State of California

Business, Transportation and Housing Agency

Memorandum

To: MR. MARK YASHINSKY
Office of Earthquake Engineering

Date: May 4, 2000

File: 01-Hum-255-0.7
01-296701

Middle Channel Bridge
Bridge No. 04-0229

From: **DEPARTMENT OF TRANSPORTATION**
ENGINEERING SERVICE CENTER
Division of Structural Foundations – MS 5
Office of Geotechnical Earthquake Engineering

Subject: Preliminary Foundation Stiffness

As per your request, this memo presents the preliminary foundation stiffness for the Middle Channel Bridge (No. 04-0229).

Pile Group Stiffness

The coordinate system and the definition of foundation stiffness as used in this memo are shown on the attached Figures 1 and 2, respectively. The recommended preliminary pile group foundation stiffness elements at each pier/abutment location are presented in the attached Tables 1 through 10. These foundation stiffnesses are evaluated based on a laterally loaded pile group analysis utilizing the computer program GROUP 4.0 (Ensoft, Inc.).

The stiffness matrices presented in this memo are preliminary and may be used in appropriate analyses to determine preliminary design loads. The foundation stiffness is a non-linear function of applied loads. This office should be contacted to provide appropriate stiffness matrices to be used in a refined structural analysis once the preliminary design loads are available.

Our preliminary analysis indicates that soil liquefaction, as presented in our memo dated March 10, 1999, should have no significant effect on the foundation stiffness at Abutment 1 provided the embankment is stable against slope failure. We will evaluate the slope stability of the Abutment 1 embankment, the effects of soil liquefaction on the foundation stiffness at Pier M2 and provide the recommended pile tip elevations at various piers once the preliminary design loads are available.

Abutment Endwall Stiffness

The initial abutment endwall stiffness can be calculated by multiplying a maximum soil pressure of 7.7 ksf by the wall area in contact with the soil and dividing the product by the total displacement at yield (i.e. gap+yield). A soil yield displacement of one (1) inch is recommended. A gap of one (1) inch may be assumed.

If you have any questions or comments, please call Mohammed S. Islam at 227-7094 or Abbas Abghari at 227-7172.

MOHAMMED S. ISLAM
NO. 2485
EXP. 06/30/03

A. Abghari

MOHAMMED S. ISLAM
Transportation Engineer

ABBAS ABGHARI, Chief
Office of Geotechnical Earthquake Engineering

Attachment

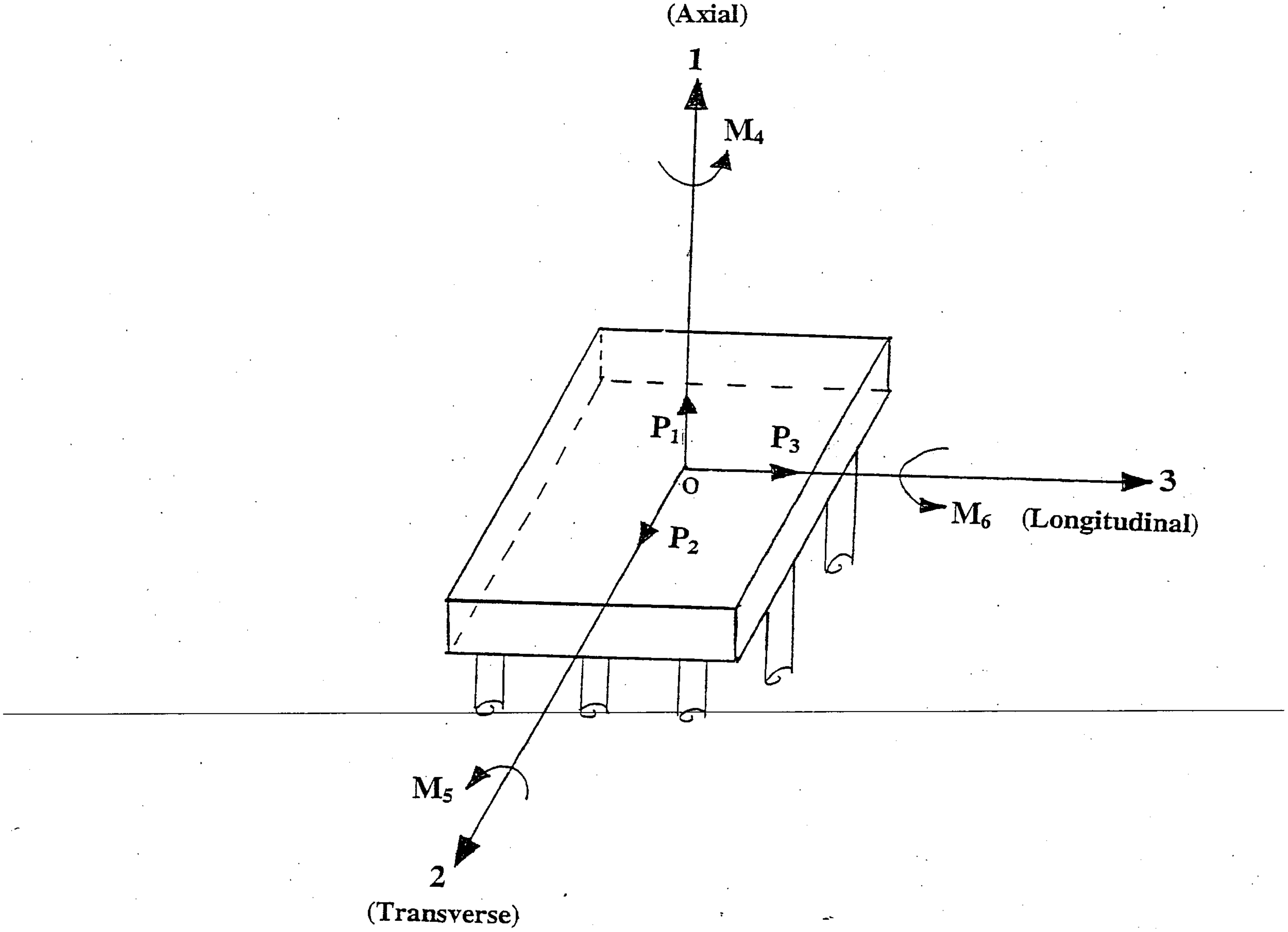

FIGURE 1. CO-ORDINATE SYSTEM

The stiffness matrix[1] for the pile group shown in Figure 1 may be written as:

$$\left[K \right] = \begin{pmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & K_{26} \\ 0 & 0 & K_{33} & 0 & K_{35} & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & K_{53} & 0 & K_{55} & 0 \\ 0 & K_{62} & 0 & 0 & 0 & K_{66} \end{pmatrix}$$

where:

K_{11} is the vertical stiffness along vertical (axial) axis 1;
K_{22} and K_{33} are the horizontal stiffnesses along axes 2 (transverse) and 3 (longitudinal);
K_{44} is the torsional stiffness about vertical axis 1;
K_{55} and K_{66} are the rocking stiffness about horizontal axes 2 and 3, respectively;
$K_{26}=K_{62}$, and $K_{35}=K_{53}$ are the cross coupling stiffnesses.

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[1] In developing this stiffness matrix, it is assumed that all foundations are symmetric about the horizontal axes. Furthermore, the stiffness matrix is considered uncoupled in the horizontal and vertical directions.

Figure 2. Definition of Stiffness Matrix for Pile Group

Table 1. Foundation Stiffness Matrix Elements for Pile Group at Abutment 1 (A1)

Element	Value	Unit
K_{11}	$1.95x10^4$	kip/in
K_{22}	$1.74x10^3$	kip/in
K_{33}	$3.56x10^3$	kip/in
K_{44}	$7.43x10^8$	kip-in/rad
K_{55}	$1.34x10^7$	kip-in/rad
K_{66}	$3.35x10^8$	kip-in/rad
K_{26}	$-8.8x10^5$	kip-in/in
K_{62}	$-8.8x10^5$	kip/rad
K_{35}	$1.12x10^5$	kip-in/in
K_{53}	$1.12x10^5$	kip/rad

Table 2. Foundation Stiffness Matrix Elements for Pile Group at Pier M2

Element	Value	Unit
K_{11}	$5.84x10^4$	kip/in
K_{22}	$2.53x10^3$	kip/in
K_{33}	$3.28x10^3$	kip/in
K_{44}	$3.10x10^7$	kip-in/rad
K_{55}	$6.40x10^8$	kip-in/rad
K_{66}	$4.28x10^8$	kip-in/rad
K_{26}	$-2.41x10^5$	kip-in/in
K_{62}	$-2.41x10^5$	kip/rad
K_{35}	$3.77x10^5$	kip-in/in
K_{53}	$3.77x10^5$	kip/rad

Table 3. Foundation Stiffness Matrix Elements for the Pile Group at Pier M3

Element	Value	Unit
K_{11}	1.593×10^5	kip/in
K_{22}	9.98×10^2	kip/in
K_{33}	6.85×10^2	kip/in
K_{44}	2.28×10^7	kip-in/rad
K_{55}	2.595×10^8	kip-in/rad
K_{66}	9.177×10^8	kip-in/rad
K_{26}	-2.786×10^5	kip-in/in
K_{62}	-2.786×10^5	kip/rad
K_{35}	3.387×10^5	kip-in/in
K_{53}	3.387×10^5	kip/rad

Table 4. Foundation Stiffness Matrix Elements for Pile Group at Pier M4

Element	Value	Unit
K_{11}	1.362×10^5	kip/in
K_{22}	9.30×10^2	kip/in
K_{33}	6.45×10^2	kip/in
K_{44}	2.146×10^7	kip-in/rad
K_{55}	3.253×10^8	kip-in/rad
K_{66}	1.039×10^9	kip-in/rad
K_{26}	-2.544×10^5	kip-in/in
K_{62}	-2.544×10^5	kip/rad
K_{35}	3.934×10^5	kip-in/in
K_{53}	3.934×10^5	kip/rad

Table 5. Foundation Stiffness Matrix Elements for Pile Group at Pier M5

Element	Value	Unit
K_{11}	1.298x10^{5}	kip/in
K_{22}	6.18x10^{2}	kip/in
K_{33}	4.85x10^{2}	kip/in
K_{44}	1.493x10^{7}	kip-in/rad
K_{55}	2.933x10^{8}	kip-in/rad
K_{66}	9.333x10^{7}	kip-in/rad
K_{26}	-5.767x10^{4}	kip-in/in
K_{62}	-5.767x10^{4}	kip/rad
K_{35}	3.566x10^{4}	kip-in/in
K_{53}	3.566x10^{5}	kip/rad

Table 6. Foundation Stiffness Matrix Elements for Pile Group at Pier M6

Element	Value	Unit
K_{11}	1.30x10^{5}	kip/in
K_{22}	6.4x10^{2}	kip/in
K_{33}	5.28x10^{2}	kip/in
K_{44}	1.614x10^{7}	kip-in/rad
K_{55}	2.977x10^{8}	kip-in/rad
K_{66}	1.194x10^{9}	kip-in/rad
K_{26}	-2.526x10^{5}	kip-in/in
K_{62}	-2.526x10^{5}	kip/rad
K_{35}	3.477x10^{5}	kip-in/in
K_{53}	3.477x10^{5}	kip/rad

Table 7. Foundation Stiffness Matrix Elements for Pile Group at Pier M7

Element	Value	Unit
K_{11}	**1.308x10^{5}**	**kip/in**
K_{22}	**7.15x10^{2}**	**kip/in**
K_{33}	**6.00x10^{2}**	**kip/in**
K_{44}	**1.83x10^{7}**	**kip-in/rad**
K_{55}	**2.921x10^{8}**	**kip-in/rad**
K_{66}	**3.751x10^{8}**	**kip-in/rad**
K_{26}	**-1.75x10^{5}**	**kip-in/in**
K_{62}	**-1.75x10^{5}**	**kip/rad**
K_{35}	**3.577x10^{5}**	**kip-in/in**
K_{53}	**3.577x10^{5}**	**kip/rad**

Table 8. Foundation Stiffness Matrix Elements for Pile Group at Pier M8

Element	Value	Unit
K_{11}	**6.10x10^{4}**	**kip/in**
K_{22}	**3.90x10^{3}**	**kip/in**
K_{33}	**3.86x10^{3}**	**kip/in**
K_{44}	**2.71x10^{7}**	**kip-in/rad**
K_{55}	**2.06x10^{8}**	**kip-in/rad**
K_{66}	**1.253x10^{9}**	**kip-in/rad**
K_{26}	**-9.35x10^{5}**	**kip-in/in**
K_{62}	**-9.35x10^{5}**	**kip/rad**
K_{35}	**4.445x10^{5}**	**kip-in/in**
K_{53}	**4.445x10^{5}**	**kip/rad**

Table 9. Foundation Stiffness Matrix Elements for Pile Group at Pier M9

Element	Value	Unit
K_{11}	$5.14x10^{5}$	kip/in
K_{22}	$6.384x10^{3}$	kip/in
K_{33}	$2.75x10^{3}$	kip/in
K_{44}	$4.58x10^{7}$	kip-in/rad
K_{55}	$2.977x10^{8}$	kip-in/rad
K_{66}	$5.10x10^{8}$	kip-in/rad
K_{26}	$-8.492x10^{5}$	kip-in/in
K_{62}	$-8.492x10^{5}$	kip/rad
K_{35}	$9.80x10^{5}$	kip-in/in
K_{53}	$9.80x10^{5}$	kip/rad

Table 10. Foundation Stiffness Matrix Elements for Pile Group at Abutment 10 (A10)

Element	Value	Unit
K_{11}	$1.898x10^{4}$	kip/in
K_{22}	$1.950x10^{3}$	kip/in
K_{33}	$3.56x10^{3}$	kip/in
K_{44}	$7.438x10^{8}$	kip-in/rad
K_{55}	$1.339x10^{7}$	kip-in/rad
K_{66}	$3.433x10^{8}$	kip-in/rad
K_{26}	$-5.0x10^{4}$	kip-in/in
K_{62}	$-5.0x10^{5}$	kip/rad
K_{35}	$1.10x10^{5}$	kip-in/in
K_{53}	$1.10x10^{5}$	kip/rad

State of California

Business, Transportation and Housing Agency

Memorandum

To: MR. MARK YASHINSKY
Office of Earthquake Engineering

Date: May 30, 2000

File: 01-Hum-255-0.7
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Middle Channel Bridge
Bridge No. 04-0229

From: **DEPARTMENT OF TRANSPORTATION**
ENGINEERING SERVICE CENTER
Division of Structural Foundations – MS 5
Office of Geotechnical Earthquake Engineering

Subject: Final Foundation Stiffness

As per your request, this memo presents the final foundation stiffness for the Middle Channel Bridge (No. 04-0229).

Pile Group Stiffness

The coordinate system and the definition of foundation stiffness as used in this memo are shown on the attached Figures 1 and 2, respectively. The recommended final pile group foundation stiffness elements at each pier/abutment location are presented in the attached Tables 1 through 10. These foundation stiffnesses are evaluated based on a laterally loaded pile group analysis utilizing the computer program GROUP 4.0 (Ensoft, Inc.).

For the piers M2, M8 and M9, two pile group stiffness matrices are computed: (1) for the existing piles only and (2) for the proposed four (4) 24" diameter new retrofit piles only. The stiffness coefficients for these matrices should be lumped at the centroid of the existing footing and the new footing, respectively. For the pier M2, additional stiffness matrices are computed by considering liquefaction. For each of the Piers M3 through M7, a combined stiffness matrix is computed for the existing and the new piles. The coefficients of these matrices should be lumped at the centroid of the combined footings.

