Pile Cap Moments and Deflections Due To Lateral Loading

by

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ABSTRACT

PILE CAP MOMENTS AND DEFLECTIONS DUE TO LATERAL LOADING

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When a pile cap is laterally loaded, moments and axial forces are transferred to the pile through the pile-cap connection. There is much uncertainty with regards to the portion of the loads the connection itself experiences due to the inability to effectively monitor the forces the connection experiences during loading. To compensate for this, pile analysis programs such as GROUP allow the user to either specify a pinned connection, fixed connection, or rotationally restrained connection. Under the same loading schedule, there are differences in the resulting pile moments between the connections due to the assumptions made when using the different pile connections. Using a set of previously generated data, a model was generated for various loading and connection conditions. For the rotationally restrained condition, a hand-calculated rotational stiffness was computed using an assumption that the connection is modeled as two dowels of no.7 rebar extending from the pile up into the pile cap. This calculation also assumed an elongation of the rebar for the displacement under the

force. The result produced an overall stiffness of 795,124 kip-inch/radian. The calculated stiffness when entered into the GROUP model produced pile moments and deflections similar to the results of the model when using fixed conditions.

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1 Introduction

Driven-pile foundations are the primary choice for buildings where a spread foundation is not feasible due to size constraints. These driven pile foundations are engineered to resist settlement and lateral movements due to seismic loads. Over the decades that pile foundations have been used, there have been many tests to determine the capacity of a pile due to these loads. One of the areas of this field in which there is still uncertainty is the capacity of pile-to-pile cap connections. Various numerical and practical models have been developed to predict the capacity of these connections under different types of loading but like many areas of engineering, it is extremely difficult to either inspect the direct results of a full scale test or develop a consistent mathematical formula that can determine the performance of a pile under every conceivable condition.

For this report, pile data were analyzed using the computer program GROUP using lateral loads ranging from 70 kips to 130 kips. The pile geometry and soil conditions were provided by a data set used in an earlier thesis (Stenlund, 2007). The primary focus in this study was the maximum axial load on the pile and determining which pile to-pile cap connection modeling procedure correlated the best with the measured data.

1.1 Lateral Loading vs. Axial Loading

Foundations must be designed to resist a combination of lateral loads and axial loads. The lateral loads may be provided by forces such as wind, seismic or tidal conditions. This loading condition produces moments on the pile that vary depending on the soil type around the pile and the length of pile. However, these lateral forces also exert axial forces on the pile due to the pile cap rotation which causes uplift on one end and compressive stress on the other end of the cap. The combined axial effects due to the shear weight of the structure and the extra force due to the lateral loading may exceed original assumptions and calculations thus causing the pile cap to fail.

1.2 Pile-Pile Cap Connections

When compiling a model of a pile within a computer program, it is important to specify how the pile-to-pile cap connection will be modeled. While it is difficult to accurately model the true behavior of the connection, there are three types of theoretical connections that can be used to model the pile within GROUP which are:

1. Rigid Connection,
2. Pinned Connection, and
3. Rotationally Restrained Connection.

1.2.1 Rigid Connection

By definition, a rigid connection is restrained from all displacements and can develop moments. A pure rigid connection allows all the moment to transfer from one member to another because of the inability of the connection itself to rotate. In foundation design, a rigid connection is typically constructed by concentrating the rebar in the central area of the pile-to-pile cap connection as shown in Figure 1-1 below.

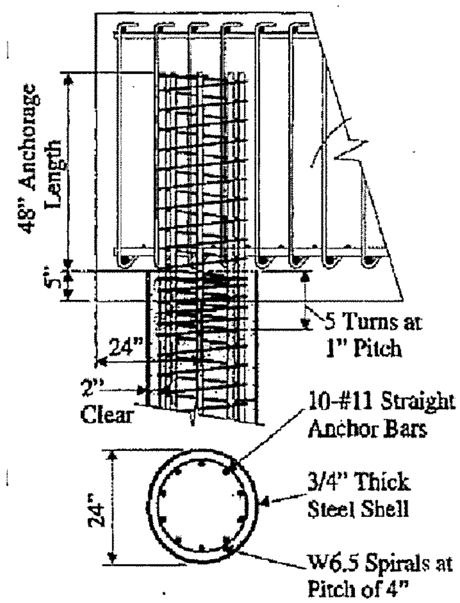

Figure 1-1 Model of fixed pile cap

As shown, the spiral rebar cage has been thoroughly embedded within the pile cap. A connection of this type restricts the lateral movement of the pile and can lead to local cracking of the concrete pile cap since the connection itself does not rotate (Silva and Sebile, 2001).

