Final Report

on

Alabama Department of Transportation
Research Project 930-608

Stability of Highway Bridges Subject to Scour – Phase II

PROJECT PHASE II FINAL REPORT

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ABSTRACT

A common design/construction procedure for highway bridges in Alabama is the use of steel HP piles driven to a firm stratum with a length above ground/water up to the level of a concrete bent cap which supports the bridge superstructure. The use of 3, 4, 5, or 6 such piles in a row with the two end piles battered are very common bridge pile bents. The bents are sometimes X-braced in the plane of the piles for lateral support and sometimes the piles are encased in concrete from the bent cap down to 3 feet below ground level (and the X-bracing eliminated).

The Alabama Department of Transportation (ALDOT) is currently performing an assessment of scour susceptibility of it bridges, and a part of this assessment requires an evaluation of the structural stability of these bridges for an estimated scour event. Because of the large number of bridges in the state, there is a compelling need to develop a simple "screening tool" which can be used, along with the scour analyses, to efficiently assess the susceptibility of the pile bridge bents to failure during an extreme scour event.

The objectives of the Phase I research work on this multi-phase project was to identify the primary parameters of importance in assessing the adequacy of pile bents for extreme scour events, and to identify the best approach to follow in developing a screen tool. The objective of this Phase II research work was to develop a screening tool, and a user's guide explaining the proper use of the tool, for use in evaluating the stability of simple pile bent supported bridges in an extreme scour event. The screening tool should address a broad range of typical

bridge layouts, substructure designs, pile bent foundations, geotechnical conditions, and scour events encountered in Alabama. It should be as simple to use as possible, within the constraint of providing reliable results, require only bridges/foundation/site parameter data which are available to ALDOT engineers, and lend itself to later automation.

ACKNOWLEDGEMENTS

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The PIs are also grateful for the assistance and guidance of several ALDOT engineers during the execution of the research work. Specifically, thanks are due to George Conner, Eric Christie, and Randall Mullins of the ALDOT.

1. INTRODUCTION

1.1 Statement of Problem

Alabama has hundreds of highway bridges that were designed and constructed prior to 1990 and therefore not designed for scour. In addition, there are hundreds of county bridges constructed using standardized designs for which scour analysis is not part of the foundation design. ALDOT is currently performing an assessment of scour susceptibility of its bridges, and a part of this assessment requires an evaluation of the structural stability of these bridges for an estimated scour event.

A common design/construction procedure for highway bridges in Alabama is the use of steel HP piles driven to a firm stratum with a length above ground/water up to the level of a concrete bent cap which supports the bridge superstructure. The use of 3, 4, 5, or 6 such piles in a row with the two end piles battered are very common bridge pile bents. The bents are sometimes X-braced in the plane of the piles for lateral support and sometimes the piles are encased in concrete from the bent cap down to 3 feet below ground level (and the X-bracing eliminated).

Because of the large number of bridges in the state, and because stability analyses of each bridge bent represents a considerable effort in time and money, there is a compelling need to develop a simple "screening tool" which can be used, along with the scour analyses, to efficiently assess the susceptibility of the bridge bents to failure during an extreme scour event. Such a tool could be used to identify those bridge bents which are most likely to be deficient and should be prioritized for more detailed study. Because of the tendency to use standardized designs with pile bent foundations for many of the smaller bridges in Alabama, it is feasible to pursue the development of such a screening tool.

1.2 Research Objective

The objective of this Phase II research was to develop a screening tool, and a user's guide explaining the proper use of the tool, for use in evaluating the stability of simple pile bent supported bridges in an extreme scour event. The screening tool should address a broad range of typical bridge layouts, substructure designs, pile bent foundations, geotechnical conditions, and scour events encountered in Alabama. It should be as simple to use as possible, within the constraint of providing reliable results, require only bridges/foundation/site parameter data which are available to ALDOT engineers, and lend itself to later automation.

1.3 Work Plan

The work plan to accomplish the research objective cited above is given below.

1. Complete the preliminary work started in Phase I on checking for possible pile plunging failure to develop a simple procedure for checking for this failure mode in the screening tool.

2. Evaluate cases of piling founded in hard layers with almost zero embedment after a scour event, and decide on the appropriate procedure for checking for possible pile tip "kick-out" failure in the screening tool.

3. Evaluate further the requirements for pile encasements to achieve composite behavior up to the buckling load for common pile loading conditions based on information available in the literature.

4. Perform pile bent/frame stiffness analyses to determine the lateral stiffness and $k_{equivalent}$ provided by the bent batter piles. If this k_{eq} is greater than k_{ideal} needed for the bent to buckle in a non-sidesway mode, then the presence of pile encasements and/or sway bracing is not vital for lateral stability.

5. Evaluate flood debris build-up and resulting bent transverse loading and possible failure under this loading.

6. Model and determine bent vertical failure load (buckling load) using GTSTRUDL Pushover Analysis procedures. This has the potential of providing an easier modeling and more accurate failure load estimation than does FB Pier for the cases requiring closer examination.

7. Draft the screening tool to assess the adequacy of bridge pile bents in the event of an extreme scour event. Include in the narrative description of the step-by-step procedure employed in the screening tool an associated commentary for each step which provides background and the "whys" and "hows" of the working of the screening tool.

8. Draft a user's guide to outline and explain the procedure in using the screening tool.

9. Meet with ALDOT bridge maintenance engineers to discuss the screening tool and user's guide and make refinements as necessary after this meeting.

10. Meet with select ALDOT personnel to test the screening tool and user's guide. ALDOT's bridge maintenance engineer will select the personnel to participate in the "Test Meeting". Further refine the screening tool and/or guide based on feedback from the "Test Meeting".

11. Prepare and conduct a training seminar at ALDOT's office in Montgomery to train ALDOT personnel in how to use the screening tool.

12. Prepare Phase II Final Report.

2. THEORETICAL CONSIDERATIONS

2.1 General

As indicated in the Phase I Report (I), possible failure modes of bridge pile bents during extreme scour events are as follows:

(1) Buckling of Bent Piles in Longitudinal Direction

(2) Buckling of Bent Piles in Transverse Direction

(3) Crushing or Reaching P_y of Piles

(4) Plunging Failure of Piles (Soil Failure)

(5) Local Yielding of Piles $\left(\sigma_z = -\frac{P}{A} \pm \frac{M_x y}{I_x} \pm \frac{M_y x}{I_y} = \sigma_y\right)$

(6) Flexural Failure of Bent Cap

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

(8) Bent failure from piles tips being "kicked" out due to zero or almost zero embedment after scour.

Failure modes (7) and (8) above were identified in post Phase I meetings with ALDOT personnel.

As indicated in the Phase I Report (I), flexural failure of the bent cap can only occur if $P_{girder\ max} > P^{pile}_{buckling}$ or $P^{pile}_{plunging}$. In such a case, flexural failure of the cap must be prevented to gain lean-on support from the adjacent piles in the bent. If $P_{girder\ max}$ is less than $P^{pile}_{buckling}$ and is less than $P^{pile}_{plunging}$ then flexural failure of the bent cap will not occur. In almost every situation, this should be the case.

Local yielding of a bent pile is normally not a catastrophic situation and only results in local permanent deformations in the pile. Note that the piles may reach a fully plastic moment state at the section of M_{max}, i.e., the pile ground line, and not have a catastrophic situation. Thus this is not a failure condition of concern.

Crushing of the pile, or the pile reaching the P_y load, is implicitly checked if inelastic buckling is considered. Also $P_{max\ applied}$ and P_y of the piles are unaffected by a scour event, and therefore crushing of the piles will not occur.

Thus, only buckling of the bent piles (either elastic of inelastic buckling), 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 will be catastrophic failure modes. Thus these are the only four modes of failure of concern and requiring checking.

2.2 Pile Tip "Kick-Out" Failure

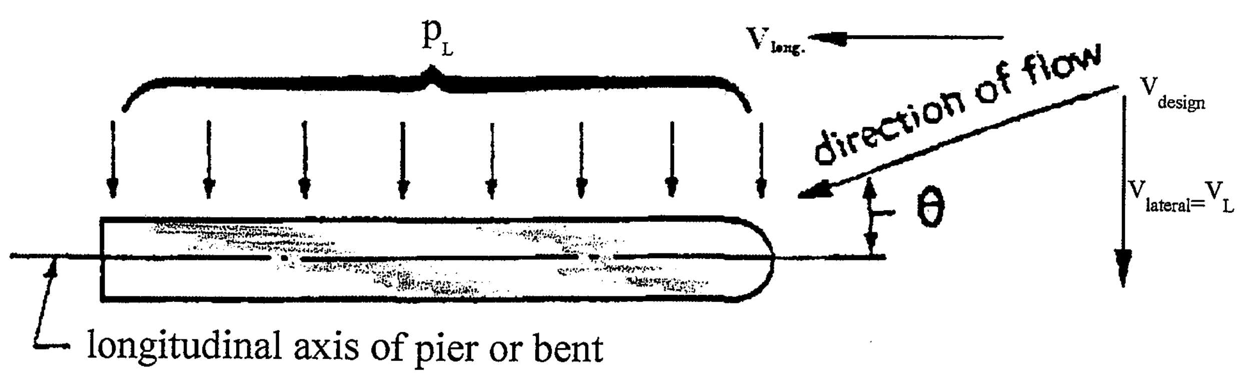
In checking for bent failure from the pile tips being "kicked-out" due to zero or almost zero embedment after scour, if we call ℓ_{re} the remaining pile embedment after scour (see Fig. 2.1b), then if

$$\ell_{re} \leq 3.0 \text{ ft}$$

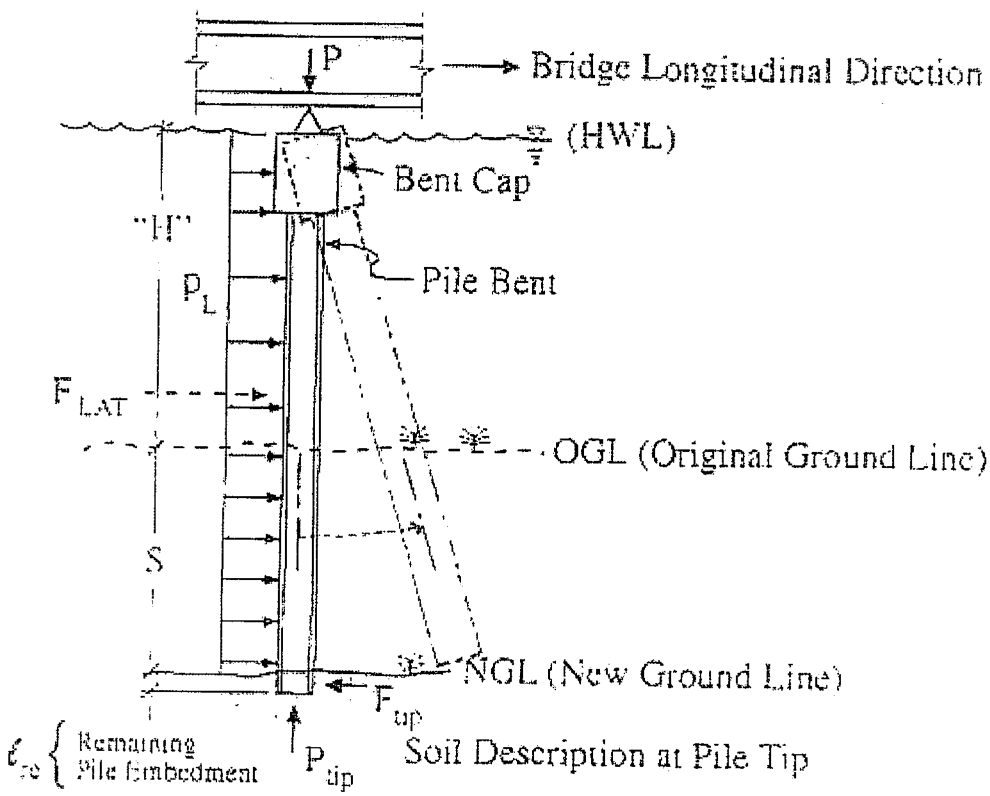
such a "kick-out" mode is very possible and corrective action should be taken in such cases immediately, i.e., before the occurrence of a major scour event. The best corrective action would probably be to place rip-rap around the bent piling.

If ℓ_{re} > 3.0 ft then the piles and bent should be safe from this mode of failure.

See Section 4.5 for a discussion of the pile tip "kick-out" force.



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 2.1. Pile Tip "Kick-Out" Failure

2.3 Pile Plunging Failure

In checking P^{max}_{pile} for possible plunging failure, if the length of a steel HP pile (with its tip founded in a firm soil stratum) below ground before scour is greater than 3.0 S, then plunging should not occur. That is (see Fig. 2.2), if

$$\ell_{bg} \geq 3.0\ S$$

then $P_{pile\ capacity} > P^{max}_{pile}$ and the pile should not plunge. For cases where this condition is not met, but $2.0\ S < \ell_{bg} < 3.0\ S$, and the pile tip is founded in a firm cohesive soil layer or the pile is a prestressed concrete pile, then the pile should be safe from plunging. If these conditions are not met then a more

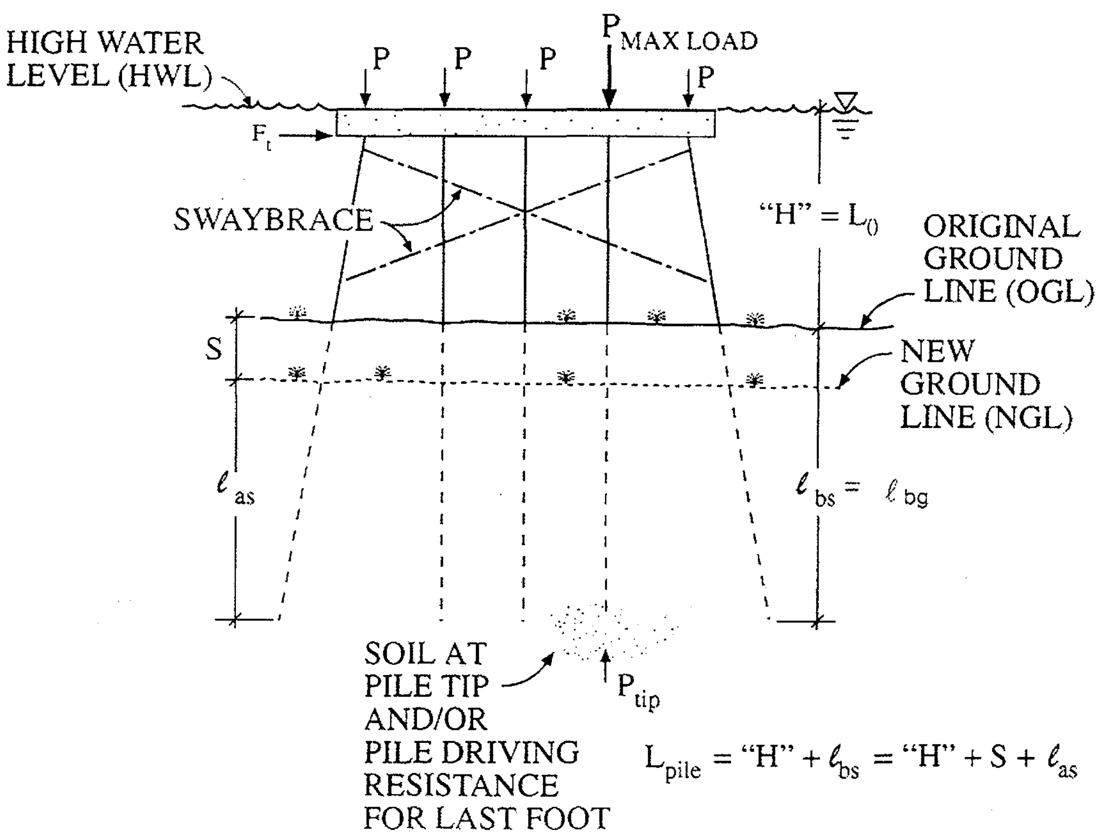


Figure 2.2. Typical Pile Bent

comprehensive analysis should be made to determine if the pile/bent is safe against a plunging failure. Obviously to make the above checks, the engineer must know the pile type and length below ground, ℓ_{bg}, and the extreme event scour, S (see Fig. 2.2). Additional information that may be needed in borderline cases is a description of the soil stratum that the pile tips are embedded in and/or the pile driving resistance over the last foot.

2.4 Pile Buckling Failure

In checking P_{pile}^{max} for possible buckling failure, the first step is to verify that the piles and bent can not sidesway a significant distance in either the longitudinal or transverse directions. To verify that the bents can not sidesway in the longitudinal direction requires that the superstructure be positively connected to the bent caps and that the superstructure is restrained from significant longitudinal movement by the bridge abutments. To verify that the bents can not sidesway in the transverse direction, the pile bents must be x-braced and have a batter pile at each end of the bent, and/or the superstructure must have continuous spans (or spans made continuous for live load) and be positively connected to the bent caps and abutments. If the pile bent can not sidesway significantly in either direction (which should be the case), then nonsway buckling of steel HP piles in the transverse direction (about their weak axis) will control and P_{CR} (either elastic of inelastic) can be determined from Fig. 2.2.

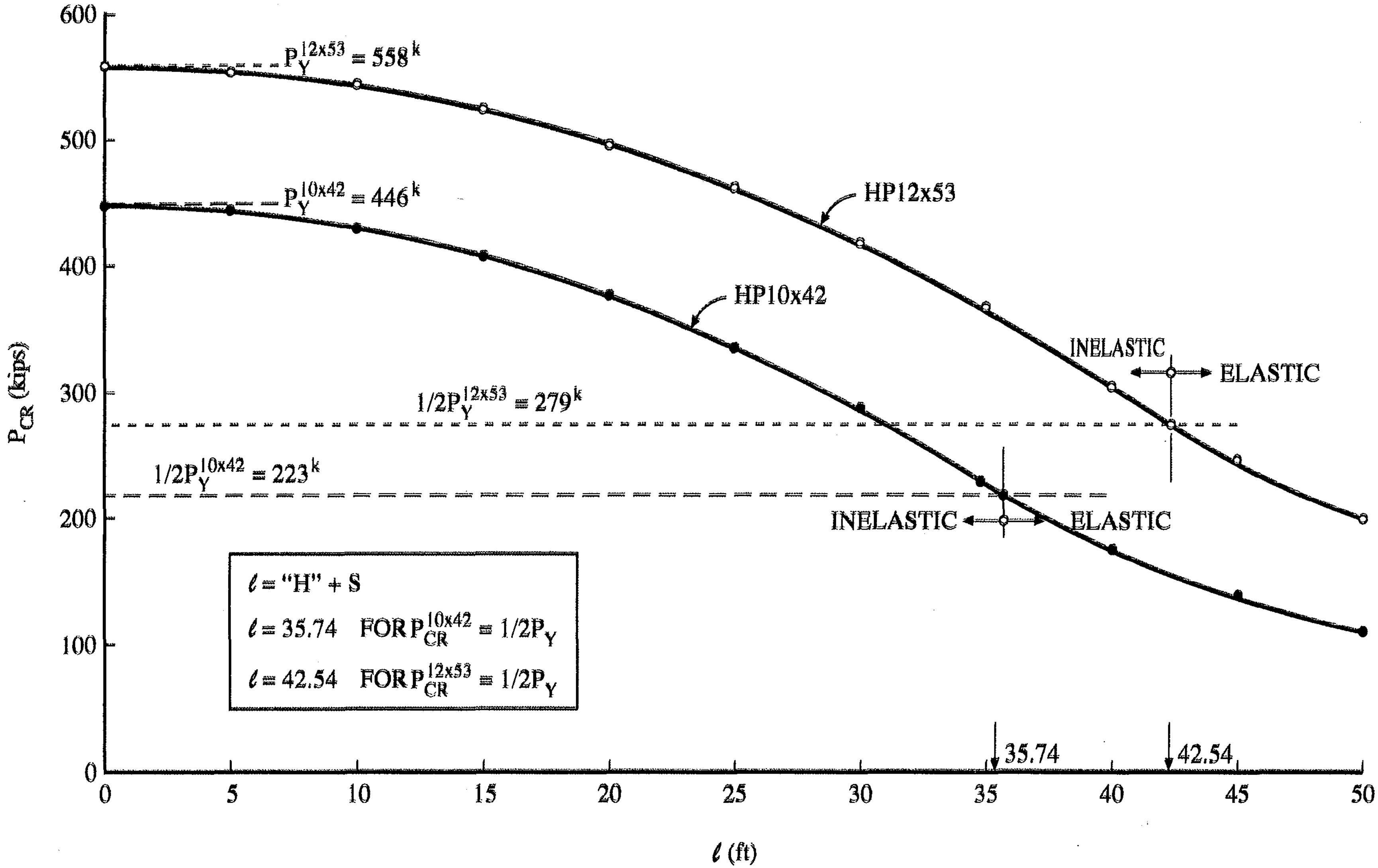


Figure 2.2. Transverse/Weak Axis Buckling of a Single Bent HP Pile of A36 Steel for a Given Length (ℓ_{max}) Above Ground Line After Scour (1).

Note however, as shown in Fig. 2.3, for simply supported (SS) bridges with large scour, we could get a transverse sidesway mode of buckling in the region from the new ground line (NGL) to approximately 4 feet above the original ground line (OGL). To determine what level of scour would be required to get this failure mode, we can use the $P_{CR}^{(2)}$ equation in Fig. 2.3 and assume a somewhat arbitrary but reasonably high value of $P_{CR}^{(2)}$ (so as to obtain a lower limit level of S_{CR} as, $P_{CR}^{(2)} = \frac{1}{2} P_y$. Thus,

$$P_{CR}^{(2)} = \frac{1}{2} P_y = \frac{1}{2} \frac{\pi^2 EI_y}{(S+4')^2}$$

$$(S+4)^2 = \frac{\frac{1}{2}\pi^2 EI_y}{\frac{1}{2} P_y}$$

For a HP 10 x 42 pile of A36 steel,

$$(S+4')^2 = \frac{\pi^2 \times 29{,}000 \times 71.7}{36 \times 12.4} = 45{,}974 \text{ in}^2$$

$$S+4' = 214 \text{ in}$$

$$S = 166 \text{ in} = 13.87 \text{ ft}$$

For buckling mode (1) to occur at this same load and scour level would require an H value of (see Eqns. (c) and (d) in Fig. 2.3)

$$(H+S)^2 = 4(S+4')^2$$

$$= 4(13.87' + 4')^2$$

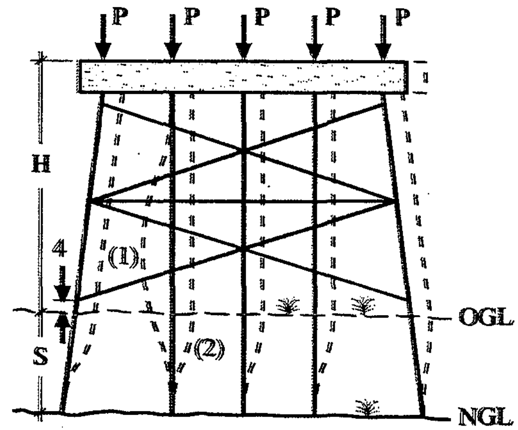
$$= 1277 \text{ ft}^2$$

or,

Buckling Mode[(1)] - Nonsidesway

$$P_{CR}^{(1)} \approx \frac{2\pi^2 EI_y}{(H+S)^2} \qquad \text{(a)}$$

Buckling Mode[(2)] - Sidesway (Lower Portions of Piles)
- Assuming the Superstructure is
- not continuous



$$P_{CR}^{(2)} \approx \frac{1}{2} x \frac{\pi^2 EI_y}{(S+4)^2} \qquad \text{(b)}$$

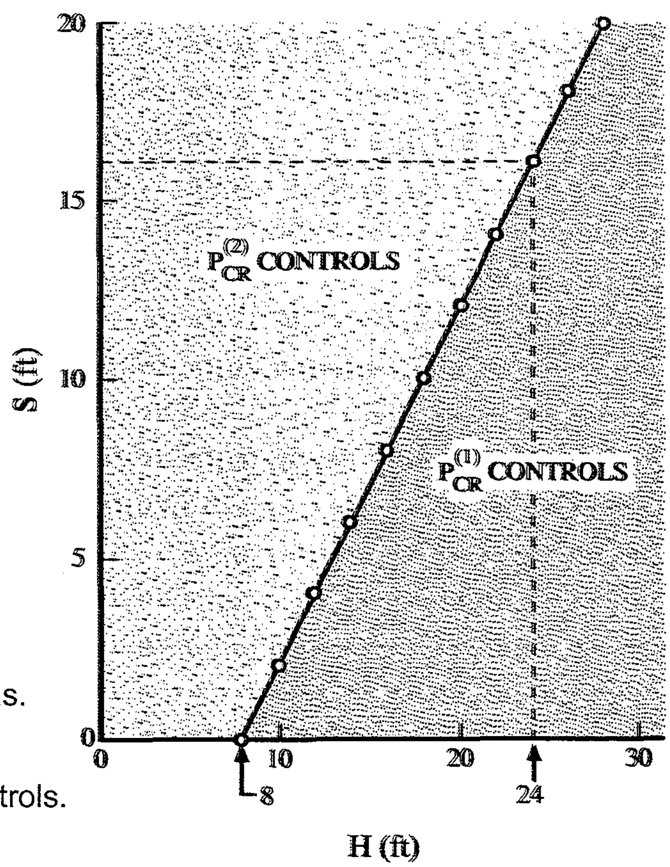
H and S for $P_{CR}^{(1)} = P_{CR}^{(2)}$ (c)

$$\frac{2\pi^2 EI_y}{(H+S)^2} = \frac{1}{2} x \frac{\pi^2 EI_y}{(S+4)^2} =$$

$$4(S+4)^2 = (H+S)^2 \qquad \text{(d)}$$

Eqns (c) and (d) are satisfied for the following H and S combinations.

H	S	H+S	S+4
8'	0	8	4
10'	2	12	6
12'	4	16	8
14'	6	20	10
16'	8	24	12
18'	10	28	14
20'	12	32	16
22'	14	36	18
24'	16	40	20
26'	18	44	22



Notes:

1. For H = 8' & S = 0, $P_{CR}^{(1)} = P_{CR}^{(2)}$
   ∴ For H= 8' and any S > 0, $P_{CR}^{(2)}$ controls.
2. For H = 24' & S = 16', $P_{CR}^{(1)} = P_{CR}^{(2)}$
   ∴ For H= 24' and any S < 16', $P_{CR}^{(1)}$ controls.
3. If bridge is continuous, $P_{CR}^{(1)}$ controls.

Figure 2.3. Controlling Transverse Buckling Modes for SS Bridges

$H + S = 35.74$ ft

$H = 35.74' - 13.87' = 21.87$ ft

Thus, if $H < 21.87$ ft then buckling mode (2) (see Fig. 2.3) controls and

$$P_{CR} = \frac{1}{2} P_y = \frac{446^k}{2} = 223^k$$

for an HP 10 x 42 pile when S = 13.87 ft. If H > 21.87 ft when S = 13.87 ft, then buckling mode (1) (see Fig. 2.3) controls and

$$P_{CR} = P_{CR} = \frac{2\pi^2 EI_y}{(H + 13.87')^2}$$

For whichever modes controls, if $P_{CR} > P_{pile}^{max\ applied}$ then there will be no pile or bent buckling failure.

Using the assumption made in Fig. 2.3, H and S combinations satisfying Eqns (c) and (d) in Fig. 2.3 are shown in columns 1 and 2 of Table 2.1. Also shown in Table 2.1 are the values of $P_{CR}^{(1)}$ and $P_{CR}^{(2)}$ ($P_{CR}^{(1)} = P_{CR}^{(2)}$) for the H and S combinations for both HP_{10x42} and HP_{12x53} bent piles. Note in Table 2.1 that the values of $P_{CR}^{(1)}$ and $P_{CR}^{(2)}$ corresponding to $P_y/2$ of each pile size are flagged/shaded. The H + S and S + 4' values corresponding to these P_{CR} values can be viewed as critical values, i.e.

If $(H + S)_{actual} > (H + S)_{CR}$ then the bent may experience mode (1) buckling and should be examined more closely.

If $(S + 4')_{actual} > (S + 4')_{CR}$ then the bent may experience mode (2) buckling and should be examined more closely.

Conversely, if $(H + S)_{actual} < (H + S)_{CR}$ and $(S + 4')_{actual} < (S + 4')_{CR}$, then the bent is safe from mode (1) or mode (2) buckling.

Table 2.1. H and S Combinations Satisfying $P_{CR}^{(1)} = P_{CR}^{(2)}$ in Figure 2.3 and Associated Values of P_{CR}

H (ft)	S (ft)	H + S (ft)	S + 4 (ft)	HP_{10x42} $P_{CR}^{(1)} = P_{CR}^{(2)}$ (kips)	HP_{12x53} $P_{CR}^{(1)} = P_{CR}^{(2)}$ (kips)
8	0	8	4	4454	7889
10	2	12	6	1979	3506
12	4	16	8	1113	1972
14	6	20	10	713	1262
16	8	24	12	495	876
18	10	28	14	364	644
20	12	32	16	278	493
22	14	36	18	220*	390
24	16	40	20	178	316
25	17	42	21	-	286**
26	18	44	22	147	260
27	19	46	23	134	238
28	20	48	24	123	218

$* \dfrac{P_y^{10x42}}{2} = 223$

$** \dfrac{P_y^{12x53}}{2} = 279^k$

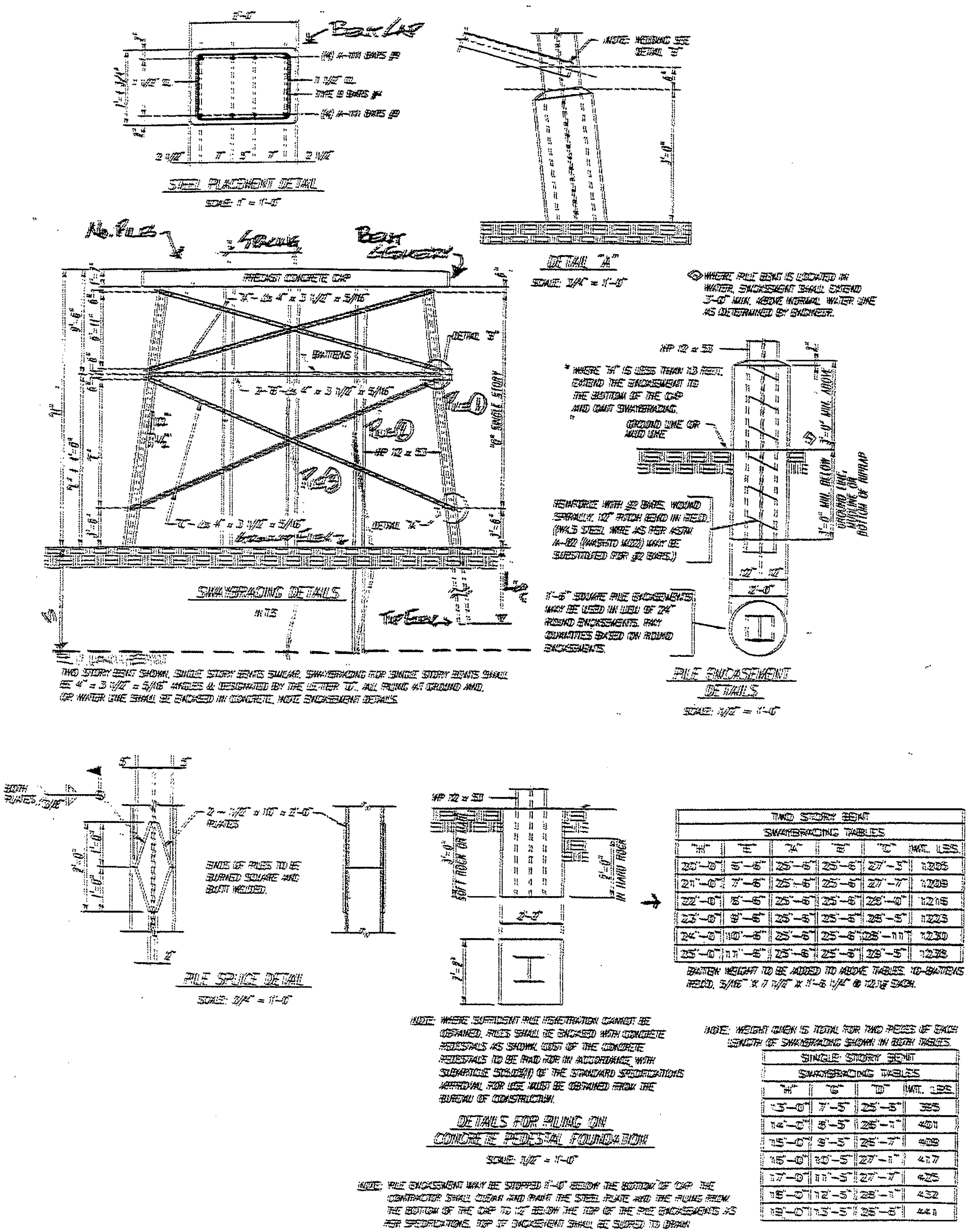
For cases where $P_{pile}^{max\ applied}$ > P_{CR}, then the bent must get "lean-on" support from adjacent piles in the bent. To achieve this, $P_{CR}^{Bent} > P_{Applied}^{Bent}$, i.e., $\sum_{Bent} P_{CR} > \sum_{Bent} P_{Applied}$. If this is the case, the flexural capacity of the bent cap must be checked as indicated in Section 3.6 of the Phase I Report (1) to be assured that it has adequate strength to allow "lean-on" support. If the above conditions are not satisfied, then a more detailed and comprehensive analysis should be undertaken.

In further considering pile/bent buckling in the transverse direction, an alternative approach to that described above is as follows.

For a typical ALDOT sway-braced pile bent such as shown in Fig. 2.4, the bent swaybracing should prevent a sidesway mode of buckling if no scour occurs at the site. However, if large levels of scour occur, the unbraced lengths of Piles 2 and 3 in the transverse direction (in the plane of the bent) in Fig. 2.4 become quite large and should be checked for nonsideway elastic buckling. As can be seen in Fig. 2.4, Pile 3 has the larger unbraced length, but Pile 2 is probably subjected to the larger applied P-load since it is approximately at the center of the roadway traffic lane. Thus, let us estimate the elastic buckling load of both of these piles for a two story bent with "H"=25 ft. For this case, "E" = 11'-6", and from Fig. 2.4, the unbraced length at the bottom of Pile 3 is

$$\ell_3 = \frac{\text{"E"}}{2} + 3'\text{-}6" + S = \frac{11.5'}{2} + 3.5 + S = 9.25' + S$$

For Pile 2, the unbraced length at the pile bottom is



TWO STORY BENT					
SWAYBRACING TABLES					
"H"	"E"	"A"	"B"	"C"	WT. LBS.
20'–0"	6'–6"	25'–6"	25'–6"	27'–5"	1205
21'–0"	7'–6"	25'–6"	25'–6"	27'–7"	1209
22'–0"	8'–6"	25'–6"	25'–6"	28'–0"	1216
23'–0"	9'–6"	25'–6"	25'–6"	28'–5"	1223
24'–0"	10'–6"	25'–6"	25'–6"	28'–11"	1230
25'–0"	11'–6"	25'–6"	25'–6"	29'–5"	1238

NOTE: WEIGHT GIVEN IS TOTAL FOR TWO PIECES OF EACH LENGTH OF SWAYBRACING SHOWN IN BOTH TABLES.

SINGLE STORY BENT			
SWAYBRACING TABLES			
"H"	"G"	"D"	WT. LBS.
13'–0"	7'–5"	25'–5"	395
14'–0"	8'–5"	26'–1"	401
15'–0"	9'–5"	26'–7"	409
16'–0"	10'–5"	27'–1"	417
17'–0"	11'–5"	27'–7"	425
18'–0"	12'–5"	28'–1"	432
19'–0"	13'–5"	28'–6"	441

Figure 2.4. Typical Pile Bent Geometry and Information (From ALDOT Pile Bent Standard)

$$\ell_2 = \frac{"E"}{4} + 3'\text{-}6" + S = \frac{11.5'}{4} + 3.5 + S = 6.38' + S$$

Assuming the piles to be fixed at the ground and pinned at the brace point,

$$P_{CR} = \frac{2\pi^2 EI_y}{\ell^2} \tag{2.1}$$

For the two frequency used HP piles employed by ALDOT, i.e.,

HP_{10x42} and HP_{12x53},

$$I_y^{10x42} = 71.7 \text{ in}^4$$

$$I_y^{12x53} = 127 \text{ in}^4$$

$$\frac{I_y^{12x53}}{I_y^{10x42}} = 1.77$$

Thus, the nonsidesway buckling loads for Piles 3 and 2 for various levels of scour are shown in Tables 2.2 and 2.3 respectively.

Note in Fig. 2.5, that as S becomes large, the swaybracing in the upper part of the bent should maintain the relative geometry of the bent in that region; however, the lower section of the bent could sidesway. If one assumes that the swaybracing in the upper section of the bent maintains the relative geometry in that section, then the bent should sidesway as shown in Fig. 2.5a rather than 2.5b. Or, for individual piles, as shown in Fig. 2.6a rather than 2.6b. Thus, in this lower region of the bent,

$$P_{CR} \approx \frac{\pi^2 EI_y}{\ell^2} \tag{2.2}$$

Thus, sidesway buckling in the transverse direction will control in the lower regions of the bent after scour occurs, and the P_{CR} values for Piles 2 and 3 will

Table 2.2. Elastic Nonsidesway Buckling Loads for Pile 3 in Fig. 2.4 for Various Levels of Scour

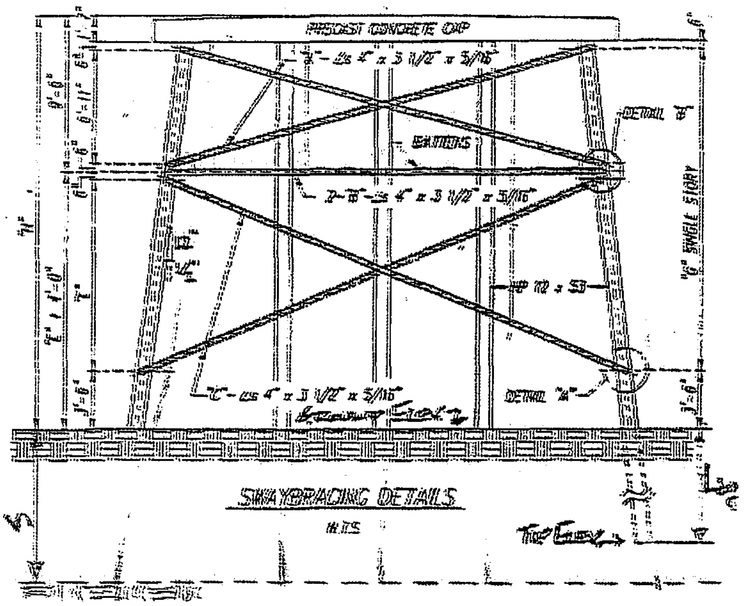
S (ft)	ℓ_3 (ft)	$P_{CR}^{HP10x42}$ (kips)	$P_{CR}^{HP12x53}$ (kips)
0	9.25	3331	5896
5	14.25	1404	2485
10	19.25	769	1361
15	24.25	485	858
20	29.25	333	590

*Divide P_{CR} values in last two columns by two to obtain P_{CR} for sidesway buckling.

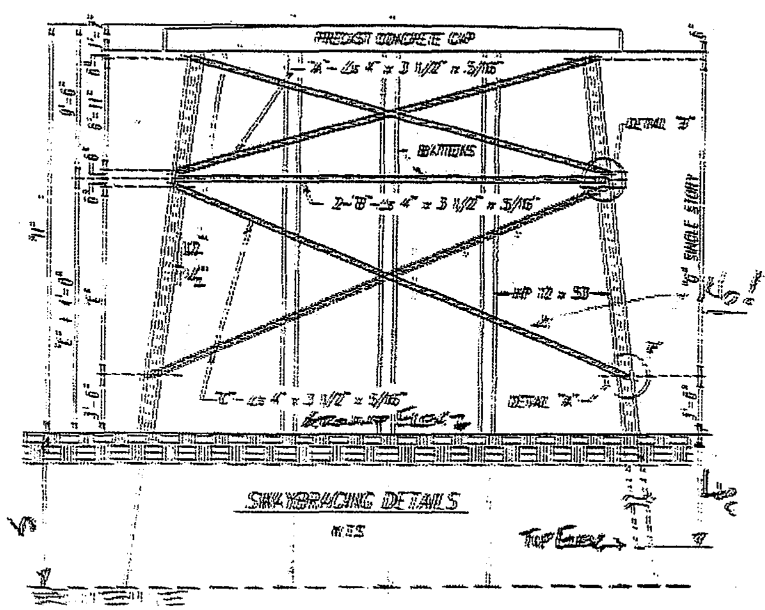
Table 2.3. Elastic Nonsidesway Buckling Loads for Pile 2 in Fig. 2.4 for Various Levels of Scour

S (ft)	ℓ_2 (ft)	$P_{CR}^{HP10x42}$ (kips)	$P_{CR}^{HP12x53}$ (kips)
0	6.38	6923	12,253
5	11.38	2187	3871
10	16.38	1057	1872
15	21.38	621	1100
20	26.38	408	723

*Divide P_{CR} values in last two columns by two to obtain P_{CR} for sidesway buckling.



a. Geometrically Compatible Lower Region Sidesway Buckling Mode



b. Geometrically Incompatible Lower Region Sidesway Buckling Mode

Figure 2.5. Typical Pile Bent with Sidesway Buckling in Lower Region Due to Large Scour

be determined by Eqn (2.2). Note that Eqn (2.2) gives P_{CR} values that are one-half of those given by Eqn (2.1) and one-half of the values shown in Tables 2.2 and 2.3.

Note in Tables 2.2 and 2.3 that the lowest value of $P_{CR}^{HP12x53}$ is 590^K, which would yield a value of 295^K for sidesway buckling, and this would exceed any $P_{max\ applied}$ to a bent pile. Likewise, the lowest value of $P_{CR}^{HP10x42}$ is 333^K which would yield a value of 167^K for sidesway buckling. This would probably also exceed any $P_{max\ applied}$, but not by a real comfortable amount. However, the 167^K value is for Pile 3 which is the bent and bridge center line pile and is probably not the most heavily loaded pile in the bent. Additionally the P_{CR} values for Pile 2 and Pile 1 (see Fig. 2.4) will be larger because their unbraced lengths are shorter (see Fig. 2.5a) than for Pile 3 and therefore Pile 3 can get "lean-on" support from the other piles in the bent.

It should be recalled that for elastic buckling,

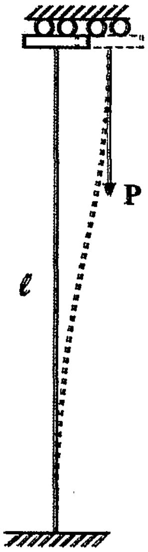
$$P_{CR} = \frac{\text{CONSTANT}\ \pi^2 EI}{\ell^2}$$

or,

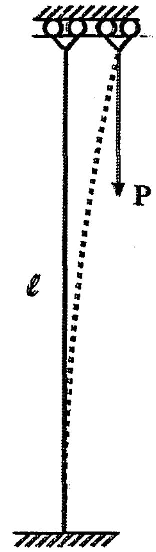
$$\ell_{CR} = \sqrt{\frac{\text{CONSTANT}\ \pi^2 EI}{P}}$$

or, for a given pile section and material,

$$\ell_{CR} = \text{CONSTANT}\sqrt{\frac{1}{P}}$$



a. Fixed- Fixed with Sidesway



b. Fixed- Pinned with Sidesway

Figure 2.6. Buckling Models of Lower Region of Bent Piles Under Large Scour

Thus, ℓ_{CR} varies inversely with square root of P, and is therefore not real sensitive to the pile loading, i.e., a small error in P will not greatly affect the predicted ℓ_{CR}. As indicated in Table 2.4 and Figure 2.7, a 100% error in P (from 100^K to 200^K) only results in a 29.3% decrease in ℓ_{CR}.

Table 2.4. Variations in ℓ_{CR} with Pile Load, P

P (kips)	$\sqrt{\frac{1}{P}}$	ℓ_{CR} = CONSTANT $\sqrt{\frac{1}{P}}$	% Decrease in ℓ_{CR} from that corresponding to P = 100^K (%)
60	0.129	0.129 C	-29.0
80	0.112	0.112 C	-12.0
100	0.100	0.100 C	0
120	0.0913	0.0913 C	8.7
140	0.0845	0.0845 C	15.5
160	0.0791	0.0791 C	20.9
180	0.0745	0.0745 C	25.5
200	0.0707	0.0707 C	29.3

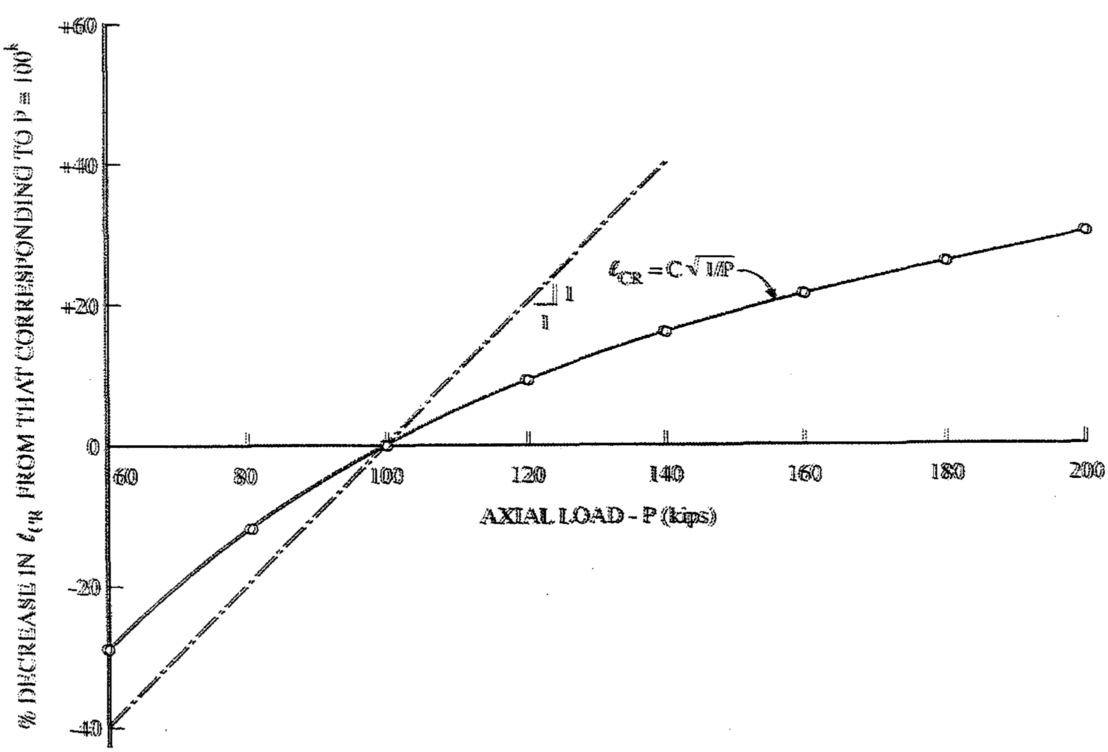


Figure 2.7. Percent Decrease in ℓ_{CR} as P Increases

For the case where "H" ≤ 13 ft and the bent piles are encased from 3' below the original ground line up to the bent cap, and the bent sway-bracing is omitted, we have the situation depicted in Figure 2.8 after scour, S. This bent condition/case is permitted by the ALDOT.

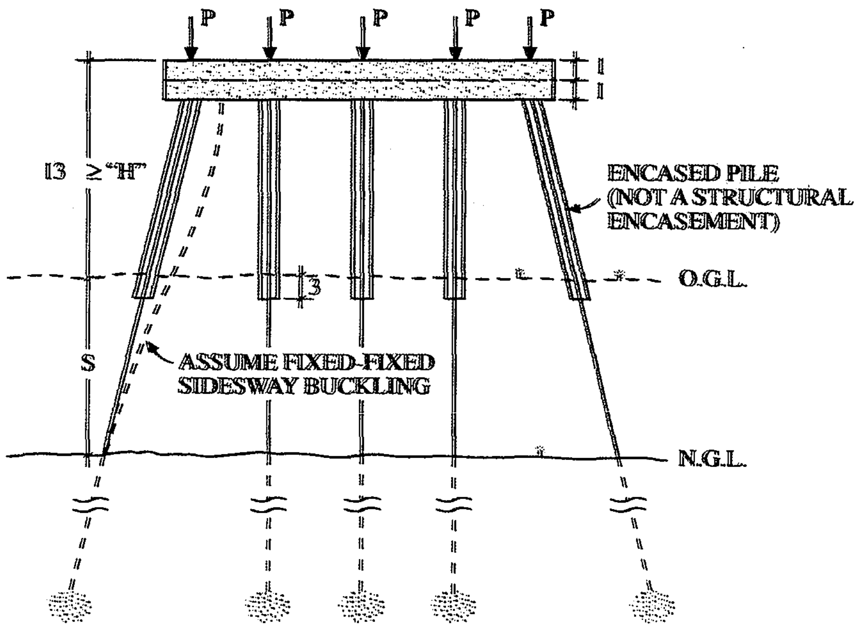


Figure 2.8. Bent with Encased Piles and No Sway-Bracing

For the case of an HP pile bent and assuming the pile encasement spalls off, we have an ℓ_{Max} = "H" - 1+S when working with the bent centerline dimensions. As can be seen in Figure 2.8, the bent piles would fail in buckling in approximately a fixed-fixed sidesway mode. As in the case of sidesway buckling for X-braced bents, due to the partial fixity at each end of the piles, we will assume

$$P_{CR} \approx \frac{1}{2}\frac{\pi EI_y}{\ell^2} \qquad (2.3)$$

or

$$\ell_{CR}^2 \approx \frac{\pi^2 EI_y}{2P_{CR}} \tag{2.4}$$

Note that the assumption of using ½ to represent a partial fixed-fixed condition at the top and bottom of the bent piles in the equations above, may in some cases be slightly unconservative. However, in light of the fact that we are totally neglecting the increase in pile stiffness and buckling capacity resulting from the pile partial height encasement, neglecting "lean-on" support that the most heavily loaded pile will receive from other piles in the bent, and neglecting the increase transverse stiffness of the pile bent due to the end batter piles, these should more than compensate for the factor of ½ overestimating the pile end fixity.

If one takes a value of $P_{CR} = 1.25P_{\text{Max Applied}}$ to have a margin of safety, then,

$$\ell_{CR}^2 \approx \frac{1}{2}\frac{\pi^2 EI_y}{\left(1.25P_{\text{Max Applied}}\right)} \tag{2.5}$$

and,

$$S_{CR} = \ell_{CR} - "H" + 1' \tag{2.6}$$

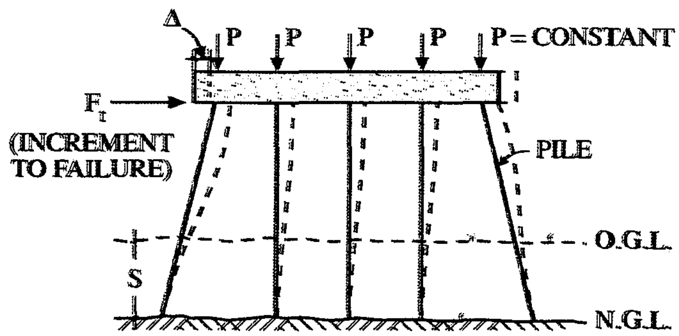
If this value of S_{CR} is greater than $S_{\text{Max Applied}}$ and if the remaining pile embedment after scour is greater than approximately 10 feet (to approximate pile fixity at the ground line), then this pile/bent without sway-bracing should be safe from buckling even if the pile encasements are loss. The determination of ℓ_{CR} and S_{CR} is examined for specific size bent piles in Section 5.8 of Chapter 5.

2.5 Pile Bent Pushover Failure

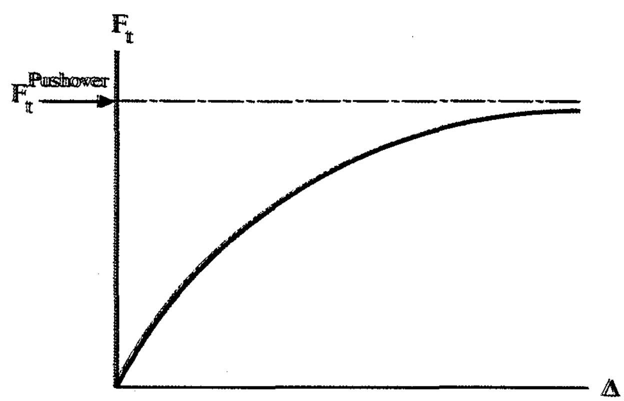
Pushover analysis is a nonlinear analysis procedure that was born in the seismic analysis community. The technique is based on the conventional displacement method of analysis. Standard elastic and geometric stiffness matrices for the structure elements are progressively modified to account for geometric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

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 (see Figure 2.9). Even for bents which are X-braced in the transverse direction, we could get a significant P-Δ effect and a bent pushover failure in the region from the new ground line (NGL) to approximately 4 feet above the original ground line (OGL) as indicated in Figure 2.9c.

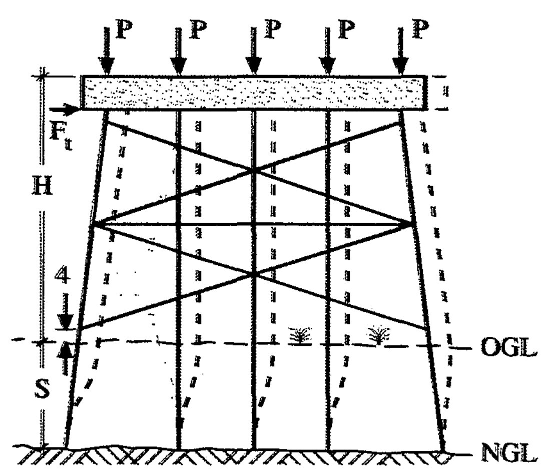
In GTSTRUDL, a Newton-Raphson solution technique based on the tangent stiffness method is used to solve the nonlinear equations resulting from the geometric and material nonlinearities. This solution technique is illustrated in Figure 2.10 (10). Load incrementation is particularly valuable for the nonlinear analysis of structures which exhibit dramatic changes in stiffness during the course of load application. Typical examples include cable structures, which demonstrate stress-stiffening behavior, and frame structures, which exhibit instability behavior (e.g. buckling). Stress stiffening behavior is characterized by rapidly increasing stiffness for small changes in strain, typically during the early



a. Gravity + Flood Water Loaded Pile Bent



b. Bent Pushover Curve



c. X-Braced Pile Bent Pushover Failure

Figure 2.9. Typical Nonlinear Pile Bent Pushover Failure and Curve

stages of loading (see Figure 2.11a) (10). Frame structure instability is characterized by rapidly decreasing stiffness for small changes in deformation during the late stages of loading when the collapse load is approached (see Figure 2.11b) (10). Bridge pile bents under combined gravity DL + LL and lateral flood water loadings behave in the manner shown in Figure 2.11b. In situations such as these, the nonlinear analysis may not converge if the total loading is applied as a single increment of sufficient magnitude to encompass the regions where the load-displacement response exhibits rapid stiffness change. Breaking the total loading into a smaller number of increments, particularly in the regions of rapid stiffness change, can significantly improve the success of the convergence and subsequent analysis.

Pushover analysis is described in GTSTRUDL Reference Manual, Vol. 3 (10) as an automated incremental load analysis which also contains a procedure that automatically searches for the load level at which structural instability or collapse occurs. In GTSTRUDL, the Pushover Analysis Data and Perform Pushover Analysis commands are used together to perform a pushover analysis. The Pushover Analysis Data command is used to specify the values for a series of parameters that control the pushover analysis procedure and must be given first. The Perform Pushover Analysis command follows and is used to execute the pushover analysis procedure. A Print Pushover Analysis Data command is used to verify the parameter values specified by the Pushover Analysis Data command.

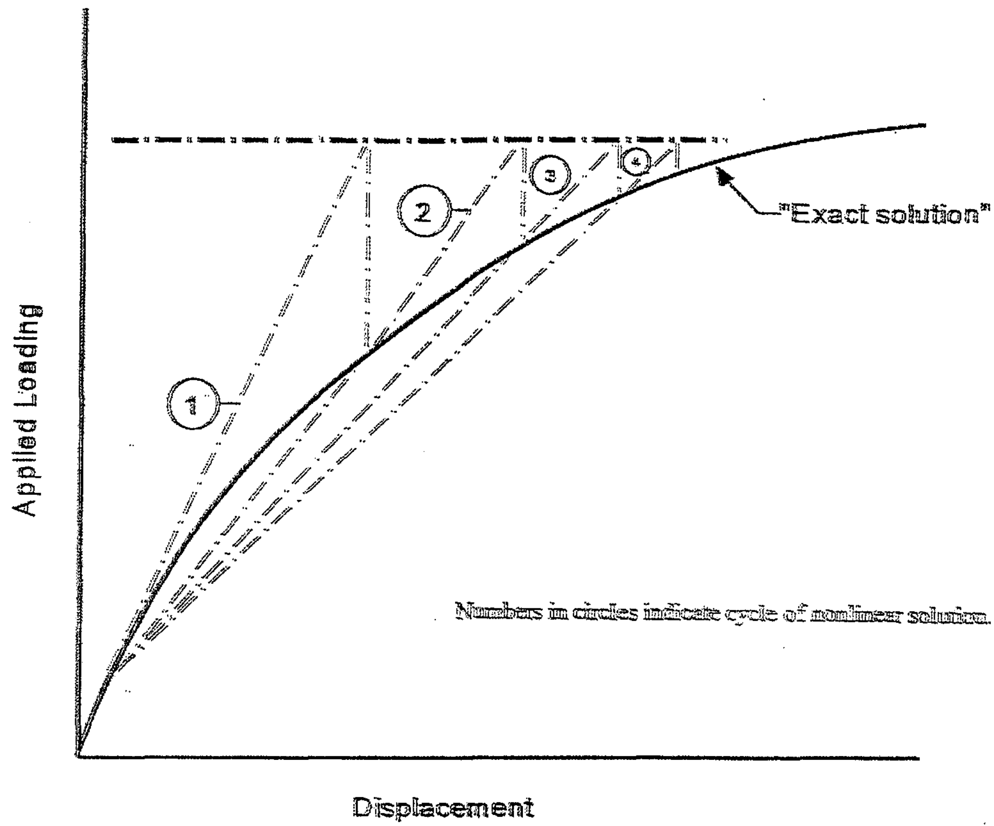
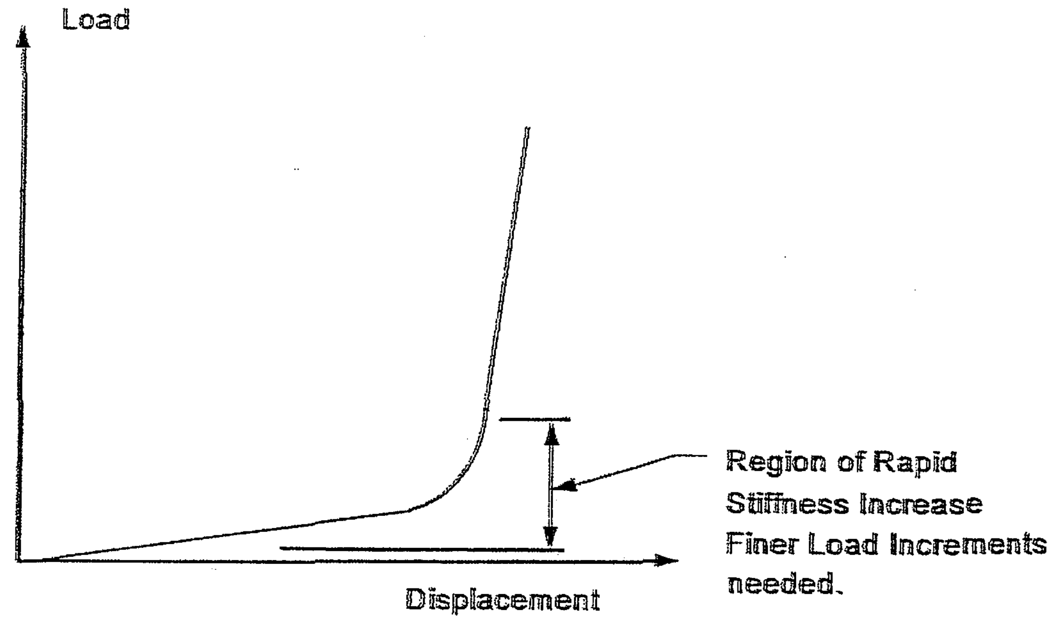
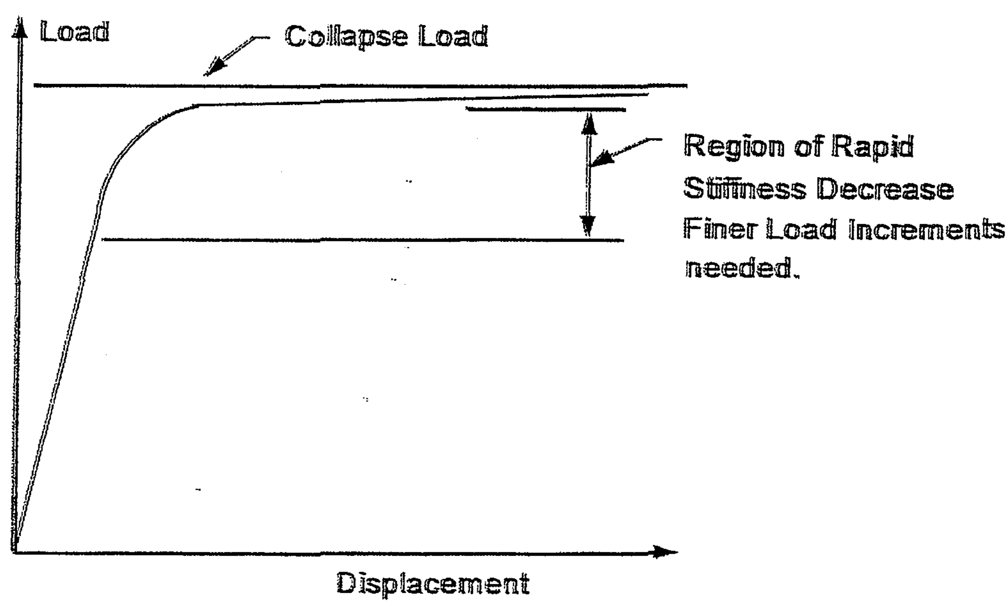


Figure 2.10. Direct Iteration Solution Procedure (10).



a) Typical Stress-Stiffening Response



b) Typical Instability Response

Figure 2.11. Examples of Nonlinear Response Requiring Load Incrementation (10).

Typical GTSTRUDL bridge pile bent pushover curves for an x-braced and unbraced bent are shown in Figure 2.12. In this figure, the gravity P-loads on the bents are held constant, and the lateral flood water load, F_t, is incrementally increased until failure occurs. 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 of the bent are included in the analysis, and this in turn provides a very accurate evaluation of the behavior and capacity of the bents. See Section 4.4 for a discussion of pile bent pushover loading.

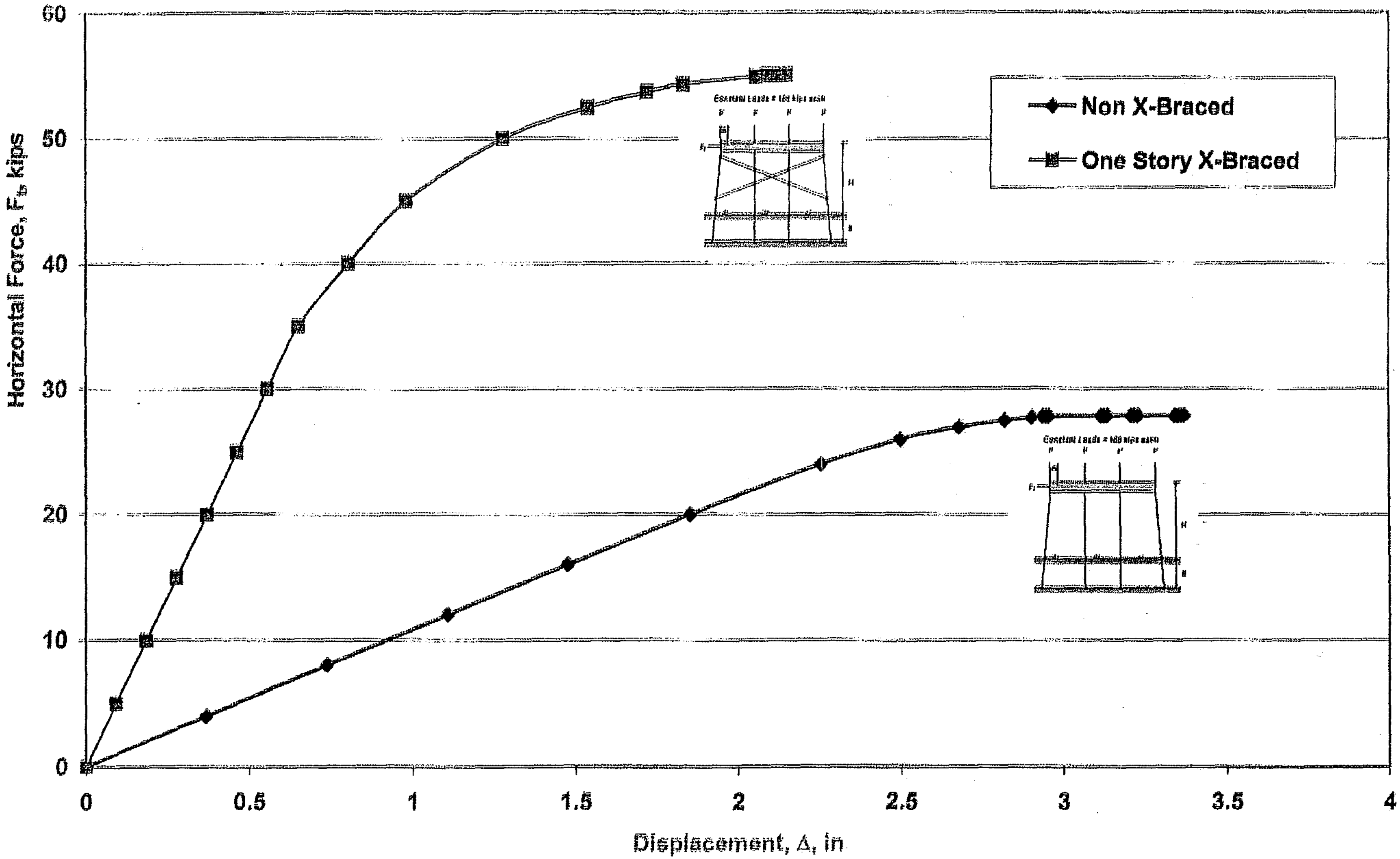


Figure 2.12. GTSTRUDL Pushover Analysis for HP10x42 4 Pile Bents, Bents Pinned at Ground, H=13ft, S=0ft, P=100^k.

3. PREPARATION WORK FOR USING THE SCREENING TOOL

3.1 General

For each bridge over water which is supported by pile bents and may require an assessment of the adequate of such bents in an extreme flood/scour event, ALDOT's current bridge/bent information database (see Section 3.2) should be expanded to include the additional bridge parameters and values shown in Section 3.3. This upgrading of ALDOT's Bridge Information Database should be performed prior to applying the "screening tool" to assess the adequacy of a bridge bent during an extreme flood/scour event.

3.2 Information on Bridge Superstructures and Bents Currently Available in ALDOT's BIS or Other Databases

The bridge information listed below is currently available in ALDOT's bridge information system (BIS) or other computer system databases. The information is broken down here into the categories, (1) stream and scour information, (2) pile bent geometry and design information, (3) pile and pile driving and support soil information, and (4) superstructure information. It should be noted that other bridge related information may be available, but is not viewed as relevant to using the "screening tool."

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

2. Pile Bent Geometry and Design Information
   - Longitudinal spacing of pile bents
   - Bent height from top of cap to original ground line, i.e., "H"
   - Original ground line (OGL) elevation of bent
   - Type, size, spacing and number of piles per bent
   - Bent has steel angle iron sway bracing
   - Bent has steel HP piles encased from 3 ft. below ground up to bottom of cap
   - Approximate size of bent cap, i.e., cap width and depth
   - Manner of connection between bent cap and piles

3. Pile Driving and Soil Profile Information
   - Pile length and tip elevation
   - Ground elevation
   - Driving resistance of last foot
   - Soil bearing strength (or descriptive 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)
   - Girder type, size, number per span, and spacing
   - Deck thickness
   - Barrier rail type and estimated weight per foot if other than Jersey barrier
   - Outside-to-outside deck width
   - Curb-to-curb deck width and number of traffic lanes
   - Design LL
   - Connection of superstructure to bent caps and abutments

3.3 Additional Bridge and Site Information Needed to Use "Screening Tool"

For each bridge over water which is supported by pile bents and may require an assessment of the adequate of such bents in an extreme flood/scour event, ALDOT's current bridge/bent information database should be expanded to include the additional bridge parameters and values listed below. This upgrading of ALDOT's Bridge Information Database should be performed prior to applying the "screening tool" to assess the adequacy of a bridge bent during an extreme flood/scour event.

Estimated flood high water level (HWL)

Max flow depth after scour = HWL – OGL + S

Is formation of a debris raft possible? $\prec^{YES}_{NO}$

Debris raft dimension B

Debris raft dimension A

Design flood flow velocity V

Water pressure on debris raft = $p(in\ psf) = 1.4V^2$
(where V is in ft/sec)

Transverse flood water loading on bent = $F_t = p\left[\frac{1}{2}AB\right]$

Location of F_t load is A/3 down from the estimated flood high water level (HWL)

Estimated maximum stream flow angle w.r.t. the longitudinal axis of the bent $= \theta = 20°$ or $30°$

Pile/Bent Maximum Load Information:

$P^{Pile}_{MaxApplied}$ (gravity DL + LL)

$P^{Bent}_{MaxApplied}$ (gravity DL + LL)

$F^{t}_{MaxApplied}$ (flood water load near top of bent in plane of bent)

$F^{tip}_{MaxApplied}$ (flood water load at pile tip normal to plane of bent)

See Section 3.4 and Chapter 4 for definitions and descriptions of the parameters above.

The updated information that should be in ALDOT's bridge information system (BIS) prior to using the checking the bent adequacy "screening tool" are given in Section 5.4 in Chapter 5.

3.4 Maximum Applied Pile and Bent Loads at a Site

Before using the ST to assess the adequacy of the pile bents during an extreme flood/scour event at a bridge site, the maximum applied loads to the piles/bent at the site should be determined. These loads are:

$P^{Pile}_{MaxApplied}$ (gravity DL + LL)

$P^{Bent}_{MaxApplied}$ (gravity DL + LL)

$F^{t}_{MaxApplied}$ (flood water load near top of bent in plane of bent)

$F^{tip}_{MaxApplied}$ (flood water load at pile tip normal to plane of bent)

It should be noted that for each ALDOT bridge at its specific stream site, all four of the maximum applied loads above can 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. Since knowing these maximum applied pile/bent loads is essential to using the ST, it is recommended that this be done beforehand and added to the ALDOT's computer database for each bridge which may require checking with the ST. Since the determination of these maximum applied loads is somewhat intricate, the procedures for doing this are presented in detail in Chapter 4.

3.5 Closure

The upgrading of ALDOT's BIS via the addition of information identified in Sections 3.3 and 3.4 should be performed prior to applying the "screening tool" (ST) in order that the ST may be used more quickly and effectively in the event of the occurrence of a major flood/scour. It is expected that the bridge information listed in Sections 3.2-3.4 can be used with the ST to predetermine S_{CR} and/or P_{CR} values prior to the occurrence of an extreme flood/scour event. This should be investigated in follow-up research work to further refine, simplify, and improve the ST.

4. DETERMINING MAXIMUM APPLIED PILE AND BENT LOADS

4.1 General

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

$P^{Pile}_{MaxApplied}(gravity DL + LL)$

$P^{Bent}_{MaxApplied}(gravity DL + LL)$

$F^{t}_{MaxApplied}(flood\ water\ load\ near\ top\ of\ bent\ in\ plane\ of\ bent)$

$F^{tip}_{MaxApplied}(flood\ water\ load\ at\ pile\ tip\ normal\ to\ plane\ of\ bent)$

The top two loads require modified determination procedures for DL and LL, and for simple span vs. continuous vs. continuous for LL support systems. The bottom two loads above require determination of stream high water level (HWL), flow velocity, possible flood debris raft build-up at a bent and other factors related to extreme flood water loading's on piles/bents. The procedures for determining the above pile/bent maximum applied loads are described in the sections below.

4.2 Maximum Applied Pile and Bent DL

Typical ADLOT 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 Thickness → In database (round up to nearest ½")

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

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

Barrier Rails → Assume Jersey barriers with w_{DL} = 390lb/ft each

Diaphragms:

Steel girders → neglect diaphragm weight

Concrete girders →9" x girder depth x center-to-center dimension between girders for P_{Max}^{Pile} or between exterior girders for P_{Max}^{Bent}

For $\ell \leq$ 30' → 1 diaphragm each end of span
(2 Diaph. Wts. per bent = No. Diaph/span)

30'< $\ell \leq$ 60'→ 1 diaphragm each end of span and one at midspan
(3 Diaph. Wts. per bent = No. Diaph/span)

60'< $\ell \leq$100'→1 diaphragm each end of span and one each at ⅓ points of span
(4 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

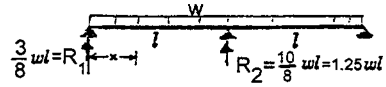
Girder Support Arrangement→ Simple support or continuous for "xx" number of spans

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

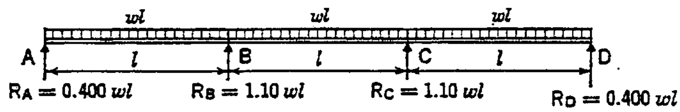
Bent Pile Cap Size = 2.5' x 2.5' x Cap Length → In database

Maximum Girder Reactions due to Uniform DL→ See Fig 4.1 for simple or continuous span bridges

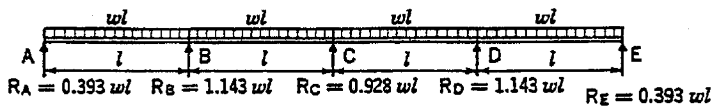
TWO EQUAL SPANS—UNIFORM LOADED



CONTINUOUS BEAM—THREE EQUAL SPANS—ALL SPANS LOADED



CONTINUOUS BEAM—FOUR EQUAL SPANS—ALL SPANS LOADED



Maximum Girder R's Due to Uniform DL*:

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

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

3-Equal Span Continuous Girder: $R_{Max} = 1.10\omega\ell$

4-Equal Span Continuous Girder: $R_{Max} = 1.15\omega\ell$

More Than 4-Equal Span Continuous Girder: $R_{Max} = 1.15\omega\ell$

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

Fig 4.1. Girder/Beam Reactions for SS, Two, Three, Four or More Equal Span Continuous Bridges Under Uniform Dead Load.

For the example bridge superstructure and bent shown in Fig 4.2, assume the bridge is SS with span lengths of 34 ft., and determine $P^{DL}_{Pile\,Max\,Applied}$ by girder line analysis and $P^{DL}_{Bent\,Max\,Applied}$.

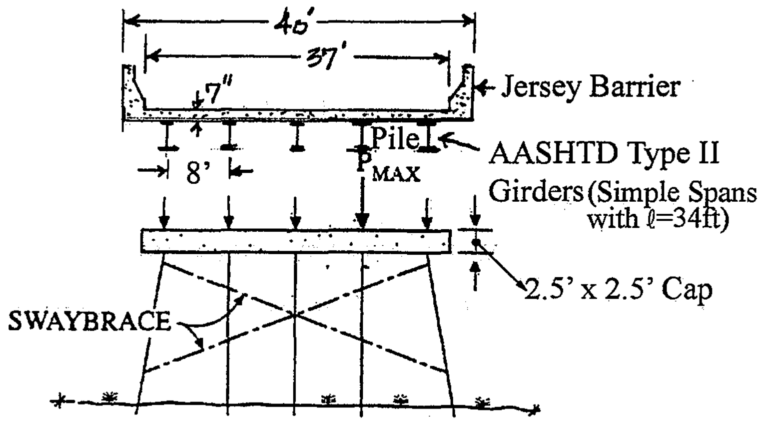


Fig 4.2. Example Pile Bent and Superstructure

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: $Cap\ Width\ x\ Cap\ Depth\ x\ Gir.\ Spac.\ x\ 0.150$

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

3-Equal Span Continuous Bridge– $P^{DL}_{Pile\,Max\,Applied}$ =1.10(45^k)+7.5^k=57.0^k

4-Or More Equal Span Continuous Bridge–

$P^{DL}_{Pile\,Max\,Applied}$ =1.15(45^k) +7.5^k=59.3^k

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

Deck: *Deck Thickness x Out-to-Out 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: *ΔOverhang Thickness x Overhang Width x Span Length x* $0.150^k / ft.^3 \,x\, 2$

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

☞Assumed Diaphragm Thickness

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

$0.150^k / ft.^3 \,x\, No. Diaph / Span$

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

3-Equal Spans Made Continuous For LL-$P^{DL}_{Bent\,Max\,Applied}$ =

223.5+1.10(26.5) +33.8=286.5^k

4-Or More Equal Spans Made Continuous For LL- LL-$P^{DL}_{Bent\,Max\,Applied}$ =

223.5+1.15(26.5) +33.8=287.8^k

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

3-Equal Spans Continuous $P^{DL}_{Bent\,Max\,Applied}$ =1.10(250.0^k) +33.8 ^{k}=308.8^k

4-Or More Equal Spans Continuous

$P^{DL}_{Bent\,Max\,Applied}$ =1.15(250.0^k) +33.8 k =321.3^k

4.3 Maximum Applied Pile and Bent 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 "xx" 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

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 designed for H20 or HS20 truck and lane loads. These standard AASHTO loadings along with the H15 and HS15 loadings are shown in Figs. 4.3 and 4.4. 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 then placed in 12 ft. traffic lanes spaced across the bridge from curb-to-curb. If the curb-to-curb width is between 20 ft. and 30 ft., two design lanes are used, each of which is half the curb-to-curb distance. The number and spacing of design traffic lanes is based on the layout which creates the maximum stress. Table 4.1 shows the number of design lanes based on a bridge's curb-to-curb width. Most of the bridges of interest in this study have widths in the range of 24-40 ft., and thus would have 2 to 3 design traffic lanes of load applied to them.

Table 4.1. Design Traffic Lanes (8)

Curb to Curb Width	No. of Lanes
20 to 30 ft.	2
30 to 42 ft.	3
42 to 54 ft.	4
54 to 66 ft.	5
66 to 78 ft.	6
78 to 90 ft.	7
90 to 102 ft.	8
102 to 114 ft.	9
114 to 126 ft.	10

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. 4.5. The loads shown in Fig. 4.5. 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 (a) or the lane loading of (b).

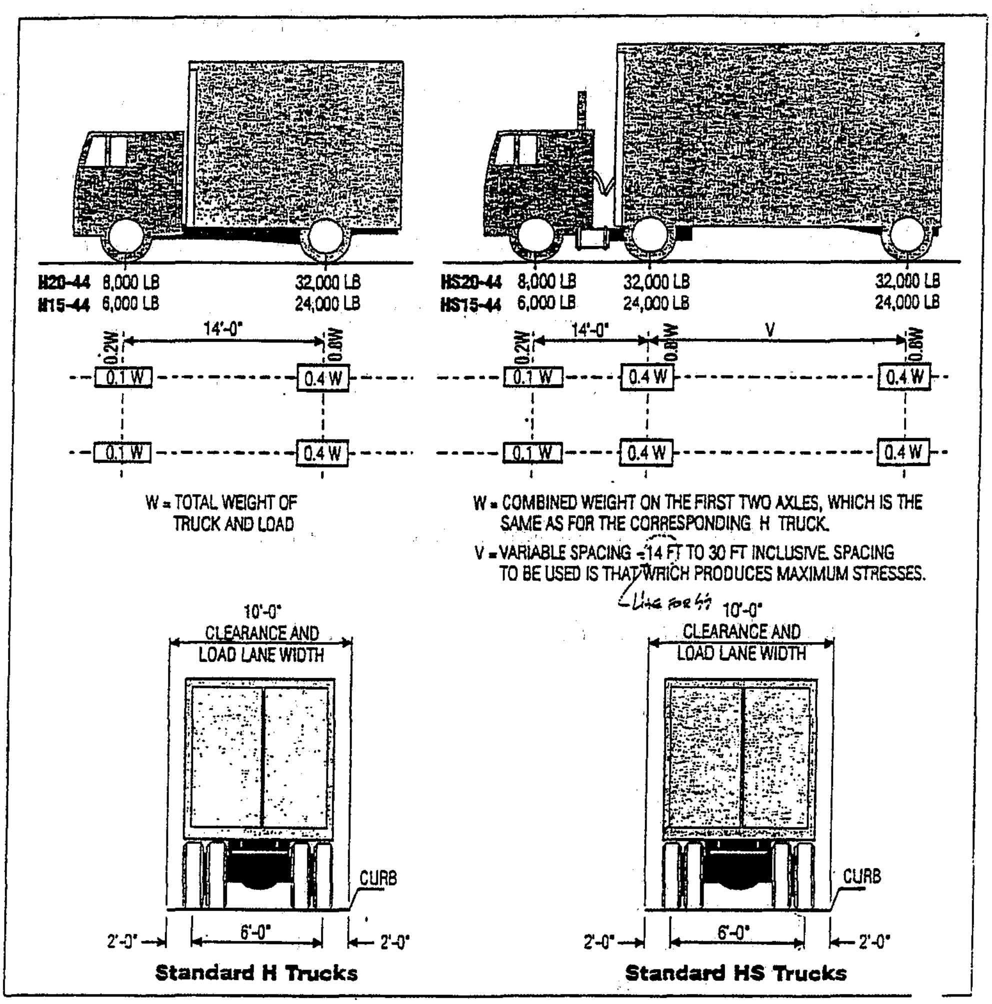


Figure 4.3. AASHTO Standard H & HS Design Trucks

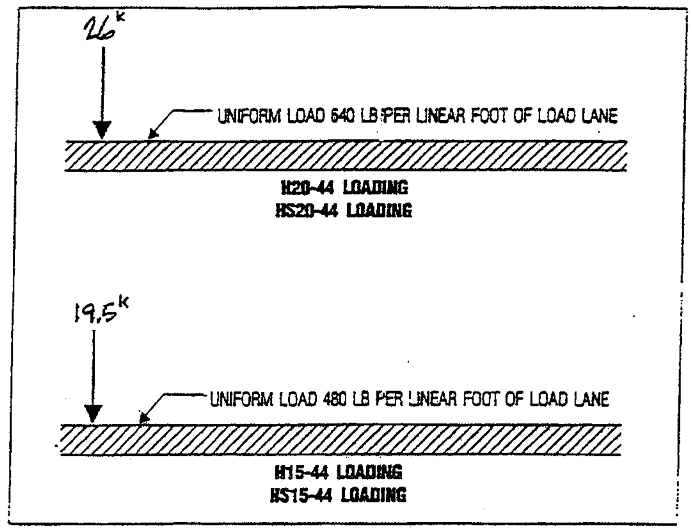
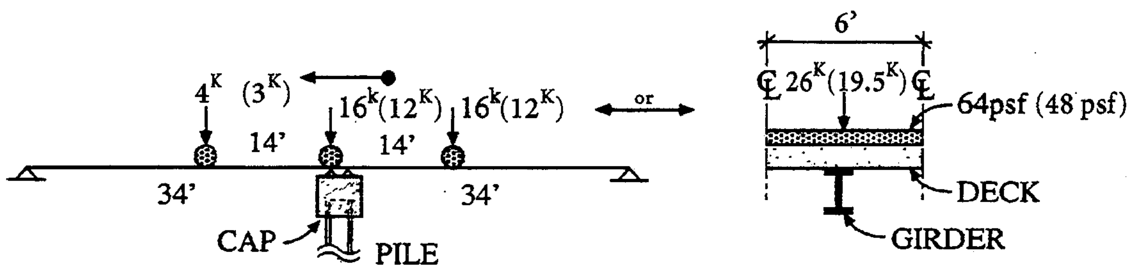


Figure 4.4. AASHTO H & HS Lane Loading



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

Fig. 4.5. Girder Lane Loading to Determine $P^{LL}_{Pile\,Max\,Applied}$

$P^{LL}_{Pile\,Max\,Applied}$ is determined from Fig 4.5. as follows:

	SS Spans	2-Span Continuous
a. Truck Line Load:	$P^{LL}_{Pile} = \left[16^k + 16^k\left(\frac{20}{34}\right) + 4^k\left(\frac{20}{34}\right)\right]1.1$	$\left[2(3.12)+16+9.36\right]1.1$
	$=\left[16+9.41+2.35\right]1.1 = 30.5^k$	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

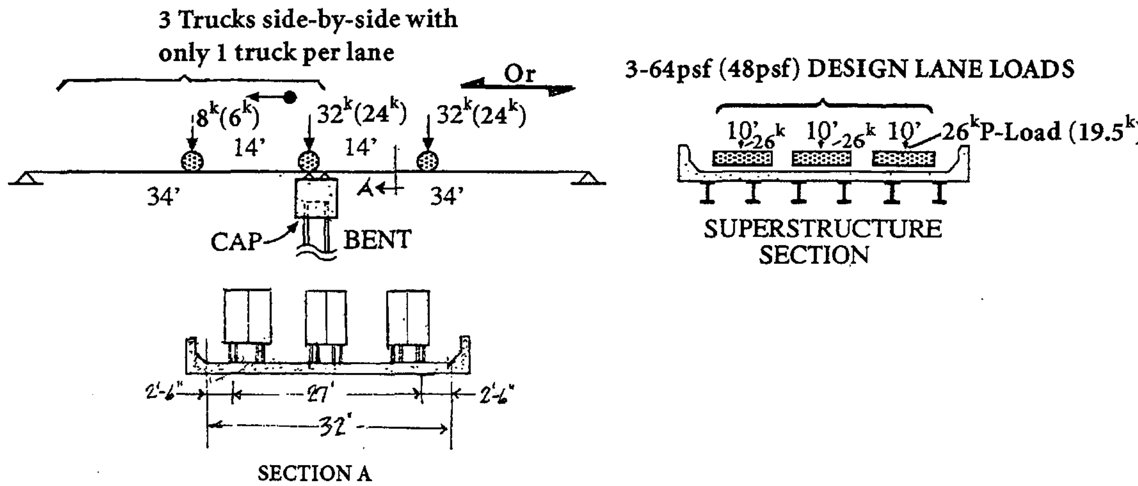
$\therefore P^{LL}_{Pile\,Max\,Applied} = 43.0^k$ for Simply Supported Bridge

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

$\therefore P^{LL}_{Pile\,Max\,Applied} = 46.6^k$ for 3 or More Span Continuous or Continuous for LL

Determining $P^{LL}_{Bent\,Max\,Applied}$

The maximum bent vehicular LL is illustrated for the same superstructure and HS20 loading in Fig. 4.5 and assuming the curb-to-curb width of the bridge is 32 ft. as shown in Fig. 4.6. Again, as with determining $P^{LL}_{Pile\,Max\,Applied}$, the $P^{LL}_{Bent\,Max\,Applied}$ is the larger of those determined from the truck lane loading of Fig. 4.6a, or the design lane loadings of Fig. 4.6b.



