

CHAPTER 6

LATERAL LOAD TESTS

6.1 INTRODUCTION

Lateral load tests were conducted at the field test facility from early June through October, 1998. Thirty-one tests were performed on three groups of piles with embedded caps, two single piles, and a buried concrete bulkhead. The tests were conducted at locations A through D, identified in Figure 3.1.

The NE and NW piles were loaded against each other at location A. Tests conducted at this location are described in Table 6.1. The SE cap and the bulkhead were loaded against each other at location B. Tests conducted at this location are described in Table 6.2.

The north pile was tested in the direction of its strong axis using the NE cap as a counter reaction (location C). Tests conducted at this location are described in Table 6.3. The south pile was tested in its strong axis direction by loading it against the north pile (location D), which was embedded in concrete to increase its resistance. Tests on the south pile are described in Table 6.4.

6.2 LOAD TESTS

In all the tests, compressive loads were applied through the vertical centroidal axis of the foundations. Tests were performed using incremental, cyclic, and sustained loading procedures, as described below.

The incremental procedure is historically the most recognized approach for performing lateral load tests on piles and drilled shafts. The procedure used in this study consisted of applying loads of increasing magnitude in 10 to 20 kip increments. A one-

minute-long pause was maintained between increments, at constant load. A typical distribution of data points obtained during the incremental procedure is shown in Figure 6.1(a). For easier viewing, intermediate points were filtered, and only the data at the end of each one-minute pause was plotted, as shown in Figure 6.1(b). A line or smooth curve was fit through the end points to facilitate comparisons among the various tests.

The cyclic procedure consisted of applying and releasing a large number of unidirectional loads. The time to complete one load cycle varied from approximately 40 seconds to 2 minutes. The loading and unloading frequency was controlled by the capacity of the hydraulic pump and the extended length of the ram plunger. After every 24 cycles the loading frequency was decreased. During the 25th cycle, loads were applied in 10 to 20 kip increments with a one-minute-long pause between increments. Readings were obtained during this cycle using same incremental procedure described in the previous paragraph.

Sustained loads were applied by incrementally increasing the load up to a predetermined level, and maintaining this level at a constant value over a 3 to 4 hour period.

The following two subsections describe the deformations and rotations that were observed during testing. Subsequent sections describe the results and their significance in more detail.

6.2.1 Deformations

Examples of load versus deflection results for the south pile, SE cap, and bulkhead are shown in Figure 6.2. These plots cover the typical range of load and deflection values that were measured during the tests. Applied loads ranged from 0 to 140 kips, and maximum deflections ranged from 0.1 to almost 3 inches. For instance, the south pile deflected about 2.9 inches in loose sand, at a load of 45 kips (Figure 6.2a). While the SE pile cap in contact with natural soil deflected about 0.1 inches, at a load of

140 kips (Figure 6.2b). The bulkhead deflected approximately 1.6 inches at a load of 137 kips in natural soil and 90 kips in compacted gravel, as shown in Figure 6.2(c).

Pile cap deflections were relatively small, often less than 0.2 inches at the maximum load of 140 kips (the capacity of the loading system). This corresponds to a lateral load per pile of 35 kips, which exceeds typical design loads for HP 10 x 42 piles by a factor of three to four. These results are significant considering that many foundations are designed for maximum deflections of 0.5 to 1 inch, with no consideration of the resistance provided by the cap. This type of design approach is clearly over-conservative if cap resistance is ignored when the overall lateral resistance of the pile group is computed.

6.2.2 Rotations

Rotations at the tops of single piles depend on the magnitude of the applied load and the pile-head restraining condition. The maximum slope measured at the groundline during load testing was slightly less than 3 degrees for the north pile in dense sand. This occurred at a 45 kip load and a deflection of approximately 3.5 inches; a situation generally considered unsuitable in most practical applications.

Terms used to describe rotations of pile caps are defined in Figure 6.3 as follows:

q = the angle of tilt in the direction of load (rotation about the horizontal axis), and

t = the angle of twist or torsion of the cap about a vertical axis.

Rotations about a horizontal axis are primarily controlled by the stiffness of the cap, the stiffness of the pile-to-cap connection, and, for piles in groups, the axial capacity of the piles. Twisting of the cap may be caused by eccentricities in the applied load or non-heterogeneous conditions in the soil or backfill.

The angles of rotation (q and t) measured during each test, are shown in Table 6.5 for the three caps and the bulkhead. The maximum value of t for the pile caps was 0.07 degrees, indicating that twisting or torsion of the pile caps was negligible in all of the tests. The angle of tilt, q , was also small. The SE pile cap, with soil removed from the cap sides and front, experienced the largest amount of tilt ($q = 0.21$ degrees). In comparison, q was negligible (less than 0.001 degrees) for the NE cap embedded in natural soil.

The bulkhead experienced greater rotations because it was loaded to failure and was not supported on piles. The rotations of the bulkhead ranged from 0.07 degrees, for natural soil, to approximately 0.5 degrees for gravel backfill.

6.3 SINGLE PILE RESISTANCE

This section describes the results of lateral load tests performed on the north pile (described in Table 6.3) and the south pile (described in Table 6.4). The load versus deflection curves shown in this dissertation are based on pile deflections at the ground-line (or ground surface), as shown in Figure 6.4.

6.3.1 Effect of Pile-Head Load Connection

Tests were performed on the north pile to evaluate the effect of two different connections on load-deflection behavior in various soils. The connections are identified as:

- 1) a pinned connection, which consisted of a unidirectional clevis that permitted rotation about the horizontal axis, as shown in Figure 6.5, and
- 2) a rigid strut connection, which consisted of a steel strut bolted rigidly to the pile, as shown in Figure 6.6.

Figure 6.7 shows the load versus deflection and load versus slope responses of the north pile, for both types of pile-head connectors, tested in natural soil and dense sand.

The pinned head tests were performed immediately after the rigid strut tests. As shown in the figure, the deflection and slope response curves are very similar for both connection devices. The slight concave upward shape in the early portion of clevis pin curve is believed to be caused by the testing sequence. The zone of soil immediately in front of the pile was preloaded or “hardened” during the initial rigid strut test. The similarity in response between the two connection devices is attributed to the following factors.

- 1) The clevis did not function as a true pin connection. It is believed that some resistance to rotation was developed because of tight clearances around the clevis pin and the steel plates that were used for the clevis tongue and yoke.
- 2) The rigid strut and clevis pin provided greater rotational restraint than the load cell because the load cell was free to rotate. Consequently, the rotational stiffness of the load cell controlled the level of rotational restraint that was provided in the loading system.

The difference in performance between the two connectors with regards to pile deflection and slope is negligible. For this reason, the remaining tests described in this chapter were performed using the rigid strut connection. This type of connection provides greater rotational restraint than a free-head connection, but less rotational restraint than a pure fixed-head connection. Although the strut was rigidly attached to the pile, bending at other more flexible locations in the loading train (primarily at the load cell) precluded a pure fixed-headed pile boundary condition. Consequently, the pile-head boundary conditions for these tests were only partially restrained.

Partially restrained boundary conditions are typically analyzed by measuring, computing, or estimating the rotational restraint, which was defined by Matlock and Reese (1961) as the moment divided by the rotation. The degree of rotational restraint involved in these tests is discussed in Section 6.3.3.

6.3.2 Effect of Soil Type and Density

The two single piles, identified as the north pile and south pile, were loaded in the direction of their strong axis at test locations C and D (Figure 3.1). The piles were initially tested in their as-driven condition, embedded in natural soil. As shown in Figure 6.8(a), the load-deflection curves for the two piles embedded in natural soil are nearly identical. This indicates quite uniform soil conditions at the site and good repeatability of testing procedures.

After testing the piles in their as-driven condition, the natural soil was excavated from around the piles and replaced with New Castle sand. The excavation and replacement extended to a depth of 7 feet at the north pile and 5.7 feet at the south pile. Tests were performed with the sand backfill in a loose condition, $D_r = 10\%$, and a dense condition, $D_r = 60\%$.

As shown in Figures 6.8(b) and 6.8(c), pile deflections increased noticeably when the natural soil was replaced by sand. At a deflection of $\frac{1}{2}$ -inch, the resistance of the north pile decreased by approximately 65% when the top 7 feet of natural soil was replaced by dense sand. The resistance of the pile in 7 feet of loose sand was reduced by approximately 80%.

At the same deflection ($\frac{1}{2}$ -inch), the resistance of the south pile decreased by 60% when the top 5.7 feet of natural soil was replaced by dense sand. The resistance of the pile in 5.7 feet of loose sand was reduced by approximately 75 %.

In summary, lateral load resistance increases with soil stiffness and density, as would be expected. An accurate evaluation of soil shear strength and stiffness, within the top 10 pile diameters, is necessary to analyze laterally loaded pile foundations reliably.

6.3.3 Effect of Pile-Head Rotational Restraint

The single piles were tested using rotationally restrained pile-head boundary conditions. Matlock and Reese (1961) quantified this type of boundary condition as the moment at the pile head divided by the rotation (M/θ). This type of connection provides greater rotational restraint than a free-head connection, but less rotational restraint than a fixed-head connection. In this dissertation, the term $k_{m\theta}$ is used to represent the rotational stiffness, M/θ .

The effects of pile head restraint were examined using the following three approaches, which are described in more detail in the following paragraphs.

- 1) the single pile response was compared to the measured response of a group pile restrained against rotation at the top by a concrete cap,
- 2) upper and lower bound response curves were calculated using free- and fixed-head boundary conditions, and
- 3) the value of rotational restraint, $k_{m\theta}$ was determined through trial and error.

Approach 1. The measured response of the north pile was compared to the average response of a pile from the NE group, as shown in Figure 6.9(a). The NE group was constrained by a 36-inch-deep cap, which provided a highly restrained pile-head boundary condition. As would be expected, the NE group pile provides a stiffer response because it represents a boundary condition approaching complete restraint. (The NE group pile response curve represents the condition in which soil was removed from around the cap.)

Approach 2. The computer program *LPILE Plus3.0* (1997) was used to generate load deflection curves using free- and fixed-head boundary conditions. p-y curves were developed using the cubic parabola formulation with Brinch Hansen's (1961) ultimate theory for soils containing both friction and cohesion. Soil parameters were estimated from field and laboratory tests.

As shown in Figure 6.9(b), the calculated response curves establish upper and lower bounds of possible behavior. The calculated fixed-head response is stiffer than the measured response of the NE group pile, which is reasonable considering a pure fixed-head condition is rarely achieved in the field. The fixed-head response curve was calculated assuming 100 % group efficiency, and thus represents a true upper bound. The calculated response would be closer to the measured results if reductions for group efficiencies were incorporated into the calculations.

Approach 3. In this approach, the pile-head boundary condition was assumed to be partially restrained, and represented by $k_{m\theta}$. The magnitude of rotational restraint ($k_{m\theta}$) at the pile-head was determined through a trial and error process. The value of $k_{m\theta}$ was varied until the calculated load-deflection results matched the observed results. A value of $k_{m\theta} = 2500$ ft-kips/rad was found to provide the best match between calculated and observed load-deflection responses. The calculated response curve for this value of $k_{m\theta}$ is shown in Figure 6.10.

In summary, pile head rotational restraint significantly affects the performance of a laterally loaded pile. Three approaches were described that can be used for evaluating this effect, they are:

1. Perform field load tests using the same rotational restraint as planned for the production piles.
2. Calculate lower and upper bound limits using free and fixed head boundary conditions. Estimate a response

between these limits using experience and engineering judgement

3. Calculate response curves using a partially restrained boundary condition by back calculating, measuring, or estimating the rotational restraint, $k_{m\theta}$.

6.3.4 Effect of Cyclic Loading

The two single piles were subjected to 150 cycles of monotonic loading to evaluate the effects of cyclic load on pile performance. Tests results for the north and south piles, embedded in natural soil, are shown in Figure 6.11. Results for the south pile embedded in dense sand are shown in Figure 6.12. The figures show the pile response every 25 cycles of load.

As shown in Figure 6.11, pile deflections in natural soil increased during the first 75 cycles, then gradually leveled off with no further change in deflection. An 80 % increase in deflection occurred as a result of cyclic loading. The maximum deflection reached at the end of loading was approximately 1.4 inches.

The south pile performance in dense sand was somewhat different, exhibiting a continual increase in deflections with load cycles, as shown in Figure 6.12(b). One hundred fifty cycles of load application resulted in a 60 % increase in deflection, at a 50 kip lateral load. The maximum deflection at the end of loading was almost 4 inches.

Increased deflections caused by cyclic loads are generally attributed to 1) gapping and subsequent scour of soil from around the pile or 2) cyclic soil degradation caused by the buildup of excess pore pressures from cyclically applied shear stresses (Brown and Reese 1985).

The first phenomenon does not apply to either of the soil conditions at this site because the water table was more than 12 feet below the ground surface.

The second phenomenon, cyclic soil degradation, occurs during undrained loading and includes a reduction of soil modulus and undrained shear strength (Poulos 1982). The natural fine-grained soils at the site may have experienced some degradation of strength caused by excess pore pressures. However, the low frequency cyclic loads used in these tests would not cause excess pore pressure development in the sand backfill.

In general, the cyclic behavior of a pile in sandy soil is usually similar to its static behavior. However, the results shown in Figures 6.11 and 6.12 indicate that cyclic loading significantly affected the single piles in both natural soil and dense sand backfill. These tests were performed at relatively large loads, resulting in deflections ranging from 10 % to almost 40 % of the pile diameter. These large loads and deflections may have exacerbated cyclic effects by stressing the soil and piles to conditions approaching their ultimate or yield strengths. Reese (1997) reported similar observations concerning load tests performed in stiff clay at a site near Manor, Texas.

In conclusion, the cyclic response observed in these tests overestimates the effects of cyclic load on the behavior of piles that are loaded at typical working stress levels. Detailed additional studies would be necessary to separate and quantify the different mechanisms that occur during cyclic loading.

6.4 PILE CAP RESISTANCE

The results described in this section were obtained from lateral load tests performed on the NE and NW pile caps (described in Table 6.1) and the SE pile cap (described in Table 6.2).

6.4.1 Resistance With and Without Cap Embedment

In the first series of tests, the pile groups were tested with the caps embedded in relatively undisturbed natural soil. The results from these tests are shown in Figure 6.13. Although loads as large as 140 kips were applied (35 kips per pile), the deflections were

small, less than 0.1 inches for the NE and NW caps, and approximately 0.13 inches for the SE cap.

As shown in Figures 6.13(a) and (b), the 18-inch-deep NW cap deflected less than the 36-inch-deep NE cap during the initial load tests in natural ground. This seemingly incongruous behavior is attributed to construction disturbances of the soil along the sides and front of the NE cap. During construction, soil was removed at three locations around the NE cap to provide room for embedding anchor rods, which were used in subsequent load tests at locations C and D (Figure 3.1). The excavations were backfilled with imported sandy soil before performing the load tests. In contrast, three sides of the 18-inch-deep NW cap were in full contact with undisturbed soil, which is stiffer than the sand backfill that was used in the trenches around the NE pile cap.

Subsequent tests were performed on the pile groups after soil was removed from the sides and front of the caps, as shown in Figure 6.14. By comparing the load-deflection responses from these tests with the initial tests in undisturbed ground, the contribution of cap resistance can readily be ascertained. As shown in Figure 6.13, the load-deflection curves clearly show that removing soil from the sides and front of the caps resulted in larger deflections at the same loads. Lateral deflections increased by approximately 150 % for the 36-inch-deep NE cap at 140-kip load, 400 % for the 18-inch-deep NW cap at 140-kip load, and 500 % for the 36-inch-deep SE cap at 90-kip load.

The percentage of overall lateral resistance provided by the pile caps are as follows:

- NE cap – 40 %, at 0.09 in deflection,
- NW cap – 50 %, at 0.05 in deflection, and
- SE cap – 50 %, at 0.125 in deflection

Results from these tests support the following conclusions:

1. The horizontal deflections of the pile caps are small considering the magnitude of the maximum lateral loads (approximately 35 kips per pile). This exceeds design loads that are often used for HP 10 x 42 piles by a factor of 3 to 4.
2. The fact that the 18-inch-deep cap deflected less than the 36-inch-deep cap is a result of trench construction disturbance along the sides and front of the 36-inch-deep cap. This indicates the important effect of cap resistance in the behavior of pile groups, and the significance of the strength and stiffness of soil around the caps in determining the magnitude of cap resistance.
3. Removing soil from the sides and front of the caps increased deflections by 150 to 500 %, further indicating the importance of the cap and the surrounding soil in resisting lateral loads.
4. Forty to fifty percent of the overall lateral load resistance was provided by the pile caps. This indicates that approximately $\frac{1}{2}$ the lateral resistance of a pile group foundation can be developed in the soil around the pile cap.

6.4.2 Resistance From Sides and Front of Caps

Figure 6.15 shows load deflection responses for the NE, NW, and SE pile caps for the following three conditions:

1. cap in full contact with soil,
2. soil removed from the sides of the cap, and
3. soil removed from the sides and front of the cap.

The tests indicate that pile cap resistance is comprised of two elements: 1) shear resistance developed in soil along the sides of the cap and 2) passive resistance developed by soil in front of the cap. The contributions from these two components are shown in Table 6.6 for the three pile caps. The percent contributions shown in this table were determined at deflections of 0.09 in for the NE cap, 0.05 in for the NW cap, and 0.06 in for the SE cap.

At these small deflections, the side shear component for the NE and NW caps appear to be greater than the passive resistance developed in front of the cap. It is expected that at larger deflections, a greater percentage of passive resistance will be mobilized in front of the cap. Research by Clough and Duncan (1971) indicate that passive pressures are not fully mobilized until wall movements approach 2 to 4 % of the wall height. The comparisons provided in Table 6.6 are for deflections less than 0.25 % of the cap height. The resistance developed along the sides of the cap is not expected to change significantly with increased load. Consequently, the percent contribution from soil along the cap sides will decrease as deflections increase, and the passive pressure component will comprise a larger and more significant share of the overall resistance.

The response of the SE cap with soil removed from the cap sides (Figure 6.15c) is not representative because of disturbances that occurred during construction. A 2.5-foot-wide trench was excavated on the north side of the cap to make room for installing dowel anchor rods. The excavation was backfilled with sand prior to testing. These activities reduced the overall lateral capacity of the SE cap. Consequently, the contribution from the cap sides is most likely 1.5 to 2 times the value of 11 % shown in Table 6.6.