When designing rigid pile cap connections for lateral loads, is very important to consider the amount of cover between piles since the rigid connection creates fractures originating from the pile cap. In normal laboratory testing and real life situations, severe lateral loads cause cracking to develop right by the pile as a result of concrete failure.

This would also reduce the rigidity of the connection and moments would not be efficiently transferred to the pile.

This type of modeling may lead to over-estimating the moment capacity of the pile because GROUP assumes that the moment is purely transferred from pile cap to the pile itself. The computer software does not account for pile cap damage which would significantly alter the true performance of the connection and resulting moments in the pile.

1.2.2 Pinned Connections

Pinned connections are connections where the connection itself resists negligible moment. Theoretically, the pile may rotate in any direction and may cause an unstable structure due to the lack of rigidity within the pile-to-pile cap connection. In general, most connections are constructed to be somewhere between pure rigid and pure pinned. One problem with this assumption within computer modeling programs is that the moment at the pile-to-pile cap connection is determined as zero due to the inability to transfer moments.

1.2.3 Rotationally Restrained Connections

Rotationally restrained connections behave like a rotational spring. This connection can transfer moments like fixed connections but unlike fixed connections, they are allowed to rotate like pinned connections. This modeling connection allows the user to specify a rotational stiffness which would allow the pile to behave in a transitional state between fixed and pinned.

2 Methods

The pile and pile cap were modeled in GROUP 7 using input parameters from Stenlund's previous model (2007). The simulation was executed for a number of lateral loads to develop relationships between the pile cap moment and lateral load. The following sections discuss in detail the sources of the data involved in the models as well as the analysis.

2.1 GROUP Model Inputs

Some of the data used in the GROUP model were obtained from Stenlund's previous research. Those categories are discussed in this section. Additional inputs were developed through hand calculations. While this section will briefly discuss the inputs used, the entire input files are located in Appendix A.

2.1.1 Pile Layout

There were two piles used in the analysis spaced at a distance of 42 inches on center. They were spaced from an equal distance from the center of the pile cap. The piles were not specified to be embedded into the pile cap within the model.

2.1.2 Pile Properties

The piles used in the model were two driven circular steel pipes. The piles were 40 feet long and were driven into the ground the entire length of the pile. The piles had a cross-sectional area of 128 square inches (in^2) for the entire length of the pile. The moment of inertia for the first 30 feet was 380 in^4 and was 330 in^4 for the rest of the pile. The piles also had a modulus of elasticity of 25 X 10^6 pounds per square inch (psi). All of the GROUP analysis used this same type of pile (Stenlund, 2007).

2.1.3 Pile Cap

The pile cap was modeled as a linearly-elastic material. There were not specific dimensions assigned to the pile cap since GROUP does not require dimensions unless the pile cap is permanently embedded within a soil stratum. For this model, the pile cap was resting on top of the soil level, so dimensions were not needed.

2.1.4 Hand Calculations for Rotationally Restrained Conditions

Another aspect of this project was to hand calculate a rotational stiffness for the pile-to-pile cap connection. The goal was to determine an equation for the rotational stiffness of the connection that would produce a moment over a certain rotation, which would counteract the moments that occurred during loading. The governing equation for the rotational stiffness of an object is defined in Equation 2.3.1

$$krot = \frac{M}{\theta} \tag{2.3.1}$$

where: krot = Rotational stiffness

M = Induced moment

Θ = Angle of resulting rotation

The equation of rotational stiffness was derived by manipulating the equation for the stiffness of a rod in tension. The connection was idealized as two dowels of no. 7 rebar connecting the top of the pile to the bottom of the pile cap. The general equation for the total stiffness of the connection is derived as shown in Equation 2.3.2.

$$k = \frac{AE}{L} \tag{2.3.2}$$

where: k = Stiffness of a dowel

A = Cross sectional area of steel

E = Modulus of Elasticity of Steel

L = Effective Length of Steel in Question, taken as 2 in.