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

Fig. 4.6. LL to Determine $P^{LL}_{Bent\,Max\,Applied}$

$P^{LL}_{Bent\,Max\,Applied}$ is determined from Fig. 4.6 as follows:

	SS Spans	2-Span Continuous
a. Truck Lane Load:	$P^{LL}_{Bent} = \left[32^k + 32^k\left(\frac{20}{34}\right) + 8^k\left(\frac{20}{34}\right)\right] x3\,x1.1$	$\left[2(6.24)+32+18.72\right]3x1.1$
	$=\left[32+18.82+4.71\right]3.3$	$\left[63.2^k\right]3.3$
	$=183.2^K \leftarrow Governs$	$208.6^K \leftarrow Governs$
b. Design Lane Load:	$P^{LL}_{Bent} = \left[0.064\frac{k}{ft^2}x10'x34'+26^k\right]3x1.1$	$\left[(0.064\ x6x34)1.25+26^k\right]3x1.1$
	$=\left[21.76+26\right]3.3$	$\left[16.32+26\right]3.3$
	$= 157.6^K$	139.7^k

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

$\therefore P^{LL}_{Bent\,Max\,Applied} = 208.6^k$ for 2 or More Span Continuous or Continuous for LL

(Note in Table 4.2 this is a fairly accurate, but upper bound, estimate of $P^{LL}_{Bent\,Max\,Applied}$

$\therefore P^{LL}_{Bent\,Max\,Applied} = 208.6^k$ for 3-Span Continuous or Continuous for LL

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

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 $p_{LL} = 64psf$ 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. 4.7, for a uniform load of w_{LL} (see yellow highlighted cases),

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

$R_B^{Max} = 1.20w\ell$ (for 3-span continuous girder)

$R_B^{Max} = 1.223w\ell$ (for 4-span continuous girder)

Thus, for the case of a 10 ft. 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, 3-span, and 4-span continuous bridges with equal span lengths of various lengths would be as shown in Table 4.2.

As can be seen from Table 4.2, for purposes of estimating the maximum P_{Pile}^{Max} applied to a bent cap and pile, using the upper bound value of $P_B^{Max-LL} = 1.25 w_{LL} \ell$ would be appropriate for the "screening tool" for equal span continuous bridges of any number of continuous spans. Also, since the uniform lane loading (rather than truck wheel loadings) controls by a sizeable margin for SS bridges, so too would we expect this loading condition to control for continuous bridges.

If the girder spacing is less than 10 ft., then the $w_{LL} = 0.64\, {}^{k}\!/_{ft}$ should be reduced to

$$w_{LL} = 0.64\, {}^{k}\!/_{ft}\, t\, x \frac{S}{10'}$$

where S=girder spacing in feet. Recall when using lane loading, we must add one concentrated P-load of 26^k (for HS20 loading) or 19.5^k (for HS15 loading) per lane on top of the lane load. To attain the maximum load on a bent cap or pile, this concentrated P-load would be applied directly over the girder intermediate reaction or support bent. Therefore, for a continuous span bridge and a HS20 loading,

$$P_{Pile\,Max}^{LL} = \left[1.25 w_{LL} \ell + P_{HS20}\right] I.F.$$

or

$$P_{Pile\,Max}^{LL} = \left[1.25\, x\, 0.64\, {}^{k}\!/_{ft}\, x \frac{S}{10'} x\, \ell + 26.0^k\right] 1.1$$

and for an HS15 loading

$$P_{Pile\,Max}^{LL} = \left[1.25\, x\, 0.48\, {}^{k}\!/_{ft}\, x \frac{S}{10'} x\, \ell + 19.5^k\right] 1.1$$

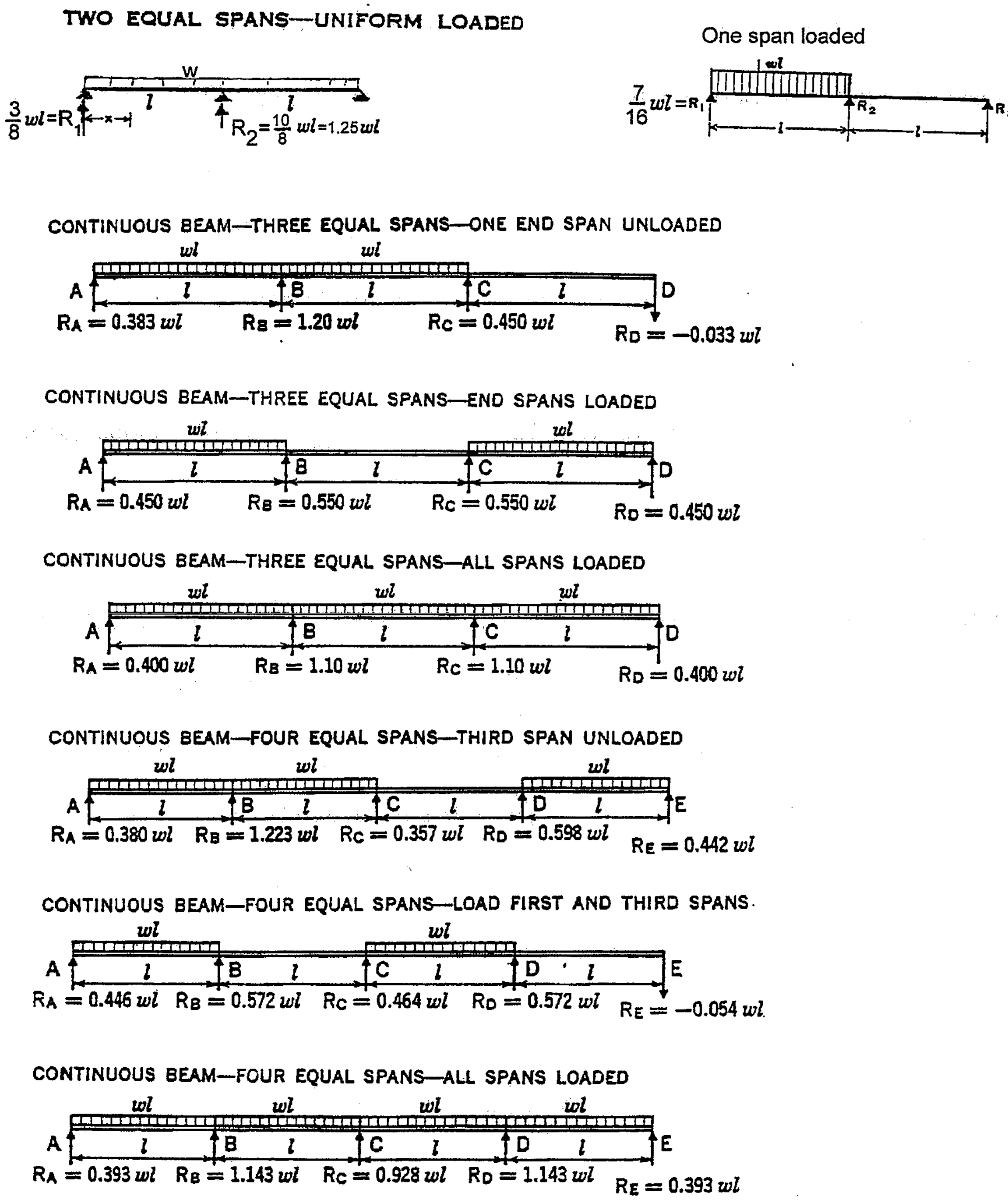


Figure 4.7. Girder/Beam Reactions for Two, Three, and Four Equal Span Continuous Bridges Under Uniform Loading

Table 4.2 Maximum Girder Reactions/Applied Bent Loads Due to a $w_{LL} = 0.64^k / ft$ Girder Loading on Equal Span Continuous Bridges*

Equal Span Lengths ℓ(ft)	Intermediate Bent $P_{W_{LL}}^{max}$ (kips)		
	2-Span Cont. $P_B = R_B = 1.25w\ell$	3–Span Cont. $P_B = R_B = 1.20w\ell$	4-Span Cont. $P_B = R_B = 1.223w\ell$
25	20.0	19.2	19.6
30	24.0	23.0	23.5
35	28.0	26.9	27.4
40	32.0	30.7	31.3
45	36.0	34.6	35.2
50	40.0	38.4	39.1
60	48.0	46.1	47.0
70	56.0	53.8	54.8
80	64.0	61.4	62.6

*Note that these are maximum values of R_B due to w_{LL} and do not include the Concentrated P-load in Fig. 3.5b nor an impact factor.

4.4 Example Determination of $P^{Pile}_{Max\ Applied}$ and $P^{Bent}_{Max\ Applied}$ for a Typical Bridge Superstucture and Pile Bent

For the bridge superstructure and bent shown in Fig. 4.8, assume the bridge is SS with span lengths of 34 ft., and determine $P_{Pile\ Max}$ by girder line analysis and $P_{Bent\ Max}$

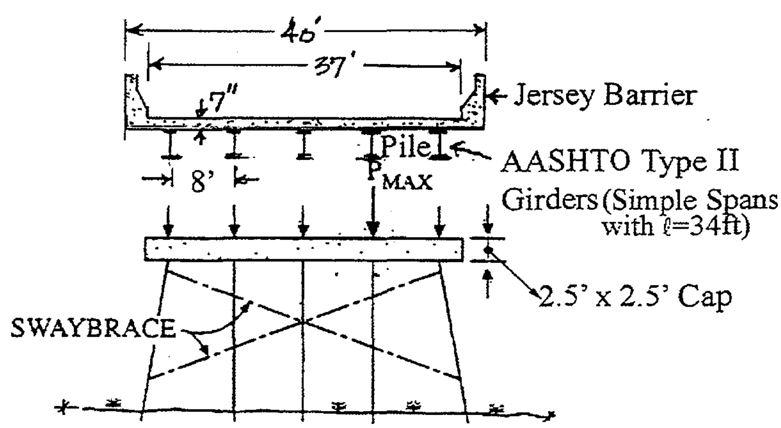


Figure 4.8. Typical Pile Bent and Superstructure

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

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

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

Assumed Diaphragm Thickness

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

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

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

$0.384^k / ft\ x\ 34'$ $= 13.1^k$

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

$2.5'\ x\ 2.5'\ x\ 8'\ x\ 0.150^{k}/ft.^3$ $= 7.5^k$

P_{DL} $= 52.5^k$

P_{LL}: Design Lane Load: $\left[0.064^k / ft.^2 x\ Gir.\ Spac.\ x\ Span\ Length + 26^k\right]$ *IF*

$$\left[0.064^k / ft.^2 x\ 8' \text{ x } 34' + 26^k\right]1.1 \qquad = 47.7^k \leftarrow \text{Governs}$$

Truck Line Load: $\left[16^k + 16^k\left(\frac{20}{34}\right) + 4^k\left(\frac{20}{34}\right)\right]1.25x1.1$ $= 38.2^k$

P_{LL} $= 47.7^k$

$$\therefore P^{Pile}_{Max\ Applied} = P_{DL} + P_{LL} = 52.5^k + 47.7^k = 100.2^k$$

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

P_{DL}: Deck: *Deck Thickness x Out-to-Out Deck Width x Span Length x* 0.150

$$\frac{7'}{12} x40' x34' x0.150^k / ft.^3 \qquad = 119.0$$

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

$\frac{2'}{12} x4' x34' x0.150^k / ft.^3 x2$ = 6.8^k

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

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

$\frac{9'}{12} x3.0' x32' x0.150^k / ft.^3 x3$ = 32.4^k

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

$0.384^k / ft. x34' x5$ = 65.3

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

$0.390^k / ft. x34' x2$ = 26.5^k

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

$2.5' x2.5' x36' x0.150^k / ft.^3$ = 33.8^k

*If Cap Length is not available use
(Distance Between Exterior Girders + 4') P_{DL} = 283.8^k

P_{LL}: Design Lane Load: $\left[0.064^k / ft.^2 x10' x34' + 26.0^k\right] 3x1.1$ = 157.6^k

Truck Lane Load: $\left[32^k + 32\left(\frac{20}{34}\right) + 8\left(\frac{20}{34}\right)\right] 3x1.1$ = 183.3^k←Governs

P_{LL} = 183.3^k

$\therefore P_{Max\ Applied}^{Bent} = P_{DL} + P_{LL} = 283.8^k + 183.3^k = 467.1^k$

∴ P-load to be used above each pile in pushover analysis $= \frac{P_{Max\ Applied}^{Bent}}{No.\ of\ Piles} = \frac{467.1^k}{5\ piles} = 93.4^k$ per pile

4.5 Maximum Applied Bent Flood Water Load, F_t

To determine the maximum applied bent flood water load, F_t, current bridge/bent information database may need to be expanded to include the additional parameter values listed below. This expansion is needed in order to check the bent for a possible pushover failure from combined gravity and flood water lateral loads in conjunction with scour. It should be performed prior to applying the "screening tool" to assess the adequacy of a bridge bent during an extreme flood/scour event.

Estimated flood high water level (HWL)

Max flow depth after scour = HWL – OGL + S

Is a formation of a debris raft possible? $\prec^{YES}_{NO}$

Debris raft dimension B

Debris raft dimension A

Design flood flow velocity V

Water pressure on debris raft = $p(in\ psf) = 1.4V^2$
(where V is in ft/sec)

Transverse flood water loading on bent = $F_t = p\left[\frac{1}{2}AB\right]$

Location of F_t load is A/3 down from the estimated flood high water level (HWL)

The parameters above are identified and/or defined in Figs. 4.8 and 4.9, and guidelines and the procedure for determining F_t are presented in Fig. 4.9. The variations in the F_t force over a wide range of debris raft dimension A and B are shown in Fig.4.10.

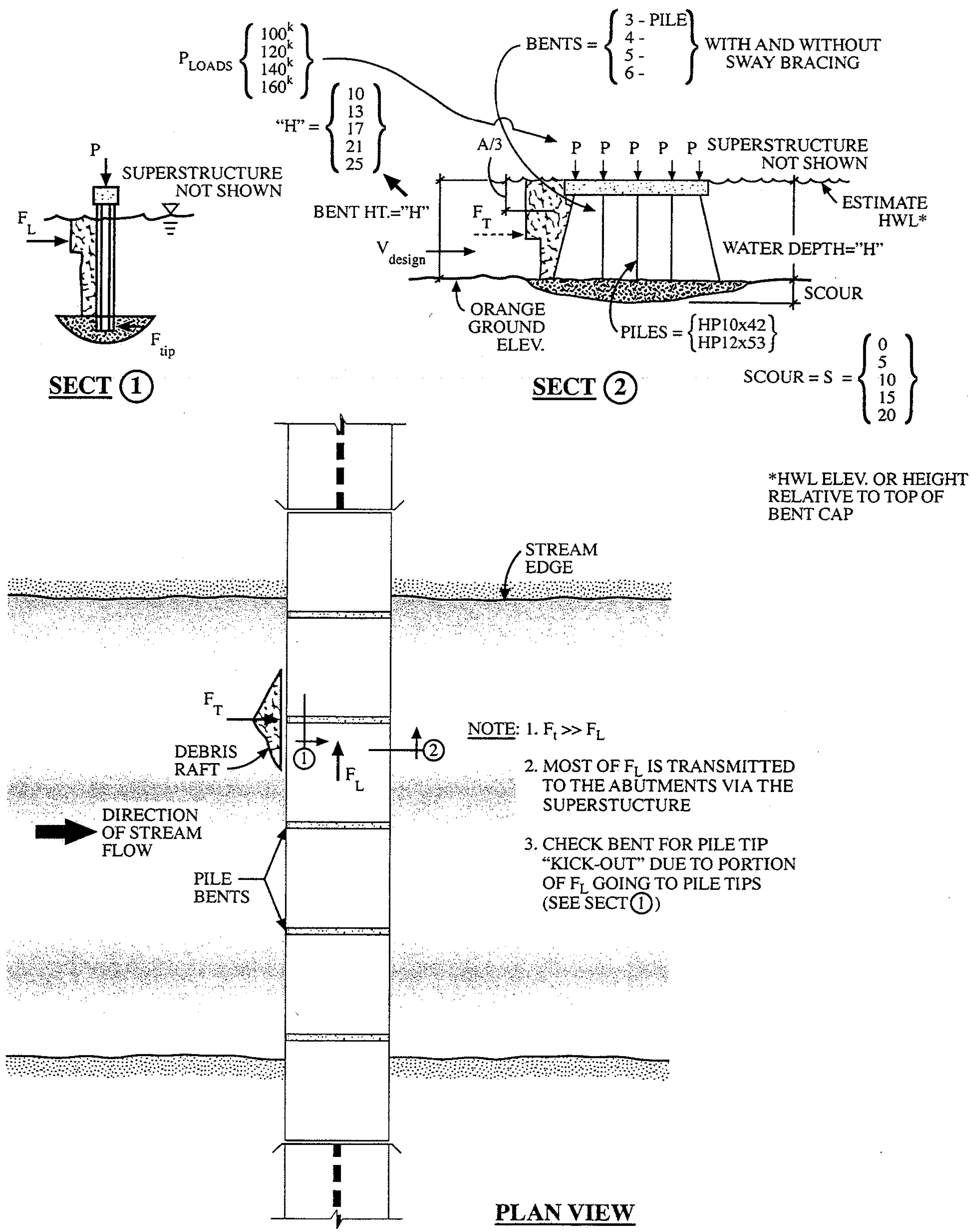
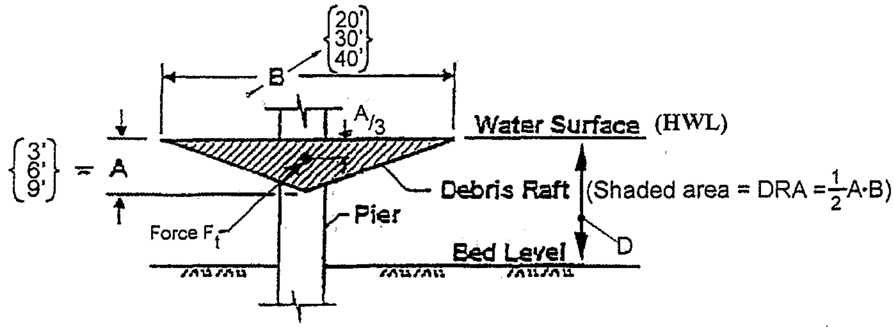


Figure 4.9. Typical Pile Bent Support Bridge Over Stream



B is determined based on bridge span length, L, as follows:

L< 25'	take B= 20'
25' ≤L ≤35'	take B= 30'
35 < L	take B = 40'

A is determined based on depth of water at bent, D, as follows:
(Note, D= HWL – OGL + S)

D < 7'	take A = 3'
7≤D ≤15'	take A = 6'
15 < D	take A = 9'

The design flood water pressure is taken as follows:

$$p = C_D \frac{\gamma}{2g} V^2 = C_D V^2$$

Where V = design flood water velocity in fps
V = 6mph = 8.80 fps (unless a higher value is know to exist)
C_D = 1.4

$$p = 1.4(8.80)^2 = 108 psf$$

The design lateral force F_t on the bent is taken as

$$F_t = p \; x \; DRA$$

$$F_t = 108PSF\left[\frac{1}{2} A \bullet B\right] x \; 54 psf \; x \; A \; x \; B$$

The variations of DRA and F_t over a wide range of A and B Values are shown in Fig 4.11.

Figure 4.10. Debris Raft And Flood Water Load For Checking Adequacy of Pile Bent During Major Flood Event

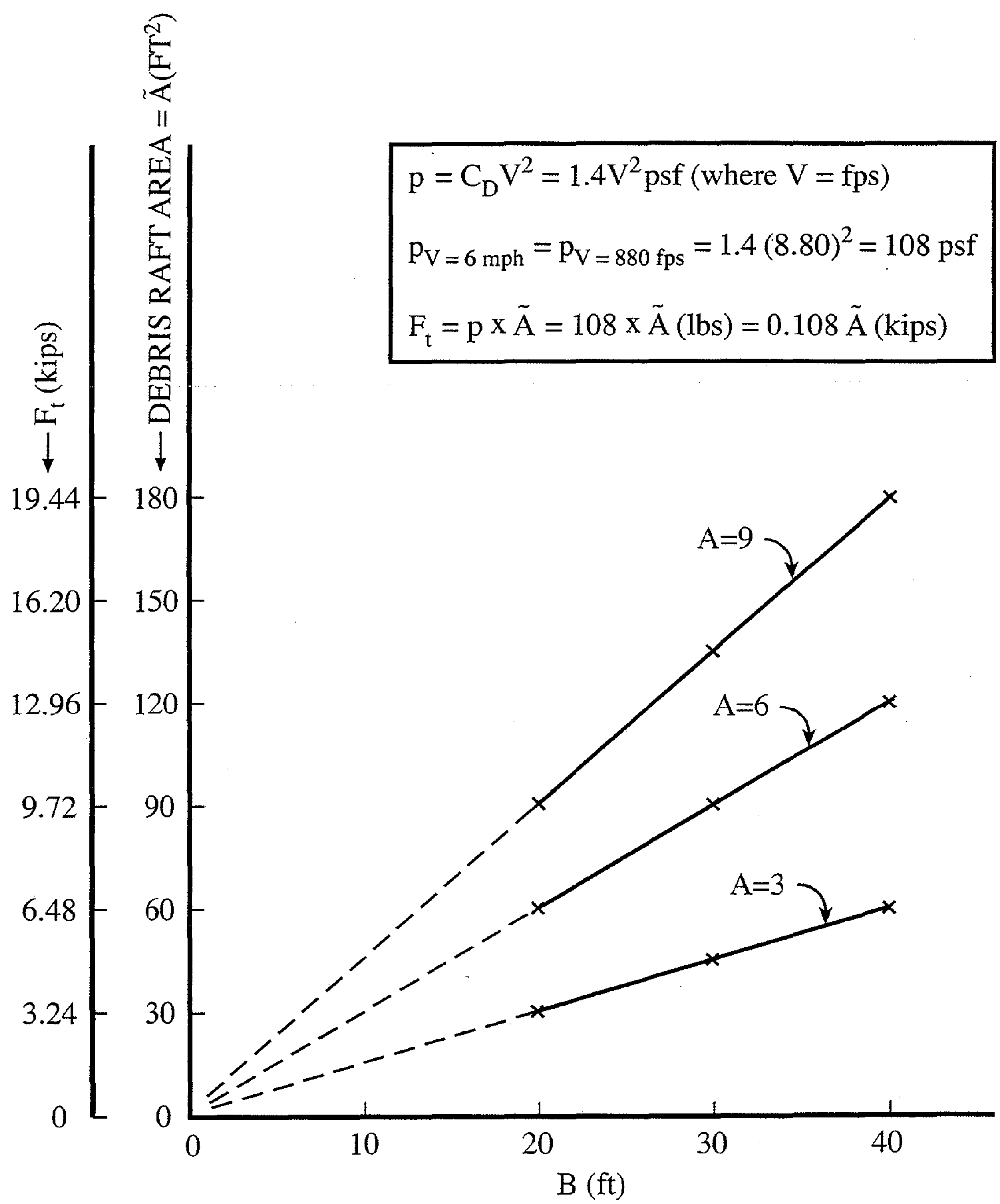


Figure 4.11. Bent F_t Force For Various Debris Raft Dimensions For V_{Design} = 6mph

4.6 Maximum Applied Pile Flood Water "Kick-Out" Force, F_{tip}

To determine the maximum applied bent "kick out" flood water force, F_{tip}, ALDOT's current bridge/bent information database may need be expanded to include the additional parameter values listed below. This expansion is needed in order to check the bent for a possible "kick-out" failure at the pile tips from the lateral flood water loads. It should be performed prior to applying the "screening tool" to assess the adequacy of a bridge bent during an extreme flood/scour event.

Estimated maximum stream flow angle w.r.t the longitudinal axis of the bent	$= \theta = 20° \; or \; 30°$
Remaining pile embedment after scour	$= \ell_{re} \; (in \; ft)$
Soil description at pile tip → In database	

AASHTO is somewhat vague in describing the stream velocity and flow direction when taking into account the lateral drag force of flood water on a bridge pier or pile bent. AASHTO states the lateral, uniformly distributed pressure on a substructure due to water flowing at an angle, Θ, to the longitudinal axis of the pier or bent shall be taken as

$$p = C_D \frac{\gamma}{2g} V^2 = C_D V^2$$

Where V = design flood water velocity in fps

C_D = pier drag coefficient

p = water pressure in psf

However, logic and physic would indicate that the V_{Design} should be broken up into $V_{Lateral}$ and $V_{Longitudinal}$ as shown in Figure 4.12. Also, C_D should be taken as the drag coefficient for $V_{Lateral}$, i.e. as C_{DL} with a value of approximately $C_{DL} \approx 2.0$ from fluid mechanics. Thus, $p_L = C_{DL} \; V_L^2$

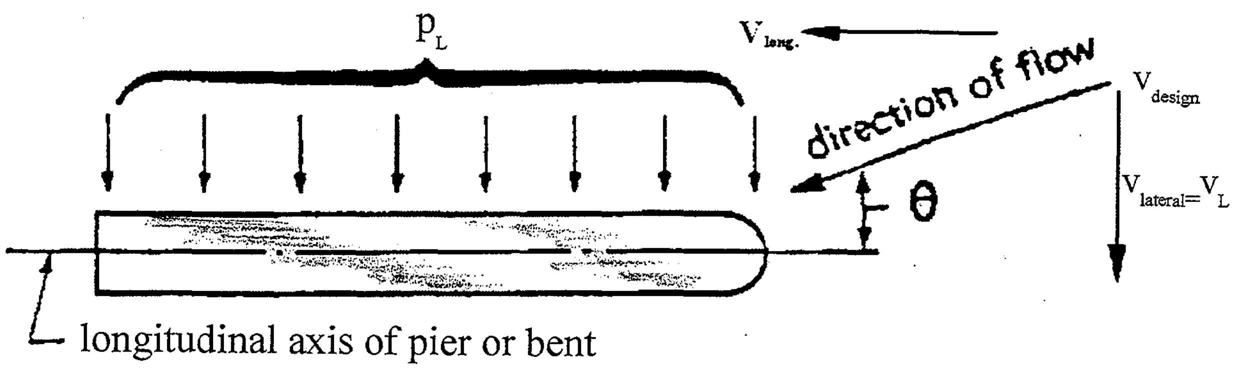


Figure 4.12. Plan View of Pier Showing Stream Flow and Lateral Pressure

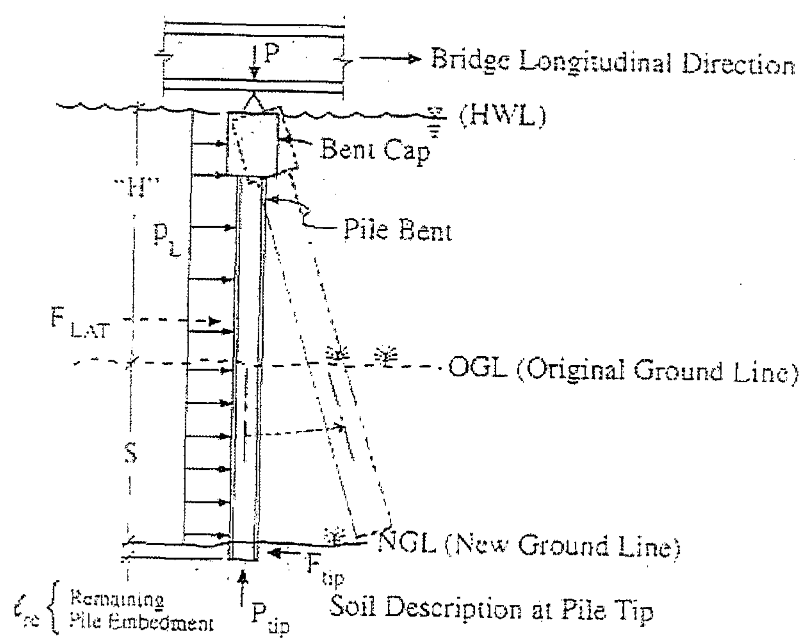


Figure 4.13. Evaluation of Bent Pile "Kick-Out" Load from Extreme Flood/Scour Event

Normally, bridge piers or bents will be aligned with their longitudinal axis parallel to the direction of stream flow. However, in an extreme flood event and with possible stream channel direction changes with time, the direction of stream flow is probably at some angle Θ w.r.t. the bent axis as indicated in Fig. 4.12. The most probable maximum value of Θ is estimated to be 20° and an upper bound value is estimated to be 30°. Using these value of Θ and assuming a design flood water velocity of 6 mph (or 8.80 fps), the resulting flood water lateral pressure, p_L, shown in Fig. 4.12 would be as shown in Table 4.3.

Table 4.3. Estimates of Maximum Flood Water Lateral Pressures on Pile Bent for V_{Design} = 6 mph

Parameter	Maximum Probably Angle, Θ = 20°	Estimated Upper Bound Angle, Θ = 30°
V_{Design}	6 mph = 8.80 fps	6 mph = 8.80 fps
C_{DL}	2.0	2.0
$V_L = V_{Design}\ Sin\ \Theta$	3.01 fps	4.40 fps
$p_L = C_{DL}\ V_L^2$	18.12 psf	38.72 psf

The lateral drag force on a pile bent (lateral to the longitudinal axis of the bent) will be the lateral pressure, p_L, times the projected area of the bent on a vertical plane perpendicular to V_L, and will be as shown in Fig. 4.13. As can be seen from Fig. 4.13,

$$F_{LAT}^{HP10x42} \approx p_L\ x \frac{10'}{12}\ x\ ("H" + S)$$

$$F_{LAT}^{HP12x53} \approx p_L\ x \frac{12'}{12}\ x\ ("H" + S)$$

$$F_{Tip} \approx \frac{1}{2} F_{LAT}$$

$$F_{Tip}^{HP10x42} \approx \frac{1}{2} x \frac{10'}{12} x \; p_L \; x \; ("H" + S) = \frac{5'}{12} x \; p_L \; x \; ("H" + S)$$

$$F_{Tip}^{HP12x53} \approx \frac{1}{2} x \frac{12'}{12} x \; p_L \; x \; ("H" + S) = \frac{1}{2} x \; p_L \; x \; ("H" + S)$$

Values of F_{Tip} for HP_{10x42} and HP_{12x53} piles for flow direction attack angles, Θ, of 20° and 30° for a wide range of "H" + S values are shown in Table 4.4.

Table 4.4. F_{Tip} *Values* **for HP_{10x42} and $HP_{12 x 53}$ Piles for Θ Values of 20° and 30° for a Range of "H" + S Values for V_{Design} of 6 mph**

"H" + S Value (ft)	$F_{tip}^{applied}$ *Values (in lbs)*			
	Θ = 20°		Θ = 30°	
	HP_{Pile}^{10x42}	HP_{Pile}^{12x53}	HP_{Pile}^{10x42}	HP_{Pile}^{12x53}
15	113	136	242	290
20	151	181	323	387
25	189	227	403	484
30	227	272	484	581
35	264	317	565	678
40	302	362	645	774
45	340	408	726	871
50	378	453	807	968

4.7 Load Combinations

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 $P_{Soil Support Capicity}^{Pile}$ 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" .

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 (elastic or inelastic buckling whichever controls), then it will be assumed that the bent will not buckle. An example determination of $P^{Pile}_{Max\,Applied}$ and $P^{Bent}_{Max\,Applied}$ for a typical ALDOT bridge superstructure and pile bent is given in Section 4.4.

Lastly, in checking against a bent pushover failure, the load combination of DL plus maximum LL gravity loads on the bent in combination with the maximum applied bent flood water load, F_t, will be checked to make sure that this F_t load is not greater than then the bent F_t pushover load under the same gravity loading condition. The pushover analysis is a nonlinear analysis which considers both the geometric and material nonlinearities present, and thus it implicitly checks for possible buckling of the bent as well as failure due to inadequate strength or stiffness

5. SCREENING TOOL

5.1 General

The Alabama Department of Transportation (ALDOT) is currently performing an assessment of the scour susceptibility of its bridges, and a part of this assessment requires an evaluation of the structural stability of these bridges for an estimated scour event. Because of the large number of bridges in the state, and because the stability analysis of each bridge represents a considerable effort in time and money, there is a compelling need to develop a simple "screening tool" which can be used to assess the adequacy of these bridges for an estimated scour event. Such a tool could be used to identify those bridges which may be deficient and should be prioritized for more detailed study. Because of the tendency to use standardized designs with pile bent foundations for many bridges in Alabama, it is feasible to pursue the development of such a screening tool.

5.2 Macro and Micro Plans for Screening Tool

The macro plan used in the development of the "screening tool" (ST) to evaluate the adequacy of ALDOT bridge pile bents for an extreme flood/scour event is shown in itemized checklist form below, and in macro flowchart form in Fig. 5.1.

What to Check:

1. Is the bridge over water and is it supported on pile bents?
2. Is the bridge at a site where significant scour (S > 3ft) can occur?
3. Number, size, type and spacing of bent pile, and bent height?
4. Bent cap width and depth?
5. Are bent piles embedded in bent cap or welded to steel plates that are embedded in cap?
6. Is bent sway-braced?
7. Does bent have a horizontal compression strut at 4' above ground in sway-bracing system?
8. Do bent piles have considerable loss of section (25% or greater) in the splash zone or elsewhere?
9. The projected maximum scour at the site/bent in an extreme flood event?
10. The projected HWL (relative to the top of the bent cap) and the design flood water velocity (V)?
11. Is the angle of attack of flood water w.r.t. bent longitudinal axis $\theta \leq 30^\circ$?
12. Maximum pile and bent applied gravity and flood water loads?
13. The length of pile embedment before (ℓ_{bs}) and after (ℓ_{as}) scour?
14. Soil description at the bent pile tips and the depth of embedment of the pile in this soil after scour?
15. Can bent pile tips kick-out due to transverse (transverse to bent longitudinal axis) flood water loading and insufficient embedment after scour?
16. Can bent piles have a plunging failure due to insufficient soil support capacity after scour?
17. Can bent piles buckle about their weak axis, i.e., in the transverse direction of the bridge?
18. Can the bent have a push-over failure under a combination of gravity and transverse flood water loading?

A detailed flowchart showing the micro plan to check the adequacy of ALDOT bridge pile bents for an extreme flood/scour event, i.e., a flowchart of the ST, is shown in Fig. 5.2. This flowchart is a detailed enactment of the macro plan shown above in checklist form and in Fig. 5.1.

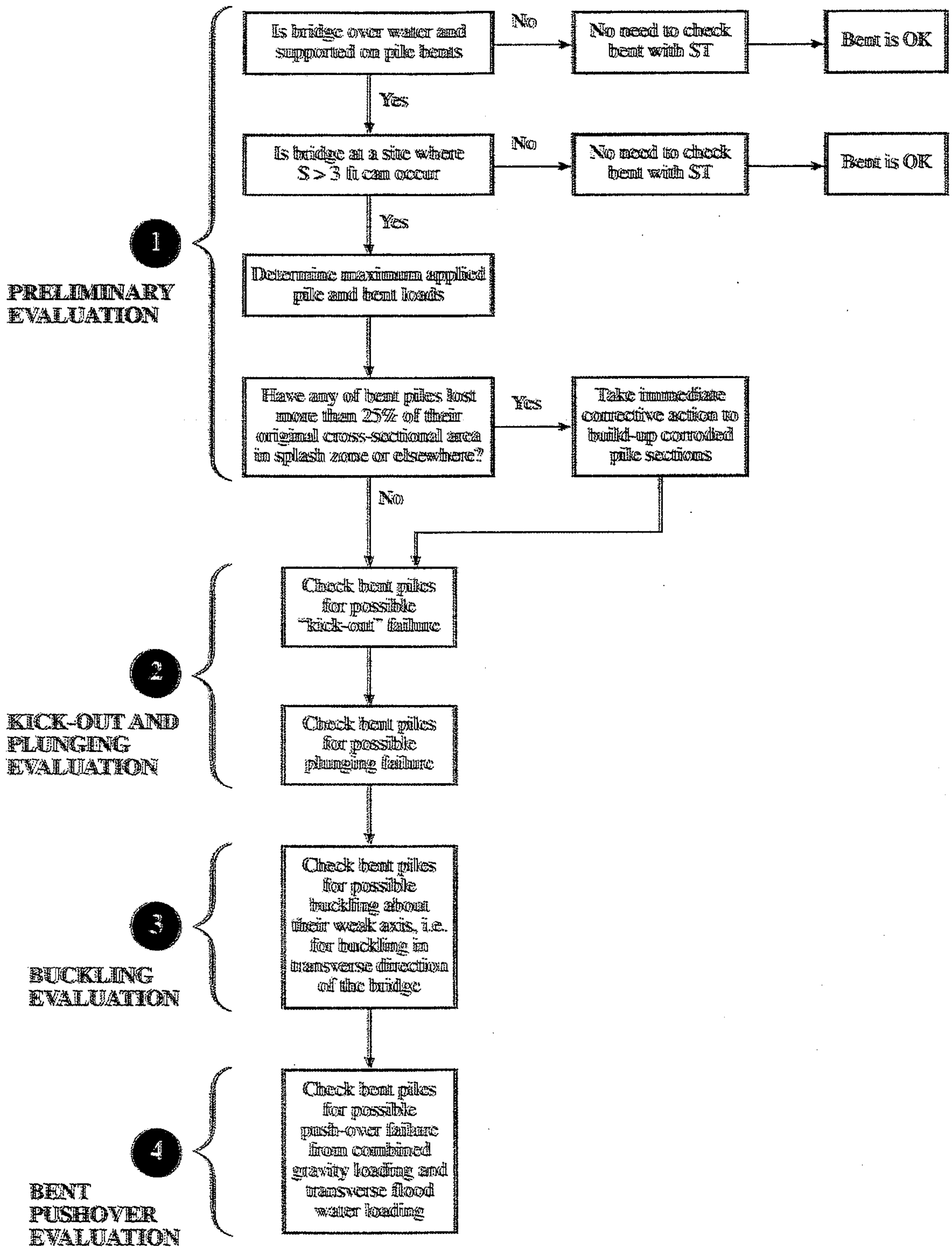
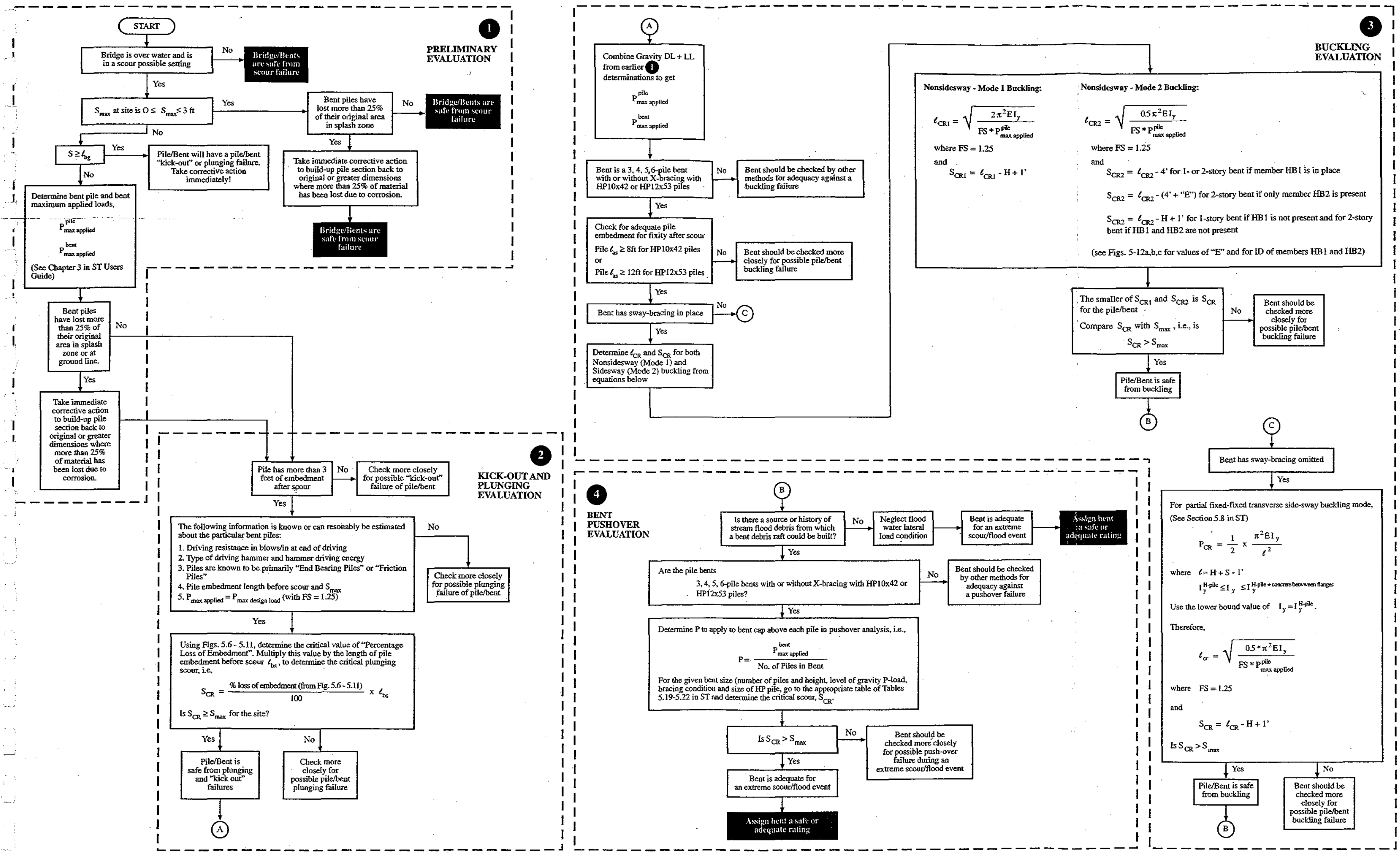


Figure 5.1. Screening Tool (ST) Macro Flowchart

Fig. 5.2. Screening Tool Flowchart for Assessing Pile Bent Adequacy During an Extreme Flood/Scour Event



5.3 Assumptions Included in the ST

Assumptions explicitly or implicitly included in checking the adequacy of bridge pile bents during an extreme flood/scour event via the “screening tool” are as follows.

1. For a given pile bent, if the pile where $P^{Pile}_{Max\ Applied}$ is acting is safe from pile “kick-out”, plunging or buckling failure, then assume the bent is safe from failure in these modes as well.
2. For a bent push-over failure in the plane of the bent, the total gravity load on the bent plus the flood water loading on the bent must be considered.
3. A pile and/or bent is considered safe from failure if $P_{Failure} > 1.25 P_{Max\ Applied}$ for pile buckling or bent pushover failures and for pile kickout or plunging failure.
4. The procedures described in Chapter 4 for determining $P^{Pile}_{Max\ Applied}$ and $P^{Bent}_{Max\ Applied}$ are based on bridges with equal span lengths which may be simply supported spans or continuous (or continuous for LL) spans. If the bridge under investigation has spans of significantly different lengths, then a modification of the procedures described in Chapter 4 should be made to determine $P_{Max\ Applied}$. Other than this, the ST can be used as shown herein.
5. Scour and/or a flood water loading does not change the gravity loading on a pile or bent, i.e., P^{Pile}_{DL+LL} and P^{Bent}_{DL+LL}, and changes the maximum

$P^{Pile}_{Vertical}$ load very little. Also, $P_{failure}$ vs. ℓ curves for the bent piles are assumed to be as shown in Figs. 5.3 and 5.4., and the bent piles were designed with a F.S. >2 against squashing. Therefore we will assume that $P_{\max applied} < P_Y / 2$ and thus if a pile or bent buckles, it will be an elastic buckling as can be seen in Fig 5.3.

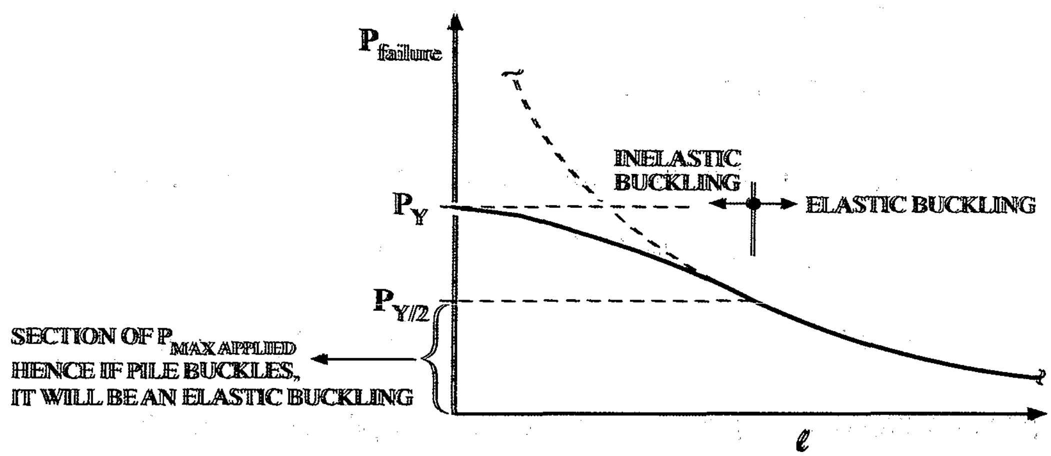


Figure 5.3. Qualitative Assessment of Pile Buckling Load About Its Weak Axis.

6. Due to the abutments, bridge superstructures and thus the bents and bent caps have very little movement capability in the longitudinal direction of the bridge. Therefore, the piles/bents cannot buckle in a sidesway mode, or be pushed-over in the longitudinal direction. Because of this, and the rather large I_{strong} / I_{weak} axis ratio for the bent piles, and the bent boundary conditions, weak axis buckling of the piles/bents will govern the buckling failure mode as indicated and discussed in the Phase I Report.

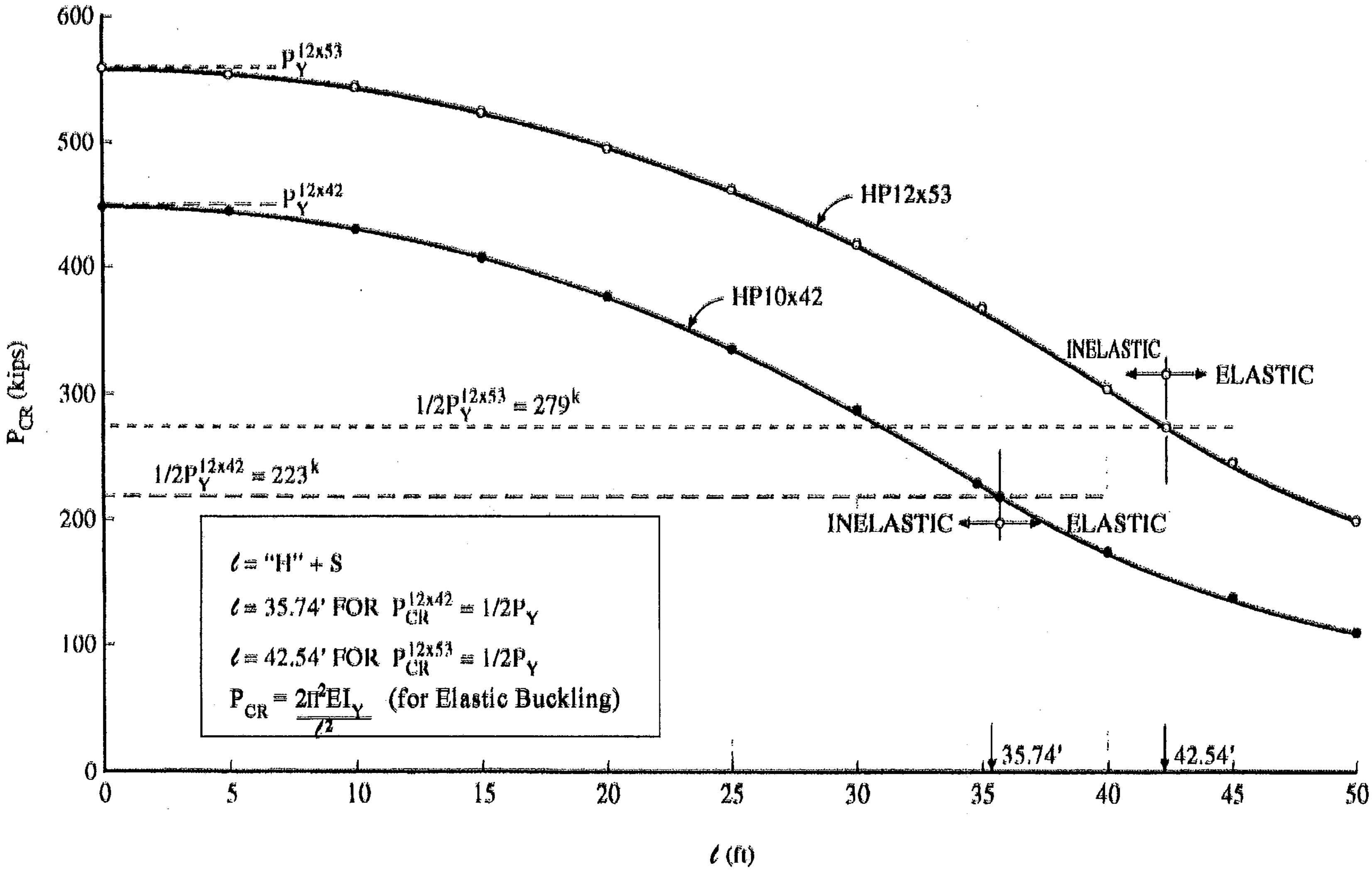


Figure 5.4. Quantitative Transverse/Weak Axis Nonsidesway Buckling of a Single Bent HP Pile of A36 Steel for a Given Length (ℓ_{max}) Above Ground Line After Scour.

7. In the transverse direction, prior to any scour, the bent X-bracing will prevent sidesway displacement and thus prevent a sidesway buckling mode, and will also greatly increase the bent transverse push-over load.

8. In the transverse direction, when scour becomes large, sidesway bending or pile buckling from the lowest horizontal compression strut in the X-bracing system to the new ground line is possible and this will control the pile/bent buckling load as well as the bent push-over load. This is discussed and the buckling and pushover loads analyzed in Sections 5.7, 5.8, and 5.9.

9. For the case of no sway-bracing and the exposed portion of the piles encased in concrete, if we use the largest allowable value of H prior to scour of H = 13' in order to determine the minimum level of scour to render the piles unstable, neglect the concrete encasement, and assume 50% fixity at the pile ends, we obtain a sidesway elastic buckling load of approximately $P_{CR} \approx \frac{1}{2}\frac{\pi^2 EI_y}{(H+S)^2}$. This equation yields the following pile elastic buckling loads.

			P_{CR}^{pile} (kips)	
H (ft)	S (ft)	H+S (ft)	HP_{10x42} (k)	HP_{12x53} (k)
13	15	28	91	161
13	20	33	65	116

This case is discussed and the buckling loads analyzed more closely in Section 5.8.

10. The bridge superstructure is positively connected to the bent caps and abutments with allowances for small longitudinal movements due to thermal expansion/contraction. Thus sidesway buckling or pushover failure of the bents in the longitudinal direction of the bridge is not possible.

11. Buckling and/or pushover failures of the piles/bent are limited to failures in the transverse direction, i.e., to failures in the plane of the bent.

12. The bridge bents are limited to single row pile bents with 3, 4, 5, or 6 unbraced or X-braced HP 10x42 or HP 12x53 steel piles. (Expansion of the ST to include 3, 4, 5, or 6 unbraced prestressed concrete pile bents, and/or to include bents with more than 6 piles can be done at a later date).

13. For bents with concrete encased HP 10x42 and HP 12x53 piles, the contribution of the concrete encasement is neglected and the bent is treated as an uncased and unbraced steel pile bent.

14. The pile tops have an attached end plate and are embedded 1 ft into the bent cap, or are welded to steel plates which are embedded in the bent cap such that the pile-to-cap connection is approximately a rigid connection in the plane of the bent.

15. Pile bent caps are adequate in strength and stiffness and will not be the cause of a bent failure.

16. The superstructure girders are placed on the bent cap directly above each pile and/or the bent cap is sufficiently strong and stiff to effectively distribute the girder loads to the piles.

17. The bridge design LL is known and is either an HS 15 or HS 20 loading.

18. The bridge soil setting, to include total depth of pile embedment in the soil, the soil layer at the pile tips and the depth of embedment of the pile tip in the tip soil layer are known.

19. The information listed in Section 5.4 is available in ALDOT's computer database for use with the ST.

20. For events of large scour, i.e., S>10ft, bridge maintenance crews will take corrective actions after the event such as back-filling and rip-rapping around the bent piles to approximately restore them to their original state.

5.4 Bridge/Site Information Needed to Make ST Checks

Information needed to perform the "checks" indicated in Section 5.2, and thus evaluate the adequacy of ALDOT bridge pile bents for extreme scour events are evident in many of the checks indicated in Section 5.2. However, in some of the "checks" in Section 5.2, such as (9)-(15), the information needed to perform the check is not self-evident. Some of the information needed to perform the "checks" is required to determine the maximum applied loads on a bent pile or on a bent, and this information is identified in various sections of Chapter 4, and some of the information is needed to determine the load capacity of a pile or bent. In either case, the information needed is given/repeated below for completeness.

1. Scour, High Water Level and Stream V_{design} Information
   - Verification that bridge is over water, supported by pile bents, and in a scour possible setting
   - Estimated magnitude of scour of extreme scour event from stream crossing hydrologic and soil setting data

- Estimated stream flood high water level (HWL) relative to top of bent cap and the design flood water velocity (V)
- Estimated maximum flow depth after scour=HWL-OGL+S
- Is formation of a debris raft at bridge site possible?
- Estimated debris raft dimensions A and B
- Water pressure on debris raft = $p=1.4V^2$ (where V is in ft/sec and p is psf)
- Estimated maximum flow angle θ w.r.t. longitudinal axis of bent, i.e., $\theta = 20^\circ$ or $\theta = 30^\circ$?

2. Pile Bent Geometry and Design Information
   - Longitudinal spacing of pile bents
   - Bent height from top of cap to original ground line, i.e., "H"
   - Original ground line (OGL) elevation of bent
   - Type, size, spacing and number of piles per bent
   - Bent has steel angle iron sway bracing
   - Bent has steel HP piles encased from 3ft. below ground up to bottom of cap
   - Approximate size of bent cap (depth and width)

3. Pile Driving and Soil Profile Information
   - Pile length and tip elevation
   - Original ground level or elevation
   - Original depth/length of pile embedment in soil before scour(ℓ_{bs})
   - Length of pile embedment in soil after scour $(\ell_{as} = \ell_{re})$
   - Pile driving resistance of last foot
   - Soil bearing strength (or descriptive 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)
   - Girder type, size, number per span, and spacing
   - Deck thickness
   - Barrier rail type and estimated weight per foot if other than Jersey barrier
   - Outside-to-outside deck width
   - Curb-to-curb deck width and number of traffic lanes
   - Design LL's

5. Pile/Bent Maximum Load Information:
   - $P^{Pile}_{Max\ Applied}$ (gravity DL + LL)
   - $P^{Bent}_{Max\ Applied}$ (gravity DL + LL)
   - $F^{t}_{Max\ Applied}$ (flood water load near top of bent in plane of bent)
   - $F^{tip}_{Max\ Applied}$ (flood water load at pile tip normal to plane of bent)

5.5 Check for Bent Pile Tip "Kick-Out" Failure

A bridge bent "kick-out" failure is described as an event where the flow of the water against the driven piles imposes forces that act transversely to the plane of the pile bent, i.e., parallel to the centerline of the bridge. If the force, F_{tip} (see Fig. 5.5b), exceeds the passive earth pressure at the tip of the driven pile, the bent might experience "kick-out" failure. See Figure 5.5a for an illustration of the acting forces. The following paragraphs are a description of how "kick-out" adequacy was determined and how the results have been included in the screening tool.

The first step to investigate possible bent "kick-out" failure was to determine F_{tip} in Fig. 5.5b. These values are presented in Table 5.1 for various design parameter values. Normally, bridge piers or bents will be aligned with their longitudinal axis parallel to the direction of stream flow. However, in an extreme flood event and with possible stream channel direction changes with time, the direction of stream flow is probably at some angle Θ w.r.t. the bent axis as indicated in Fig. 5.5a. The most probable maximum value of Θ is estimated to be 20° and an upper bound value is estimated to be 30°. Using these values of Θ and assuming a design flood water velocity of 6 mph (or 8.80 fps), the resulting flood water maximum values of $F_{tip}^{applied}$ were determined to be as shown in Table 5.1 for various "H" + S bent heights (see Section 4.6).

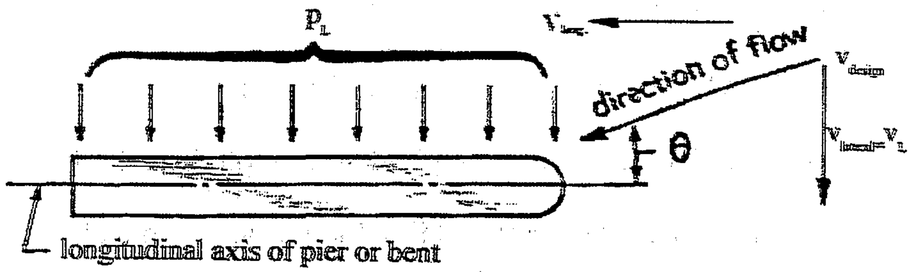
In order to determine the required embedment depth in order to provide resistance for these forces, it was assumed that the soil would resist such forces through passive pressures. The equation for the passive earth pressure is given as:

$$(FS)xP_p = \frac{1}{2}\gamma H^2 K_p$$

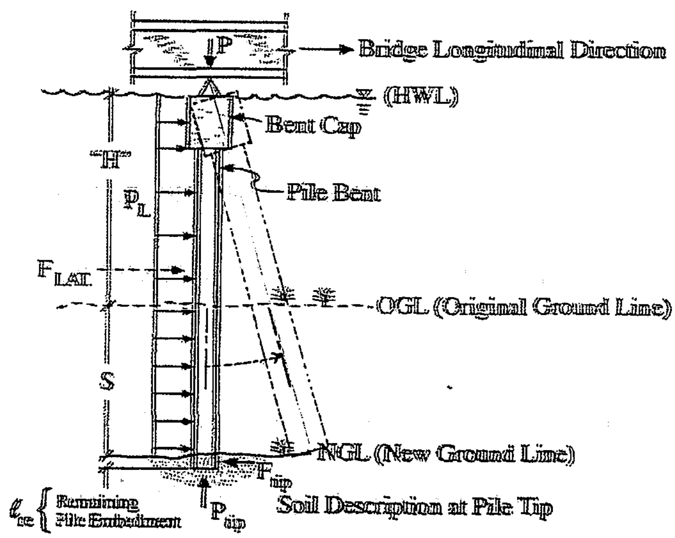
A factor of safety (FS) of 1.5 was used. The buoyant weight of the soil, γ, was assumed to be 60 lb/ft^3, and the coefficient of passive lateral earth pressure, K_p, was assumed conservatively to be 2.

The first calculations were only run on the highest loadings in Table 5.1 to determine the largest value of required embedment for safety against "kick-out" failure. This value was determined to be 2.89 feet. Rounding up, to be conservative, we would not want to have a pile with less than 3 feet embedment. Therefore, 3 feet has been established as the minimum required embedment depth to avoid "kick-out" failure.

This analysis was only an investigation of one individual pile; therefore, it was assumed that if the individual pile was safe from kick-out failure, then the entire bent was safe from kick-out failure. In the screening tool flowchart, the Section labeled as "Block 2" checks against kick-out and plunging failure. If a pile has less than three feet embedment, the screening tool will conclude that the pile bent be examined more closely for possible kick-out failure.



a. Plan View of Pier/Bent



b. Side Elevation View of Bent

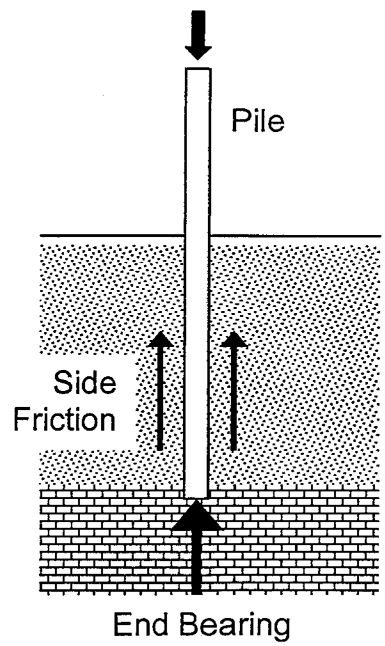
Figure 5.5. Bent Pile "Kick-Out" Load from Extreme Flood/Scour Event

Table 5.1. F_{Tip} *Values* for HP_{10x42} and HP $_{12 \times 53}$ Piles for Θ Values of 20° and 30° for a Range of "H" + S Values for V_{Design} of 6 mph

"H" + S Value (ft)	$F_{tip}^{applied}$ *Values (in lbs)*			
	Θ = 20°		Θ = 30°	
	HP_{Pile}^{10x42}	HP_{Pile}^{12x53}	HP_{Pile}^{10x42}	HP_{Pile}^{12x53}
15	113	136	242	290
20	151	181	323	387
25	189	227	403	484
30	227	272	484	581
35	264	317	565	678
40	302	362	645	774
45	340	408	726	871
50	378	453	807	968

5.6 Check for Possible Bent Pile Plunging Failure

A possible mode of failure for bridge bents exposed to extreme flood/scour events occurs when the pile has inadequate axial resistance to support the axial pile loads, with the result that the pile bearing capacity is exceeded and the pile fails by "plunging." For purposes of this simple analysis, it is assumed that all of the individual H piles must be safe from plunging to ensure that the entire bent is also safe from plunging. Thus, the maximum load on any individual pile is used to analyze for plunging failure.



The axial resistance of a pile is provided by a combination of side friction and end bearing (as illustrated at right) and the magnitude of these load resisting forces is a function of the soil properties. Information on soil properties at each specific bent is often inadequate or 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. The major variables affecting the axial resistance of a pile (after scour) as indicated by the driving resistance during pile driving are:

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 driving resistance to axial static pile capacity have been developed using a simple pile driving formula. The most appropriate model to correlate driving resistance to axial static capacity is provided by the wave equation computer modeling technique as is required by ALDOT to establish pile driving criteria for new projects. However, in order to be effective this model requires a greater level of knowledge about the pile driving system than is commonly available from records on older projects. A simple but crude method to develop similar correlations is provided by pile driving formulae; 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:

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

   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 3 to 8 bpi were considered. A common refusal criterion is 10 bpi, beyond which additional pile driving would probably cease. In order to maintain a degree of conservatism in a rather uncertain scenario, it is suggested that 8 bpi be used as a maximum.

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.

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 loss of embedment. In a homogeneous 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.

The results of the analyses described above are presented in tabular form in Table 5.2 and in graphical form in Figures 5.6 through 5.11. In order to use these table/figures, 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/steam	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 also that rated driving energy of a wide variety of hammers can be obtained from www.pilehammerspecs.com.

2. Driving resistance, blows per inch. The driving resistance at the end of driving must be obtained from the pile driving records from the job. In some cases these pile 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. The figures provide for a range of 3 to 8 bpi, and interpolation between figures is acceptable.
3. End bearing pile or friction pile. Two sets of charts are provided, one for piles which derive capacity from predominantly end bearing and one for piles which derive capacity from predominantly side friction. The interpretation of which condition best represents the situation at hand requires some knowledge of the soil conditions either by borings or from

an examination of the driving records. Dense sand strata, hard clays or marl, or rock underlying soft alluvial soil all likely 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 figures are developed to express the scour in terms of percentage loss of embedment.

With the information above, Table 5.2 or Figures 5.6-5.11 can be used to estimate the pile capacity (with a factor of safety of 1.25) against plunging failure as indicated in the example below.

Example Problem: The estimated axial load for an extreme scour event on a pile is 80 kips (40 tons). The pile is a 12HP53 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 pound ram and a 3 foot drop. The pile was driven to an estimated final driving resistance of 8 blows per inch or more. 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. Using the figure for end bearing piles with 8 bpi final driving resistance (i.e. Figure 5.8), 50% loss of embedment, 10 ft-k driving hammer, the indicated capacity of the pile is slightly more than 60 tons with a F.S. of 1.25. The 60 tons estimated capacity exceeds the 40 ton demand and thus this pile does not appear subject to failure in the plunging mode.

Alternate tables and figures to Table 5.2 and Figures 5.6-5.11 which present pile capacities for four different final driving resistances given in inches per 10 blows and in blows per foot (bpf) are given in Appendix C.

Table 5.2 PILE CAPACITY IN TONS 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
4000	3	25	25	22	19	16	13	25	21	17	12	8
6000	3	40	40	35	30	25	20	40	33	26	19	12
8000	3	52	52	46	39	33	26	52	43	34	25	16
10000	3	63	63	55	48	40	32	63	52	41	30	19
12000	3	73	73	64	55	46	37	73	60	48	35	22
15000	3	87	87	76	65	54	43	87	71	56	41	26
20000	3	106	106	93	80	66	53	106	88	69	50	32
4000	5	35	35	31	26	22	18	35	29	23	17	11
6000	5	52	52	46	39	33	26	52	43	34	25	16
8000	5	66	66	58	50	41	33	66	55	43	32	20
10000	5	79	79	69	59	49	39	79	65	51	37	24
12000	5	90	90	79	68	56	45	90	74	59	43	27
15000	5	106	106	92	79	66	53	106	87	69	50	32
20000	5	128	128	112	96	80	64	128	106	83	61	38
4000	8	44	44	39	33	28	22	44	37	29	21	13
6000	8	63	63	55	47	39	32	63	52	41	30	19
8000	8	79	79	69	59	49	40	79	65	51	38	24
10000	8	93	93	82	70	58	47	93	77	61	44	28
12000	8	106	106	93	79	66	53	106	87	69	50	32
15000	8	123	123	108	92	77	62	123	102	80	58	37
20000	8	148	148	130	111	93	74	148	122	96	70	45

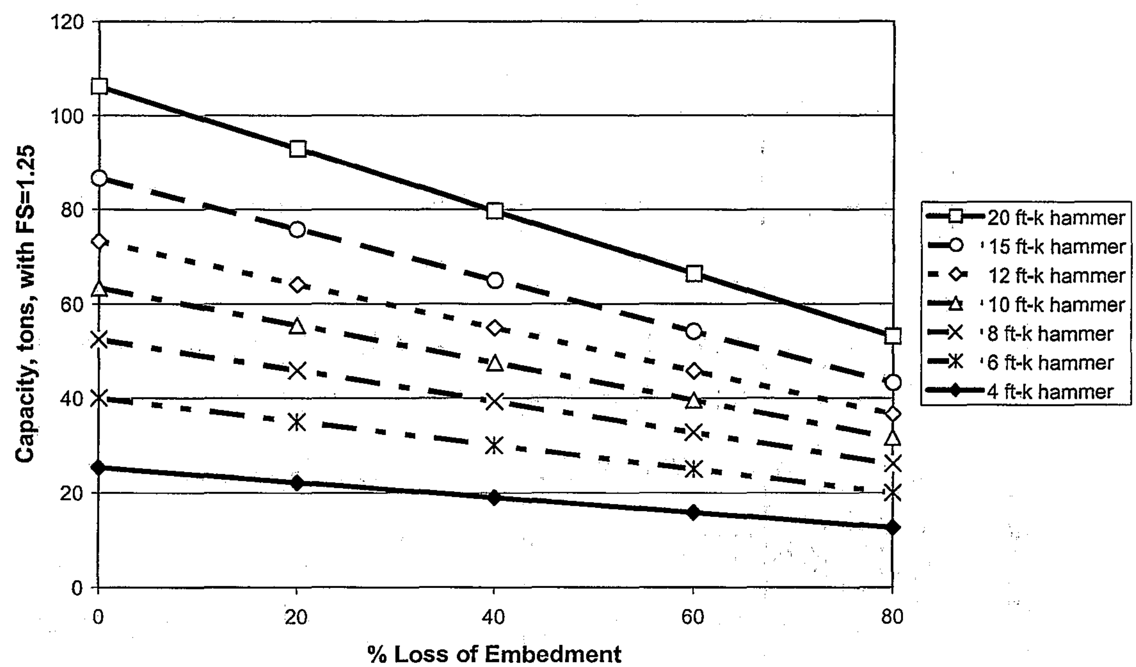


Figure 5.6. End Bearing Piles, 3 blows/inch Driving Resistance at End of Driving

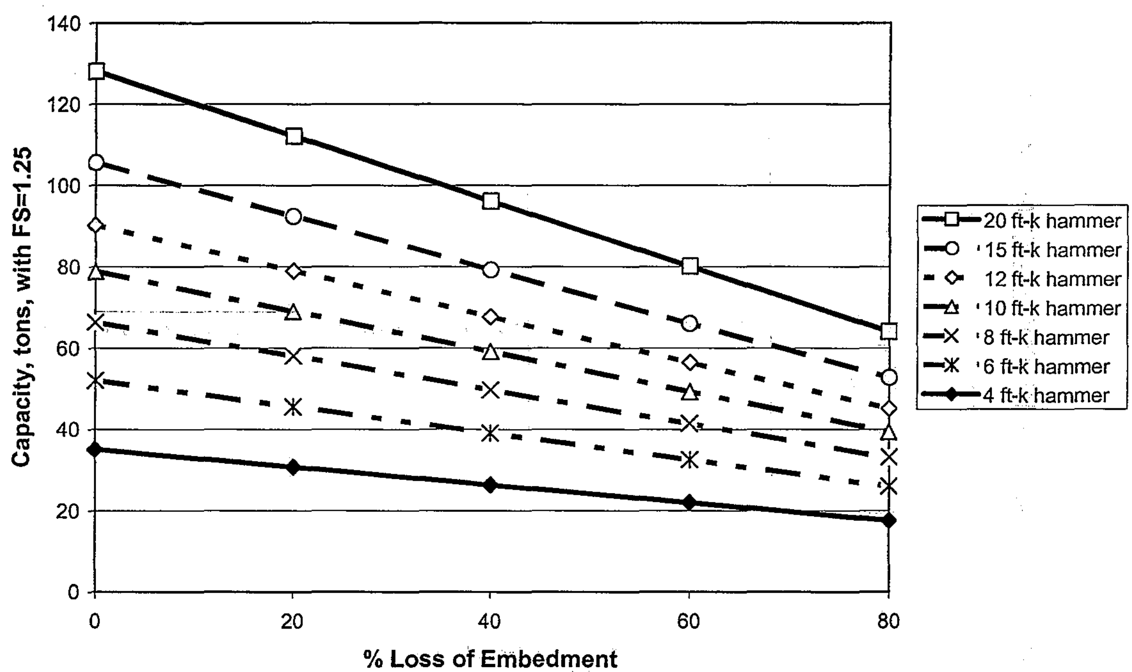


Figure 5.7. End Bearing Piles, 5 blows/inch Driving Resistance at End of Driving

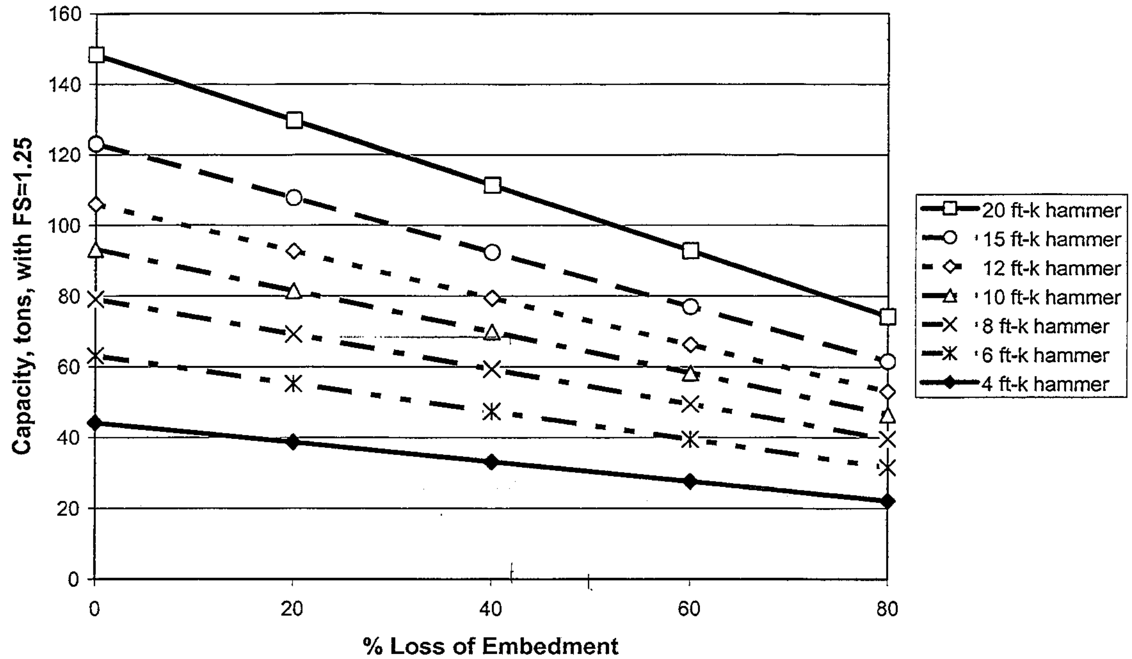


Figure 5.8. End Bearing Piles, 8 blows/inch Driving Resistance at End of Driving

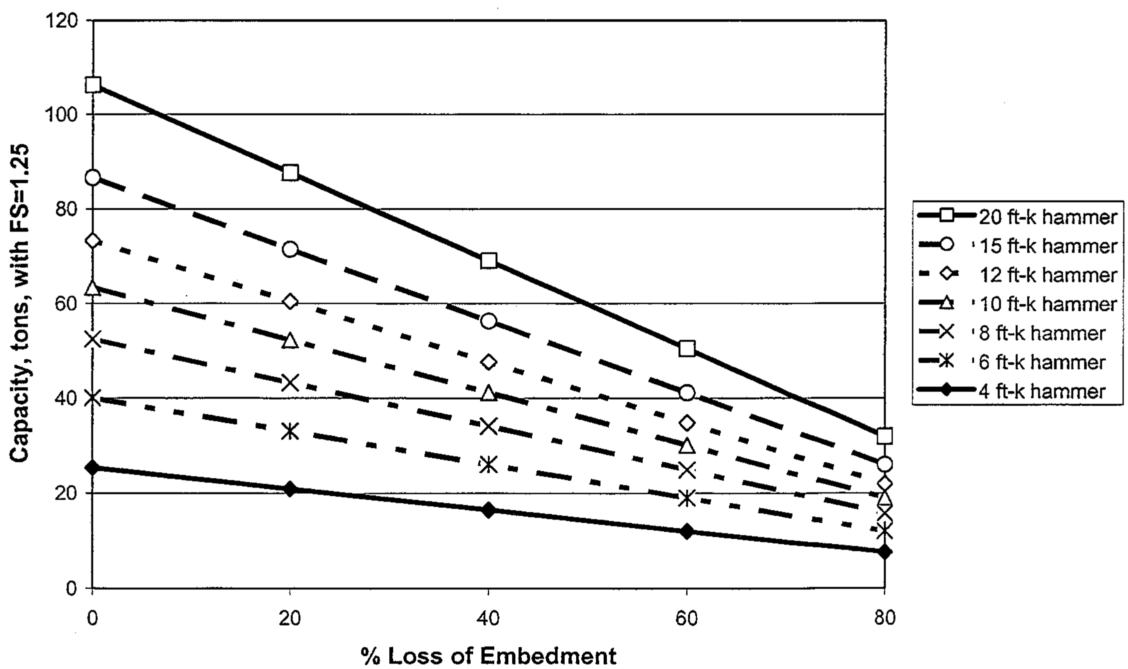


Figure 5.9. Friction Piles, 3 blows/inch Driving Resistance at End of Driving

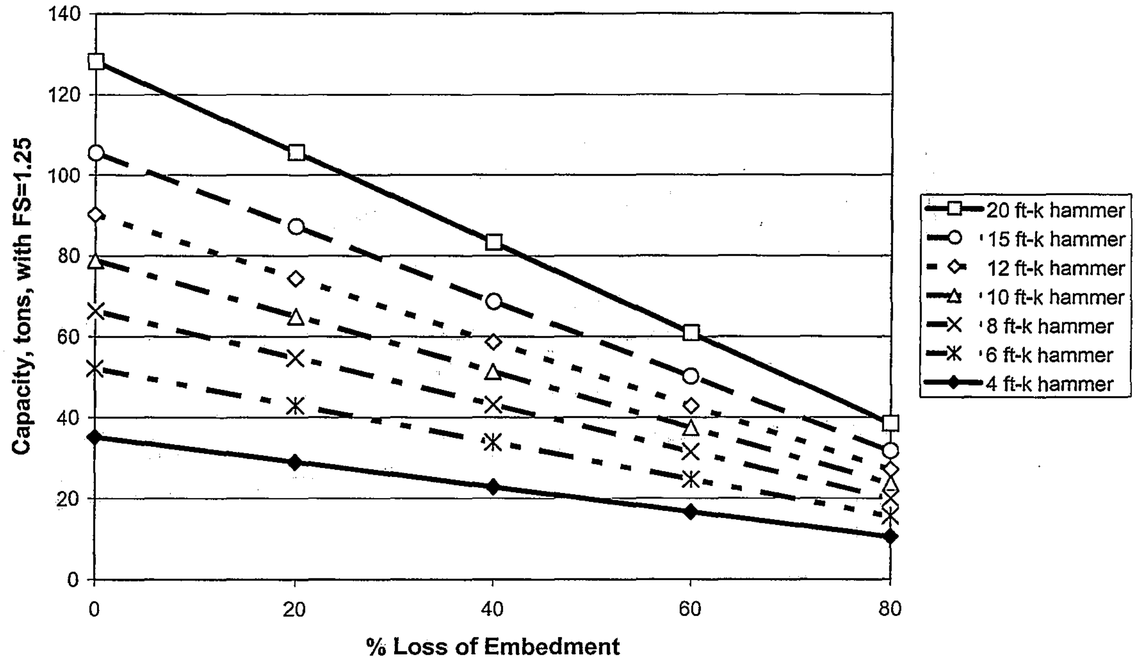


Figure 5.10. Friction Piles, 5 blows/inch Driving Resistance at End of Driving

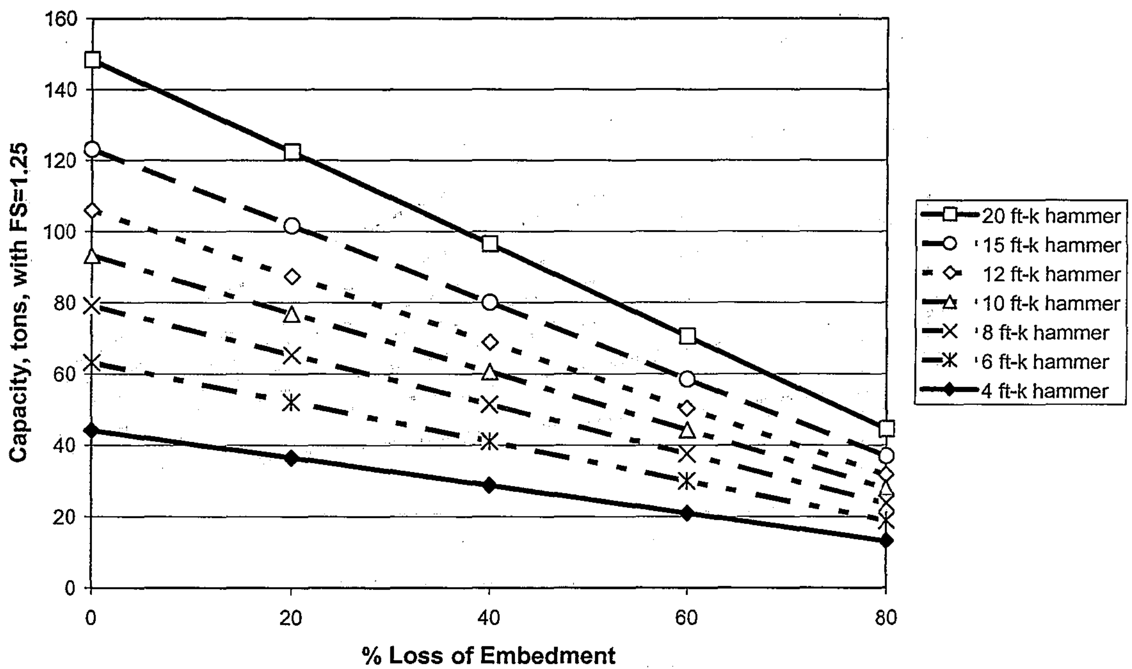


Figure 5.11. Friction Piles, 8 blows/inch Driving Resistance at End of Driving

5.7 Check for Possible X-Braced Bent Pile Buckling About Weak Axis

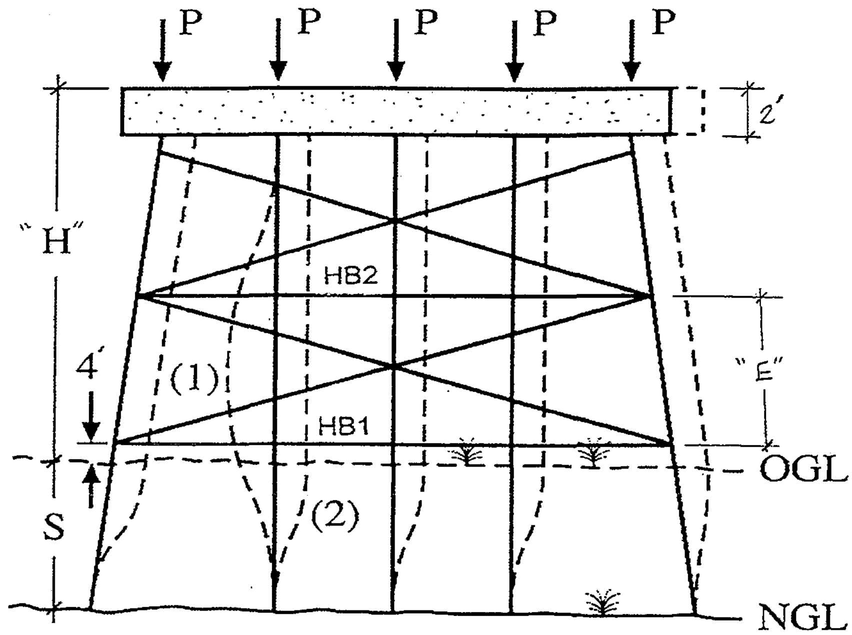
To investigate pile/bent buckling, we should recall that due to bridge abutments and connectivity of the bridge superstructure to the abutments and bent caps, bent piles can not buckle in a sidesway mode in the longitudinal direction of the bridge. Additionally, the bent piles will not buckle in a nonsidesway mode in the longitudinal direction of the bridge as this would constitute the piles buckling about their strong axis which have an $I_{Strong\,Axis} \approx 3I_{Weak\,Axis}$. Thus, if the bent piles buckle, they will buckle about their weak axis, i.e., in the transverse direction of the bridge.

For an X-braced bent, the bracing will prevent sidesway buckling when the scour, S, is zero or is a small value. For this case, Mode 1 (Nonsidesway) Buckling in the transverse direction will control as shown in Fig. 5.12a. For Mode 1 buckling, we assume the light angle iron diagonal X-braces will themself buckle and the horizontal compression struts HB1 and HB2 (if present) will undergo rigid-body horizontal movement as all piles in the bent buckle and will not provide a bracing point for the piles. Thus, in Mode 1, we assume a buckled shape from the bent cap down to the new ground line (NGL) as shown in Fig. 5.12a.

When S is not small, the X-braced bent could buckle in a transverse sidesway mode from approximately 4 feet above the original ground line (if the bent has a horizontal bracing strut at this location) down to the new ground line after scour as shown in Fig. 5.12a if the bridge spans are simply supported. If the bent does not have a horizontal bracing strut at approximately 4 feet above the original ground line, then the transverse sidesway buckling mode will assume to occur from the location of the lowest horizontal bracing strut down to the new ground line after scour. If the bent does not have a horizontal bracing strut, then the transverse sidesway buckling mode will assume to occur from the bent cap down to the new ground line after scour, i.e., the X-braced bent will assume to buckling like an unbraced bent. The above is indicated in Fig. 5.12a.