6.4.3 Effect of Repetitive Load Applications

Five load cycles were performed with the caps embedded in natural soil to examine the effect of repetitive load applications on the load-deflection response curves. Results from the first and fifth cycles are shown in Figure 6.16 for the NE and NW pile caps. The plots represent the load-deflection response after removing permanent set by resetting the deflection to zero, at the beginning of each load cycle. The same incremental load procedure was used in these tests, and the time lag between cycles (1 to 6 days) was representative of the time period between the different incremental tests. As shown in Figure 6.16, there is no discernable difference in behavior between the first and fifth cycles.

Therefore, it appears that the application of a small number of repetitive loads has no significant effect on the load-deflection behavior of the pile caps, particularly at the small deflections measured during this study.

6.4.4 Effect of Pile Cap Depth

The effect of cap depth or thickness on the lateral behavior of pile caps was examined by performing tests on two caps having the same plan dimensions (5 ft by 5 ft) and pile lengths (19 ft), but different depths. The piles were embedded more than 12 inches into the caps, which were heavily reinforced in both top and bottom faces. Cracking of concrete around the pile heads was not a factor because of the large amount of reinforcing steel, and the small deflections and rotations during testing. Load-deflection response curves for the NE 36-inch-deep and the NW 18-inch-deep pile caps are shown in Figure 6.17.

The response curves for the caps embedded in natural soil are shown in Figure 6.17(a). As previously described, the test on the NE cap in natural soil is not representative because of temporary trenches that were excavated at three locations around the cap during construction.

The results shown in Figure 6.17(b) were obtained from tests performed after soil was removed from around the caps. In this condition, the caps are isolated from the surrounding soil and, consequently, the lateral behavior is controlled by the resistance developed in the underlying piles. The two foundations behaved nearly identically in these tests, further indicating the presence of relatively homogeneous soil conditions around the piles. These results indicate that cap thickness has little to no effect on the lateral behavior of a pile group, if the cap is not embedded. A similar conclusion could be inferred for pile caps backfilled with very loose uncompacted soil.

The results of tests performed on the two caps backfilled with compacted crusher run gravel are shown in Figure 6.17(c). In this case, the 18-inch-deep NW cap deflected 20 % more than the 36-inch deep NE cap, at a lateral load of approximately 140 kips. This indicates that cap thickness influences the lateral response of a pile group. The magnitude of this effect depends on the shear strength and density of soil around the cap, the size of the cap, and the rotational restraint provided at the connection between the piles and cap.

In summary, a thicker pile cap is expected to deflect less than a thinner cap. As deflections increase, so will the disparity in performance between two caps of different size. This is because resistance developed by passive pressure in front of the caps will become increasingly significant at larger movements.

6.4.5 Effect of Pile Length

The effect of pile length on the lateral behavior of pile groups was examined by performing comparable tests on two caps having the same dimensions (5 ft by 5 ft by 3 ft deep), but different lengths of piles. Load-deflection responses for the NE cap with 19-foot-long piles and the SE cap with 10-foot-long piles are shown in Figure 6.18 for the following three conditions.

- 1. Pile caps embedded in natural soil, Figure 6.18(a):**

The resistance provided by the SE group (10-ft-long piles)

was 14 % less than the resistance provided by the NE group (19-ft-long piles), at 0.1 inches of deflection.

2. Pile caps with no passive or side resistance, Figure 6.18(b): The resistance provided by the SE group (10-ft-long piles) was 35 % less than the resistance provided by the NE group (19-ft-long piles), at 0.2 inches of deflection.

3. Pile caps backfilled with compacted gravel, Figure 6.18(c): The resistance provided by the SE group (10-ft-long piles) was 33 % less than the resistance provided by the NE group (19-ft-long piles), at 0.1 inches of deflection.

Pile group rotational stiffness, and, consequently, the lateral load behavior is affected by the vertical or axial capacity of piles in the group. The piles in the NE group were 19-feet-long, while the piles in the SE group were only 10-feet-long. As discussed in Chapter 7, rotational stiffness is primarily a function of pile side resistance. The longer piles in the NE group were able to develop larger side resistance forces than the shorter piles in the SE group. Consequently, the SE pile cap had a greater tendency to rotate as its leading piles were forced deeper into the ground and its trailing piles moved vertically upward. Larger cap deflections occurred as a result of these increased rotations. This explains the large difference in the load-deflection responses shown in Figure 6.18(b), when soil was removed from around the caps. As shown in Table 6.5, the SE cap rotated approximately 3 times as much as the NE cap during these tests.

6.4.6 Effect of Backfill Type and Density

Lateral load tests were performed on the NE, NW and SE caps to examine the effects of backfill type and density on pile cap lateral behavior. Response curves for tests in natural soil and gravel backfill are shown in Figure 6.19(a) for the NE cap, Figure 6.19(b) for the NW cap, and Figure 6.19(c) for the SE cap. In each case, caps embedded

in the stiff overconsolidated natural soils exhibited stiffer responses (smaller deflections) than caps backfilled with compacted gravel.

Tests were performed on the SE cap using four different backfill conditions, to further study the effect of soil strength on lateral load response. Direct comparisons are shown in Figure 6.20 for the following conditions:

1. Figure 6.20(a) – natural soil versus dense sand,
2. Figure 6.20(b) – dense sand versus loose sand,
3. Figure 6.20(c) – dense gravel versus dense sand, and
4. Figure 6.20(d) – loose sand versus no soil.

The most obvious trend in these comparisons is the direct relationship between backfill strength and lateral load behavior. Smaller deflections were observed in the stiffer, stronger soils, and deflections noticeably increased as soil strength and stiffness decreased. The stiffest, strongest soils are the natural undisturbed soils (smallest measured deflections) followed in decreasing order by dense gravel, dense sand, loose sand, and no soil (largest measured deflections).

These results further support the significance of cap resistance in the overall lateral behavior of pile groups. Not only does the cap provide a significant share of the resistance, but the magnitude of this resistance depends on the strength and stiffness of soil around the cap.

6.4.7 Effect of Cyclic Loading

The NE and NW pile groups were subjected to a large number of unidirectional loads to evaluate the effects of cyclic loading on the lateral resistance of caps backfilled with dense gravel. The load-deflection response at every 25 load cycles, and the deflection versus number of load cycles, is shown in Figure 6.21 for the NE and NW

caps. The effect of cyclic loading was small and appeared to level off after approximately 20 cycles. For instance, the NE cap deflections increased by 0.02 inches during the first 20 cycles and did not increase further over the following 130 cycles. The total increase in deflection for the NW cap was 0.035 inches, and 70 % of this occurred during the first 20 cycles.

Figure 6.22 shows the cyclic response of the SE cap embedded in natural soil. One hundred twenty unidirectional loads were applied during the test. The deflection versus load response for every 20 cycles of load is shown in Figure 6.22(a), and the deflection versus number of load cycles, is shown in Figure 6.22(b). As for the NE and NW caps, the effect of cyclic loading leveled off after approximately 20 cycles. The total increase in deflection was 0.034 in, and 80 % of this occurred during the first 20 cycles.

6.4.8 Ground Surface Movements

Vertical deflections of the backfill surface, in front of the NE cap, were monitored during the cyclic tests. Linear potentiometers were spaced 1 to 4 feet in front of the cap, as shown in Figure 6.23. Vertical deflections during the first load cycle (at 120 kip load and at zero load) are shown in Figure 6.23(a). Similar information is shown in Figure 6.23(b) for the 150th load cycle.

The vertical deflections were all in an upward direction, and the maximum values at peak load were observed in the potentiometers located one foot from the cap face. The vertical deflections were small, approximately 50 % of the horizontal cap deflections. The maximum permanent vertical deformation (the residual deflection after the 120 kip load was decreased to zero) was upward and occurred 2 feet in front of the cap.

Because the measured vertical deflections are very small, it is difficult to draw any firm conclusions from the results. The most significant observation is the upward movement of the backfill surface. This is caused by a combination of factors including dilatant behavior in the dense gravel backfill and the initial development of a passive soil wedge. As cap movements increase, the passive soil wedge will have a tendency to move

upward, as the cap rotates downward. The amount of this movement is controlled by the cap displacement and the interface friction between the front face of the cap and the backfill soil.

6.4.9 Effect of Sustained Loading

The effect of sustained lateral loads on pile cap performance was investigated for two soil conditions:

1. NE and NW caps backfilled with gravel (Figure 6.24)
2. SE cap embedded in natural ground (Figure 6.25).

Loads were incrementally increased to 135 kips and then held constant. As shown in Figures 6.24 and 6.25, there were no significant changes in horizontal deflections during sustained application of load. These results are comparable to the long-term performance of vertically loaded footings founded in dense granular soils or in overconsolidated low-plasticity fine-grained soils (same types of soil used in this study).

6.5 PASSIVE LOAD RESISTANCE WITHOUT PILES

Lateral load tests were performed on the bulkhead, which was located at the west end of test trench B (Figure 3.1), to provide a means of experimentally studying passive pressure resistance without the influence of piles.

6.5.1 Effect of Backfill Type on Passive Load Resistance

The bulkhead was initially loaded against undisturbed natural ground. The load-deflection response curve for this test is shown in Figure 6.26. Loads were applied in 15 kip increments, up to a load of about 137 kips. Maintaining this load was difficult because the deflections did not stabilize over time, as shown in Figure 6.27. The resistance dropped off dramatically after about 90 minutes of loading, indicating failure within the soil mass. Cracks were observed extending outward from the lead corners of

the bulkhead, in a direction roughly parallel to the direction of loading. The cracks ranged in width from hairline to 1/4-inch. The most visible crack was 45 inches long.

After completing the first series of tests, the natural soil was excavated from the front side of the bulkhead and replaced with compacted gravel backfill. The excavation extended to the bottom of the bulkhead, 3.5 feet, and extended outward in front of the bulkhead 7.5 feet. The bulkhead was then incrementally loaded to failure. As shown in Figure 6.26, failure occurred at a load of 90 kips and a deflection of approximately 1.6 inches.

In summary, the passive resistance of the bulkhead backfilled with dense gravel was 35 % less than the resistance obtained by the bulkhead embedded in natural soil.

6.5.2 Effect of Cyclic Loading

Figure 6.28 shows the response of the bulkhead backfilled with crusher run gravel and monotonically loaded 120 times at a 70 kip load. The deflection versus load response for every 20 cycles of load is shown in Figure 6.28(a) and the deflection versus number of load cycles, is shown in Figure 6.28(b) for every 20 cycles of 70 kip load. The effect of cyclic loading appeared to level off after approximately 20 cycles. The total increase in deflection was 0.33 in, and 70 % of this occurred during the first 20 cycles.

As shown in Figure 6.28(b), the deflections decreased after 120 cycles of load, at the maximum applied load of 100 kips. This is attributed to the soil preloading or “hardening”, which occurred during the application of 120 cycles of 70 kip load.

Vertical deflections of the backfill surface, on the front side of the bulkhead, were monitored during the cyclic tests. Linear potentiometers were spaced from 1 to 4.5 feet in front of the bulkhead, as shown in Figure 6.29(c). Vertical deflections during the first load cycle (at 70 kip load and zero load) are shown in Figure 6.29(a). Figure 6.29(b) shows similar deflection distributions for the 120th load cycle. The vertical deflections

were upward, and the maximum values at peak load were measured in the potentiometers located 4.5 feet from the front face of the bulkhead.

The vertical deflections were relatively large, approximately 60 % of the horizontal cap deflections. The maximum permanent vertical deformation (the measured deflection after the load was decreased to zero) was 0.47 inches, and occurred 4.5 feet from the cap face.

The backfill surface moved upward, similar to the pile cap tests, except the bulkhead displacements were considerably greater. A noticeable bulge developed on the surface of the backfill, extending 7.5 feet in front of the bulkhead, and parallel to the bulkhead face. Surface cracks extended from the front corners of the bulkhead out to the bulge. Based on the surface crack pattern and location of bulging soil, it appears that the failure surface intersected the ground surface approximately 7.5 feet in front of the bulkhead. The bulkhead and the passive failure wedge appeared to move in a lateral and upward direction, as the load was increased.

6.6 SUMMARY

A field test facility was developed to perform full-scale lateral load tests on single piles, pile groups, and pile caps embedded in natural soil and backfilled with granular soil. The facility was designed specifically for this project to evaluate the lateral resistance provided by pile caps. A total of thirty-one tests were performed using incremental, cyclic, and sustained loading procedures.

Results from the testing program clearly support the research hypothesis that pile caps provide significant resistance to lateral load. The pile caps that were tested in this study provided approximately $\frac{1}{2}$ of the overall lateral resistance of the pile group foundations.

The lateral resistance provided by a pile group/pile cap foundation depends on many interacting factors, which were isolated during this study to evaluate their significance. In order of importance, these are:

1. **Stiffness and density of soil in front of the cap.** The passive resistance that can be developed in front of a pile cap is directly related to the backfill strength. As shown in Figure 6.20, the lateral resistance increases as the stiffness and density of soil around the cap increases.
2. **Depth of cap embedment.** Increasing cap thickness or depth will result in smaller lateral deflections, as shown in Figure 6.17.
3. **Rotational restraint at the pile head.** The rotational restraint available at the pile head can most often be described as a partially restrained condition. As shown in Figure 6.9(b), this condition results in response that falls between that of a fixed-head and free-head boundary condition. Response curves can be calculated using partially restrained boundary conditions by calculating, measuring, or estimating the rotational restraint, k_{mq} , as shown in Figure 6.10.
4. **Pile group axial capacity.** Lateral behavior of a pile group is directly related to the vertical or axial capacity of the piles. As shown by the results in Figure 6.18, pile groups comprised of longer piles (greater axial capacity) have significantly greater lateral resistance than groups with shorter piles. The rotation of the cap and the passive resistance developed in front of the cap are both affected by the axial capacity of the piles.
5. **Stiffness and density of soil around the piles.** Lateral load resistance increases as the stiffness and density of soil around the piles increase, as shown in Figure 6.8. The soil within the top 10 pile diameters has the greatest effect on lateral pile response.

6. **Cyclic and sustained loads.** For the conditions tested in this study, the effects from cyclically applied loads and long-term sustained loads were minor, or secondary, in comparison to the other factors described above. In other situations, such as high groundwater or soft compressible soils, the effect of cyclic loading or long term sustained loading could be more significant.

In conclusion, the load tests performed in this study clearly indicate that pile caps provide considerable resistance to lateral loads. The lateral resistance of a pile group is largely a function of the passive resistance developed by the cap and the rotational restraint of the pile-cap system. The passive resistance of the cap is controlled by the stiffness and density of the backfill soil and the interface friction angle. The rotational restraint is a function of the pile-to-cap connection and the axial capacity of the piles.

Table 6.1. Summary of lateral load tests conducted at setup location A - NE pile cap versus NW pile cap.

| Test No. | Test date | Foundation conditions | Type of test | Ground-water (ft) | Instrumentation comments |
|----------|-----------|---|---|-------------------|--|
| 1 | 6/8/98 | Both caps in full contact with natural ground | Baseline (no loads) | 11.7 | Evaluated instrumentation response over an 8 hour period. |
| 2 | 6/12/98 | Both caps in full contact with natural ground | Incrementally loaded to 134 kips | 11.7 | 6 Celesco and 6 Longfellow transducers (some sticking noted in Longfellow's) |
| 3 | 6/12/98 | Both caps in full contact with natural ground | Cyclically loaded to 132.5 kips (10 cycles) | 11.7 | 6 Celesco and 6 Longfellow transducers |
| 4 | 6/12/98 | Both caps in full contact with natural ground | Performed 10 load cycles to 100 kips | 11.7 | 6 Celesco and 6 Longfellow transducers |
| 5 | 6/18/98 | Both caps in full contact with natural ground | Incrementally loaded to 136 kips | 12.1 | 6 metal Celescos only, 3 per cap |
| 6 | 6/18/98 | Both caps in full contact with natural ground | Cyclically loaded to 137 kips (4 cycles) | 12.1 | 6 metal Celescos only, 3 per cap |
| 7 | 7/2/98 | Soil removed from the sides of both caps | Incrementally loaded to 137 kips | 13.1 | 12 Celesco transducers, 6 per cap |
| 8 | 7/2/98 | Soil removed from the sides of both caps | Cyclically loaded to 137 kips (4 cycles) | 13.1 | 12 Celesco transducers, 6 per cap |

Table 6.1. Concluded.

| Test No. | Test date | Foundation conditions | Type of test | Ground-water (ft) | Instrumentation comments |
|----------|-----------|--|--|-------------------|---|
| 9 | 7/9/98 | Soil removed from sides and front of both caps | Incrementally loaded to 136 kips | 13.4 | 12 Celesco transducers, 6 per cap |
| 10 | 7/9/98 | Soil removed from sides and front of both caps | Cyclically loaded to 137 kips (4 cycles) | 13.4 | 12 Celesco transducers, 6 per cap |
| 11 | 7/20/98 | Sides and front of both caps backfilled with crusher run aggregate | Incrementally loaded to 136 kips | 14.1 | 12 Celesco transducers, 6 per cap, and 4 Longfellows on NE cap backfill |
| 12 | 7/20/98 | Sides and front of both caps backfilled with crusher run aggregate | Performed 150 load cycles from 0 to 120 kips | 14.1 | 12 Celesco transducers, 6 per cap, and 4 Longfellows on NE cap backfill |
| 13 | 7/24/98 | Sides and front of both caps backfilled with crusher run aggregate | Sustained load test at 135 kips for 190 min | 14.4 | 12 Celesco transducers, 6 per cap, and 4 Longfellows on NE cap backfill |

Table 6.2. Summary of lateral load tests conducted at setup location B - SE pile cap versus bulkhead.

| Test No. | Test date | Foundation conditions | Type of test | Ground-water (ft) | Instrumentation comments |
|----------|-----------|--|--|-------------------|--|
| 14 | 8/1/98 | Pile cap and bulkhead in full contact with natural ground | Incrementally loaded to 135 kips | 14.7 | 6 Celescopes on cap, 4 on abutment, abutment failed at 135 kip sustained load (84 min) |
| 15 | 8/26/98 | Soil removed from sides of cap, bulkhead backfilled with crusher run aggregate | Incrementally loaded to 90 kips | 14.8 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |
| 16 | 8/29/98 | Soil removed from sides and front of cap, bulkhead backfilled with crusher run aggregate | Incrementally loaded to 95 kips | 15.0 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |
| 17 | 8/31/98 | Cap backfilled with uncompacted New Castle sand, bulkhead b/f with crusher run aggregate | Incrementally loaded to 100 kips | 15.0 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |
| 18 | 8/31/98 | Cap backfilled with compacted New Castle sand, bulkhead b/f with crusher run aggregate | Incrementally loaded to 100 kips | 15.0 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |
| 19 | 9/3/98 | Cap backfilled with compacted crusher run agg., bulkhead b/f with crusher run aggregate | Incrementally loaded to 100 kips | 15.3 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |
| 20 | 9/3/98 | Cap backfilled with compacted crusher run agg., bulkhead b/f with crusher run aggregate | Performed 150 cycles from 0 to 60 kips | 15.3 | 6 Celescopes on cap, 4 on abutment, and 4 Longfellow transducers on abutment backfill |

Table 6.3. Summary of lateral load tests conducted on the individual north pile.

| Test No. | Test date | Foundation conditions | Type of test | Ground-water (ft) | Instrumentation comments |
|----------|-----------|---|--|-------------------|--|
| 21 | 9/21/98 | North pile with rigid strut connection in natural soil | Incrementally loaded to 50 kips | 15.8 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 22 | 9/21/98 | North pile with clevis pin connection in natural soil | Incrementally loaded to 50 kips | 15.8 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 23 | 9/21/98 | North pile with clevis pin connection in natural soil | Performed 150 cycles from 0 to 50 kips | 15.8 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 24 | 9/30/98 | North pile with rigid strut connection, top 7' of pile embedded in loose sand | Incrementally loaded to 20 kips | 16.0 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 25 | 9/30/98 | North pile with rigid strut connection, top 7' of pile embedded in compacted sand | Incrementally loaded to 40 kips | 16.0 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 26 | 9/30/98 | North pile with clevis pin connection, top 7' of pile embedded in compacted sand | Incrementally loaded to 40 kips | 16.0 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |

Table 6.4. Summary of lateral load tests conducted on the individual south pile.