Recommendations presented in our memo dated May 3, 2000 regarding the abutment endwall stiffness are still applicable.

Slope Stability

The approach embankment at abutment A1 is comprised of about 35 feet of compacted granular fill underlain by a 20 feet thick layer of potentially liquefiable native granular soil over dense sand. Based on our analysis, the embankment has a factor of safety of about 1.4 against static slope failure. The critical acceleration for the slope corresponding to a factor of safety of 1.0 was found to be about 0.13g. The peak ground acceleration at the site is estimated to be about 0.4g (see our memo, dated March 10, 1999). The corresponding permanent slope displacement is estimated to be on the order of 2 to 3 feet. However, a collapse type failure is not anticipated, as the compacted fill embankment should experience, if any, a relatively rigid block type movement.

Recommended Pile Tip Elevations

The recommended tip elevations for the proposed 24-inch diameter pile at piers M2, M8 and M9 are –55 feet –40 feet and –65 feet, respectively, and at piers M3 through M7 is –55 feet.

If you have any questions or comments, please call Mohammed S. Islam at 227-7094 or Abbas Abghari at 227-7172.

A. Abghari

MOHAMMED S. ISLAM
Transportation Engineer

ABBAS ABGHARI, Chief
Office of Geotechnical Earthquake Engineering

Attachment

MOHAMMED S. ISLAM
NO. 2485
EXP. 06/30/03

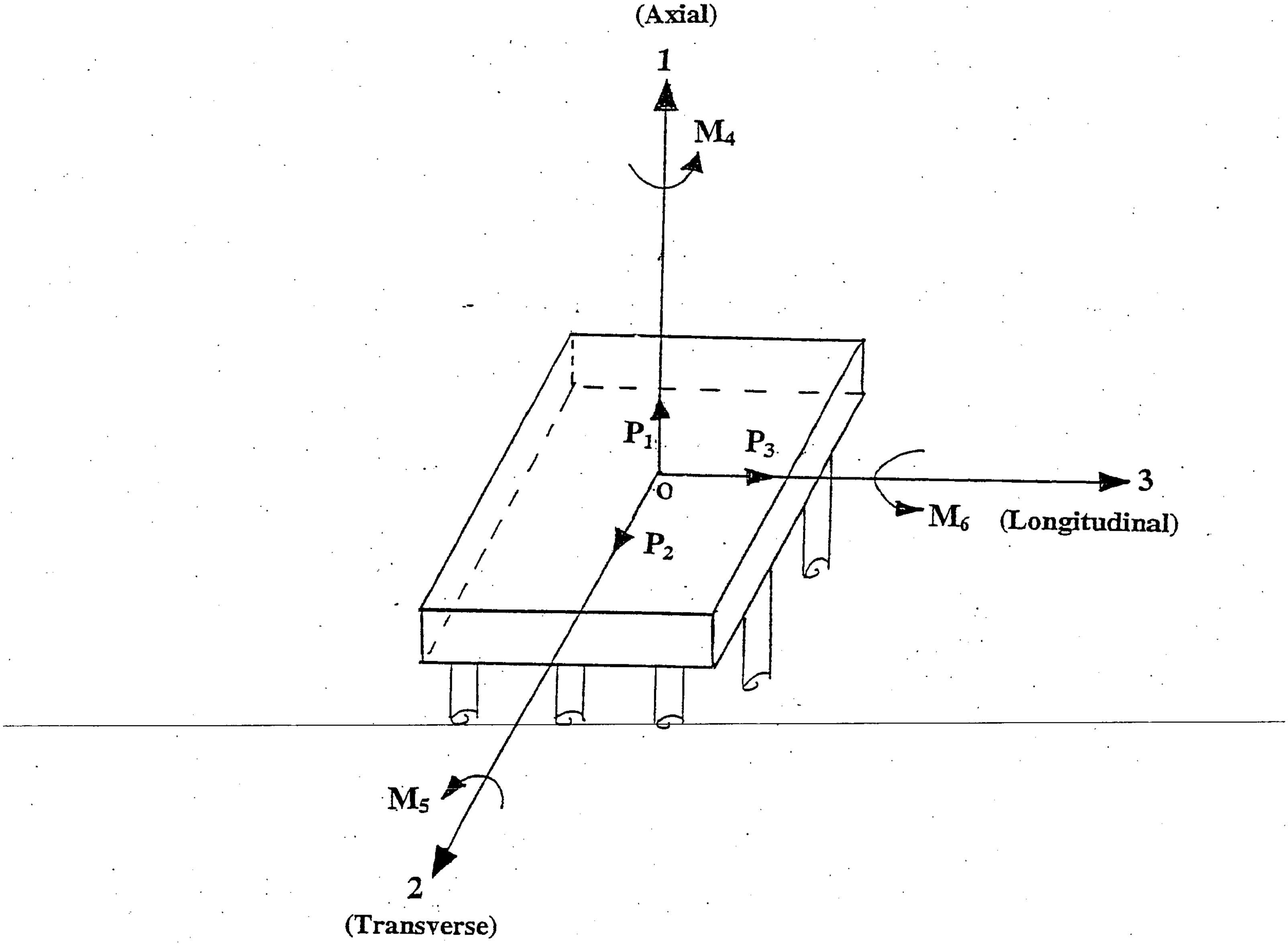

FIGURE 1. CO-ORDINATE SYSTEM

The stiffness matrix[1] for the pile group shown in Figure 1 may be written as:

$$\begin{bmatrix} K \end{bmatrix} = \begin{pmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & K_{26} \\ 0 & 0 & K_{33} & 0 & K_{35} & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & K_{53} & 0 & K_{55} & 0 \\ 0 & K_{62} & 0 & 0 & 0 & K_{66} \end{pmatrix}$$

where:

K_{11} is the vertical stiffness along vertical (axial) axis 1;
K_{22} and K_{33} are the horizontal stiffnesses along axes 2 (transverse) and 3 (longitudinal);
K_{44} is the torsional stiffness about vertical axis 1;
K_{55} and K_{66} are the rocking stiffness about horizontal axes 2 and 3, respectively;
$K_{26}=K_{62}$, and $K_{35}=K_{53}$ are the cross coupling stiffnesses.

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[1] In developing this stiffness matrix, it is assumed that all foundations are symmetric about the horizontal axes. Furthermore, the stiffness matrix is considered uncoupled in the horizontal and vertical directions.

Figure 2. Definition of Stiffness Matrix for Pile Group

Table 1. Stiffness Matrix Elements for Pile Group at Abutment 1 (A1)

Element	Value	Unit
K_{11}	1.95×10^4	kip/in
K_{22}	1.91×10^3	kip/in
K_{33}	1.19×10^3	kip/in
K_{44}	2.53×10^8	kip-in/rad
K_{55}	9.60×10^6	kip-in/rad
K_{66}	3.08×10^8	kip-in/rad
K_{26}	-9.64×10^4	kip-in/in
K_{62}	-9.64×10^4	kip/rad
K_{35}	2.24×10^4	kip-in/in
K_{53}	2.24×10^4	kip/rad

Table 2a. Stiffness Matrix Elements for the Existing Pile Group at Pier M2

Element	No Liquefaction	Liquefaction	Unit
K_{11}	2.93×10^4	2.75×10^4	kip/in
K_{22}	2.00×10^3	2.69×10^2	kip/in
K_{33}	1.80×10^3	2.07×10^2	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	2.30×10^7	5.50×10^7	kip-in/rad
K_{66}	8.87×10^7	7.44×10^7	kip-in/rad
K_{26}	-1.57×10^5	-1.36×10^5	kip-in/in
K_{62}	-1.57×10^5	-1.36×10^5	kip/rad
K_{35}	5.81×10^4	1.43×10^5	kip-in/in
K_{53}	5.81×10^4	1.43×10^5	kip/rad

Table 2b. Stiffness Matrix Elements for the New Pile Group at Pier M2

Element	No Liquefaction	Liquefaction	Unit
K_{11}	9.25x10^{3}	8.35x10^{3}	kip/in
K_{22}	2.96x10^{2}	1.29x10^{2}	kip/in
K_{33}	2.85x10^{2}	1.36x10^{2}	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	4.80x10^{7}	5.10x10^{7}	kip-in/rad
K_{66}	2.27x10^{8}	2.06x10^{8}	kip-in/rad
K_{26}	-4.72x10^{4}	-8.35x10^{4}	kip-in/in
K_{62}	-4.72x10^{4}	-8.35x10^{4}	kip/rad
K_{35}	4.72x10^{4}	4.9x10^{4}	kip-in/in
K_{53}	4.72x10^{4}	4.9x10^{4}	kip/rad

Table 3. Foundation Stiffness Matrix Elements for the Combined Pile Group at Pier M3

Element	Value	Unit
K_{11}	1.41x10^{5}	kip/in
K_{22}	6.35x10^{2}	kip/in
K_{33}	3.89x10^{2}	kip/in
K_{44}	N/A	kip-in/rad
K_{55}	2.184x10^{8}	kip-in/rad
K_{66}	7.78x10^{8}	kip-in/rad
K_{26}	-2.64x10^{5}	kip-in/in
K_{62}	-2.64x10^{5}	kip/rad
K_{35}	2.77x10^{5}	kip-in/in
K_{53}	2.77x10^{5}	kip/rad

Table 4. Foundation Stiffness Matrix Elements for the Combined Pile Group at Pier M4

Element	Value	Unit
K_{11}	$1.34x10^5$	kip/in
K_{22}	$6.89x10^2$	kip/in
K_{33}	$4.04x10^2$	kip/in
K_{44}	N/A	kip-in/rad
K_{55}	$2.50x10^8$	kip-in/rad
K_{66}	$8.50x10^8$	kip-in/rad
K_{26}	$-2.35x10^5$	kip-in/in
K_{62}	$-2.35x10^5$	kip/rad
K_{35}	$3.17x10^5$	kip-in/in
K_{53}	$3.17x10^5$	kip/rad

Table 5. Foundation Stiffness Matrix Elements for the Combined Pile Group at Pier M5

Element	Value	Unit
K_{11}	$1.25x10^5$	kip/in
K_{22}	$4.44x10^2$	kip/in
K_{33}	$2.63x10^2$	kip/in
K_{44}	N/A	kip-in/rad
K_{55}	$2.24x10^8$	kip-in/rad
K_{66}	$8.18x10^8$	kip-in/rad
K_{26}	$-3.62x10^4$	kip-in/in
K_{62}	$-3.62x10^4$	kip/rad
K_{35}	$2.61x10^4$	kip-in/in
K_{53}	$2.61x10^5$	kip/rad

Table 6. Foundation Stiffness Matrix Elements for the Combined Pile Group at Pier M6

Element	Value	Unit
K_{11}	$1.293x10^5$	kip/in
K_{22}	$4.53x10^2$	kip/in
K_{33}	$2.80x10^2$	kip/in
K_{44}	N/A	kip-in/rad
K_{55}	$1.97x10^8$	Kip-in/rad
K_{66}	$7.55x10^8$	Kip-in/rad
K_{26}	$-3.93x10^5$	kip-in/in
K_{62}	$-3.93x10^5$	kip/rad
K_{35}	$2.40x10^5$	kip-in/in
K_{53}	$2.40x10^5$	kip/rad

Table 7. Foundation Stiffness Matrix Elements for the Combined Pile Group at Pier M7

Element	Value	Unit
K_{11}	$1.26x10^5$	kip/in
K_{22}	$5.19x10^2$	kip/in
K_{33}	$3.09x10^2$	kip/in
K_{44}	N/A	Kip-in/rad
K_{55}	$2.05x10^8$	Kip-in/rad
K_{66}	$7.64x10^8$	Kip-in/rad
K_{26}	$-3.33x10^5$	kip-in/in
K_{62}	$-3.33x10^5$	kip/rad
K_{35}	$2.57x10^5$	kip-in/in
K_{53}	$2.57x10^5$	kip/rad

Table 8. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M8

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$2.632x10^{4}$	$1.03x10^{4}$	kip/in
K_{22}	$3.53x10^{3}$	$2.37x10^{2}$	kip/in
K_{33}	$2.62x10^{3}$	$2.10x10^{2}$	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$5.71x10^{8}$	$1.852x10^{8}$	kip-in/rad
K_{66}	$5.92x10^{8}$	$5.55x10^{7}$	kip-in/rad
K_{26}	$-5.03x10^{4}$	$-8.10x10^{4}$	kip-in/in
K_{62}	$-5.03x10^{4}$	$8.10x10^{4}$	kip/rad
K_{35}	$1.10x10^{5}$	$4.21x10^{4}$	kip-in/in
K_{53}	$1.10x10^{5}$	$4.12x10^{4}$	kip/rad

Table 9. Foundation Stiffness Matrix Elements for Pile Groups at Pier M9

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$2.773x10^{5}$	$1.20x10^{4}$	kip/in
K_{22}	$1.93x10^{3}$	$7.70x10^{2}$	kip/in
K_{33}	$2.08x10^{3}$	$4.13x10^{2}$	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$4.21x10^{7}$	$5.55x10^{7}$	kip-in/rad
K_{66}	$5.84x10^{7}$	$3.76x10^{8}$	kip-in/rad
K_{26}	$-9.6x10^{4}$	$-1.0x10^{5}$	kip-in/in
K_{62}	$-9.6x10^{4}$	$-1.0x10^{5}$	kip/rad
K_{35}	$4.57x10^{4}$	$5.60x10^{4}$	kip-in/in
K_{53}	$4.57x10^{4}$	$5.60x10^{4}$	kip/rad

Table 10. Foundation Stiffness Matrix Elements for Pile Group at Abutment 10 (A10)

Element	Value	Unit
K_{11}	$1.90x10^{4}$	kip/in
K_{22}	$2.25x10^{3}$	kip/in
K_{33}	$1.13x10^{3}$	kip/in
K_{44}	$2.43x10^{8}$	kip-in/rad
K_{55}	$1.31x10^{7}$	kip-in/rad
K_{66}	$3.314x10^{8}$	kip-in/rad
K_{26}	$-1.40x10^{5}$	kip-in/in
K_{62}	$-1.40x10^{5}$	kip/rad
K_{35}	$7.20x10^{4}$	kip-in/in
K_{53}	$7.20x10^{4}$	kip/rad

State of California

Business, Transportation and Housing Agency

Memorandum

To: MR. MARK YASHINSKY
Office of Earthquake Engineering

Date: June 1, 2000

File: 01-Hum-255-0.7
01-296701

Middle Channel Bridge
Bridge No. 04-0229

From: **DEPARTMENT OF TRANSPORTATION**
ENGINEERING SERVICE CENTER
Division of Structural Foundations – MS 5
Office of Geotechnical Earthquake Engineering

Subject: Foundation Stiffnesses for the Existing and the New Pile Groups

As per your request, this memo presents foundation stiffnesses computed separately for the existing and the new pile groups.

The coordinate system and the definition of foundation stiffness as used in this memo are shown on the attached Figures 1 and 2, respectively. The recommended pile group foundation stiffness elements at each pier/abutment location are presented in the attached Tables 1 through 10. These foundation stiffnesses are evaluated based on a laterally loaded pile group analysis utilizing the computer program GROUP 4.0 (Ensoft, Inc.).

For each of the piers M2 through M9, two pile group stiffness matrices are computed: (1) for the existing piles only and (2) for the proposed four (4) 24" diameter new retrofit piles only. The stiffness coefficients for these matrices should be lumped at the centroid of the existing footing and the new footing, respectively. For the pier M2, additional stiffness matrices are computed by considering liquefaction. Combined stiffness matrices for each of the piers M7 through M7 were presented in our memo dated May 30, 2000.

