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COLLEGE OF ENGINEERING

Final Report 1

STABILITY OF HIGHWAY BRIDGES SUBJECT TO SCOUR – PHASE IV

MILESTONE #1 REPORT

SCREENING TOOL FOR BRIDGES SUPPORTED BY TIMBER PILE BENTS

Submitted to

The Alabama Department of Transportation
Research Project 930-776

Prepared by

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SEPTEMBER 2011

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ABSTRACT

Most bridges in Alabama that are over shallow bodies of water, including small creeks, wetlands, and marshes, were designed so that the bridge superstructure is supported on pile bents. During major flood events, excessive scour can occur at these bridge bent sites. Hundreds of Alabama's bridges were designed and constructed without recognizing the impact of scour events on the bridge pile bents. To address this problem, the Alabama Department of Transportation (ALDOT) is currently assessing the scour susceptibility of its bridges, including an evaluation of the structural stability of these bridges for an estimated flood/scour event.

Approximately eight years ago, the ALDOT began investing in a three-phase research project to develop a "screening tool" for bridges supported on steel WF pile bents, with the results that they now have an automated "screening tool" which can assess the susceptibility of steel WF pile bent supported bridges to extreme flood/scour events. This "screening tool" is now widely used and has proven to be very helpful to the ALDOT.

Unfortunately, bridges supported on timber pile bents is a common bridge substructure type used by local and county governments in Alabama. The majority of the bridges in Alabama that still require scour susceptibility analyses are owned by local governments and the number of timber pile bents that require a stability screening is quite large.

The objective of this Phase IV research work was to expand the ALDOT's current capabilities for evaluating the adequacy of steel pile bent supported bridges during extreme flood/scour events to include bridges supported on timber pile bents. This expansion was accomplished by developing a "sister" screening tool which can assess the adequacy of timber pile bent supported bridges. This new screening tool allows for screening a broad range of timber pile bent geometries and layouts, bridge superstructures, and estimated maximum scour events which may occur at bridge sites in Alabama. The new screening tool is consistent with the definitions, approach, and analyses procedures employed in ALDOT's current "screening tool," but necessarily utilizes different pile/bent capacity prediction equations when checking for pile plunging, pile buckling, beam column adequacy and bent push-over. This report describes the assumptions, checking sequence and procedures and underlying equations defining the adequacy checks in the new "screening tool."

ACKNOWLEDGEMENTS

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The authors are also grateful for the assistance and guidance of several ALDOT engineers during the execution of the research work. Specifically, thanks are due to James Bearrentine, Eric Christie, and George Connor of the ALDOT.

I. Introduction

1.1 Statement of Problem

The Alabama Department of Transportation (ALDOT) is currently performing an assessment of the scour susceptibility of its bridges that are supported on timber pile bents as well as county owned bridges that are also supported on timber pile bents. Because of the large number of such bridges, and because stability analyses of each bridge represents a considerable effort in time and money, there was a compelling need to develop a simple "screening tool" which could be used, along with scour analyses, to efficiently assess the susceptibility of these bridges to bridge support bent scour problems.

Approximately eight years ago, the ALDOT began investing in a three-phase research project to develop such a "screening tool" for bridges supported on steel WF pile bents, with the results that they now have an automated "screening tool" which can assess the susceptibility of steel WF pile bent supported bridges to extreme flood/scour events. This "screening tool" is now widely used and has proven to be very helpful to the ALDOT. Unfortunately, bridges supported on timber pile bents is a common bridge substructure type used by local and county governments in Alabama. The majority of the bridges in Alabama that still require scour susceptibility analyses are owned by local governments and the number of timber pile bents that require a stability screening is quite large. Hence, adding a "sister" screening tool for timber pile bents to ALDOT's existing steel H-pile bent screening tool would be a great benefit to ALDOT. This was the purpose of this research.

1.2 Research Objective

The objective of this Phase IV research work was to expand the ALDOT's current capabilities for evaluating the adequacy of steel pile bent supported bridges during extreme flood/scour events to include bridges supported on timber pile bents. This expansion was accomplished by developing a "sister" screening tool which can handle timber pile bent supported bridges. This new screening tool allows for screening a broad range of timber pile bent geometries and layouts, bridge superstructures, and estimated maximum scour events which may occur at bridge sites in Alabama. The new screening tool is consistent with the definitions, approach, and analyses procedures employed in ALDOT's current "screening tool", but necessarily utilizes different pile/bent capacity prediction equations when checking for pile plunging, pile buckling, beam column adequacy and bent push-over. The new "screening tool" will be automated in a manner similar to that of the current "screening tool".

1.3 Work Plan

Because of ALDOT's need to begin performing stability screenings on a number of timber pile bent supported bridges as soon as possible, the project work plan has been broken into Milestones #1 and #2 to assist ALDOT in doing this. Intermediate project reports will be submitted to ALDOT immediately upon completion of each of the milestones. A description of the work and activities involved in each milestone is given below.

Milestone #1. Development of a "Screening Tool" (ST) to Assess the Stability/Adequacy of Timber Pile Bents During Extreme Flood/Scour Events.

It should be noted that the "ST" development of Milestone #1 is for manual implementation and descriptions of the work tasks needed to achieve this milestone are given below. Also, because the ALDOT needs to begin performing stability screening as soon as possible, a **Milestone #1 Report** should be submitted to ALDOT immediately upon its completion.

Task No. 1. - Revisit and determine the needed input information and/or assumptions required to allow an assessment of the stability/adequacy of deck/girder bridges supported on timber pile bents during extreme flood/scour events, and develop a "Screening Tool" flowchart for making this assessment.

Task No. 2. - Revisit and modify as needed the procedures and assumption to determine the dead and live loads (DL and LL) acting on timber pile bents as well as the lateral flood water loading acting on the bents.

Task No. 3. - Finalize the timber pile bent geometries, pile sizes, bracing conditions, P-loads and scour levels indicated in Fig. 1.1 via visiting with ALDOT prior to performing bent pushover analyses.

Task No. 4. - Model bridge bents and perform ABACUS pushover analyses to generate new tables of timber pile bent pushover capacities for a family of P-load levels for families of bent heights, number of bent piles, diameters of bent piles, bent bracing configuration, and scour levels. These parameters and family sizes are shown in Fig. 1.1. It should be noted that the generation of these new tables of bent pushover capacities for the parameter values shown in Fig. 1.1 will be the most time consuming task in this Phase IV work.

Task No. 5. - Model and determine pile and bent vertical buckling loads and the adequacy of the piles and bent for buckling.

Task No. 6. - Model and determine the bent upstream pile loads and check its adequacy as a beam-column for these loads.

Task No. 7. - Revisit the procedures and assumptions used to check the adequacy of given pile/bent for plunging and make changes as necessary to render them valid for timber pile bents. This will require generating a new table of pile axial load capacities based on the Modified Gates Formula for timber piles for

- Various Hammer Energy
- Various Final Driving Resistance
- End Bearing Piles with Various Percent Loss of Embedment
- Friction Piles with Various Percent Loss of Embedment

It should be noted that the generation of this new table for pile plunging capacities will also require lead-in time to determine the common hammers used to drive timber piles and their energies and efficiencies.

Task No 8. - Manually execute the "ST" developed in Tasks 1 - 7 using the assumptions and analysis equations identified therein along with the needed databases generated in Tasks 4 - 7 to assess the adequacy of some sample timber pile bent supported bridges.

Task No. 9. - Prepare a Milestone #1 Report and conduct a training session for ALDOT engineers performing bridge stability analyses for extreme flood/scour events on how to manually use the new “ST” to perform these analyses.

Milestone #2. Automation of the “ST” Developed in Milestone #1.

A description of the work tasks involved in achieving **Milestone #2** is given below.

Task No. 1. - Automate the pile/bent analysis procedures described in Milestone #1 above via creating a new “ST” computer program employing the same definitions, nomenclature, programming language, and input/output formats as those used in ALDOT’s current “ST”.

Task No. 2. - Conduct a training seminar for ALDOT engineers performing bridge stability analyses for extreme flood/scour events on how to use the new automated “ST” to perform these analyses.

Task No. 3. - Prepare a Milestone #2 Report

Prepare project final report and computer program source code and other project deliverables.

It should be noted that this report is the project **Milestone #1 Report.** A **Milestone #2 Report** will be submitted upon completing the last three tasks listed above.

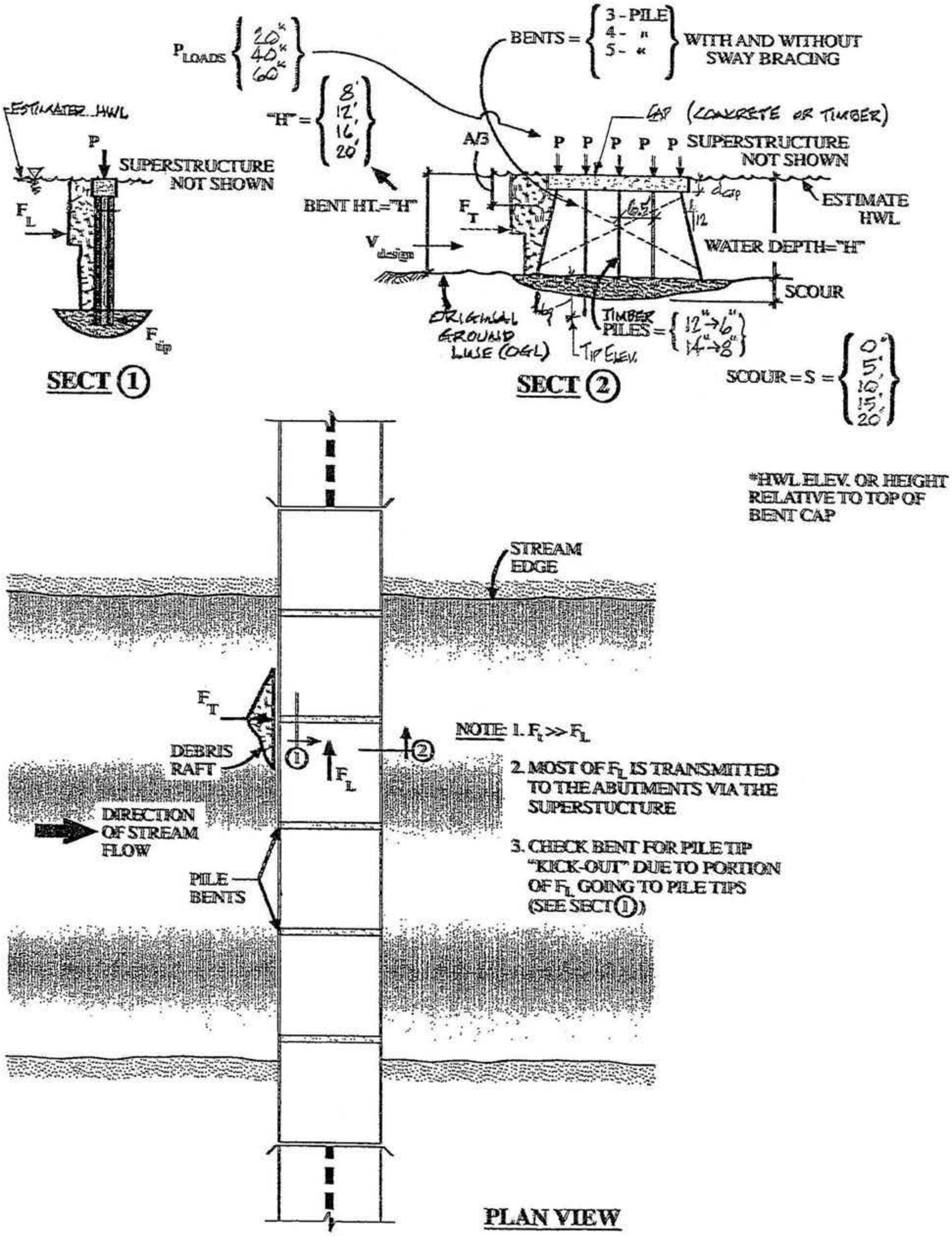


FIG 1.1 Typical Timber Pile Bent Supported Bridge Over Stream

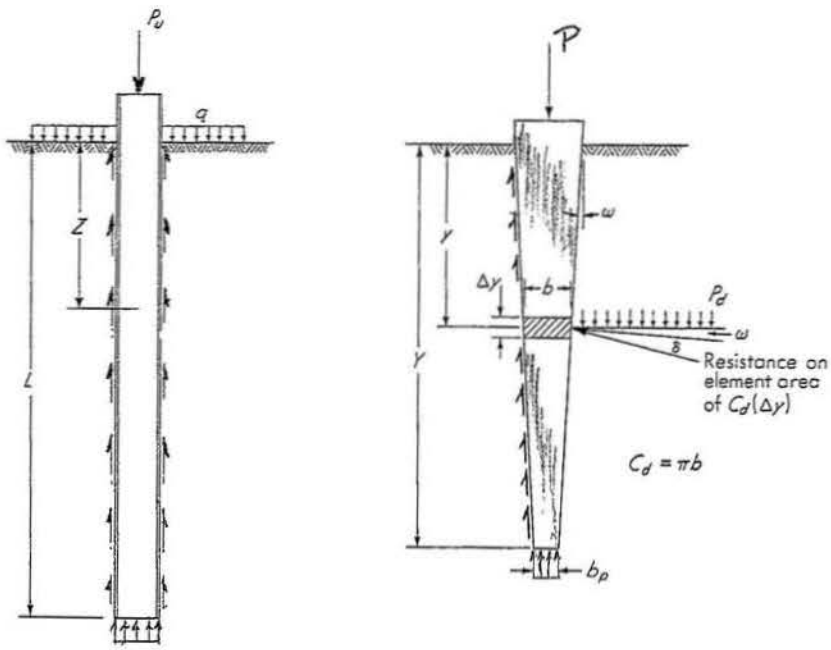
2. Timber Pile Geometry, Properties, and Buckling/Design Considerations

2.1 General

The ability of the soil to support the load transmitted to it by the piles is usually the factor that determines the adequacy of pile foundations. The permissible working stresses for piles of any material are seldom fully utilized. It makes no difference to the soil what material composes piles of equal dimensions. Failure to recognize this fact has resulted in the use of loads for wood piles much below those of concrete piles, even though the allowable unit stress of wood may be above that of concrete. In the past, design loads for timber piles were typically 15-20 tons whereas for concrete and other piles they were typically 30 tons or more. However, design loads for timber piles of 25-30 tons are now becoming common and sometimes loads of 40 tons where soil conditions warrant.

2.2 Typical Geometry, Uses and Limiting Dimensions of Timber Piles

Because of their taper, timber piles develop significant wedge action and reactive side pressures from the soil and thus induce large skin friction resistance forces. Relative to steel WF piles, timber piles act much more as friction piles as illustrated in Fig. 2.1. Because of its taper, a timber pile has excellent skin friction resistance and because of its large tip area (relative to a steel WF pile), it also has excellent tip resistance. A schematic drawing of a typical timber pile is shown in Fig. 2.2. Note the significant pile taper, i.e., a change in pile diameter (Δd) of approximately 10” for a 50 ft. long pile.



a. Steel WF Pile

b. Timber Pile

Fig. 2.1. Elevation Schematics of Timber and Steel WF Piles

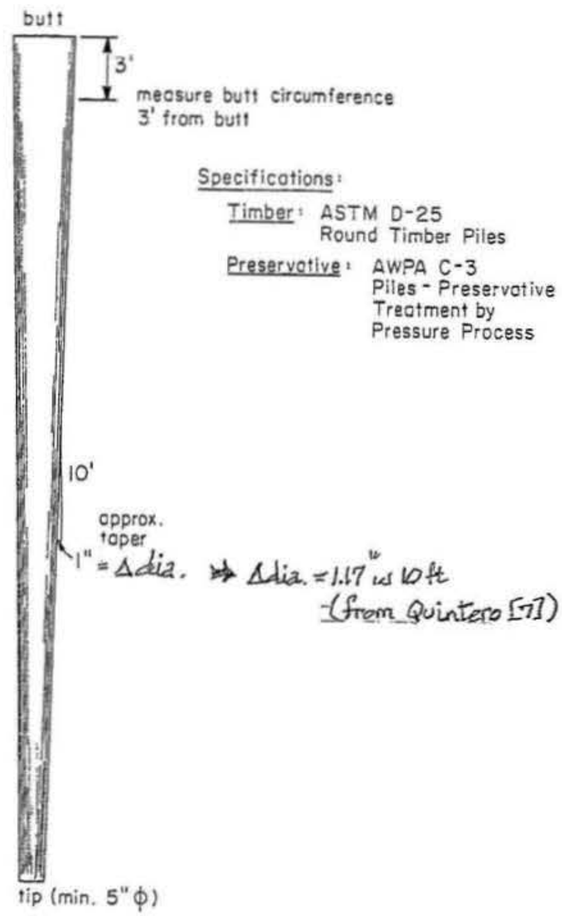


Fig. 2.2. Typical Timber Pile [4]

If we assume a typical pile length to be $\ell = 50'$, then

for $12''^{\Phi} \rightarrow 6''^{\Phi} \Rightarrow \Delta d = 6''$ in 50 ft

$$\text{or } \Delta d_{\text{per } 10'} = \frac{6''}{5} = 1.2'' \text{ per } 10'$$

For $14''^{\Phi} \rightarrow 8''^{\Phi} \Rightarrow \Delta d = 6''$ in 50 ft

$$\text{or } \Delta d_{\text{per } 10'} = \frac{6''}{5} = 1.2'' \text{ per } 10'$$

Note that the above Δd of 1.2" in 10' is very close to the Δd = 1.17" per 10' that Quintero [7] found for timber utility poles in a region of Birmingham, AL hit by a severe tornado in 1977.

Typical uses and characteristics of timber piles are given in Table 2.1 and geometrical and alignment criteria for the piles are shown in Fig. 2.3. It should be noted that alternate wetting and drying of piles, such as occurs near the water line for wood pile bents supporting bridges over water, are subject to wood rot and fungus growths and marine animal and insect attack. The severity of the wood decay due to these causes can be greatly reduced by chemical treatment of the wood piles, but such treatment will not entirely prevent decay. This is especially true where the pile is exposed to the air and alternately wet and dry periods.

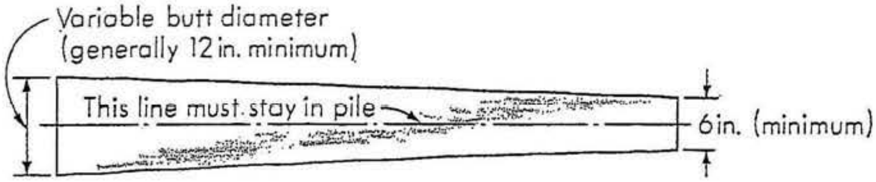
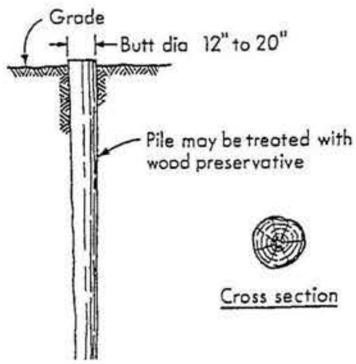


Fig. 2.3. Typical Geometrical and Alignment Criteria for Timber Piles [5]

Table 2.1. Typical Timber Pile Characteristics and Uses [5]

Pile type	*Timber*
Maximum length	110 ft
Optimum length	30–60 ft
Applicable material specifications	ASTM-D25 for piles. P1-54 for quality of creosote. C1-60 for creosote treatment. (Standards of American Wood Preservers Assoc.)
Recommended maximum stresses	Measured at midpoint of length: 600–850 psi for cedar, western hemlock, Norway pine, spruce, and depending on Code 800–1,200 psi for southern pine, Douglas fir, oak, cypress, hickory
Maximum load for usual conditions	30 tons
Optimum-load range	15–25 tons
Disadvantages	Difficult to splice Vulnerable to damage in hard driving Vulnerable to decay unless treated, when piles are intermittently submerged
Advantages	Comparatively low initial cost Permanently submerged piles are resistant to decay Easy to handle
Remarks	Best suited for friction pile in granular material
Typical illustrations	

Limiting dimensions of some common timber piles are given in Table 2.2. The wood species indicated in Table 2.2 are the ones most commonly used for timber piles in the U.S.

Table 2.2. Limiting Dimensions of Piles, Inches [1]

	Southern pine and Douglas fir[a]					Oak, cypress, and chestnut[b]			Cedar		
Place measured	Less than 40 ft long	40–50 ft long	51–70 ft long	71–90 ft long	Over 90 ft long	Less than 30 ft long	30–40 ft long	Over 40 ft long	Less than 30 ft long	30–40 ft long	Over 40 ft long
ASCE, ASTM, ASA, and CESA Class *A* piles AREA First-class piles for railway bridges											
3 ft from butt:											
Minimum	14	14	14	14	14	14	14	14	14	14	14
Maximum	18	18	18	20	20	18	18	18	22	22	22
Tip (minimum)	10	9	8	7	6	10	9	8	10	9	8
ASCE, ASTM, ASA, and CESA Class *B* piles AREA First-class piles for highway bridges											
3 ft from butt:											
Minimum	12	12	13	13	13	12	13	13	12	13	13
Maximum	20	20	20	20	20	18	20	20	22	22	22
Tip (minimum)	8	7	7	6	5	8	8	7	8	8	7
ASCE, ASTM, ASA, and CESA Class *C* piles (Values in boldface are for ASTM, ASA, and CESA)[c] AREA Second-class piles											
3 ft from butt:											
Minimum	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**	12 **12**
Maximum	18 **20**	18 **20**	18 **20**	18 **20**	18 **20**	18 **20**	18 **20**	18 **20**	18 **22**	18 **22**	18 **22**
Tip (minimum)	8 **8**	6 **6**	6 **6**	6 **6**	6 **5**	8 **8**	8 **8**	6 **6**	8 **8**	8 **8**	6 **7**

[a] For ASTM and ASA, where larch, lodgepole or Norway pine, spruce or tamarack piles are specified, their dimensions shall correspond to the requirements shown for Douglas fir and southern pine. For CESA, where spruce, pine, larch, tamarack, or other softwoods are specified, their dimensions shall correspond to the requirements shown for Douglas fir. No values for southern pine are given for CESA.

[b] For ASTM and ASA include black-oak, pin-oak, post- or burr-oak, red-oak, white-oak, and willow-oak piles. For CESA, include birch, beech, and maple, and omit cypress and chestnut.

[c] For ASTM and ASA Class *C* piles a minimum diameter (at cutoff) of 10 in. may be specified for lengths of 20 ft and under.

2.3 Typical Material Properties of Timber Piles Used in Alabama

The approximate modulus of elasticity and crushing and bending strength of timber piles most commonly used in Alabama are shown in Table 2.3.

Table 2.3. Approximate Elastic Modulus and Strengths of Woods Commonly Used for Timber Piles in Alabama

Wood Species	Green (untreated)			Air-Seasoned (untreated)		
	Elastic Modulus, E(psi)	Crushing Strength (psi)	Bending Strength (psi)	Elastic Modulus, E(psi)	Crushing Strength (psi)	Bending Strength (psi)
Pine-Longleaf	1,600,000	4,300	8,700	1,990,000	8,440	14,700
Pine – Shortleaf	1,390,000	3,430	7,300	1,760,000	7,070	12,800
Douglas Fir	1,550,000	3,890	7,600	1,920,000	7,420	11,700
Southern Cypress	1,180,000	3,580	6,600	1,440,000	6,360	10,600
Oak - White	1,200,000	3,520	8,100	1,620,000	7,040	13,900

***Select extractions from Ref [1]**

Shaeffer [6] states that when the duration of loading is known, the allowable stresses for timber may be modified by the following factors:

Load Duration	Modification Factor
Two Months (Snow)	1.15
Seven Days	1.25
Wind or Earthquake	1.33
Impact	2.00

By interpolation, for a flood water loading, an allowable stress modification factor of 1.30 would be appropriate. Shaeffer states that the modulus of elasticity values are not subject to such modifications.

In the screening tool, we will assume the pile strength and Young's Modulus values shown on the bottom line of Table2. 4.

Table 2.4. Timber Pile Material Properties

Pile Timber Specie	E (ksi)	Bending Strength (ksi)	Crushing Strength (ksi)
Douglas Fir	1,920	12.8	7.07
Southern Pine (short leaf)	1,760	11.7	7.42
Values Use in 'ST'	1,800	12.0	7.00

Figure 2.4a summarizes the timber pile geometry and material property assumptions that were made and used in "ST" except for the material properties in the push-over analyses.

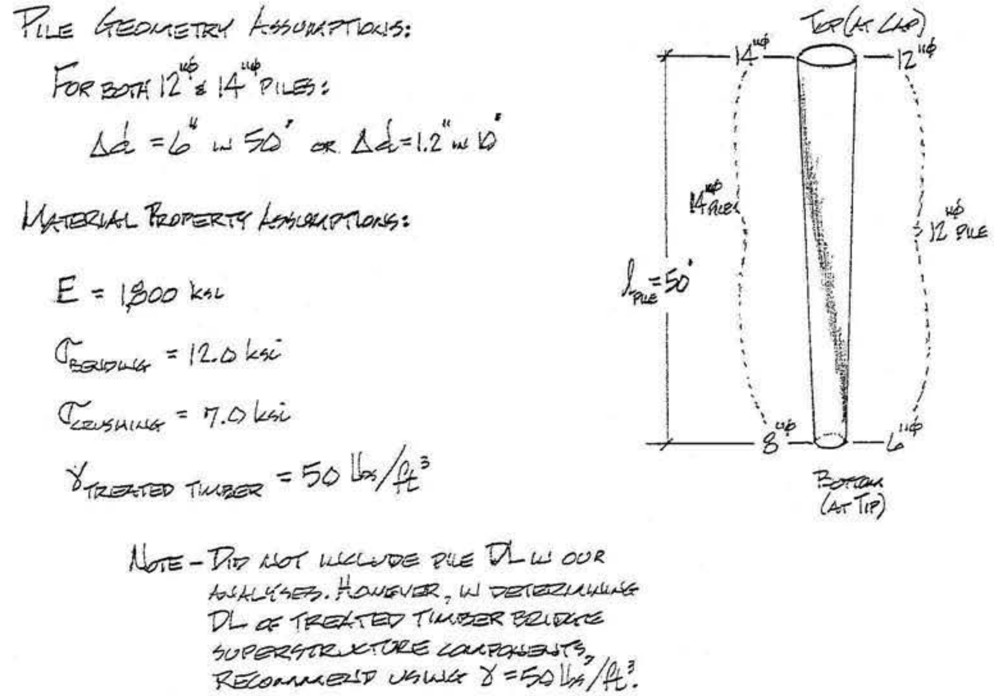


Fig. 2.4a. Timber Pile Assumptions Used in "ST"

It should be noted that in performing pushover analyses of timber pile bents, one needs to know or assume an appropriate stress-strain curve for the timber piles, not just the elastic modules of elasticity, E, and material strength. Thus, in the "ST" we assumed the stress-strain curve shown in Fig. 2.4b in modeling the wood in the pile bents. This stress-strain curve was used in determining the Lateral Load vs. Lateral Displacement curves in our bent pushover analyses, which in-turn were used to determine the bent pushover load, F_t.

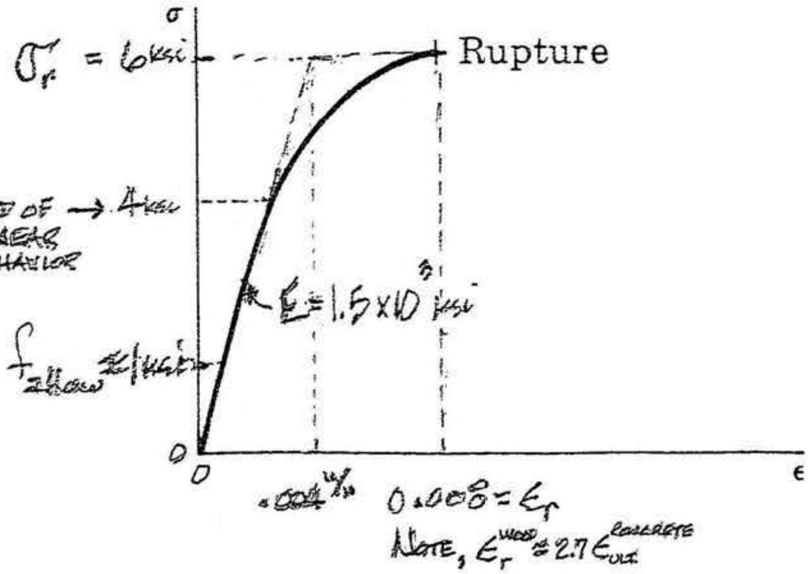


Fig. 2.4b. Timber Pile Material $\sigma - \varepsilon$ Curve Assumed in "ST" Pushover Analyses

2.4 Effective Section Properties of Timber Piles

From [1], for timber piles,

$$I_{eff} = \frac{\pi {d_{eff}}^4}{64} \qquad (2.1a)$$

where $d_{eff} = d_1$ in Fig. 2.5a

and,

$$S_{eff} = \frac{I_{eff}}{d_{eff}/2}$$

or,

$$S_{eff} = \frac{\pi d^3_{eff}}{32} \qquad (2.1b)$$

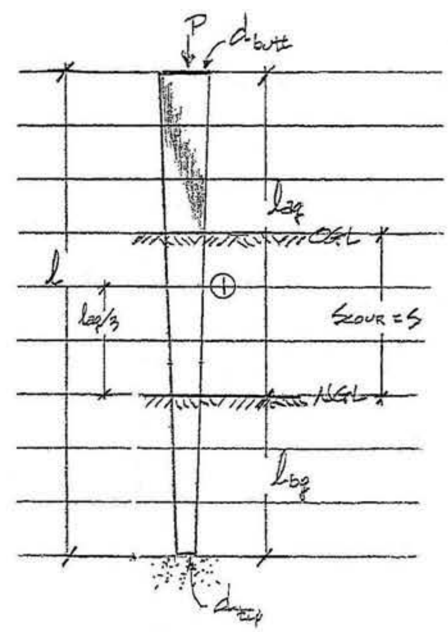


Fig. 2.5a. Embedded Timber Pile

A plot illustrating the dramatic increase in I_{eff} for timber piles with increases in the pile effective diameter is shown in Fig. 2.5b. Note that the timber pile buckling load would exhibit this same dramatic increase with the pile effective diameter.

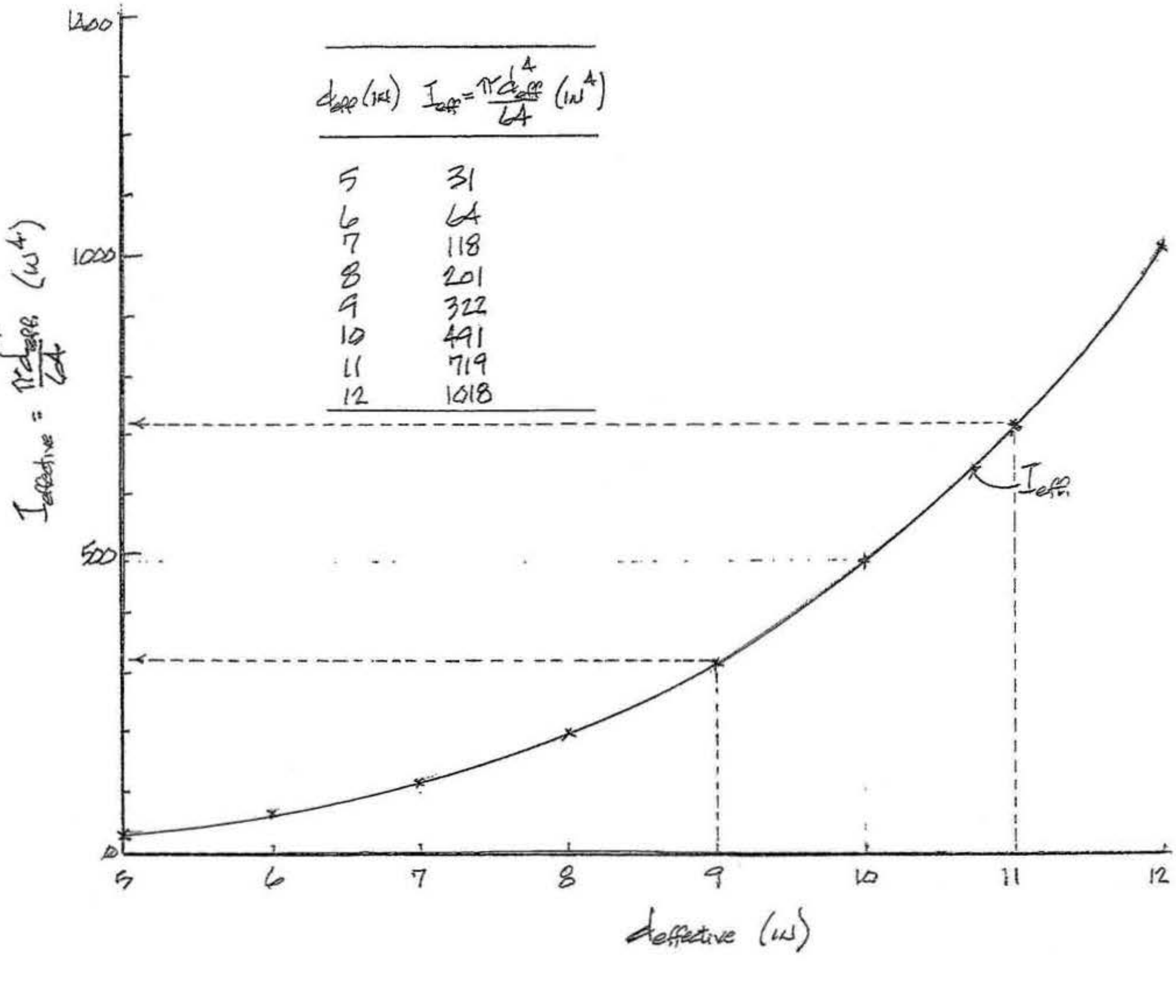


Fig. 2.5b. Variation of Pile $I_{effective}$ with Pile $d_{effective}$

Therefore in checking for timber pile buckling due to scour, use

$$I_{eff} = \frac{\pi {d_{eff}}^4}{64}$$

where $d_{eff} = d_1 = d_{0.33\,\ell ag\ from\ the\ NGL}$ (See Fig. 2.5a)

Additionally, in the "ST" we will assume the timber piles to have the geometries indicated below for a pile length of 50 ft..

$$\{d_{butt}\} = \begin{Bmatrix} 12" \\ 14" \end{Bmatrix} \text{ with corresponding } \{d_{tip}\} \approx \begin{Bmatrix} 6" \\ 8" \end{Bmatrix}$$

Thus, $\{d_{eff}\} = \{d_{0.33\,\ell ag\ from\ the\ NGL}\} \approx \begin{Bmatrix} 8.8" \\ 10.8" \end{Bmatrix}$

And, $\{I_{eff}\} = \left\{\frac{\pi d^4{}_{eff}}{64}\right\} \approx \frac{\pi}{64}\begin{Bmatrix} 9^4 \\ 11^4 \end{Bmatrix} \approx \begin{Bmatrix} 294 \\ 668 \end{Bmatrix}$ in^4

Assuming an E = 1,800,000 psi for treated timber piles, the corresponding $\{EI_{eff}\}$ is,

$$\{EI_{eff}\} = 1800\ {}^{k}/_{in^2} \begin{Bmatrix} 294 \\ 668 \end{Bmatrix} \text{ in}^4 = \begin{Bmatrix} 529{,}200 \\ 1{,}202{,}000 \end{Bmatrix} k\text{-}in^2$$

For comparative purposes, for steel HP 10 x 42 piles,

$$EI^{HP\ 10\ X\ 42} = 29{,}000\ {}^{k}/_{in^2} \times 71.7\ in^4 = 2{,}079{,}000\ k - in^2$$

Or,

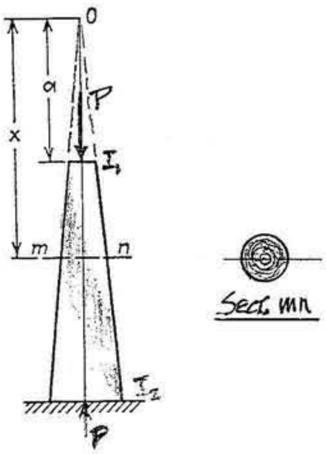
$$\left\{\frac{EI^{timber}}{EI^{HP\ 10\ x\ 42}}\right\} = \begin{Bmatrix} 0.255 \\ 0.578 \end{Bmatrix}$$

Also, in checking bent pushover capacities when subject to gravity P-loads and flood water lateral loading, F_t, the appropriate bending stiffness of the tapered timber piles needs to be used. This can be done by using an appropriate I_{eff} for the piles in the manner indicated in Fig. 2.5a and Eqn (2.1a).

In checking stresses or axial and moment capacities in an P-M interaction equation for adequacy of the upstream battered pile in a bent subject to a P-load and a debris raft lateral loading, the effective area and section modulus of the pile at the location of the maximum pile moment should be used. In determining these effective section properties, the taper of the timber piles as indication in Figs. 2.2 and 2.3 should be considered in the manner indicated in Fig. 2.5a and Eqn's (2.1).

2.5 Buckling Consideration of Timber Piles

Timber piles are basically inverted tree trunks and as such their diameters continuously decrease from a maximum value at the top to a minimum value at the tip. Timoshenko and Gere [8] derived the buckling equation for a normal tree trunk shaped column with the small diameter at the top and large diameter at the base as shown in Fig. 2.6 while using Eqn (2.2) to express the moment of inertia at any cross-section mn.



WHERE,

$$I_x = I_1\left(\frac{x}{a}\right)^4 \qquad (2.2)$$

WHERE I_1 = MOMENT OF INERTIA AT THE TOP OF THE COLUMN

$$I_1 = \frac{\pi d_1^4}{64}$$

Fig. 2.6 Solid Conical Column

In describing the deflection curve of the buckled column, the coordinate axes were taken as shown in Fig. 2.7.

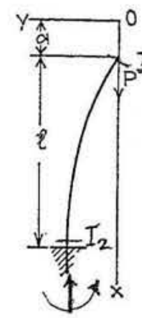


Fig. 2.7 Bucked Shape and Coordinate Axes

Thus, the differential equation of bending of the deflection curve is

$$EIy'' = -M \tag{2.3a}$$

or,
$$E\left(I_1\left(\frac{x}{a}\right)^4\right)y'' = -Py \tag{2.3b}$$

or,
$$\frac{EI_1}{a^4}\ x^4\ \frac{d^2y}{dx^2} = -Py \tag{2.3c}$$

Timoshenko and Gere's [8] solution of Eqn (2.3c) for the buckling load is as follows.

If the substitution $x = {}^1\!/_t$ is made, Eqn (2.3c) can be brought to the form

$$\frac{d^2y}{dt^2} + \frac{2}{t}\frac{dy}{dt} + \frac{Pa^4}{EI_1}\,y = 0 \tag{2.4}$$

which is a form of Bessel's differential equation and has the solution

$$y = t^{-1/2}\left[A_1 J_{-1/2}(\alpha t) + B_1 Y_{-1/2}(\alpha t)\right] \tag{2.5}$$

where A_1 and B_1 are constants of integration, $J_{-1/2}(\alpha t)$ and $Y_{-1/2}(\alpha t)$ represent Bessel functions of the order $-\frac{1}{2}$ of the first and the second kind, respectively, and

$$\alpha = \sqrt{\frac{Pa^4}{EI_1}} \tag{2.6}$$

The Bessel functions of order $-\frac{1}{2}$ are expressible in the form

$$J_{-\frac{1}{2}}(\alpha t) = \frac{\cos(\alpha t)}{\sqrt{(\pi/2)\alpha t}}$$

$$Y_{-\frac{1}{2}}(\alpha t) = \frac{\sin(\alpha t)}{\sqrt{(\pi/_2)\alpha t}}$$

and therefore the solution of Eqn (2.4) is

$$y = \frac{1}{t}\sqrt{\frac{2}{\pi\alpha}}\,[A_1 \cos\,(\alpha t) + B_1 \sin\,(\alpha t)] \tag{2.7}$$

and the general solution of Eqn (2.3c) is

$$y = x\left[A\,cos\frac{\alpha}{x} + B\sin\frac{\alpha}{x}\right] \tag{2.8}$$

where A and B are constants of integration.

Using the conditions at the two ends of the column gives the equation

$$\tan\frac{\alpha l}{a\,(a+l)} = -\,\frac{\alpha}{a+l}$$

or

$$\frac{\tan\gamma}{\gamma} = -\,\frac{a}{l} \tag{2.9}$$

where

$$\gamma = \frac{\alpha l}{a(a+l)} = \frac{l}{a+l}\sqrt{\frac{Pa^2}{EI_1}} \tag{2.10}$$

Equation (2.9) can be solved for γ, for any particular value of $^a/_l$, by using tables of $^{(\tan x)}/_x$. Knowing γ, the critical load can be found from Eqn (2.10) and expressed in the form given by Eqn (2.9).

$$P_{cr} = \frac{mEI_2}{l^2} \tag{2.11}$$

where I_2 is the moment of inertia at the lower end of the column ($x = a + l$). The factor m depends on the ratio $^a/_l$ only, and values are given in Table 2.5. Note that as $^{I_1}/_{I_2}$ approaches unity, the factor m approaches $^{\pi^2}/_4$.

Table 2.5. Values of the Factor m in Eqn. (2.11)

I_1/I_2	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
m	1.202	1.505	1.710	1.870	2.002	2.116	2.217	2.308	2.391	$\pi^2/4$

The above derivation and equations are for a tapering conical column with the larger diameter base at the bottom. However, bridge timber pile bents have the large pile diameter at the top, i.e. at the cap, and the small diameter at the pile tip. For this case, the bent can sidesway (after a major scour event) in the transverse direction from the bottom of the X-bracing down to near the pile tip as indicated in Fig. 2.8 for Mode 2 buckling. If one assumes the pile to be fixed at the location of the bottom horizontal brace (see Fig. 2.8) and pinned at the pile tip and can sidesway, then the buckled configuration would be as shown in Fig. 2.9. With these assumptions, which we feel are reasonable, one can then use Eqn (2.11) and Table 2.5 to estimate the transverse buckling of timber pile bents. It should be noted that when using Eqn (2.11), I_2 should be the value of the pile moment of inertia at the level of the bent HB, i.e., at 1.25' above the OGL (see Fig. 2.8).

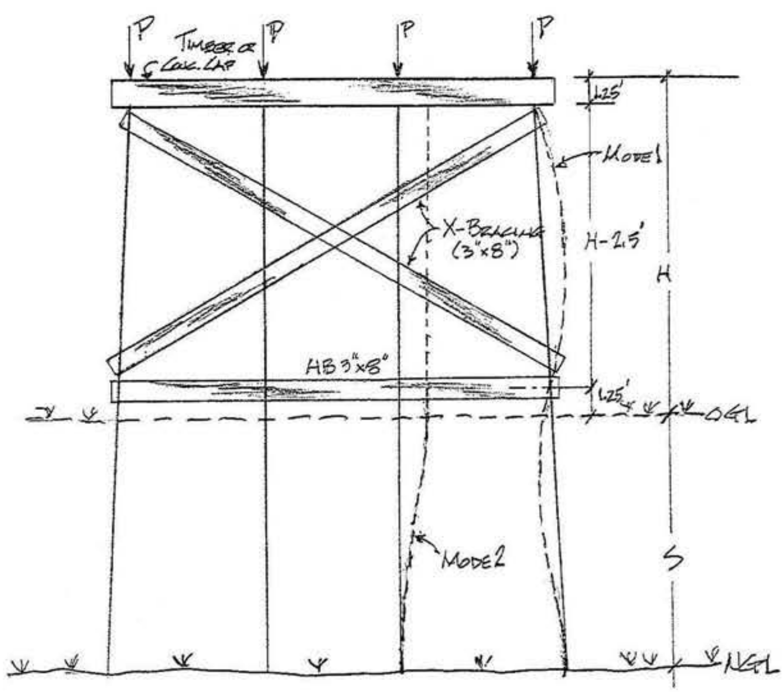


Fig. 2.8 Typical Pile Bent Configuration

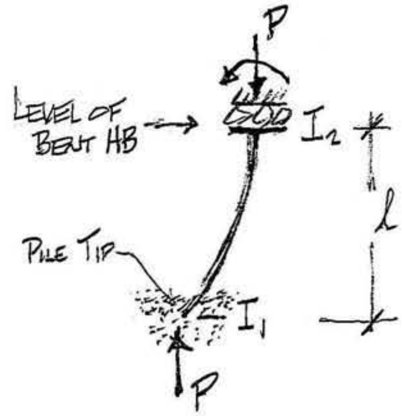
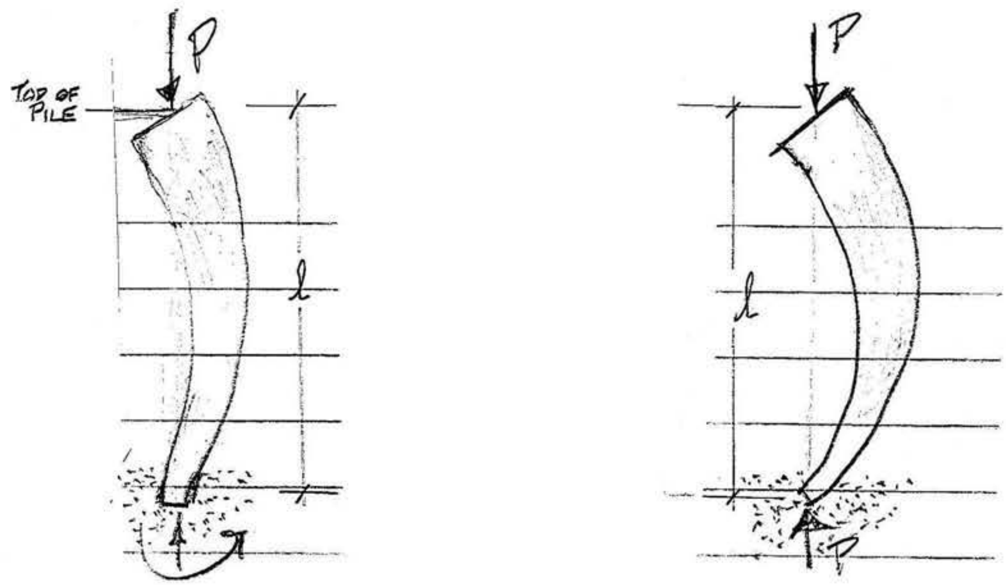


Fig. 2.9 Assumed Transverse Buckled Configuration of Lower Portion of Bent Pile

In checking buckling of the timber pile bents in the longitudinal direction, the piles will buckle as indicated in Fig. 2.10.



(a) Actual: Partially Fixed at Base (b) Assumed: Pin-Pin Condition

Fig. 2.10 Longitudinal Buckled Configuration of Bent Pile

To help gain a sense of depth of pile embedment to achieve a “fixity” or “approximate fixity” end condition in checking bent pile buckling after a major flood/scour event, we looked into some of the timber utility pole embedment specifications/ standards of the Alabama Power Company. Table 2.6 shows some select geometrical properties of ground embedded Timber Utility Poles. The table was extracted from reference [7] which extracted the table from select tables of the Alabama Power Company Specifications and Standards and is of approximately 1980 vintage.

If we define,

$L_t = L$ in Table 2.6 = total pole length

$L_{bg} = E$ in Table 2.6 = length of pole embedded in ground

$L_{ag} = H$ in Table 2.6 = $L_t - E =$ length of pole above ground

and only look at poles (and later piles) in the length range of $30' \leq L_t \leq 50'$, then from Table 2.6,

$$30' \leq L_t \leq 50'$$

and,

$$5.5' \leq L_{bg} \leq 7.0'$$

Therefore,

$$24.5' \leq L_{ag} \leq 43'$$

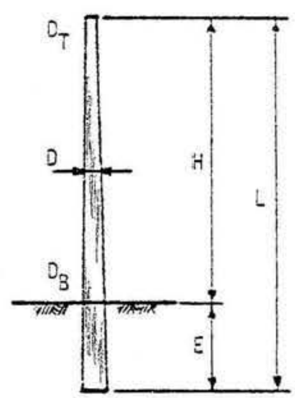
Also, note in Table 2.6 that $E/_L$ or $^{L_{bg}}/_{L_t}$ ratios are shown penned-in and these are typically

$$\frac{L_{bg}}{L_t} \approx 0.15$$

Table 2.6 Geometrical Properties of Select Timber Utility Poles*

POLE	L (ft)	E (ft)	E/L	H (ft)	D_B (in)	D_T (in)	D (in)	S (in^3)
30/7	30	5.5		24.5	7.54	4.78	6.16	42
30/6	30	5.5	0.18	24.5	8.01	5.41	6.71	50
30/5	30	5.5		24.5	8.81	6.05	7.43	67
35/6	35	6.0		29.0	8.59	5.41	7.00	62
35/5	35	6.0	0.15	29.0	9.23	6.05	7.64	77
35/4	35	6.0		29.0	10.03	6.68	8.36	99
40/6	40	6.0		34.0	9.07	5.41	7.24	73
40/5	40	6.0	0.15	34.0	9.87	6.05	7.96	94
40/4	40	6.0		34.0	10.66	6.68	8.67	119
45/6	45	6.5		38.5	9.50	5.41	7.46	84
45/4	45	6.5	0.14	38.5	11.08	6.68	8.88	134
45/2	45	6.5		38.5	12.83	7.96	10.40	207
50/4	50	7.0	0.14	43.0	11.51	6.68	9.10	150
50/3	50	7.0		43.0	12.30	7.32	9.81	183
55/3	55	7.5	0.14	47.5	12.72	7.32	10.02	202
60/2	60	8.0	0.13	52.0	14.09	7.96	11.02	275

Pile Max L≈50'



L = overall pole length

E = embedment length

H = pole height

D_B = pole diameter at base

D_T = pole diameter at top

D = average pole diameter $\left(\frac{D_B + D_T}{2}\right)$

S = section modulus at pole base $\left(\frac{\pi D_B^3}{32}\right)$

R = modulus of rupture of pine poles = 6800 psi

*From Alabama Power Company's Distribution Standards Dwg. A-194823: Southern Pine Pole Specifications and Setting Depths.

It is important to note that timber utility poles have the butt-end embedded and are subjected to small vertical loads and larger lateral loads, whereas with timber bridge bent piles it is just the reverse. However, the depths of embedment of utility poles gives us a feel of what embedments might be required to develop a reasonable moment resistant fixity at the ground. A significant fixity at the ground is required for both timber utility poles and unbraced timber bent piles. For timber bent piles a significant fixity at the ground is essential for stability if the bent is not X-braced, and greatly influences the pile/bent buckling capacity in the longitudinal direction of the bridge which will probably be the controlling failure mode for all timber pile bents during major flood/scour events.

2.6 Design of Timber Piles

The theoretical buckling equation of the previous section for continuously varying cross-section of timber piles was taken into account in Eqn (2.11) and should be quite accurate. However, the formulas below pertaining to the design of timber piles are more widely used and were extracted from Ref [1]. Extending above ground support, wood piles should be well braced. The portion below water level remains as an unsupported column, but the piles may be stiffened by cross-bracing above water. Unless otherwise required by local building codes, the safe load for unsupported wood piles may be obtained by the following formulas which include a reduction factor/safety factor of 3 [2].

$$R = Ap \qquad \text{(when } {}^{l}/_{d} \leqq 11) \qquad (2.12a)$$

$$R = Ap\left[1 - 0.33\left(\frac{l}{Kd}\right)^4\right] \qquad \text{(when } 11 < {}^{l}/_{d} < K) \qquad (2.12\,b)$$

$$R = \frac{0.274AE}{({}^{l}/_{d})^2} \qquad \text{(when } {}^{l}/_{d} \geqq K) \qquad (2.12c)$$

where $R =$ safe load, in pounds;

$p =$ allowable unit compression parallel to grain, in pounds per square inch;

$l =$ unsupported height, in inches;

$d =$ least dimension of square column having same area as a round pile at one-third point of unsupported height from small end, in inches;

$A =$ area at one-third point of unsupported height from small end, in square inches; and

$K = 0.64\sqrt{E/P}$.

Alternatively, in terms of allowable compressive stress, F_c' (where $F_c' = R/A$), the National Forest Products Association (NFPA) classifies timber columns into three groups based on failure mode as short, intermediate, and long columns as indicated in Fig. 2.11. A **short column** is one that will fail by crushing, an **intermediate column** will fail by a combination of crushing and buckling, and a **long column** will fail by Euler buckling alone.

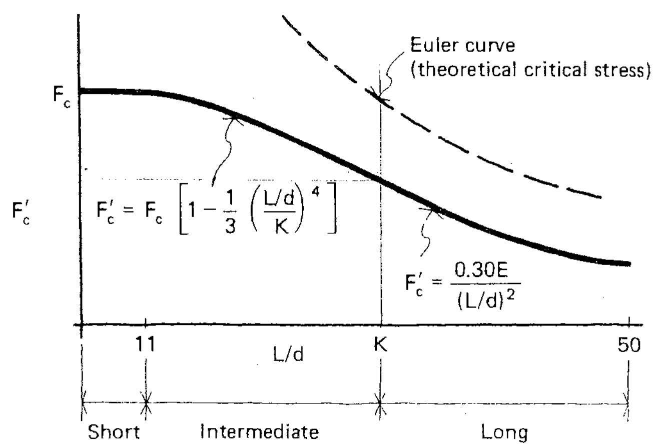


Fig. 2.11. Allowable Stresses for Axially Loaded Timber Columns [6]

The following formula for allowable fiber stress, f, in wood piles acting as columns, and also in bending and compression, is given by the War Department [3] based on allowable working stress of 1,000 psi for continuously wet wood of the grade carried in depot stocks:

$$f = 1{,}000\left(1 - \frac{l}{60d_{ave}}\right) \qquad (2.13)$$

Also, no pile should be used as a column in which the unsupported length is greater than fifty times the diameter.

2.7 Closure

Because of their significant taper, timber piles develop good wedge action and thus large skin friction resistance forces. Also, because of their relatively large tip area, they develop good bearing resistance at their tip. Timber piles have good strength, approximately 7.0 ksi crushing (unfactored) and 12.0 bending (unfactored) and are fairly ductile (relative to concrete). These characteristics and strengths allow maximum axial load limits on timber piles to be governed by the strength of the soil setting rather than that of the pile. They also allow the bent upstream pile to simultaneously withstand lateral flood water loads acting on a debris raft and in-turn on the pile as well as the normal axial dead plus live loads. Even though the other piles in a timber bent act as solid conical columns, their analyses and design are typically as prismatic columns having an effective diameter equal to the pile diameter at a section located 1/3 of the length of the pile above ground when measured up from the ground line. The fact that the moment of inertia of a circular section varies as the 4^{th} power of the diameter, one can see that a timber pile's buckling capacity can be significantly reduced by flood water scour.

Chapter 3. Alabama County Bridges Supported on Timber Pile Bents

3.1 General

Approximately 50 years ago, two-lane highway timber trestle bridges designed for H-20-44 traffic were commonly used by counties as well as some states in the U.S. for their bridges. These bridges typically had a minimum 24 ft. width of roadway and bents at 17 ft. spacing. A transverse section of such a timber trestle bridge is shown in Fig. 3.1. Some of these bridges are still in existence, and some counties still build such bridges on their secondary roads. Also, over time some of these bridges have had their timber superstructure replaced with combinations of steel or concrete girders with a concrete deck, but continuing to use the original timber pile bent substructure.

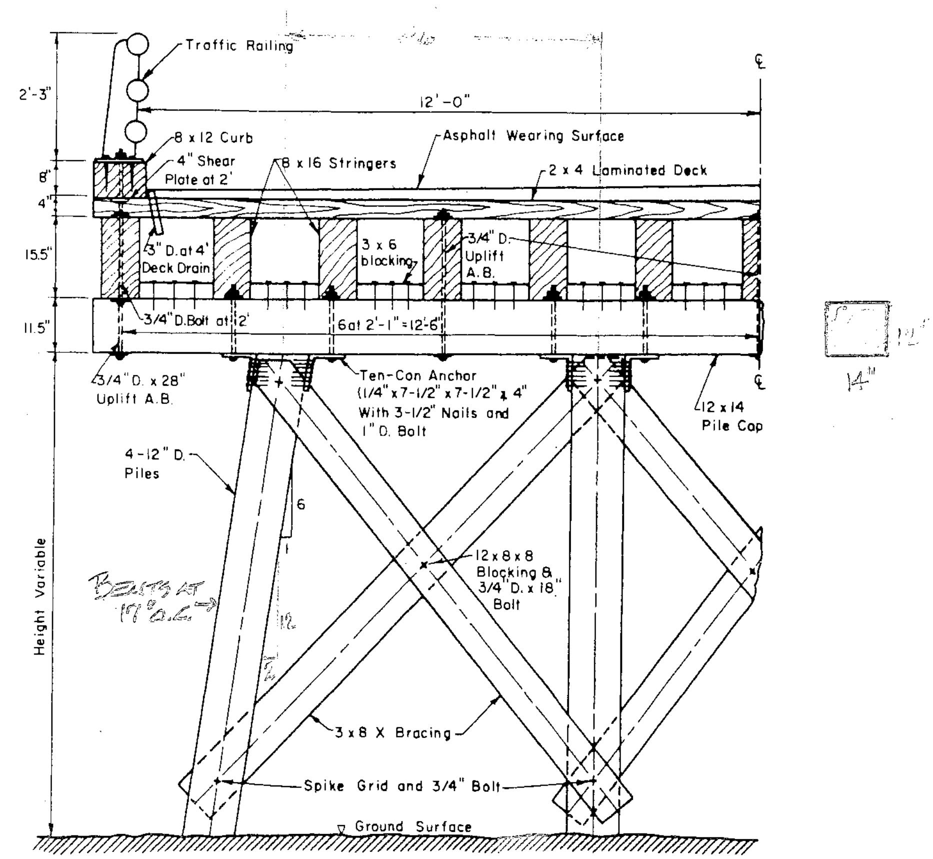


Fig. 3.1 Transverse Section of a Typica. .imber Trestle Bridge [9]

As with any bridge over water with support bents located in the water, extreme flood conditions can arise and cause extreme scouring to occur at the support bents and in turn, this can potentially result in unstable support bents and thus unstable bridges during or after the flooding. Thus, there is a continuing need for bridge owners to check and verify the structural adequacy of bridge supported bents located at such scour prone sites during and after extreme flood/scour events.

3.2 Bridge/Site Parameter Values Needed to Assess Bridge Adequacy

In order to assess a bridges adequacy during major flood/scour events, bridge owners to need to know vital information pertaining to the

- bridge superstructure and live loads acting thereon
- support pile bent geometry and member sizes
- pile driving and support soil conditions
- river/stream high water level, flow velocity, level of possible scour

The specific information needed is summarized in the listing presented in Table 3.1 and is also illustrated graphically in Fig. 3.2 in the form of given dimensioned parameters and parameter values that need to be identified, ie, the ones with questions marks in Fig. 3.2.

Table 3.1 Information on Bridge Settings, Bents, Piles and Superstructures in Bridge Information or Other Databases Available to ALDOT

1. High Water Level, Stream V_{design}, and Scour Information
- Verification that Bridge is over water, supported by pile bents, and in a scour possible setting
- Estimated stream flood high water level (HWL) relative to top of bent cap
- Estimated design flood water velocity (V_{design})
- Estimated magnitude of scour in extreme scour event from stream crossing hydrologic and soil setting data

2. Pile Bent Geometry and Design Information
- Longitudinal spacing of pile bents, i.e., bridge span lengths
- Bent height from top of cap to original ground line (OGL)
- Original ground line (OGL) elevation of bent
- Pile size/diameter, spacing and number of timber piles per bent
- Bent has sway bracing or is without sway bracing
- Bent end piles battered or not battered
- Approximate size of bent cap, i.e., cap width and depth, and cap material
- Manner of connection between bent cap and piles (assumed to be pinned)

3. Pile Driving and Soil Profile Information
- Pile length and tip elevation
- Ground elevation at bents
- Probable driving resistance of last foot
- Probable driving hammer used
- Probable soil setting/characteristics at pile tip

4. Bridge Superstructure Information
- SS or continuous spans (or made continuous for LL). If continuous, for how many spans
- Number of bents or spans
- Span length(s) and bridge length
- Girder type, size, number per span, and spacing
- Deck material and thickness
- Barrier rail type and material and estimated weight per foot
- Outside-to-outside deck width
- Curb-to-curb deck width
- Number of traffic lanes
- Design LL
- Connection of superstructure to bent caps and abutments

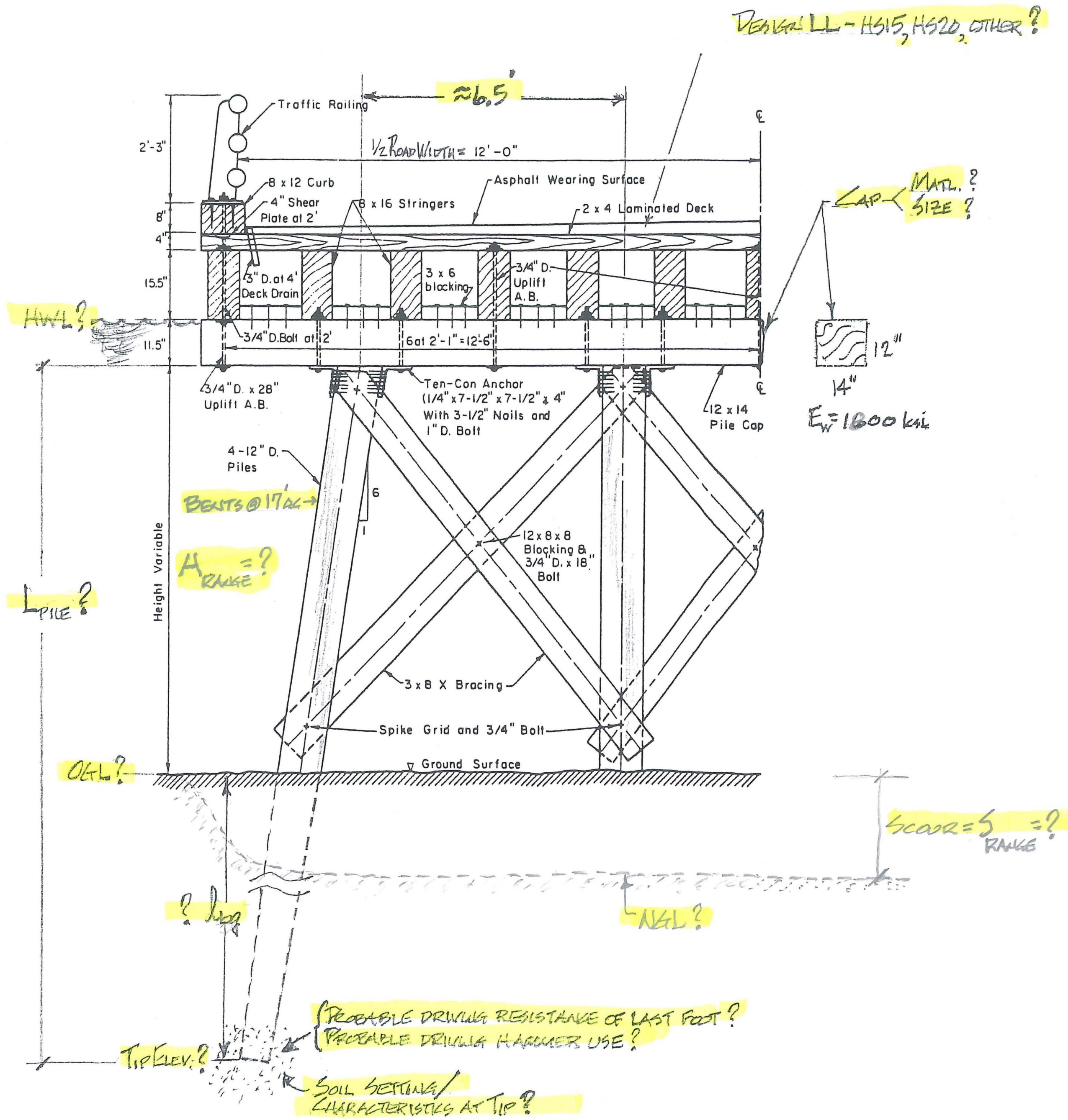


Fig. 3.2 Transverse Section of a Typical Timber Trestle Bridge with Information Needed to Access Adequacy During an Extreme Flood/Scour Event

3.3 Possible Failure Modes of Bridge Timber Pile Bents

Based on our past experience in screening ALDOT bridge as indicated in Phase I, II, III Reports [11-15], possible failure modes of bridge pile bents during extreme scour events are as follows:

(1) Crushing of Piles

(2) Buckling of Bent Piles in Longitudinal or Transverse Directions

(3) Bent failure from piles tips being “kicked” out due to zero or almost zero embedment after scour.

(4) Plunging Failure of Piles (Soil Failure)

(5) Failure of Upstream Bent Pile as a Beam-Column from combined lateral flood water loading and axial gravity loading.

(6) Bent pushover failure from combined superstructure gravity load and transverse flood water load on pile bent.

It should be noted that crushing of a pile during an extreme scour event is really not a viable failure mode for timber piles since $\sigma_{crushing}^{timber} \approx 7.0\ ksi$ and $6"^{\phi}$ tip diameter is the smallest diameter pile used. This means that

$$P_{crushing}^{min} = 7.0\ ksi\ \left(\frac{\pi 6^2}{4}\right) = 198^k$$

which is much larger than $P_{\text{max applied}}$ of 60^k. Also $P_{\text{max applied}}$ and P_{crushing} of the piles are unaffected by a scour event and therefore crushing of the piles will not occur during an extreme scour event.

Thus, only buckling of the bent piles, plunging of the piles (soil failure), bent pushover failure from combined superstructure gravity and flood water lateral loads, or bent failure from the pile tips “kicking-out” due to excessive scour and flood water loads, or failure of the upstream pile as a beam-column from combined flood water and axial loadings will be the only possible catastrophic failure modes. Thus these are the only five modes of failure of concern and requiring checking. Each of these possible failure modes and the manner to check each of them is discussed in detail in the following chapter.

3.4 Timber Pile Bent Supported Bridge/Site Parameter Values or Ranges of Values for Alabama Bridges

Based on our past experience in screening ALDOT bridges supported on steel WF pile bents for their adequacy during extreme flood/scour events, along with the result of a survey of Timber Pile Bent supported bridges in Alabama conducted by the ALDOT for us, a summary of the critical bridge assessment parameters, or ranges of parameters, are shown in Fig. 3.3. Analyses of the adequacy of the timber pile bents during extreme flood/scour events were conducted in the same manner as for our earlier steel WF pile bent analyses using the parameter values and ranges and discreet values in the ranges indicated in Fig. 3.3. The results of these analyses are presented in later chapters of this report.

3.5 Closure

The adequacy of Alabama county timber pile bent supported bridges for extreme flood/scour events requires that one knows vital information about (1) the bridge superstructure and loads acting thereon, (2) the supporting timber pile bent macro and micro geometry, (3) pile driving and support soil conditions, and (4) the stream high water level, flow velocity, and level of possible scour. Values or ranges of values of these vital parameters were provided by ALDOT or were estimated from our past experience with steel WF pile bents. These parameter values were used in a similar manner of analyses as was done in our earlier “screening tool” work for steel WF pile bents and the results are presented in later chapters.

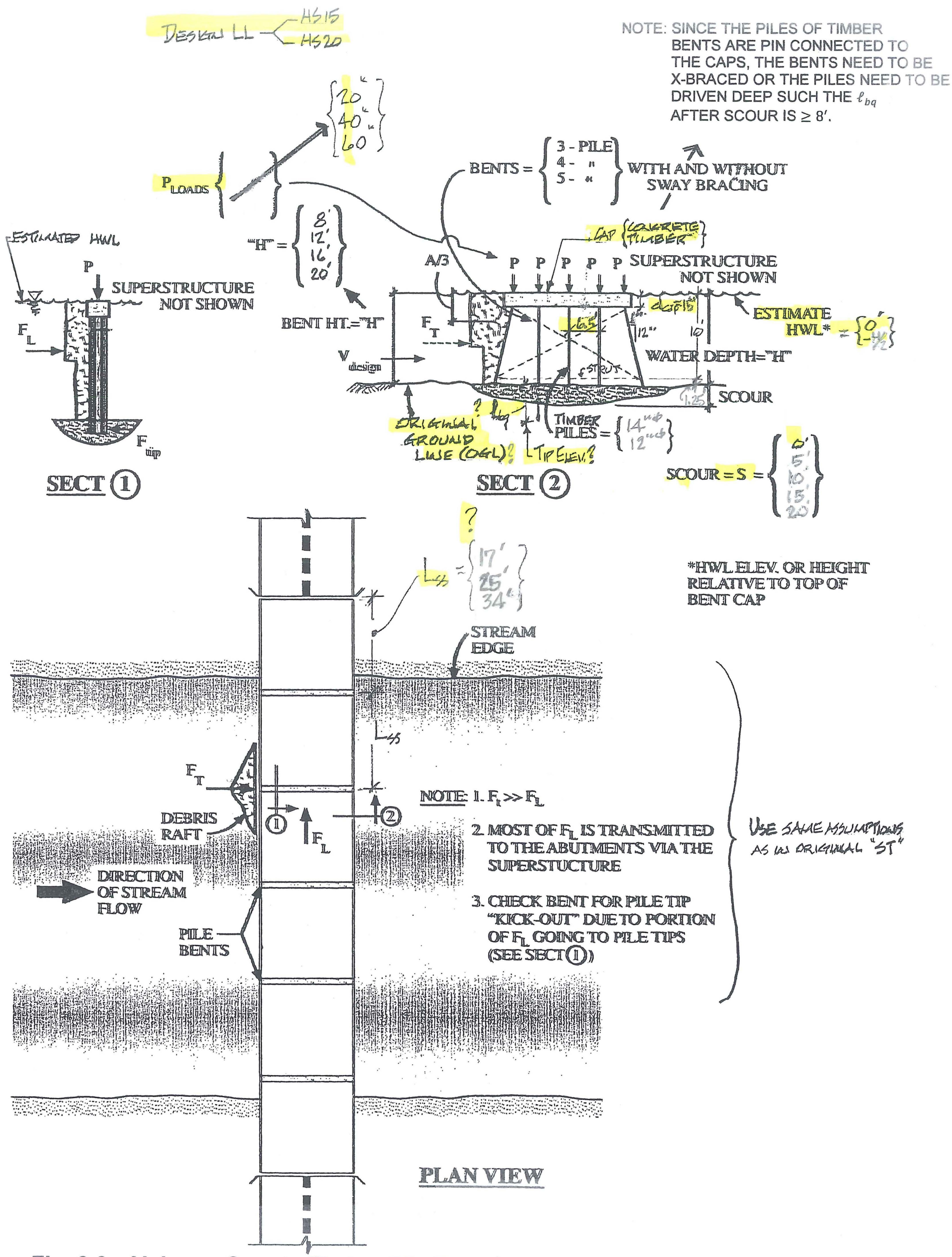


Fig. 3.3 Alabama County Timber Pile Bent Supported Bridges Over Streams- Ranges of Critical Assessment Parameters

4. Screening Tool for Checking Adequacy of Timber Pile Bents for Extreme Flood/Scour Events

4.1 General

As indicated in Chapter 3, possible failure modes of timber pile bents during extreme flood/scour events are

(1) "Kick-Out" of the pile tips due to zero or almost zero embedment after scour.