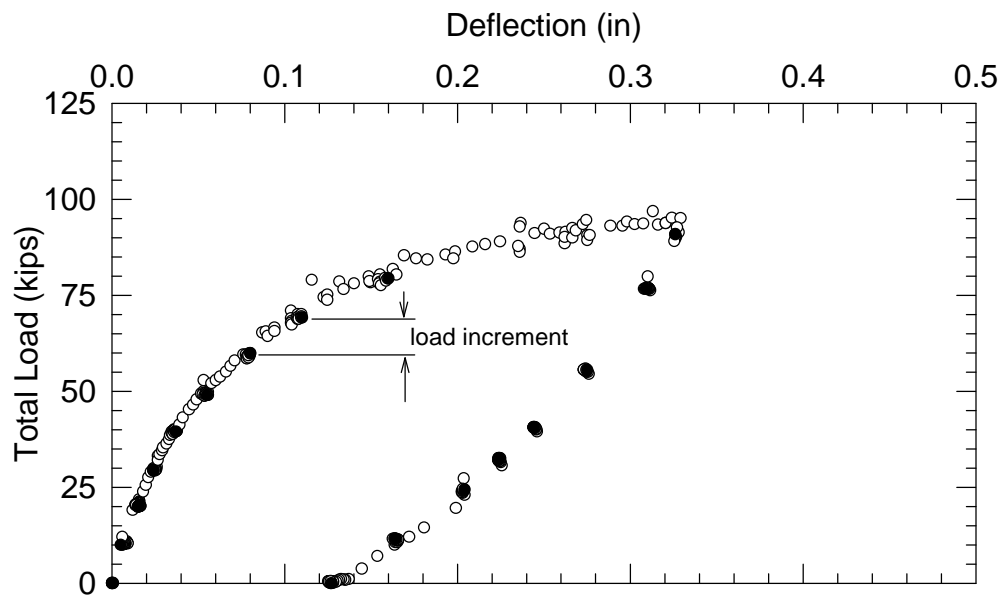
| Test No. | Test date | Foundation conditions | Type of test | Ground-water (ft) | Instrumentation comments |
|----------|-----------|---|--|-------------------|--|
| 27 | 10/7/98 | South pile with rigid strut connection in natural soil | Incrementally loaded to 74 kips | 16.1 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 28 | 10/7/98 | South pile with rigid strut connection in natural soil | Performed 150 cycles from 0 to 50 kips | 16.1 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 29 | 10/9/98 | South pile with rigid strut connection, top 5.7' of pile embedded in loose sand | Incrementally loaded to 45 kips | 15.9 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 30 | 10/9/98 | South pile with rigid strut connection, top 5.7' of pile embedded in compacted sand | Incrementally loaded to 50 kips | 15.9 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |
| 31 | 10/9/98 | South pile with rigid strut connection, top 5.7' of pile embedded in compacted sand | Performed 150 cycles from 0 to 50 kips | 15.9 | 3 Celescos mounted along pile C.L. and 3 mounted on tell-tale attached at G.S. |

Table 6.5. Measured angular rotations.

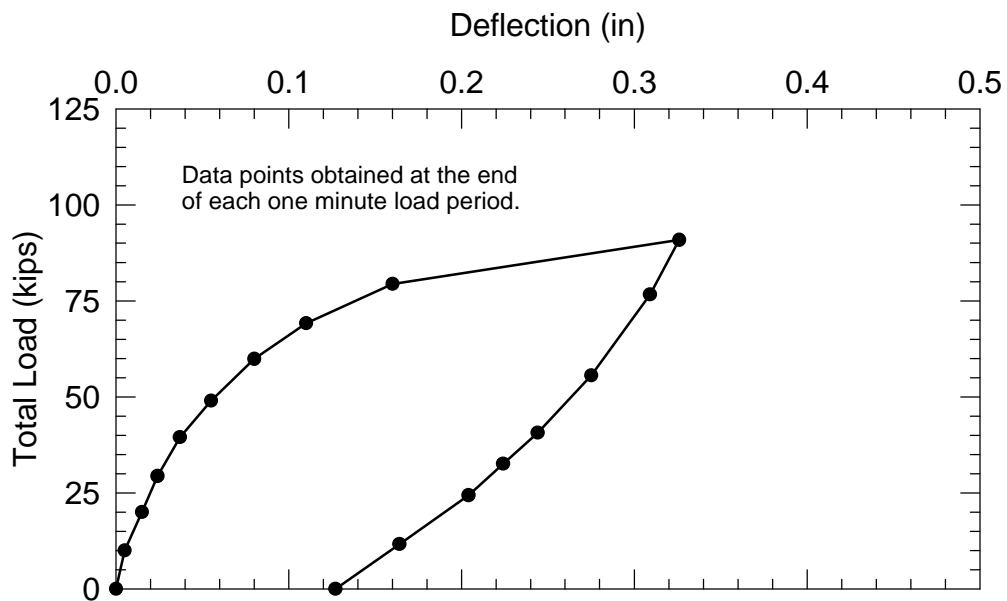
| Foundation | Soil condition around cap | Load (kips) | Tilt in the direction of load q (deg) | Torsional rotation t (deg) |
|------------|---------------------------|-------------|---|------------------------------|
| NE cap | natural soil | 136 | 0.001 | 0.001 |
| NE cap | gravel backfill | 136 | 0.044 | 0.002 |
| NE cap | no soil | 136 | 0.072 | 0.003 |
| NW cap | natural soil | 136 | 0.069 | 0.001 |
| NW cap | gravel backfill | 136 | 0.044 | 0.002 |
| NW cap | no soil | 136 | 0.083 | 0.003 |
| SE cap | natural soil | 92 | 0.026 | 0.003 |
| SE cap | gravel backfill | 92 | 0.019 | 0.002 |
| SE cap | dense sand | 92 | 0.070 | 0.000 |
| SE cap | loose sand | 92 | 0.106 | 0.000 |
| SE cap | no soil | 92 | 0.209 | 0.016 |
| Bulkhead | natural soil | 92 | 0.192 | 0.073 |
| Bulkhead | gravel backfill | 92 | 0.56 | 0.21 |

Table 6.6. Distribution of pile cap lateral resistance in natural soil.

| Test location | Contribution from sides of cap (%) | Contribution from front of cap (%) | Contribution from pile group (%) | Deflection (in) |
|---------------|------------------------------------|------------------------------------|----------------------------------|-----------------|
| NE cap | 24 | 16 | 60 | 0.09 |
| NW cap | 37 | 13 | 50 | 0.05 |
| SE cap | 11 | 39 | 50 | 0.06 |

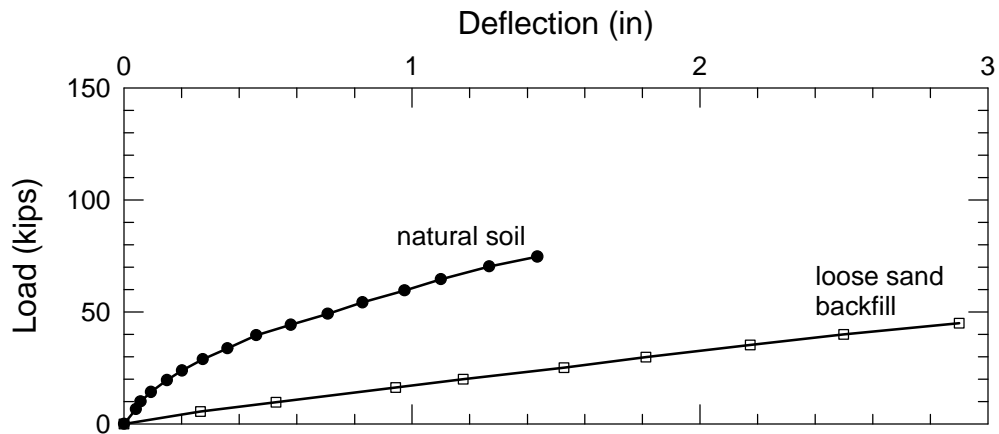


(a) Raw data from pile cap load test.

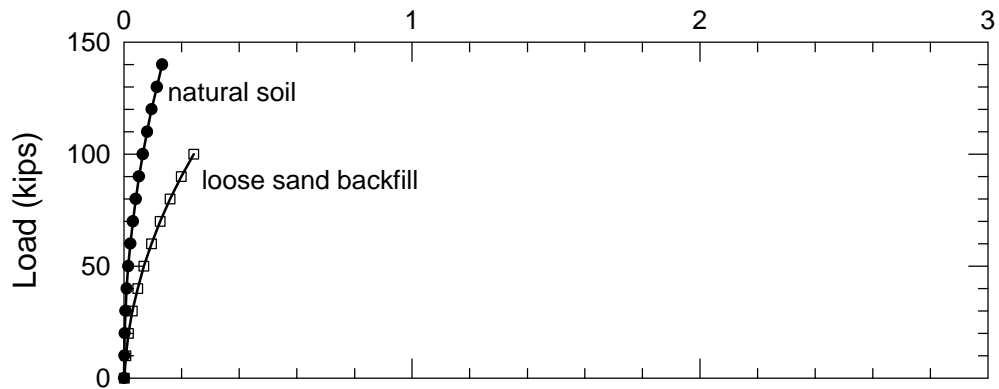


(b) Filtered data.

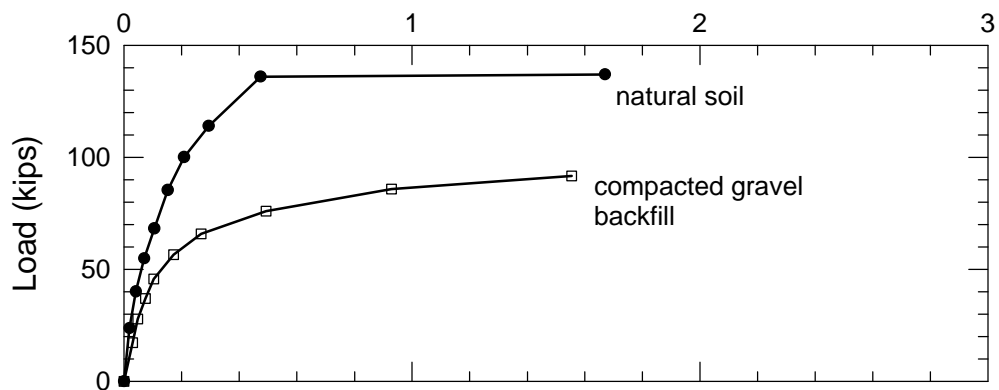
Figure 6.1. Typical load-deflection curve for SE pile cap backfilled with compacted gravel.



(a) South pile measured response.

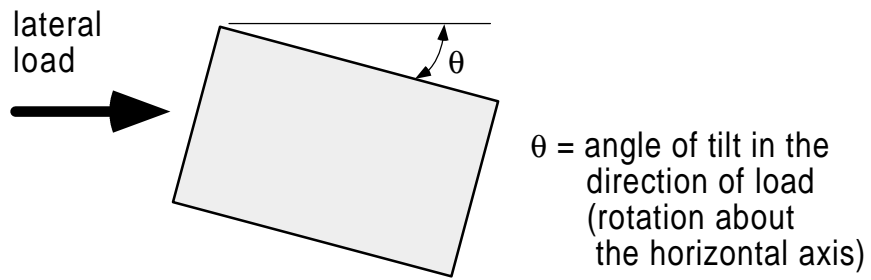


(b) SE pile cap measured response.

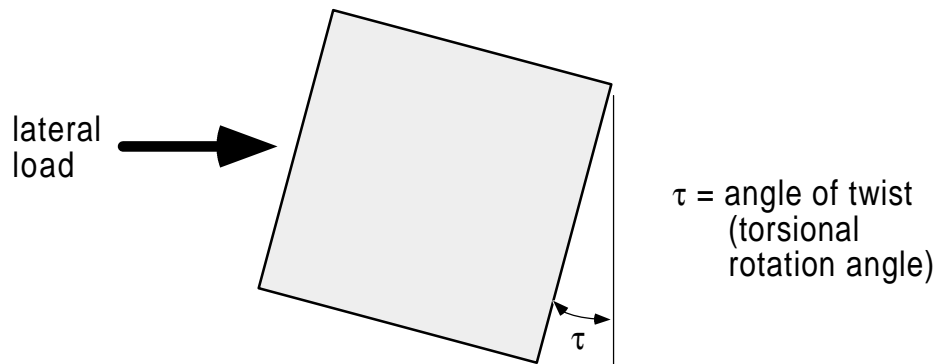


(c) Bulkhead measured response.

Figure 6.2. Typical results from lateral load tests performed at the field test facility.



(a) Cross-section of laterally loaded pile cap (exaggerated behavior).



(b) Plan view of laterally loaded pile cap (exaggerated behavior).

Figure 6.3. Description of pile cap rotation angles.

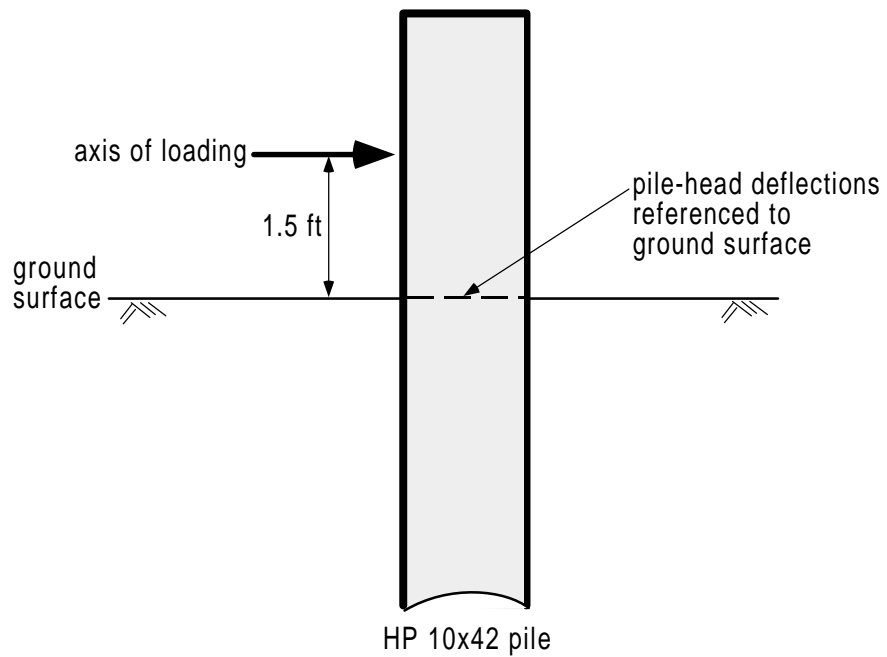


Figure 6.4. Single pile load testing arrangement.

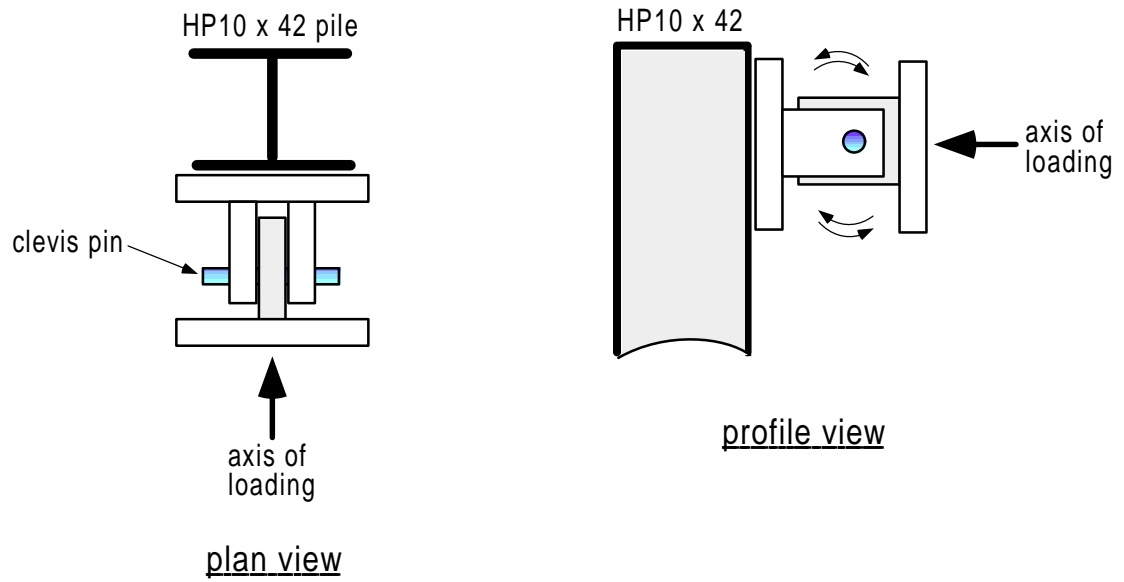


Figure 6.5. Pinned connection - clevis yoke and tongue.

