlex sheets, which is consistent with the direction of field loading. The room temperature during testing was approximately 77 degrees Fahrenheit. Descriptions of the test procedures and materials, tests performed, and results from these tests are provided in the following sections.

3.2 Test Materials and Procedures

The testing of the TerraFlex made use of a consolidometer device, with two steel plates, 3 inches square by 0.25 inches thick, serving as load plattens. A TerraFlex specimen was placed between the two steel plates, and loads from the consolidometer were then applied. Compression measurements were made with a dial gage with a 1-inch travel range.

3.3 Tests Performed

Two types of laboratory testing were performed on the TerraFlex: creep testing and cyclic testing. Creep testing was performed to develop a set of isochronous stress-strain curves for the TerraFlex. For these tests, a known stress is applied to a specimen and strain measurements are taken over time. Each measurement defines a value of stress and strain on an isochronous stress-strain curve.

Four creep tests were performed at compressive stresses of 200, 300, 400, and 500 psf. Deflection readings were taken at 0.1 hours, 1 hour, 10 hours, and 100 hours for each test, with these times representing the total duration from the beginning of load application. Deflection readings were then converted to values of strain. This testing produced isochronous stress-strain curves for load durations of 0.1 hours, 1 hour, 10 hours, and 100 hours.

Cyclic testing involved the application of time-specific loading/unloading periods to a TerraFlex specimen. A cycle began by loading the sample to a specific value of stress for a specific amount of time, and a deflection value was recorded. The samples were then unloaded for the same amount of time as the loading phase to complete a cycle. The same load/unload process was then repeated until the test was terminated.

Two cyclic tests were performed for this study with time-specific loading and unloading periods of 0.1-hour and 1-hour duration. For each test cycle, samples were loaded to a compressive stress of 500 psf and rebounded to a stress of 55 psf.

3.4 Results of Laboratory Testing

This section provides a presentation and discussion of the creep and cyclic testing of TerraFlex specimens.

3.4.1 Creep Testing

The isochronous stress-strain curves from the creep tests are shown in Figure 3.1. As can be seen from this figure, there is a progressive decrease in the slope of each curve between 0 psf and 400 psf compressive stress. Above 400 psf, the slopes of the curves begin to increase.

3.4.2 Cyclic Testing

The experimental results from the 0.1-hour duration cyclic tests are shown in Figure 3.2. As can be seen from this figure, two tests were performed with 7 load/unload

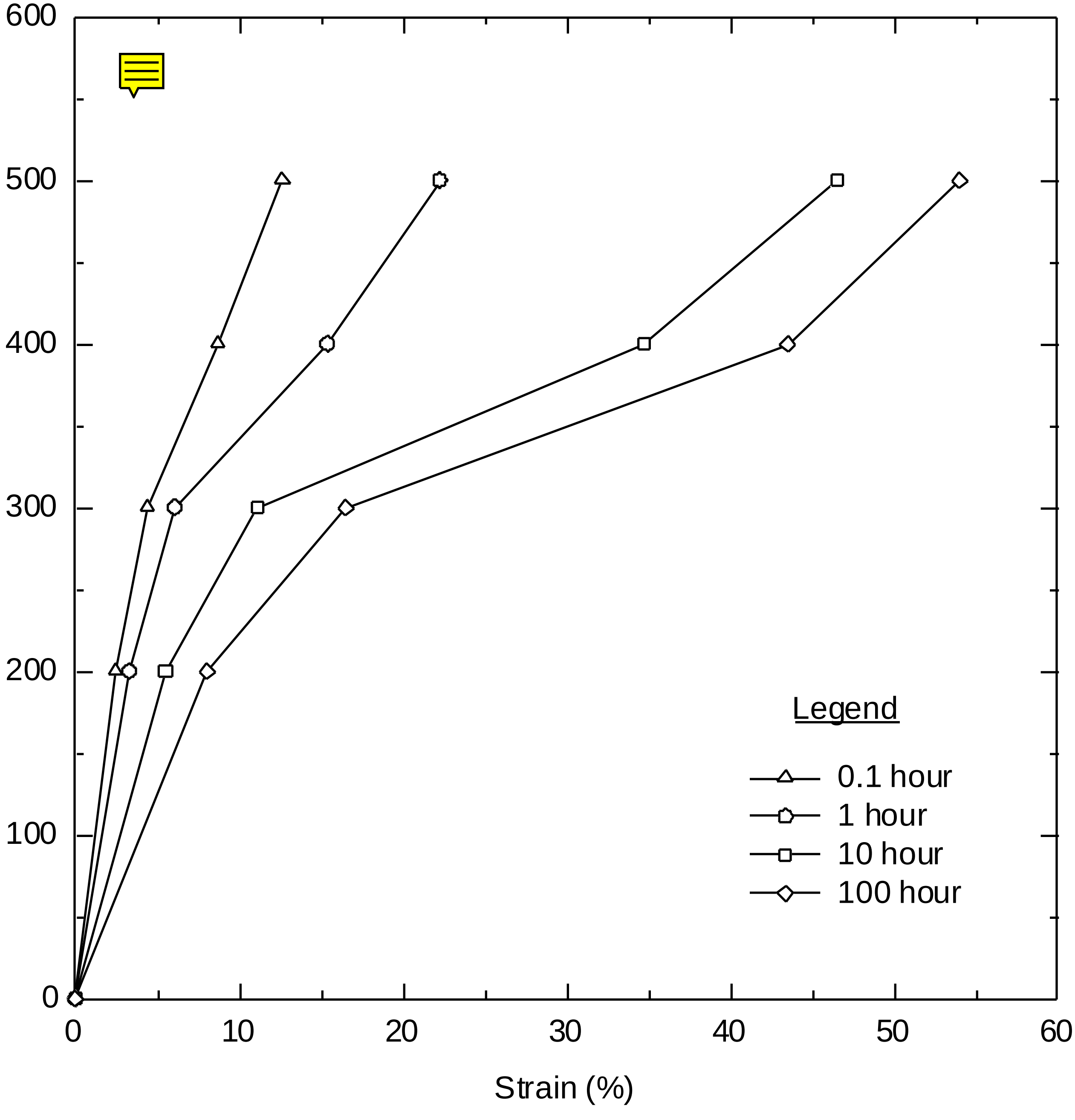


Figure 3.1: Results of Creep Testing Showing Isochronous Stress-Strain Curves

cycles. There was a significant amount of permanent deformation in the material, especially after the first loading cycle, which can be seen by the strain offset between the first loading and unloading stages. The strain-offset behavior continued to occur for all the cycles, but to a lesser degree than the first cycle. The amount of strain on the seventh loading cycle was on the order of approximately 20 percent for both tests. The data also show that the slopes of the load curves increase due to cyclic loading.

The experimental data for the 1-hour duration tests is shown in Figure 3.3. This figure shows that there was significant permanent deformation of the TerraFlex with each cycle. For these tests, the TerraFlex samples experienced strains on the order of 40 percent after seven cycles. Again, the data show that the slopes of the loading curves increase due to cyclic loading.

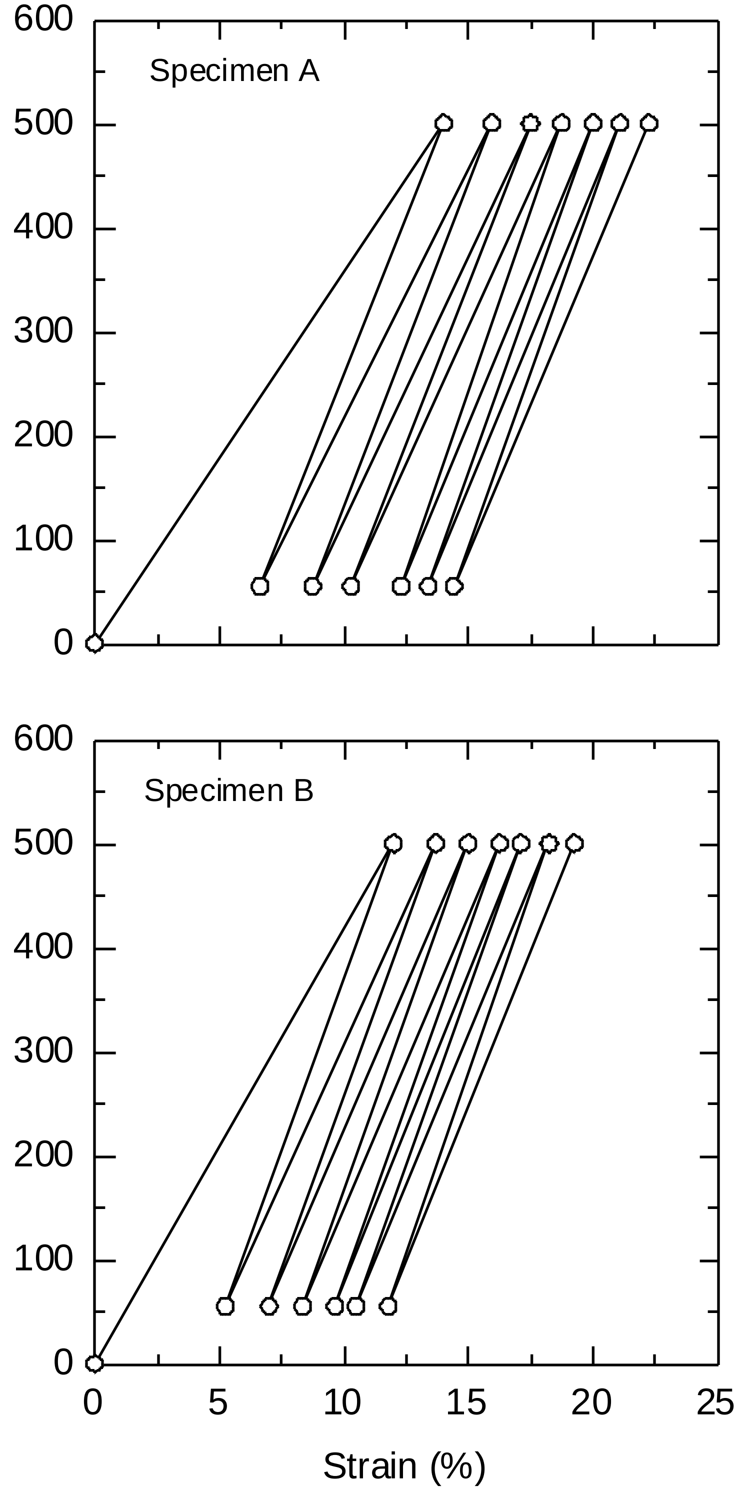


Figure 3.2: Experimental Laboratory Results from 0.1-hour Duration Cyclic Tests on Two Samples of TerraFlex