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 P_{CR}^{Pile} than continuous span bridges because continuous span superstructures will prevent transverse sidesway buckling of the bents. For purposes of the screening tool, we will assume that 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% larger loads (see Chapter 4(1)). However, continuous span superstructures will provide transverse support to the intermediate bents and prevent sidesway buckling and thus increase their P_{CR} value substantially, i.e., from approximately $P_{CR} \approx \frac{1}{2}\frac{\pi^2 EI_y}{\ell^2}$ to approximately $P_{CR} \approx 2\frac{\pi^2 EI_y}{\ell^2}$. 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



Buckling Mode 1 – Nonsidesway (assuming bracing members buckle and piles have a 50% fixity at the cap and ground)

$$P_{CR1} \approx \frac{2\pi^2 EI_y}{\ell^2_{CR1}} \qquad \text{where } \ell_{CR1} = \text{S+“H”-1'} \tag{5.1}$$

Buckling Mode 2 – Sidesway (lower portions of piles)

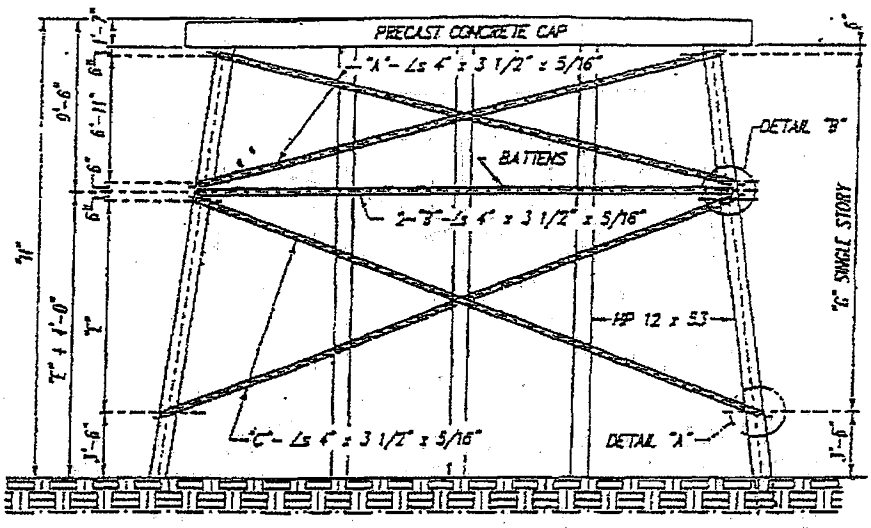
$$P_{CR2} \approx \frac{1}{2} x \frac{\pi^2 EI_y}{\ell^2_{CR2}} \tag{5.2}$$

where $\ell_{CR2} = S + 4'$ for 1 or 2-story bent if member HB1 is present

$\ell_{CR2} = S + (4' + "E")$ for 2-story bent if only member HB2 is present

$\ell_{CR2} = S + ("H" - 1')$ for 1-story bent if HB1 is not present and for 2-story bent if HB1 and HB2 are not present

Figure 5.12a. Transverse Buckling Modes and Equations for X-Braced Bents

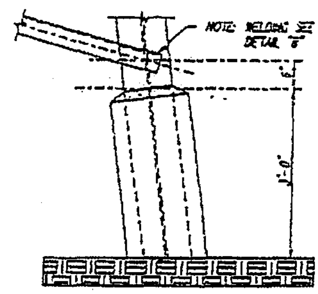


SWAYBRACING DETAILS

N.T.S.

TWO STORY BENT SWAYBRACING TABLES					
"H"	"E"	"A"	"B"	"C"	WT. LBS.
20'-0"	6'-1"	29'-10"	30'-0"	31'-6"	1407
21'-0"	7'-1"	29'-10"	30'-0"	31'-10"	1412
22'-0"	8'-1"	29'-10"	30'-0"	32'-2"	1417
23'-0"	9'-1"	29'-10"	30'-0"	32'-7"	1423
24'-0"	10'-1"	29'-10"	30'-0"	33'-0"	1430
25'-0"	11'-1"	29'-10"	30'-0"	33'-5"	1436

BATTEN WEIGHT TO BE ADDED TO ABOVE TABLES. 10-BATTENS REQUIRED. 5/6" X 7 1/2" X 1'-6 1/4" @ 12.1# EACH.



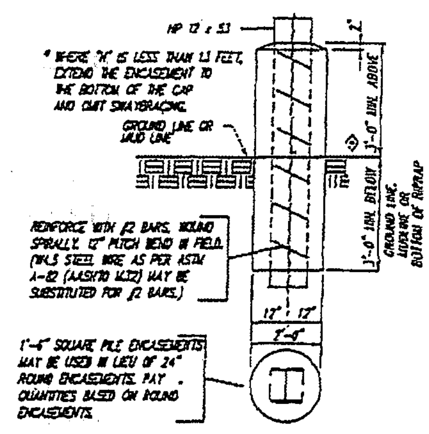
DETAIL "A"

SCALE: 3/4" = 1'-0"

NOTE: WEIGHT GIVEN IS TOTAL FOR TWO PIECES OF EACH LENGTH OF SWAYBRACING SHOWN IN BOTH TABLES.

SINGLE STORY BENT SWAYBRACING TABLES			
"H"	"G"	"D"	WT. LBS.
13'-0"	7'-0"	29'-10"	459
14'-0"	8'-0"	30'-3"	466
15'-0"	9'-0"	30'-8"	472
16'-0"	10'-0"	31'-1"	478
17'-0"	11'-0"	31'-6"	485
18'-0"	12'-0"	32'-0"	493
19'-0"	13'-0"	32'-6"	501

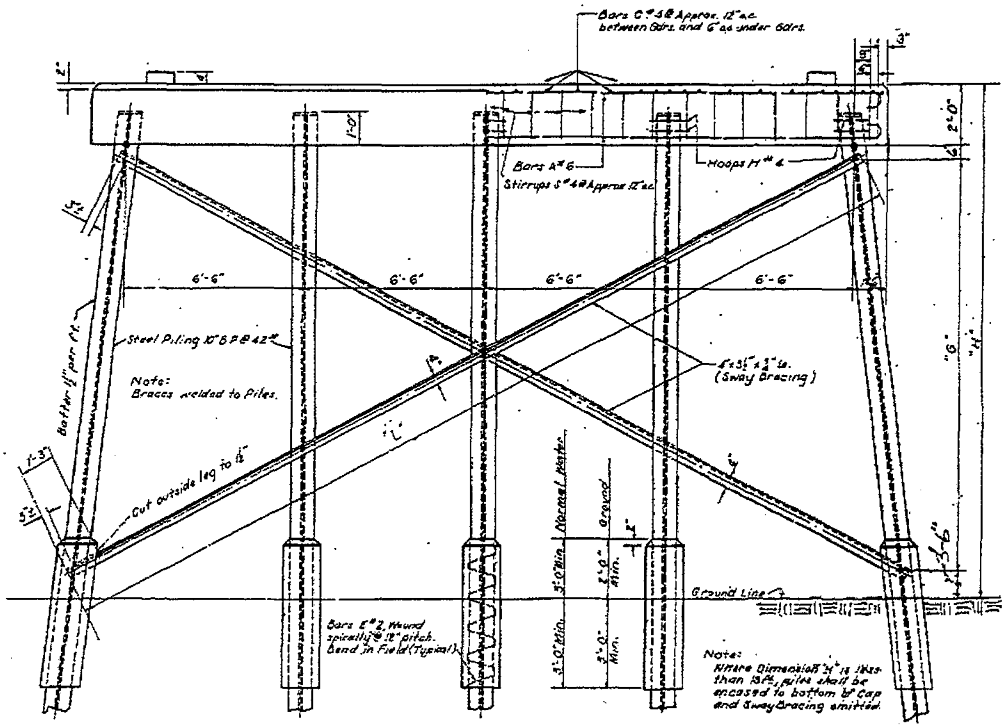
◇ WHERE PILE BENT IS LOCATED IN WATER, ENCASEMENT SHALL EXTEND 3'-0" MIN. ABOVE NORMAL WATER LINE AS DETERMINED BY ENGINEER.



PILE ENCASEMENT DETAILS

SCALE: 1/2" = 1'-0"

Figure 5.12b. Typical ALDOT X-Braced Pile Bent Geometry



SINGLE STORY BENT			
SWAYBRACING TABLES			
"H"	"G"	"D"	WT. LBS.
13'-0"	7'-0"	29'-10"	459
14'-0"	8'-0"	30'-3"	466
15'-0"	9'-0"	30'-8"	472
16'-0"	10'-0"	31'-1"	478
17'-0"	11'-0"	31'-6"	485
18'-0"	12'-0"	32'-0"	493
19'-0"	13'-0"	32'-6"	501

Figure 5.12c. Typical ALDOT Single-Story X-Braced Pile Bent Geometry

for simply supported spans where sidesway in the lower regions of the bent are possible as indicated by Mode 2 in Fig 5.12a (this is very conservative).

The levels of scour necessary to approach Mode 1 and Mode 2 (within a FS = 1.25) 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.

For Mode 1 (Nonsidesway) Buckling shown in Fig. 5.12a,

$$P_{CR1} \approx \frac{2\pi^2 EI_y}{\ell^2_{CR1}} \tag{5.3a}$$

where ℓ_{CR1} = S+"H"-1' (5.3b)

Therefore, $$\ell_{CR1} = \sqrt{\frac{2\pi^2 EI_y}{FS * P^{Pile}_{Max\ Applied}}} \tag{5.3c}$$

and $S_{CR1} = \ell_{CR1}$+1'-"H" (5.3d)

$P^{Pile}_{Max\,Applied}$ will be known for the particular bridge/bent under investigation and thus ℓ_{CR1} can be determined from Eqn(5.3c) and then S_{CR1} from Eqn(5.3d).

For Mode 2 (Sidesway) Buckling shown in Fig. 5.12a,

$$P_{CR2} \approx \frac{1}{2} x \frac{\pi^2 EI_y}{\ell^2_{CR2}} \tag{5.4a}$$

where ℓ_{CR2} = S+4' for 1-or 2-story bent if member HB1 is in place

ℓ_{CR2} = S+(4'+"E")   for 2-story bent if only member HB2 is in place (5.4b)

ℓ_{CR2} = S+"H"-1'   for 1-story bent if HB1 is not present and for 2-story bent if HB1 and HB2 are not present

Therefore, $$\ell_{CR2} = \sqrt{\frac{1}{2} x \frac{\pi^2 EI_y}{FS * P^{Pile}_{Max\ Applied}}} \quad (5.4c)$$

and $S_{CR2} = \ell_{CR2} - 4'$ for 1- or 2-story bent if member HB1 is in place

$S_{CR2} = \ell_{CR2}$ - (4'+"E")   for 2-story bent if only member HB2 is in place (5.4d)

$S_{CR2} = \ell_{CR2}$ –"H"+1'   for 1-story bent if HB1 is not present and for 2-story bent if HB1 and HB2 are not present

Again, $P^{Pile}_{Max\ Applied}$ will be known for the particular bridge/bent under investigation and thus ℓ_{CR2} can be determined from Eqn(5.4c) and then S_{CR2} from Eqn(5.4d).

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

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

then the bent is safe from buckling.

It should be noted that if both bent horizontal bracing members HB1 and HB2 are not in place, then the bent should be considered to be unbraced. If this is the case, then the bent can be checked by the procedure described above or the one described in Section 5.8.

5.8 Check for Possible Unbraced Bent Pile Buckling About Weak Axis

For the case where "H" ≤ 13 ft and the bent piles are encased from 3' below the original ground line up to the bent cap, and the bent sway-bracing is omitted, we have the situation depicted in Fig 5.13 after scour, S. This bent condition/case is permitted by the ALDOT. It should be noted that ALDOT engineers find many unbraced pile bents where "H">13 ft. The procedure in checking for P_{CR} and S_{CR} for cases where "H">13 ft. is identical to the procedure for "H" ≤ 13 ft. Hence the procedure described below is valid and applicable for any value of "H".

For the case of an HP_{10x42} pile bent and assuming the pile encasement spalls off, we have an ℓ_{Max} above ground after scour of ℓ_{Max} = "H" – 1'+S when working with the bent centerline dimensions. As can be seen in Fig. 5.13, the bent piles would fail in buckling in approximately a fixed-fixed sidesway mode. As in the case of sidesways buckling for X-braced bents, due to the partial fixity at each end of the piles, we will assume

$$P_{CR} \approx \frac{1}{2}\frac{\pi^2 EI_y}{\ell^2} \tag{5.5}$$

or

$$\ell^2_{CR} \approx \frac{\pi^2 EI_y}{2P_{CR}} \tag{5.6}$$

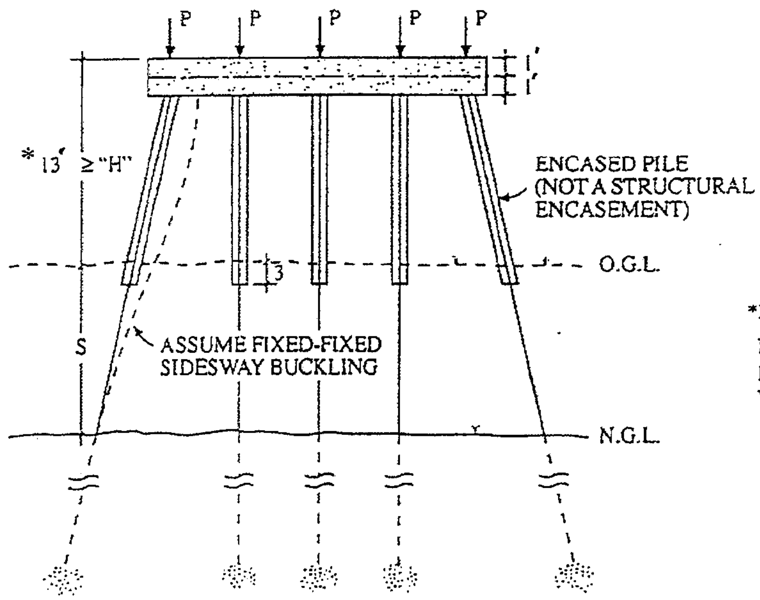


Figure 5.13. Bent with Encased Piles and No Sway-Bracing

Note that the assumption of using ½ to represent a partial fixed-fixed condition at the top and bottom of the bent piles in the equations above may, in some cases, be slightly unconservative. However, in light of the fact that we are totally neglecting the increase in pile stiffness and buckling capacity resulting from the pile partial height encasement, neglecting "lean-on" support that the most heavily loaded pile will receive from other piles in the bent, and neglecting the increase transverse stiffness of the pile bent due to the end batter piles, these should more than compensate for the factor of ½ overestimating the pile end fixity.

If we take a value of P_{CR} = 1.25 $P_{Max\ Applied}$ to have a margin of safety, then,

$$\ell_{CR}^2 \approx \frac{1}{2} \quad \frac{\pi^2 EI_y}{1.25 P_{Max\ Applied}} \qquad (5.7)$$

For the case of $P_{Max\ Applied}$ =125^k and a HP_{10x42} pile,

$$\ell_{CR} = \sqrt{\frac{\pi^2\ x\ 29,000\ x\ 71.7}{2x1.25\ x\ 125}} = 256 in. = 21.3 ft.$$

Thus,

$$S_{CR} = \ell_{CR} - \text{“H”} + 1' \qquad (5.8)$$

$$S_{CR} = 21.3 - 13' + 1' = 9.3\ \text{ft.}$$

If this value of S_{CR} is greater than $S_{Max\ Applied}$ and if the remaining pile embedment after scour is greater than 8 feet for HP_{10x42} piles and 12 feet for HP_{12x53} piles (to approximate pile fixity at the ground line), then this pile/bent without sway-bracing should be safe from buckling even if the pile encasements are loss. For bent/piles with other pile sizes and $P_{Max\ Applied}$ loadings, go to Eqn (5.7) and determine ℓ_{CR} and then to Eqn (5.8) and determine S_{CR}.

For the case of an HP12x53 pile bent, if we make the same assumptions as above, then,

$$\ell_{CR} = \sqrt{\frac{\pi^2\ x\ 29,000\ x\ 127}{2x1.25\ x\ 125}} = 341 in. = 28.4 ft.$$

and

$$S_{CR} = \ell_{CR} - \text{“H”} + 1'$$

$$S_{CR} = 28.4 - 13' + 1' = 16.4\ \text{ft.}$$

Again, if this value of S_{CR} is greater than $S_{Max\ Predicted}$ and if the remaining pile embedment after scour is greater than 12 feet (to approximate pile fixity at the ground line), then this pile/bent without sway-bracing should be safe from buckling even if the pile encasements are loss.

For the cases of the HP_{10x42} and HP_{12x53} pile bents above, we assumed the largest allowable value for the bent height “H” for an unbraced bent. Thus using the maximum value of “H” will provide somewhat conservative values for S_{CR} for bents with “H” < 13 ft.

We may generalize the analysis shown above and say,

$$\ell_{CR} = \sqrt{\frac{\pi^2 EI_y}{2\,x\,F.S.\,x\,P_{\text{max applied}}}} \tag{5.9}$$

and

$$S_{CR} = \ell_{CR} + 1' - "H" \tag{5.10}$$

For $P_{\text{max applied}}$ values of 60, 80, 100, 120, 140, and 160 kips and a F.S.=1.25, Eqn. (5.9) and (5.10) yield the values of ℓ_{CR} and S_{CR} shown in Table 5.3 for HP_{10x42} and HP_{12x53} bent piles. For various values of H, the S_{CR} data in Table 5.3 is plotted versus H for P-loads of 60, 80, 100, 120, 140, and 160 kips in Fig. 5.14. It should be noted that the S_{CR} vs. “H” curves and equations shown in Fig. 5.14 may be extended beyond “H”=13 ft. and still be valid.

Table 5.3. Values of ℓ_{CR} and S_{CR} for Non X-Braced Bents (with F.S.=1.25)

$P_{max\ applied}$ (kips)	ℓ_{CR} (ft)		S_{CR} (ft)	
	HP_{10x42}	HP_{12x53}	HP_{10x42}	HP_{12x53}
60	30.82	41.02	31.82-"H"	42.02-"H"
80	26.69	35.53	27.69-"H"	36.53-"H"
100	23.88	31.78	24.88-"H"	32.78-"H"
120	21.80	29.00	22.80-"H"	30.00-"H"
140	20.18	26.86	21.18-"H"	27.86-"H"
160	18.88	25.12	19.88-"H"	26.12-"H"

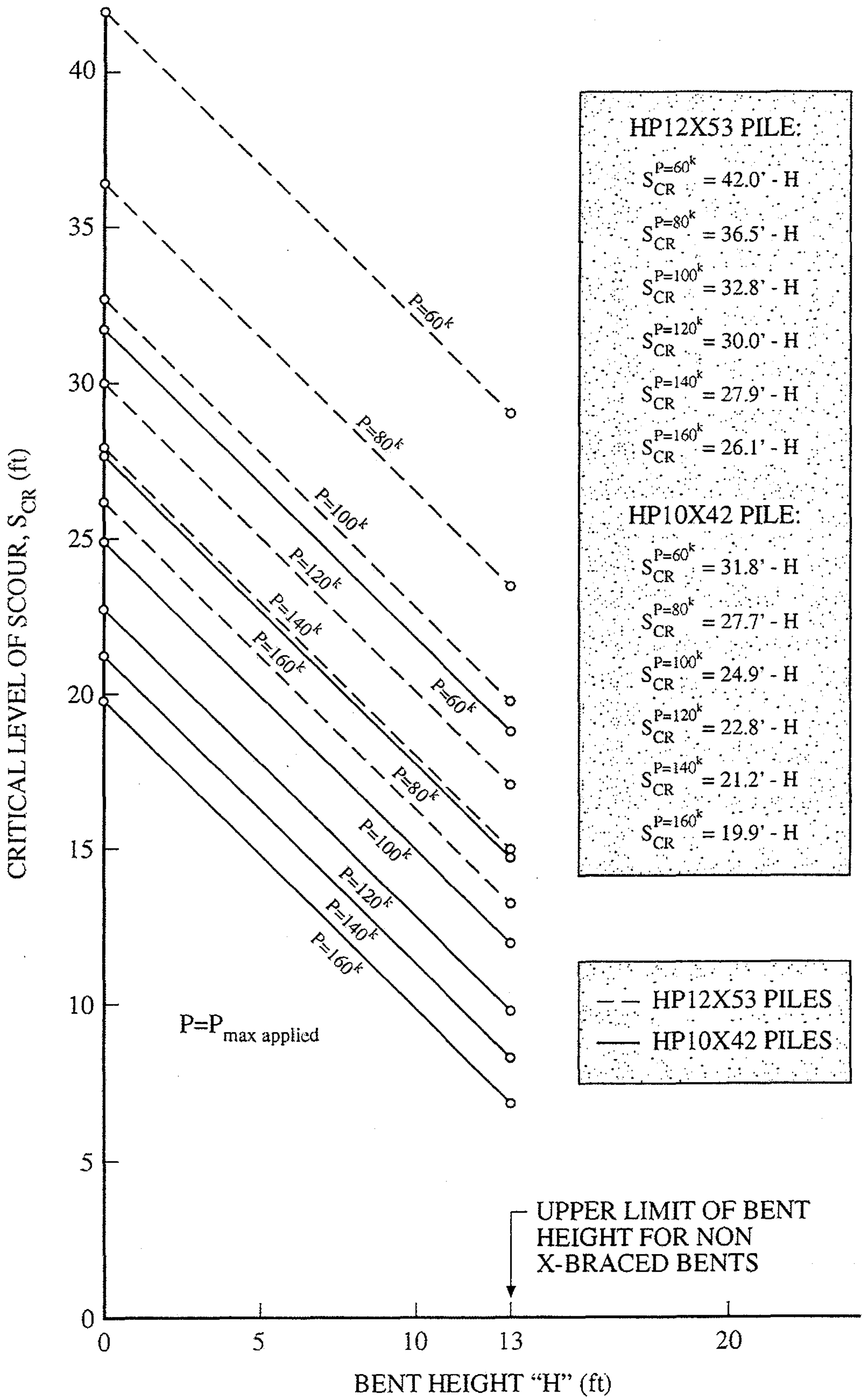


Figure 5.14. S_{CR} vs. "H" for Non X-Braced Pile Bents with F.S.=1.25

Values of "H" for typical unbraced bridge bent will be less than or equal to 13 ft, but the $P_{max\ applied}$ load and/or the factor of safety, *F.S.*, may not be the values used above. If this is the case, one must use Eqns (5.9) and (5.10) to determine S_{CR} for non X-braced pile bents.

5.9 Check for Possible Bent Pushover Failure

To check for a possible pile bent pushover failure from a combined bent gravity loads of P_{DL+LL} acting on the bent cap above each pile, and a lateral (lateral to the bridge or in the plane of the bent) flood water loading applied near the top of the bent, nonlinear analyses (considering geometric and material nonlinearity) of the bent were performed using the pushover analysis subprogram in GTSTRUDL. This subprogram basically models the pile bent as shown in Fig 5.15a and works with F_t as fixed and increments the P-loads until failure, or works with the P-loads as fixed and increments the F_t load until failure. We worked with the latter loading variation. The program modifies the bent stiffness matrix after each load increment, via working with the deformed geometry and member stress-strain relation, and thus E values, for each load increment. In this manner the bent load-lateral deflection curve, i.e., pushover curve, is generated as is the bent F_t pushover load for a given bent and P-load level. A nonlinear bent pushover curve is shown in Fig 5.15b, and typical GTSTRUDL bent pushover curves are shown in Fig. 5.16. In this manner, the bent pushover or failure load is generated be it a strength or lack of strength issue, or an elastic or inelastic bent buckling issue.

Bent pushover loads, $F_t^{Pushover}$, for various bent sizes and number and size of piling, heights, levels of P-load, levels of scour, and with and without X-bracing are given in tabular form in Tables 5.4-5.9. The pushover loads, F_t^{cap}, shown in these tables were determined from the bent pushover curves shown in Appendices A and B of reference (1).

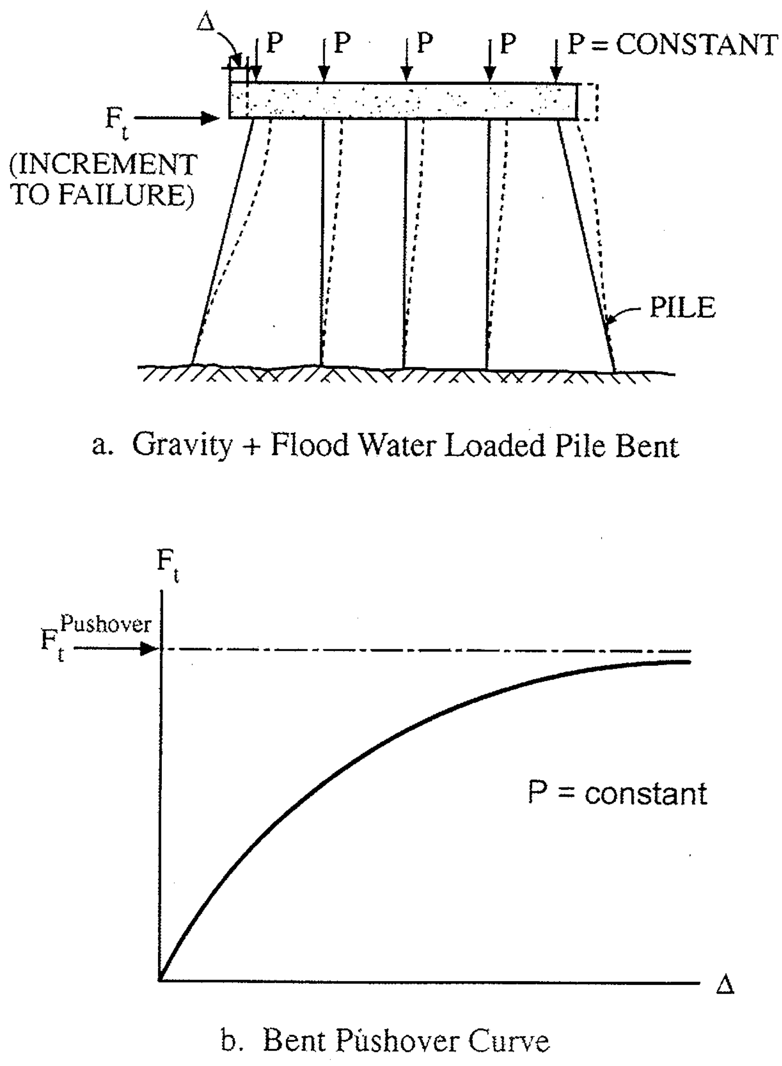


Figure 5.15. Typical Nonlinear Pile Bent Pushover Curve

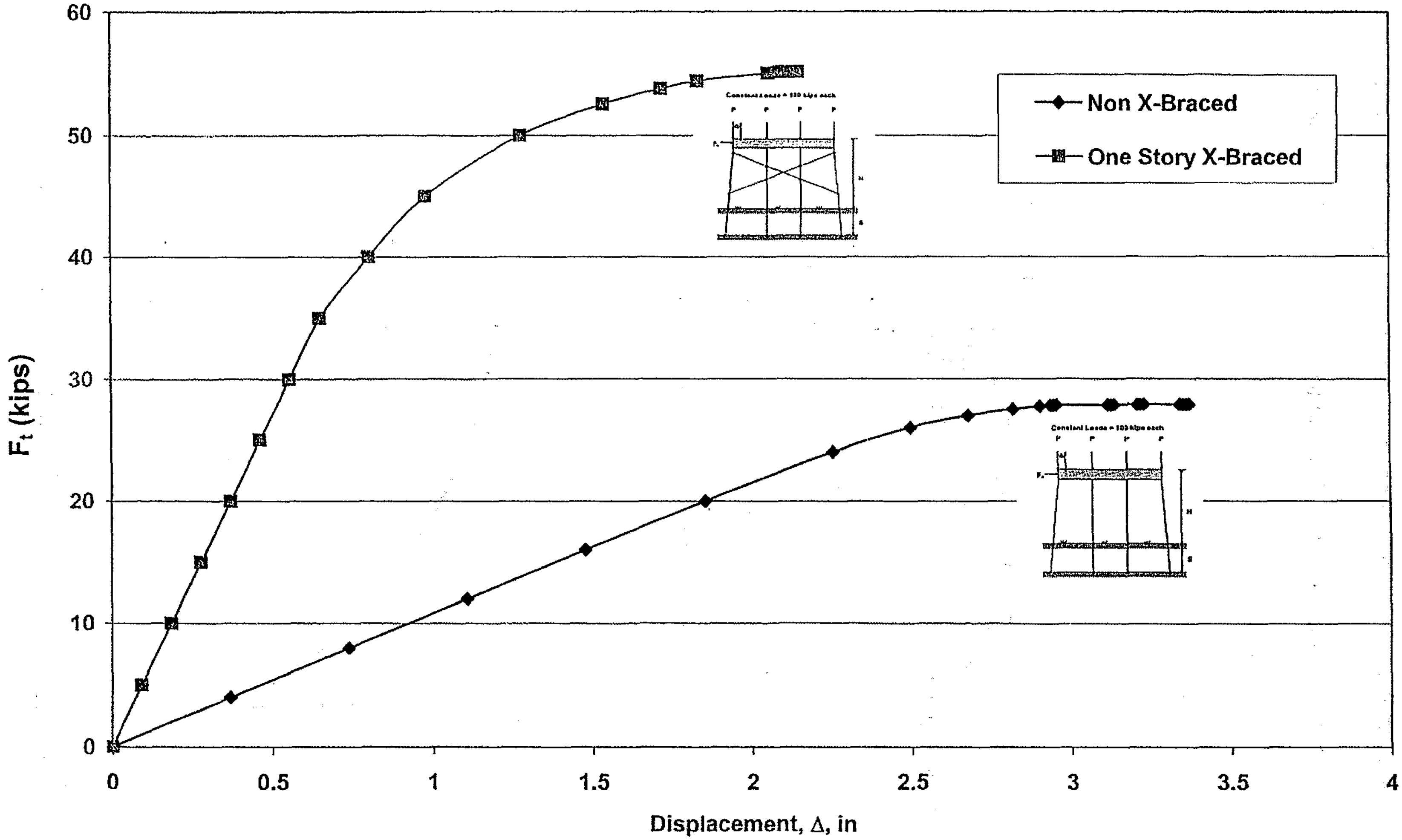


Figure 5.16. GTSTRUDL Pushover Analysis for HP_{10x42} 4-Pile Bents, Bents Pinned at Ground, H=13 ft, S=0 ft, $P=100^k$

The pushover load, $F_t^{Pushover}$, for the applicable level of bent gravity loads P, can thus be determined and compared with $F_t^{Max\,Applied}$. If

$$F_t^{Pushover} > 1.25 F_t^{Max\,Applied}$$

then the bent is assumed to be safe from a pushover failure.

Bent pushover loads, $F_t^{Pushover}$, for various bent sizes and number of piling, heights, levels of P-load, levels of scour, and with and without X-bracing are given in Appendices A (for HP_{10x42}) and B (for HP_{12x53} piles) of reference (1) in the form of $F_t vs\, \Delta$ pushover curves.

Bent pushover capacities, $F_t^{cap.}$, were determined from the F_t vs. Δ pushover curves in Appendices A and B of reference (1), and these are presented in Tables 5.4-5.9. Table 5.7 summarizes the pushover capacities of HP_{10x42} pile bents without X-bracing for 3, 4, 5, and 6-pile bents where the pushover load, F_t, is assumed to be applied at the bottom of the pile cap, and the pile concrete encasement is neglected. Table 5.5 summarizes the pushover capacities of HP_{10x42} pile bents with X-bracing for 3, 4, 5-pile bents with X-bracing where the pushover load, F_t, is assumed to be applied at the bottom of the pile cap. Table 5.6 summarizes the pushover capacities of HP_{10x42} pile bents with X-bracing for 6-pile bents of varying configurations where the pushover load, F_t, is assumed to be applied at the bottom of the pile cap. Tables 5.7-5.9 are sister tables to those above for bents with HP_{12x53} piles.

Table 5.4 Pushover Capacities of HP_{10x42} 3, 4, 5, 6-Pile Bents without X-Bracing

No. of Piles in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips)			
			P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	10	0	21.23	19.96	18.77	17.59
		5	10.48	8.90	7.27	5.64
		10	4.40	2.29	unstable	unstable
		15	unstable	unstable	unstable	unstable
		20	unstable	unstable	unstable	unstable
	13	0	13.79	12.41	10.99	9.52
		5	6.59	4.69	2.78	unstable
		10	1.49	unstable	unstable	unstable
		15	unstable	unstable	unstable	unstable
		20	unstable	unstable	unstable	unstable
4	10	0	37.28	34.78	32.29	29.90
		5	27.78	24.75	21.76	18.93
		10	25.75	21.97	18.48	15.11
		15	18.26	14.82	11.56	8.39
		20	12.13	9.00	6.25	3.75
	13	0	30.23	27.50	24.81	22.00
		5	25.98	22.67	19.27	15.97
		10	21.66	17.79	14.31	10.93
		15	14.42	11.13	8.00	5.25
		20	9.25	6.50	4.13	2.50
5	10	0	45.58	42.28	39.23	36.26
		5	36.06	31.73	27.82	24.09
		10	36.63	31.34	26.33	21.64
		15	27.69	22.91	18.13	13.81
		20	19.31	15.00	11.25	7.75
	13	0	38.07	34.05	30.66	27.28
		5	34.99	30.67	26.28	21.87
		10	32.39	26.91	21.91	16.95
		15	22.43	17.77	13.58	9.75
		20	15.50	12.00	8.38	5.50
6	10	0	50.42	47.03	43.53	40.26
		5	37.32	32.73	28.47	24.30
		10	36.92	30.48	24.86	19.00
		15	29.48	23.28	17.38	12.00
		20	20.63	15.50	10.63	6.50
	13	0	40.13	36.16	32.41	28.55
		5	35.83	30.59	25.61	20.68
		10	34.02	26.86	20.74	14.89
		15	23.63	18.00	13.00	8.27
		20	16.50	12.00	8.00	4.50

Table 5.5 Pushover Capacities of HP_{10x42} 3, 4, 5, 6-Pile Bents with X-Bracing

No. of Piles in Bent	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_u (kips) P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	ONE-STORY	13	0	43.03	41.46	39.71	38.33
			5	15.96	14.41	12.81	11.17
			10	6.88	4.02	2.81	unstable
			15	1.15	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
		17	0	41.50	39.85	38.32	36.75
			5	14.40	12.55	10.64	8.71
			10	5.25	2.94	0.77	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
	TWO-STORY	21	0	46.92	45.09	43.37	42.02
			5	16.90	15.11	13.24	11.34
			10	6.69	4.28	2.01	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
		25	0	45.22	43.55	41.94	40.17
			5	15.07	12.91	10.66	8.38
			10	4.76	2.12	unstable	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
4	ONE-STORY	13	0	54.49	51.18	48.24	45.27
			5	27.82	24.73	21.96	19.31
			10	20.77	17.32	14.03	10.89
			15	17.22	13.14	9.40	5.79
			20	11.19	8.00	5.00	1.75
		17	0	48.85	45.49	42.59	40.22
			5	24.73	21.36	18.27	15.45
			10	18.04	14.28	10.71	7.38
			15	13.97	9.74	5.78	2.14
			20	8.50	5.00	2.13	unstable
	TWO-STORY	21	0	54.41	51.01	47.94	45.06
			5	25.19	22.04	19.35	16.72
			10	16.57	13.04	9.60	6.32
			15	12.03	7.89	3.92	unstable
			20	7.36	3.50	unstable	unstable
		25	0	49.08	46.07	43.57	41.20
			5	22.06	18.67	15.66	12.67
			10	13.75	9.90	6.28	2.80
			15	9.20	4.83	unstable	unstable
			20	5.00	1.38	unstable	unstable
5	ONE-STORY	13	0	63.59	59.53	55.73	52.02
			5	34.76	30.67	26.92	23.23
			10	28.58	23.79	19.31	15.16
			15	27.86	22.02	16.49	11.55
			20	20.42	15.25	10.53	6.32
		17	0	57.10	52.62	48.67	44.99
			5	30.88	26.62	22.50	18.67
			10	25.94	20.69	15.87	11.50
			15	24.11	18.13	12.61	7.59
			20	16.97	11.86	7.34	3.50
	TWO-STORY	21	0	62.95	58.58	54.57	50.79
			5	31.98	27.82	23.95	20.34
			10	23.95	19.11	14.56	10.38
			15	21.60	15.48	10.03	5.09
			20	16.25	10.63	5.52	1.50
		25	0	56.38	51.83	47.98	44.58
			5	27.89	23.48	19.40	15.68
			10	20.93	15.71	10.89	6.47
			15	18.22	12.05	6.59	1.56
			20	13.07	7.50	3.03	unstable

Table 5.6 Pushover Capacities of HP10x42 6-Pile Bents with X-Bracing

No. of Piles in Bent	Configuration	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{Lat} (kips)			
					P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
6	SINGLE X PER STORY	ONE-STORY	13	0	69.18	64.39	59.91	55.48
				5	37.31	32.41	27.82	23.46
				10	29.82	24.12	18.85	13.88
				15	29.87	22.57	15.69	9.74
				20	22.75	16.44	10.59	5.35
			17	0	61.94	56.71	52.01	47.90
				5	33.17	28.10	23.34	18.93
				10	26.92	20.76	15.07	9.95
				15	26.19	18.62	11.87	5.91
				20	19.59	13.14	7.42	2.75
		TWO-STORY	21	0	68.25	62.61	57.57	53.01
				5	35.06	30.02	25.33	20.91
				10	26.35	20.35	14.91	9.87
				15	24.10	16.38	9.70	3.88
				20	18.72	11.84	5.50	1.00
			25	0	60.98	55.59	50.89	46.79
				5	30.65	25.51	20.76	16.52
				10	23.03	16.71	10.94	5.72
				15	20.46	12.71	6.14	0.63
				20	15.56	8.64	3.00	unstable
6	DOUBLE X PER STORY	ONE-STORY	13	0	84.56	80.16	75.99	72.47
				5	39.30	34.54	30.33	26.54
				10	31.02	25.37	20.31	15.73
				15	30.09	23.40	17.11	11.19
				20	23.16	16.84	11.13	6.29
			17	0	76.84	72.97	69.48	65.45
				5	35.08	30.21	26.00	22.08
				10	28.28	22.22	17.05	12.23
				15	27.32	20.31	13.85	7.81
				20	20.06	14.07	8.75	4.34
		TWO-STORY	21	0	85.81	81.43	77.51	74.11
				5	38.56	33.74	29.68	25.92
				10	29.29	23.54	18.57	13.84
				15	27.04	20.40	14.15	8.33
				20	21.38	14.75	9.00	3.92
			25	0	79.14	75.50	71.93	67.84
				5	34.50	29.82	25.60	21.68
				10	26.48	20.47	15.39	10.53
				15	24.53	17.65	11.36	5.45
				20	18.50	12.25	6.77	2.25

Table 5.7 Pushover Capacities of HP_{12x53} 3, 4, 5, 6-Pile Bents without X-Bracing

No. of Piles in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t (kips)			
			P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	10	0	35.35	34.23	33.10	31.95
		5	20.24	18.89	17.62	16.31
		10	12.85	11.24	9.56	7.84
		15	7.92	5.81	3.59	1.36
		20	3.86	1.14	unstable	unstable
	13	0	24.78	23.52	22.23	21.07
		5	15.34	13.89	12.38	10.85
		10	9.74	7.83	5.86	3.82
		15	5.43	2.94	unstable	unstable
		20	1.56	unstable	unstable	unstable
4	10	0	57.01	54.44	52.29	50.05
		5	41.80	38.72	36.16	33.67
		10	36.89	34.04	31.00	27.84
		15	35.30	31.38	28.13	24.40
		20	27.23	23.43	19.89	16.54
	13	0	45.45	42.84	40.48	38.09
		5	38.44	35.28	32.42	29.56
		10	36.68	33.13	29.61	26.33
		15	30.09	26.90	23.05	19.53
		20	22.68	19.25	16.00	12.75
5	10	0	68.10	65.20	62.57	60.13
		5	52.83	48.10	44.12	41.02
		10	52.27	46.06	42.19	35.77
		15	51.47	45.35	40.80	35.36
		20	40.59	34.88	30.14	25.36
	13	0	55.95	52.30	49.00	46.03
		5	51.57	47.82	40.88	37.04
		10	50.29	45.31	40.43	36.04
		15	44.25	39.60	34.16	29.22
		20	34.13	29.44	24.88	20.38
6	10	0	77.11	73.98	71.02	68.09
		5	55.36	51.06	47.33	43.80
		10	53.81	49.13	44.38	35.75
		15	52.63	46.88	40.30	32.70
		20	43.41	36.61	30.56	24.80
	13	0	61.00	57.10	53.73	50.47
		5	52.21	46.56	41.99	37.94
		10	51.92	45.33	40.30	34.61
		15	46.00	39.81	33.03	28.01
		20	36.81	30.94	25.00	20.00

Table 5.8 Pushover Capacities of HP_{12x53} 3, 4, 5, 6-Pile Bents with X-Bracing

No. of Piles in Bent	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips)			
				P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	ONE-STORY	13	0	66.93	64.82	63.09	61.36
			5	28.52	26.87	25.17	23.79
			10	16.20	14.52	12.84	11.11
			15	9.57	7.46	5.30	3.14
			20	4.70	2.09	unstable	unstable
		17	0	63.36	61.31	59.24	57.15
			5	26.81	25.09	23.54	21.95
			10	14.90	13.00	11.06	9.06
			15	8.20	5.82	3.41	1.11
			20	3.29	unstable	unstable	unstable
	TWO-STORY	21	0	71.00	68.92	66.90	64.84
			5	30.58	28.71	26.97	25.44
			10	17.03	15.08	13.09	11.05
			15	9.48	7.01	4.49	2.05
			20	3.92	unstable	unstable	unstable
		25	0	68.33	66.25	64.13	61.98
			5	28.69	26.85	25.07	23.26
			10	15.44	13.22	10.95	8.60
			15	7.87	5.09	2.36	unstable
			20	2.28	unstable	unstable	unstable
4	ONE-STORY	13	0	83.44	79.98	76.73	73.73
			5	45.18	41.92	38.84	35.88
			10	34.37	30.96	27.76	24.68
			15	30.52	26.61	22.94	19.43
			20	26.35	22.16	18.19	14.44
		17	0	79.62	76.26	72.70	68.99
			5	41.77	38.21	34.94	31.82
			10	31.92	28.13	24.64	21.33
			15	27.78	23.50	19.68	15.94
			20	23.04	18.73	14.57	10.70
	TWO-STORY	21	0	86.73	82.73	78.89	75.22
			5	43.32	39.83	36.58	33.53
			10	30.96	27.30	23.86	20.60
			15	25.53	21.33	17.57	13.91
			20	21.21	16.66	12.51	8.51
		25	0	81.69	76.25	70.13	69.25
			5	39.71	35.90	32.52	29.48
			10	28.16	24.13	20.53	17.27
			15	22.48	18.28	14.27	10.42
			20	18.25	13.65	9.27	5.02
5	ONE-STORY	13	0	95.82	91.16	87.16	83.47
			5	55.78	51.51	47.38	43.49
			10	44.72	40.17	35.78	31.50
			15	42.92	37.72	32.51	27.64
			20	41.66	35.98	30.07	24.56
		17	0	88.89	83.21	78.97	74.95
			5	51.77	47.04	42.73	38.70
			10	41.73	36.74	32.11	27.80
			15	40.98	34.97	29.26	24.11
			20	37.73	31.70	25.78	20.11
	TWO-STORY	21	0	100.17	94.50	89.16	83.95
			5	53.94	49.25	44.74	40.68
			10	41.53	36.56	31.93	27.51
			15	38.01	32.16	26.77	21.75
			20	36.01	29.28	23.06	17.33
		25	0	93.06	85.77	80.02	74.43
			5	49.56	44.67	40.11	35.99
			10	37.88	32.68	27.87	23.43
			15	35.51	29.09	23.13	17.92
			20	32.38	25.51	19.20	13.55

Table 5.9 Pushover Capacities of HP12x53 6-Pile Bents with X-Bracing

No. of Piles in Bent	X-Bracing Configuration	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_L (kips)			
					P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
6	SINGLE X PER STORY	ONE-STORY	13	0	104.26	98.79	94.02	89.67
				5	60.94	55.79	50.93	46.20
				10	48.07	42.29	37.06	31.96
				15	45.77	39.21	32.97	27.13
				20	45.21	38.94	31.41	24.33
			17	0	95.11	89.40	84.28	79.72
				5	55.85	50.31	45.23	40.62
				10	44.97	38.87	33.34	28.11
				15	43.48	36.47	29.59	23.48
				20	42.75	35.20	27.31	20.19
		TWO-STORY	21	0	109.13	101.77	94.52	87.84
				5	60.29	54.22	48.58	43.48
				10	46.12	39.84	34.11	28.83
				15	42.47	35.19	28.53	22.37
				20	41.28	32.80	24.88	17.63
			25	0	96.43	89.77	83.63	78.27
				5	54.41	48.46	43.00	38.13
				10	42.09	35.69	29.82	24.52
				15	39.43	31.45	24.44	18.15
				20	37.48	28.71	20.65	13.70
6	DOUBLE X PER STORY	ONE-STORY	13	0	130.28	125.62	121.72	118.11
				5	63.77	59.11	54.78	50.51
				10	49.00	43.59	38.59	33.81
				15	46.83	40.10	34.15	28.67
				20	46.44	39.36	32.40	25.79
			17	0	126.39	121.45	116.72	112.06
				5	59.51	54.09	49.36	45.18
				10	47.24	40.89	35.11	29.95
				15	44.78	37.49	31.17	25.44
				20	43.89	36.38	29.33	22.61
		TWO-STORY	21	0	134.38	128.97	123.95	119.63
				5	64.41	59.68	55.17	50.93
				10	48.54	43.00	37.85	33.07
				15	44.98	38.10	32.23	26.90
				20	43.80	36.12	29.13	22.63
			25	0	130.44	124.92	119.66	114.98
				5	60.07	54.60	50.13	46.09
				10	46.52	39.98	34.41	29.67
				15	42.83	35.72	29.56	23.99
				20	41.44	33.70	26.63	19.91

Assuming that the flood water debris raft dimensions and design flood water velocity values previously assumed to computer $F_{t\ max\ applied}$ are valid, i.e.,

$A = 6'$

$B = 30'$

$V_{design} = 6\ mph$

Then, $F_{t\ max\ applied} = 9.72\ kips$

Assuming a *F.S. = 1.25 (Factor of Safety),* then

$F_{t\ max\ design} = 9.72\ kips \times 1.25 = 12.15\ kips$

Using this value of $F_{t\ max\ design}$, Tables 5.4-5.9 can be modified to reflect whether a bent is safe for combined flood water pushover loads, gravity loads, and level of scour. The modified tables are shown as Tables 5.10-5.15, where for a given bent size (number of piles and height), level of scour, and level of gravity P-load, one can directly determine if the bent is adequate for the projected maximum design pushover load of $F_{t\ max\ design} = 12.15\ kips$ shown above. In the modified tables, if the bent size, level of scour, and level of P-load provides a pushover capacity in the unshaded regions of the tables, then the bent is adequate or safe. If the pushover capacity is in the shaded regions, then the bent may be inadequate for safety against pushover and should be investigated more closely.

One can note in Tables 5.13-5.15, which are for the HP_{12x53} pile bents, that all of the 6 and 5-pile bents are adequate/safe for pushover loading, and almost all of the 4-pile bents are adequate/safe. For the HP_{12x53} pile bents, only the 3-pile bents are of significant concern for adequacy for pushover capacity.

Table 5.10 Pushover Capacities of HP_{10x42} 3, 4, 5, 6-Pile Bents without X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No. of Piles in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips)			
			P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	10	0	21.23	19.96	18.77	17.59
		5	10.48	8.90	7.27	5.64
		10	4.40	2.29	unstable	unstable
		15	unstable	unstable	unstable	unstable
		20	unstable	unstable	unstable	unstable
	13	0	13.79	12.41	10.99	9.52
		5	6.59	4.69	2.78	unstable
		10	1.49	unstable	unstable	unstable
		15	unstable	unstable	unstable	unstable
		20	unstable	unstable	unstable	unstable
4	10	0	37.28	34.78	32.29	29.90
		5	27.78	24.75	21.76	18.93
		10	25.75	21.97	18.48	15.11
		15	18.26	14.82	11.56	8.39
		20	12.13	9.00	6.25	3.75
	13	0	30.23	27.50	24.81	22.00
		5	25.98	22.67	19.27	15.97
		10	21.66	17.79	14.31	10.93
		15	14.42	11.13	8.00	5.25
		20	9.25	6.50	4.13	2.50
5	10	0	45.58	42.28	39.23	36.26
		5	36.06	31.73	27.82	24.09
		10	36.63	31.34	26.33	21.64
		15	27.69	22.91	18.13	13.81
		20	19.31	15.00	11.25	7.75
	13	0	38.07	34.05	30.66	27.28
		5	34.99	30.67	26.28	21.87
		10	32.39	26.91	21.91	16.95
		15	22.43	17.77	13.58	9.75
		20	15.50	12.00	8.38	5.50
6	10	0	50.42	47.03	43.53	40.26
		5	37.32	32.73	28.47	24.30
		10	36.92	30.48	24.86	19.00
		15	29.48	23.28	17.38	12.00
		20	20.63	15.50	10.63	6.50
	13	0	40.13	36.16	32.41	28.55
		5	35.83	30.59	25.61	20.68
		10	34.02	26.86	20.74	14.89
		15	23.63	18.00	13.00	8.27
		20	16.50	12.00	8.00	4.50

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

Table 5.11 Pushover Capacities of HP_{10x42} 3, 4, 5-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No. of Piles in Bent	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips)			
				P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	ONE-STORY	13	0	43.03	41.46	39.71	38.33
			5	15.96	14.41	12.81	11.17
			10	6.88	4.02	2.81	unstable
			15	1.15	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
		17	0	41.50	39.85	38.32	36.75
			5	14.40	12.55	10.64	8.71
			10	5.25	2.94	0.77	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
	TWO-STORY	21	0	46.92	45.09	43.37	42.02
			5	16.90	15.11	13.24	11.34
			10	6.69	4.28	2.01	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
		25	0	45.22	43.55	41.94	40.17
			5	15.07	12.91	10.66	8.38
			10	4.76	2.12	unstable	unstable
			15	unstable	unstable	unstable	unstable
			20	unstable	unstable	unstable	unstable
4	ONE-STORY	13	0	54.49	51.18	48.24	45.27
			5	27.82	24.73	21.96	19.31
			10	20.77	17.32	14.03	10.89
			15	17.22	13.14	9.40	5.79
			20	11.19	8.00	5.00	1.75
		17	0	48.85	45.49	42.59	40.22
			5	24.73	21.36	18.27	15.45
			10	18.04	14.28	10.71	7.38
			15	13.97	9.74	5.78	2.14
			20	8.50	5.00	2.13	unstable
	TWO-STORY	21	0	54.41	51.01	47.94	45.06
			5	25.19	22.04	19.35	16.72
			10	16.57	13.04	9.60	6.32
			15	12.03	7.89	3.92	unstable
			20	7.36	3.50	unstable	unstable
		25	0	49.08	46.07	43.57	41.20
			5	22.06	18.67	15.66	12.67
			10	13.75	9.90	6.28	2.80
			15	9.20	4.83	unstable	unstable
			20	5.00	1.38	unstable	unstable
5	ONE-STORY	13	0	63.59	59.53	55.73	52.02
			5	34.76	30.67	26.92	23.23
			10	28.58	23.79	19.31	15.16
			15	27.86	22.02	16.49	11.55
			20	20.42	15.25	10.53	6.32
		17	0	57.10	52.62	48.67	44.99
			5	30.88	26.62	22.50	18.67
			10	25.94	20.69	15.87	11.50
			15	24.11	18.13	12.61	7.59
			20	16.97	11.86	7.34	3.50
	TWO-STORY	21	0	62.95	58.58	54.57	50.79
			5	31.98	27.82	23.95	20.34
			10	23.95	19.11	14.56	10.38
			15	21.60	15.48	10.03	5.09
			20	16.25	10.63	5.52	1.50
		25	0	56.38	51.83	47.98	44.58
			5	27.89	23.48	19.40	15.68
			10	20.93	15.71	10.89	6.47
			15	18.22	12.05	6.59	1.56
			20	13.07	7.50	3.03	unstable

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

Table 5.12 Pushover Capacities of HP10x42 6-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No. of Piles in Bent	Configuration	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, $F_t^{cap.}$ (kips) P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
6	SINGLE X PER STORY	ONE-STORY	13	0	69.18	64.39	59.91	55.48
				5	37.31	32.41	27.82	23.46
				10	29.82	24.12	18.85	13.88
				15	29.87	22.57	15.69	9.74
				20	22.75	16.44	10.59	5.35
			17	0	61.94	56.71	52.01	47.90
				5	33.17	28.10	23.34	18.93
				10	26.92	20.76	15.07	9.95
				15	26.19	18.62	11.87	5.91
				20	19.59	13.14	7.42	2.75
		TWO-STORY	21	0	68.25	62.61	57.57	53.01
				5	35.06	30.02	25.33	20.91
				10	26.35	20.35	14.91	9.87
				15	24.10	16.38	9.70	3.88
				20	18.72	11.84	5.50	1.00
			25	0	60.98	55.59	50.89	46.79
				5	30.65	25.51	20.76	16.52
				10	23.03	16.71	10.94	5.72
				15	20.46	12.71	6.14	0.63
				20	15.56	8.64	3.00	unstable
6	DOUBLE X PER STORY	ONE-STORY	13	0	84.56	80.16	75.99	72.47
				5	39.30	34.54	30.33	26.54
				10	31.02	25.37	20.31	15.73
				15	30.09	23.40	17.11	11.19
				20	23.16	16.84	11.13	6.29
			17	0	76.84	72.97	69.48	65.45
				5	35.08	30.21	26.00	22.08
				10	28.28	22.22	17.05	12.23
				15	27.32	20.31	13.85	7.81
				20	20.06	14.07	8.75	4.34
		TWO-STORY	21	0	85.81	81.43	77.51	74.11
				5	38.56	33.74	29.68	25.92
				10	29.29	23.54	18.57	13.84
				15	27.04	20.40	14.15	8.33
				20	21.38	14.75	9.00	3.92
			25	0	79.14	75.50	71.93	67.84
				5	34.50	29.82	25.60	21.68
				10	26.48	20.47	15.39	10.53
				15	24.53	17.65	11.36	5.45
				20	18.50	12.25	6.77	2.25

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

Table 5.13 Pushover Capacities of HP_{12x53} 3, 4, 5, 6-Pile Bents without X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No. of Piles in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips) *			
			P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	10	0	35.35	34.23	33.10	31.95
		5	20.24	18.89	17.62	16.31
		10	12.85	11.24	9.56	7.84
		15	7.92	5.81	3.59	1.36
		20	3.86	1.14	unstable	unstable
	13	0	24.78	23.52	22.23	21.07
		5	15.34	13.89	12.38	10.85
		10	9.74	7.83	5.86	3.82
		15	5.43	2.94	unstable	unstable
		20	1.56	unstable	unstable	unstable
4	10	0	57.01	54.44	52.29	50.05
		5	41.80	38.72	36.16	33.67
		10	36.89	34.04	31.00	27.84
		15	35.30	31.38	28.13	24.40
		20	27.23	23.43	19.89	16.54
	13	0	45.45	42.84	40.48	38.09
		5	38.44	35.28	32.42	29.56
		10	36.68	33.13	29.61	26.33
		15	30.09	26.90	23.05	19.53
		20	22.68	19.25	16.00	12.75
5	10	0	68.10	65.20	62.57	60.13
		5	52.83	48.10	44.12	41.02
		10	52.27	46.06	42.19	35.77
		15	51.47	45.35	40.80	35.36
		20	40.59	34.88	30.14	25.36
	13	0	55.95	52.30	49.00	46.03
		5	51.57	47.82	40.88	37.04
		10	50.29	45.31	40.43	36.04
		15	44.25	39.60	34.16	29.22
		20	34.13	29.44	24.88	20.38
6	10	0	77.11	73.98	71.02	68.09
		5	55.36	51.06	47.33	43.80
		10	53.81	49.13	44.38	35.75
		15	52.63	46.88	40.30	32.70
		20	43.41	36.61	30.56	24.80
	13	0	61.00	57.10	53.73	50.47
		5	52.21	46.56	41.99	37.94
		10	51.92	45.33	40.30	34.61
		15	46.00	39.81	33.03	28.01
		20	36.81	30.94	25.00	20.00

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

Table 5.14 Pushover Capacities of HP_{12x53} 3, 4, 5-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No of Piles in Bent	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, $F_t^{cap.}$ (kips)			
				P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
3	ONE-STORY	13	0	66.93	64.82	63.09	61.36
			5	28.52	26.87	25.17	23.79
			10	16.20	14.52	12.84	11.11
			15	9.57	7.46	5.30	3.14
			20	4.70	2.09	unstable	unstable
		17	0	63.36	61.31	59.24	57.15
			5	26.81	25.09	23.54	21.95
			10	14.90	13.00	11.06	9.06
			15	8.20	5.82	3.41	1.11
			20	3.29	unstable	unstable	unstable
	TWO-STORY	21	0	71.00	68.92	66.90	64.84
			5	30.58	28.71	26.97	25.44
			10	17.03	15.08	13.09	11.05
			15	9.48	7.01	4.49	2.05
			20	3.92	unstable	unstable	unstable
		25	0	68.33	66.25	64.13	61.98
			5	28.69	26.85	25.07	23.26
			10	15.44	13.22	10.95	8.60
			15	7.87	5.09	2.36	unstable
			20	2.28	unstable	unstable	unstable
4	ONE-STORY	13	0	83.44	79.98	76.73	73.73
			5	45.18	41.92	38.84	35.88
			10	34.37	30.96	27.76	24.68
			15	30.52	26.61	22.94	19.43
			20	26.35	22.16	18.19	14.44
		17	0	79.62	76.26	72.70	68.99
			5	41.77	38.21	34.94	31.82
			10	31.92	28.13	24.64	21.33
			15	27.78	23.50	19.68	15.94
			20	23.04	18.73	14.57	10.70
	TWO-STORY	21	0	86.73	82.73	78.89	75.22
			5	43.32	39.83	36.58	33.53
			10	30.96	27.30	23.86	20.60
			15	25.53	21.33	17.57	13.91
			20	21.21	16.66	12.51	8.51
		25	0	81.69	76.25	70.13	69.25
			5	39.71	35.90	32.52	29.48
			10	28.16	24.13	20.53	17.27
			15	22.48	18.28	14.27	10.42
			20	18.25	13.65	9.27	5.02
5	ONE-STORY	13	0	95.82	91.16	87.16	83.47
			5	55.78	51.51	47.38	43.49
			10	44.72	40.17	35.78	31.50
			15	42.92	37.72	32.51	27.64
			20	41.66	35.98	30.07	24.56
		17	0	88.89	83.21	78.97	74.95
			5	51.77	47.04	42.73	38.70
			10	41.73	36.74	32.11	27.80
			15	40.98	34.97	29.26	24.11
			20	37.73	31.70	25.78	20.11
	TWO-STORY	21	0	100.17	94.50	89.16	83.95
			5	53.94	49.25	44.74	40.68
			10	41.53	36.56	31.93	27.51
			15	38.01	32.16	26.77	21.75
			20	36.01	29.28	23.06	17.33
		25	0	93.06	85.77	80.02	74.43
			5	49.56	44.67	40.11	35.99
			10	37.88	32.68	27.87	23.43
			15	35.51	29.09	23.13	17.92
			20	32.38	25.51	19.20	13.55

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

Table 5.15 Pushover Capacities of HP_{12x53} 6-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{t\ max\ design}$ = 12.15 kips *

No. of Piles in Bent	X-Bracing Configuration	No. of Stories in Bent	Bent Height, H (ft)	Scour, S (ft)	Pushover Force, F_t^{cap} (kips)			
					P = 100 kips	P = 120 kips	P = 140 kips	P = 160 kips
6	SINGLE X PER STORY	ONE-STORY	13	0	104.26	98.79	94.02	89.67
				5	60.94	55.79	50.93	46.20
				10	48.07	42.29	37.06	31.96
				15	45.77	39.21	32.97	27.13
				20	45.21	38.94	31.41	24.33
			17	0	95.11	89.40	84.28	79.72
				5	55.85	50.31	45.23	40.62
				10	44.97	38.87	33.34	28.11
				15	43.48	36.47	29.59	23.48
				20	42.75	35.20	27.31	20.19
		TWO-STORY	21	0	109.13	101.77	94.52	87.84
				5	60.29	54.22	48.58	43.48
				10	46.12	39.84	34.11	28.83
				15	42.47	35.19	28.53	22.37
				20	41.28	32.80	24.88	17.63
			25	0	96.43	89.77	83.63	78.27
				5	54.41	48.46	43.00	38.13
				10	42.09	35.69	29.82	24.52
				15	39.43	31.45	24.44	18.15
				20	37.48	28.71	20.65	13.70
6	DOUBLE X PER STORY	ONE-STORY	13	0	130.28	125.62	121.72	118.11
				5	63.77	59.11	54.78	50.51
				10	49.00	43.59	38.59	33.81
				15	46.83	40.10	34.15	28.67
				20	46.44	39.36	32.40	25.79
			17	0	126.39	121.45	116.72	112.06
				5	59.51	54.09	49.36	45.18
				10	47.24	40.89	35.11	29.95
				15	44.78	37.49	31.17	25.44
				20	43.89	36.38	29.33	22.61
		TWO-STORY	21	0	134.38	128.97	123.95	119.63
				5	64.41	59.68	55.17	50.93
				10	48.54	43.00	37.85	33.07
				15	44.98	38.10	32.23	26.90
				20	43.80	36.12	29.13	22.63
			25	0	130.44	124.92	119.66	114.98
				5	60.07	54.60	50.13	46.09
				10	46.52	39.98	34.41	29.67
				15	42.83	35.72	29.56	23.99
				20	41.44	33.70	26.63	19.91

* Bents with a pushover capacity, $F_t^{cap.}$, in unshaded region of table are safe.

* Bents with a pushover capacity, $F_t^{cap.}$, in shaded region of table may be unsafe.

It should be noted that for the smaller bents, primarily the 3-pile bents, the P-load level on the bent may be below P=100^k. For this case, we can use linear extrapolation to check the pushover adequacy of these bents as indicated below.

Pushover capacities of the 3-pile bents with and without X-bracing for both the HP_{10x42} and HP_{12x53} piles shown in Tables 5.4-5.5 and 5.7-5.8, respectively, are shown plotted for the P-load levels of P=100, 120, 140, and 160 kips in Figures 5.15-5.18. As can be seen in these figures, the pushover capacities, $F_t^{capacity}$, vary in a linear manner with the P-load for almost all cases. For the few cases with a nonlinear variation, the $F_t^{capacity}$ vs. P-load curve is concave up with $F_t^{capacity}$ increasing at a larger than linear rate as the P-load is reduced. Thus, for the 3-pile bent, linear extrapolation may be used to check whether the $F_t^{capacity}$ for P-load levels smaller than 100^k is larger than the $F_t^{max\,design}$ value of 12.15^k. If it is, then the bent is safe from pushover failure.

Linear extrapolation may also be used for bents with more than 3-piles, though this will probably not be necessary. In all cases, if extrapolation to determine $F_t^{capacity}$ at a P-load level lower than 100^k is used, then simply use the slope of a $F_t^{capacity}$ vs. P-load curve between P=100^k and P=120^k to extrapolate to $F_t^{capacity}$ value at the lower level of P-load. If numerical values of $F_t^{capacity}$ are not available in Tables 5.10-5.15 due to the bent being unstable, then extrapolation can not be performed and the safety of the bent should be investigated more closely.

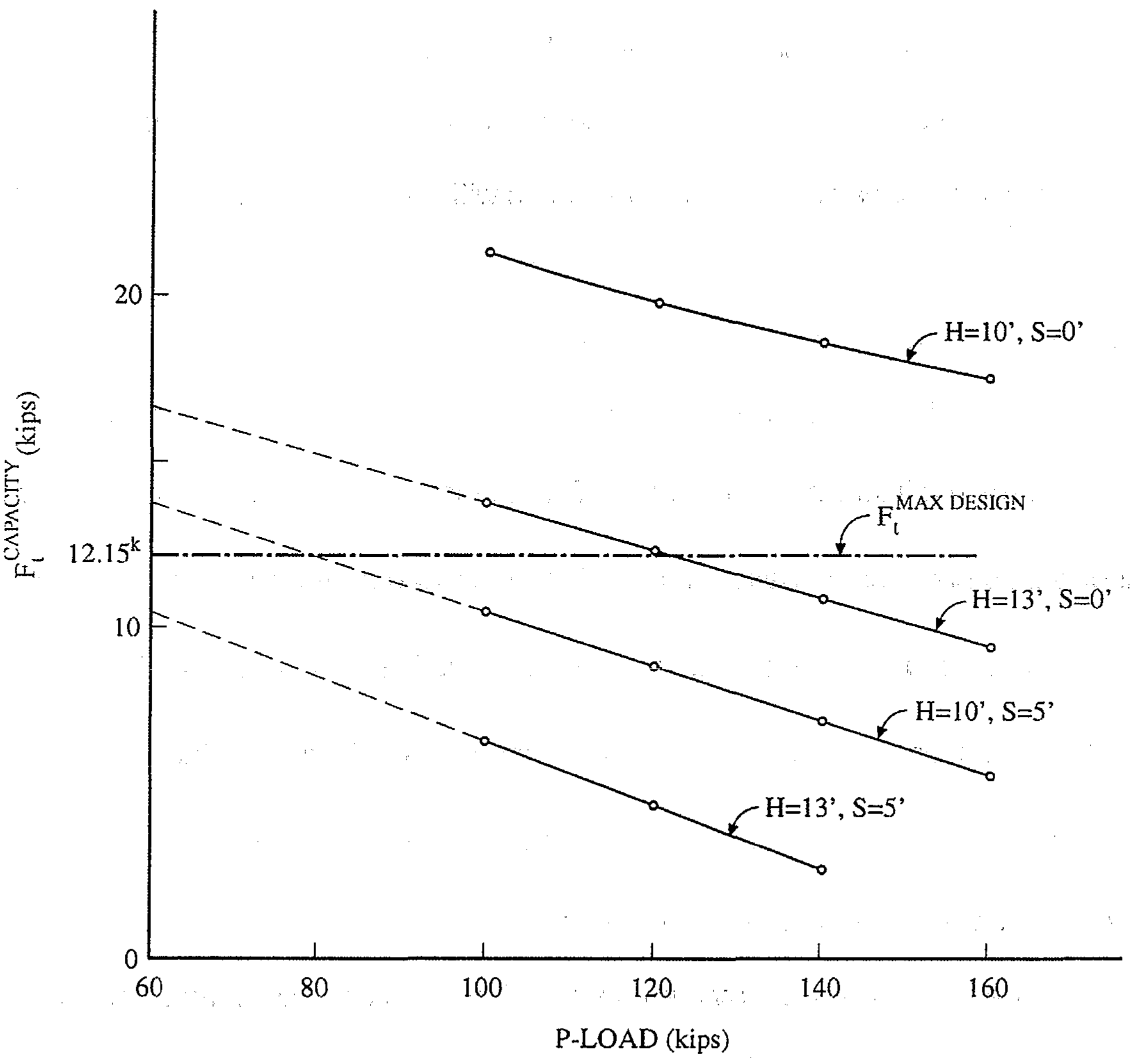


Figure 5.15. $F_t^{capacity}$ vs. P-Load Curves for 3-Pile Bents of HP_{10x42} Piles without X-Bracing.

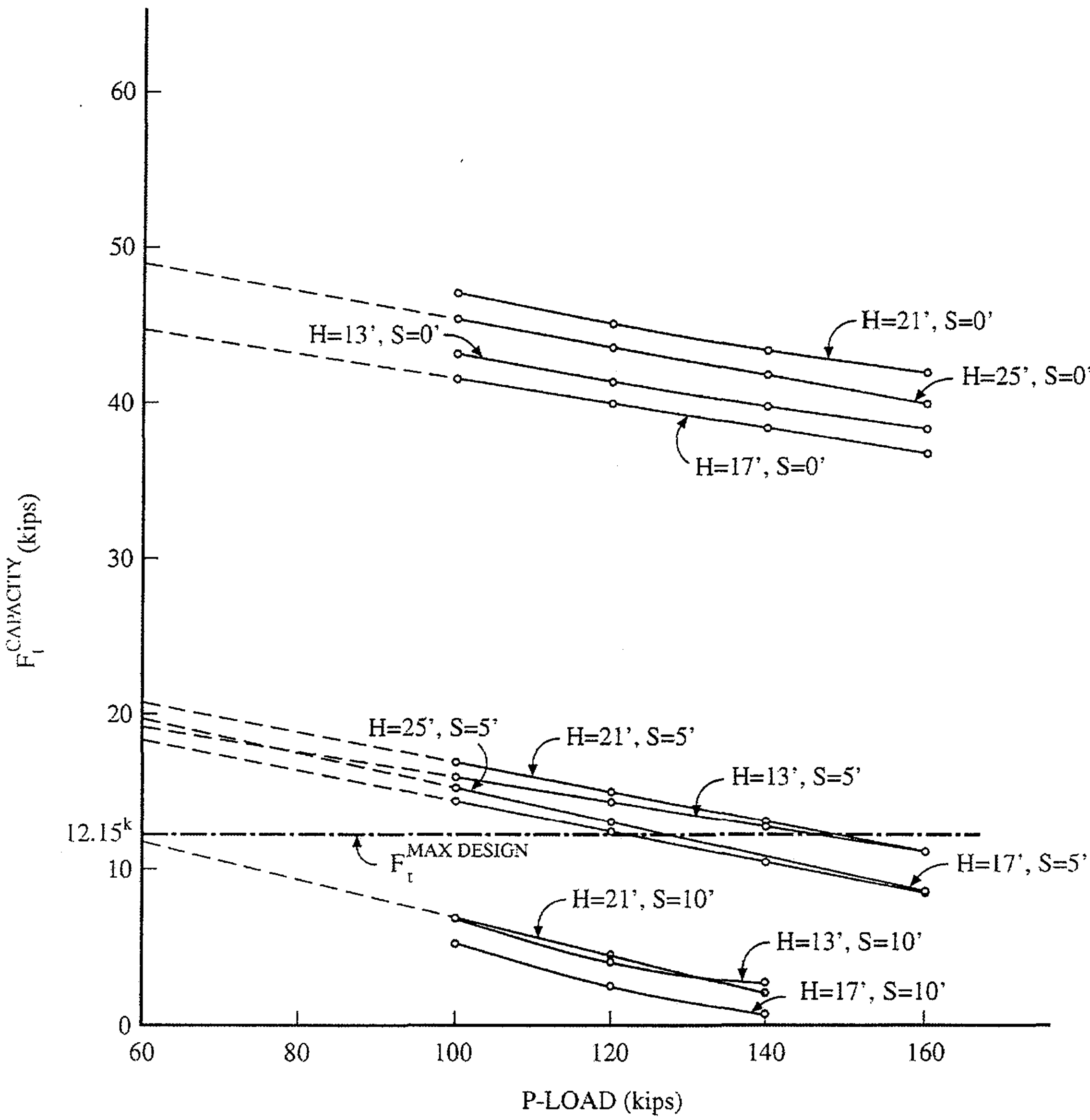


Figure 5.16. $F_t^{capacity}$ vs. P-Load Curves for 3-Pile Bents of HP_{10x42} Piles with X-Bracing.

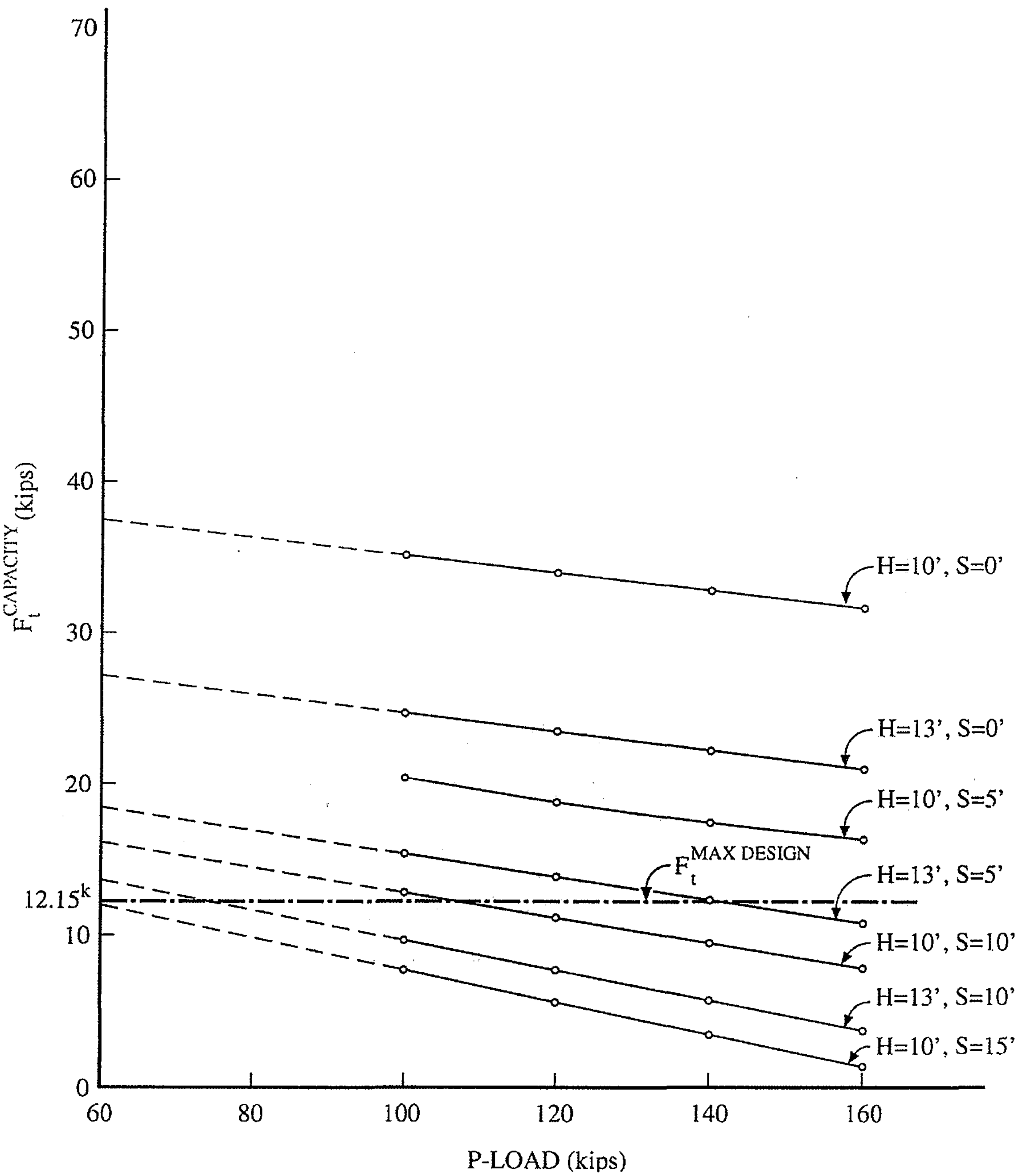


Figure 5.17. $F_t^{capacity}$ vs. P-Load Curves for 3-Pile Bents of HP_{12x53} Piles without X-Bracing.

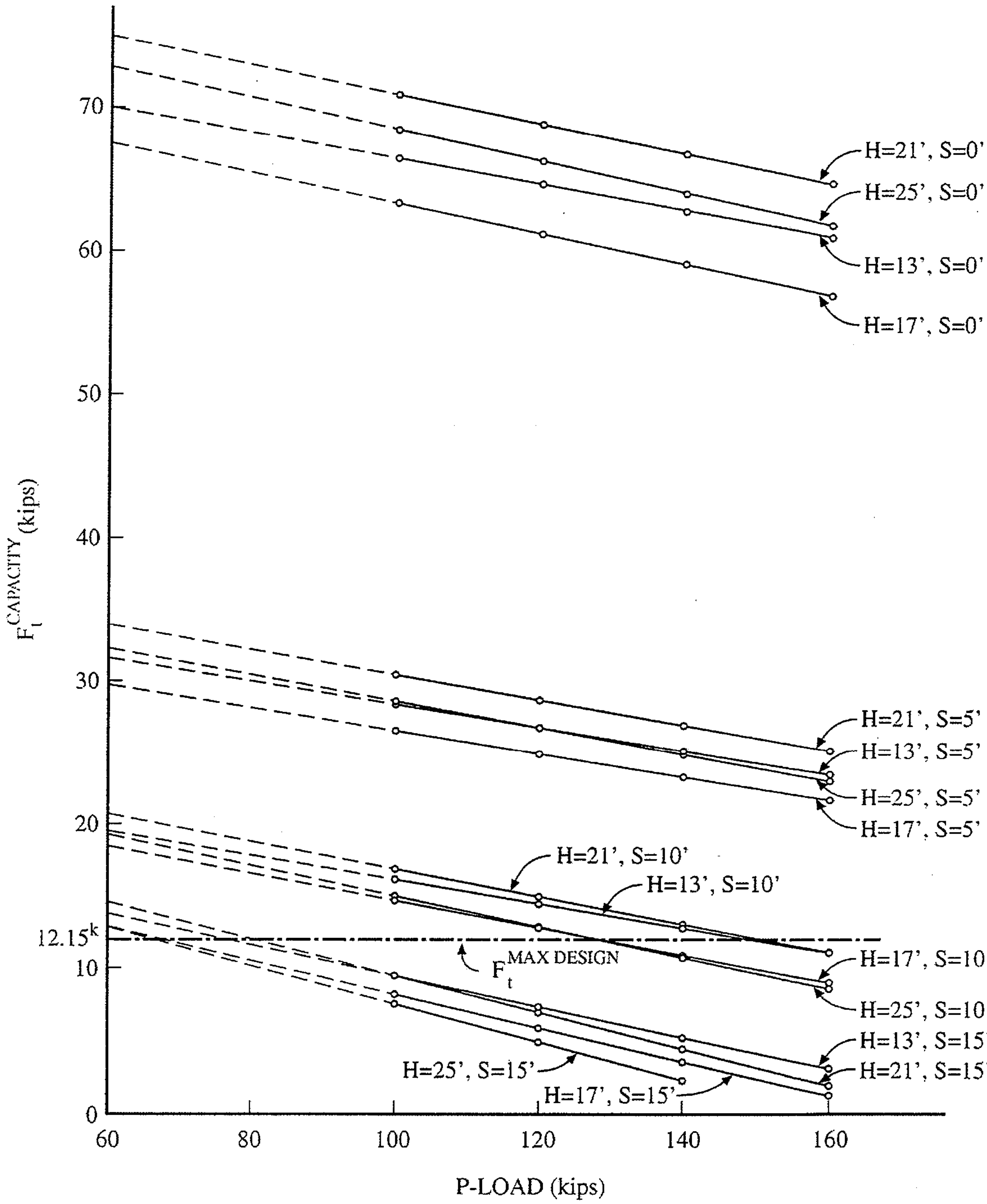


Figure 5.18. $F_t^{capacity}$ **vs. P-Load Curves for 3-Pile Bents of HP_{12x53} Piles with X-Bracing.**

Alternatively, if we assume that we may perform linear interpolation on the $F_t^{capacity}$ vs. S (or H+S) data in Tables 5.10-5.15, we can use these data to generate tables of critical scour, S_{CR}, for different levels of P-loads. These tables can in turn be used to determine S_{CR} for a given bent geometry and level of P-load. If the resulting $S_{CR}>S_{max\ applied}$ at the site, then the bent is safe from pushover failure.

Since the piles in a bent subject to an increasing horizontal flood water loading, F_t, have an approximate constant level of P-load, i.e., gravity axial load, there is a linear relationship between F_t and lateral deflection, Δ, so long as the pile stresses do not exceed the proportional limit. However, as scour occurs and as the piles reach higher stress levels, the piles and bent will behave in a nonlinear manner, i.e., we get the nonlinear pushover curve due to both geometric and material nonlinearity. In this case, the F_t vs. Δ curve may be closer to a cubic variation in Δ with the bent height (H+S). For this situation, the use of linear interpolation of F_t values between values of F_t determined for bent height (H+S) values which are 5 ft apart yields sufficiently accurate results as illustrated in Fig. 5.19. Thus, Tables 5.10-5.15 were used to interpolate values of S_{CR} corresponding to $F_t^{failure} = 12.15^k$ for each bent geometry configuration, height, and level of P-load. These values of S_{CR} are presented in Tables 5.16-5.19.

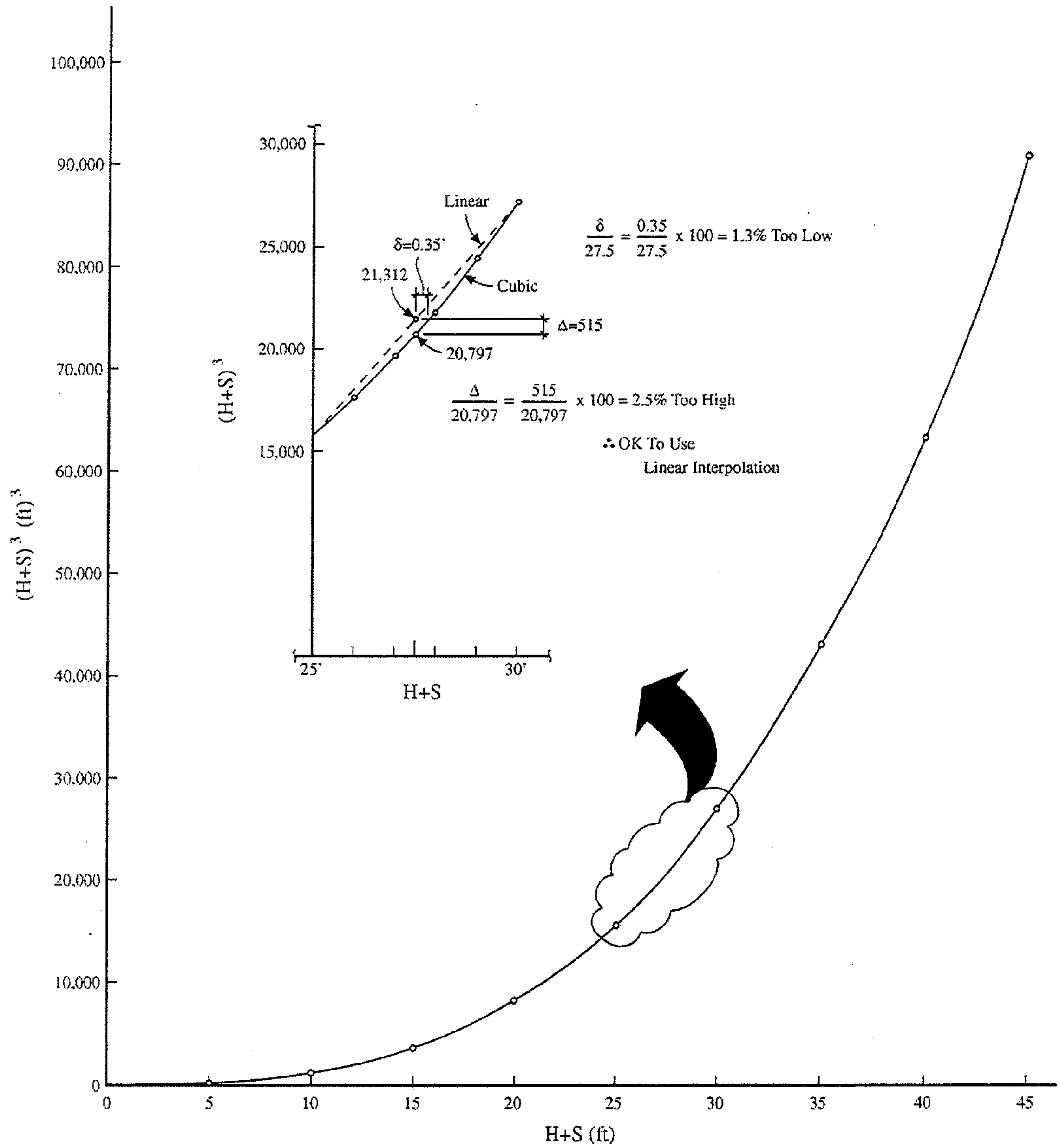


Figure 5.19. Illustration of Satisfactory Accuracy in Using Linear Interpolation to Determine S_{CR} from $F_t^{Capacity}$ vs. S Data in Tables 2.10-2.15

Table 5.16. Critical Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design}=12.15^k$ (includes a FS=1.25)

No. of Piles in Bent	Bent Height (ft)	Critical Scour, S_{CR} (ft)[1,2]			
		$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	4.2	3.5	2.9	2.3
	13	1.1	0.2	unstable	unstable
4	10	20.0	17.3	14.6	12.2
	13	17.2	14.2	11.7	8.8
5	10	>20.0	>20.0	19.3	16.4
	13	>20.0	19.9	16.4	13.3
6	10	>20.0	>20.0	18.9	14.9
	13	>20.0	19.9	15.8	12.1

[1] Includes a FS=1.25 on the Pushover Force, F_t.

[2] If $S_{max\,applied}<S_{CR}$ at the site, the bent is safe from pushover failure.

Table 5.17. Critical Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\ max\ design}$ =12.15^k (includes a FS=1.25)

No. of Piles in Bent	X-Bracing Configuration	No. of Stories in Bent	Bent Height (ft)	Critical Scour, S_{CR} (ft)[3,4]			
				P=100^k	P=120^k	P=140^k	P=160^k
3	Single-X per Story	1-Story	13	7.1	6.1	5.3	4.8
			17	6.2	5.2	4.7	4.4
		2-Story	21	7.3	6.4	5.5	4.9
			25	6.4	5.3	4.8	4.4
4	Single-X per Story	1-Story	13	19.2	16.0	12.0	9.2
			17	16.7	12.3	9.0	7.0
		2-Story	21	14.9	10.9	8.7	7.2
			25	11.8	8.7	6.9	5.3
5	Single-X per Story	1-Story	13	>20.0	>20.0	18.6	14.2
			17	>20.0	19.8	15.4	9.5
		2-Story	21	>20.0	18.4	12.7	9.1
			25	>20.0	14.9	9.3	6.9
6	Single-X per Story	1-Story	13	>20.0	>20.0	18.5	12.1
			17	>20.0	>20.0	14.6	8.8
		2-Story	21	>20.0	19.7	12.6	9.0
			25	>20.0	15.7	9.4	7.0
6	Double-X per Story	1-Story	13	>20.0	>20.0	19.1	13.9
			17	>20.0	>20.0	16.7	10.1
		2-Story	21	>20.0	>20.0	16.9	11.5
			25	>20.0	>20.0	14.0	9.3

[3] Includes a FS=1.25 on the Pushover Force, F_t.

[4] If $S_{max\ applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

Table 5.18. Critical Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design}$=12.15[k] (includes a FS=1.25)

No. of Piles in Bent	Bent Height (ft)	Critical Scour, S_{CR} (ft)[5,6]			
		P=100[k]	P=120[k]	P=140[k]	P=160[k]
3	10	10.7	9.4	8.4	7.5
	13	7.8	6.4	5.2	4.4
4	10	>20.0	>20.0	>20.0	>20.0
	13	>20.0	>20.0	>20.0	>20.0
5	10	>20.0	>20.0	>20.0	>20.0
	13	>20.0	>20.0	>20.0	>20.0
6	10	>20.0	>20.0	>20.0	>20.0
	13	>20.0	>20.0	>20.0	>20.0

[5] Includes a FS=1.25 on the Pushover Force, F_t.
6 If Smax applied<SCR at the site, the bent is safe from pushover failure.