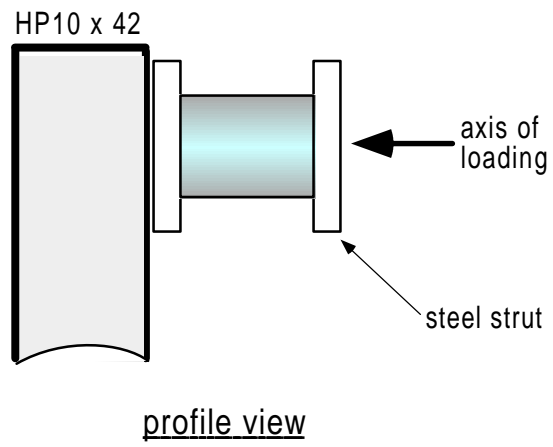


Figure 6.6. Rigid strut connection.

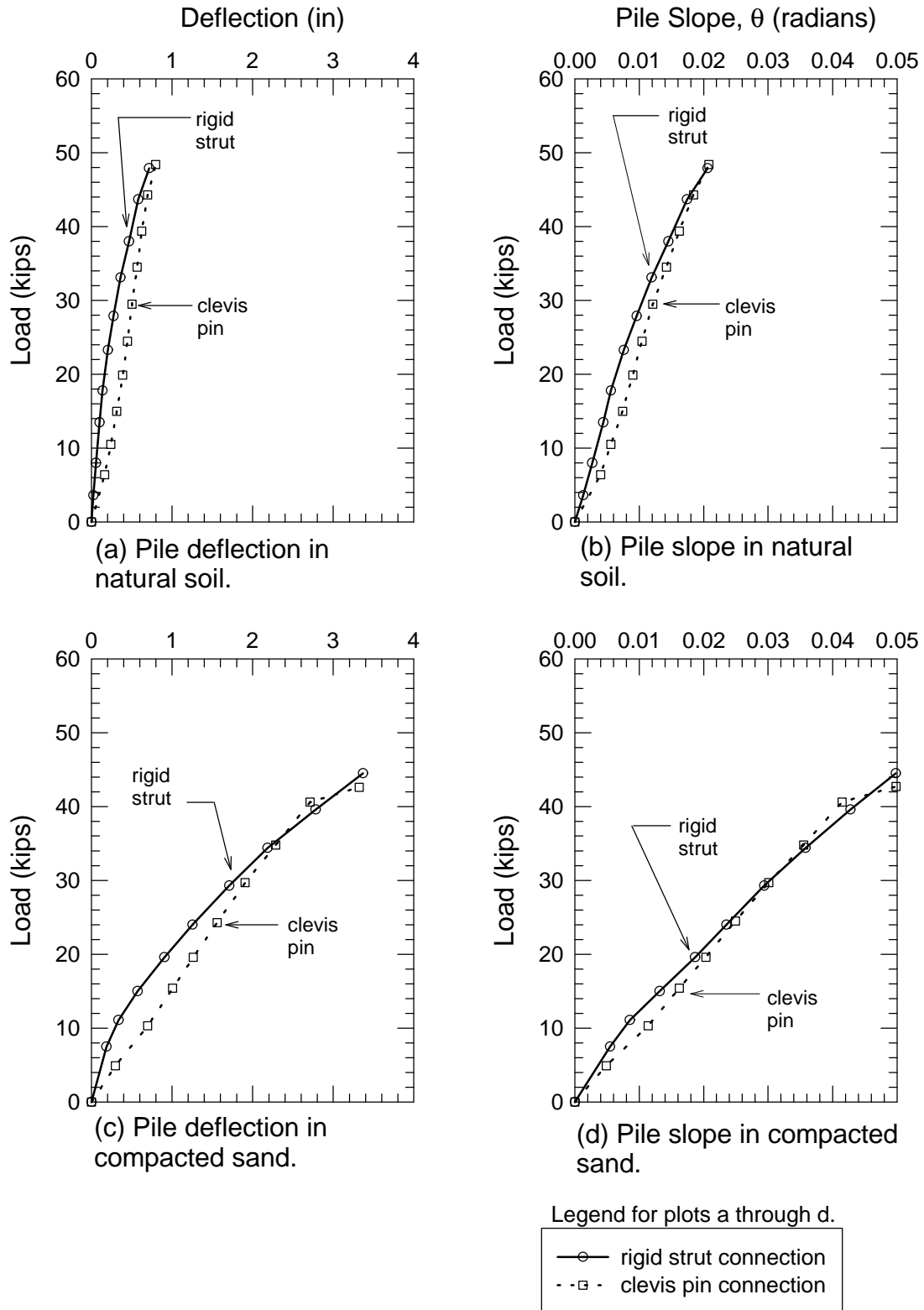


Figure 6.7. Comparison of load connectors used at the north pile.

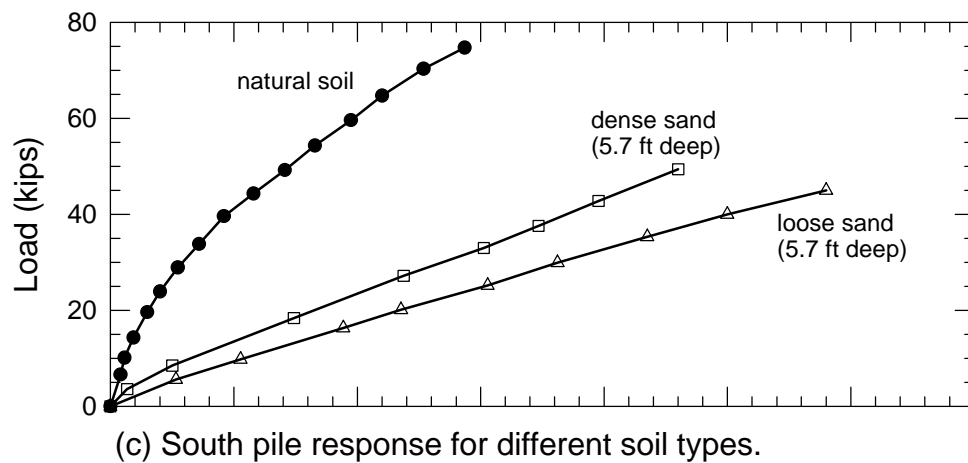
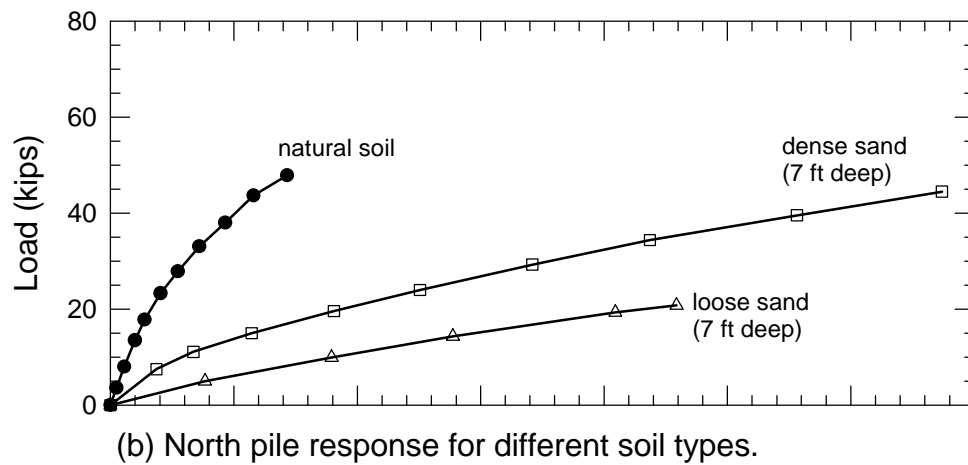
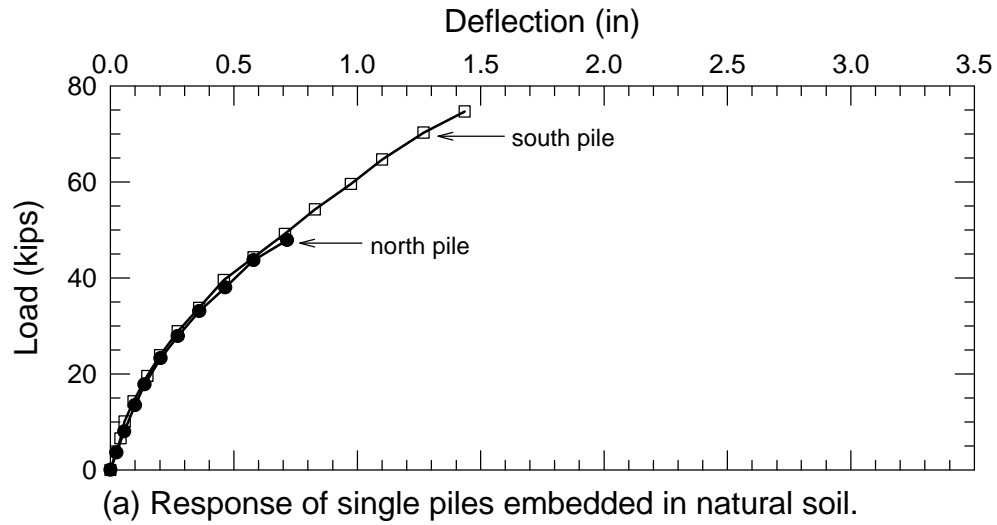


Figure 6.8. Effect of soil type and density on load deflection response of single piles.

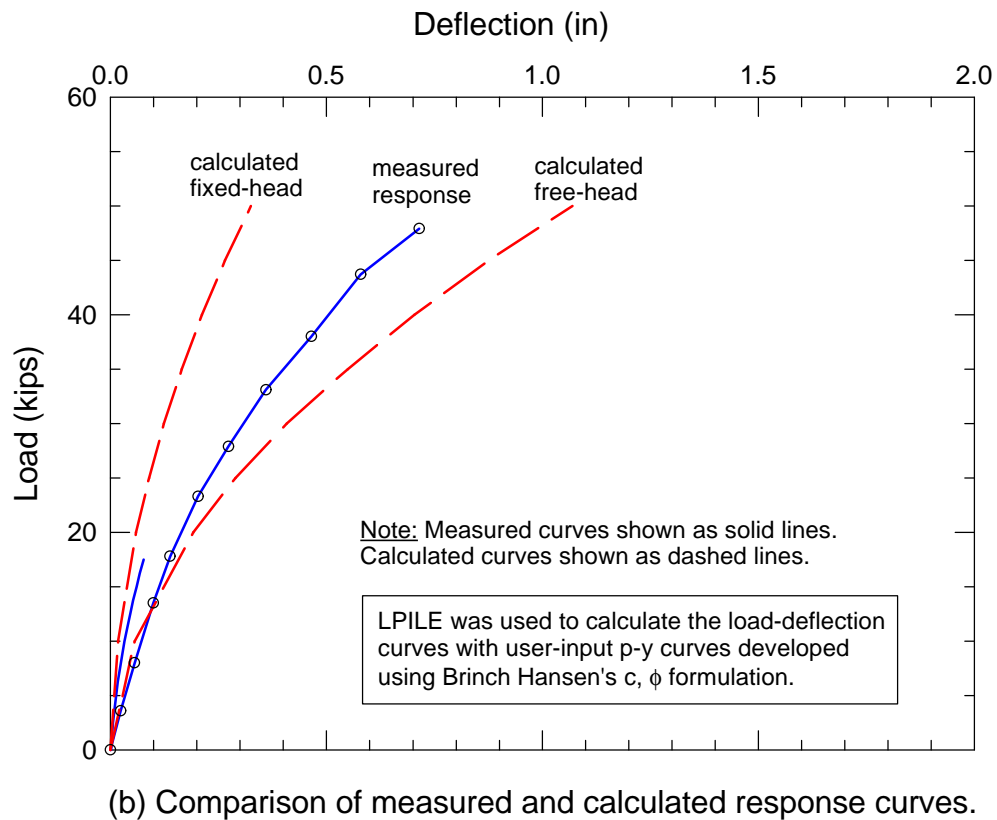
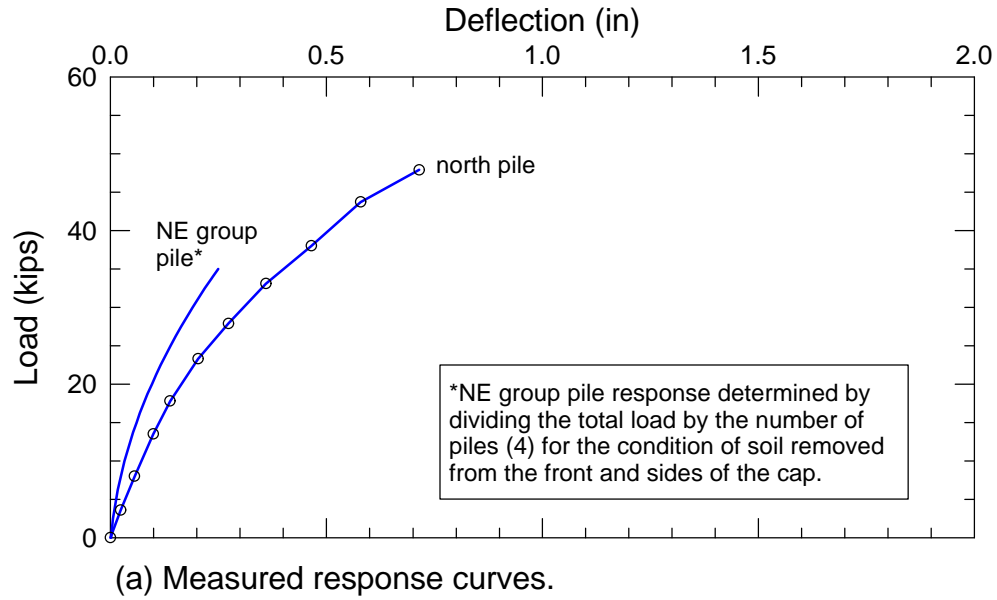


Figure 6.9. Effect of pile-head rotational restraint.

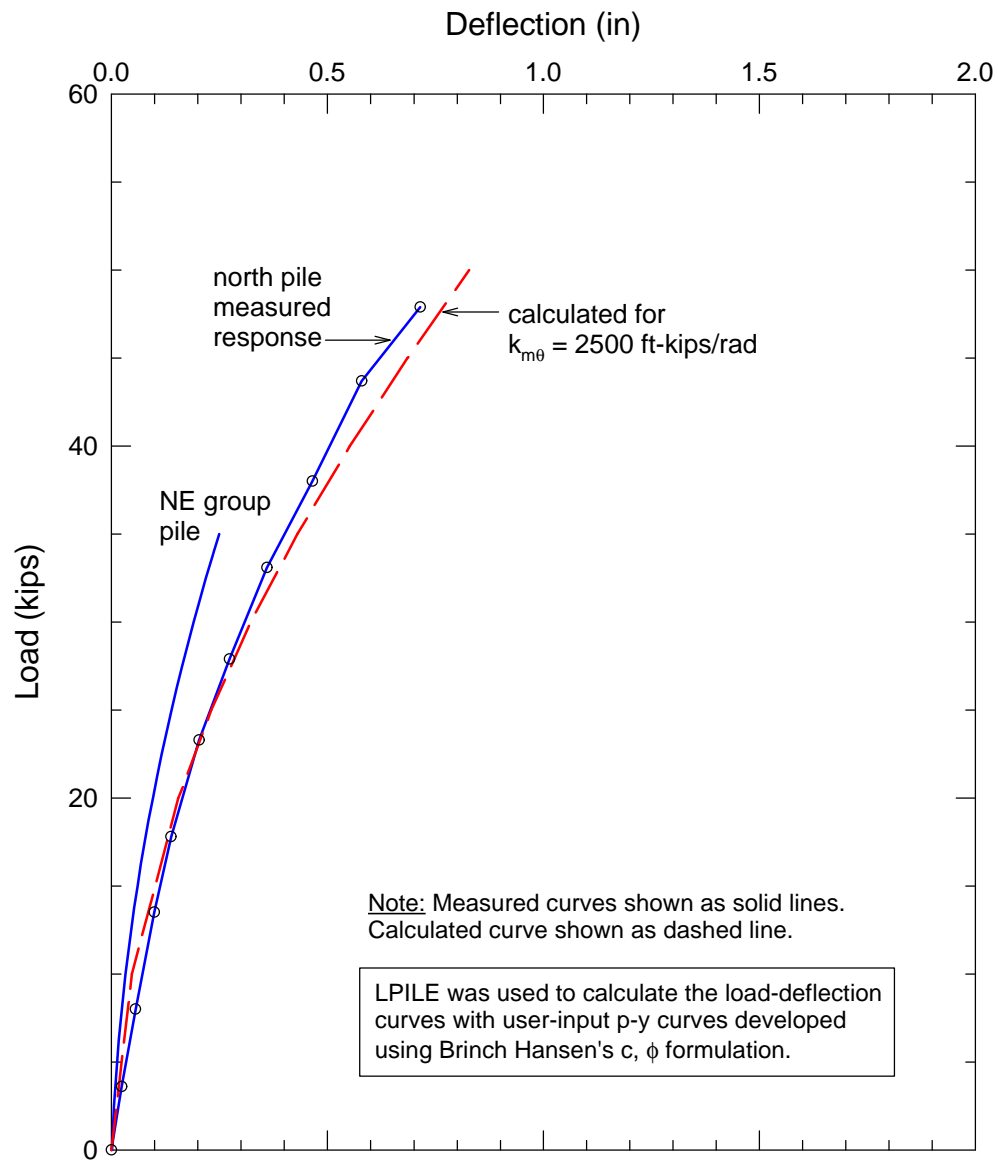


Figure 6.10. Response curve based on back calculated k_{mq} value for pile in natural soil.