If you have any questions or comments, please call Mohammed S. Islam at 227-7094 or Abbas Abghari at 227-7172.

MOHAM[illegible]
Transportation Engineer

Attachment

MOHAMMED S. ISLAM
NO. 2485
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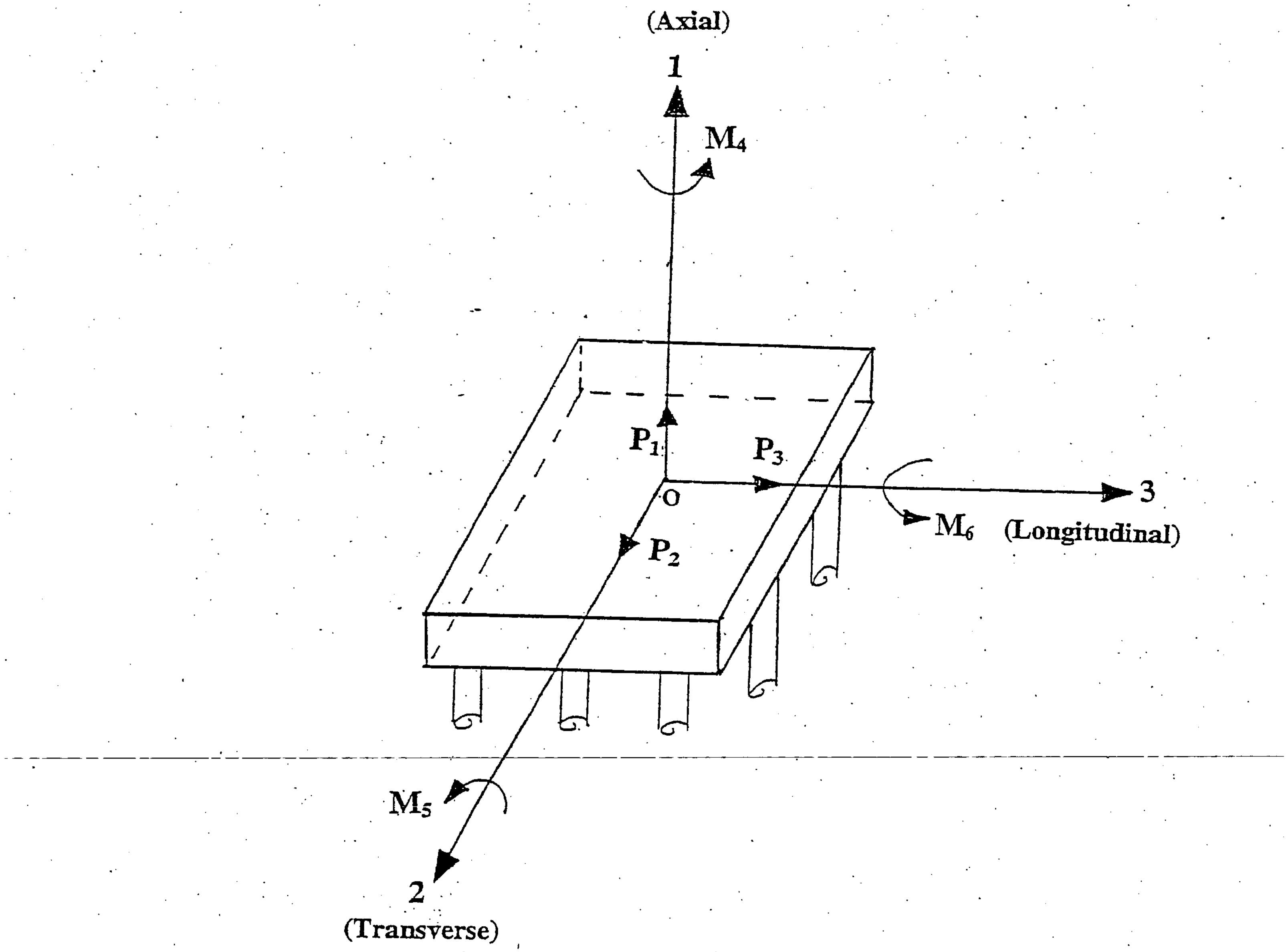


FIGURE 1. CO-ORDINATE SYSTEM

The stiffness matrix[1] for the pile group shown in Figure 1 may be written as:

$$[K] = \begin{pmatrix} K_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & K_{22} & 0 & 0 & 0 & K_{26} \\ 0 & 0 & K_{33} & 0 & K_{35} & 0 \\ 0 & 0 & 0 & K_{44} & 0 & 0 \\ 0 & 0 & K_{53} & 0 & K_{55} & 0 \\ 0 & K_{62} & 0 & 0 & 0 & K_{66} \end{pmatrix}$$

where:

K_{11} is the vertical stiffness along vertical (axial) axis 1;
K_{22} and K_{33} are the horizontal stiffnesses along axes 2 (transverse) and 3 (longitudinal);
K_{44} is the torsional stiffness about vertical axis 1;
K_{55} and K_{66} are the rocking stiffness about horizontal axes 2 and 3, respectively;
$K_{26}=K_{62}$, and $K_{35}=K_{53}$ are the cross coupling stiffnesses.

---

[1] In developing this stiffness matrix, it is assumed that all foundations are symmetric about the horizontal axes. Furthermore, the stiffness matrix is considered uncoupled in the horizontal and vertical directions.

Figure 2. Definition of Stiffness Matrix for Pile Group

Table 1. Stiffness Matrix Elements for Pile Group at Abutment 1 (A1)

Element	Value	Unit
K_{11}	1.95×10^4	kip/in
K_{22}	1.91×10^3	kip/in
K_{33}	1.19×10^3	kip/in
K_{44}	2.53×10^8	kip-in/rad
K_{55}	9.60×10^6	kip-in/rad
K_{66}	3.08×10^8	kip-in/rad
$K_{26}=K_{62}$	-9.64×10^4	kip-in/in
$K_{35}=K_{53}$	2.24×10^4	kip-in/in

Table 2a. Stiffness Matrix Elements for the Existing Pile Group at Pier M2

Element	No Liquefaction	Liquefaction	Unit
K_{11}	2.93×10^4	2.75×10^4	kip/in
K_{22}	2.00×10^3	2.69×10^2	kip/in
K_{33}	1.80×10^3	2.07×10^2	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	2.30×10^7	5.50×10^7	kip-in/rad
K_{66}	8.87×10^7	7.44×10^7	kip-in/rad
$K_{26}=K_{62}$	-1.57×10^5	-1.36×10^5	kip-in/in
$K_{35}=K_{53}$	5.81×10^4	1.43×10^5	kip-in/in

Table 2b. Stiffness Matrix Elements for the New Pile Group at Pier M2

Element	No Liquefaction	Liquefaction	Unit
K_{11}	$9.25x10^3$	$8.35x10^3$	kip/in
K_{22}	$2.96x10^2$	$1.29x10^2$	kip/in
K_{33}	$2.85x10^2$	$1.36x10^2$	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$4.80x10^7$	$5.10x10^7$	kip-in/rad
K_{66}	$2.27x10^8$	$2.06x10^8$	kip-in/rad
$K_{26}=K_{62}$	$-4.72x10^4$	$-8.35x10^4$	kip-in/in
$K_{35}=K_{53}$	$4.72x10^4$	$4.9x10^4$	kip-in/in

Table 3. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M3

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$7.10x10^4$	$6.74x10^4$	kip/in
K_{22}	$5.37x10^2$	97.~~2~~71	kip/in
K_{33}	~~4.67~~$x10^2$ 4.76	83.4	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$1.48x10^8$	$4.37x10^7$	kip-in/rad
K_{66}	$4.18x10^8$	$5.58x10^8$	kip-in/rad
$K_{26}=K_{62}$	$-5.13x10^5$	$-2.43x10^4$	kip-in/in
$K_{35}=K_{53}$	$2.46x10^5$	$5.11x10^4$	kip/rad

Table 4. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M4

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$7.16x10^4$	$5.95x10^4$	kip/in
K_{22}	$6.42x10^2$	96.3	kip/in
K_{33}	$5.84x10^2$	83.0	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$2.21x10^8$	$4.38x10^7$	kip-in/rad
K_{66}	$3.66x10^7$	$5.50x10^8$	kip-in/rad
$K_{26}=K_{62}$	$-2.81x10^5$	$-2.41x10^4$	kip-in/in
$K_{35}=K_{53}$	$3.19x10^5$	$5.17x10^4$	kip-in/in

Table 5. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M5

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$6.38x10^4$	$5.75x10^4$	kip/in
K_{22}	$4.12x10^2$	61.0	kip/in
K_{33}	$3.68x10^2$	54.4	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$2.06x10^8$	$3.61x10^7$	kip-in/rad
K_{66}	$4.75x10^8$	$4.83x10^8$	kip-in/rad
$K_{26}=K_{62}$	$-4.80x10^5$	$-1.75x10^4$	kip-in/in
$K_{35}=K_{53}$	$2.82x10^5$	$3.29x10^4$	kip-in/in

Table 6. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M6

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$6.67x10^4$	$5.78x10^4$	kip/in
K_{22}	$4.20x10^2$	63.6	kip/in
K_{33}	$3.69x10^2$	59.3	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	$1.79x10^8$	$3.44x10^7$	Kip-in/rad
K_{66}	$4.20x10^8$	$4.80x10^8$	Kip-in/rad
$K_{26}=K_{62}$	$-4.23x10^5$	$-1.81x10^4$	kip-in/in
$K_{35}=K_{53}$	$2.52x10^5$	$3.30x10^4$	kip-in/in

Table 7. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M7

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	$6.43x10^4$	$5.55x10^4$	kip/in
K_{22}	$4.83x10^2$	76.8	kip/in
K_{33}	$4.18x10^2$	72.2	kip/in
K_{44}	N/A	N/A	Kip-in/rad
K_{55}	$1.86x10^8$	$3.38x10^7$	Kip-in/rad
K_{66}	$4.03x10^8$	$4.90x10^8$	Kip-in/rad
$K_{26}=K_{62}$	$-4.11x10^5$	$2.01x10^4$	kip-in/in
$K_{35}=K_{53}$	$2.71x10^5$	$3.32x10^4$	kip-in/in

Table 8. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M8

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	2.632x10^4	1.03x10^4	kip/in
K_{22}	3.53x10^3	2.37x10^2	kip/in
K_{33}	2.62x10^3	2.10x10^2	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	5.71x10^8	1.852x10^8	kip-in/rad
K_{66}	5.92x10^8	5.55x10^7	kip-in/rad
K_{26}=K_{62}	-5.03x10^4	-8.10x10^4	kip-in/in
K_{35}=K_{53}	1.10x10^5	4.21x10^4	kip-in/in

Table 9. Foundation Stiffness Matrix Elements for the Pile Groups at Pier M9

Element	Existing Piles Only	New Piles Only	Unit
K_{11}	2.773x10^5	1.20x10^4	kip/in
K_{22}	1.93x10^3	7.70x10^2	kip/in
K_{33}	2.08x10^3	4.13x10^2	kip/in
K_{44}	N/A	N/A	kip-in/rad
K_{55}	4.21x10^7	5.55x10^7	kip-in/rad
K_{66}	5.84x10^7	3.76x10^8	kip-in/rad
K_{26}=K_{62}	-9.6x10^4	-1.0x10^5	kip-in/in
K_{35}=K_{53}	4.57x10^4	5.60x10^4	kip-in/in

Table 10. Foundation Stiffness Matrix Elements for Pile Group at Abutment 10 (A10)

Element	Value	Unit
K_{11}	1.90×10^4	kip/in
K_{22}	2.25×10^3	kip/in
K_{33}	1.13×10^3	kip/in
K_{44}	2.43×10^8	kip-in/rad
K_{55}	1.31×10^7	kip-in/rad
K_{66}	3.314×10^8	kip-in/rad
$K_{26}=K_{62}$	-1.40×10^5	kip-in/in
$K_{35}=K_{53}$	7.20×10^4	kip-in/in

State of California

Business, Transportation and Housing Agency

Memorandum

To: MR. MARK YASHINSKY
Office of Earthquake Engineering

Date: June 5, 2000

File: 01-Hum-255-0.7
01-296701

Middle Channel Bridge
Bridge No. 04-0229

From: **DEPARTMENT OF TRANSPORTATION**
ENGINEERING SERVICE CENTER
Division of Structural Foundations – MS 5
Office of Geotechnical Earthquake Engineering

Subject: Axial (Compression and Tension) Load-Settlement Curves

As per your request, this memo presents single pile axial load-settlement curves for the Middle Channel Bridge (Br. No. 04-229).

Single pile axial load-settlement curves for the existing and the proposed new retrofit piles, when applicable, are presented in the attached Figures 1 through 10. The axial (compression and tension) stiffness at any settlement level for a given single pile at a given foundation location may be taken as the secant slope of the respective load-settlement curve. Please note that the compression load and the downward settlement are taken as positive in these figures.

If you have any questions or comments, please call Mohammed S. Islam at 227-7094 or Abbas Abghari at 227-7172.

MOHAMMED S. ISLAM
Transportation Engineer

ABBAS ABGHARI, Chief
Office of Geotechnical Earthquake Engineering

Attachment

MOHAMMED S. ISLAM
NO. 2485
EXP. 06/30/03

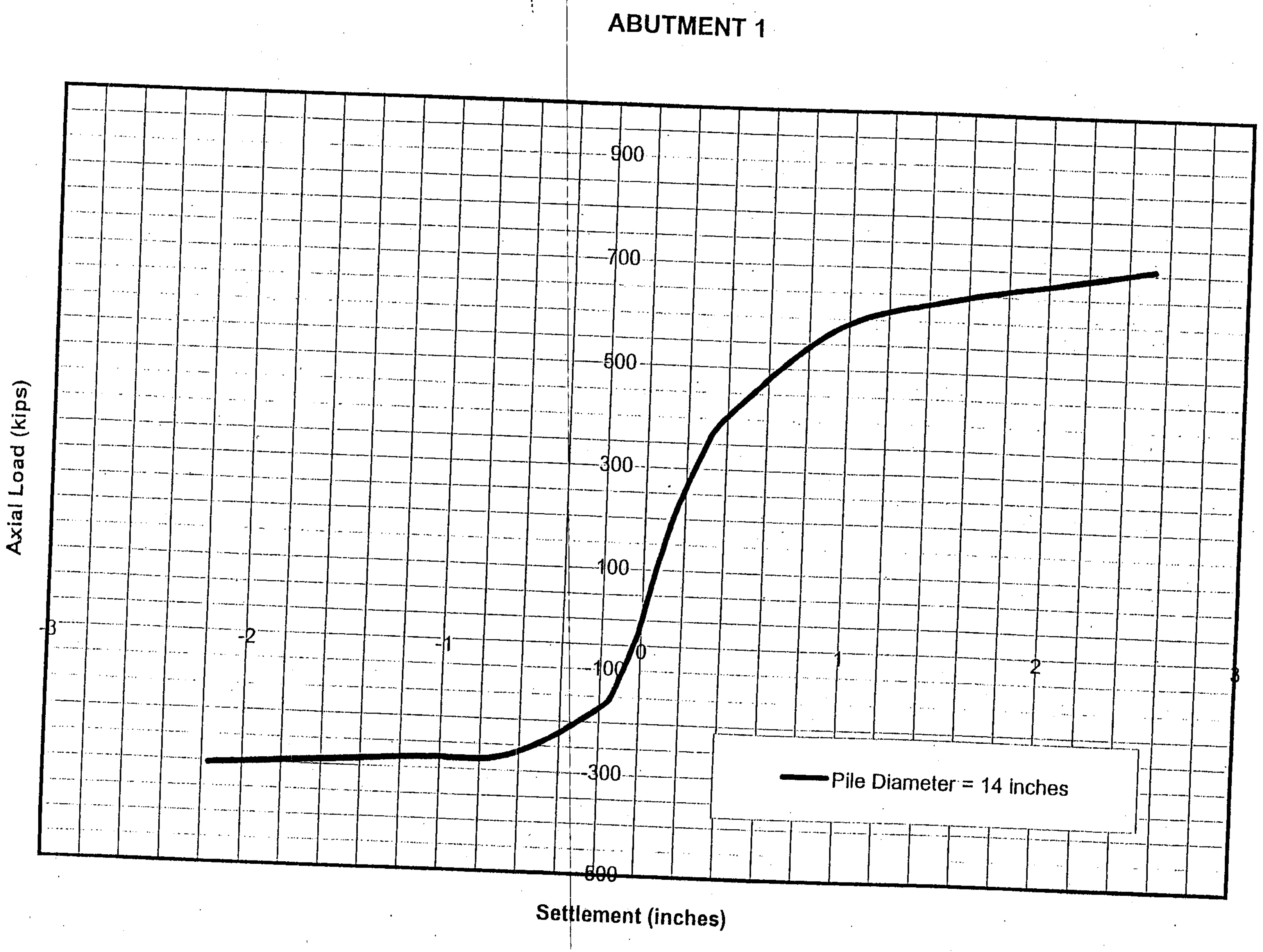


Figure 1. Axial Load - Settlement Curve for the Existing 14" Diameter Piles at Abutment A1