Table 5.19. Critical Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\ max\ design}$ =12.15^k (includes a FS=1.25)

No. of Piles in Bent	X-Bracing Configuration	No. of Stories in Bent	Bent Height (ft)	Critical Scour, S_{CR} (ft)[7,8]			
				P=100^k	P=120^k	P=140^k	P=160^k
3	Single-X per Story	1-Story	13	13.0	11.7	10.5	9.6
			17	12.0	10.6	9.6	8.8
		2-Story	21	13.2	11.8	10.5	9.6
			25	12.2	10.7	9.6	8.8
4	Single-X per Story	1-Story	13	>20.0	>20.0	>20.0	>20.0
			17	>20.0	>20.0	>20.0	18.6
		2-Story	21	>20.0	>20.0	>20.0	16.6
			25	>20.0	>20.0	17.1	13.7
5	Single-X per Story	1-Story	13	>20.0	>20.0	>20.0	>20.0
			17	>20.0	>20.0	>20.0	>20.0
		2-Story	21	>20.0	>20.0	>20.0	>20.0
			25	>20.0	>20.0	>20.0	>20.0
6	Single-X per Story	1-Story	13	>20.0	>20.0	>20.0	>20.0
			17	>20.0	>20.0	>20.0	>20.0
		2-Story	21	>20.0	>20.0	>20.0	>20.0
			25	>20.0	>20.0	>20.0	>20.0
6	Double-X per Story	1-Story	13	>20.0	>20.0	>20.0	>20.0
			17	>20.0	>20.0	>20.0	>20.0
		2-Story	21	>20.0	>20.0	>20.0	>20.0
			25	>20.0	>20.0	>20.0	>20.0

[7] Includes a FS=1.25 on the Pushover Force, F_t.

[8] If $S_{max\ applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

5.10 Summary

The screening of bridge pile bents to determine their adequacy during an extreme flood/scour event for the possible failure modes of

- Bent/pile tip "kick-out" failure
- Pile/bent plunging failure
- Pile/bent transverse-buckling failure
- Bent transverse pushover failure

have been discussed and the checking/screening procedures described in detail in Section 5.1-5.9. The final recommended checking/screening procedure and sequence is summarized below.

Preliminary Evaluations. Prior to performing quantitative screening evaluations, the preliminary evaluations listed below need to be performed.

1. Verify that bridge is over water and supported on pile bents.
2. Verify that significant scour (S > 3 ft) may occur at the site.
3. Verify that the pile bent is a single row of steel H-piles with 3, 4, 5 or 6-piles of HP_{10x42} or HP_{12x53} with the end-piles battered.
4. Determine if bent is sway-braced or not braced.
5. If the bent is sway-braced, determine if bracing members HB1 and HB2 are present.
6. Determine bent height, H, above the original ground line.
7. Determine the maximum projected scour, S, at the site.
8. Determine the length of pile embedment before scour (ℓ_{bs}) and after scour (ℓ_{as}).

9. Determine the driving system used to install the piling, i.e., determine the type of hammer used, its rated energy, and its driving efficiency.

10. Determine the final pile driving resistance in blows per inch (bpi).

11. Determine if the pile is an end bearing or friction pile.

12. Determine the following maximum pile/bent loads,

- $P^{pile}_{max\,applied}$ (gravity DL+LL)
- $P^{bent}_{max\,applied}$ (gravity DL+LL)
- $P_{applied} = P^{bent}_{max\,applied} / No.\ of\ Piles$ (in bent pushover analysis)
- Note a value of $F^{t}_{max\,applied} = 9.72^{k}$ push-over load was determined based on assumed maximum size of debris raft and stream V_{design}. This value was multiplied by a FS = 1.25 to yield

$$F^{t}_{max\,design} = 1.25\ F^{t}_{max\,applied}$$

$$= 1.25x9.72^{k} = 12.15^{k}$$

and was assumed to be applied at 2 ft down from the HWL which was assumed to be at the elevation of the top of the bent cap.

Pile/Bent "Kick-Out" and Plunging Evaluations. Screening/checking for pile/bent "kick-out" failure was integrated into the tables that assess the safe depths of pile embedment after scour for adequacy against either a "kick-out" or plunging failure of the most heavily loaded bent pile. These safe depths of embedment are given in Tables 5.3-5.6. Based on the relatively low horizontal F_{tip} "kick-out" force, the maximum safe embedment depth required to avoid "kick-out" failure was determined to be 3 ft. Therefore in Tables 5.3-5.6 if an embedment depth to avoid plunging was determined to be less than 3 ft, then 3 ft is shown in the tables to avoid a "kick-out" failure mode.

Pile plunging failure is checked/screened via using the SPT blow counts N_{tip} and N_{side} at the pile tip and side, the pile size, the depth of embedment after scour, $P^{pile}_{max\,applied}$ and Tables 5.3-5.6 in the manner described in Section 5.6. For both the plunging and "kick-out" failure modes, it is assumed that if the most heavily loaded pile in the bent is safe from failure, then the bent is safe from failure.

Pile/Bent Buckling Evaluation. In checking for pile/bent buckling, the most heavily loaded pile in the bent is checked for transverse buckling, i.e., buckling about the pile's weak axis. If this pile is safe from buckling, then we say the bent is safe from buckling. The ST buckling checking procedure is as follows:

1. Check pile for adequate embedment for approximate fixity after scour.
2. Check to see if bent has sway-bracing. If it does, are bracing members HB1 and HB2 present.
3. Determine ℓ_{CR1} and S_{CR1} for nonsidesway (Mode 1) buckling.
4. Determine ℓ_{CR2} and S_{CR2} for sidesway (Mode 2) buckling.
5. Determine S_{CR} for pile which is the smaller of S_{CR1} and S_{CR2}.
6. If $S_{CR}>S_{Max\ Applied}$ then the pile/bent is safe from buckling.
7. If the bent is not sway-braced, then only sidesway (Mode 2) buckling is checked as shown in Fig. 5.2.

The exact sequence, procedure, and equations for making the above checks are given in Box ③ of the "screening tool" flowchart in Fig. 5.2.

Bent Pushover Evaluation. Use the value of $F_{t\ max\ design}$=12.15 kips, which includes a F.S. = 1.25, along with Tables 5.10-5.15 to determine the adequacy of pile bents for safety from a pushover failure. Using Tables 5.10-5.15, one can determine for a given set of bent parameters (see below) if the bent is adequate/safe from pushover failure.

- Bent piles - HP_{10x42} or HP_{12x53}
- Number of piles - 3, 4, 5, 6-pile bent
- Bracing Configuration - Not braced, X-braced one story, X-braced two story
-
- Bent height (H) - 10', 13', 17', 21', 25'
- Level of scour (S) - 0', 5', 10', 15', 20'
- Level of gravity P-load - 100^k, 120^k, 140^k, 160^k

In Tables 5.10-5.15 if the bent size, configuration, height, pile size, level of scour, and level of P-load provide a pushover capacity in the unshaded region of the tables, then the bent is adequate/safe from pushover failure. If the pushover capacity is in the shaded region, then the bent may not be safe for pushover and should be investigated more closely.

For bents with P-load levels lower than P=100^k, linear extrapolation may be used to determine $F_t^{capacity}$ for the given level of P-load. This procedure is described in Section 5.9. If the extrapolated value of $F_t^{capacity} > F_t^{max\ design}$ of 12.15^k, then the bent is safe from pushover failure.

Alternatively, for a given pile bent configuration and height and level of P-load, one can use Tables 5.16-5.19 to determine the critical scour, S_{CR}. This value includes a FS=1.25 on the pushover load, $F_t^{Capacity}$. If $S_{CR}>S_{max\ applied}$ at the site, then the bent is safe from pushover failure.

6. IMPLEMENTATION PROCEDURE FOR THE SCREENING TOOL

6.1 General

Each of ALDOT's bridges over water and supported by pile bents may require an assessment of the adequacy of such bents in an extreme flood/scour event. Thus, ALDOT's current bridge/bent information database should be expanded to include the additional bridge parameters and information shown in Chapters 3 and 5. This expansion of ALDOT's bridge information database should be performed prior to applying the "screening tool" (ST) in order that the ST may be used more quickly and effectively in the event of the occurrence of a major flood/scour. It is expected that the bridge information listed in Chapter 3 can be used with the ST to predetermine critical depths of scour, S_{CR}, prior to the occurrence of an extreme flood/scour event. This should be investigated in follow-up research work to further refine, simplify, and improve the ST.

6.2 What to Check to Assess the Adequacy of a Bent and Bridge

The macro plan to evaluate the adequacy of ALDOT bridge pile bents for an extreme flood/scour event is shown in itemized checklist form below, and in macro flowchart form in Fig. 6.1. The checking sequence shown basically moves from general checks such as is the bent in water with scour possible and has significant corrosion of the bent pile sections occurred, to checking the bent piles for "kick-out" or plunging, to checking the bent piles for buckling, to checking the bent for pushover from combined gravity and flood water loadings.

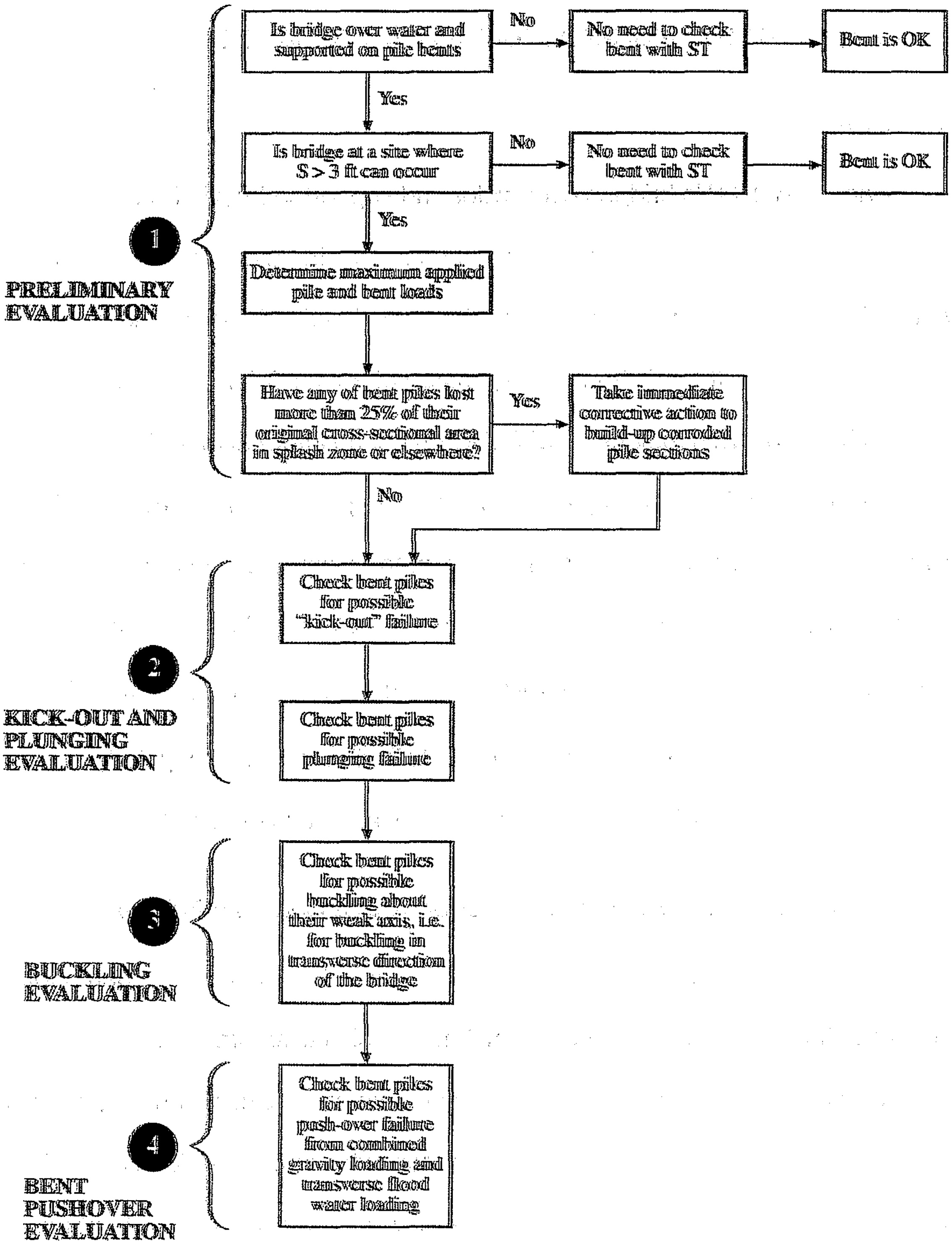


Figure 6.1. Screening Tool (ST) Macro Flowchart

1. Is the bridge over water and is it supported on pile bents?

2. Is the bridge at a site where significant scour (S > 3ft) can occur?

3. What is the size, type and spacing of bent piles, pile bent height, bent cap width and depth, and is bent sway-braced?

4. Do bent piles have considerable loss of section (25% or greater) in the splash zone or elsewhere?

5. What is the projected maximum scour at the site/bent in an extreme flood event?

6. What is the projected HWL (relative to the top of the bent cap) and the design flood water velocity (V)?

7. What is the length of pile embedment before (ℓ_{bs}) and after (ℓ_{as}) scour?

8. What is the soil description at the bent pile tips and the depth of embedment of the pile in this soil?

9. Can the bent pile tips "kick-out" due to transverse (transverse to the longitudinal axis of the bent) flood water loading and insufficient embedment after scour?

10. Can the bent piles have a plunging failure due to insufficient soil support capacity after scour?

11. Can the bent piles buckle about their weak axis, i.e., in the transverse direction of the bridge?

12. Can the bent have a push-over failure under the combination of gravity and transverse flood water loading?

Assumptions explicitly or implicitly included in checking the adequacy of bridge pile bents during an extreme flood/scour event via the "screening tool" are given in Section 5.3 in Chapter 5. In general, however, the checks required and checking sequence is as follows:

1. Preliminary checks and evaluations as indicated in Item 1 of Fig. 6.1.

2. Making the geotechnical related failure checks indicated in Item 2 of Fig. 6.1. In doing this, a typical bent pile is checked for possible "kick-out" failure due to scour and flood water lateral loading (lateral to the bent longitudinal axis). If this typical pile can fail by "kick-out," it is assumed that the bent can fail by "kick-out." Also under Item 2 of Fig. 6.1, the most heavily gravity loaded pile in the bent is checked for possible plunging failure due to insufficient soil support capacity after scour. If this pile can fail by plunging, it is assumed that the bent can fail by plunging.
3. Making the structural related failure check indicated in Item 3 of Fig. 6.1. In doing this, a girder line analysis is performed to determine the maximum gravity load on the most heavily loaded bent pile. This pile is then checked for buckling about its weak axis. If this pile can fail by buckling, it is assumed that the bent can fail by buckling about the weak axes of the bent piles.
4. Making the structural related failure check indicated in Item 4 of Fig. 6.1. In doing this, the maximum gravity load applied to the bent is determined, and it is assumed that this load is evenly distributed to the bent piles. With these gravity loads in place on the bent cap, a horizontal load is applied to the bent near its top and in the plane of the bent. This load is incrementally increased (with the gravity P-loads held constant) until a pushover failure of the bent occurs. The horizontal pushover load, F_t, so determined is compared with the maximum possible flood water loading

$F_t^{max\ applied}$ to assess the adequacy of the bent for avoiding a pushover failure.

6.3 Preparations for Using the Screening Tool

Prior to the Auburn PI's finalizing the manual version (Version 1) of the "Screening Tool" and "User's Guide," they will meet with ALDOT's Bridge Maintenance Engineer and other members of the project advisory committee to discuss draft copies of the "Screening Tool" and "Users Guide." It is anticipated that improvements and refinements to both documents will be the result of that meeting. After making these improvements/refinements, a "trial run" meeting will be set up for select ALDOT personnel to evaluate the adequacy and user friendliness of the "Screening Tool" and the "User's Guide." It is expected that further improvements and refinements will be forthcoming from this meeting. After incorporating these improvements and refinements in the "ST" and the "User's Guide," the PI's will prepare and conduct a full blown training seminar at ALDOT's office in Montgomery to train ALDOT personnel on how to use the "Screening Tool."

For ALDOT personnel unable to attend the training seminar, and for personnel joining ALDOT after the seminars, it is recommended that prior to trying to use the screening tool (ST) that they closely read and study the "Screening Tool User's Guide." This Guide describes the step-by-step procedure to employ in using the ST. It includes "Commentaries" for each step which provides background information and the "why's" and "how's" of the working of the ST. It also includes the assumptions explicitly or implicitly incorporated in the

ST. The Guide also includes the bridge/bent/site information needed as input to the ST and guidance as to the most likely location of this information. Expected output from the ST is also discussed in the Guide.

Prior to using the ST for an actual bridge evaluation, it is recommended that the user make a couple of "dry runs" on "Example Bridge Evaluations" in the Guide. These "Examples" show values of input information for the Example Bridge and the results one should get from executing the ST. Once the user is comfortable in working through one of both of the Example Bridges, he/she should be ready to move on to using the ST to evaluate the adequacy of a bridge of their choosing.

6.4 Closure

The ST discussed in this report is a dynamic tool and will be being automated, expanded in capabilities, simplified and improved upon with time. As it is, the "User's Guide" will likewise be being improved and kept current with the ST. The manual implementation procedure described in this report for Version 1 of the ST should be most helpful to users in understanding the workings of the ST when they later used automated versions of the ST.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 General

Alabama has hundreds of highway bridges that were designed and constructed prior to 1990 and therefore not designed for scour. In addition, there are hundreds of county bridges constructed using standardized designs for which scour analysis is not part of the foundation design. ALDOT is currently performing an assessment of the scour susceptibility of its bridges, and a part of this assessment requires an evaluation of the structural stability of these bridges for an estimated scour event.

A common design/construction procedure for highway bridges in Alabama is the use of steel HP piles driven to a firm stratum with a length above ground/water up to the level of a concrete bent cap which supports the bridge superstructure. The use of 3, 4, 5, or 6 such piles in a row with the two end piles battered are very common bridge pile bents. The bents are typically X-braced for lateral support; however when the height of the bents are 13 ft or less, the HP piles may be encased in concrete from the bent cap down to 3 feet below ground level (and the X-bracing eliminated).

Because of the large number of bridges in the state, and because stability analyses of each bridge bent represents a considerable effort in time and money, there is a compelling reason to develop a simple “screening tool” which can be used, along with the scour analyses, to efficiently assess the susceptibility of the bridge bents to failure during an extreme flood/scour event. Because of the tendency to use standardized designs with pile bent foundations for many of the smaller bridges in Alabama, it is feasible to pursue the development of such a screening tool. This was the impetus and purpose of this research project.

7.2 Conclusions

The objectives of Phase I of this research were to determine the feasibility of developing a “screening tool” for use in evaluating the stability and adequacy of pile bents, and thus pile bent supported bridges, in an extreme flood/scour event. Secondly, assuming that a “screening tool” was determined to be feasible, to develop a plan for creating an effective “screening tool.” The results of the Phase I investigation indicated that indeed it was feasible to develop such a tool, and a plan for developing the tool was identified. The objective of this Phase II research was to develop the “screening tool,” and a user’s guide explaining the proper use of the tool.

Based on the work conducted during Phases I and II of the research, the following conclusions have been drawn.

1. The development of a “screening tool” to assess the adequacy of pile bents and bridges during an extreme flood/scour event is an excellent idea, is quite feasible, and can be developed without great difficulty.
2. The plan to evaluate the adequacy of ALDOT bridge pile bents for an extreme flood/scour event is presented in macro flowchart form in Fig. 5.1 and in more detailed micro flowchart form in Fig. 5.2. The bent checking sequence shown in these flowcharts basically moves through the sequence below.

a. general checks such as the bridge bents being in water with scour possible,
b. checking the bent piles for possible “kick-out” or plunging failure,
c. checking the bent piles for transverse (transverse to the bridge center-line) buckling failure,
d. checking the bent for transverse (transverse to the bridge center-line) pushover failure from combined gravity and flood water loadings.

3. Since each of ALDOT’s bridges over water which are supported by pile bents will probably require an assessment of the adequacy of the bents for an extreme flood/scour event, ALDOT’s current bridge/bent information database should be expanded to include the additional information shown in Section 5.4 in Chapter 5 to allow the use of the screening tool.
4. ALDOT personnel having a need to use the “screening tool” should attend a training seminar on how to use the “screening tool.”
5. ALDOT personnel having a need to use the “screening tool” and unable to attend a training seminar, should closely read and study the “Screening Tool User’s Guide.”
6. ALDOT bridge maintenance personnel should continue to work with the research PIs to automate the screening/checking process and have a user friendly and automated final version of the “screening tool.”
7. ALDOT bridge maintenance personnel should continue to work with the research PIs to expand the capabilities of the “screening tool” with regard

to other types of piles and pile bent supports that may exist at a particular bridge water crossing.

7.3 Recommendations

Based on the research work done to date, the following recommendations are offered.

1. Since the “screening tool” described in this report is not applicable to all bridge pile bents used by ALDOT, the “screening tool” should be expanded in scope to include all, or almost all, of ALDOT’s river crossing bridge support pile bents.
2. Since the “screening tool” described in this report is not in an automated form, for reasons of increased speed and efficiency in checking and evaluating bridges, the “screening tool” as described herein should be automated via an appropriate user friendly computer program/system.
3. It is expected that the bridge information listed in Section 5.4 in Chapter 5 and currently available in ALDOT’s Bridge Information Database can be used with the “screening tool” to predetermine the critical depth of scour, S_{CR}, for a particular bridge and site prior to the occurrence of an extreme flood/scour event. This should be investigated in follow-up research work to further refine, simplify, and improve the “screening tool.”
4. For those bridge bents identified by the “screening tool” as requiring further examination to determine their safety/adequacy, a refined analysis procedure should be identified to make a final evaluation of the bent/bridges safety in an extreme flood/scour event. This refined analysis

procedure should be automated and compatible for use as a follow-up evaluation to that used in the basic “screening tool.”

8.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 understanding and using the "Screening Tool."

H	=	Bent height from top of bent cap to OGL
"E"	=	Vertical height of bent X-bracing from lowest to highest points of X-bracing for lower X-brace for two-story bents
"G"	=	Vertical height of bent X-bracing from lowest to highest points of X-bracing for single-story bents
I_y	=	Pile moment of inertia about its weak axis
HB1	=	Battened double angle bent horizontal brace at 4 ft above the OGL
HB2	=	Battened double angle bent horizontal brace at 4'+"E" above the OGL for two-story bents
$P_{girder\ max}$	=	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_y	=	Pile yield strength ($P_y = \sigma_y A$)

P_{cr}	=	Pile elastic buckling load, i.e, $P_{cr} = \frac{\text{constant } \pi^2 EI_y}{\ell^2}$ where the constant depends on the pile bracing and boundary conditions.
ℓ_{CR}	=	Pile unbraced length needed to have an elastic buckling failure, i.e., $\ell_{CR} = \sqrt{\frac{\text{constant } \pi^2 EI_y}{P_{\text{max applied}}}}$ 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 material (assumed to be E=29,000 ksi in this report)
F.S.	=	Factor of Safety
LL	=	Live load
DL	=	Dead load
HWL	=	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 "kickout" force and possible failure
V_{design}	=	Design flood water velocity at the bent location (V_{design} assumed to be 6 mph)
$F^{t}_{\text{max applied}}$	=	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)

$F^{tip}_{max\ applied}$	=	Maximum horizontal flood water load applied at the pile tip perpendicular to the plane of the bent (used in checking pile "kickout" failure)
$F^{capacity}_{t}$	=	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 the bent required to cause pushover failure of the bent under a given set of gravity P-loads on the bent. This force was determined via the nonlinear Pushover Analysis capabilities of GTSTRUDL.
$F^{t}_{max\ design}$	=	$F_{t\ max\ design} = 12.15^{k}$ (includes a F.S. = 1.25)
B	=	Base dimension of assumed flood water triangular debris raft
A	=	Altitude or height of assumed flood water triangular debris raft
DRA	=	Vertical projected area of assumed flood water triangular debris raft (DRA = $1/2\,A \cdot B$)
S	=	Scour depth, or OGL-NGL
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
S_{max}	=	Maximum estimated scour at the bridge/bent site
OGL	=	Original ground line elevation
NGL	=	New ground line elevation (after scour)

ℓ_{bs}	=	Length of pile embedment in supporting soil before scour
ℓ_{as}	=	Length of pile embedment in supporting soil after Scour
ℓ_{re}	=	Length of remaining pile embedment after scour, i.e., $\ell_{re} = \ell_{as}$
P_{tip}	=	Vertical force applied or resisted at the pile tip
End Bearing Pile	=	Pile where 75% of the applied vertical load is assumed to be carried by end bearing
Friction Pile	=	Pile where 75% of the applied vertical load is assumed to be carried by side friction
bpi	=	Blows per inch of final pile driving resistance

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APPENDIX A

Pushover Analysis Results for
HP10x42 Pile Bents of Various
Geometrical Configurations,
P-Loadings, and Scour Levels

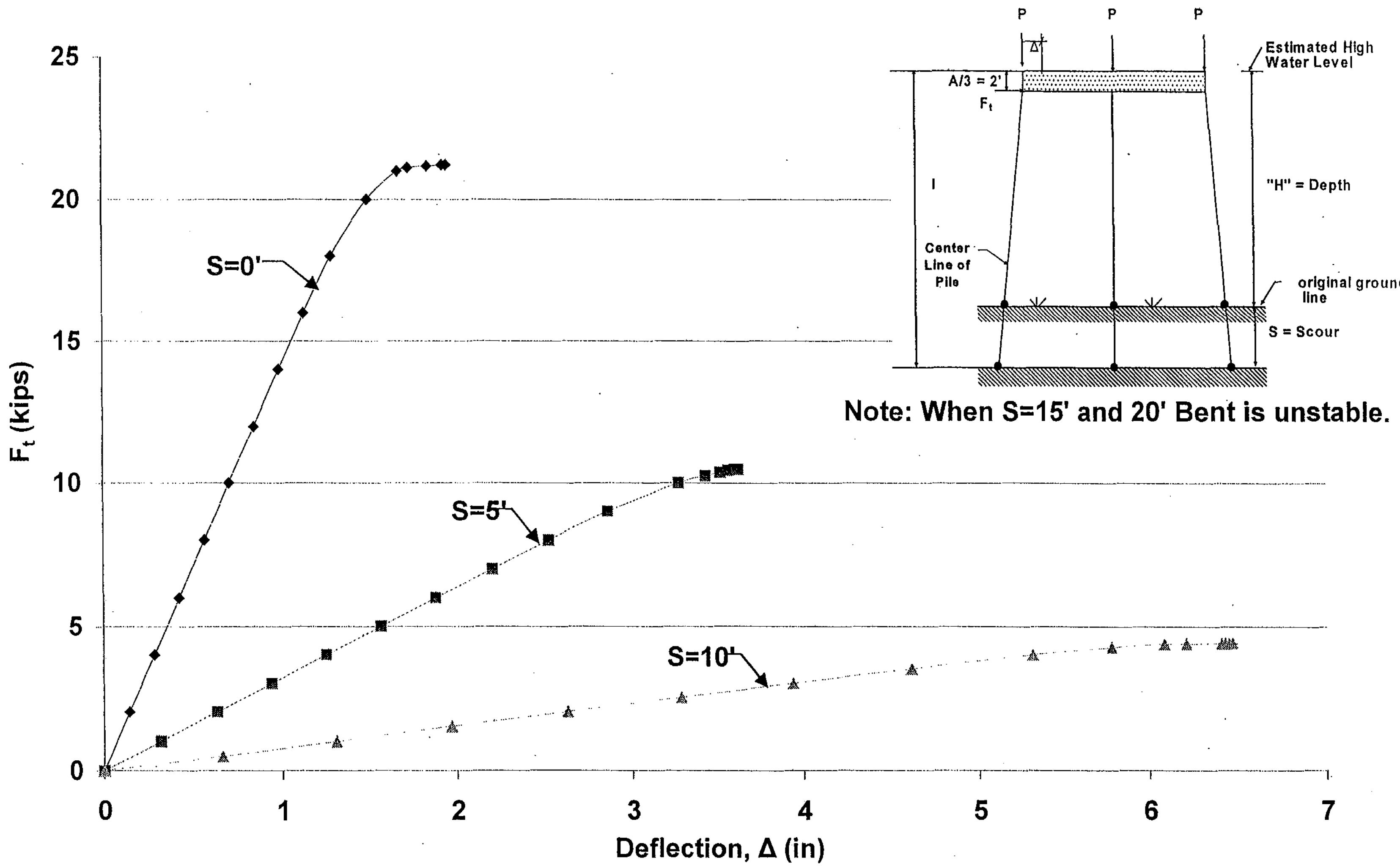


Figure A.1 HP10x42 Unbraced 3-Pile Bent with H=10', P=100kips, and A=6' Pushover Analysis Results

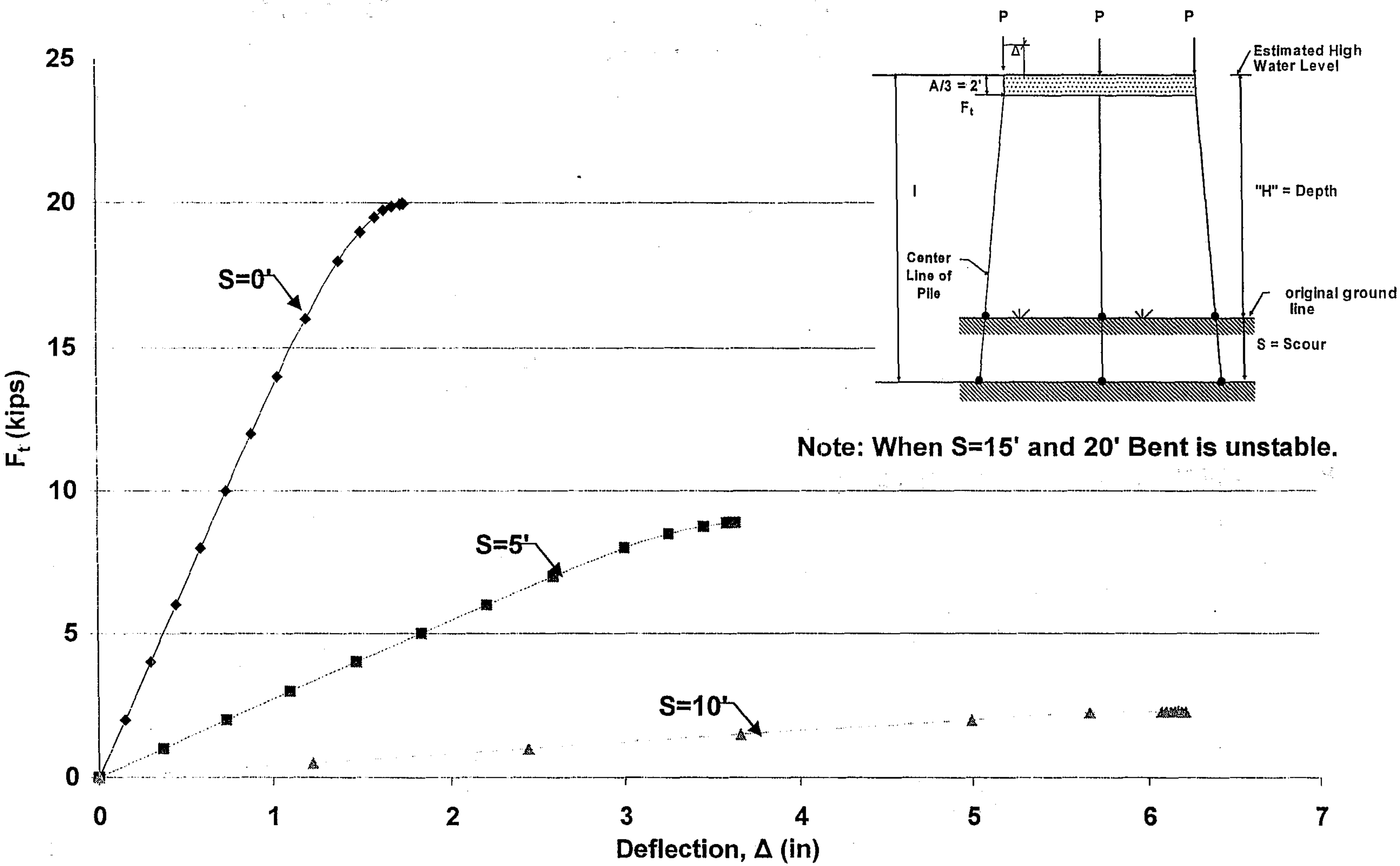


Figure A.2 HP10x42 Unbraced 3-Pile Bent with H=10', P=120kips, and A=6' Pushover Analysis Results

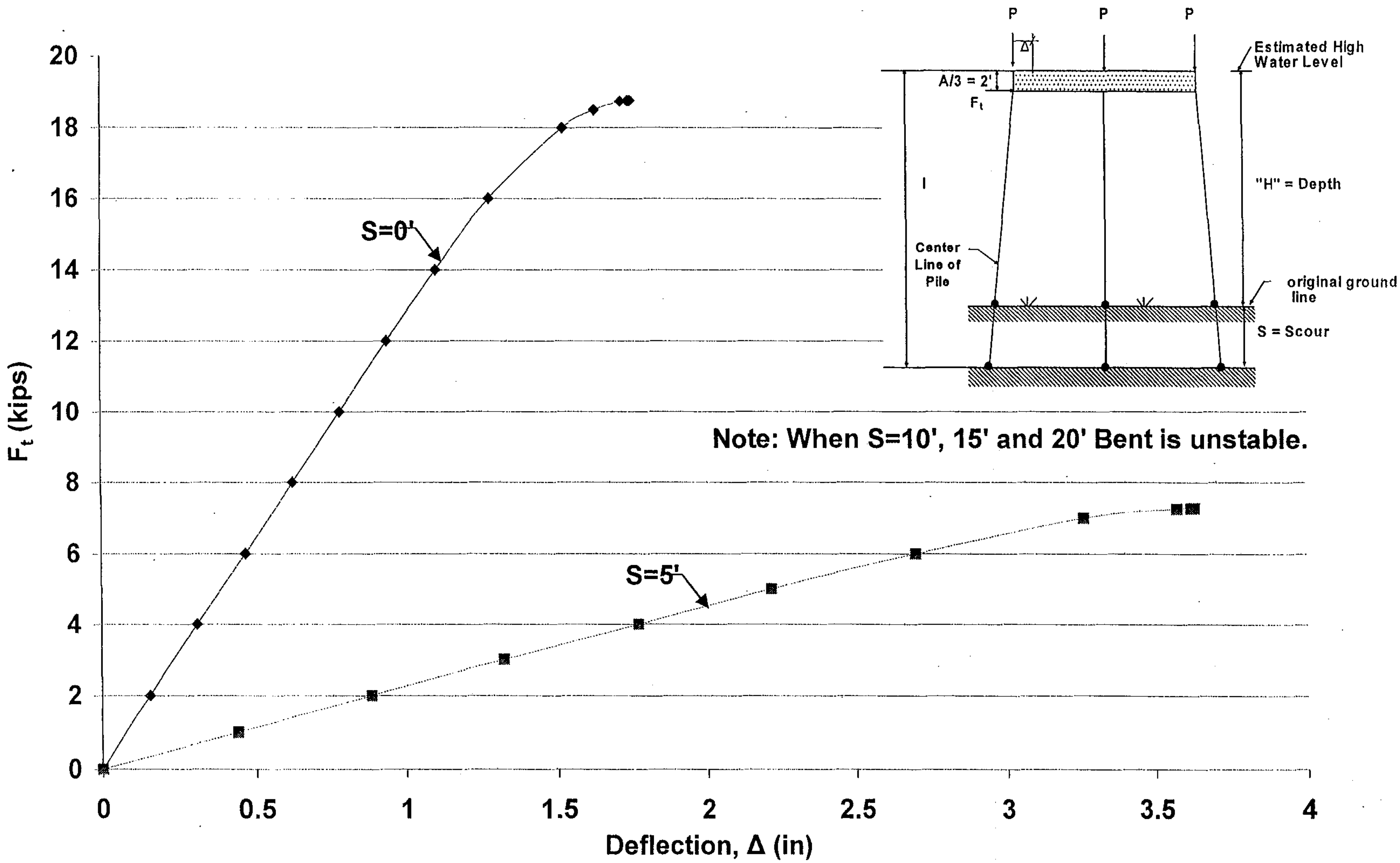


Figure A.3 HP10x42 Unbraced 3-PileBent with H=10', P=140kips, and A=6'
Pushover Analysis Results

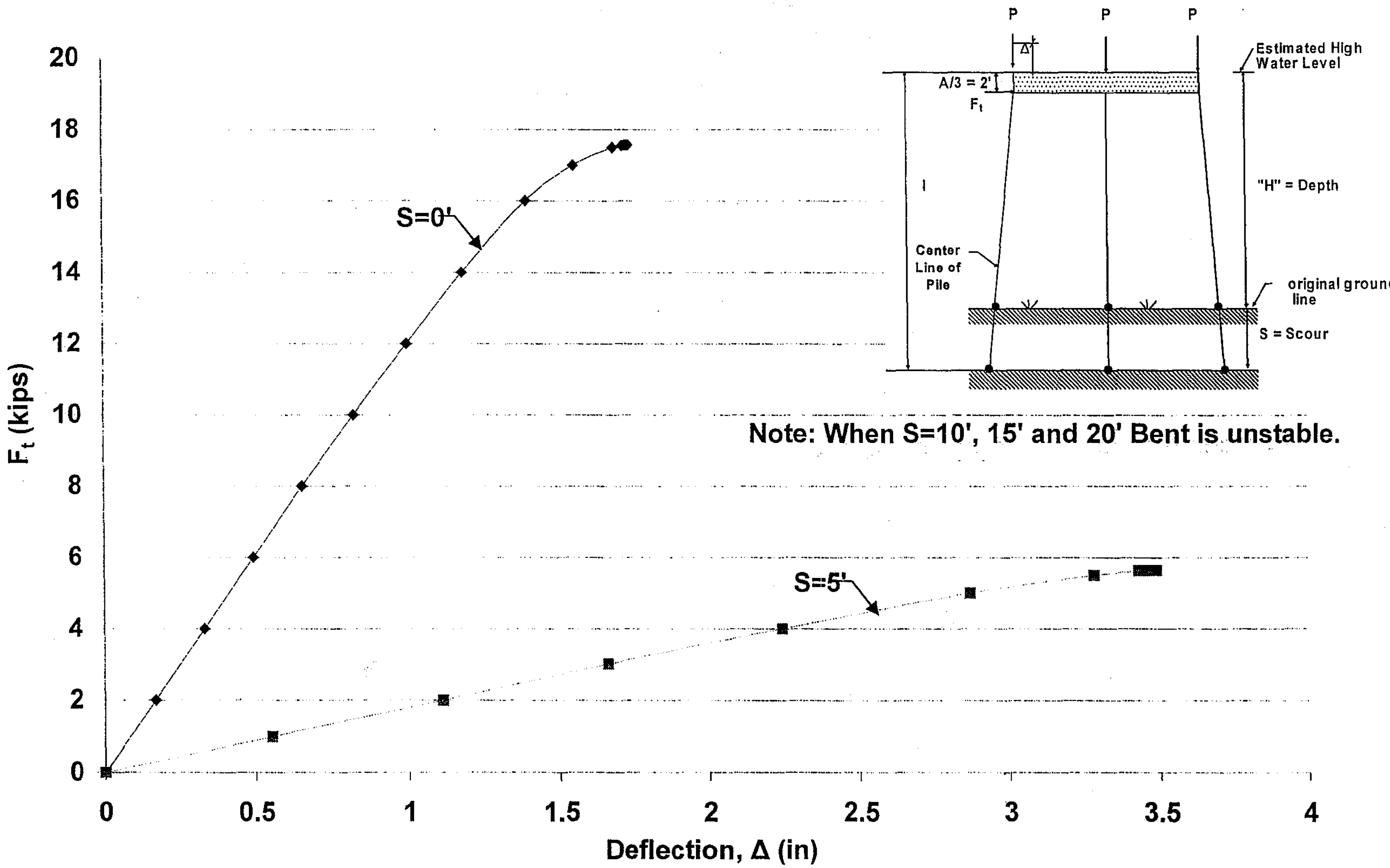


Figure A.4 HP10x42 Unbraced 3-Pile Bent with H=10', P=160kips, and A=6' Pushover Analysis Results

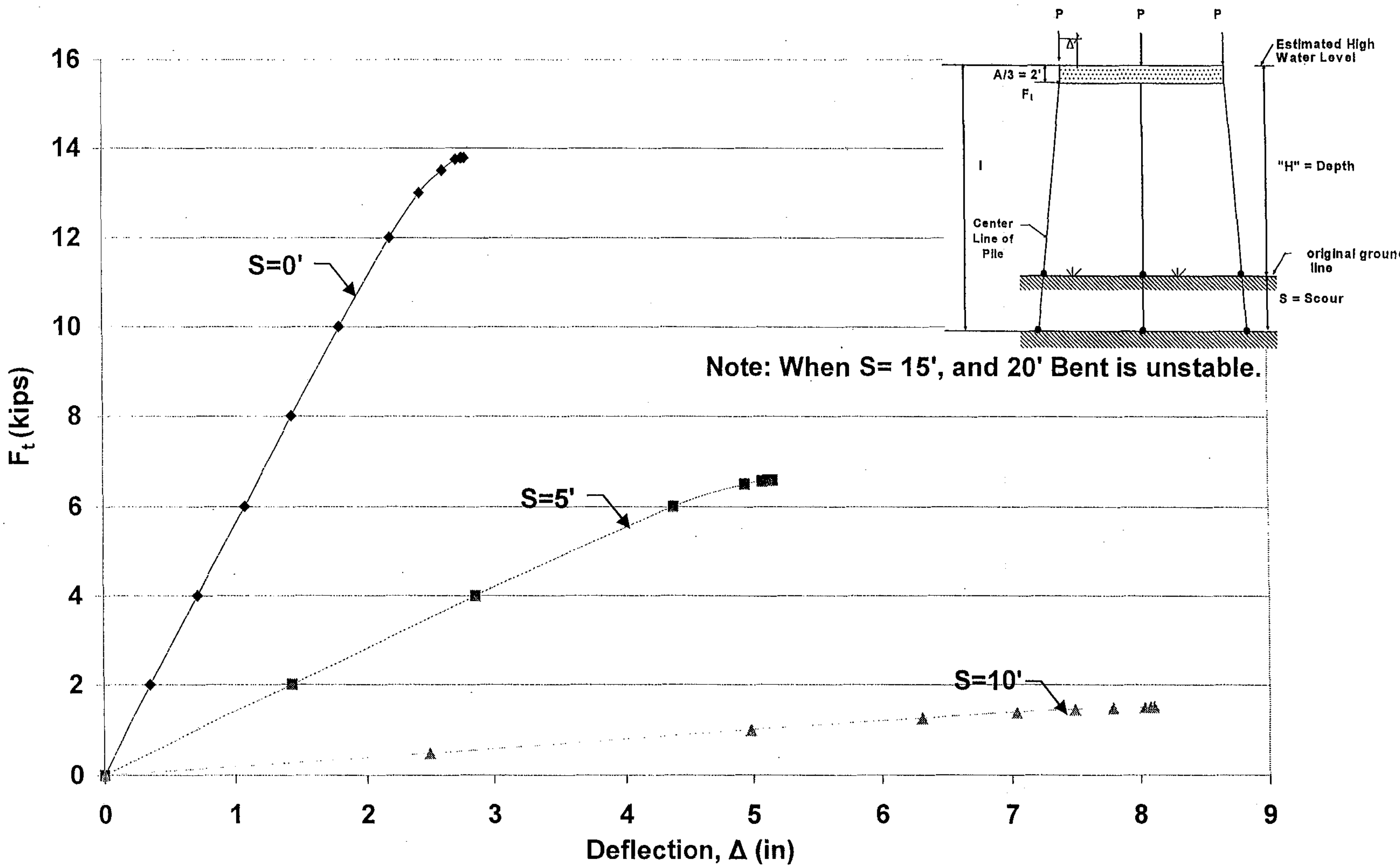


Figure A.5 HP10x42 Unbraced 3-Pile Bent with H=13', P=100kips, and A=6'
Pushover Analysis Results

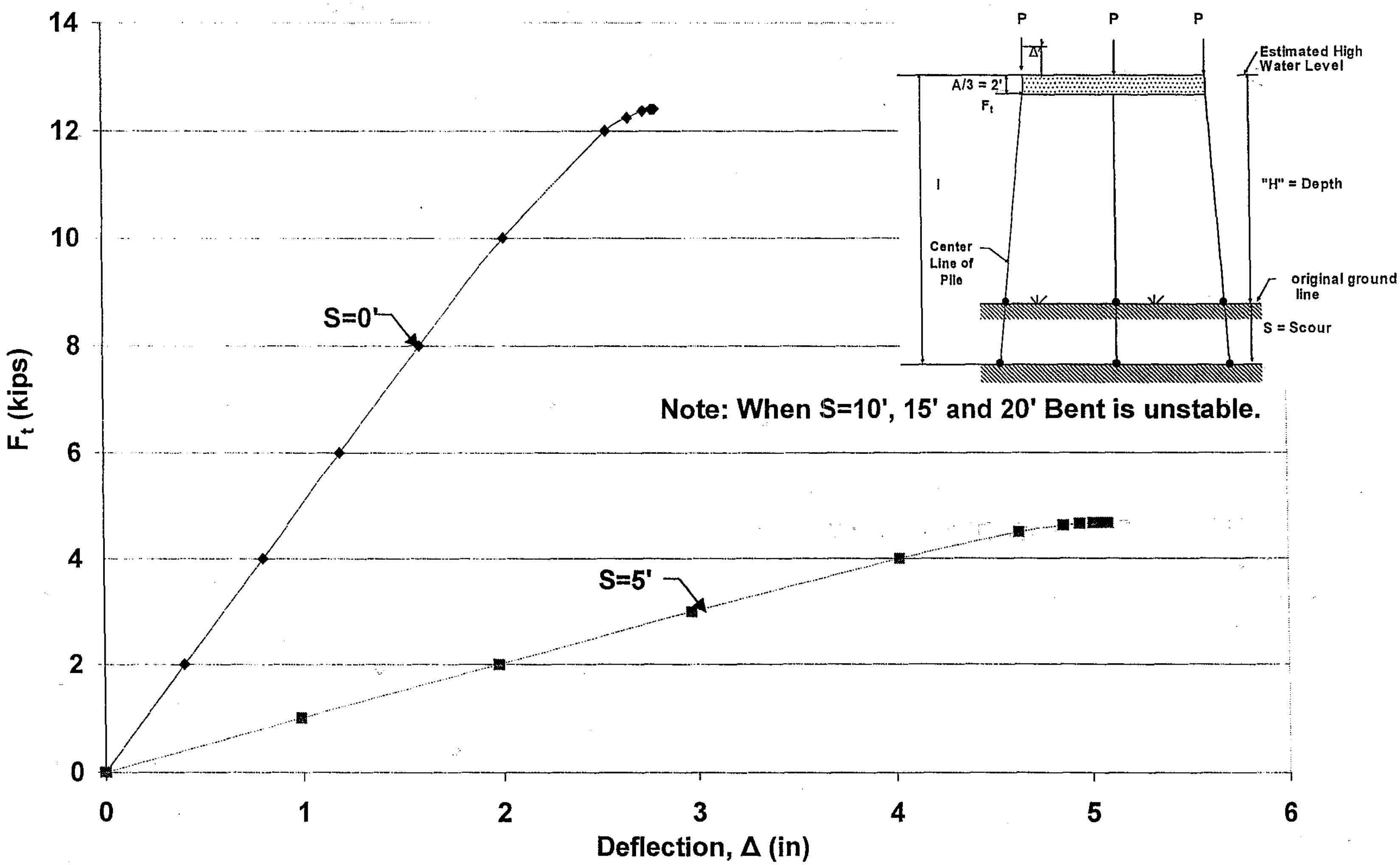


Figure A.6 HP10x42 Unbraced 3-Pile Bent with H=13', P=120kips, and A=6' Pushover Analysis Results

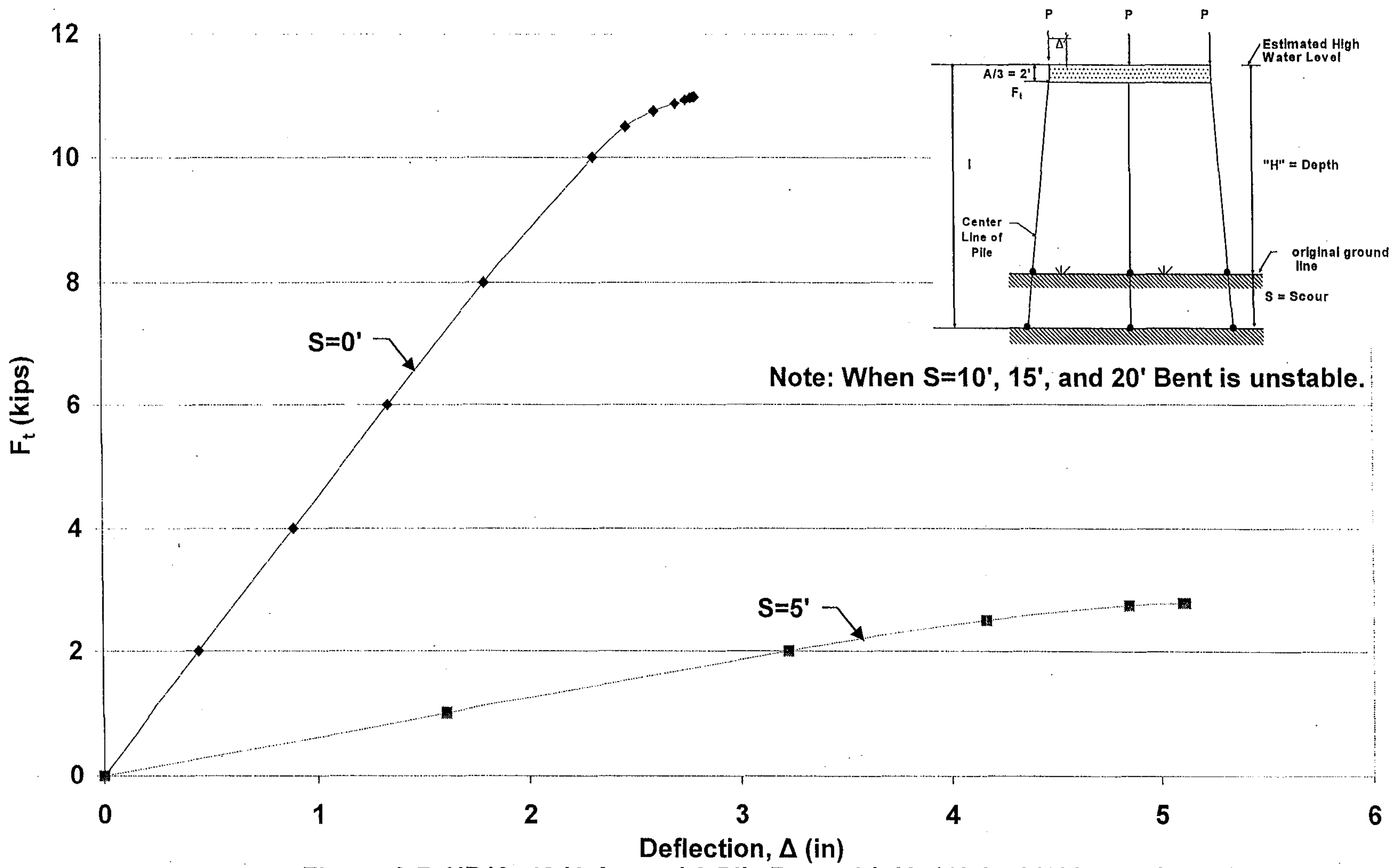


Figure A.7 HP10x42 Unbraced 3-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

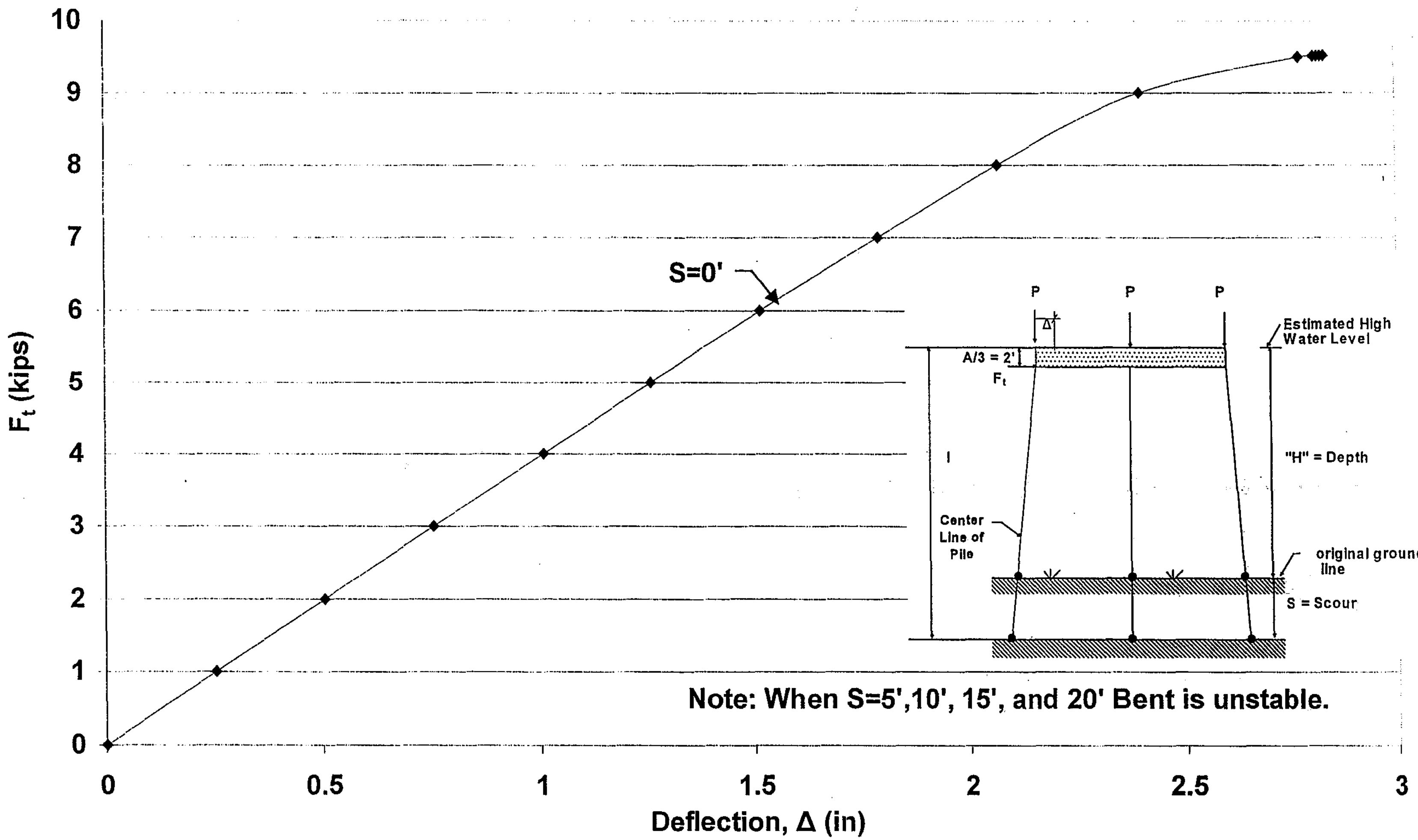


Figure A.8 HP10x42 Unbraced 3-Pile Bent with H=13', P=160 kips and A=6' Pushover Analysis Results

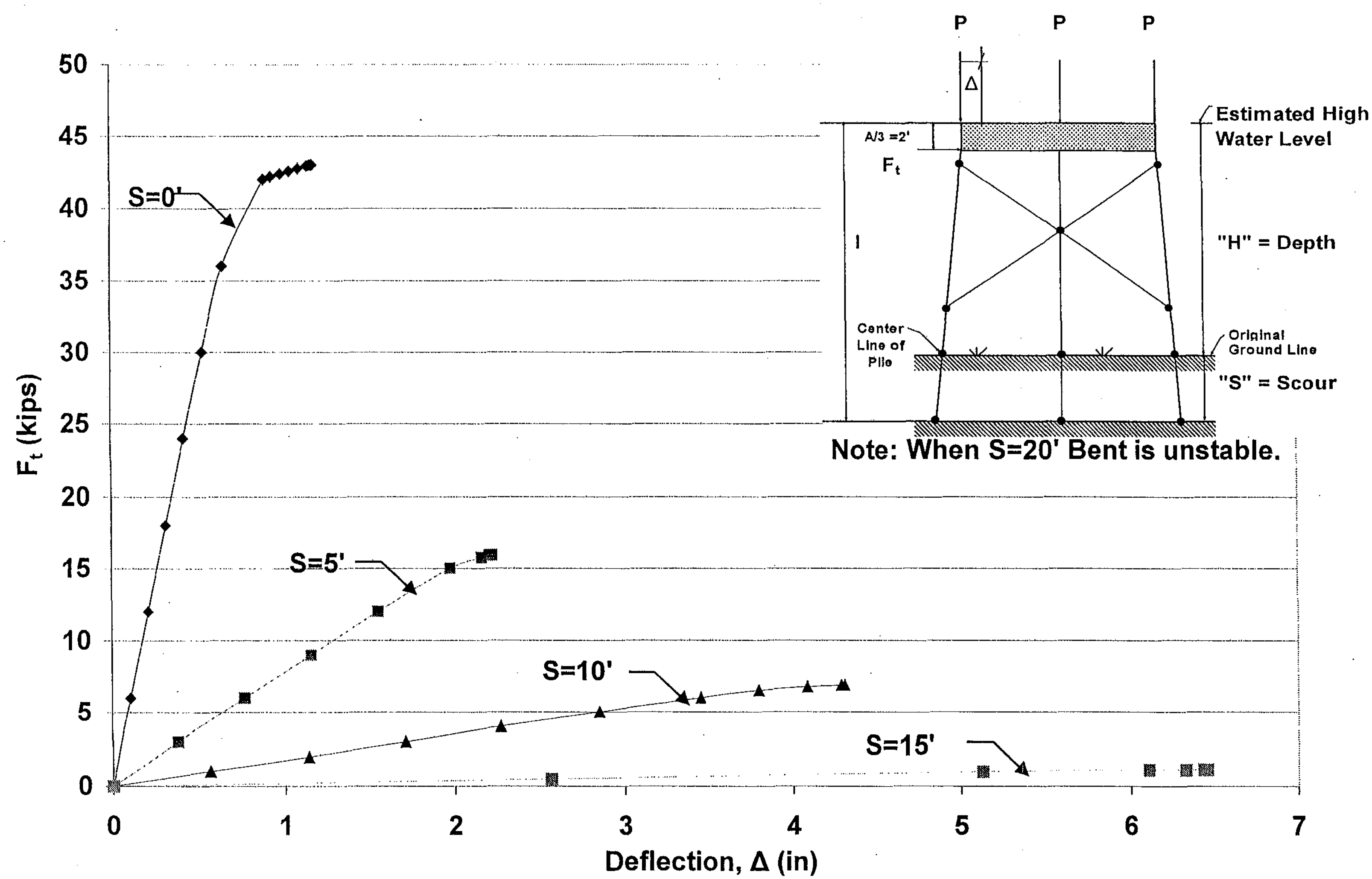


Figure A.9 HP10x42 X-Braced 3-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

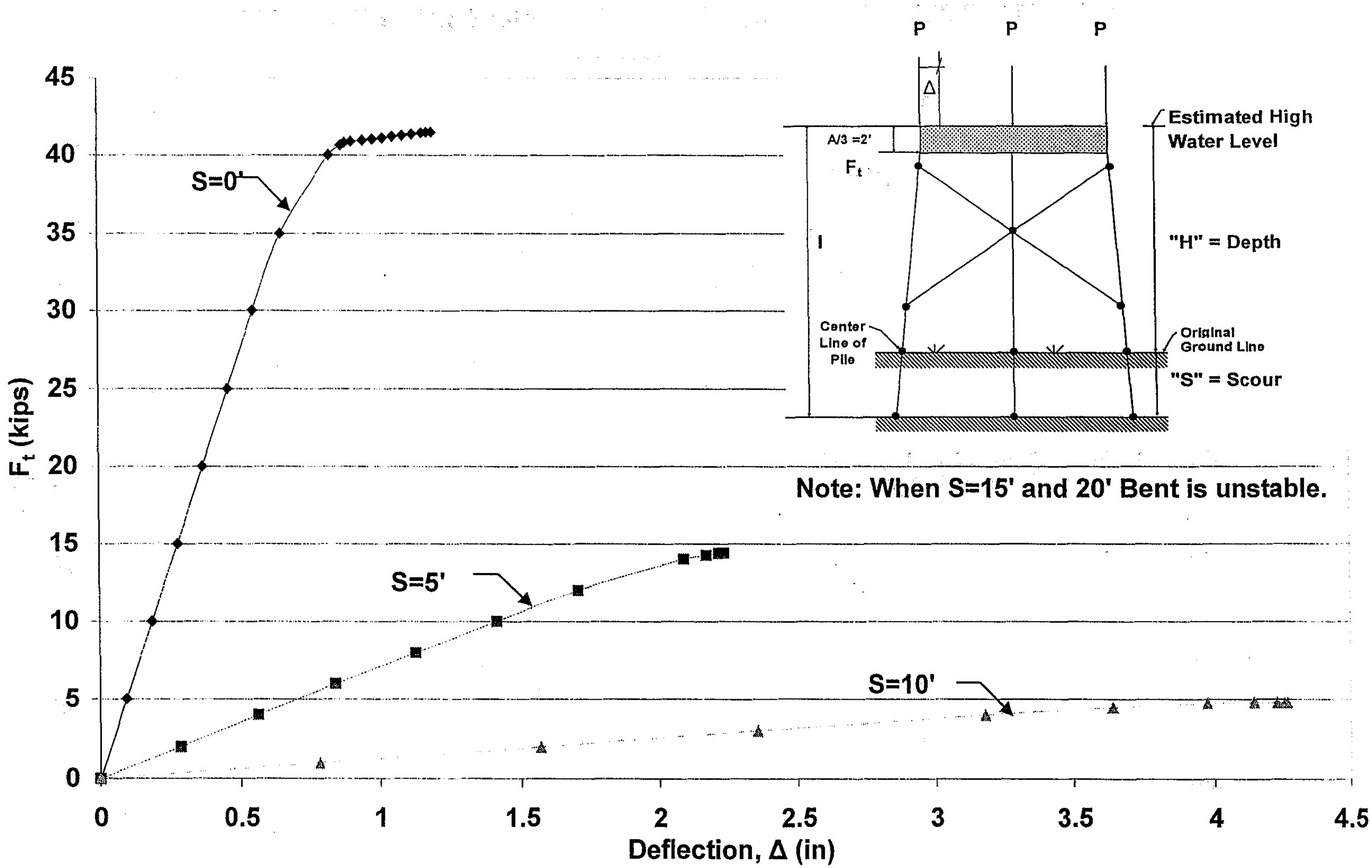


Figure A.10 HP10x42 X-Braced 3-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

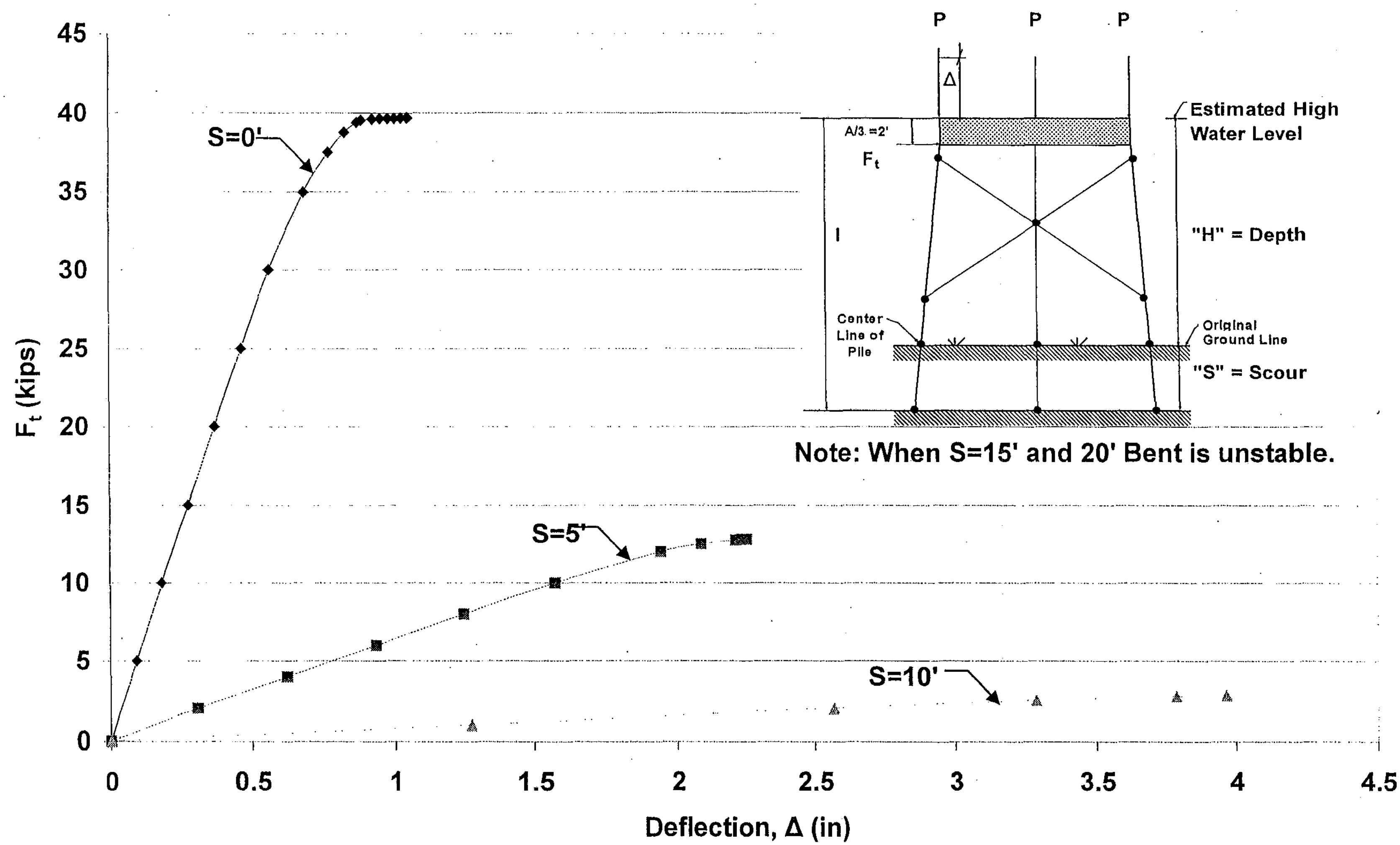


Figure A.11 HP10x42 X-Braced 3-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

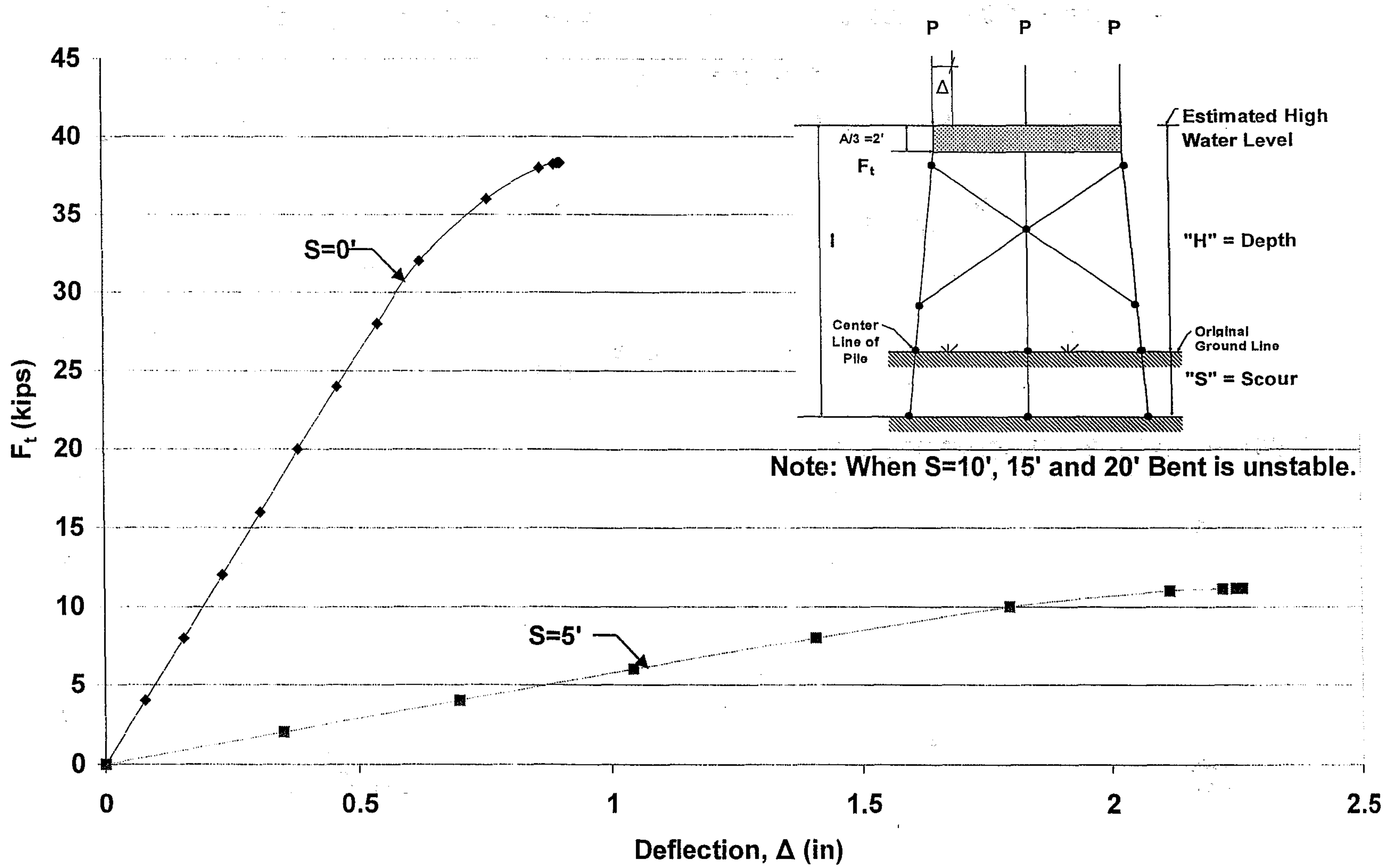


Figure A.12 HP10x42 X-Braced 3-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

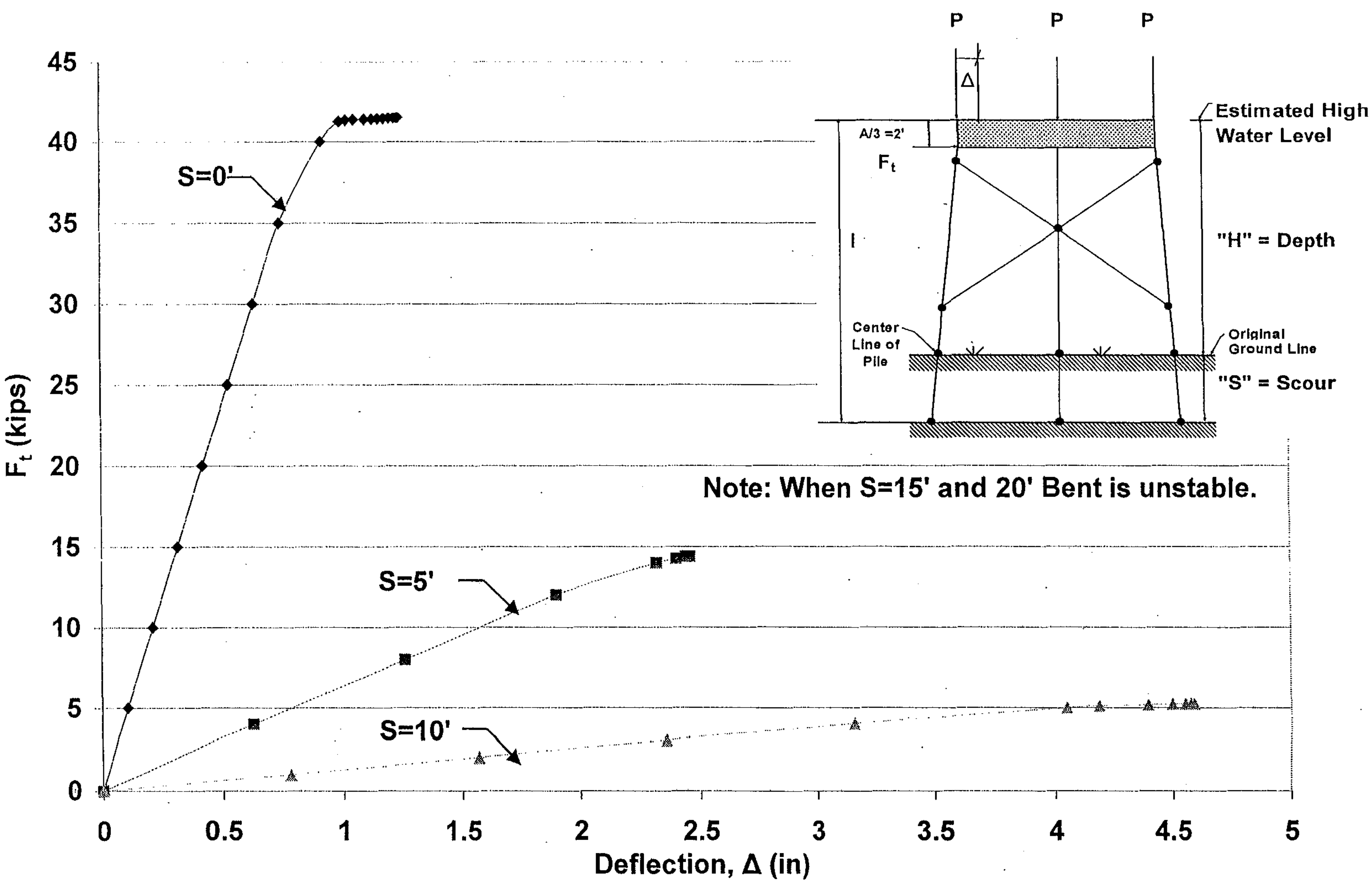


Figure A.13 HP10x42 X-Braced 3-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

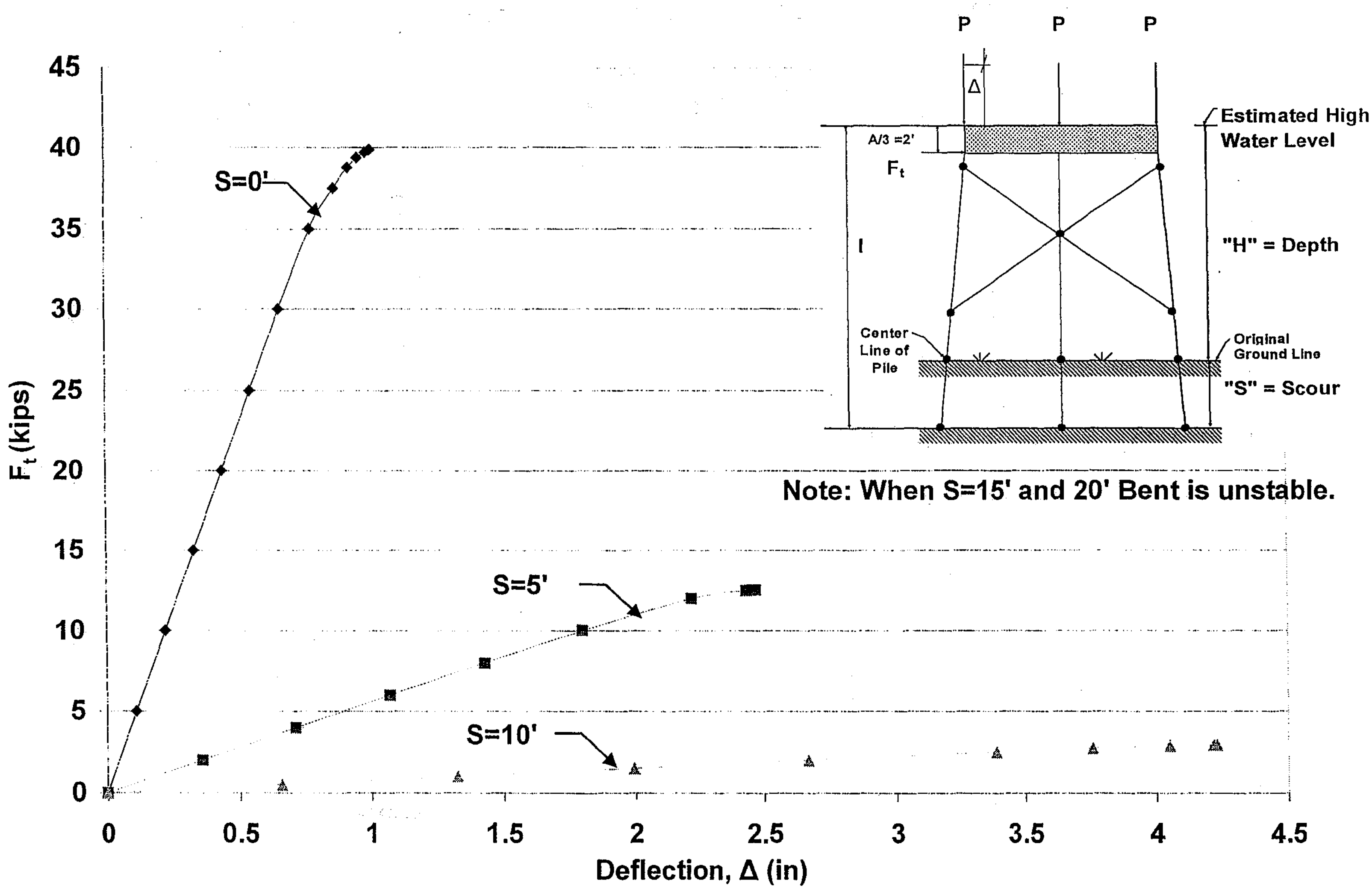


Figure A.14 HP10x42 X-Braced 3-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

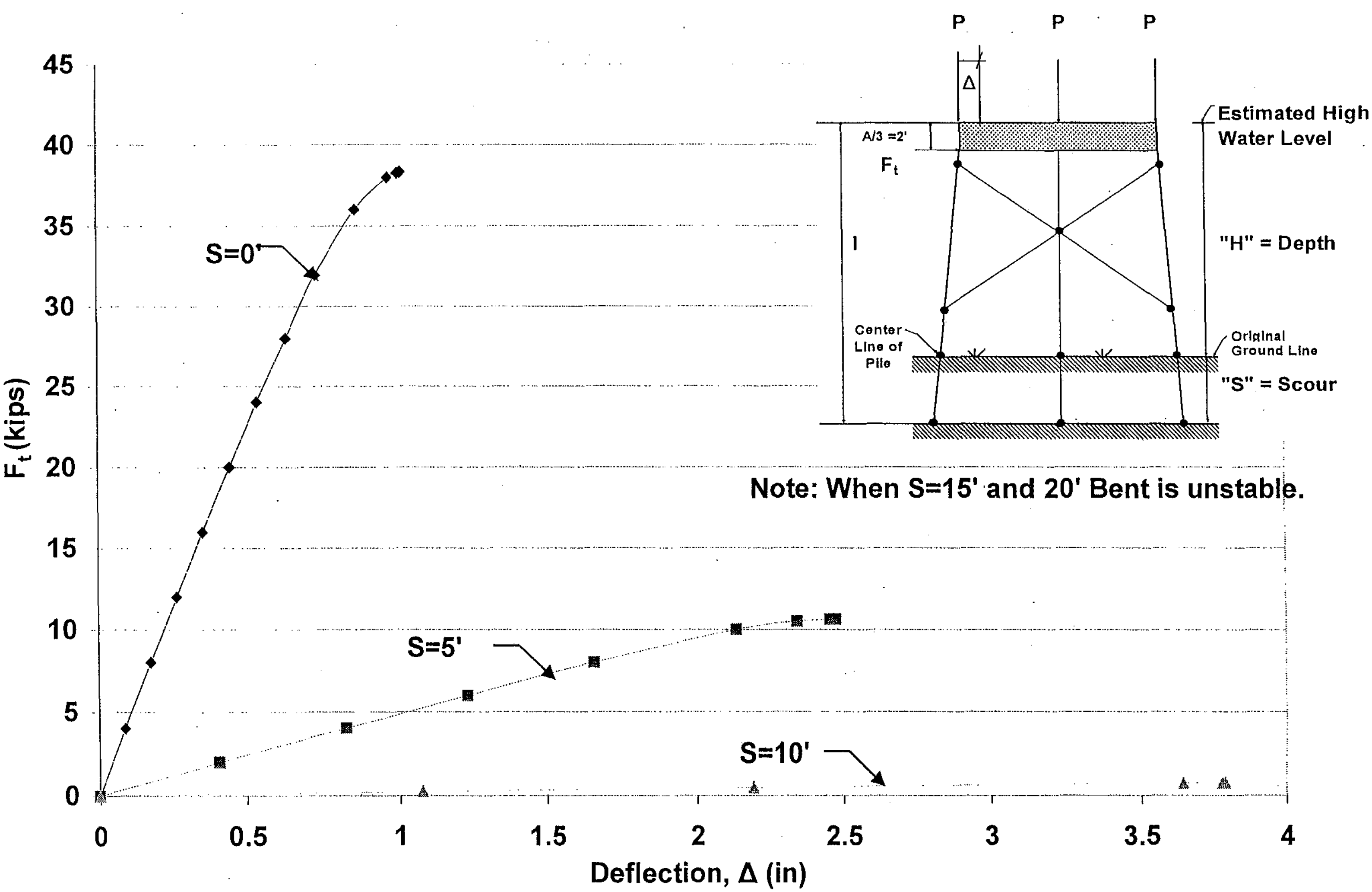


Figure A.15 HP10x42 X-Braced 3-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

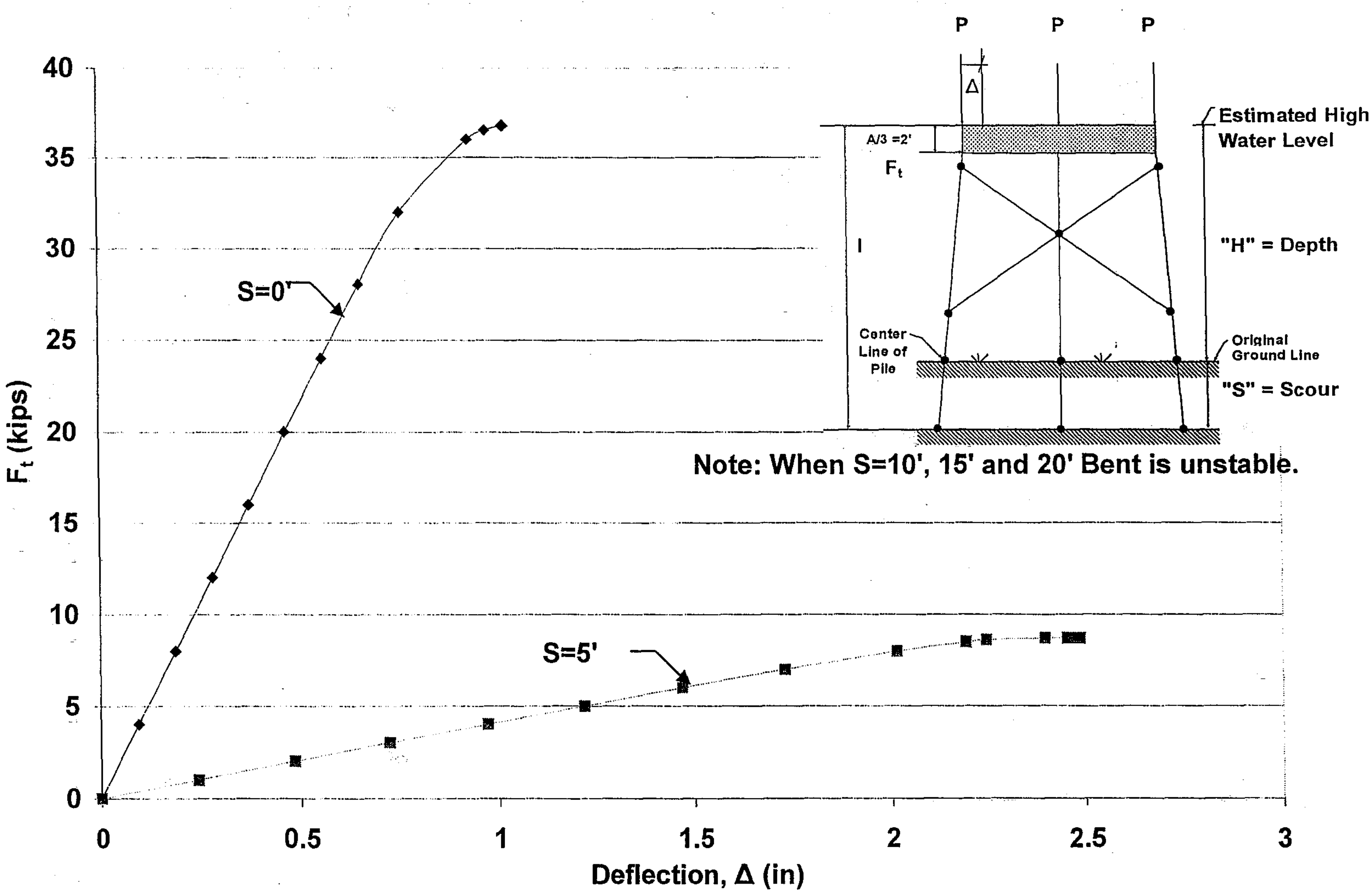


Figure A.16 HP10x42 X-Braced 3-Pile Bent with H=17', P=160kips and A=6'
Pushover Analysis Results