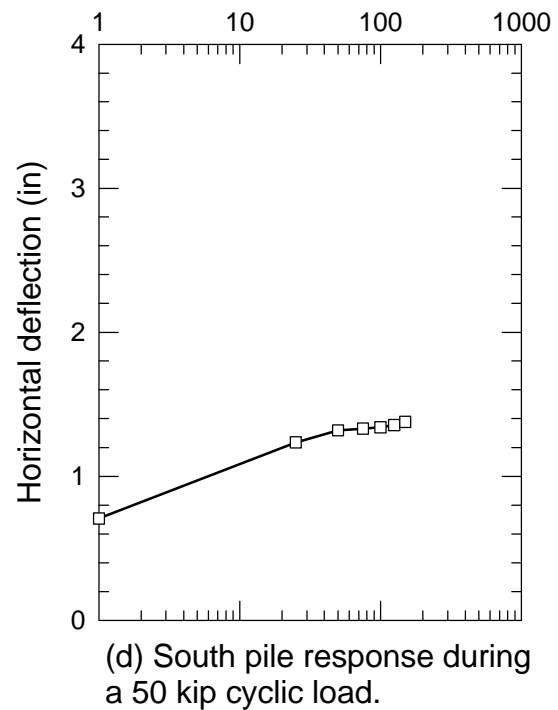
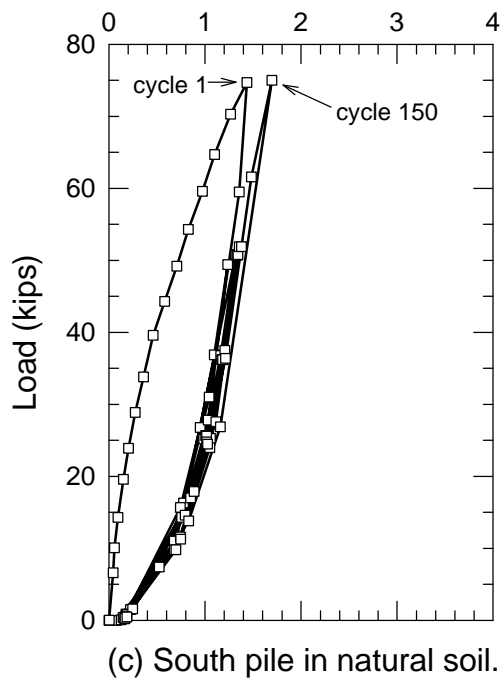
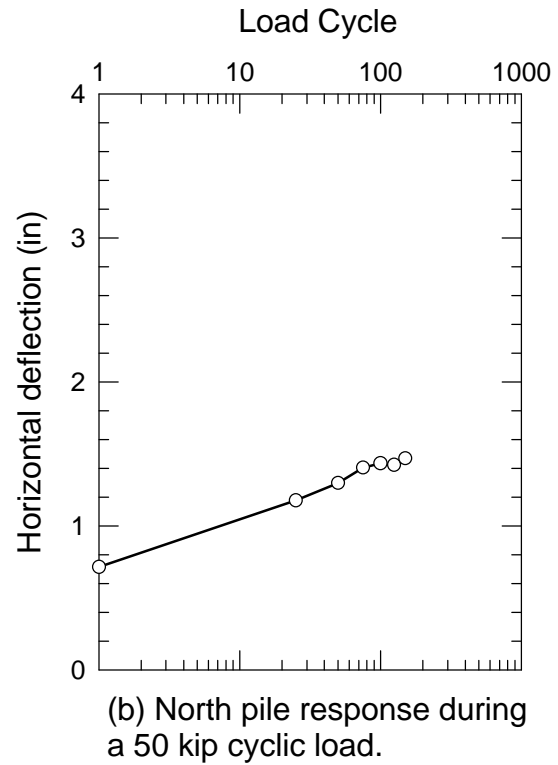
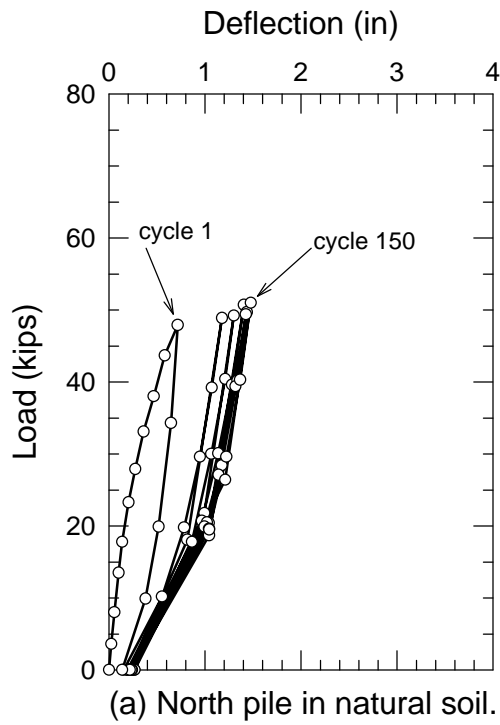


Figure 6.11. Effect of cyclic loading on single piles embedded in natural soil.

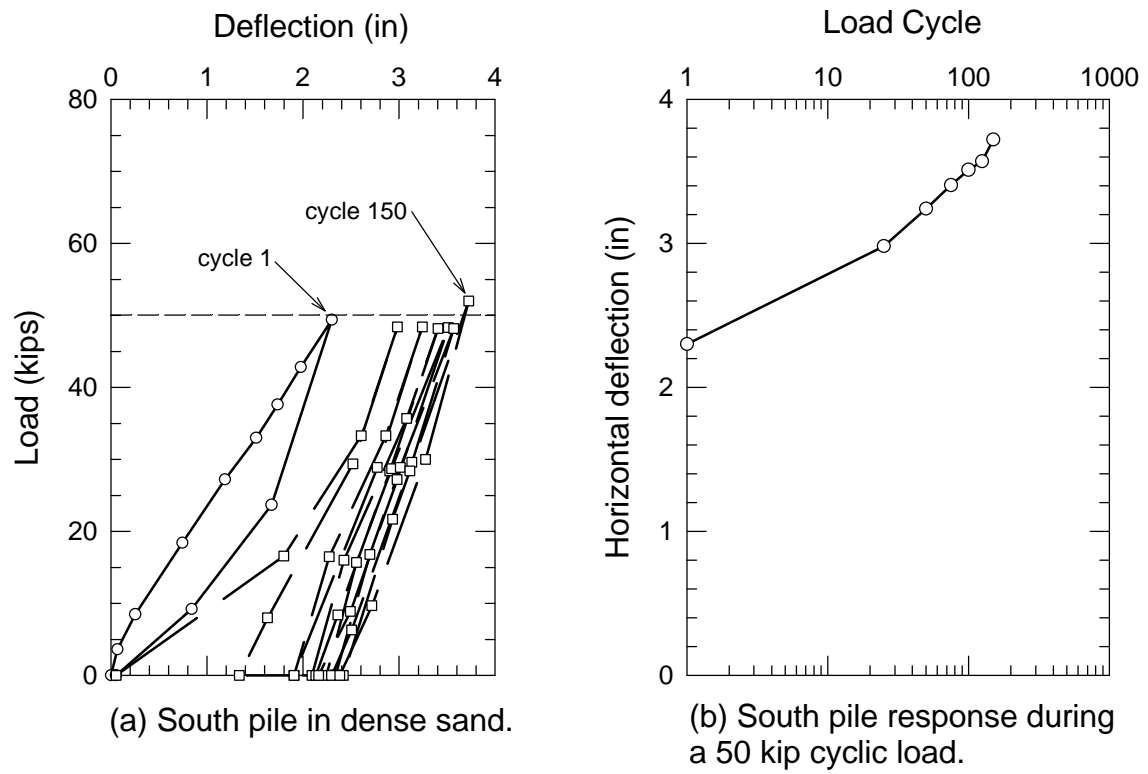


Figure 6.12. Effect of cyclic loading on south pile backfilled with 5.7 feet of compacted sand.

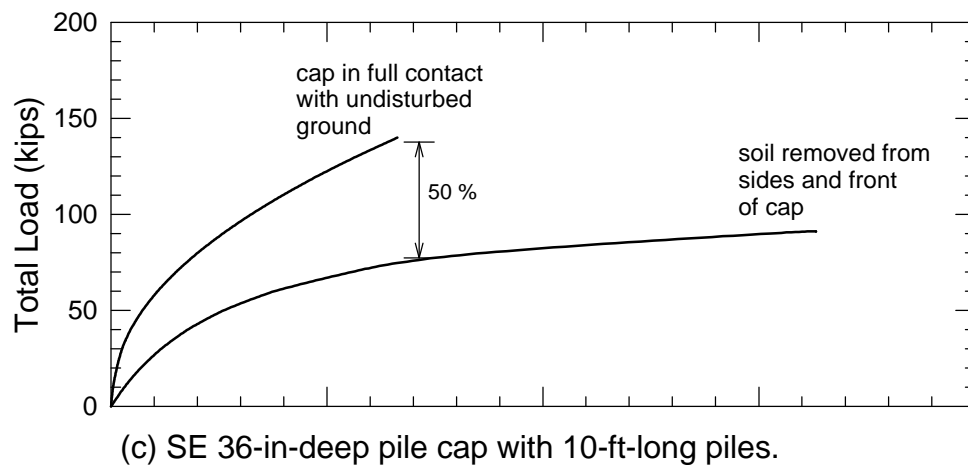
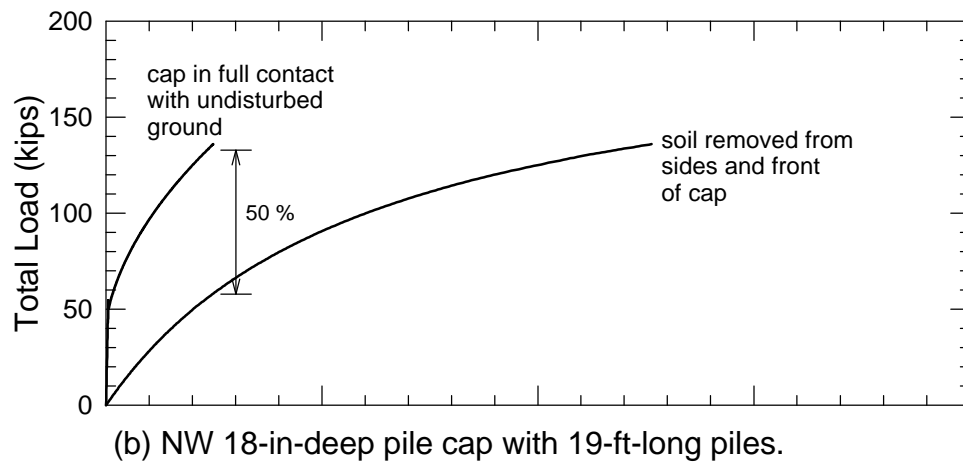
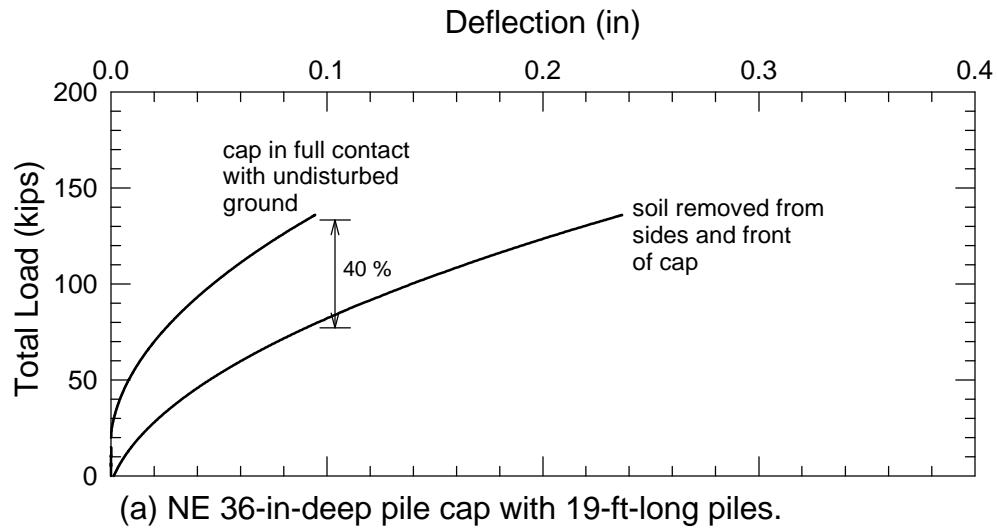
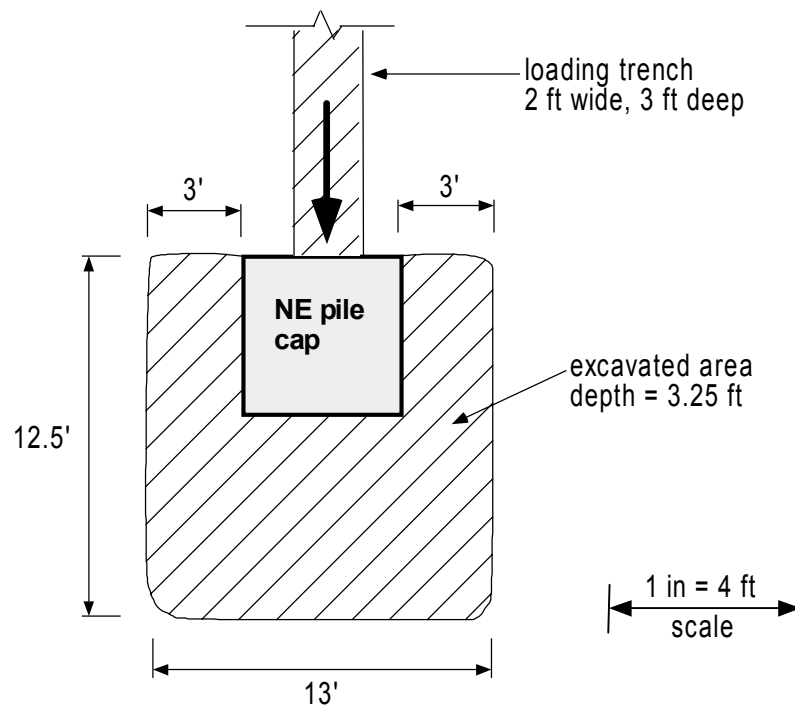


Figure 6.13. Load deflection response with and without pile cap embedment in natural soil.



(a) Photograph of soil excavation around pile cap.



(b) Plan view of excavation around NE pile cap.

Figure 6.14. NE pile cap with soil excavated from sides and front.

