Lateral Loads and Bending Moments Associated with Steel Pier Foundation Brackets Used for Underpinning Existing Structures

by Howard A. Perko, Ph.D., P.E.
Consulting Engineer for Magnum Piering, Inc.

July 7, 2002

Abstract

The fundamental mechanics of a bracket and foundation connection are demonstrated. A static analysis was performed on an example steel pier foundation bracket used for underpinning an existing foundation. Strain compatibility between the connection to the structure and the bending resistance of the pier was investigated using a computer program for the analysis of pile foundations under eccentric loads. The lateral load and overturning moment exerted on an existing foundation due to eccentricity of steel pier foundation brackets were quantified for various soil types. The results of these analyses were used to examine the viability of steel pier underpinning given the strength of an existing foundation.

Introduction

There exist a number of possible methods for repair of a footing or mat foundation that has undergone excessive total or differential movement. One common method of repair is the use of hydraulically-jacked steel pipe micropiles (steel push piers) for underpinning. This method consists of installing a steel pier adjacent to an existing foundation and then attaching the pier to the foundation by application of a bracket.

Steel pier foundation brackets must be placed as close to the center of the existing foundation as possible. Often, the process of attaching a bracket involves chipping away a section of the footing so the bracket can be aligned with the outside face of the foundation wall. A typical steel pier underpinning foundation bracket is shown in Fig. 1. Despite considerable care in placing the bracket, some eccentricity is inevitably introduced, since the pier cannot be placed directly under the centerline of the foundation wall for practical reasons.

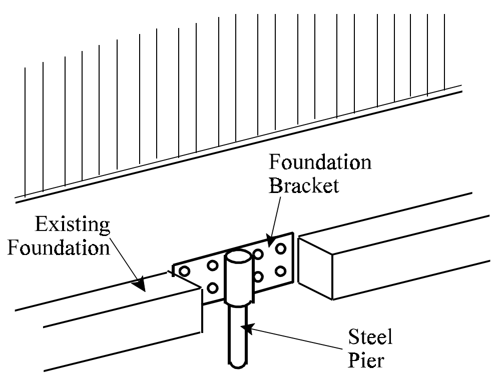

Fig. 1 Example Steel Pier Foundation Bracket

One of the common concerns regarding the application of steel pier underpinning is the susceptibility of the existing foundation to damage caused by forces and moments in the connection between the bracket and existing concrete foundation elements. In order to evaluate the viability of using steel pier underpinning, it is necessary to compute the applied lateral loads and overturning moments resulting from eccentricity of the bracket and pier assembly. With this information, it is possible to compute the factor of safety between applied loads and the available strength of the foundation.

A static analysis was conducted to evaluate the stability of an example foundation bracket for steel pier underpinning. Strain compatibility between the connection to structure and the bending resistance of the pier were investigated using a computer program, LPILE Plus for Windows by Ensoft, Inc. The lateral load and overturning moment exerted on an existing foundation due to eccentricity of an example steel pier foundation bracket were quantified for various soil types. The results of these analyses were applied to examine the viability of steel pier underpinning.

Static Analysis

There are several manufacturers of steel pier underpinning foundation brackets. In general, foundation brackets can be categorized as either plate brackets or angle brackets. A cross-sectional view of an example plate bracket is shown in Fig. 2. This assembly is manufactured by Magnum Piering, Inc. of Cincinnati, OH and is protected under U.S. Patent No. 5,234,287 (Magnum Piering, Inc., 2002). Atlas Systems, Inc. also manufactures a plate bracket, however it differs from the Magnum bracket in the way that the pier is connected to the bracket (Atlas Systems, Inc. 2000). An example of an angle bracket is shown in Fig. 3. This example is not modeled after any particular manufacturer, however it is similar to several that are currently available.