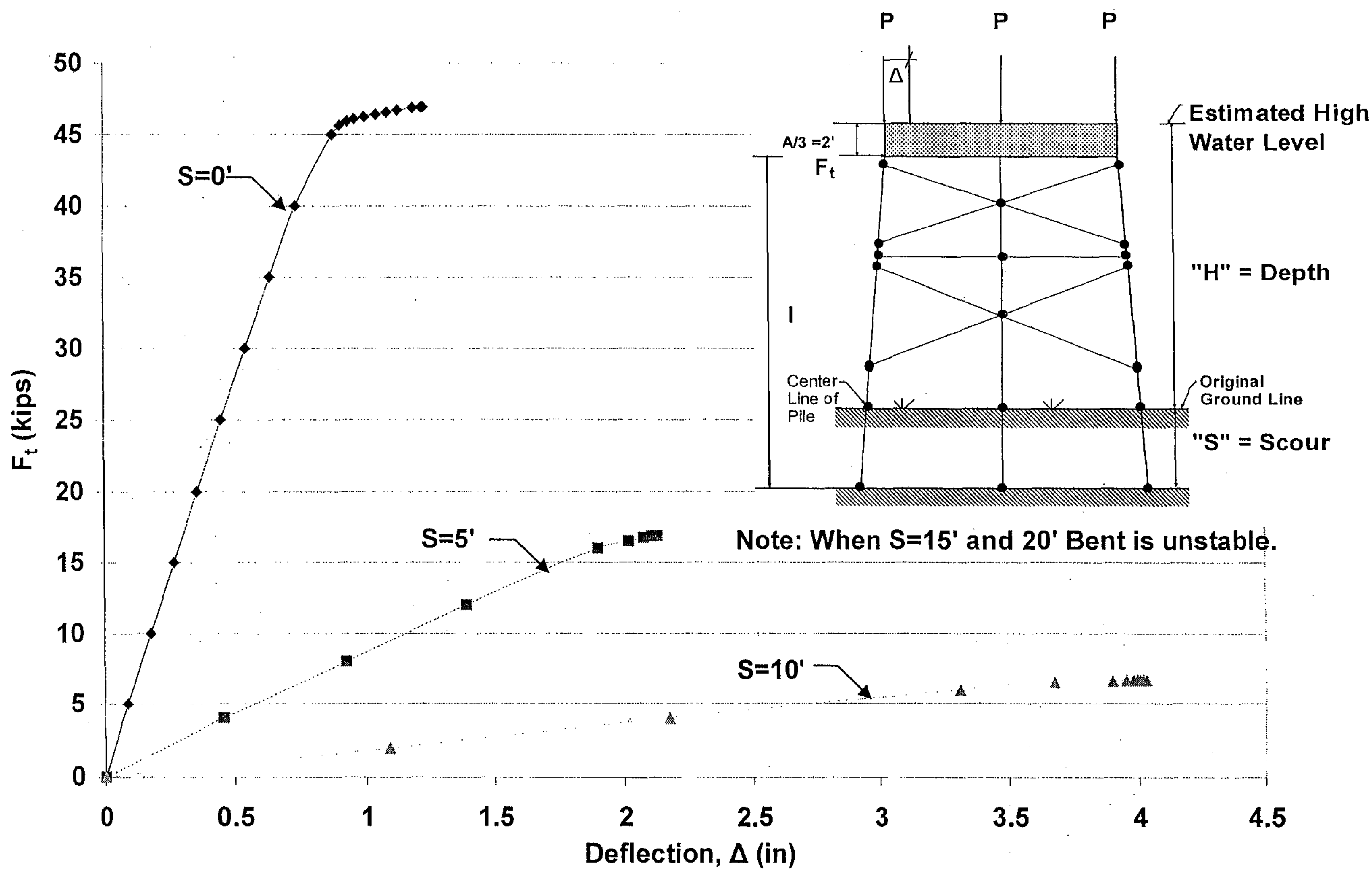


Figure A.17 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=100kips, and A=6'
Pushover Analysis Results

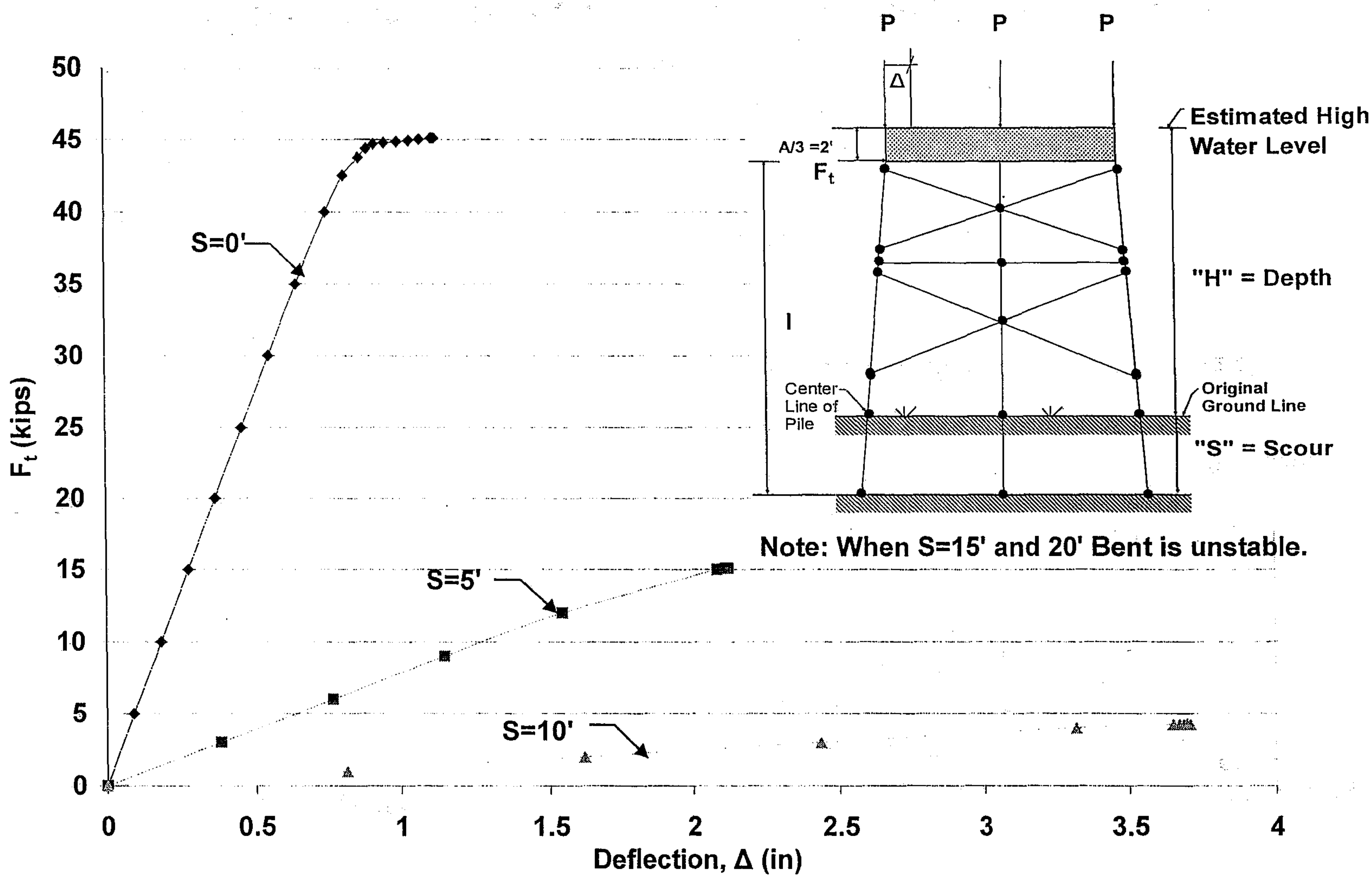


Figure A.18 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=120kips, and A=6' Pushover Analysis Results

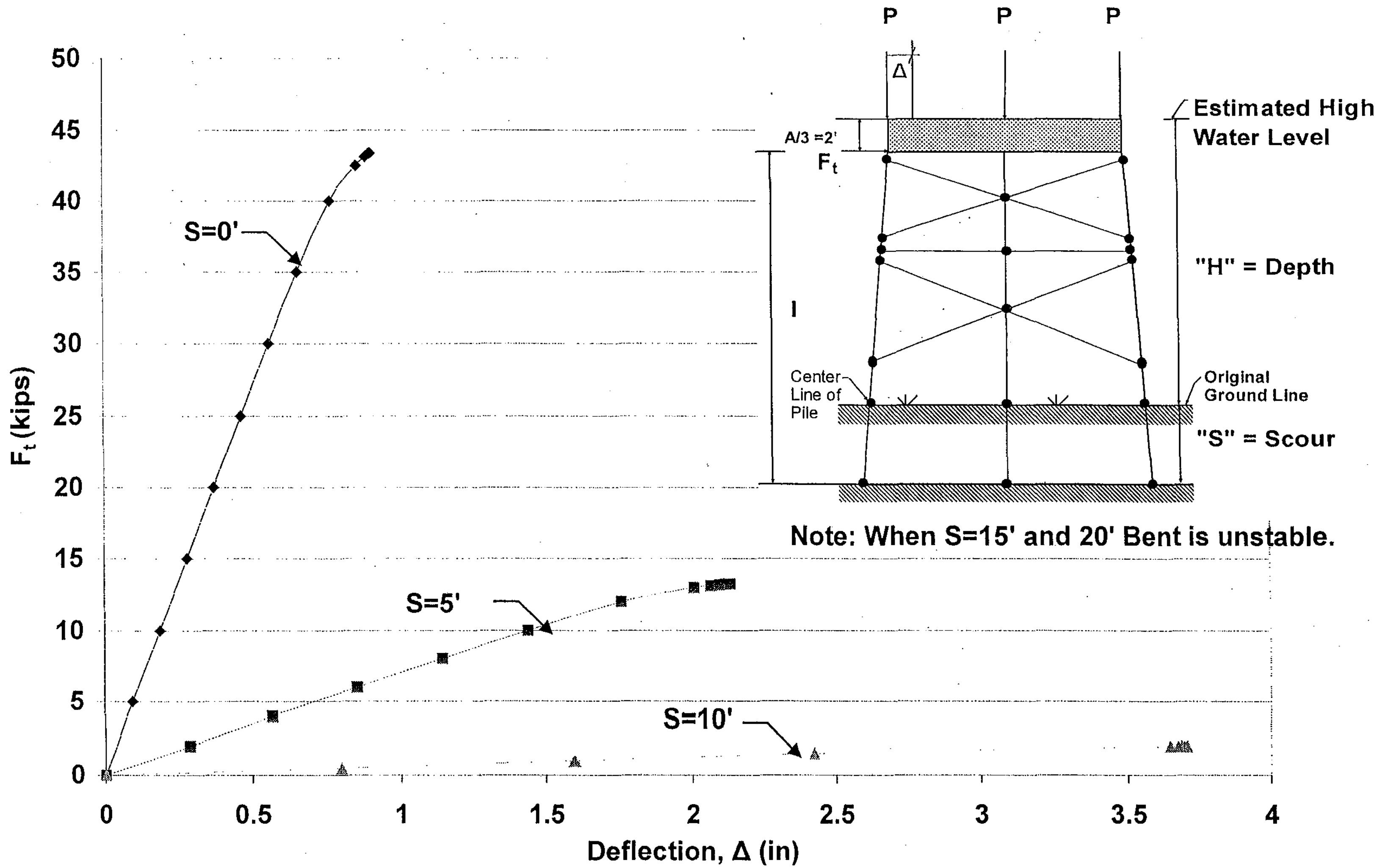


Figure A.19 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=140kips and A=6'
Pushover Analysis Results

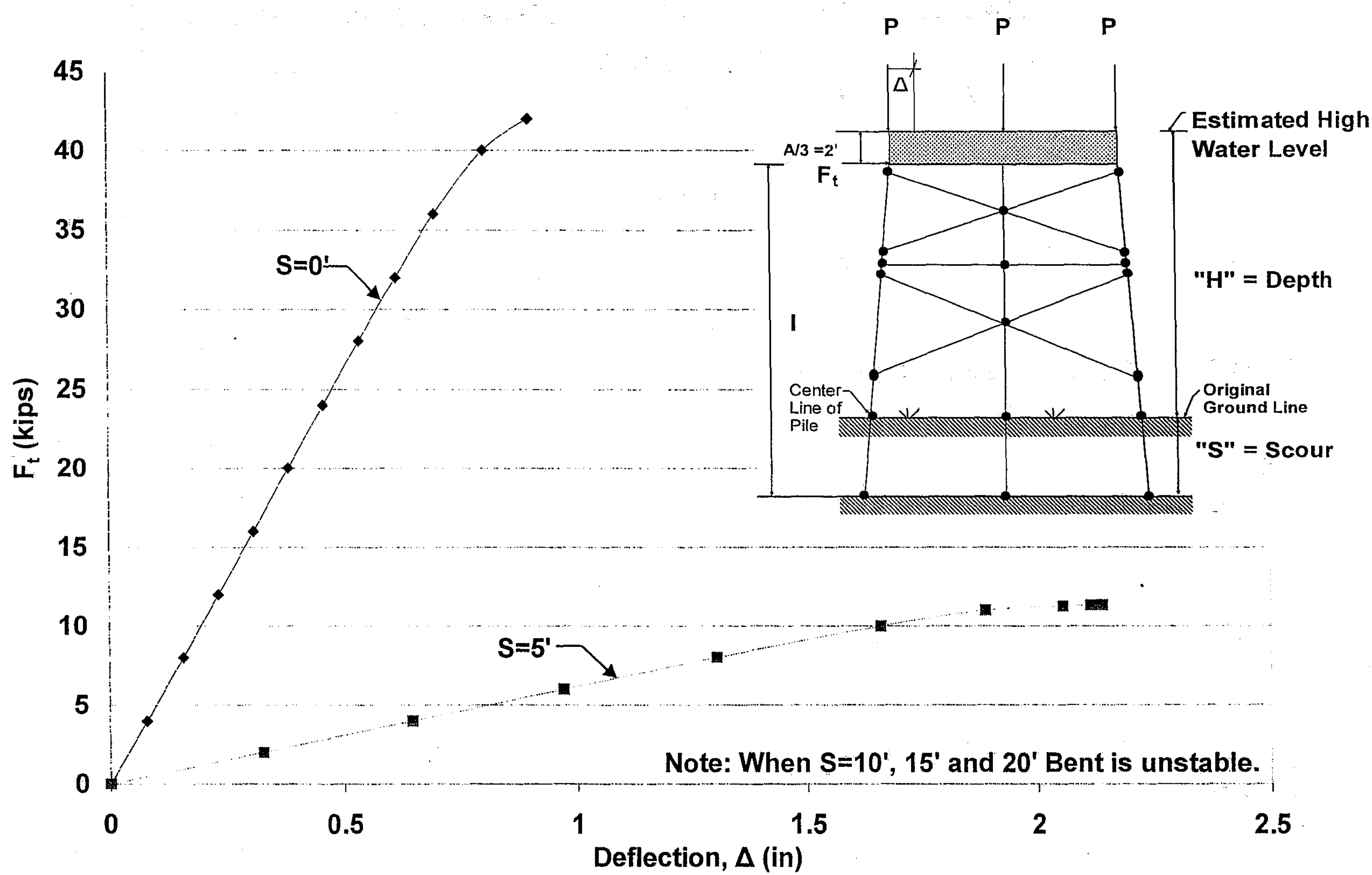


Figure A.20 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=160kips, and A=6' Pushover Analysis Results

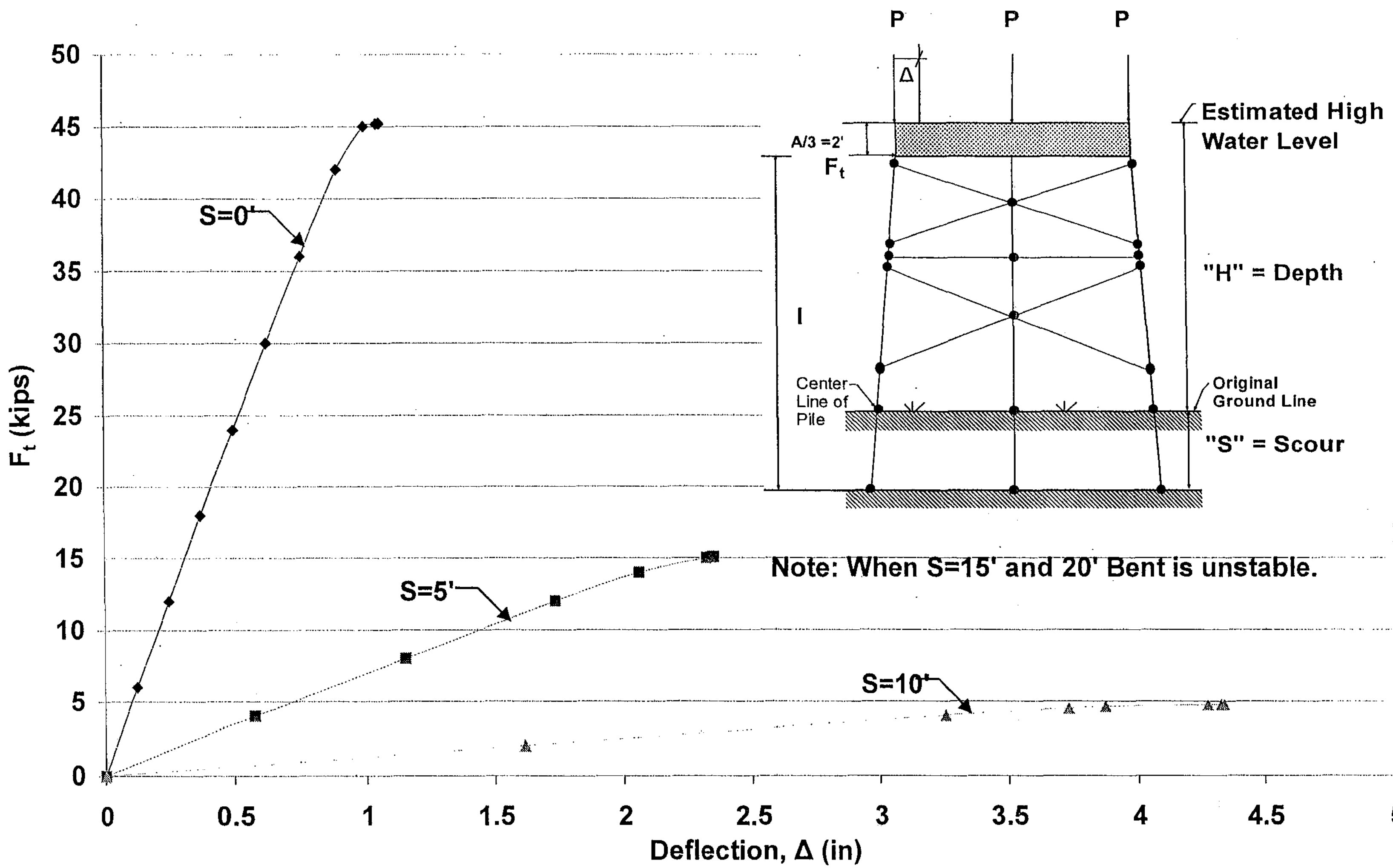


Figure A.21 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=100kips, and A=6' Pushover Analysis Results

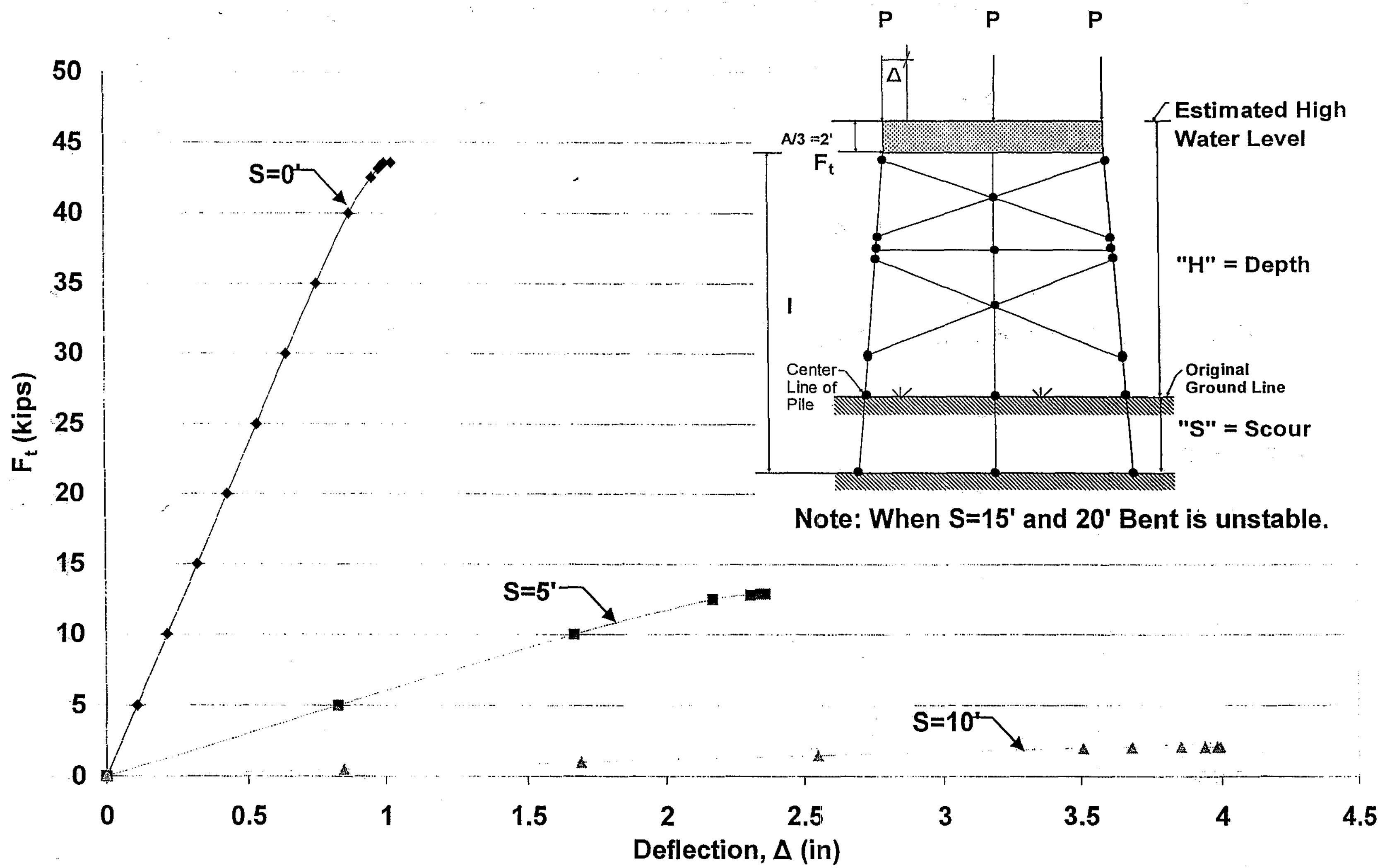


Figure A.22 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=120kips, and A=6' Pushover Analysis Results

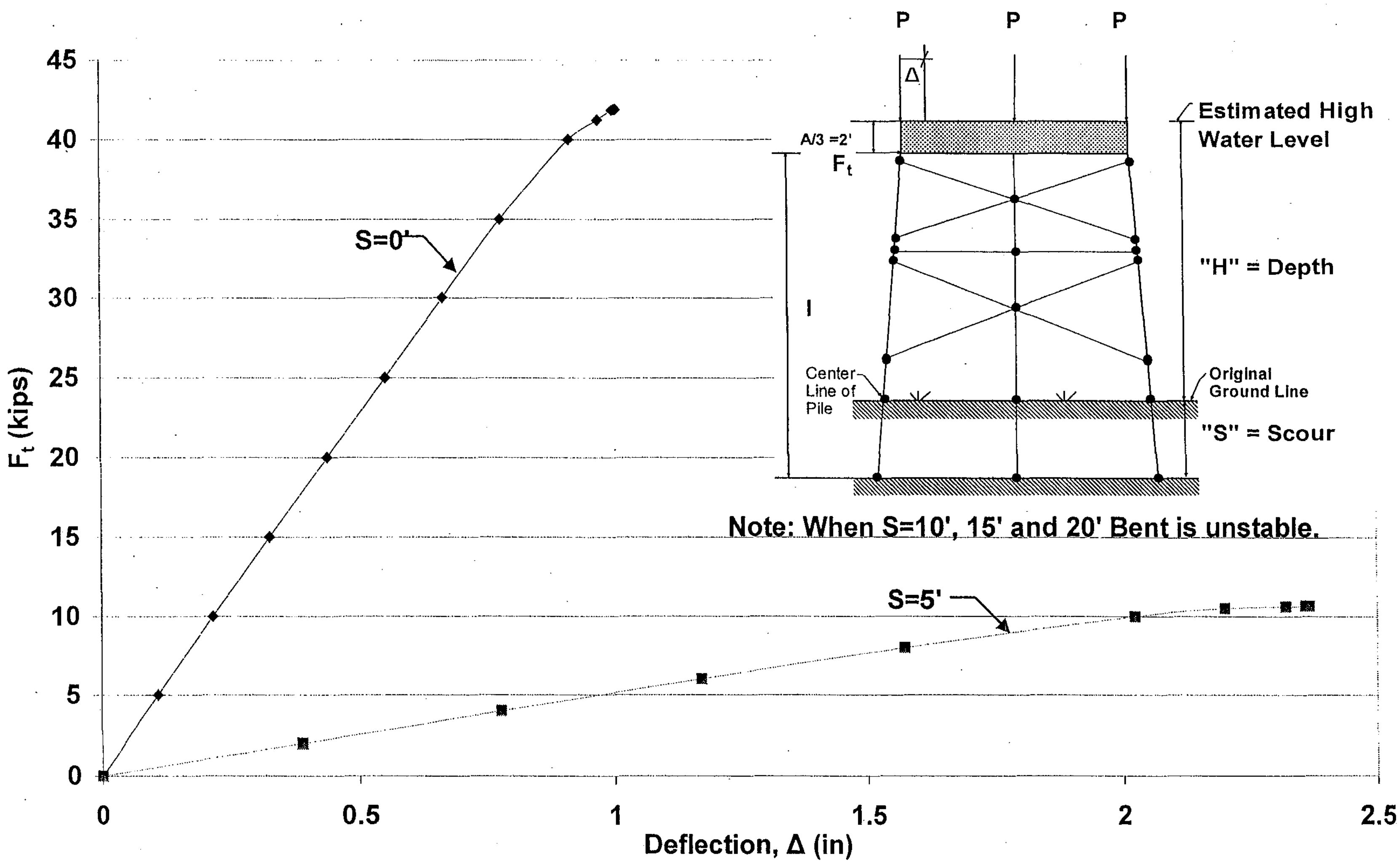


Figure A.23 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

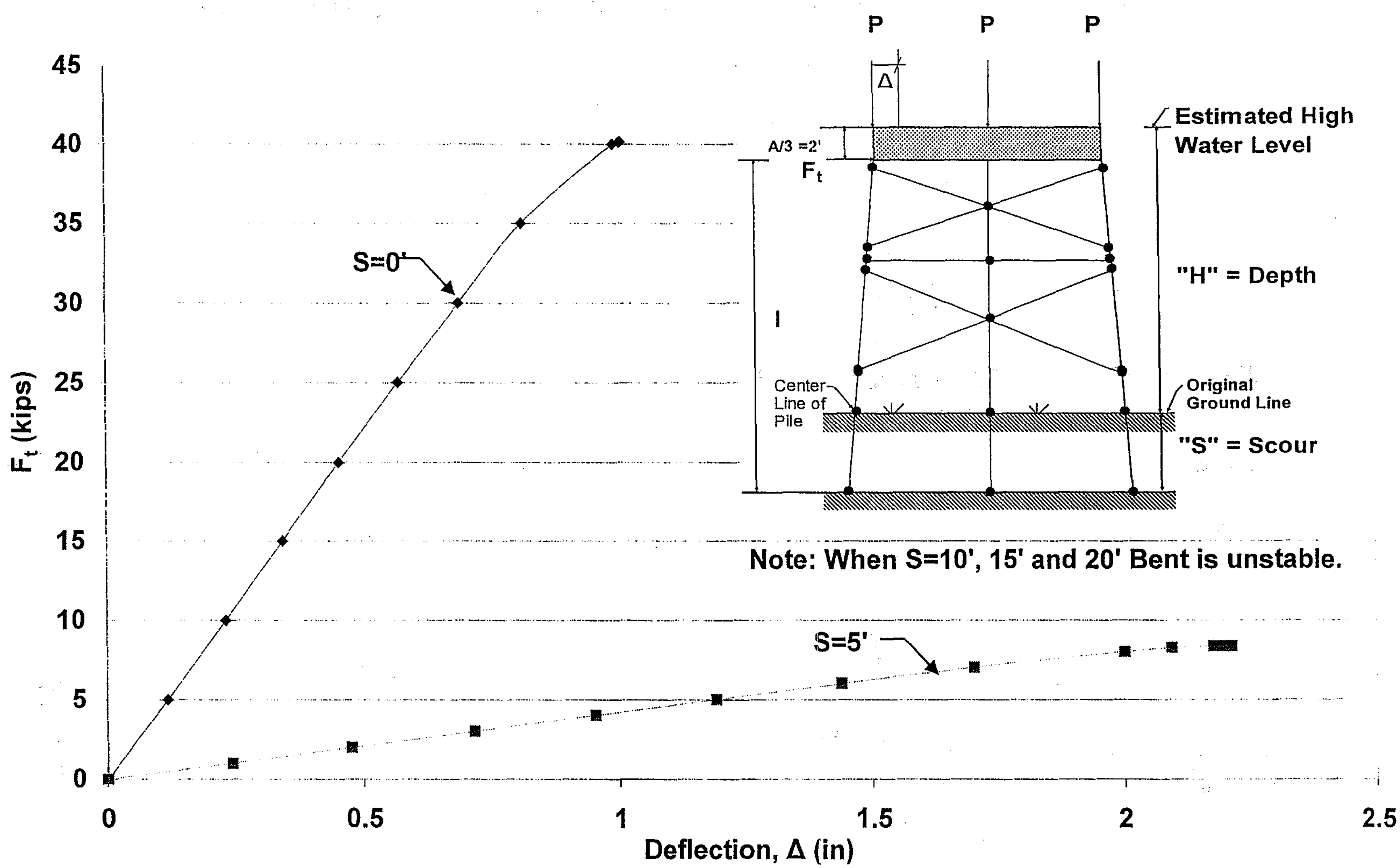


Figure A.24 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=160kips and A=6'
Pushover Analysis Results

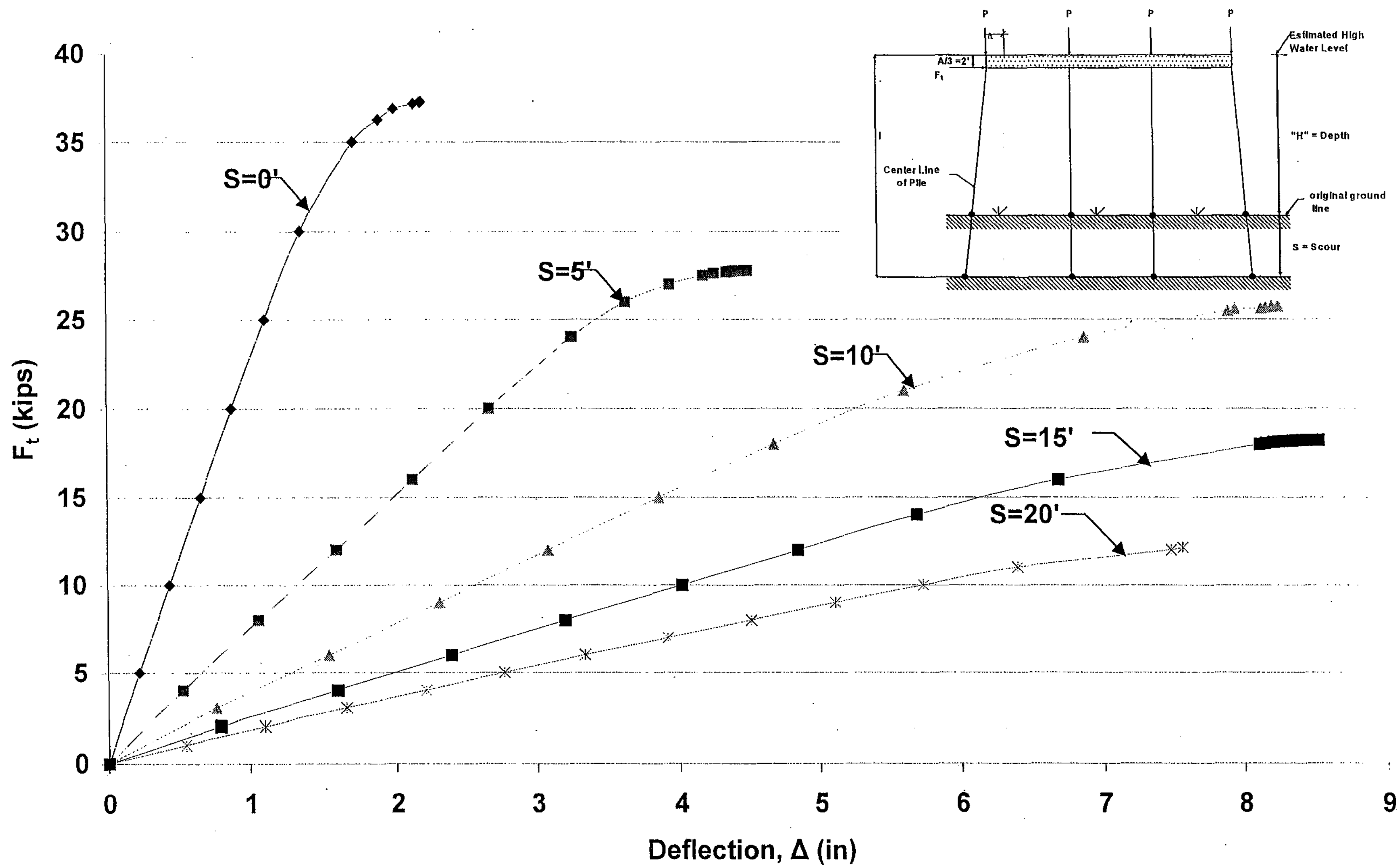


Figure A.25 HP10x42 Unbraced 4-Pile Bent with H=10', P=100kips, and A=6' Pushover Analysis Results

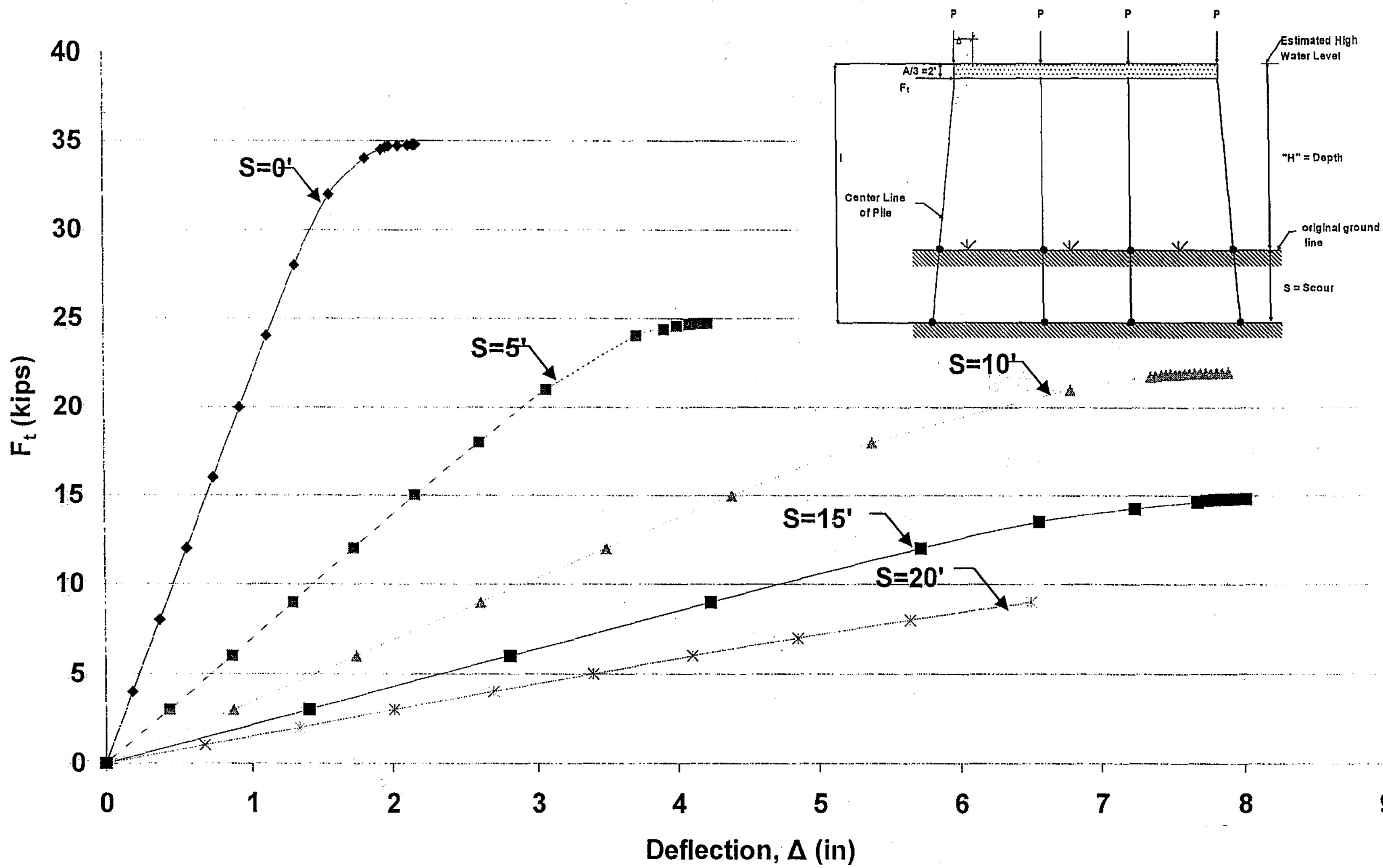


Figure A.26 HP10x42 Unbraced 4-Pile Bent with H=10', P=120kips, and A=6' Pushover Analysis Results

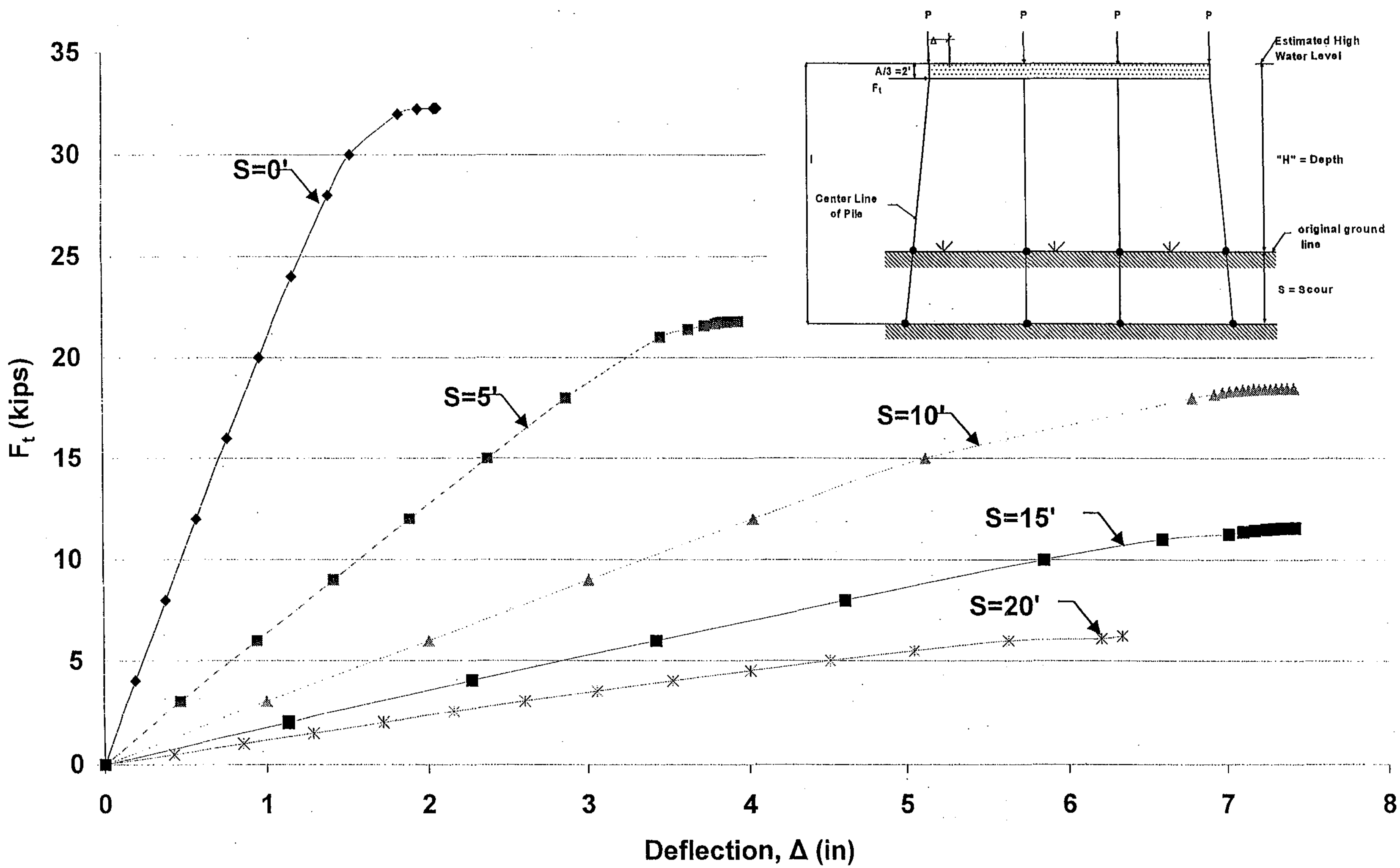


Figure A.27 HP10x42 Unbraced 4-Pile Bent with H=10', P=140kips, and A=6' Pushover Analysis Results

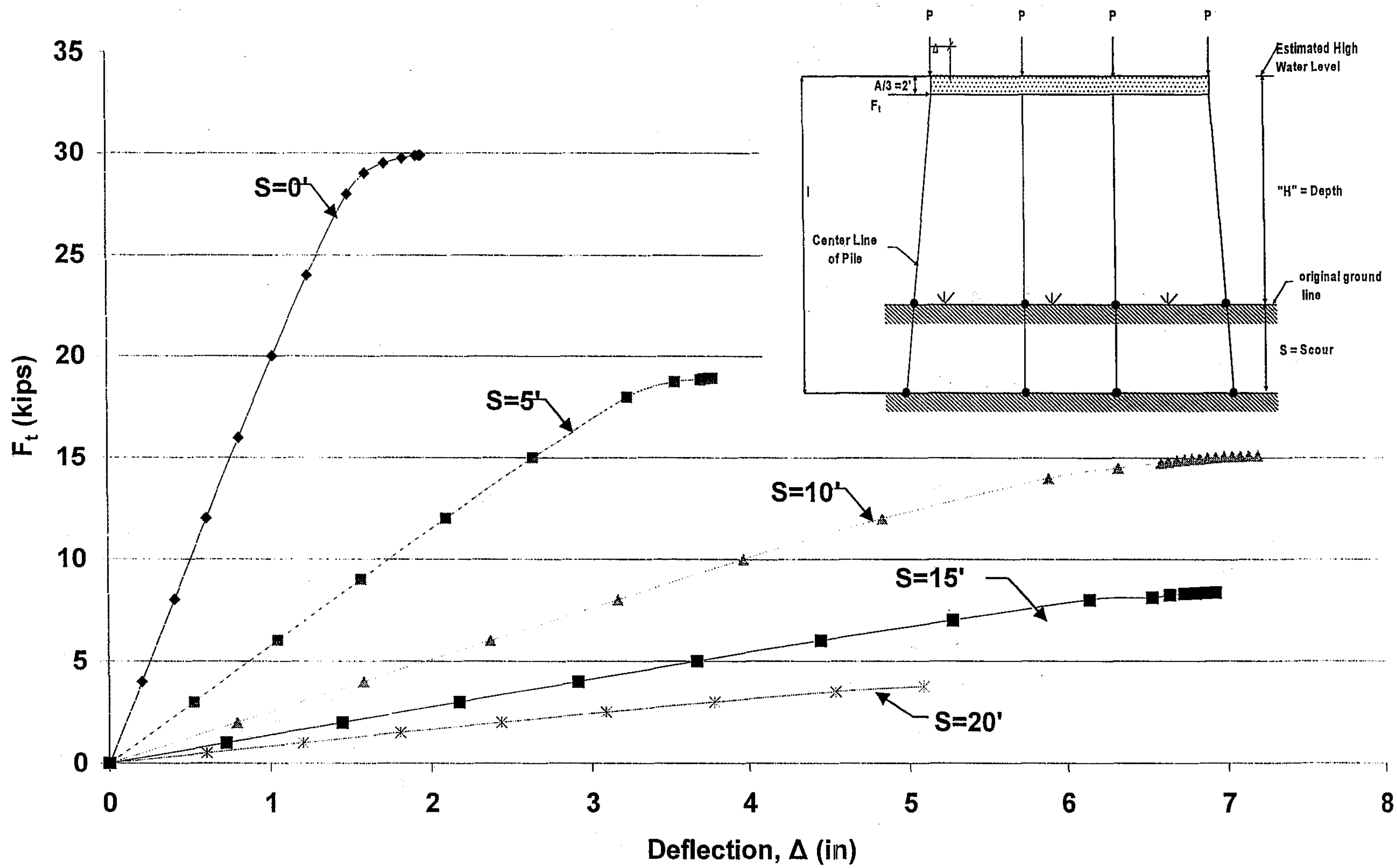


Figure A.28 HP10x42 Unbraced 4-Pile Bent with H=10', P=160kips, and A=6' Pushover Analysis Results

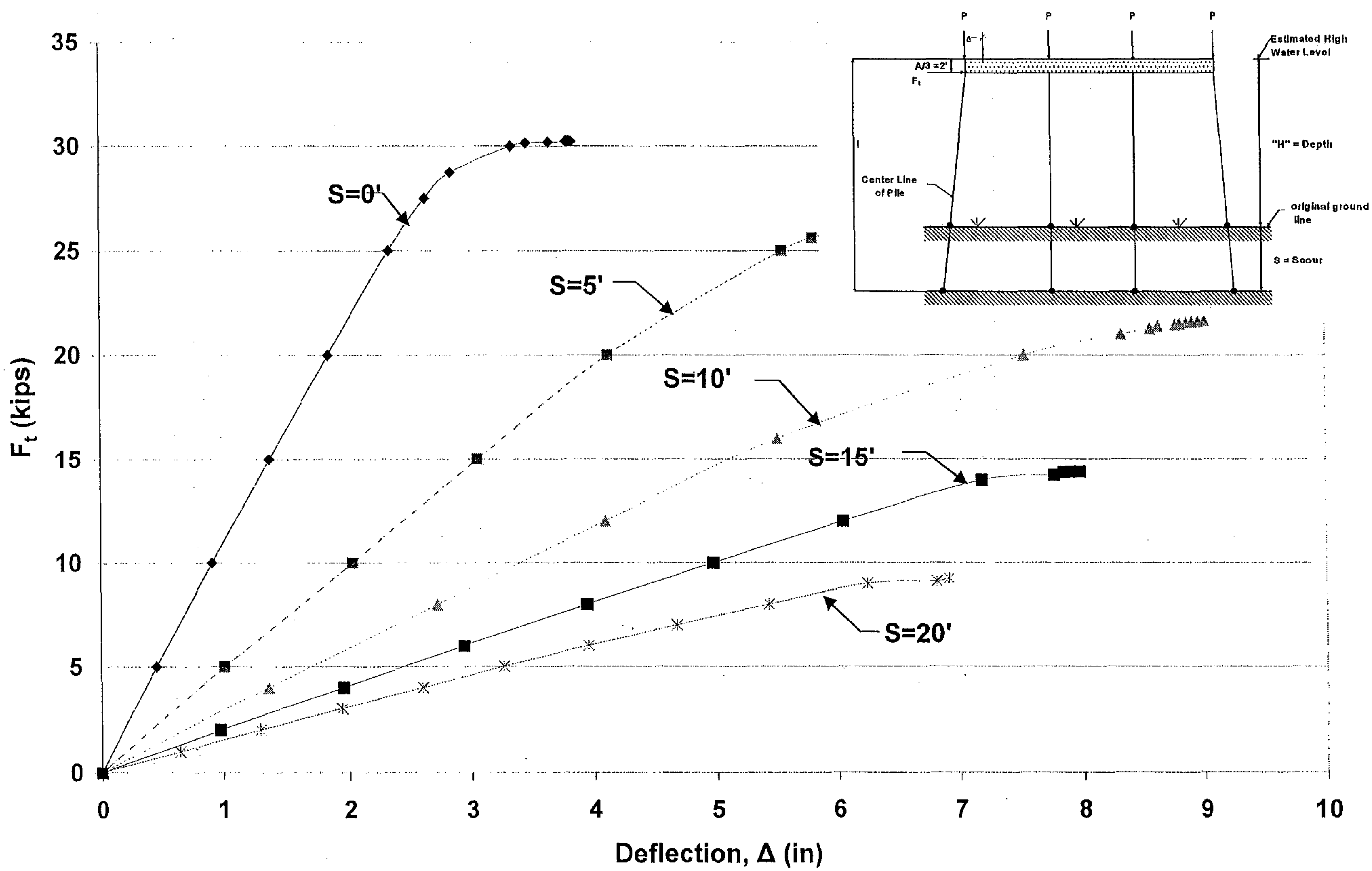


Figure A.29 HP10x42 Unbraced 4-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

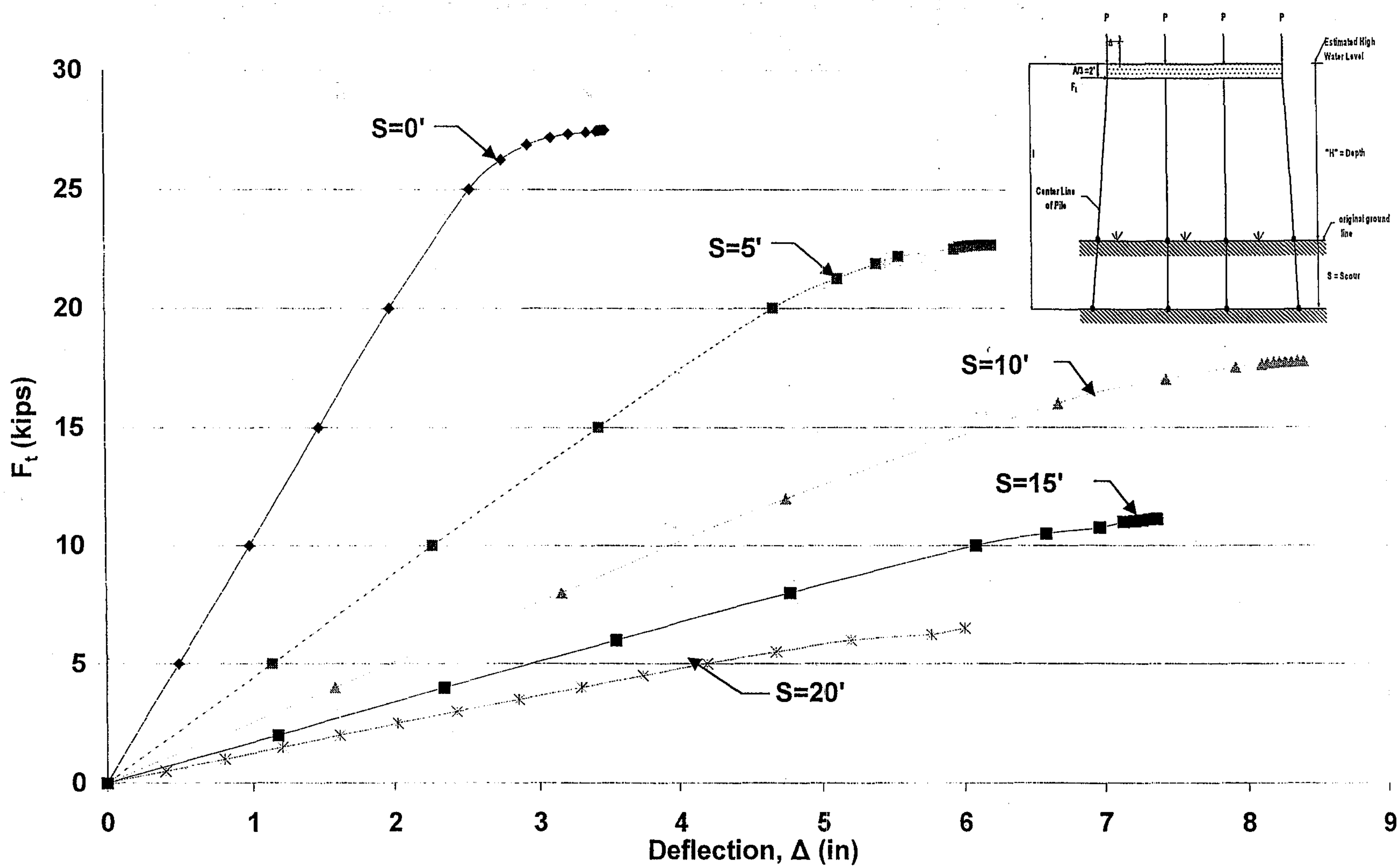


Figure A.30 HP10x42 Unbraced 4-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

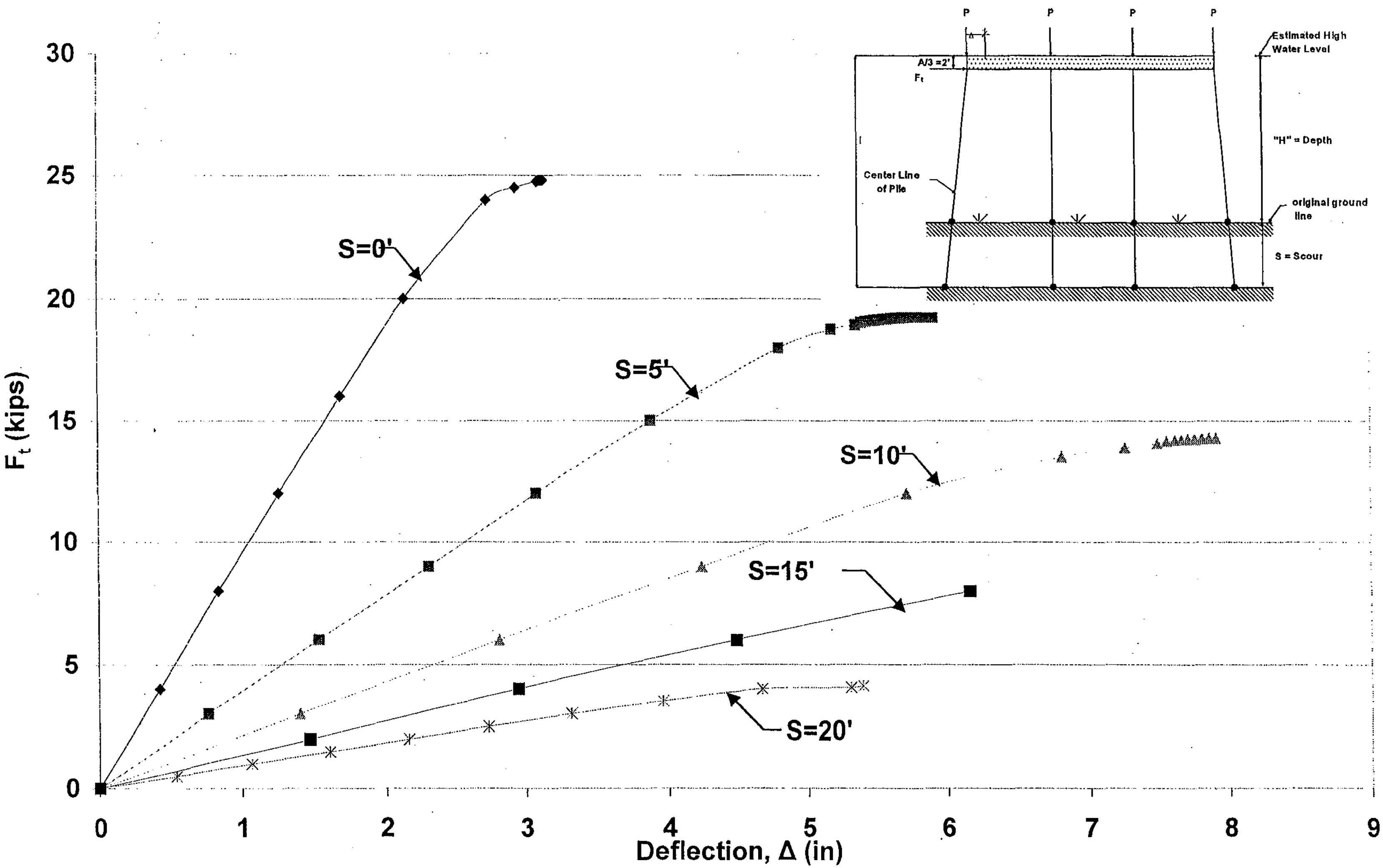


Figure A.31 HP10x42 Unbraced 4-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

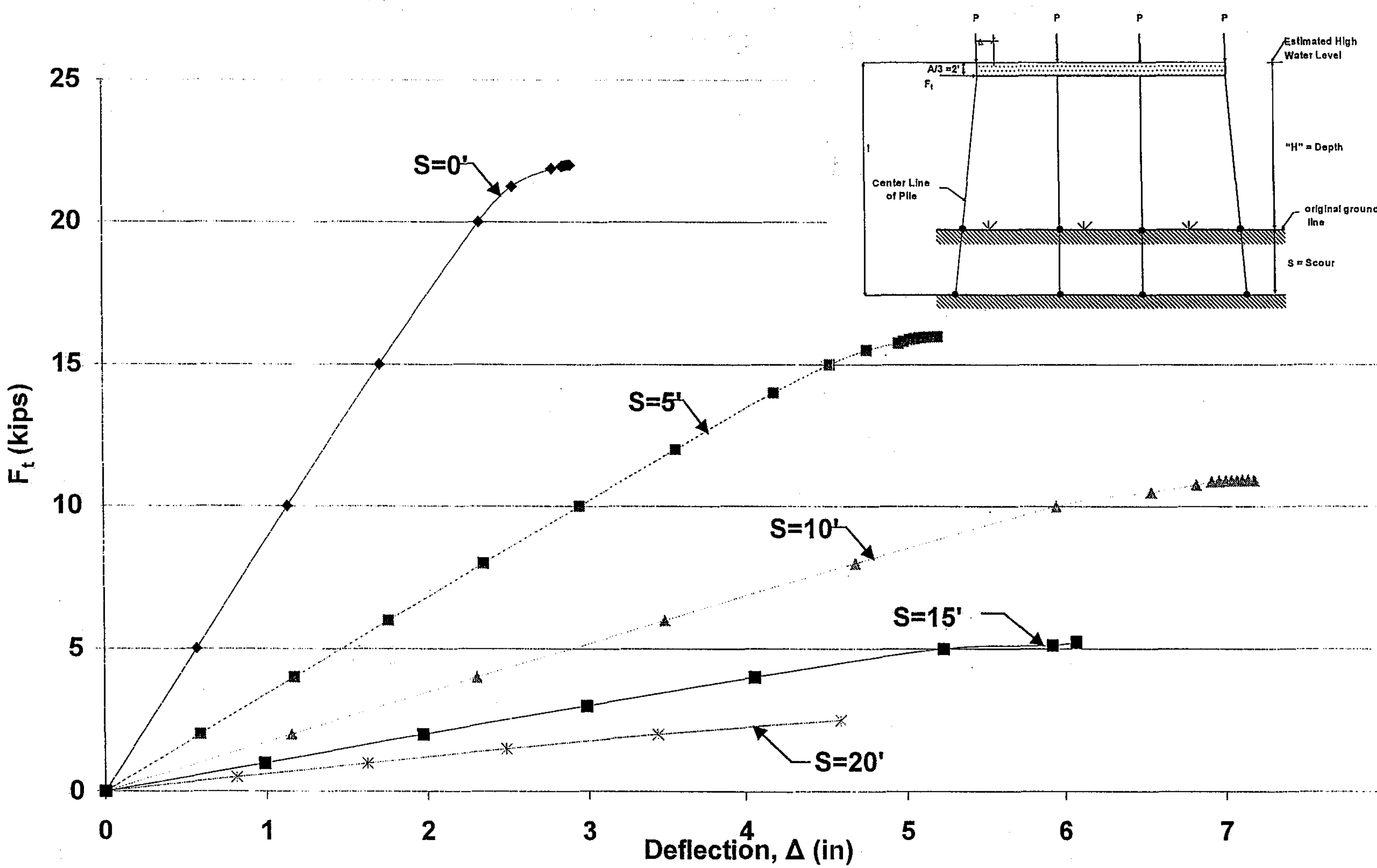


Figure A.32 Unbraced 4-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

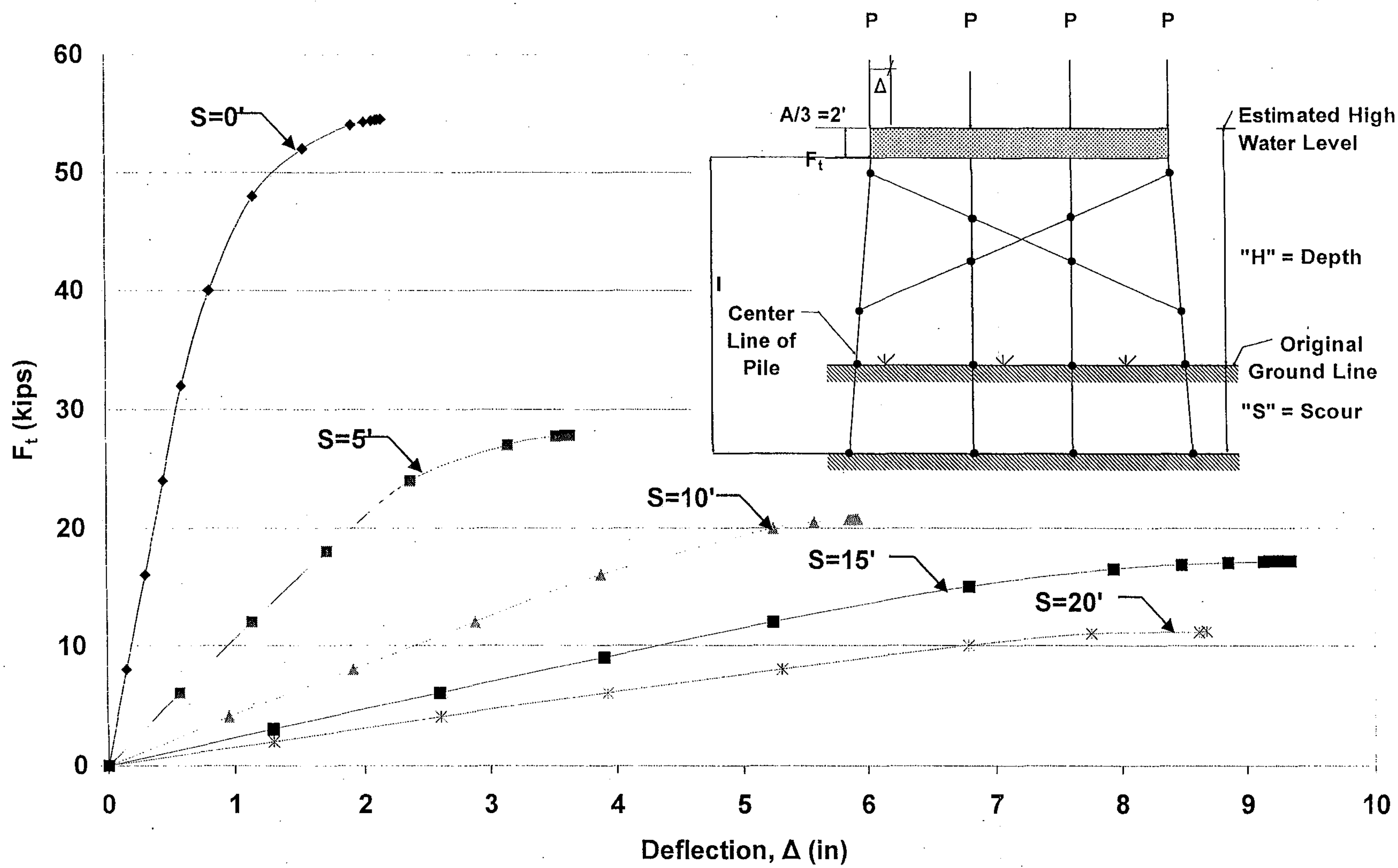


Figure A.33 HP10x42 X-Braced 4-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

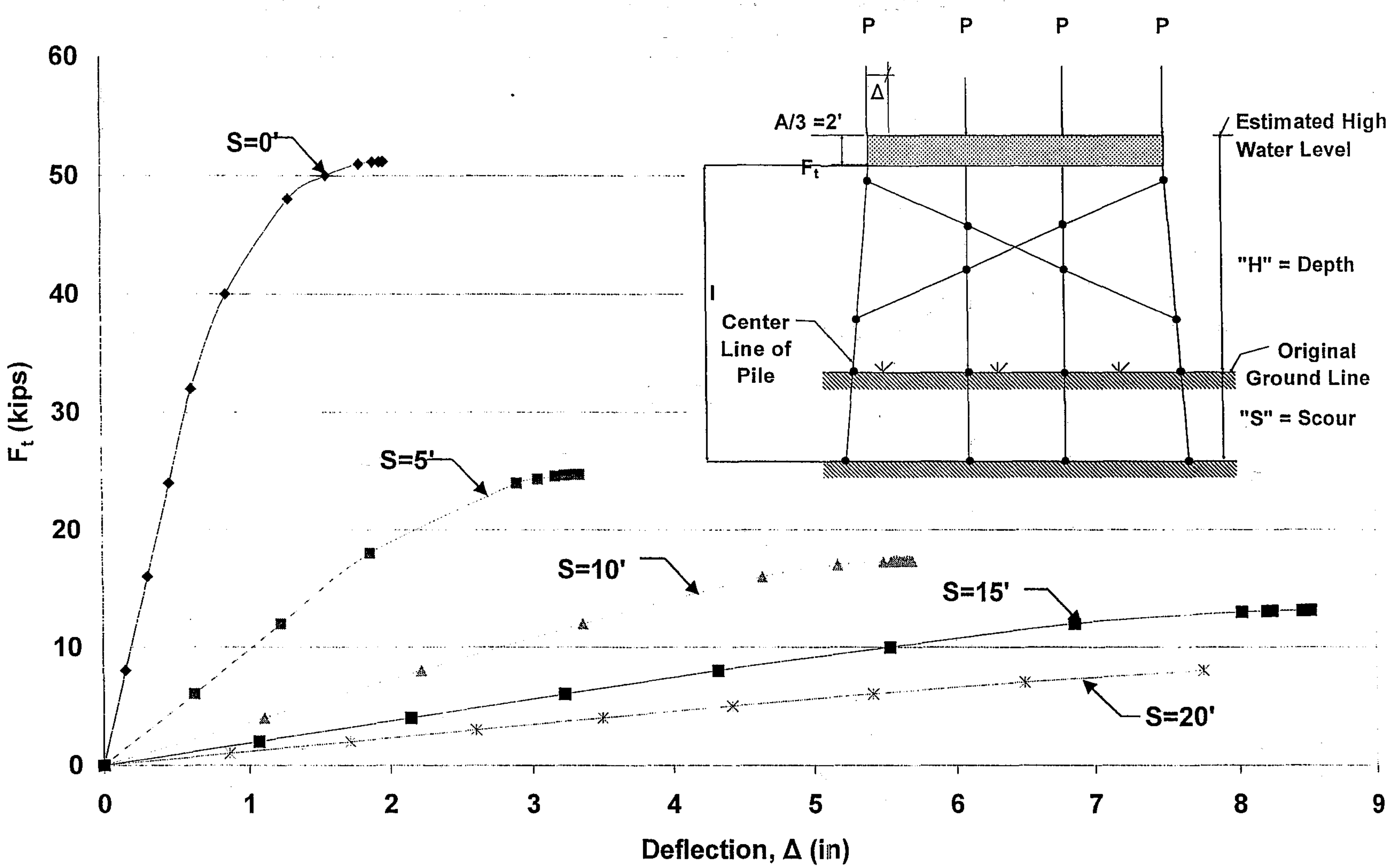


Figure A.34 HP10x42 X-Braced 4-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

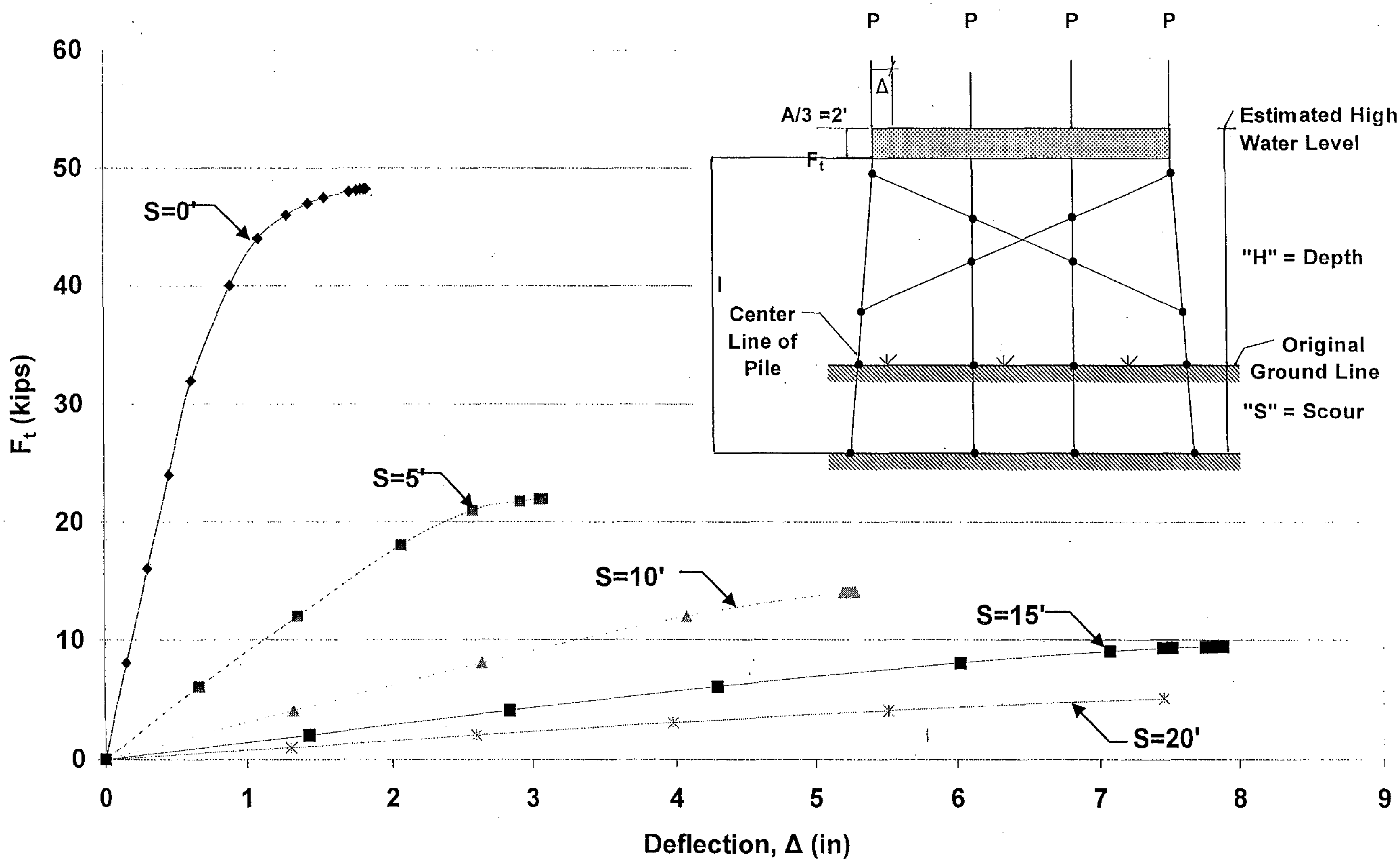


Figure A.35 HP10x42 X-Braced 4-Pile Bent with H=13', P=140kips, and A=6' Pushover Analysis Results

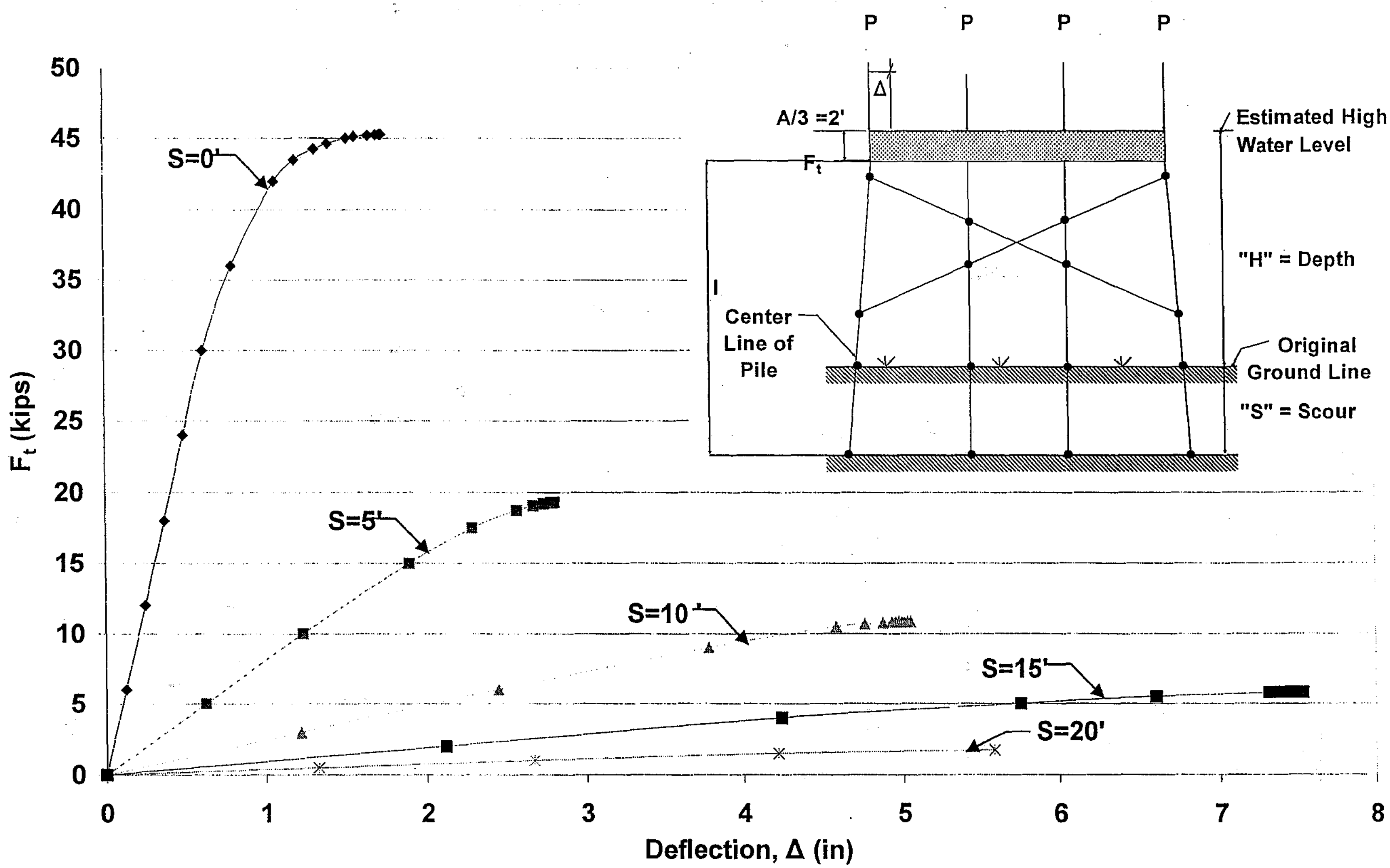


Figure A.36 HP10x42 X-Braced 4-Pile Bent with H=13', P=160 kips and A=6' Pushover Analysis Results

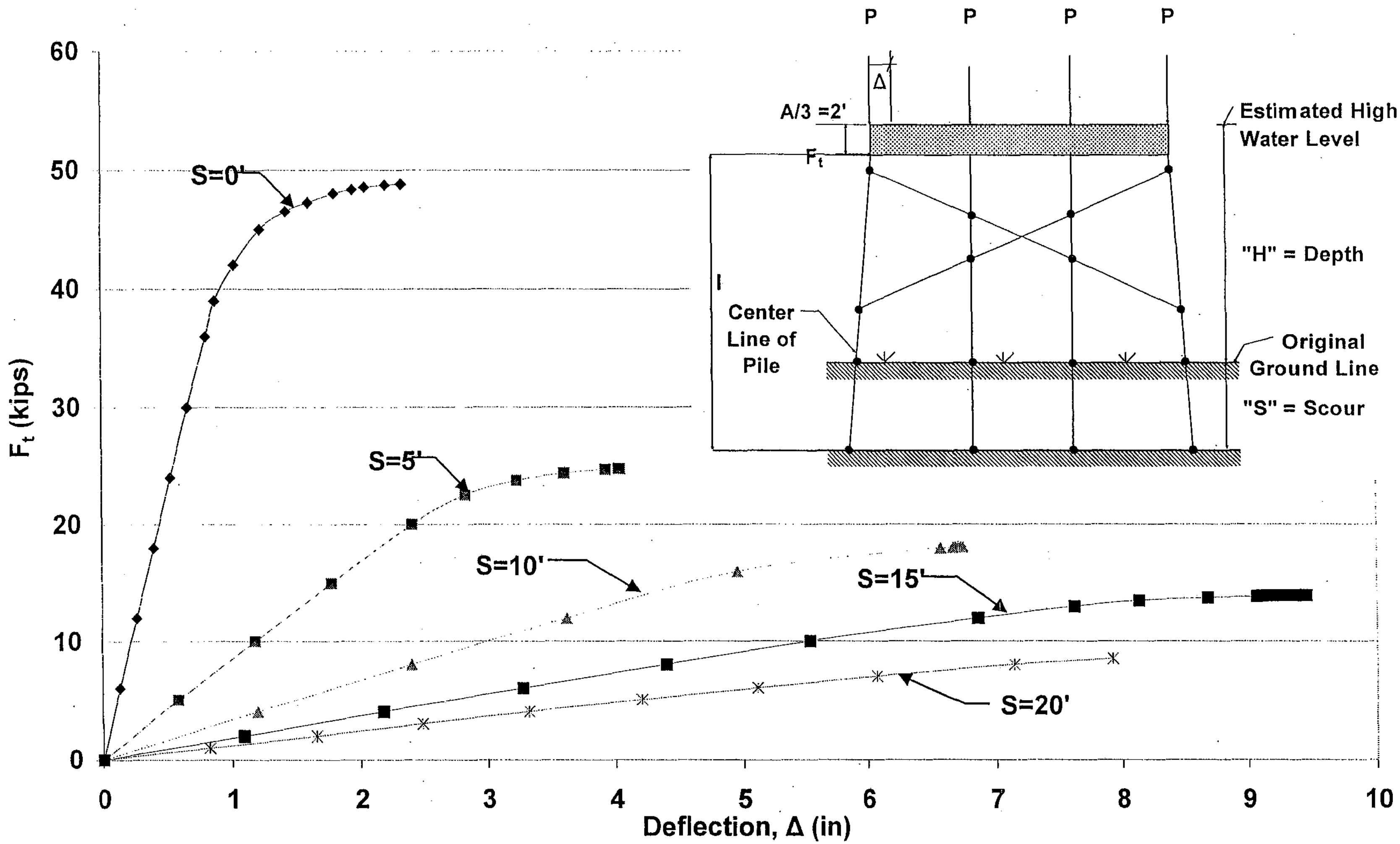


Figure A.37 HP10x42 X-Braced 4-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

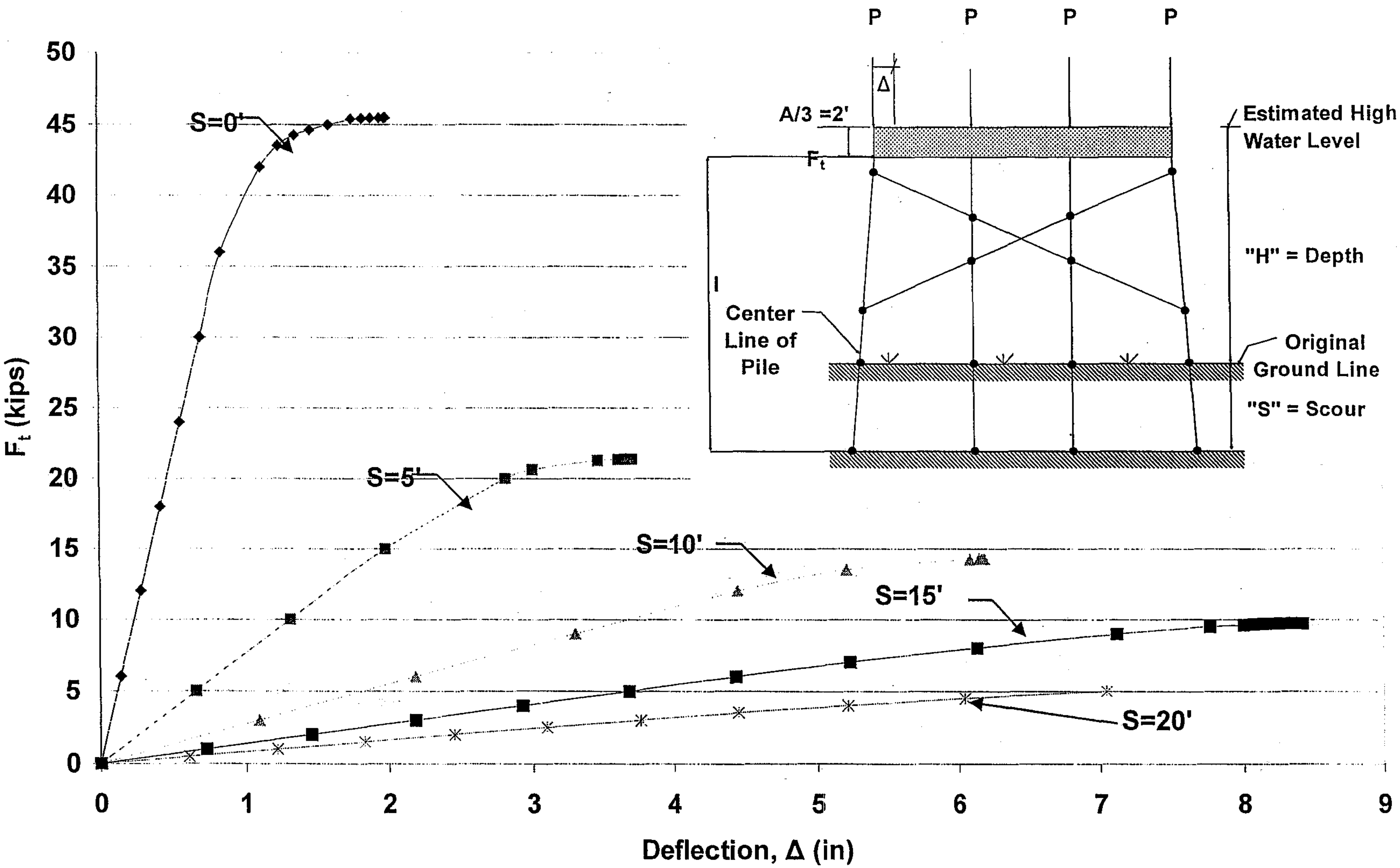


Figure A.38 HP10x42 X-Braced 4-Pile Bent with H=17',P=120kips, and A=6' Pushover Analysis Results

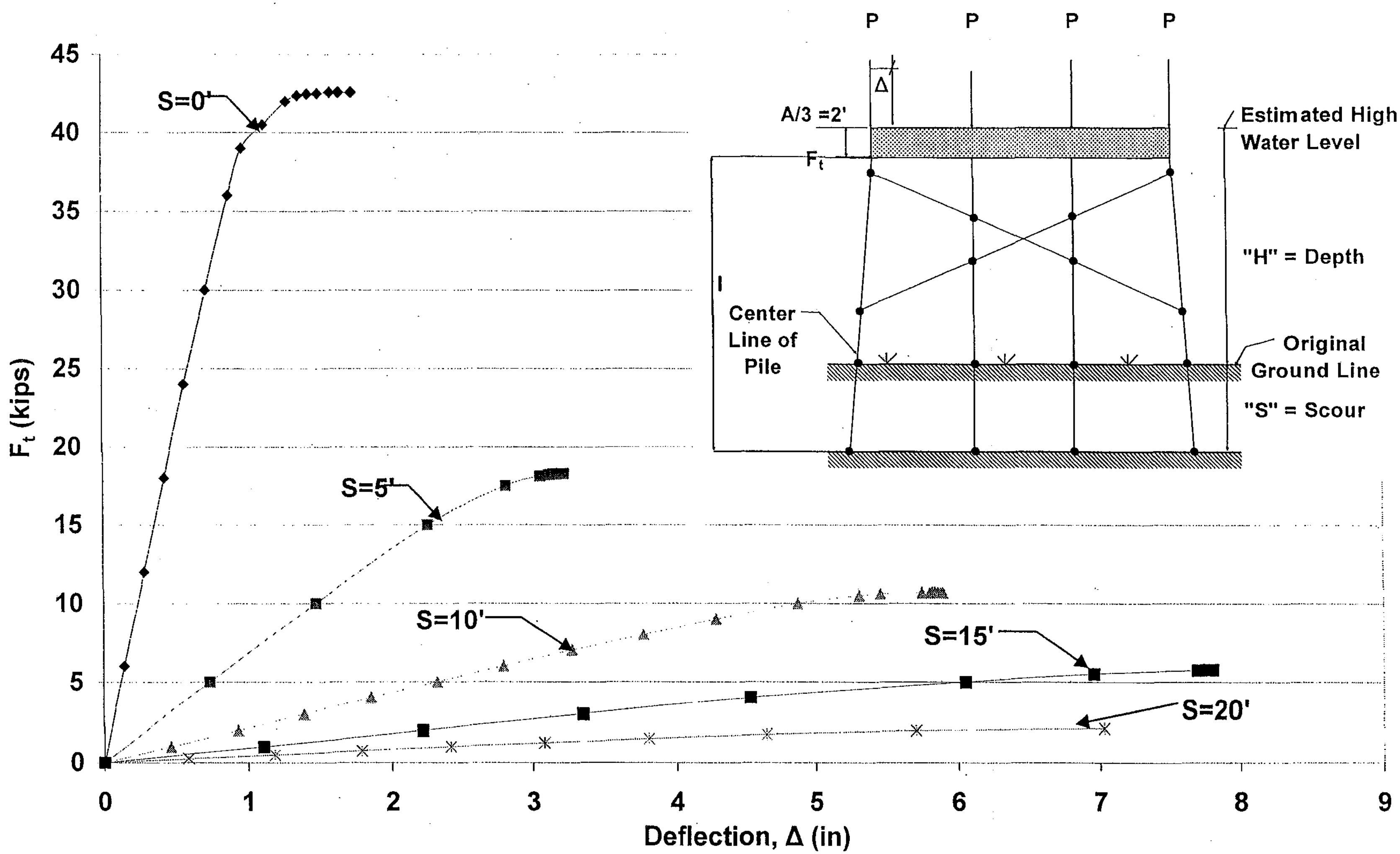


Figure A.39 HP10x42 X-Braced 4-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