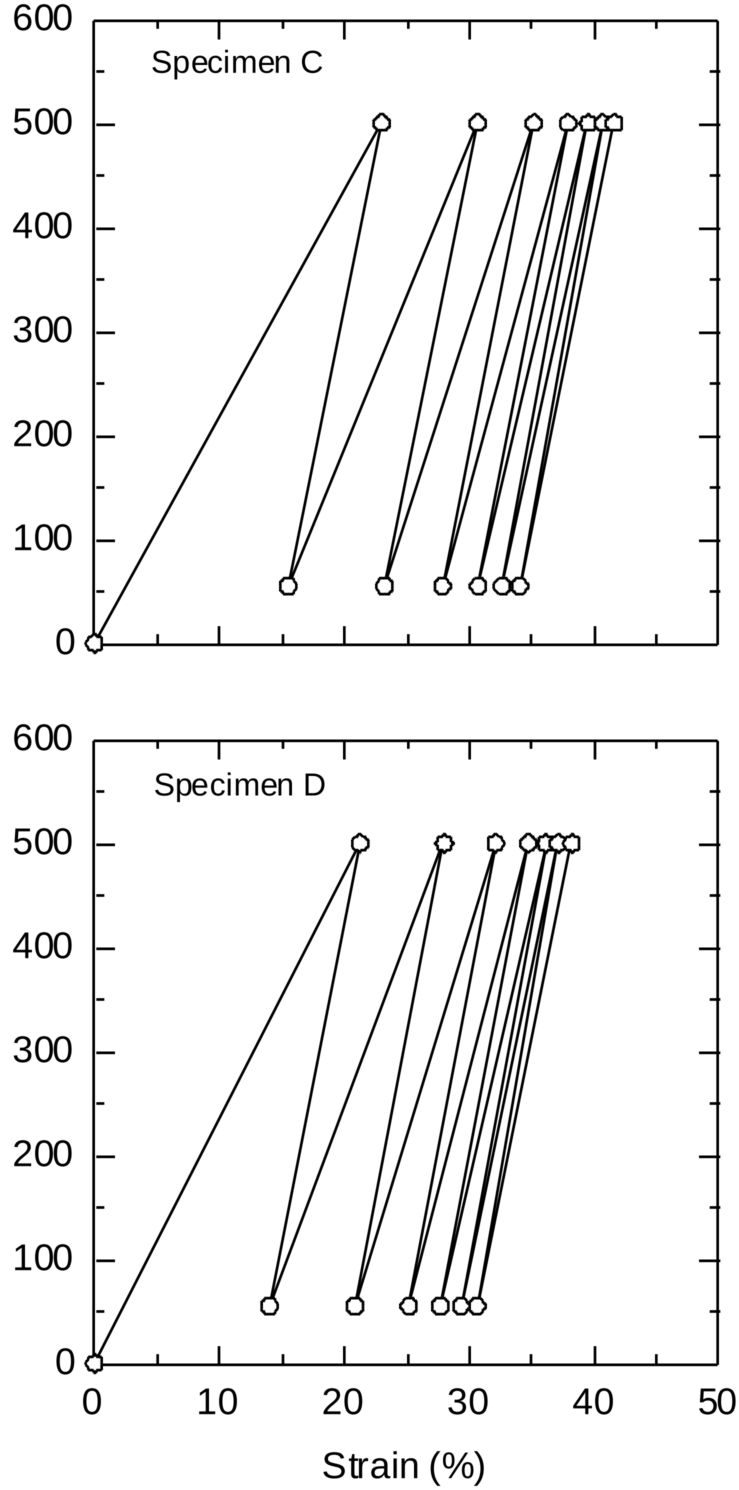


Figure 3.3: Experimental Laboratory Results from 1-hour Duration Cyclic Tests on Two Samples of TerraFlex

CHAPTER 4 – INSTRUMENTED RETAINING WALL TESTS

4.1 Introduction

Five tests were performed for this study using the instrumented retaining wall facility. The test procedures, materials, and results for the instrumented retaining wall tests are presented in the following sections.

4.2 Test Procedures and Materials

This section describes the test procedures and materials used in the instrumented retaining wall tests. The backfill material, compaction equipment, wall preparation activities, backfill placement and compaction procedures, cyclic testing procedures, and the instrumented retaining wall test schedule are described.

4.2.1 Backfill

The backfill used for the instrumented retaining wall tests is Light Castle sand obtained from a quarry in Craig County, Virginia. Light Castle sand is a clean, fine sand consisting predominantly of subangular quartz grains. Filz and Duncan (1992) performed various laboratory tests on Light Castle sand. For this sand, it was found that 68 percent of the material passes the No. 40 sieve and less than 1 percent passes the No. 200 sieve. The coefficient of uniformity and coefficient of curvature were determined to be 1.8 and 0.9, respectively. Therefore, the sand classifies as a poorly graded sand (SP) according to the Unified Soil Classification System. The specific gravity of solids is 2.65. The maximum and minimum densities determined by ASTM D4253-83 and ASTM D4254-83 are 106 and 88.5 pounds per cubic foot, respectively.

Filz and Duncan (1992) performed two instrumented retaining wall tests using Light Castle sand, but without a compressible inclusion. The average unit weight of the compacted sand was approximately 105.5 pcf, corresponding to a relative density of nearly 100 percent. The estimated friction angle of the compacted sand was 42 degrees.

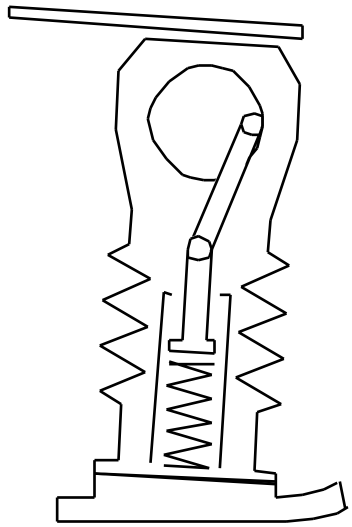
4.2.2 Compaction Equipment

For this study, two hand-operated compactors were used: a Wacker model BS60Y (rammer compactor) and a Wacker model BPU 2240A (vibrating plate compactor). Schematic diagrams of both compactors are shown in Figure 4.1. The rammer compactor is powered by a 4 horsepower, 2-cycle engine that drives a steel ramming shoe into contact with the soil at a percussion rate of 10 blows per second. The operating weight of the rammer compactor is 137 pounds. The vibrating plate compactor is powered by a 5 horsepower, 4-cycle engine that drives counter-rotating eccentric weights. These weights rotate at a frequency of about 100 Hz and are connected by axles to a steel plate that contacts the soil. The operating weight of the vibrating plate compactor is 275 pounds.

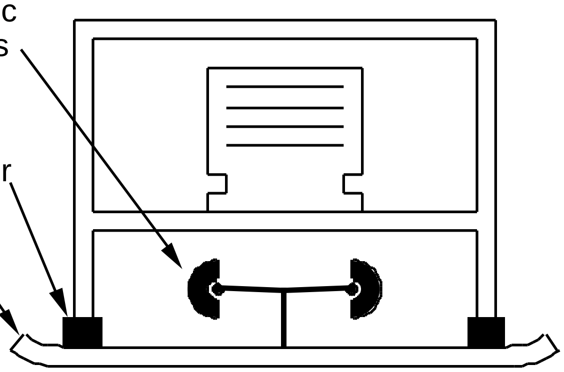
The rammer and vibrating plate compactor used for this study are commonly employed for compaction in confined areas and adjacent to retaining wall structures.
These compactors are different in their mode of operation. In a study by Filz and Duncan (1992) on the two compactors used for this research, it was found that the rammer compactor delivered higher peak contact forces to the soil than the vibrating plate compactor. Thus, higher compaction-induced earth pressures can be expected in backfill compacted with the rammer compactor than in backfill compacted with the vibrating plate compactor.

4.2.3 Wall Preparation Prior to Compaction

Wall preparation consisted of lubricating the end and far walls of the backfill area and placing TerraFlex on the instrumented wall. Lubrication of the end and far walls was



a) Rammer compactor



b) Vibrating plate compactor

Figure 4.1: Schematic diagrams of a) Rammer Compactor and b) Vibratory Plate Compactor (After Filz and Duncan 1992)

performed in order to minimize the buildup of shear stresses along these walls, which could influence the test results. Lubrication allows the facility to more closely model a 2-D case of an infinitely long wall and infinitely wide backfill area (Filz and Duncan 1992). To lubricate the end and far walls, a sheet of 6-mil polyethylene was taped in place on these walls. A thin layer of wheel bearing grease was applied to the polyethylene sheet, which was then covered with a second polyethylene sheet. The walls were lubricated for all five tests performed.

The TerraFlex was delivered in pre-cut blocks of the desired thickness. The TerraFlex was then placed on the face of the instrumented retaining wall using GeoTech DB-784 adhesive supplied by GeoTech Systems Corporation. The TerraFlex was applied over the full height and length of the instrumented wall and extended 2.5 feet from the instrumented panels onto the wall in the access ramp area.

4.2.4 Backfill Placement and Compaction

Before it was used as backfill in the instrumented retaining wall test facility, the Light Castle sand was dried to less than 0.1 percent hydroscopic moisture and placed in a dry stockpile area. The sand was moved from the stockpile area to the backfill area by a hopper lifted by an overhead crane. After depositing the sand in the backfill area, it was spread by hand in loose lifts of sufficient thickness to produce a compacted lift thickness of 6 inches. Backfill was placed approximately 6.5 feet high against the instrumented wall for each test.

The rammer compactor delivers higher peak forces to the soil than the vibrating plate compactor. For tests using the rammer compactor, each backfill lift was compacted with 2 passes. For tests using the vibrating plate compactor, 5 passes were used to compact each lift. Both procedures produced relative densities near 100 percent.

4.2.5 Cyclic Instrumented Retaining Wall Testing

Cyclic testing of the backfill involved translating the instrumented retaining wall toward and away from the backfill. This testing was performed in an attempt to simulate the abutment behavior of integral bridges when subjected to expansion/contraction cycles due to seasonal temperature changes.

Cyclic testing was performed by moving the wall 0.3 inches (plus 0.3-inch position) toward the backfill, 0.5 inches away from the backfill (minus 0.2-inch position), and then 0.2 inches back toward the backfill to the initial wall position. This pattern was repeated for multiple cycles of displacement. Sets of data readings were taken at specific movement intervals during each cycle. A cycle could be completed in approximately 20 to 40 minutes, depending on the number of times data readings were taken.

The initial goal of each cyclic instrumented retaining wall test was to perform 30 cycles, each with 0.5 inches of travel. However, the number of cycles completed was limited by the buildup of lateral loads on the instrumented wall. The cyclic testing was terminated when the lateral load magnitude reached about 11,000 pounds per panel in order to avoid exceeding the capacity of the instrumented retaining wall.

Each cyclic test was completed in one or two days, depending upon the number of cycles performed. When a cyclic test required two days, the wall was left in the minus 0.2-inch position overnight. The testing was then resumed on the second day.

Changes in lateral loads between end of day 1 and beginning of day 2 were monitored.

4.2.6 Testing Performed

Five instrumented retaining wall tests were performed for this study. A summary of the test conditions is provided in Table 4.1.

Table 4.1: Instrumented Retaining Wall Tests Performed

Test number	TerraFlex Thickness (inches)	Compactor
1	2	Rammer
2	4	Rammer
3	10	Rammer
4	0*	Rammer
5	6	Vibrating plate

*No TerraFlex

As can be seen from Table 4.1, Tests 1 through 4 were performed using the rammer compactor with TerraFlex thicknesses ranging from 0 to 10 inches. Test 5 was performed using the vibrating plate compactor with a TerraFlex thickness of 6 inches.

Reliable cyclic load test data was obtained from Tests 2 through 5.

The backfill placement time for all tests, excluding Test 1, was approximately 8 hours. Test 1 was a learning phase for the compaction activities and had a longer completion time than the remaining tests. The backfill placement for Test 1 consisted of approximately 12 hours of continuous work, followed by 10 hours of overnight delay, and then 3 hours of work for completion of the compaction activities. Thus, the total backfill placement time for Test 1 was approximately 25 hours.

4.3 Instrumented Retaining Wall Tests

Five instrumented retaining wall tests were performed, and the experimental results are separated into two categories: stationary wall results and cyclic wall movement results. The stationary wall condition is representative of a basement wall in that the wall remains rigid with negligible lateral movement. The cyclic wall movement condition is intended to provide insight into abutment behavior of integral bridges where seasonal expansion/contraction cycles force the abutment to move toward and away from its backfill.

4.3.1 Properties of Compacted Backfill

The average unit weight of the compacted backfill was approximately 105 pcf for each test. This corresponds to a relative density of almost 100 percent. The friction angle of the compacted sand was assumed to be 42 degrees, consistent with that estimated by Filz and Duncan (1992).

4.3.2 Stationary Wall Results

For each test, loads on the instrumented wall were recorded at the end of backfill placement, and readings were continued until there was little change over time. Pressure readings were also recorded after compaction; however, these data exhibited a great degree of scatter and are inconclusive. The load measurements were used to back- calculate average values of horizontal earth pressure coefficient (K_h).

The horizontal earth pressure coefficient is the ratio of the horizontal and vertical normal stresses in the soil, as shown in the following expression:

$$K_h = \frac{\sigma_h}{\sigma_v} \qquad (4.1)$$

where

σ_h = horizontal stress (psf)

σ_v = vertical stress (psf)

For level ground without surcharge loading, pore water pressures in the backfill, or shear stresses at the wall, the vertical stress is given by the following expression:

$$\sigma_v = \gamma z \tag{4.2}$$

where

γ = the unit weight of the backfill soil (pcf)

z = depth below the backfill surface (ft)

If the value of K_h is constant with depth, equations 4.1 and 4.2 can be solved for σ_h and integrated to give the lateral earth force on the wall:

$$F_h = \frac{1}{2} K_h \gamma H^2 \tag{4.3}$$

where

F_h = the lateral earth force on the wall (lb/ft)

H = the height of the backfill against the wall (ft)

Compaction-induced lateral earth pressures create conditions in which K_h is not constant with depth, but is higher near the ground surface. Nevertheless, average values of K_h can be obtained from the instrumented retaining wall tests by solving Equation 4.3 for K_h:

$$K_h = \frac{2F_h}{\gamma H^2} \tag{4.4}$$

The following sections present the experimental results of the instrumented retaining wall tests in terms of the influences of time after backfill placement and TerraFlex thickness on the values of K_h.