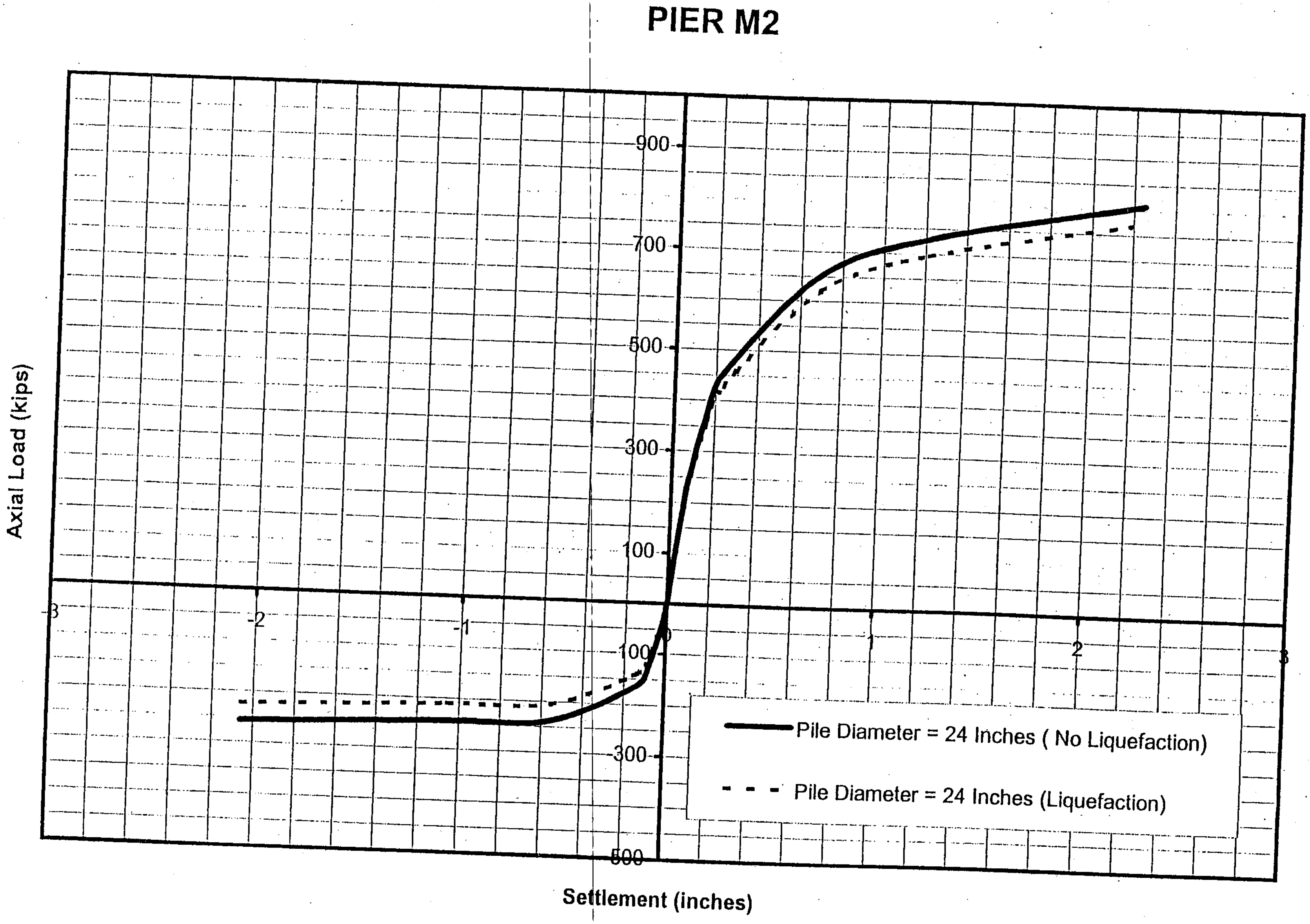


Figure 2b. Axial Load - Settlement Curve for the New 24" Diameter Piles at Pier M2

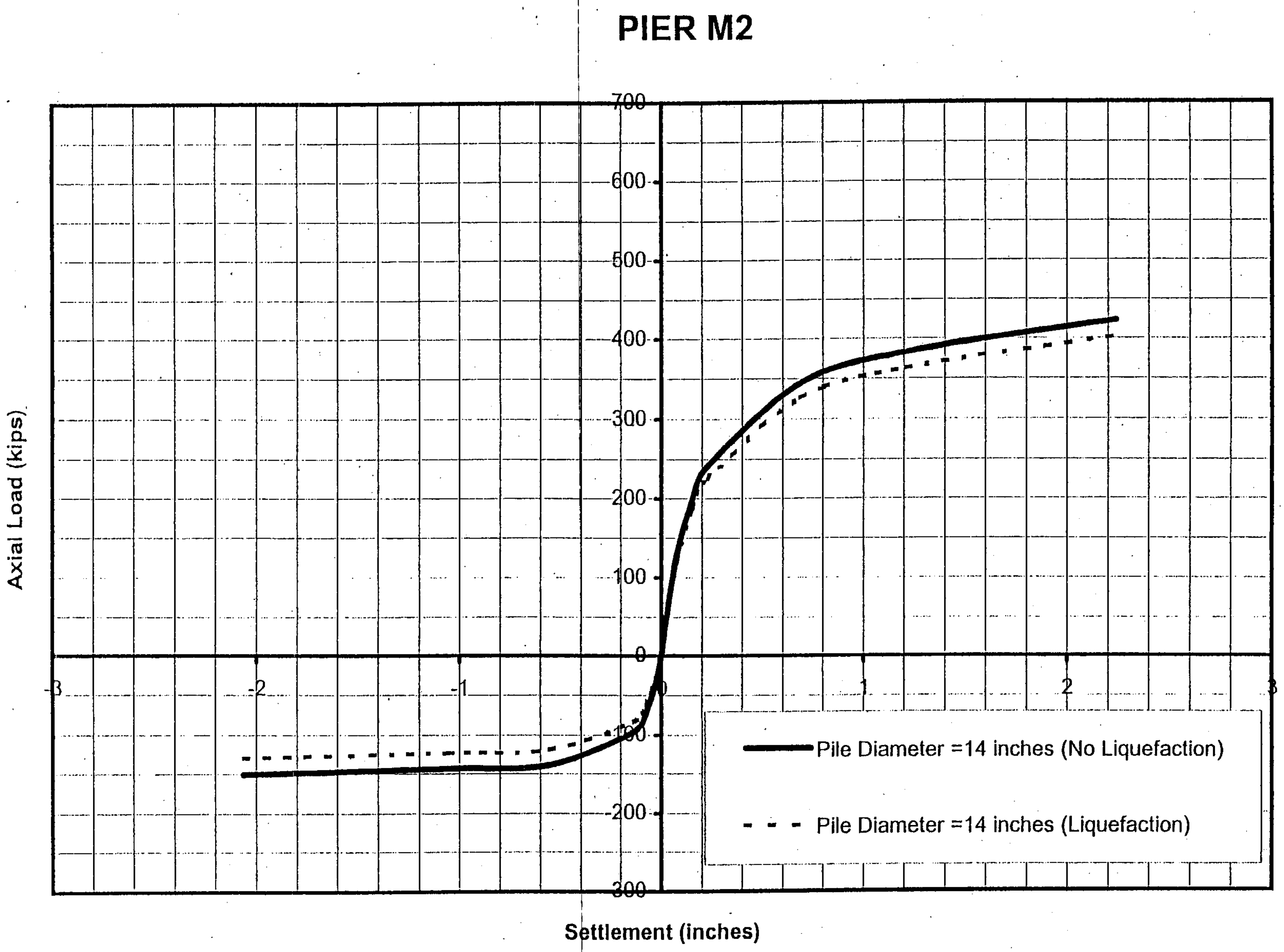


Figure 2a. Axial Load - Settlement Curve for the Existing 14" Diameter Piles at Pier M2

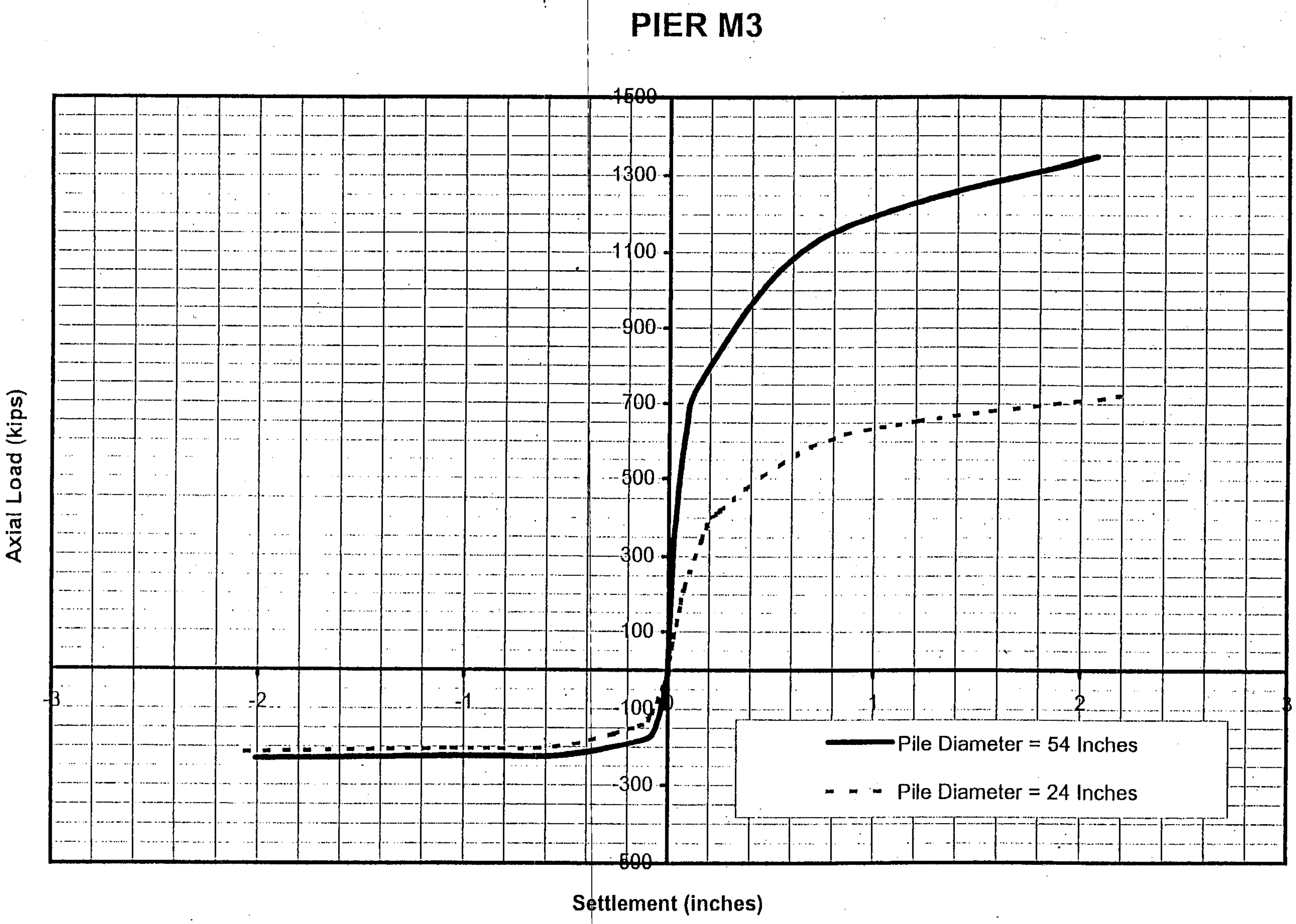


Figure 3. Axial Load - Settlement Curve for the Existing 54" and the New 24" Diameter Piles at Pier M3

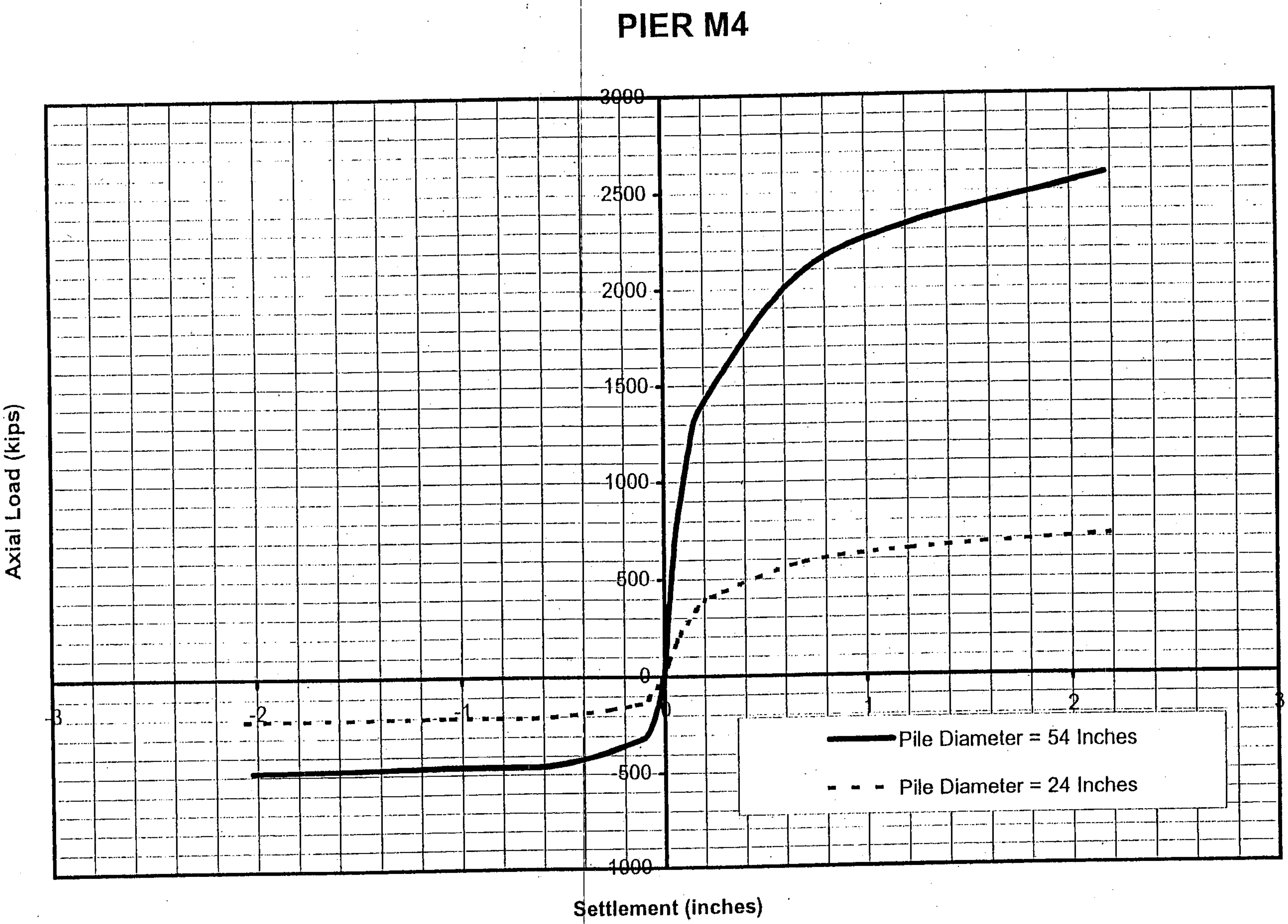


Figure 4. Axial Load - Settlement Curve for the Existing 54" and the New 24" Diameter Piles at Pier M4