The rotationally stiffened connection's rotation would be modeled by having one rebar act as the point of rotation while the opposite rebar would elongate a distance Δ. This is shown in Figure 2-1 below.

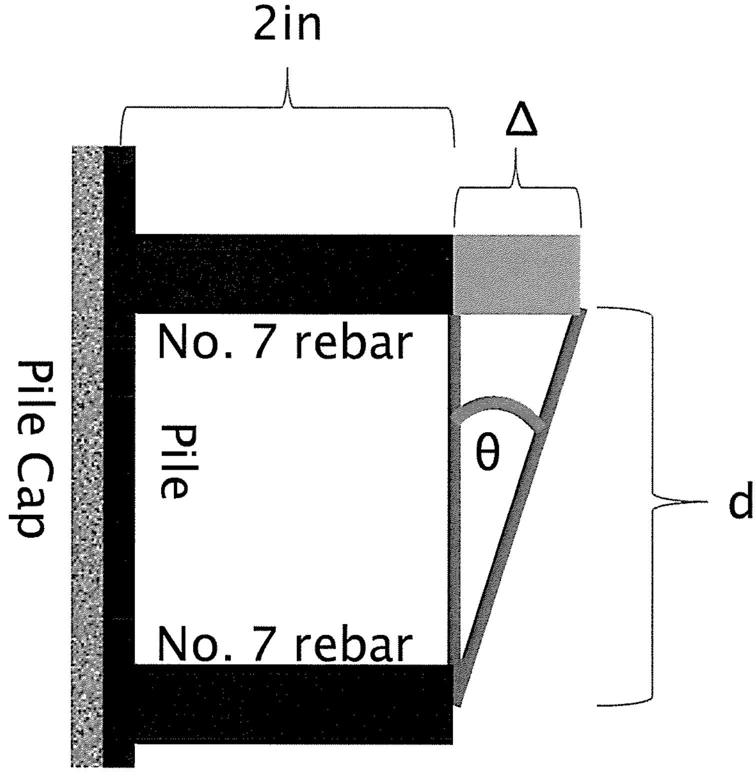

Figure 2-1 Modeled connection

From the diagram shown above, the force required to elongate the steel would become Equation 2.3.3.

$$F = \left(\frac{AE}{2}\right) * (\Delta) \tag{2.3.3}$$

where: F = Resulting Force in Rebar

A = Cross Sectional Area of Rebar in Bending

E = Modulus of Elasticity of Steel

Δ = The elongation of the dowel

The moment arm for the system is the distance between the two dowels, represented by d. Also, for small angles of θ the deflection would equal the moment arm, d, multiplied by the angle of rotation, θ. Substituting this relationship into Equation 2.3.1, the angle of rotation cancels out and Equation 2.3.4 is left as shown below:

$$krot = \frac{AEd^2}{2in} \tag{2.3.4}$$

where: krot = Rotational Stiffness

A = Cross Sectional Area of Rebar in Bending

E = Modulus of Elasticity of Steel

d = Moment Arm of System, taken as 9.56 in.

For the model, the length of steel in question was assumed to be two inches; having one inch above and below the point directly across from the point of rotation on the left bar. The rebar was assumed to be a #7 having a cross sectional area of 0.6 in^2. A modulus of elasticity of $30X10^6$ psi was also used.

These values were entered into the equation and a spring constant of $2.56 \text{ X } 10^8$ pound-inch was obtained. This value was entered into the GROUP model as the rotational stiffness parameter in the connection input area. There were no other changes to the model except for the different magnitudes of loading. The results of the GROUP model were then compiled into Excel graphs which will be shown and discussed in the results section.