(2) Pile Plunging Failure (soil failure)

(3) Pile Buckling Failure (in longitudinal or transverse directions)

(4) Bent Pushover Failure from combined superstructure gravity loading and transverse flood water load on pile bent

(5) Failure of Upstream Bent Pile as a beam-column from combined lateral flood water loading and axial gravity loading

These are the same possible failure modes and types of loadings requiring checking for our earlier steel WF pile bent checks. However, with the exception of pile "kick-out," the resistance capacities for each of the above possible failure modes are completely different for timber pile bents compared to steel WF pile bents. These new resistances, capacities, and adequacy checking procedures are given below.

4.2 Checking Pile Tip "Kick-Out" Failure

In checking for bent failure from the pile tips being "kicked-out" due to zero or almost zero embedment after scour, if we call ℓ_{as} the remaining pile embedment after scour (see Fig. 4.1b), then for steel WF pile with $\theta = 30°$, if

$$\ell_{as} \leq 3.0\, ft$$

such a “kick-out” mode is very possible and corrective action should be taken immediately, i.e. before the occurrence of a major scour event. However, the water drag coefficient on a timber pile vs. a WF pile would be

$$C_D^{timber} = 1.2 \qquad \text{or} \qquad \frac{C_D^{timber}}{C_D^{WF}} = \frac{1.2}{2.0} = 0.6$$
$$C_D^{WF} = 2.0$$

Therefore the water drag force on the timber pile would be 0.60 times that for a steel WF pile, and

$$F_{tip}^{timber} = 0.6\, F_{tip}^{WF}$$

Therefore, the minimum required resistance force at the tip of a timber pile will be approximately 0.60 times that required for a steel WF pile, and the minimum required depth of pile embedment after scour will be approximately 0.60 times that required for steel WF piles.

For steel WF piles, we used a F.S. = 1.5, and determined that

$$\ell_{as}^{minimum\ required} = 3.0\ ft.$$

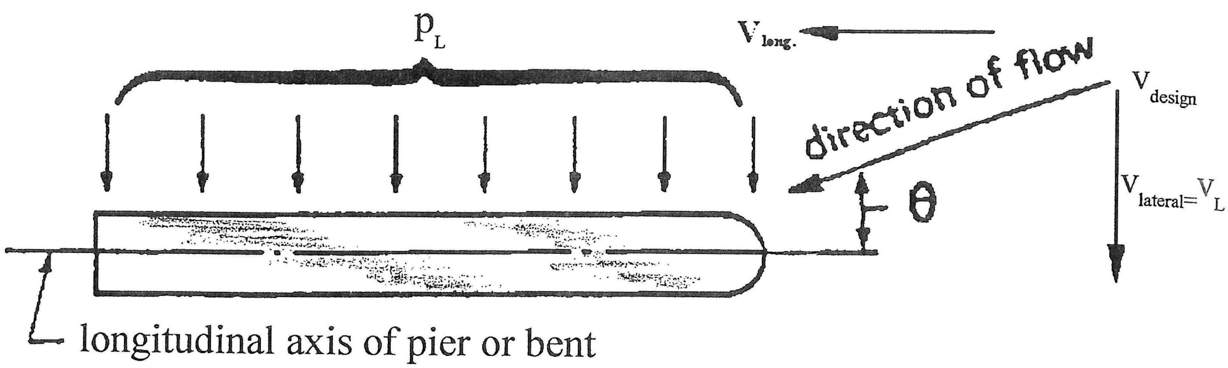
Thus, for timber piles, using this same F.S. = 1.5,

$$\ell_{as}^{minimum\ required} = 3.0\ \times 0.6 = 1.8\ ft.$$

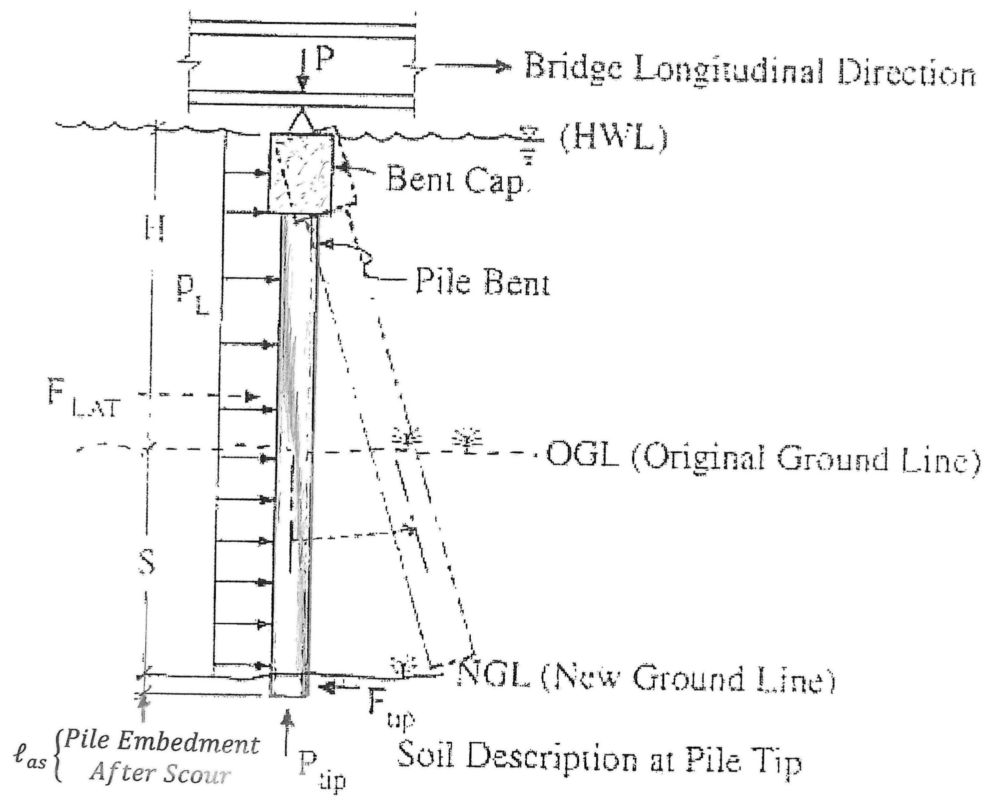
However, because, we do not know the exact locations of the pile tips relative to the OGL or NGL, we will say that for timber piles

$$\ell_{as}^{minimum\ required} = 2.5\ ft.$$

Thus, if $\ell_{as} < 2.5\ ft$, corrective action should be taken and probably the best such action would be place rip-rap around the bent piling.



a. Plan View of Pier Showing Stream Flow and Lateral Pressure



b. Side Evaluation View of Bent Pile Showing "Kick-Out" Load and Failure from Extreme Flood/Scour Event

Figure 4.1 Pile Tip "Kick-Out" Failure

If $\ell_{as} > 2.5\ ft$. then the pile and bent should be safe from this mode of failure; however, if

$$2.5\ ft. < \ell_{as} \le 5.0\ ft$$

there is not much margin for safety against a “kick-out” failure during the next extreme flood/scour event. Given the catastrophic consequences of a bent “kick-out” failure, some sort of corrective action should be taken if $\ell_{as} \le 5.0\ ft$. Probably placing rip-rap around the bent piling should be employed for this case as well.

4.3 Checking Bent Pile Plunging Failure

A possible mode of failure for bridge bents exposed to extreme flood/scour events occurs when the pile geological setting has inadequate load resistance to support the axial pile loads, with the result that the pile bearing capacity and side friction capacity are exceeded and the pile fails by “plunging.” For purposes of this simple screening tool, it is assumed that all of the individual timber piles must be safe from plunging to ensure that the bent is safe from plunging. Thus, the maximum load on any individual pile is used to analyze for possible plunging failure of that pile and in turn for that bent.

The axial resistance of a pile is provided by a combination of side friction and end bearing as illustrated in Fig. 4.2. The magnitude of these load resisting forces are functions of the geometry and surface characteristics of the pile and of the soil properties.

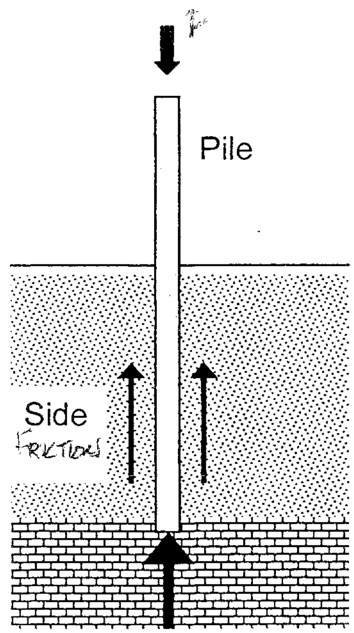


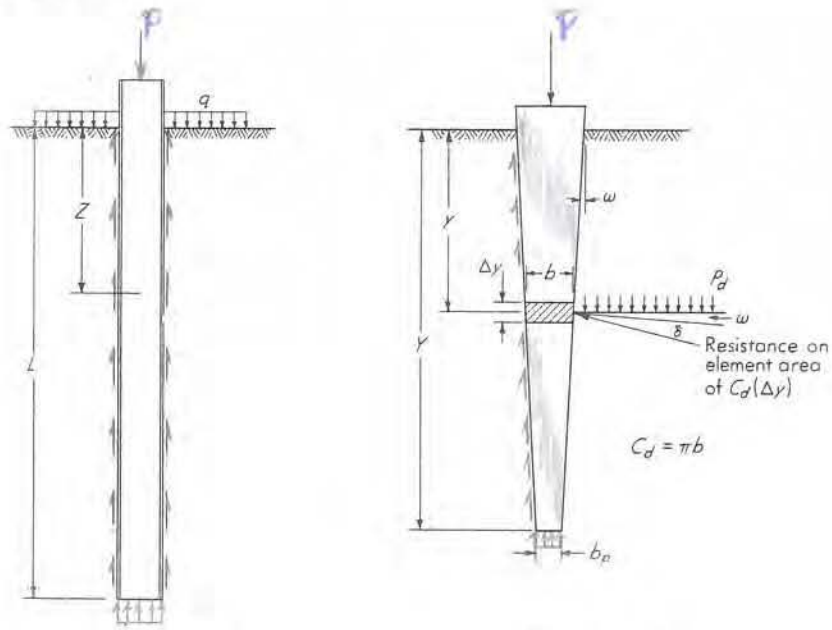
Fig. 4.2 Pile Axial Load and Resisting Forces

It should be noted that the ability of the soil to support the load transmitted to it by the piles is usually the factor that determines the adequacy of pile foundations. The permissible working stresses for piles of any material are seldom fully utilized. For example, $P_{max} = 60^k$ on a timber pile and the minimum pile tip diameter is 6". Thus,

$$\sigma_{axial}^{pile} = \frac{60^k}{\pi^{(6)^2}/_4} = \frac{60^k}{28.3\ in^2} = 2.12\ ksi$$

if the full P-load is carried down to the pile tip, and this would still be OK for the pile itself.

It should also be noted that because of their taper, timber piles develop significant wedge action and reactive side pressures from the soil and thus large skin friction resistance forces. Relative to steel WF piles, timber piles act much more as friction piles as illustrated in Fig. 4.3. Because of their taper, a timber pile has excellent skin friction resistance and because of its large tip area (relative to a steel WF pile), it also has excellent tip resistance.



a. Steel WF Pile b. Timber Pile

Fig. 4.3 Elevation Schematics of Timber and Steel WF Piles

Information on soil properties at each specific bent is typically inadequate/ incomplete. However, the driving resistance (blows per foot of penetration during pile driving) of the pile at the time of construction provides a crude, but reasonably reliable indication of the magnitude of soil resistance that has been mobilized by the pile. In addition, information on the driving resistance of the pile is often the most commonly available information that can be used to indicate pile capacity. In driving piles, when the required driving resistance is reached, driving should be stopped. Common required driving resistances used are [5],

Timber Piles	4-5 blows/in
Concrete Piles	6-8 blows/in
Steel Piles	12-15 blows/in

The major variables affecting the axial resistance of a timber pile (after scour) as indicated by the driving resistance during pile driving are the same as those for steel WF piles, i.e.:

1. The driving resistance at the end of pile driving, usually indicated in blows per foot (bpf) or blows per inch (bpi, = bpf/12) of penetration.
2. The energy of the hammer used to drive the pile, usually expressed in kip-feet and related to the weight of the ram (kips) times the height of the drop (feet).
3. The type of soil which provides the resistance, specifically the relative contribution of end bearing to pile resistance as a proportion of the total resistance. A greater proportion of end bearing would mean less loss of resistance for a given amount of scour.
4. The amount of scour which has occurred, as well as the nature of the scour event. Local scour, which is confined to a small area around the pile, will reduce the amount of soil in contact with the sides of the pile and thereby reduce the side friction. However, local scour does not have a major effect on the magnitude of the confining pressures on the soil at the tip and therefore does not reduce the end bearing resistance in proportion to the amount of soil removed alongside the pile. General scour of the entire streambed around the bent would be likely to reduce the confining pressures in the ground at the pile tip and therefore may reduce the end bearing resistance as well as the side shearing resistance.

Correlations of pile driving resistance to axial static pile capacity have been developed using a number of simple pile driving formulas. The current AASHTO specifications recognize and allow the use of the Modified Gates equation where insufficient information is available to perform a wave equation model.

For this project, the method used to develop correlations of axial static resistance as a function of scour was as follows:

1. The Modified Gates formula was used to develop correlations of pile capacity with hammer driving energy and driving resistance at the end of driving (EOD) for a range of pile hammer energy. The Gates formula is referenced in the most recent draft of the AASHTO specification as follows:

   $$P = 0.875\, E^{0.5}\, Log\,(10N_b) - 50 \qquad (4.0)$$

   Where:

   P = nominal resistance in tons

   E = energy produced by the hammer per blow in foot-pounds

   N_b= the blow count in blows per inch

   EOD blow counts ranging from 2 to 6 bpi were considered. A common refusal criterion is 10 bpi for steel WF piles, beyond which additional pile driving would probably cease. However, because of possible “brooming” of the top of timber piles, a lower EOD blow count is used. In order to maintain a degree of conservatism in a rather uncertain scenario, it is suggested that 6 bpi be used as a maximum. Also, somewhat smaller energy producing hammers are use in driving timber piles relative to those used for steel WF piles. Thus, a range of hammer energies of 2,000-15,000 ft.-lbs. was used.
2. The axial resistance prior to scour was assumed to be represented reasonably well by one of two cases: a) a **predominantly tip bearing pile** in which 75% of

the axial resistance would be provided by end bearing and 25% by side shear, or b) a **predominantly friction pile** in which 25% of the axial resistance would be provided by end bearing and 75% by side shear. The latter case is obviously more susceptible to scour, as removal of the soil alongside the pile would have a greater effect on side shear than on end bearing. As indicated earlier, because of the wedge action developed, timber piles tend to resist more load by friction than do steel WF piles.

3. After scour (represented as a percentage loss of embedment), the axial resistance in side shear was assumed to be reduced by a percentage of the total side shearing resistance which is proportional to the percentage of loss embedment. In a homogenous soil profile with general scour of the streambed instead of localized scour, it is conceivable that the reduction could be greater than the proportional percentage due to the reduction in confining stress associated with scour. However, it is anticipated that a significant proportion of the scour loss will usually be due to localized scour which will not have a significant effect on confining pressure. It is also expected that the more common situation is one in which side shearing resistance increases with increasing depth, and so a proportional reduction in side shear is thought to be conservative.
4. In order to account for the reduction in confining stress at the pile tip associated with scour, the end bearing resistance is reduced by an amount equal to ½ of the proportional loss of embedment due to scour. This reduction is probably realistic

for piles bearing in cohesionless sand, and conservative for cemented bearing strata which have significant cohesion.

Equation (4.0) was used repeatedly for a family of different driving hammer energies and a family of different EOD values and a family of different scour values. The resulting predicted pile capacities are presented in tabular form in Table 4.1. It can be noted in Table 4.1 that a F.S. of 1.25 was used in checking pile plunging adequacy. This lower F.S. was used because the variable properties of timber are not factors in checking pile plunging. Rather, the strength properties of the soil setting itself primarily govern pile plunging, and for a given soil setting, the geometry of a timber pile, relative to that of a steel WF pile, will provide superior pile plunging capacity. Thus, since we used a F.S. = 1.25 in checking steel pile plunging adequacy, it was logical to use this same F.S. in checking timber pile plunging adequacy.

In order to use Table 4.1, the following information is required:

1. Hammer driving energy. The driving system used for installing the pile must be known or estimated. Hammer driving energy is often given as a “rated energy” which corresponds to the weight of the ram times the drop height for a simple single acting hammer. However, the rated energy must then be reduced by some factor less than 1.0 to account for losses due to inefficiency inherent in the driving system (friction losses, etc.). Piles for small bridges in Alabama have typically been driven by one of several types of hammers, with estimated energy as follows:

Hammer Type	Estimated Efficiency (in percent)
Single acting air/steam	67

Double acting air/stream	50
Diesel	80
Drop hammers	50*

***** note that drop hammers can vary widely and are not currently used on ALDOT projects. However, these have been used on many older bridges. With very high drop heights (more than 3 to 5 feet) and low ram weights, the energy losses can result in significantly lower efficiency than 50%.

Note that Hammer Energy in Table 4.1 is the Hammer Rated Energy x Hammer Efficiency.

2. Driving resistance, blows per inch. The driving resistance at the end of the driving must be obtained from the pile driving records from the job. In some cases these piles driving records may not be available, in which case the engineer must make a best estimate of the likely conditions under which pile driving would have been allowed to stop. Often, piles may have been driven to some commonly accepted refusal criterion (or near to refusal) without detailed recording of the blow counts. In such a case, prudent engineering would suggest that one err on the side of caution by using a conservative (i.e., low) estimated driving resistance. Table 4.1 provides for a range of 2, 4, or 6 bpi, and interpolation between these values is acceptable.
3. End bearing pile or friction pile. Two sets of predicted pile capacity are provided in Table 4.1, one for piles which derive capacity from predominantly end bearing and one for piles which derive capacity from predominantly side friction. The interpretation requires some knowledge of the soil conditions either by boring or

from an examination of the driving records. Dense sand strata, hard clays or marl, or rock underlying soft alluvial soil all likely to represent a case where end bearing dominates resistance. Similarly, pile driving records which show relatively low blow counts followed by a dramatic increase in the driving resistance at some depth just prior to the end of driving would suggest a strong bearing layer. Friction piles would be likely used where there are deep clay strata with no hard bearing layer; in such a case the pile embedded lengths would likely be great.

4. Pile embedded length, and scour. In order to assess the effect of scour, it is necessary to know the embedded length of the pile and the amount of scour relative to this length. The predicted capacities shown in Table 4.1 were developed by expressing the scour in terms of percentage loss of embedment as indicated in the Example Problem below.

With the information above, Table 4.1 can be used to estimate the pile capacity (with a factor of safety of 1.25) against a plunging failure as indicated in the example below.

Example Problem: The estimated maximum axial load for an extreme scour event on a pile is 60 kips (30 tons). The pile is a timber pile with 12" butt and 6" tip diameters and driven to an embedment of 30 feet in a sandy soil profile with a Vulcan 1 hammer, which is a single acting air hammer with a 5000 pounds ram and a 3 foot drop. The pile was driven to an estimated final driving resistance of 6 or more blows per inch. The driving resistance increased substantially in the last 4 feet, indicating that the pile encountered a dense bearing layer and achieved a high proportion of its resistance in end bearing. Scour of 15 feet is possible at the bent location.

Solution: The Vulcan 1 hammer has a rated energy of 15 kip-feet, and with a 67% efficiency as is typical for a single acting air hammer, the estimated driving energy is 10 kip-feet. The 15 feet of scour represents 50% of the embedded length. Assume the pile to be an end bearing pile with 6 bpi final driving resistance, 50% loss of embedment, and driven with a 10 ft-k driving hammer. Using Table 4.1, and linear interpolation, the indicated capacity of the pile is approximately 57 tons with a F.S. of 1.25. The 57 tons estimated capacity exceeds the 30 ton demand and thus this pile should not fail in a plunging mode. Alternatively, for a

P_{max}^{pile} = 60^{k} = 30 tons

and going to Table 4.1 with,

S_{max} = 15 ft

Pile is an end bearing pile

Hammer driving energy = 10,000 ft-lbs

Final driving resistance = 6 bpi

Yields,

Critical % loss of embedment > 80% by a considerable margin

Assume critical % loss of embedment = 90%

∴ S_{CR} = 0.90 x ℓ_{bs} = 0.90 (30’) = 27 ft (includes F.S. = 1.25)

∴ S_{CR} > S_{max} and pile bent is safe from a plunging failure

Table 4.1. PREDICTED PILE CAPACITY OF TIMBER PILES WITH FS = 1.25 (BASED ON MODIFIED GATES FORMULA)

Hammer Energy (ft-lb)	Final Driving Resistance (blows/inch)	Allowable Resistance (tons)	End Bearing Pile Load Capacity (tons) (assume 75% tip resistance)					Friction Pile Load Capacity (tons) (assume 25% tip resistance)				
			% loss of embedment					% loss of embedment				
			0	20	40	60	80	0	20	40	60	80
2000	2	1	1	1	1	0	0	1	1	0	0	0
4000	2	18	18	15	13	11	9	18	15	12	9	5
6000	2	30	30	26	22	19	15	30	25	19	14	9
8000	2	41	41	36	31	26	20	41	34	27	19	12
10000	2	51	51	44	38	32	25	51	42	33	24	15
12000	2	60	60	52	45	37	30	60	49	39	28	18
15000	2	71	71	62	53	44	35	71	59	46	34	21
2000	4	10	10	9	7	6	5	10	8	6	5	3
4000	4	31	31	27	23	19	15	31	26	20	15	9
6000	4	47	47	41	35	29	23	47	39	31	22	14
8000	4	60	60	52	45	37	30	60	50	39	28	18
10000	4	72	72	63	54	45	36	72	59	47	34	22
12000	4	83	83	73	62	52	41	83	68	54	39	25
15000	4	97	97	85	73	61	48	97	80	63	46	29
2000	6	16	16	14	12	10	8	16	13	10	8	5
4000	6	39	39	34	29	24	19	39	32	25	19	12
6000	6	56	56	49	42	35	28	56	46	36	27	17
8000	6	71	71	62	53	44	35	71	59	46	34	21
10000	6	84	84	73	63	52	42	84	69	55	40	25
12000	6	96	96	84	72	60	48	96	79	62	46	29
15000	6	112	112	98	84	70	56	112	92	73	53	34

4.4 Checking Bent Pile Buckling Failure

To investigate timber pile/bent buckling, we should recall that due to the bridge abutments and the connectivity of the bridge superstructure to the abutments and the bent caps, bent piles cannot buckle in a sidesway mode in the longitudinal direction of the bridge. Timber bent piles are not embedded in the bent cap, which is usually timber or concrete, but rather are approximately pinned to the cap. In our buckling check, we will assume a 100%, 50 %, or 0% fixity condition at the ground line based on the depth of remaining pile embedment after scour and a pin condition at the top of the piles as indicated in Fig. 4.4.

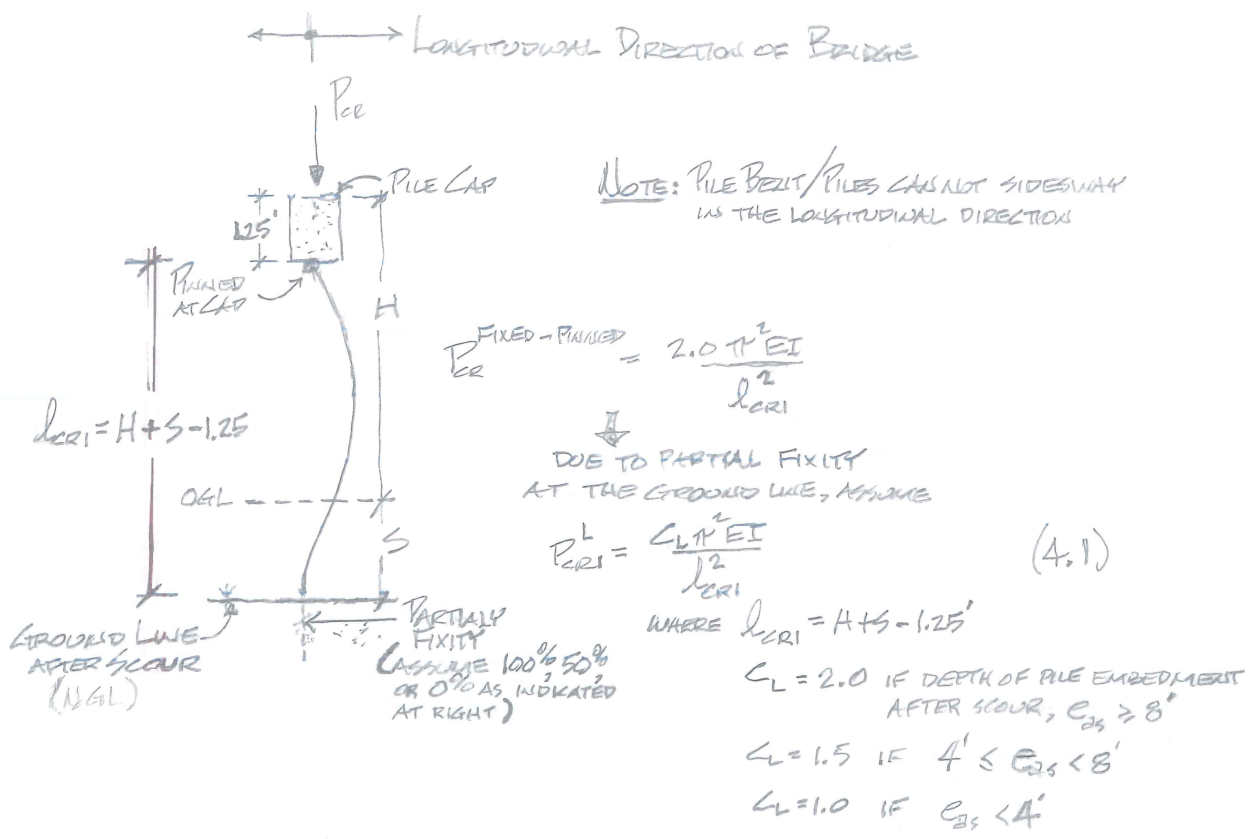


Fig. 4.4 Timber Pile Bent Buckling Mode and Equations for Buckling in the Longitudinal Direction of Bridge

Because of their lack of moment resistant connectivity to the pile cap, timber pile bents should be X-braced for lateral stability, and almost all are. However, ALDOT has indicated that they must check some that are not and hence in this chapter we will look at buckling of both X-braced and unbraced timber pile bents in the sections below.

It should be noted that because timber piles have the same moment of inertia, I, resisting buckling in both the longitudinal and transverse directions, which is not the case for steel WF piles, buckling of the timber piles in a nonsidesway mode in the longitudinal direction will probably be the controlling mode of buckling failure for timber pile bents. However, the sidesway mode of buckling in the transverse direction below the level of the X-bracing, i.e., from the bottom of the x-bracing down to the NGL brings the lower regions of the timber piles where the pile diameter is smaller more into play. Since the flexural stiffness of the pile varies with the diameter to the 4th power, the piles have a significantly reduced flexural stiffness in this lower region, and that along with the sidesway mode of buckling may end up controlling the pile buckling load. Hence, both nonsidesway pile buckling in the longitudinal direction and pile sidesway buckling in the transverse direction below the X-bracing must be checked when checking for adequacy of a timber pile bent for stability.

a. Check for Pile Buckling in Longitudinal Direction. For pile buckling in the longitudinal direction, we will assume,

$$P^L{}_{CR} = \frac{C^L \pi^2 EI}{L^2} \tag{4.1}$$

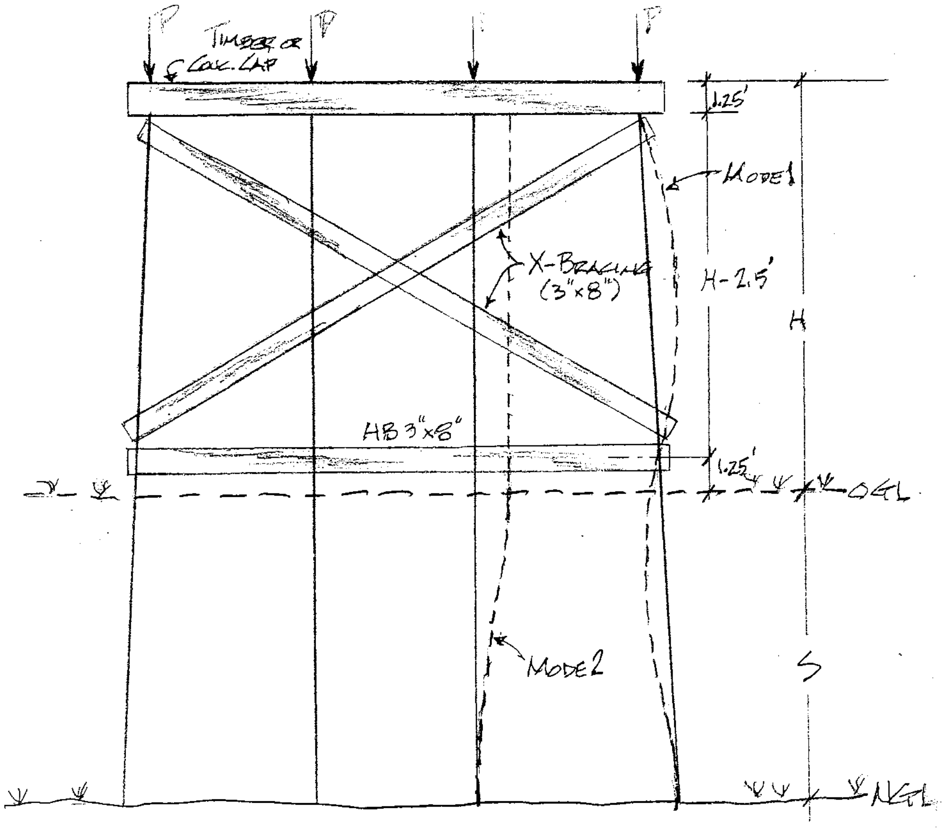
where L = H + S - 1.25 '

and C^L = 1.0, 1.5, or 2.0

as indicated in Fig. 4.4 It should be noted that the buckling mode and equations shown in Fig. 4.4 are applicable to timber pile bent buckling in the longitudinal direction for both X-braced and unbraced bents.

b. Check for Pile Buckling in Transverse Direction. In the transverse direction of the bridge, for an X-braced bent, which all timber pile bents should be, the bracing will prevent sidesway buckling when the scour, S, is zero or is a small value, i.e., $S \leq 3$ ft. For this case, Mode 1 (Nonsidesway) Buckling in the transverse direction will yield a larger P_{CR} than that in the longitudinal direction (because of the smaller ℓ_{CR}), and thus buckling in the longitudinal direction will control. However, when $S > 3$ ft., bents with X-bracing may still buckle in a sidesway mode below the X-bracing, and thus buckling in the transverse direction may control. Thus both nonsidesway buckling in the longitudinal direction and sidesway buckling (below the X-bracing) in the transverse direction must be checked, and the one yielding the smallest P_{CR} will control. For Mode 1 buckling in the transverse direction, we assume a buckled shape from the bent cap down to the new ground line (NGL) as shown in Fig. 4.5. Note that the timber piles are not embedded in the bent cap and the connection of the piles to the cap is close to being a pinned connection as indicated in the buckled shapes in Fig. 4.5. Also note in Fig. 4.5 that pile Mode 1 buckling in the longitudinal direction would have a length of approximately $\mathrm{H} + \mathrm{S}$. Thus, if a pile were to buckle in Mode 1, it would buckle in the longitudinal direction.

As indicated above, when S is not small, i.e., $S > 3$ ft, the X-braced bent could buckle in a transverse sidesway mode from approximately 1.25 feet above the original



Buckling Mode 1 - Nonsidesway Buckling: Assume bracing members prevent lateral displacement and the piles have 50% fixity at the ground and are pinned at the cap.

- Note that the bent exterior piles have fewer bracing points relative to the interior piles and thus will control P_{CR} in the braced regions of the bent.

- In the bracing region of a bent, we will assume

$$P_{CR} = \frac{1.25\pi^2 EI}{\ell_1^2}, \quad \text{where } \ell_1 = H - 2.5' \qquad (4.2)$$

- In the regions below the X-bracing, we will assume

$$P_{CR} = \frac{1.5\pi^2 EI}{\ell_2^2}, \quad \text{where } \ell_2 = S + 1.25' \qquad (4.3)$$

for bent shown in Fig. 4.5

where $\ell_2 = S + 1.25' + d_w$

for bent shown in Fig. 4.6

- P_{CR1} = smaller of the two values above

Buckling Mode 2 - Sidesway buckling in region below the X-bracing for noncontinuous span bridges, i.e. for SS bridges.

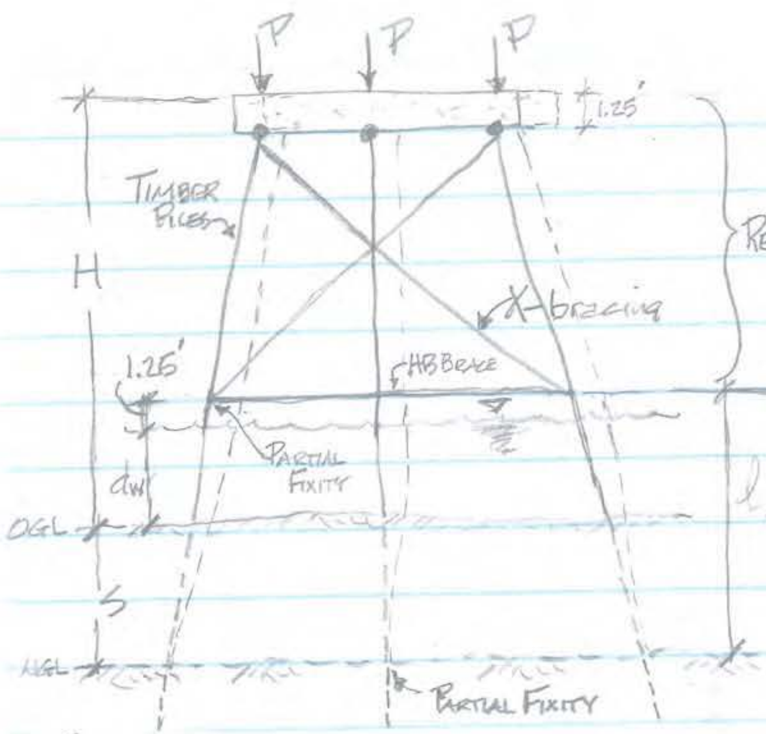
$$P_{CR2} = \frac{1}{2}\frac{\pi^2 EI}{\ell_2^2}, \quad \text{where } \ell_2 = S + 1.25' \qquad (4.4)$$

for bent shown in Fig. 4.5

where $\ell_2 = S + 1.25' + d_w$

for bent shown in Fig. 4.6

Figure 4.5 Transverse Buckling Modes and Equations for X-Braced Timber Pile Bents



NOTE, DUE TO THE X-BRACING, THE PILE BENT WILL MAINTAIN ITS GEOMETRY IN THE REGION OF THE X-BRACING, REGION "A" ABOVE, EXCEPT FOR MOVING AS A RIGID BODY DUE TO THE PILES SIDE-SWAYING BELOW REGION "A"

l for sidesway buckling $= l_{ss}$

$$l_{ss} = S + d_w + 1.25'$$

THUS,

$$P_{CR}^{\text{UPPER BOUND}} = \frac{1.0\pi^2 EI}{l_{ss}^2} \quad (4.6)$$

HOWEVER, DUE TO ONLY PARTIAL FIXITY AT THE TOP AND BOTTOM OF l_{ss},

$$P_{CR} \approx \frac{\frac{1}{2}\pi^2 EI}{l_{ss}^2} \quad (4.7)$$

DUE TO BENT PILES PROVIDING LEAN-ON SUPPORT TO EACH OTHER,

$$P_{CR}^{\text{BENT}} = \sum_{n=1}^{\text{No. PILES}} P_{CR}^{\text{PILES}} \quad (4.8)$$

IF

$$P_{CR}^{\text{BENT}} > \sum_{n=1}^{\text{No. PILES}} P_{\text{APPLIED}}$$

THEN THE BENT IS SAFE FROM TRANSVERSE SIDESWAY BUCKLING.

Figure 4.6 Transverse Sidesway Buckling of X-Braced Bents Below the Bracing

ground line (OGL), i.e. from the lower horizontal brace down to the new ground line (NGL) after scour as shown by the Mode 2 buckling in Fig. 4.5. It should be noted that we are assuming that the bridge spans are simply supported, which they usually are for timber bridges. Because of the possibility of transverse sidesway buckling in the lower unbraced regions of pile bents after scour, simply supported bridge spans will have smaller values of transverse buckling P_{CR}^{Pile} than continuous span bridges because the continuous span superstructure will prevent transverse sidesway buckling of the bents. Also, due to adjacent piles in a bent providing lean- on support to other piles in the bent,

$$P_{CR}^{Bent} = \sum_{n=1}^{No.Piles} \mathrm{P}_{\mathrm{CR}}^{\mathrm{Piles}} \tag{4.5}$$

as indicated in Fig. 4.6.

For purposes of the screening tool, we will assume that bridge spans are simply supported and if the most heavily loaded pile in a bent will not buckle, then the bent will not buckle.

In determining $P_{Max\ Applied}^{Pile}$, continuous span bridges will result in larger $P_{Max\ Applied}^{Pile}$ loads at intermediate supports/bents than for simple spans of the same span length by as much as 25%. However, continuous span superstructures will provide transverse support to the intermediate bents and prevent transverse sidesway buckling and thus increase their P_{CR} value substantially, i.e., from approximately $P_{CR} \approx \frac{1}{2}\frac{\pi^2 EI}{\ell^2}$ to approximately $P_{CR} \approx 2\frac{\pi^2 EI}{\ell^2}$. This is a factor of four increase in P_{CR}. For purposes of the screening tool, for continuous span superstructures, we will assume a conservative scenario, i.e., that $P_{Max\ Applied}$ values are equal to those for simple spans (this is somewhat unconservative), and P_{CR}^{Pile} values are equal to those for simply supported spans where sidesway in the lower regions of the bent are possible as indicated by Mode 2 in Fig. 4.5 (this is very conservative). It should be noted that we must still check for Mode 1 buckling in the longitudinal direction for continuous span bridges.

The levels of scour necessary to approach Mode 1 buckling in the longitudinal direction and Mode 2 buckling in the transverse direction (within a $FS = 1.33$) are given below and labeled S_{CR1} and S_{CR2} respectively. The S_{CR} value for the pile/bent under investigation will be the smaller of these two S_{CR} values.

c. Longitudinal Nonsidesway (Mode 1) Buckling $\boldsymbol{\ell_{CR}}$ and $\boldsymbol{S_{CR}}$ Values. For Mode 1 (Nonsidesway) Buckling in the longitudinal direction shown in Fig. 4.4,

$$P_{CR1} \approx \frac{C^L \pi^2 EI}{\ell^2{}_{CR1}} \quad (4.9a)$$

where $\ell_{CR1} = S + H - 1.25'$ (4.9b)

and C^L = 1.0, 1.5, 2.0 as indicated in Fig. 4.4.

Therefore, $\ell_{CR1} = \sqrt{\frac{C^L \pi^2 EI}{FS^* P^{Pile}_{Max\ Applied}}}$, where FS = 1.33 (4.9c)

and $S_{CR1} = \ell_{CR1} + 1.25' - H$ (4.9d)

$P^{Pile}_{Max\ Applied}$ will be known for the particular bridge/bent under investigation and thus ℓ_{CR1} can be determined from Eqn (9c) and then S_{CR1} from Eqn (4.9d).

Using Eqns (9c) and (9d), ℓ_{CR1} and S_{CR1} values for nonsidesway (Mode 1) buckling of timber bent piles in the longitudinal direction for various pile parameter values and P-load levels are shown in Table 4.2. Values shown in the table include a F.S. = 1.5 on the buckling load. A subset of the $\boldsymbol{S_{CR1}}$ values shown in Table 4.2 are plotted in Fig. 4.7 to graphically illustrate how $\boldsymbol{S_{CR1}}$ varies with the bent height, H, the pile diameter, d, and the applied pile load, P.

Table 4.2. Nonsidesway (Mode 1) Buckling of Timber Bent Piles in the Longitudinal Direction for Various Pile Parameter Values and P-Load Levels (with E = 1800 ksi and F.S. = 1.33 on buckling load)

Tip of Pile Fixity Condition, C_L Value	Pile Parameters	Pile d_{eff}, I_{eff}, EI_{eff} Values						
	Pile d_{eff} (in)	6	7	8	9	10	11	12
	Pile I_{eff} (in^4)	64	118	201	322	491	719	1018
	Pile EI_{eff}(kin^2)	114,500	212,400	361,800	579,600	883,800	1,294,200	1,832,400
1.0 (Pinned)	$P_{\max applied}$ **(kips)**	ℓ_{CR1} **(ft) Values**						
	20	17.2	23.4	30.5	38.7	47.7	57.8	68.6
	30	14.0	19.1	25.0	31.5	39.0	47.2	56.1
	40	12.1	16.6	21.6	27.3	33.8	40.8	48.5
	50	10.8	14.9	19.3	24.4	32.0	36.5	43.4
	60	9.89	13.5	17.6	22.3	27.6	33.3	39.7
	$P_{\max applied}$ **(kips)**	S_{CR1} **(ft) Values**						
	20	18.4 - H	24.6 - H	31.7 - H	39.9 - H	48.9 - H	59.0 - H	69.8- H
	30	15.2 - H	20.3 - H	26.2 - H	32.7 - H	40.2 - H	48.4 - H	57.3 - H
	40	13.3 - H	17.8 - H	22.8 - H	28.5 - H	35.0 - H	42.0 - H	49.7 - H
	50	12.0 - H	16.1 - H	20.5 - H	25.6 - H	33.2 - H	37.7 - H	44.6 - H
	60	11.1 - H	14.7 - H	18.8 - H	23.5 - H	28.8 - H	34.5 - H	41.0 - H
1.5 (Partial Fixity)	$P_{\max applied}$ **(kips)**	ℓ_{CR1} **(ft) Values**						
	20	21.1	28.7	37.4	47.4	58.4	70.7	84.1
	30	17.2	23.4	30.6	38.7	47.7	57.8	68.7
	40	14.9	20.3	26.4	33.5	41.3	50.0	59.5
	50	13.3	18.2	23.7	29.9	37.0	44.7	53.2
	60	12.1	16.6	21.6	27.3	33.8	40.9	48.6
	$P_{\max applied}$ **(kips)**	S_{CR1} **(ft) Values**						
	20	22.3 - H	29.9 - H	38.6 - H	48.6 - H	59.6 - H	71.9 - H	85.3 - H
	30	18.4 - H	24.6 - H	31.8 - H	39.9 - H	48.9 - H	59.0 - H	69.9 - H
	40	16.1 - H	21.5 - H	27.6 - H	34.7 - H	42.5 - H	51.2 - H	60.7 - H
	50	14.5 - H	19.4 - H	24.9 - H	31.1 - H	38.2 - H	45.9 - H	54.4 - H
	60	13.3 - H	17.8 - H.	22.8 - H	28.5 - H	35.0 - H	42.1- H	49.8 - H
2.0 (Fixed)	$P_{\max applied}$ **(kips)**	ℓ_{CR1} **(ft) Values**						
	20	24.4	33.1	43.1	54.7	67.4	81.7	97.1
	30	19.9	27.0	35.3	44.6	55.0	66.7	79.3
	40	17.2	23.4	30.5	38.6	47.7	57.8	68.6
	50	15.3	20.9	27.3	34.6	42.7	51.6	61.4
	60	14.0	19.1	24.8	31.5	39.0	47.1	56.2
	$P_{\max applied}$ **(kips)**	S_{CR1} **(ft) Values**						
	20	25.6- H	34.3 - H	44.3 - H	55.9 - H	68.6 - H	82.9 - H	98.3 - H
	30	21.1 - H	28.2 - H	36.5 - H	45.8 - H	56.2 - H	67.9 - H	80.5 - H
	40	18.4 - H	24.6 - H	31.7 - H	39.8 - H	48.9 - H	59.0 - H	69.8 - H
	50	16.5 - H	22.1 - H	28.5 - H	35.8 - H	43.9 - H	52.8 - H	62.6 - H
	60	15.2 - H	20.3 - H	26.0 - H	32.7 - H	40.2 - H	48.3 - H	57.4 - H

H = Bent Height

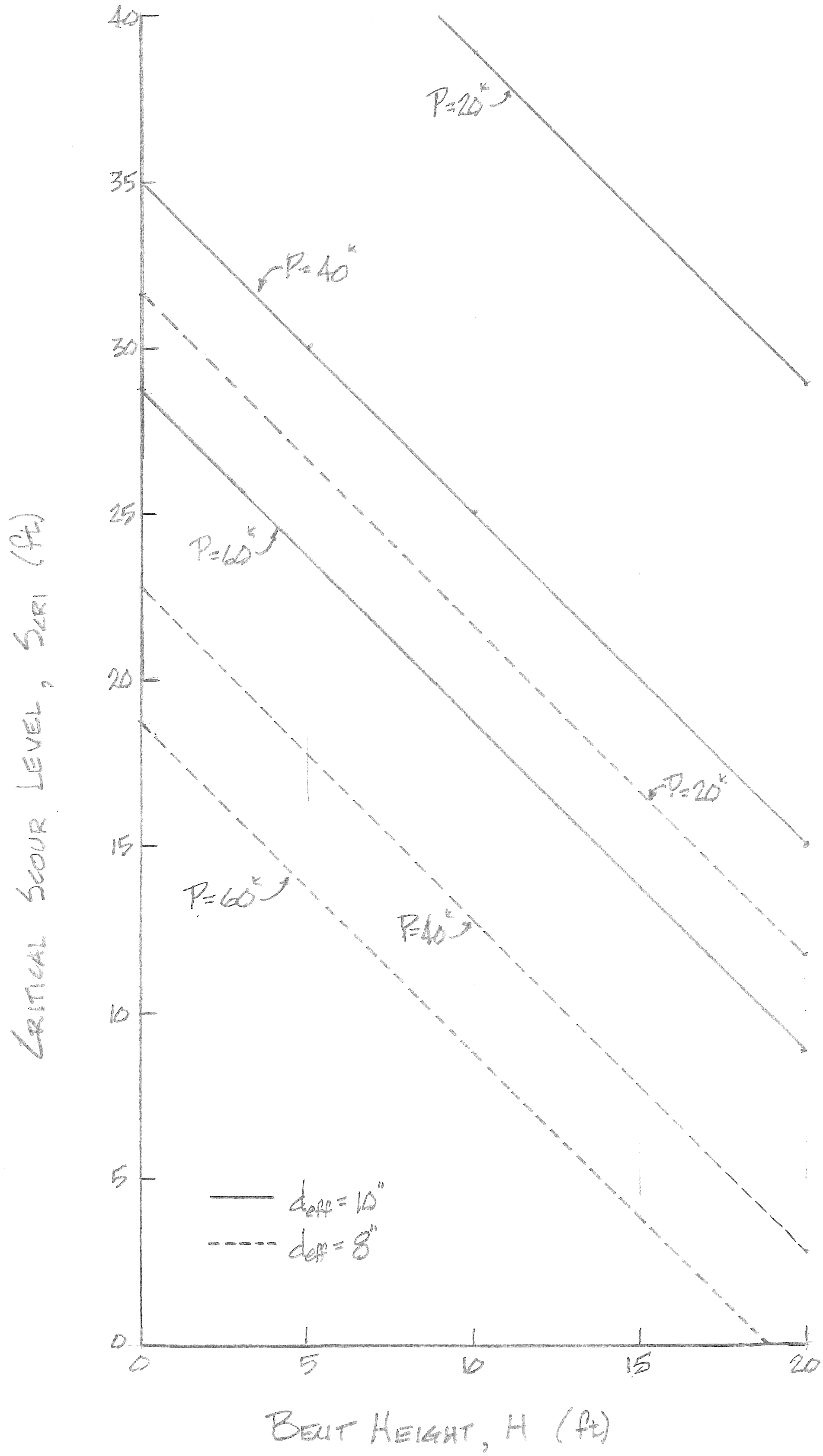


Fig. 4.7 S_{CR1} **vs** H **for Nonsidesway (Mode 1) Buckling of Timber Pile Bents with Pinned Condition at Tip (with** $F.S.$ **= 1.33 on** P_{CR}**)**

d. Transverse Sidesway (Mode 2) Buckling ℓ_{CR} and S_{CR} Values. For Mode 2 (Sidesway) Buckling in the transverse direction shown in Figs. 4.5 and 4.6,

$$P_{CR2} \approx \frac{1}{2} \times \frac{\pi^2 EI}{\ell^2{}_{CR2}} \tag{4.10a}$$

where $\ell_{CR2} = S + 1.25'$ for X-braced bents if bent is out of water as shown in Fig. 4.5. (4.10b)

or $\ell_{CR2} = S + (1.25' + d_w)$ for X-braced bents if bent is in water as shown in Fig. 4.6. (4.10c)

Therefore, $\ell_{CR2} = \sqrt{\frac{1}{2} \times \frac{\pi^2 EI}{FS^* P^{Pile}_{Max\ Applied}}}$, where FS = 1.50 (4.10d)

and $S_{CR2} = \ell_{CR2} - 1.25'$ for X-braced bent if bent is out of water as shown in Fig. 4.5. (4.10e)

or $S_{CR2} = \ell_{CR2} - (1.25' + d_w)$ for X-braced bent if bent is in in water as shown in Fig. 4.6. (4.10f)

Again, $P^{Pile}_{Max\ Applied}$ will be known for the particular bridge/bent under investigation and thus ℓ_{CR2} can be determined from Eqn (4.10b or 4.10c) and then S_{CR2} from Eqn (4.10e or 4.10f).

Using Eqn (4.10d), ℓ_{CR2} values can be determined for various piles sizes and $P_{\max applied}$ values, and in turn, Eqns (4.10e) or (4.10f) as appropriate can be used to determine the associated S_{CR2} values. This was done, and the ℓ_{CR2} and S_{CR2} values for sidesway (Mode 2) buckling of timber bent piles for various pile parameter values and P-load levels are shown in Table 4.3. Values shown in the table include a F.S. = 1.5 on the buckling load.

The S_{CR} for the pile/bent will be the smaller of S_{CR1} and S_{CR2}, and if

$$S_{CR} \geq S_{Max\ Applied}$$

then the bent is safe from buckling.

Table 4.3 Sidesway (Mode 2) Buckling of Timber Bent Piles in the Transverse Direction in Region of Bent Below the X-Bracing for Various Pile Parameter Values and P-Load Levels (with E = 1800 ksi and F.S. = 1.33 on buckling load).

Pile Parameters	Pile d_{eff}, I_{eff}, EI_{eff} Values						
Pile d_{eff} (in)	6	7	8	9	10	11	12
Pile I_{eff} (in^4)	64	118	201	322	491	719	1018
Pile EI_{eff}(kin^2)	114,500	212,400	361,800	579,600	883,800	1,294,200	1,832,400
$P_{\max applied}$ (kips)	ℓ_{CR2} (ft) Values						
20	12.1	16.6	21.6	27.3	33.8	40.9	48.6
30	9.92	13.5	17.6	22.3	27.5	33.3	39.7
40	8.59	11.7	15.3	19.3	23.9	28.9	34.4
50	7.68	10.5	13.7	17.3	21.3	25.8	30.7
60	7.01	9.55	12.4	15.8	19.4	23.6	28.0
$P_{\max applied}$ (kips)	S_{CR2} (ft) Values*						
20	10.8	15.3	20.3	26.1	32.6	39.7	47.4
30	8.67	12.2	16.3	21.1	26.3	32.1	38.5
40	7.34	10.4	14.1	18.1	22.7	27.7	33.2
50	6.43	9.25	12.5	16.1	20.1	24.6	29.5
60	5.76	8.30	11.3	14.7	18.2	22.4	26.8

*If the bent lower horizontal brace (HB) is elevated higher than 1.25 ft above the OGL, subtract this additional height from S_{CR} to determine the S_{CR} for this case (see d_w in Fig. 4.6)

e. Transverse Sidesway Buckling of Unbraced Timber Piles. It should be noted that the ALDOT reports that they find some timber pile bents that are not X-braced. Such an unbraced bent is shown in Fig. 4.8. If the pile end conditions were truly pinned (at the bent cap) and fixed (at the ground level), then for such bent piles,

$$P_{CR} = \frac{1}{4}\frac{\pi^2 EI}{\ell^2} \tag{4.11}$$

However, such idealized end conditions will not exist and due to only partial fixity at the ground and partial rotational restraint at the bent cap, we will assume.

$$P_{CR} = \frac{1}{6}\frac{\pi^2 EI}{\ell^2} \tag{4.12a}$$

or,

$$\ell_{CR} = \sqrt{\frac{1}{6}\frac{\pi^2 EI}{P_{CR}}} = \sqrt{\frac{\pi^2 EI}{6 \times F.S. \times P_{\max applied}}} \tag{4.12b}$$

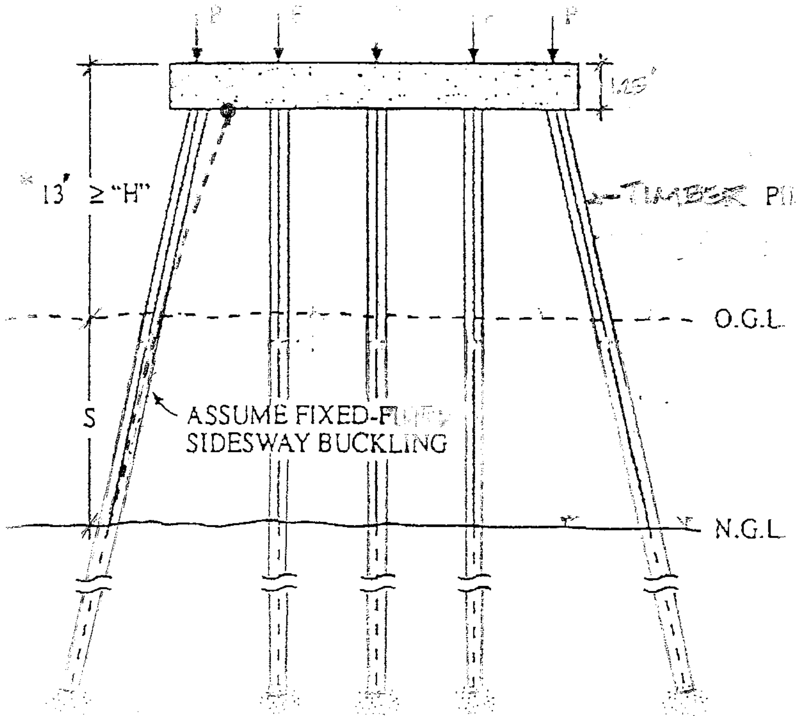


Fig. 4.8 Unbraced Timber Pile Bent

Using a $F.S. = 1.33$,

$$\ell_{CR} = \sqrt{\frac{\pi^2 EI}{9\, P_{\max appl.}}} \tag{4.12c}$$

and,

$$S_{CR} = \ell_{CR} - H + 1.25' \tag{4.12d}$$

for cases where the timber pile bents are not X-braced. There is no need to check an unbraced bent for buckling the longitudinal direction as it is obvious from comparing Eqns (4.1) and (4.11) that Eqn (4.11) and thus transverse sidesway buckling controls.

Using Eqns (4.12c) and (4.12d), ℓ_{CR} and S_{CR} values for transverse sidesway buckling for various pile parameter values and P-load levels were determined for various pile sizes and P-loads and these are shown in Table 4.4. Values shown in the table include a F.S. = 1.33 on the buckling load.

Table 4.4. Sidesway (Mode 2) Buckling of Non X-Braced Timber Bent Piles in Transverse Direction for Various Pile Parameter Values and P-Load Levels (with E = 1800 ksi and F.S. = 1.33 on buckling load)

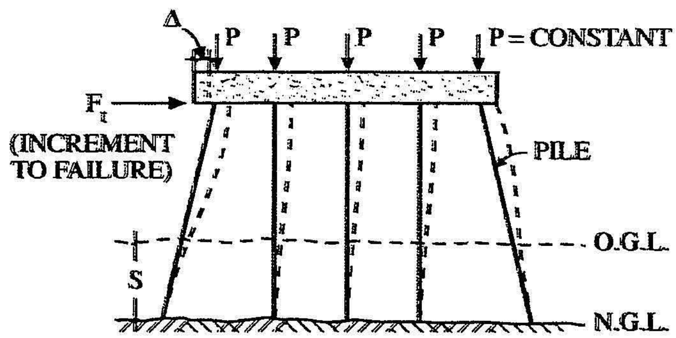
Pile Parameters	**Pile d_{eff}, I_{eff}, EI_{eff} Values**						
Pile d_{eff} (in)	6	7	8	9	10	11	12
Pile I_{eff} (in^4)	64	118	201	322	491	719	1018
Pile EI_{eff}(kin^2)	114,500	212,400	361,800	579,600	883,800	1,294,200	1,832,400
$P_{\max applied}$ **(kips)**	**ℓ_{CR} (ft) Values**						
20	7.01	9.55	12.5	15.8	19.4	23.6	28.0
30	5.72	7.80	10.2	12.8	15.9	19.2	22.9
40	4.96	6.75	8.81	11.1	13.8	16.7	19.8
50	4.44	6.04	7.88	9.98	12.3	14.9	17.7
60	4.05	5.51	7.20	9.11	11.2	13.6	16.1
$P_{\max applied}$ **(kips)**	**S_{CR} (ft) Values**						
20	8.26 - H	10.8 - H	13.8 - H	17.0 - H	20.6 - H	24.8 - H	29.2 - H
30	6.97 - H	9.05 - H	11.4 - H	14.0 - H	17.1 - H	20.4 - H	24.1 - H
40	6.21 - H	8.00 - H	10.1 - H	12.3 - H	15.0 - H	17.9 - H	21.0 - H
50	5.69 - H	7.29 - H	9.13 - H	11.2 - H	13.5 - H	16.1 - H	19.0 - H
60	5.30 - H	6.76 - H	8.45 - H	10.4 - H	12.4 - H	14.8 - H	17.3 - H

H = Bent Height

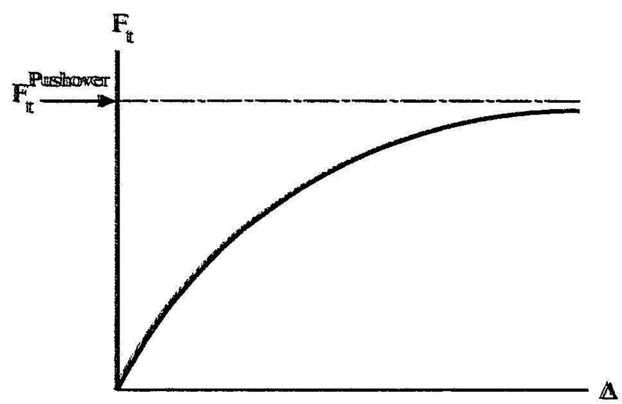
4.5 Checking Bent for Pushover Failure

Pushover analysis is a nonlinear analysis procedure that was born in the seismic analysis community. The technique is based on the conventional displacement method of analysis. Standard elastic and geometric stiffness matrices for the structure elements are progressively modified to account for geometric and/or material non-linearity under constant gravity loads and incrementally increasing lateral loads.

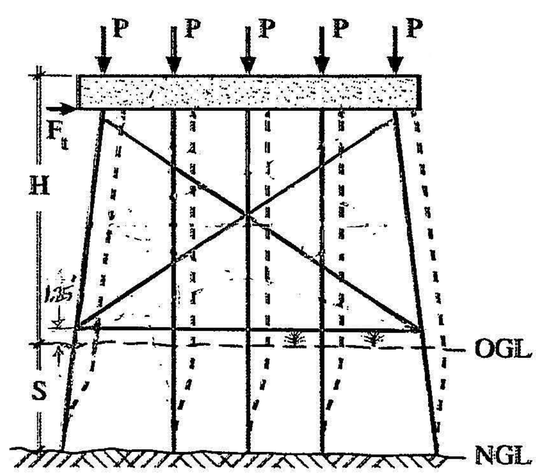
Extreme flood/scour event loadings, in conjunction with ever present gravity P-loads on a bridge pile bent can be a controlling load condition if the bent transverse load, F_t, and scour, S, are large as shown in Fig. 4.9. Even for bents which are X-braced in the transverse direction, a significant P-Δ effect can occur and induce a bent



a. Gravity + Flood Water Loaded Pile Bent



b. Bent Pushover Curve



c. X-Braced Pile Bent Pushover Failure

Fig. 4.9 Typical Nonlinear Pile Bent Pushover Failure and Curve

pushover failure in the region from the NGL to approximately 1.25 feet above the OGL as indicated in Fig. 4.9c.

In simple cases, linear eigenvalue analyses may be sufficient for design evaluation. However, the failure of timber bridges subjected to scour may be defined by a combination of large deflection instability and material softening or rupture. Therefore nonlinear incremental analyses were performed using the Riks method to solve for the nonlinear equilibrium path (ABAQUS analysis user's manual v6.7). This approach provides solutions regardless of whether the response is stable or unstable. A typical pushover load-displacement curve for an X-braced timber bridge is shown in Figure 4.10. The gravity P-loads on the bents are applied before the Riks procedure begins, and are held constant through the analysis. After application of the P-loads, the lateral flood water load, F_t, is incrementally increased until the system becomes unstable. After initial load increment is provided, subsequent iterations and load increments are computed automatically. After each load increment, the bent stiffness matrix is modified to account for changes in geometry due to deformations of the members of the bent and the stress-strain levels occurring in the members. Thus, both geometric and material nonlinearity of the members are included in the analysis, and this in turn provides an accurate evaluation of the pushover curves and loads for the bents.

Figure 4.10 shows an example pushover curve for a X-braced, 3-pile, 14" diameter timber pile bent. The gravity P-load is 20 kips and scour is not present (S = 0 ft). For the braced pile bent, the pushover force is 260 kips. Bent pushover curves obtained from ABACUS are given in Appendix A for X-braced bents and in Appendix B for Non-X-braced bents. Analyzed bent scenarios can be seen in Table 4.5 below.

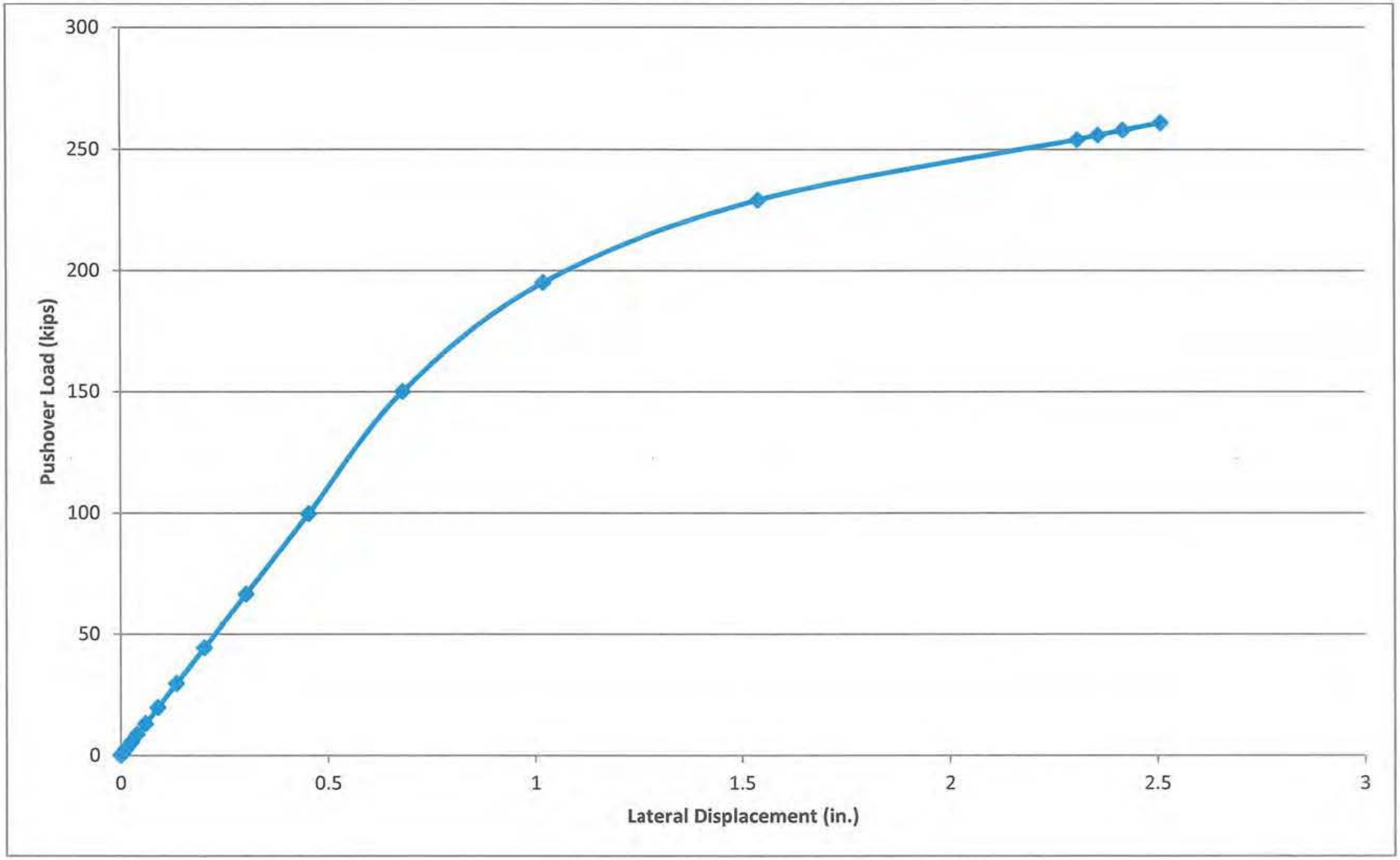


Figure 4.10 Typical Pushover Curve for Timber Pile Bents

(3-Pile X-Braced Bent, H = xx ft, 14" Diameter, P-load = 20kips, S = 0ft)

Table 4.5 Analyzed Timber Pile Bents for Bent Pushover Check

Parameter	Scenarios Considered
Bracing Condition	X-braced and Non-X-braced
Number of Piles in Bent	3, 4, 5
Height (ft)	8, 12, 16, 20
Pile Diameter (in)	12, 14
P-Load Applied (kips)	20, 40, 60
Scour (ft)	0, 5, 10, 15, 20

The pushover forces, $F_t^{Pushover}$, corresponding to the pushover curves in Appendices A and B are presented in Tables 4.6 - 4.9 below. In checking a bent's adequacy for pushover, the maximum applied lateral flood load, $F_t^{Max\ Applied}$, should be determined prior to using the screening tool as demonstrated in Fig. 4.11. From Fig. 4.11, depending on the bridge span length,

$$F_t^{Max\ Applied} = 6.48^k$$

$$F_t^{Max\ Applied} = 9.72^k$$

Thus, one should determine $F_t^{Pushover}$ from Table 4.6 – 4.9 and check,

$$If\ F_t^{Pushoer} \geq 1.33 F_t^{Max\ Applied} \rightarrow SAFE$$

Table 4.6 Pushover Loads F_t for X-Braced, 12" Pile Diameter Bents

Number of Piles in Bent	Bent Height (ft)	Scour (ft)	Pushover Loads (kips) Pile Load (kips) 20	40	60
3	8	0	250	249	247
		5	150	149	148
		10	113	112	110
		15	99.9	97.7	93.2
		20	85.5	82.9	80.3
	12	0	256	255	254
		5	167	167	166
		10	108	107	112
		15	122	118	108
		20	98.0	81.4	101
	16	0	228	227	226
		5	180	191	178
		10	145	137	143
		15	135	132	130
		20	113	109	102
	20	0	228	227	153
		5	143	174	146
		10	138	127	145
		15	113	110	109
		20	101	97.2	90.1
4	8	0	258	255	253
		5	166	163	160
		10	127	123	121
		15	88.3	86	83.9
		20	72.8	74.1	71.6
	12	0	278	271	275
		5	166	164	179
		10	146	144	142
		15	109	107	105
		20	91.8	91.4	88.7
	16	0	284	283	280
		5	166	162	191
		10	155	162	159
		15	105	111	102
		20	118	114	110
	20	0	198	196	195
		5	189	188	186
		10	156	153	147
		15	147	143	137
		20	128	118	109
5	8	0	256	248	243
		5	162	157	152
		10	97.2	108	99.3
		15	80.2	77.5	74.8
		20	70.2	67.1	64.0
	12	0	257	253	274
		5	160	158	178
		10	131	131	132
		15	112	105	103
		20	94.1	90.9	87.5
	16	0	236	230	234
		5	206	191	190
		10	147	159	158
		15	108	106	103
		20	90.7	87.5	84.2
	20	0	263	247	248
		5	207	206	207
		10	165	158	114
		15	101	146	143
		20	117	109	77.3

Table 4.7 Pushover Loads F_t for X-Braced, 14" Pile Diameter Bents

Number of Piles in Bent	Bent Height (ft)	Scour (ft)	Pushover Loads (kips) Pile Load (kips)		
			20	40	60
3	8	0	250	249	247
		5	162	161	159
		10	123	122	120
		15	89.3	99.4	86.7
		20	78.7	77.6	76.6
	12	0	261	260	253
		5	192	191	190
		10	135	130	136
		15	115	113	114
		20	104	99.3	97.9
	16	0	228	227	226
		5	159	158	157
		10	155	154	155
		15	134	142	140
		20	107	106	104
	20	0	229	228	227
		5	171	173	178
		10	140	100	138
		15	136	135	133
		20	115	113	119
4	8	0	258	255	252
		5	165	163	160
		10	126	123	121
		15	86.7	85.6	84.1
		20	75.3	73.9	72.0
	12	0	280	278	277
		5	205	202	202
		10	135	134	133
		15	114	113	111
		20	101	99.1	97.2
	16	0	283	281	280
		5	190	186	186
		10	162	160	159
		15	119	115	106
		20	103	103	101
	20	0	215	251	250
		5	149	183	182
		10	161	162	160
		15	147	145	144
		20	134	133	131
5	8	0	253	248	243
		5	162	131	131
		10	97.3	99.3	97.7
		15	85.8	84.4	75.5
		20	69.6	66.9	64.6
	12	0	254	234	244
		5	172	203	166
		10	130	127	127
		15	123	108	106
		20	96.8	94.7	92.5
	16	0	236	232	221
		5	238	236	233
		10	147	146	157
		15	123	121	119
		20	105	103	101
	20	0	275	273	248
		5	228	194	166
		10	163	161	160
		15	114	112	111
		20	131	128	125

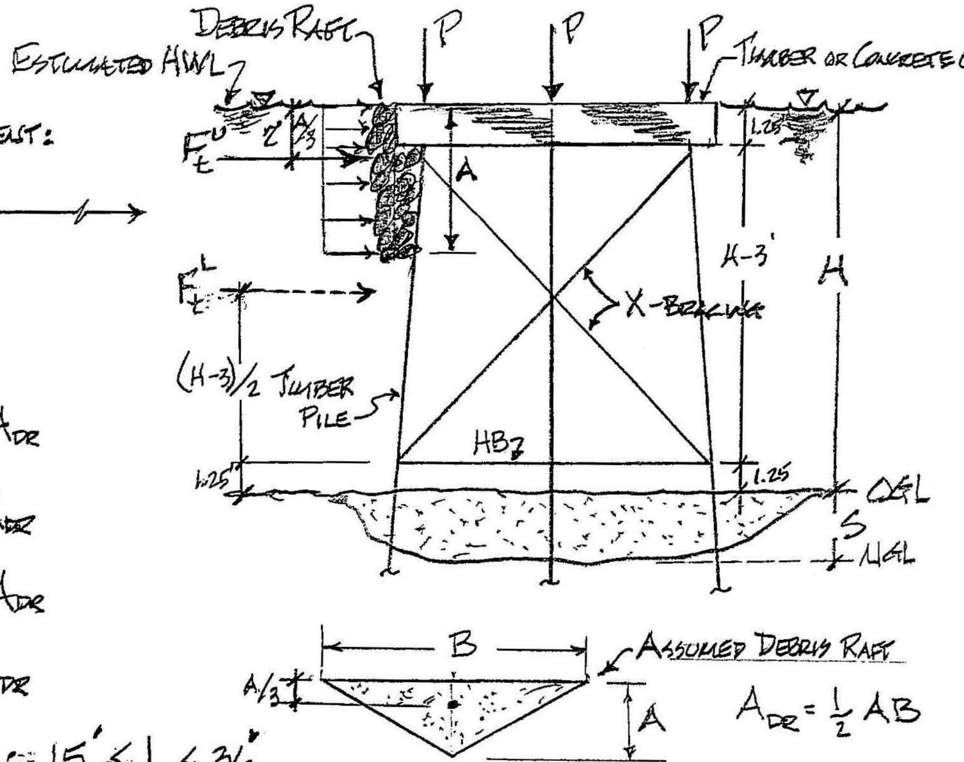
Table 4.8 Pushover Loads F_t for Unbraced, 12" Pile Diameter Bents

Number of Piles in Bent	Bent Height (ft)	Scour (ft)	Pushover Loads (kips) Pile Load (kips)		
			20	40	60
3	8	0	289	289	288
		5	163	162	164
		10	104	102	98.3
		15	69.4	64.9	61.0
		20	46.8	41.3	37.0
	12	0	183	181	164
		5	115	108	99.9
		10	75.6	71.0	61.5
		15	50.5	46.0	40.7
		20	29.5	28.8	23.1
	16	0	122	120	107
		5	80.3	78.1	67.5
		10	53.3	50	44.9
		15	37.1	31.8	26.3
		20	19.9	18.4	12.3
4	8	0	411	231	408
		5	224	222	221
		10	133	131	135
		15	95.2	92.7	88.1
		20	68.5	47.0	59.4
	12	0	289	231	230
		5	152	153	148
		10	104	100	95.9
		15	73.6	68.8	60.0
		20	55.2	47.0	43.8
	16	0	164	155	154
		5	113	109	103
		10	63.4	62.7	68.4
		15	65.3	59.7	53.5
		20	43.8	38.5	31.9
5	8	0	501	231	230
		5	287	153	149
		10	180	100	95.9
		15	73.6	68.8	60.0
		20	55.2	47.0	43.8
	12	0	291	290	288
		5	191	188	186
		10	132	128	123
		15	94.5	89.2	83.8
		20	70.1	63.4	56.7
	16	0	210	202	193
		5	142	139	148
		10	101	97.4	61.3
		15	75.5	67.4	61.3
		20	58.3	47.3	42.4

Table 4.9 Pushover Loads F_t for Unbraced, 14" Pile Diameter Bents

Number of Piles in Bent	Bent Height (ft)	Scour (ft)	Pushover Loads (kips)		
			Pile Load (kips)		
			20	40	60
3	8	0	495	451	450
		5	277	276	275
		10	180	178	174
		15	121	119	116
		20	86.7	83.3	78.6
	12	0	289	288	283
		5	198	187	186
		10	131	129	125
		15	92.1	89.8	86.0
		20	67.5	55.2	58.3
	16	0	203	208	206
		5	142	138	136
		10	97.3	95	92.4
		15	72.2	64.9	54.7
		20	46.2	47.2	41
4	8	0	644	643	642
		5	376	374	364
		10	242	240	238
		15	166	164	161
		20	88.9	85.5	115.0
	12	0	410	409	408
		5	258	258	257
		10	142	160	159
		15	129	126	122
		20	69.0	91.9	87.0
	16	0	281	279	277
		5	191	189	187
		10	139	136	131
		15	118	110	106
		20	54.2	48.7	68.9
5	8	0	744	743	741
		5	440	470	468
		10	289	302	297
		15	212	206	203
		20	155	136	145
	12	0	501	499	504
		5	329	327	324
		10	228	221	218
		15	166	161	153
		20	125	119	111
	16	0	340	354	351
		5	231	229	227
		10	178	172	163
		15	134	126	118
		20	104	95.4	88.7

Assumed Extreme Event Flood Water Load on Bent:



$V_{DESIGN} = 6$ mph

$= 8.80$ fps

$F_t = P_{WATER} \times A_{DR}$

$= C_D \frac{\gamma}{2g} V^2 \times A_{DR}$

$\approx 1.4 \times 1 \times V^2 \times A_{DR}$

$= 1.4(8.80)^2 \times A_{DR}$

$= 108\text{ psf} \times A_{DR}$

Bridge Span Lengths: $15' \leq L \leq 36'$

If $15' \leq L \leq 25'$ use $B = 20'$ and $A = 6'$, $\Rightarrow A_{DR} = 60\text{ ft}^2$

If $25' < L \leq 36'$ use $B = 30'$ and $A = 6'$ $\Rightarrow A_{DR} = 90\text{ ft}^2$

$\therefore \; F_t^{\text{SMALLER RAFT}} = 108\text{ psf} \times 60\text{ ft}^2 = 6{,}480\text{ lbs} = 6.48^k$

$F_t^{\text{LARGER RAFT}} = 108\text{ psf} \times 90\text{ ft}^2 = 9{,}720\text{ lbs} = 9.72^k$

Using a F.S. = 1.33 for Bent Pushover,

$F_{t_{\text{MAX DESIGN}}}^{\text{SMALLER RAFT}} = F.S. \times F_t = 1.33 \times 6.48^k = 8.62^k$

$F_{t_{\text{MAX DESIGN}}}^{\text{LARGER RAFT}} = F.S. \times F_t = 1.33 \times 9.72 = 12.93^k$

Note, in checking the adequacy of the upstream pile as a beam column, we will assume the debris raft forms lower as shown by F_t^L in the above sketch. The magnitude of F_t^L is the same as F_t^U.