4.3.2.1 Influence of Time after Backfill Placement

The value of K_h decreased significantly over time after the end of backfill placement for all tests using TerraFlex. The relationship of K_h with time after backfill placement, for Tests 2 through 5, is shown in Figure 4.2. Note that experimental data for Test 1 is not shown because this test required more backfill placement time and is not consistent with the backfill placement times of Tests 2 through 5. As can be seen from the figure, all the tests using TerraFlex (Tests 2, 3, and 5) showed a significant decrease in K_h versus time after backfill placement, especially after the first 24 hours. However, there was little change in K_h for Test 4, in which no TerraFlex was used. The value of K_h was monitored for each test until there was little additional change in its value. The monitoring time was 130 to 140 hours (5.8 days) after backfill placement for Tests 1, 2, 3, and 5, and approximately 60 hours (2.5 days) for Test 4. A summary of the K_h values at the end of backfill placement and the final K_h values are shown in Table 4.2.

4.3.2.2 Influence of TerraFlex Thickness

The value of K_h decreased with increasing TerraFlex thickness for both the rammer and vibrating plate compactors. The relationship of K_h with TerraFlex thickness for each compactor is shown in Figure 4.3. The experimental data is represented by two curves, one for the rammer compactor and another for the vibrating plate compactor. The experimental data for the rammer compactor curve were generated from the final calculated K_h measurements from Tests 1 through 4. The experimental data for the vibrating plate compactor curve were obtained from the final K_h measurement in Test 5

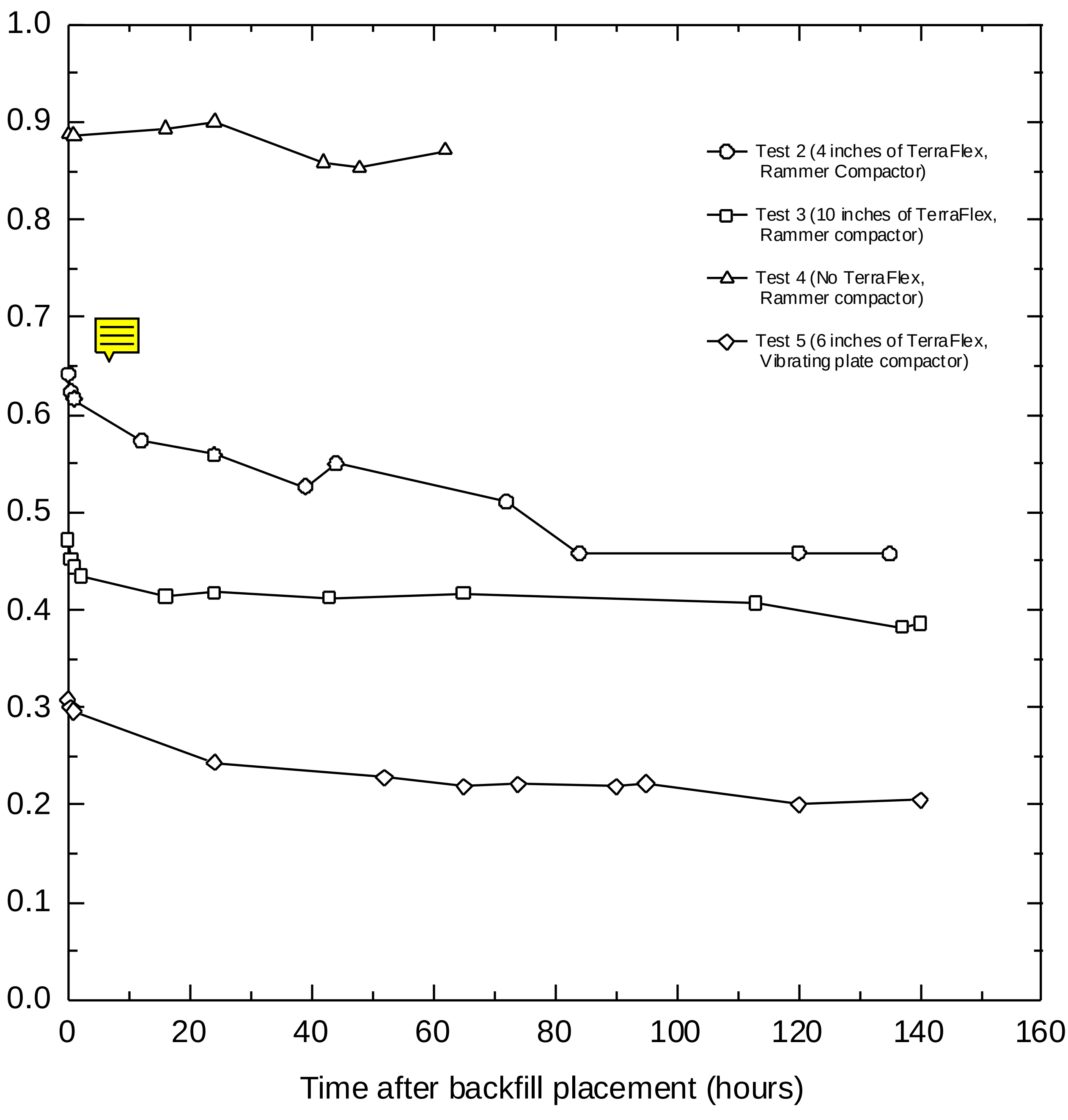


Figure 4.2: Influence of Time after Backfill Placement on Horizontal Earth Pressure Coefficient Horizontal (K_h) for Tests 2 through 5

Table 4.2: Summary of K_h Values after Backfill Placement

Test	TerraFlex thickness (inches)	Compactor type	K_h		Time of final value (hours)
			End of backfill placement*	Final value	
1	2	Rammer	0.62	0.54	131
2	4	Rammer	0.64	0.46	135
3	10	Rammer	0.47	0.38	140
4	0	Rammer	0.89	0.87	62
5	6	Vibrating plate	0.31	0.20	140

*Backfill placement time took about 8 hours for Tests 2 through 5 and about 25 hours for Test 1

for 6 inches of TerraFlex and data from Filz and Duncan (1992). Filz and Duncan performed an instrumented retaining wall test with Light Castle sand using the vibrating plate compactor and no compressible inclusion.

Figure 4.3 shows that, initially, there is a very significant decrease in the value of K_h as the TerraFlex thickness increases. Beyond the first few inches, the decrease in K_h becomes much less with increasing TerraFlex thickness. The value of K_h was reduced by 56 percent when 10 inches of TerraFlex was used for the rammer compactor, compared to using no TerraFlex. The value of K_h was reduced by 56 percent for the vibrating plate compactor when 6 inches of TerraFlex was used, compared to using no TerraFlex. A summary of the percent reductions in K_h values with TerraFlex thickness is shown in Table 4.3.

4.3.3 Cyclic Wall Movement Results

Reliable data for cyclic wall movements were obtained for Tests 2 through 5. For each cyclic test, values of K_h were calculated at movement intervals within each cycle.

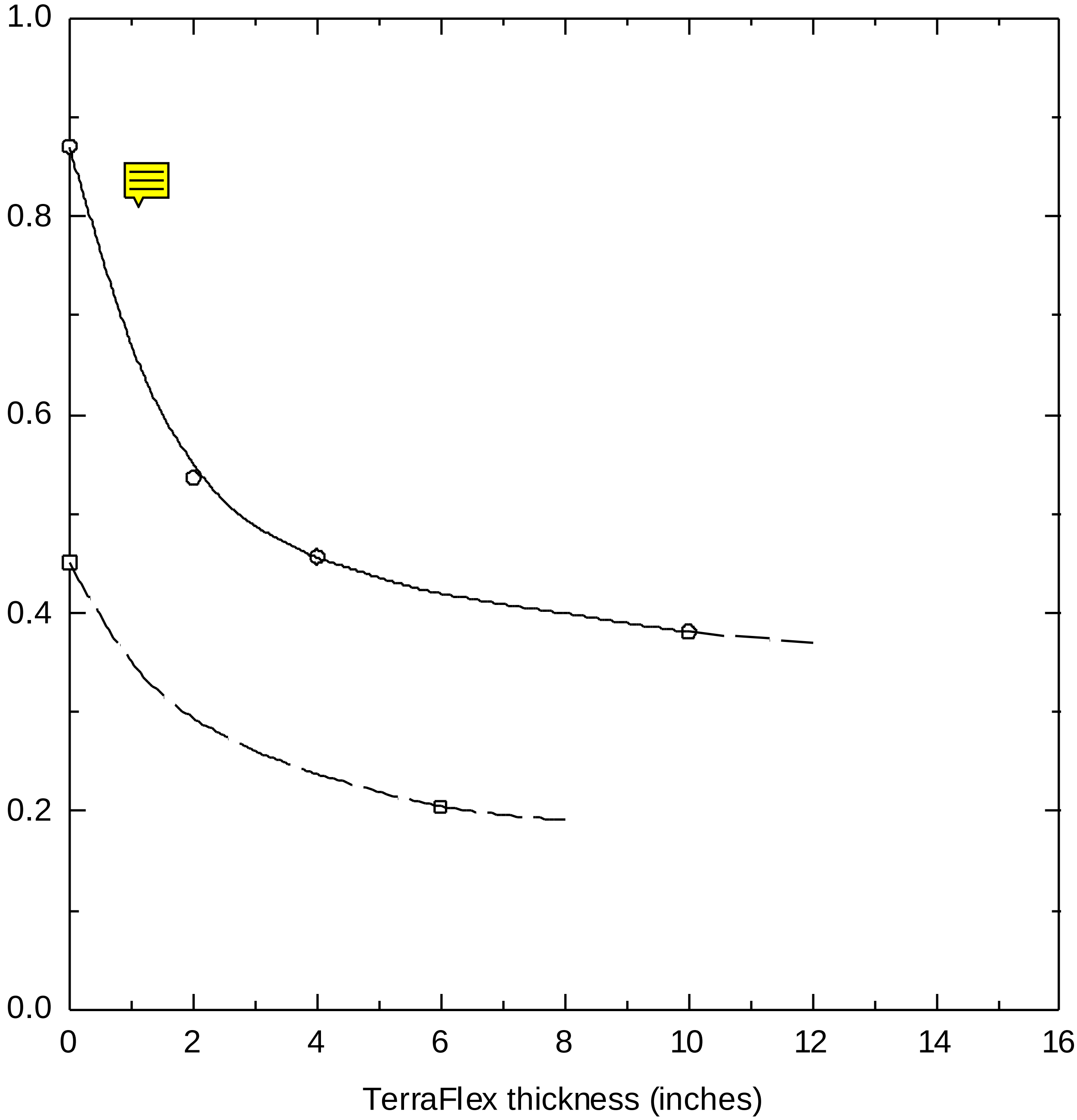


Figure 4.3: Relationship of K_h with TerraFlex Thickness for Rammer and Vibrating Plate Compactors

Table 4.3: Summary of Percent Reduction in K_h with TerraFlex Thickness

Test	TerraFlex thickness (inches)	Compactor type	K_h	Percent Reduction in K_h (%)
1	2	Rammer	0.54	38
2	4	Rammer	0.46	47
3	10	Rammer	0.38	56
4	0	Rammer	0.87	0
Filz and Duncan (1992)	0	Vibrating plate	0.45	0
5	6	Vibrating plate	0.20	56

The experimental data from the tests are presented as hysteretic curves showing K_h versus wall displacement.

The effect of time on the value of K_h was observed on several occasions. For the cyclic tests that required two days, observations could be made for the overnight time span with the wall held in the minus 0.2-inch position. Where the testing schedule permitted, the effect of time on K_h was also monitored after cyclic testing, in which the wall was held in the plus 0.3-inch position.

Settlement adjacent to the instrumented wall was recorded for Test 5. The following sections summarize the experimental results from cyclic testing.