2.1.5 Pile-To-Pile Cap Connection Conditions

One source for variation between the analyses was the type of connections used to connect the pile to the pile cap. For each loading case, the piles were modeled using fixed, pinned or rotationally restrained conditions. As mentioned in the introduction, the difference between pile-to-pile-cap connections can produce different results when using the same pile layout and loading conditions.

2.1.6 Soil Conditions

The soil used in the GROUP models was divided into 9 different layers containing stiff clay, soft clay or sand. The soil conditions are summarized on Table 1 shown below.

Table 1 Soil profile for GROUP model

Layer	Depth of Layer (inches)	Soil Type	Modulus of Subgrade Reaction (pcf)
Layer 1	42.13	Stiff Clay	499
Layer 2	10.63	Stiff Clay	499
Layer 3	12.2	Sand	95
Layer 4	53.04	Stiff Clay	994
Layer 5	18.11	Sand	95
Layer 6	24.01	Stiff Clay	994
Layer 7	41.74	Sand	110
Layer 8	183.07	Soft Clay	99
Layer 9	104.17	Stiff Clay	994

As shown, the predominant soil type for this model was stiff clay with small sand lenses interspersed within the profile (Stenlund, 2007).

2.1.7 Loads

The loading for these models was modeled by a single lateral load applied to the side of the pile cap. The magnitudes of the lateral loads used in the model were ranging from 30 kips to 140 kips. For loads of 30, 40, 50, 60, 70, 80, 90, 110, 120, 130 and 140 kips, the deflection of the pile was noted for comparison purposes. In addition to the deflection, for the 70, 90, 110, and 130 kip loads, the pile moments and axial loads were recorded for later analysis. Each of the pile-to-pile-cap connections used this loading schedule.

2.2 Analysis

The following section will describe the analysis portion of the project using the inputs from the section above. There were charts formulated to investigate the following relationships.

1. Lateral Load vs. Axial Force at top of pile,
2. Depth versus Moment at top of pile, and
3. Pile Head Deflections.

2.2.1 Lateral Load vs. Axial Force at top of pile

For this comparison, the GROUP models were run for their respective loading configuration. From the output file, the axial force was the same for both piles with the exception that the pile closest to the lateral load was in tension and the pile furthest away from the load was in compression. The loads were compared to the resultant axial force using charts formed in Excel. There was a chart formulated for each of the pile-to-pile cap connection conditions and then they were combined to show the overall effect of the different connections on the axial load due to the lateral force.

2.2.2 Depth vs. Moment at top of pile

The load vs. moment at the top of the pile was determined from the GROUP analysis. The moments and depths were collected for each of the loading and connection conditions. The data from the output file was exported into Excel and the data was compiled onto a chart for the individual piles with respect to their connection conditions.

2.2.3 Pile Head Deflections

This comparison was to monitor the amount of predicted deflection of the pile cap from the applied lateral load. The data for this comparison also came from the GROUP output file. The load and deflection were tabulated in Excel and were placed on a chart. There were separate trend lines for each of the connection modeling conditions.

3 Results and Discussion

3.1 Lateral Loading vs. Axial Loading

The findings of the comparison between lateral loading and axial loading are displayed below in Fig 3-1. Before the GROUP analysis, it was theorized that there would have been a linear relationship between the amount of lateral force and the axial force experienced by the connection.