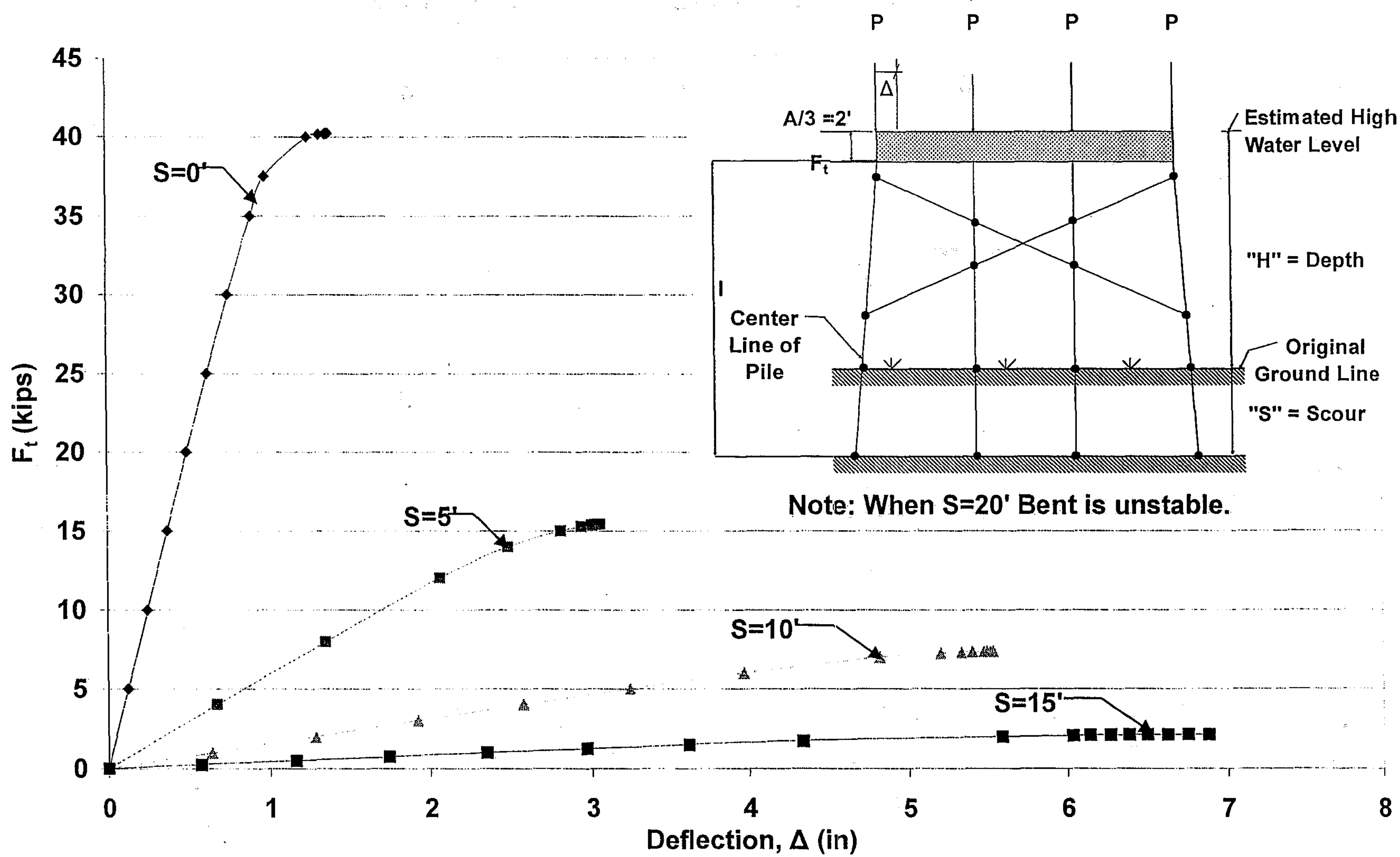


Figure A.40 HP10x42 X-Braced 4-Pile Bent with H=17', P=160kips, and A=6'
Pushover Analysis Results

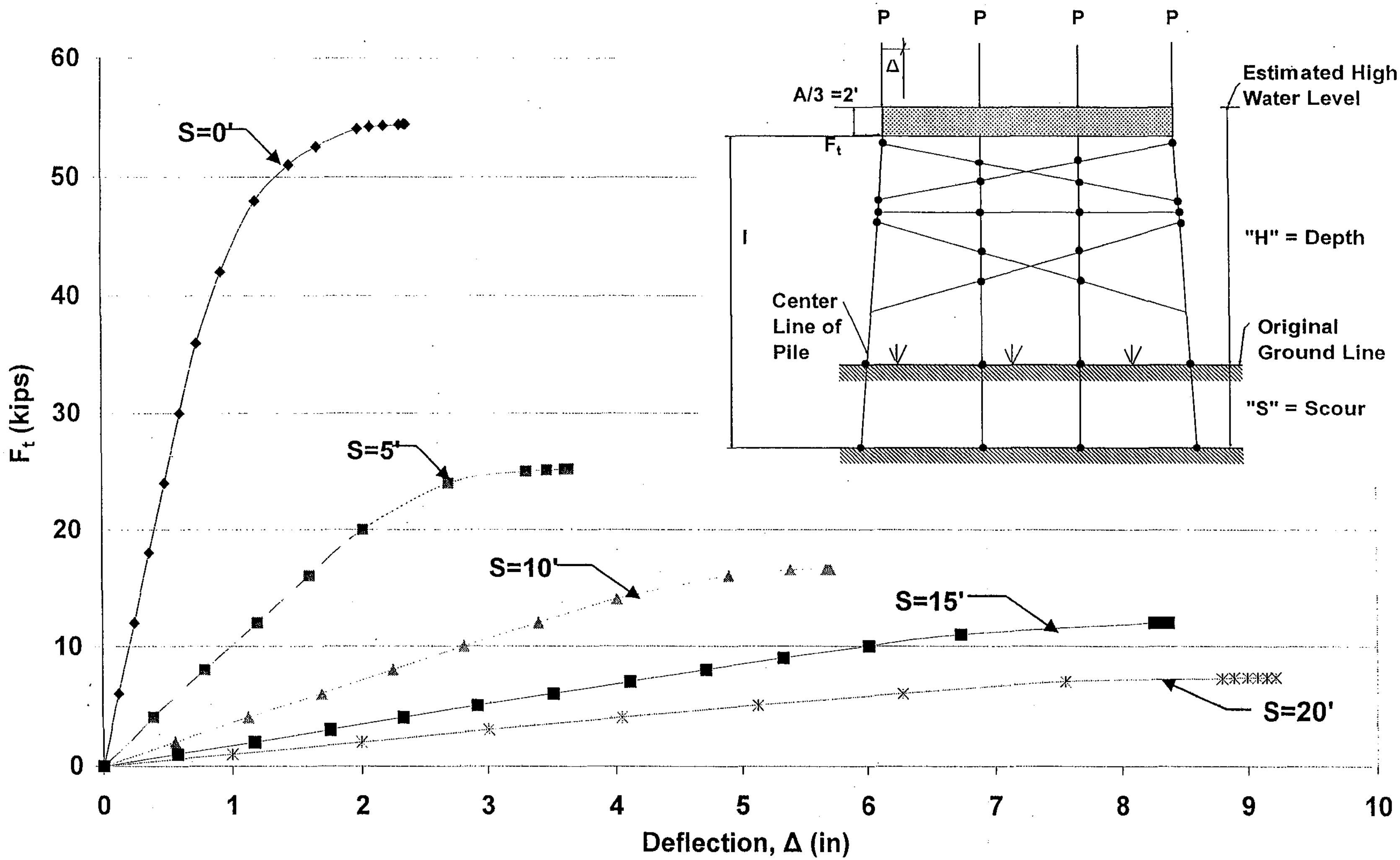


Figure A.41 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

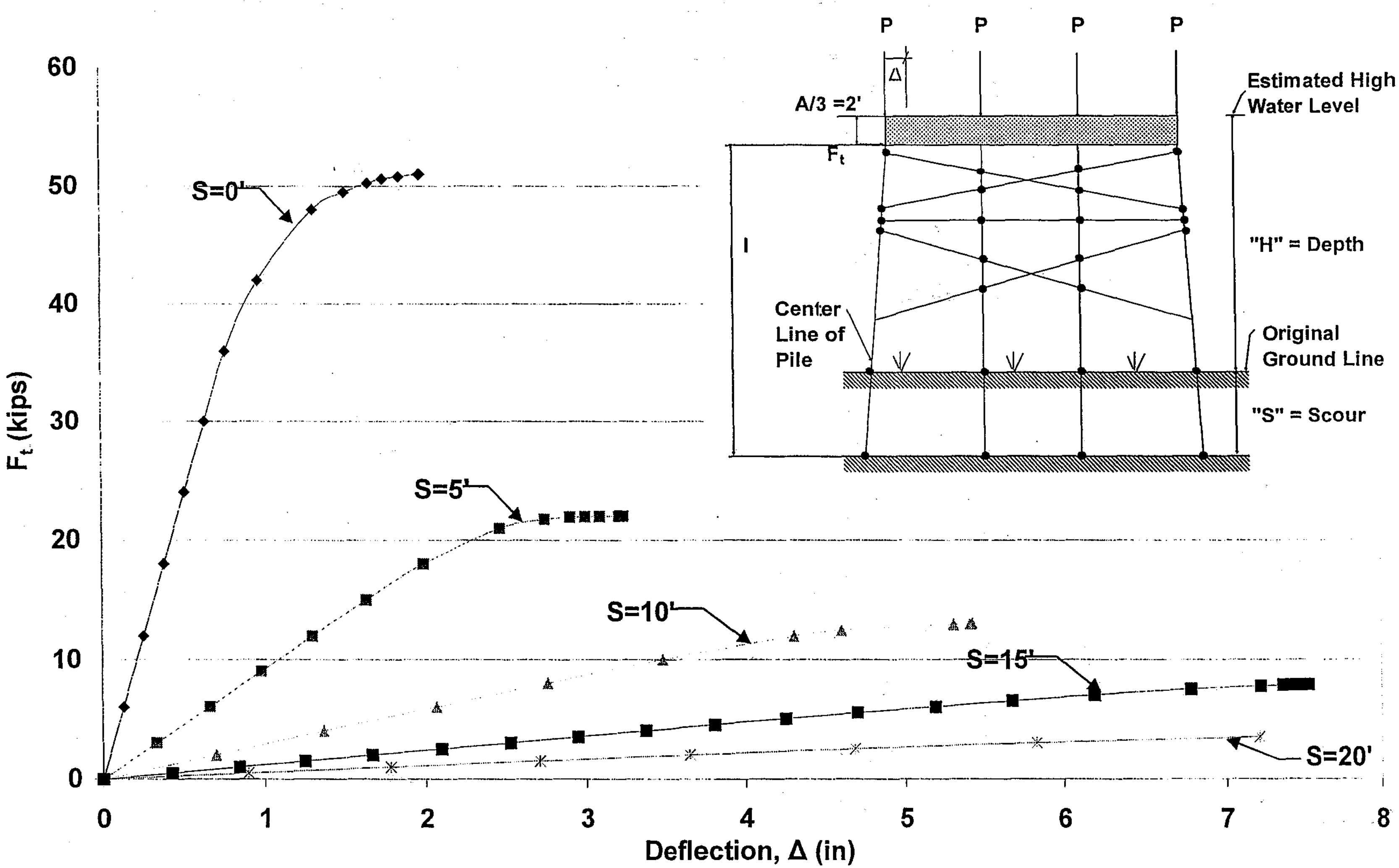


Figure A.42 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=120kips, and A=6' Pushover Analysis Results

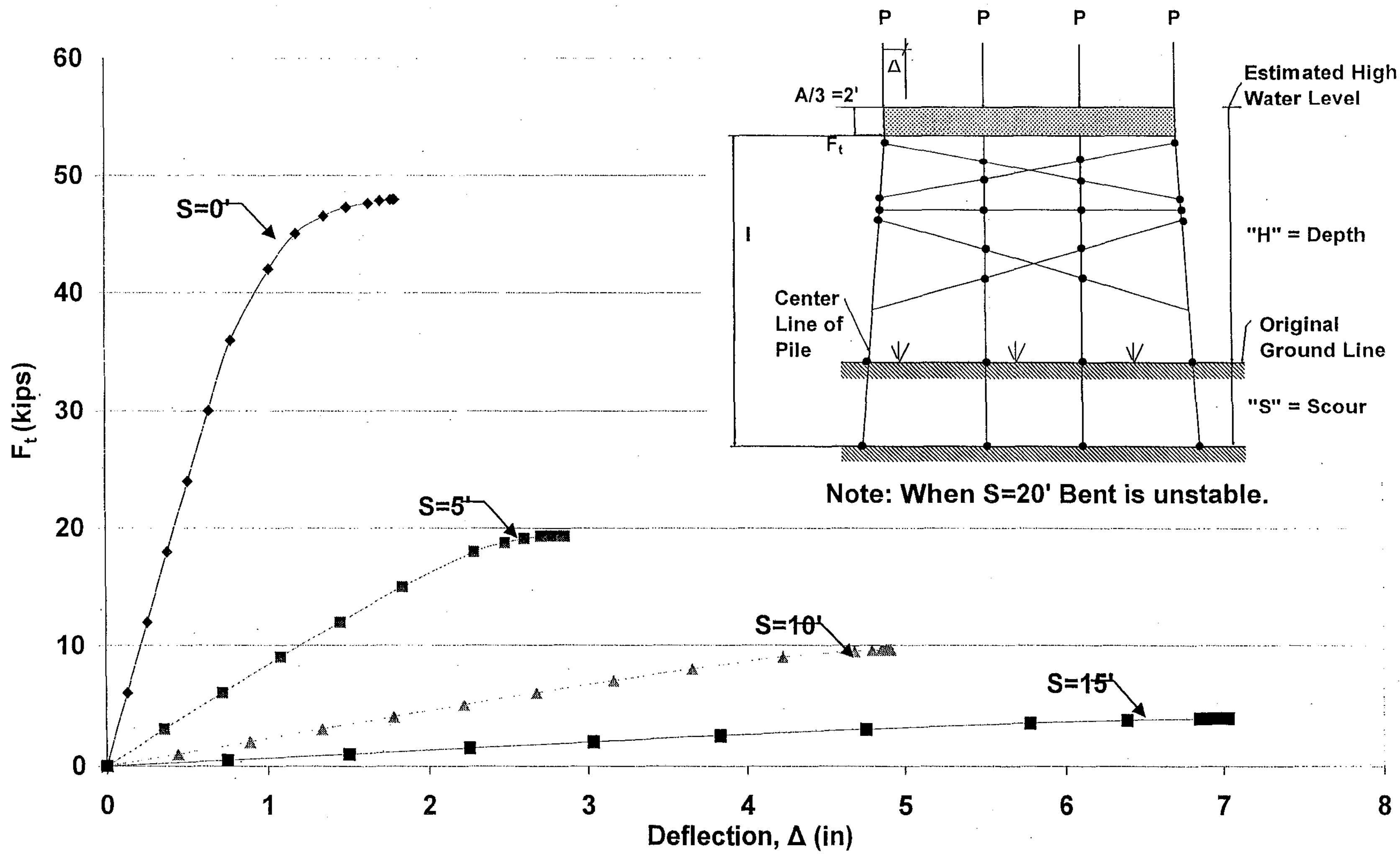


Figure A.43 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=140kips,and A=6' Pushover Analysis Results

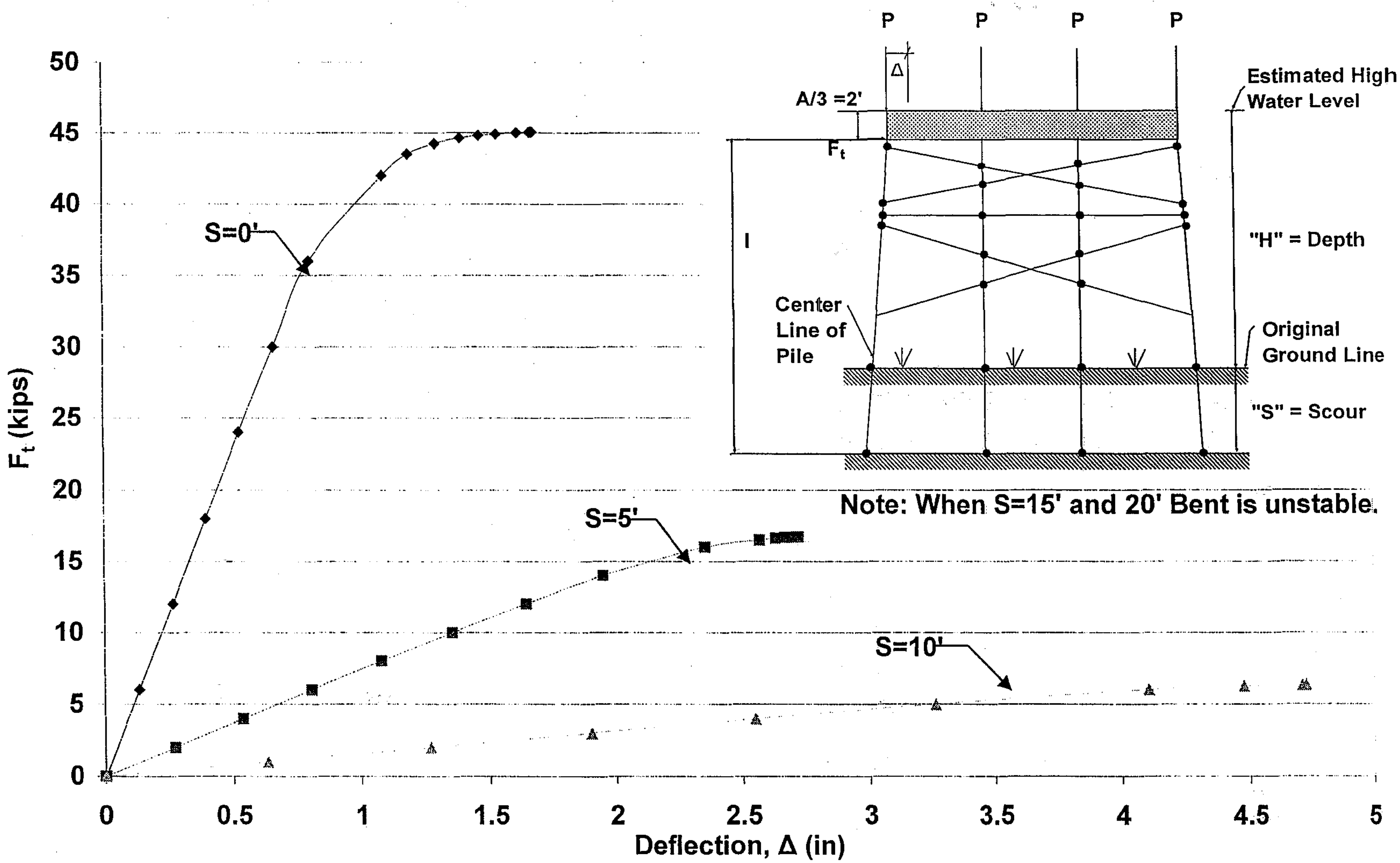


Figure A.44 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=160kips, and A=6' Pushover Analysis Results

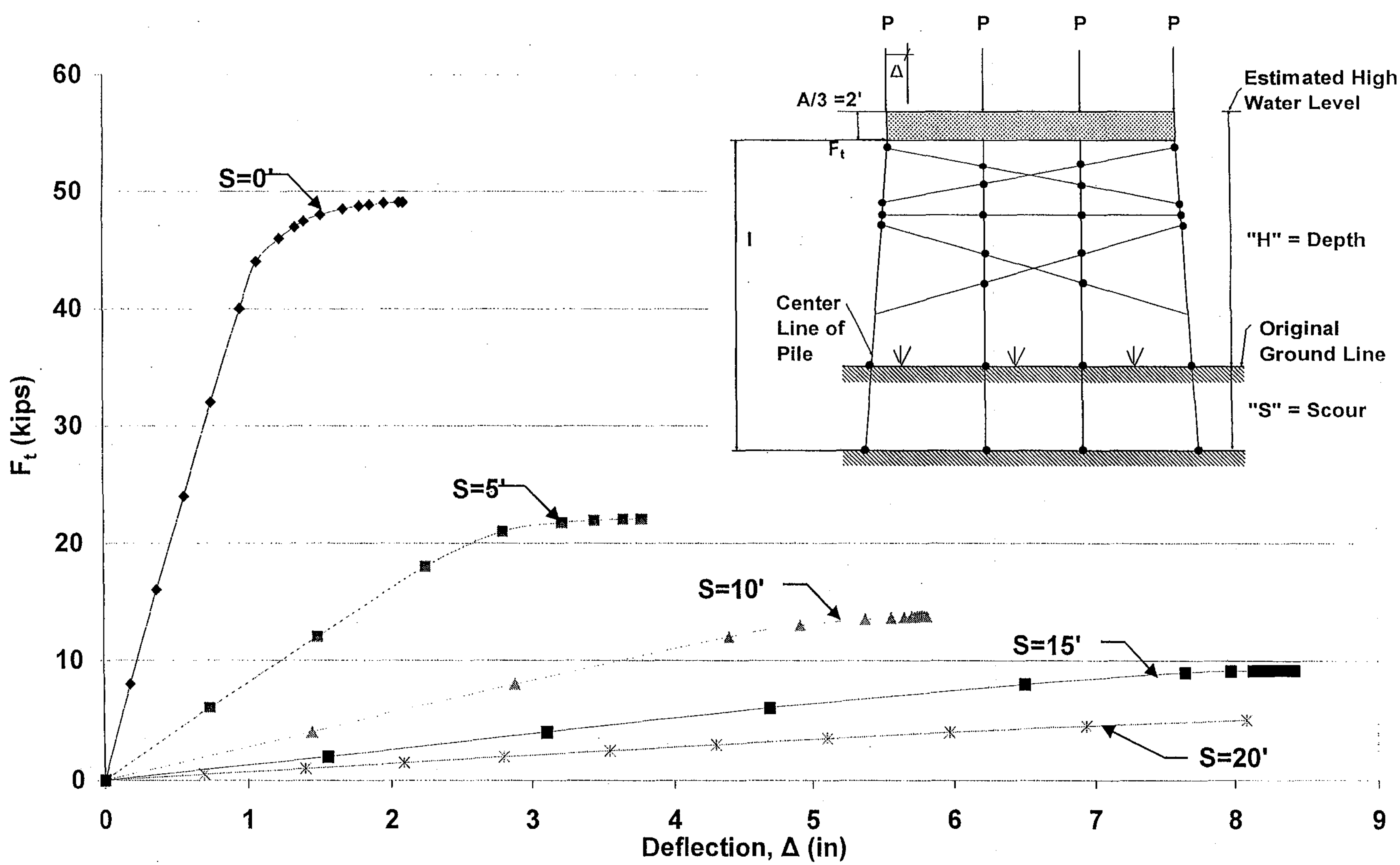


Figure A.45 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=100kips, and A=6' Pushover Analysis Results

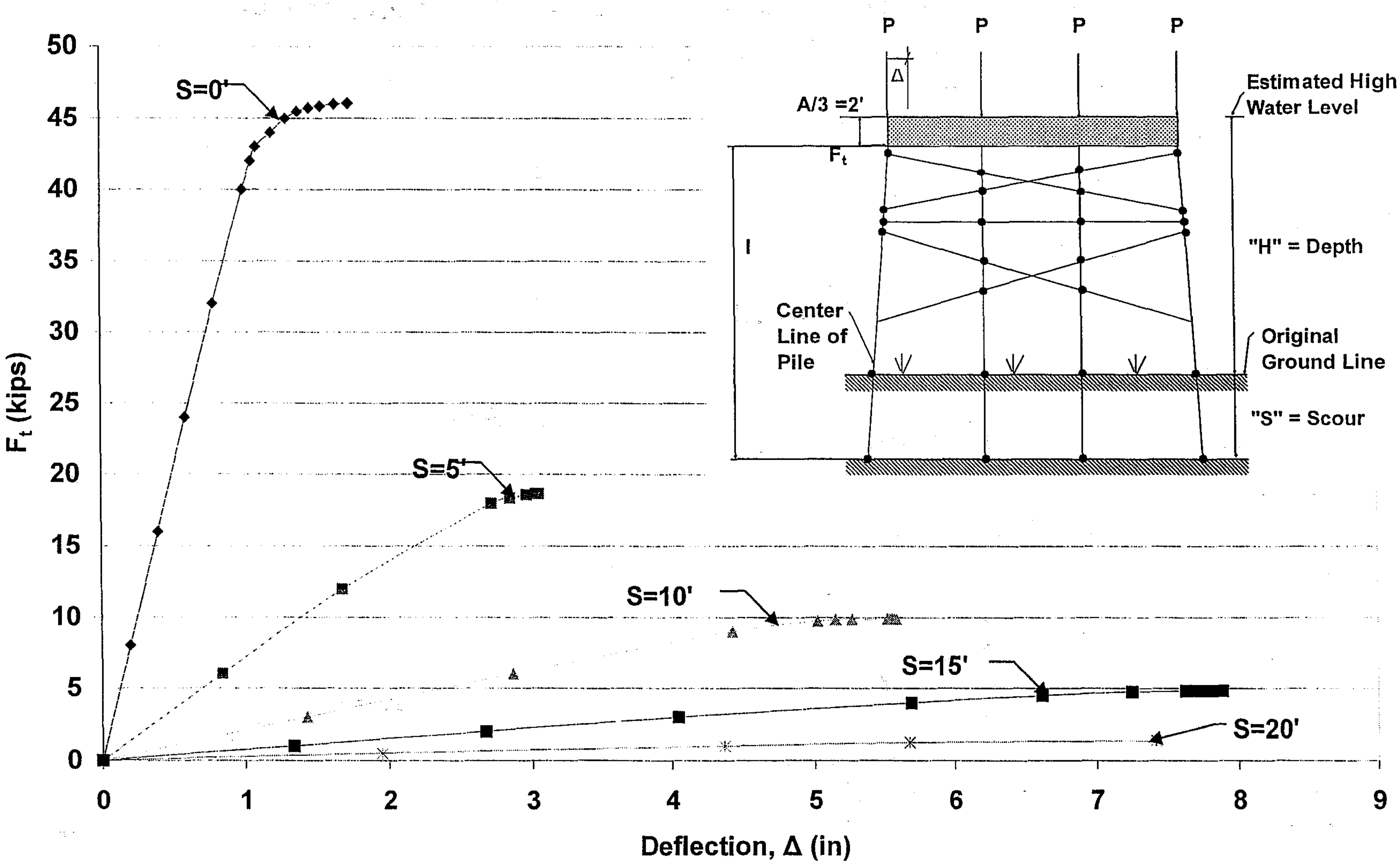


Figure A.46 HP10x42 Two-Story X-Braced 4-Pile bent with H=25',P=120kips, and A=6' Pushover Analysis Results

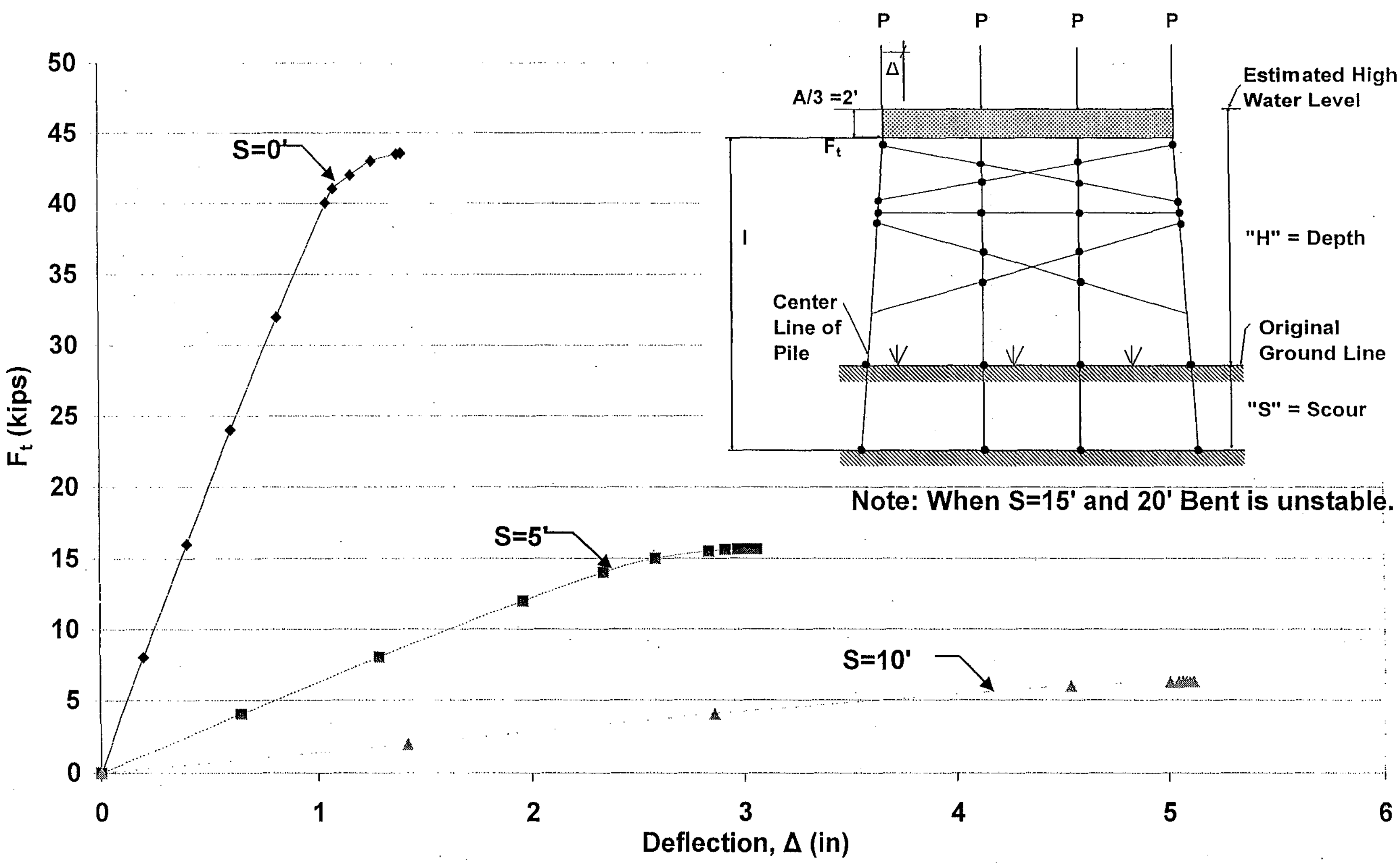


Figure A.47 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=140kips, and A=6' Pushover Analysis Results

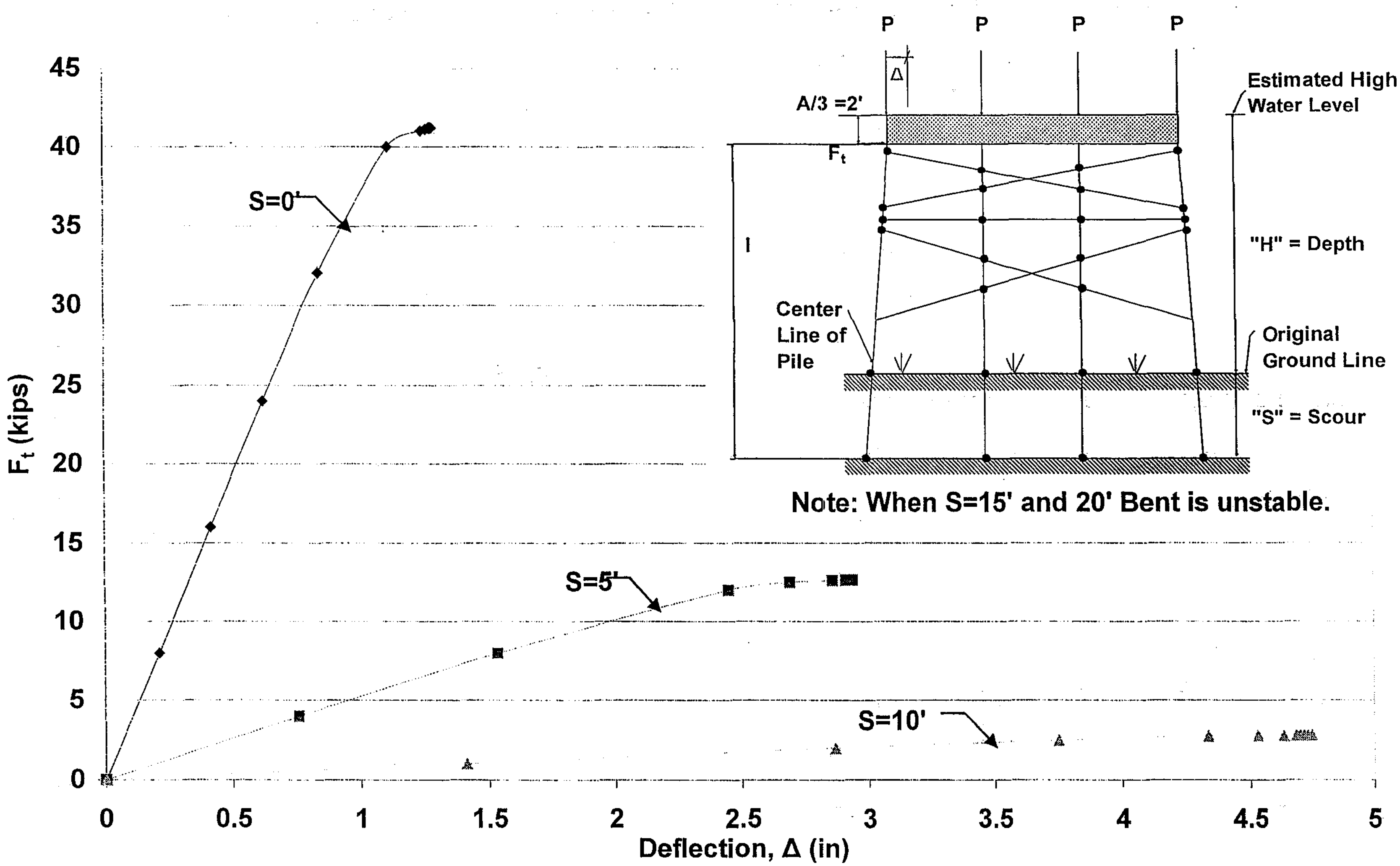


Figure A.48 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=160kips,and A=6'
Pushover Analysis Results

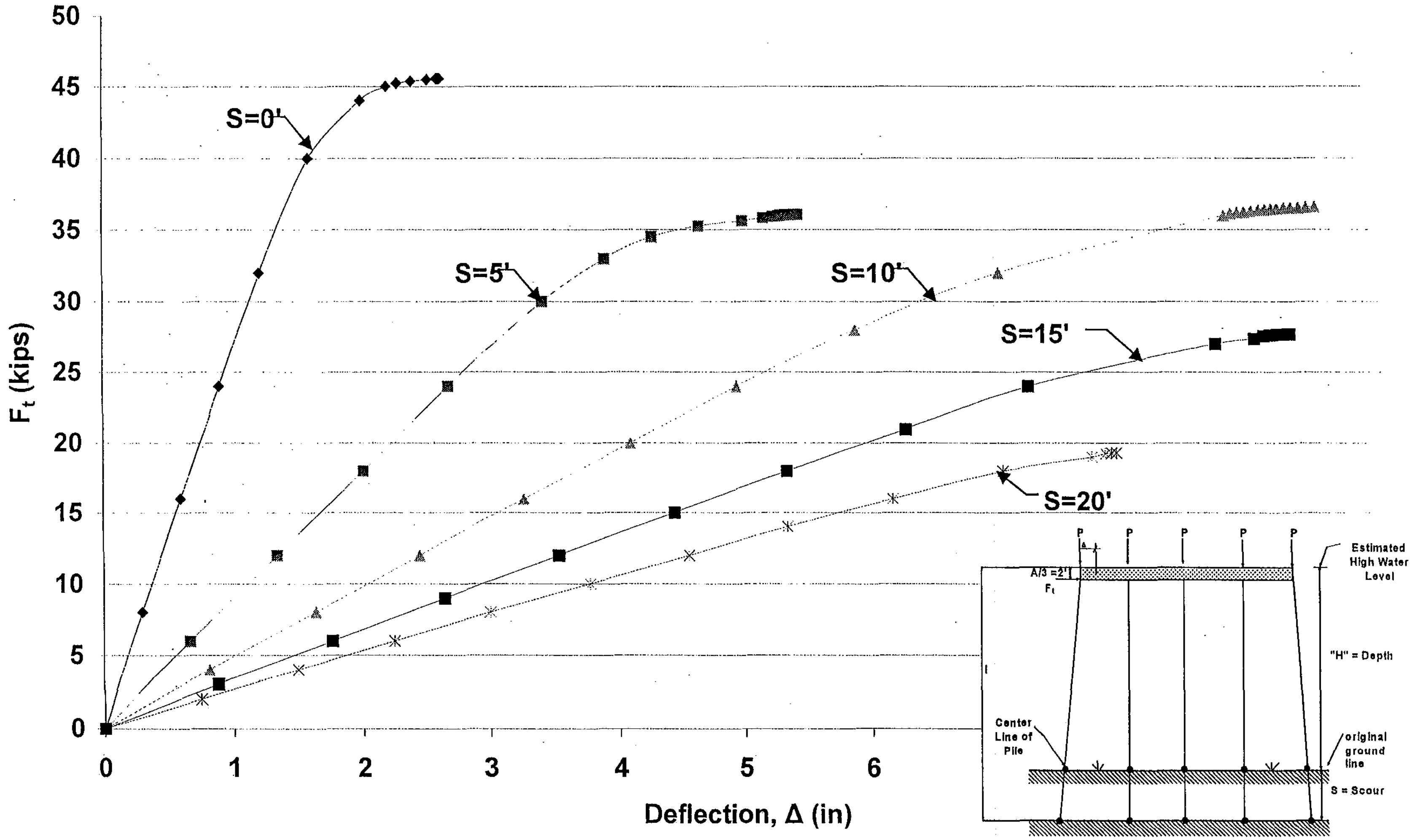


Figure A.49 HP10x42 Unbraced 5-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

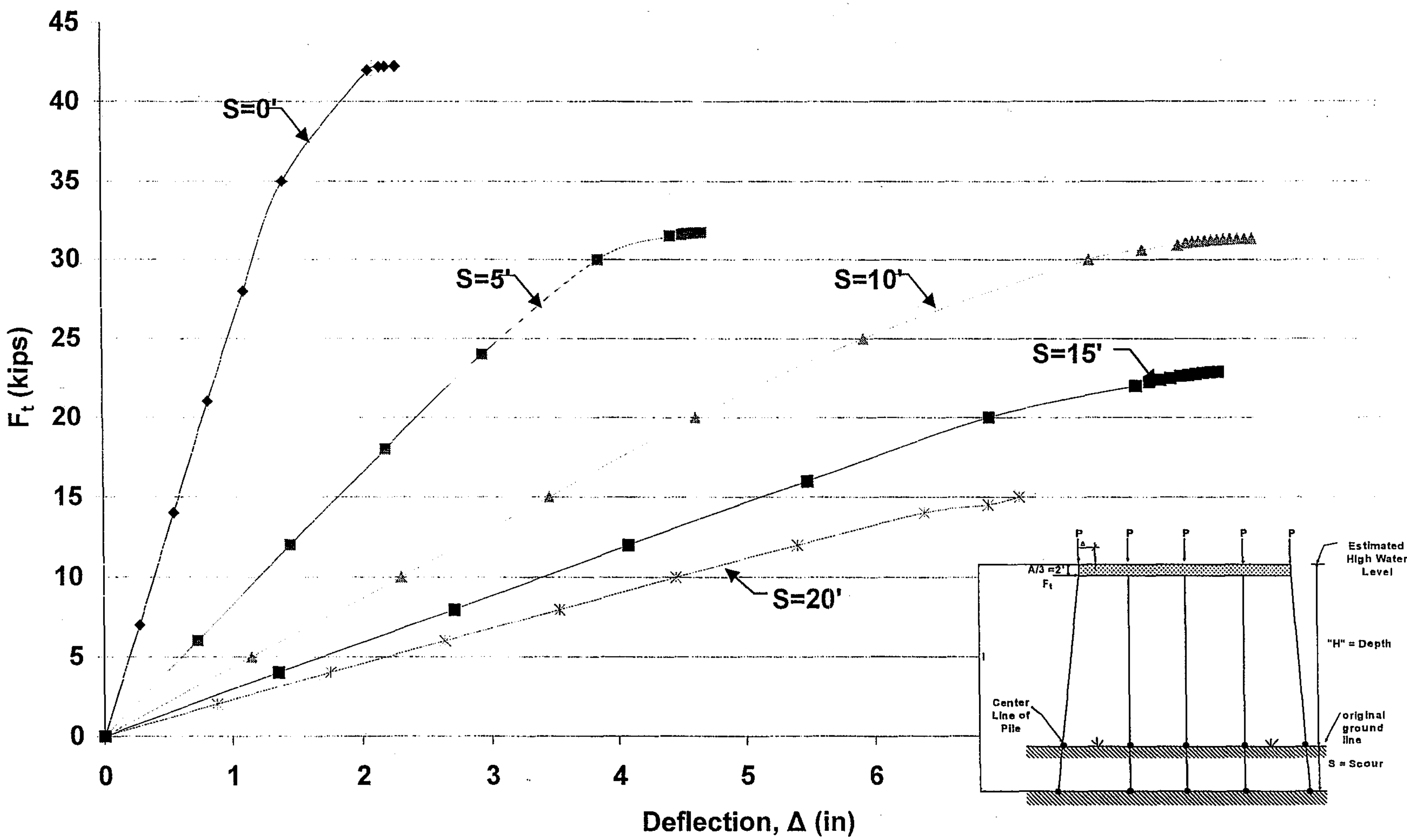


Figure A.50 HP10x42 Unbraced 5-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

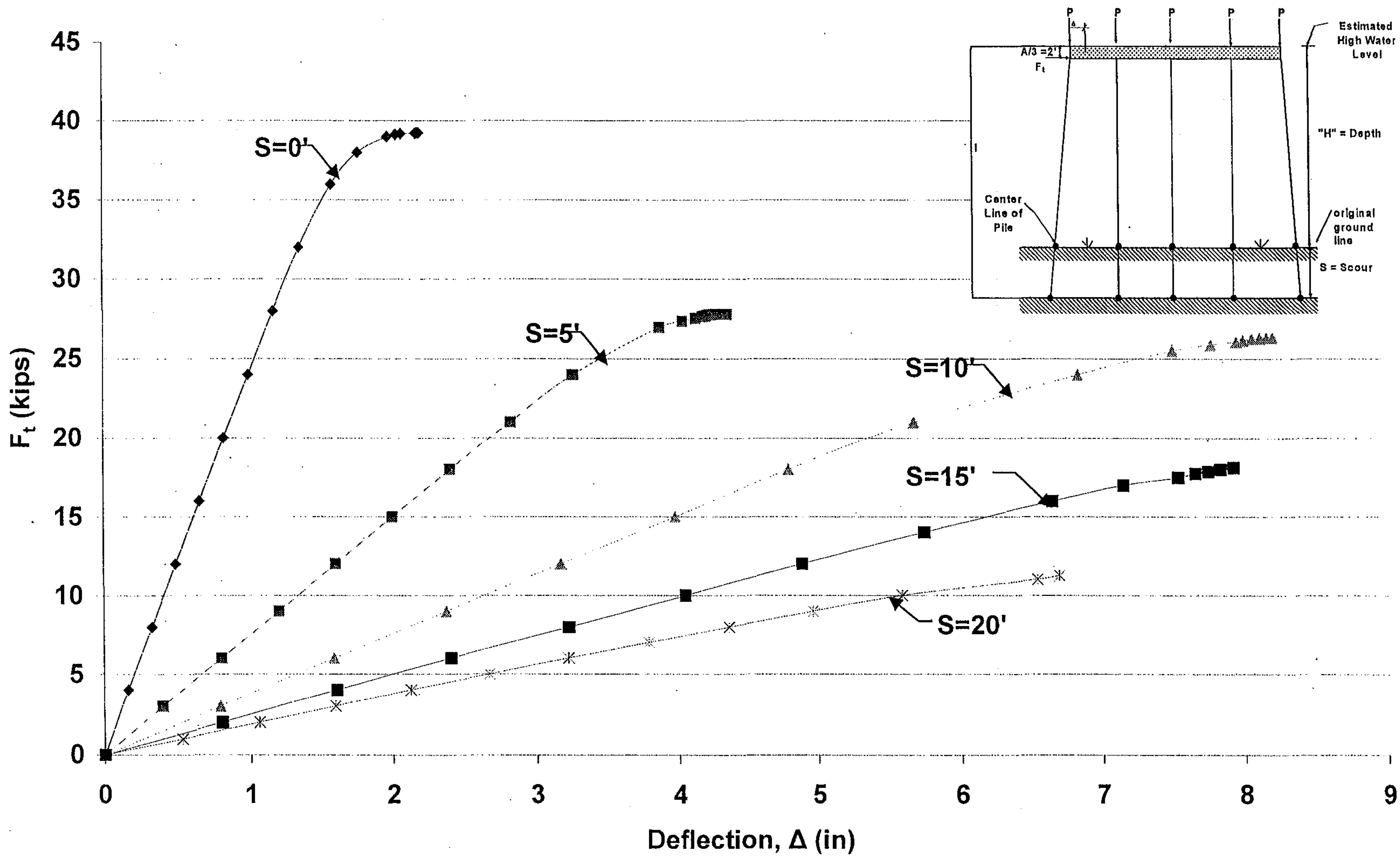


Figure A.51 HP10x42 Unbraced 5-Pile Bent with H=10', P=140kips and A=6'
Pushover Analysis Results

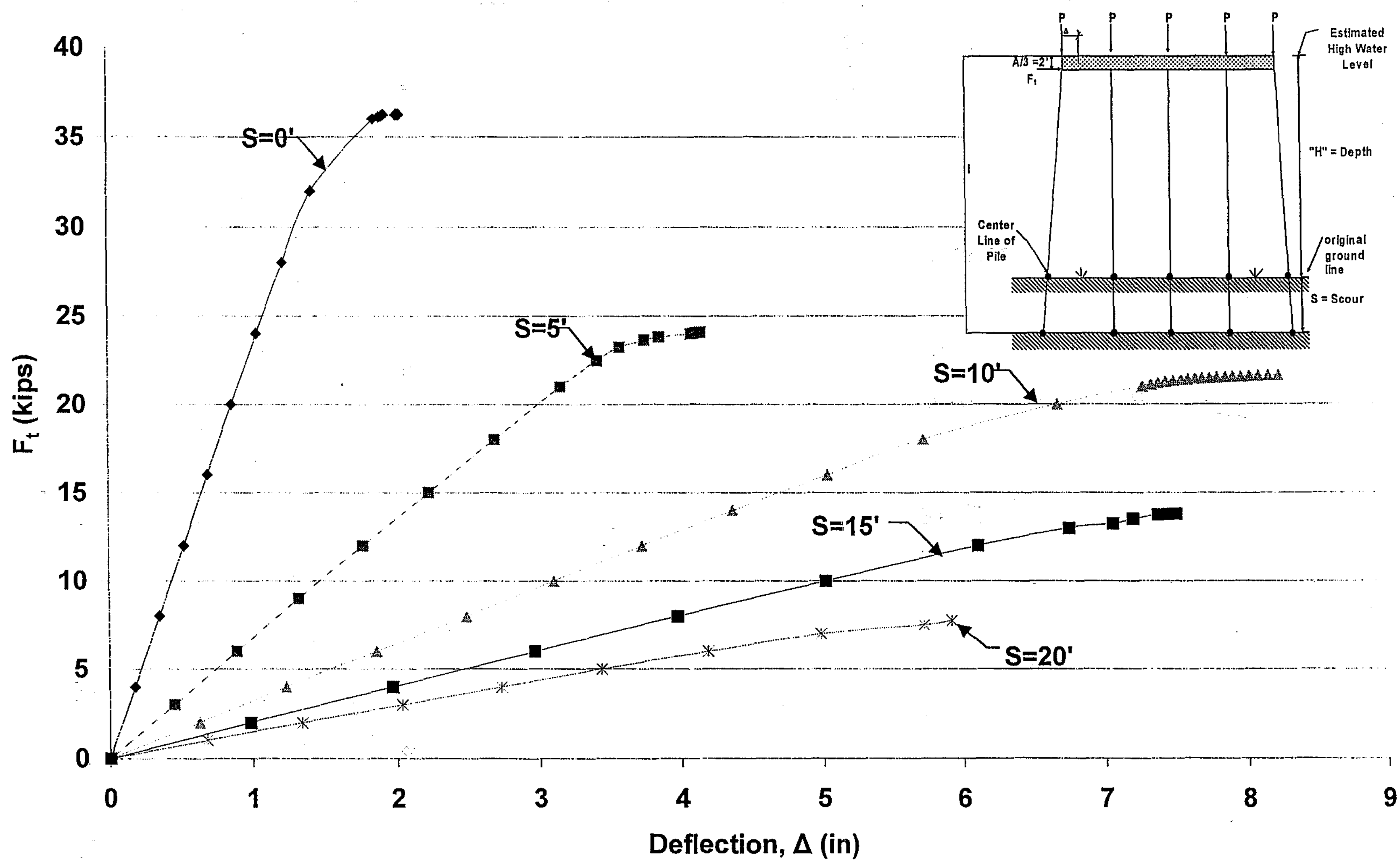


Figure A.52 HP10x42 Unbraced 5-Pile Bent with H=10', P=160kips and A=6' Pushover Analysis Results

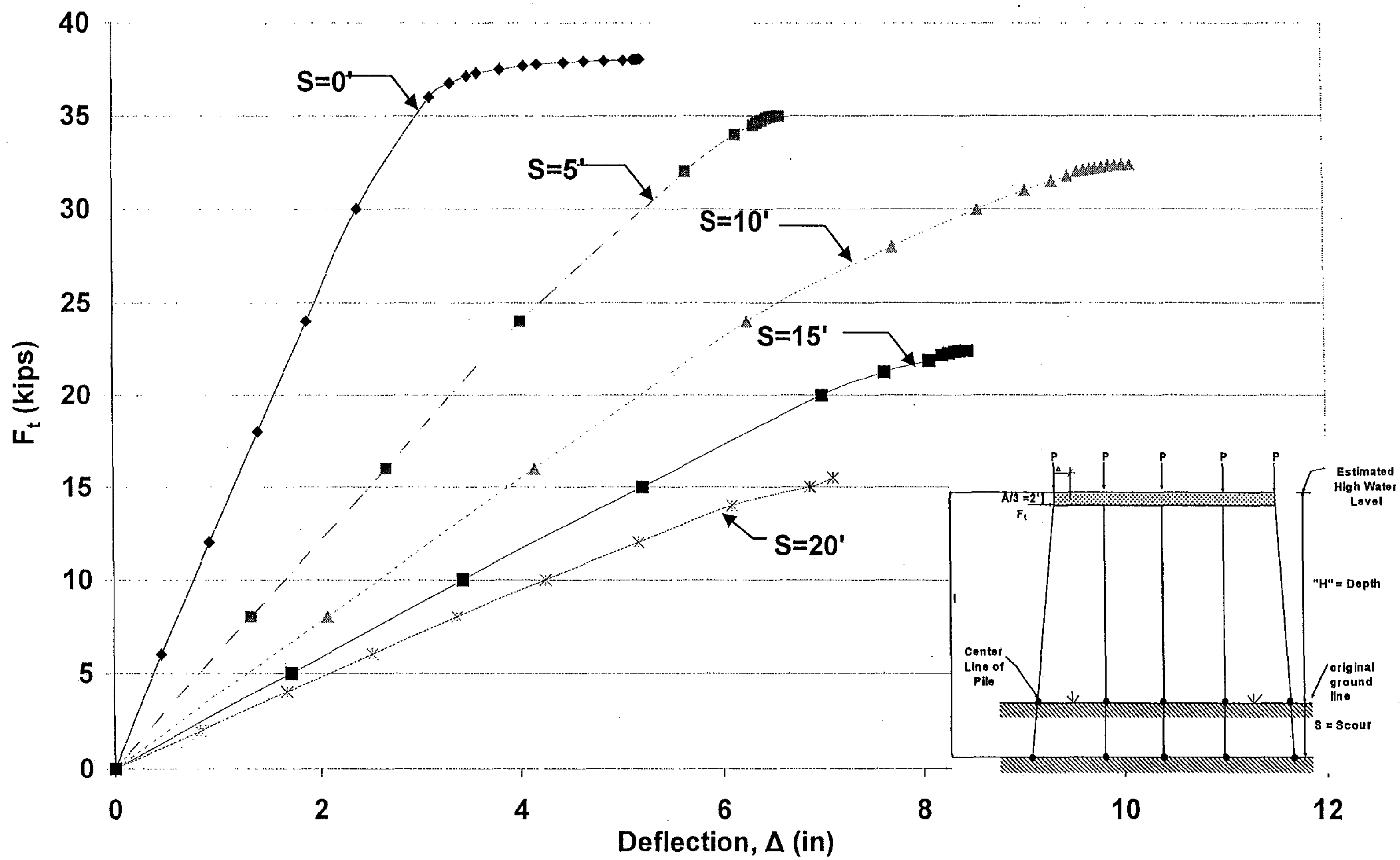


Figure A.53 HP10x42 Unbraced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

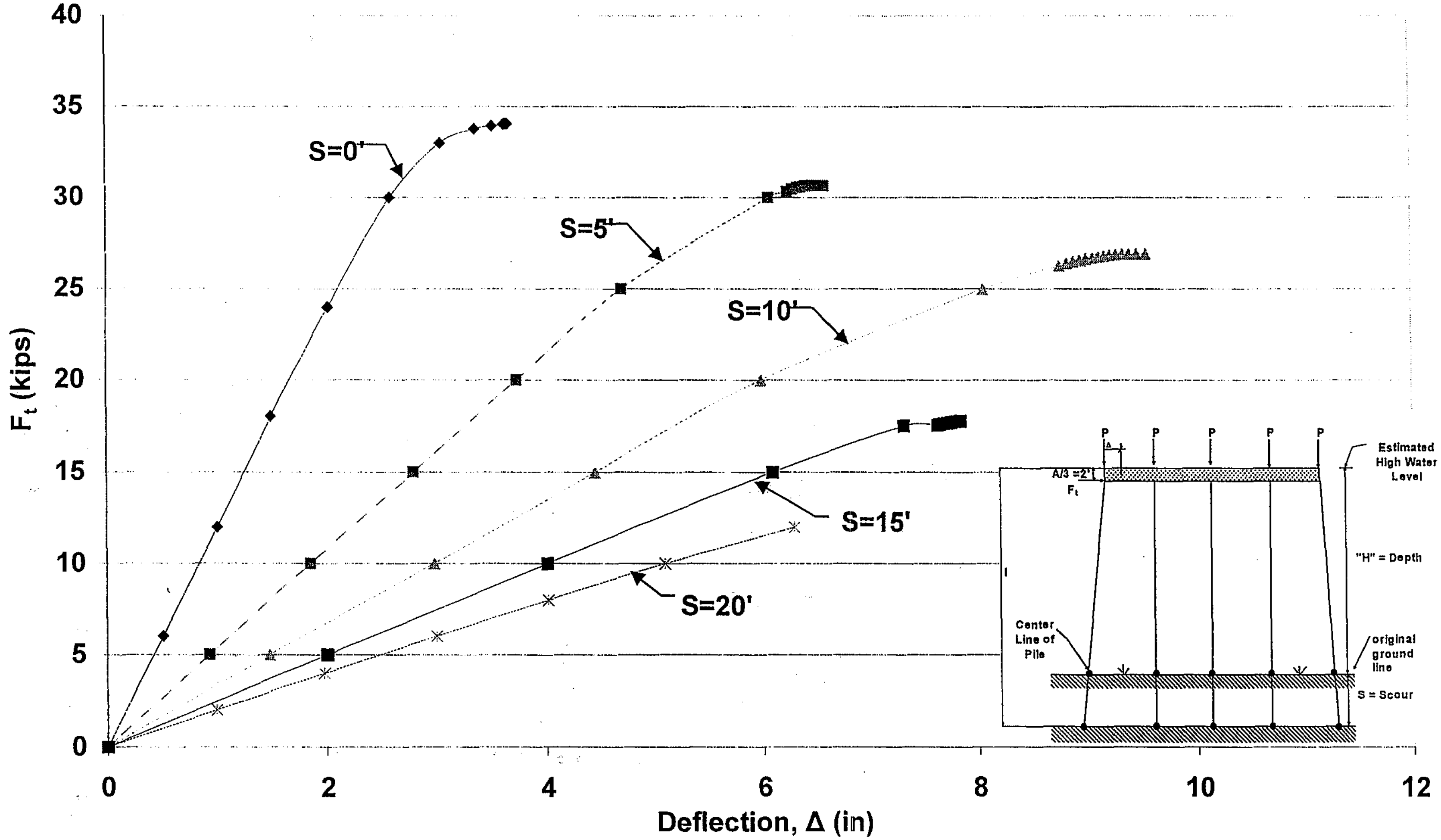


Figure A.54 HP10x42 Unbraced 5-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

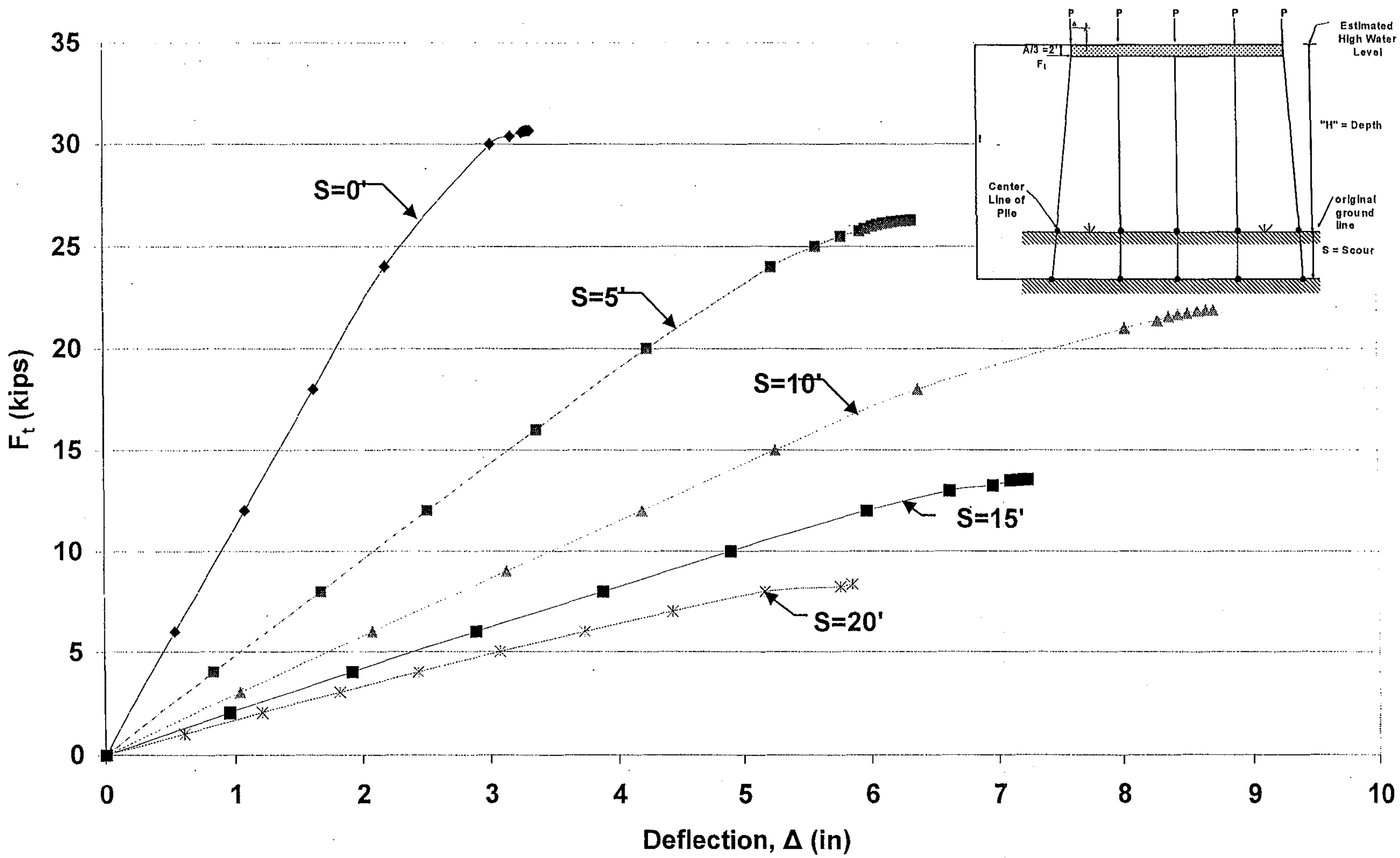


Figure A.55 HP10x42 Unbraced 5-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

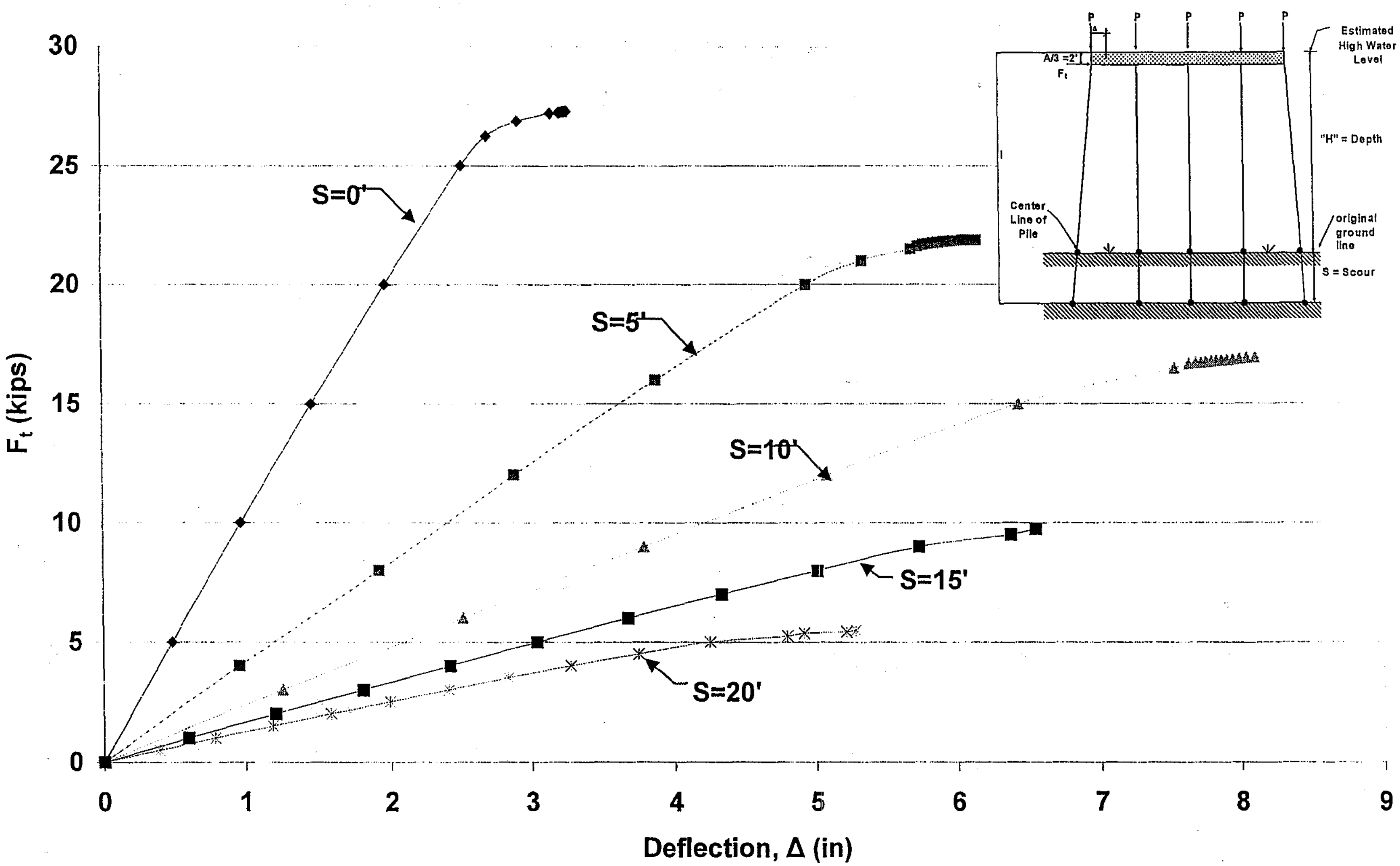


Figure A.56 HP10x42 Unbraced 5-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

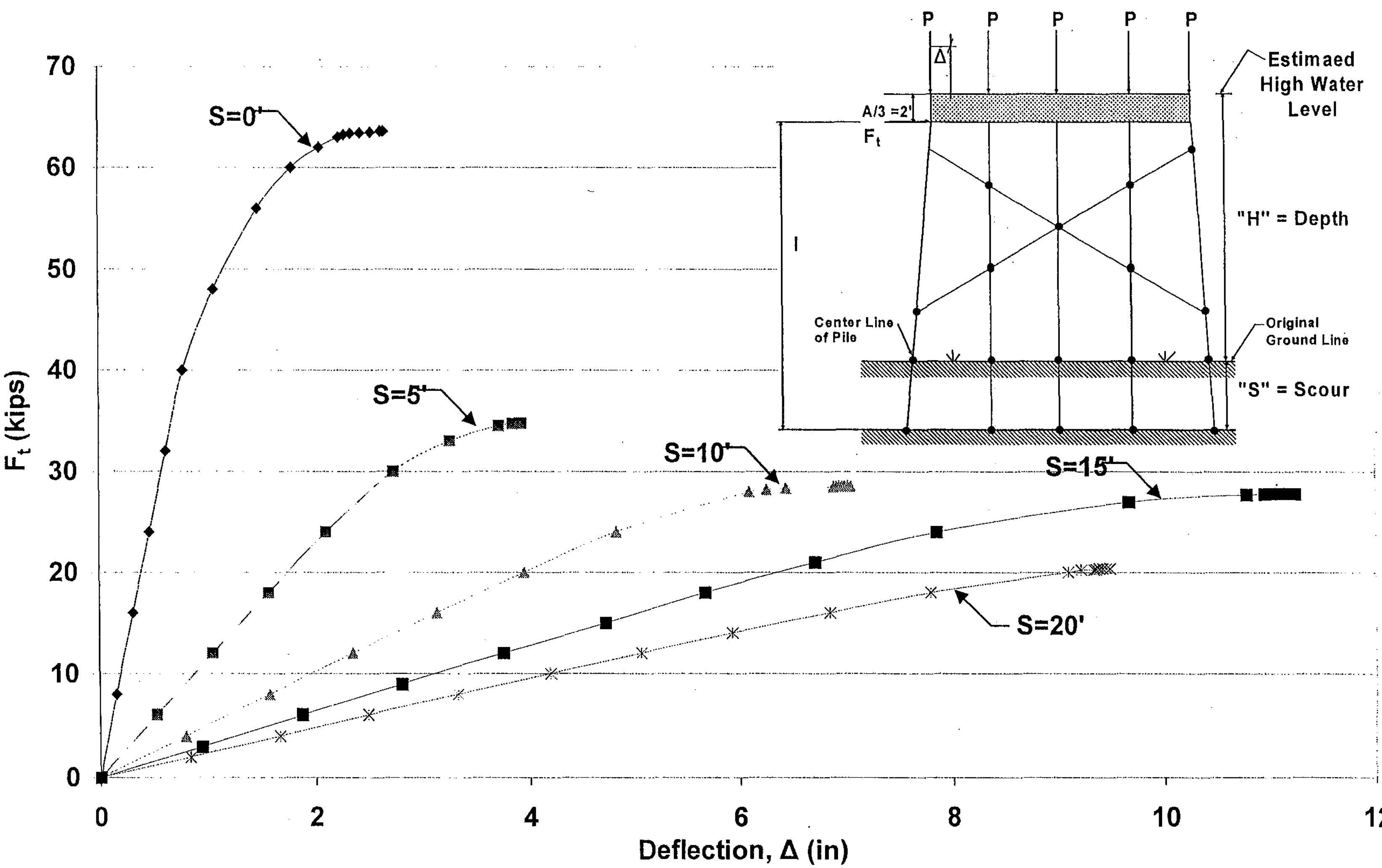


Figure A.57 HP10x42 X-Braced 5-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

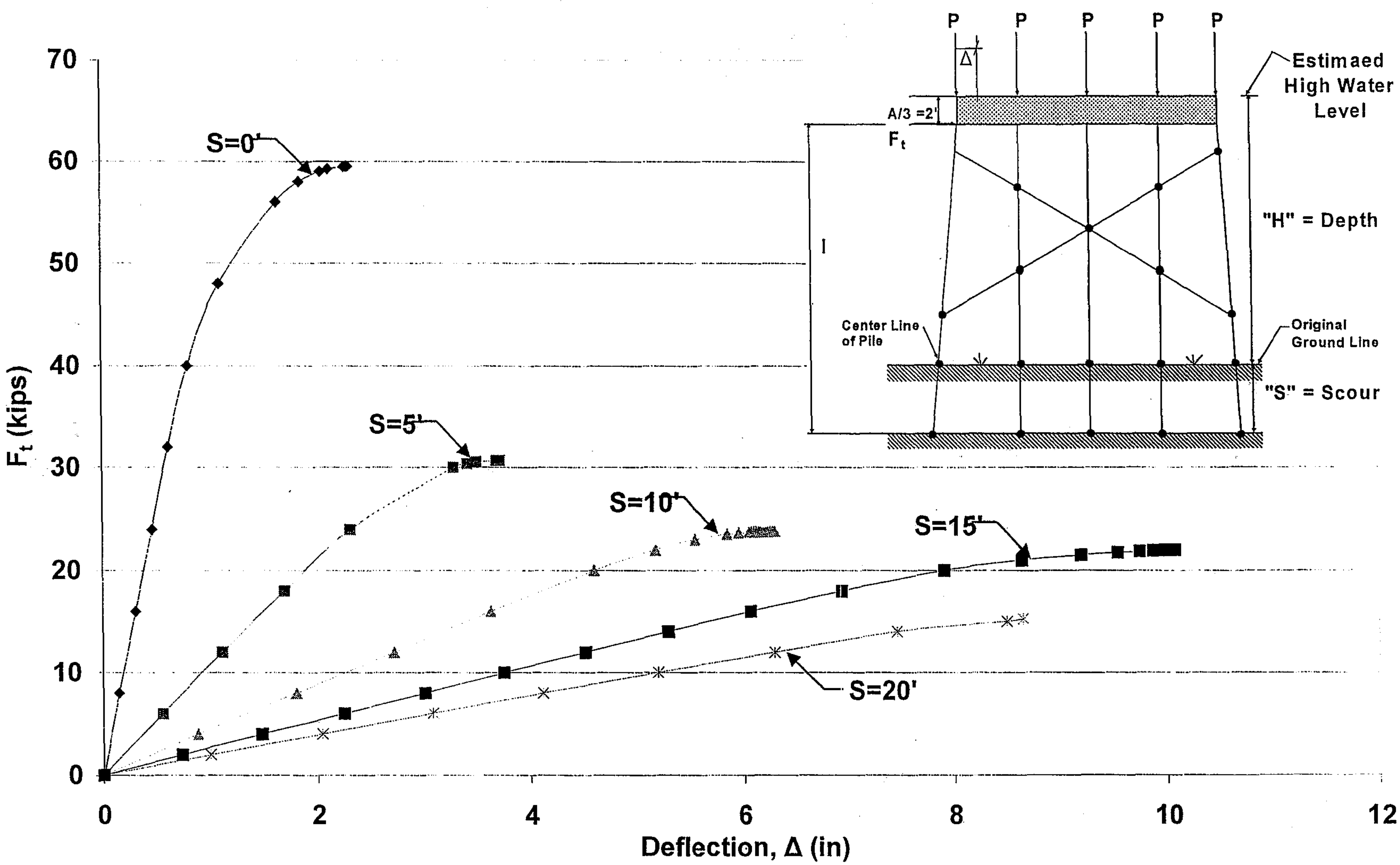


Figure A.58 HP10x42 X-Braced 5-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

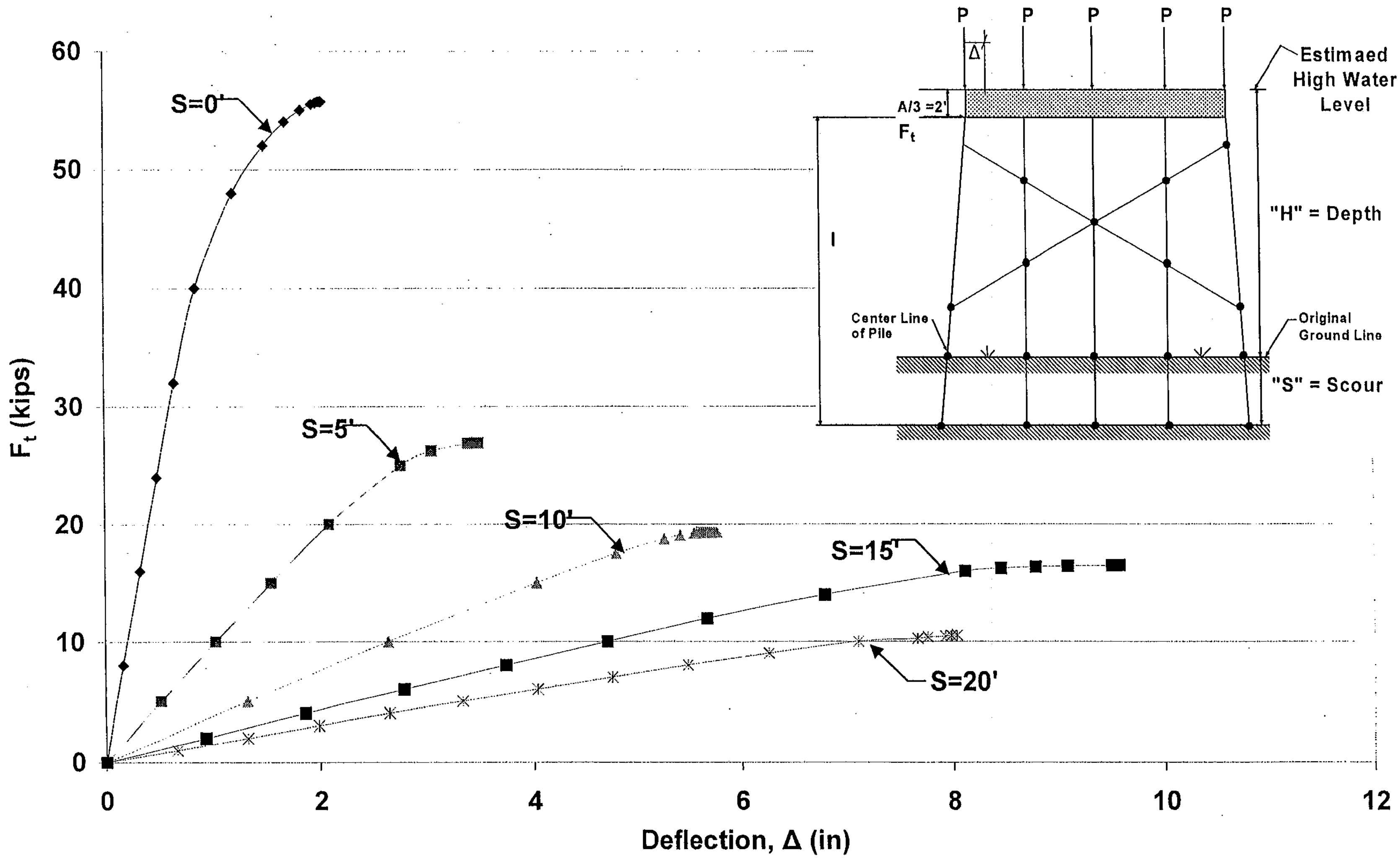


Figure A.59 HP10x42 X-Braced 5-Pile Bent with H=13',P=140kips and A=6'
Pushover Analysis Results

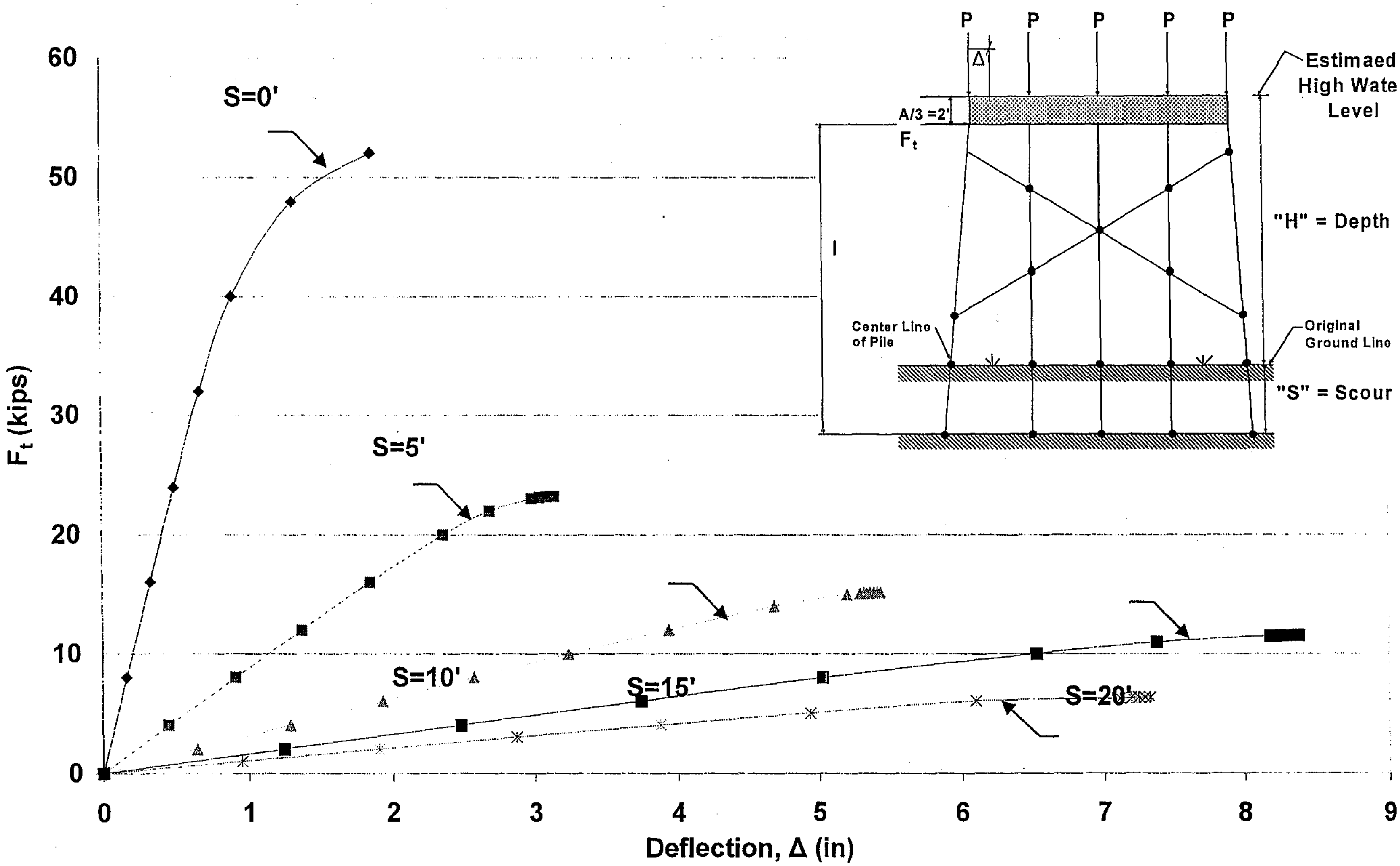


Figure A.60 HP10x42 X-Braced 5-Pile Bent with H=13',P=160kips and A=6'
Pushover Analysis Results

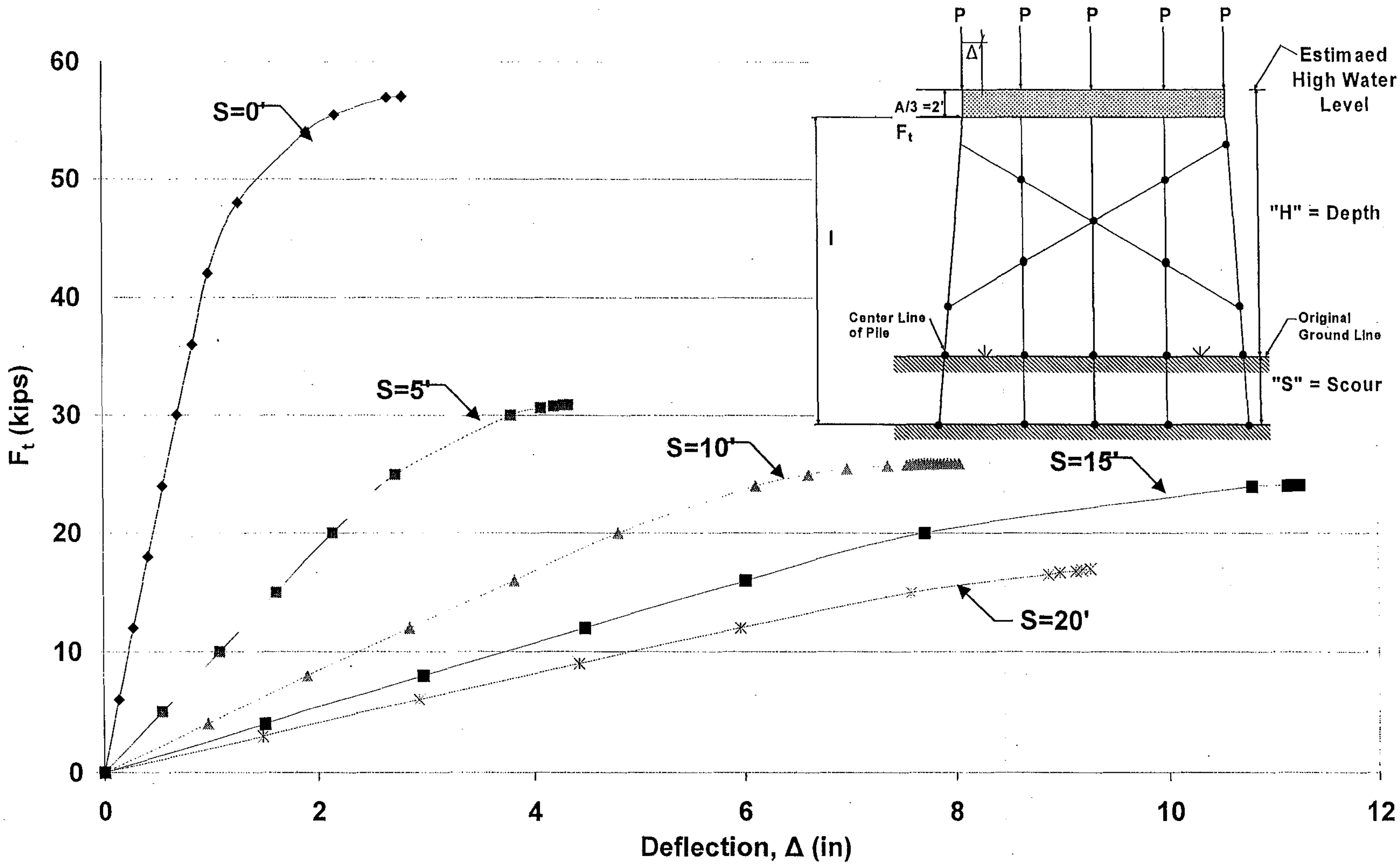


Figure A.61 HP10x42 X-Braced 5-Pile Bent with H=17',P=100kips and A=6' Pushover Analysis Results