4.3.3.1 Effect of Wall Movement Cycles on K_h

The hysteretic curves for Test 2, which used the rammer compactor with 4 inches of TerraFlex, are shown in Figure 4.4. As can be seen from this figure, four cycles of experimental data were collected before the test was terminated. For the first movement cycle, wall movement began at a K_h value of approximately 0.46, at a displacement of 0 inches. The value of K_h increased to approximately 1.60 as the wall was moved to plus

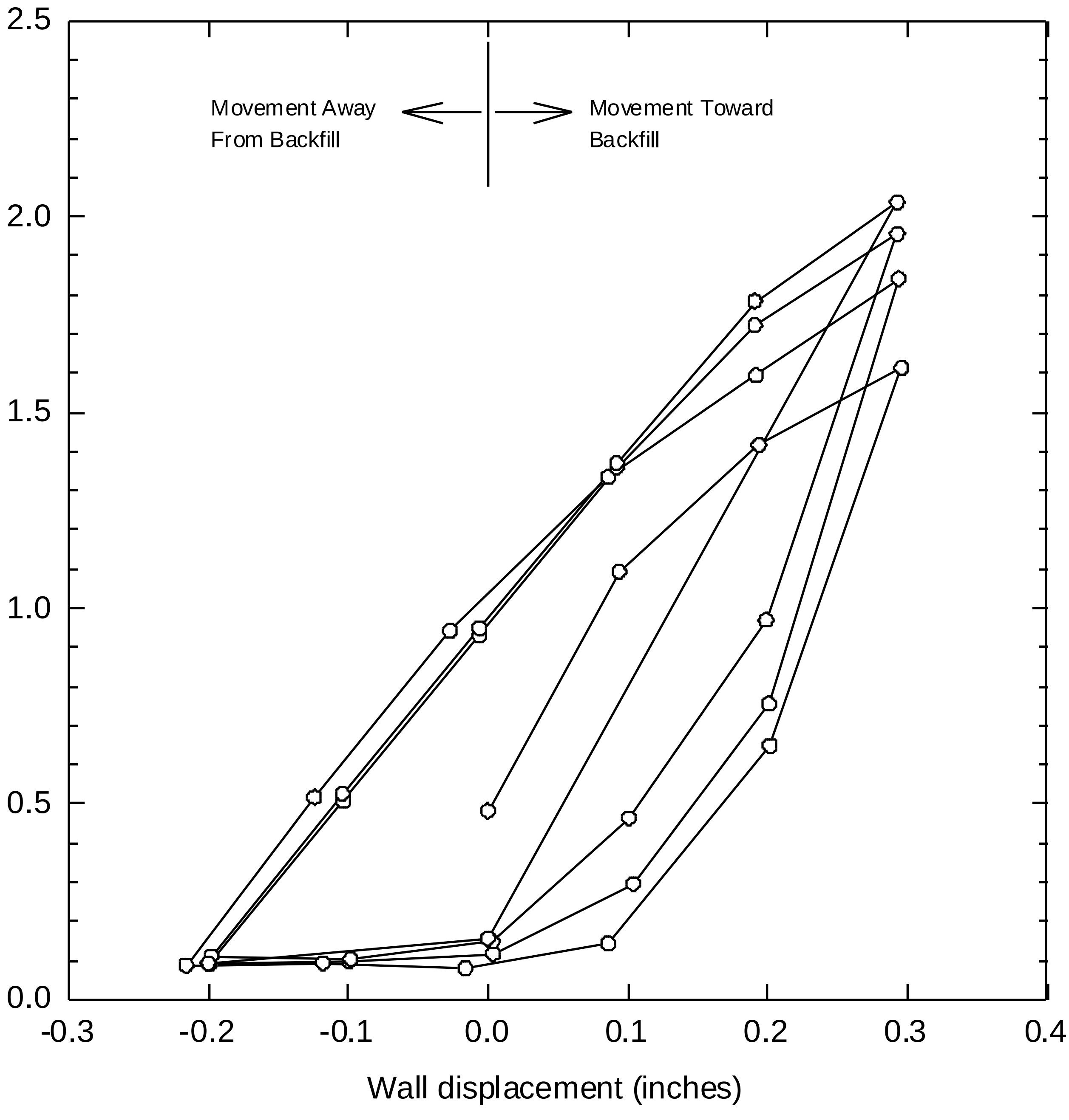


Figure 4.4: Hysteretic Curves Showing K_h Versus Wall Displacement for Test 2 (Rammer Compactor, 4 Inches of TerraFlex)

0.3 inches of displacement. The wall was then moved away from the backfill to minus 0.2 inches. The value of K_h decreased very rapidly during the movement away from the backfill and was reduced to a value of about 0.08 at minus 0.2 inches of displacement. The wall was then moved back to its initial position and another cycle began. The value of K_h at the plus 0.3-inch position increased progressively with each cycle until the test was terminated at the end of the cycle in which the K_h value first exceeded 2.00.

Thirty cycles were performed for Test 3, which used the rammer compactor with 10 inches of TerraFlex. Hysteretic curves for the first and thirtieth cycle are shown in Figure 4.5. Cyclic testing began at a K_h value of approximately 0.38. As the wall was moved, the value of K_h increased to about 1.20 at plus 0.3 inches of displacement and decreased rapidly to a value 0.09 at minus 0.2 inches of displacement. The value of K_h at plus 0.3 inches of displacement increased progressively with each cycle, reaching a value near 1.4 by the thirtieth cycle.

The hysteretic curves for Test 4 are shown in Figure 4.6, which used the rammer compactor without any TerraFlex. As can be seen from this figure, only 2 cycles of data were collected before the test was terminated. The first cycle began at a K_h value of about 0.87, and K_h increased very rapidly to approximately 2.25 at a displacement near plus 0.02 inches. Thus, the K_h value of about 2.25 was generated in less than one tenth of the movement applied in Tests 2 and 3. The wall was then moved away from the backfill, and K_h decreased to approximately 0.10 at a wall position of about minus 0.024 inches. The value of K_h near plus 0.02 inches of displacement increased to about 2.30 during for the second cycle.

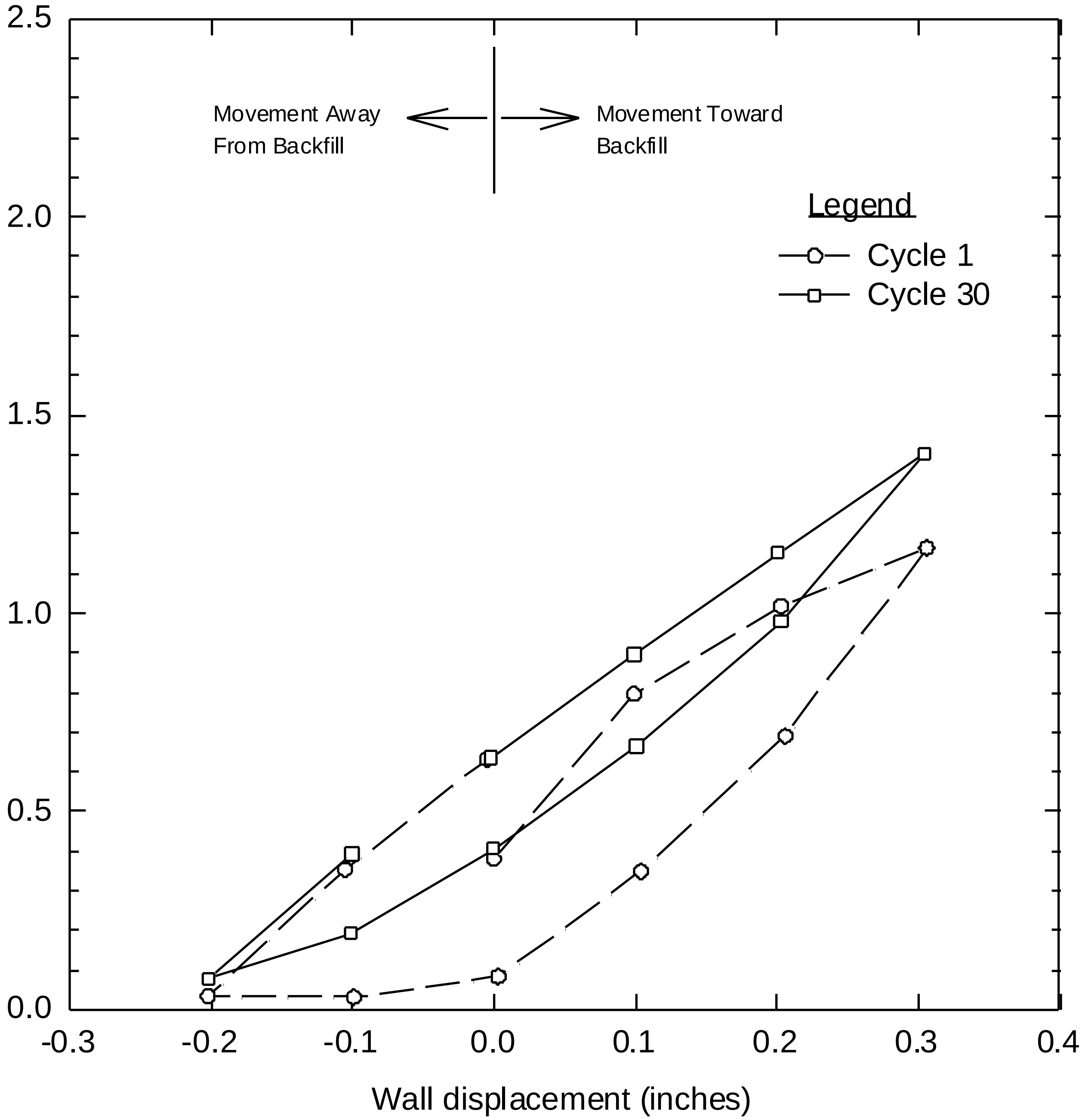


Figure 4.5: Hysteretic Curves Showing K_h Versus Wall Displacement for Test 3 (Rammer Compactor, 10 Inches of TerraFlex)

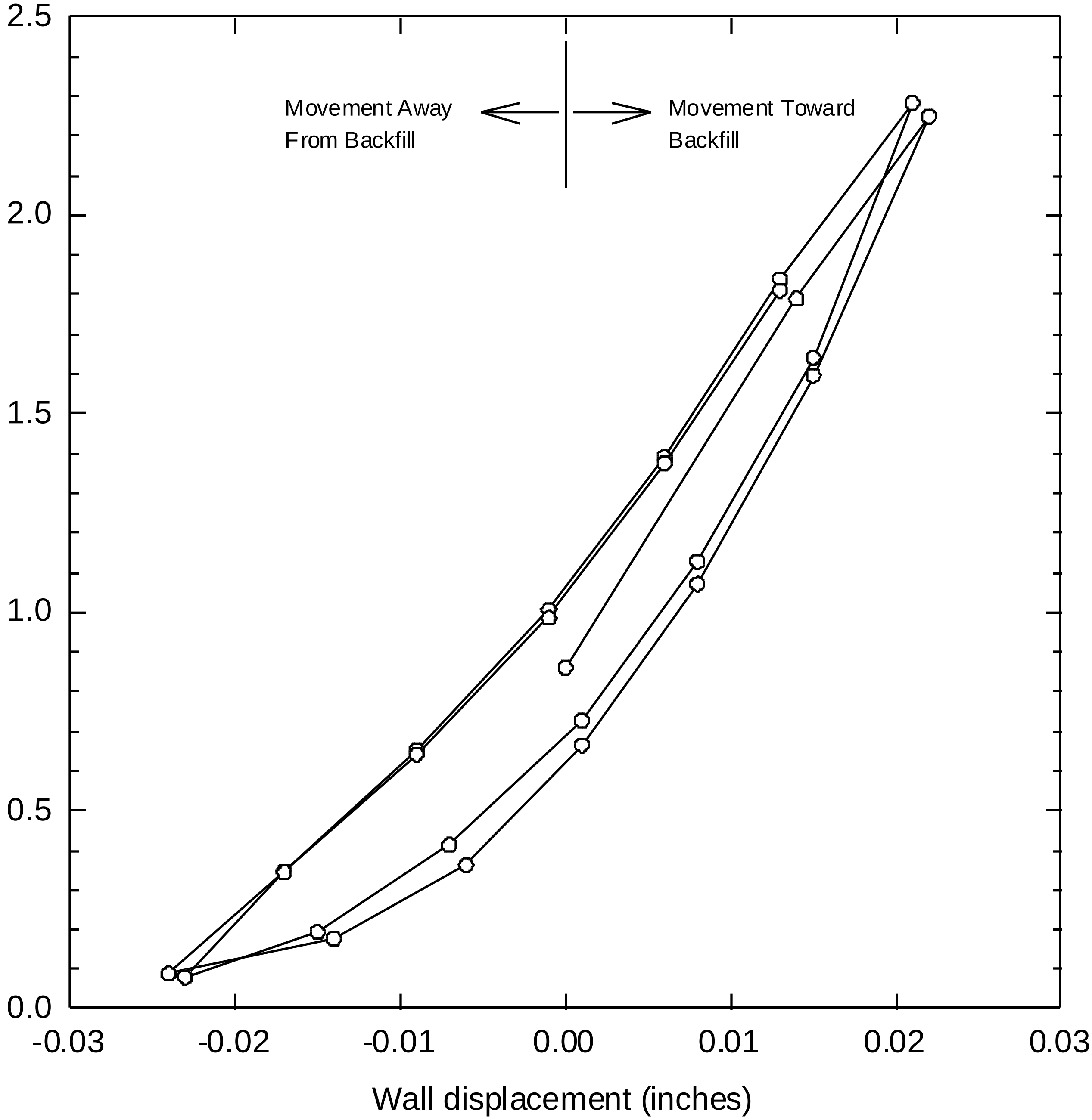


Figure 4.6: Hysteretic Curves Showing K_h Versus Wall Displacement for Test 4 (Rammer Compactor, No TerraFlex)

Thirty cycles were completed for Test 5, which used the vibrating plate compactor with 6 inches of TerraFlex. The hysteretic curves for Test 5 are shown in Figure 4.7. The first cycle began at a K_h value of approximately 0.20 and K_h increased to a value of about 1.1 at plus 0.3 inches of displacement. As the wall was moved away from the backfill, K_h decreased to a value near 0.10. The value of K_h at plus 0.3 inches of displacement increased progressively with each cycle and to a value near 1.7 during the thirtieth cycle.