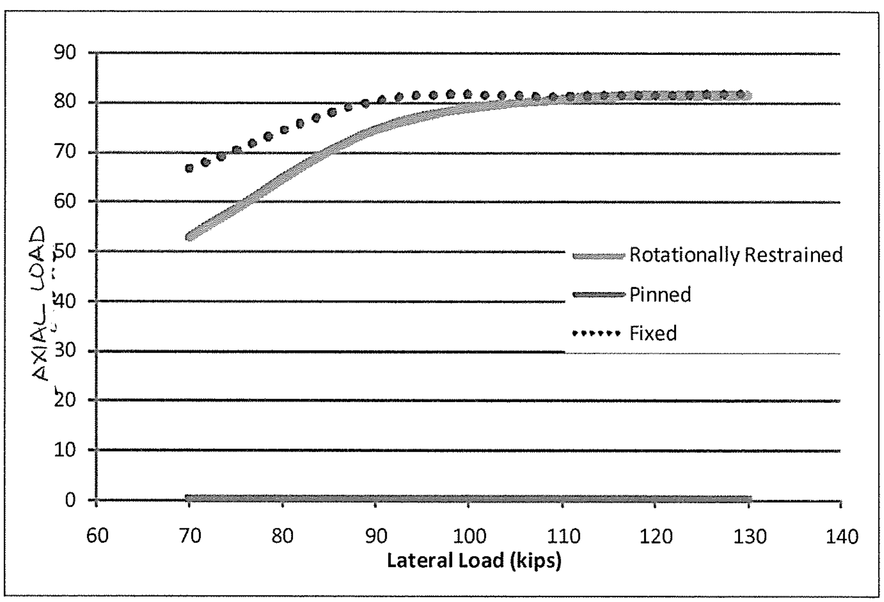

Figure 3-1 Lateral load vs. axial force

From the analysis, it is shown that there was a slight linear relationship between 70 and 90 kips for both the fixed and rotationally restrained connections. Beyond 90 kips of lateral force, the trend line smoothes out and the linear relationship is lost. It was surprising to observe that the pinned connection experienced minimal axial loads. These loads were on the order of 3*10^-13 lbs. From the data, the pinned and rotationally restrained connections were almost the same in the 110-130 kip range. This shows that as the lateral load increases, the rotationally stiff connections behaves more and more like a fixed connection.

3.2 Depth vs. Moment Graphs

From the GROUP analysis, the moments induced by the pile cap rotation were compiled into Excel and were sorted with regards to their pile-to-pile-cap connection. Figure 3-2 represents the relationship of calculated moment vs. depth of pile.