Two characteristics that are shared by all brackets are a face plate that mounts vertically on the existing foundation (A) and a sleeve or pair of clamps that prevent the pier

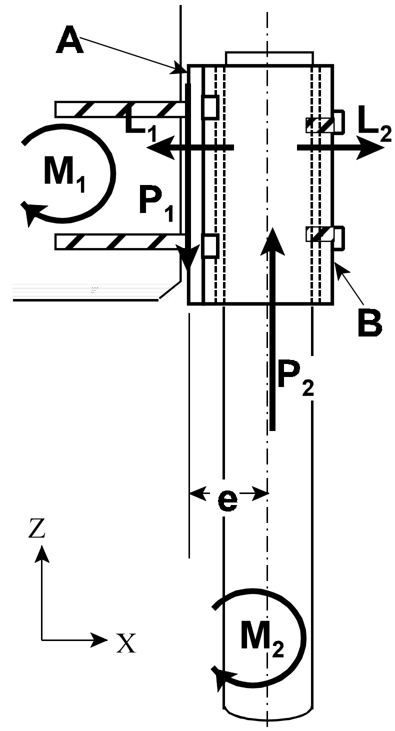

Fig. 2 Plate Bracket Free Body Diagram

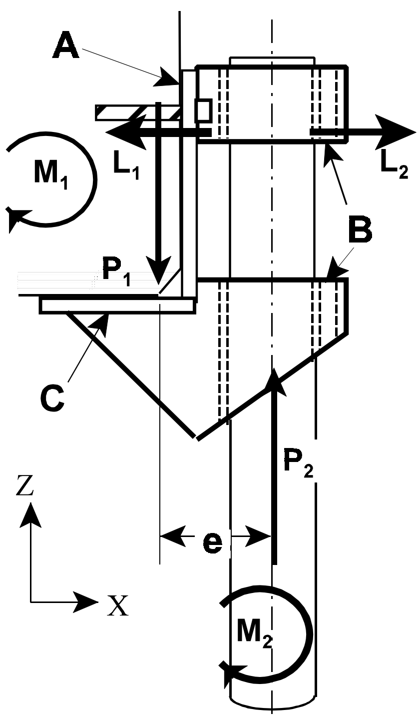

Fig. 3 Angle Bracket Free Body Diagram

from moving laterally (B). Angle brackets also have an angle plate that extends below the foundation (C).

Provided the sleeve or clamps (B) are sufficient to prevent rotation of the pier with respect to the bracket, the total vertical load supported by the pier can be represented as a single resultant force, P_2, located at the central axis of the pier shaft. If the existing foundation upon which the bracket is mounted is sufficiently rigid, then the total force applied by the existing foundation can be represented as a single resultant force, P_1, located close to the face plate (A).

The exact location of the applied force, P_1, on the bracket depends on the connection of the bracket to the structure. For plate brackets, such as the one shown in Fig. 2, the applied force, P_1, is transferred by concrete anchors and acts immediately adjacent to the face plate (A).

For most angle brackets, such as the one shown in Fig. 3, the majority of the applied force, P_1, is transferred through the bottom of the foundation concrete to the angle plate (C). The distance from the face plate of an angle bracket to the resultant applied force, P_1, depends on the roughness of the existing concrete, occurrence of exposed aggregate, and mechanical rigidity of the bracket itself.

The total overturning moment, M_0, resulting from eccentricity of steel piering brackets is given by

$$M_0 = \frac{(P_1 + P_2)}{2} e$$

where e = total eccentricity. In order for static equilibrium in the z-direction, parallel with the face of the bracket (A), the total vertical load supported by the pier, P_2, must be equal to the total force applied to the existing foundation, P_1, and hence

$$M_0 = P_1 \ e$$

Resistance to overturning is provided by the moment resistance of the connection between the bracket and the structure, M_1, and the moment resistance of the pier in the soil, M_2. The magnitude of each of these moment reactions depends on the strain compatibility between them. If the connection to the structure is very rigid compared to the strain necessary to mobilize the moment resistance of the pier in the soil, then M_1 will be much greater than M_2. A strain compatibility analysis was performed and the results are given in the next section.

The lateral force, L_1, is the horizontal component of force exerted by the connection between the existing structure and the bracket. It is a combination of horizontal loads in the anchor bolts, compression behind the face plate (A), and friction along the angle plate (C). In order for the condition of static equilibrium in the x-direction, perpendicular to the face of the bracket (A), this force must be equal and opposite to the horizontal component of force at the top of the pier, L_2. The horizontal component of force at the top of the pier may be due to a departure of the pier from plumbness. Lateral force in the connection between the existing structure and the bracket may be due to horizontal loads on the structure such as wind or active earth pressures. These causes of lateral force are ubiquitous to all foundations, can be addressed using conventional techniques, and will not be discussed further herein.