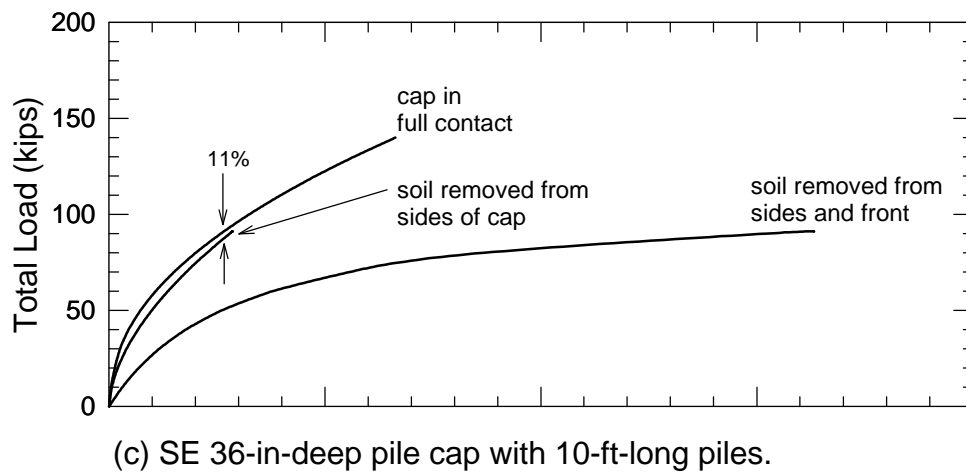
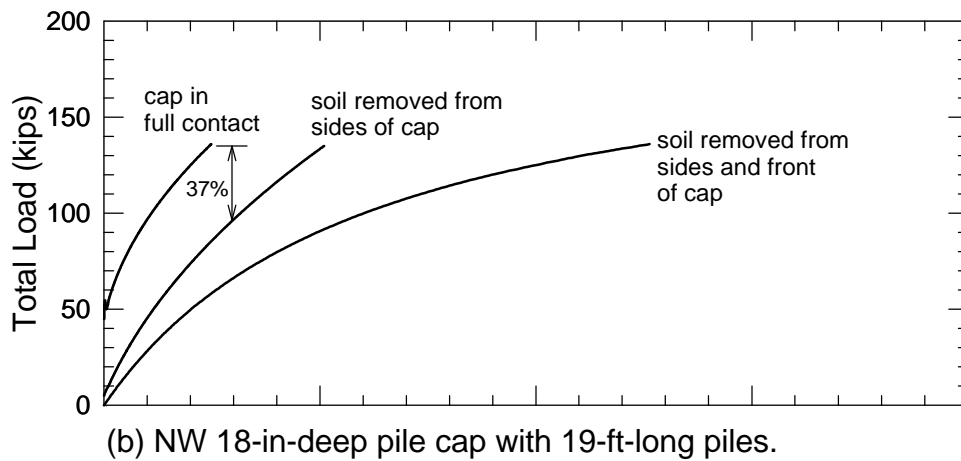
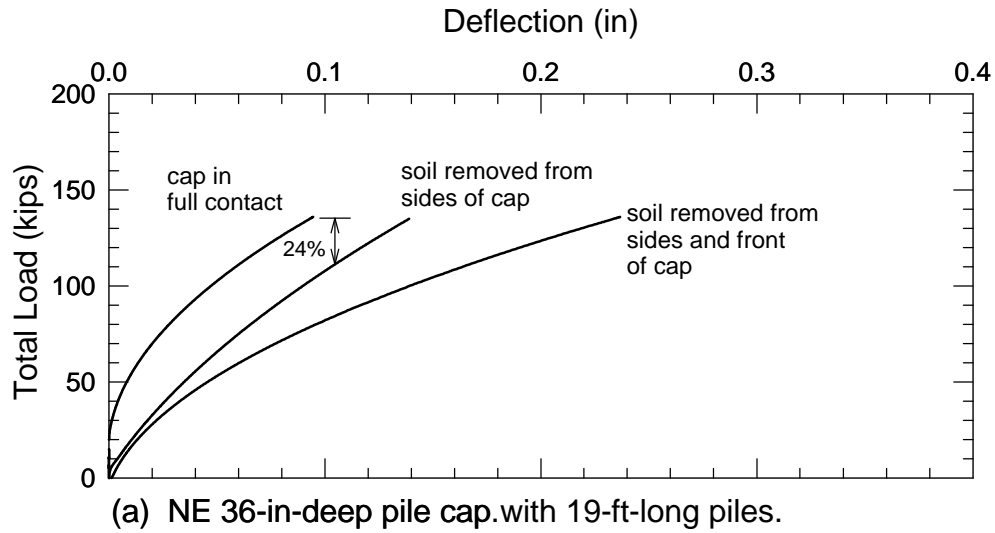
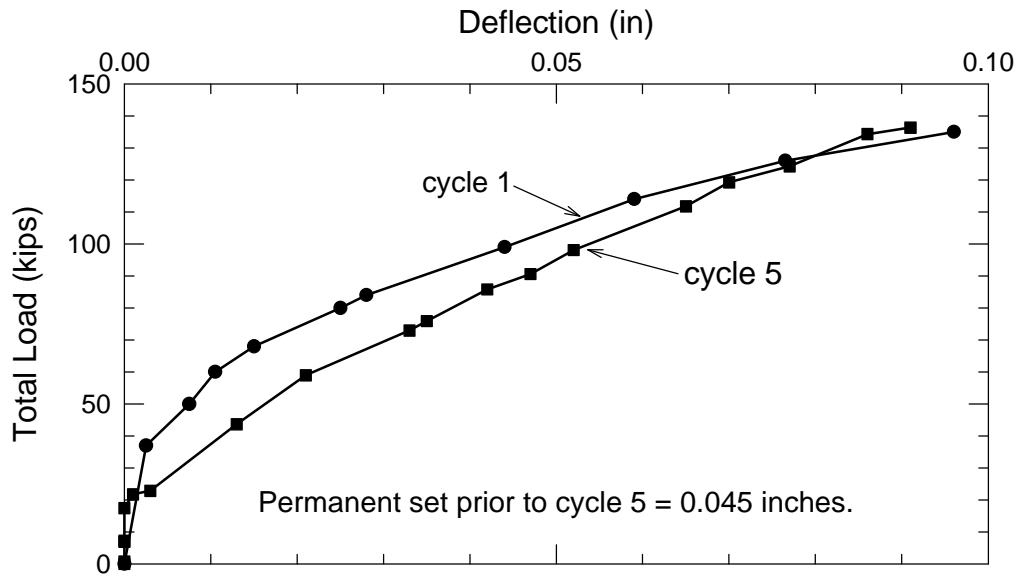
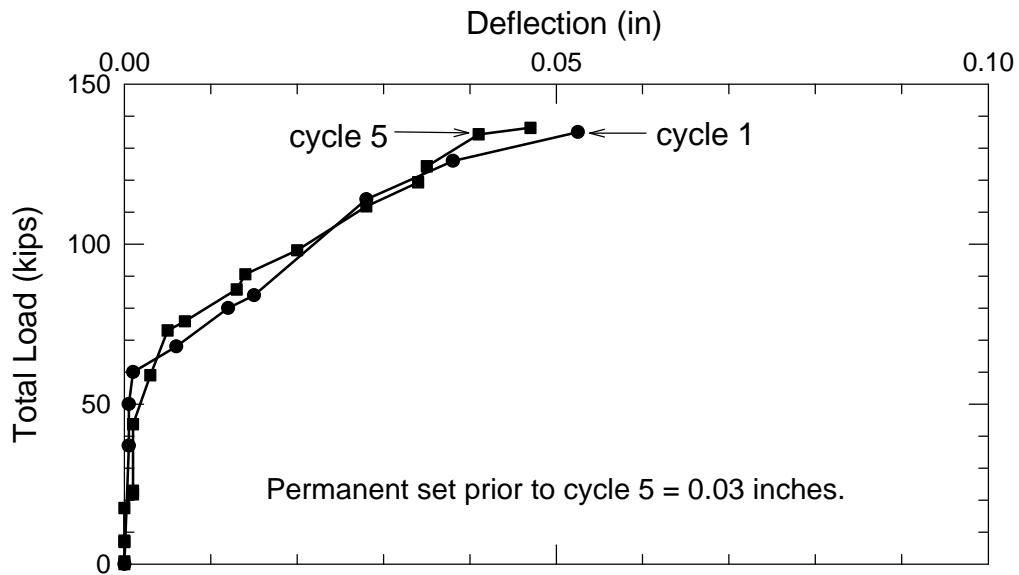


Figure 6.15. Effect of pile cap side resistance.



(a.) NE 36-in-deep cap in contact with natural soil.



(b.) NW 18-in-deep cap in contact with natural soil.

Note: Load cycle 5 was applied six days after cycle 1. Cycle 5 was initiated at an assumed net deflection of zero. Permanent set prior to cycle 5 is noted in the plots.

Figure 6.16. Effect of repetitive loading on pile cap deflections.

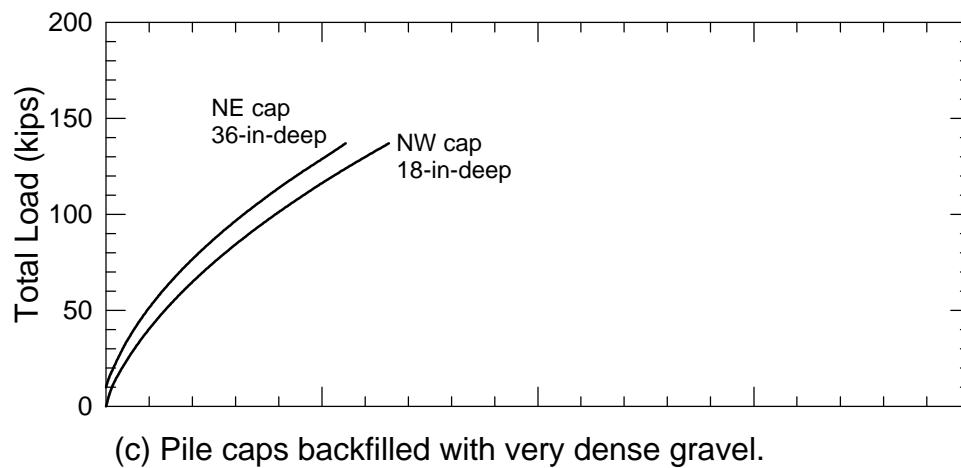
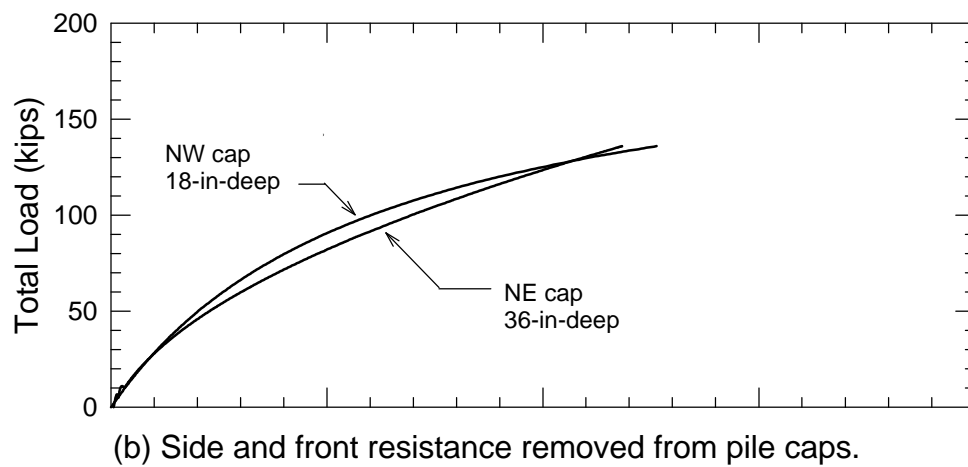
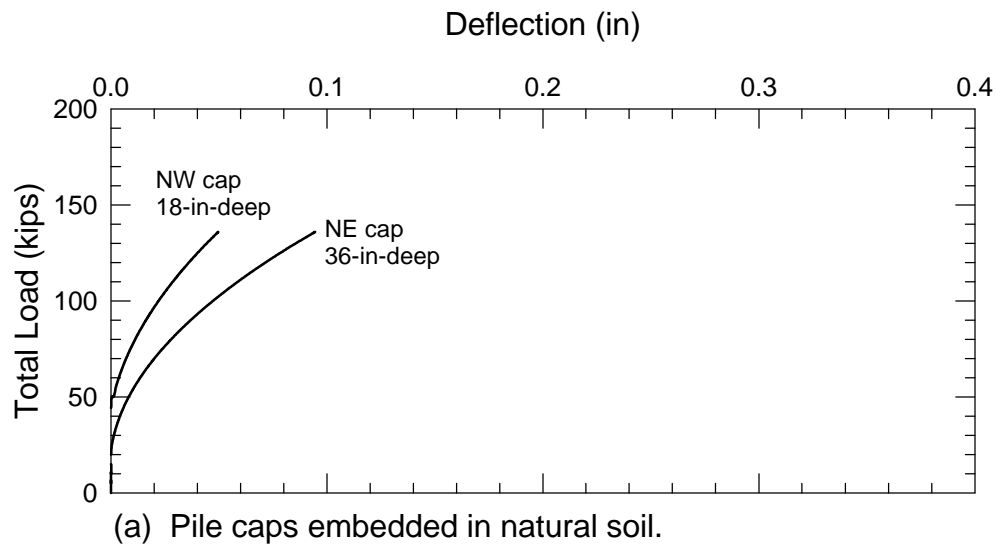


Figure 6.17. Effect of pile cap depth on load-deflection response.

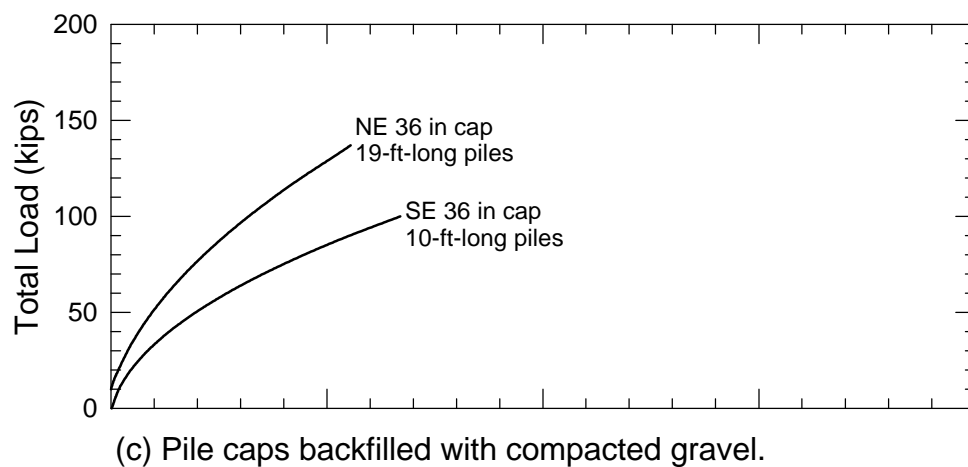
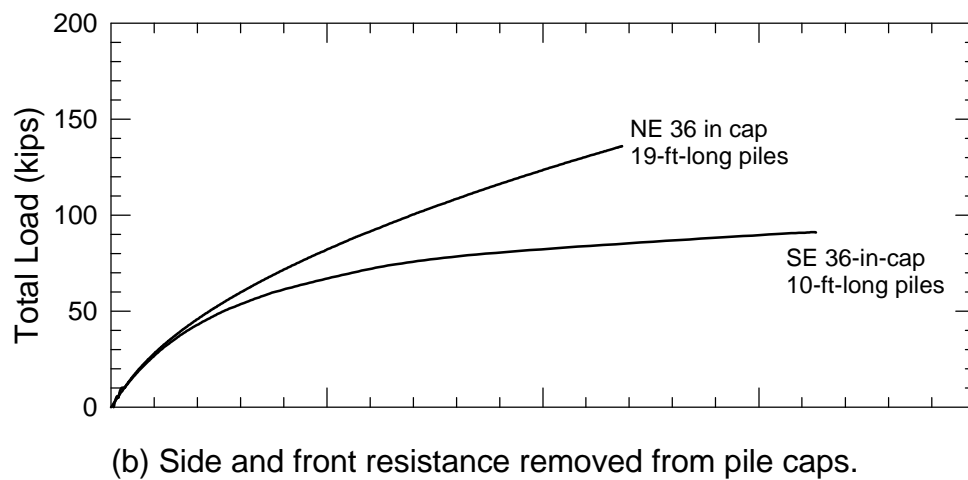
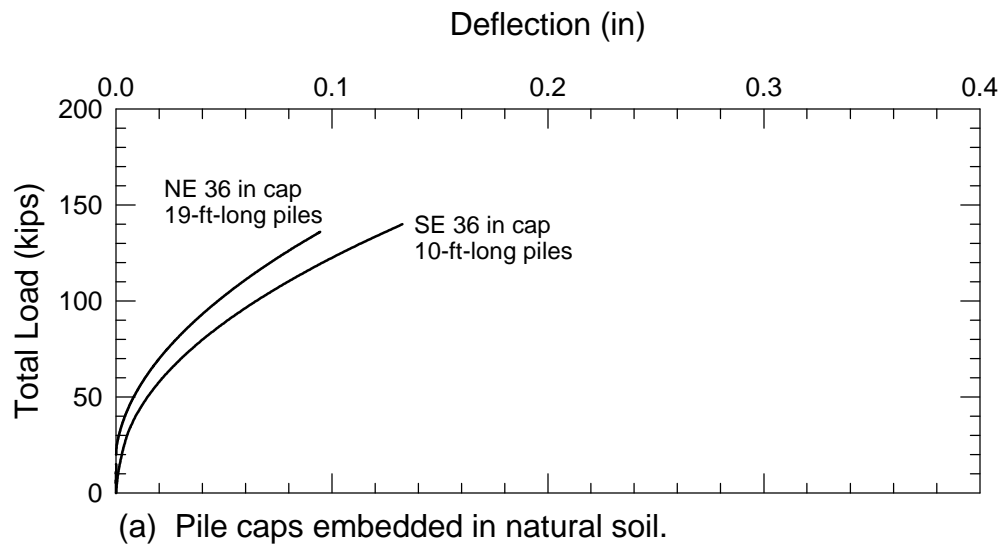
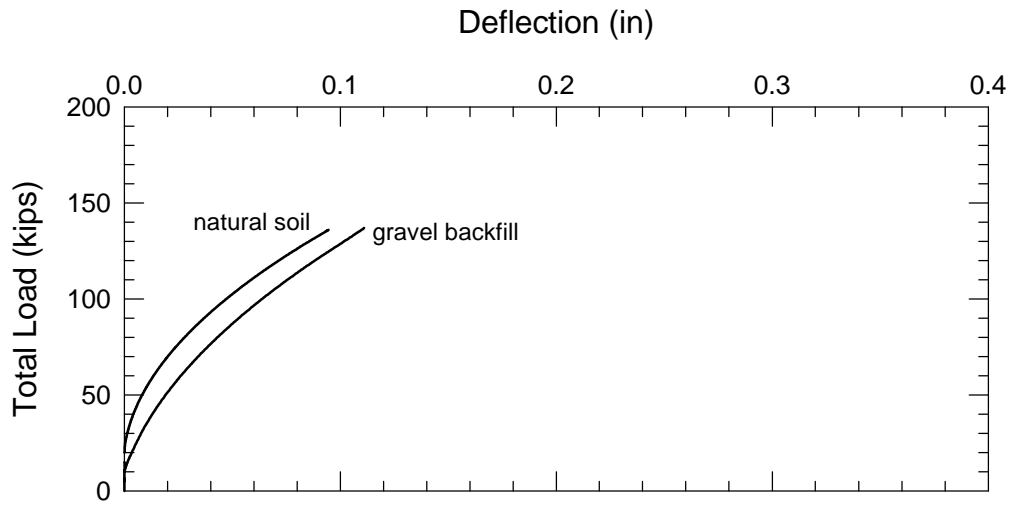
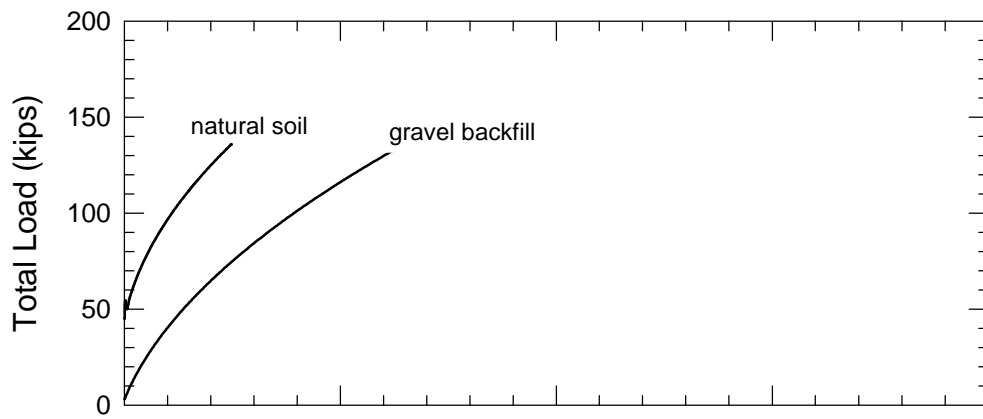


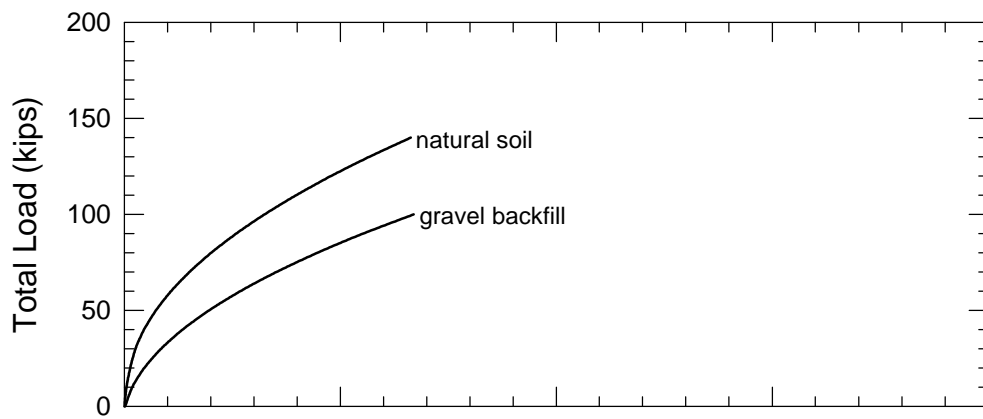
Figure 6.18. Effect of pile length on load-deflection response.