Fig. 4.11 Debris Raft and Flood Water Loading for Checking Adequacy of Timber Pile Bent During Major Flood Event

4.6 Checking Upstream Pile for Beam-Column Failure from Debris Raft and P-Loadings

In extreme flood/scour events, a debris raft and flood water loadings, F_t, on this raft may occur at a bridge support bent. The raft and loading is assumed to be applied to a pile bent as high as 2 ft. below the top of the bent cap (see HWL^1 and F_t^1 in Fig. 4.12), and this would be the critical location in checking for bent pushover adequacy. This is where the F_t loading was applied in all of the pushover analyses in this work. However, the F_t loading could also be applied at a lower position on the bent (see HWL^2 and F_t^2 in Fig.4.12), and this would be the critical location in checking the upstream bent pile for failure as a beam-column.

In checking the adequacy of the upstream pile, we will use the approximate straight-line interaction equation

$$\frac{P_{Max\ Appl.}}{P_{CR}} + \frac{M_{Max\ Appl.}}{M_R} \leq \frac{1.0}{F.S.} \tag{4.13}$$

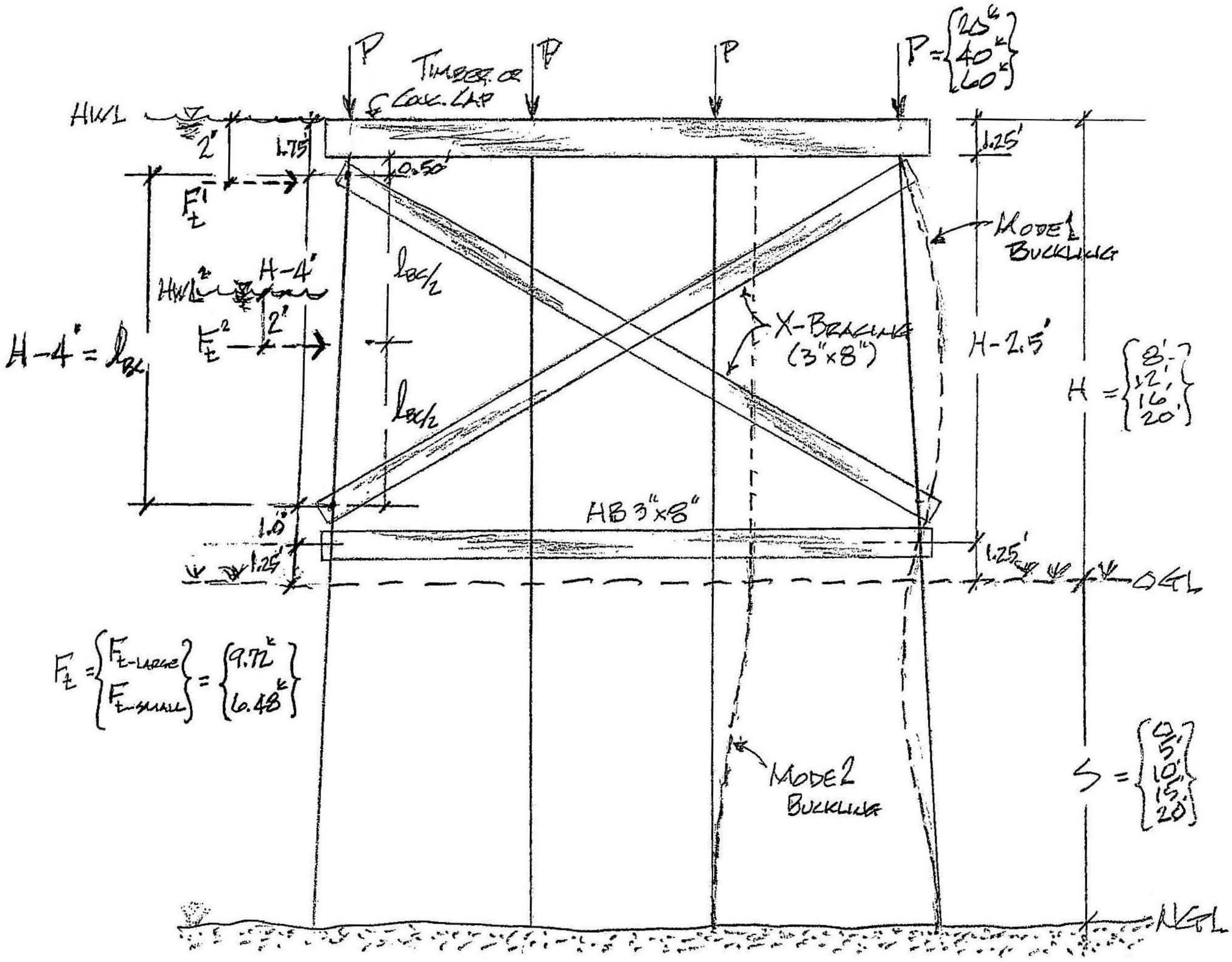
where,

$$P_{CR} = smaller\ of \quad \begin{array}{l} P_{CRUSHING} = \sigma_{CRUSHING} \times A \\ P_{BUCKLING} = \dfrac{\pi^2 EI_{eff}}{(kl)^2} \end{array}$$

$$M_R = \sigma_{rupture} \times S_{at\ M_{Max}}$$

$$F.S. = 1.33$$

to determine its adequacy.



Notes:

1. ℓ_{BC} = Pile length used for Checking Beam-Column

$$\ell_{BC} = \begin{Bmatrix} 4' \\ 8' \\ 12' \\ 16' \end{Bmatrix} \text{ For } H = \begin{Bmatrix} 8' \\ 12' \\ 16' \\ 20' \end{Bmatrix}$$

2. F_t^1 = Debris Raft Load and Location for Checking Bent Push-Over

3. F_t^2 = Debris Raft Load and Location for Checking Upstream Bent Pile for Adequacy as a Beam-Column

4. HWL^1 and HWL^2 = Assumed Flood High Water Lines

Fig. 4.12 Typical X-Braced Timber Pile Bent with Known or Assumed Dimensions and Parameter Values Shown

Figure 4.13 shows a plot of the straight-line ultimate interaction equation, i.e., Eq. 4.13 with F.S. = 1.0, and an allowable loading straight-line interaction equation, i.e., Eq. 4.13 with F.S. = 1.33. This latter equation is the one used in the "ST."

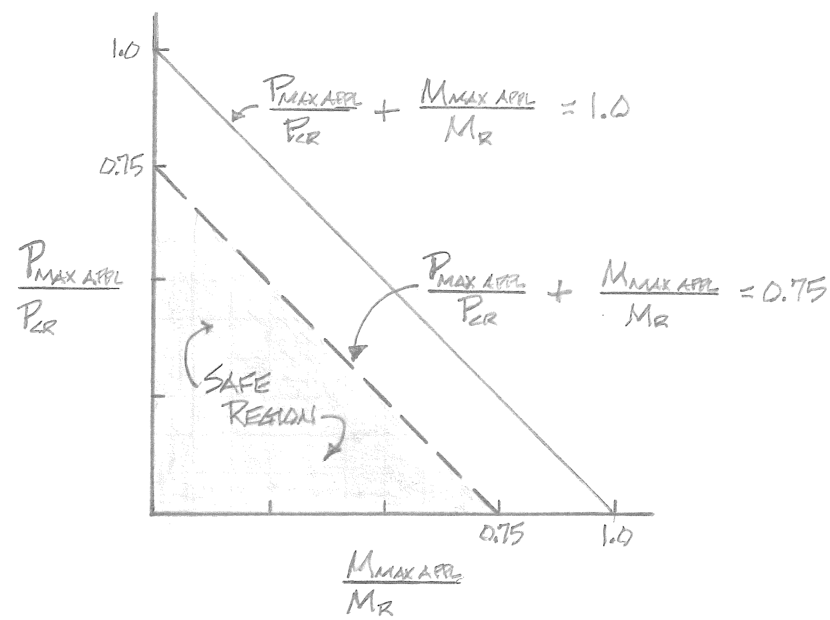


Fig. 4.13 Assumed Ultimate and Allowable Load Interaction Equation and Plots

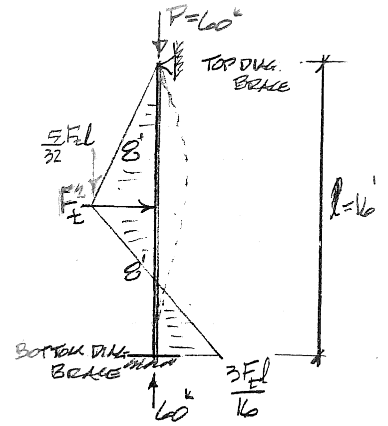
Checking X-Braced Bent Upstream Pile. For the case where H = 20' and S = 0', the upstream beam-column pile in the X-braced bent in Fig. 4.12 would have a loading and M-diagram as shown in Fig. 4.14. As can be seen in Fig. 4.14, the upstream beam-column is OK for H = 20' and S = 0'. When H = 20' and S = 20', Fig. 4.15 indicates that the upstream pile is also OK. Thus, for X-braced bents, the upstream pile is adequate as a beam column for all pile sizes, P-loads, bent heights, and scour levels.

FOR X-BRACED BENT OF FIG. 4.12,

FOR $H = 20'$ AND $S = 0'$

WHERE PILE IS $12'' \rightarrow 6''$

SEE LOADING AND M-DIAG FOR UPSTREAM PILE AT RIGHT.



$F_t^2 = 9.72^k$ FOR $25' < L \leq 36'$

$= 6.48^k$ FOR $15' \leq L \leq 25'$

↑ NO LOAD FACTOR OF F.S. INCLUDED

$P = 60^k$ (LARGER P-LOAD)

$$M_{FIXITY} = \frac{3 \times 9.72^k \times 16}{16} = 29.2^{k'}$$

$$M_{@F_t} = \frac{5 \times 9.72^k \times 16}{32} = 24.3^{k'}$$

$$d_{AT\ FIXITY} = 12'' - 0.12''/' \times 16.5'$$
$$= 12'' - 1.98'' = 10.02''$$

$$A_{AT\ FIXITY} = \frac{\pi (10.02)^2}{4} = 78.8\ in^2$$

$$S_{AT\ FIXITY} = \frac{\pi (10.02)^3}{32} = 98.8\ in^3$$

FROM ABOVE, $M_{AT\ FIXITY}$ LOCATION CONTROLS,

$$\sigma^M = \frac{M}{S} = \frac{29.2^{k'} \times 12''/'}{98.8\ in^3} = 3.55\ ksi$$

$$\sigma^P = \frac{P}{A} = \frac{60^k}{78.8\ in^2} = 0.76\ ksi$$

CHECKING STRESS RATIO FORM OF I.E. AT FIXITY LOCATION,

$$\frac{f_a}{f_{crushing}} + \frac{f_b}{f_{rupture}} \leq \frac{1}{F.S.} = \frac{1}{1.33} = 0.75$$

$$\frac{0.76}{7.0} + \frac{3.55}{12.0} = 0.11 + 0.30 = 0.41 < 0.75 \quad \therefore OK$$

CHECKING FORCE RATIO FORM OF I.E.

AT $l_{eq}/3$ LOCATION, ⇒ $d_{eff} \approx 12'' - 0.12 \times 12' = 10.56''$ ⇒ $A_{eff} = \frac{\pi (10.56)^2}{4} = 87.6$

$$S_{eff} = \frac{\pi (10.56)^3}{32} = 115.6$$

$$I_{eff} = \frac{\pi (10.56)^4}{64} = 610\ in^4$$

$$\therefore M_R = \frac{12.0 \times 115.6}{12} = 115.6^{k'}$$

$$P_{CRUSH} = 7.0 \times 87.6 = 613^k$$

$$P_{CR} \approx \frac{2\pi^2 EI}{l^2} = \frac{2 \times \pi^2 \times 1800 \times 610}{16^2 \times 12^2} = 588^k$$

$$\therefore \frac{60^k}{588} + \frac{29.2^{k'}}{115.6} = 0.10 + 0.25 = 0.35 < 0.75 \quad \therefore OK$$

Fig. 4.14. Checking Upstream Pile of Maximum Height X-Braced Timber Pile Bent as a Beam-Column for Scour, S = 0 ft.

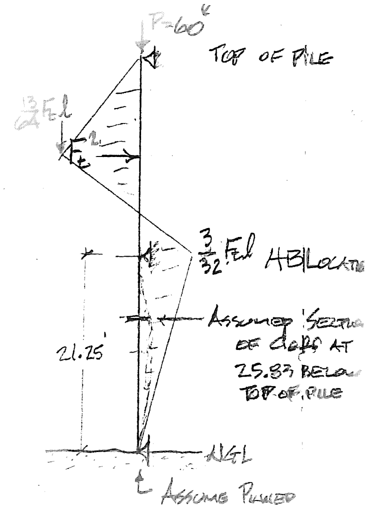
FOR X-BRACED BENT OF FIG 4.12,

FOR $H = 20'$ AND $S = 20'$
WHERE PILE IS $12''\phi \rightarrow 6''\phi$

$M_{F_t^2} = \frac{13}{64} \times 9.72^k \times 16' = 31.6^{'k}$

$M_{HB} = \frac{3}{32} \times 9.72^k \times 16' = 14.6^{'k}$

SEE LOADING AND M-DIAGRAM FOR UPSTREAM PILE AT RIGHT.



NOTE, THAT $M_{AT\ F_t^2}$ IS LARGER FOR THIS CASE, BUT SO ARE A_{eff} AND S_{eff}

CHECK AT F_t^2 LOCATION:

$d_{AT\ F_t^2} = 12'' - 0.12 \times 8.5' = 10.98'' \Rightarrow A = \frac{\pi (10.98)^2}{4} = 94.7 in^2$

$S = \frac{\pi (10.98)^3}{32} = 130 in^3$

$\therefore \sigma^M_{@F_t^2} = \frac{31.6^{'k} \times 12''/'}{130 in^3} = 2.92 ksi$

$\sigma^P_{@F_t^2} = \frac{60^k}{94.7 in^2} = 0.63 ksi$

$\therefore \frac{0.63}{7.0} + \frac{2.92}{12.0} = 0.09 + 0.24 = 0.33 < 0.75 \therefore OK$

CHECK BELOW X-BRACE: (ASSUME d_{eff} AT $25.83'$ BELOW TOP OF PILE)

$d_{eff} = 12'' - 0.12(25.83') = 12.0'' - 3.10'' = 8.90''$

$\begin{cases} H + S - 1.25' = 38.75' \\ \frac{2}{3} \times 38.75 = 25.83' \end{cases}$

$I_{eff} = \frac{\pi (8.90)^4}{64} = 308 in^4$

$P_{CR} = \frac{2\pi^2 E I_{eff}}{l^2} = \frac{2\pi^2 \times 1800 \times 308}{21.25^2 \times 12^2} = 168.3^k$

$S_{eff} = \frac{\pi (8.90)^3}{32} = 69.2 in^3$

$M_R = S_{eff} \times \sigma_R = \frac{69.2 \times 12.0}{12} = 69.2^{'k}$

CHECK FORCE RATIO FORM OF I.E.

$\frac{14.6^{'k}}{69.2^{'k}} + \frac{60^k}{168.3^k} = 0.21 + 0.36 = 0.57 < 0.75 \therefore OK$

Fig. 4.15. Checking Upstream Pile of Maximum Height X-Braced Timber Pile Bent as a Beam-Column for Scour, S = 20 ft.

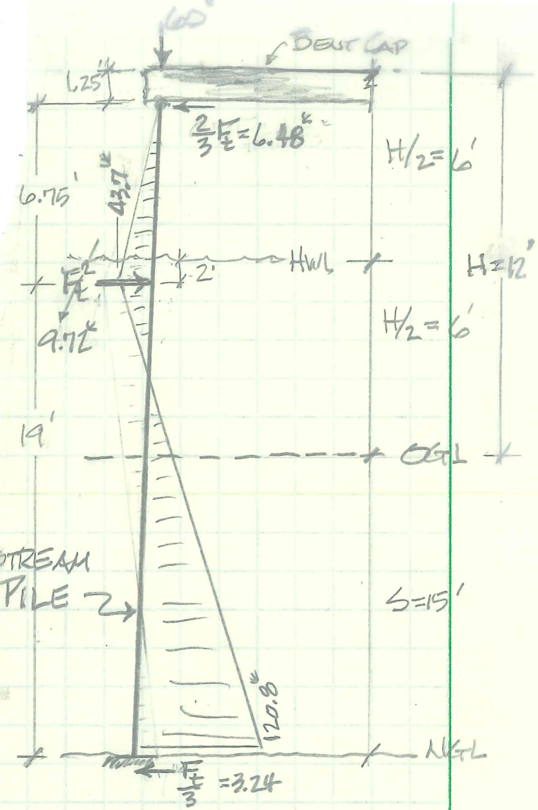
Checking Unbraced Bent Upstream Pile. For an unbraced timber pile bent, when the lateral flood water loading, F_t, is near the top of the bent (at 2 ft below the top of the bent cap), the upstream pile is not acting as a beam-column and hence only needs to be checked for “kick-out,” plunging, and pile buckling like all of the other bent piles in addition to checking the entire bent for push-over. However, when the F_t loading is lower, which it may well be for taller bents, then the upstream pile will be subjected to both axial load and lateral beam loading and needs to be checked for adequacy as a beam-column. We will assume a possible flood water F_t loading on the upstream pile of an unbraced bent as shown in Fig. 4.16. Note, that for the cases shown in Fig. 4.16, the upstream pile is not adequate for both the $12''^{\phi} \longrightarrow 6''^{\phi}$ and the $14''^{\phi} \dashrightarrow 8''^{\phi}$ pile sizes.

ASSUME AN UNBRACED 3-PILE BENT:

ASSUME H, S, HWL, P-LOAD AS SHOWN AT RIGHT

ASSUME THE LATERAL LOAD, F_t, IS EQUALLY RESISTED BY ALL 3 PILES. THUS

ASSUME PILE IS $12''\phi \to 6''\phi$ $\qquad \frac{F_t}{3} = \frac{9.72^k}{3} = 3.24^k/\text{PILE}$



$l_{eq} = 19' + 6.75 = 25.75' \Rightarrow \frac{l_{eq}}{3} = 8.58$

$d_{eff} = d_{@\, l_{eq}/3} = 12'' - 0.12(17.17') = 9.94''$

$I_{eff} = \frac{\pi (9.94)^4}{64} = 479.2\ \text{in}^4$

$S_{eff} = \frac{\pi (9.94)^3}{32} = 96.4\ \text{in}^3$

$M_{rupture} = \sigma_{rup} \times S = \frac{12\,\text{ksi} \times 96.4}{12} = 96.4^{\prime k}$

CHECK PILE BUCKLING,

$$P_{CR} = \frac{\pi^2 E I_{eff}}{4 l^2} = \frac{9.87 \times 1800 \times 479.2}{4 \times (25.75)^2 \times 144} = 22.3^k$$

No Good

CHECK IF PILE IS $14''\phi \to 8''\phi$,

$$d_{eff} = 14'' - 0.12(\overset{2.06}{17.17'}) = 11.84''$$

$$I_{eff}^{14''} = \frac{\pi (11.60)^4}{64} = 964.7\ \text{in}^4$$

$$P_{CR}^{14''} = \frac{9.87 \times 1800 \times 889}{4 \times 25.75^2 \times 144} = 44.9^k$$

STILL No Good

CHECK FOR S=10':

$$l_{eq} = 14 + 6.75' = 20.75' \Rightarrow \frac{l_{eq}}{3} = 6.92' \text{ AND } \frac{2 l_{eq}}{3} = 13.83'$$

$$d_{eff}^{12} = 12'' - 0.12(13.83') = 10.3'' \quad ; \quad d_{eff}^{14} = 14'' - 0.12(13.83') = 12.34''$$

$$I_{eff}^{12} = \frac{\pi (10.3)^4}{64} = 552.5 \quad ; \quad I_{eff}^{14} = \frac{\pi (12.34)^4}{64} = 1138\ \text{in}^4$$

$$P_{CR}^{12''} = \frac{9.87 \times 1800 \times 552.5}{4 \times 20.75^2 \times 144} = 39.6^k \ (\text{No Good}) \quad ; \quad P_{CR}^{14''} = \frac{9.87 \times 1800 \times 1038}{4 \times 20.75^2 \times 144} = 81.6^k \ \text{No Good}$$

FROM ABOVE, FOR H=12', S=10', P=60^k ⇒ NOT ADEQUATE

P=40^k ⇒ NOT ADEQUATE

P=20^k,

$$d_{BASE} = 12'' - 0.12(20.75') = 9.51''$$

$$S_{BASE} = \frac{\pi (9.51)^3}{32} = 84.4\ \text{in}^3$$

$$M_R^{BASE} = \sigma_{rup} \times S = \frac{12\,\text{ksi} \times 84.4\ \text{in}^3}{12} = 84.4^{\prime k}$$

$$\overbrace{0.51 + 0.54}^{1.05}$$

$$\frac{20^k}{39.6^k} + \frac{45.3}{84.4} > 0.75$$

∴ No Good FOR 12''φ PILE AND FOR 14''φ PILE

Fig. 4.16. Checking Upstream Pile of a Maximum Height Unbraced Timber Pile Bent As a Beam-Column

We now need to check the adequacy of the upstream pile of unbraced timber pile bents for the various parameter values shown in Fig. 4.17 using the adequacy requirement indicated in that figure. These checks are shown in Figs. 4.18 - 4.20 on the following pages.

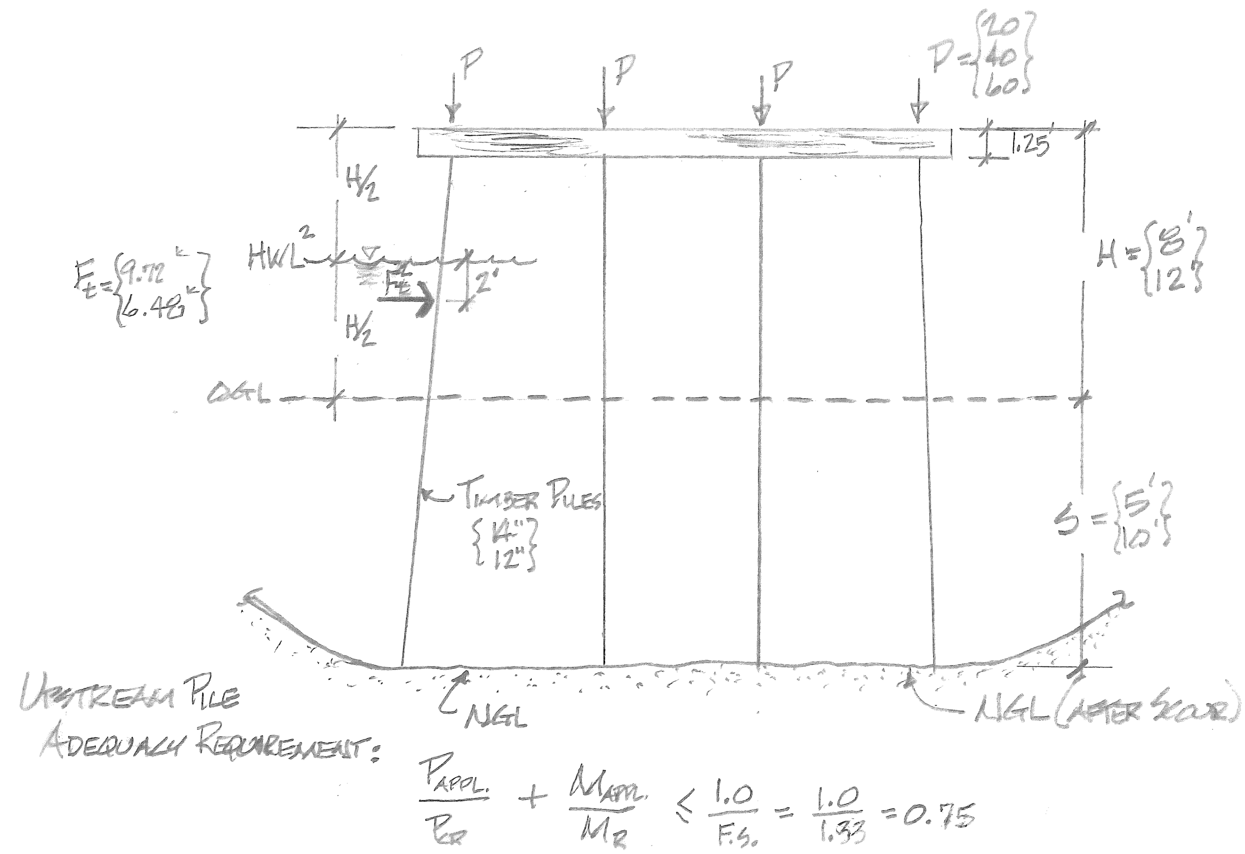
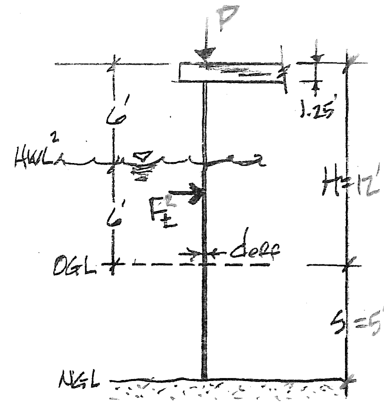


Fig. 4.17. Other Unbraced Bent Cases to Check for Adequacy of Upstream Pile

FOR 12"ϕ PILE:



$$P_{cr} = \frac{\pi^2 E I_{eff}}{4 l^2} = \frac{9.87 \times 1800 \times 653}{4 \times 15.75^2 \times 144} = 81.2^k$$

$l_{eq} = 12+5-1.25 = 15.75'$

$d_{eff} = d_{AT \frac{l_{eq}}{3}} = 12'' - 0.12(10.5)$
$= 10.74''$

$I_{eff} = \frac{\pi(10.74)^4}{64} = 653 in^4$

For M_{BASE}, USE $\frac{F_E}{3} \times l_{eq} = \frac{9.72^k}{3} \times 15.75' = 51^{k}$

$d_{base} = 12'' - 0.12(15.75)$
$= 10.1''$

$S_{base} = \frac{\pi(10.1)^3}{32} = 101 in^3$

$M_r^{base} = \frac{101 \times 12 ksi}{12} = 101^{k'}$

For $P = 60^k$,

$$\frac{60}{81.2} + \frac{51}{101} = 0.74 + 0.51 = 1.25 > 0.67 \quad 0.75$$

No Good

For $P = 40^k$, BY INSPECTION → No Good

For $P = 20^k$,

$$\frac{20^k}{81.2^k} + \frac{51}{101} = 0.25 + 0.50 = 0.75 = 0.75$$

∴ OK.

FOR 14"ϕ PILE:

$$P_{cr} = \frac{9.87 \times 1800 \times 1293}{4 \times 15.75^2 \times 144} = 160.7^k$$

$d_{eff} = 14'' - 0.12(10.5) = 12.74''$

$I_{eff} = \frac{\pi(12.74)^4}{64} = 1293 in^4$

$d_{base} = 14 - 0.12(15.75) = 12.11''$

$S_{base} = \frac{\pi(12.11)^3}{32} = 174 in^3$

$M_r^{base} = \frac{174 \times 12}{12} = 174^{k'}$

For $P = 60^k$ ⇒ $\frac{60^k}{160.7} + \frac{51}{174} = 0.37 + 0.29 = 0.66 < 0.75$ ∴ OK

∴ WHEN S = 5' THE UPSTREAM PILE IS
ADEQUATE IF IT IS 14"→8"ϕ OR LARGER
NOT ADEQUATE IF IT IS 12"→6" OR SMALLER
EXCEPT WHEN P ≤ 20^k

Fig. 4.18. Check Upstream Pile of Unbraced Bent as Beam-Column When H=12' and S=5'

FOR 12"ϕ PILE:

$l_{eq} = 10' + 8' - 1.25' = 16.75'$

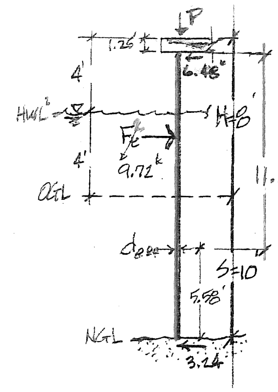
$F_{top} = 6.48^k$ & $F_{bottom} = 3.24^k$

$M_{BASE} \approx \frac{F_E}{3} \times l_{eq} = \frac{9.72}{3} \times 16.75'$

$\approx 54.3^{1k}$ (for 3-Pile Bent) $\Rightarrow$ $M_{BASE} \approx \frac{6.48}{3} \times 16.75' \approx 36.2^{1k}$ (FOR SMALL RAFT)

$M^{rupture}_{BASE} = \sigma_r \times S_{BASE} = \frac{12ksi \times 98.2 in^3}{12} = 98.2^{1k}$

$P_{CR} = \frac{\pi^2 E I_{eff}}{4 l^2} = \frac{9.87 \times 1800 \times 634}{4 \times 16.75^2 \times 144} = 69.7^k$



$d_{NGL} = 12" - 0.12(16.75') = 10.0"$

$d_{eff} = 12" - 0.12(11.17) = 10.66"$

$I_{eff} = \frac{\pi(10.66)^4}{64} = 634 in^4$

$S_{BASE} = \frac{\pi(10.0)^3}{32} = 98.2 in^3$

BASED ON THE LINEAR INTERACTION EQN,
BY INSPECTION,

FOR $P = 60^k$ $\Rightarrow$ NOT ADEQUATE

FOR $P = 40^k$ $\Rightarrow$ NOT ADEQUATE

FOR $P = 20^k$ $\Rightarrow$ NOT ADEQUATE

NOTE, FOR $P = 20^k$ AND $F_E = 6.48$ (SMALL RAFT F_E),
CHECKING, $\frac{6.48}{3} \times 16.75' = 36.2^{1k}$

$\frac{P_{appl.}}{P_{CR}} + \frac{M_{appl}}{M_{rupture}} = \frac{20^k}{69.7} + \frac{36.2}{98.2}$

$= 0.29 + 0.37 = 0.66 < 0.75$

$\therefore$ OK

$\therefore$ WHEN,
H = 8',
S = 10',
PILE = 12"ϕ

THE UPSTREAM PILE IS ADEQUATE ONLY WHEN THE SMALL DEBRIS RAFT LOADING OF $F_E = 6.48^k$ AND THE SMALLEST P-LOAD OF $P = 20^k$ ARE ACTING.

FOR 14"ϕ PILE:

$d_{eff} = 14 - 0.12(11.17') = 12.66$

$d_{base} = 14 - 0.12(16.75') = 11.99"$

$I_{eff} = \frac{\pi(12.66)^4}{64} = 1261 in^4$

$S_{base} = \frac{\pi(11.99)^3}{32} = 169\ in^3$

$\therefore P_{CR} = \frac{9.87 \times 1800 \times 1176}{4 \times 16.75^2 \times 144} = 138.6^k$

$M^{rupture}_{BASE} = \frac{12ksi \times 155.6}{12} = 169.^{1k}$

FOR $P = 60^k$ $\Rightarrow$ $\frac{60^k}{138.6} + \frac{54.3^{1k}}{169.} = 0.43 + 0.32 = 0.75 = 0.75$

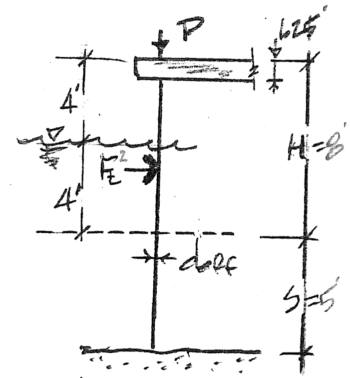
$\therefore$ OK

$\therefore$ WHEN,
H = 8',
S = 10',
PILE = 14"ϕ

THE UPSTREAM PILE IS ADEQUATE AS A BEAM-COLUMN FOR $P \leq 60^k$

Fig 4.19. Check Upstream Pile of Unbraced Bent as Beam-Column When H=8' and S=10'

CHECK FOR H = 8' AND S = 5' (SEE FIG AT RIGHT)



FOR 12"φ PILE:

USE $M_{BASE} = \frac{F_E}{3} \times l_{aq} = \frac{9.72^k}{3} \times 11.75 = 38.1^{'k}$

$P_{cr} = \frac{9.87 \times 1800 \times 734.5}{4 \times 11.75^2 \times 144} = 164^k$

FOR $P = 60^k \Rightarrow \frac{60^k}{164^k} + \frac{38.1}{116.6} = 0.37 + 0.33$

$= 0.70 < 0.75$

$\therefore$ OK

$l_{aq} = 13 - 1.25 = 11.75'$

$d_{eff} = 12 - 0.12(7.83') = 11.06"$

$I_{eff} = \frac{\pi(11.06)^4}{64} = 734.5$

$d_{base} = 12 - 0.12(11.75) = 10.59"$

$S_{base} = \frac{\pi(10.59)^3}{32} = 116.6 \text{ in}^3$

$M_r^{base} = \frac{116.6 \times 12}{12} = 116.6^{'k}$

$\therefore$ WHEN H = 8', S = 5' } THE UPSTREAM PILE IS ADEQUATE AS A BEAM-COLUMN FOR ~~ALL~~ BOTH 12"φ AND 14"φ PILES

Fig. 4.20. Check Upstream Pile of Unbraced Bent as Beam-Column When H = 8' and S = 5'

Based on the checks shown in Figs. 4.18 - 4.20, the adequacy of unbraced bent upstream piles as a beam-column are summarized below.

- For H = 12' (this if H_{max} for an unbraced bent),

  When $S \geq 10' \rightarrow$ Upstream Pile is Not Adequate as a Beam-Column For all P-Load Levels for Both Pile Sizes.

  When $S \geq 5' \rightarrow$ Upstream Pile is Not Adequate if Pile is $12''^{\phi} \longrightarrow 6''^{\phi}$ and if $P > 20^k$
  Upstream Pile is Adequate if Pile is $14''^{\phi} \dashrightarrow 8''^{\phi}$ For All P-Loads and Debris Raft Sizes

- For H = 8' and S = 10',

  Upstream Pile is Inadequate for all P-Load Levels if Pile is $12''^{\phi} \longrightarrow 6''^{\phi}$
  Upstream Pile is Adequate for $P \leq 60^k$ if Pile is $14''^{\phi} \dashrightarrow 8''^{\phi}$

- For H = 8' and S = 5',

  Upstream Pile is OK as Beam-Col. for All P-Load Levels and Debris Rafts.

The checking procedure and adequacy of the upstream pile is shown in flowchart form in Fig. 5.7 in Chapter 5.

4.7 Closure

The pile/bent plunging, buckling, pushover and bent upstream pile beam-column capacities were determined in the manners indicated in sections above. This then allowed checking of these capacities against the corresponding maximum applied loads to assess the adequacy of the pile/bent against failure. The procedure and assumptions used are indicated for each of the possible failure modes in the sections above. Thus, execution of each of the checks indicated in this chapter would allow one to manually assess the adequacy of a given timber pile bent for a given extreme flood/scour event. The next step now, is to automate the above bent checking process via preparing a computer program to execute the above screening/checking procedure.

This will be done in Milestone#2 of this research project.

5. “ST” Flowchart for Checking Adequacy of Timber Pile Bents

5.1 General

To assist in systematically checking the inventory of timber pile bent supported bridges in Alabama in an effective and efficient manner, automation of the screening tool (“ST”) checking procedure developed and described in Chapter 4 should be preformed. The first step in doing this is to develop macro and micro flowcharts for the “ST.” These flowcharts will be helpful whether the “ST” is automated or not, and will be essential for developing, and later explaining to users, the automated “ST.” These flowcharts are presented below.

5.2 “ST” Macro Flowchart

The “ST” macro flowchart to evaluate the adequacy of Alabama bridge timber pile bents for extreme flood/scour events is shown in macro flowchart form in Fig. 5.1. As can be seen in Fig. 5.1, the checking sequence basically moves from general checks such as is the bent in water with scour possible, has significant decay of the bent pile section in the splash occurred, to checking the bent piles for “kick-out” or plunging, to checking the bent piles for buckling, to checking the bent pushover from combined gravity and flood water loadings, to checking the bent upstream pile’s adequacy as a beam-column.

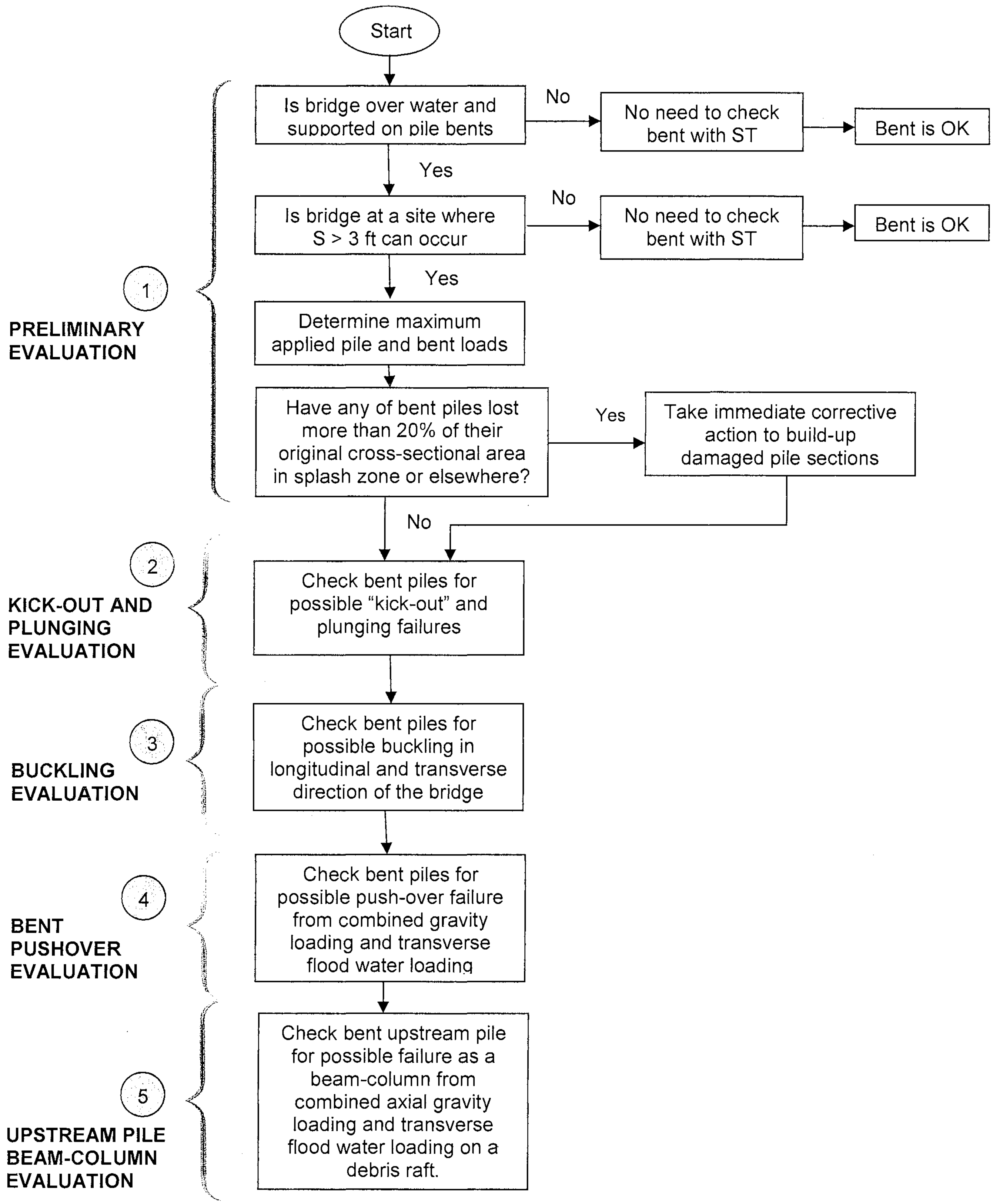


Fig. 5.1 Screening Tool “ST” Macro Flowchart

5.3 "ST" Micro Flowchart

A micro flowchart showing the procedure to check the adequacy of Alabama's bridge timber pile bents for an extreme flood/scour event, i.e., a detailed flowchart of the "ST", is shown in Fig. 5.2. Enlargements of each of the five major blocks of the "ST", i.e.,

1. Preliminary Evaluation
2. Kick-out and Plunging Evaluation
3. Buckling Evaluation
4. Bent Pushover Evaluation
5. Upstream Pile Beam-Column Evaluation

are shown in Figs. 5.3 - 5.7 for ease of reading.

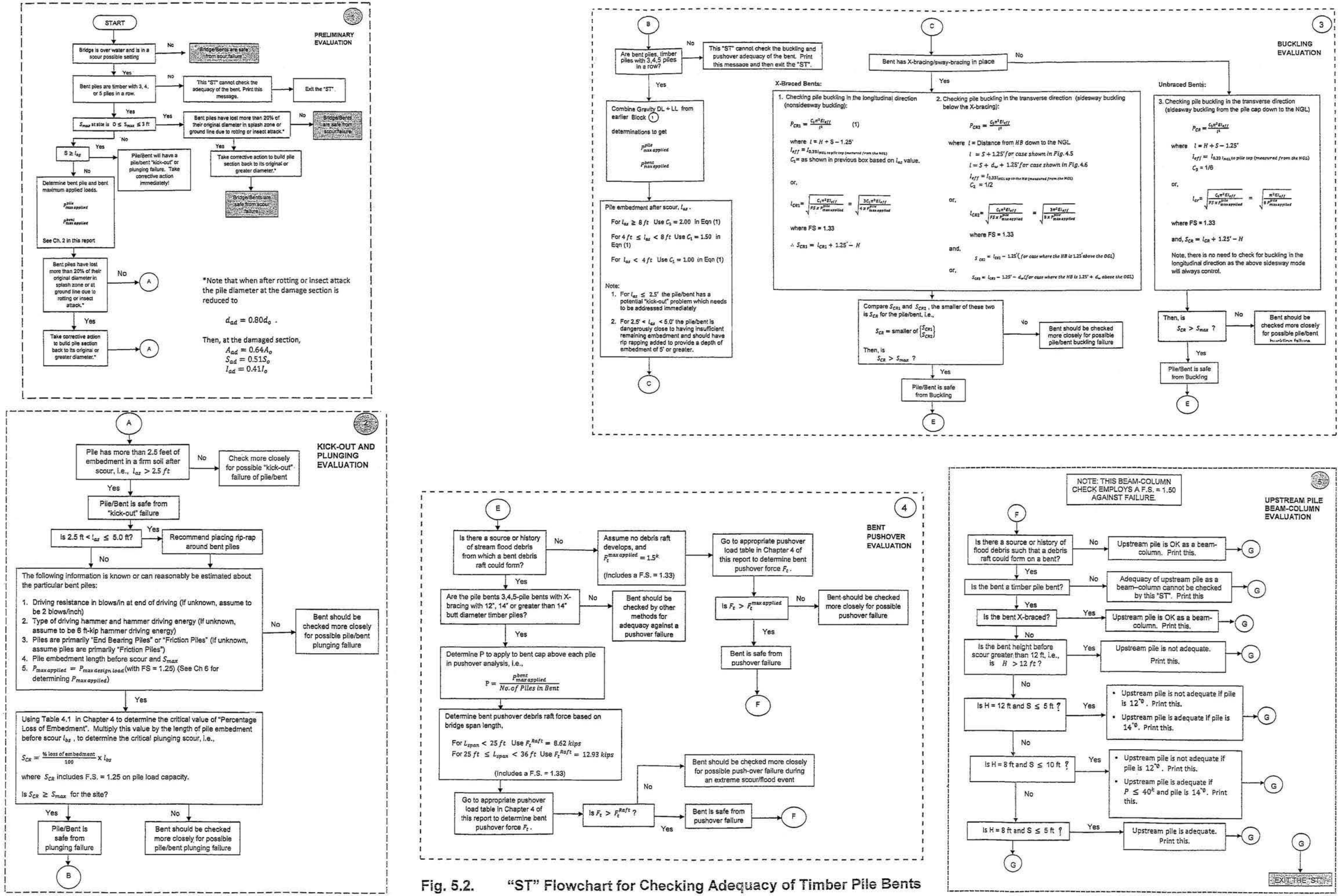
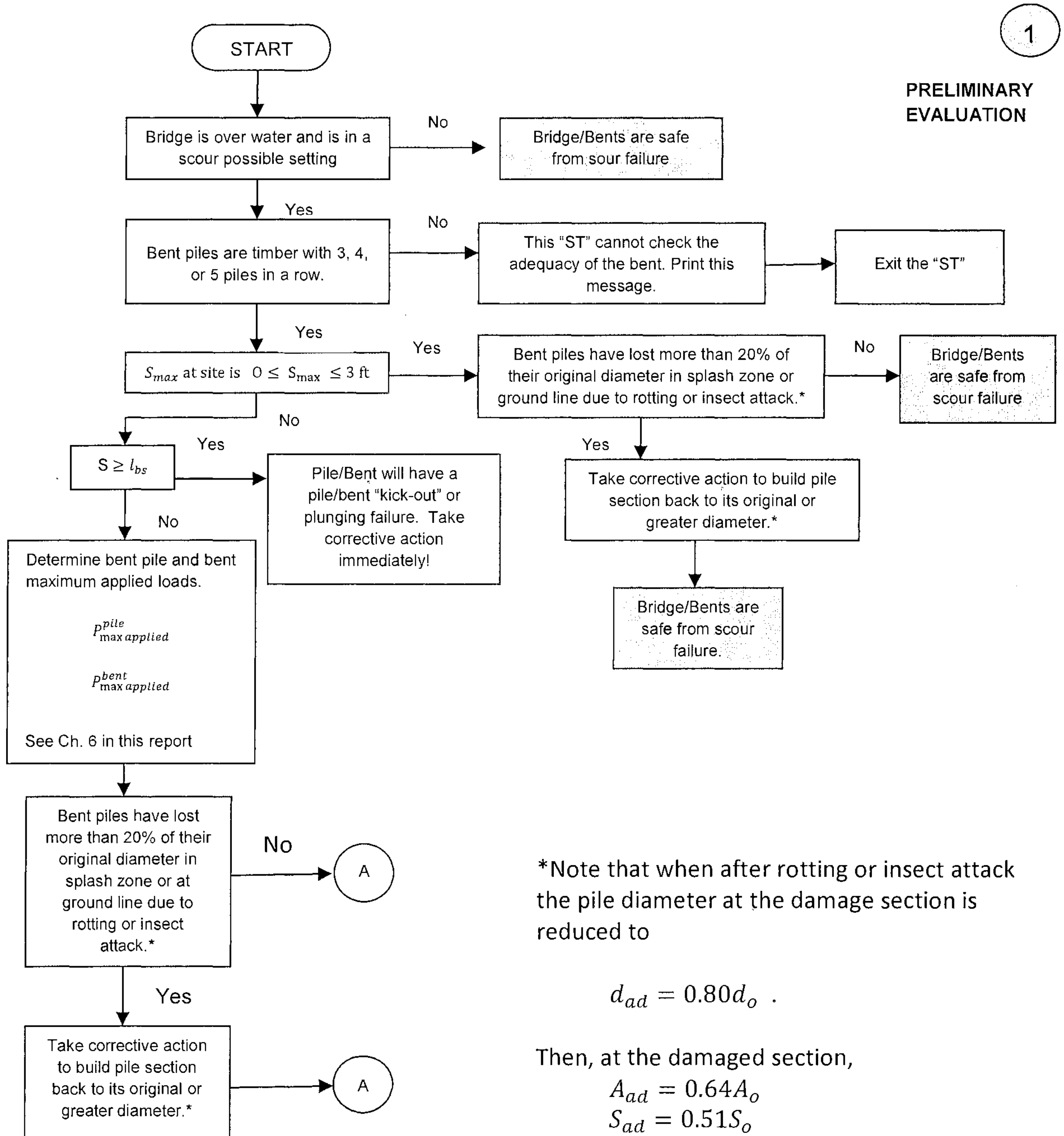


Fig. 5.2. "ST" Flowchart for Checking Adequacy of Timber Pile Bents



*Note that when after rotting or insect attack the pile diameter at the damage section is reduced to

$$d_{ad} = 0.80 d_o \ .$$

Then, at the damaged section,

$$A_{ad} = 0.64 A_o$$
$$S_{ad} = 0.51 S_o$$
$$I_{ad} = 0.41 I_o$$

Fig. 5.3. "ST" Block 1 Preliminary Evaluation

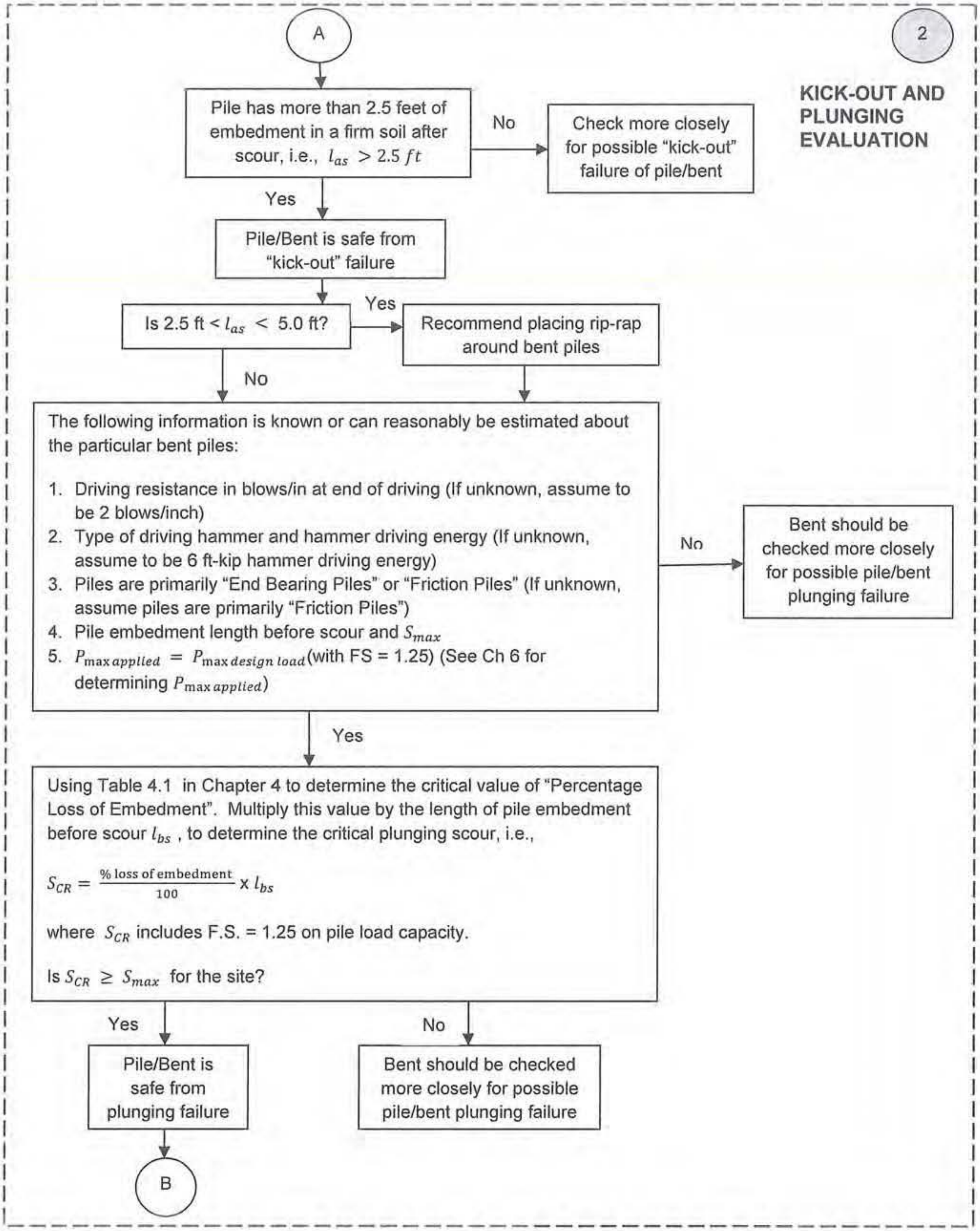


Fig. 5.4. "ST" Block 2 Kick-Out and Plunging Evaluation

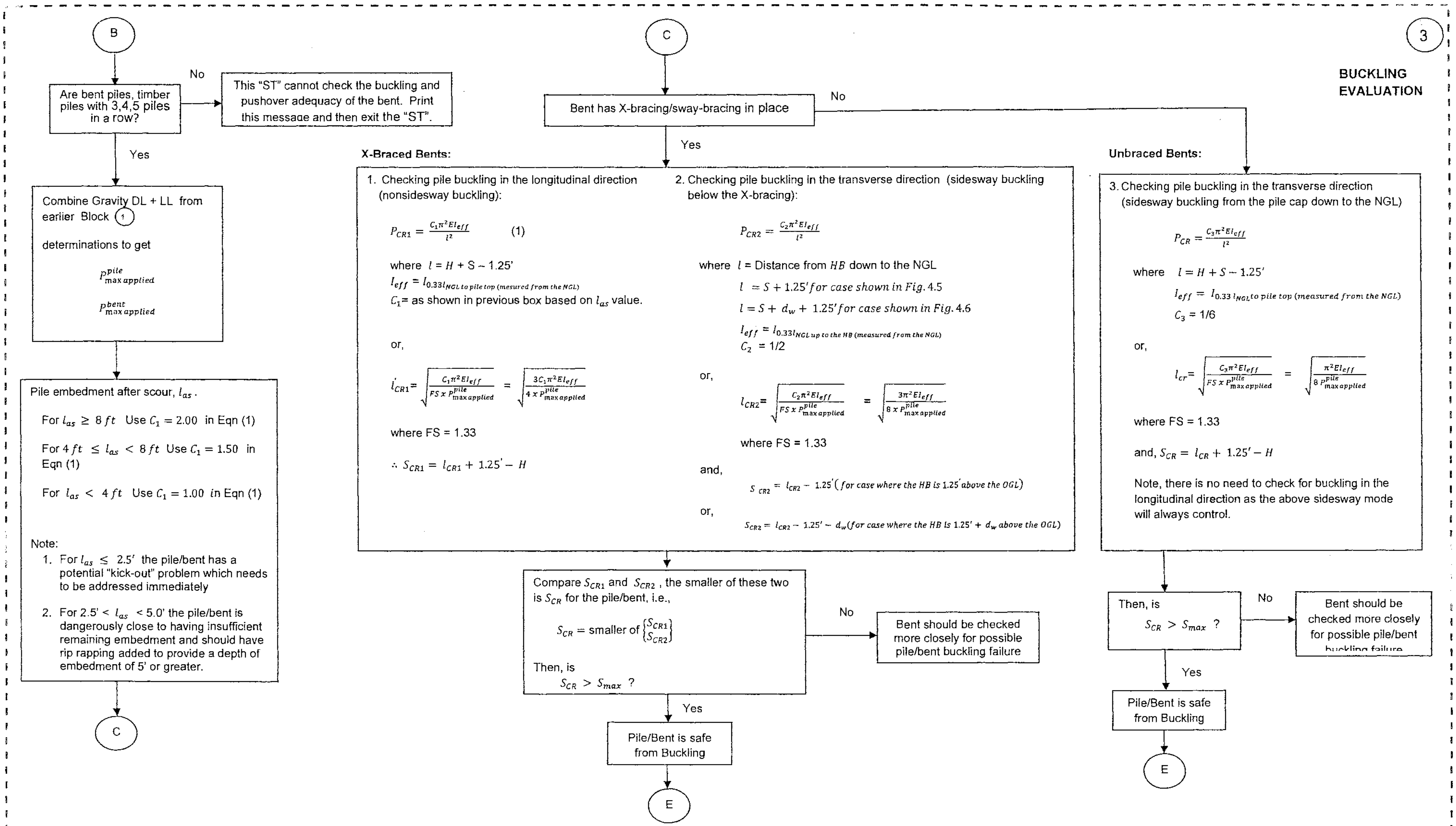


Fig. 5.5. "ST" Block 3 Buckling Evaluation

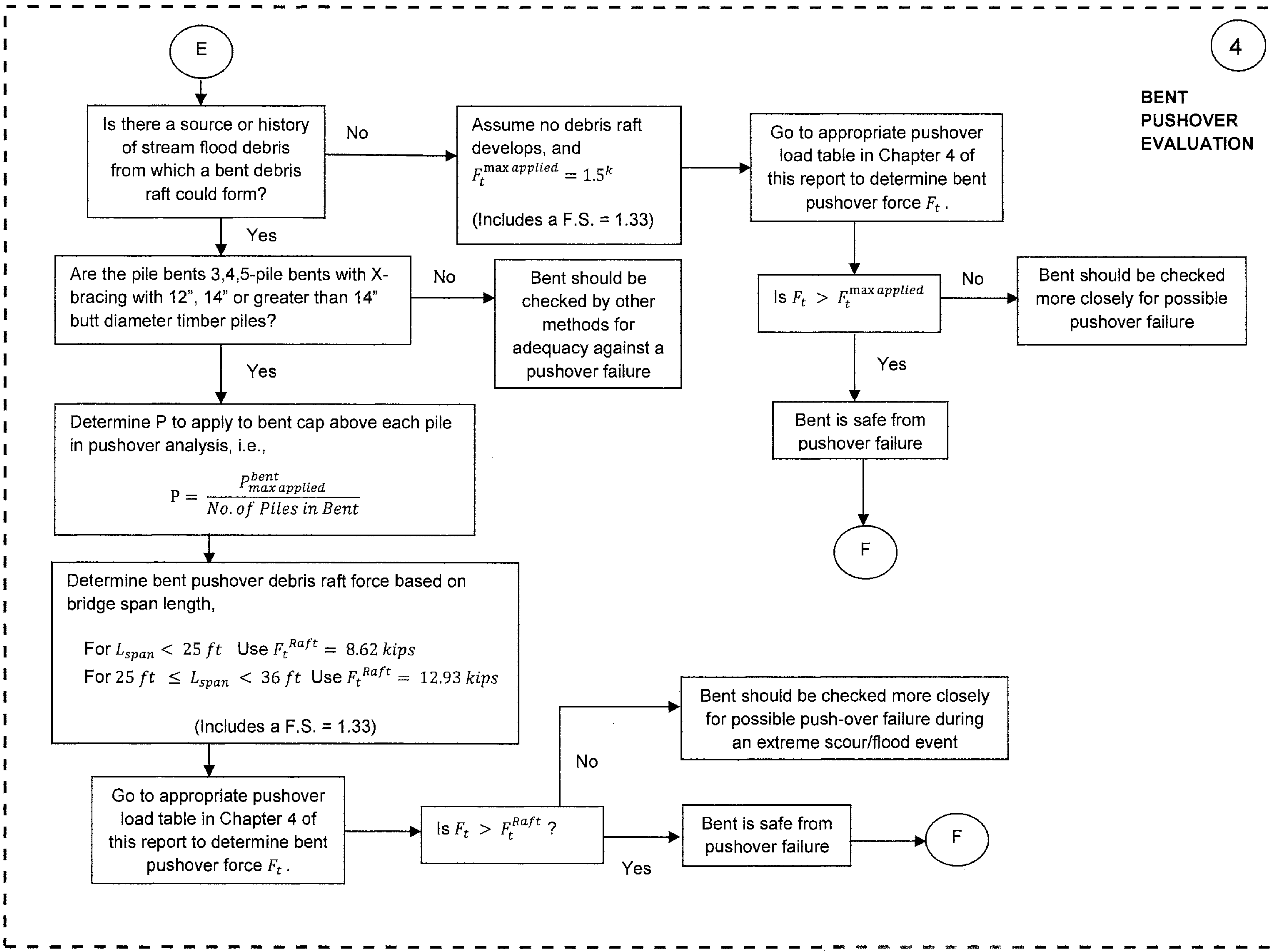


Fig. 5.6. "ST" Block 4 Bent Pushover Evaluation

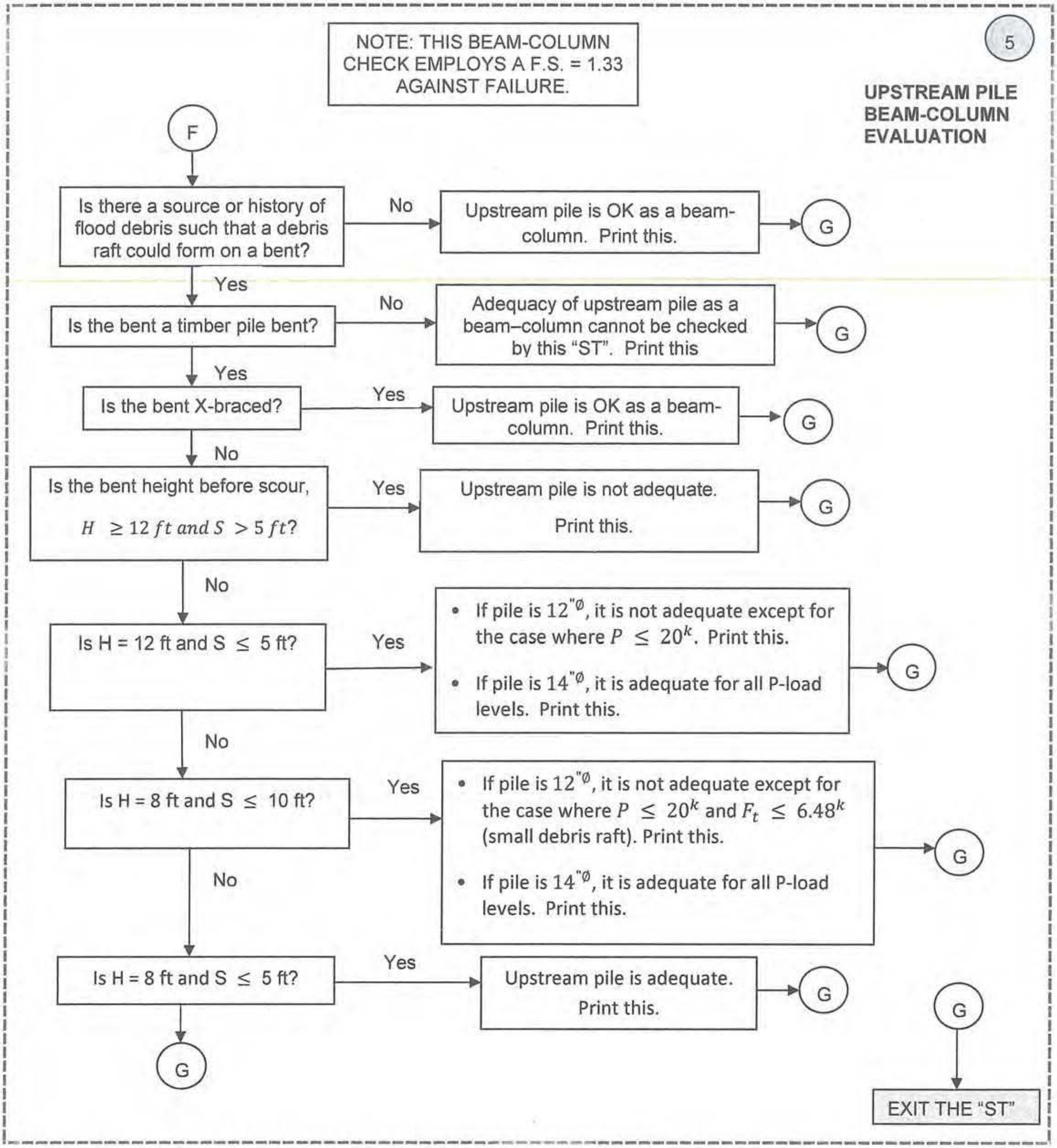


Fig. 5.7. "ST" Block 5 Upstream Pile Beam-Column Evaluation

5.4 Closure

The macro and micro “ST” flowcharts of Figs. 5.1 and 5.2 respectively help a user to understand and use the “ST” whether doing so in a manual or automated manner. They are essential in developing an automated version of the “ST” and essential in explaining what the “ST” does and how it works. As indicated earlier, the next step is to automate the “ST” via preparing a computer program to execute the Fig. 5.2 “ST” Flowchart. This will be done in Milestone #2 of this research project.