Another cause of lateral loads is inherent to the application of eccentric loads and their resulting moments to the tops of steel piers. If a moment is applied to the free end of a steel pier embedded in the ground, the pier will move laterally as the soil becomes mobilizes to resist the applied moment. If the pier head is prevented from moving laterally, then a horizontal component of force must be applied to maintain the position of the pier head. The magnitude of this reaction was determined for steel piers in different soils. A description of the analysis and the results are given in a later section.

Stain Compatibility

It is well known in the field of mechanics of materials that stress and strain are intimately related. Loads and moments must be accompanied by displacements and rotations. In order to generate a resisting moment, M_1, in the connection between the existing foundation and the bracket, a small amount of rotation must occur. Likewise, in order to generate a resisting moment in the pier, M_2, some rotation of the pier in the soil must occur. The angles of rotation are shown in Fig. 4. Assuming that the connection between the bracket and pier is very rigid and the structure itself is very rigid, the rotation of the pier in the soil and the rotation of the bracket connection with respect to the structure must be equal.

$$\theta_1 = \theta_2$$

The first step in determining rotational compatibility is to establish the relationship between bracket rotation and applied moment. The amount of rotation in the connection between the existing structure and the bracket, θ_1, as a function of applied moment, M_1, is different for the many types of foundation brackets available. An example calculation is provided here using a Magnum Piering bracket with 6 anchor bolts located 7" from the top of the bracket (Magnum Piering, Inc., 2002).

The rotation of a bracket that incorporates the use of concrete anchors can be roughly estimated by examination of the displacement of the anchor bolts under tensile loads. According to the acceptance criteria for expansion anchors in concrete (ICBO Report AC01-0402-R1), the allowable displacement of ½" diameter anchor bolts under design tensile loads is 0.0500 inches. If the anchor bolts are have a design tensile capacity of 3.5 kips, which is typical for anchors spaced 3" O.C. and embedded 4" in 4,000 psi concrete (Illinois Toolworks, Inc., 2001), then the moment generated in the connection is on the order of 150 kip-in and the rotation of the bracket, θ_1, is approximately 0.4 deg (arcsin 0.0500"/7").

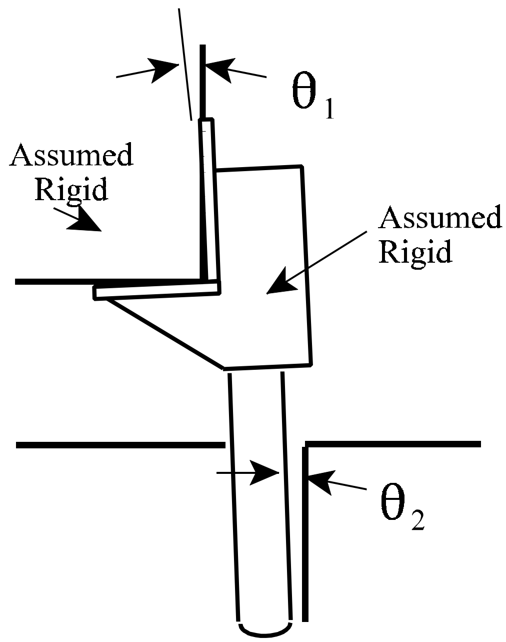

Fig. 4 Rotation Compatibility

The second step in determining rotational compatibility is to determine the relationship between rotation of the top of the pier, θ_2, and the moment generated in the soil, M_2. This relationship is a function of the rigidity of the pier and the stiffness of the soil. An example set of relationships was generated using 3" O.D., 1/4" thick wall and 1/8" thick wall Magnum Push Piers (Magnum Piering, Inc., 2002).