4.3.3.2 Effect of Time on K_h

The effect of time on K_h was observed during Tests 3 and 5. Both tests required a second day to complete the cyclic tests. For each test, the wall was held in the minus 0.2-inch position until the next day. On the twenty-first cycle for Test 3, the value of K_h increased from 0.04 to 0.21 in about 12 hours. During Test 5, the value of K_h increased from 0.09 to 0.22 in approximately 12 hours.

The project schedule allowed observation of the effect of time on K_h after Tests 3 and 5. After all cycles were completed, the wall was moved to the plus 0.3-inch position and data readings were recorded over time. For Test 3, the value of K_h decreased from 1.41 to about 0.90 in 24 hours. Test 5 was the last test performed and allowed more time to observe time effects compared to Test 3. Figure 4.8 shows the effect of time on the value of K_h for Test 5, after completion of the cyclic testing. The value of K_h decreased from about 1.7 to 0.82 in 24 hours and to about 0.52 in 786 hours (32 days).

4.3.3.3 Backfill Settlement Adjacent to Instrumented Wall

Backfill settlement measurements were recorded for Test 5. Figure 4.9 shows the settlement profiles for progressive wall cycles during Test 5.

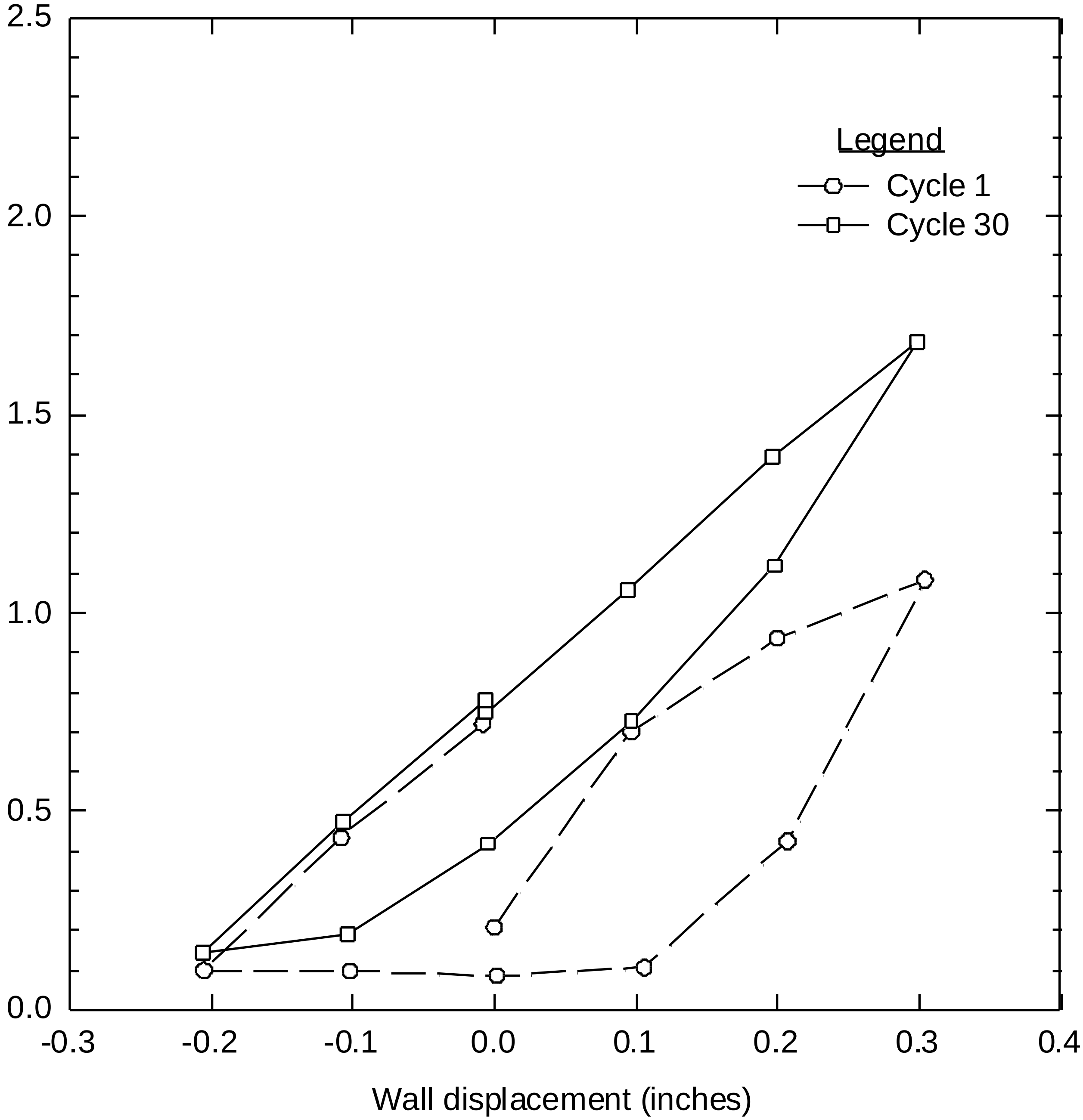


Figure 4.7: Hysteretic Curves Showing K_h Versus Wall Displacement for Test 5 (Vibrating Plate Compactor, 6 Inches of TerraFlex)

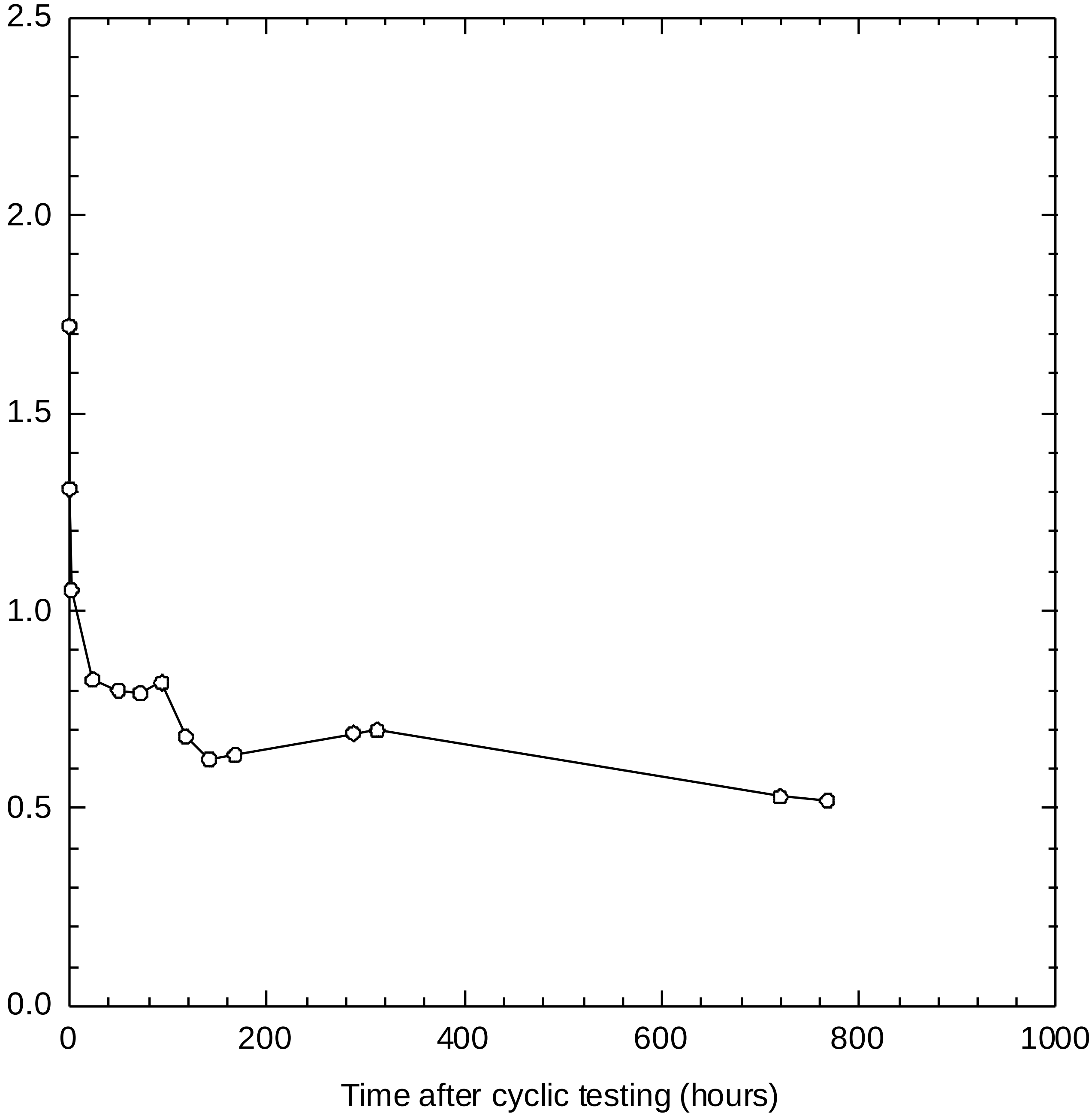


Figure 4.8: Effect of Time on the Value of K_h after Cyclic Movement Test 5 (Vibrating Plate Compactor, 6 Inches of TerraFlex)