6. Determining Maximum Applied Pile and Bent Gravity Loads

6.1 General

The maximum applied gravity loads to a bridge's pile support bent must be rather accurately determined before one can assess the adequacy of the bridge's bents and piles during an extreme flood/scour event. These loads are,

$P^{Pile}_{Max\ Applied}\ (DL + LL)$

$P^{Bent}_{Max\ Applied}\ (DL + LL)$

and should be predetermined prior to the occurrence of an extreme flood/scour event, or prior to applying the "ST" to assess the adequacy of the bridge in the event of a major flood/scour event. The procedures for determining the above pile/bent maximum applied loads for simple span and for 2-span continuous bridges are described in the sections below.

6.2 Maximum Applied Pile and Bent DL

Typical ALDOT bridge superstructure information needed and assumptions made for making an accurate estimate of DL for purposes of determining $P^{DL}_{Pile\ Max\ Applied}$ and $P^{DL}_{Bent\ Max\ Applied}$ for use with the "Screening Tool" are as follows:

Deck Material → In database is either concrete ($\gamma_{conc.} = 150\ lb/ft^3$)
or timber ($\gamma_{timb.} = 50\ lb/ft^3$)

Deck Thickness → In database (round up to the nearest ½")

Deck Thickness outboard of exterior girders = deck thickness + 2"

Deck overhang beyond center of exterior girders = 4' - 0" each side

Barrier Rail → For Jersey barrier, W_{DL} = 390 lb/ft each

→ Or, A(in ft^2) x 1' x $\gamma_{conc.}$ or $\gamma_{timb.}$ (in lb/ft^3) = W_{DL} (lb/ft each)

Diaphragms:

Steel Girders → neglect diaphragm weight

Concrete Girders → $\gamma_{conc.}$ x 9” x girder depth x center-to-center dimension between girders for P_{Max}^{Pile} or between exterior girders for P_{Max}^{Bent}

Timber Girders → neglect diaphragm weight

For ℓ ≤ 20’ → 1 diaphragm each end of span
(2 Diaph. Wts. per bent = No. Diaph/span)

20’ < ℓ < 36’ → 1 diaphragm each end of span and one at midspan
(3 Diaph. Wts. per bent = No. Diaph/span)

Deck Width → In Database → Out-to-Out width of superstructure or roadway width +3’

Deck Length → Span length → In database

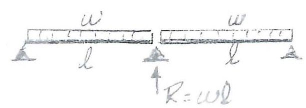
Deck Support Girders → Number, spacing, type/size/weight per ft.
→ In database

Girder Support Arrangement → Simple support or continuous for 2-spans

Bent Cap Length = Girder/Pile spacing x (No. Piles -1) + 4ft.

Bent Pile Cap Size = 2.5’ x 2.5’ x Cap Length (for concrete caps) → In database
= 1.5’ x 1.5’ x Cap Length (for timber caps) → In database

Maximum Girder Reactions due to Uniform DL → See Fig. 6.1 for simple or 2-span continuous bridges



Two Equal Simple Spans - Uniforms Load

Two Equal Spans - Uniform Load

Maximum Girder R's Due to Uniform DL*:

SS Girder: R_{max} = 1.0 $\omega\ell$

2-Equal Span Continuous Girder : R_{max} = 1.25 $\omega\ell$

*Note that these Rs do not include the Bent Cap weight.

Fig. 6.1. Girder/Beam Reactions for SS or 2-Equal Span Bridges Under Uniform Dead Load

For the example bridge superstructure and bent shown in Fig. 6.2, assume the bridge is SS with span lengths of 34 ft., and determine $P^{DL}_{Pile\ Max\ Applied}$ by girder line analysis and $P^{DL}_{Bent\ Max\ Applied}$.

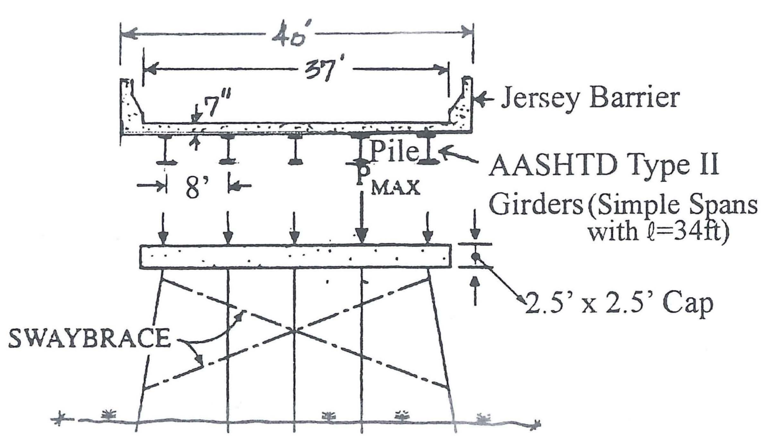


Fig. 6.2. Example Pile Bent and Superstructure

Determine $P^{DL}_{Pile\ Max\ Applied}$

Deck: *Deck Thickness x Gir. Spac. x Span Length x* 0.150^k/ft.^{3}

$\frac{7'}{12}\ x\ 8'x\ 34'x\ \ 0.150^k/_{ft.^3}$ =23.8^k

Assumed Diaphragm Thickness

Diaph: $\frac{9'}{12}\ x\ Gir.Depth\ x\ Gir.Spac.x\ 0.150x\ No.Diaph./Span$

$\frac{9'}{12}\ x\ 3.0'x\ 8'x\ \ 0.150^k/_{ft.^3}\ \ x\ 3$ =8.1^k

Girder: *Girder Wt. / ft. x Span Length*

0.384^k / ft x 34' =13.1^k // 45^k

Cap: *Cap Width x Cap Depth x Gir. Spac. x* 0.150^k / *ft.*^{3}

$2.5'x\ 2.5'x\ 8'x\ 0.150^k/ft^3$ =7.5^k // 52.5^k

Superstructure Supports:

Simply Supported Bridge - $P^{DL}_{Pile\ Max\ Applied}$ = 52.5^k

Bridge Made Continuous For LL - $P^{DL}_{Pile\ Max\ Applied}$ = 52.5^k

2-Equal Span Continuous Bridge - $P^{DL}_{Pile\ Max\ Applied}$ =1.25(45^k) + 7.5^k =63.8^k

Determine $P^{DL}_{Bent\ Max\ Applied}$

Deck: *Thickness x Out-to-Deck Width x Span Length x* 0.150^k / *ft.*^{3}

$\frac{7'}{12}\ x\ 40'x\ 34'x\ \ 0.150^k/_{ft.^3}$ =119.0^k

Thickened Deck Overhang: *∆Overhang Thickness x Overhang Width x Span Length x* 0.150^k / *ft.*^{3}

$\frac{2'}{12}\ x\ 4'x\ 34'x\ 0.150^k/_{ft.^3}\ x\ 2$ =6.8^k

Assumed Diaphragm Thickness

Diaph: $\frac{9'}{12}\ x\ Girder\ Depth\ x\ Distance\ Between\ Exterior\ Girders\ x$

0.150^k / *ft.*^{3} *x No. Diaph / Span*

$\frac{9'}{12}\ x\ \ 3.0'\ x\ 32'\ x\ 0.150^k\ x\ ft.^3\ \ x\ 3$ =32.4^k

Girder: *Girder wt. / ft x Span Length x No. Girders/Span*

0.384^k / *ft. x* 34' *x* 5 =65.3 // 223.5^k

Barrier Rail: *Jersey Barrier Wt. / ft. x Span Length x 2*

0.390^k / *ft* x 34' x 2 =26.5^k // 250.0^k

Cap: *Cap Width x Cap Depth x Cap Length* x* 0.150^k / *ft.*^{3}

2.5' *x* 2.5' *x* 36' *x* 0.150^k / *ft.* =33.8^k // 283.8^k

* If Cap Length is not available, use (Distance Between Exterior Girders + 4')

Superstructure Supports:

Simply Supported Bridge - $P^{DL}_{Bent\ Max\ Applied}$ = 283.8^k

2-Equal Spans Made Continuous For *LL*

$P^{DL}_{Bent\ Max\ Applied}$ = 223.5^k + 1.25 (26.5^k) + 33.8^k = 290.4^k

2-Equal Spans Continuous $P^{DL}_{Bent\ Max\ Applied}$ = 1.25(250.0^k) + 33.8^k = 346.3^k

6.3 Maximum Applied Pile Bent and LL

Bridge superstructure and LL information needed and assumptions made to determine $P^{LL}_{Pile\ Max\ Applied}$ and $P^{LL}_{Bent\ Max\ Applied}$ for use with the “Screening Tool” are as follows:

Girder Support Arrangement → SS or continuous for two spans → In database

Girder Spacing → In database

Span length → In database

Impact Factor → Assume to be 1.1

Roadway Width → curb-to-curb width → In database

Number of Traffic Lanes → In database → 1 if roadway width < 18’

→ 2 if roadway width > 18’

Design LL → In database

An impact factor of 1.1 was assumed in determining maximum applied pile and bent LL rather than 1.3 due to the fact that we are investigating failure of the bridge piles/bents which are far removed from the point of truck impact loadings, and secondly we are investigating pile/bent buckling and plunging failures which require a more sustained load to cause these failures.

Most of ALDOT’s bridge superstructures and pile bents of interest in this investigation were assumed to be designed for H20 or HS20 truck and lane loads. These standard AASHTO loadings along with the H15 and HS15 loadings are shown in Figs. 6.3 and 6.4. In placing truck and lane loads in traffic lanes, the AASHTO design truck and lane loadings are meant to cover a 10 ft. width. These loads are placed in two equal width traffic lanes across the bridge from curb-to-curb.

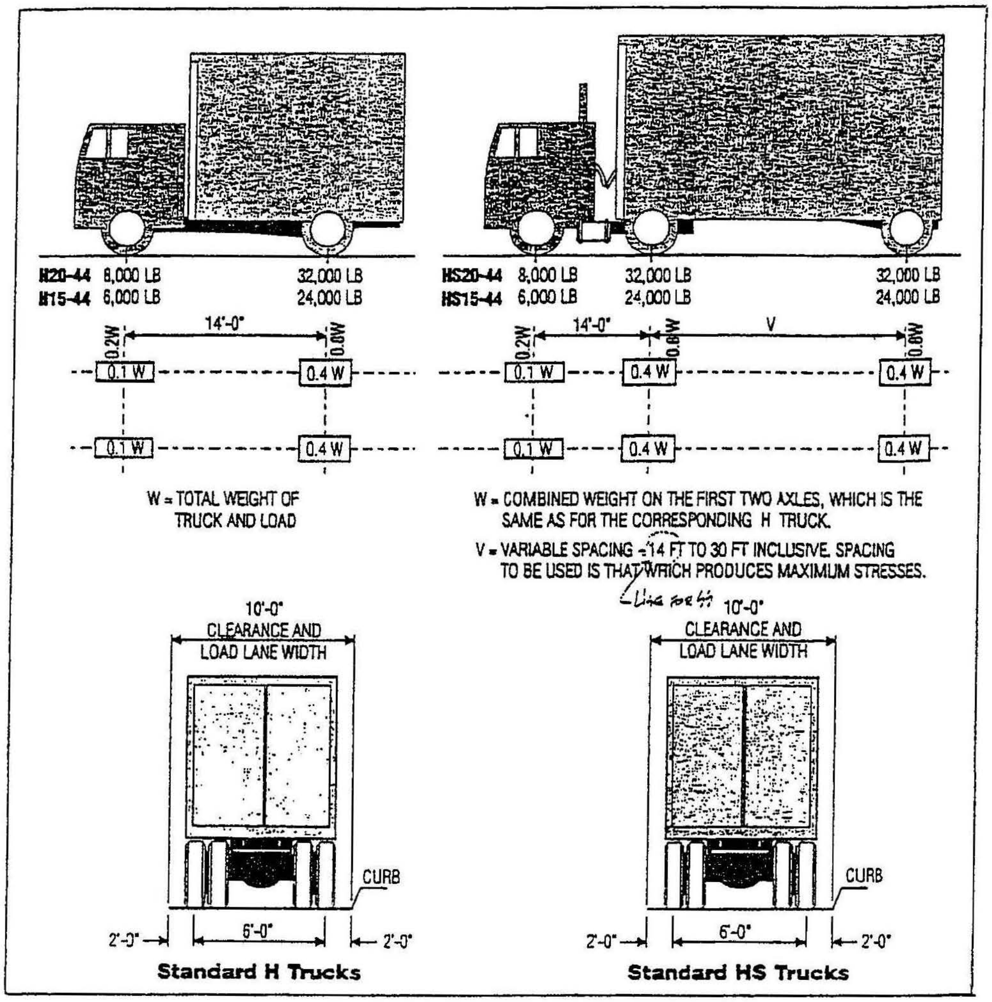


Fig.6.3. AASHTO Standard H & HS Design Trucks

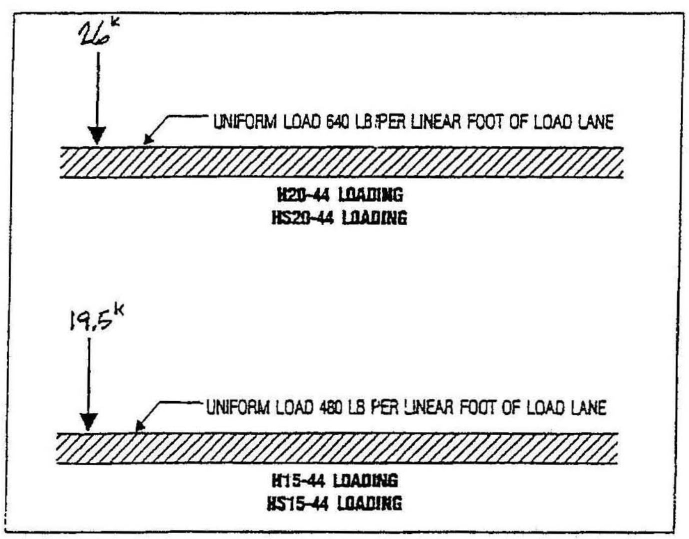
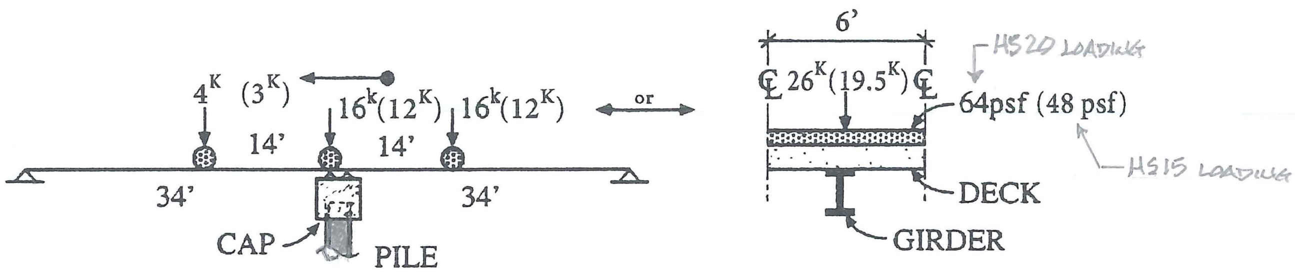


Fig. 6.4. AASHTO H & HS Lane Loading

Determining $P^{LL}_{Pile\ Max\ Applied}$:

A girder-line approach is taken to estimate the maximum vehicular LL (plus impact) on a bent pile, and the approach is illustrated with its application to a simple supported superstructure, with span lengths of 34' and a girder spacing of 6' as shown in Fig. 6.5. These loads shown in Fig. 6.5 are for an HS20 loading with those in parenthesis being for an HS15 loading. $P^{LL}_{Pile\ Max\ Applied}$ is the larger of those determined from truck line load of Fig. 6.5a or the lane loading of Fig. 6.5b.



a. Truck Line Load **b. Design Lane Loading**

Fig. 6.5. Girder Line Loading to Determine $P^{LL}_{Pile\ Max\ Applied}$

$P^{LL}_{Pile\ Max\ Applied}$ is determined from Fig. 6.5. as follows:

	SS Spans	2-Span Continuous
a. Truck Line Load:	$P^{LL}_{Pile} = \left[16^k + 16^k\left(\frac{20}{34}\right) + 4^k\left(\frac{20}{34}\right)\right]1.1$	[2(3.12) +16 +9.36]1.1
	$= [16 + 9.41 + 2.35]1.1 = 30.5^k$	34.8^k
	SS Spans	2-Span Continuous
b. Design Lane Load:	$P^{LL}_{Pile} = \left[0.064\frac{k}{ft^2}x6'x34' + 26^k\right]1.1$	[(0.064x6x34)1.25+26]1.1
	$= [13.1+26]1.1 = 43.0^k$ ← Governs	$[16.32+26]1.1 = 46.6^k$ ← Governs

Note that design lane load controls in both cases.

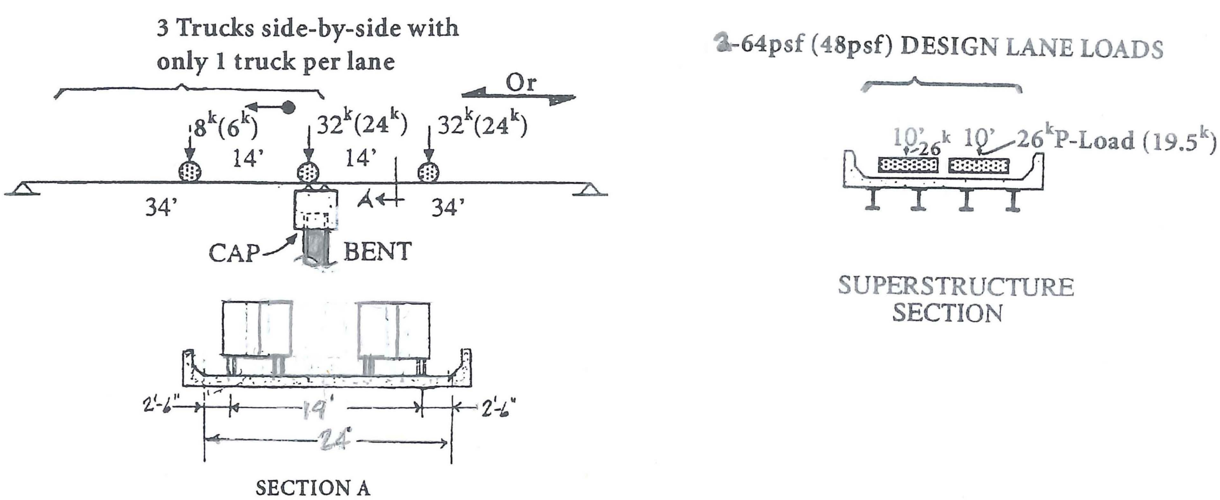
$\therefore P^{LL}_{Pile\ Max\ Applied} = 43.0^k$ for Simply Supported Bridge

$\therefore P^{LL}_{Pile\ Max\ Applied} = 46.6^k$ for 2-Span Continuous or Continuous for LL

Determining $P^{LL}_{Bent\ Max\ Aplied}$

The maximum bent vehicular LL is illustrated for the same superstructure and HS20 loading in Fig. 6.5 and assuming the curb-to-curb width of the bridge is 24 ft. as shown in Fig. 6.6. Again, as with determining $P^{LL}_{Pile\ Max\ Apllied}$, the $P^{LL}_{Bent\ Max\ Applied}$ is the larger of those determined from the truck lane loading of Fig. 6.6a, or the design loadings of Fig. 6.6b.

$P^{LL}_{Bent\ Max\ Applied}$ is determined from Fig. 6.6. as follows:



a. Truck Lane Load **b. Design Lane Loading**

Fig. 6.6. LL to Determine $P^{LL}_{Bent\ Max\ Applied}$

	SS Spans	2-Span Continuous
a. Truck Lane Load:	$P_{Bent}^{LL} = \left[23^k + 32^k\left(\frac{20}{34}\right) + 8^k\left(\frac{20}{34}\right)\right]x3x1.1$	[2(6.24) +32+18.72] 3*x*1.1
	= $[32 + 18.82 + 4.71]3.3$	[63.2^k]3.3
	= 183.2^k ← Governs	208.6^k ← Governs

	SS Spans	2-Span Continuous
b. Design Lane Load:	$P_{Bent}^{LL} = \left[0.064\frac{k}{ft^2}x10'x34' + 26^k\right]3x1.1$	[(0.064x10'x34)1.25+26'] 3x1.1
	= [21.76+26]3.3	[27.20+26]3.3
	= 157.6^k	175.6^k

Note that the truck lane load governs in both cases.

$\therefore P_{Bent\ Max\ Applied}^{LL} = 183.2^k$ for Simply Supported Bridge

$\therefore P_{Bent\ Max\ Applied}^{LL}$ = 208.6^k for 2-Span Continuous or Continuous for LL

Note in the above, that the design lane loads governed $P_{Max\ Pile\ Applied}^{LL}$ while the truck lane loads governed $P_{Max\ Bent\ Applied}^{LL}$.

To determine the maximum continuous span girder reactions and/or P-loads on a bent cap when under a uniform lane live load, let's look at the case of p_{LL} = 64 *psf* and thus a lane uniform load of w_{LL} = 0.64^k / *ft*, with all of the lane load assumed to be going to one support girder. First, from Fig. 6.1, for a uniform load of w_{LL},

$R_B^{Max} = 1.25w\ell$ (for 2-span continuous girder)

Thus, for the case of a 10ft. girder spacing, w_{LL}= 0.64^k / *ft* as indicated above, and the maximum girder reactions/maximum girder load applied to the bent cap for 2-span continuous bridges with equal span lengths of various lengths would be as shown in Table 6.2.

Table 6.2 Maximum Girder Reactions/Applied Bent Loads Due to a w_{LL}=0.64^{k} / *ft* Girder Loading on Equal Span 2-Span Continuous Bridges*

Equal Span Lengths ℓ(ft)	Intermediate Bent $P_{w_{LL}}^{max}$ 2-Span Cont. $P_B = R_B = 1.25\, w\ell$ (kips)
15	12.0
20	16.0
25	20.0
30	24.0
35	28.0

*These are maximum values of R_B due to w_{LL} and do not include the effect of P-load in Fig. 6.5b nor an impact factor.

6.4 Closure

Each bridge over water which is supported by timber pile bents and may require an assessment of the adequate of such bents in an extreme flood/scour event, should be examined to determine $P_{Max\ Applied}^{Pile}$ and $P_{Max\ Applied}^{Bent}$. This examination should be done beforehand and before trying to use a “ST” to assess the pile/bents adequacy during an extreme flood/scour event. After these maximum applied loads are determined, the “ST” can then be used to check the adequacy of the pile/bent for these maximum applied loads.

In checking for a bent plunging failure due to insufficient soil strength after scour to support the maximum applied gravity DL plus LL loading, the bent pile carrying $P_{Max\ Applied}^{Pile}$ will be checked to make sure that the $P_{Soil\ Support\ Capacity}^{Pile}$ is not exceeded. If this pile is safe then it will be assumed that the bent will not fail in plunging. This same approach will be taken in checking for pile tip “kick-out”, i.e. if a single bent pile will not fail in pile tip “kick-out”, then it will be assumed that the bent will not fail in “kick-out”. Lastly, the $P_{Max\ Applied}^{Pile}$ from a DL plus LL combination will also be used in checking against a buckling failure. If the most heavily loaded pile in a bent, i.e. $P^{Pile}_{Max\ Applied}$ will not buckle, then it will be assumed that the bent will not buckle.

7. Example Applications of “ST”

7.1 General

Example manual applications of the “screening tool” developed in the research reported on herein for timber pile bents are presented in the sections below. These examples should assist a user in understanding the information needed to make the various checks of a bent’s adequacy. The information must be known before making a check, or must be assumed by the user using the guidelines indicated in Section 7.2.

Just as with the steel HP pile bents, the questions below should be answered at the very beginning of a bent adequacy check to determine the need to apply the “ST”, or to determine the applicability of the “ST” to the bridge bent/site under investigation. These are questions, and/or checks, incorporated in Block 1 – Preliminary Evaluation of the “ST.”

- Is the bridge over water or in a flood plain where it may become over water during an extreme flood?

  If answer is <u>NO</u>, the bridge bents do not need to be checked by the ST.

- Is the bridge at a site where the maximum estimated scour, S_{max}, is $0 \leq S_{max} \leq 3$ ft?

  If answer is <u>YES</u>, the bridge bents do not need to be checked by the ST.

- Is the bridge at a site where the maximum estimated scour, S_{max}, is greater than the pile embedment length, ℓ_{bg}, i.e., is $S_{max} \geq \ell_{bg}$?

  If the answer is <u>YES</u>, the bridge pile/bent will have a pile/bent “kick-out” or plunging failure and there is no need to check with the ST. Immediate corrective action should be taken.

- Are the bridge pile bents 3, 4, 5, 6, 7, 8-pile bents with piles in a row with or without X-bracing and with the piles being timber piles?

  If the answer is <u>NO</u>, the bridge bents cannot be checked by ST.

7.2 Acceptable Assumptions in Using the "ST"

If information regarding the bent pile driving operations or system is missing in the data base, then make what should be the following conservative assumptions:

- If driving resistance at end of driving (EOD) is unknown, assume a Final Driving Resistance = 4 blows/inch
- If type of driving hammer and hammer driving energy is unknown, assume a 6 ft-kip hammer driving energy.
- If piles are primarily "End Bearing" or "Friction" is unknown, assume the piles are primarily "Friction Piles."

If Information about the bridge span being SS or continuous or that relates to calculating $P^{bent}_{\max applied}$ and $P^{pile}_{\max applied}$ do the following:

- Assume each bridge span supported by the bent under investigation is a SS span loaded with LL on only the bridge's actual traffic lanes.
- Determine $P^{bent}_{\max applied}$ based on the assumption above.
- Assume $P^{pile}_{\max applied} = \frac{P^{bent}_{\max applied}}{No.Piles}$

Regarding bent pushover adequacy, recognize and/or do the following:

- For bents with piles larger than $14''^{\phi}$butt - $8''^{\phi}$tip, check the bent pushover adequacy by treating it as a $14''^{\phi}$butt - $8''^{\phi}$tip pile bent.
- If the bent has more than 5-piles in a row (No. Piles ≥ 6), the bent will have adequate pushover capacity for maximum scour levels anticipated anywhere in Alabama, and thus is safe for pushover.

7.3 Example #1 Braced Pile Bent

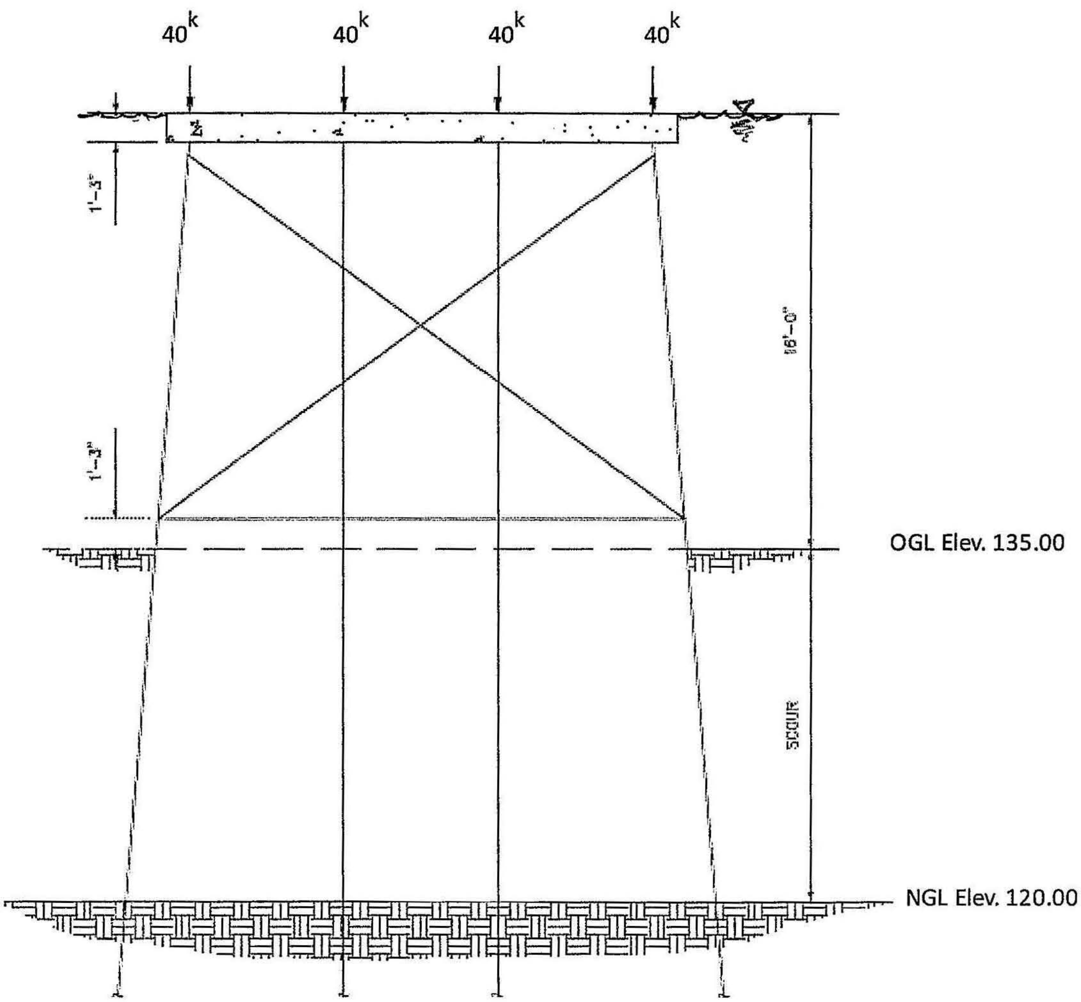
A braced timber pile bent example "check for adequacy" using the new "ST" discussed in the earlier chapter is given below.

Given: 4-Pile X-Braced Bent with 12" Diameter Timber Piles

Span Length = 36 ft
OGL = 135.00 Elev. (ft)
NGL = 120.00 Elev. (ft)
Height Bent (H) = 16 ft
P_{pile} = 40 kips, P_{bent} = 160 kips

From Driving Record:
Length Piles = 40 ft
Hammer Energy = 12 kip-ft
Final Driving Resistance = 4 bpi

Required: Assessment of timber bent using Manual Screening Tool (ST)



Solution: Preliminary Calculations

Determine scour (S)

S_{max} = OGL - NGL = 135.0 - 120.0 = 15.00 ft

Determine embedment before scour, L_{bs}

L_{bs} = Length pile - Height Bent (H) = 40 ft - 16 ft = 24 ft

Determine embedment after scour, L_{as}

$L_{as} = L_{bs}$ - Scour (S) = 24 ft - 15 ft = 9 ft

Determine % Loss of Embedment

$$\% \text{ Loss} = \frac{L_{bs} - L_{as}}{L_{bs}} = \frac{24 - 9}{24} \times 100\% = 62.5\% \text{ Loss Embedment}$$

Check 1: Kick-out Failure (Section 4.2 in Milestone Report #1 or Block 2 in Figure 5.2)

L_{as} = 9 ft > 5.0 ft $\therefore$ Safe from Kick-out and No Riprap Required

Check 2: Plunging Failure (Section 4.3 in Milestone Report #1 or Block 2 in Figure 5.2)

Because unknown, will assume piles are "Friction Piles"

P_{pile} = 40 kips = 20 tons

Therefore, from Table 4.1 with 12,000 ft-lb energy and 4 bpi final driving resistance:

Critical % Loss Embedment = 80% for 25 tons which is > 20 tons = P_{pile}

S_{cr} = Critical % Loss x L_{bs} = 0.80 x 24ft = 19.2 ft

S_{max} = 15ft < 19.2 ft = $S_{crPlunging}$ $\therefore$ Safe from Plunging

Check 3: Buckling Evaluation (Section 4.4 in Milestone Report #1 or Block 3 in Figure 5.2)

$L_{as} \geq 8$ ft $\therefore$ C_1 = 2.0 (Assuming 100% Fixity Condition)

Bent has sway bracing, so will check for non-sidesway buckling in the longitudinal directions and sidesway buckling below the X-bracing

$EI_{eff} = EI_{0.33ft_{L_{NGL}}}$ (where L_{NGL} measured from NGL to pile cap) $\therefore$ $d_{eff} \approx 9$ in

Assume EI_{eff} = 579,600 k-in^2 for $d_{eff} \approx 9$ in (as per Table 4.2 in Milestone Report #1)

Longitudinal Non-Sidesway Buckling Evaluation

$$L_{cr1} = \sqrt{\frac{C_1 \cdot \pi^2 \cdot EI_{eff}}{FS \cdot P_{pile}}} = \sqrt{\frac{2.0 \cdot \pi^2 \cdot 579,600}{1.33 \cdot 40}} = 38.6 \text{ ft}$$

$S_{cr1} = L_{cr1}$ + 1.25 ft - H = 38.6 ft - 1.25 ft - 16 ft = 21.4 ft

Transverse Sidesway Buckling Evaluation

$$L_{cr2} = \sqrt{\frac{C_2 \cdot \pi^2 \cdot EI_{eff}}{FS \cdot P_{pile}}} = \sqrt{\frac{0.5 \cdot \pi^2 \cdot 579,600}{1.33 \cdot 40}} = 19.3 \text{ ft}$$

Assuming horizontal brace is 1.25 ft above OGL

$S_{cr2} = L_{cr2}$ - 1.25 ft = 19.3 ft - 1.25 ft = 18.1 ft

By comparing S_{cr1} for longitudinal buckling to S_{cr2} for transverse buckling, it can be determined that transverse sidesway buckling below the bracing will control (i e. $S_{cr2} < S_{cr1}$)

$S_{max} = 15ft < 18.1\ ft = S_{crBuckling}$ ∴ Safe from Buckling

Check 4: Bent Pushover Evaluation (Section 4.5 in Milestone Report #1 or Block 4 in Figure 5.2)

Assuming a debris raft will from, from Figure 4.11 in Section 4.5, for 36 ft spans the larger debris raft will form

∴ $F_t = 12.93$ kips

From Table A.1 for 12" Diameter X-Braced Bents with $P_{pile} = 40$ kips, $F_{tMax} = 111$ kips

$F_t = 12.93\ kips < 111\ kips = F_{tMax}$ ∴ Safe from Bent Pushover

Check 5: Upstream Pile Beam-Column Evaluation (Section 4.6 in Milestone Report #1 or Block 5 in Figure 5.2)

All X-Braced piles are safe from beam-column failure

∴ Safe from Upstream Beam-Column Failure

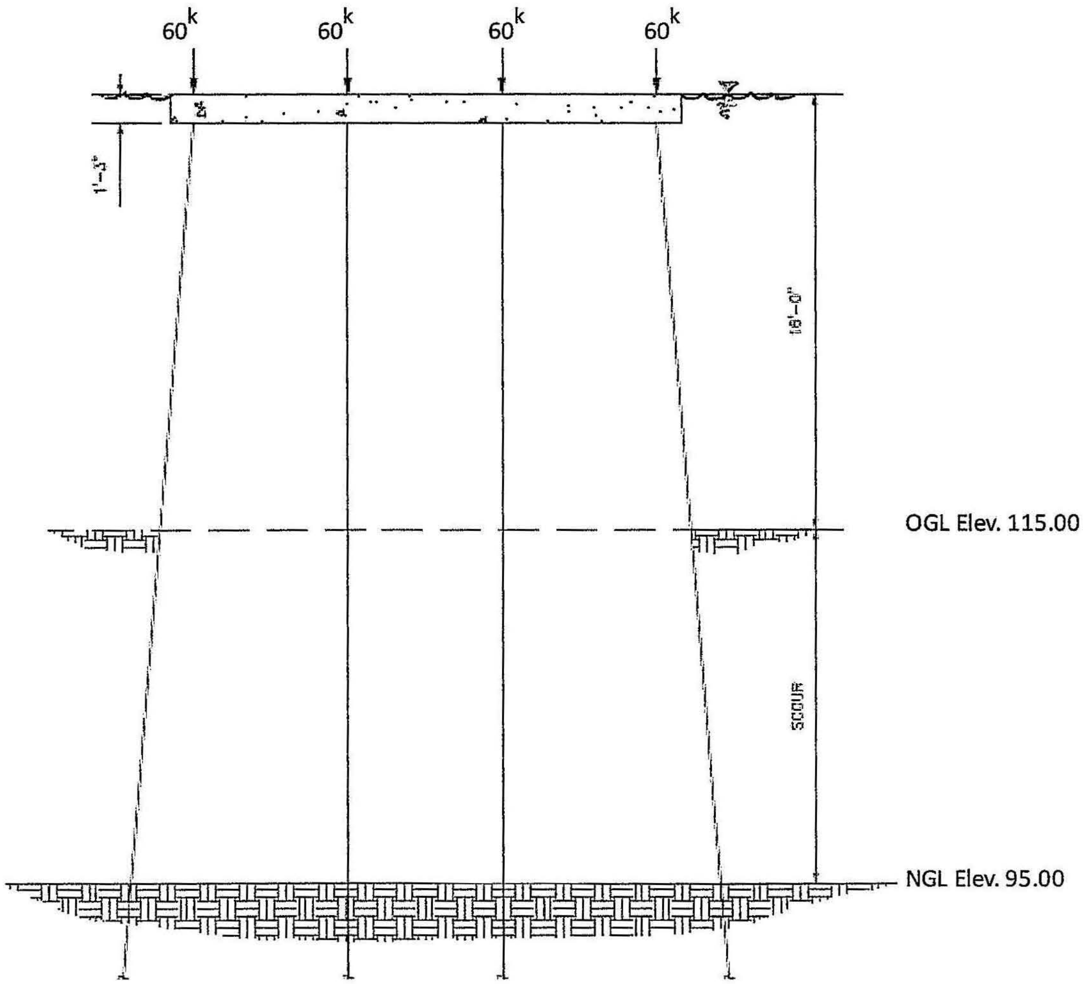
<u>Final Conclusion: Bent is Safe from All Failure Modes (OK)</u>

7.4 Example #2 Unbraced Timber Pile Bent

An unbraced timber pile bent example "check for adequacy" using the new "ST" discussed in the earlier chapter is presented below.

Given: 4-Pile Unbraced Bent with 14" Diameter Timber Piles
Span Length = 24 ft
OGL = 115.00 Elev. (ft)
NGL = 95.00 Elev. (ft)
Height Bent (H) = 16 ft
P_{pile} = 60 kips, P_{bent} = 240 kips
From Driving Record:
Length Piles = 40 ft
Hammer Energy = 10 kip-ft
Final Driving Resistance = 6 bpi
End Bearing Piles

Required: Assessment of timber bent using Manual Screening Tool (ST)



7.5 Closure

Questions of applicability and/or the need to apply the “ST” in a given situation to determine a bent’s adequacy in a given flood/scour event are summarized in Section 7.1. Section 7.2 gives some assumptions that can be made when some of the information needed to check a pile/bent’s adequacy is missing from the pile/bents data base. Sections 7.3-7.6 present four example applications of the “ST” wherein different possible failure checks are made to illustrate the checks made by the “ST.” These example applications should help the user to understand the workings and assumptions incorporated in the “ST.” In turn, they should help the user to understand and become comfortable in using the automated version of the “ST”

8. Conclusions and Recommendations

8.1. General

Approximately eight years ago, the ALDOT began investing in a three-phase research project to develop a simple “screening tool” for bridges supported on a steel WF pile bents, with the results that they now have an automated “screening tool” which can assess the susceptibility of steel WF pile bent supported bridges to extreme flood/scour events. This “screening tool” is now widely used and has proven to be very helpful to the ALDOT. Currently, the majority of bridges in Alabama that still require scour susceptibility analyses are owned by local governments and are supported on timber pile bents and the number of these bridges is quite large. Hence, adding a “sister” screening tool for timber pile bents to ALDOT’s existing steel H-pile bent screening tool would be a great benefit to ALDOT. This was the purpose and objective of this research.

8.2. Conclusions

Based on the work as outlined and presented in Chapters 1-7, the following conclusion are offered.

1. Because of their significant taper, timber piles develop good wedge action and thus large skin friction resistance forces. Also, because of their relatively large tip area, timber piles also develop good bearing resistance at their tip.

2. Timber piles have good strength, approximately 7.0 ksi crushing (unfactored) and 12.0 bending (unfactored) and are fairly ductile (relative to concrete).

3. The geometrical characteristics and strengths indicating in Nos. 1 and 2 above allow maximum axial load limits on timber piles to be governed by the strength of the soil setting rather than that of the pile.

4. They also allow the bent upstream pile to simultaneously withstand significant lateral flood water loads acting on a debris raft, and in-turn on the pile, as well as the normal axial dead plus live loads.

5. Even though the other piles in a timber bent act as solid conical columns, their analyses and design are typically as prismatic columns having an effective diameter equal to the pile diameter at a section located 1/3 of the length of the pile above ground when measure up from the ground line.

6. The fact that the moment of inertia of a circular section varies as the 4^{th} power of the diameter, and for timber piles the diameter decreases as one moves toward the embedded pile tip, one can see that a timber pile's buckling capacity and the upstream piles beam-column capacity can be significantly reduced by flood water scour.

7. In order to accurately assess a bridges adequacy during major flood/scour events, bridge owners need to know vital information pertaining to the
   - bridge superstructure and live loads acting thereon
   - support pile bent geometry and member sizes
   - pile driving and support soil conditions
   - river/stream high water level, flow velocity, level of possible scour

8. Based on our past experience in screening ALDOT bridge bents, possible failure modes of bridge timber pile bents during extreme scour were initially identified as:

   - Crushing of piles

   - Buckling of bent piles in longitudinal or transverse directions

   - Bent failure from piles tips being “kicked-out” due to zero or almost zero embedment after scour.

   - Plunging failure of piles (soil failure)

   - Failure of upstream bent pile as a beam-column from combined lateral flood water loading and axial gravity loading.

   - Bent pushover failure from combined superstructure gravity load and transverse flood water load on pile bent.

9. An early check revealed that crushing of a pile during an extreme scour event is really not a viable failure mode for timber piles since $\sigma_{crushing}^{timber} \approx 7.0\ ksi$ and $6"^{\phi}$tip diameter is the smallest diameter pile used. This means that

$$P_{crushing}^{min} = 7.0\ ksi\ \left(\frac{\pi 6^2}{4}\right) = 198^k$$

   which is much larger than $P_{max\ applied}$ of 60k. Also $P_{max\ applied}$ and $P_{crushing}$ of the piles are unaffected by a scour event and therefore crushing of the piles will not occur during an extreme scour event.

10. Thus, based on Nos. 8 and 9 above, only buckling of the bent piles, plunging of the piles (soil failure), bent pushover failure from combined superstructure gravity and flood water lateral loads, bent failure from the piles tips “kicking-out” due to excessive scour and flood water loads, or failure of the upstream pile as a beam-column from combined flood water and axial loadings will be the only possible catastrophic failure modes. These are the only five modes of failure of concern and requiring checking.

11. To systematically check the adequacy of a timber pile bent for a given extreme flood/scour event, macro and micro flowcharts similar to those employed earlier for steel WF pile bents were developed. The checking procedure proceeds in the order indicated below.

    1. Preliminary Evaluation
    2. Kick-Out and Plunging Evaluation
    3. Buckling Evaluation
    4. Bent Pushover Evaluation
    5. Upstream Pile Beam-Column Evaluation

    Figures 5.1 and 5.2 in Chapter 5 present the detailed macro and micro flowcharts respectively.

12. The maximum applied gravity loads to a bridge’s pile support bent must be rather accurately determined before one can assess the adequacy of the bridge’s timber pile bents and piles during an extreme flood/scour event. These loadings are,

$$P^{Pile}_{Max\ Applied}\ (DL + LL)$$

$$P^{Bent}_{Max\ Applied}\ (DL + LL)$$

and should be predetermined prior to the occurrence of an extreme flood/scour event, and prior to applying the "ST" to assess the adequacy of the bridge in the event of a major flood/scour event. The procedures for determined the above pile/bent maximum applied loads for simple span and for 2-span continuous bridges are described in Chapter 6.

13. In checking for a bent plunging failure due to insufficient soil strength after scour to support maximum applied gravity DL plus LL loading, the bent pile carrying $P^{Pile}_{Max\ Applied}$ should be checked to make sure that the $P^{Pile}_{Soil\ Support\ Capcity}$ is not exceeded. If this pile is safe, then it will be assumed that the bent will not fail in plunging. This same approach should be taken in checking for pile tip "kick-out". Lastly, the $P^{Pile}_{Max\ Applied}$ from a DL plus LL combination will also be used in checking against a buckling failure. If the most heavily loaded pile in a bent, i.e. $P^{Pile}_{Max\ Applied}$ will not buckle, then it will be assumed that the bent will not buckle.

14. If we call ℓ_{as} the remaining pile embedment after scour, then for steel WF piles we determined that if

$$\ell_{as} \leq 3.0\ ft$$

such a "kick-out" mode of failure is very possible and corrective action should be taken immediately. However, the water drag force on timber piles is approximately 0.60 of that on steel WF piles and thus the required lateral resisting force at the pile tip and minimum embedment length is 0.60 times that for a steel WF pile, i.e., for timber piles,

$$\ell^{minimum\ required}_{as} \leq 3.0\ x\ 0.6 = 1.8\ ft$$

However, because we do not know the exact locations of the pile tips relative to the OGL or NGL, we will assumed that for timber piles

$$\ell^{minimum\ required}_{as} = 2.5\ ft$$

Thus, if $\ell_{as} < 2.5\ ft$, corrective action should be taken and probably the best such action would be place rip-rap around the bent piling.

15. If $\ell_{as} > 2.5\ ft$, then the pile and bent should be safe from a "kick-out" mode of failure. However, if

$$2.5\ ft. < \ \ell_{as} \ \leq 5.0\ ft$$

there is not much margin for safety against a "kick-out" failure during the next extreme flood/scour event. Given the catastrophic consequences of a bent "kick-out" failure, some sort of corrective action should be taken if $\ell_{as} \leq 5.0\ ft$. Probably placing rip-rap around the bent piling should be employed for this case as well.

16. A lower F.S. was used (F.S. = 1.25 rather than 1.33) in the "ST" for checking pile plunging adequacy. This was done because the variable properties of timber are not factors in checking pile plunging. Also, the taper of timber piles results in good "wedge action" and side friction relative to that of a steel WF pile and the tip area is large relative to that of a steel WF pile giving it a superior tip bearing capacity.

17. The Modified Gates formula (see Eqn. (4.0)) was used to generate a table of predicted pile capacities of timber piles for a range of pile hammer energies and a range of driving resistance at the end of driving (EOD). The table generated is shown in Table 4.1. This table was used in checking pile adequacy from a plunging failure.

18. Unlike steel WF piles, timber piles, because of their circular section, are not weaker in bending about 1-axis or more prone to buckle about one axis.

19. Because timber bent supported bridges are typically short with the superstructure connected to the abutment and to the bents, the bent piles cannot buckling a sidesway mode in the longitudinal direction of the bridge. Additional piles are not embedded in the bent cap, but rather are approximately pinned to the cap.

20. Timber bents are X-braced in the plane of the bent. Thus, in the other direction, i.e., the longitudinal direction of the bridge, a piles' end conditions will be pinned at the top and pinned, fixed, or partially fixed at the ground level depending on the pile embedment after scour as indicated in Fig. 4.4.

21. An X-braced bent pile can buckling in a sidesway mode (Mode 2) from the bottom horizontal brace down to the new ground line after scour if the bridge superstructure is simply supported. See Mode 2 buckling in Figure 4.5. Alternatively, the pile could buckle in a nonsidesway mode in the longitudinal direction of the bridge from the bent cap down to the new

ground line as indicated in Fig. 4.4. Whichever of these modes gives the smaller buckling load will govern and provide the correct buckling load.

22. A bent's upstream pile is checked for adequacy as a beam-column when subjected to a axial P-load and bending moment caused by a debris raft flood water lateral loading acting on the pile as indicated in Fig. 4.12. A straight-line interaction equation with F.S,. = 1.33 as shown in Eqn. (4.13) and in Fig. 4.13 is used to check the adequacy of the upstream pile. Several numerical beam-column adequacy checks are shown in Figs. 4.14 – 4.20.

23. Execution of each of the checks indicated in Chapter 4 will allow one to manually assess the adequacy of a given timber pile bent for a given flood/scour event.

24. The next step now, is to automate the bent checking procedure described in Chapters 4 and 5 via preparing a computer program to execute this screening/checking procedure. This will be done in Milestone #2 of this research project.

8.3. Recommendations

Readers interest in the workings of this new "ST" and that plan to use it as a work tool to screen timber pile bent supported bridges to assess their adequacy for extreme flood/scour events should recognize and do the following:

- The "ST" is a screening tool to determine the adequacy of timber pile bridge bents for an estimated extreme flood/scour event.
- The "ST" checks for possible timber pile/bent failure via
    - Pile "kick-out" due to insufficient pile embedment after scour.
    - Pile plunging due to insufficient soil tip bearing and side friction capacity (the "ST" employs a F.S. = 1.25 in this determination).
    - Pile buckling (the "ST" employs a F.S. = 1.33 in this determination).
    - Bent pushover due to flood water lateral loading on the pile cap and/or on a debris raft lodged against the bent (the "ST" employs a F.S. = 1.33 in this determination).

- Upstream pile failure as a beam-column due to a combined P-load and a lateral flood water loading on a debris raft forming at an elevation of approximately 7.5 ft below the top of the bent cap (the “ST” employs a F.S. = 1.33 in this determination).

- Perform an overview reading of this report to develop an understanding of the workings of the “ST” and the changes that were made in developing this timber pile bent “ST” from the original steel H-pile bent “ST”.

- Perform a close reading of Chapter 4 to assist in accomplishing the above bullet.

- Perform a close reading of Chapters 5 and 7 and the flowcharts therein to gain a better understanding of the workings of the “ST” and to understand the workings of the soon to be available automated version of the “ST”.

- Closely read this last chapter, i.e. Chapter 8 – “Conclusions and Recommendations” which summarizes the major procedures, sequences and assumptions incorporated in the “ST”.

- Manually use the “ST” to check the adequacy of some timber pile bents in ALDOT’s list of bridges/bents waiting to be assessed.

- Attend the training session on the **Timber Pile Bent “ST”** which will be held later this summer at ALDOT’s offices in Montgomery, AL.

9. Notations

The following symbols, definitions and nomenclature are used throughout this report. It should be noted that other symbols and notations are used in the report, but those listed below are the primary ones needed in understand and using the "Screening Tool."

H	=	Bent height from top of bent cap to OGL
M_R	=	$\sigma_{rupture}$ x Section Modulus at section in question
HB	=	3" x 8" timber bent horizontal brace a 1.25 ft. above the OGL
$P_{girder\ max}$	=	Bridge superstructure maximum girder vertical load on a bent
$P_{bent\ max}$	=	Bridge superstructure maximum total vertical load on a bent
$P^{pile}_{max\,applied}$	=	$P_{girder\ max}$ plus portion of bent cap weight going to the Pile
$P^{bent}_{max\,applied}$	=	$P_{bent\ max}$ plus weight of bent cap
$P_{crushing}$	=	Pile crushing strength ($P_{crushing} = \sigma_{crushing} A$)
P_{CR}	=	Pile elastic buckling load, i.e., $P_{CR} = \frac{constant\ \pi^2 EI}{\ell^2}$ where the constant depends on the pile bracing and boundary conditions.
I	=	Column or pile moment of inertia
ℓ_{CR}	=	Pile unbraced length needed to have an elastic buckling failure, i.e., $\ell_{CR} = \frac{\sqrt{constant\ \pi^2\, EI}}{P_{\max applied}}$ where the constant depends on the pile bracing and boundary conditions.
ℓ_{CR1}	=	Pile critical unbraced length for Mode 1 (Nonsidesway) buckling
ℓ_{CR2}	=	Pile critical unbraced length for Mode 2 (Sidesway) buckling

E	=	Young's modulus of elasticity of pile timber (assumed to be E = 1,800 ksi in pile buckling section of report)
	=	Energy produced by driving hammer per blow in foot-pounds in pile plunging section of report
F.S.	=	Factor of Safety
LL	=	Live Load
DL	=	Dead Load
HWL	=	Assumed flood high water level relative to the top of the bent cap
F_{tip}	=	Horizontal flood water force applied or resisted at the pile tip perpendicular to the plane of the bent
θ	=	Maximum flood water flow angle measured from the longitudinal axis of the bent. Used in determining the maximum pile tip "kick-out" force and possible failure. Assumed to be 30º.
V_{design}	=	Design flood water velocity at the bent location (V_{design} assumed to be 6 mph)
$F^{t}_{max\,applied}$	=	Maximum horizontal flood water load applied at the bottom of the bent cap in the plane of the bent (used in checking bent pushover failure), or applied at the midpoint of the pile cap and lower HB in checking adequacy of upstream pile as a beam-column.
$F^{tip}_{max\,applied}$	=	Maximum horizontal flood water load applied at the pile tip perpendicular to the plane of the bent (used in checking pile "kickout" failure)
$F^{capcity}_{t}$	=	Flood water bent pushover force capacity for horizontal force applied at the bottom of the bent cap in the plane of the bent for a given level of bent gravity P-loads
$F^{pushover}_{t}$	=	Horizontal force applied at the bottom of the bent cap in the plane of bent required to cause pushover failure of the bent under a given set of gravity P-loads on the bent. This force was determine via the nonlinear Pushover Analysis capabilities of GTSTRUDL.

$F^{t}_{\text{max design}}$	=	$F_{t\ max\ design}$ = 12.93 (includes F.S. = 1.33) for large debris raft = 8.62 (includes F.S. = 1.33) for small debris raft
B	=	Base dimension of assumed flood water triangular debris raft. B = 20' if 15' ≤ L ≤ 25 and B = 30' if 25' < L ≤ 36'
A	=	Altitude or height of assumed flood water triangular debris raft. A = 6ft.
DRA	=	Vertical projected area of assumed flood water triangular debris raft (DRA = ½ A•B)
OGL	=	Original ground line elevation
NGL	=	New ground line elevation (after scour)
S	=	Scour depth, or OGL-NGL
S_{max}	=	Maximum estimated scour at the bridge/bent site
S_{CR}	=	Level of scour required to cause a bent/pile plunging, buckling or pushover failure
S_{CR1}	=	Level of scour required to cause a nonsidesway (Mode 1) buckling failure
S_{CR2}	=	Level of scour required to cause a sidesway (Mode 2) buckling failure
ℓ_{ag}	=	Length of pile above ground and is equal to distance from the bottom of the pile cap down to the ground line
ℓ_{bs}	=	Length of pile embedment in supporting soil <u>before scour</u>
ℓ_{as}	=	Length of pile embedment in supporting soil <u>after scour</u>
P	=	Nominal axial resistance of pile in tons by Gates formula
P_{tip}	=	Vertical force applied or resisted at the pile tip
End Bearing Pile	=	Pile where 75% or more of the applied vertical load is assumed to be carried by end bearing
Friction Pile	=	Pile where 75% or more of the applied vertical load is assumed to be carried by side friction

bpi = Blows per inch of final pile driving resistance

N_b = Blow count in blows per inch when using the Gates formula to estimate a piles axial load capacity.

d_{eff} = Effective diameter of a timber pile and is assumed to be the diameter at a location of $\ell_{ag}/3$ feet up from the ground line

S_{eff} = Effective section modulus, or $\pi d_{eff}^3/32$

I_{eff} = Effective section moment of inertia, or $\pi d_{eff}^4/64$

$\sigma_{crushing}$ = Compressive axial failure stress

$\sigma_{rupture}$ = Bending failure stress

γ_{wood} = Unit weight of treated structural grade timber

APPENDIX A

X-Braced Timber Pile Bent

F_t vs Δ Pushover Curves

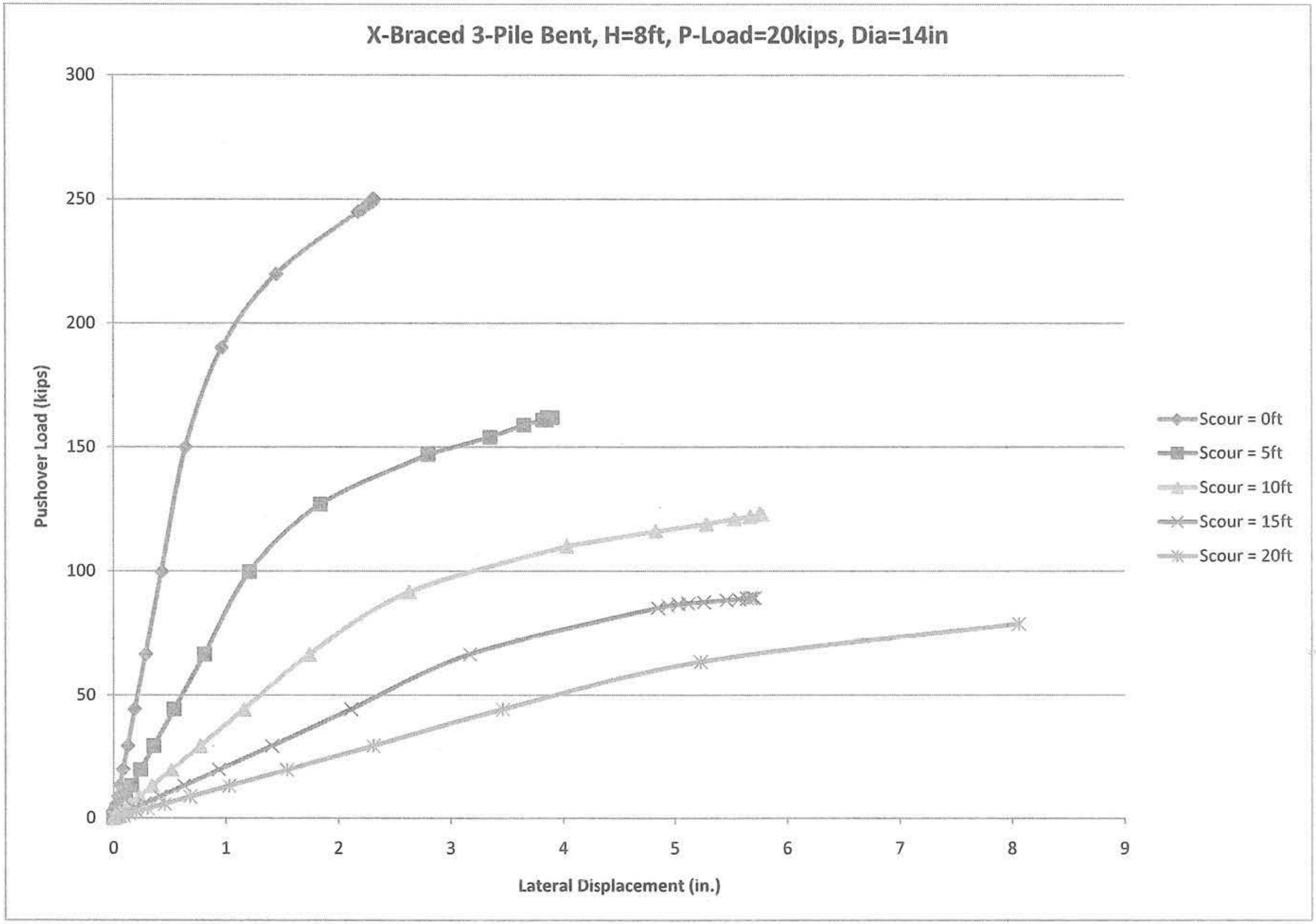


Figure A.1 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=20kips, Diameter=14in, Multiple Levels of Scour

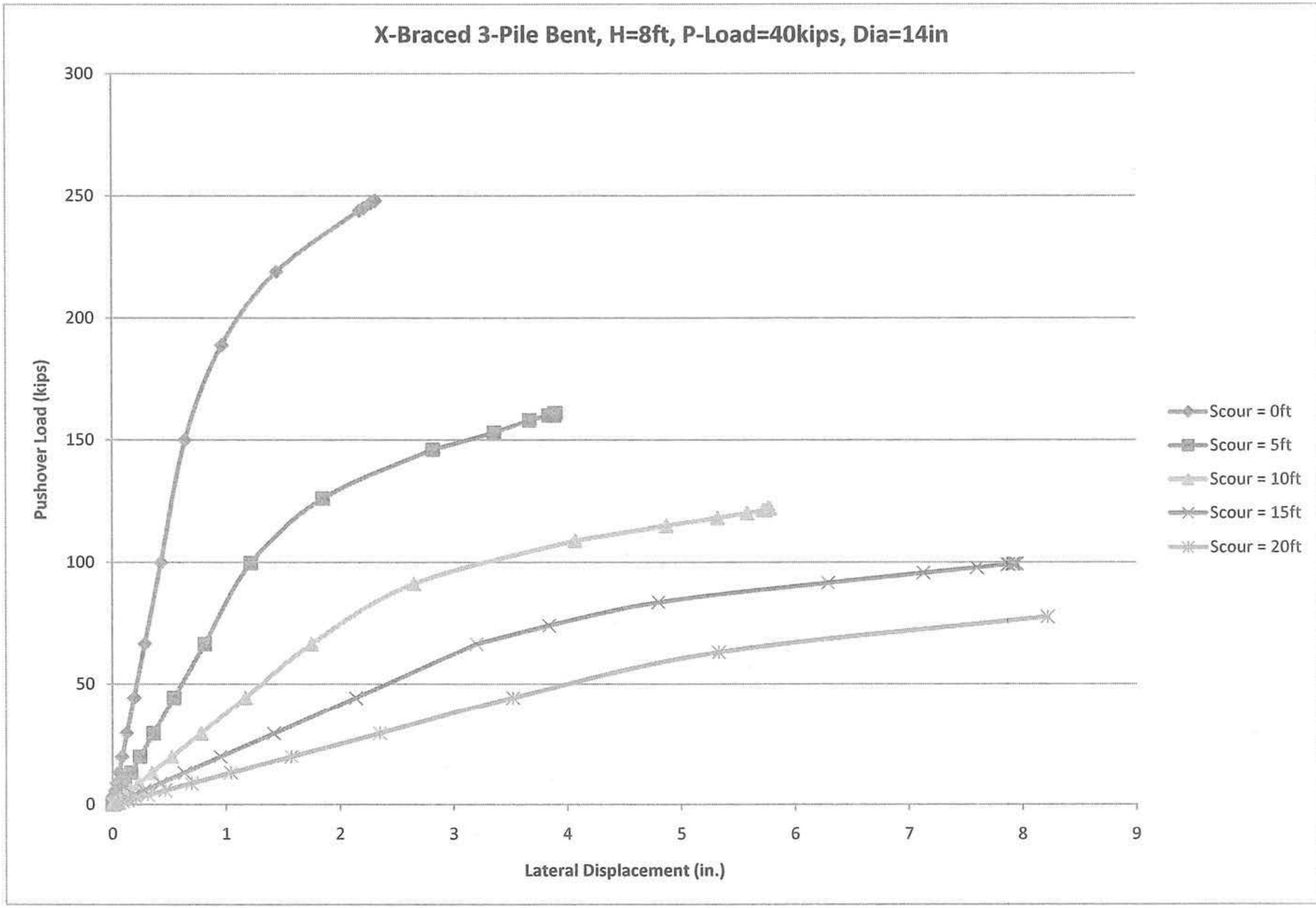


Figure A.2 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=40kips, Diameter=14in, Multiple Levels of Scour

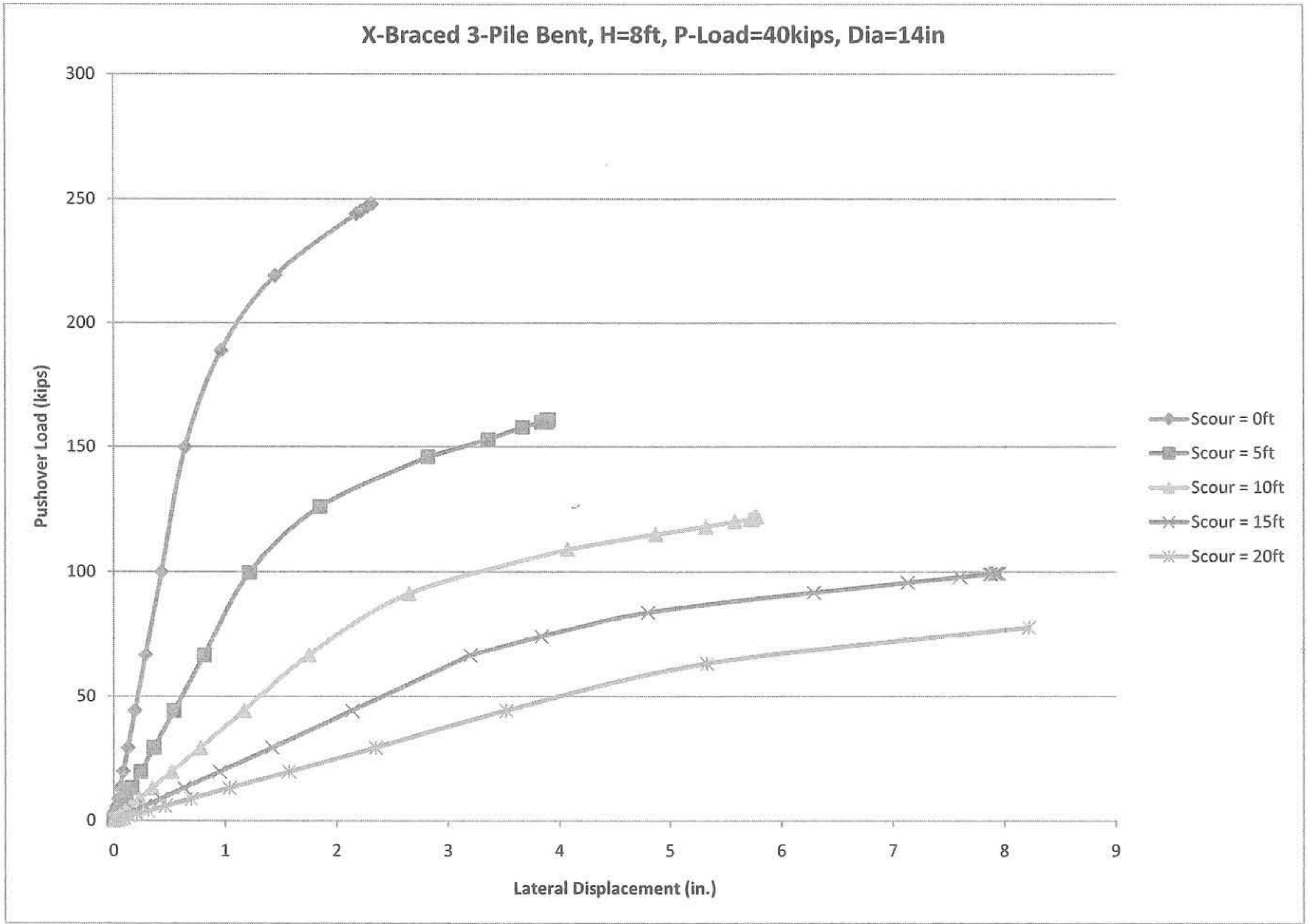


Figure A.2 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=40kips, Diameter=14in, Multiple Levels of Scour

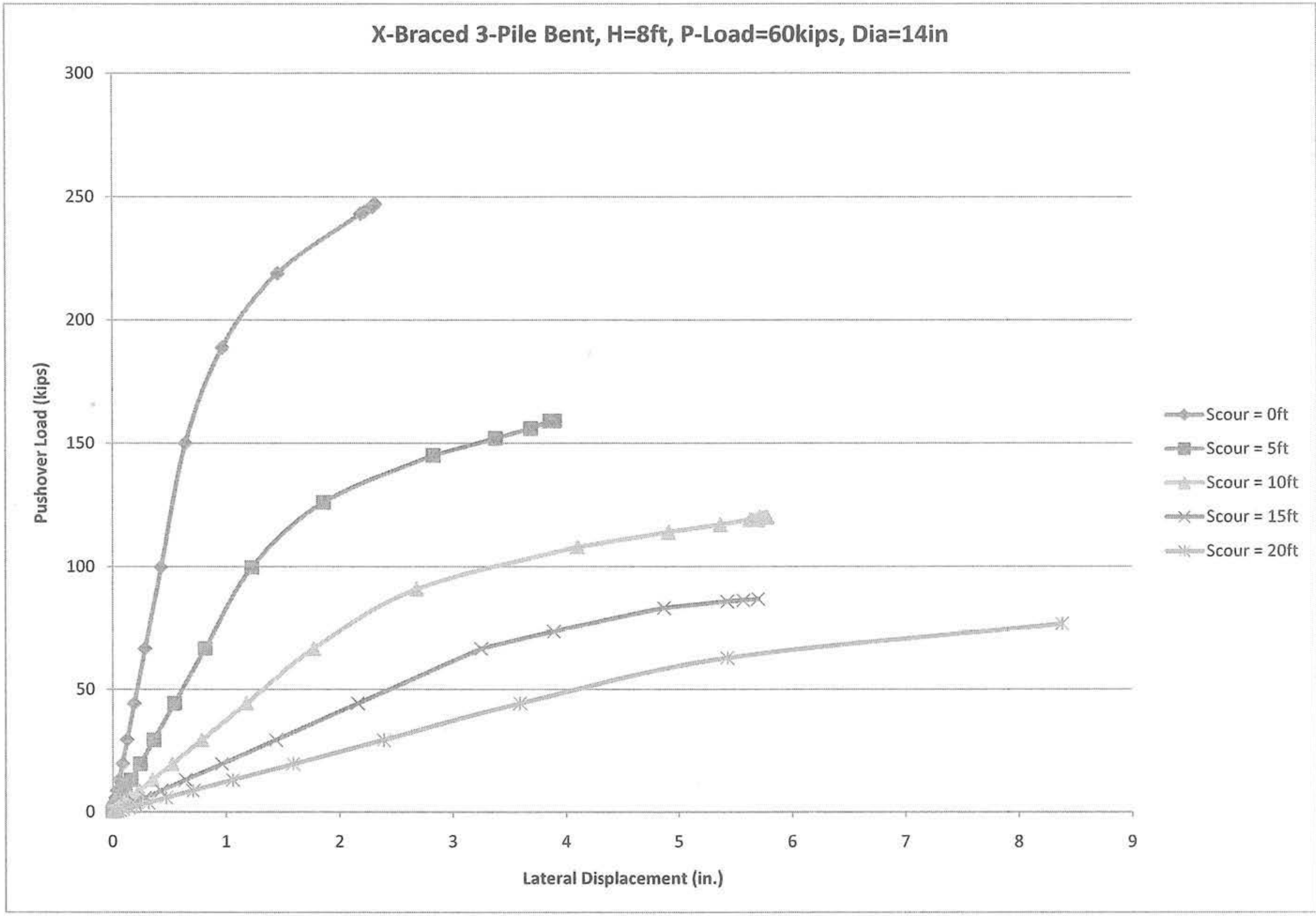


Figure A.3 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=60kips, Diameter=14in, Multiple Levels of Scour