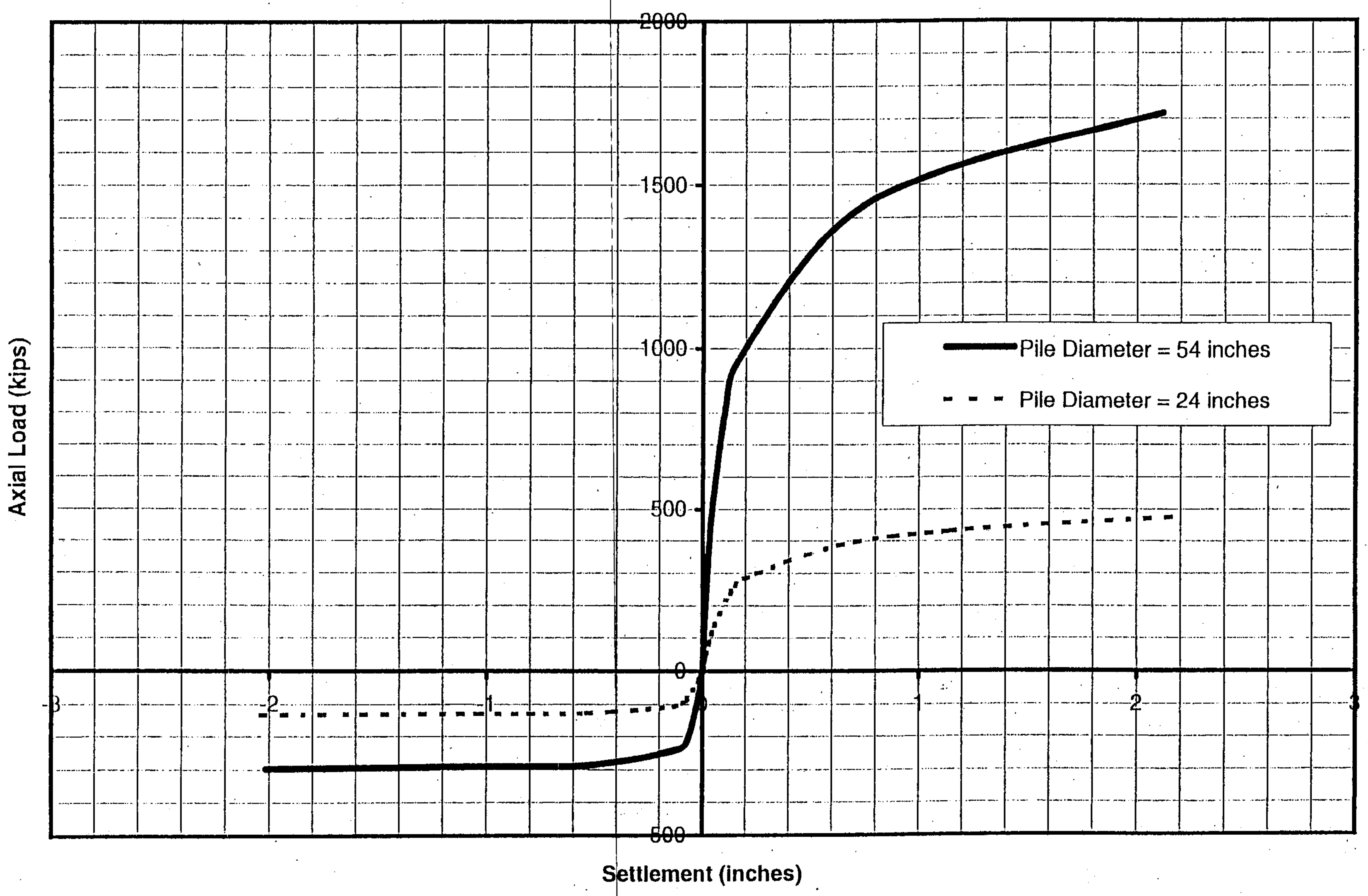

PIER M5

Figure 5. Axial Load - Settlement Curve for the Existing 54" and the New 24" Diameter Piles at Pier M5

PIER M6

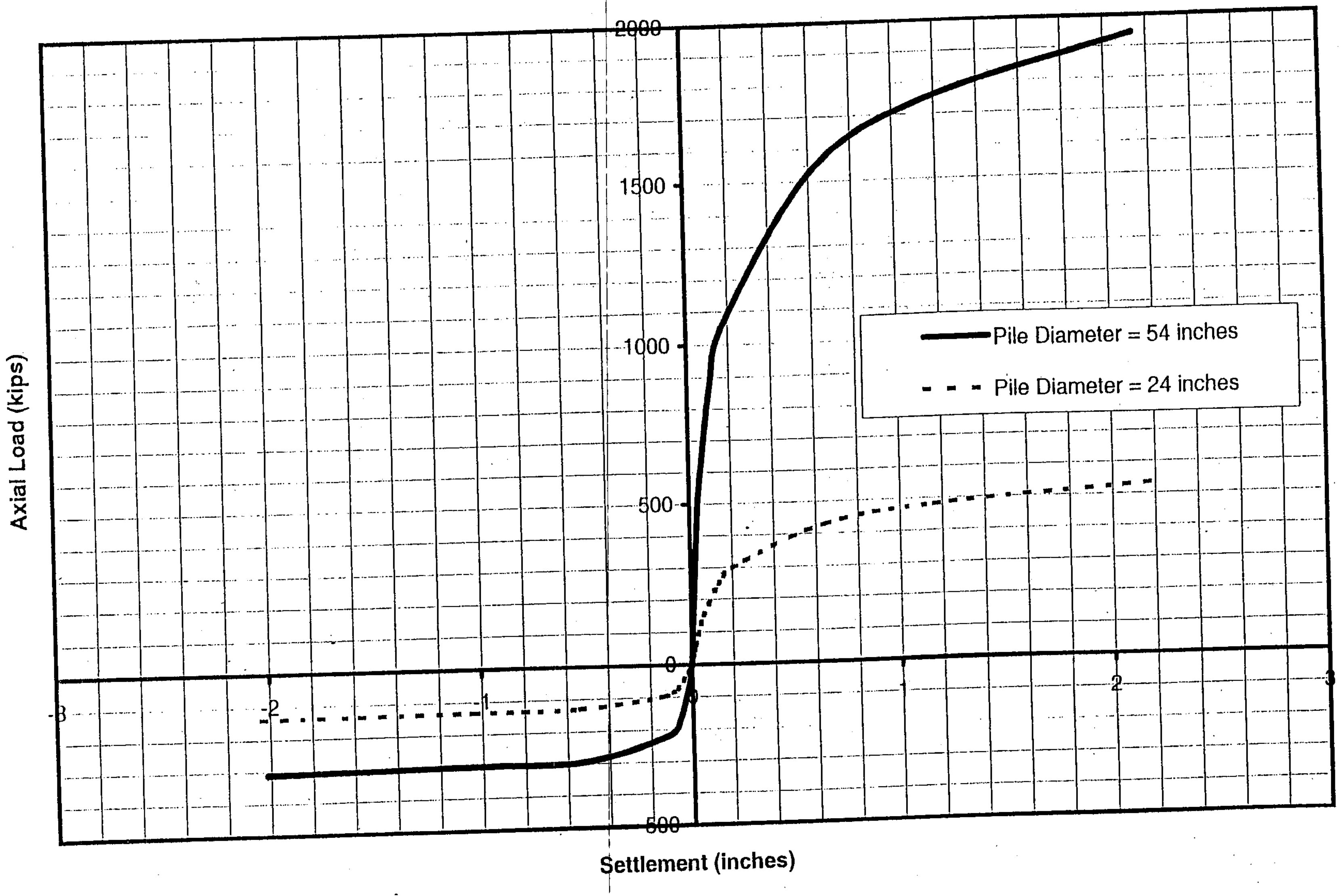


Figure 6. Axial Load - Settlement Curve for the Existing 54" and the New 24" Diameter Piles at Pier M6

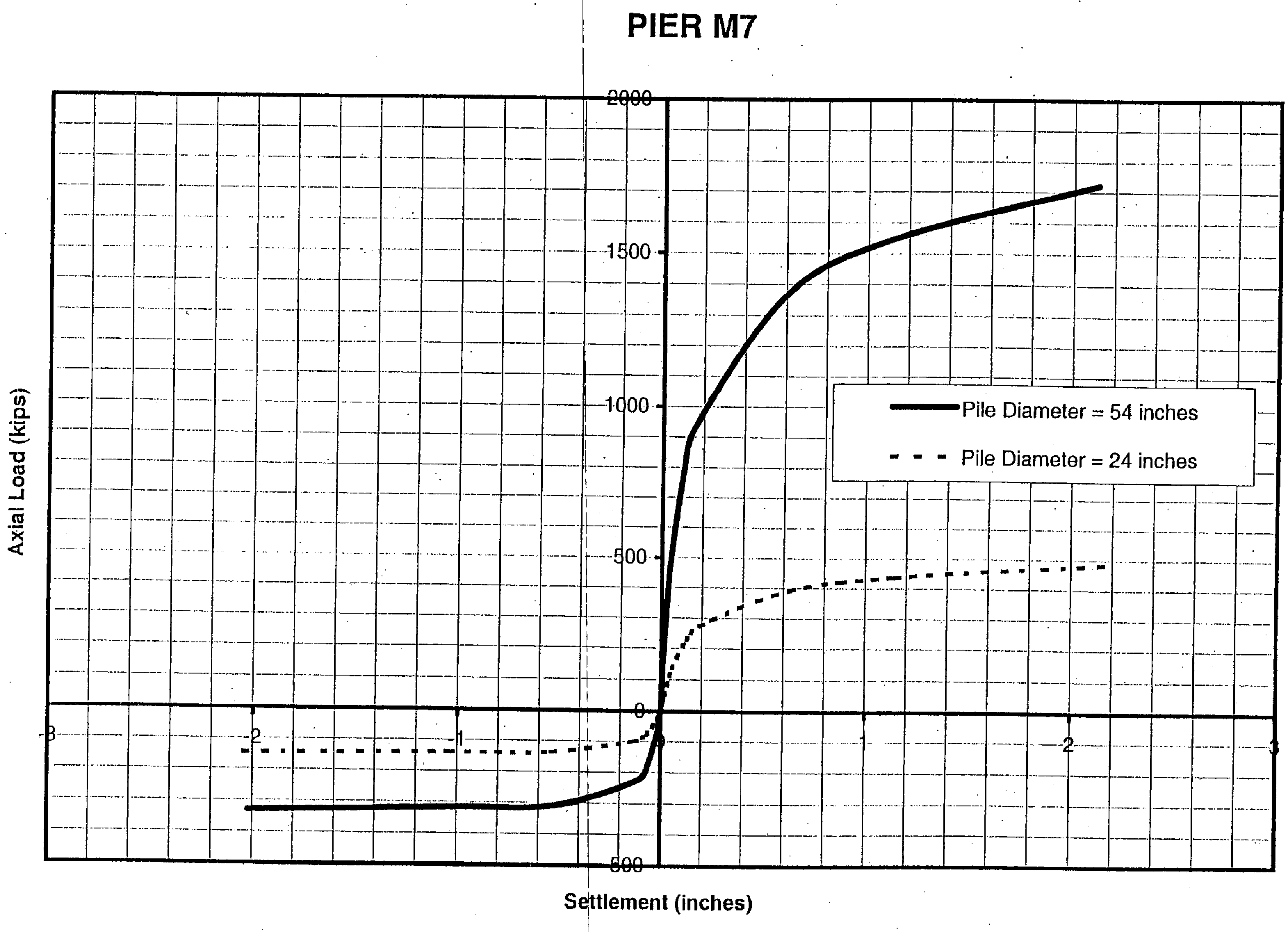


Figure 7. Axial Load - Settlement Curve for the Existing 54" and the New 24" Diameter Piles at Pier M7