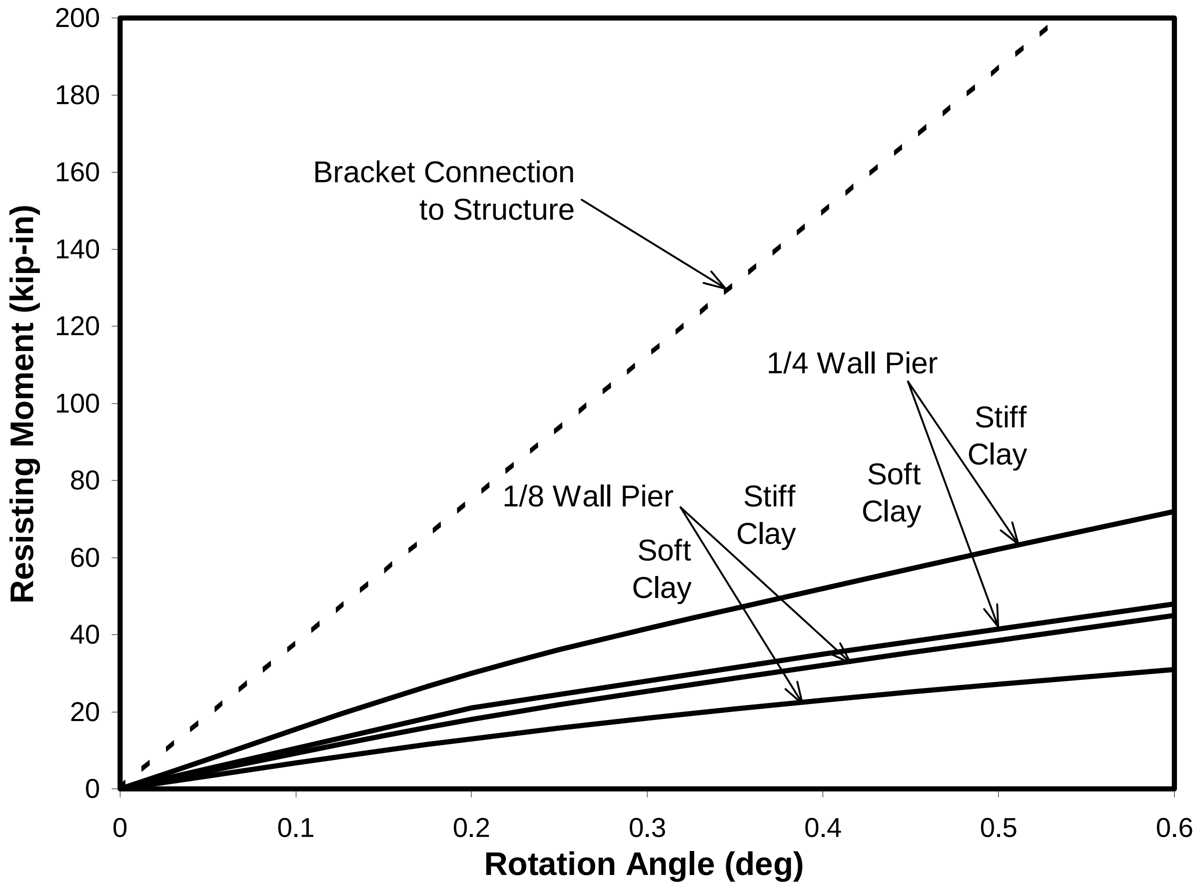

Fig. 5 Rotational Compatibility

The rotation of the example pier was determined using LPILE Plus for Windows software. Typical properties for various soils were assumed (Reese, L.C., et al., 2000). The top of the pier was fixed with respect to lateral displacement. A small range of rotation angles was input as boundary conditions and the resulting moments at the top of the pier were computed. Results are shown in Fig. 5.

As can be seen in Fig. 5, the rotation required to generate resisting moments of the pier in the soil are much greater than the rotation necessary to generate the same moment for the bracket connection to the structure. According to the condition of rotational compatibility, the rotation angle of the pier and the bracket connection must be equal ($\theta_1=\theta_2$). For the example case presented here, the bracket connection to the structure has approximately 3 to 7 times as much moment resistance as the pier in different soils.

In order for static equilibrium, the summation of the reaction moment in the connection of the pier to the structure and the reaction moment of the pier in the soil must be equal to the applied moment due to eccentricity of the vertical loads, as given by

$$M_1 + M_2 = M_0$$

If a single new parameter, λ, is defined to account for rotational compatibility, where λ

is the ratio of M_2 to M_1, then the equation for moment equilibrium can be rewritten, as given by

$$M_1 (1 + \lambda) = M_0 = P_1 e$$

The rotational compatibility factor, λ, is a function of soil conditions, pier shaft rigidity, and bracket connection to the existing structure. For the Magnum Push Pier used in the example herein, the rotational compatibility factor has the following values.