(a) NE 36-in-deep pile cap, 19-ft-long piles.

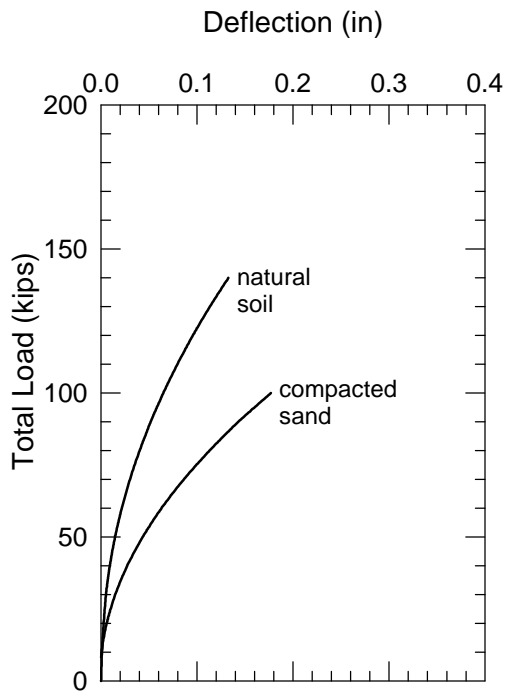


(b) NW 18-in-deep cap, 19-ft-long piles.

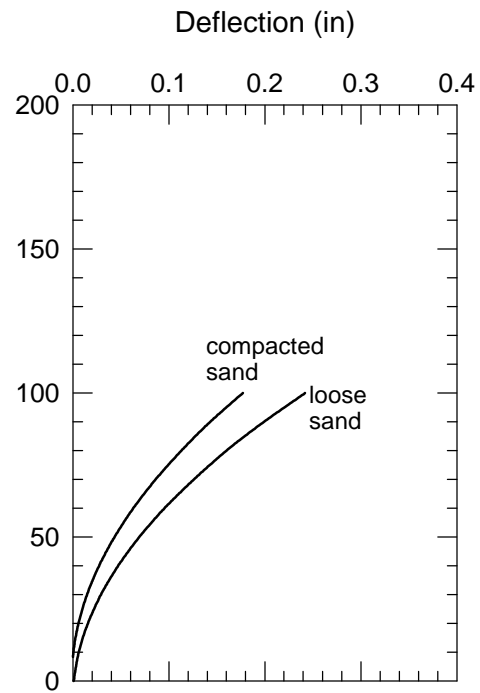


(c) SE 10-in-deep cap, 10-ft-long piles.

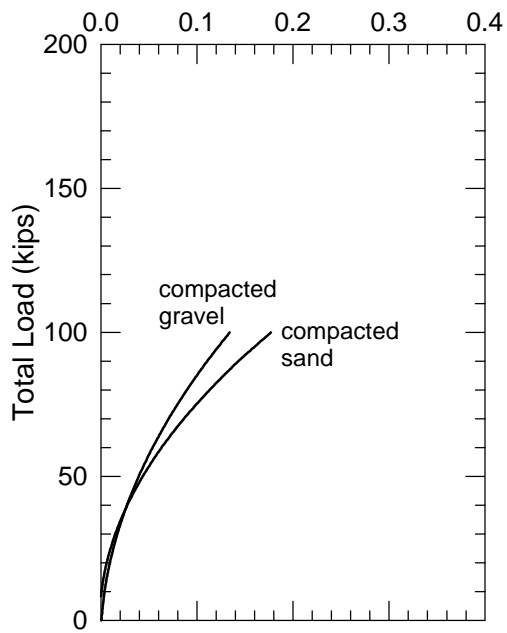
Figure 6.19. Comparison between natural soil and compacted gravel backfill.



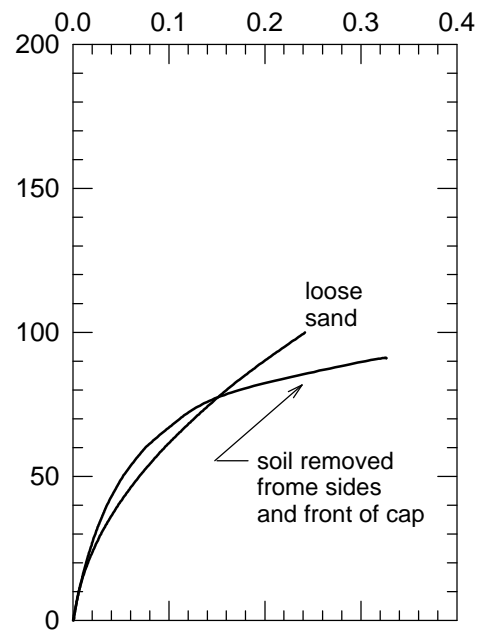
(a) Natural soil vs. compacted sand.



(b) Compacted sand vs. loose sand.



(c) Compacted gravel vs. dense sand.



(d) Loose sand vs. no backfill.

Figure 6.20. Effect of backfill type and density on load-deflection response of SE pile group.

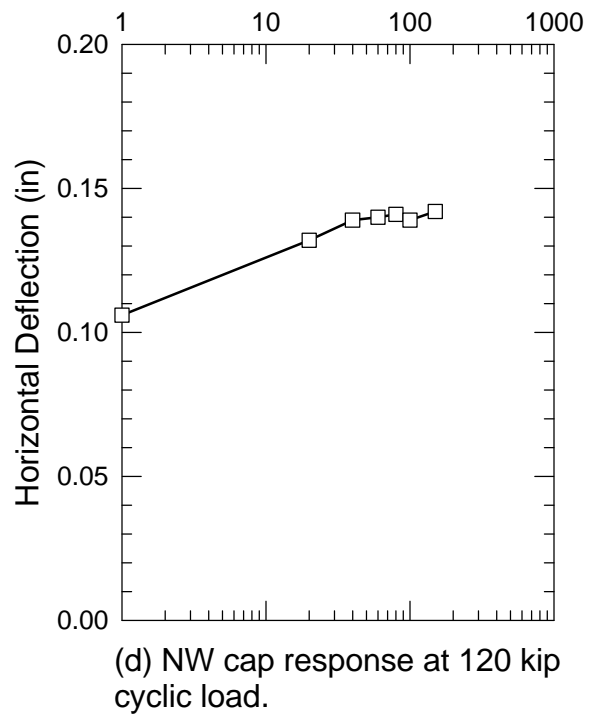
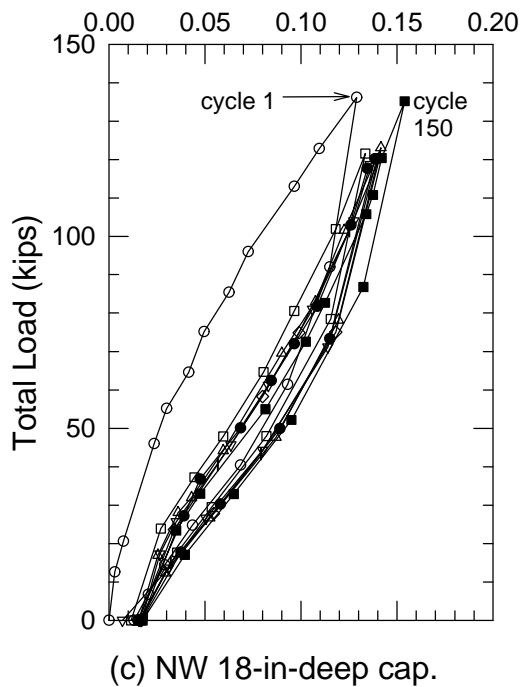
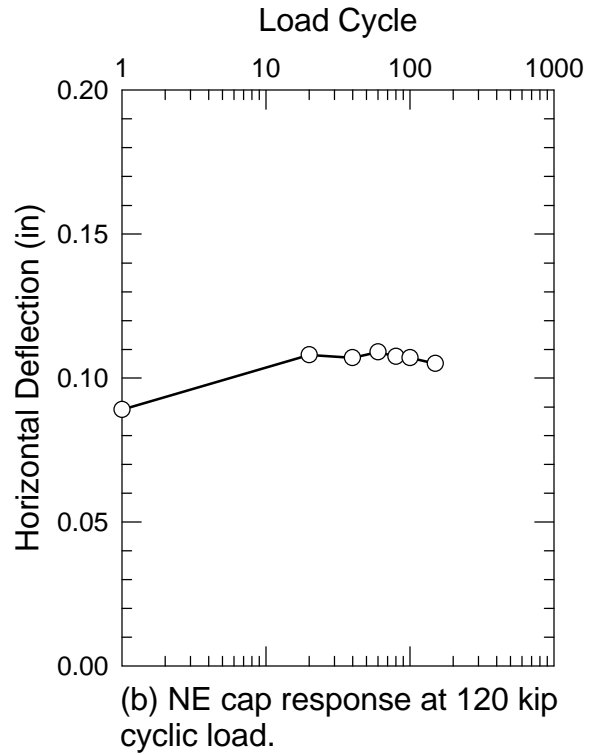
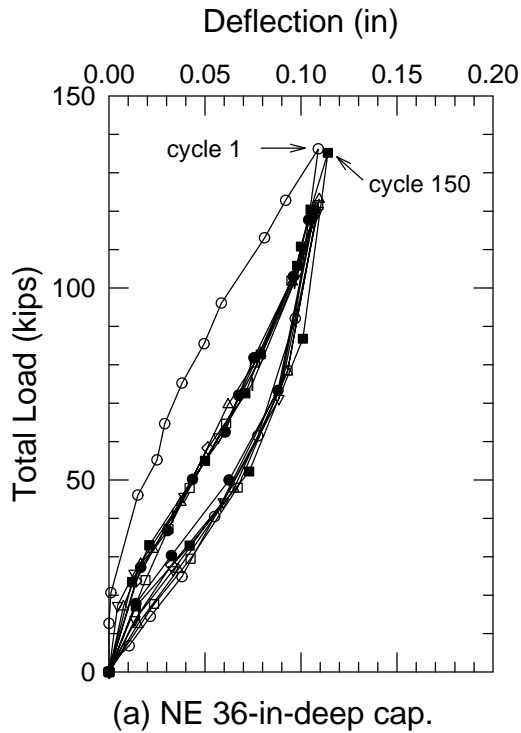


Figure 6.21. Cyclic response of NE and NW caps backfilled with compacted gravel.

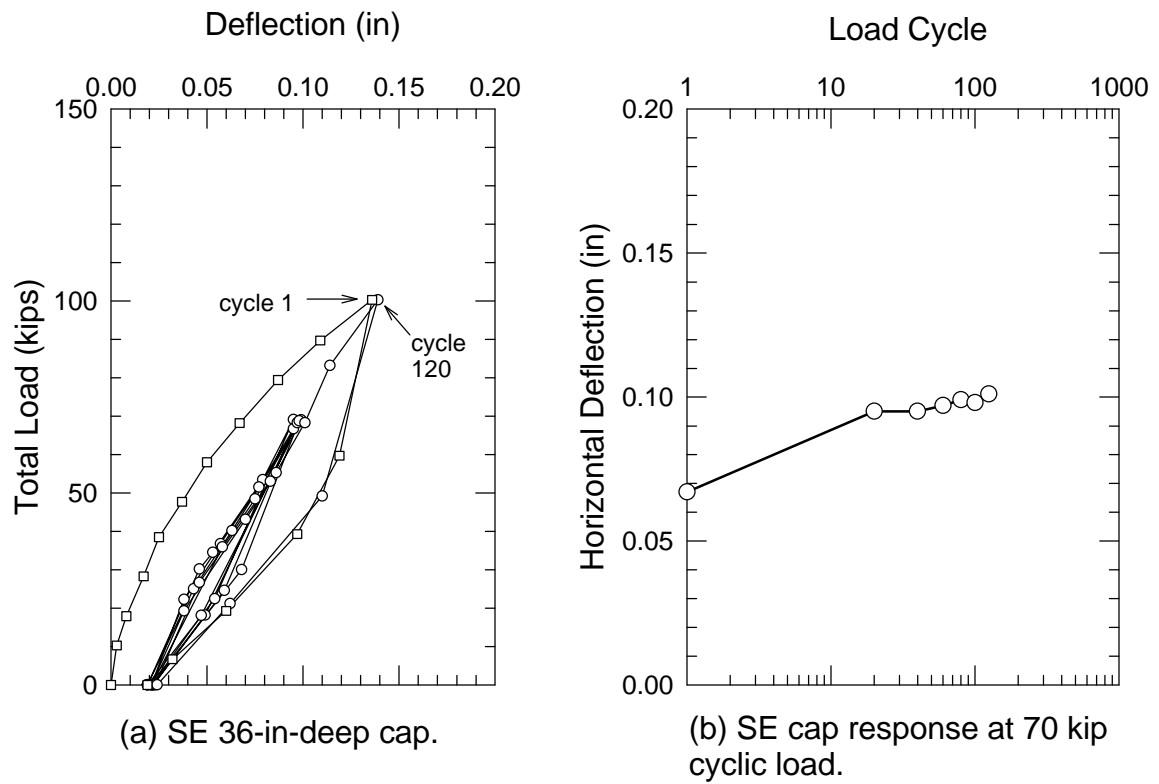
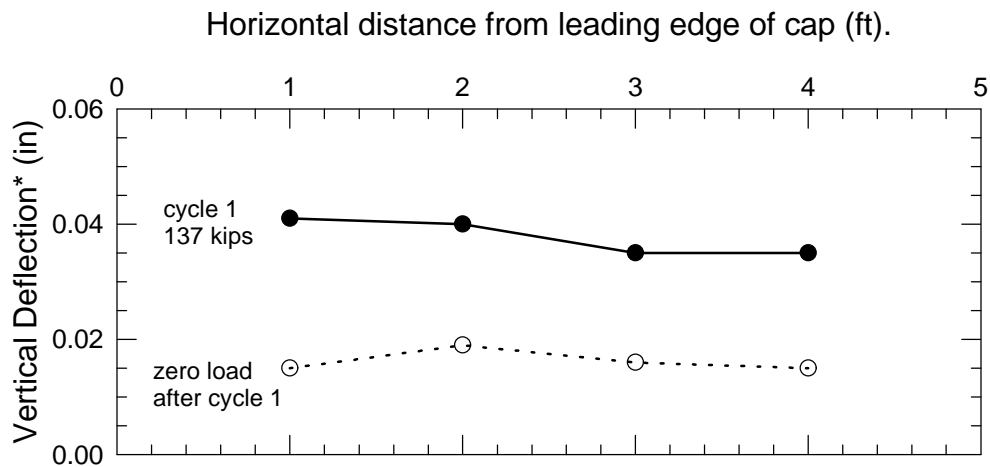
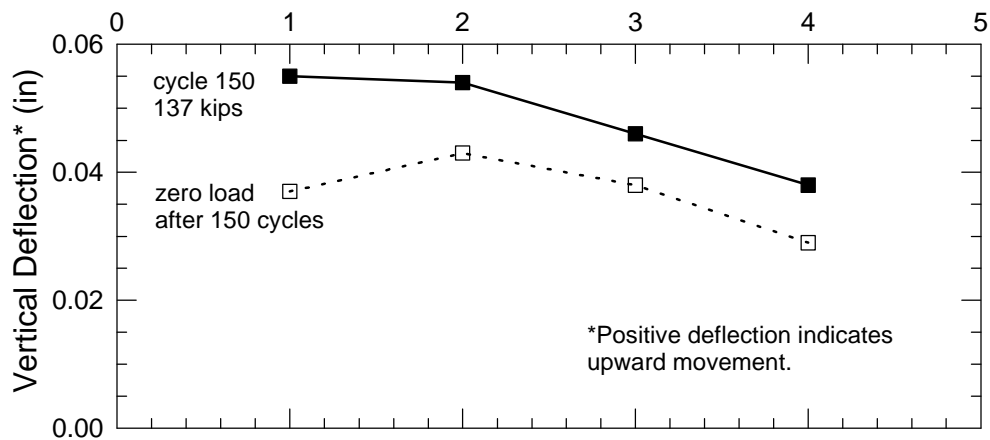


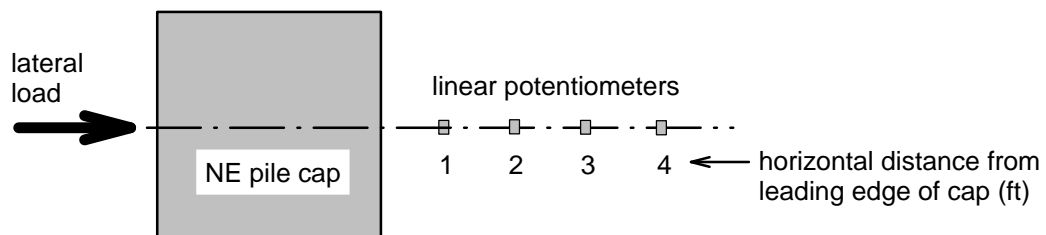
Figure 6.22. Cyclic response of SE cap backfilled with compacted crusher run gravel.