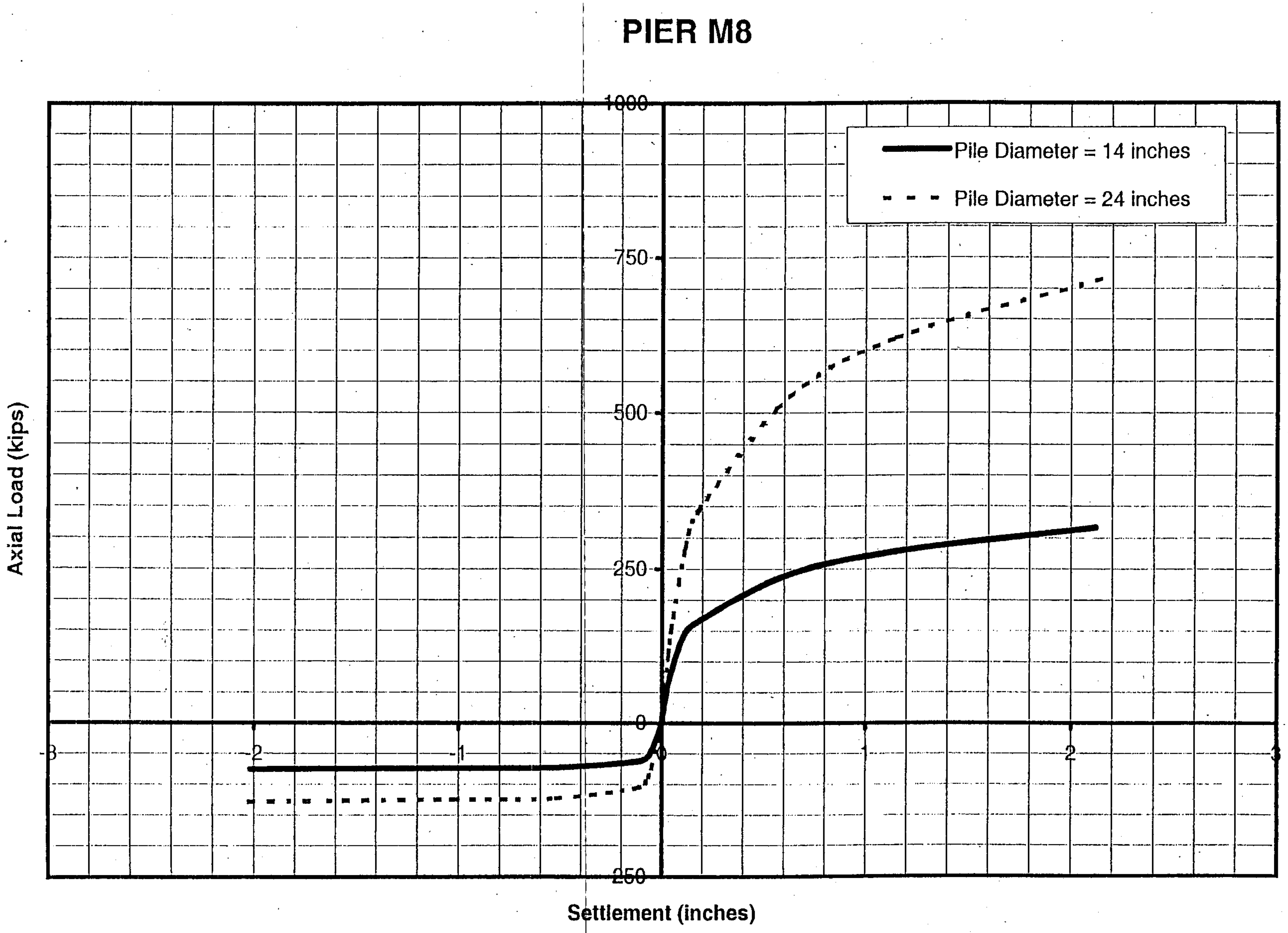


Figure 8. Axial Load - Settlement Curve for the Existing 14" and the New 24" Diameter Piles at Pier M8

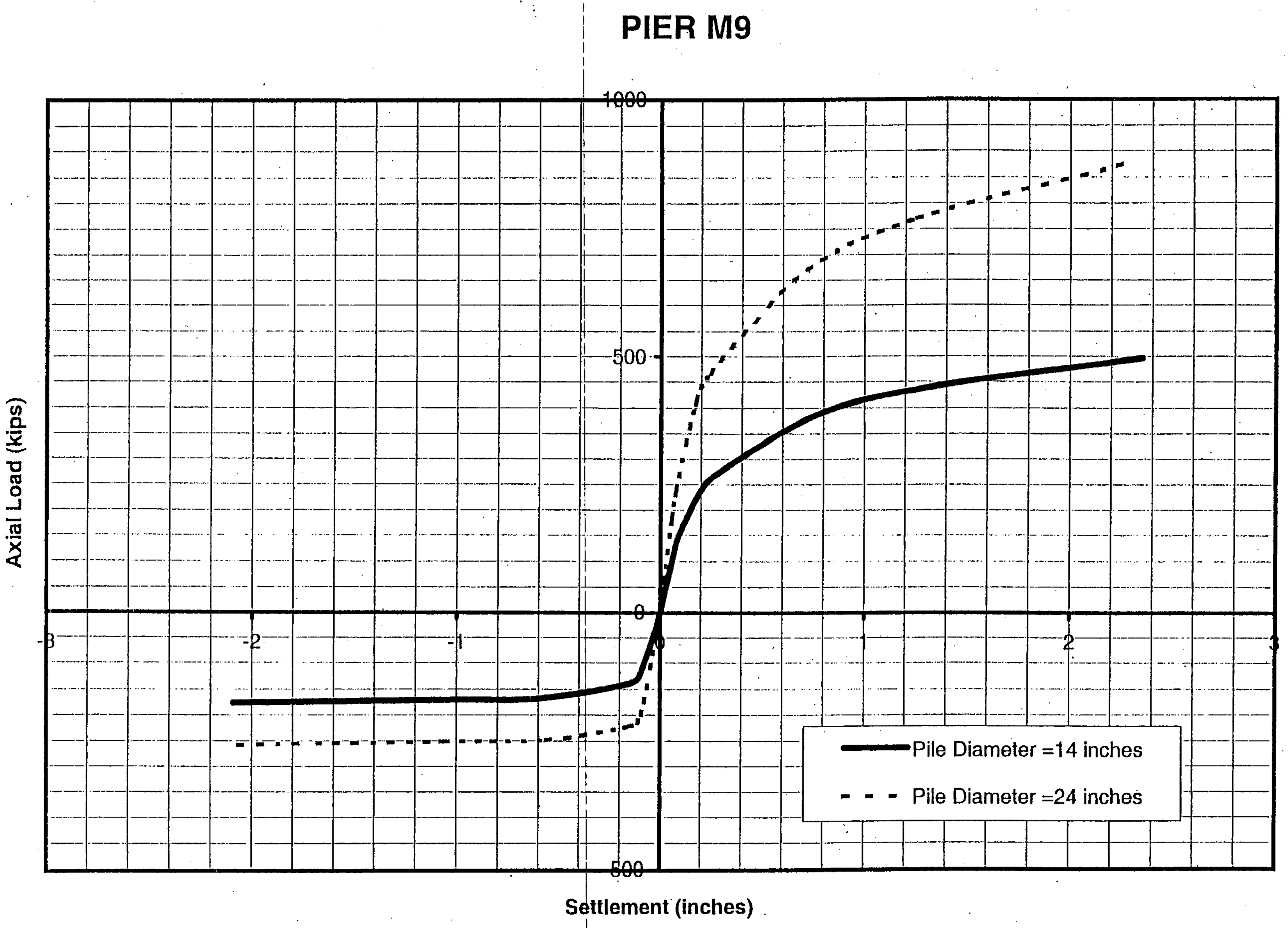


Figure 9. Axial Load - Settlement Curve for the Existing 14" and the New 24" Diameter Piles at Pier M9

ABUTMENT A10

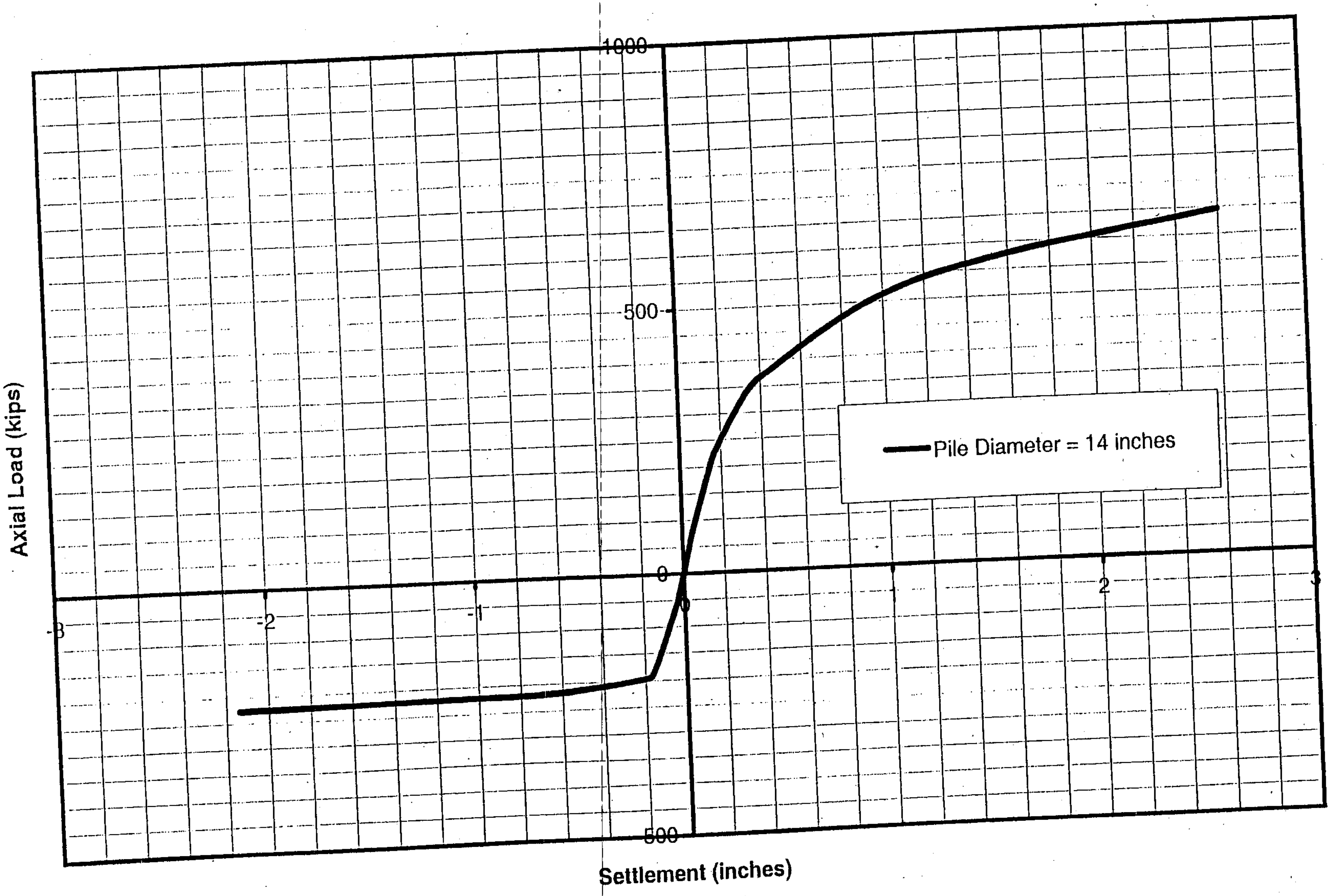


Figure 10. Axial Load - Settlement Curve for the Existing 14" Diameter Piles at Abutment A10

State of California

Business, Transportation and Housing Agency

Memorandum

To: MR. MARK YASHINSKY
Office of Earthquake Engineering

Date: July 17, 2000

File: 01-Hum-255-0.7
01-296701

Middle Channel Bridge
Bridge No. 04-0229

From: **DEPARTMENT OF TRANSPORTATION**
ENGINEERING SERVICE CENTER
Division of Structural Foundations – MS 5
Office of Geotechnical Earthquake Engineering

Subject: Axial (Compression and Tension) Load-Settlement Curves for 36" Diameter Pile

As per your request, this memo presents axial load-settlement curves for the proposed 36" diameter piles at Bents M2 through M9 of the Middle Channel Bridge (Br. No. 04-229).

Single pile axial load-settlement curves for the proposed 36" diameter are presented in the attached Figures 1 through 8. The axial (compression and tension) stiffness at any settlement level for a given single pile at a given bent location may be taken as the secant slope of the respective load-settlement curve. Please note that the compression load and the downward settlement are taken as positive in these figures.

If you have any questions or comments, please call Mohammed S. Islam at 227-7094 or Abbas Abghari at 227-7172.