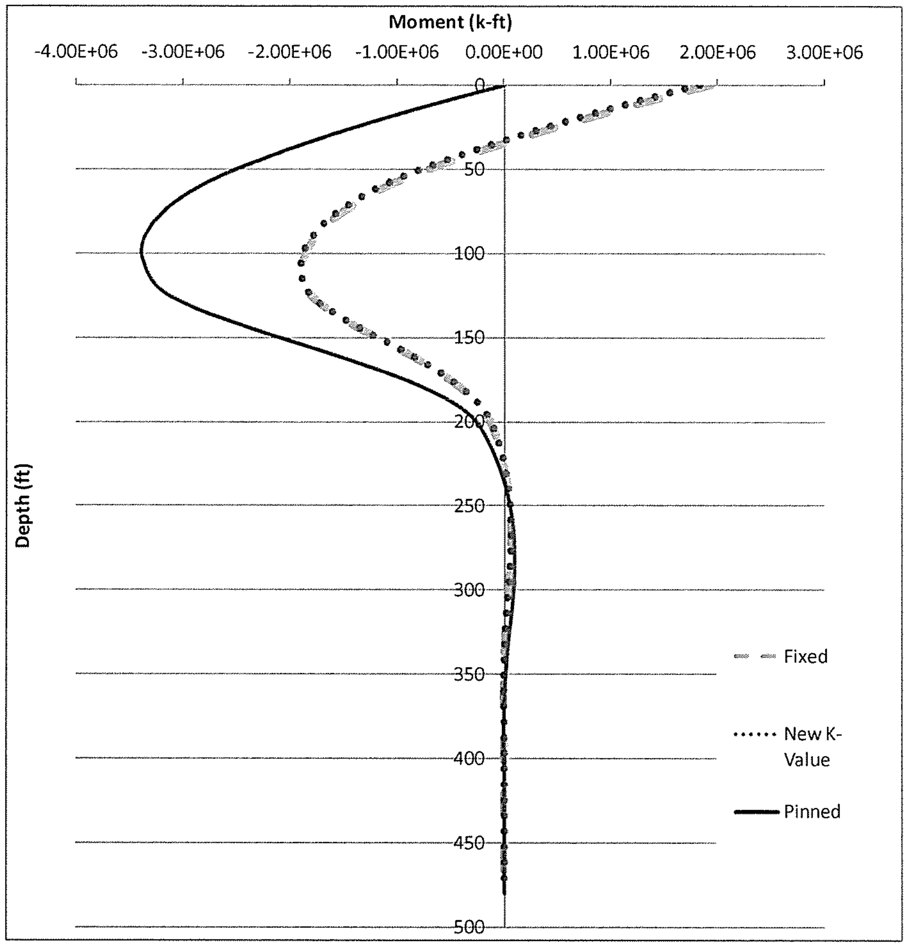

Figure 3-2 Moment vs. depth

As shown, the pile experienced the maximum positive moment at the connection and the maximum negative moment about 100 feet down from the pile cap. As the force acting on the pile was increased, the magnitude of the positive moment increased, however, the negative moment experienced more of an increase than the positive moment at 130 kips. It is interesting to note the trend for the pinned connection paying close attention to the moment experienced by the connection. By definition, a pinned connection is not able to transfer a load from one joint to another. So with this connection, there would be an absence of moment felt by the pile at the top, but it would compensate by experiencing a larger negative moment around 100 feet down. This would lead to an underestimation of the pile moment at the top of the pile and an over-estimation of the moment near 100 ft. of depth.

3.3 Pile cap deflections

In comparing the pile cap deflections, the pile cap with the pinned connection deflected the most over the entire spread of loads. The model where a new stiffness value was calculated had deflections similar to the fixed conditions. A summary plot of the deflection vs. loading is shown below in Figure 3-3.

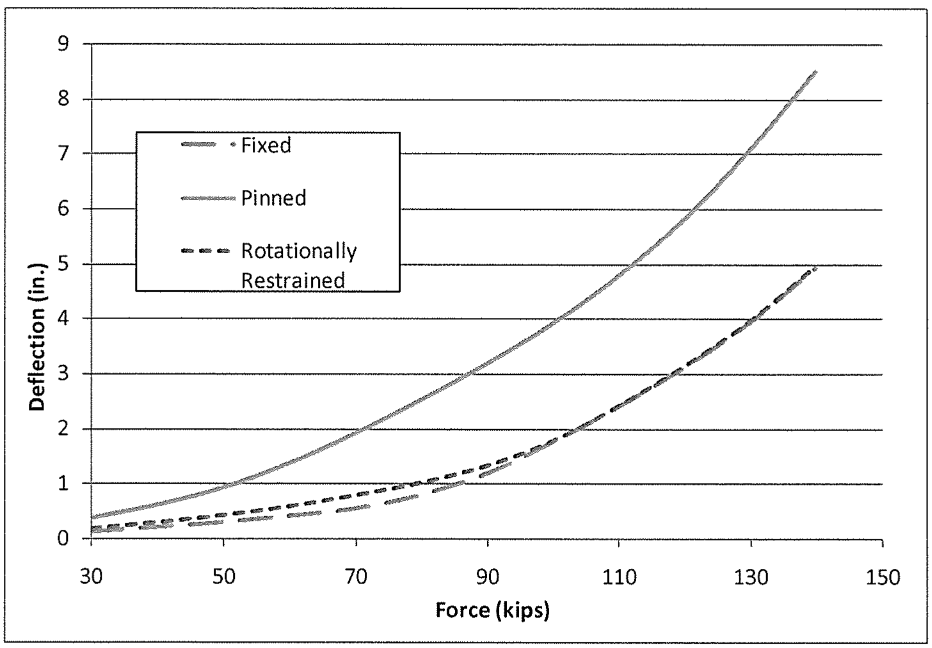

Figure 3-3 Pile head deflections

Once again, due to the nature of pinned connections, the pile cap experienced significant deflections. A pinned connection, in a similar fashion as with moment, does not resist lateral loads like a fixed connection. This lack of stiffness causes increased deflections which would be over conservative when compared to how the pile may deflect under its true connection's fixidity.

3.4 Calculated Rotational Stiffness Calculations

From the previously mentioned stiffness calculations, the rotational stiffness coefficient that was entered into the GROUP model was a value of 795,124 kip-inch/radian. When entered, the model behaved almost exactly like a fixed condition rather than a pinned connection. This calculation is confirmed by results from experimental testing as shown below in Figure 3-4 which shows data collected from an experiment by Richards et.al (2009.)