Table 1. Rotational Compatibility Factor for Magnum Push Piers and Brackets

λ factor	Shaft Thickness	Soil Type
.23	0.250	soft clay
.35	0.250	stiff clay
.22	0.250	loose sand
.27	0.250	med. sand
.15	0.125	soft clay
.22	0.125	stiff clay
.14	0.125	loose sand
.17	0.125	med. sand

Lateral Forces

As stated previously, the generation of moments in the pier without lateral movement can only be accomplished if the existing structure is capable of providing a lateral restraining force. The magnitude of lateral load required to restrain the pier head can be determined by again incorporating LPILE Plus for Windows software. Required lateral restraint is a function of the pier shaft rigidity and the stiffness of the soil. Example lateral loads were determined for 3" O.D., 1/4" and 1/8" thick tubular shafts which are indicative of Magnum Push Piers (Magnum Piering, Inc., 2002) and other manufactured steel piers. Results are provided in Figs. 6 though 9.

The results of the lateral force analysis indicate that pier stiffness differences between the 0.125" thick and 0.250" thick wall pipe piers produce negligible differences in the magnitude of lateral force as a function of the applied moment to the top of the pier. The results also indicate that larger lateral forces are produced in more dense or more stiff soils. The graphs shown in Figs. 6 through 9 can be used to estimate the lateral force exerted on an existing foundation due to steel pier underpinning if the brackets and piers are the same as or similar to those manufactured by Magnum Piering, Inc. In the next section, the results of the static, strain compatibility, and lateral load analyses are used to predict the lateral and overturning moments exerted on an existing foundation due to steel pier underpinning.

Bracket Reactions

An example calculation of the lateral forces and overturning moments caused by steel pier underpinning is presented using the Magnum Piering brackets and push pier products used in prior sections of this report. Similar calculations can be performed using the steel piering products of other manufacturers if the specifications of those products are known. The goal of this exercise is to provide a working example that demonstrates the fundamental mechanics of a steel pier and bracket connection to an existing structure. Although the specifications for Magnum Piering products are used in the example, it is recognized that other manufacturers systems may be analyzed in a similar manner.