A. Abghari

MOHAMMED S. ISLAM
Transportation Engineer

ABBAS ABGHARI, Chief
Office of Geotechnical Earthquake Engineering

Attachment

MOHAMMED S. ISLAM
NO. 2485
EXP. 06/30/03

MIDDLE CHANNEL BRIDGE
PIER M2

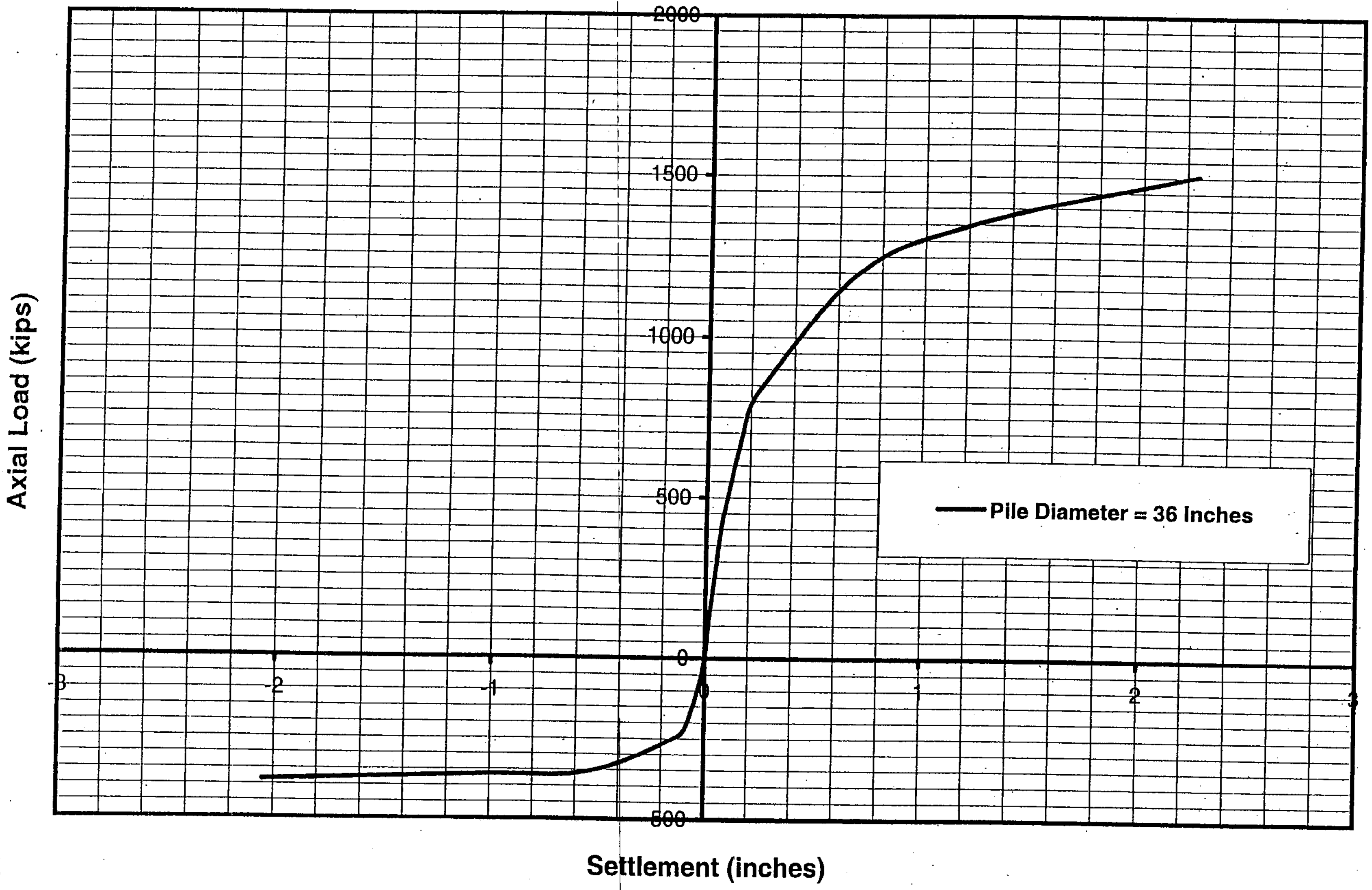


Figure 1. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M2

MIDDLE CHANNEL BRIDGE
PIER M2

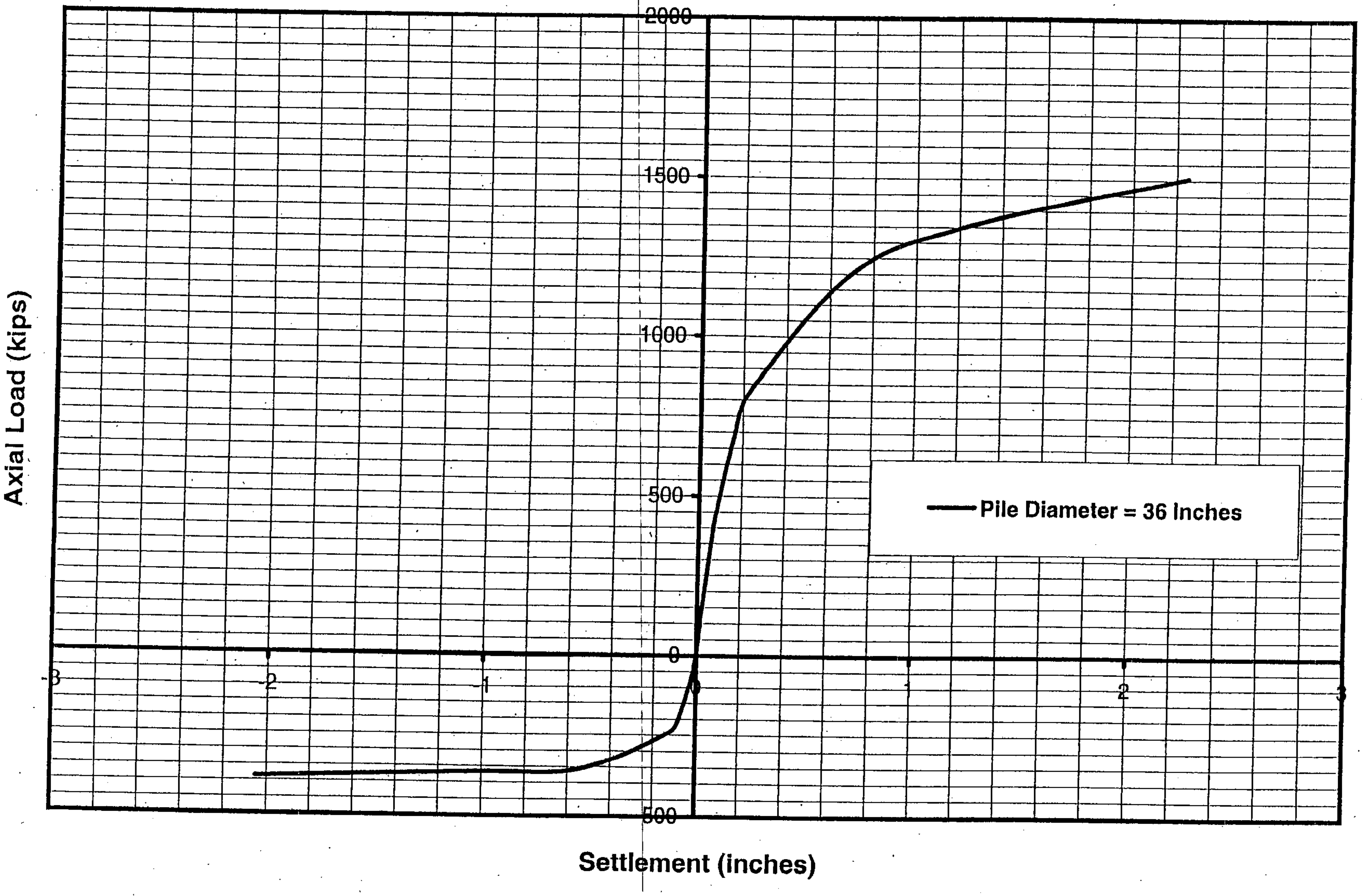


Figure ~~2~~ 1. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M2

MIDDLE CHANNEL BRIDGE
PIER M3

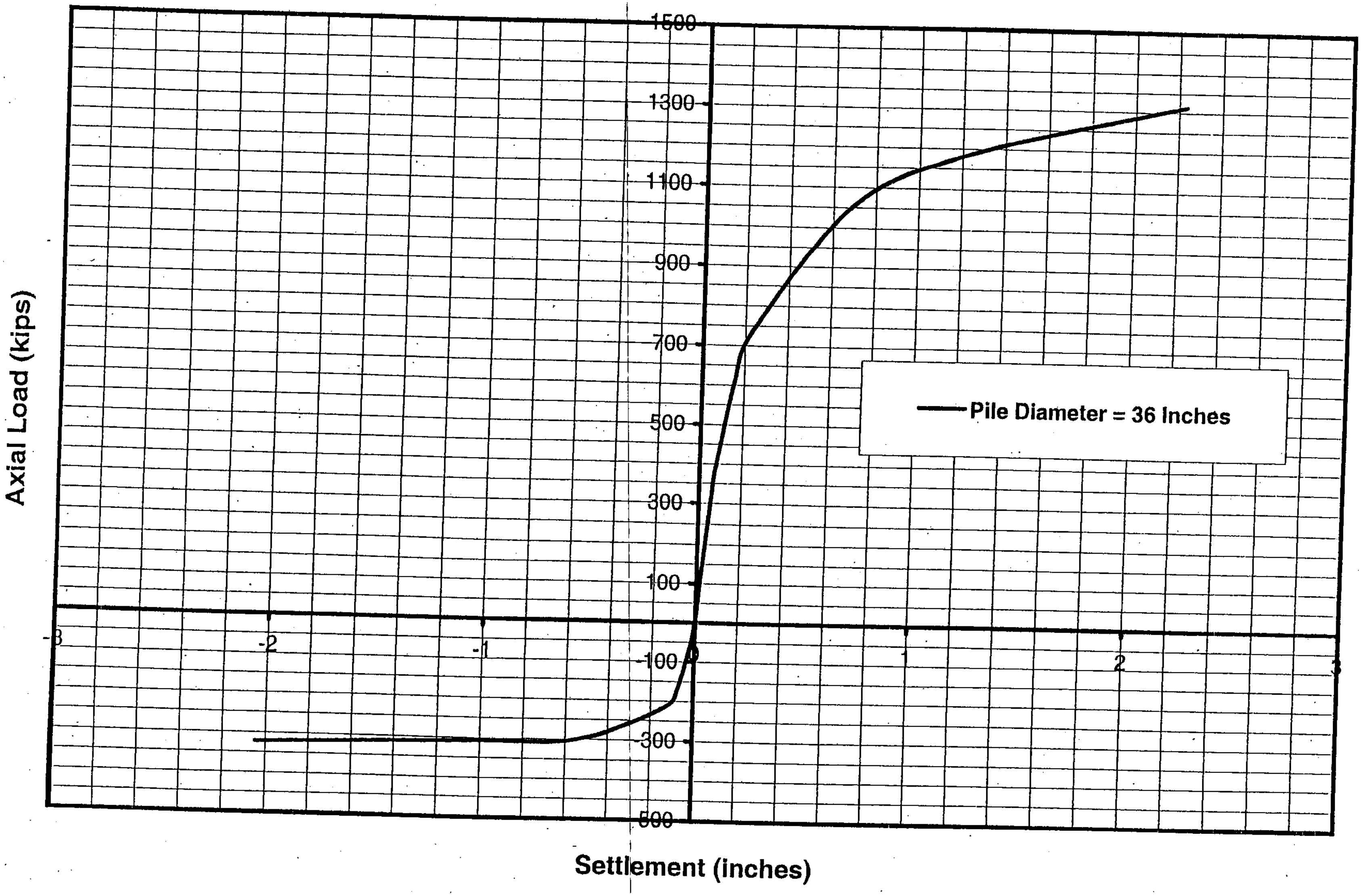


Figure 2. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M3

MIDDLE CHANNEL BRIDGE
PIER M4

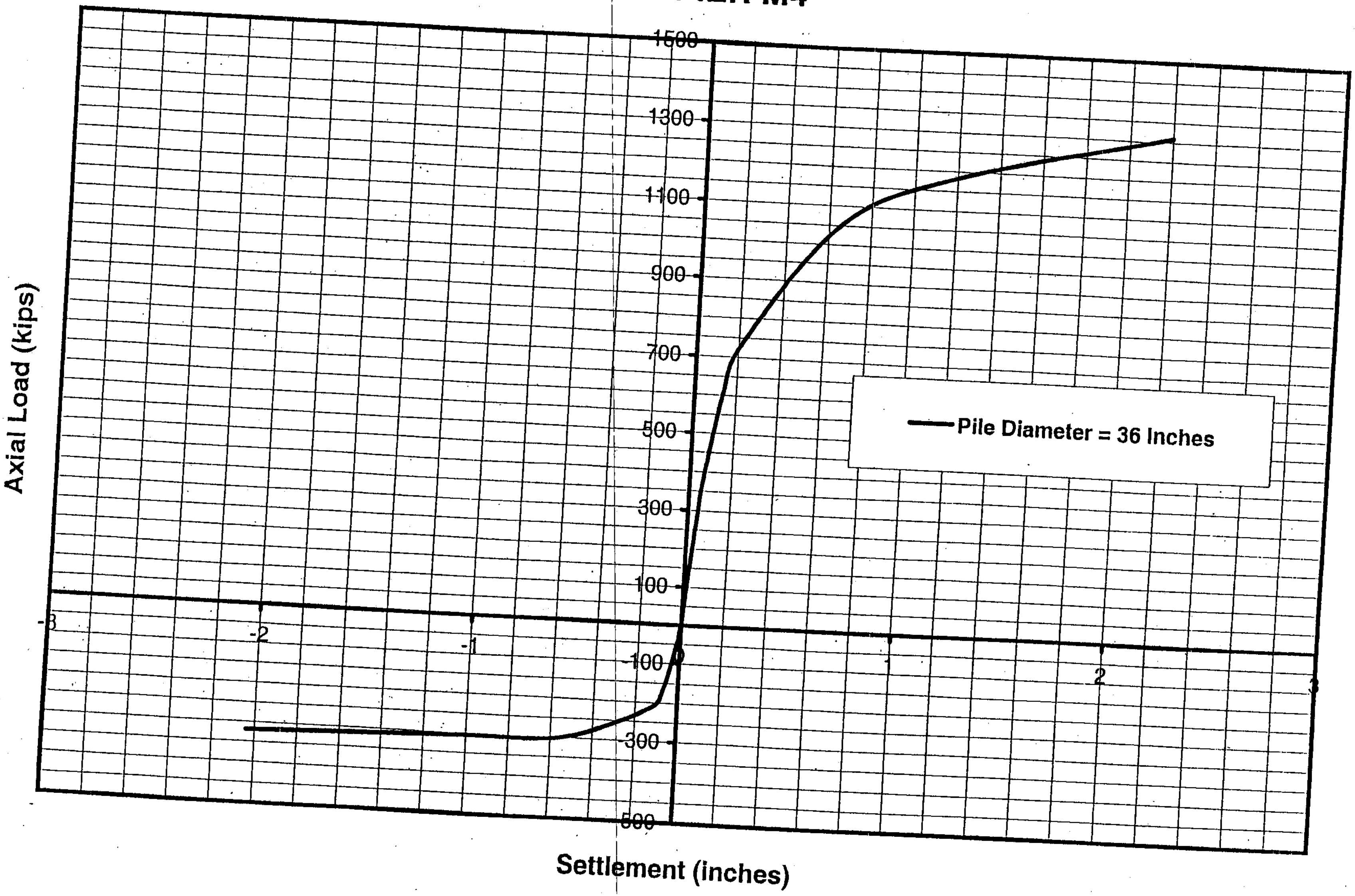
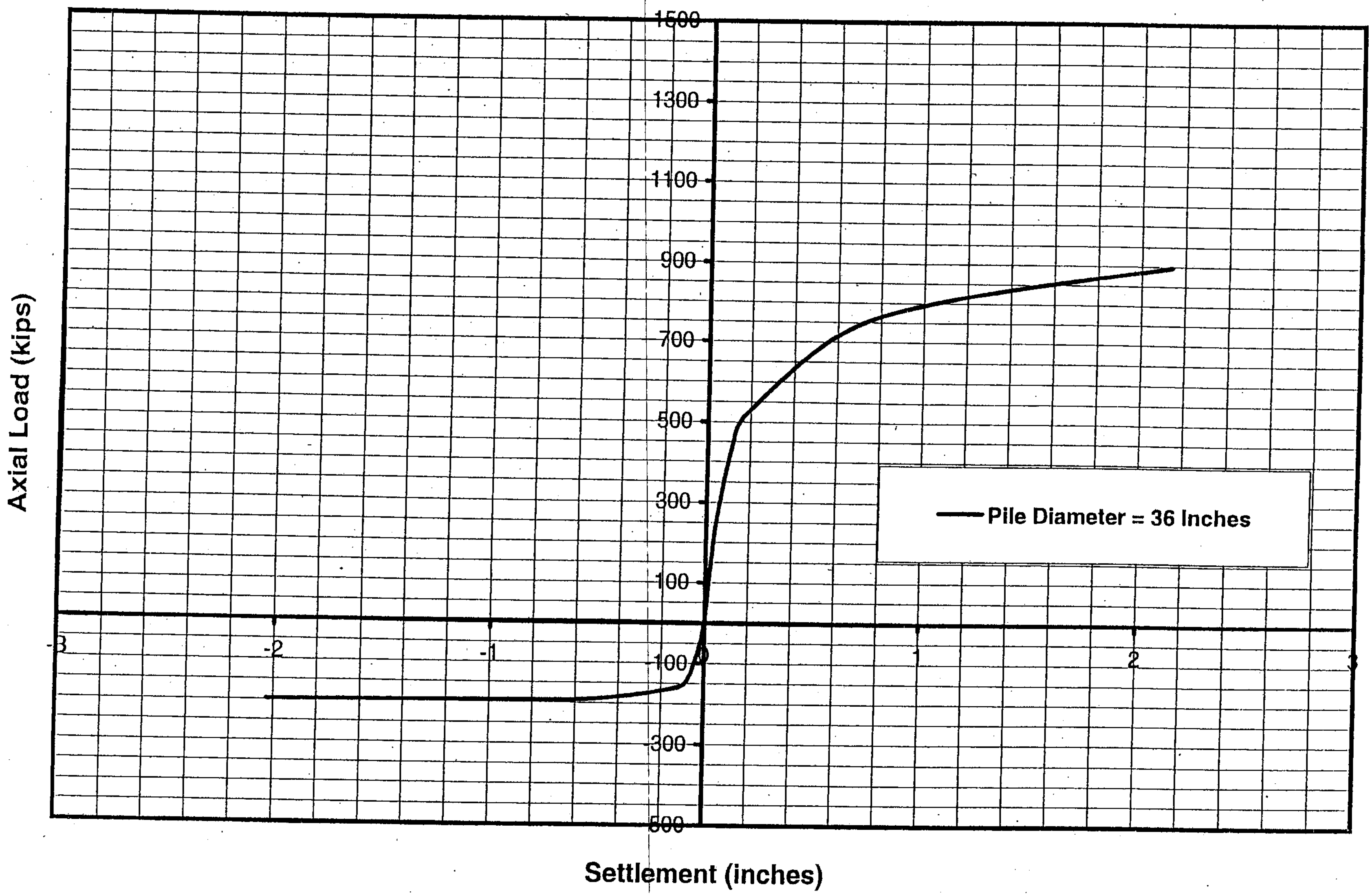