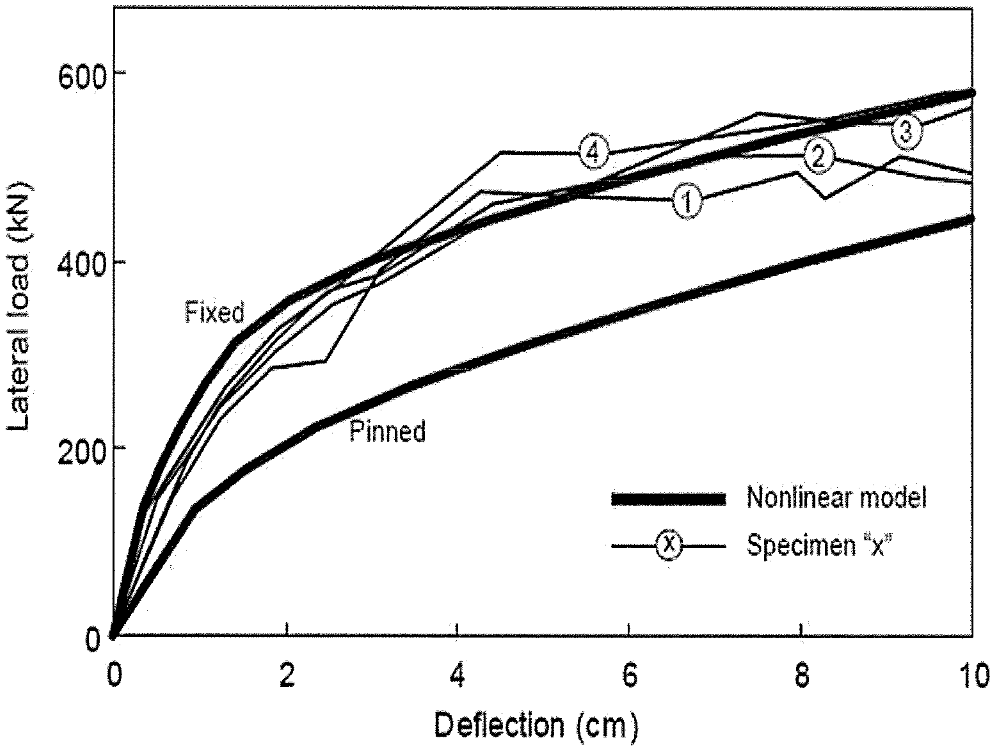

Figure 3-4 Physical Test Data

4 Conclusions

From the results of the various models, it was determined that using both fixed and pinned conditions provide limits to what the pile-to-pile cap connection experienced once constructed. As it is nearly impossible or financially logical to construct a fully pinned or fully fixed connection, it is important to consider the implications of what the entire pile or the connection itself would theoretically experience under both extreme conditions.

If the connection behaves more like a pinned connection, the pile will theoretically experience more moment distributed through the entire length and the connection itself may be under-designed due to the zero moment at the connection which resulted from the model data. The same problem would occur with axial loads on the pile. The modeled pinned connection experienced negligible axial loads right at the top of the pile due to the lateral loading. By neglecting the axial loads, the pile cap may experience crushing failure at the interface region due to an under-designed connection. Also, within the bounds of construction, it is difficult to construct a connection with a "free head" in a pile formation since there would have to be certain restrictions on the degrees of freedom of the system.

If the pile is fully fixed once constructed, the moments throughout the pile may be underestimated and lateral buckling could occur within the pile. Another drawback of creating a connection with high fixidity would be that a lot of money would be wasted in the design and construction of a connection that can withstand a moment it may never experience during its service lifetime.

From the methods of hand-calculating a pile-to-pile cap rotational stiffness, it has been shown that using the assumptions previously mentioned, the four pile caps behaved like a fixed connection. The hand calculations support the results of previously performed experimental testing. It can also be concluded that even though the fixed pile head condition provided the upper bound with moments and axial loads, typically constructed pile-to-pile-cap connections behave more like fixed-head connections. With this knowledge, designers can use the values generated from the fixed-head pile cap condition models with confidence.

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