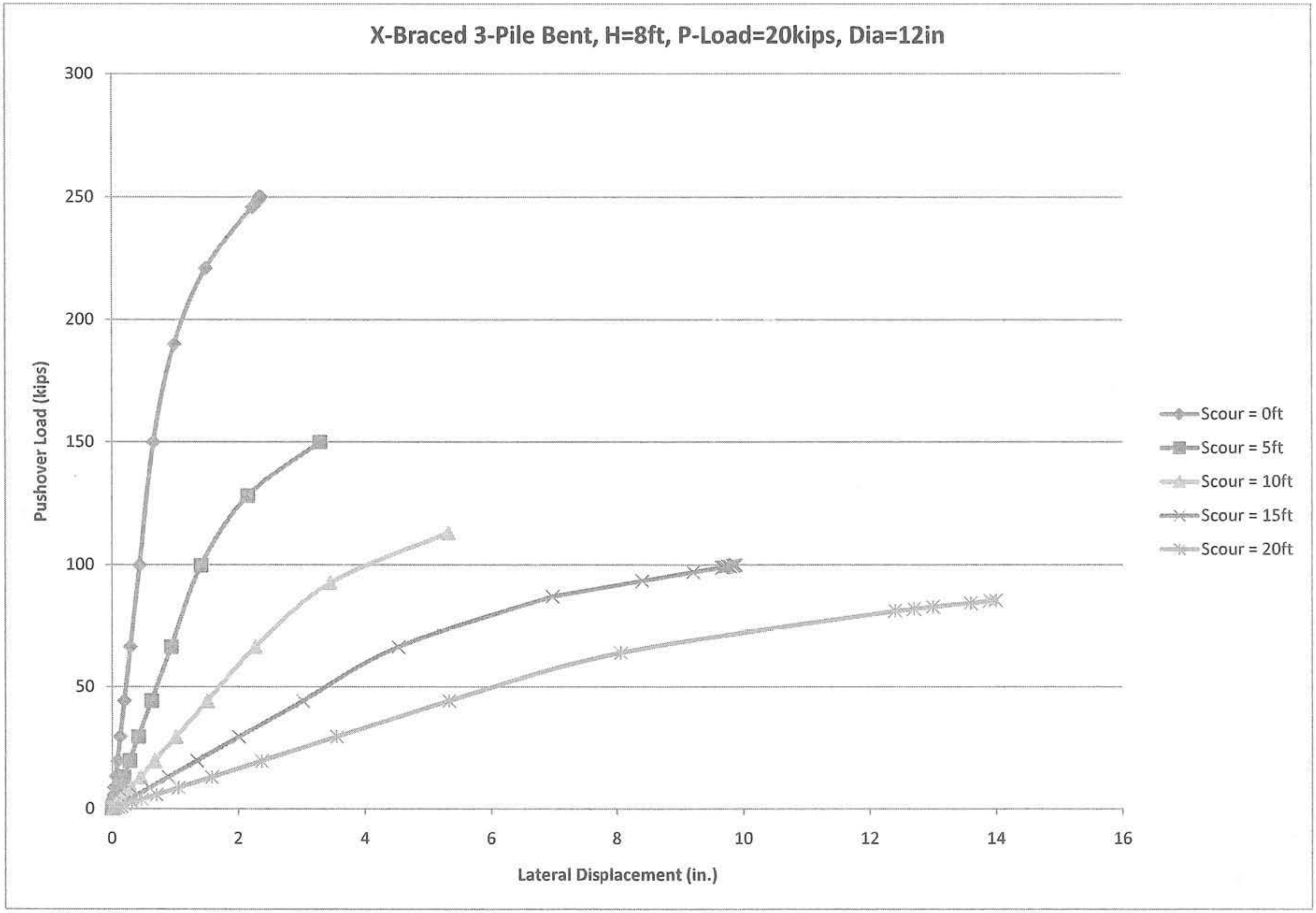


Figure A.4 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=20kips, Diameter=12in, Multiple Levels of Scour

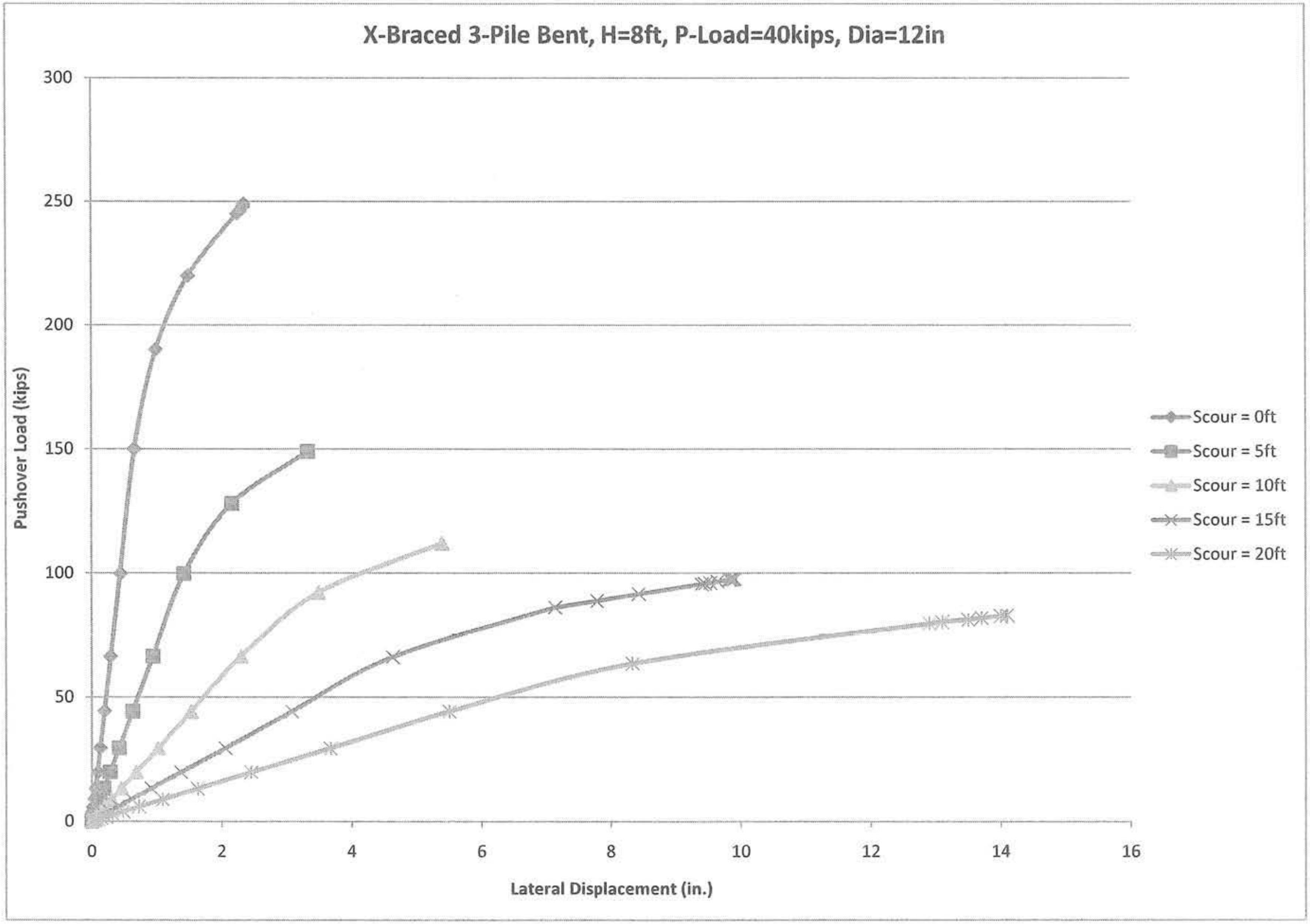


Figure A.5 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=40kips, Diameter=12in, Multiple Levels of Scour

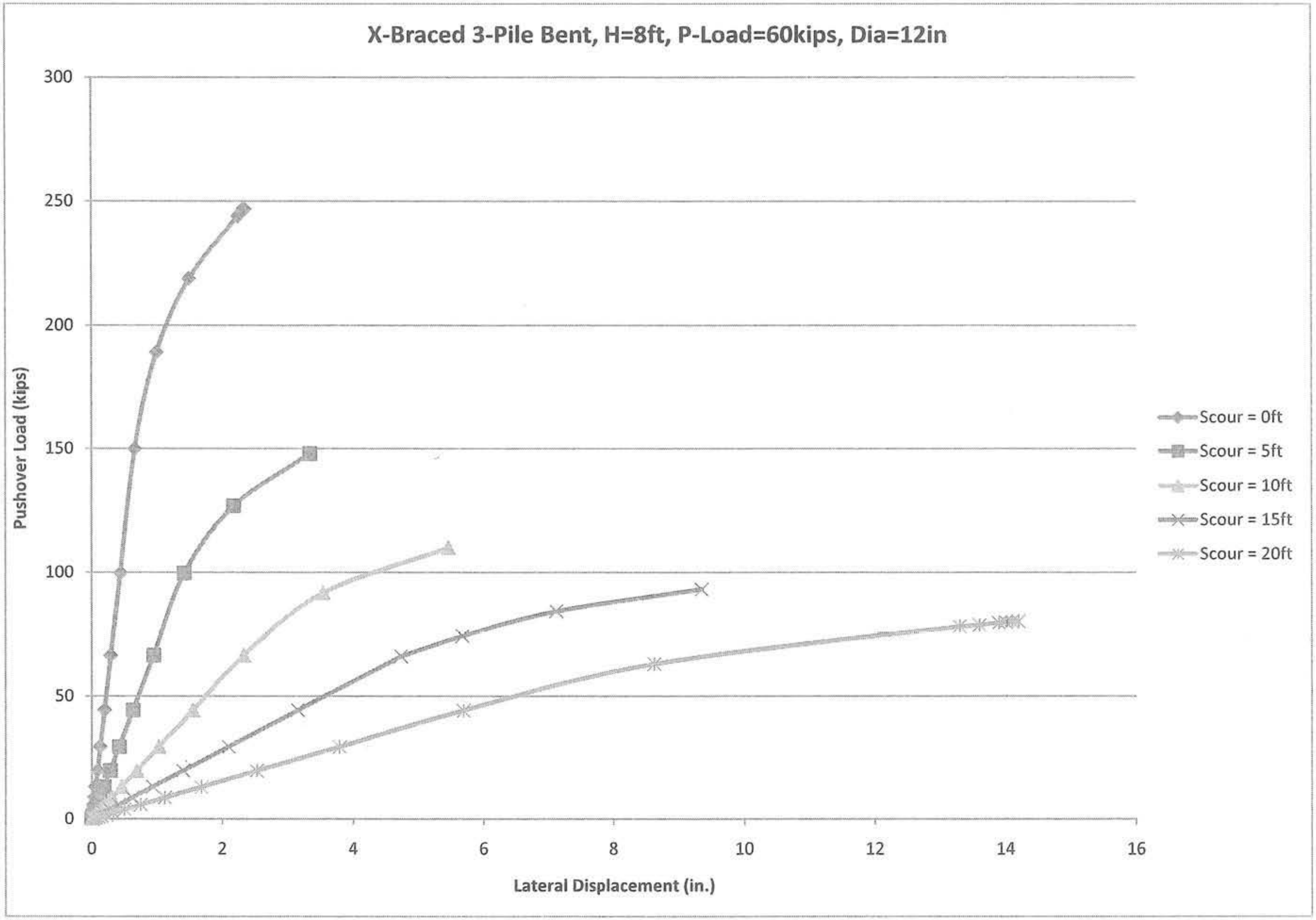


Figure A.6 Pushover Curves for X-Braced 3-Pile Bent, H=8ft, P=60kips, Diameter=12in, Multiple Levels of Scour

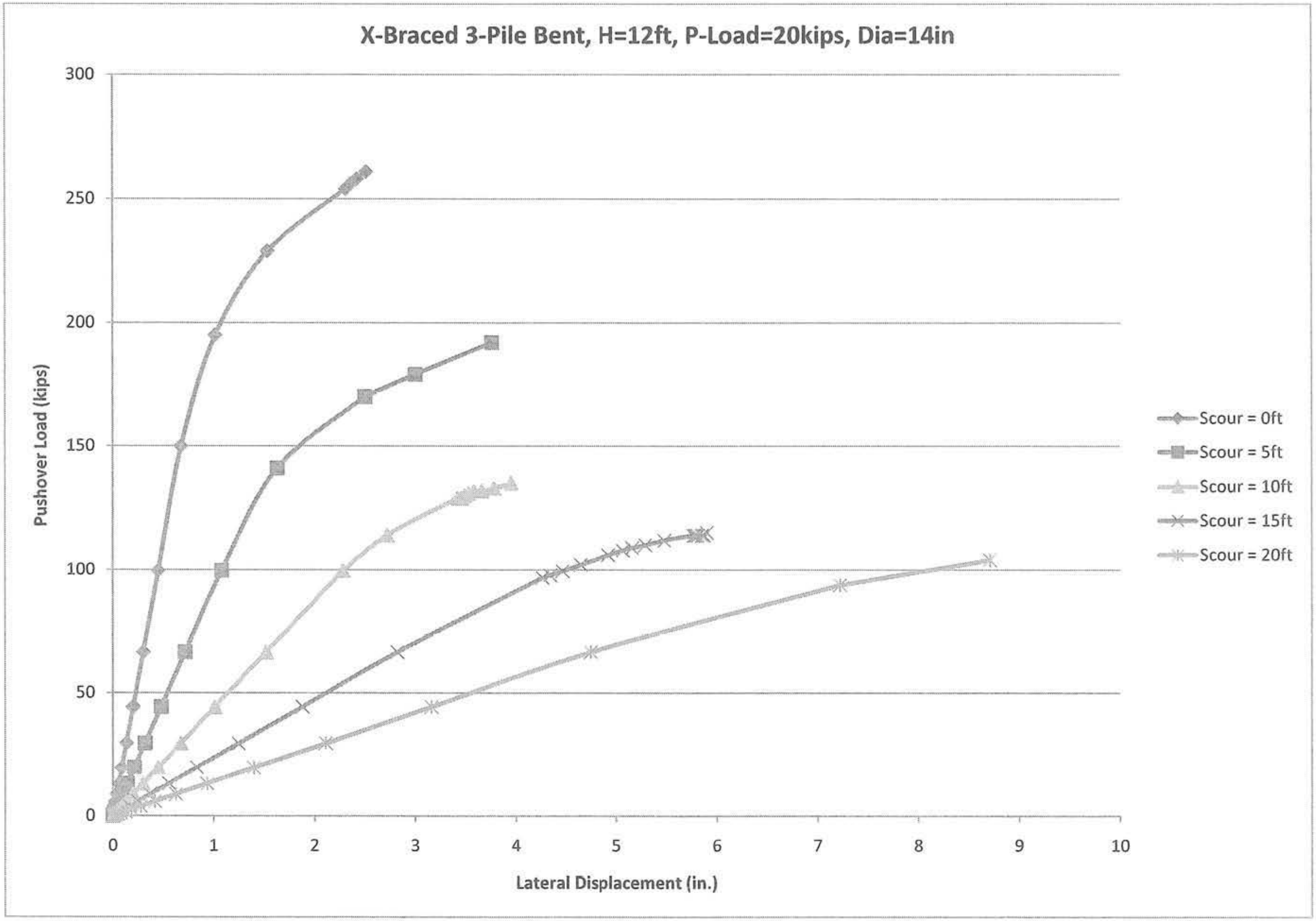


Figure A.7 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=20kips, Diameter=14in, Multiple Levels of Scour

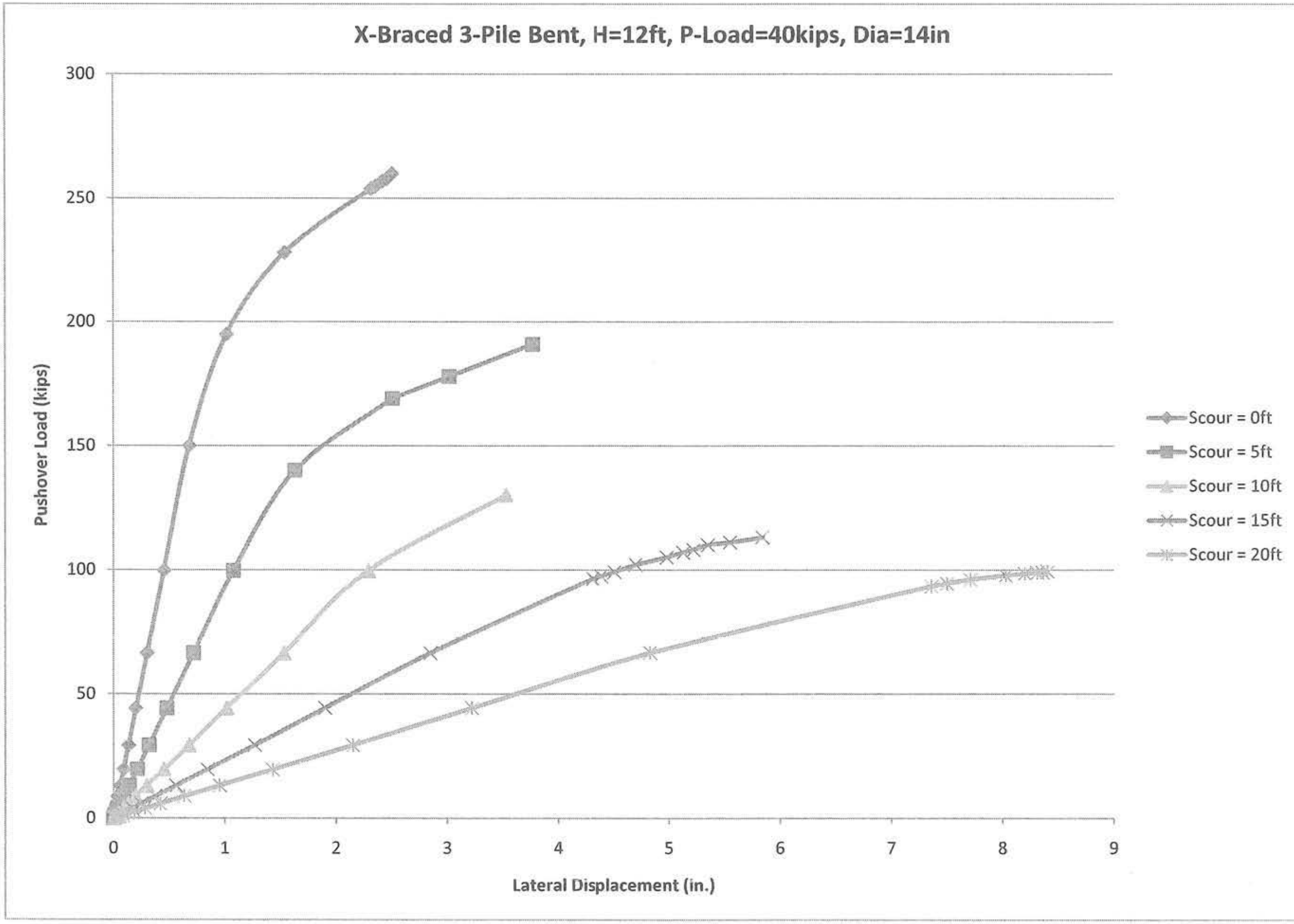


Figure A.8 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=40kips, Diameter=14in, Multiple Levels of Scour

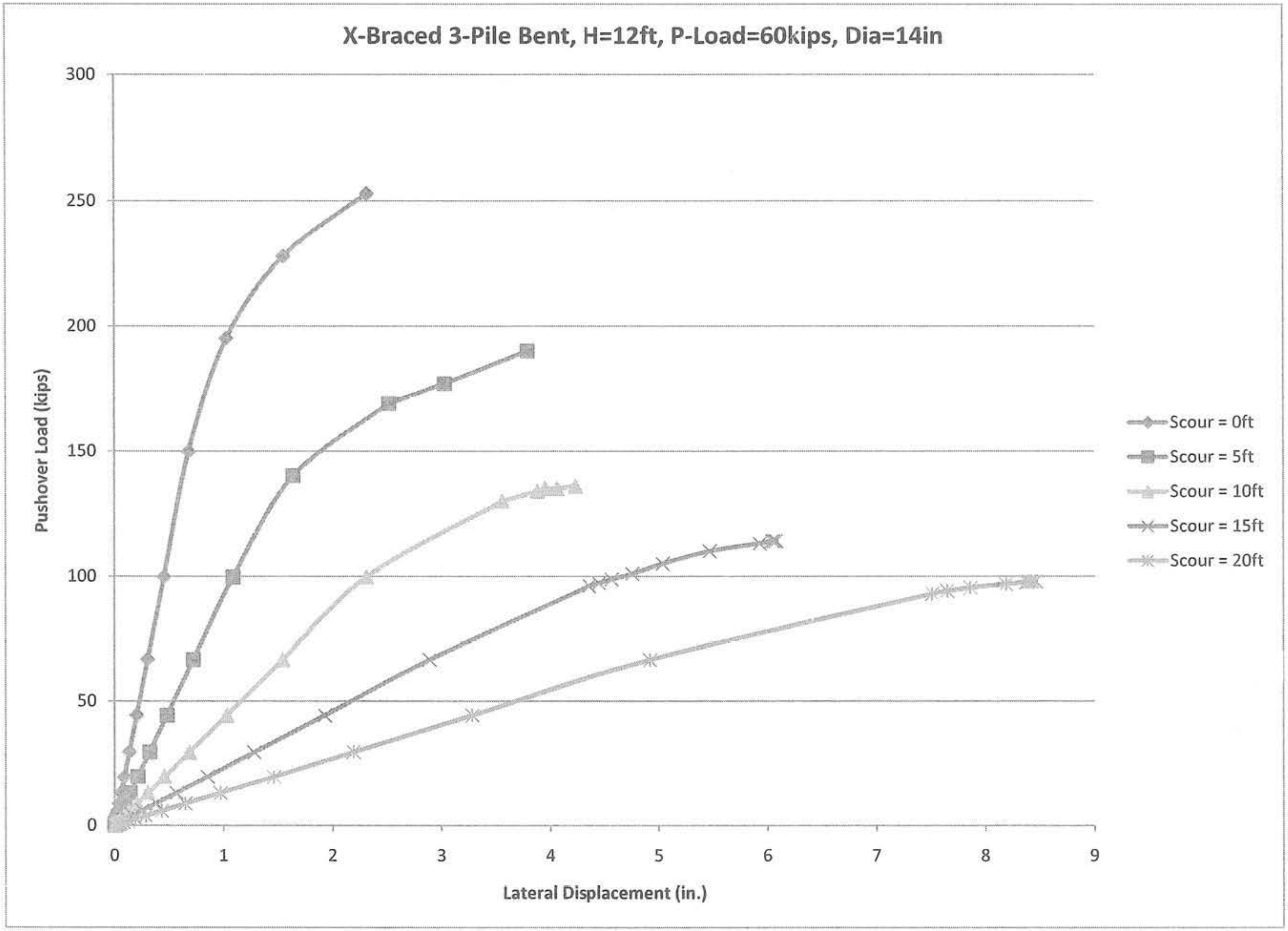


Figure A.9 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=60kips, Diameter=14in, Multiple Levels of Scour

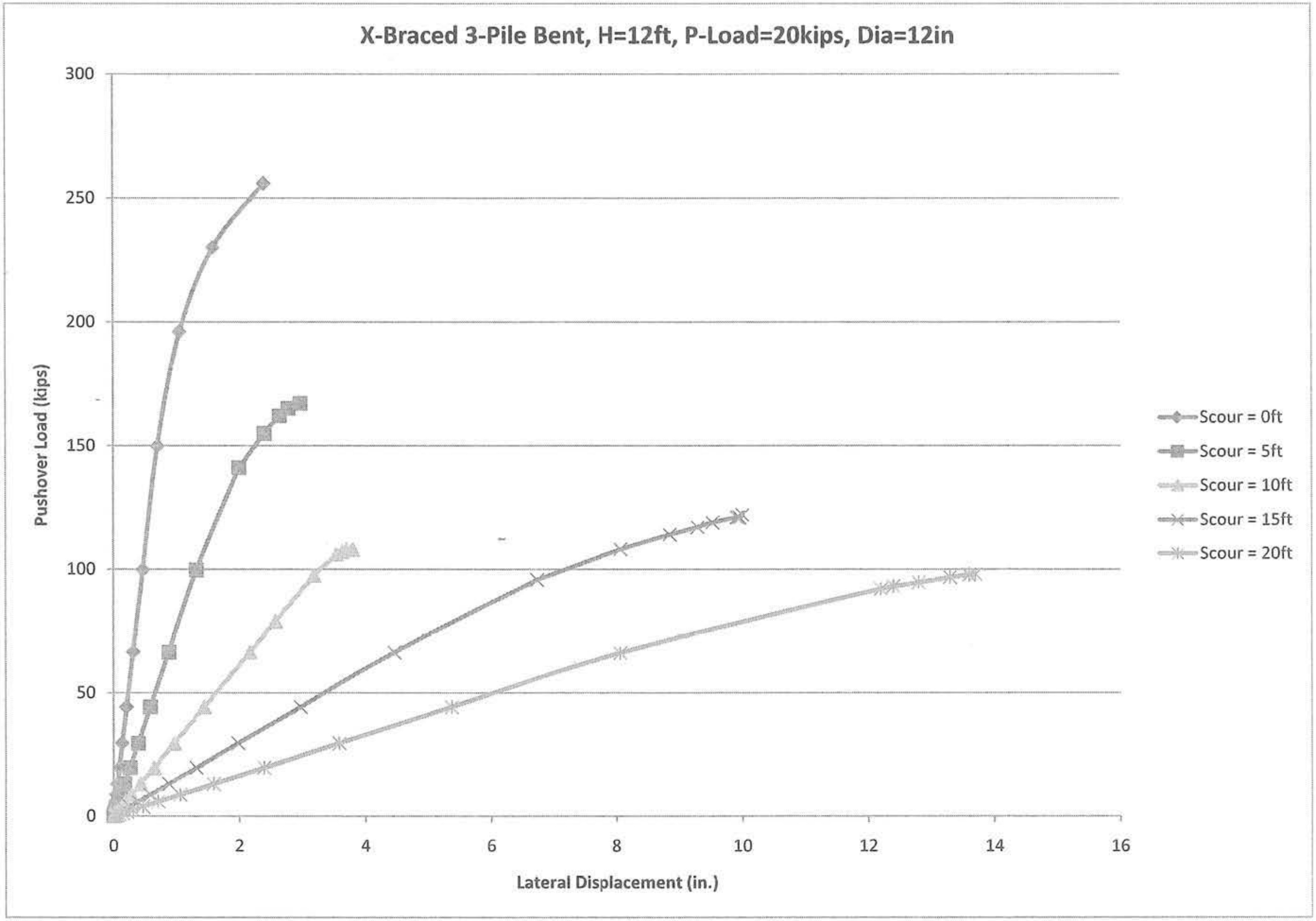


Figure A.10 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=20kips, Diameter=12in, Multiple Levels of Scour

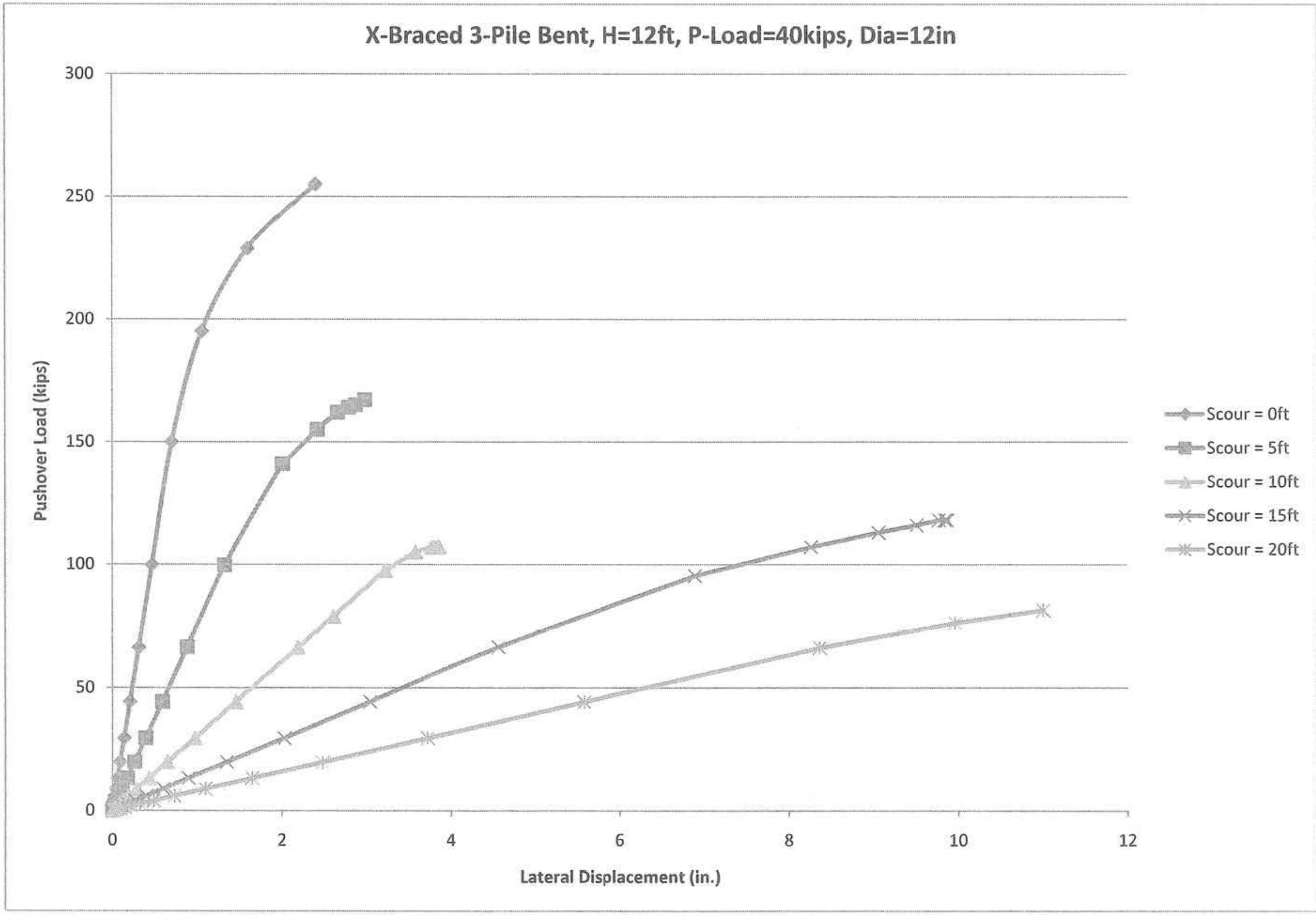


Figure A.11 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=40kips, Diameter=12in, Multiple Levels of Scour

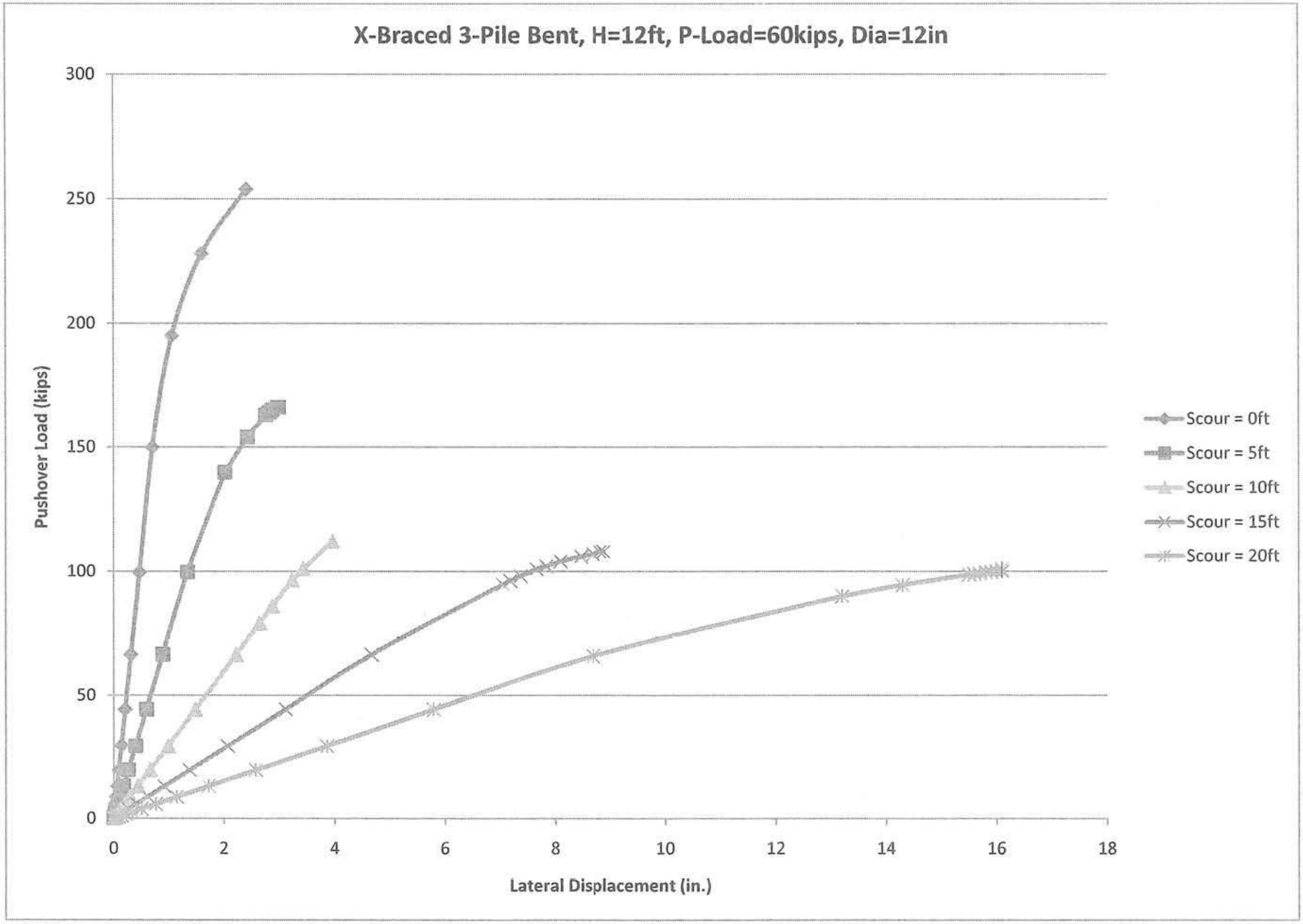


Figure A.12 Pushover Curves for X-Braced 3-Pile Bent, H=12ft, P=60kips, Diameter=12in, Multiple Levels of Scour

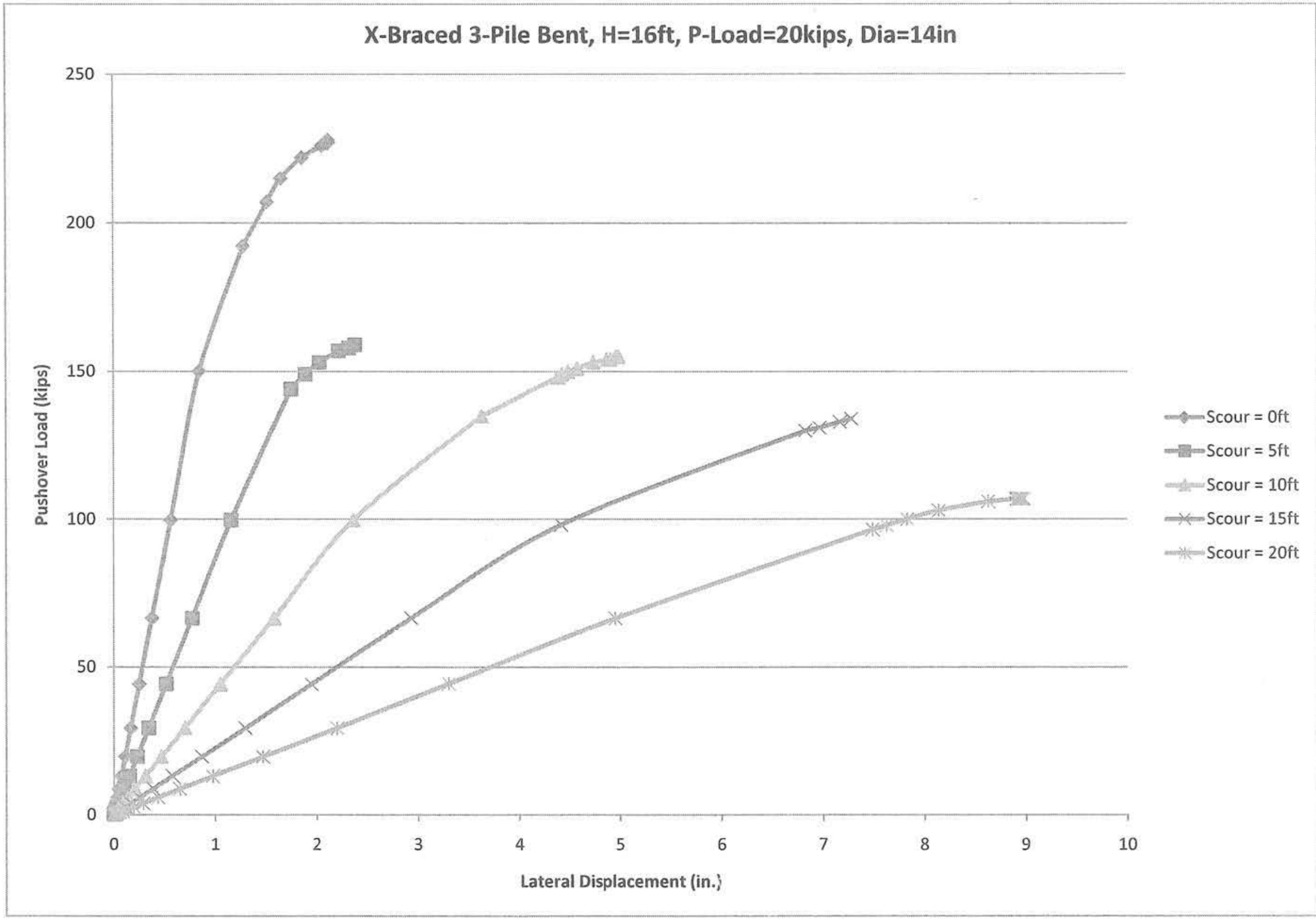


Figure A.13 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=20kips, Diameter=14in, Multiple Levels of Scour

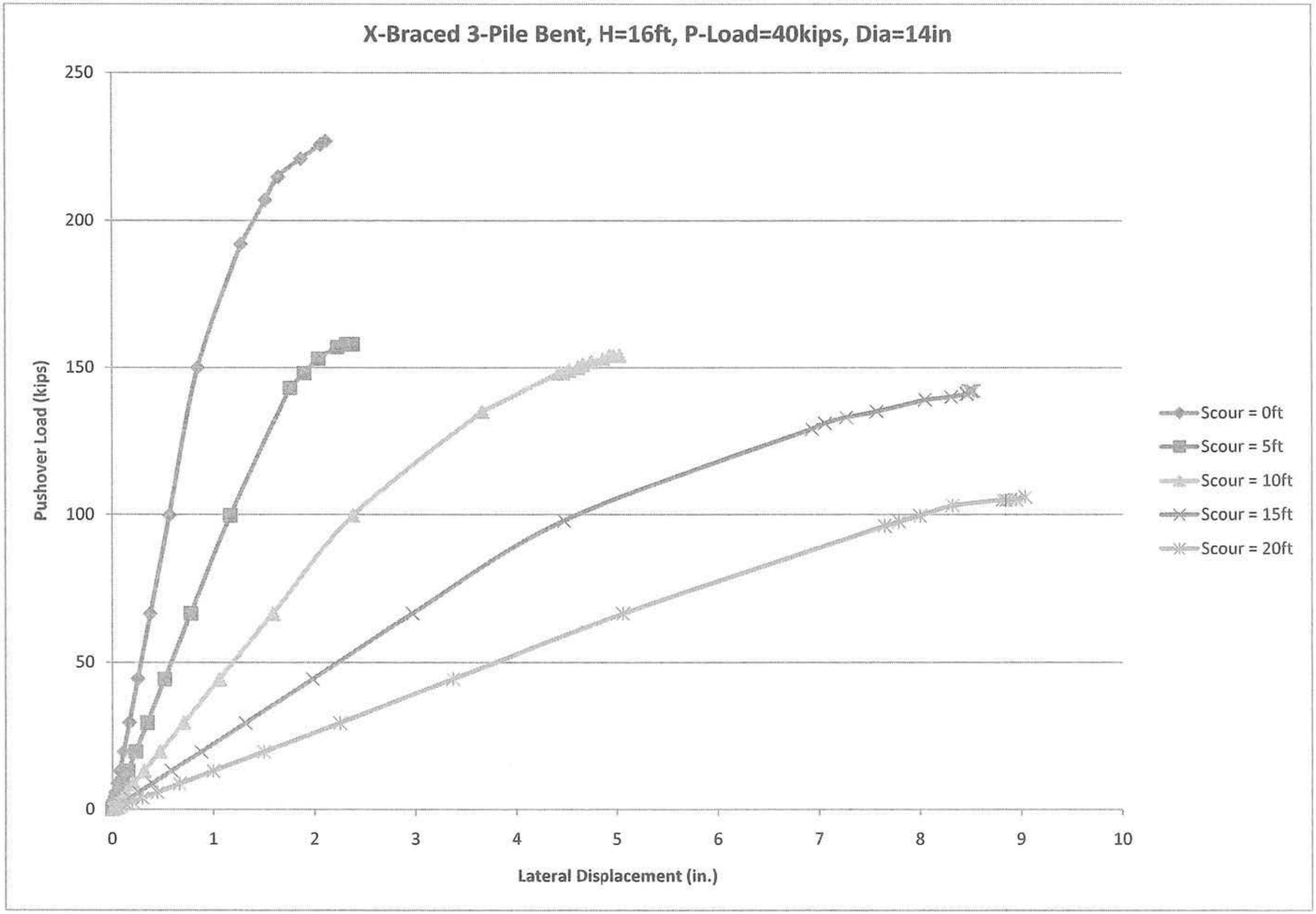


Figure A.14 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=40kips, Diameter=14in, Multiple Levels of Scour

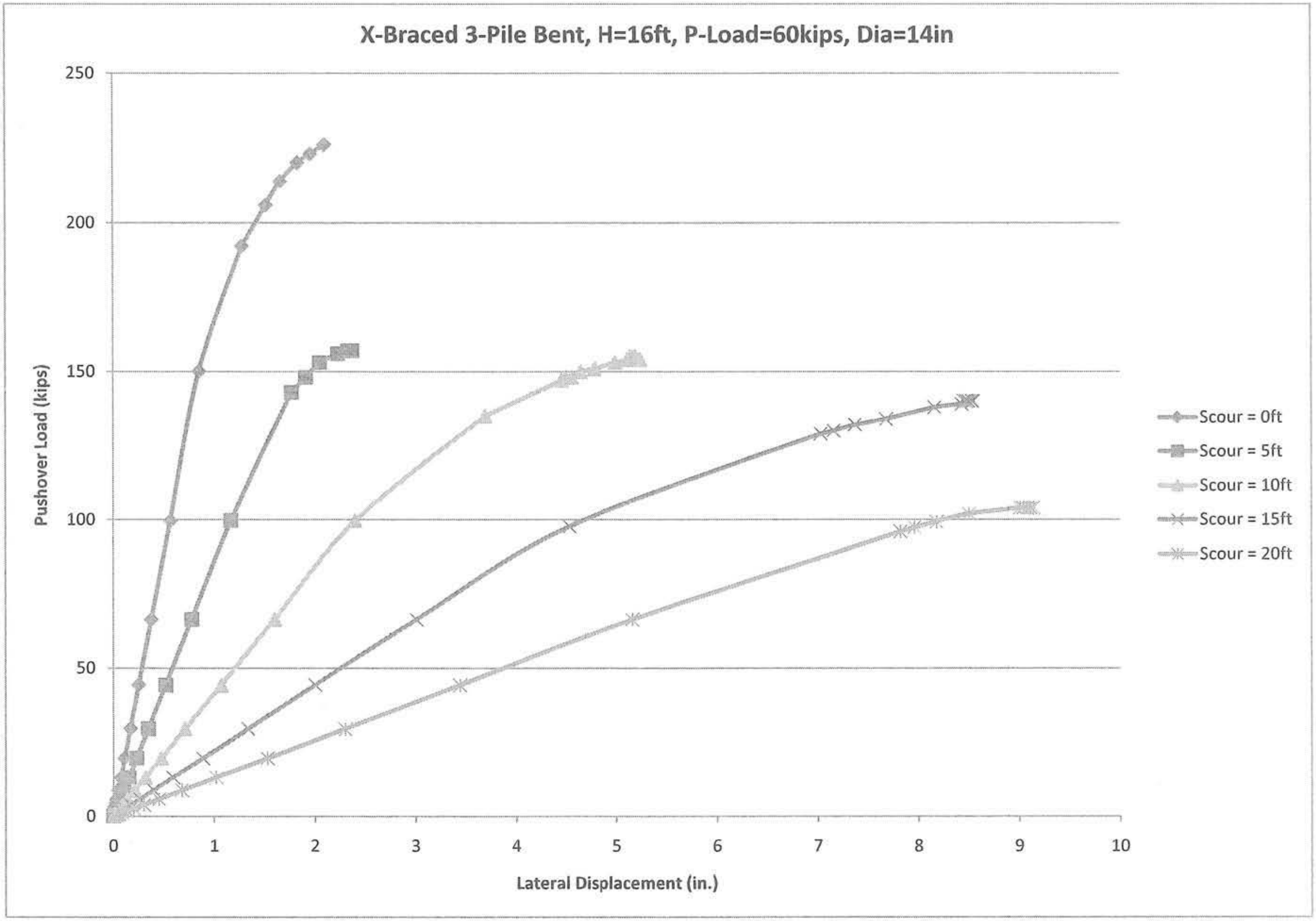


Figure A.15 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=60kips, Diameter=14in, Multiple Levels of Scour

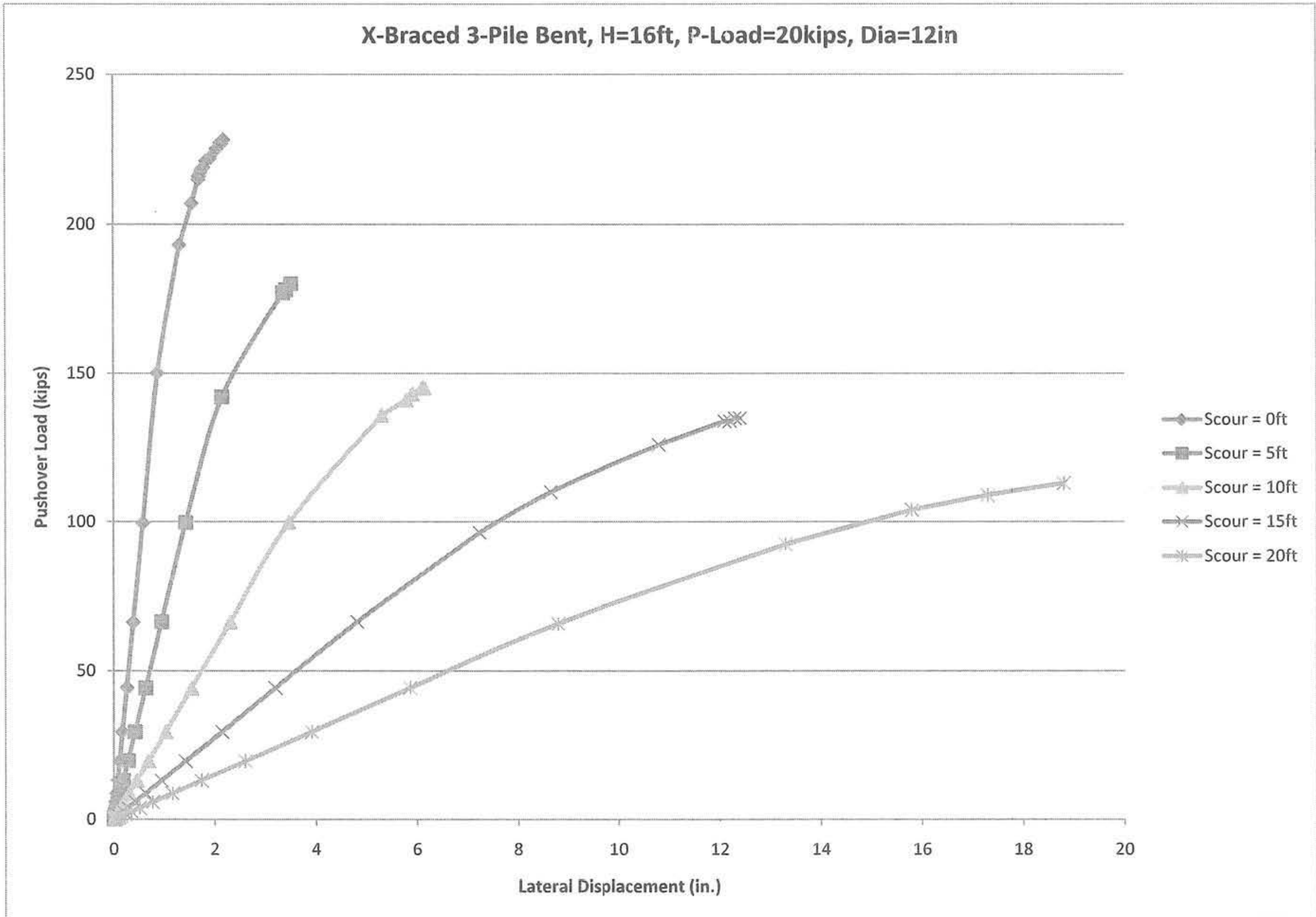


Figure A.16 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=20kips, Diameter=12in, Multiple Levels of Scour

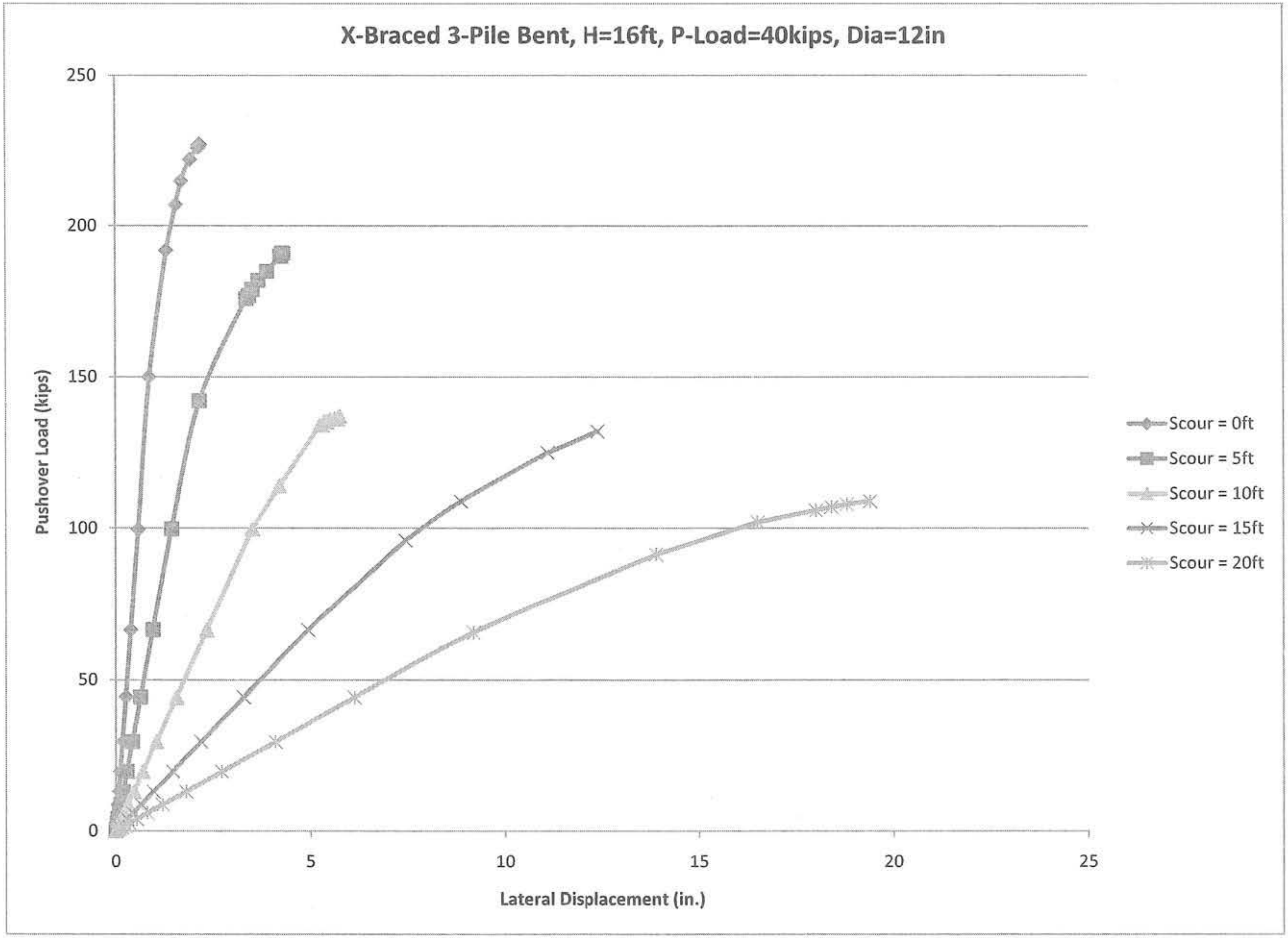


Figure A.17 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=40kips, Diameter=12in, Multiple Levels of Scour

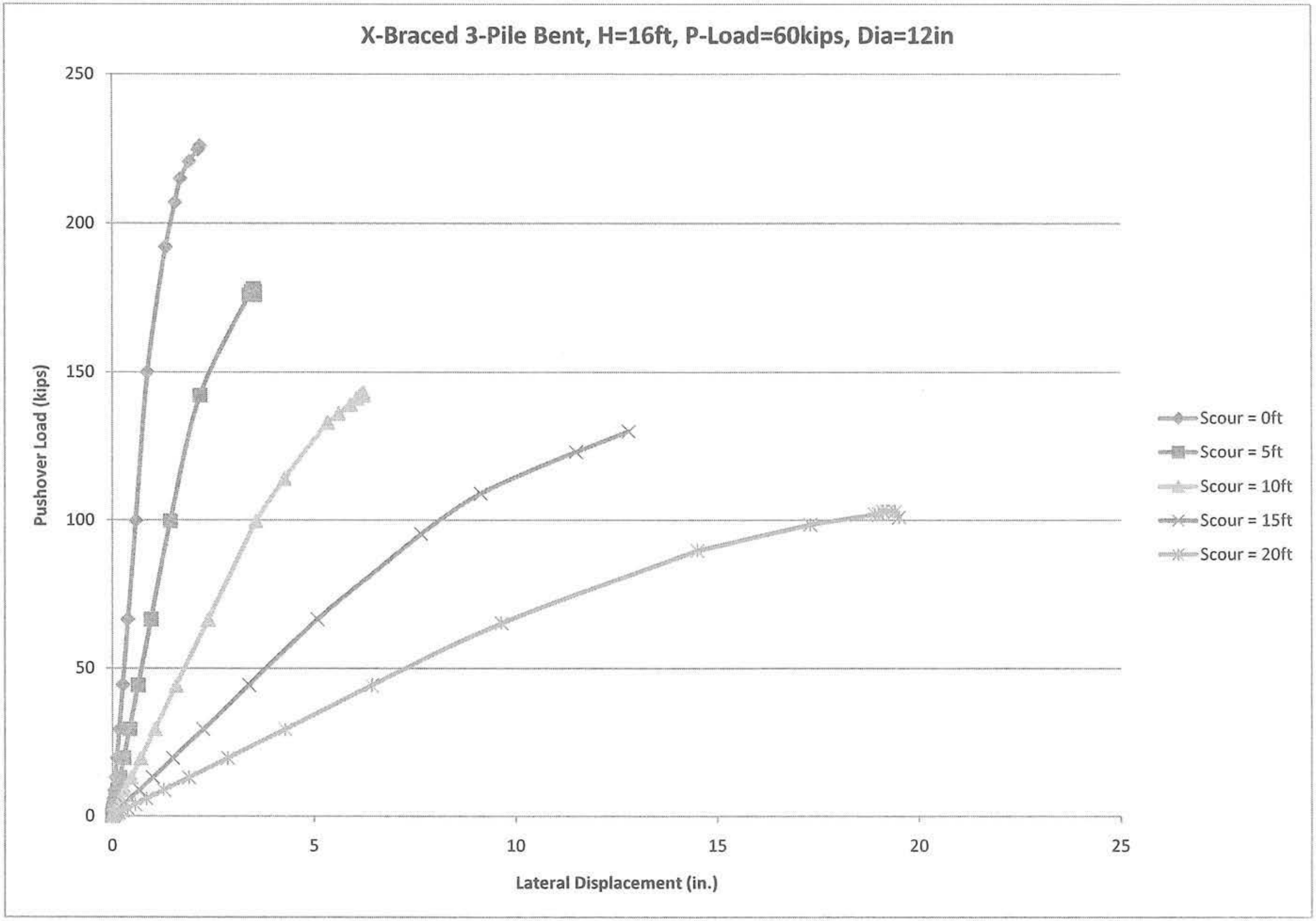


Figure A.18 Pushover Curves for X-Braced 3-Pile Bent, H=16ft, P=60kips, Diameter=12in, Multiple Levels of Scour

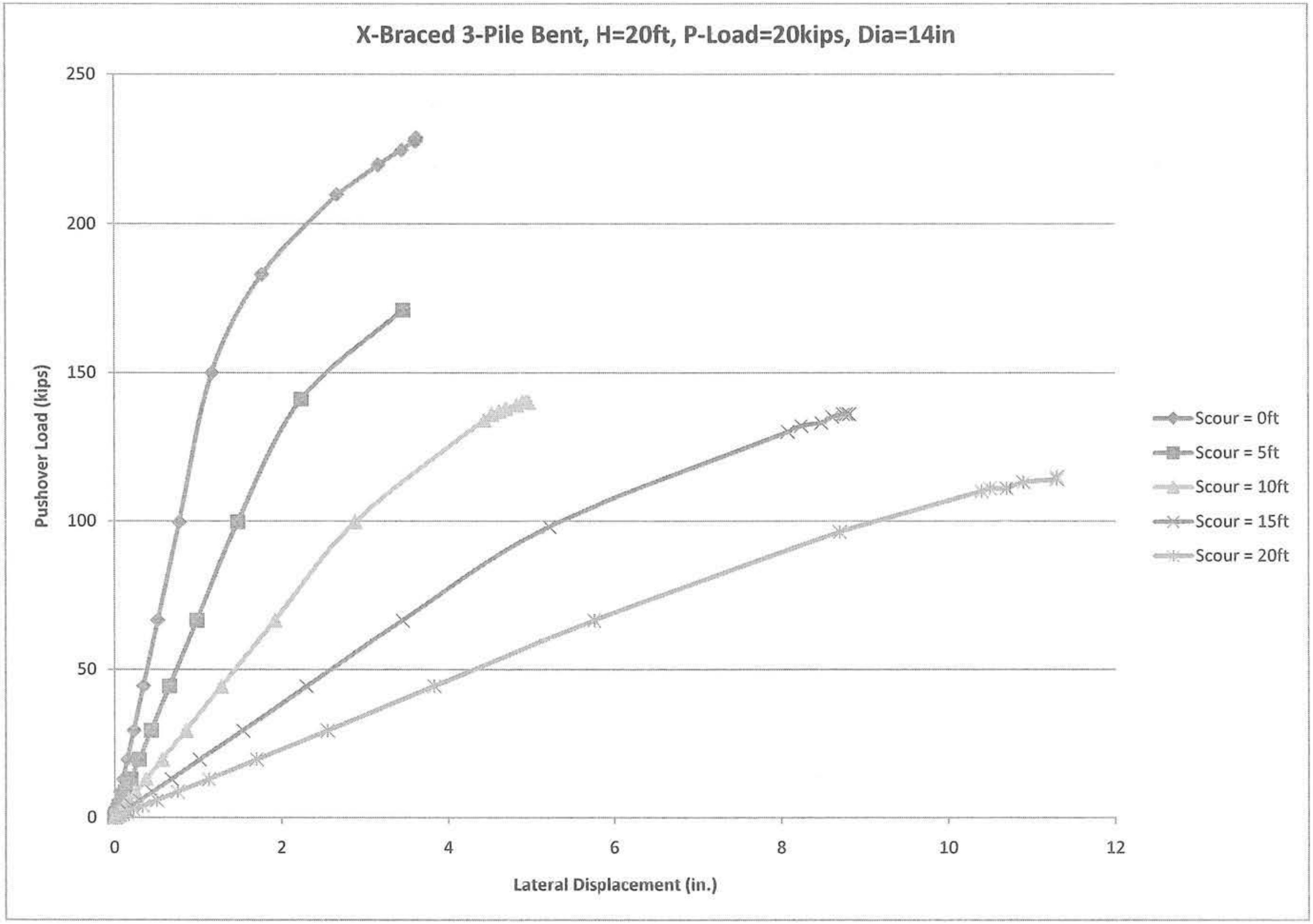


Figure A.19 Pushover Curves for X-Braced 3-Pile Bent, H=20ft, P=20kips, Diameter=14in, Multiple Levels of Scour

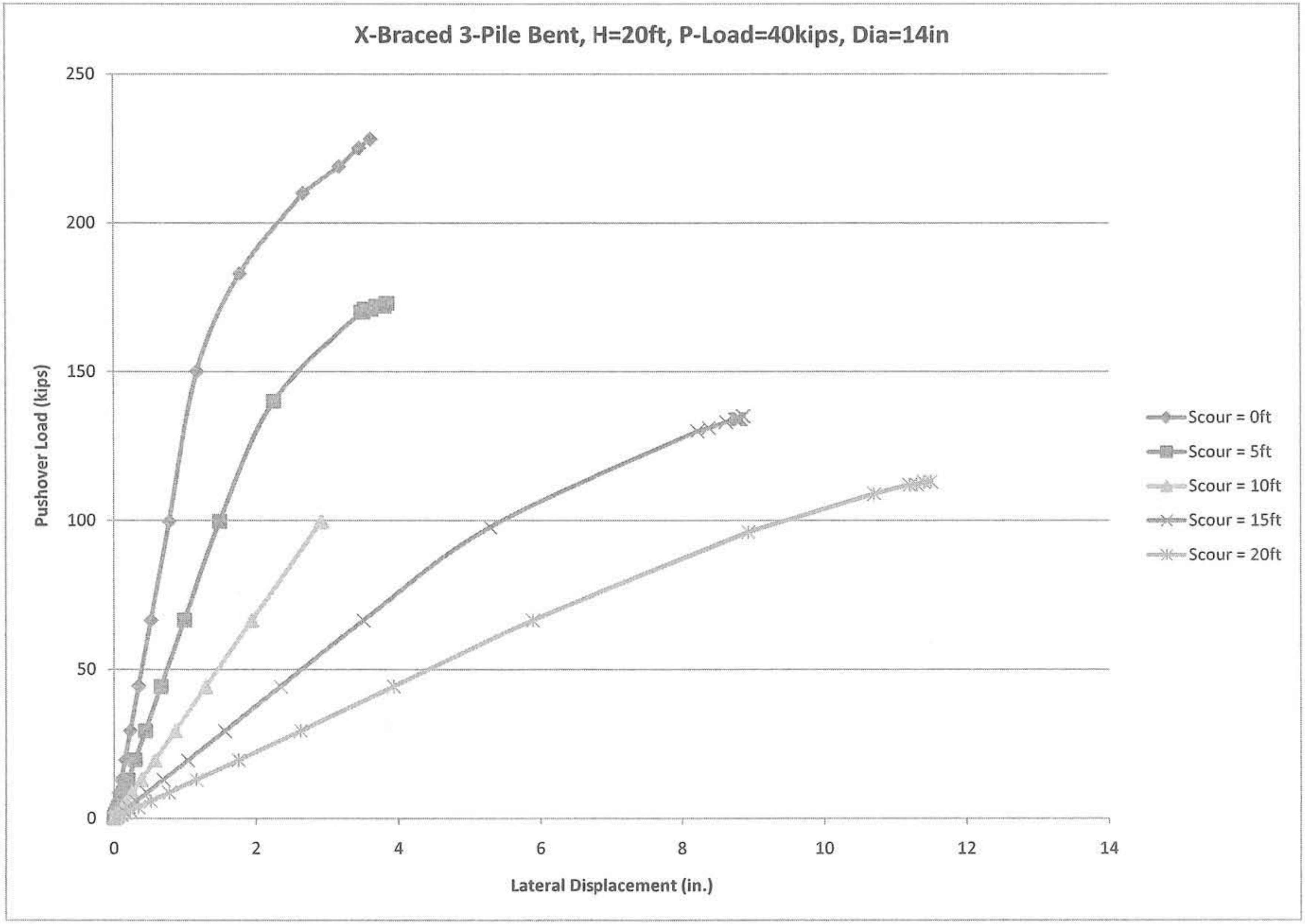


Figure A.20 Pushover Curves for X-Braced 3-Pile Bent, H=20ft, P=40kips, Diameter=14in, Multiple Levels of Scour

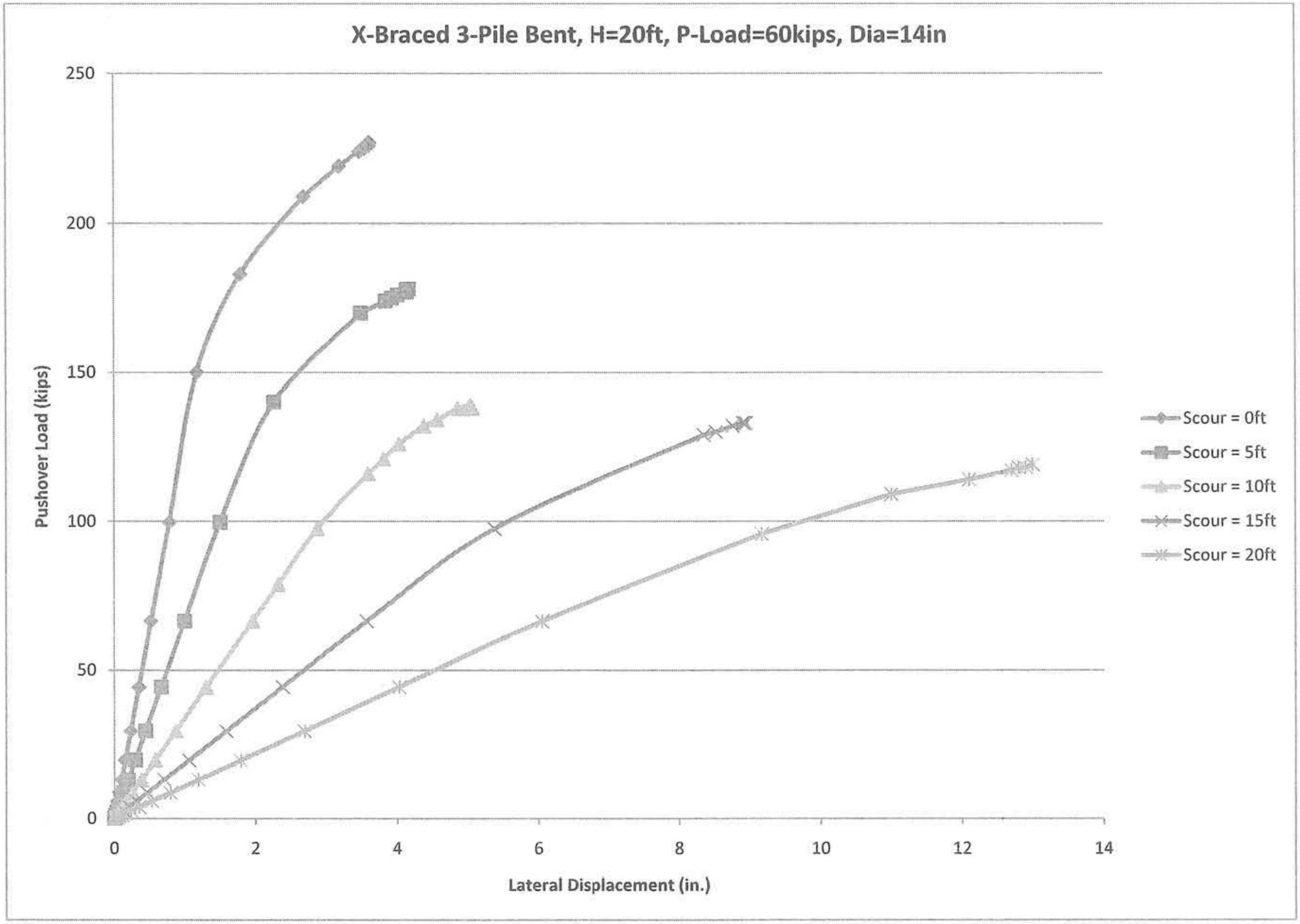


Figure A.21 Pushover Curves for X-Braced 3-Pile Bent, H=20ft, P=60kips, Diameter=14in, Multiple Levels of Scour