3" O.D., 0.125 Thick Wall Pipe Pier	3" O.D., 0.250 Thick Wall Pipe Pier

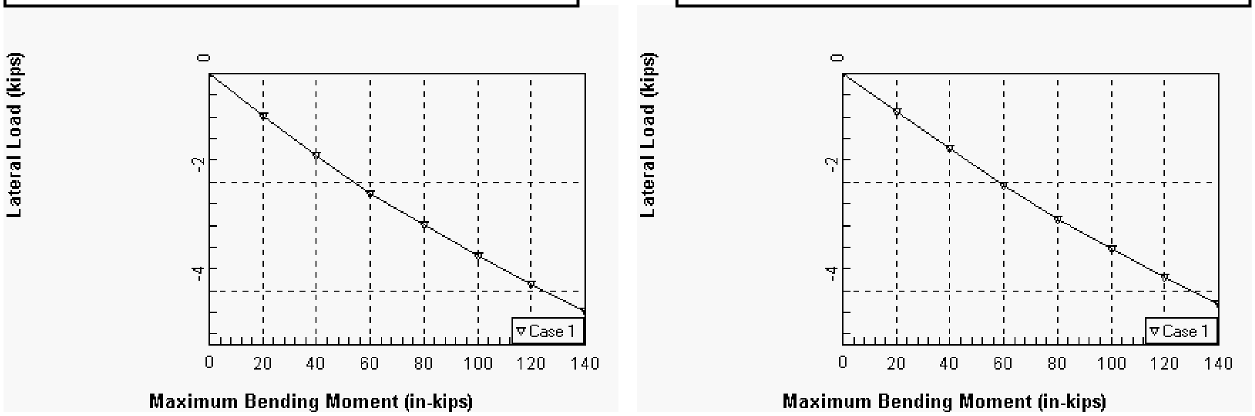

Fig. 6 Lateral Loads for Fixed-Head Steel Piers in Loose Sand

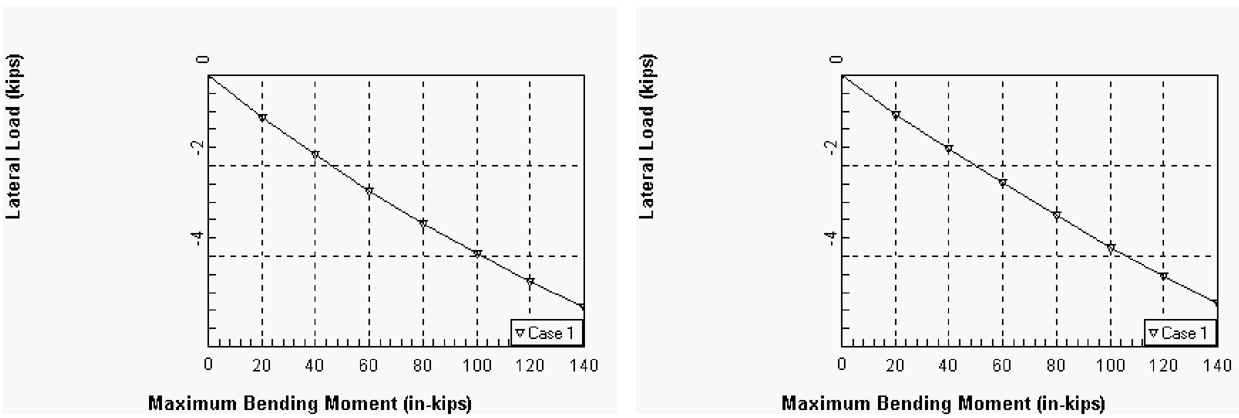

Fig. 7 Lateral Loads for Fixed-Head Steel Piers in Medium Dense Sand

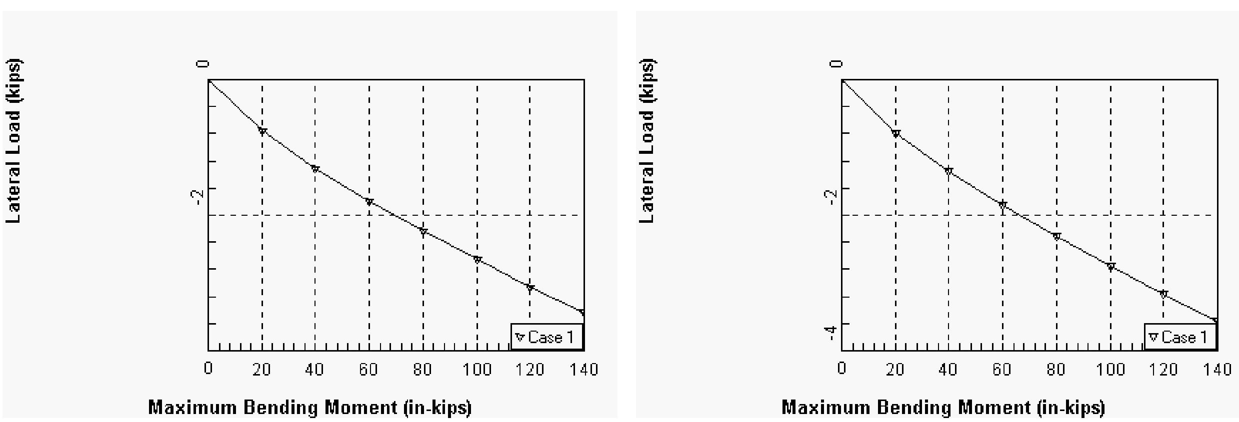

Fig. 8 Lateral Loads for Fixed-Head Steel Piers in Soft Clay

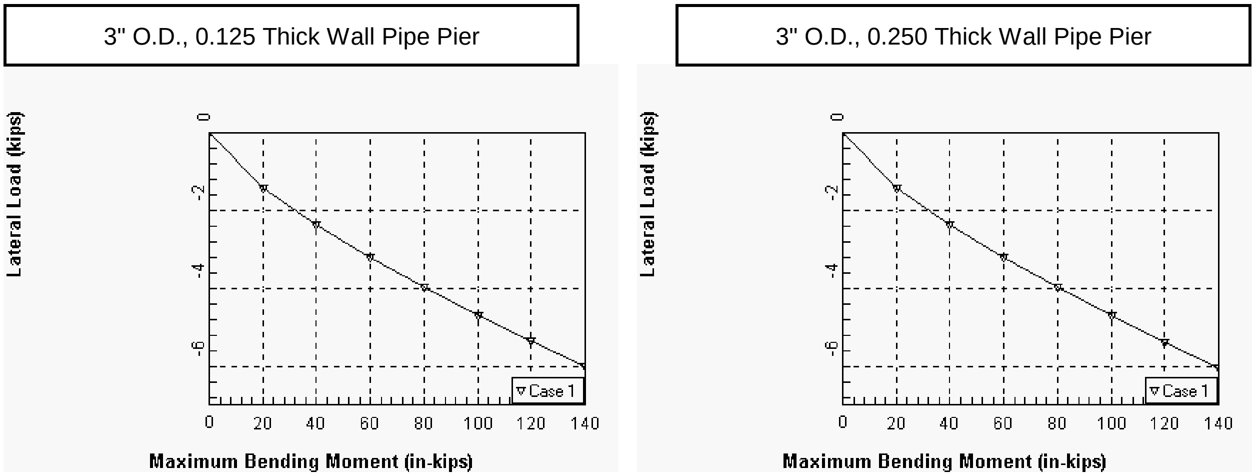

Fig. 9 Lateral Loads for Fixed-Head Steel Piers in Stiff Clay

For the example calculation, it will be assumed that 3" O.D., 0.250" thick wall push piers are used to underpin an existing foundation, the piers penetrate a stiff layer of clay soils, and that the design load on each pier is 30 kips. Magnum Piering plate and angle brackets have an eccentricity, e, between the center axis of the pier and the face of the bracket of about 2". Hence, the applied moment, M_0, is given by

$$M_0 = (30\,kips)\,\left(2\ inches\right) = 60\ kip\,in$$

According to Table 1, the rotational compatibility factor, λ, for a 3" O.D., 0.250 thick steel pipe pier in stiff clays with a Magnum Piering or similar bracket is 0.35. Hence, the overturning moment exerted on the existing foundation due to the underpinning is given by

$$M_1 = \frac{1}{1 + 0.35}(60\,kip\,in) = 44\,kip\,in$$

and the moment resisted by the pier in the soil is simply given by

$$M_2 = 60\,kip\,in - 44\,kip\,in = 16\,kip\,in$$

According to the right-hand chart in Fig. 9, the lateral load on the existing foundation caused by a bending moment of 16 kip-in for a 3" O.D., 0.250 thick steel pipe pier in stiff clays is approximately -1 kip. The negative sign indicates that the bracket is being pulled away from the foundation due to the bending of the pier under the applied eccentric loads.

Discussion

In summary, the example underpinning application examined in the previous section would exert on the existing foundation an overturning moment equal to 44 kip-in and a lateral load of -1 kip where the negative sign indicates tension. These loads are in addition to the more obvious design vertical load of 30 kips. In order for steel pier underpinning to be a viable alternative for repair of an existing foundation under these example conditions, the existing concrete foundation elements must be capable of withstanding these loads.