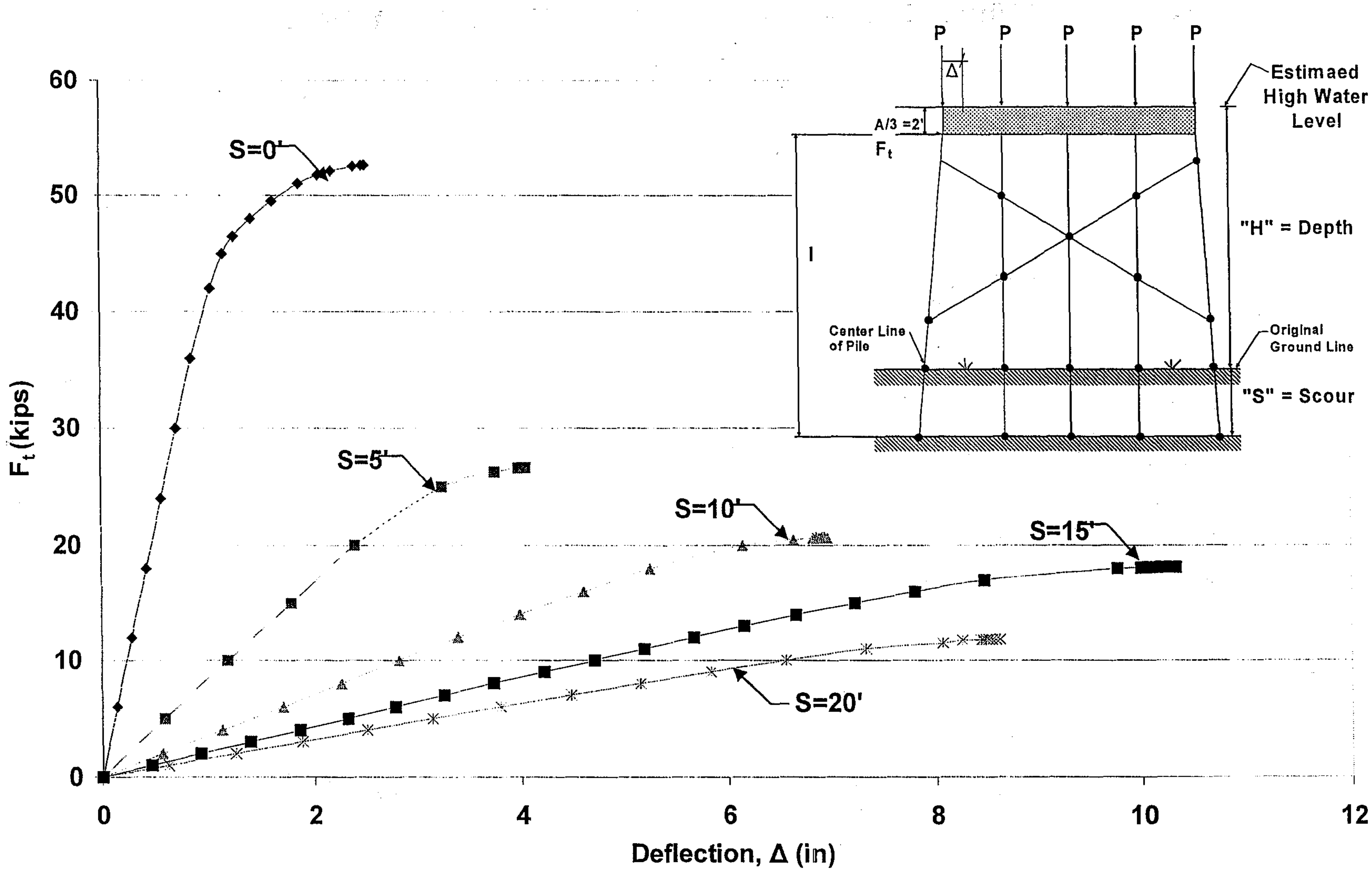


**Figure A.62 HP10x42 X-Braced 5-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results**

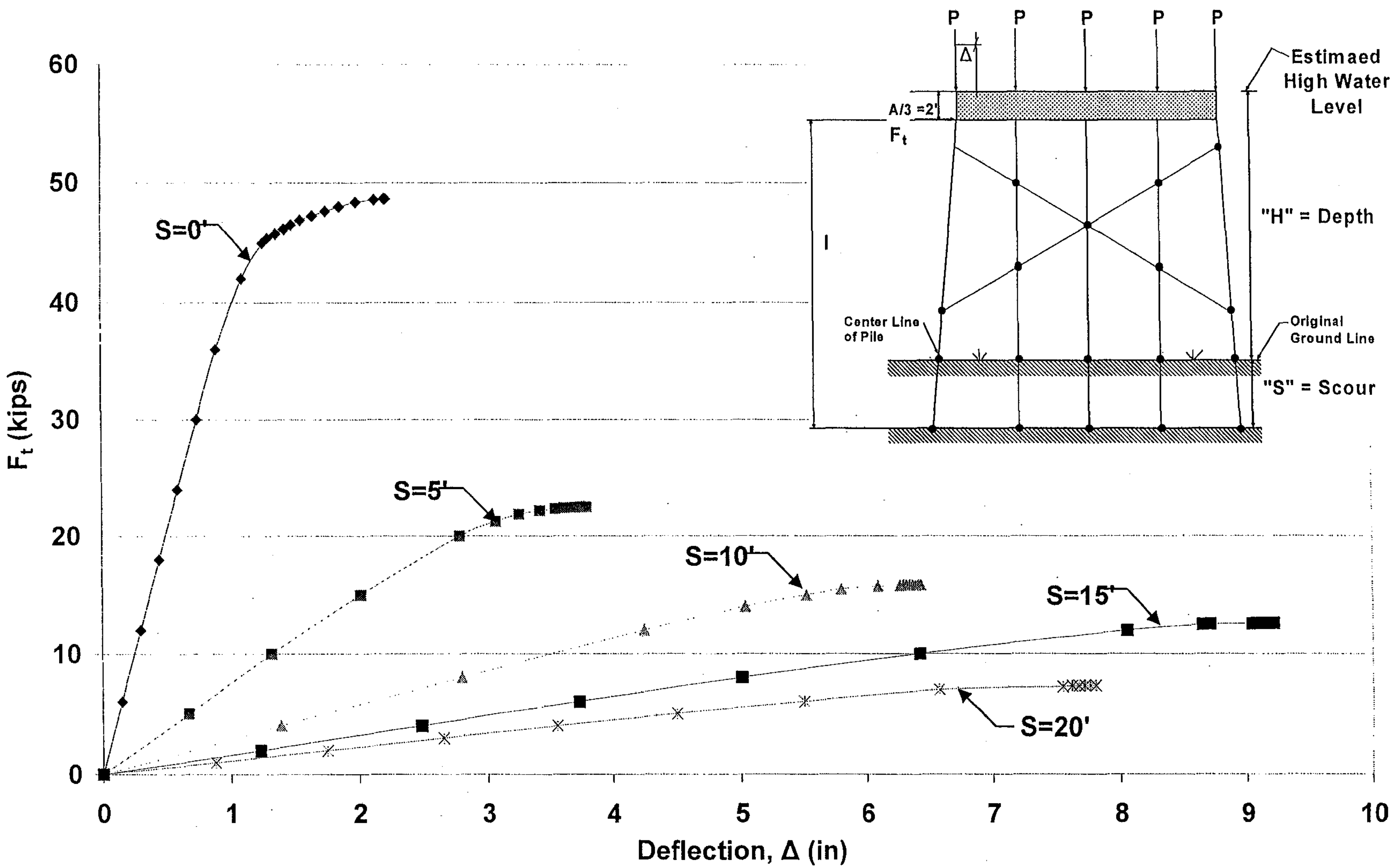


Figure A.63 HP10x42 X-Braced 5-Pile Bent with H=17', P=140kips and A=6'
Pushover Analysis Results

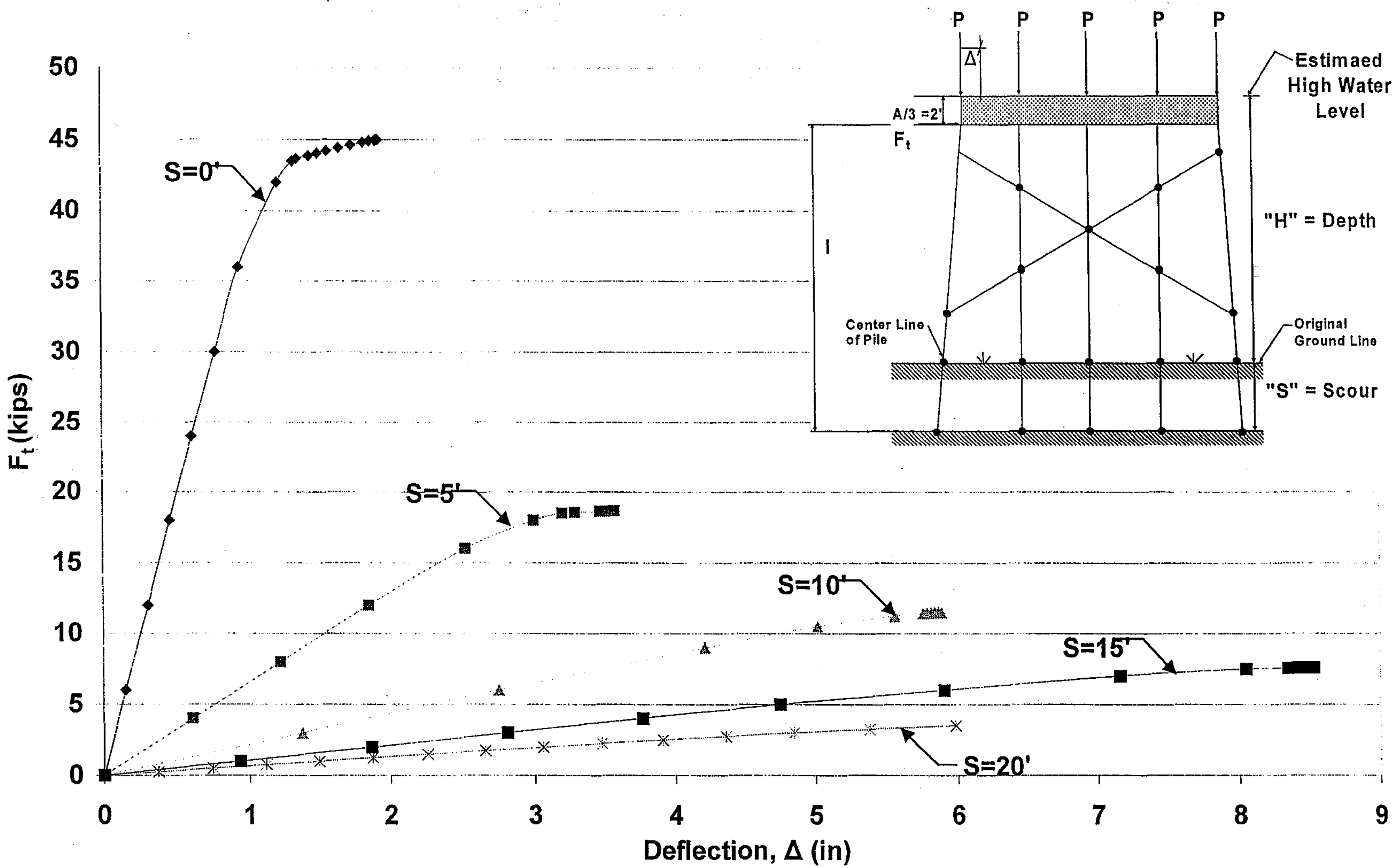


Figure A.64 HP10x42 X-Braced 5-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

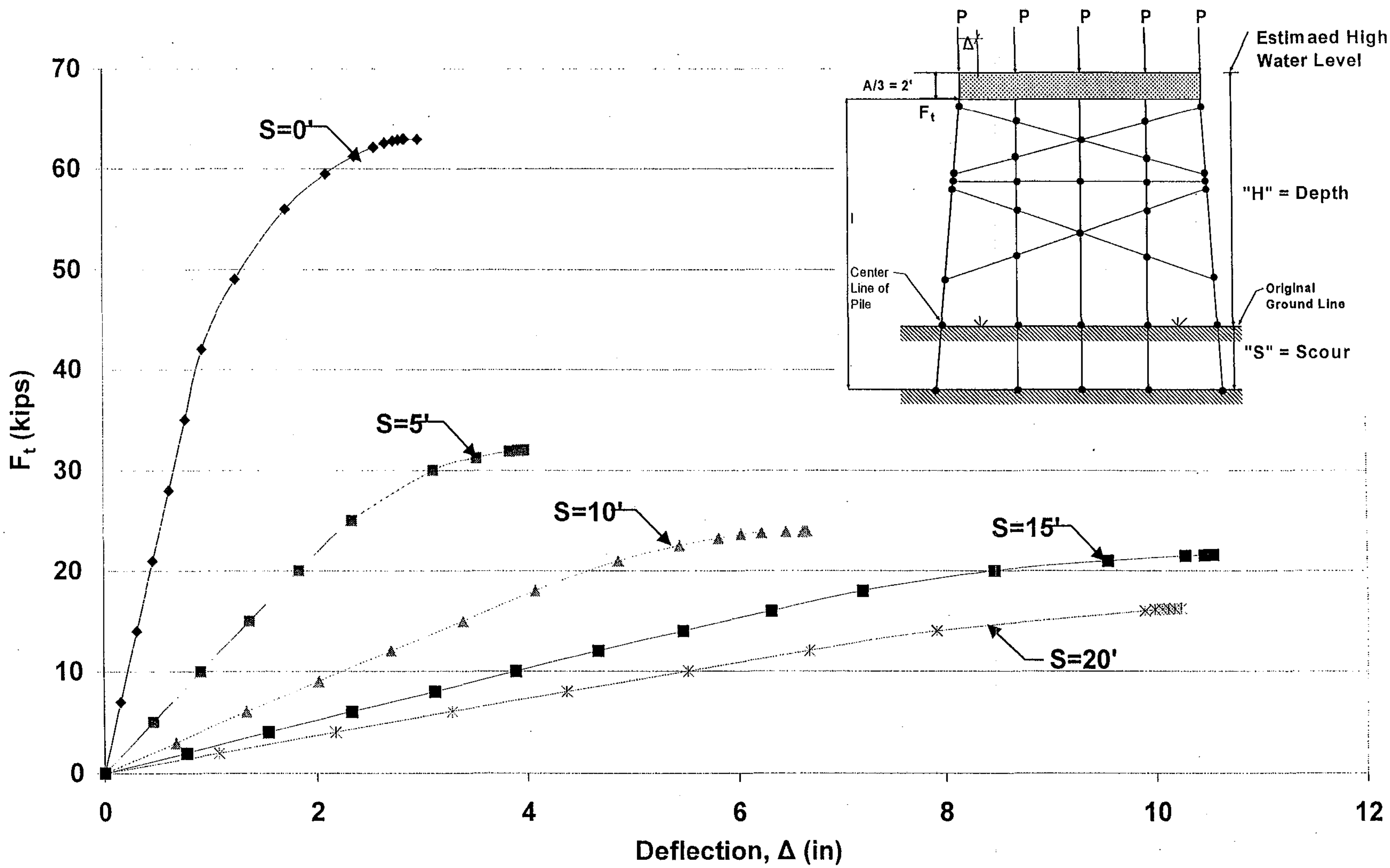


Figure A.65 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

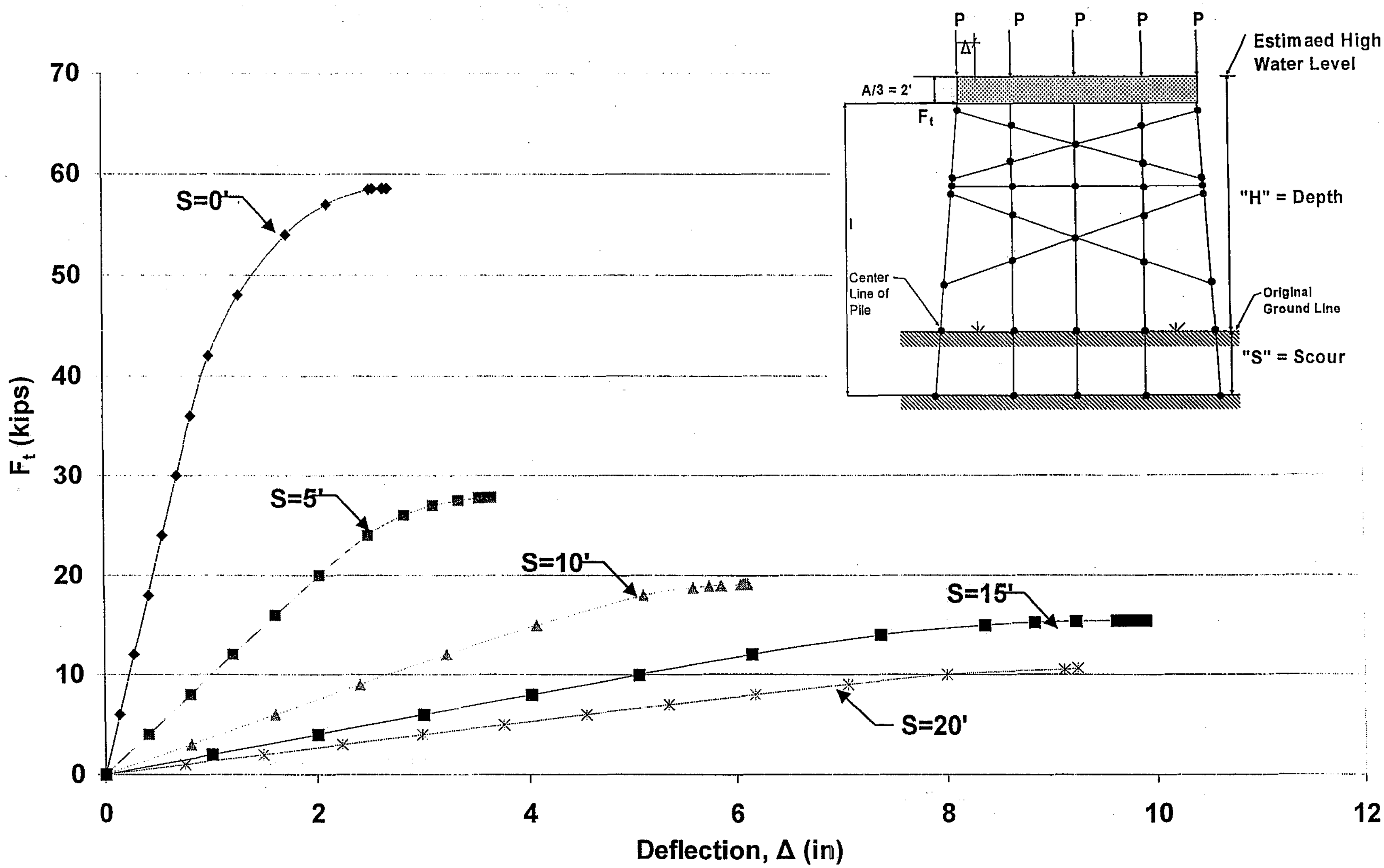


Figure A.66 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

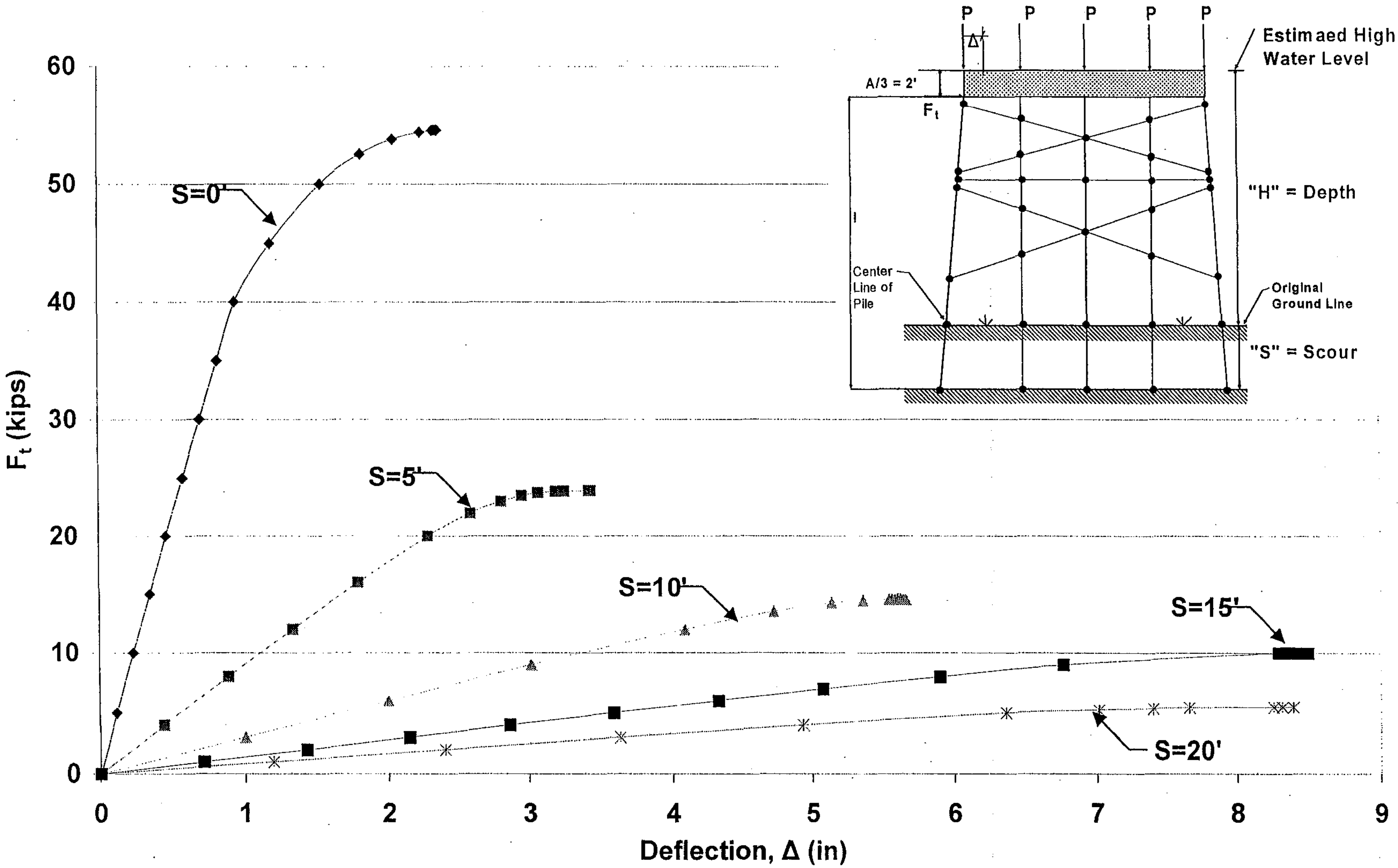


Figure A.67 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

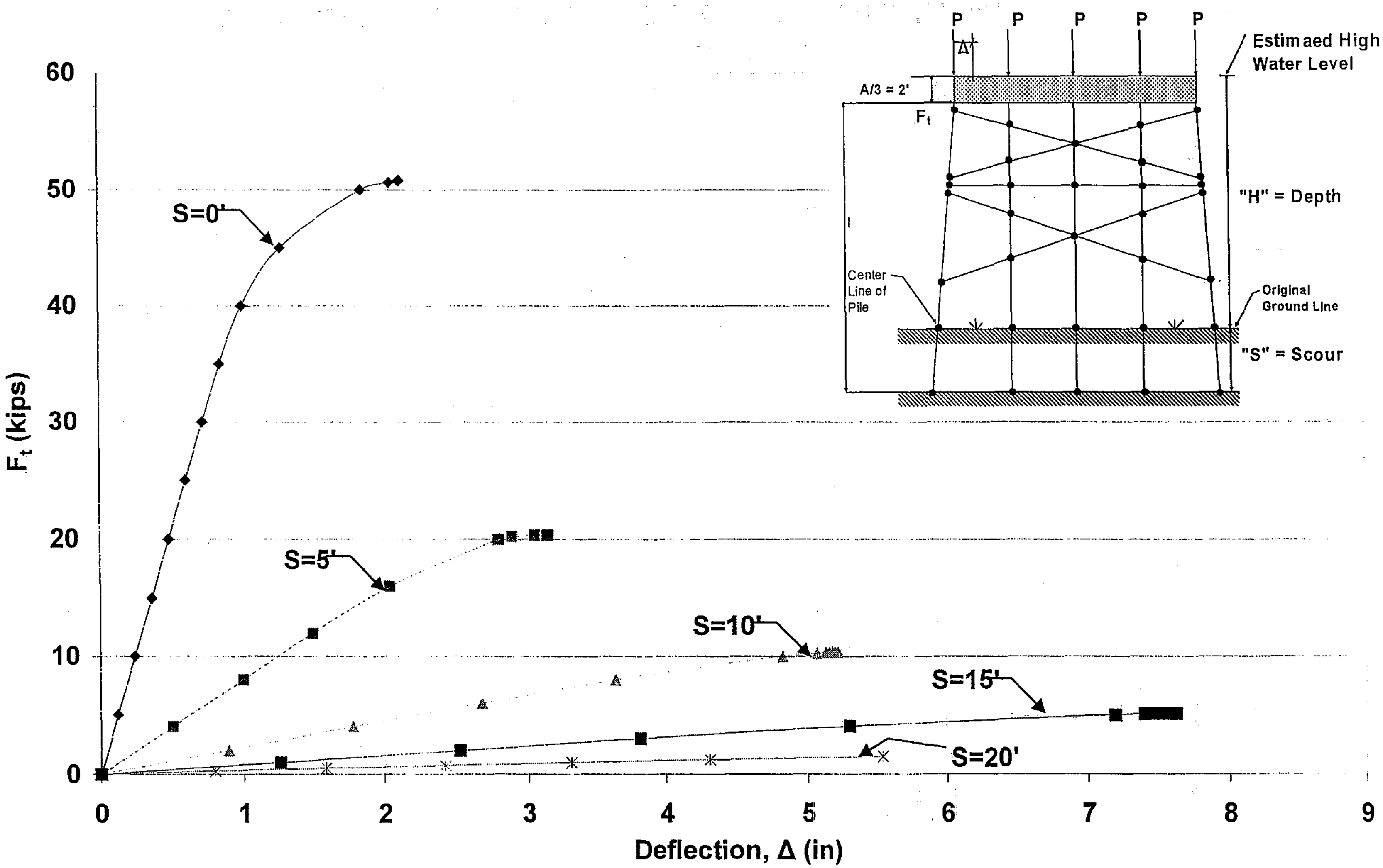


Figure A.68 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=160kips and A=6'
Pushover Analysis Results

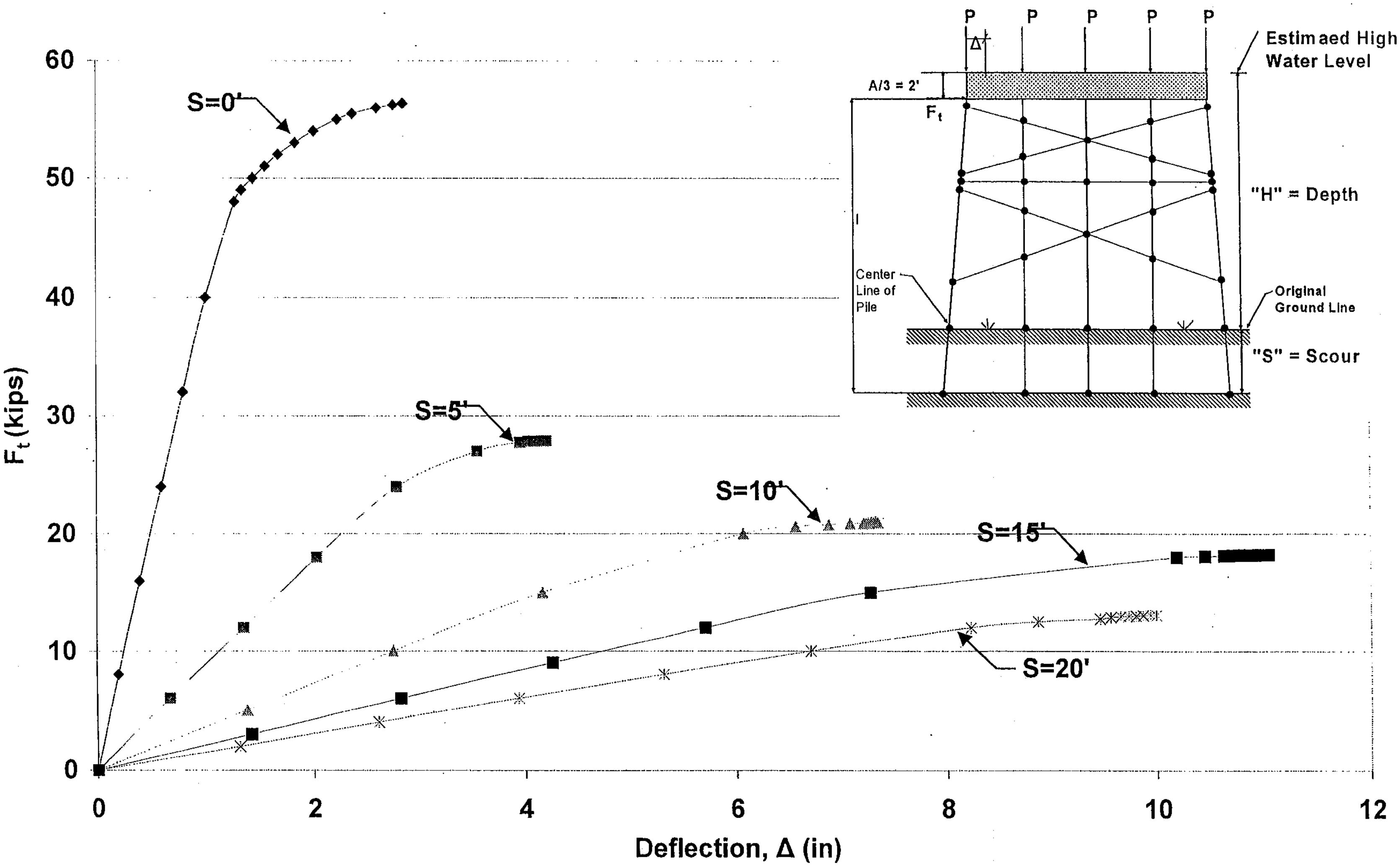


Figure A.69 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

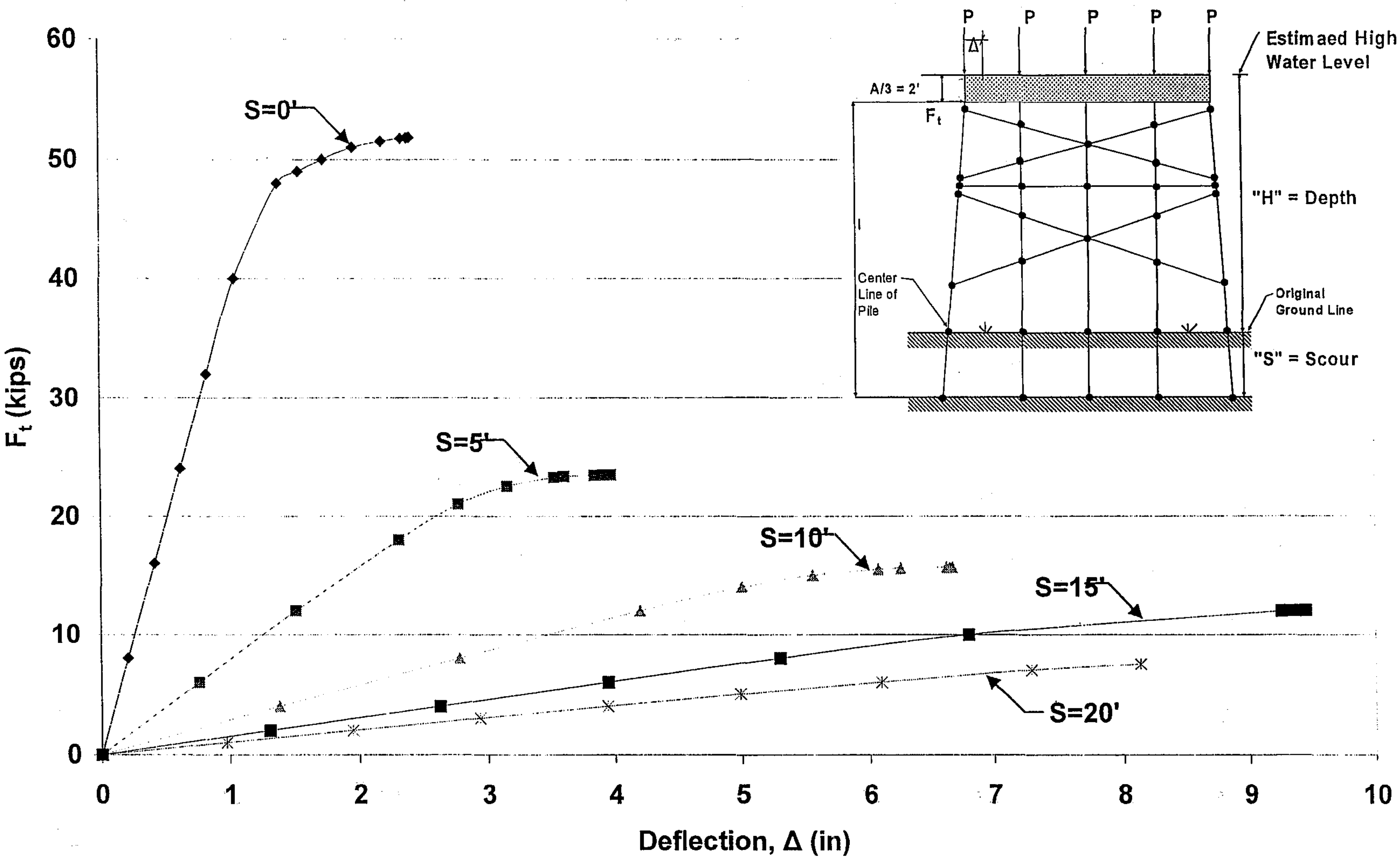


Figure A.70 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

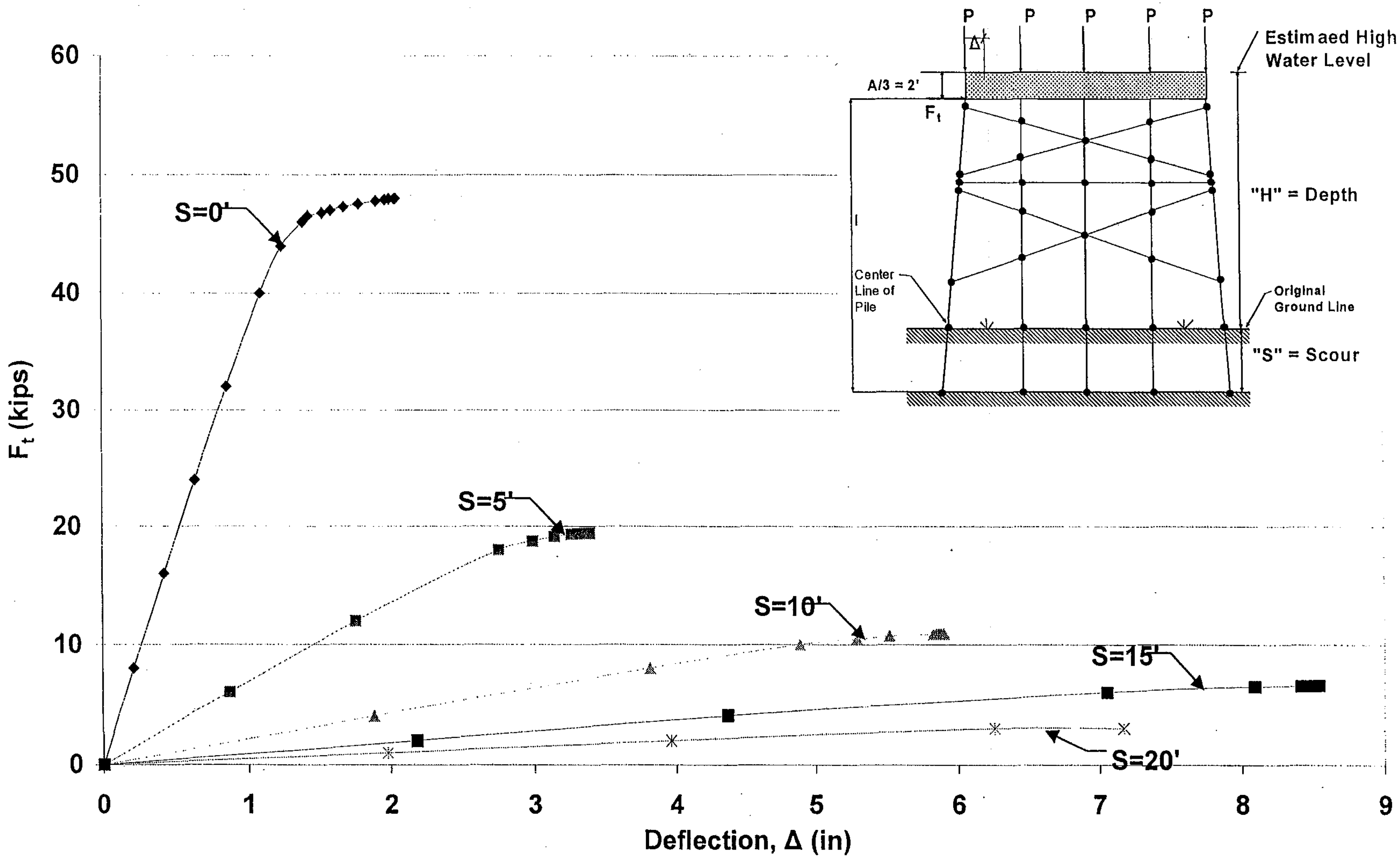


Figure A.71 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

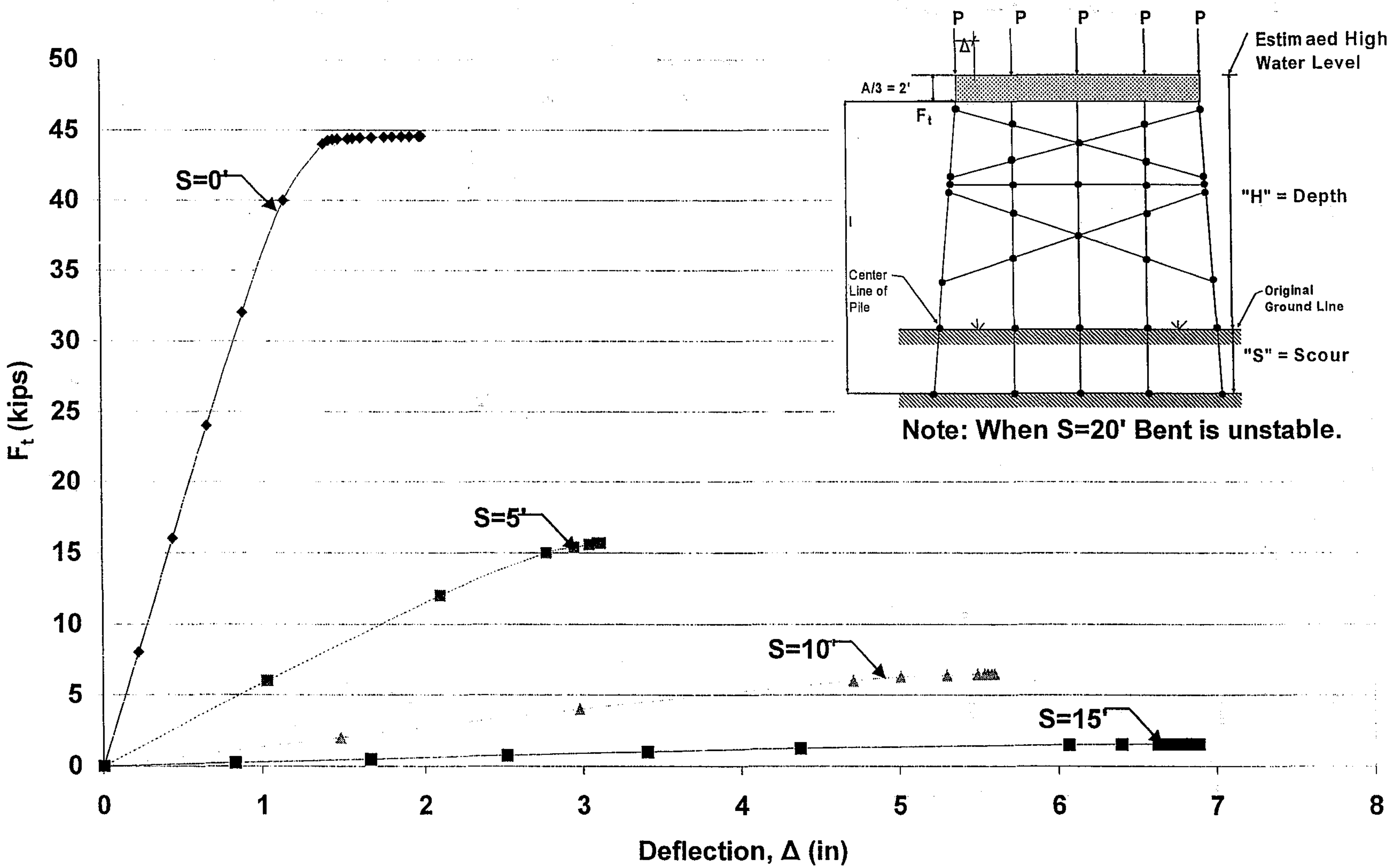


Figure A.72 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

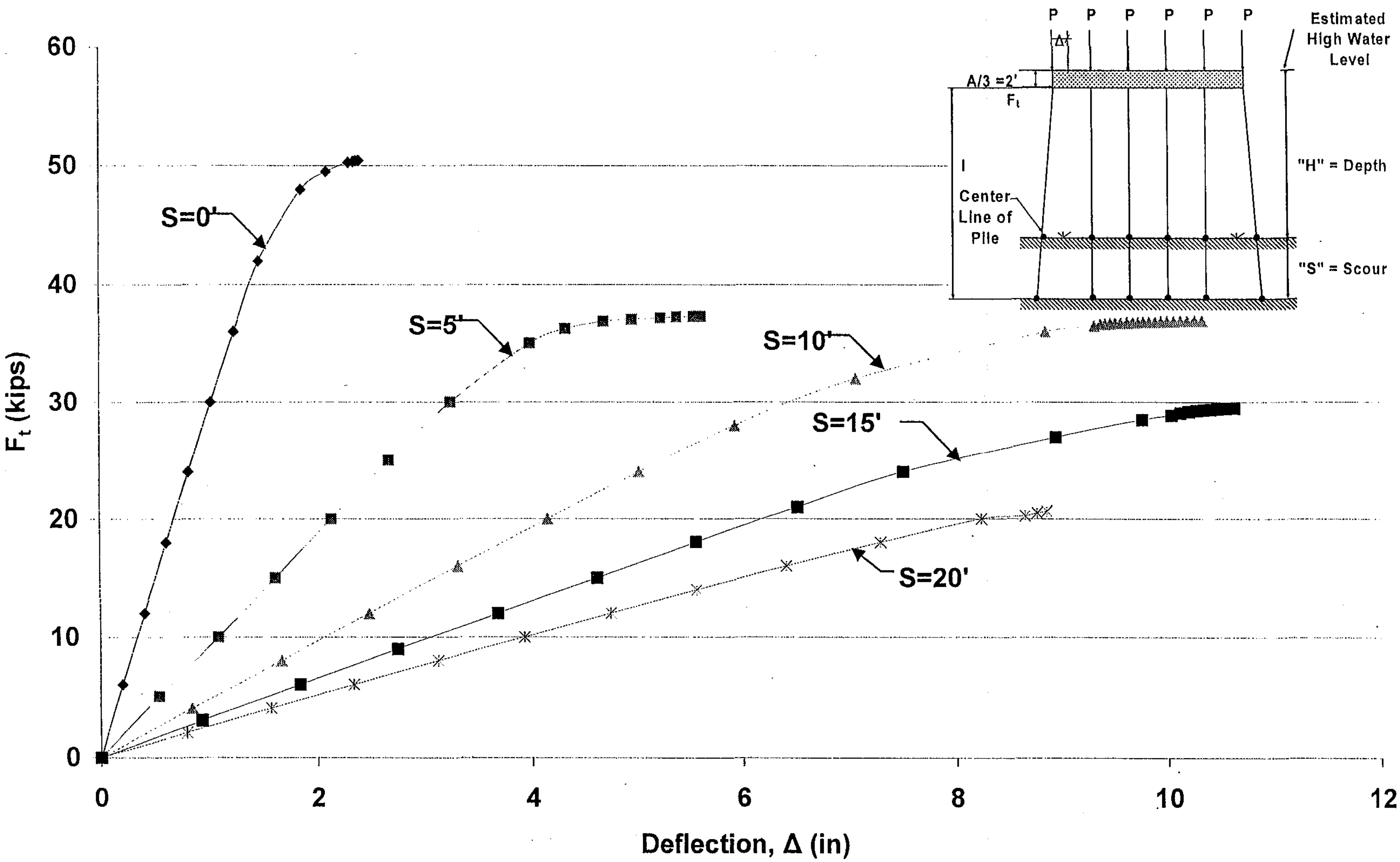


Figure A.73 HP10x42 Unbraced 6-Pile Bent with H=10', P=100kips and A=6' Pushover Anlaysis Results

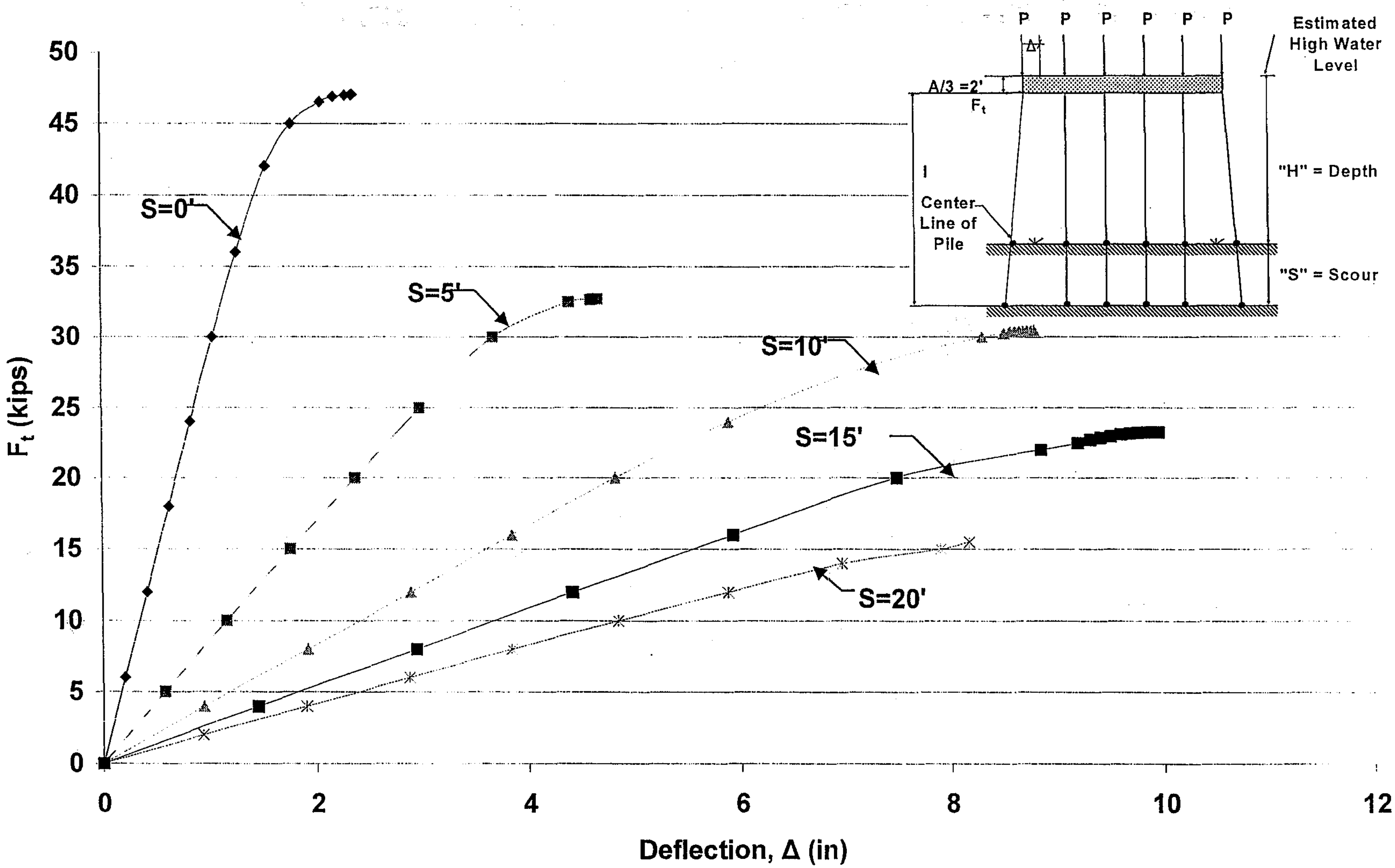


Figure A.74 HP10x42 Unbraced 6-Pile Bent with H=10', P=120kips and A=6' Pushover Anlaysis Results

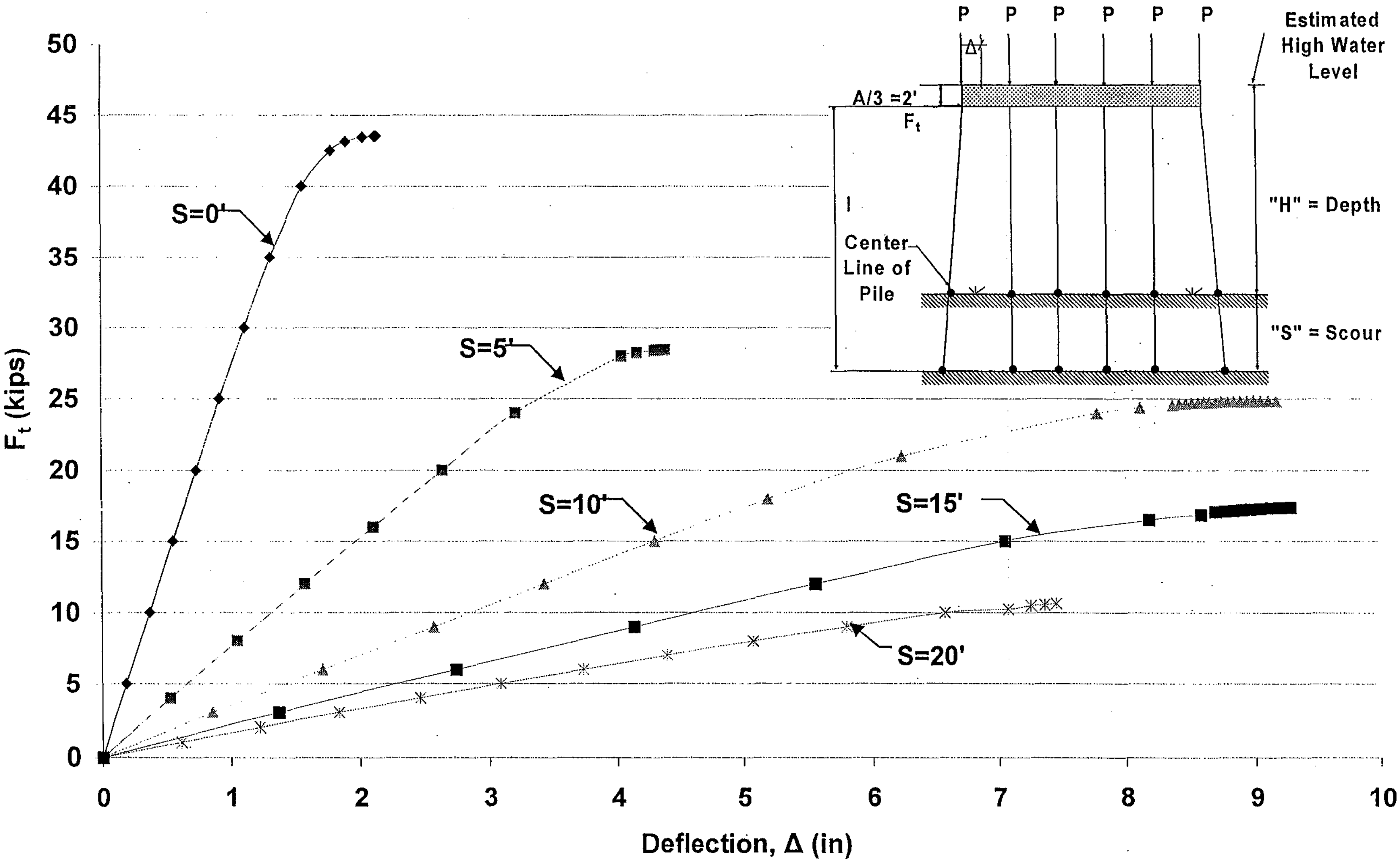


Figure A.75 HP10x42 Unbraced 6-Pile Bent with H=10', P=140kips and A=6'
Pushover Anlaysis Results

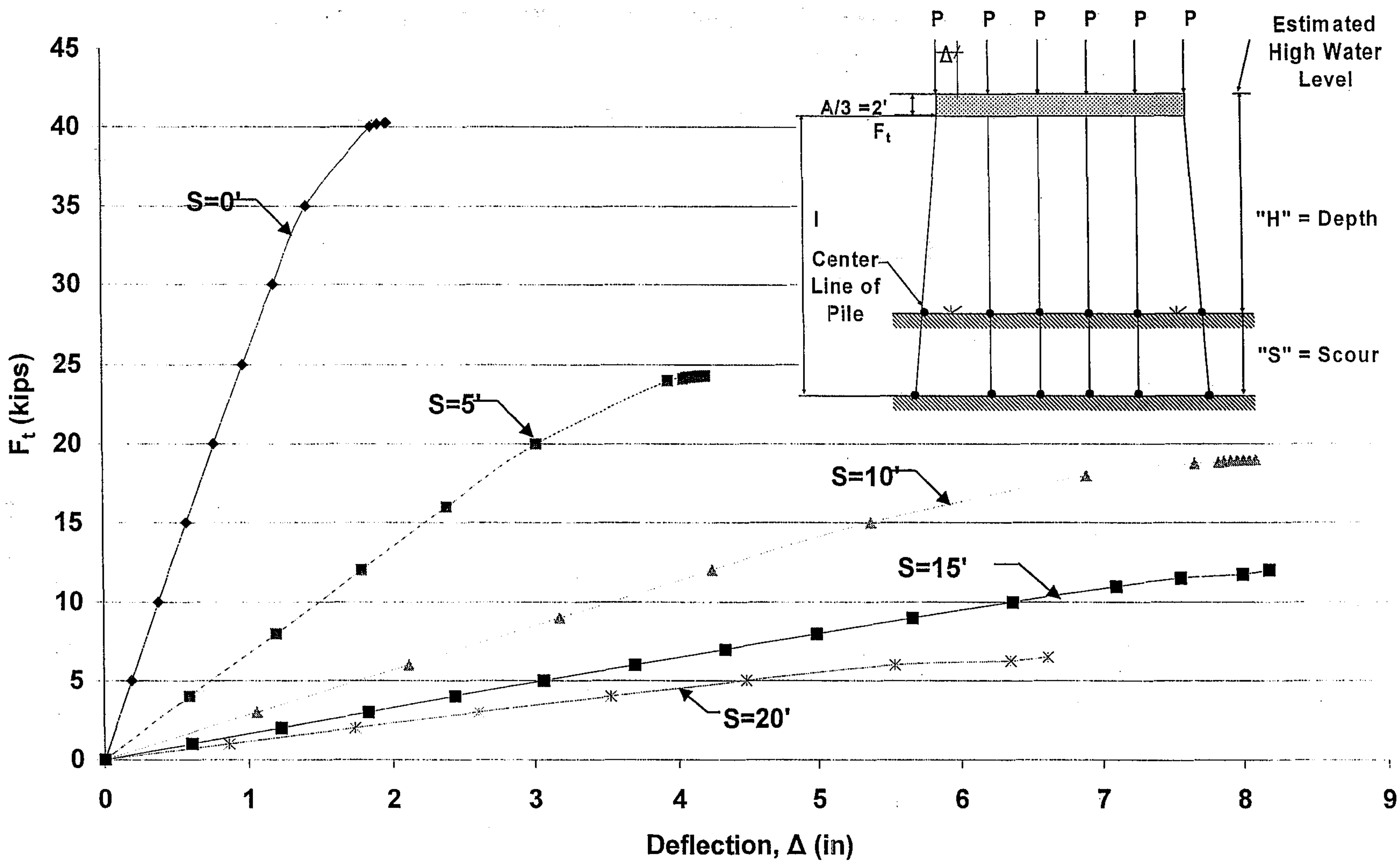


Figure A.76 HP10x42 Unbraced 6-Pile Bent with H=10', P=160kips and A=6'
Pushover Anlaysis Results

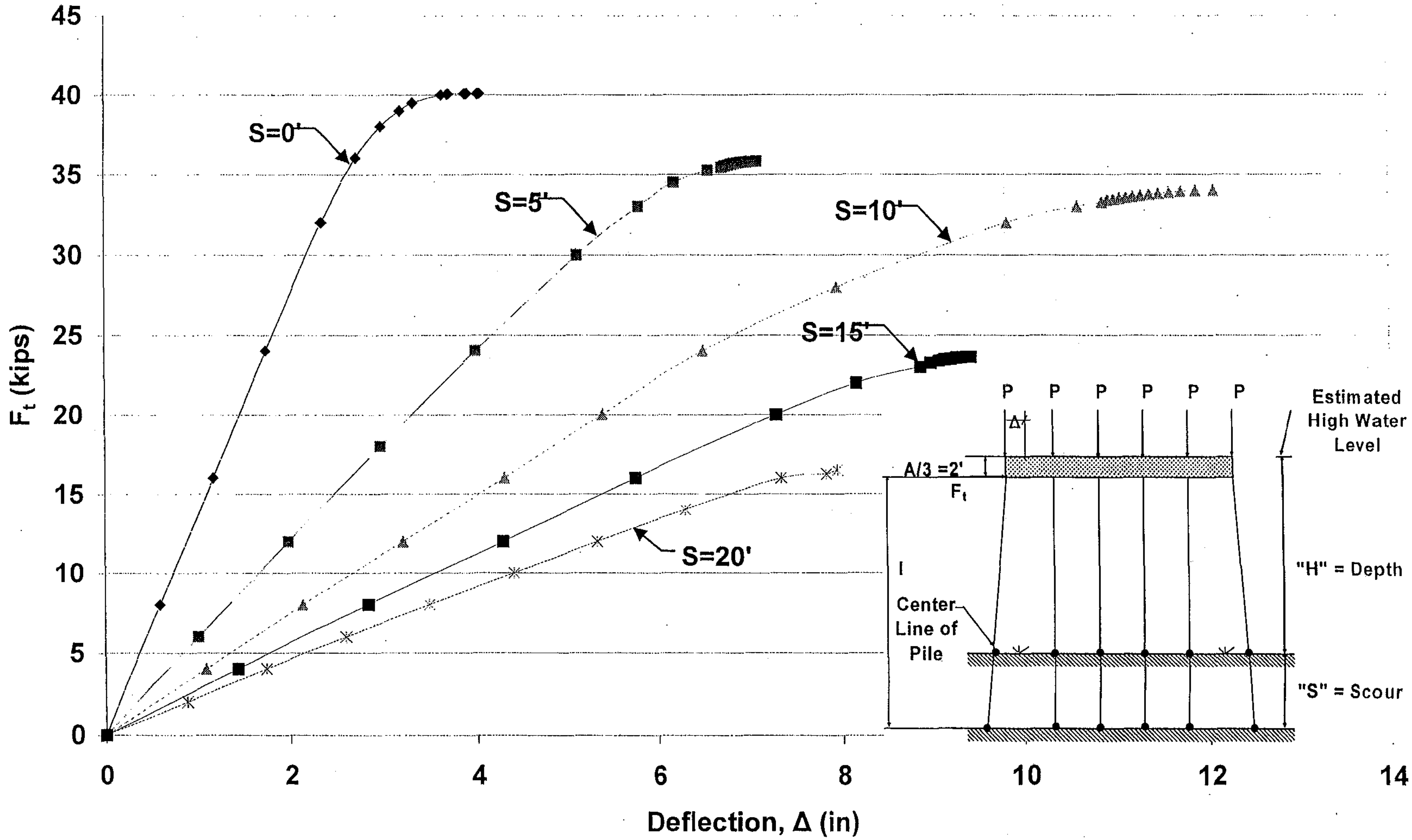


Figure A.77 HP10x42 Unbraced 6-Pile Bent with H=13',P=100kips and A=6' Pushover Analysis Results

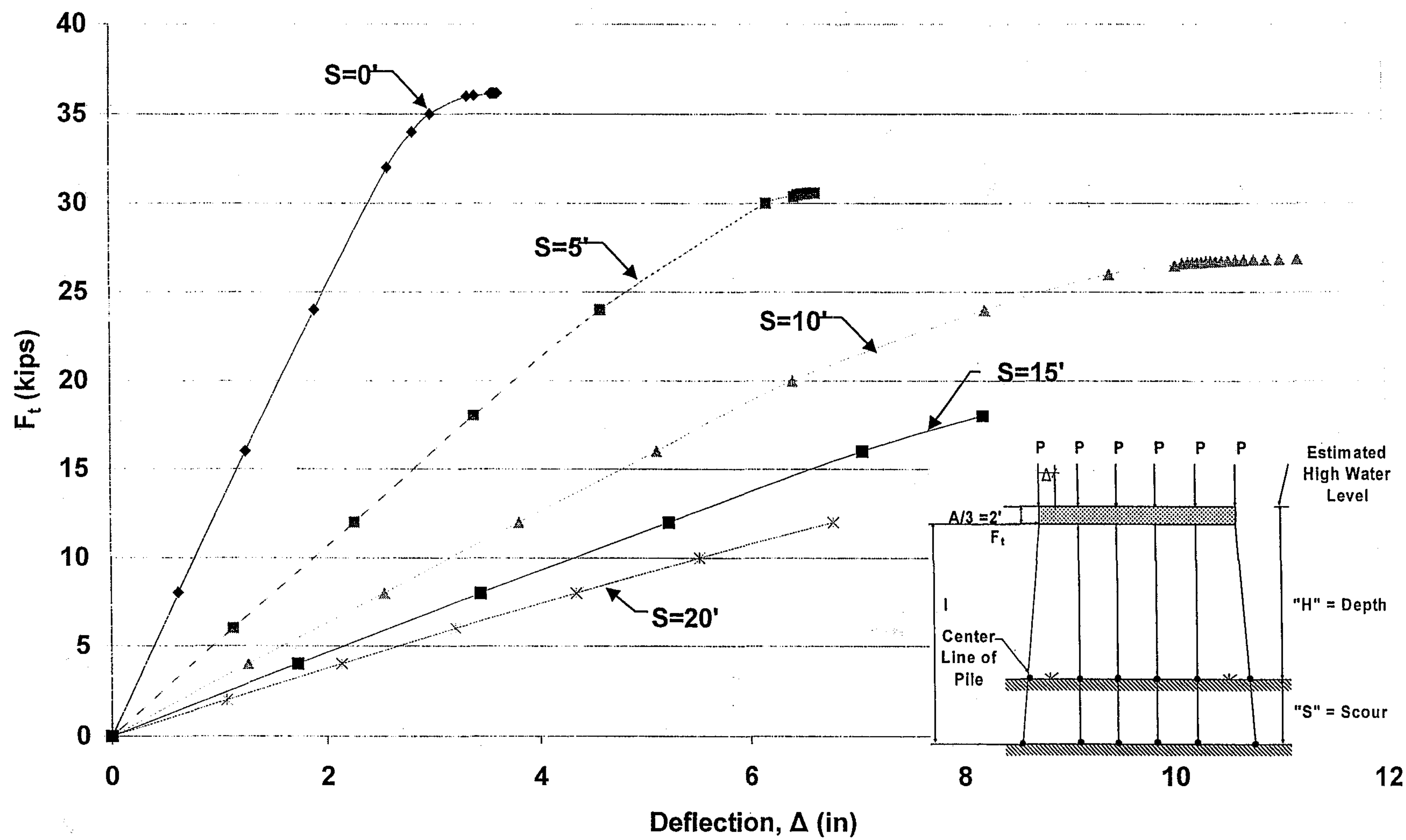


Figure A.78 HP10x42 Unbraced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

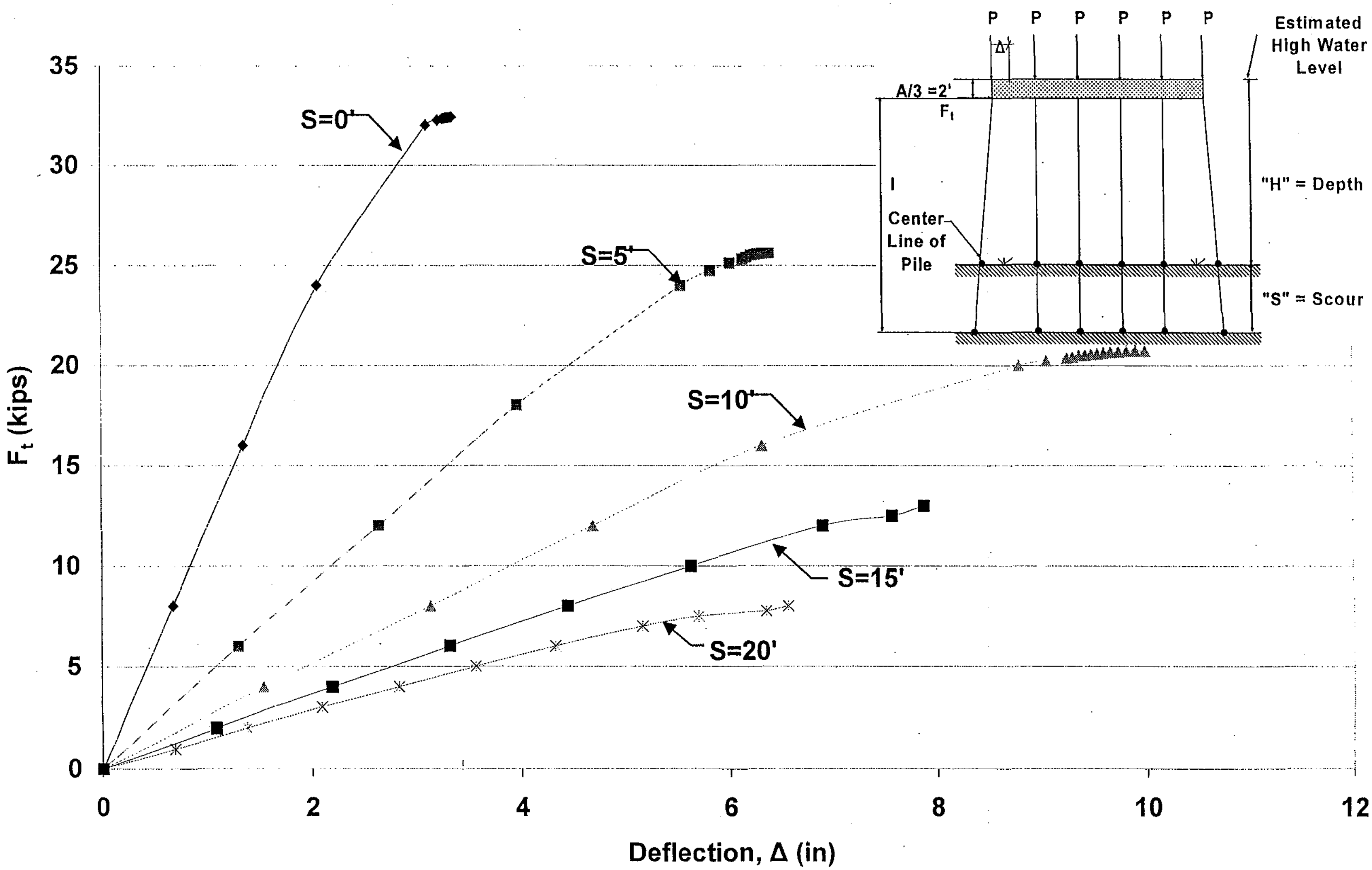


Figure A.79 HP10x42 Unbraced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

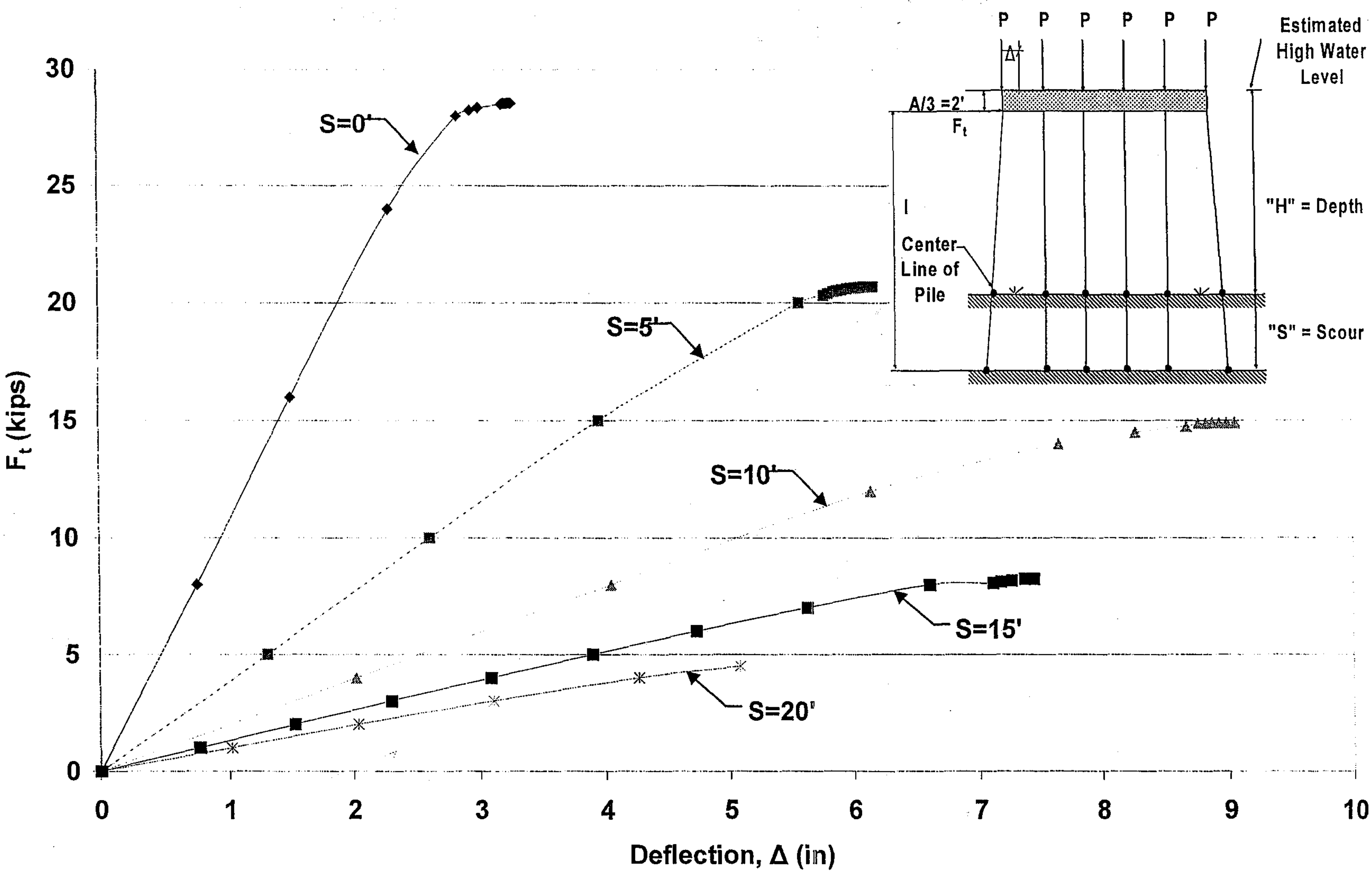


Figure A.80 HP10x42 Unbraced 6-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

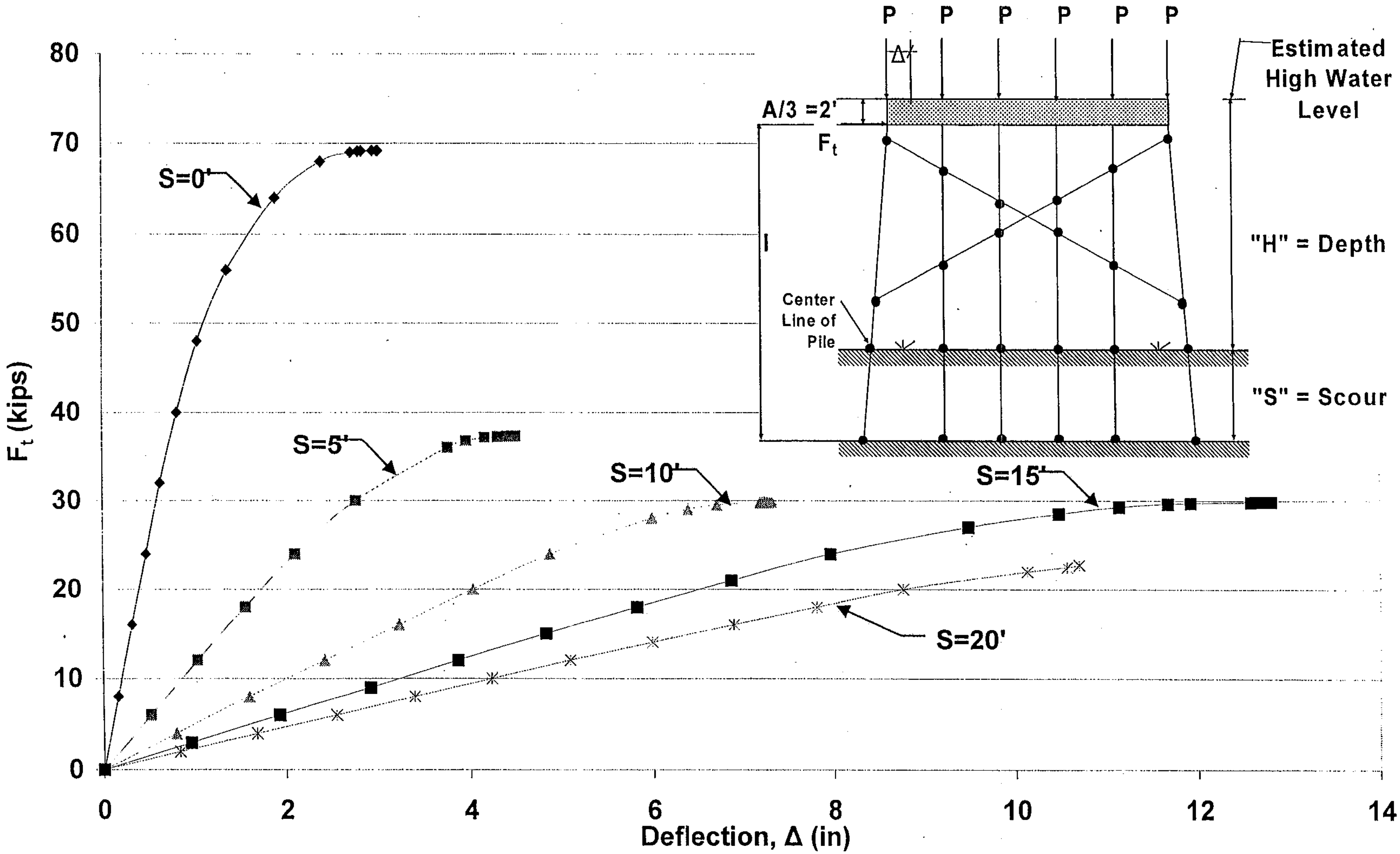


Figure A.81 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

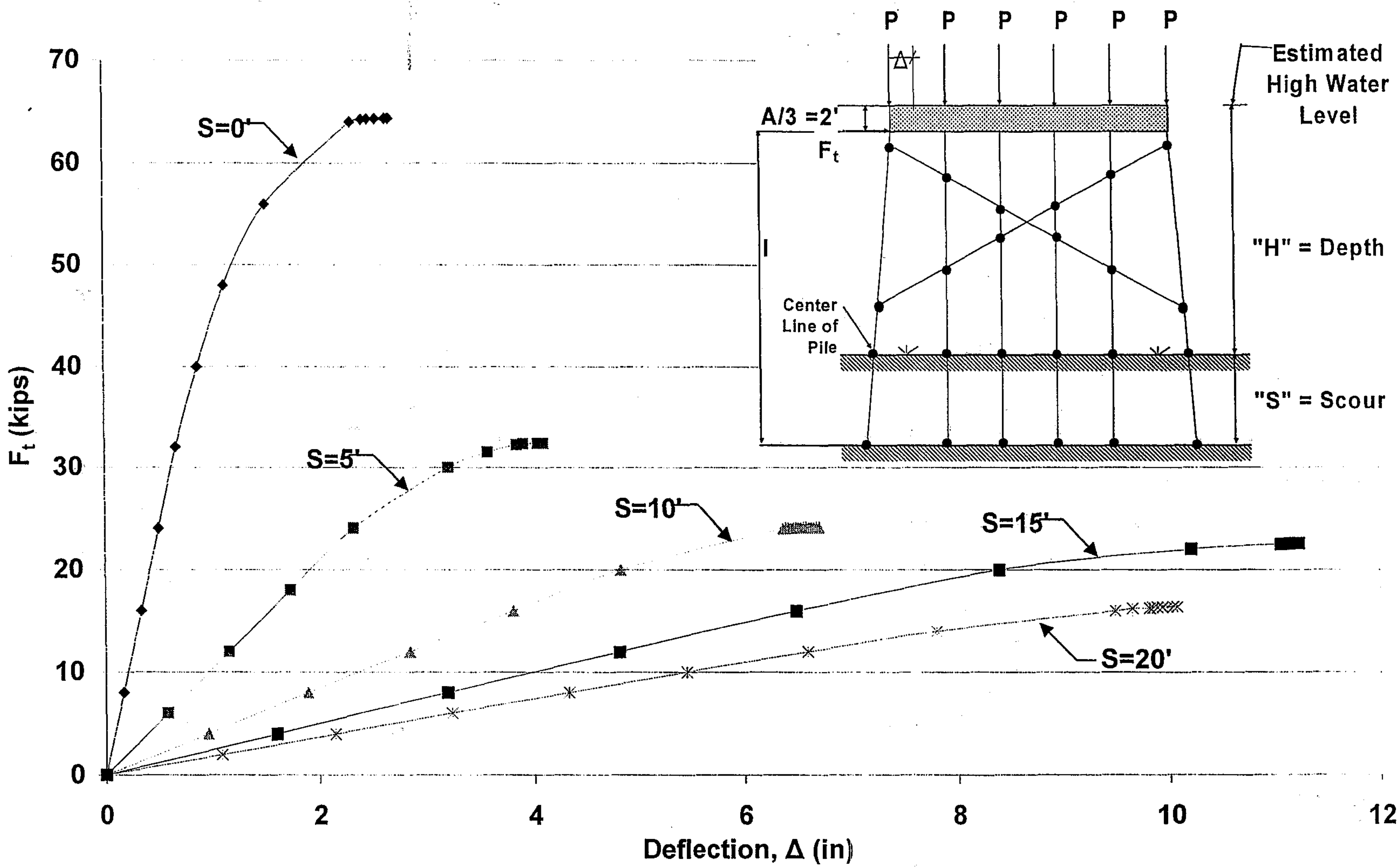


Figure A.82 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

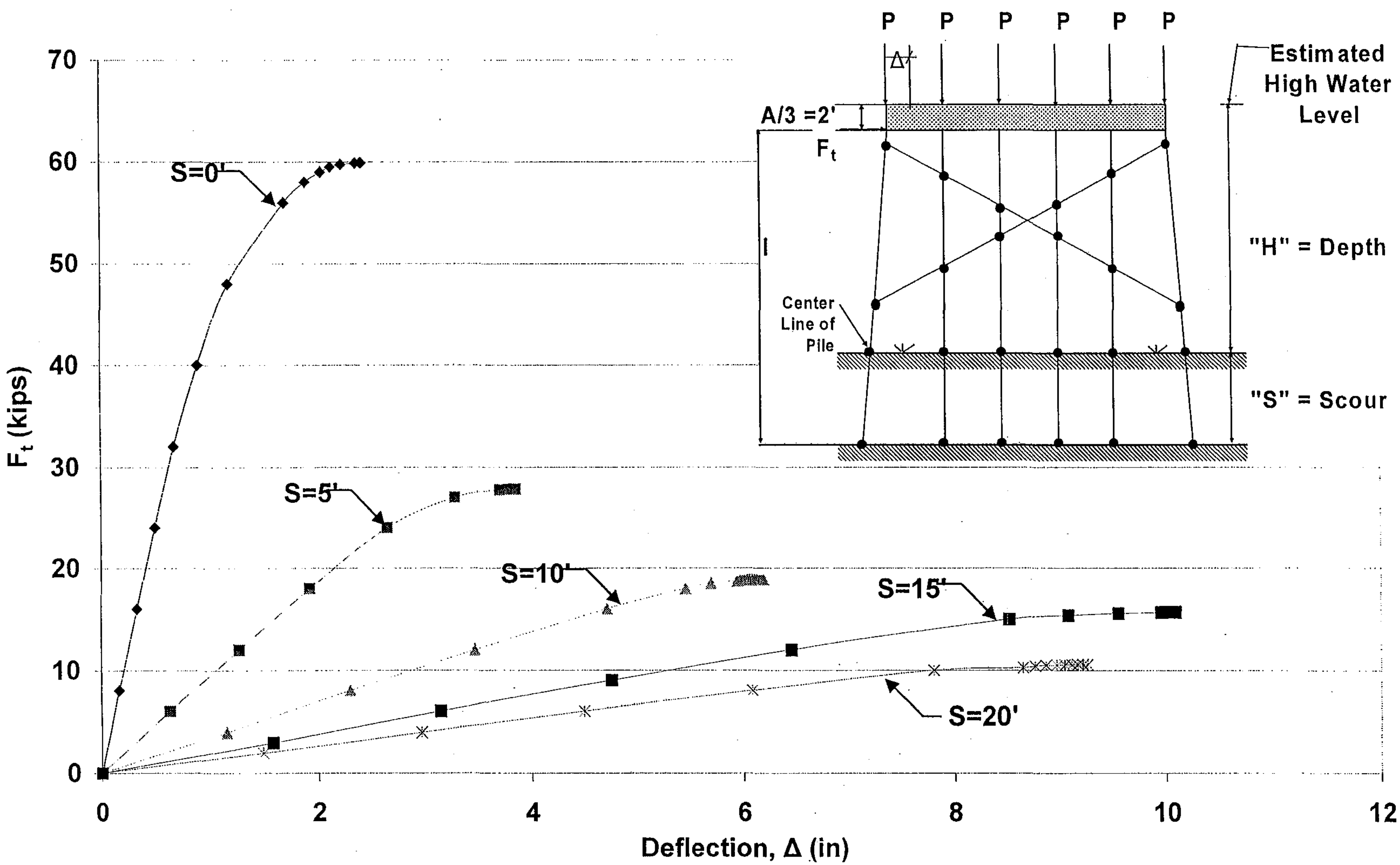


Figure A.83 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

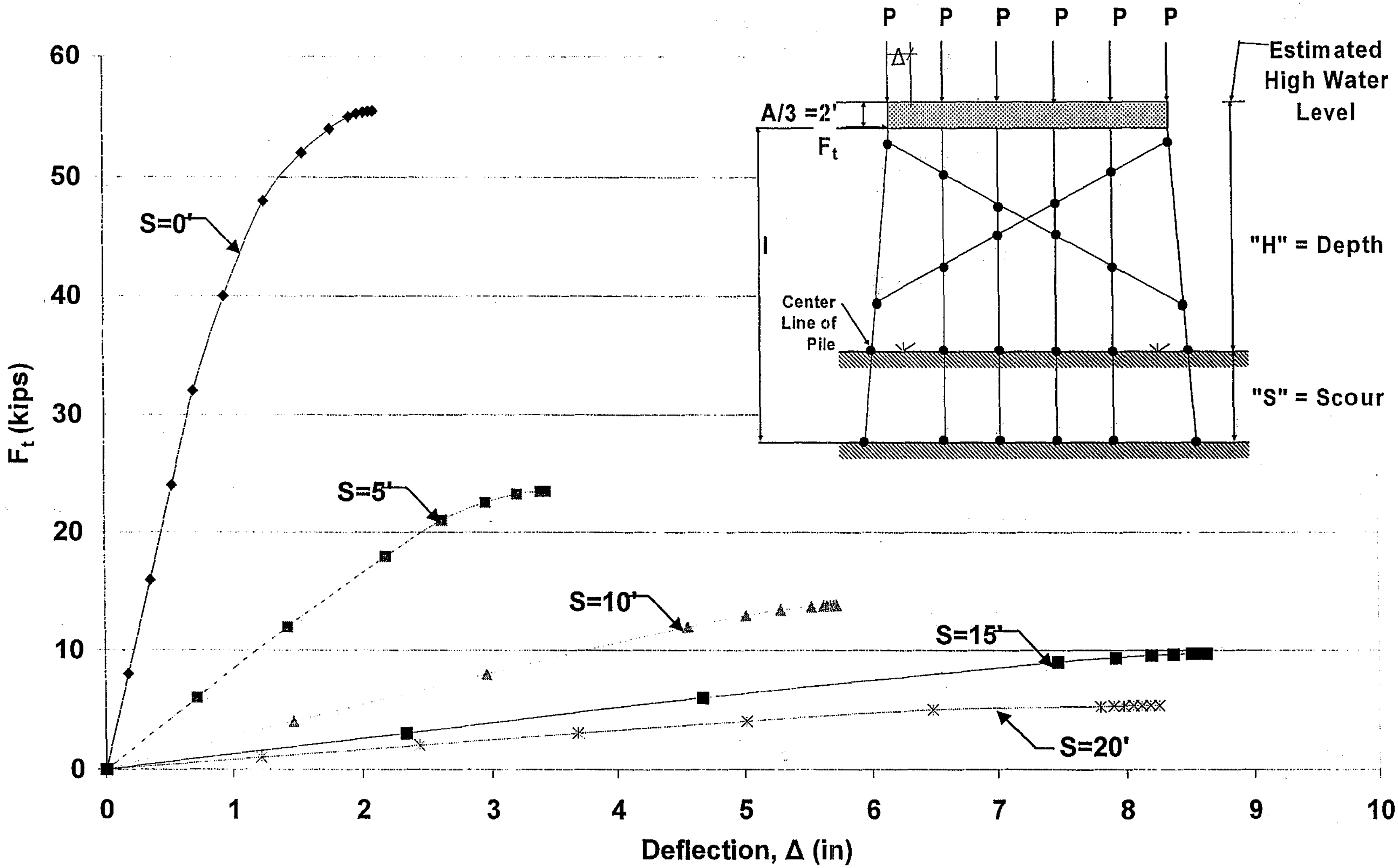


Figure A.84 HP10x42 Single X-Braced 6-Pile Bent with H=13',P=160kips and A=6' Pushover Analysis Results