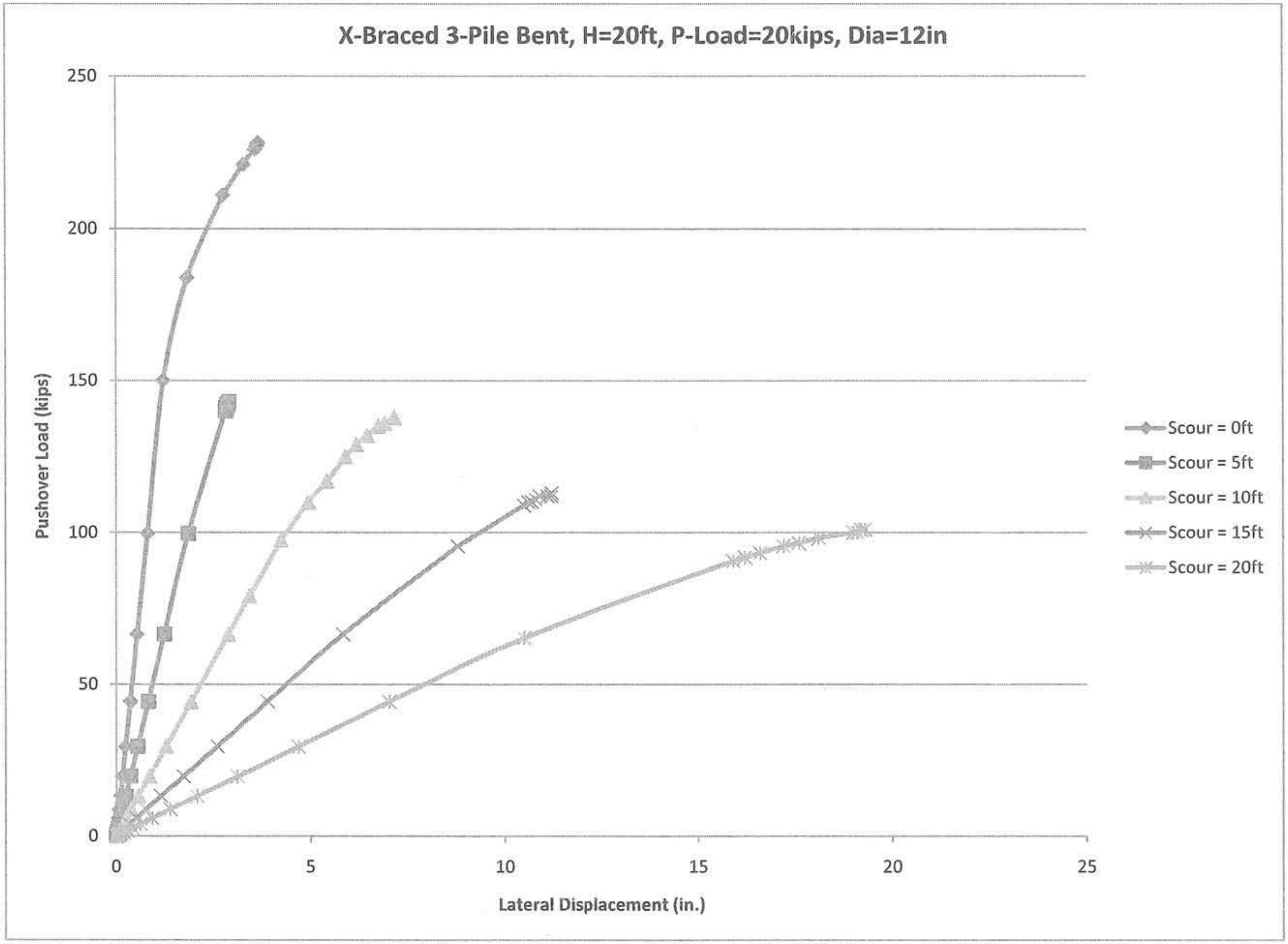


Figure A.22 Pushover Curves for X-Braced 3-Pile Bent, H=20ft, P=20kips, Diameter=12in, Multiple Levels of Scour

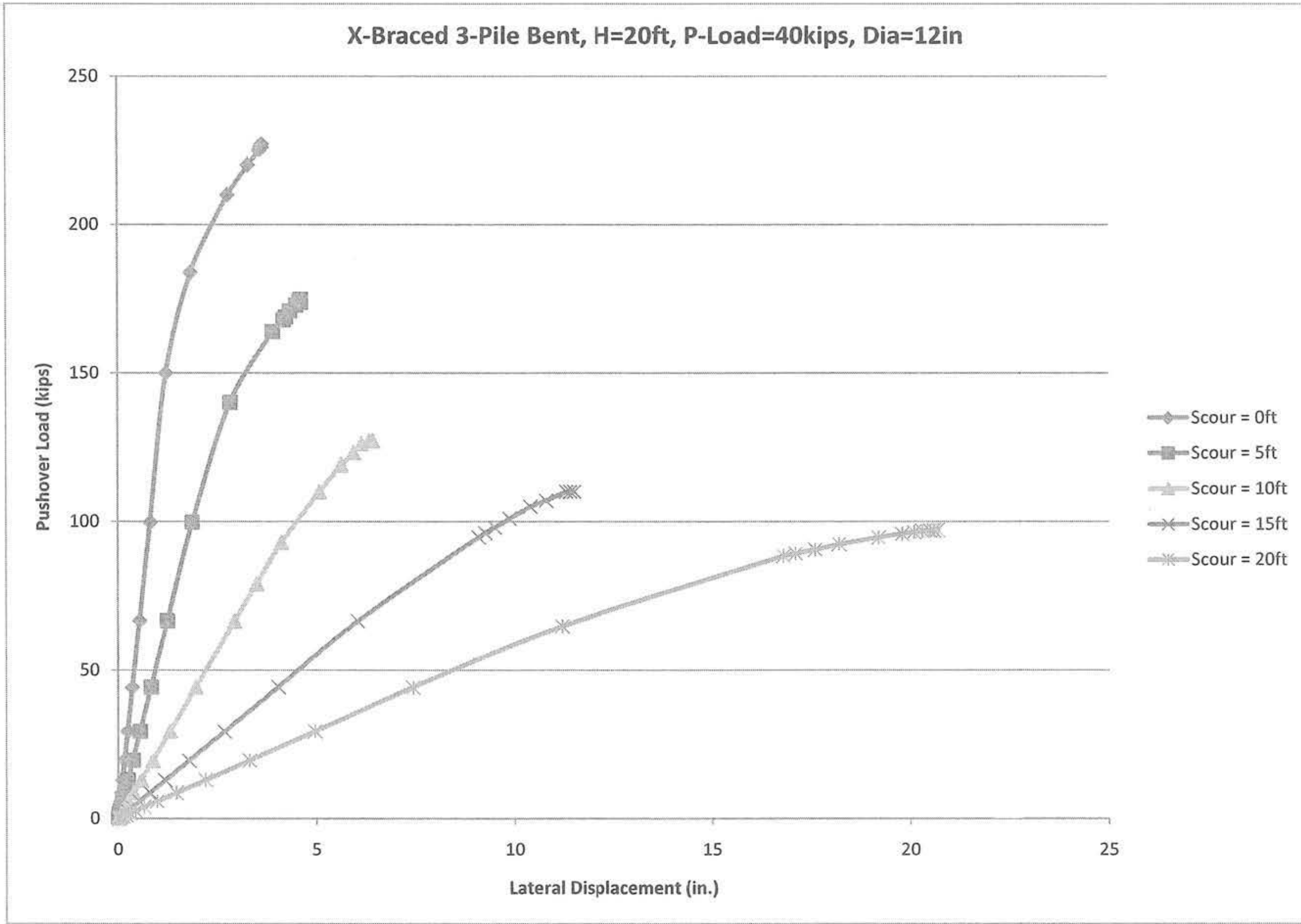


Figure A.23 Pushover Curves for X-Braced 3-Pile Bent, H=20ft, P=40kips, Diameter=12in, Multiple Levels of Scour

APPENDIX B

Unbraced Timber Pile Bent

F_t vs Δ Pushover Curves

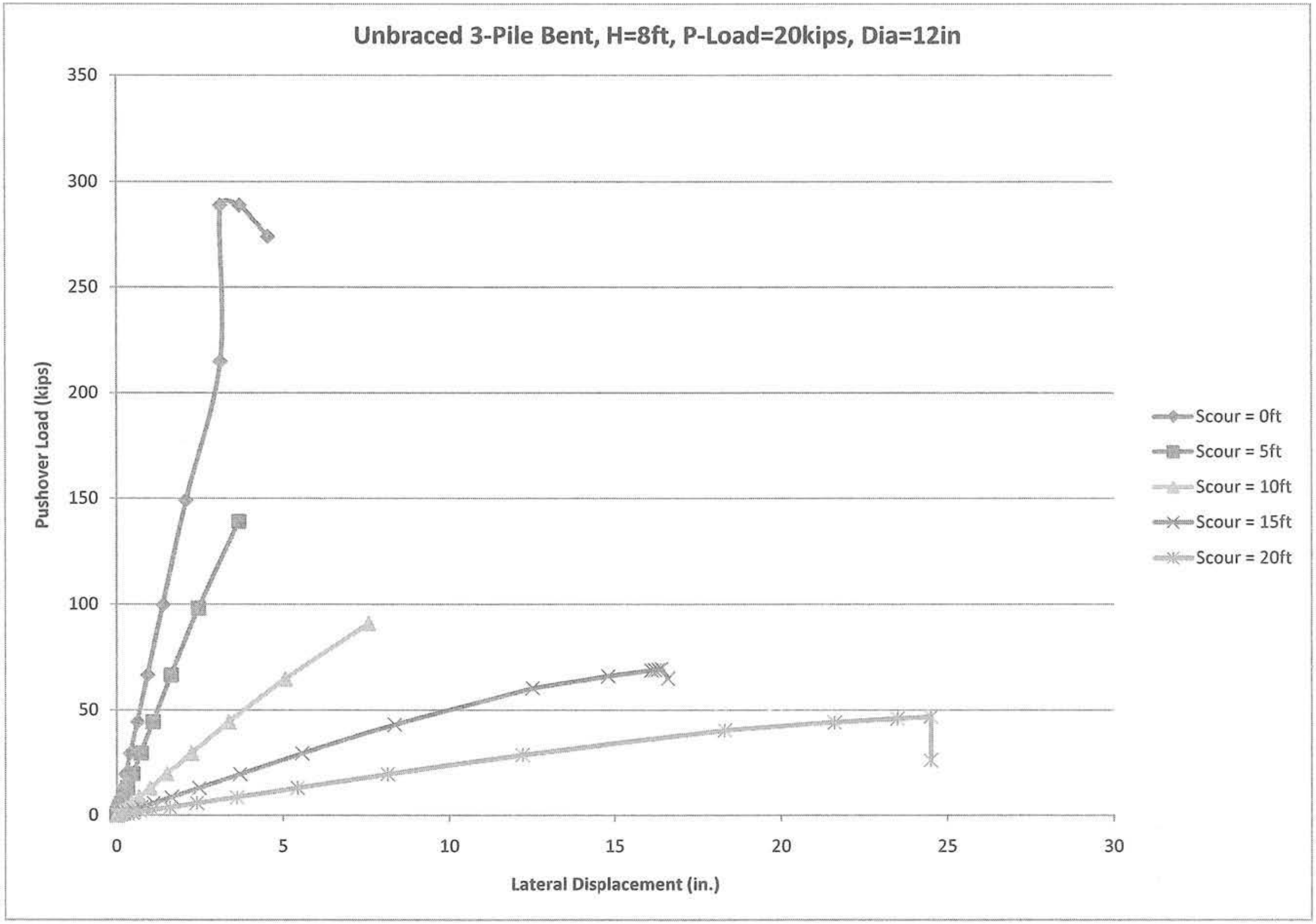


Figure B.1 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=20kips, Diameter=12in, Multiple Levels of Scour

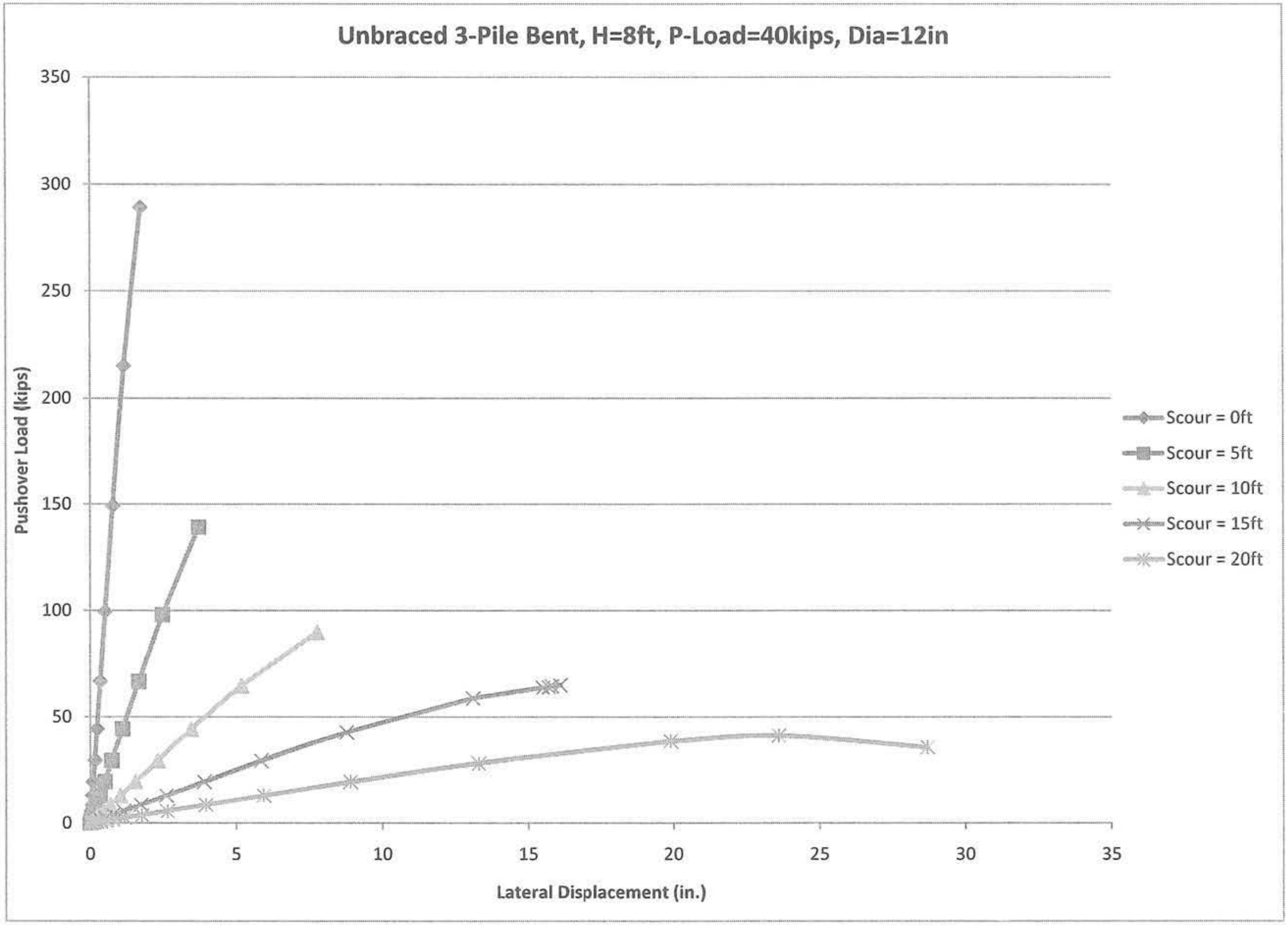


Figure B.2 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=40kips, Diameter=12in, Multiple Levels of Scour

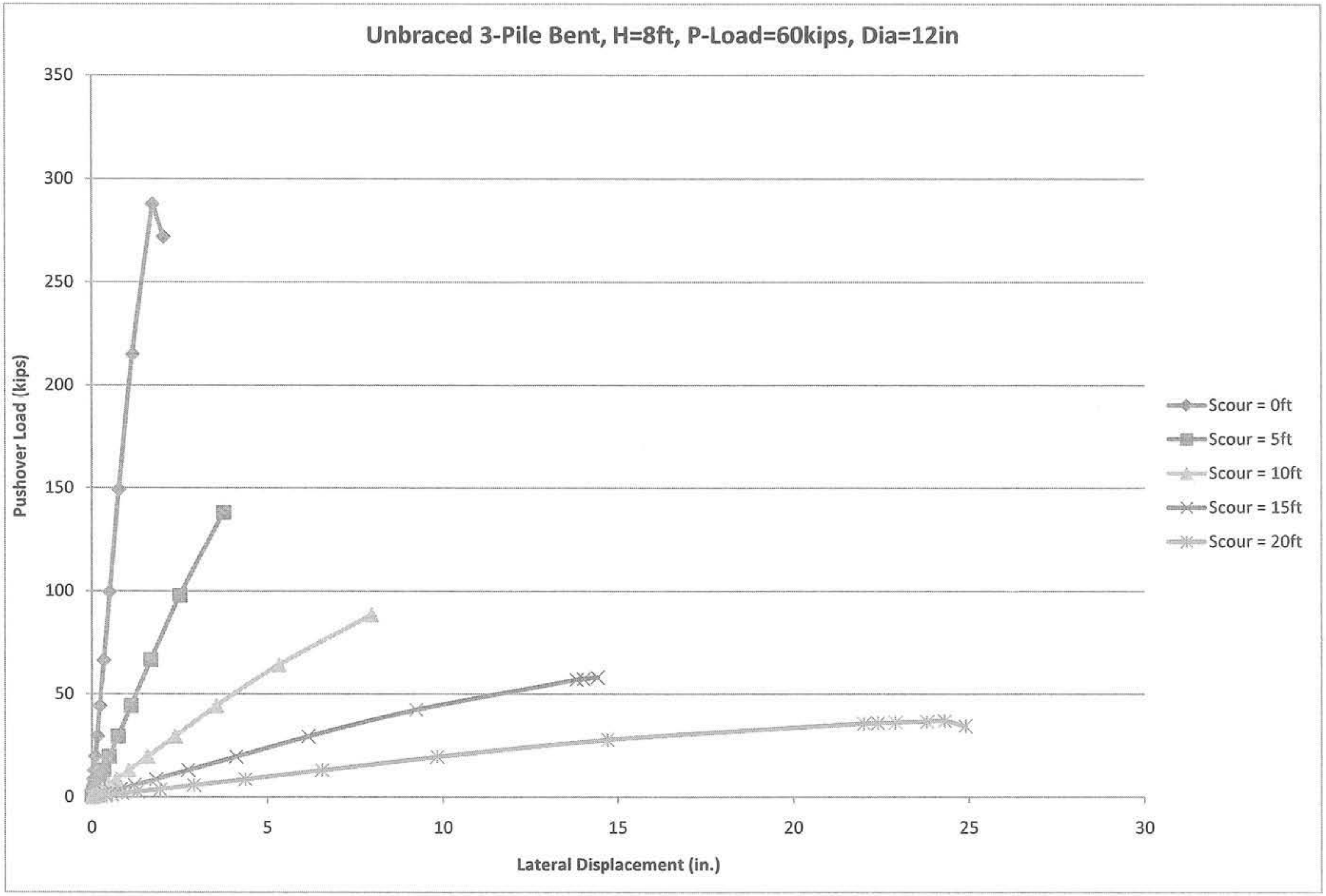


Figure B.3 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=60kips, Diameter=12in, Multiple Levels of Scour

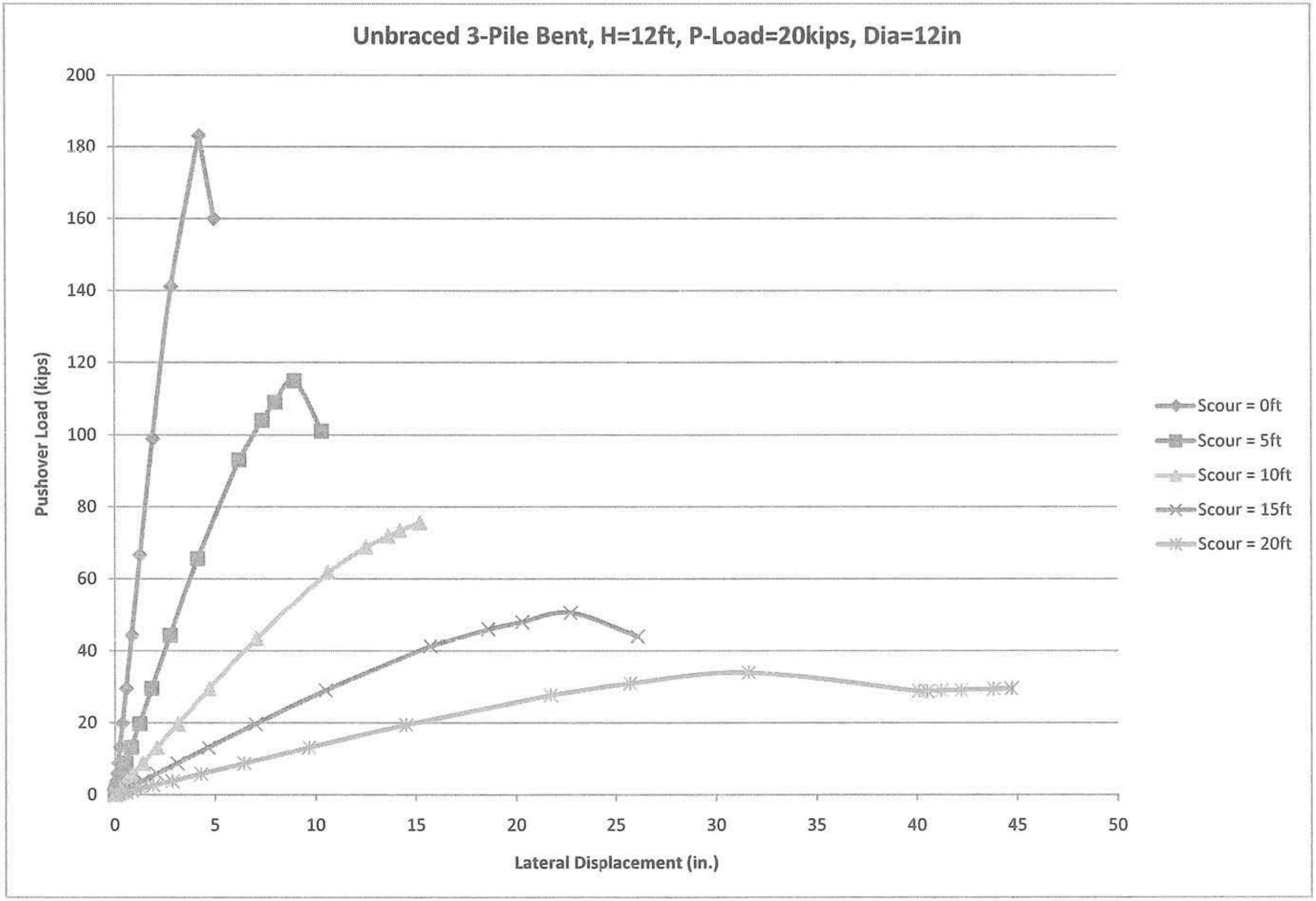


Figure B.4 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=20kips, Diameter=12in, Multiple Levels of Scour

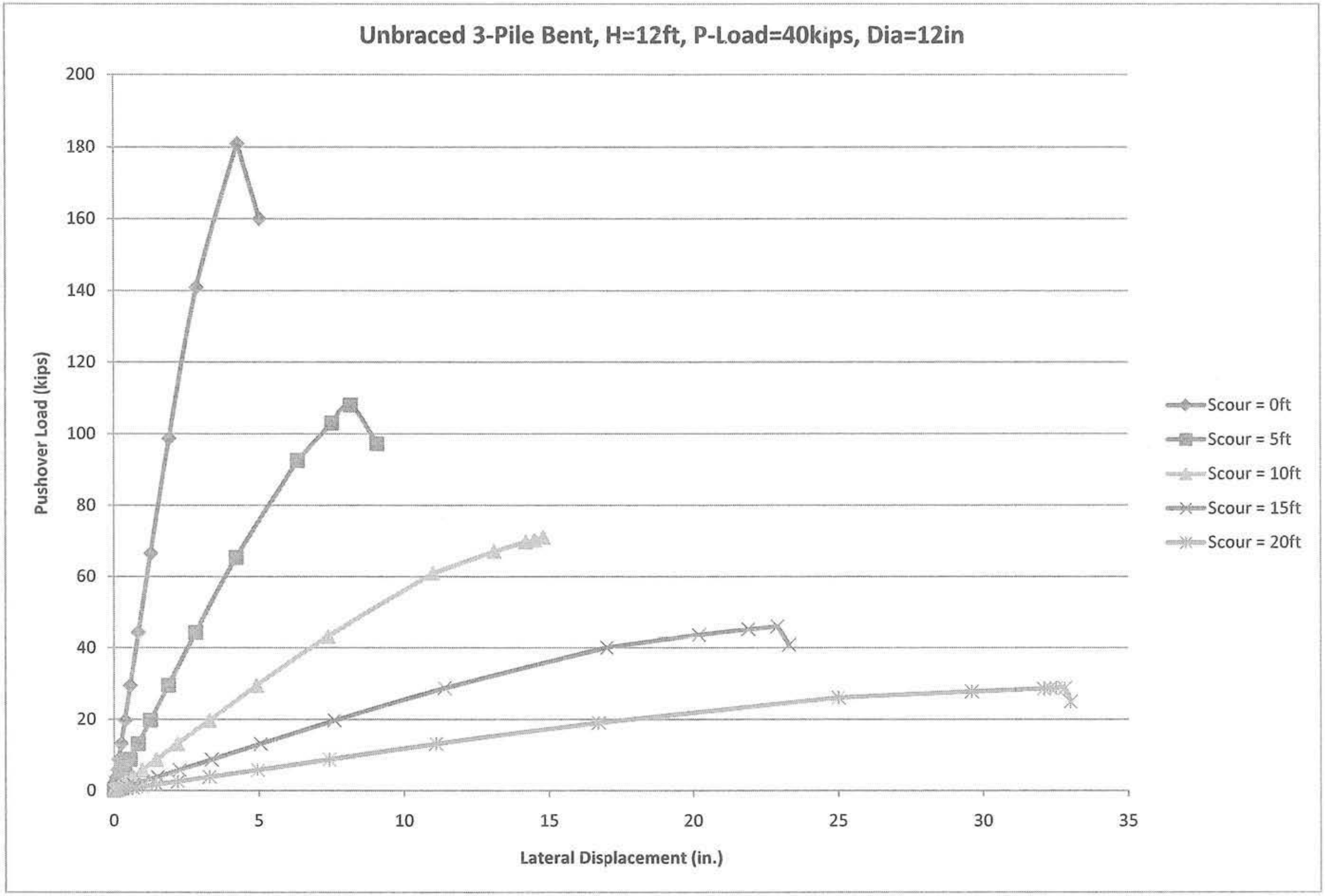


Figure B.5 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=40kips, Diameter=12in, Multiple Levels of Scour

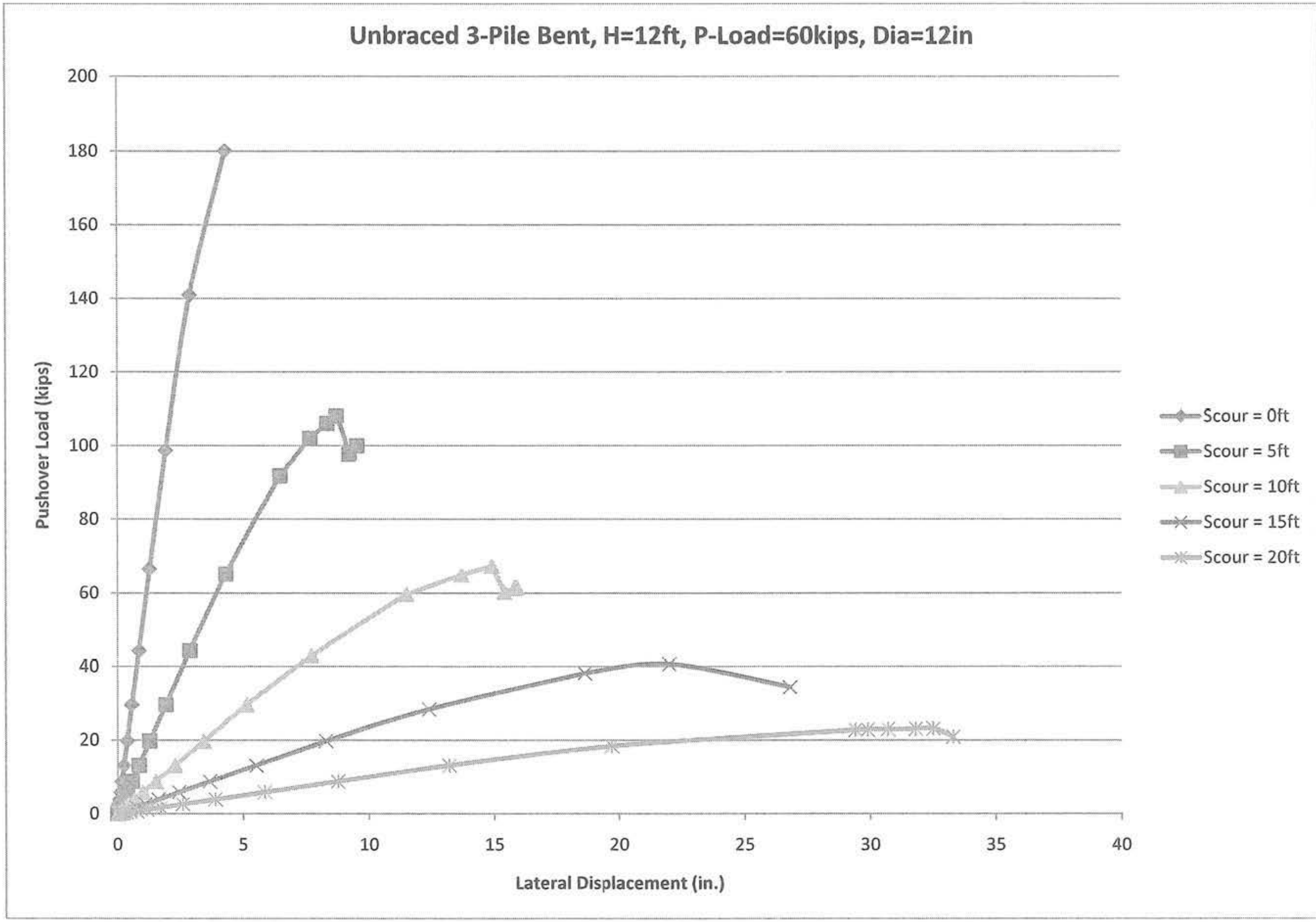


Figure B.6 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=60kips, Diameter=12in, Multiple Levels of Scour

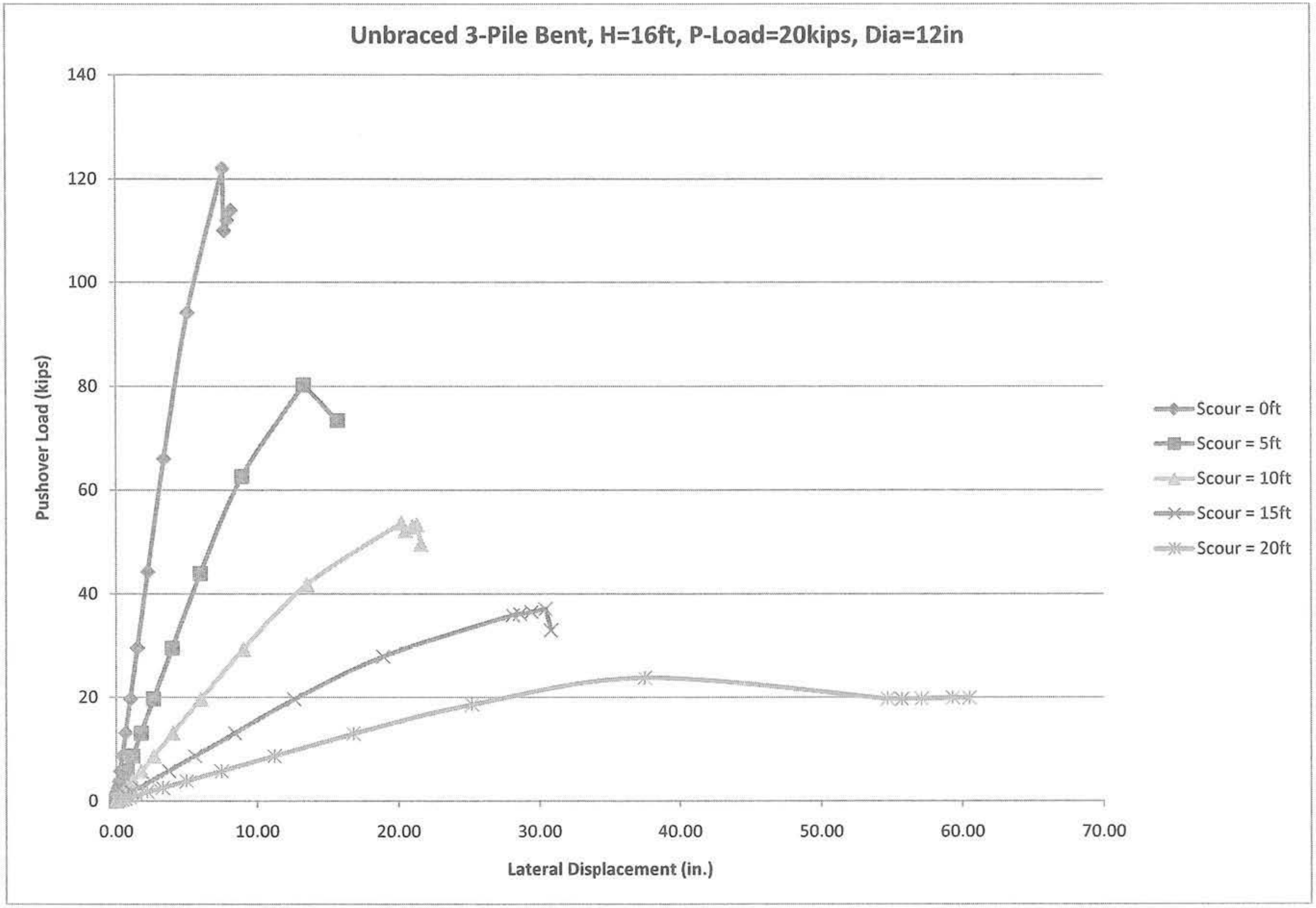


Figure B.7 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=20kips, Diameter=12in, Multiple Levels of Scour

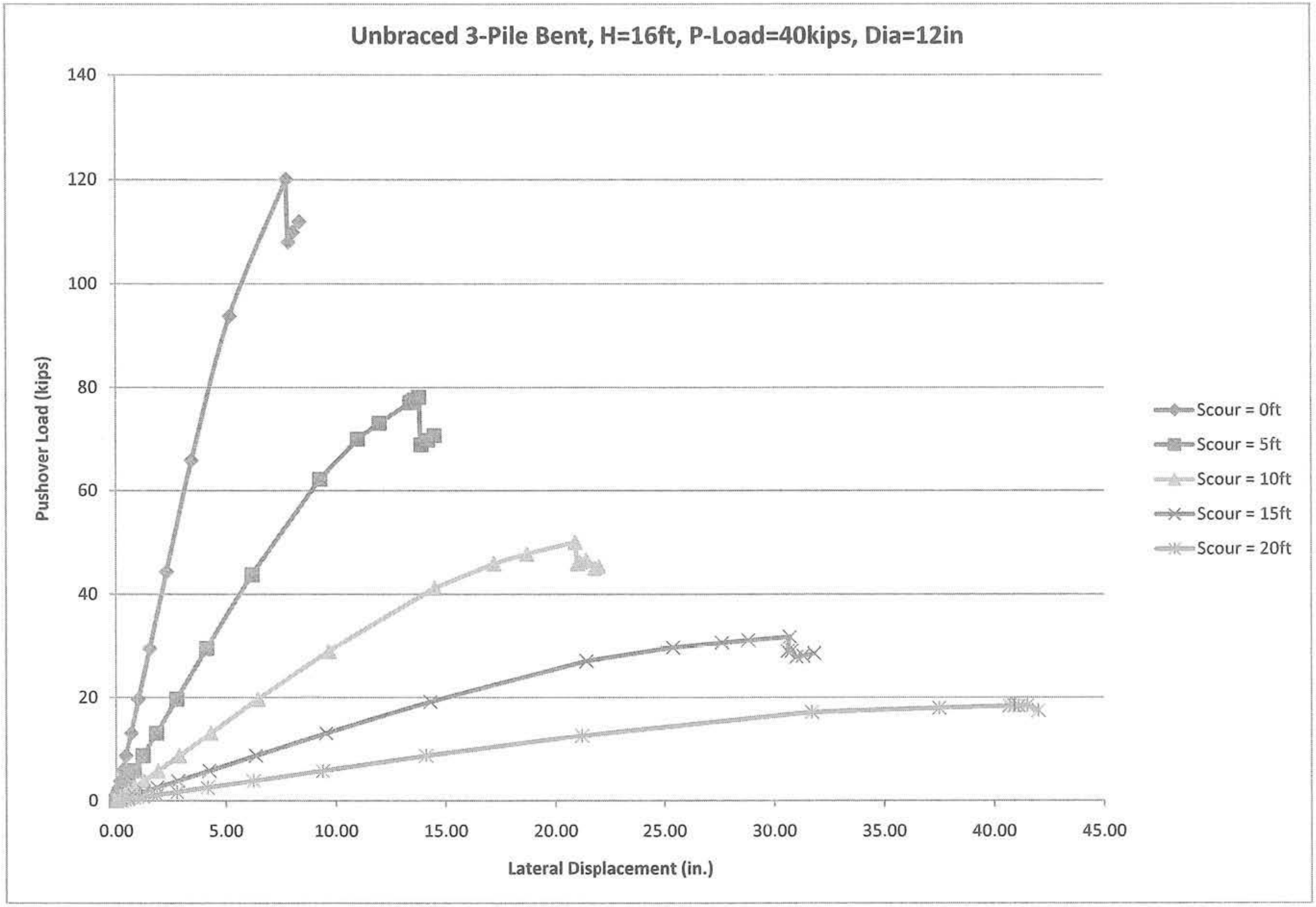


Figure B.8 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=40kips, Diameter=12in, Multiple Levels of Scour

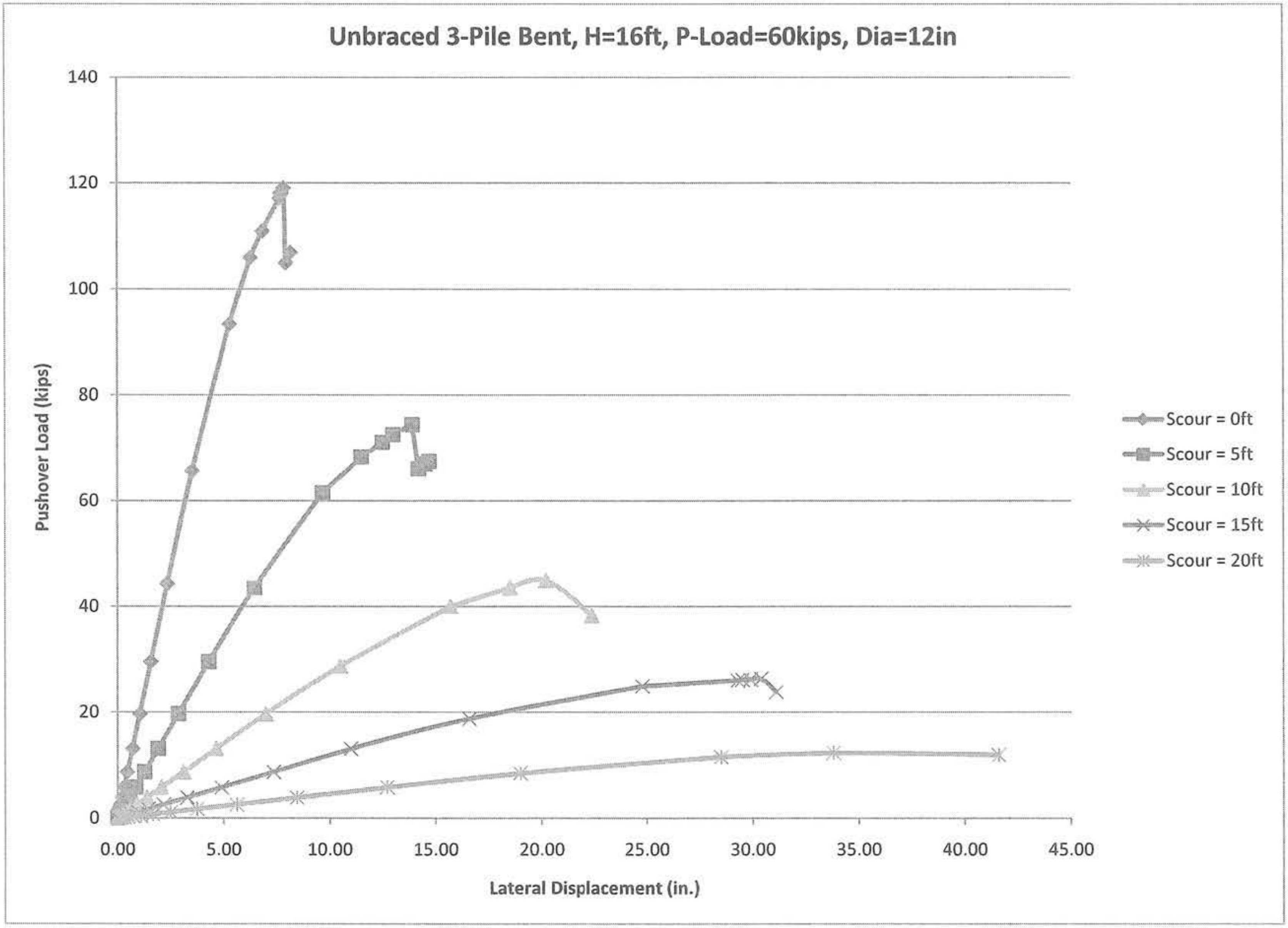


Figure B.9 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=60kips, Diameter=12in. Multiple Levels of Scour

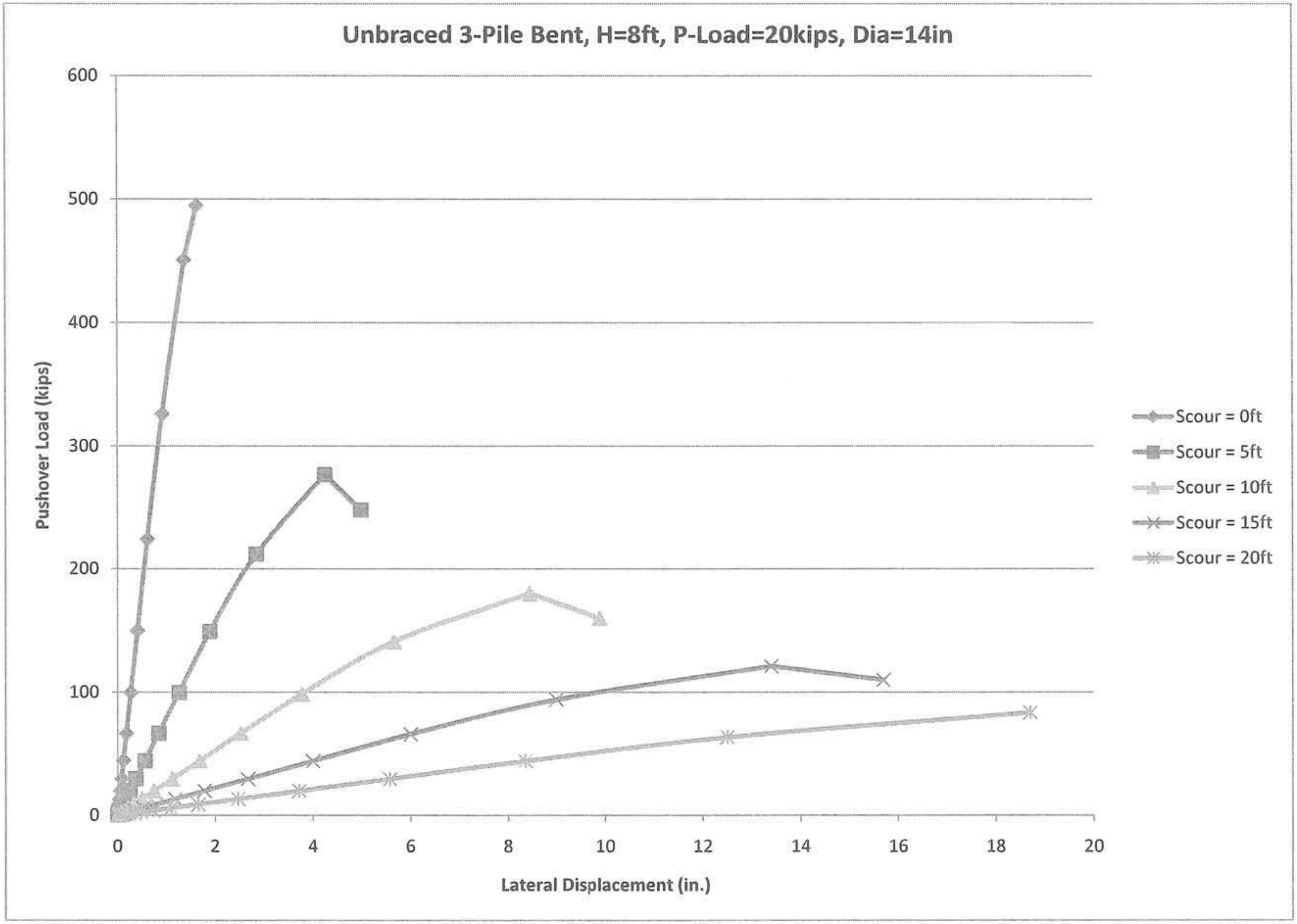


Figure B.10 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=20kips, Diameter=14in, Multiple Levels of Scour

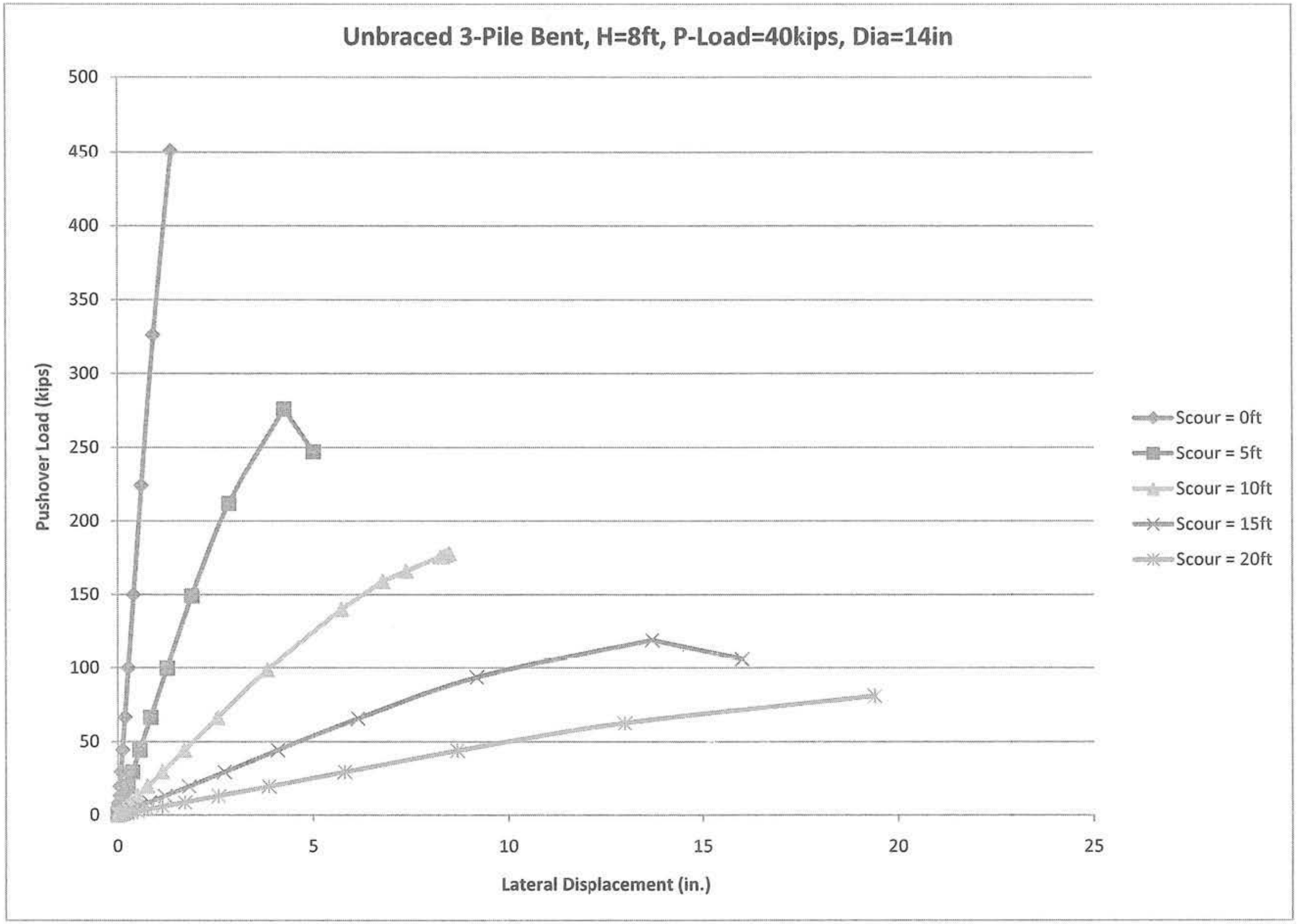


Figure B.11 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=40kips, Diameter=14in, Multiple Levels of Scour

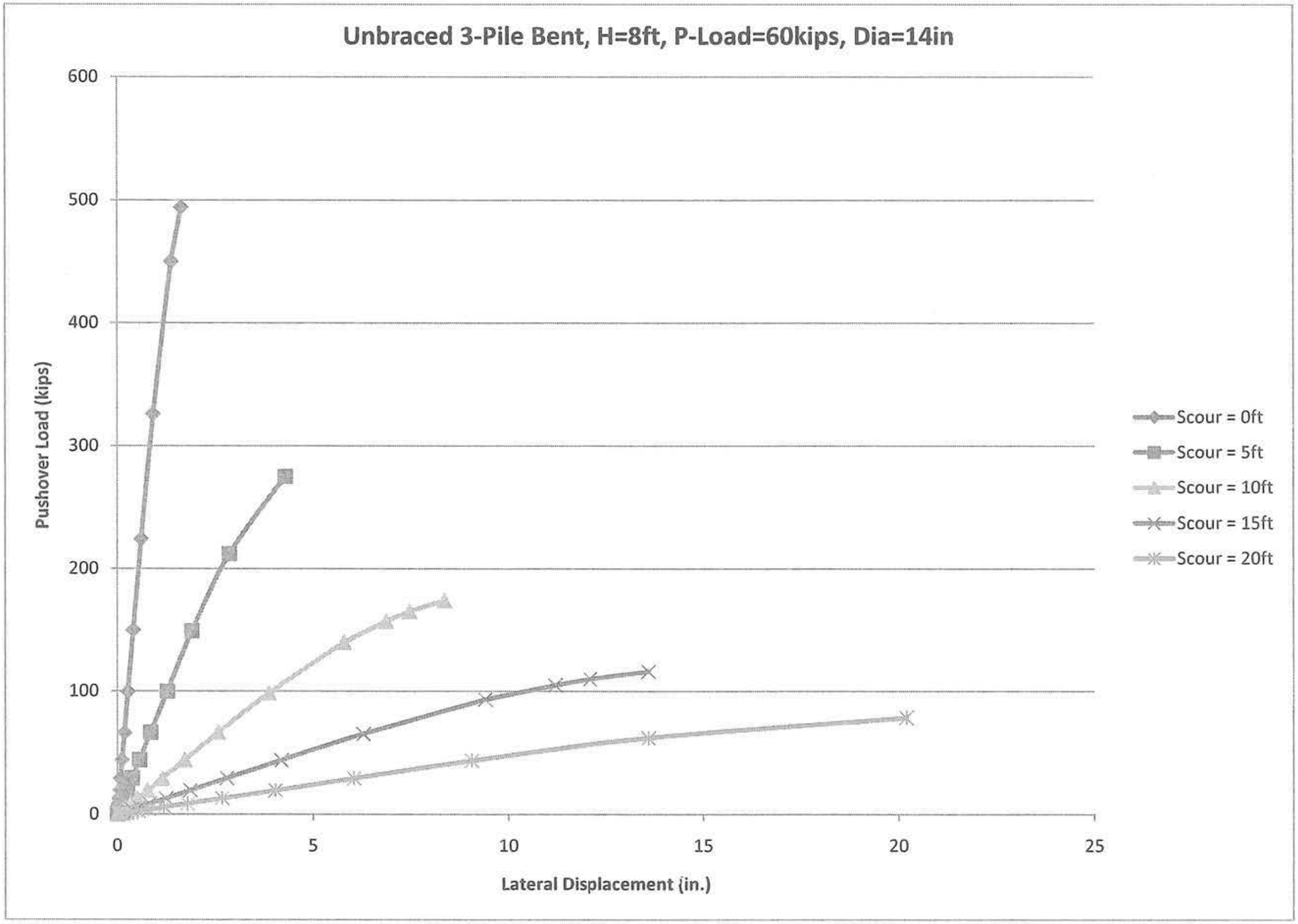


Figure B.12 Pushover Curves for Unbraced 3-Pile Bent, H=8ft, P=60kips, Diameter=14in, Multiple Levels of Scour

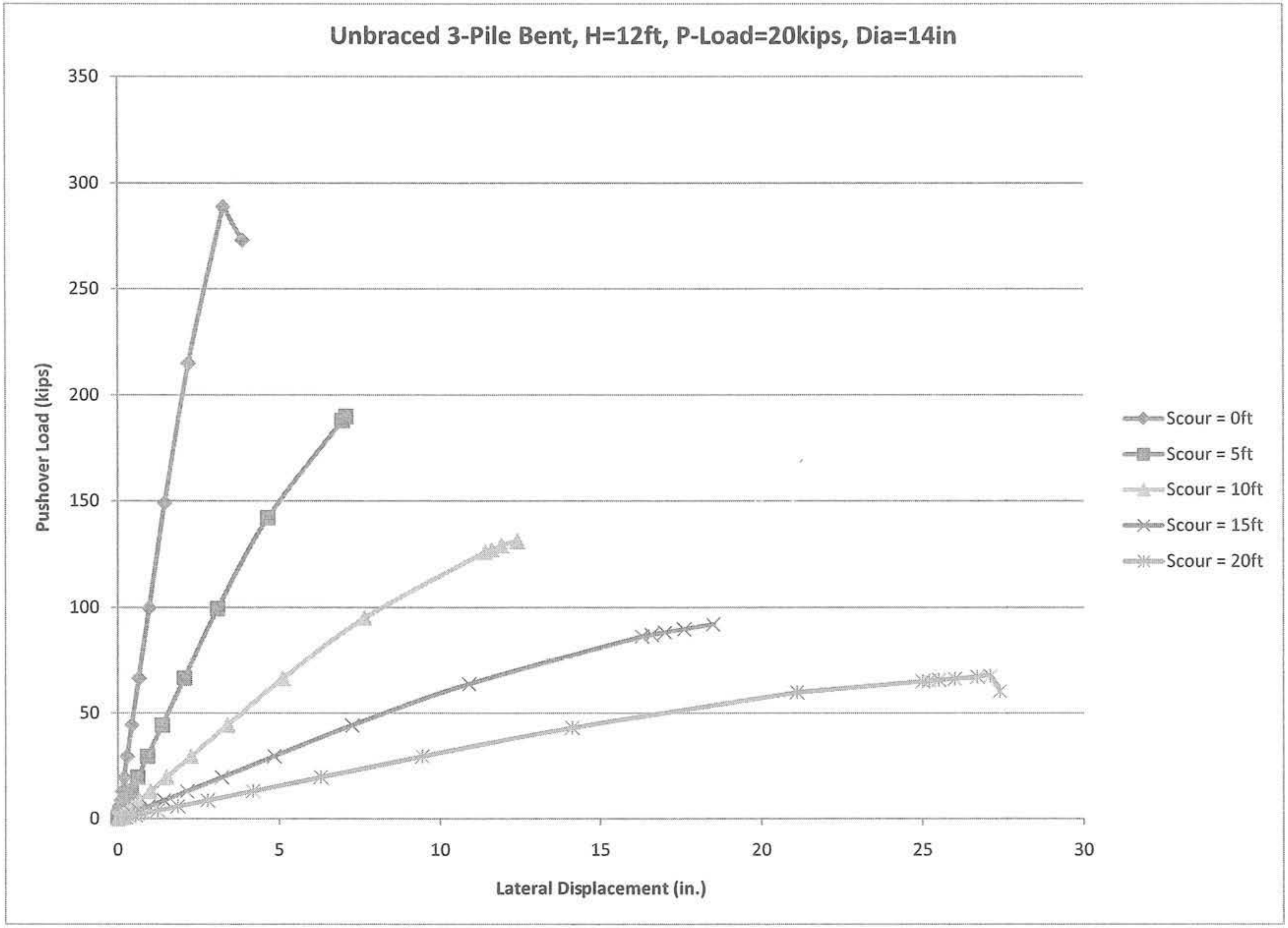


Figure B.13 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=20kips, Diameter=14in, Multiple Levels of Scour

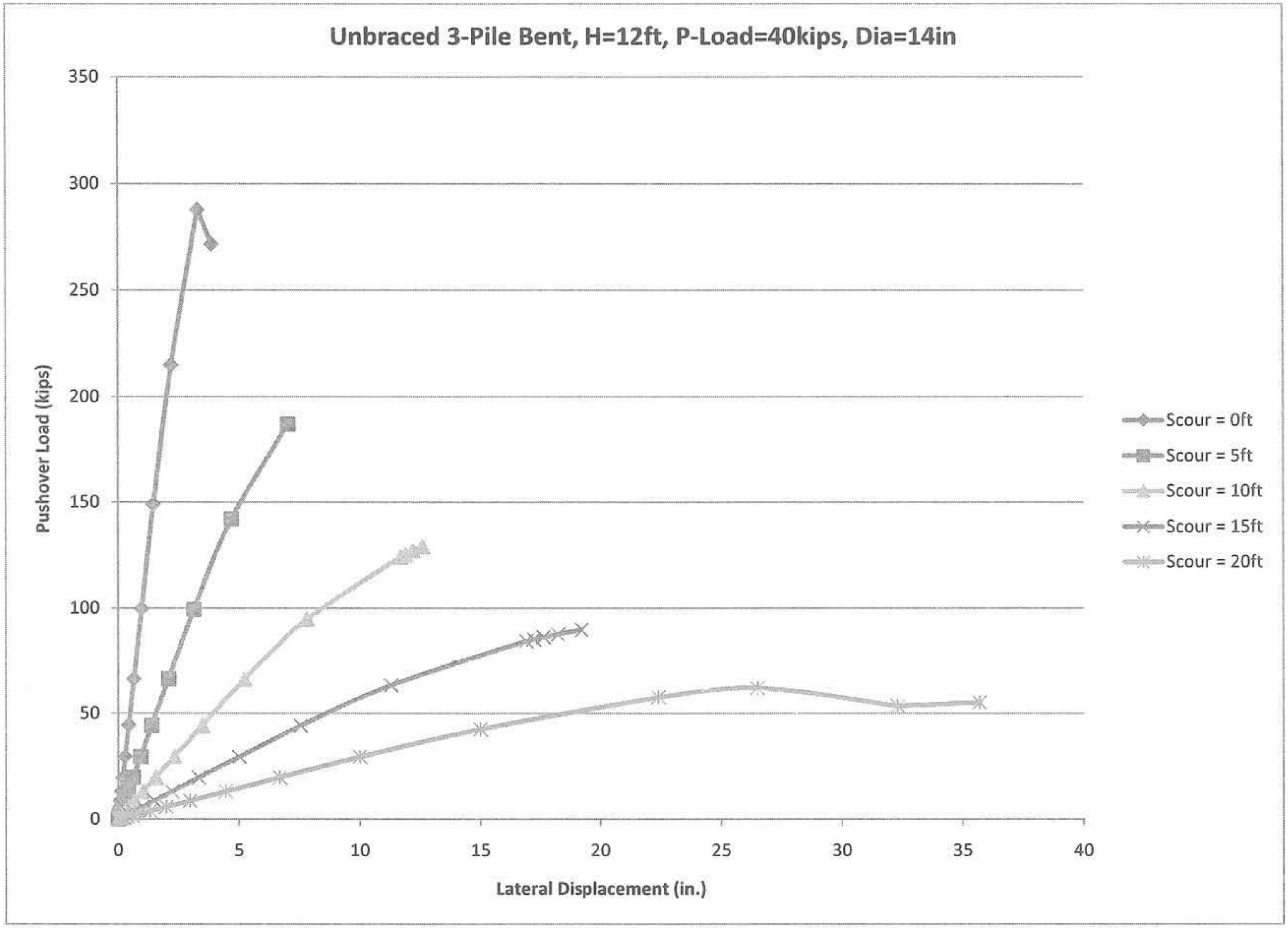


Figure B.14 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=40kips, Diameter=14in, Multiple Levels of Scour

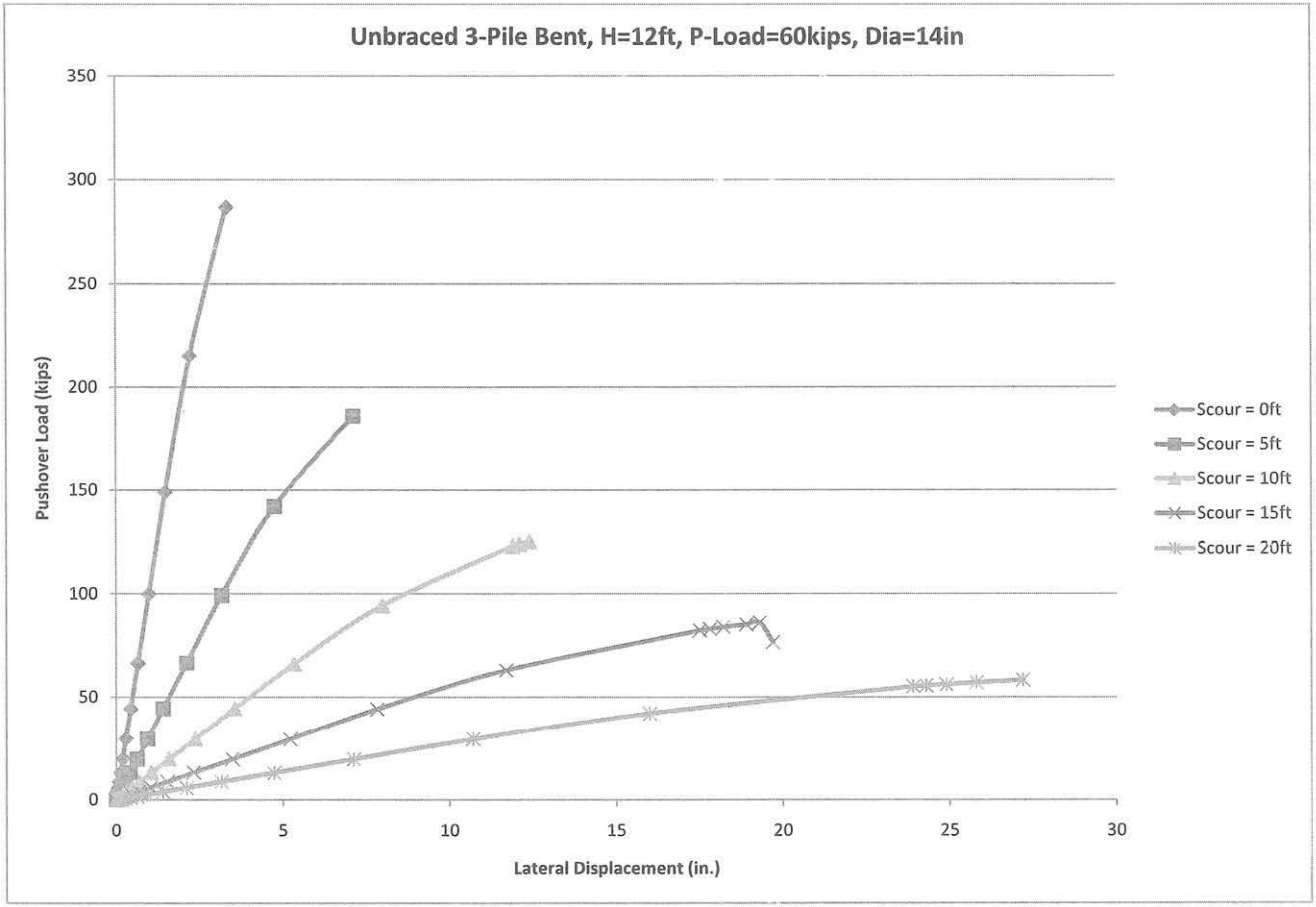


Figure B.15 Pushover Curves for Unbraced 3-Pile Bent, H=12ft, P=60kips, Diameter=14in, Multiple Levels of Scour

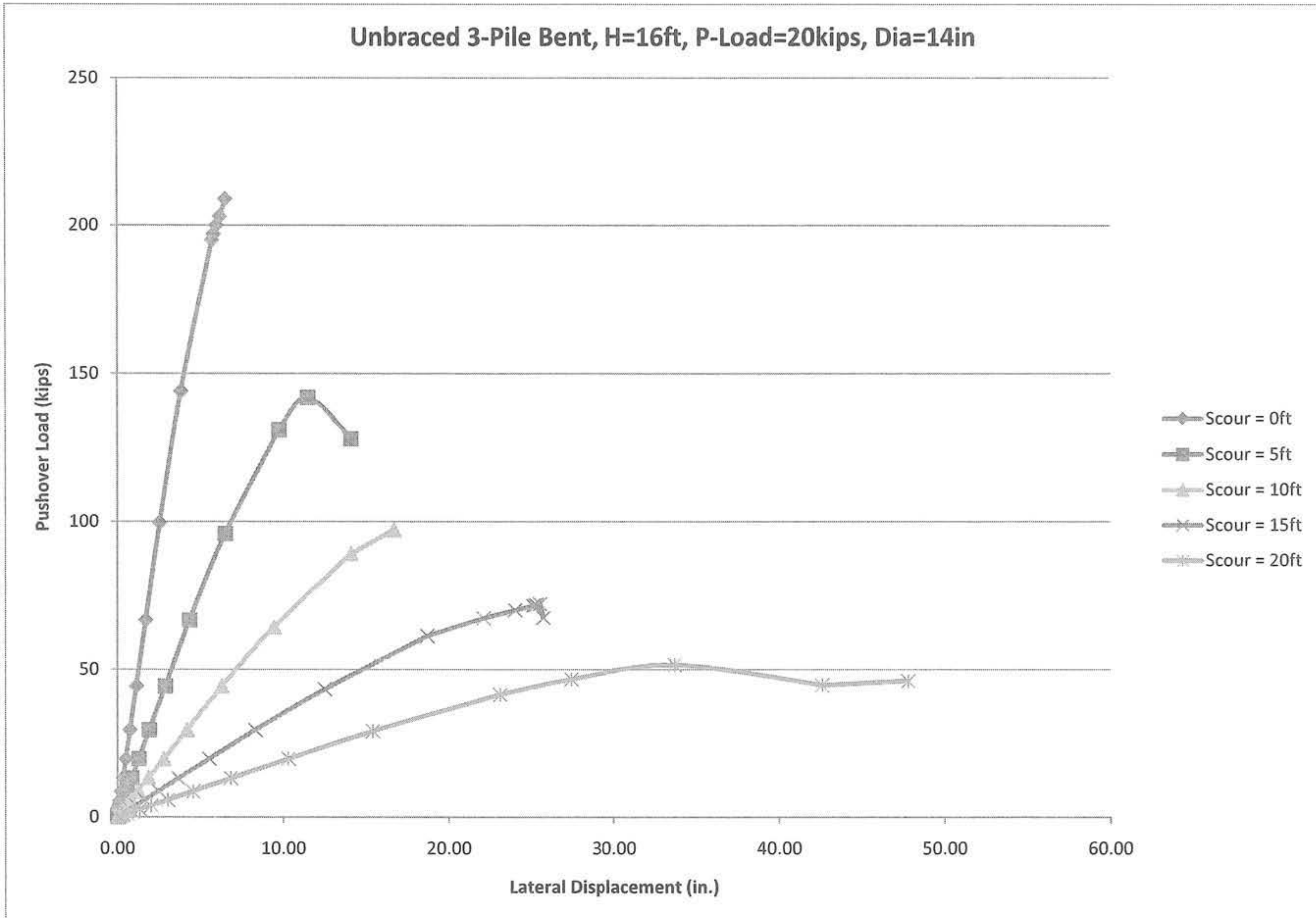


Figure B.16 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=20kips, Diameter=14in, Multiple Levels of Scour

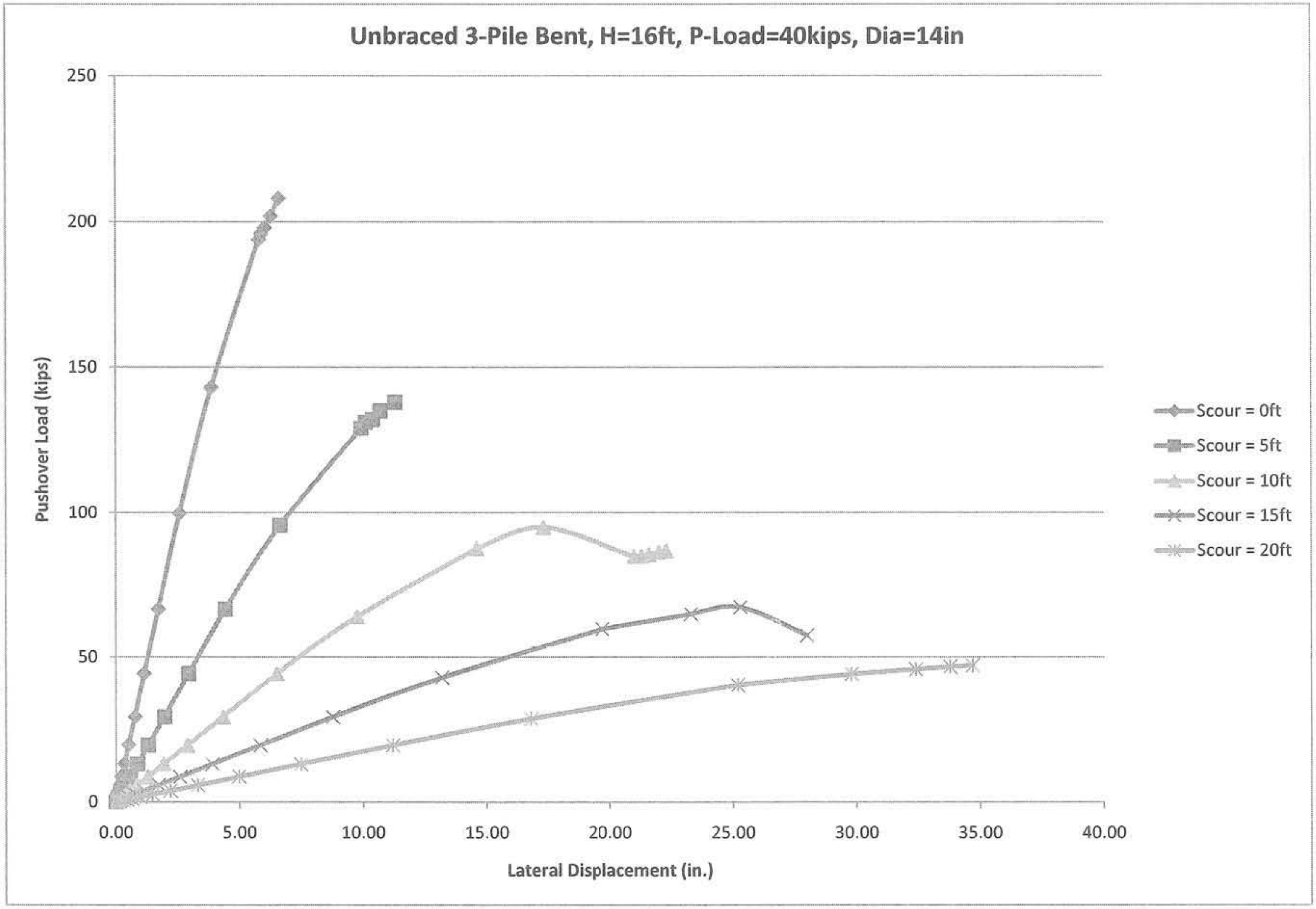


Figure B.17 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=40kips, Diameter=14in, Multiple Levels of Scour