In the preparation of this work, push piers were assumed to be rigidly fixed to their brackets so that rotation between the bracket and pier is negligible. During steel push pier installation, the pier is typically not integrally attached to the bracket. However, the ram assembly used to install the pier often is attached in a manner that limits pier rotation relative to the bracket. It is possible and perhaps probable that some small amount of rotation of the pier with respect to the bracket may occur during installation and prior to bolting the pier to the bracket. This rotation would increase the reaction moment carried by the pier in the soil and, consequently would result in a larger rotational compatibility factor, λ. Hence, the foregoing analysis is conservative with regard to moments in that it tends to overestimate the moment transferred to the existing foundation, whereas, it is unconservative with regard to lateral loads, because it tends to underestimate the lateral loads exerted on the existing foundation.

A literature search was performed in the preparation of this study. Specific references regarding the analysis and determination of lateral loads and bending moments associated with underpinning brackets were not found. Yet, steel pier underpinning has been used to repair structures in the United States for at least 50 years. There are more than 6 manufacturers of steel pier underpinning systems and hundreds of installation contractors. Due to their widespread use, academic study of steel pier underpinning and bracket connections to structures is an important area of research that should be encouraged.

References

ICBO Evaluation Service, Inc. (2002) “Acceptance Criteria for Expansion Anchors in Concrete and Masonry Elements” ICBO Report #AC01-0402-R1

Magnum Piering, Inc. (2002) “Magnum Push Pier Technical Reference Manual” Corporate Literature, Cincinnati, OH

Atlas Systems, Inc. (2002) “Piering Products Manual”, Corporate Literature

Reese, L.C., et al. (2000) “Computer Program LPILE Plus Version 4.0 User’s Guide” Ensoft, Inc., Austin, TX 78718

Illinois Toolworks, Inc. (2001) “ITW Ramset/Redhead Product & Resource Book” Form No. FLC-6/01, Wood Dale, IL