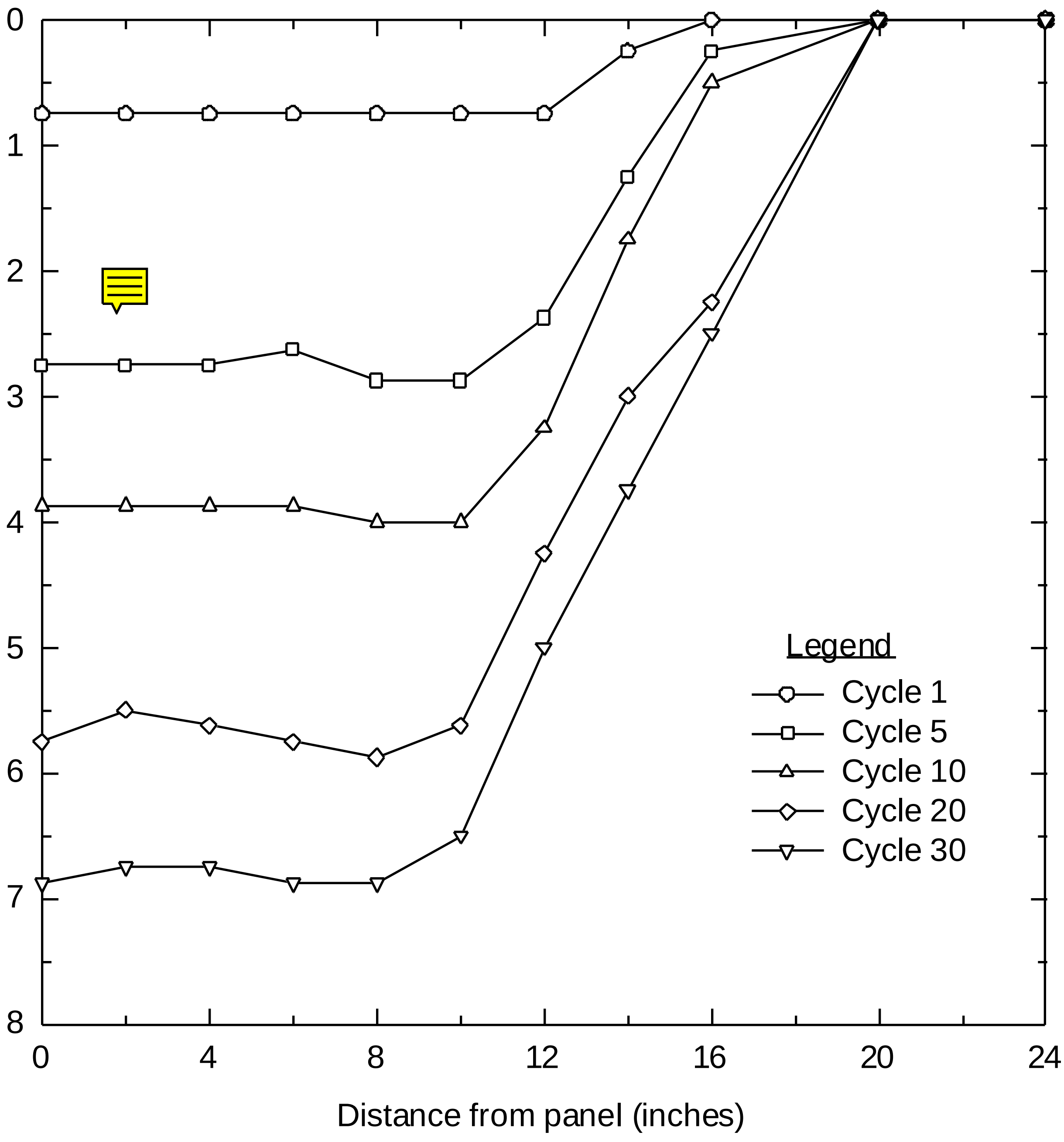


Figure 4.9: Backfill Settlement Profiles during Cyclic Movement Test 5 (Vibrating Plate Compactor, 6 Inches of TerraFlex)

Settlement measurements were recorded with the wall in the minus 0.2-inch position, for each cycle. As can be seen from this figure, the maximum settlement adjacent to the instrumented wall was almost 7 inches. The settlement profile extended approximately 20 inches behind the wall.

CHAPTER 5 – ENGINEERING ECONOMIC IMPACT OF TERRAFLEX

5.1 Introduction

In this chapter, the potential economic impact of TerraFlex on reinforced concrete basement walls and on gravity retaining walls is presented.

5.2 Potential Impact on Basement Wall Design

The following sections describe the economic analyses performed for reinforced concrete basement walls. The assumed design conditions and results from these analyses are summarized.

5.2.1 Basement Wall Design Conditions

An idealized cross-section of the design conditions assumed for reinforced concrete basement walls is shown in Figure 5.1. As can be seen from this figure, the reinforced concrete wall is simply-supported at the top and bottom of its span length, H. Reinforcing steel is provided for flexural strength and extends over the wall span length. The lateral pressure distribution on the wall is assumed to be triangular over the span length for the purposes of these economic evaluations. The lateral pressure on the wall is given by the following expression:

$$p = K_h \gamma z \qquad (5.1)$$

where

p = lateral pressure on the wall at depth of interest (psf)

γ = unit weight of the backfill soil (pcf)

z = depth of interest (ft)

An idealized plan view of the reinforced concrete design section is shown in Figure 5.2. As can be seen from this figure, the section is defined by a width (b) of 12

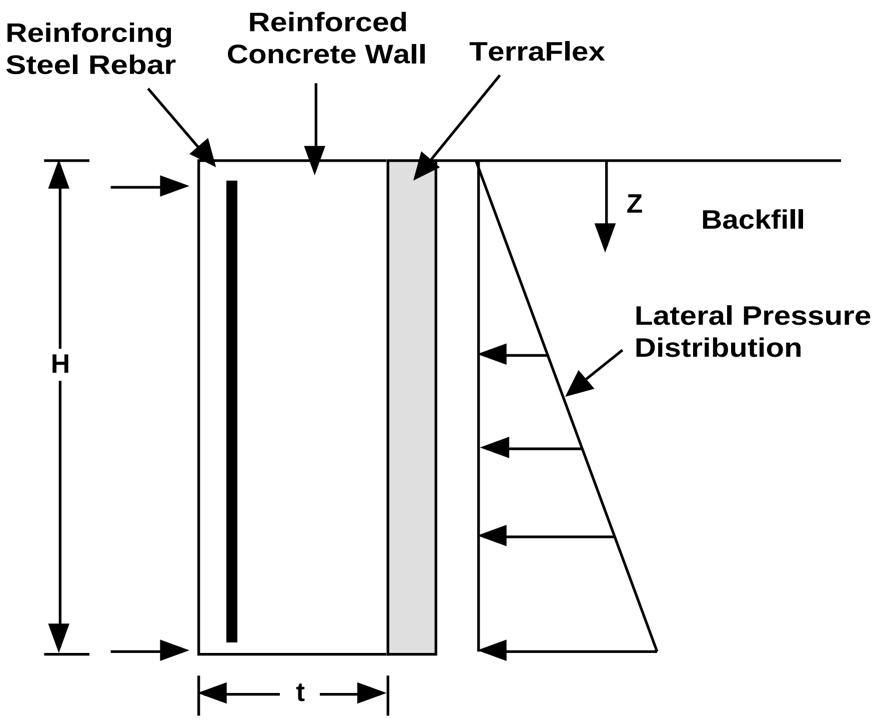


Figure 5.1: Idealized Elevation View of Design Conditions for Reinforced Concrete Basement Wall

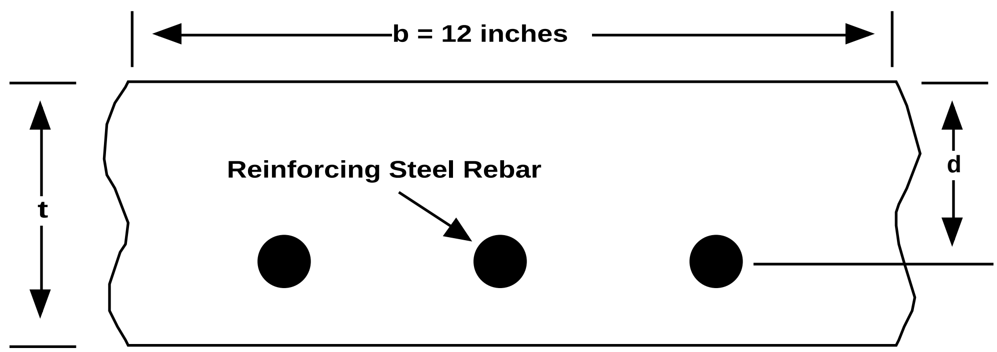


Figure 5.2: Idealized Plan View of Reinforced Concrete Design Section

inches and a thickness, t. The location of the reinforcing steel is designated by the effective depth (d), which is the distance from the backfill side of the section to the center of the reinforcing steel rebar. In order to prevent damage to the steel, a concrete cover is required. The American Concrete Institute (ACI) Building Code requires that the minimum concrete cover shall be _ inches (Nawy 1990). Thus, the minimum section thickness is defined by the following expression:

$$t = d + 1/2d_b + \text{cover} \tag{5.2}$$

where

d_b = diameter of rebar (inches)

cover = 3/4 inches

Assuming a minimum # 4 rebar size (d_b = 0.50 inches), the minimum section thickness would be d + 0.25 inches + 3/4 inches, or d + 1 inch. The section thickness is typically assigned an integer value. It is common practice to design concrete walls no smaller than 8 inches in thickness. Assuming a minimum # 4 rebar size, 8 inches of thickness would correspond to a d value of 7 inches. For this study, the minimum acceptable d and t values were taken as 7 inches and 8 inches, respectively.

The value of d and d_b will vary depending on the value of K_h applied to the wall, the backfill unit weight, and the wall span length. Flexural and shear design procedures, as defined by the ACI building code, are used to determine the required values of d and d_b. The flexural design procedure is used to select a required steel area for the section, thus determining an acceptable rebar size (d_b) and the required horizontal rebar spacing.

Shear steel reinforcement, in the form of stirrups, is typically not used in basement walls, and was not used in any of the designs for this study. Where additional shear resistance was needed, the value of d was increased, thus producing an increase in t.

5.2.2 Basement Wall Analysis

A study was performed to determine the effects of H, γ, and K_h on the value of d. Values of H were varied from 10 feet to 30 feet. The values of γ and K_h were expressed as one combined variable, γK_h, which varied from 30 pcf to 130 pcf. The concrete compressive strength and steel yield strength were assumed to be 4,000 psi and 60,000 psi, respectively. Figure 5.3 summarizes the results of the study. In this figure, the minimum value of d is expressed as a function of H and γK_h. If H and γK_h are known, the minimum value of d can be estimated using Figure 5.3. If a minimum # 4 rebar size is assumed, the minimum value of t would be equal to d + 1 inch, and would be rounded up to the nearest integer value. Note that there is a limiting envelope for the d values in Figure 5.3 to satisfy wall deflection criteria, as established by the ACI code for a simply-supported wall. The minimum wall thickness to satisfy deflection criteria is defined by the following equation:

$$t = \frac{H}{20} \qquad (5.3)$$

where

H = Wall span length (inches)

Thus, the minimum effective depth to satisfy deflection criteria would be:

$$d = \frac{H}{20} - 1\ \text{inch} \qquad (5.4)$$

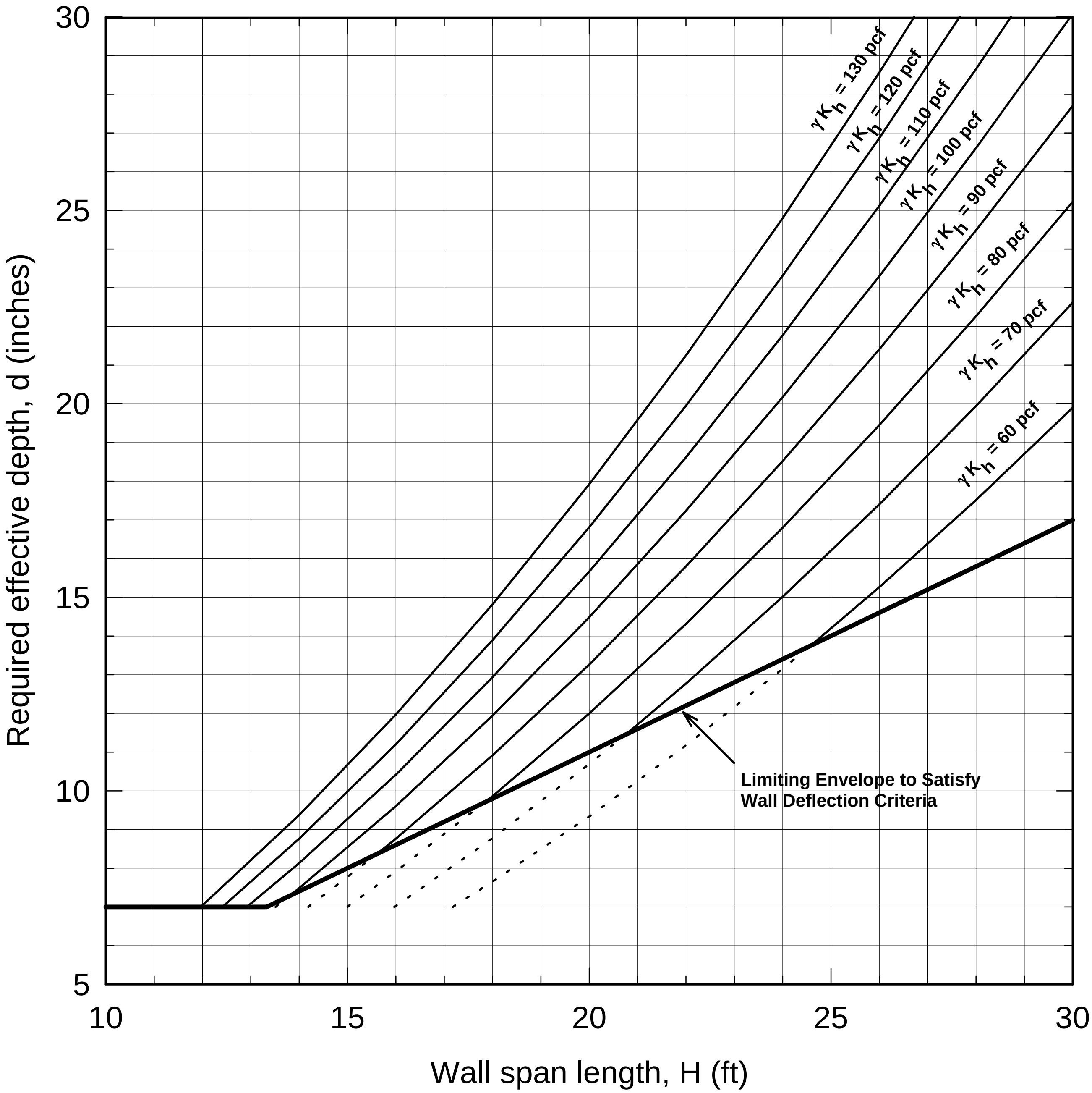


Figure 5.3: Required Values of Effective Depth (d) for Varying Wall Span Lengths and Values of γK_h