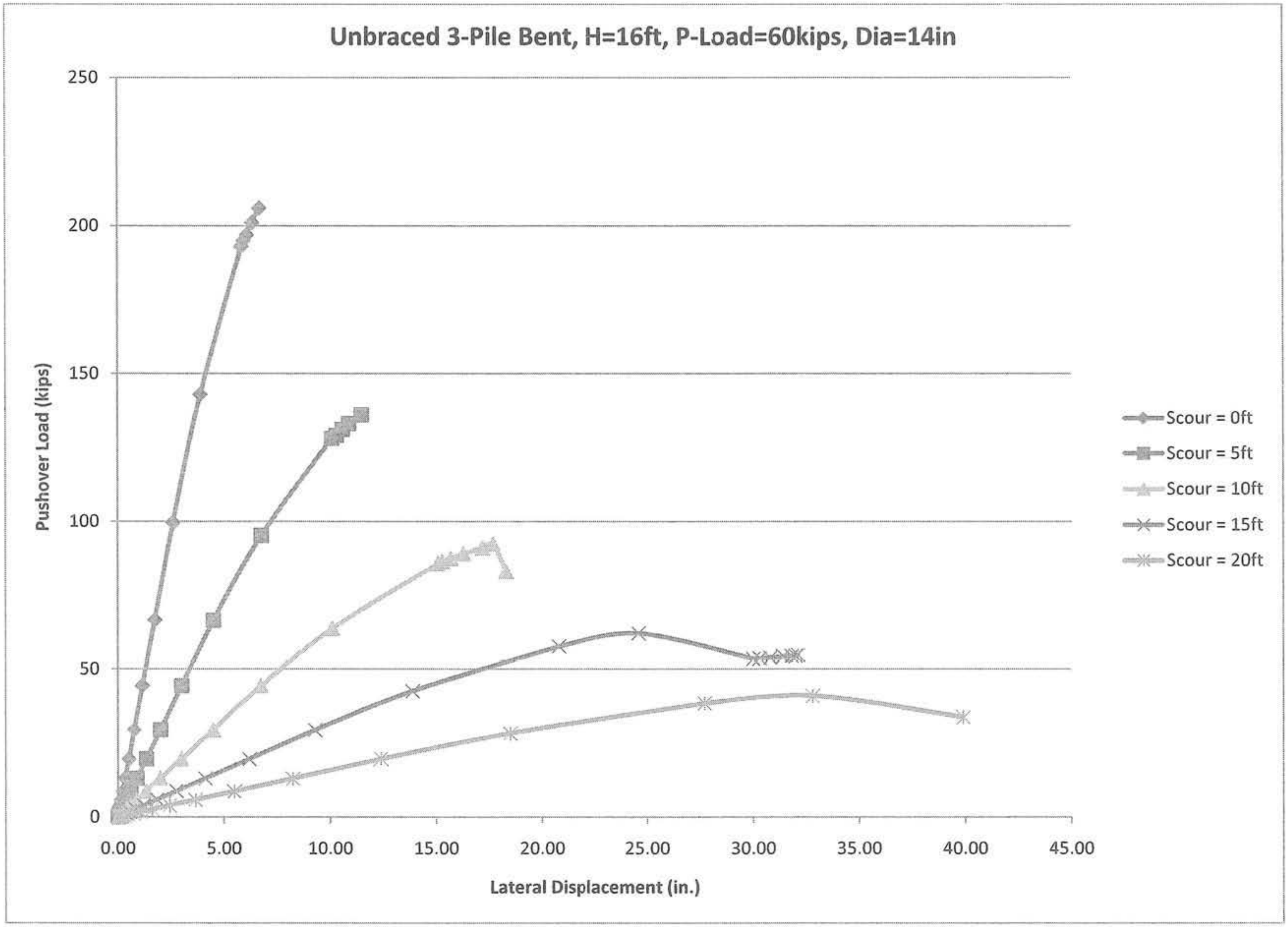


Figure B.18 Pushover Curves for Unbraced 3-Pile Bent, H=16ft, P=60kips, Diameter=14in, Multiple Levels of Scour

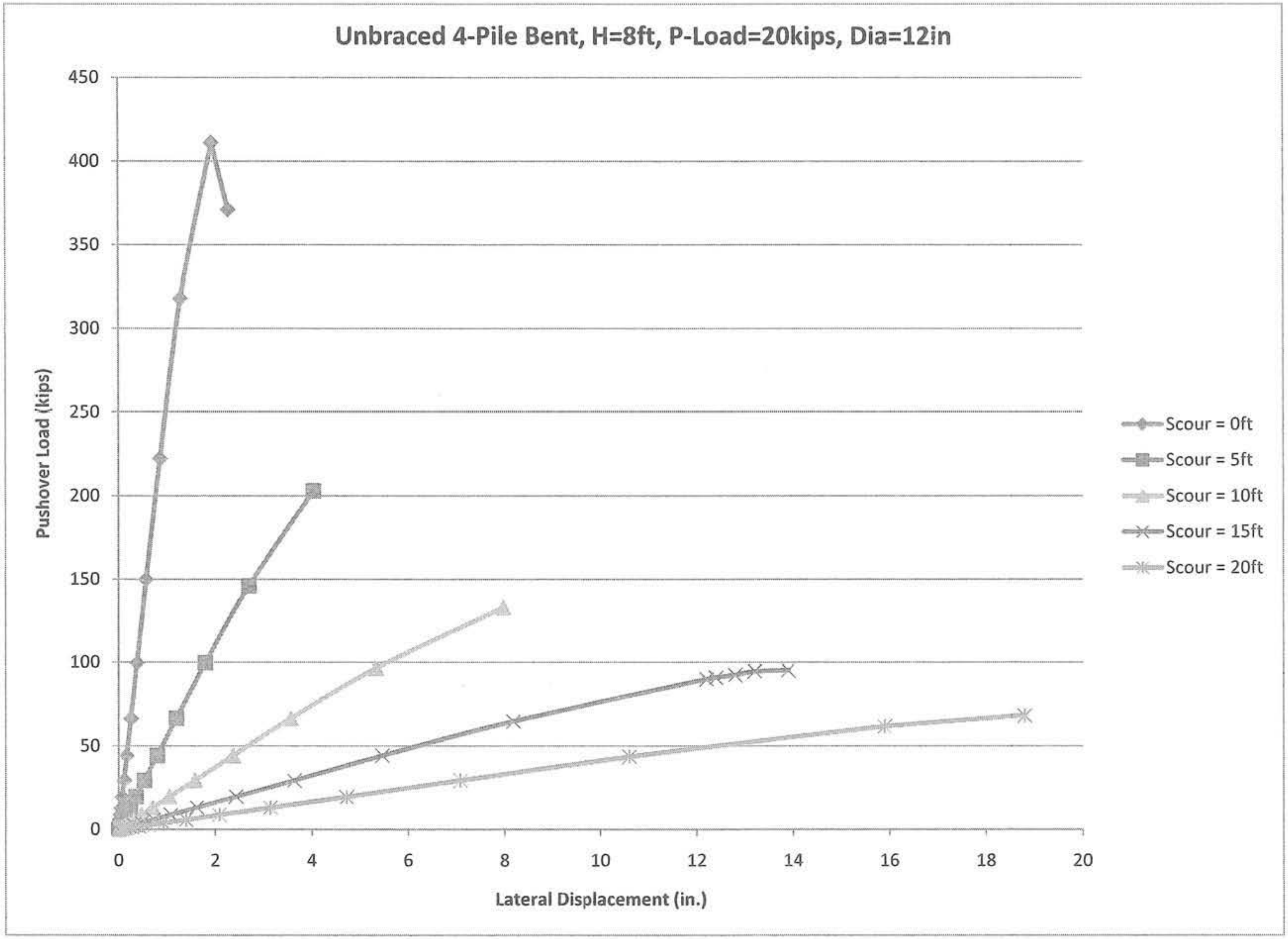


Figure B.18 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=20kips, Diameter=12in, Multiple Levels of Scour

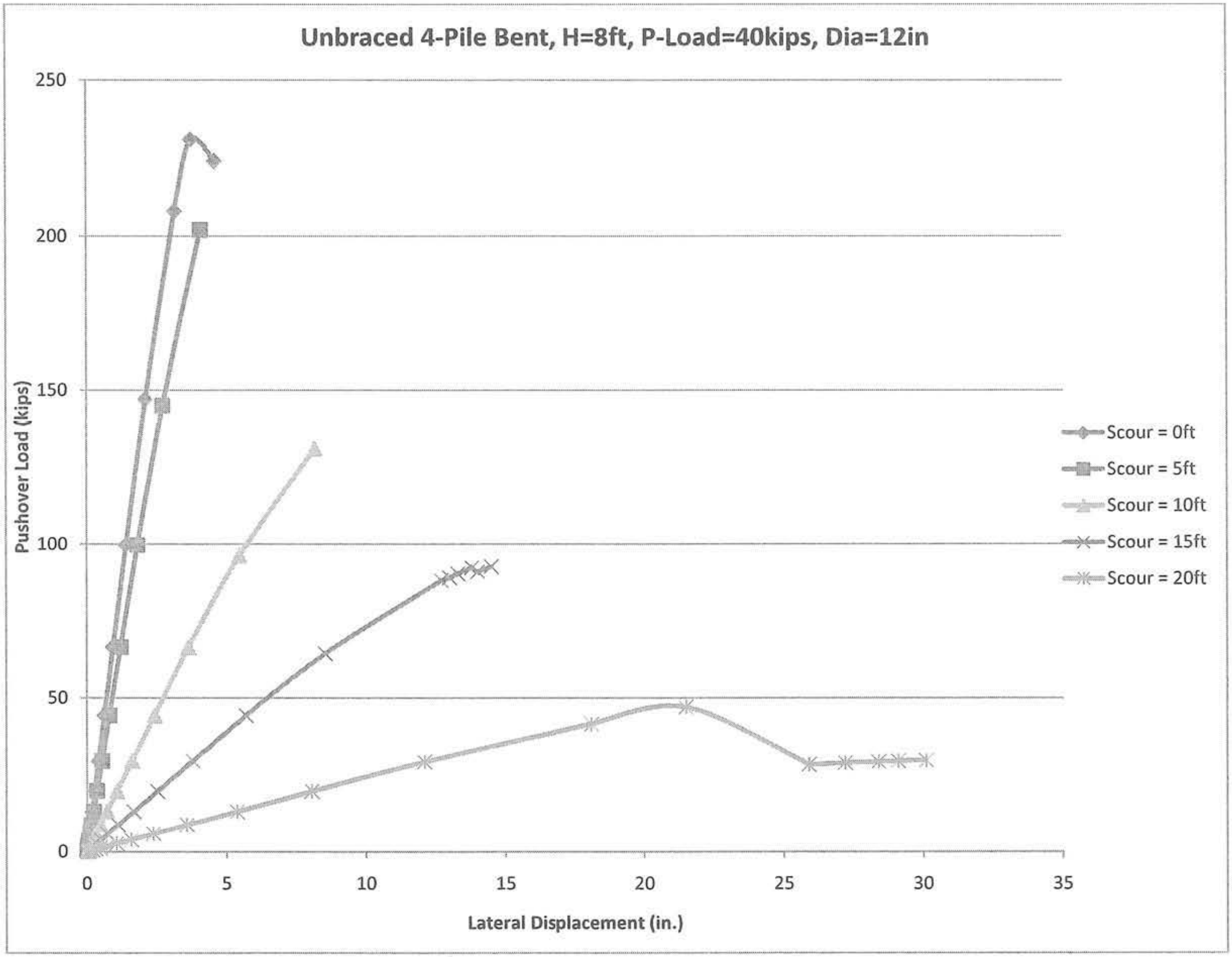


Figure B.19 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=40kips, Diameter=12in, Multiple Levels of Scour

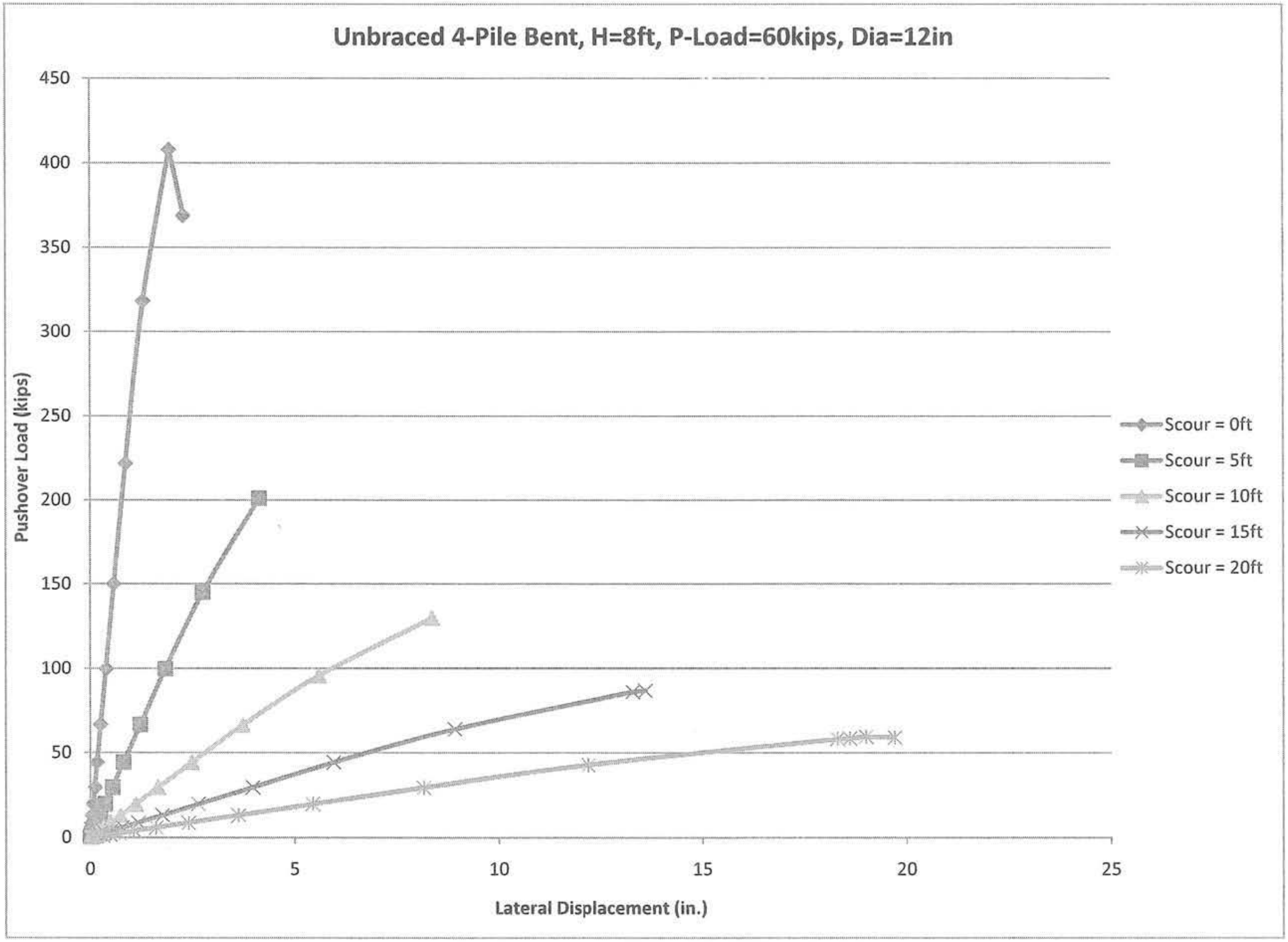


Figure B.21 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=60kips, Diameter=12in, Multiple Levels of Scour

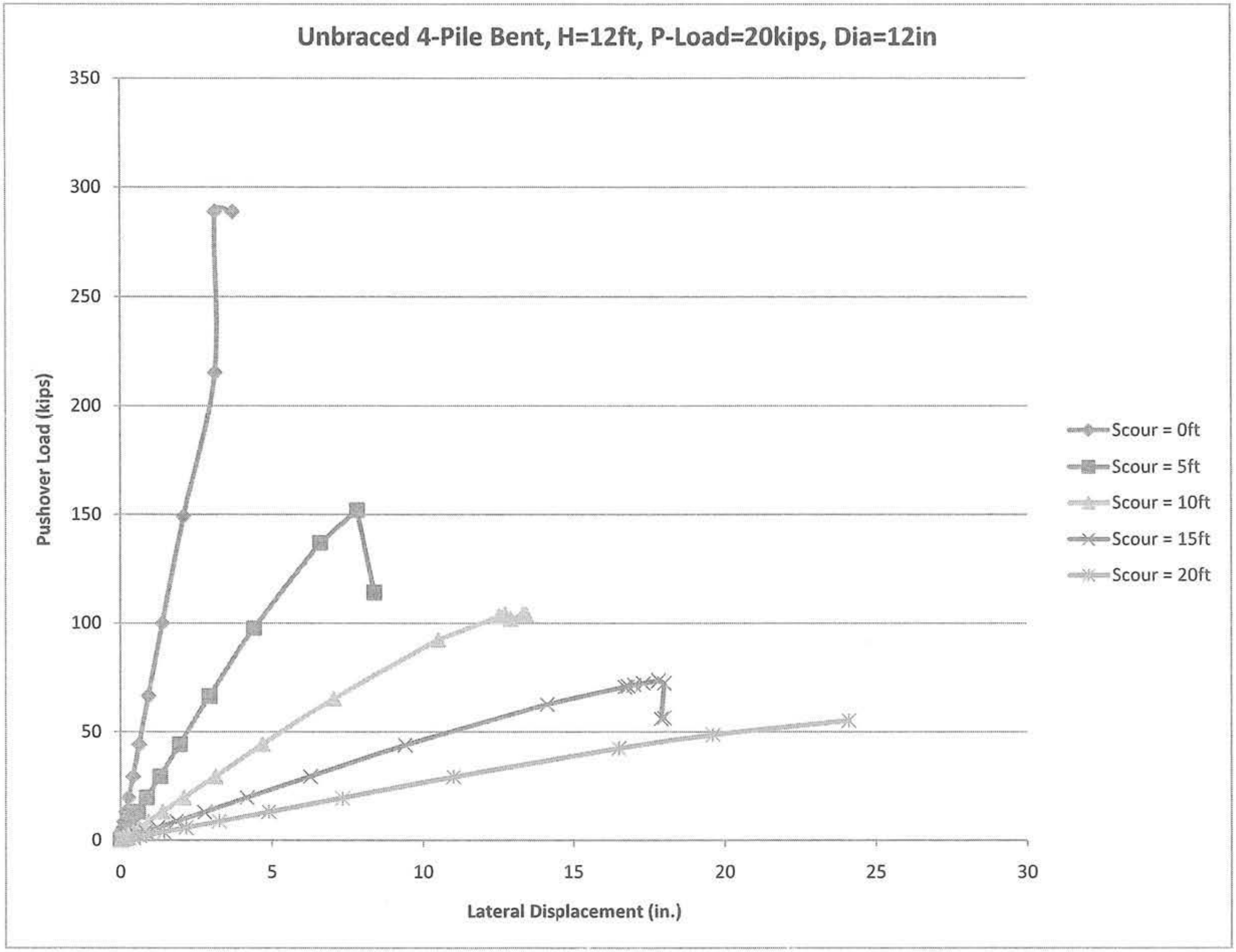


Figure B.22 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=20kips, Diameter=12in, Multiple Levels of Scour

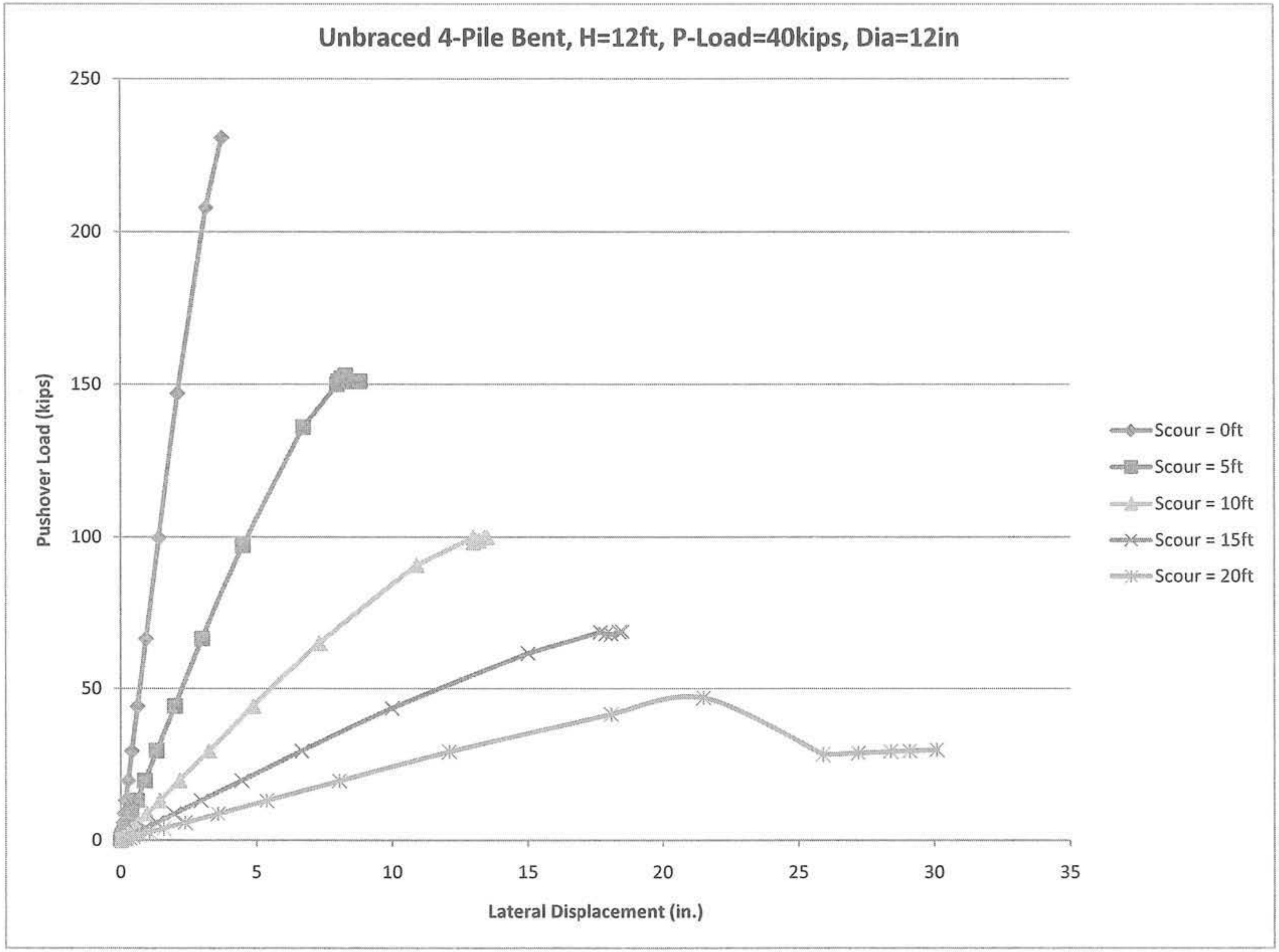


Figure B.23 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=40kips, Diameter=12in, Multiple Levels of Scour

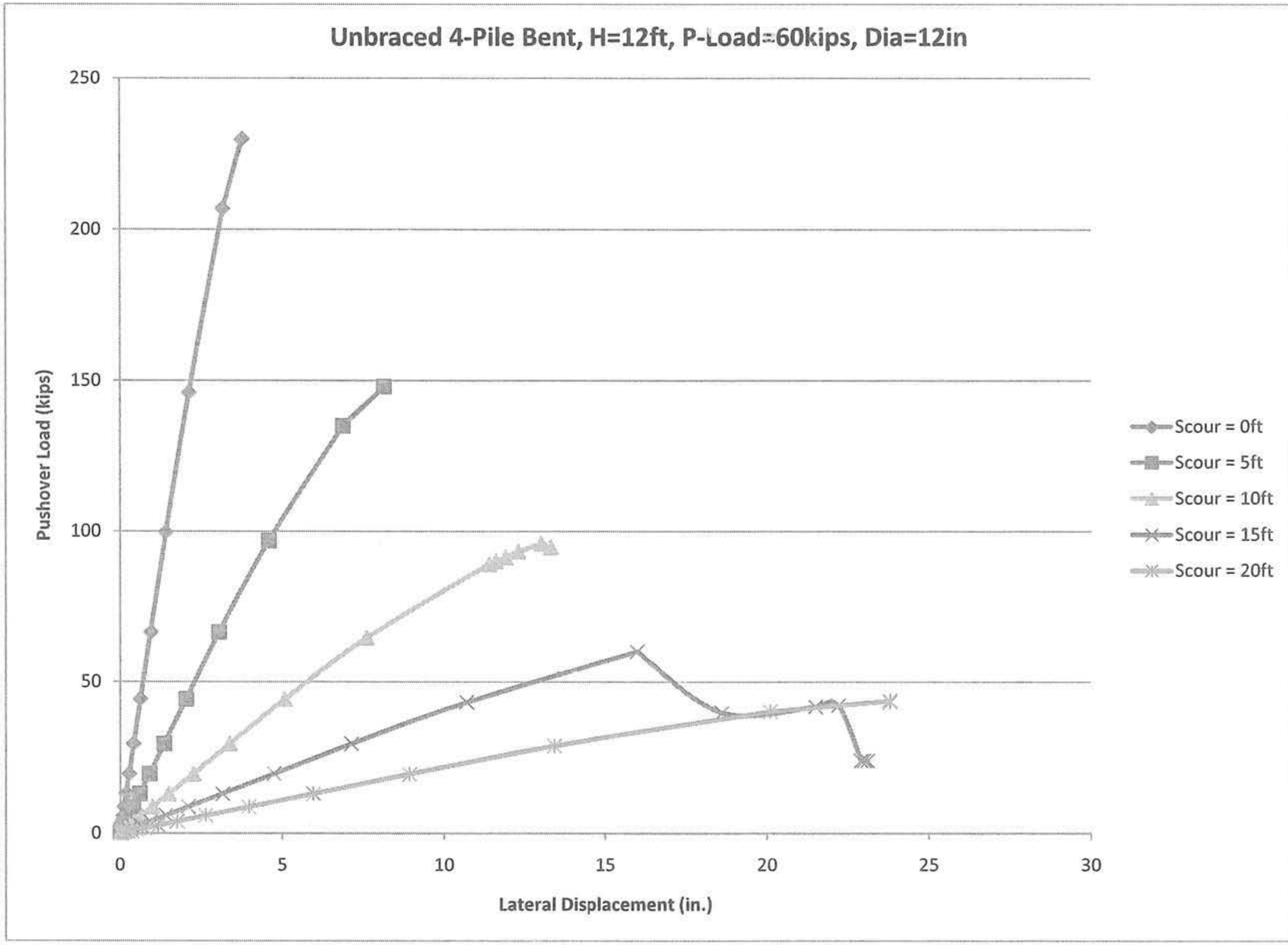


Figure B.24 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=60kips, Diameter=12in, Multiple Levels of Scour

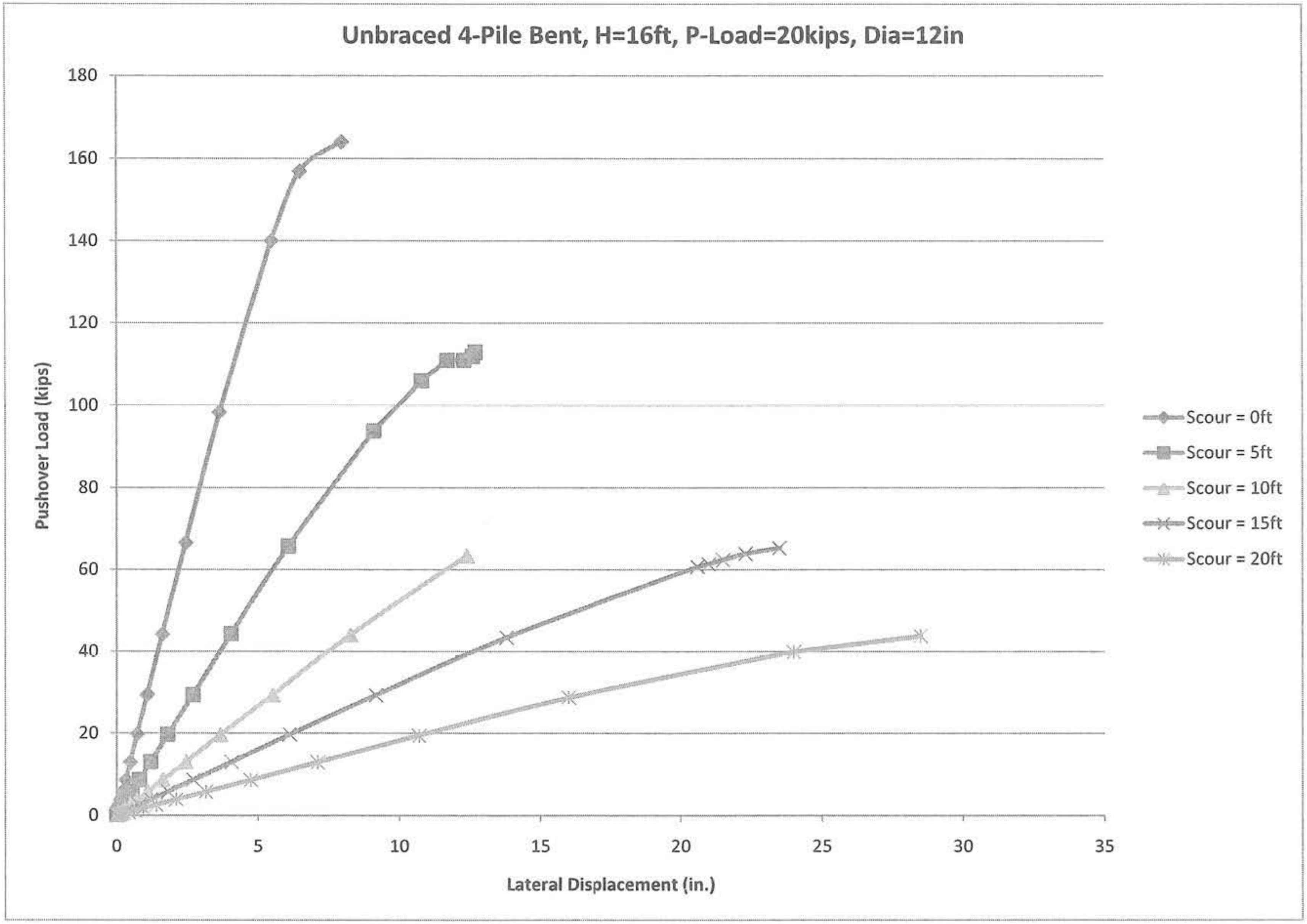


Figure B.25 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=20kips, Diameter=12in, Multiple Levels of Scour

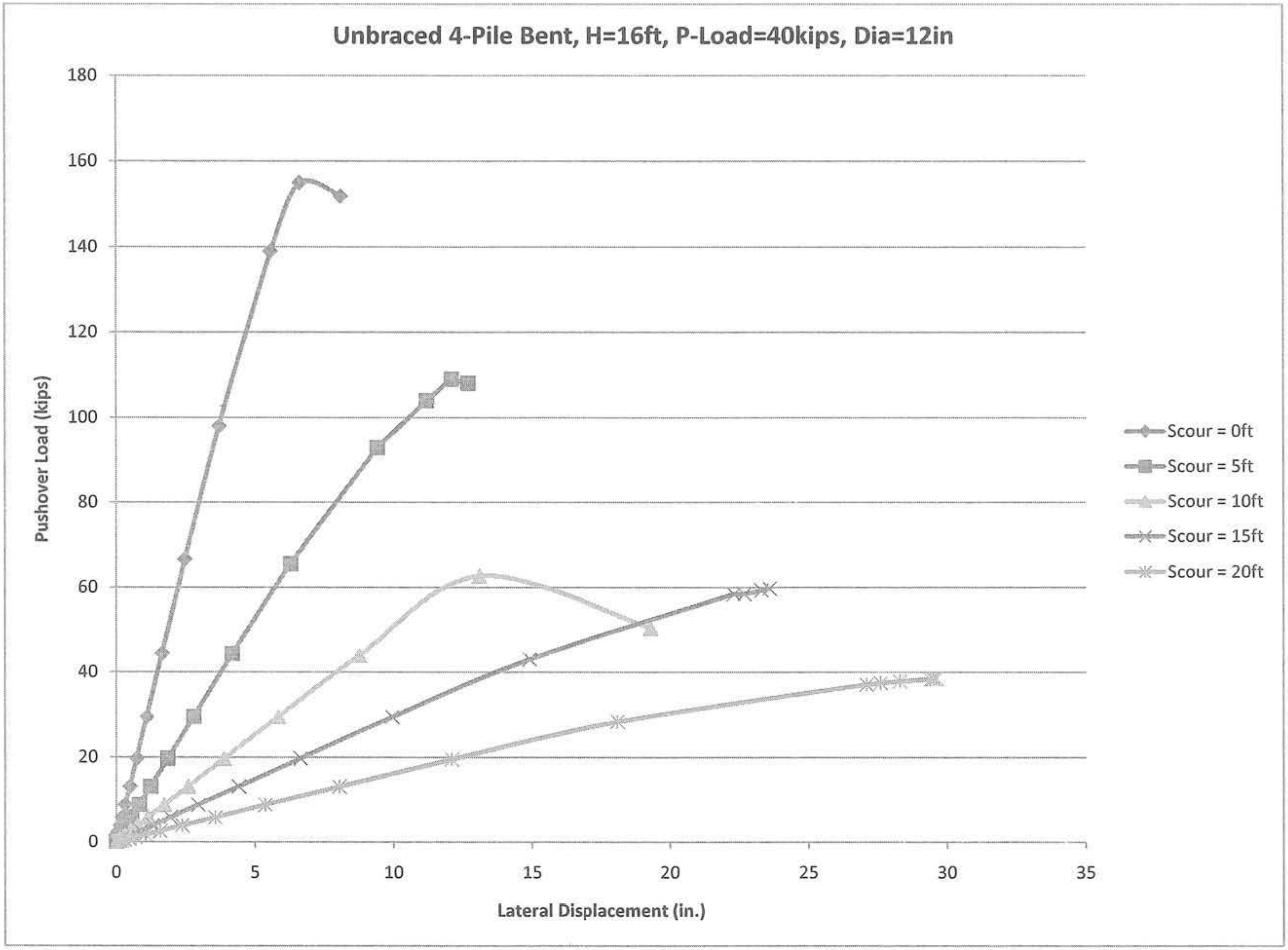


Figure B.26 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=40kips, Diameter=12in, Multiple Levels of Scour

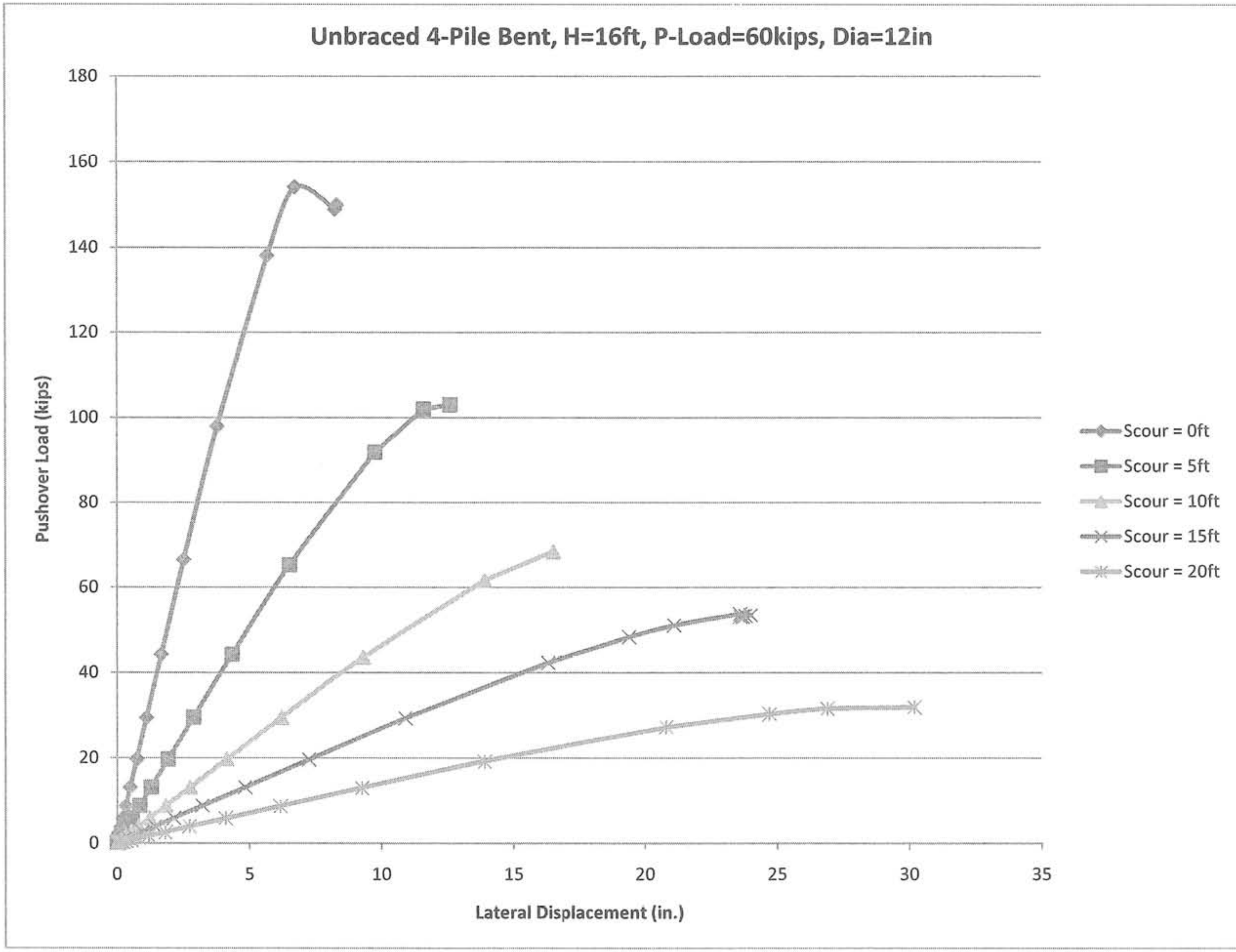


Figure B.27 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=60kips, Diameter=12in, Multiple Levels of Scour

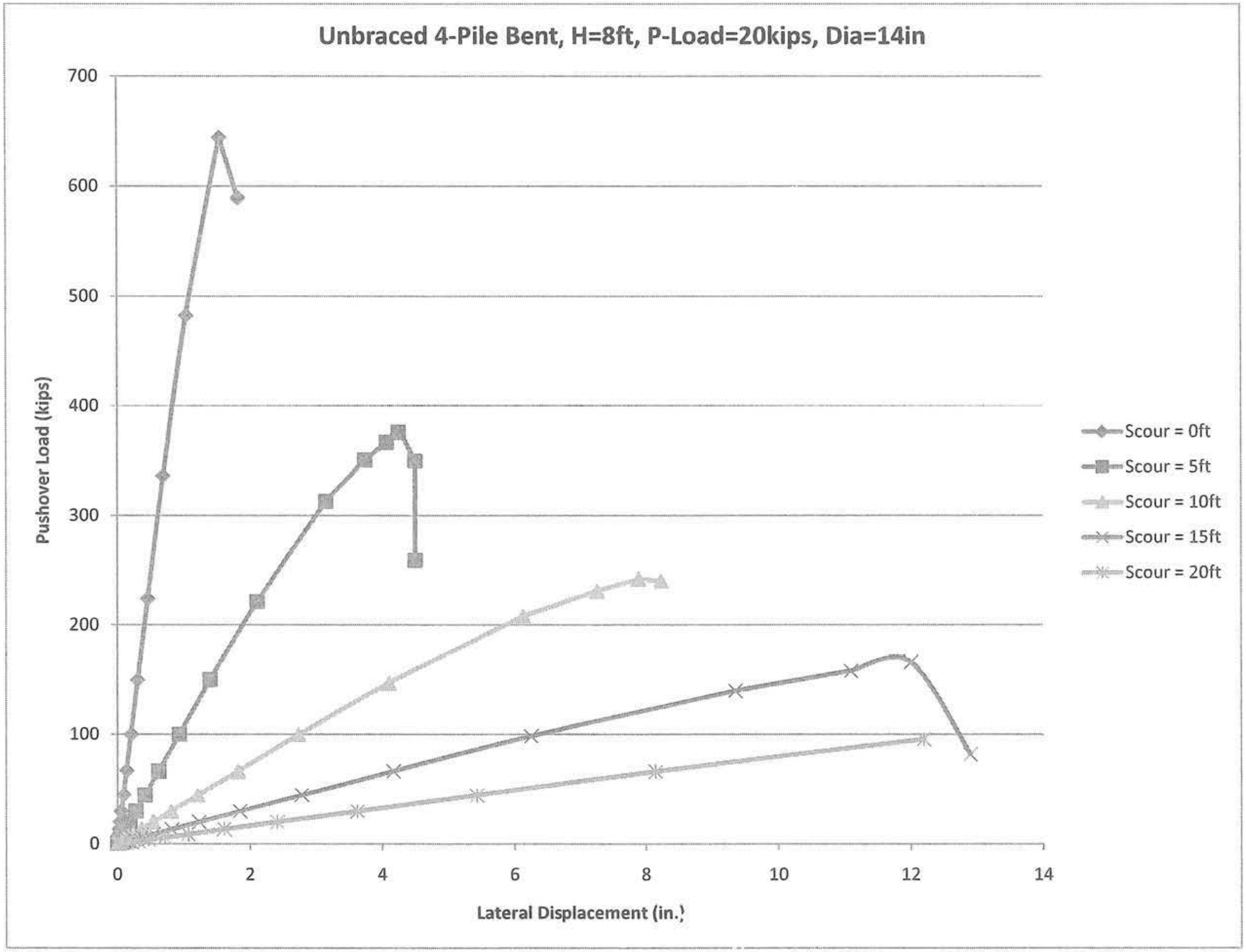


Figure B.28 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=20kips, Diameter=14in, Multiple Levels of Scour

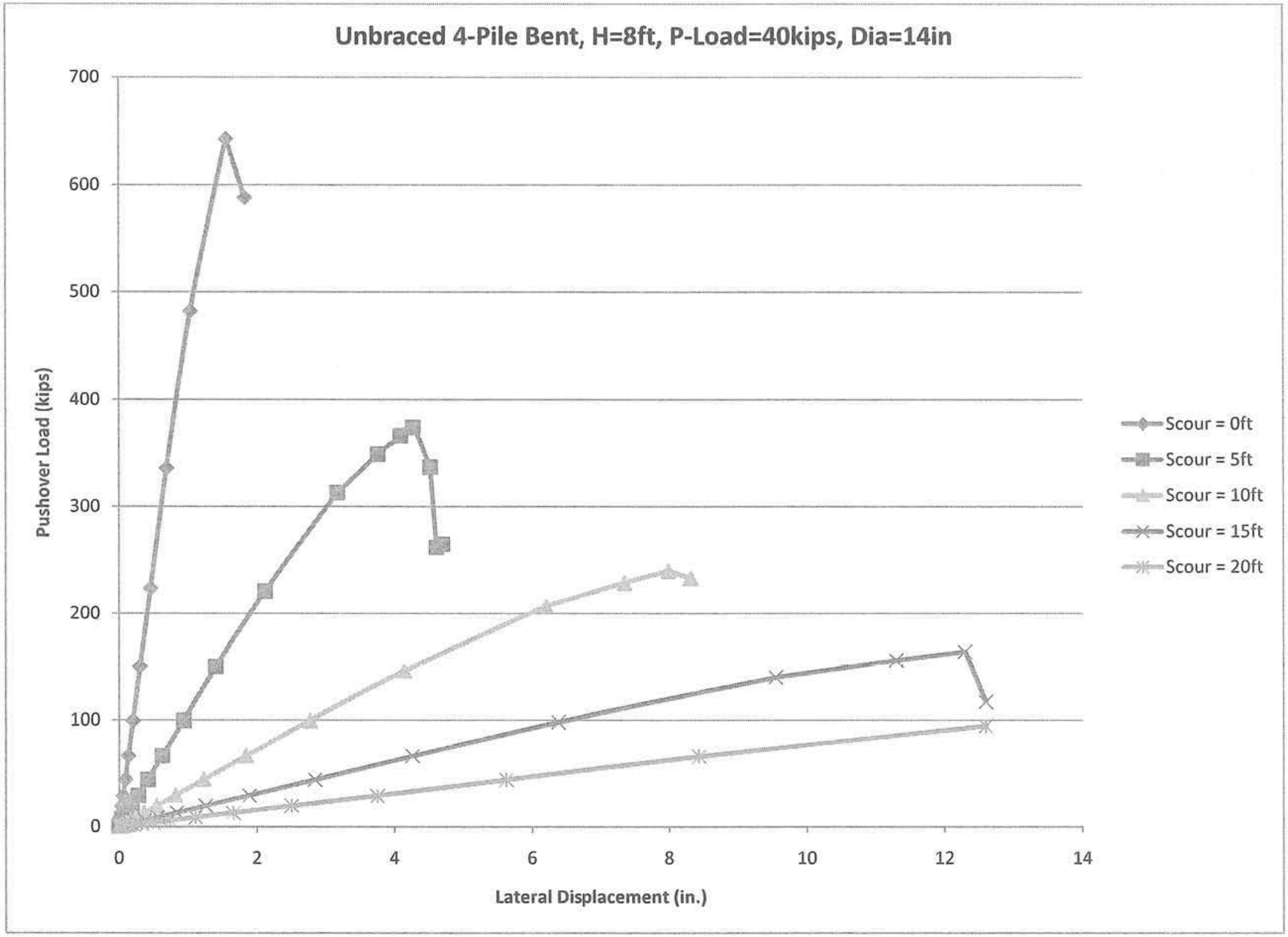


Figure B.29 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=40kips, Diameter=14in, Multiple Levels of Scour

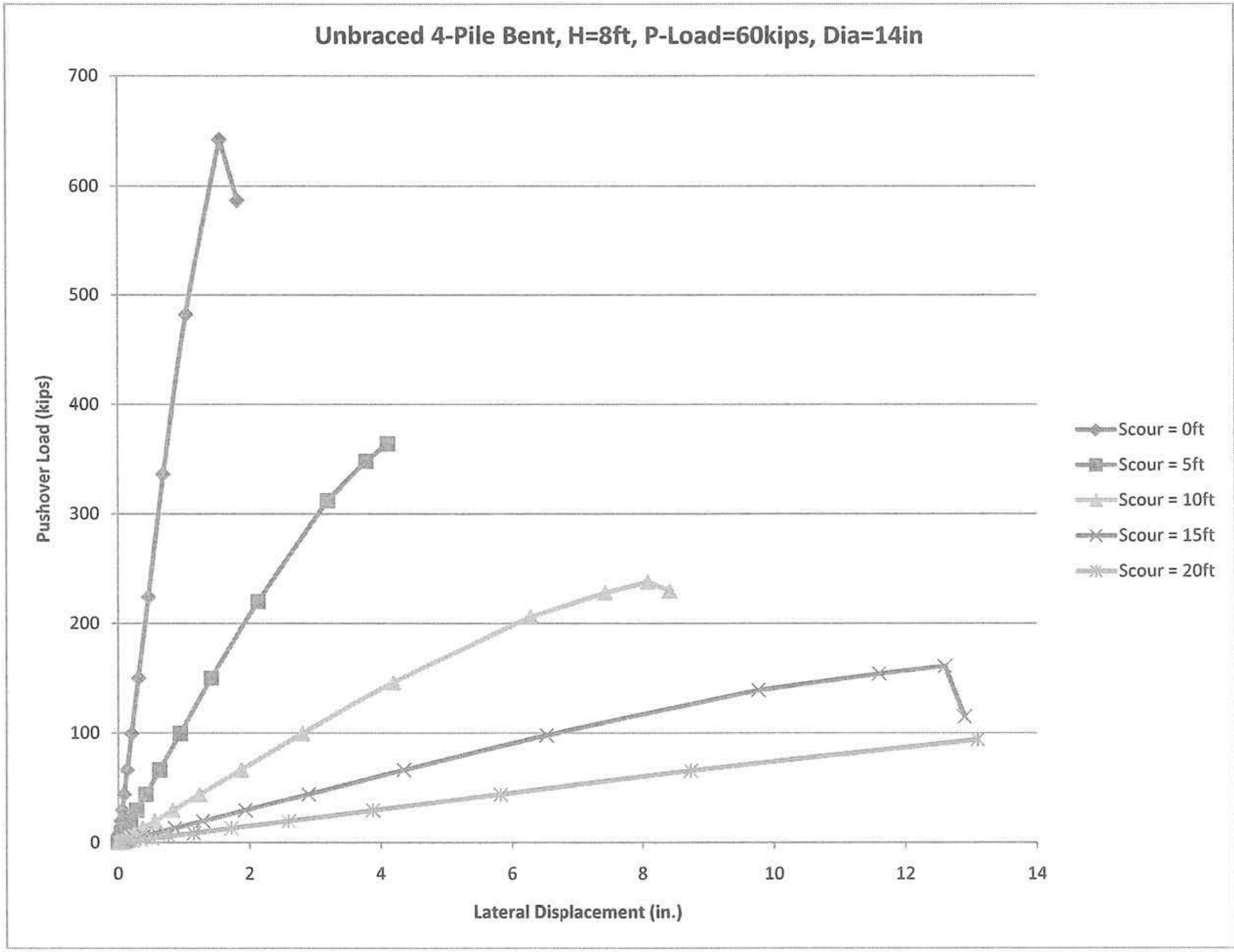


Figure B.30 Pushover Curves for Unbraced 4-Pile Bent, H=8ft, P=60kips, Diameter=14in, Multiple Levels of Scour

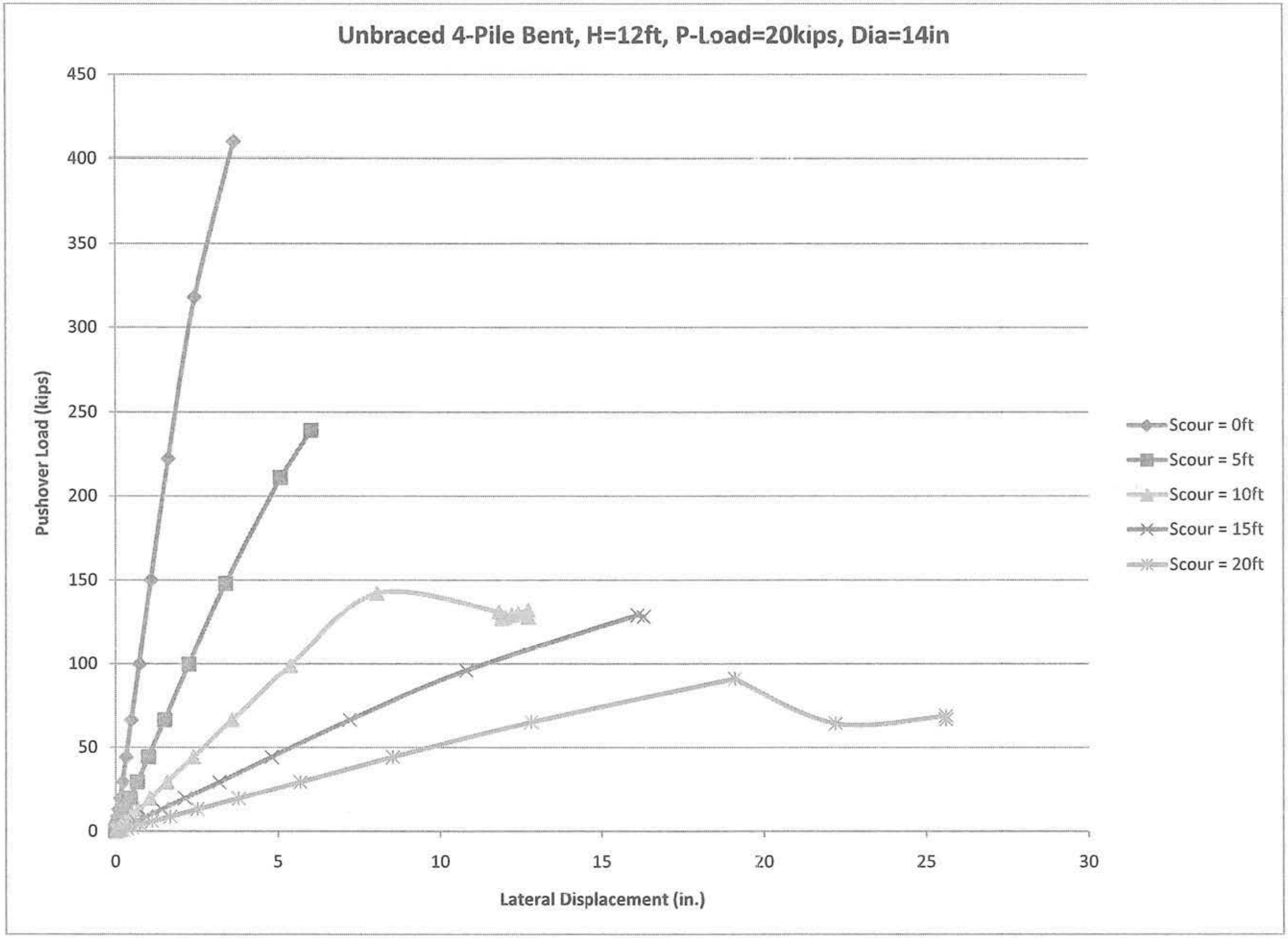


Figure B.31 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=20kips, Diameter=14in, Multiple Levels of Scour

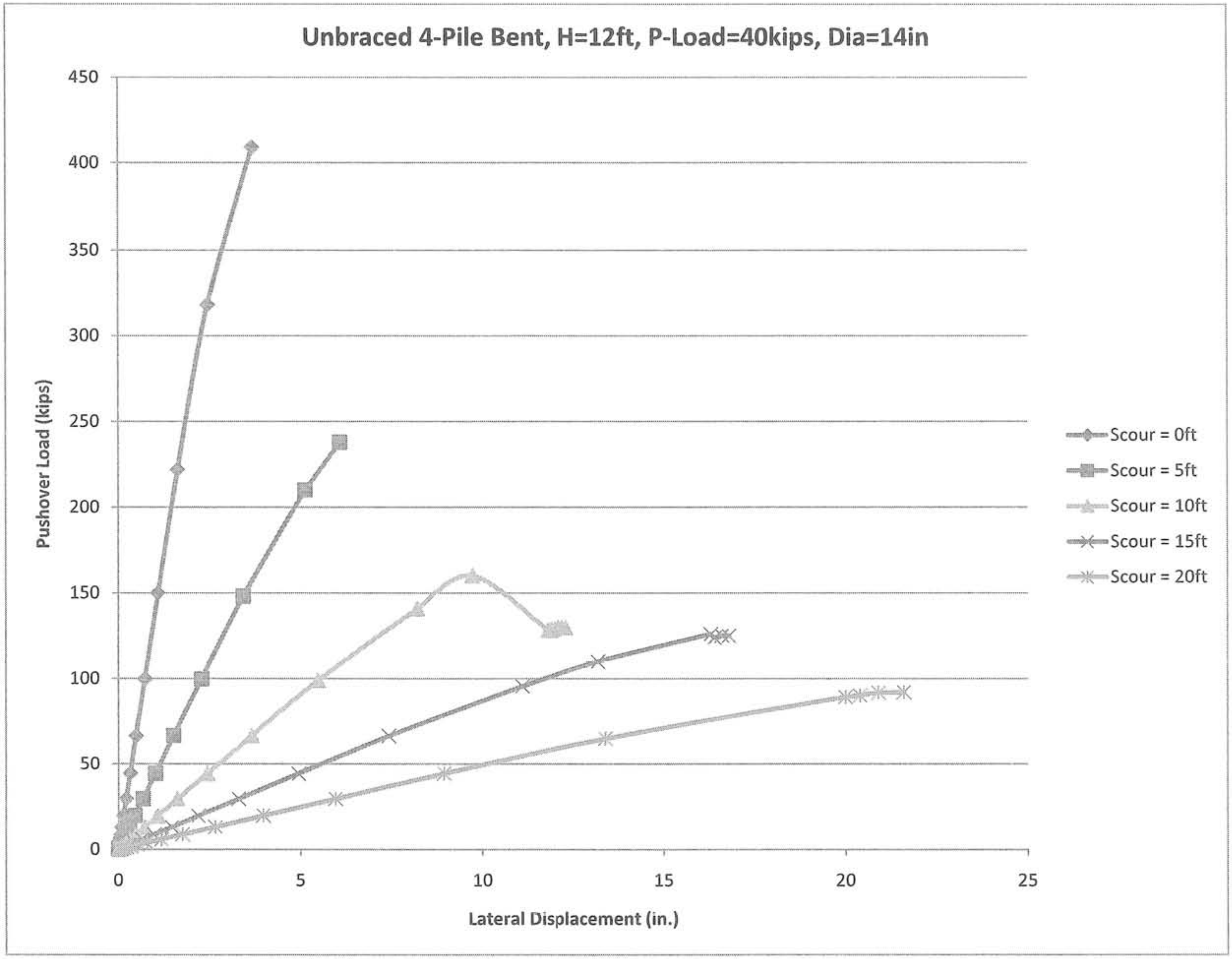


Figure B.32 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=40kips, Diameter=14in, Multiple Levels of Scour

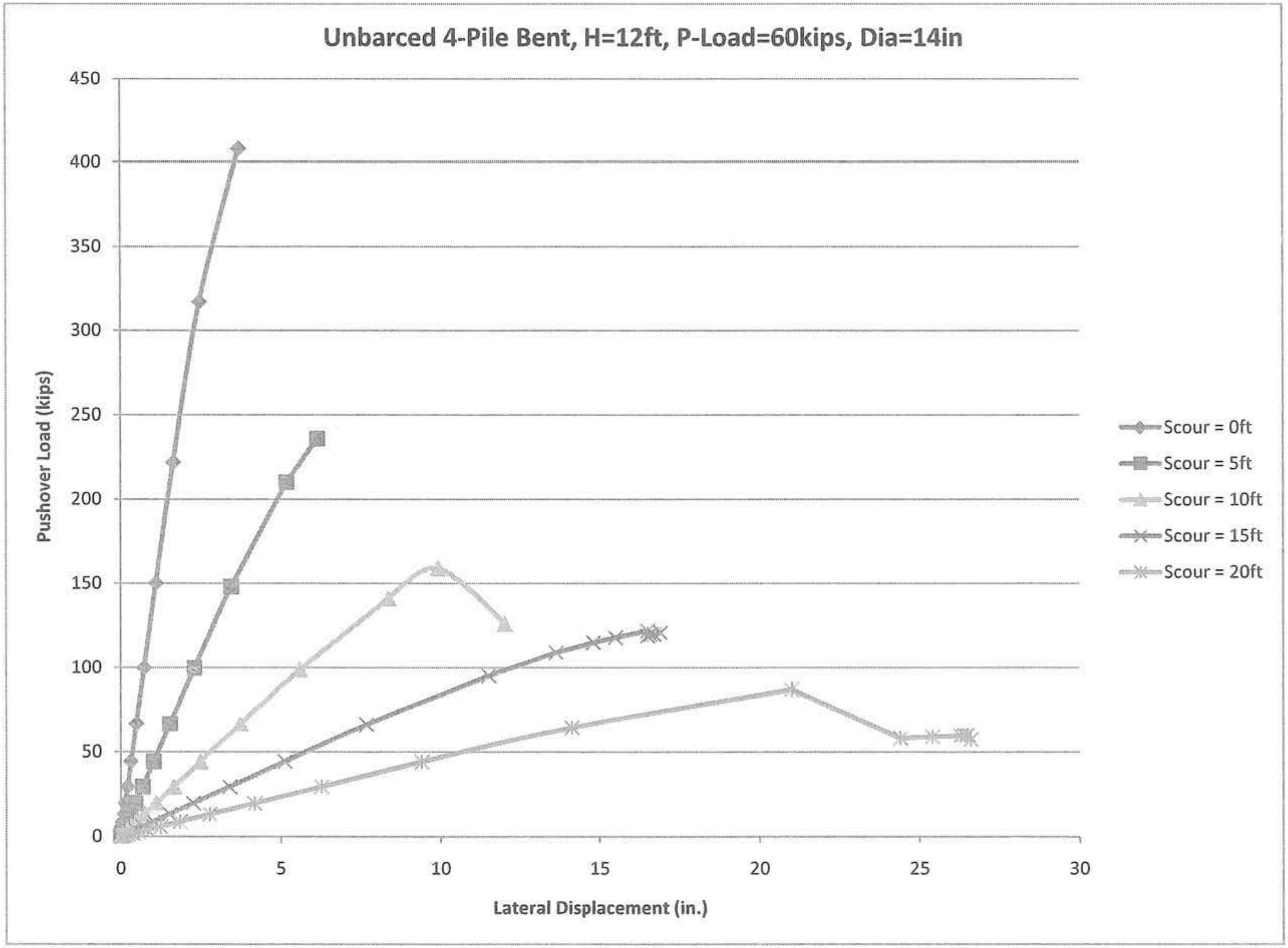


Figure B.33 Pushover Curves for Unbraced 4-Pile Bent, H=12ft, P=60kips, Diameter=14in, Multiple Levels of Scour

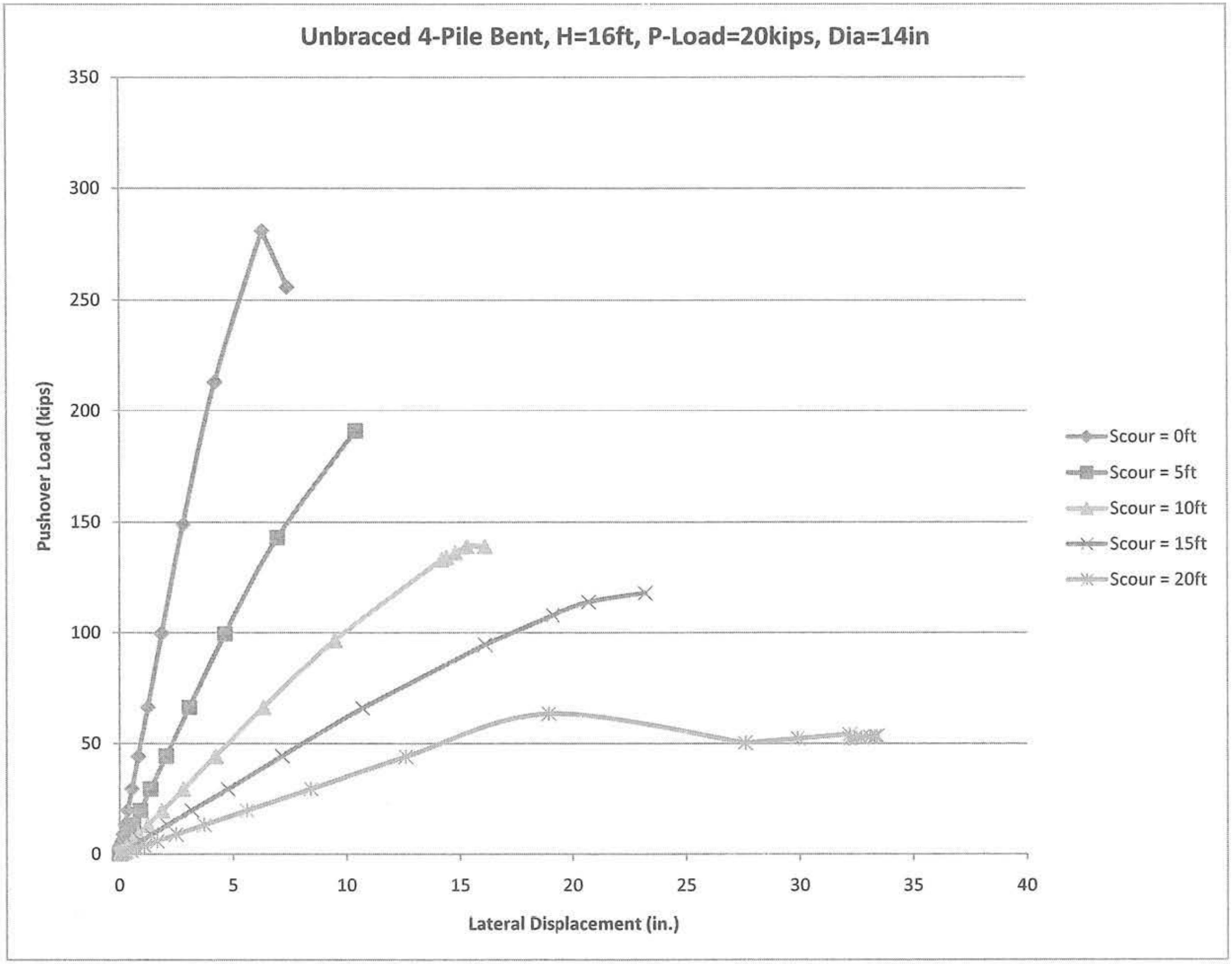


Figure B.34 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=20kips, Diameter=14in, Multiple Levels of Scour

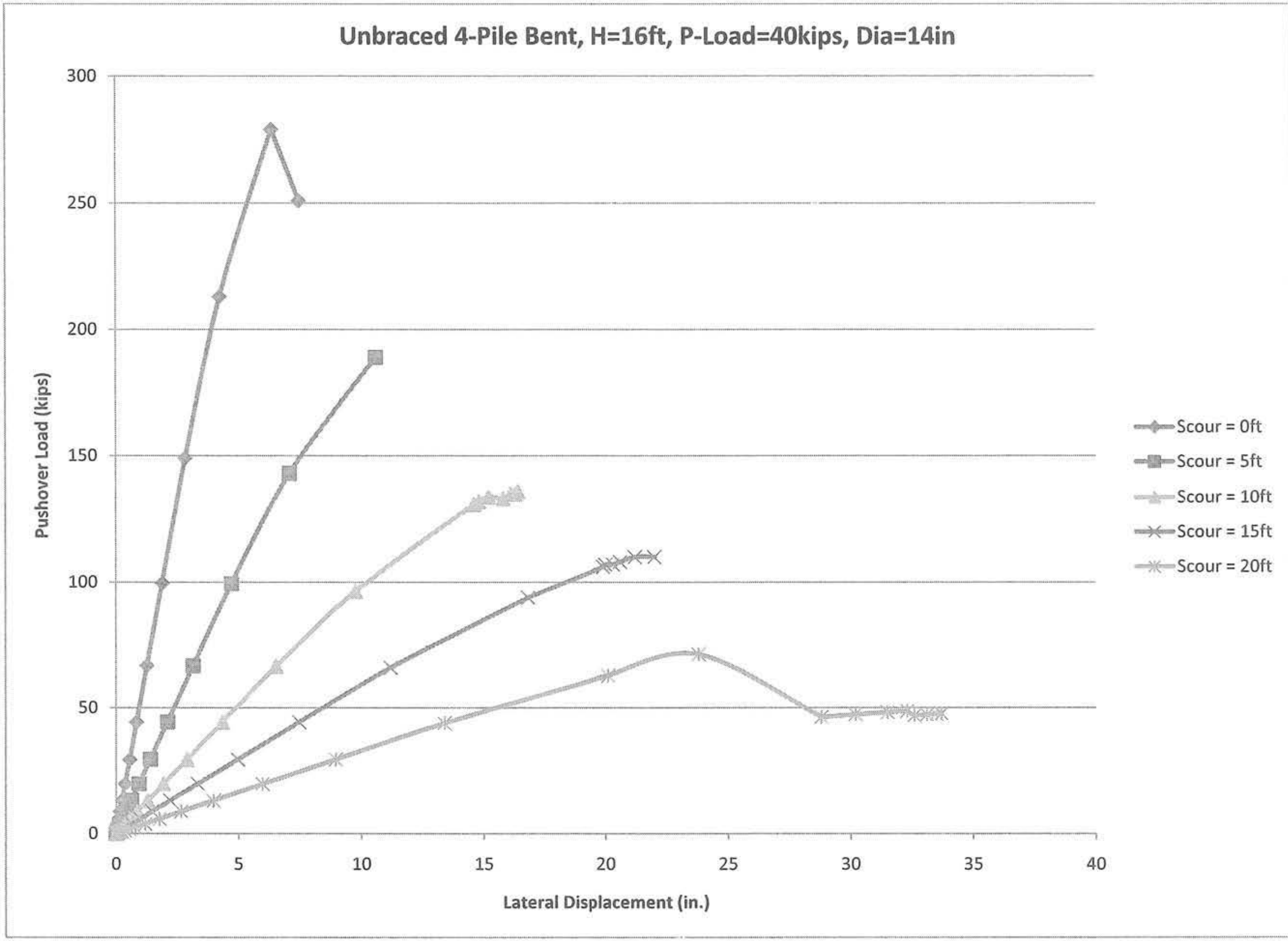


Figure B.35 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=40kips, Diameter=14in, Multiple Levels of Scour