Figure 3. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M4



MIDDLE CHANNEL BRIDGE
PIER M5

Figure 4. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M5

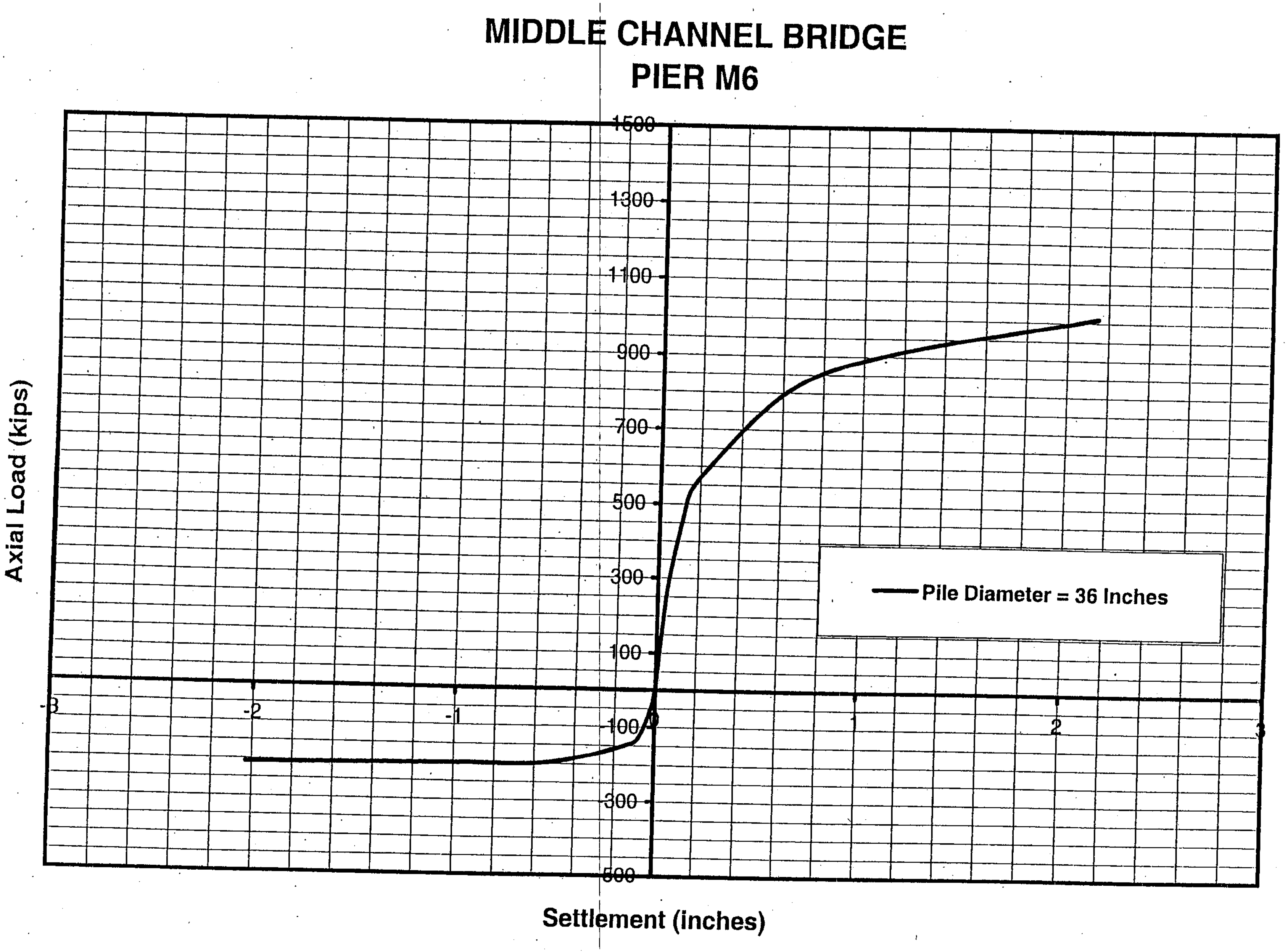


Figure 5. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M6

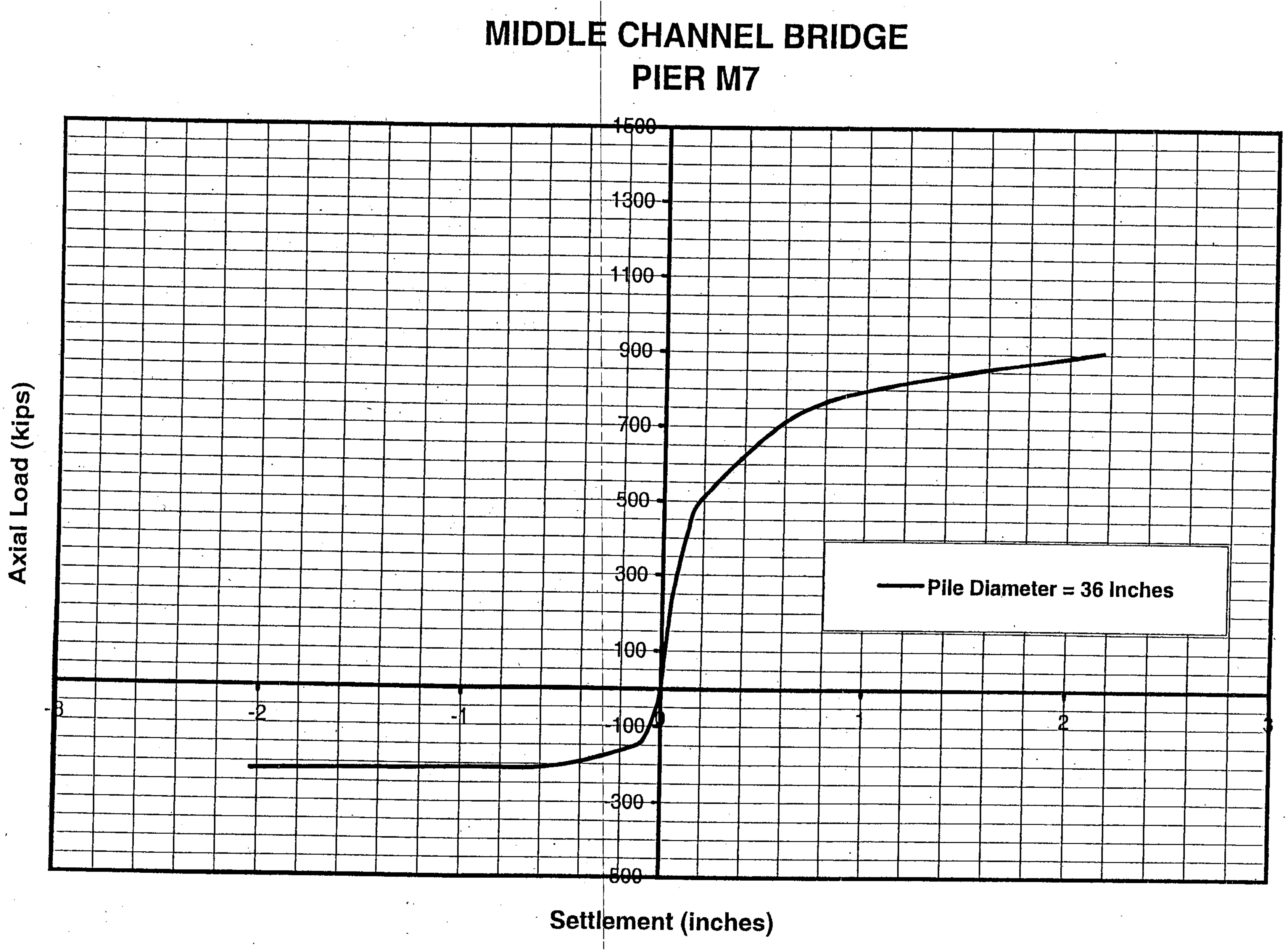


Figure 6. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M7

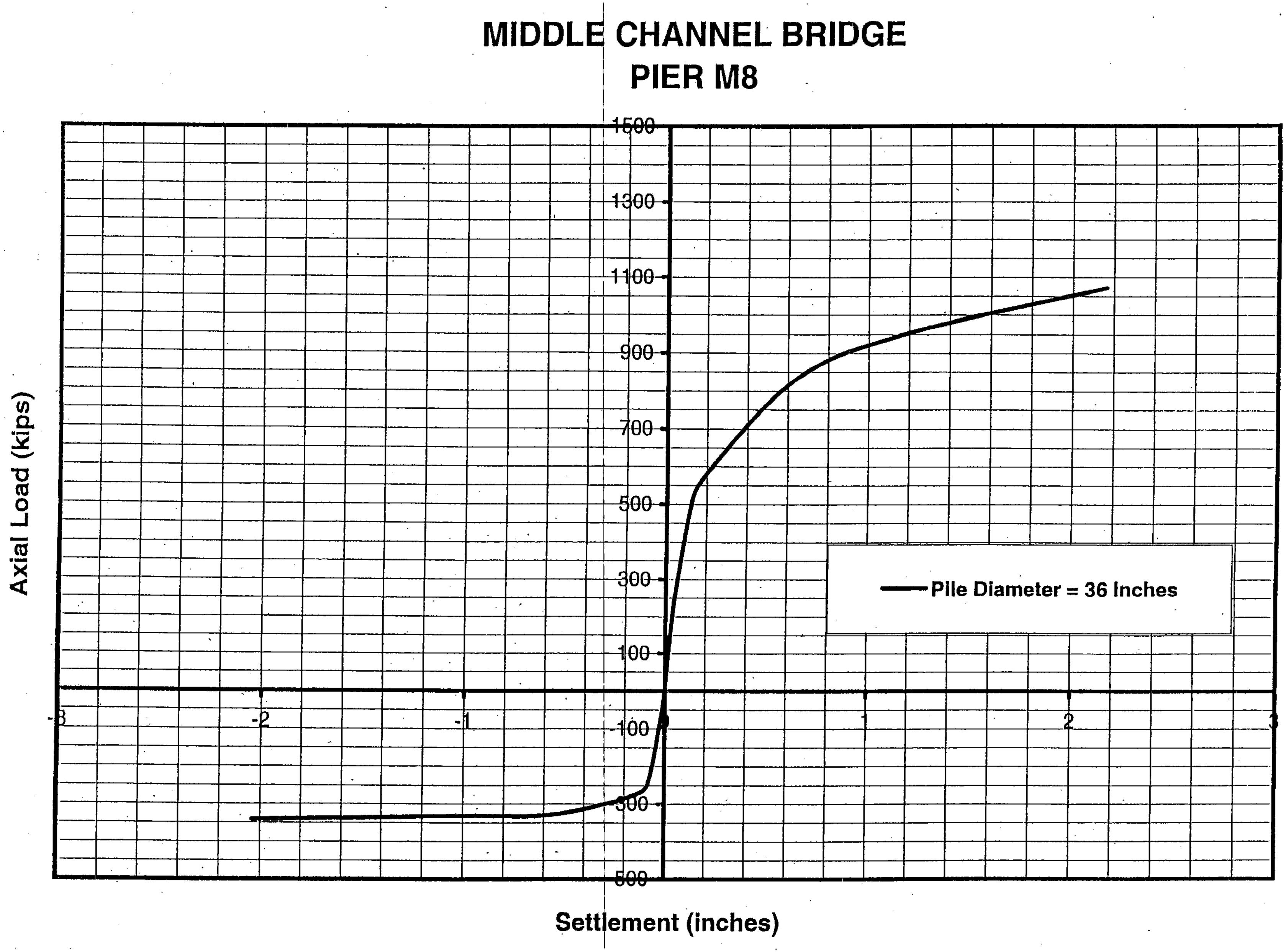


Figure 7. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M8

MIDDLE CHANNEL BRIDGE
PIER M9

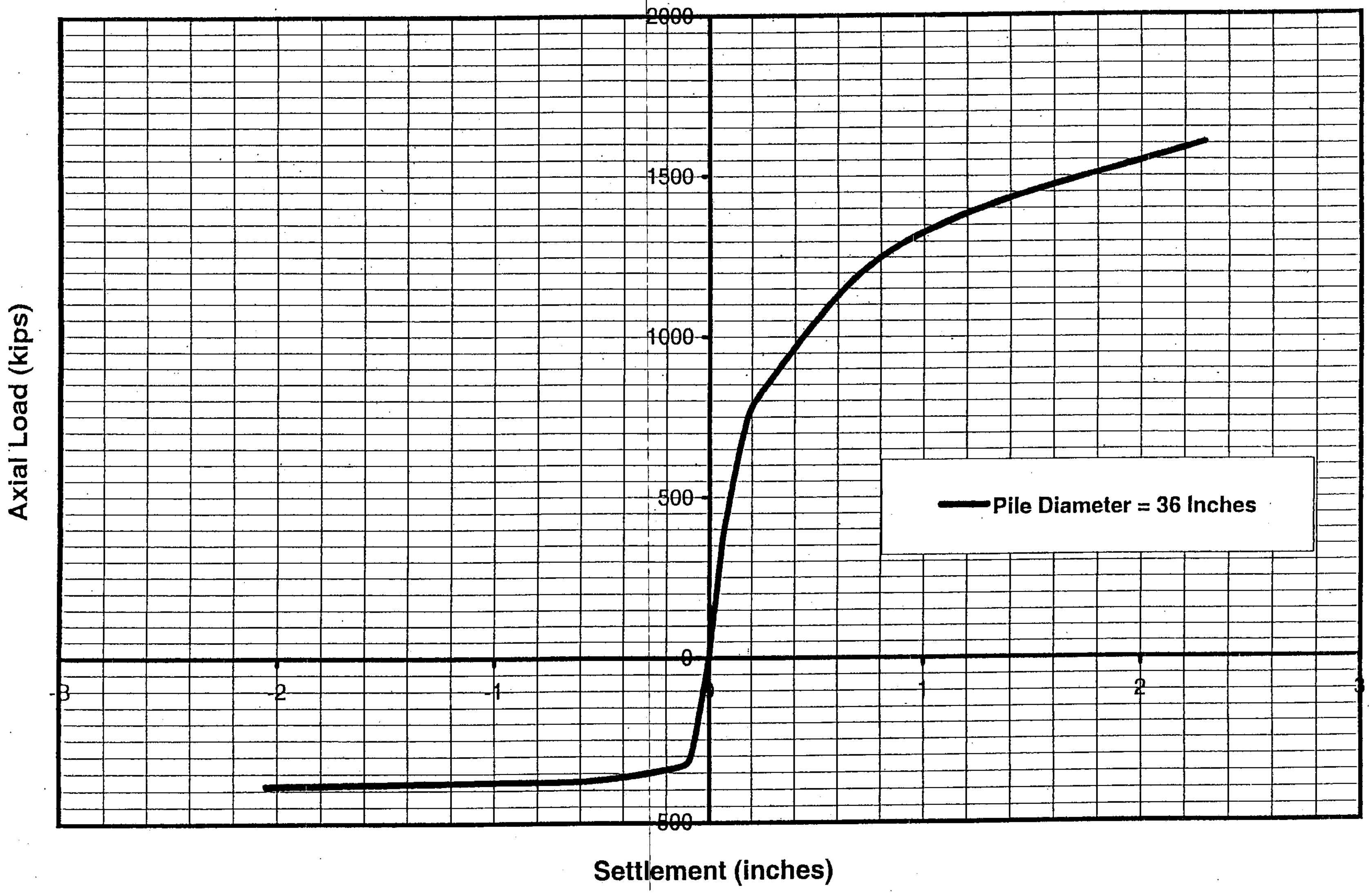


Figure 8. Axial Load - Settlement Curve for the Proposed 36" Diameter Pile at Pier M9