(a) Vertical movement caused by first load cycle.

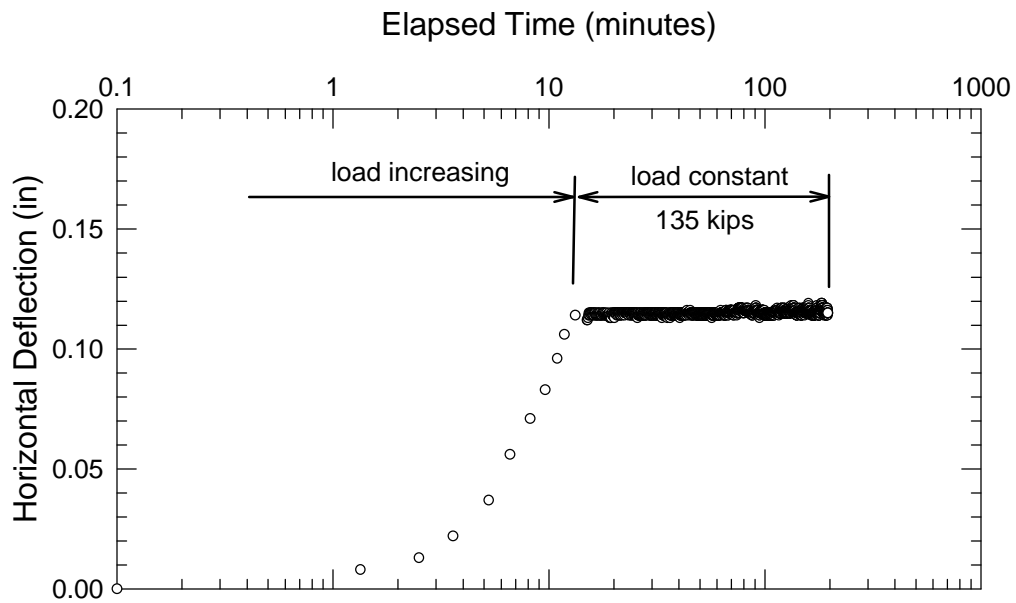


(b) Vertical backfill movement after 150 load cycles.

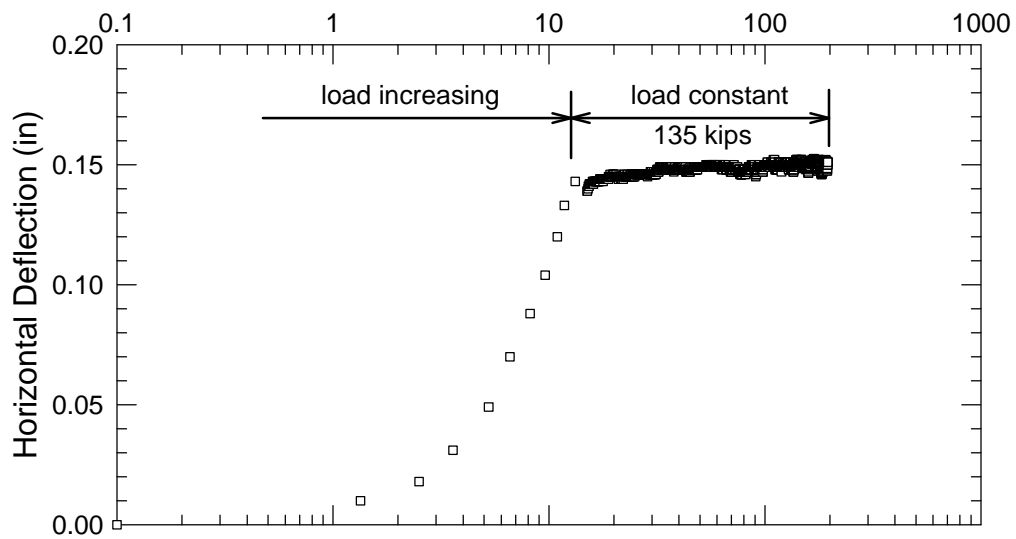


(c) Plan view of setup for measuring backfill surface deflection.

Figure 6.23. Vertical deflection of gravel backfill surface in front of NE 36-in-deep pile cap.



(a) NE pile cap response at a sustained load of 135 kips.



(b) NW pile cap response at a sustained load of 135 kips.

Figure 6.24. Effect of sustained load on NE and NW pile caps backfilled with compacted gravel.

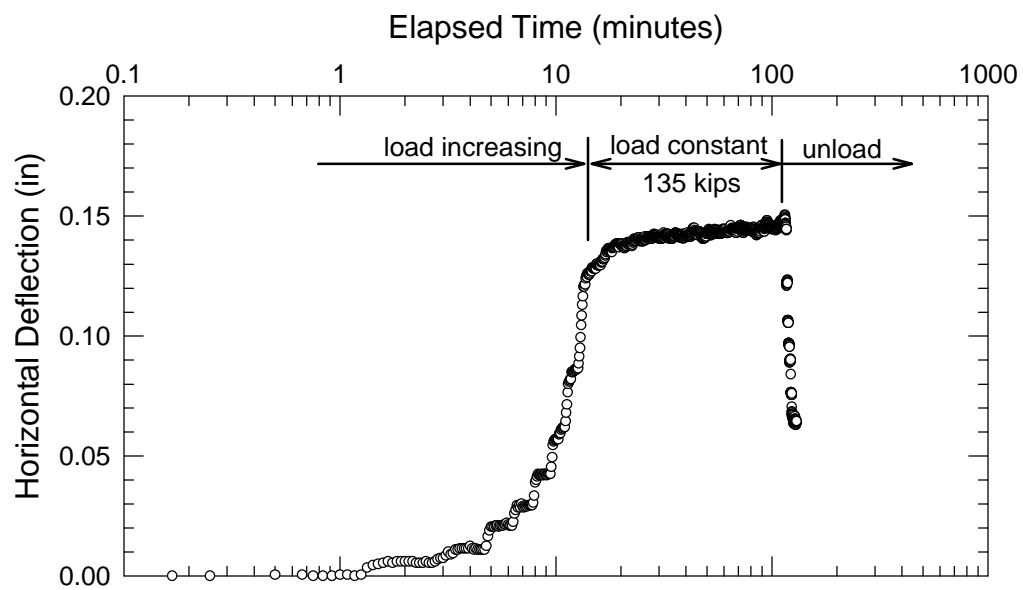


Figure 6.25. Effect of sustained load on SE cap embedded in natural soil.

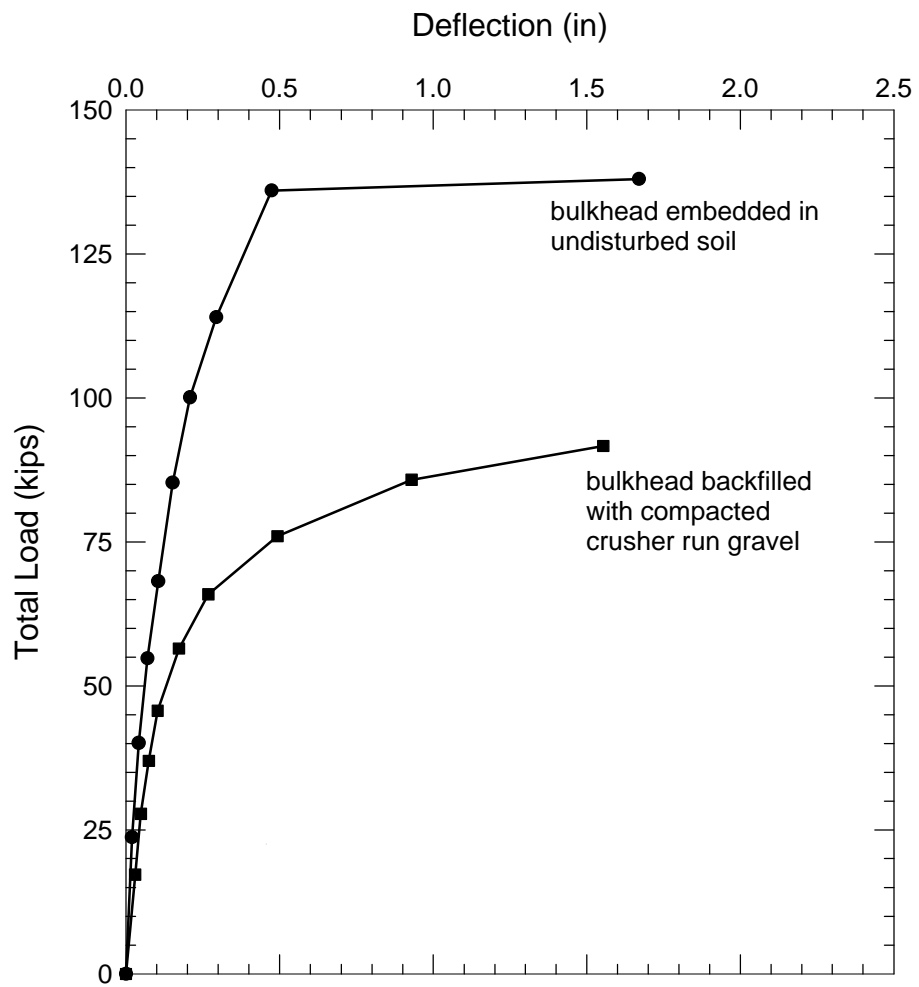


Figure 6.26. Passive resistance of embedded bulkhead in undisturbed soil and compacted gravel.

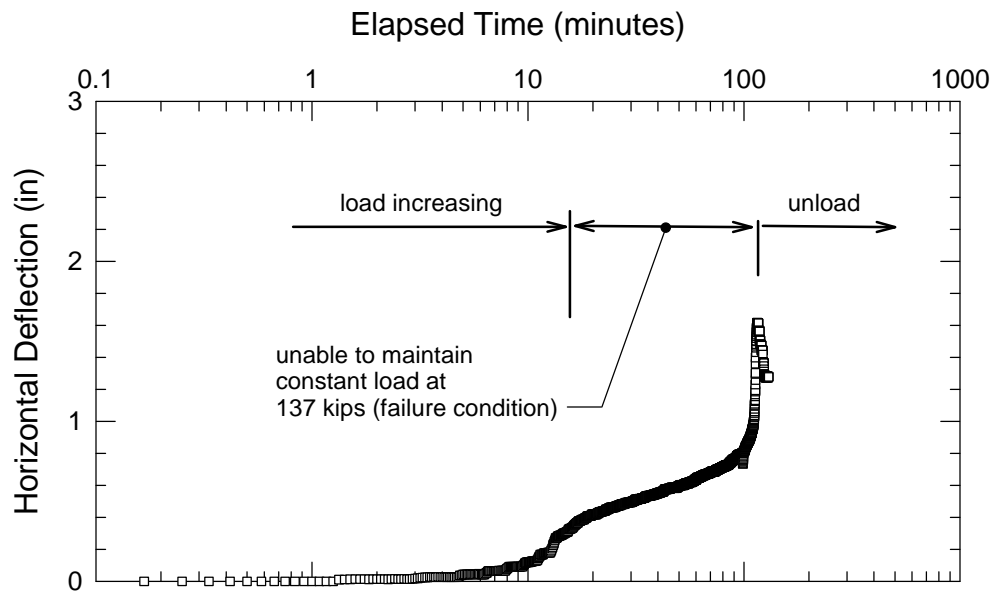
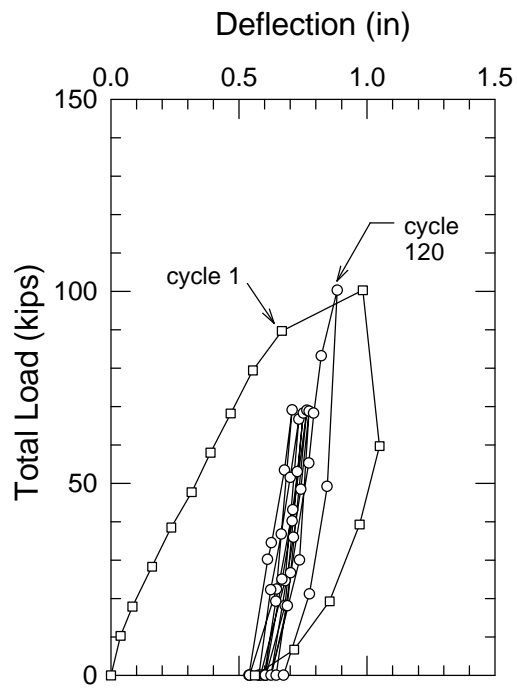
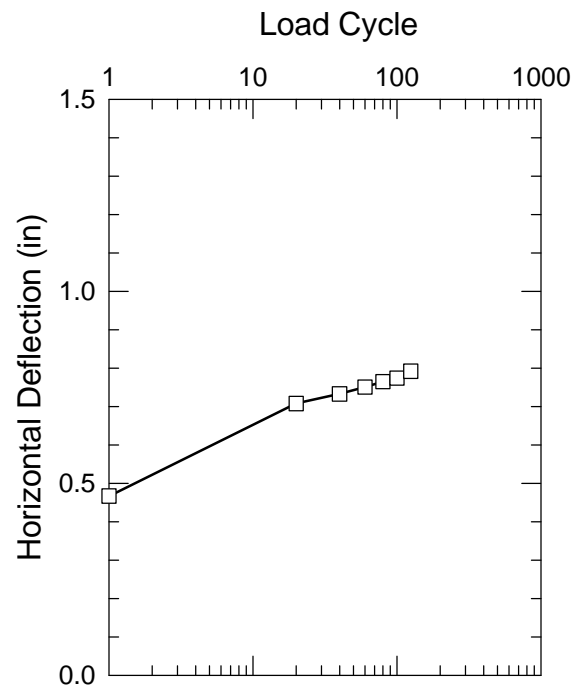


Figure 6.27. Effect of sustained load on bulkhead embedded in natural soil.

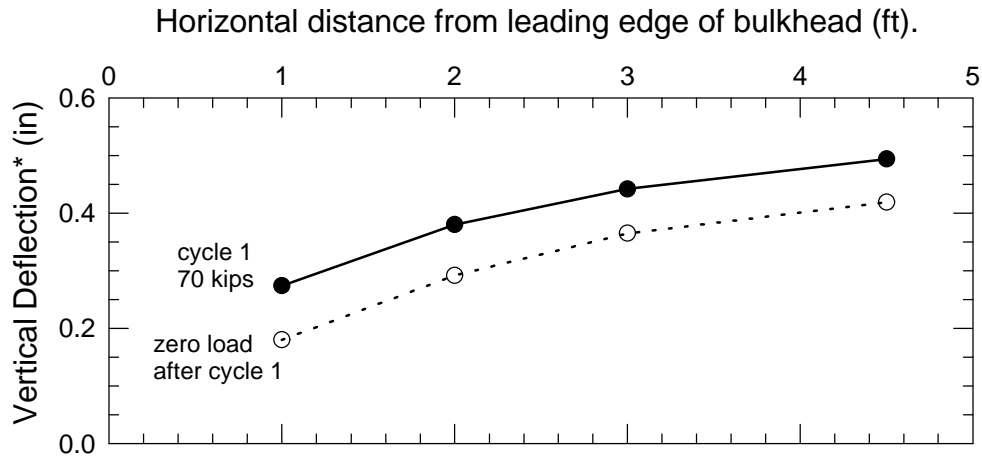


(a) Embedded bulkhead.

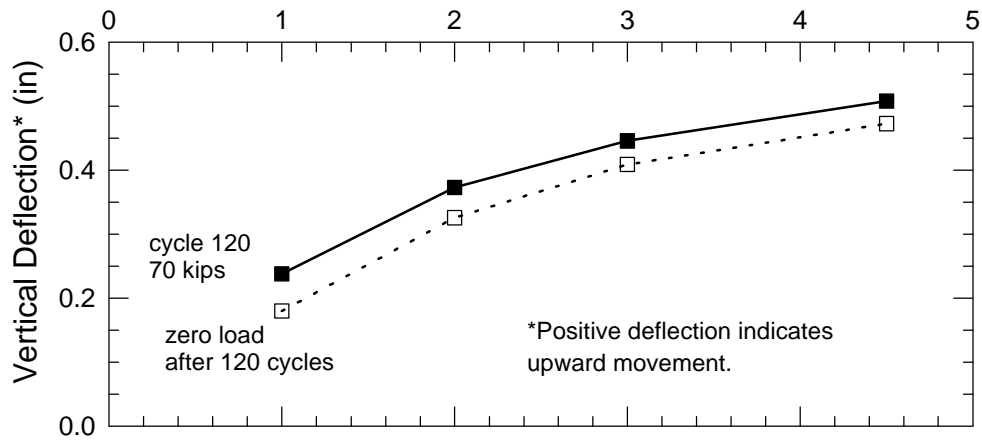


(b) Bulkhead response at 70 kip cyclic load.

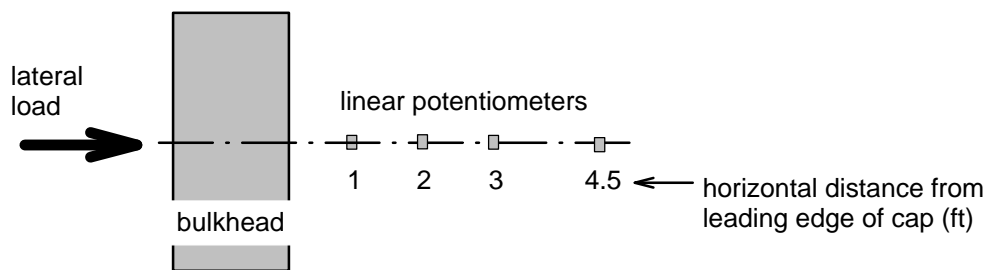
Figure 6.28. Cyclic response of bulkhead backfilled with dense crusher run gravel.



(a) Vertical movement caused by first load cycle.



(b) Vertical backfill movement after 120 load cycles.



(c) Plan view of setup for measuring backfill surface deflection.

Figure 6.29. Vertical deflection of gravel backfill surface in front of embedded bulkhead.