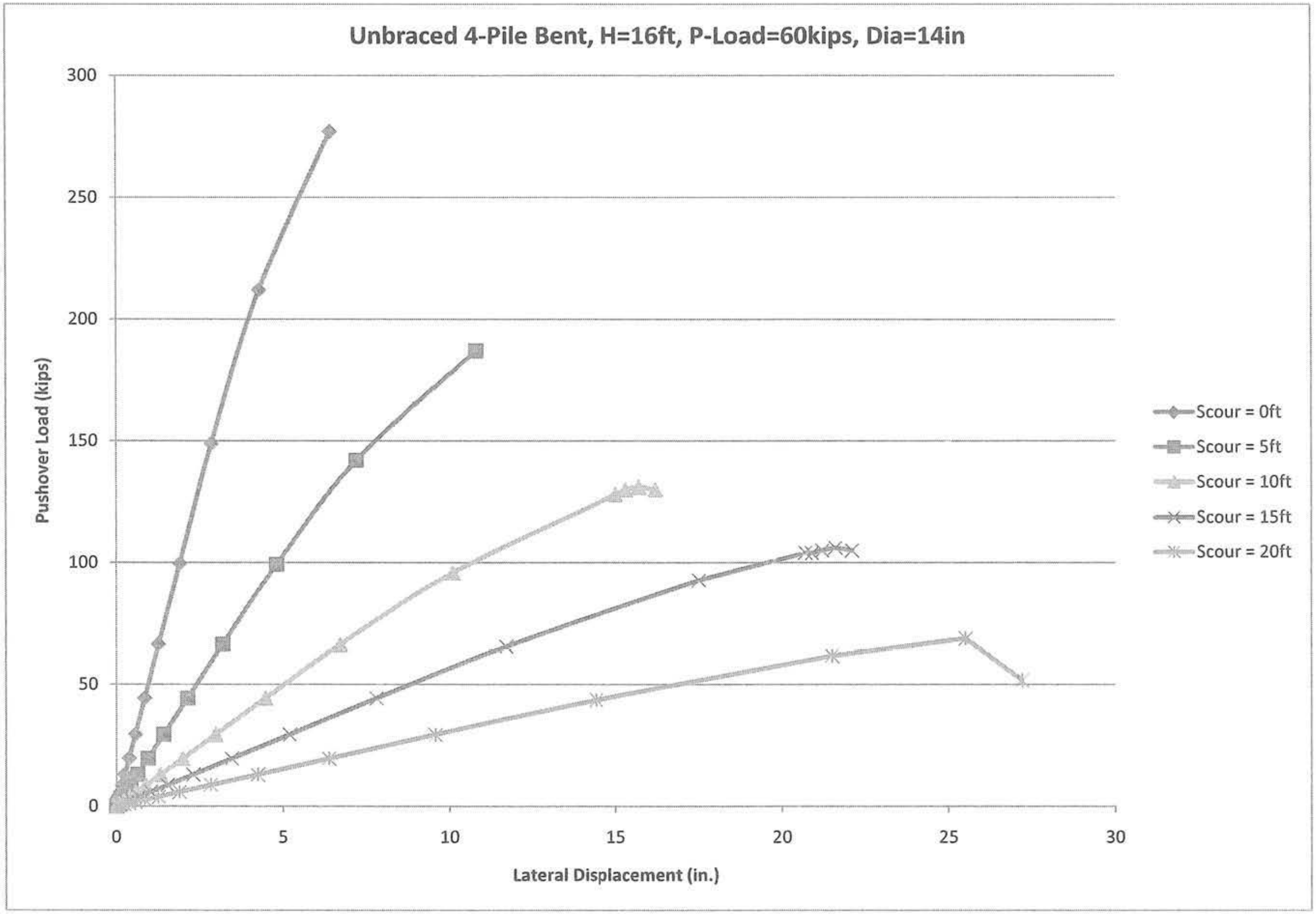


Figure B.36 Pushover Curves for Unbraced 4-Pile Bent, H=16ft, P=60kips, Diameter=14in, Multiple Levels of Scour

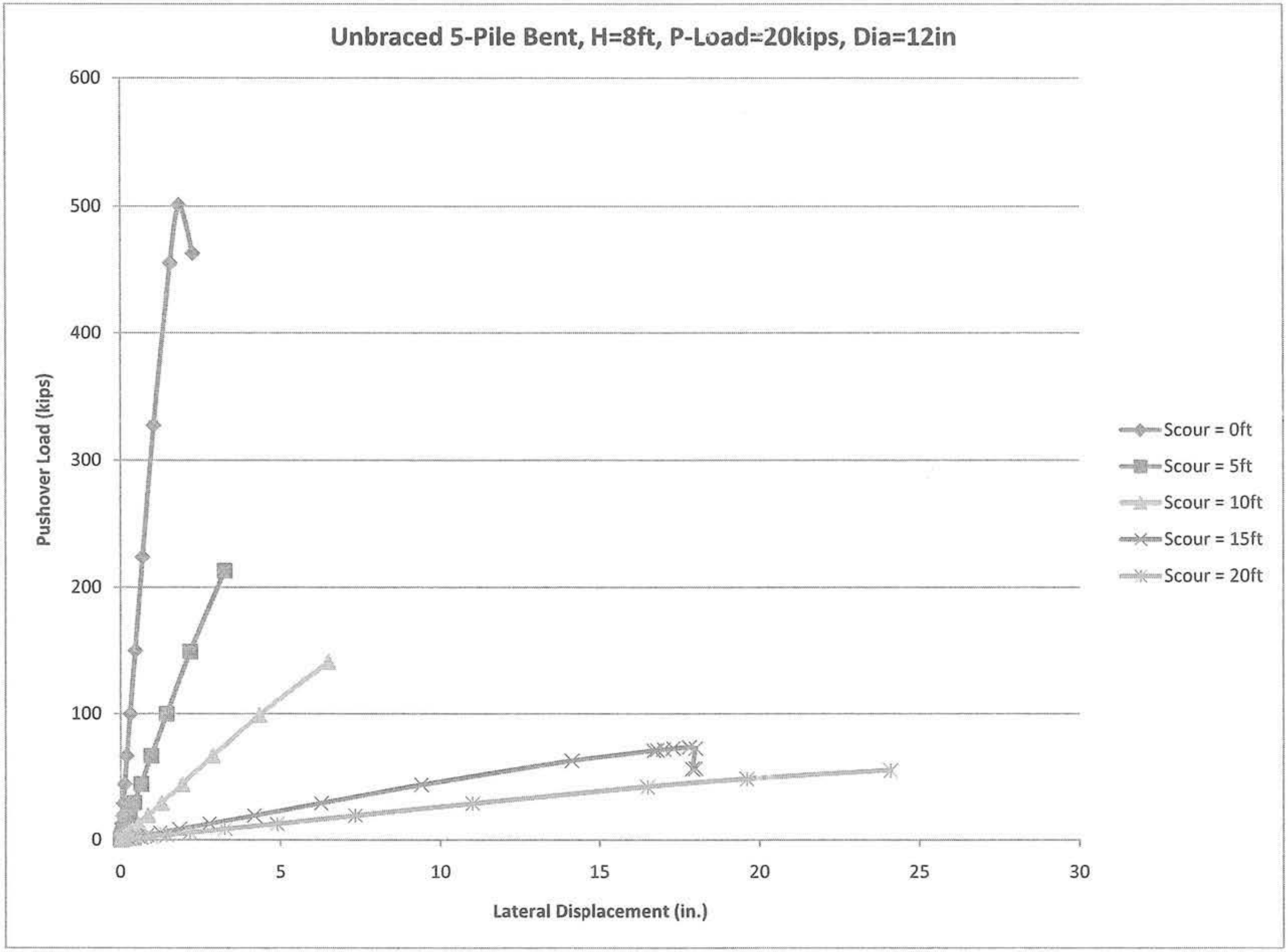


Figure B.37 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=20kips, Diameter=12in, Multiple Levels of Scour

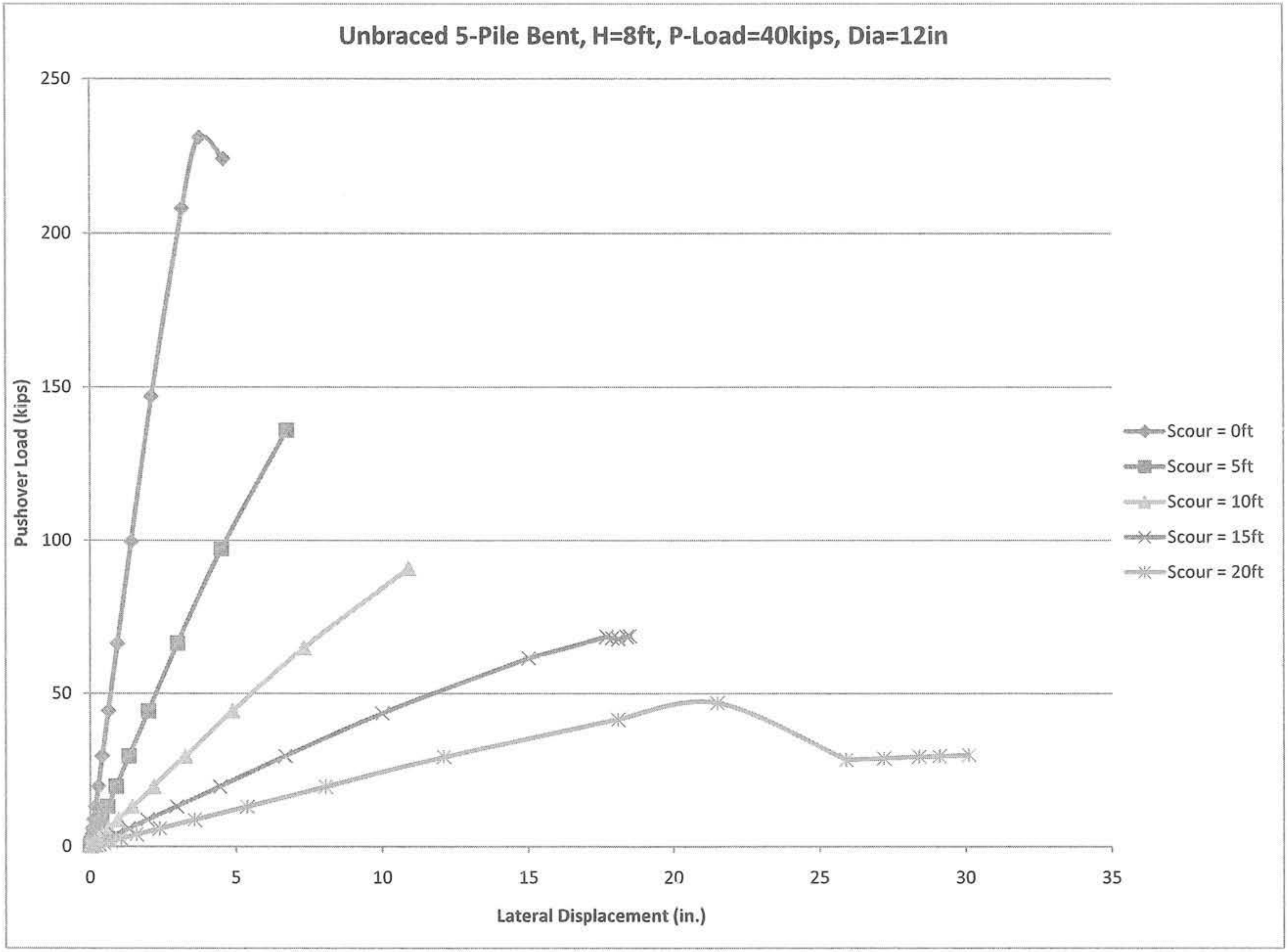


Figure B.38 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=40kips, Diameter=12in, Multiple Levels of Scour

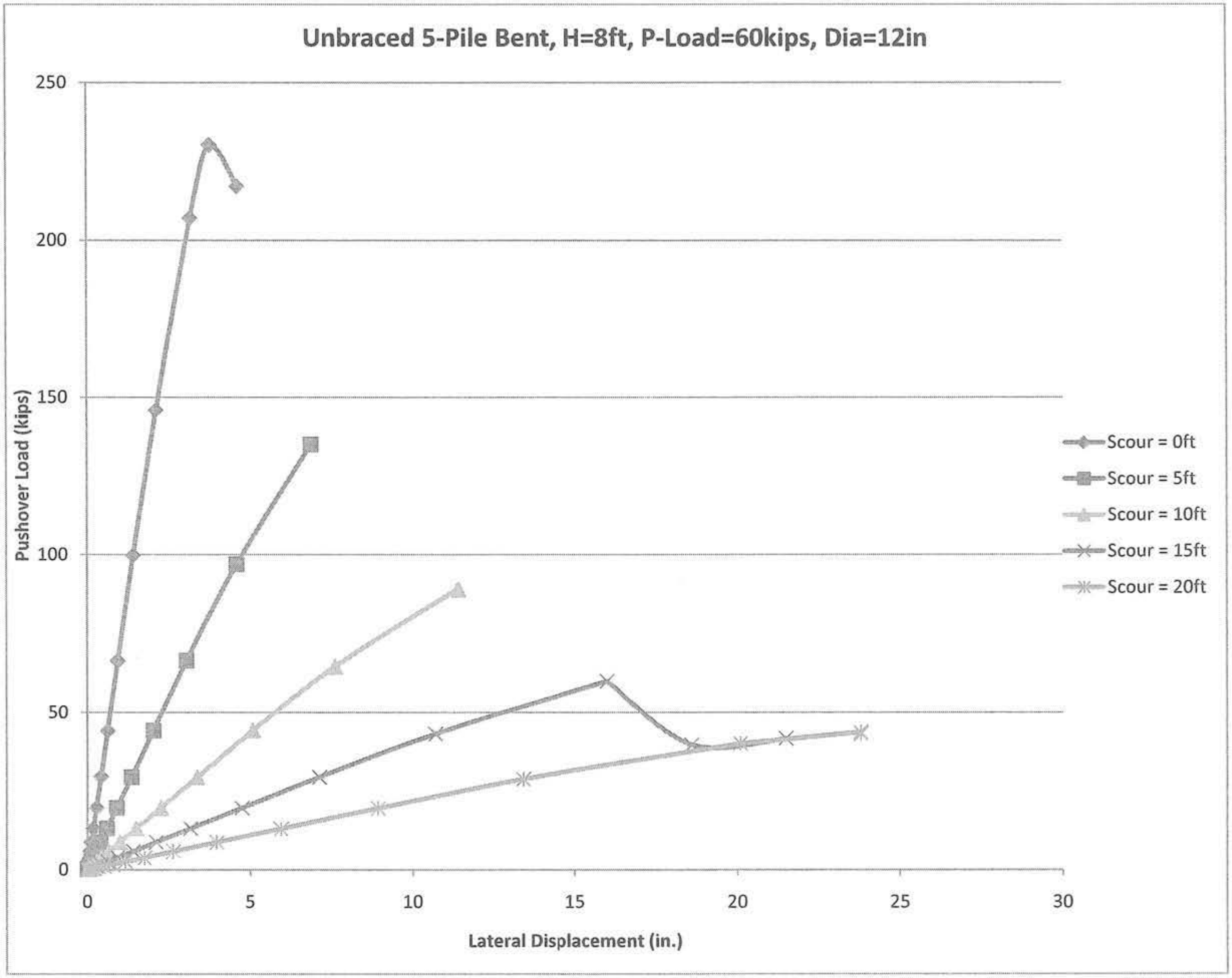


Figure B.39 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=60kips, Diameter=12in, Multiple Levels of Scour

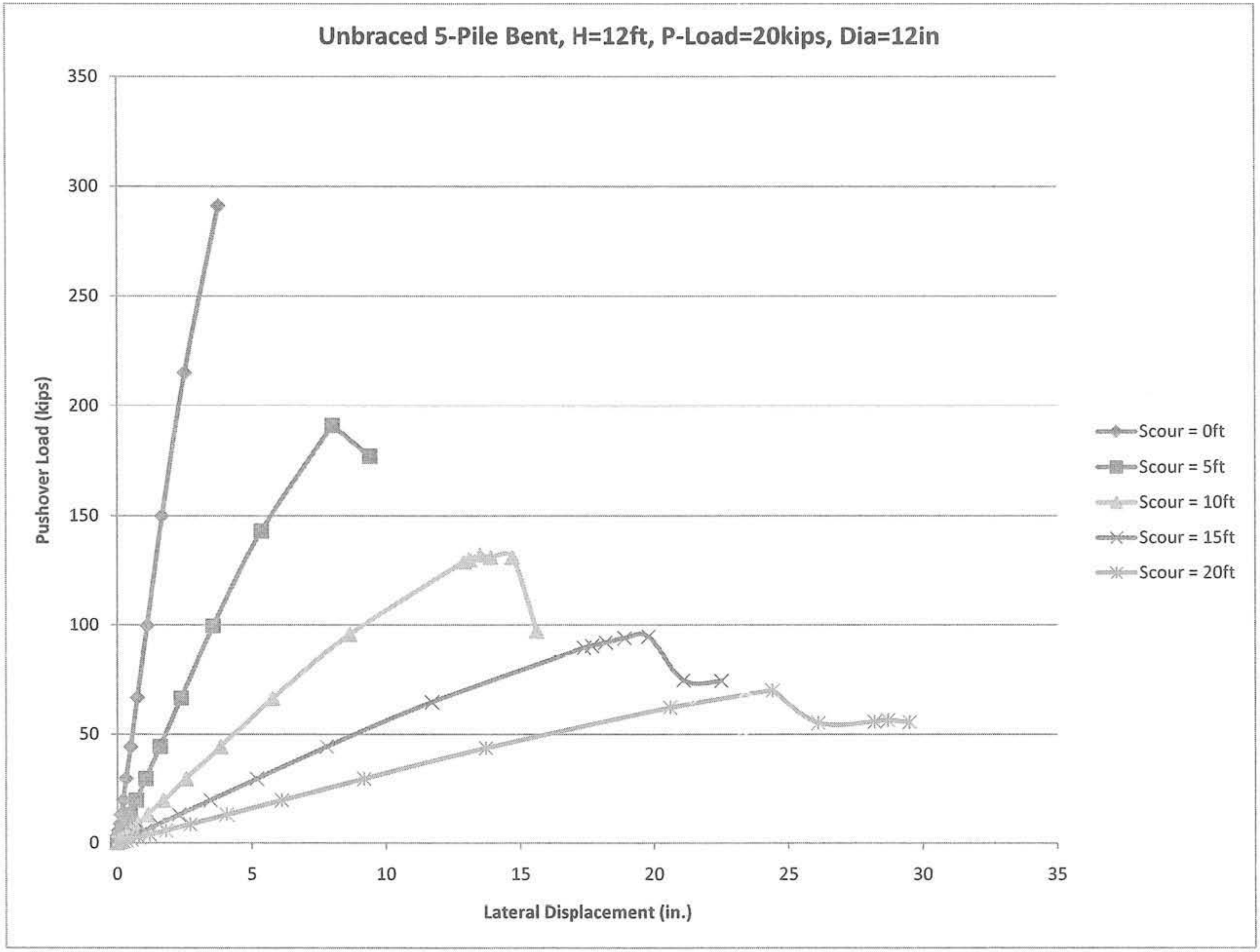


Figure B.40 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=20kips, Diameter=12in, Multiple Levels of Scour

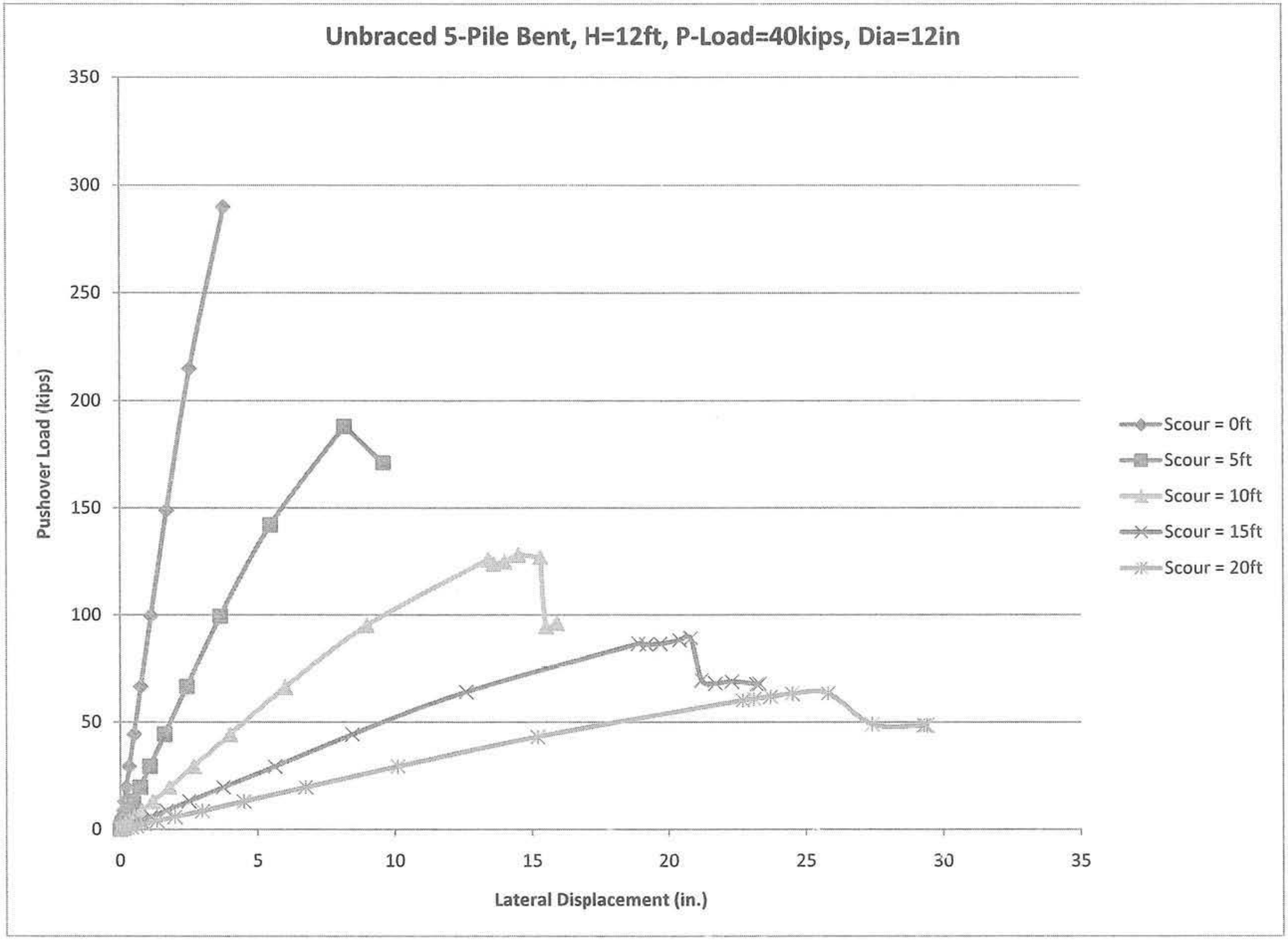


Figure B.41 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=40kips, Diameter=12in, Multiple Levels of Scour

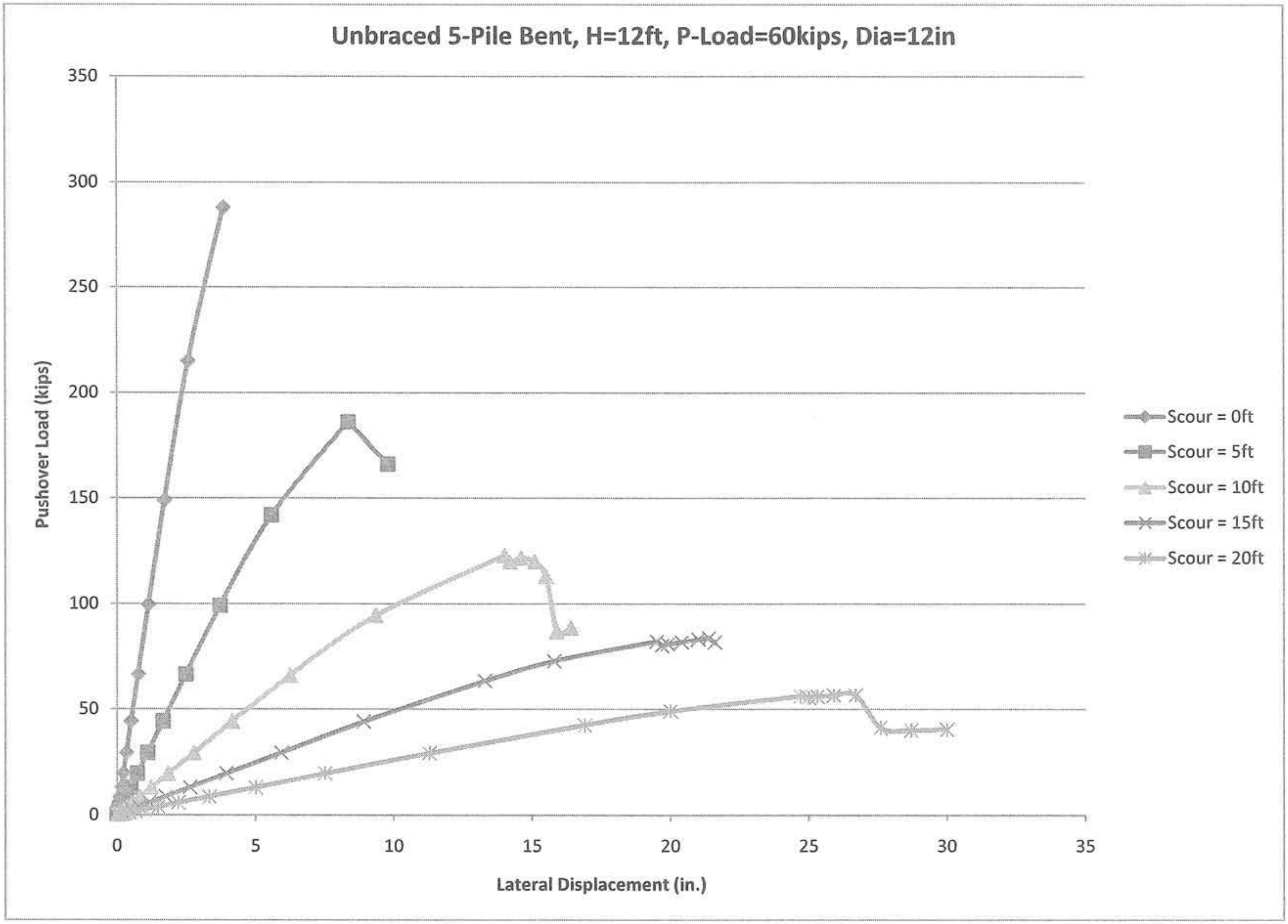


Figure B.42 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=60kips, Diameter=12in, Multiple Levels of Scour

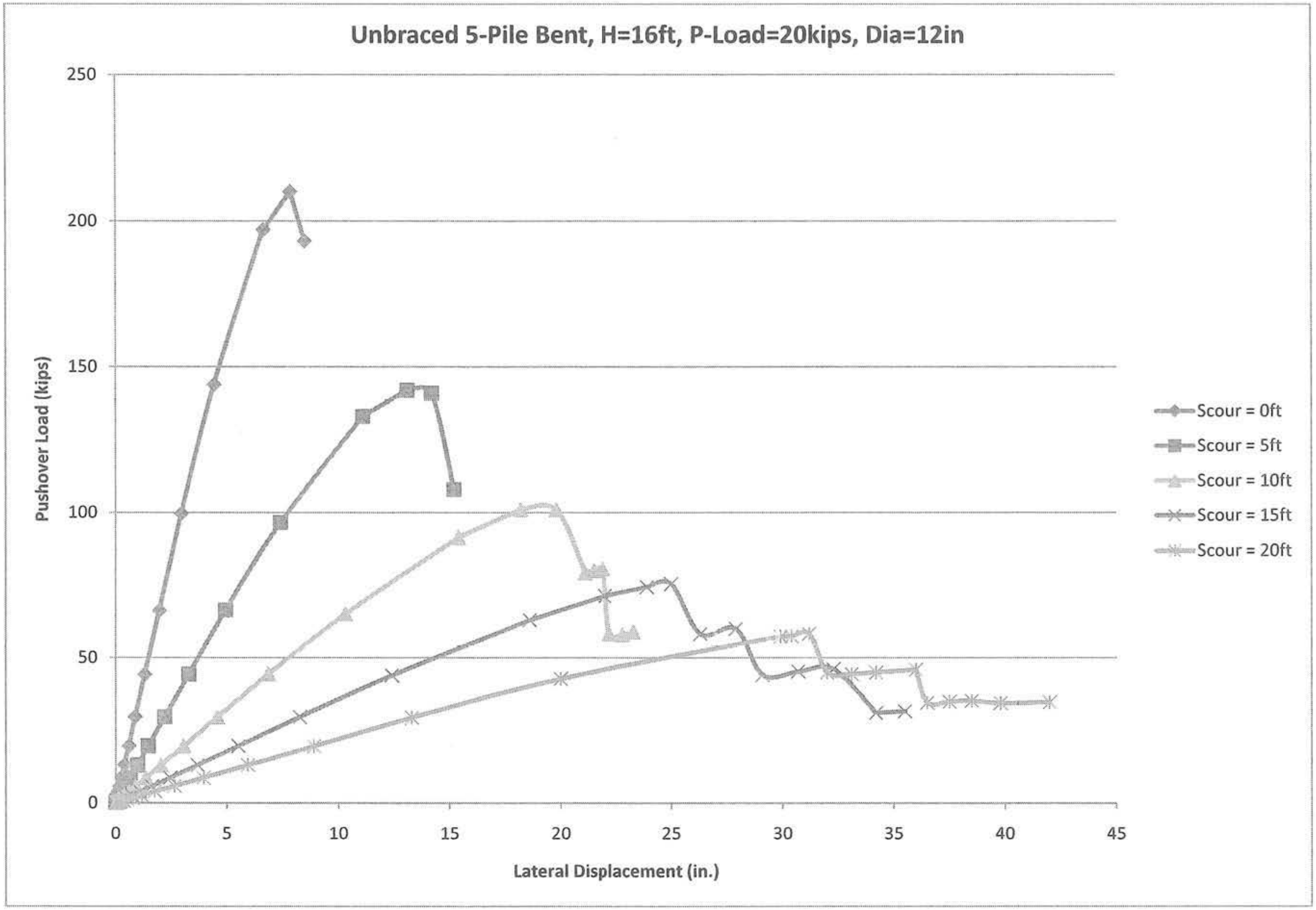


Figure B.43 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=20kips, Diameter=12in, Multiple Levels of Scour

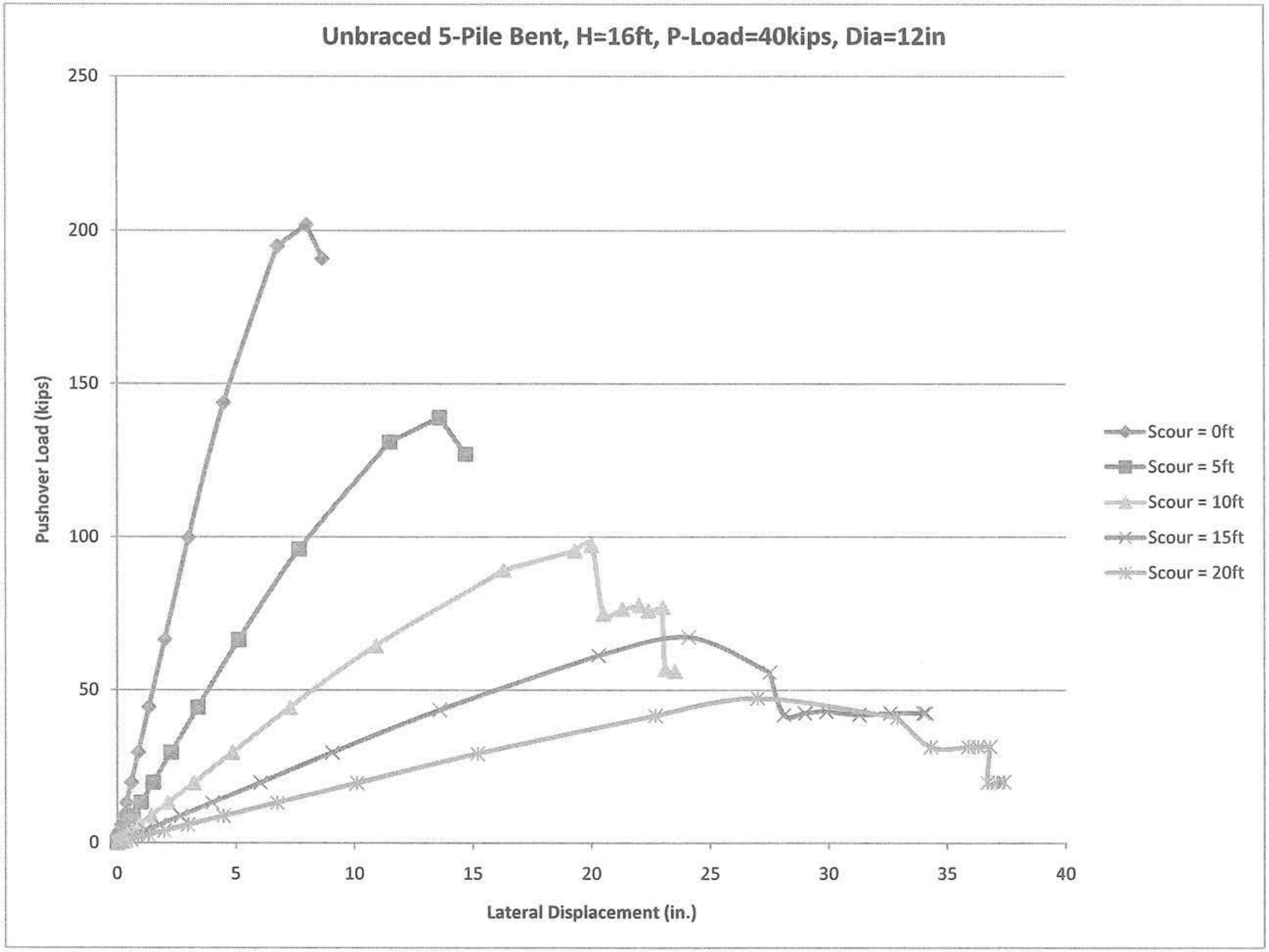


Figure B.44 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=40kips, Diameter=12in, Multiple Levels of Scour

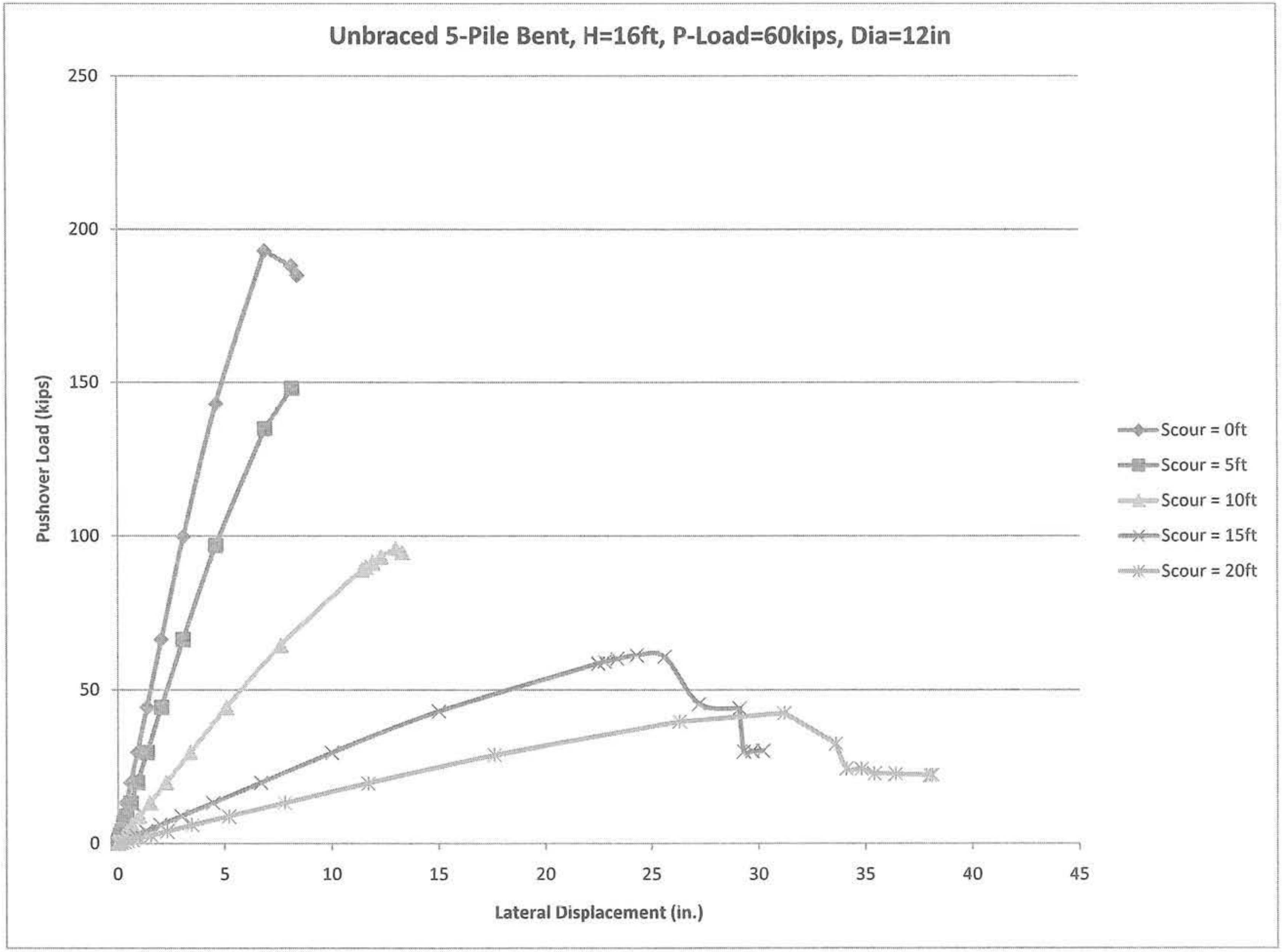


Figure B.45 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=60kips, Diameter=12in, Multiple Levels of Scour

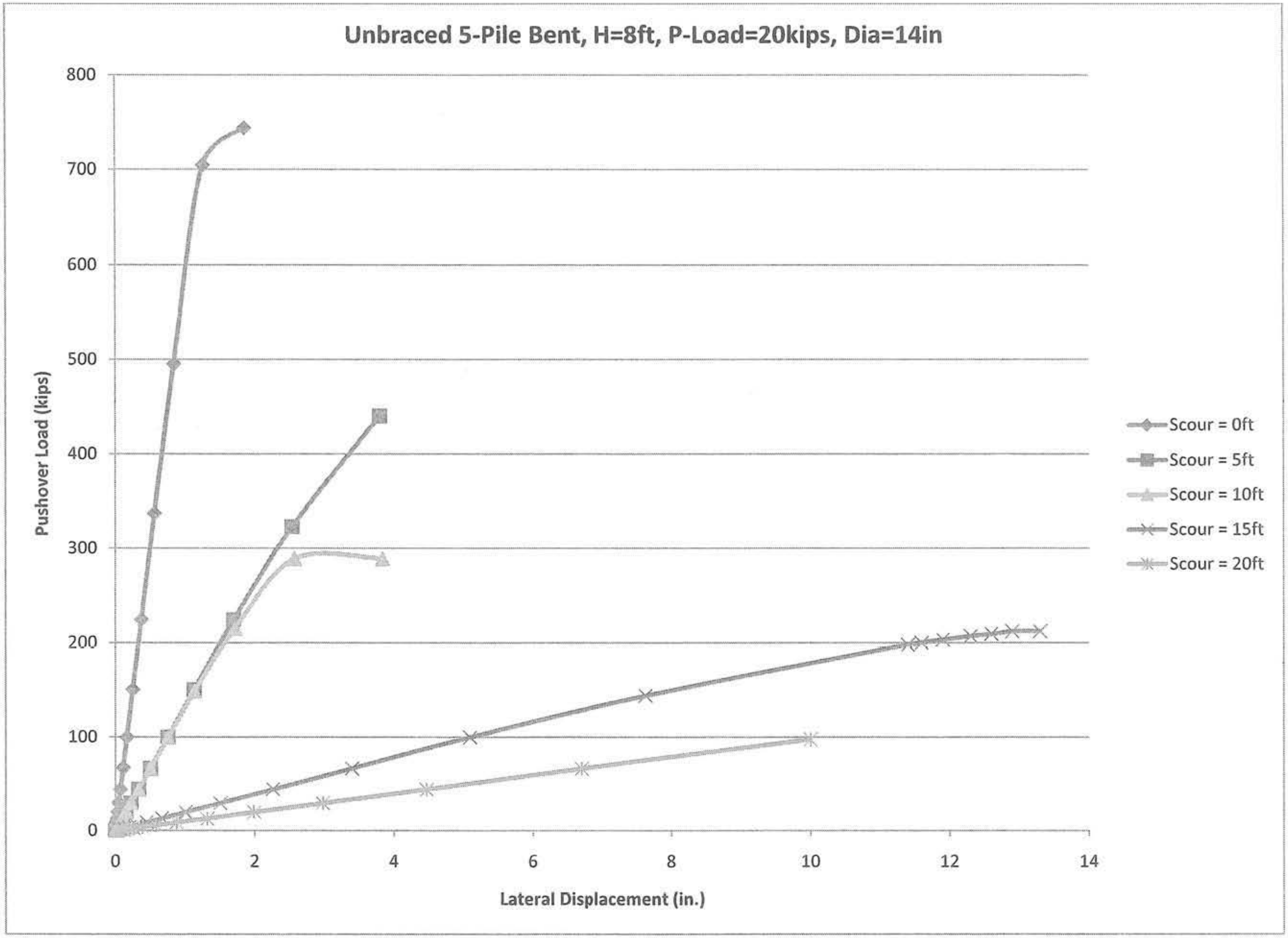


Figure B.46 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=20kips, Diameter=14in, Multiple Levels of Scour

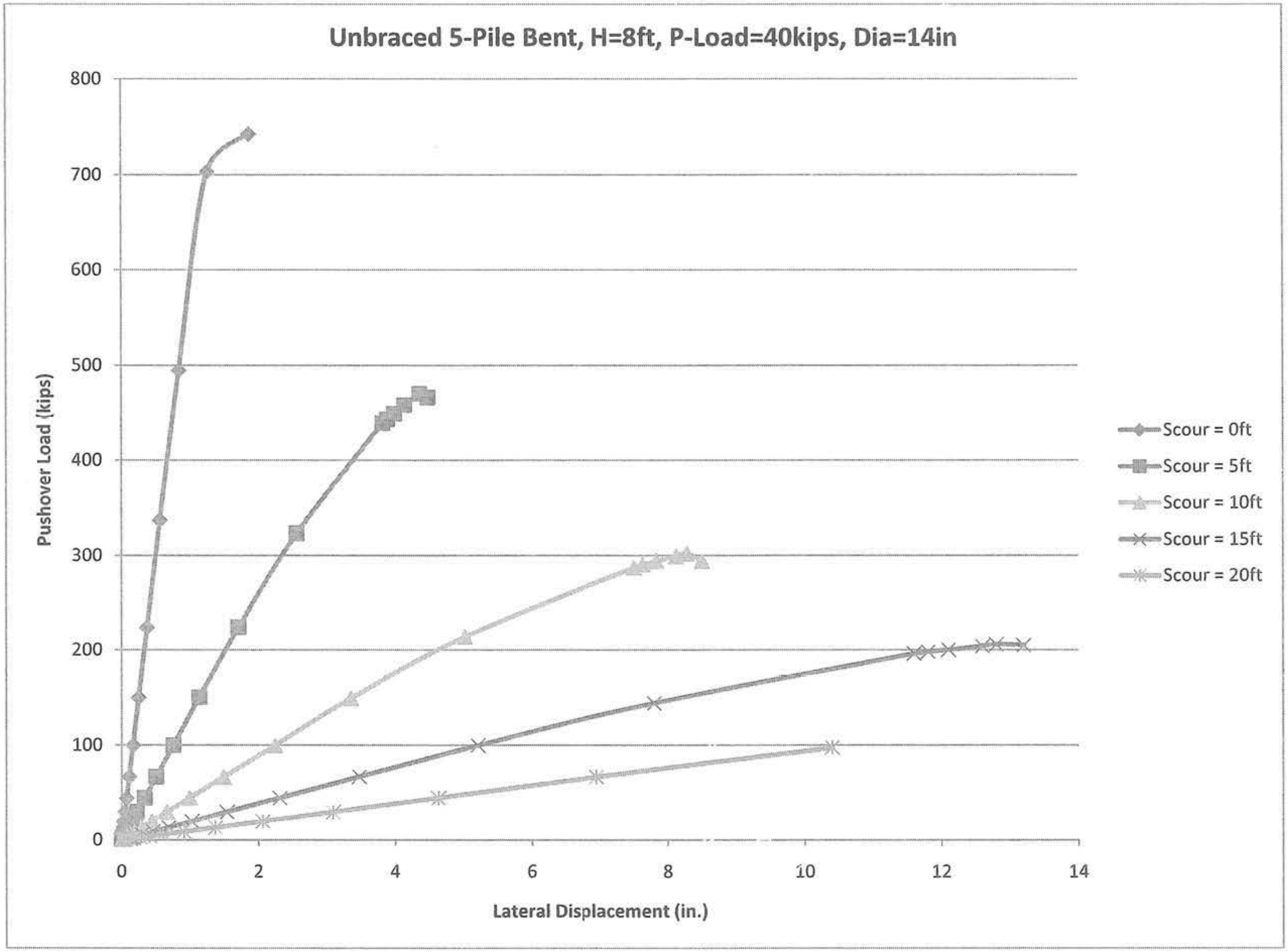


Figure B.47 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=40kips, Diameter=14in, Multiple Levels of Scour

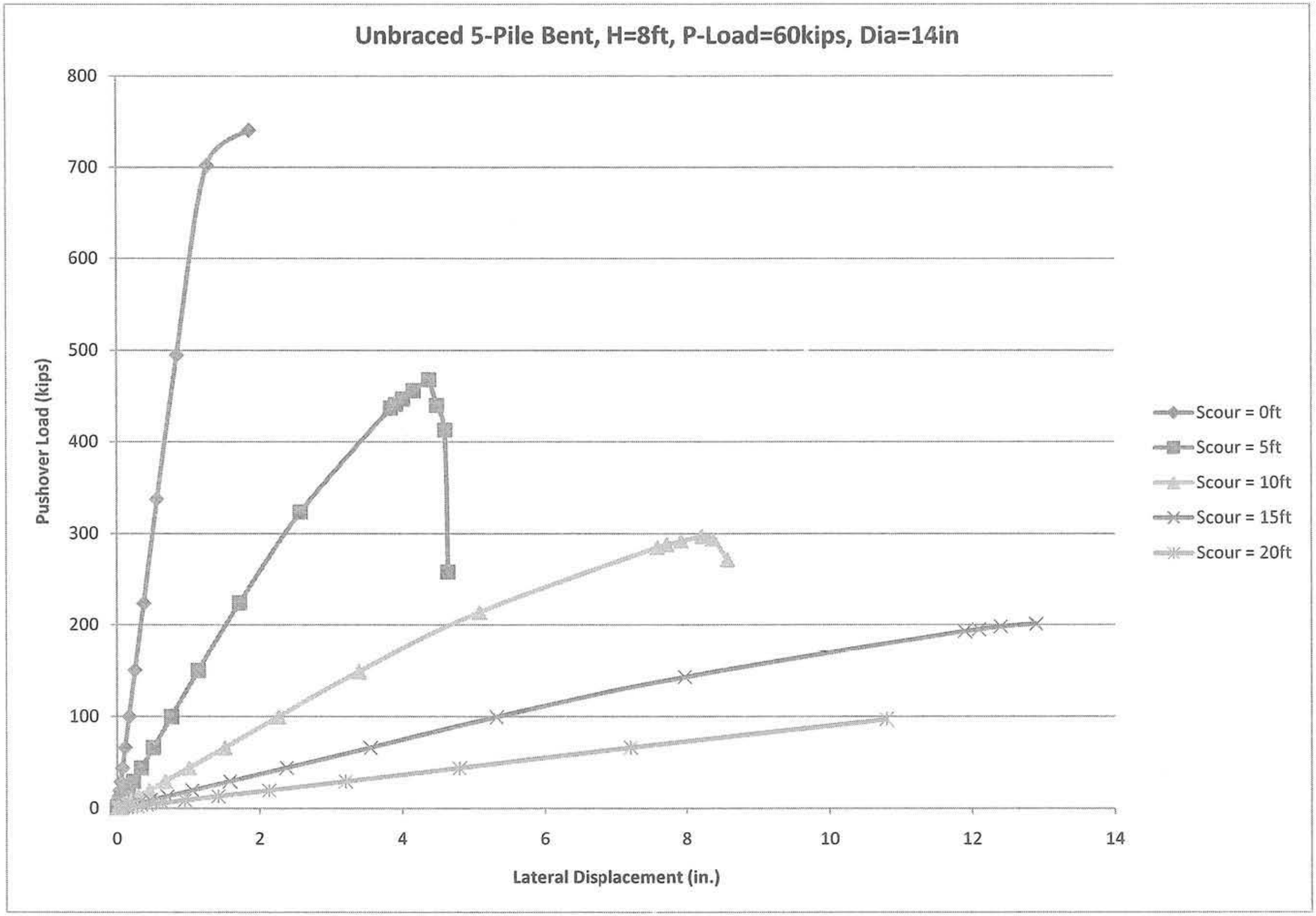


Figure B.48 Pushover Curves for Unbraced 5-Pile Bent, H=8ft, P=60kips, Diameter=14in, Multiple Levels of Scour

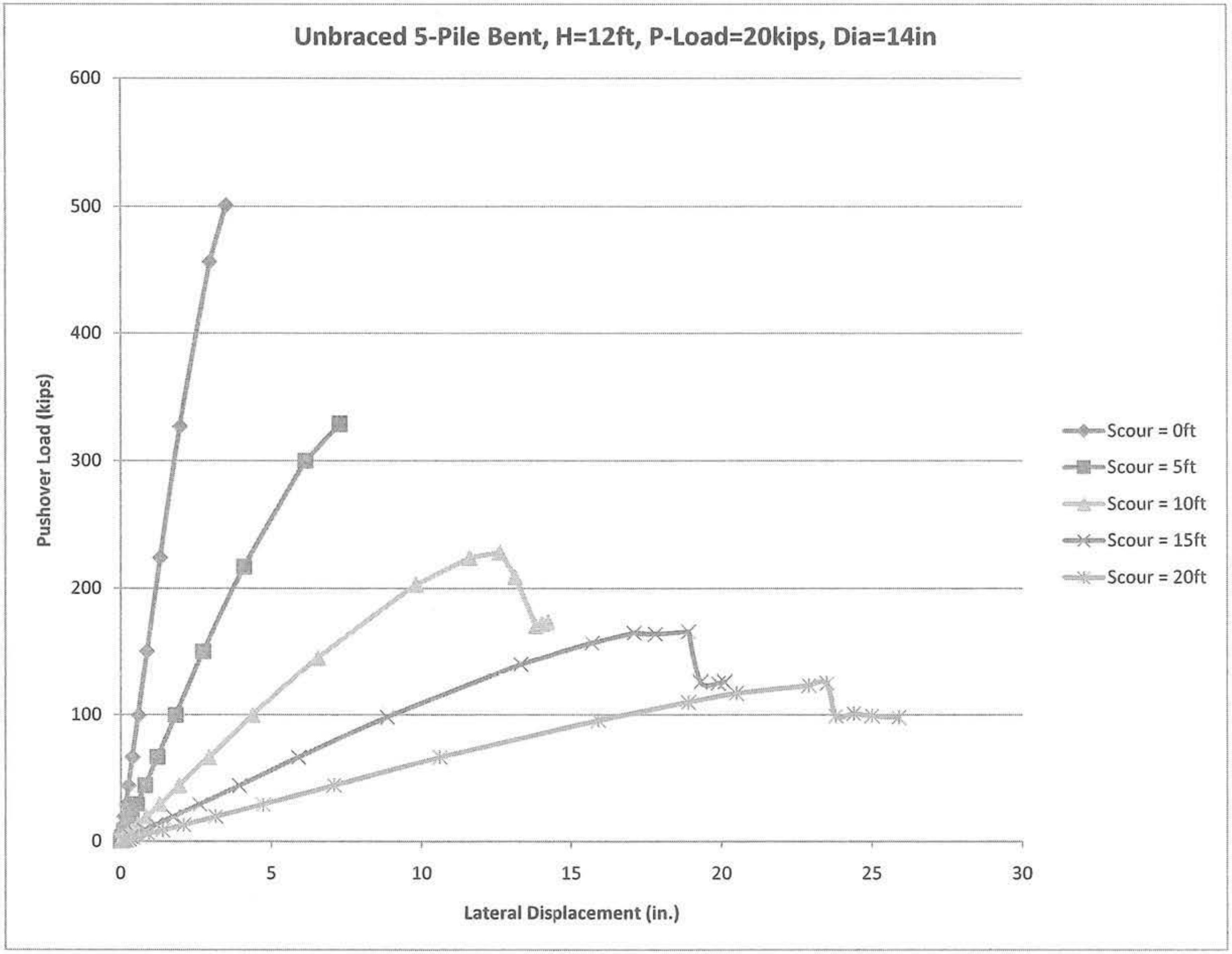


Figure B.49 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=20kips, Diameter=14in, Multiple Levels of Scour

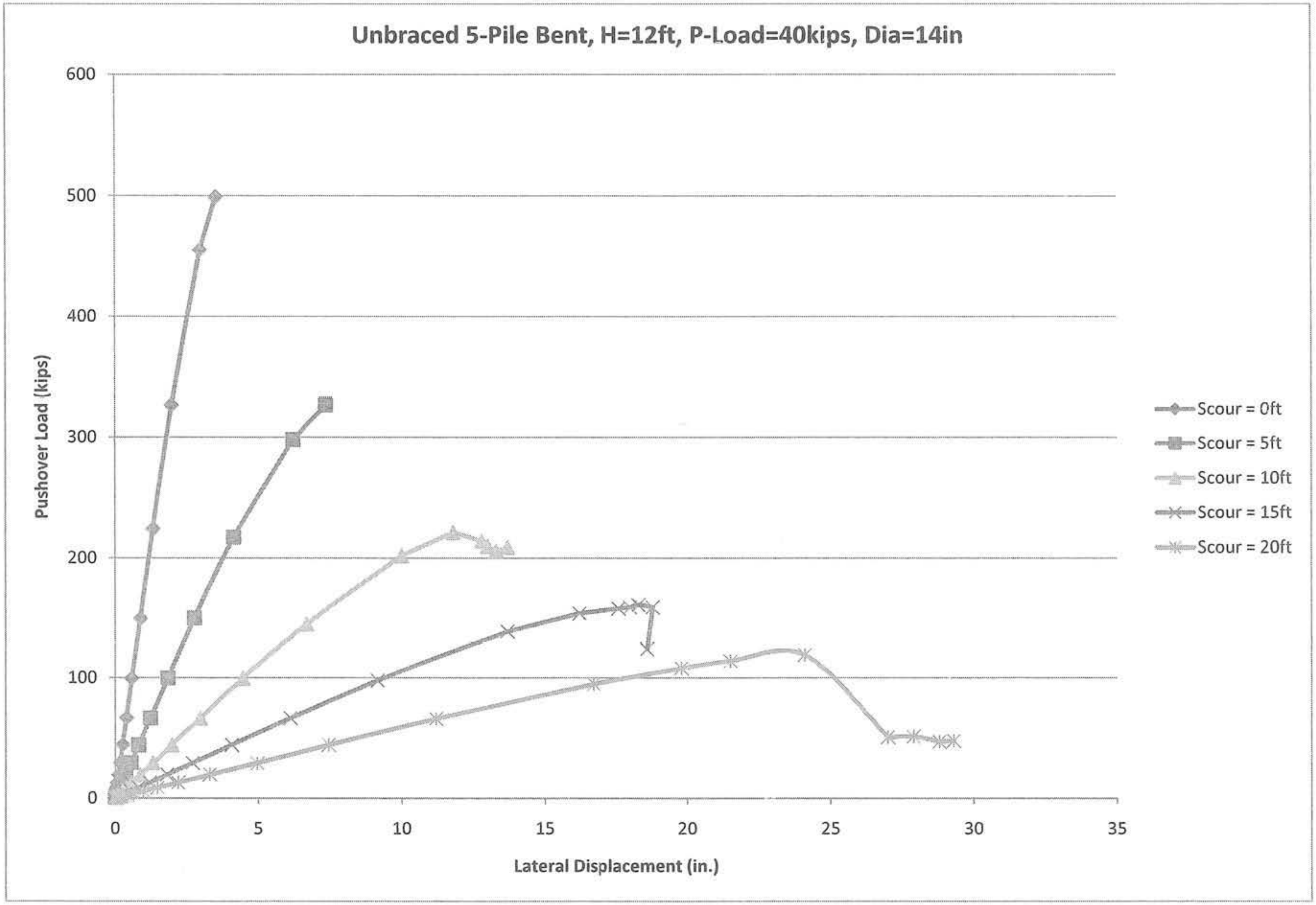


Figure B.50 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=40kips, Diameter=14in, Multiple Levels of Scour

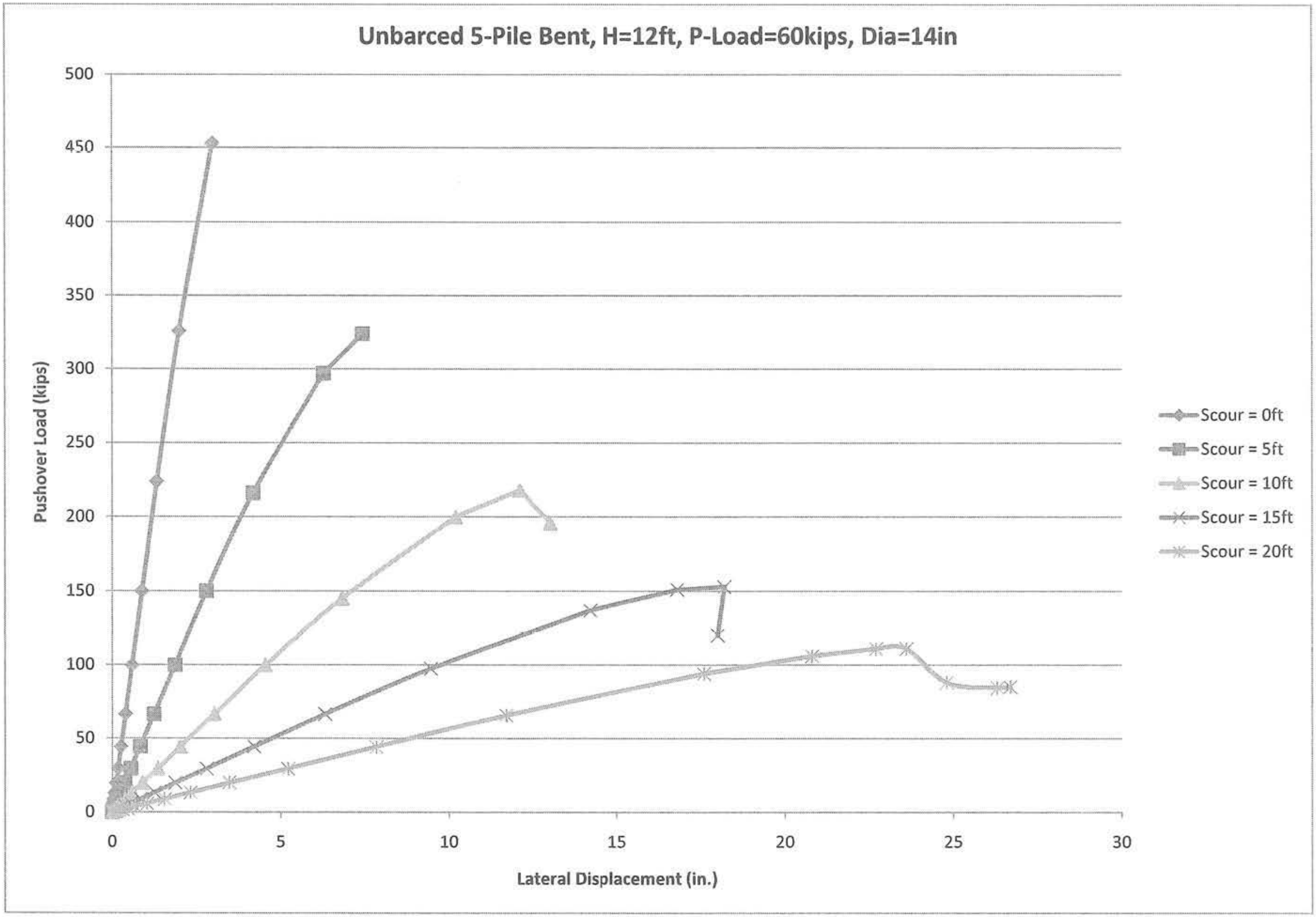


Figure B.51 Pushover Curves for Unbraced 5-Pile Bent, H=12ft, P=60kips, Diameter=14in, Multiple Levels of Scour

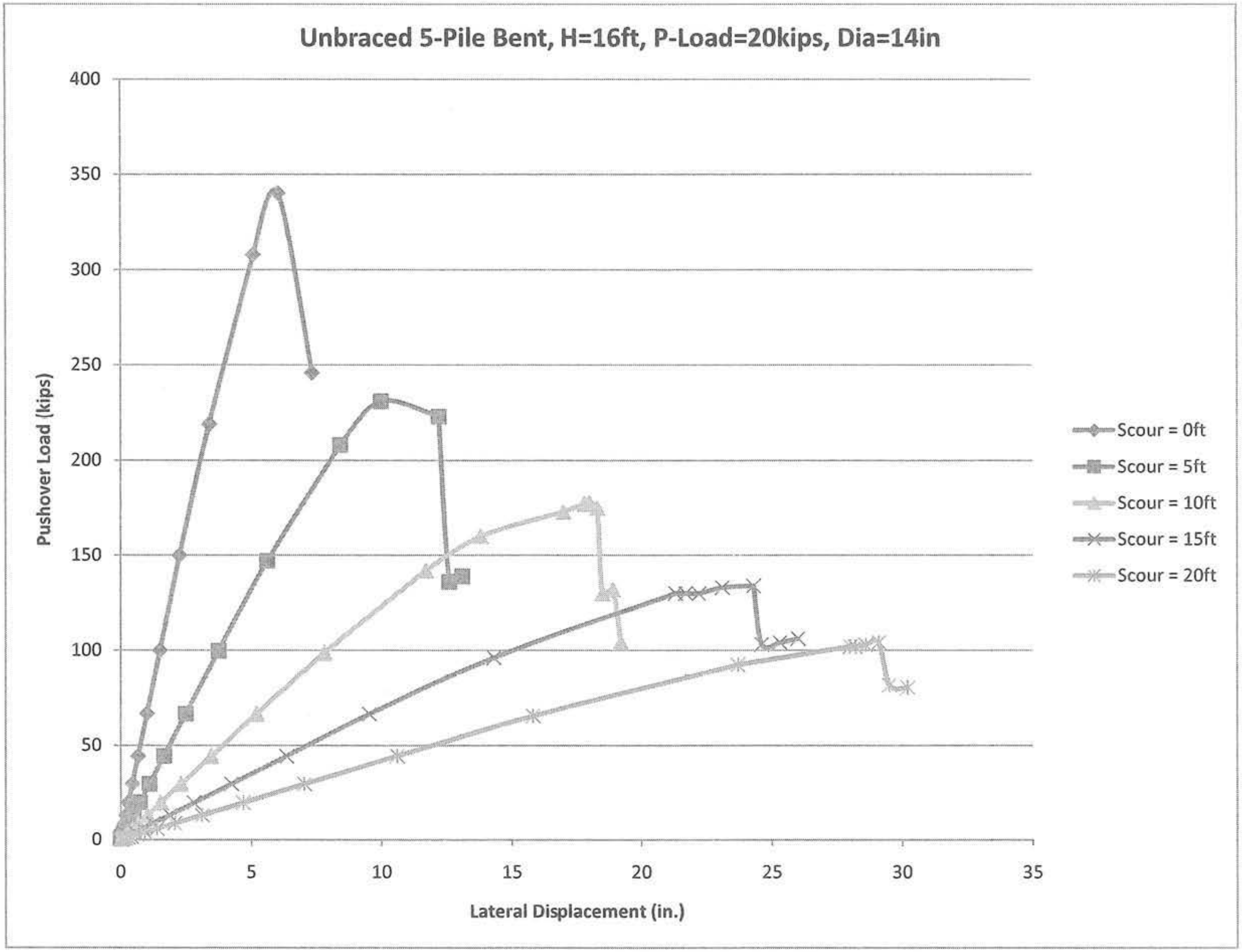


Figure B.52 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=20kips, Diameter=14in, Multiple Levels of Scour

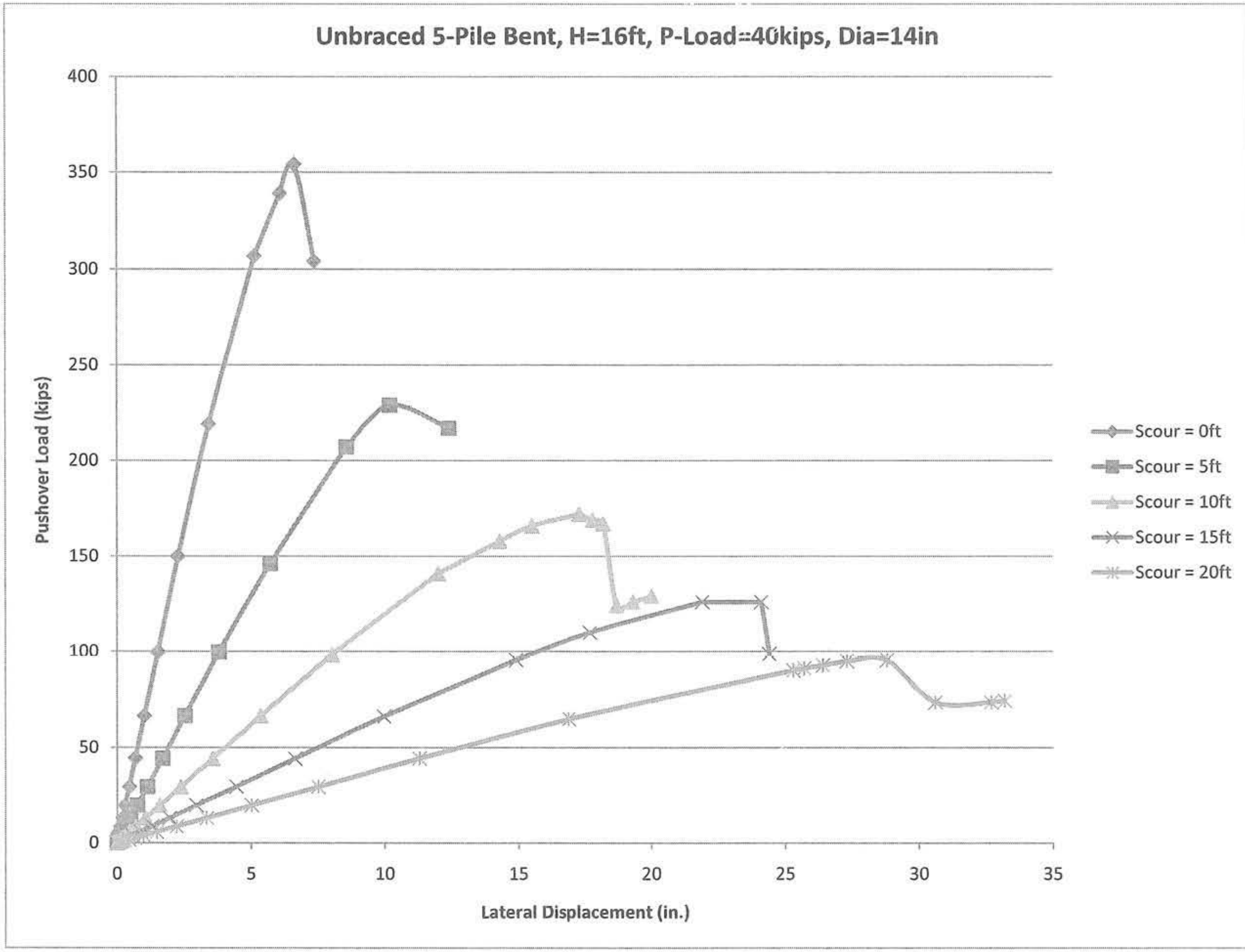


Figure B.53 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=40kips, Diameter=14in, Multiple Levels of Scour

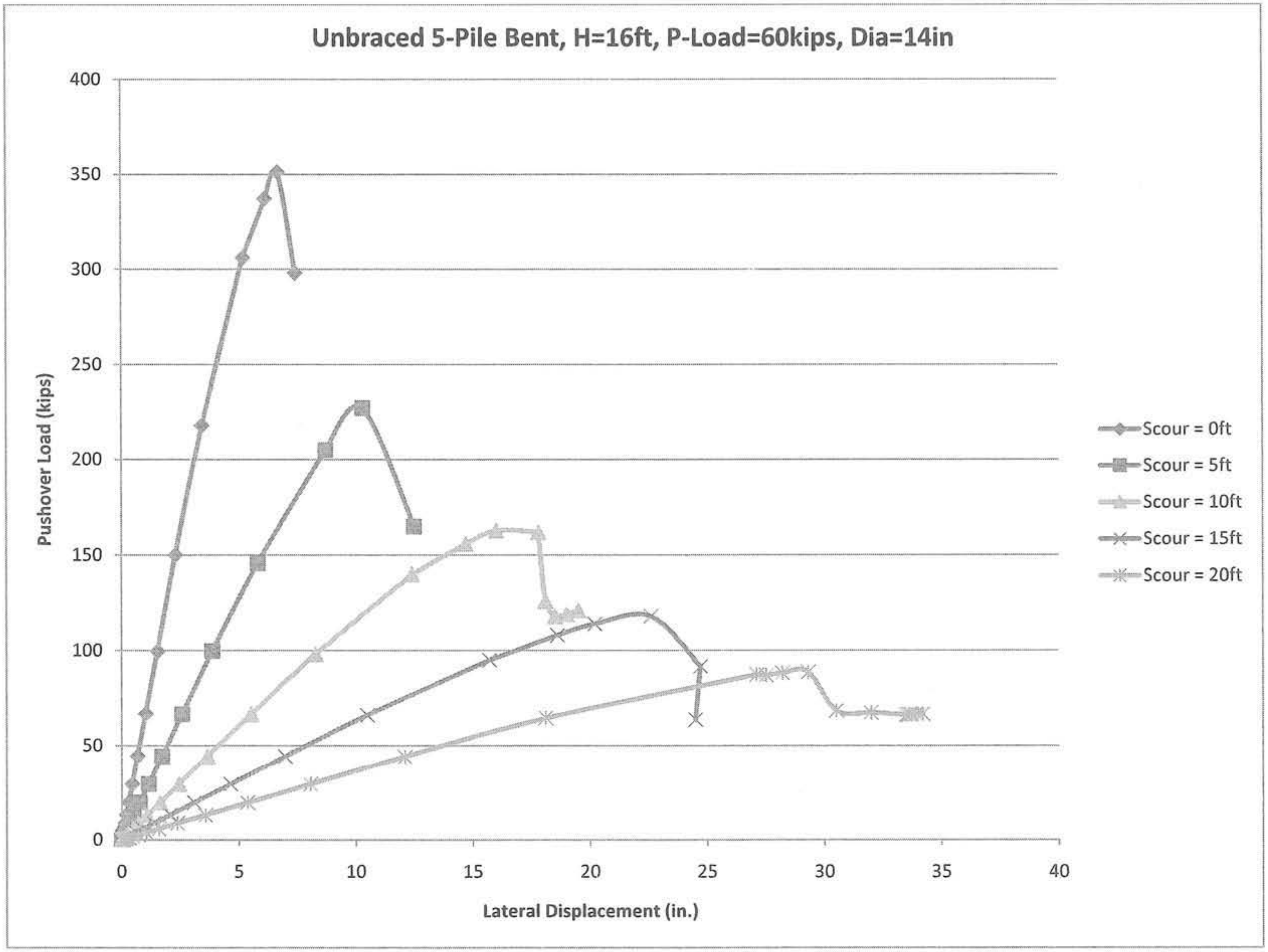


Figure B.54 Pushover Curves for Unbraced 5-Pile Bent, H=16ft, P=60kips, Diameter=14in, Multiple Levels of Scour