The minimum d values from Figure 5.4 can be used to develop estimates of cost versus H and γK_h. By assuming a minimum t value of d + 1 inch and a cost per unit volume of in-place reinforced concrete, the vertical axis from Figure 5.3 can be changed to represent minimum cost of the wall. Figure 5.4 shows the minimum wall cost in dollars per square foot of wall versus H and γK_h. The cost data was generated by assuming an in-place, reinforced concrete cost of \$300 per cubic yard (\$11.11 per cubic foot), an average value obtained from RS Means Building Construction Cost Data (1996).

If the wall span length and value of γK_h can be estimated, Figures 5.3 and 5.4 can be used to establish a minimum value of t and a minimum cost of the wall. With estimates of these values, a basis for economic comparisons between different wall thicknesses is established.

5.2.3 Basement Wall Economic Analysis

The potential economic impact of TerraFlex can be studied by comparing the required reinforced concrete section thickness for a wall with no TerraFlex to one with TerraFlex. The concept is that for a particular value of H, a layer of TerraFlex can decrease the value of γK_h on the wall sufficiently to require a smaller section thickness compared to the section thickness using no TerraFlex. Economic benefit occurs when the combined cost of the smaller concrete wall and TerraFlex is less than the cost of the wall using no TerraFlex.

The data from the stationary instrumented retaining wall tests can be used to illustrate the benefits of using TerraFlex. For the comparisons that follow, the potential benefits of using 4 inches of TerraFlex versus no TerraFlex are studied. The 4-inch thickness represents a common thickness sold by GeoTech Systems Corporation. The final values of K_h, using no TerraFlex

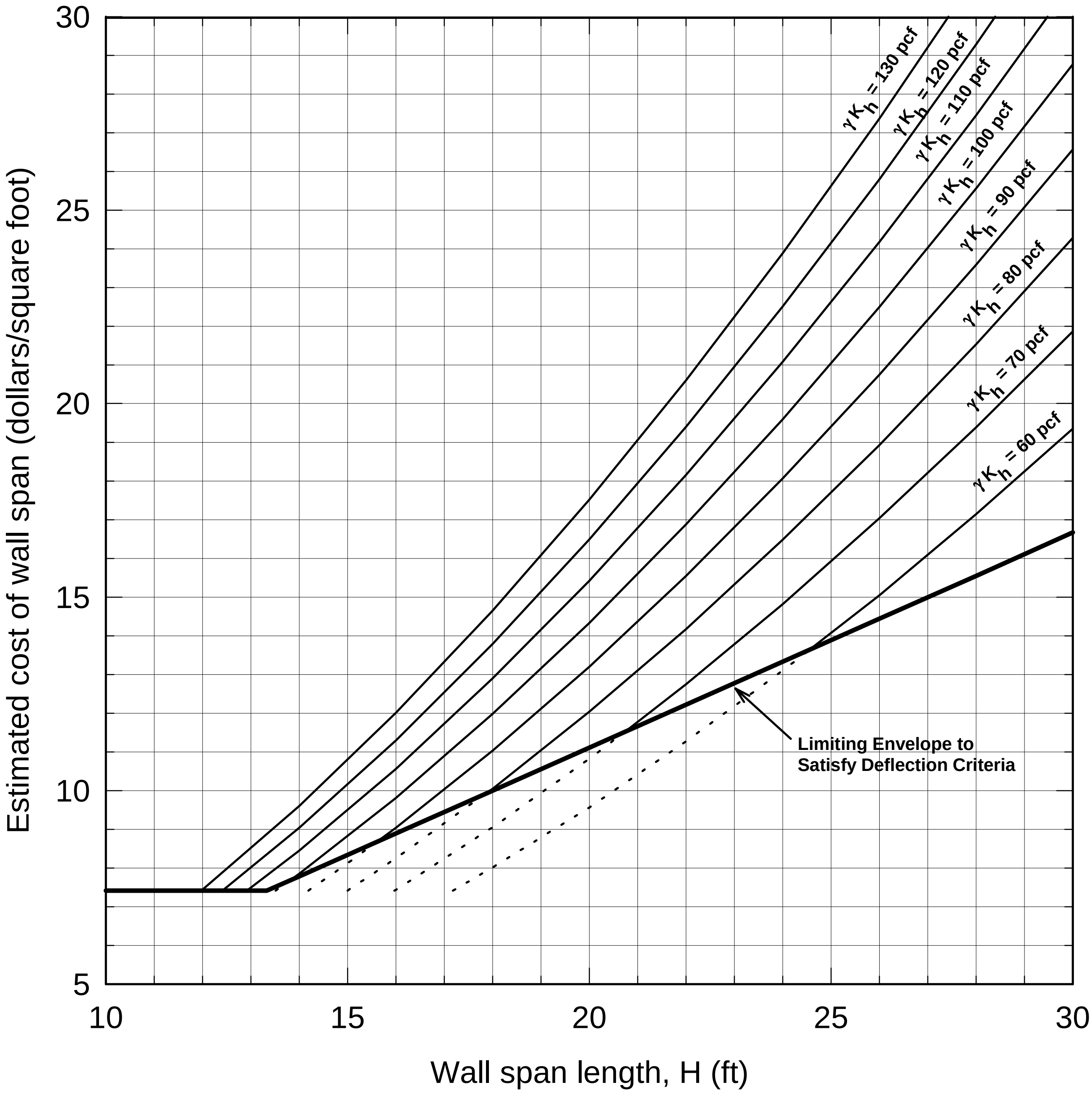


Figure 5.4: Estimated Cost of Wall Span for Varying Wall Span Lengths and Values of γK_h

and 4 inches of TerraFlex, were summarized in Table 4.2 for the instrumented retaining wall tests.

Using the final values of K_h from Table 4.2 and a backfill unit weight of 105 pcf, Test 4 (Rammer compactor, no TerraFlex) and Test 2 (Rammer compactor, 4 inches of TerraFlex) resulted in γK_h values of approximately 91 pcf and 48 pcf, respectively. Using these values of γK_h for varying wall span lengths, minimum d values can be determined for each span length from Figure 5.3. An economic comparison can be made between using no TerraFlex and 4 inches of TerraFlex by assuming relevant material costs for in-place reinforced concrete and TerraFlex. The material costs used in this comparison are \$300 dollars per cubic yard of in-place reinforced concrete and \$0.75 per square foot of 4-inch thick TerraFlex, as estimated by GeoTech Systems Corporation. The cost for using no TerraFlex would be that for reinforced concrete alone, and the cost for using 4 inches of TerraFlex would be the cost for both reinforced concrete and TerraFlex.

Using the γK_h values measured in the instrumented retaining wall tests and wall span lengths ranging from 20 feet to 26 feet, an economic comparison was made between using no TerraFlex and 4 inches of TerraFlex. This comparison is shown in Table 5.1.

Table 5.1 shows that smaller wall thicknesses can be used when 4 inches of TerraFlex is used, compared to using no TerraFlex. It can also be seen that the cost savings per square foot of wall generally increase as the wall span length increases. However, it should be noted that data measured in the instrumented retaining wall tests were for a 6.5-foot high wall. The appropriate values of γK_h and required TerraFlex thickness may differ for walls higher than 6.5 feet.

Table 5.1: Economic Comparison between Use of No TerraFlex and 4 Inches of TerraFlex for Reinforced Concrete Basement Walls

H (ft)	No TerraFlex			4 Inches of TerraFlex			Potential Cost Savings from Using TerraFlex	
	γK_h (pcf)	Minimum t (inches)	Cost[1] ($/sq. ft.)	γK_h (pcf)	Minimum t (inches)	Cost[2] ($/sq. ft.)	($/ sq. ft.)	Percent
20	91	15	13.89	48	12	11.86	2.03	15
22	91	17	15.74	48	14	13.71	2.03	13
24	91	20	18.52	48	15	14.64	3.88	21
26	91	23	21.29	48	16	15.56	5.73	27

1) Cost is for reinforced concrete wall without any TerraFlex
2) Cost is for reinforced concrete wall with 4 inches of TerraFlex

For 4 inches of TerraFlex, the concrete wall thicknesses and costs shown in Table 5.1 are controlled by the deflection criteria established in equations 5.3 and 5.4. It should be noted that if the required wall deflection criteria differs from that assumed for this study, the concrete thickness and cost can differ from those shown for 4 inches of TerraFlex.

5.3 Potential Impact on Gravity Retaining Wall Design

The following sections describe the economic analysis performed for gravity retaining walls. The assumed design conditions and results from these analyses are summarized.

5.3.1 Gravity Wall Design Conditions

An idealized cross-section of the design conditions assumed for gravity retaining walls is shown in Figure 5.5. For simplicity, a rectangular wall geometry was adopted. As can be seen from the figure, the wall is composed of mass concrete and is defined by a height H and base width B. A triangular lateral pressure distribution (as defined by

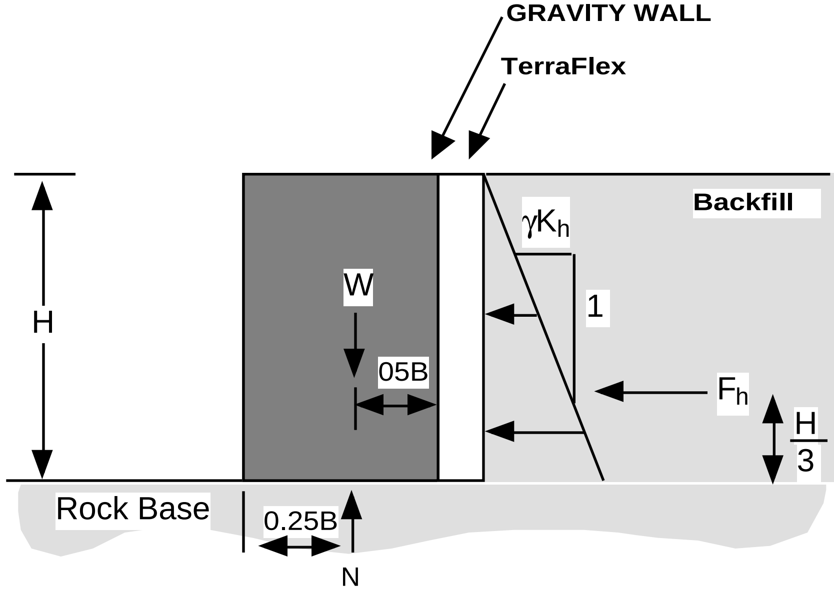


Figure 5.5: Idealized Elevation View of Design Conditions for Gravity Retaining Wall

equation 5.1) was assumed to act against the wall. The forces acting on the wall are the lateral earth force F_h (as defined by equation 4.3), the weight of the wall W acting vertically downward, and a normal force N acting perpendicular to the wall's base. The wall rests upon a rock base and is assumed to be non-deflecting under loads from the backfill.

5.3.2 Gravity Wall Analysis

A study was performed to determine the effects of lateral earth force on the required values of base width for varying wall heights. The wall was analyzed by force and moment equilibrium to determine the required base widths when wall heights were varied. For this analysis, the wall dimensions must be sufficient to satisfy wall stability criteria. The criteria are sliding of the wall on the rock base, wall overturning, and bearing capacity of the wall base. The bearing capacity stability was assumed to be sufficient for any wall dimensions since the wall is founded upon a rock base. Thus, bearing capacity was not assumed to be a controlling condition. However, sliding or overturning will control wall dimensions.

To evaluate sliding stability, a coefficient of sliding friction μ for the rock/mass-concrete interface was assumed to be a value of 0.7 (NAVFAC DM-7.2 1982). Assuming a factor of safety against sliding of 1.5 and satisfying horizontal force equilibrium, an equation was developed defining the base width to wall height ratio (B/H) to satisfy sliding stability:

$$\frac{B}{H} = 1.07\frac{\gamma K_h}{\gamma_{conc}} \tag{5.5}$$

where

γ_{conc} = the unit weight of the mass concrete (pcf)

An analysis was also conducted to determine the required values of B/H to satisfy wall overturning stability. For walls on rock foundations, overturning stability is satisfied when the normal force N acts within the middle half of the base (Duncan et al. 1990). By satisfying moment equilibrium on the wall and assuming that the normal force N acts at the limiting location shown in Figure 5.5, an equation was developed to satisfy overturning stability:

$$\frac{B}{H} = \sqrt{\frac{2\gamma K_h}{3\gamma_{conc}}} \tag{5.6}$$

Equations 5.5 and 5.6 can be used to estimate the value of B/H required to satisfy sliding and overturning stability for the assumed gravity wall geometry. The stability equation that gives the higher B/H value should be used for design. If the values of γK_h, γ_{conc}, and wall height H are known, the required base width can be determined.

An analysis was conducted to determine the effects of γK_h on the required values of B/H. For this analysis, the unit weight of concrete was assumed to be 150 pcf.

The values of B/H were determined when γK_h values ranged from 20 to 140 pcf. The stability condition the resulted in the higher value of B/H was taken as that required for design. The results of this analysis are summarized in Figure 5.6. From this figure, an estimate of B/H can be made for a specific value of γK_h, and then a value of B determined for a given wall height. With estimates of the base width, a basis for economic comparisons between different wall thicknesses is established.

5.3.3 Gravity Wall Economic Analysis

The potential economic impact of TerraFlex can be studied by comparing the cost for a wall with no TerraFlex to the cost of a wall with TerraFlex. For the comparisons

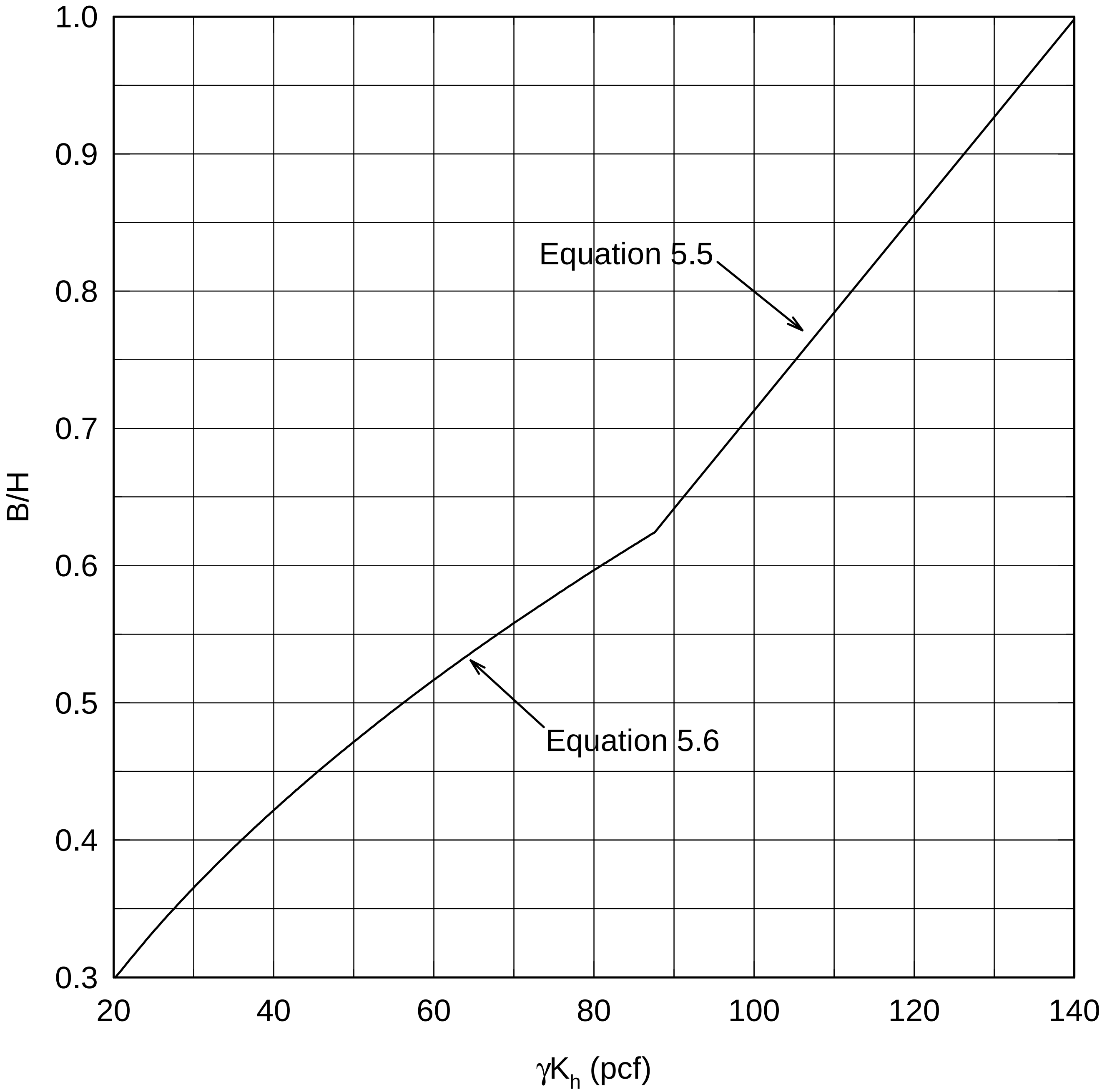


Figure 5.6: Values of Wall Base Width to Height Ratio (B/H) Versus γK_h Values for Gravity Retaining Walls

that follow, the potential benefits of using 4 inches of TerraFlex versus no TerraFlex are studied.

The data from the stationary instrumented retaining wall tests can be used to illustrate the benefits of using TerraFlex. Using the data from these tests, the 4 inches of TerraFlex thickness used in Test 2 resulted in a γK_h value of about 48 pcf, and the use of no TerraFlex in Test 4 resulted in a γK_h value of about 91 pcf. Using these values of γK_h for varying wall heights, the required B/H value can be determined for each wall height from Figure 5.6. An economic comparison can be made between using no TerraFlex and 4 inches of TerraFlex by assuming relevant material costs for mass concrete and TerraFlex. The material costs used in this comparison are \$140 dollars per cubic yard (\$5.18 per cubic foot) of mass concrete (R.S Means Building Construction Cost Data 1996) and \$0.75 per square foot of 4-inch thick TerraFlex. The cost for using no TerraFlex would be that for mass concrete alone, and the cost for using 4 inches of TerraFlex would be the cost for both mass concrete and TerraFlex.

Using the γK_h values measured in the instrumented retaining wall tests and Figure 5.6, the required B/H ratios are 0.46 and 0.65 for γK_h values of 48 pcf and 91 pcf, respectively. By varying the wall heights from 10 feet to 40 feet, an economic comparison was made between the use of no TerraFlex and 4 inches of TerraFlex. This comparison is shown in Table 5.2.

Table 5.2 shows that smaller base widths can be used when 4 inches of TerraFlex is used, compared to using no TerraFlex. The percent cost savings are significant but vary little with increasing wall heights.

Table 5.2: Economic Comparison Between Use of No TerraFlex and 4 Inches of TerraFlex for Gravity Retaining Walls

H (ft)	No TerraFlex			4 Inches of TerraFlex			Potential Cost Savings from Using TerraFlex	
	γK_h (pcf)	B (ft)	Cost[1] ($/sq. ft.)	γK_h (pcf)	B (ft)	Cost[2] ($/sq. ft.)	($/ sq. ft.)	Percent
10	91	6.5	33.76	48	4.6	24.58	9.18	27
20	91	13.0	67.34	48	9.2	48.41	18.93	28
30	91	19.5	101.01	48	13.8	72.23	28.78	28
40	91	26.0	134.68	48	18.4	96.06	38.62	29

1) Cost is for gravity wall without any TerraFlex
2) Cost is for gravity wall with 4 inches of TerraFlex

The use of gravity walls for the range of wall heights in Table 5.2 are not uncommon in engineering practice and may exceed this range in some cases, such as large lock walls built by the US Army Corps of Engineers. However, it should be noted that the estimated unit price of $140 per cubic yard of mass concrete might decrease for large wall heights.

CHAPTER 6 – SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter presents a summary of the work accomplished, conclusions drawn from the work, and recommendations for research to address unresolved issues.

6.1 Summary and Conclusions

This research project included laboratory testing of TerraFlex specimens, stationary and cyclically-moving instrumented retaining wall tests, and an analysis of the potential effects of TerraFlex on retaining wall costs.

The laboratory work consisted of creep testing and cyclic testing of TerraFlex specimens. The creep tests show that the slopes of the stress-strain curves gradually decrease with increasing stress up to a value near 400 psf and then begin to increase again for stresses between 400 psf and 500 psf. The cyclic tests show that there is a significant amount of permanent deformation of the TerraFlex associated with loading/unloading cycles. The amount of permanent deformation increased when the load/unload duration was increased from 0.1 hours to 1 hour.

Five instrumented retaining wall tests were completed for this study; both stationary wall tests and cyclically-moving tests were performed. The results of the stationary wall tests show that the value of K_h can be reduced significantly by the application of TerraFlex over the entire height of the wall, when either the rammer or the vibrating plate compactors are used for backfill compaction. When the rammer compactor was used, the value of K_h was reduced to 0.38 when 10 inches of TerraFlex was applied to the wall, versus a K_h value of 0.87 with no TerraFlex. When the vibrating plate compactor was used, the value of K_h was reduced to 0.20 with 6 inches of TerraFlex, versus a K_h value of 0.45 with no TerraFlex.

The cyclic wall movement tests show that there is a progressive increase in the peak value of K_h with each cycle. However, it was observed that when 10 inches and 6 inches of TerraFlex were used, in Tests 3 and 5 respectively, the value of K_h did not exceed 2.00 after thirty wall movement cycles. The cyclic testing also shows that when no TerraFlex is applied to the wall, the value of K_h increases above 2.00 during the first cycle at very small displacements compared to the magnitudes of displacement applied for tests using TerraFlex. These results suggest that there may be very significant benefits associated with using TerraFlex on bridge abutments.

An economic analysis was performed to study the potential economic benefit of using TerraFlex in reinforced concrete basement wall applications and gravity retaining wall applications. For each of these analyses, the economic benefit of using 4 inches of TerraFlex was evaluated. For the basement wall analysis, it was demonstrated that the use of TerraFlex may have potential cost savings in basement wall heights of 20 feet or more. The economic analysis showed that the cost savings increase as the wall height increases. For the gravity wall analysis, it was demonstrated that significant cost savings could be obtained by the use of TerraFlex. In this case, the percent cost savings is approximately 28 percent for a range of wall heights from 10 to 40 feet. These economic analyses required several simplifying assumptions, and they show the general trends of the economic benefit expected when using TerraFlex in retaining wall applications.

6.2 Recommendations for Further Research

The results of this research suggest that additional benefits could be obtained by accomplishing the following research tasks:

1) Develop a general theory to relate TerraFlex thickness to the reduction of compaction induced earth pressures. Such a theory would consider the following variables: compaction energy, stress-strain behavior, thickness of the compressible inclusion, backfill properties, and wall height. With availability of a general theory, a reliable design procedure using TerraFlex could be established.

2) Perform cyclically moving wall tests at slow displacement rates. The limitations of the cyclic movement tests described herein are that they were performed at a faster rate than that experienced by integral bridge abutments in a field environment. The progressive increase in K_h that was observed in the instrumented retaining wall tests with TerraFlex should be even less pronounced with slower displacement rates.

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