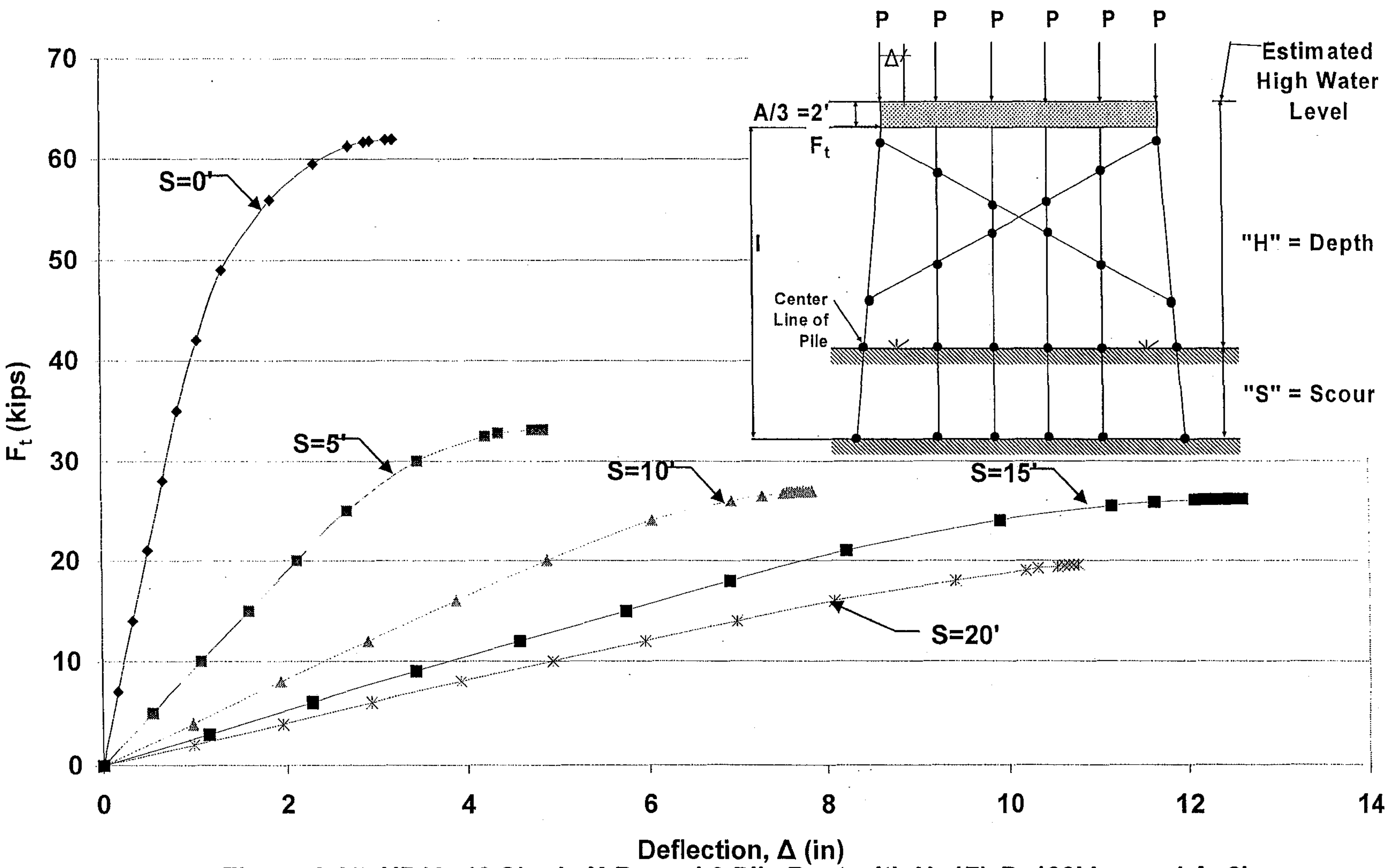


Figure A.85 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

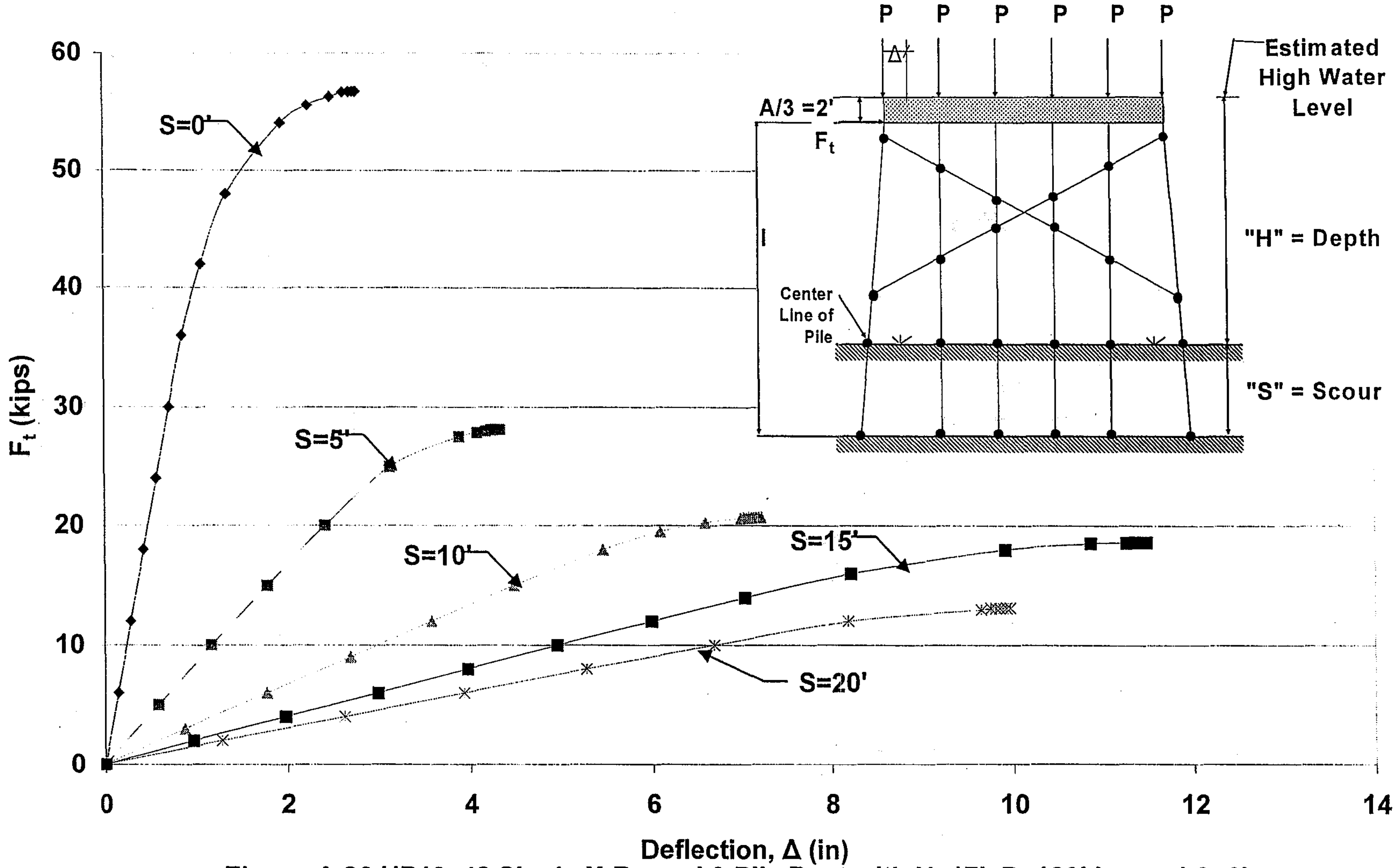


Figure A.86 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

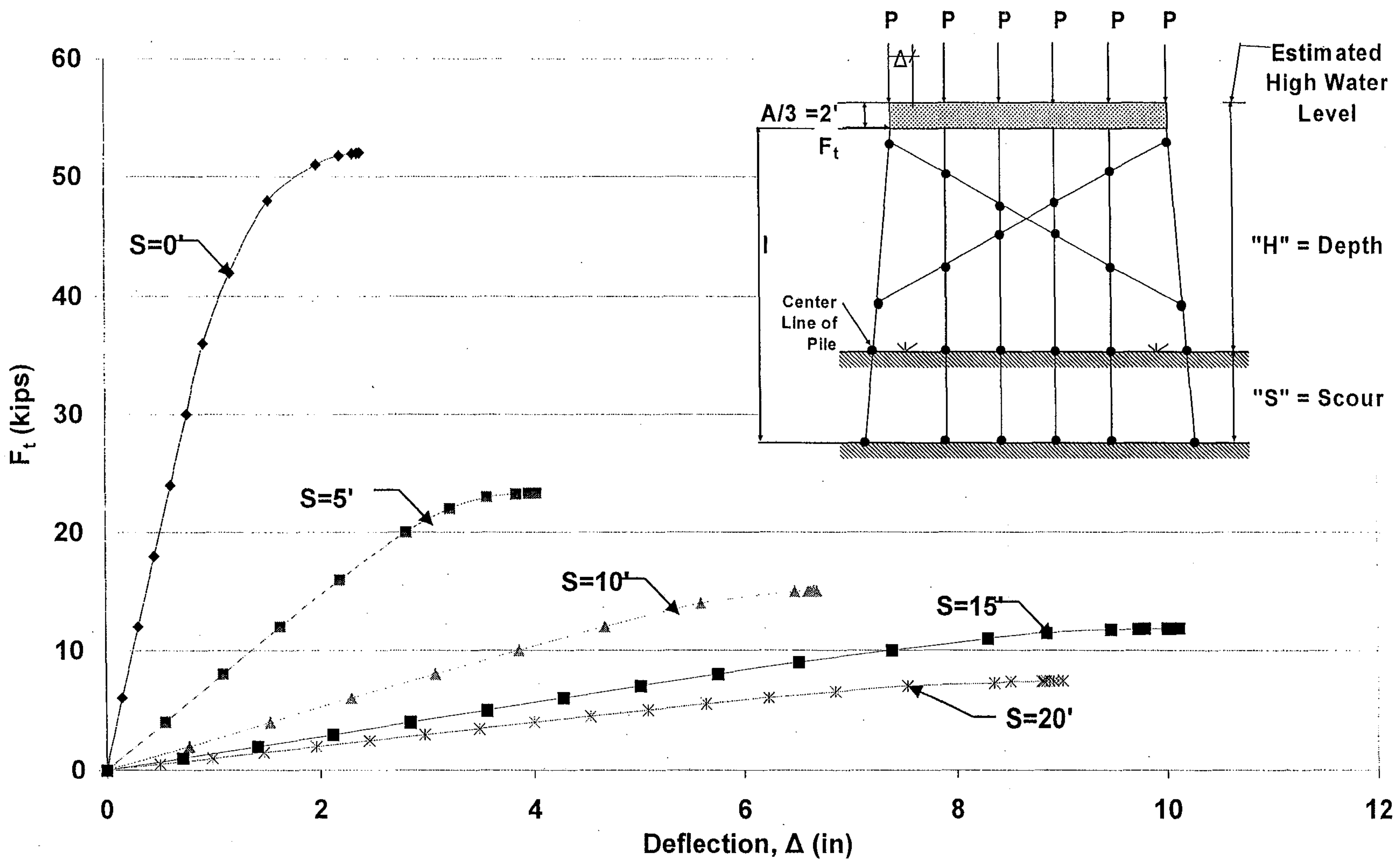


Figure A.87 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

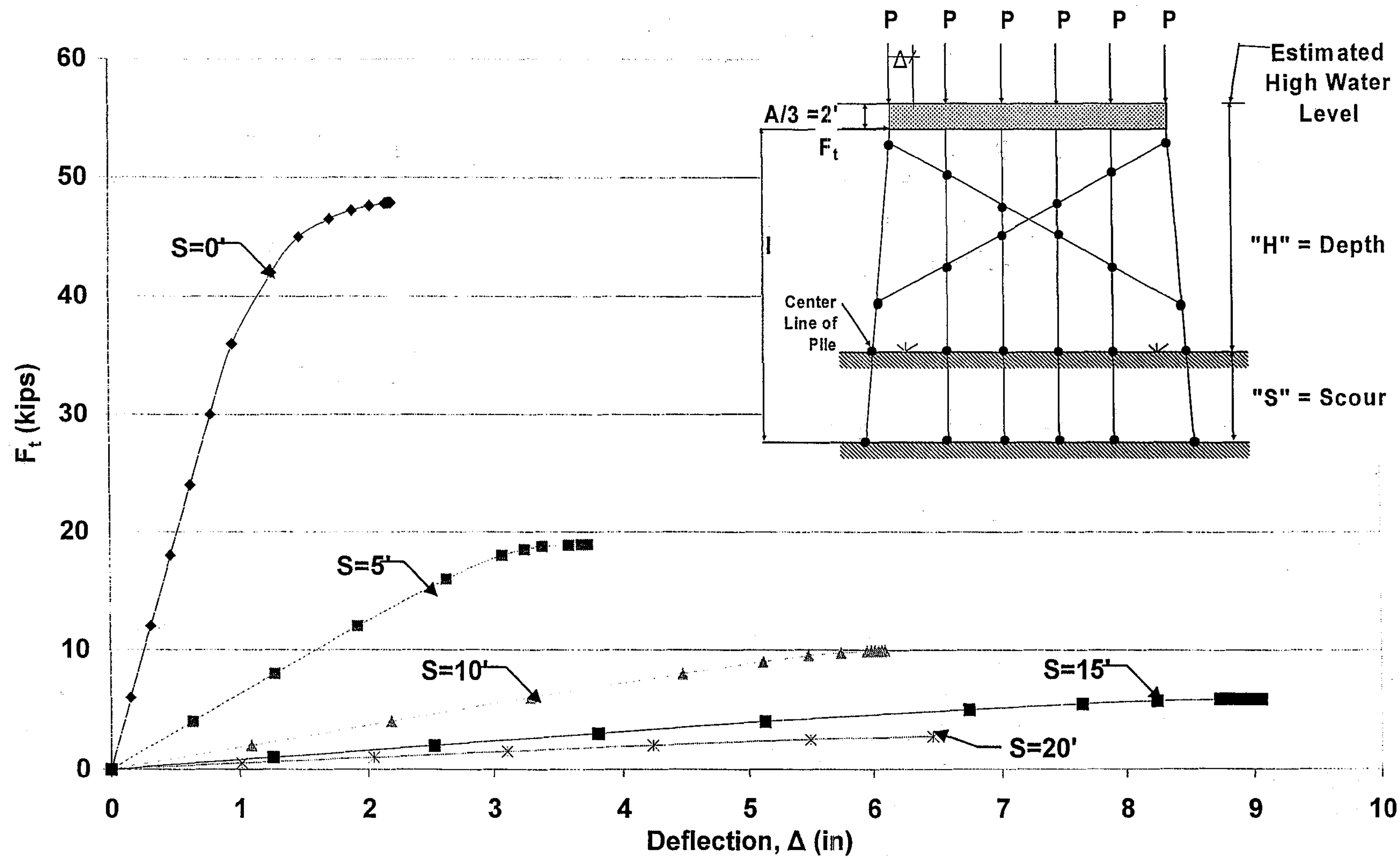


Figure A.88 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

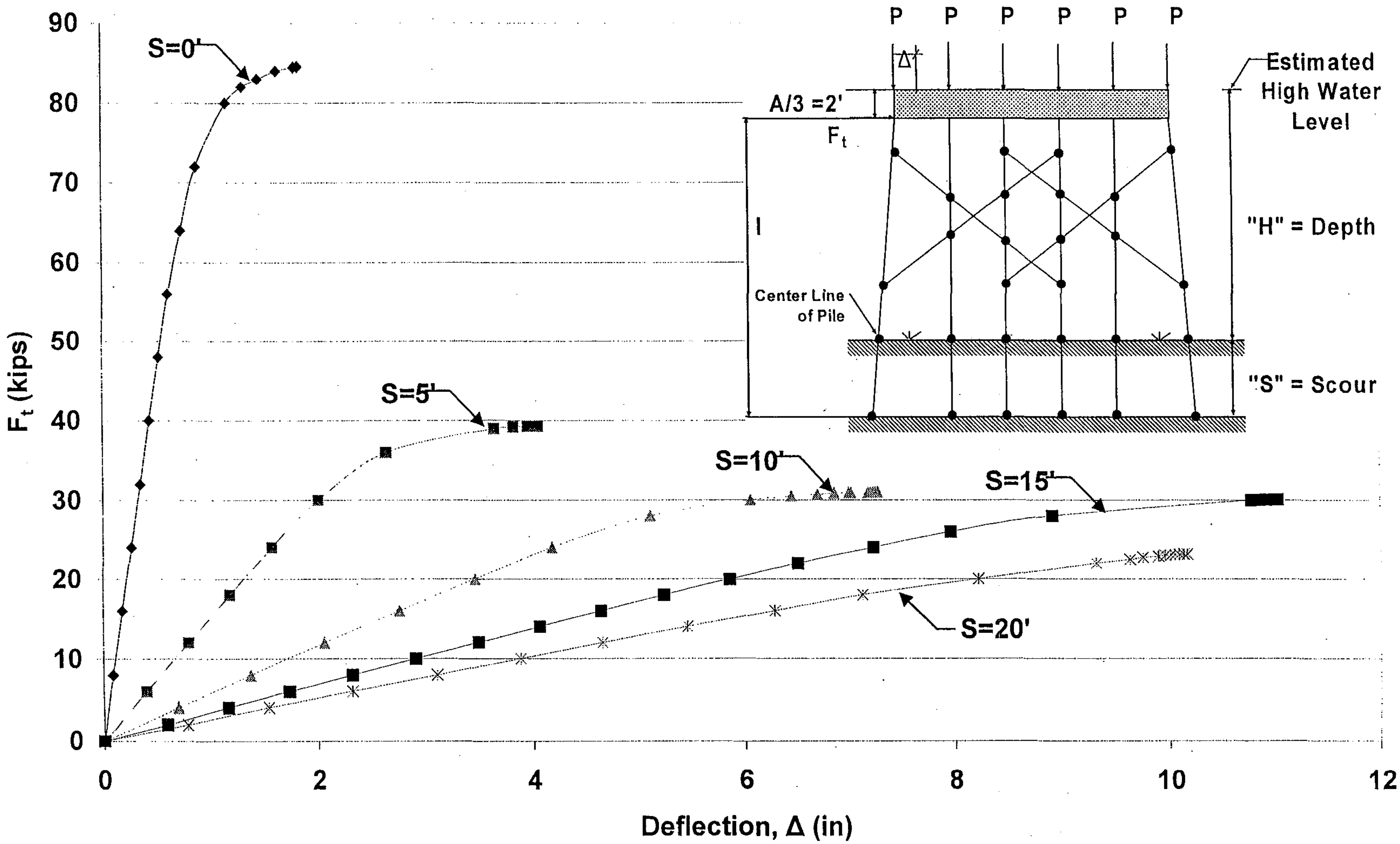


Figure A.89 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis

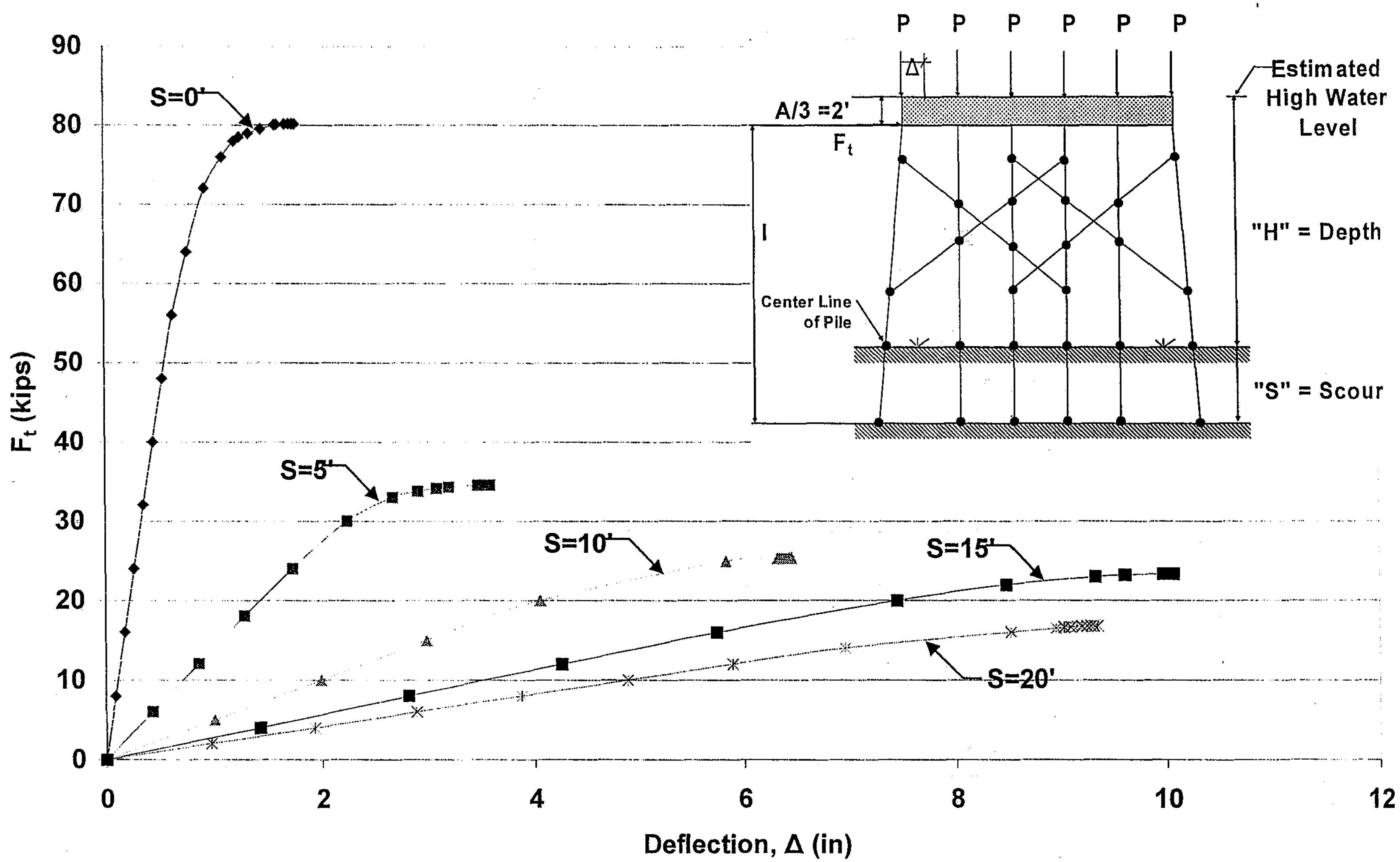


Figure A.90 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

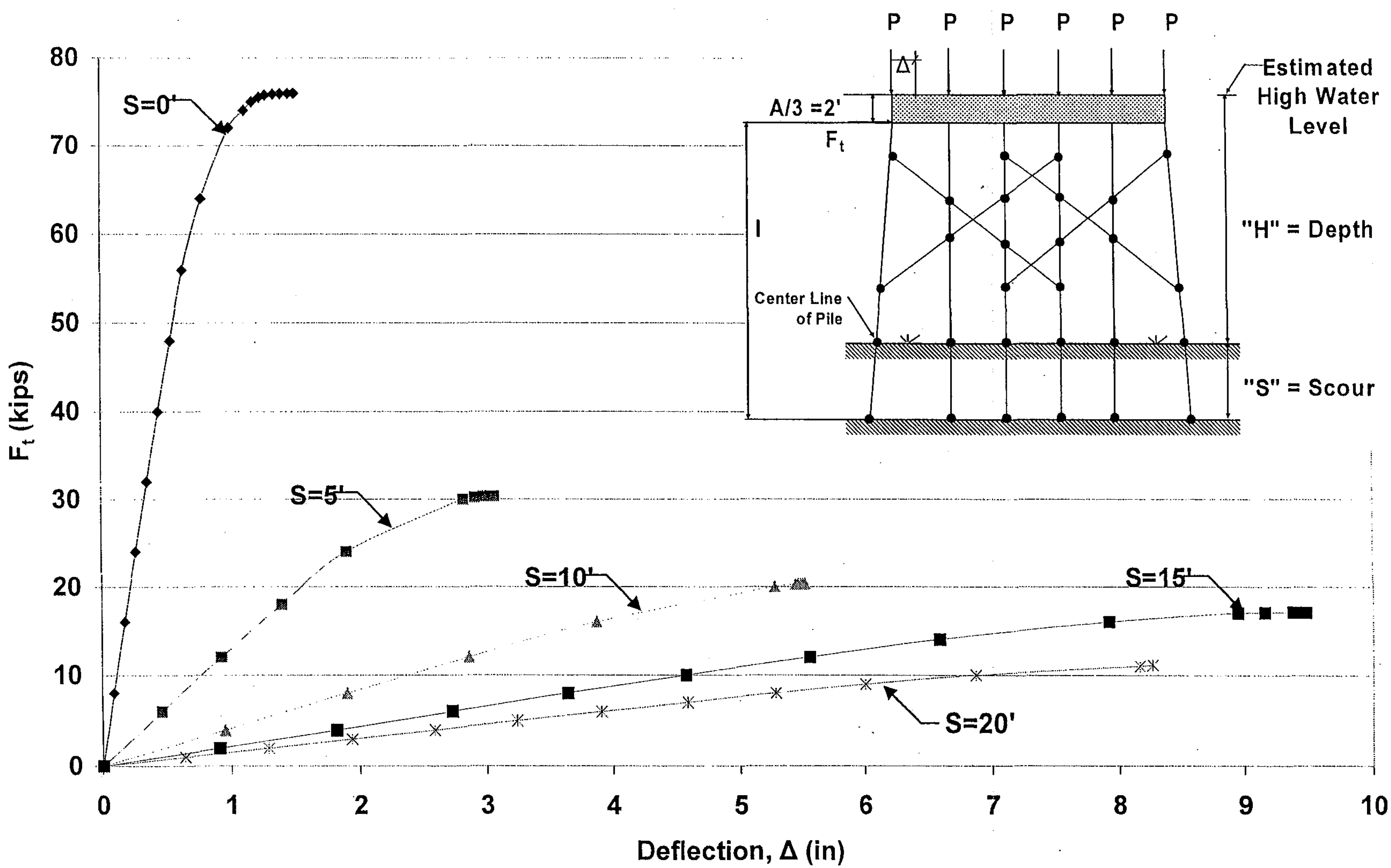


Figure A.91 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

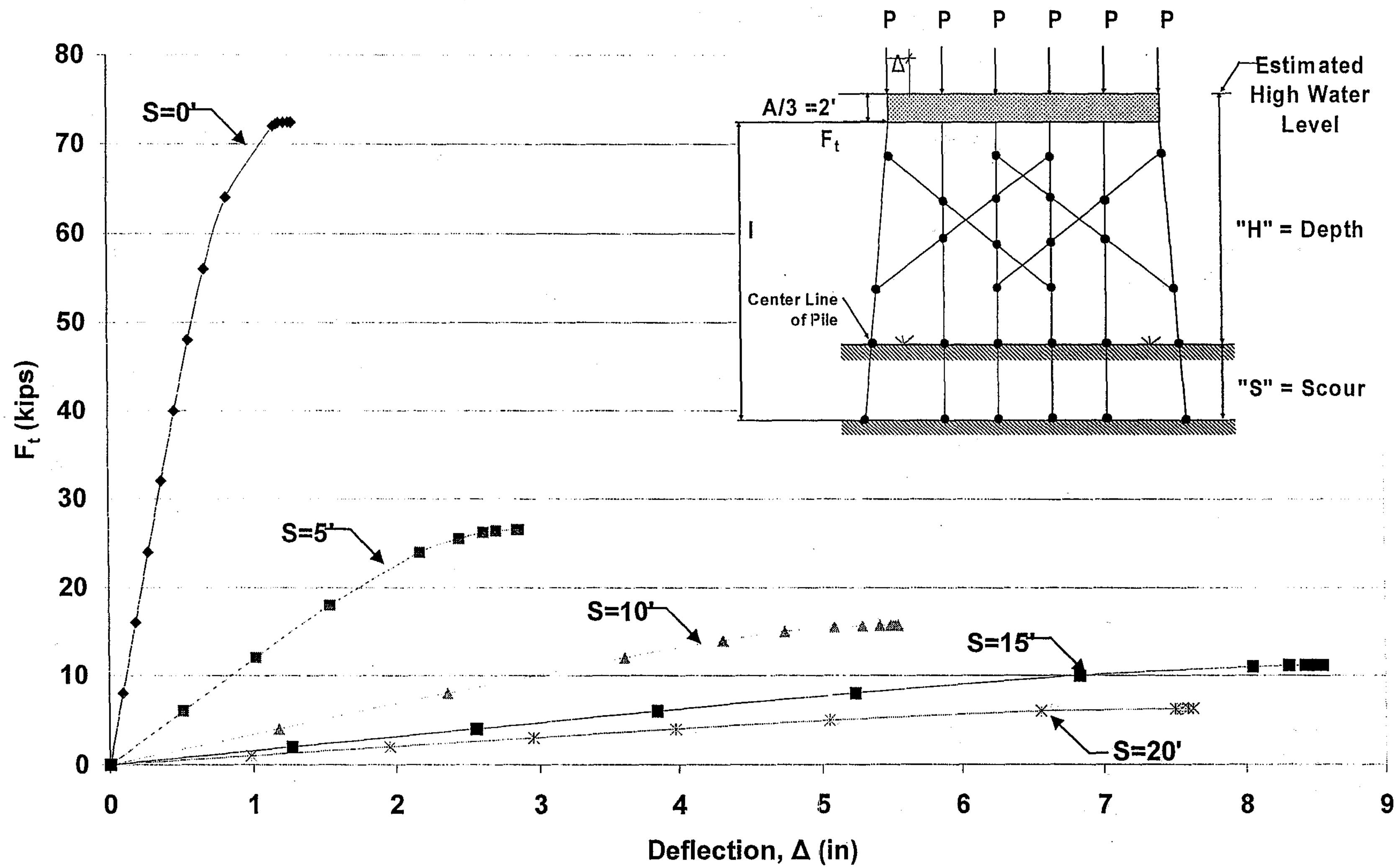


Figure A.92 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

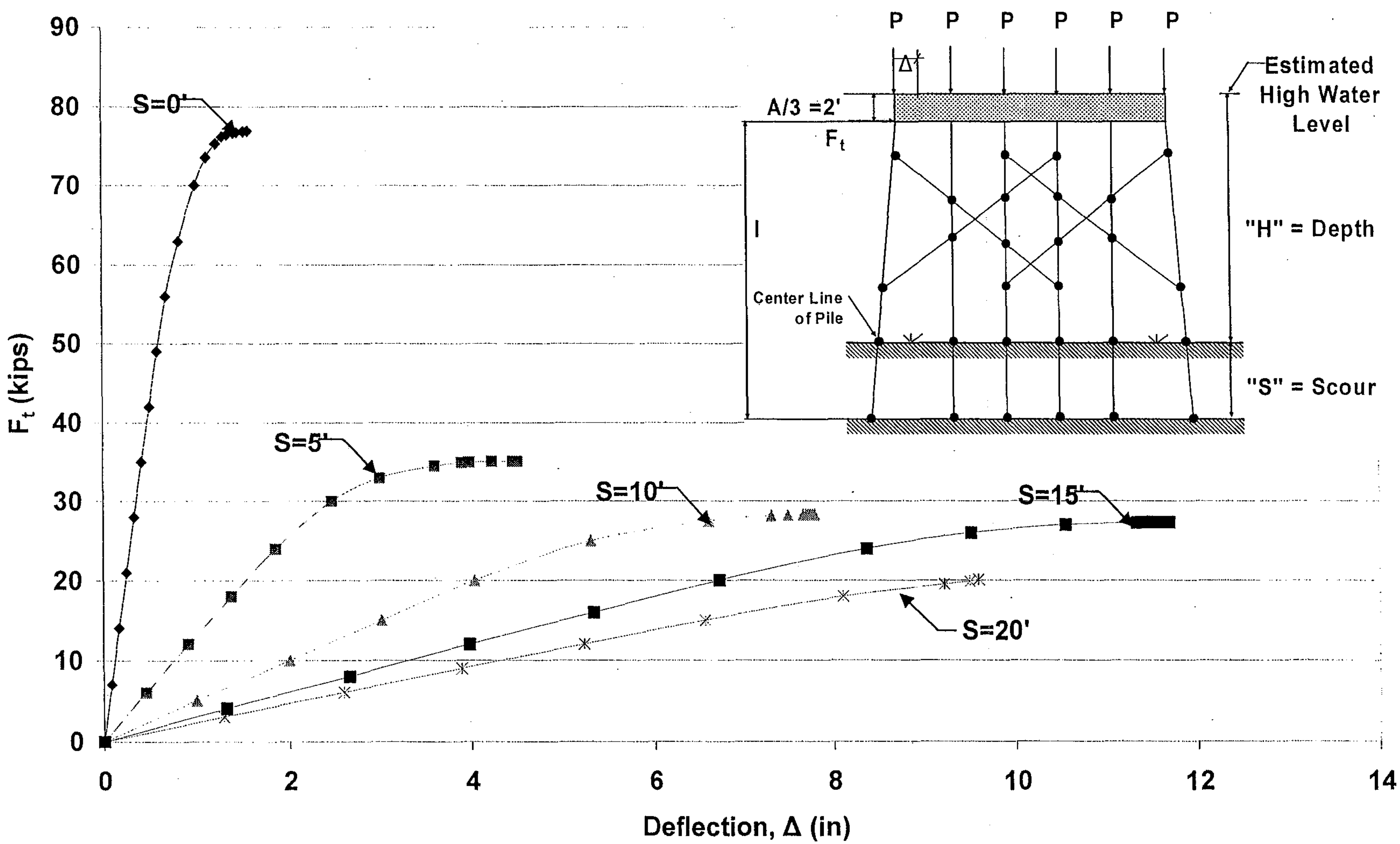


Figure A.93 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

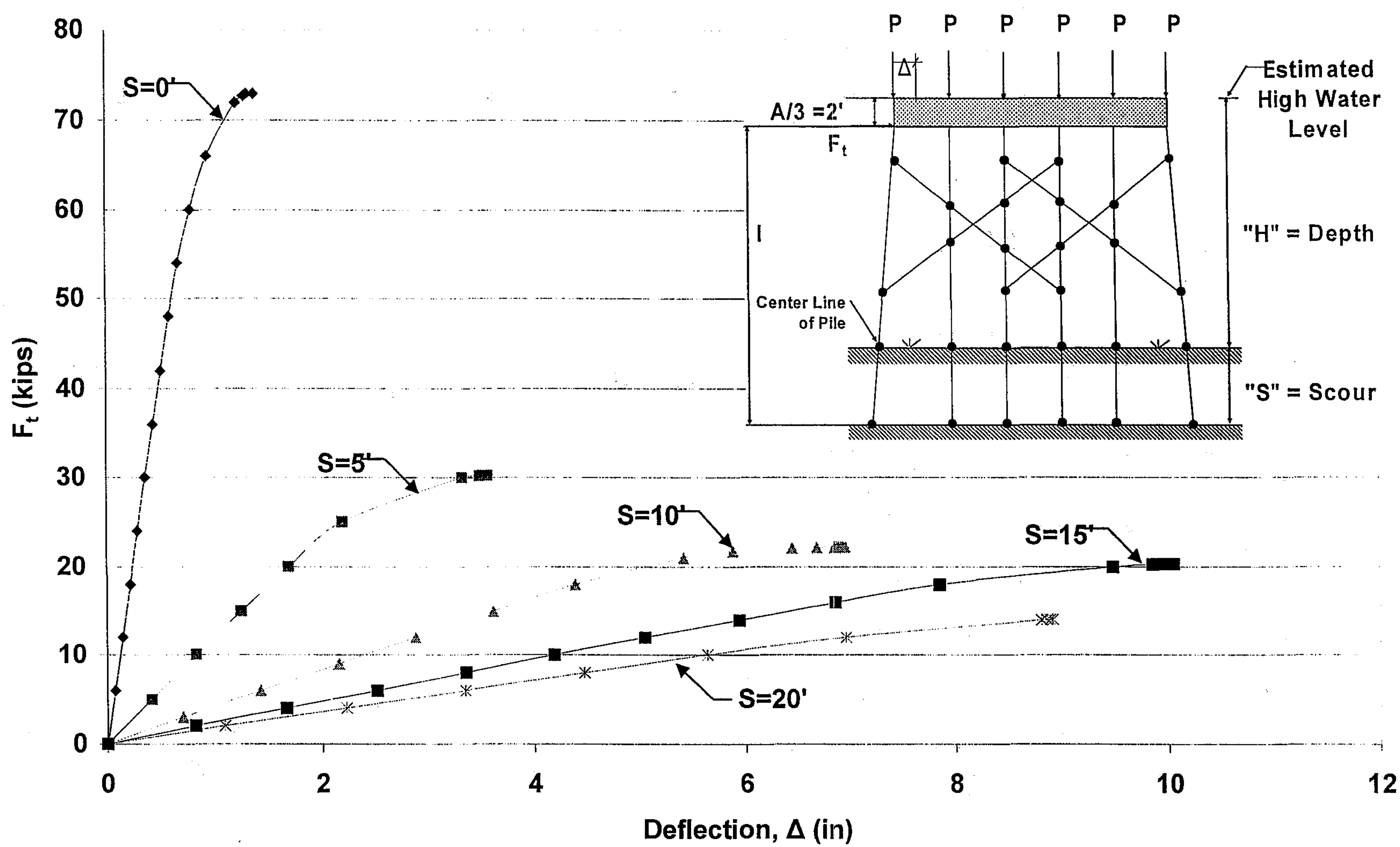


Figure A.94 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

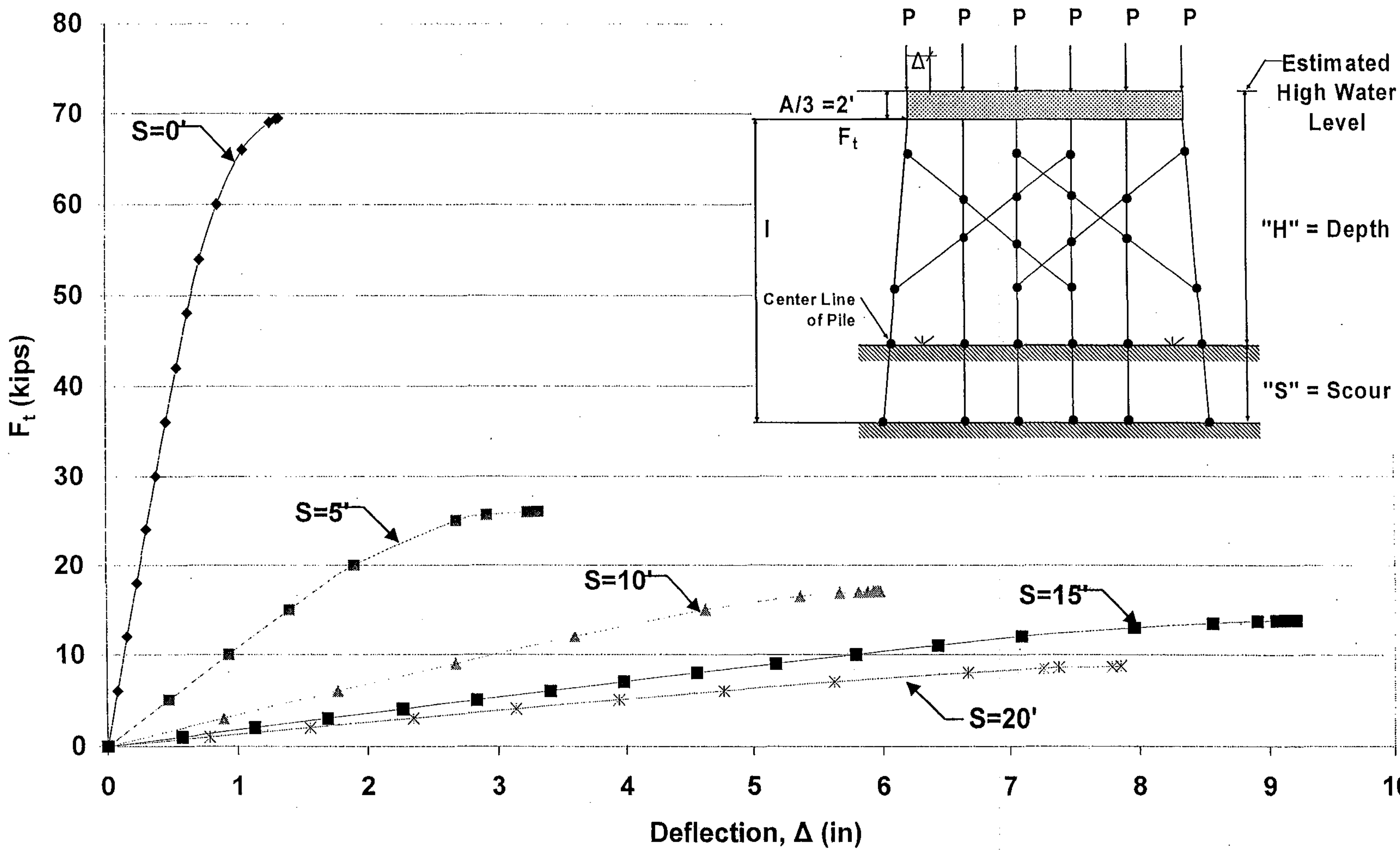


Figure A.95 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

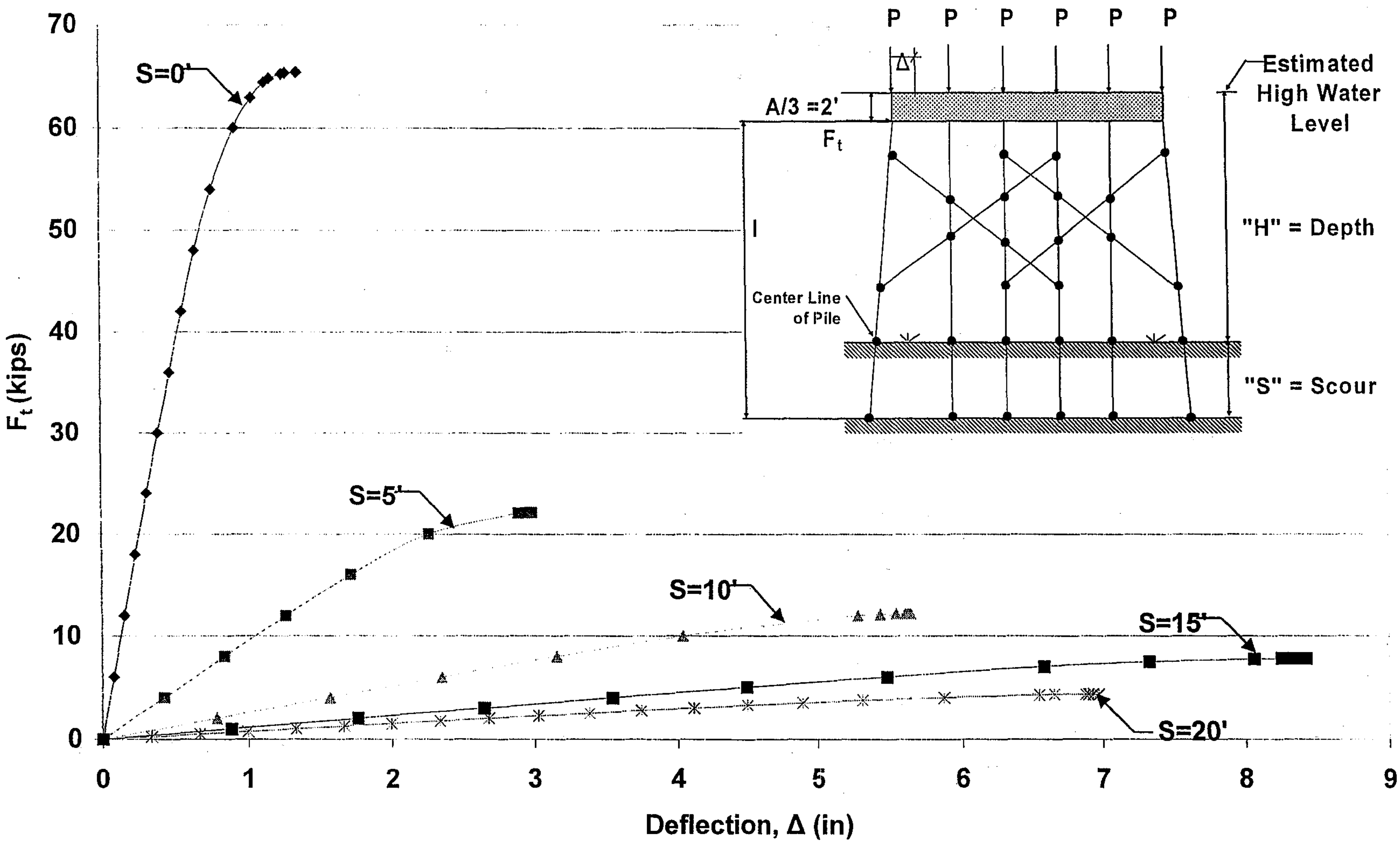


Figure A.96 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

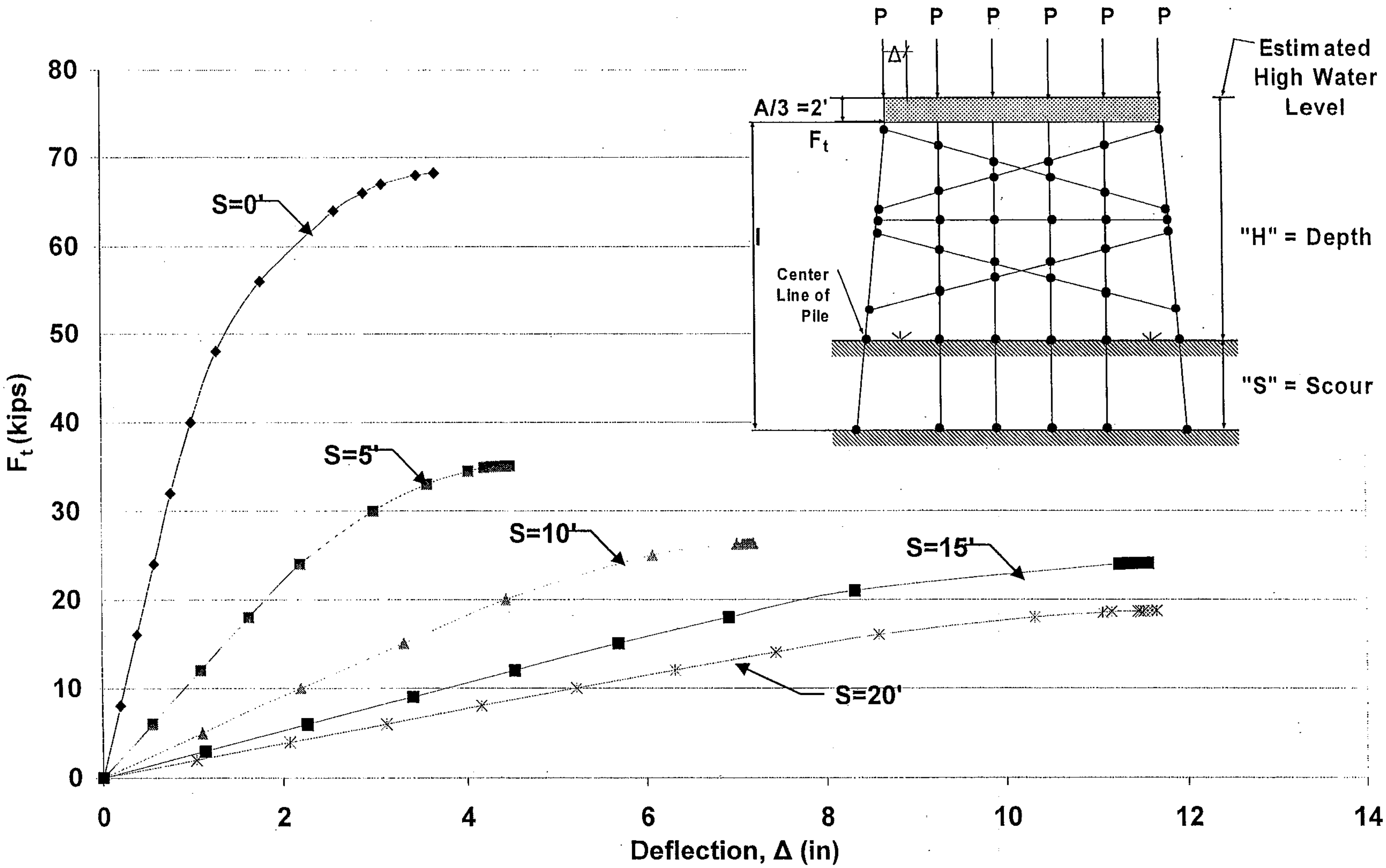


Figure A.97 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

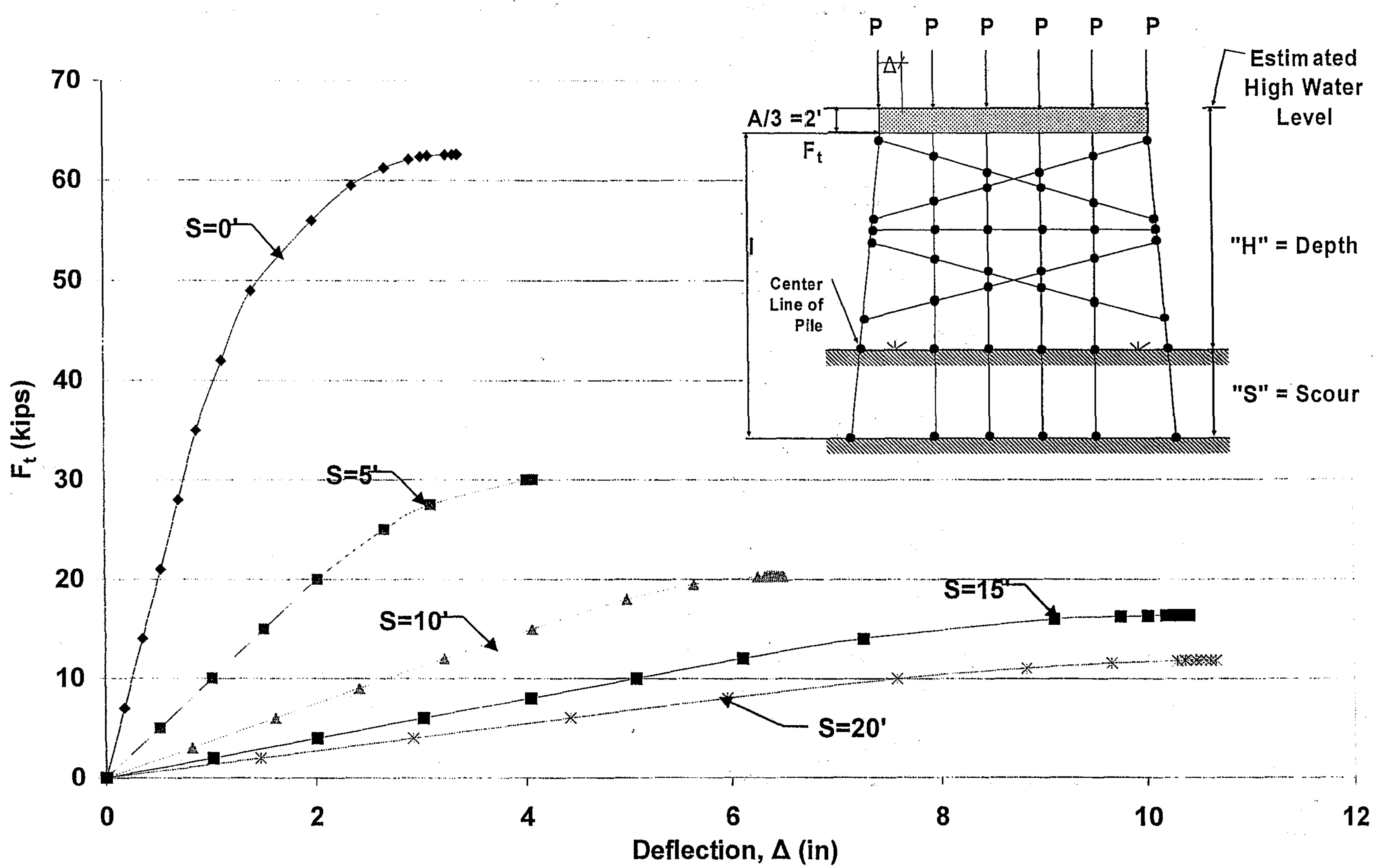


Figure A.98 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

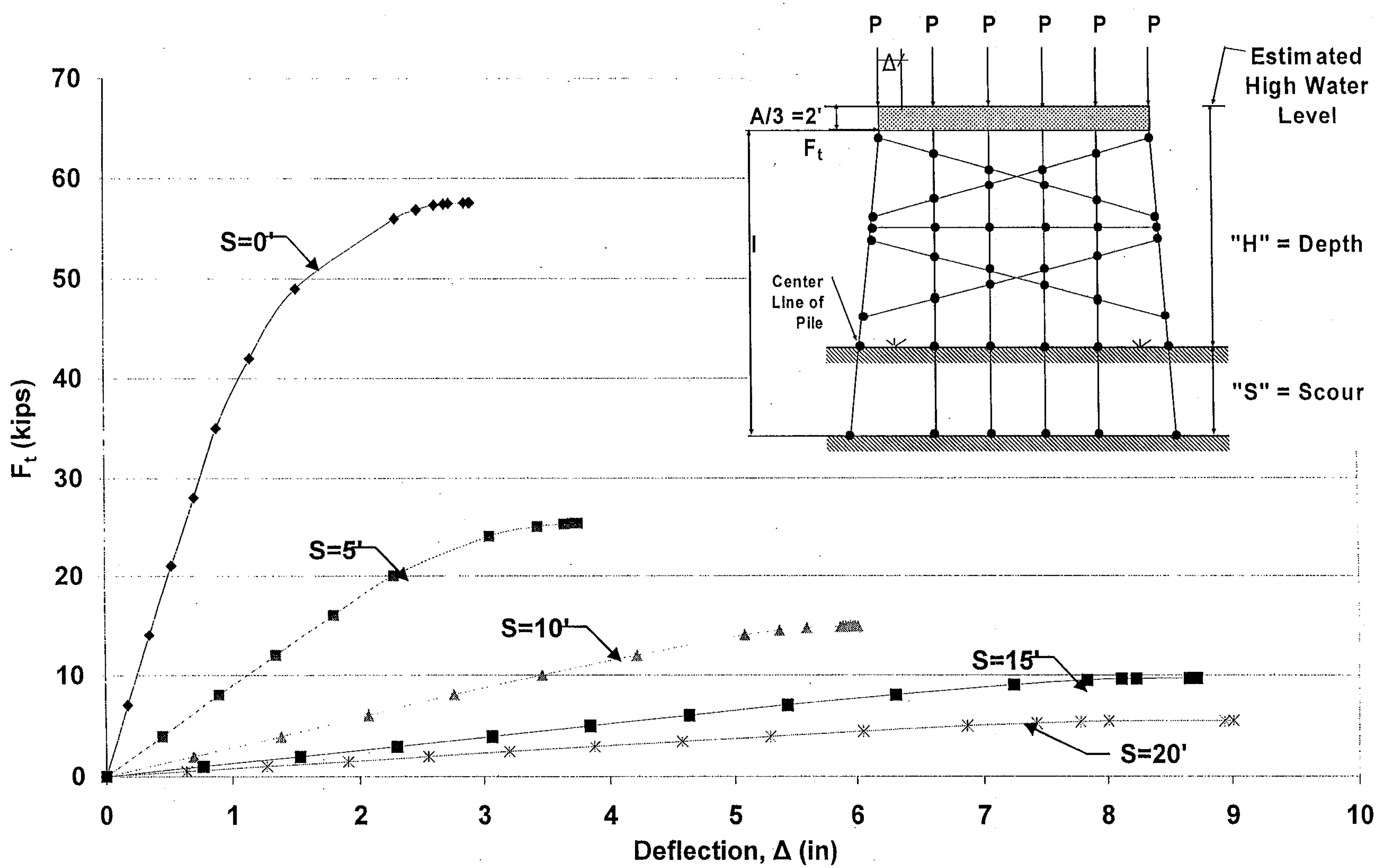


Figure A.99 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

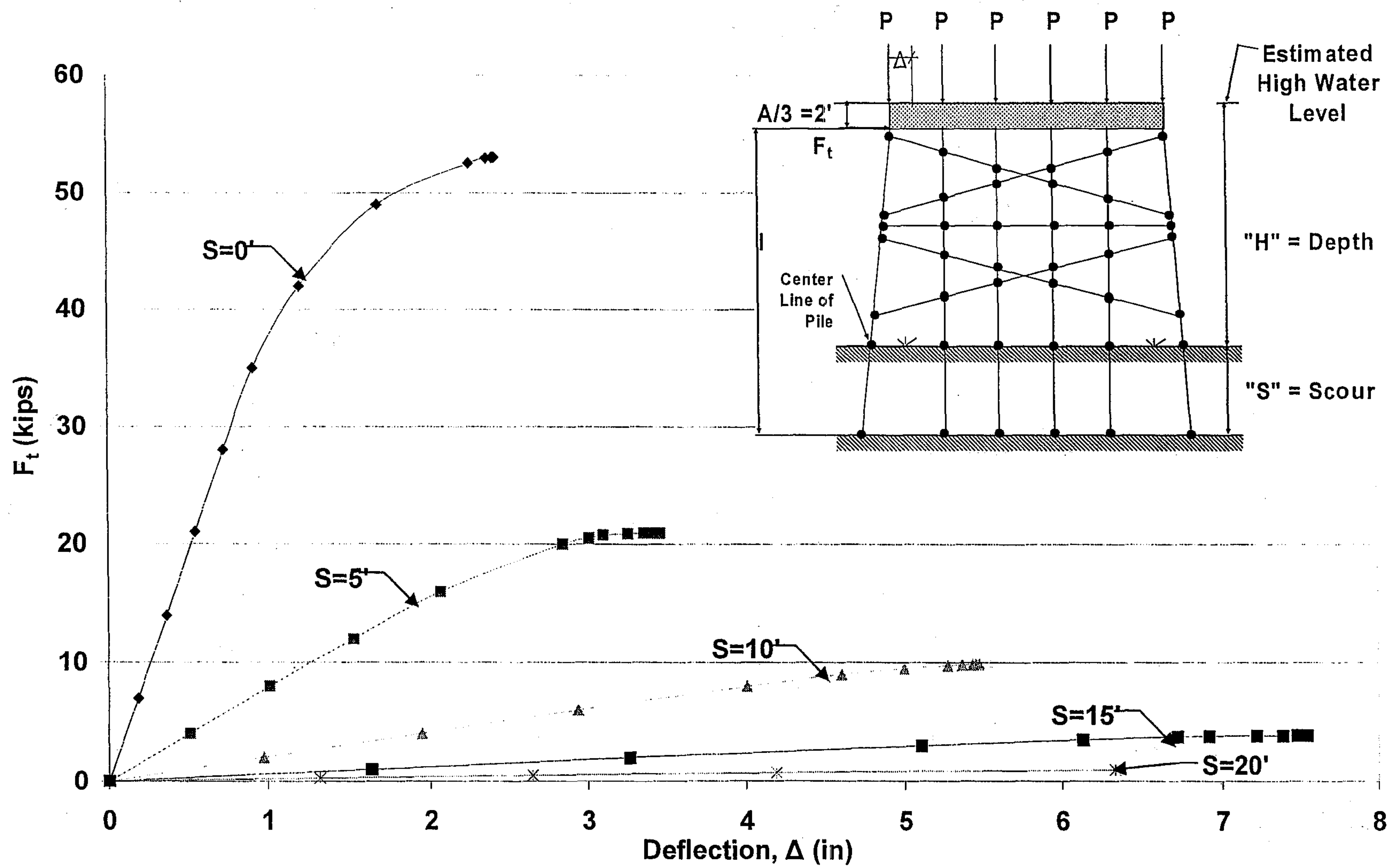


Figure A.100 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

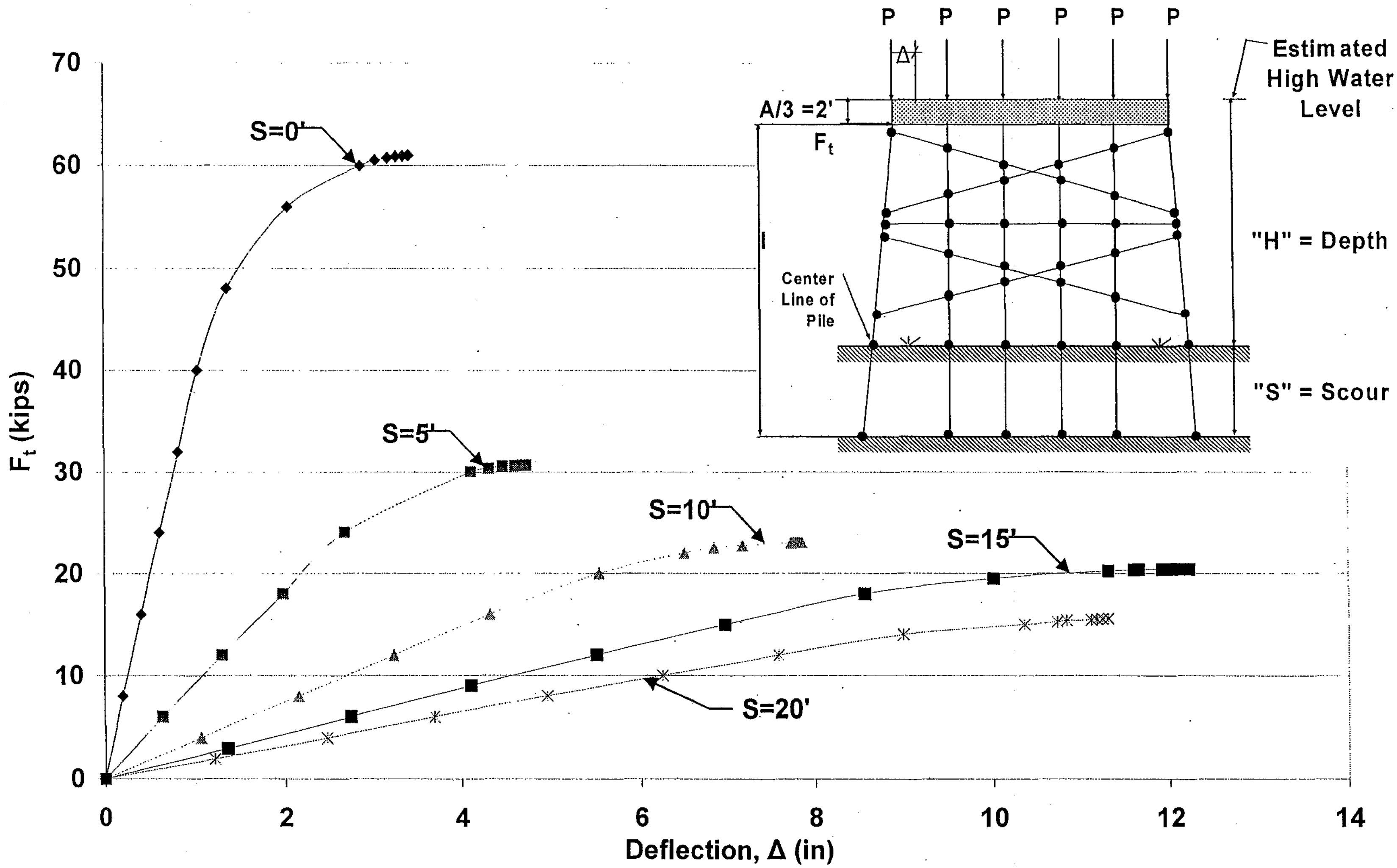


Figure A.101 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

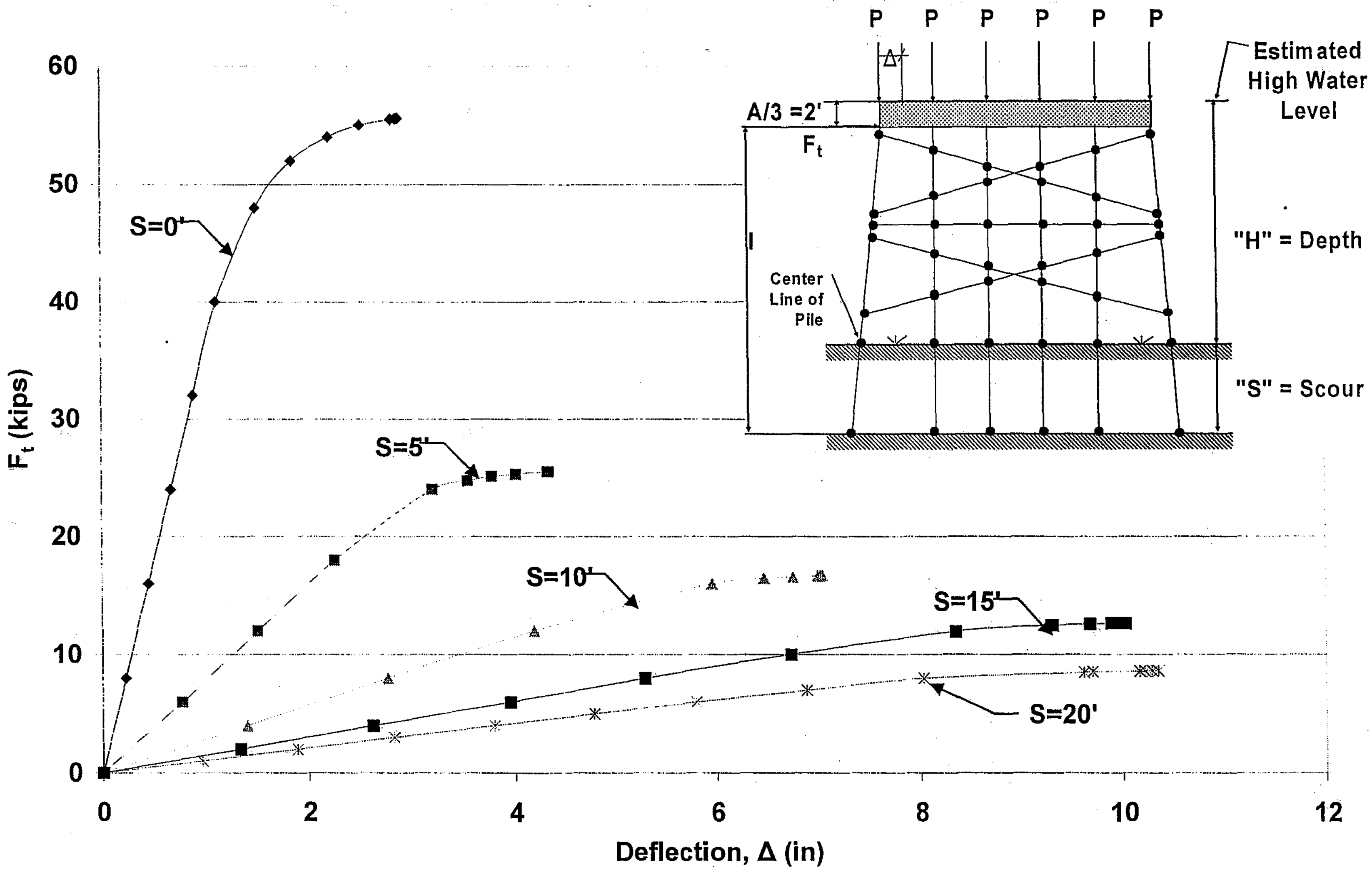


Figure A.102 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

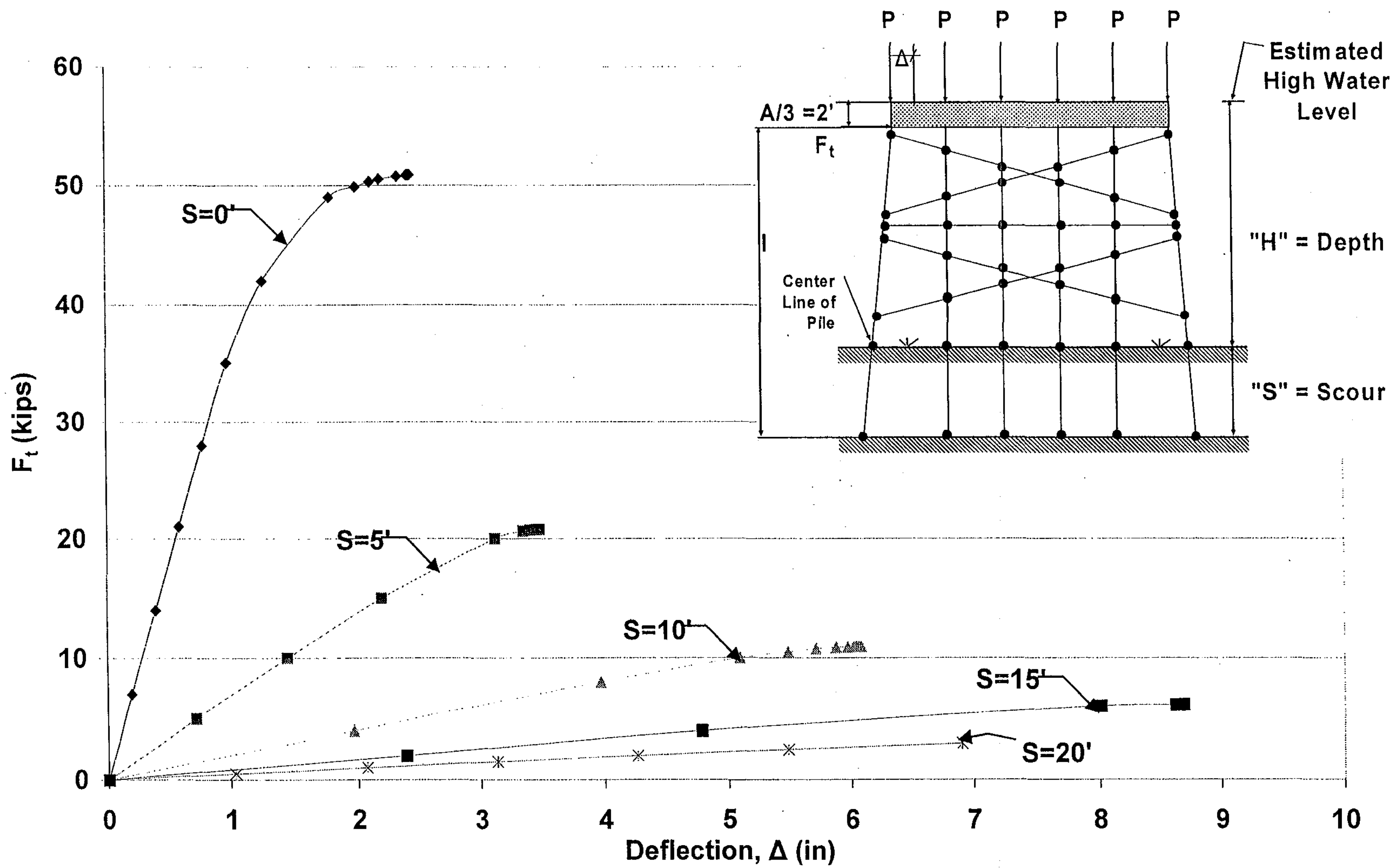


Figure A.103 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

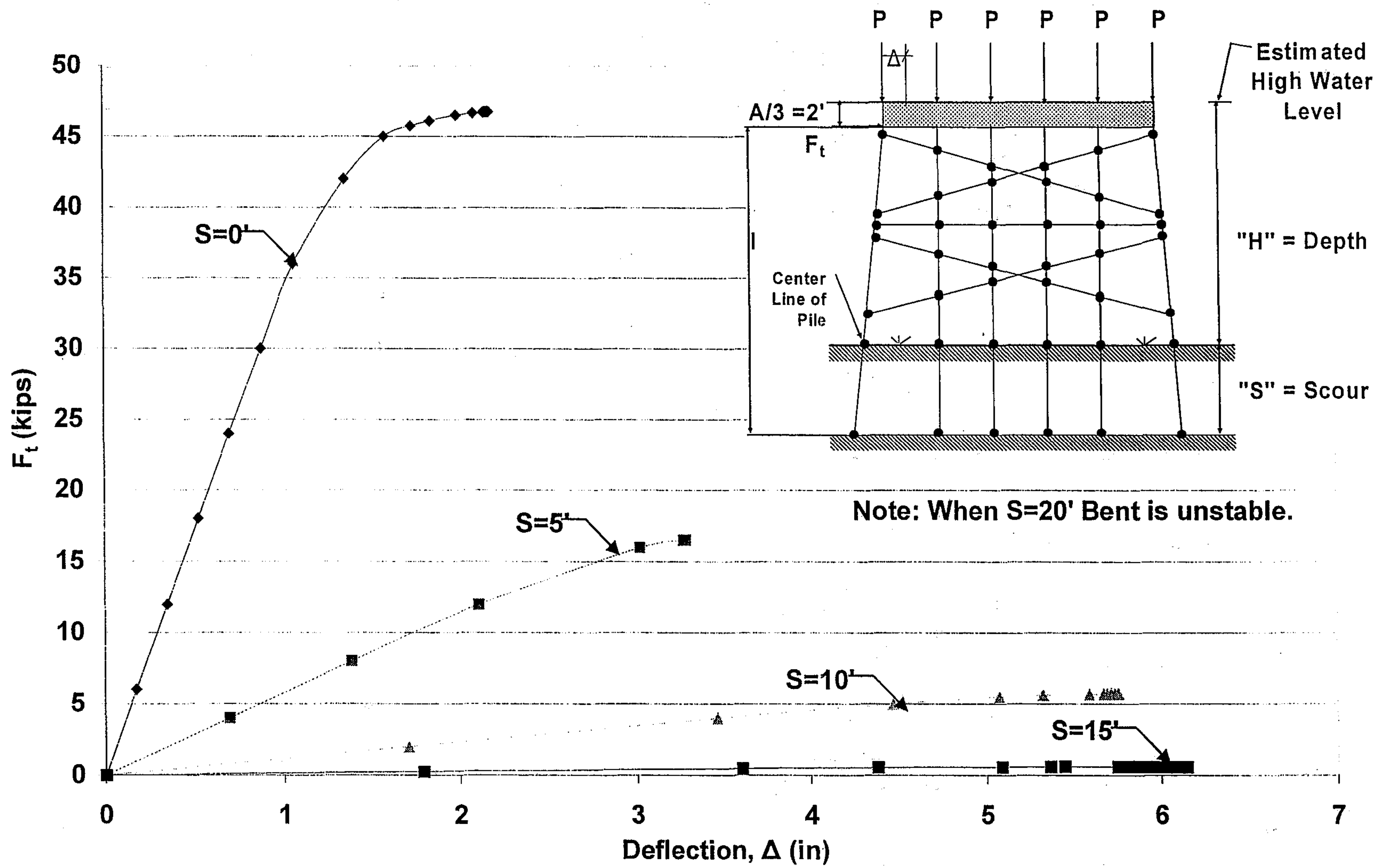


Figure A.104 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

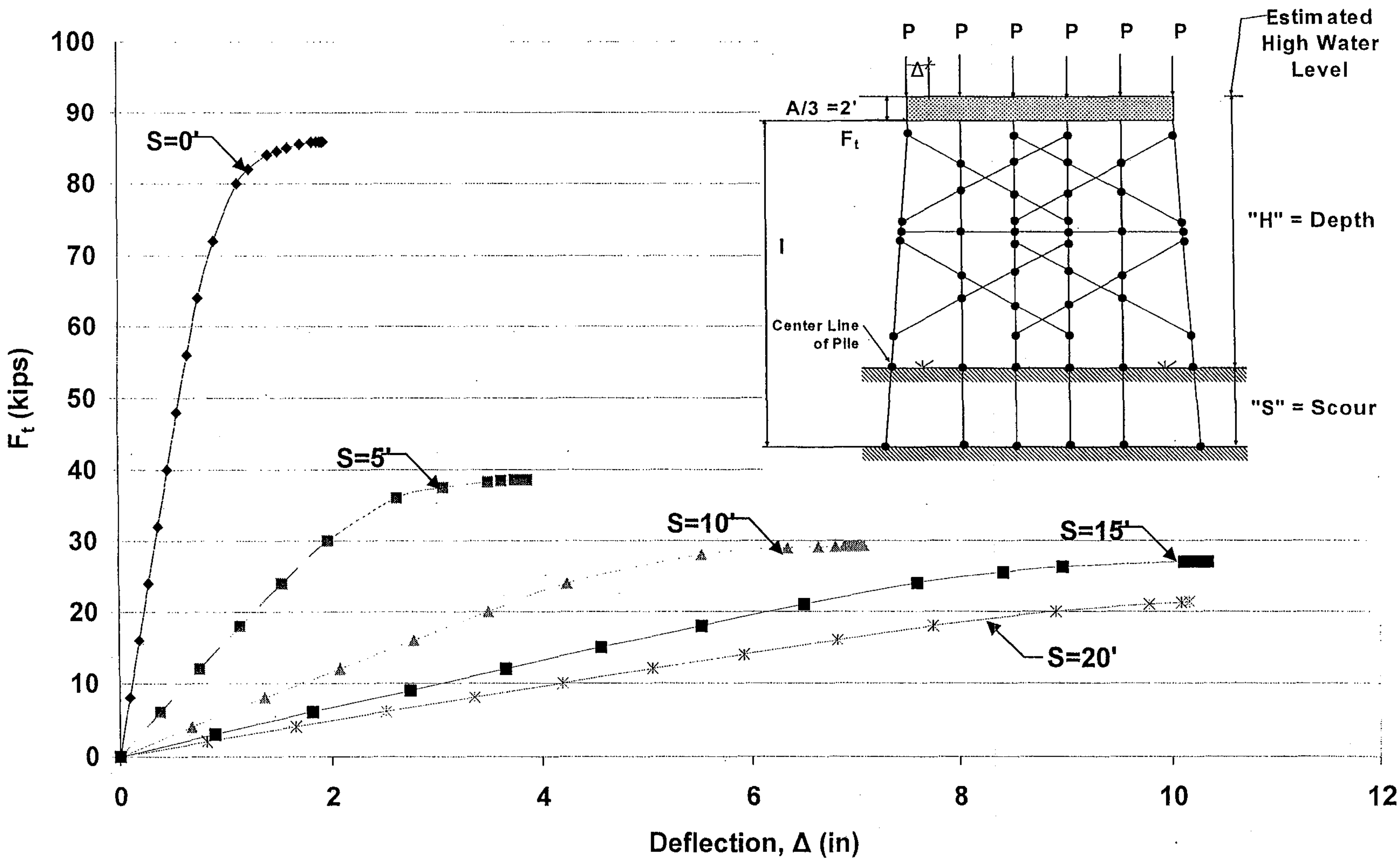


Figure A.105 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

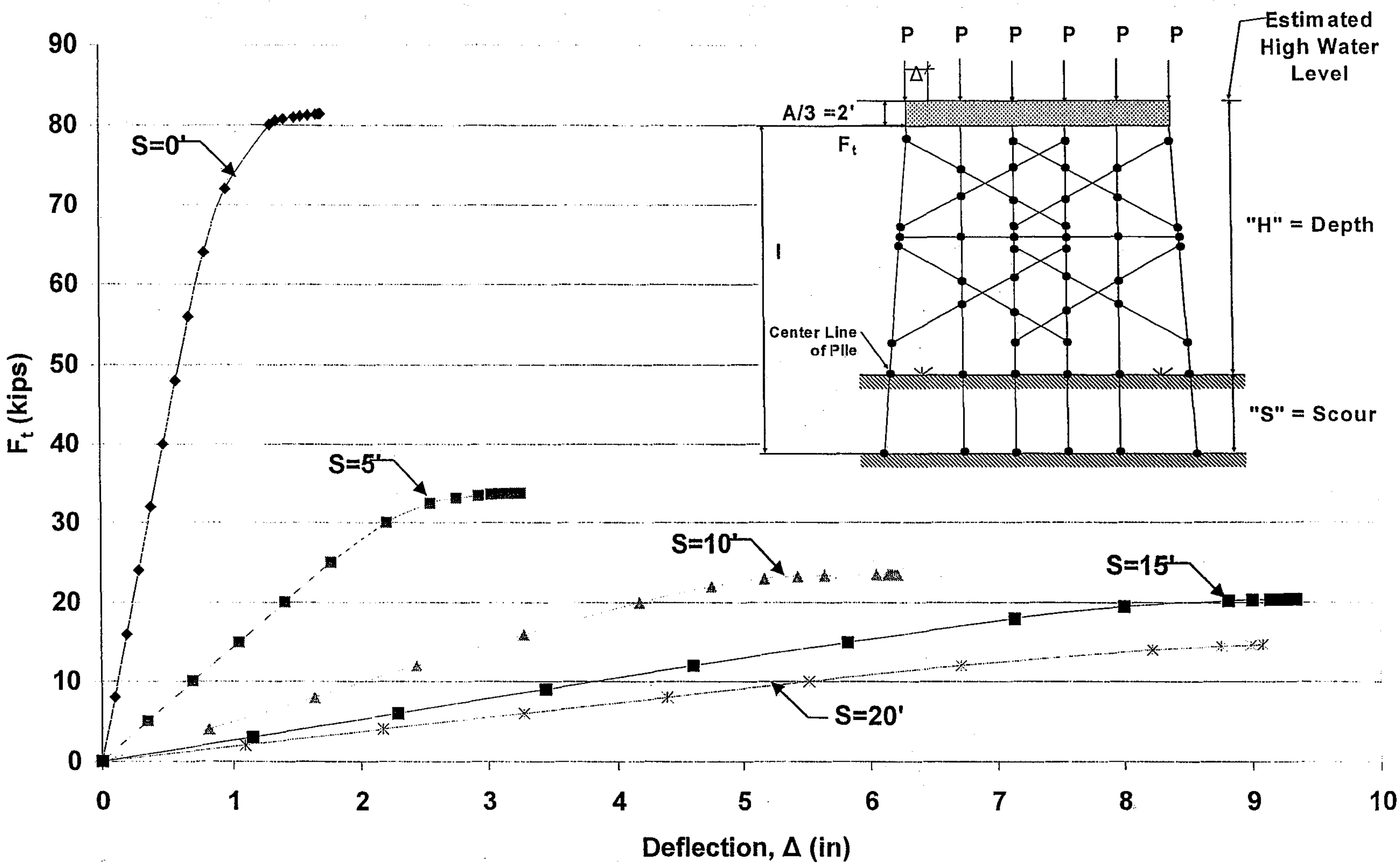


Figure A.106 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

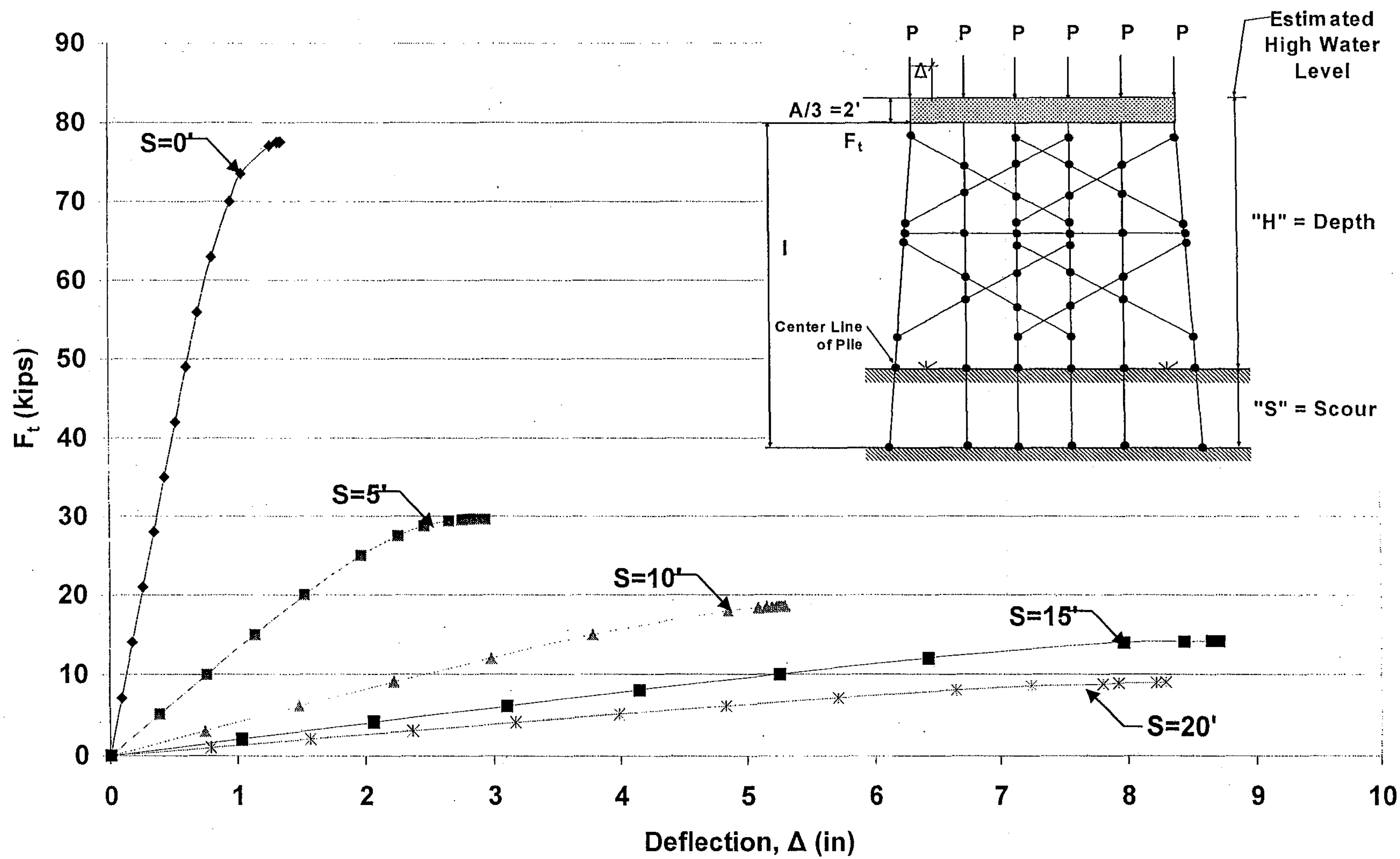


Figure A.107 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

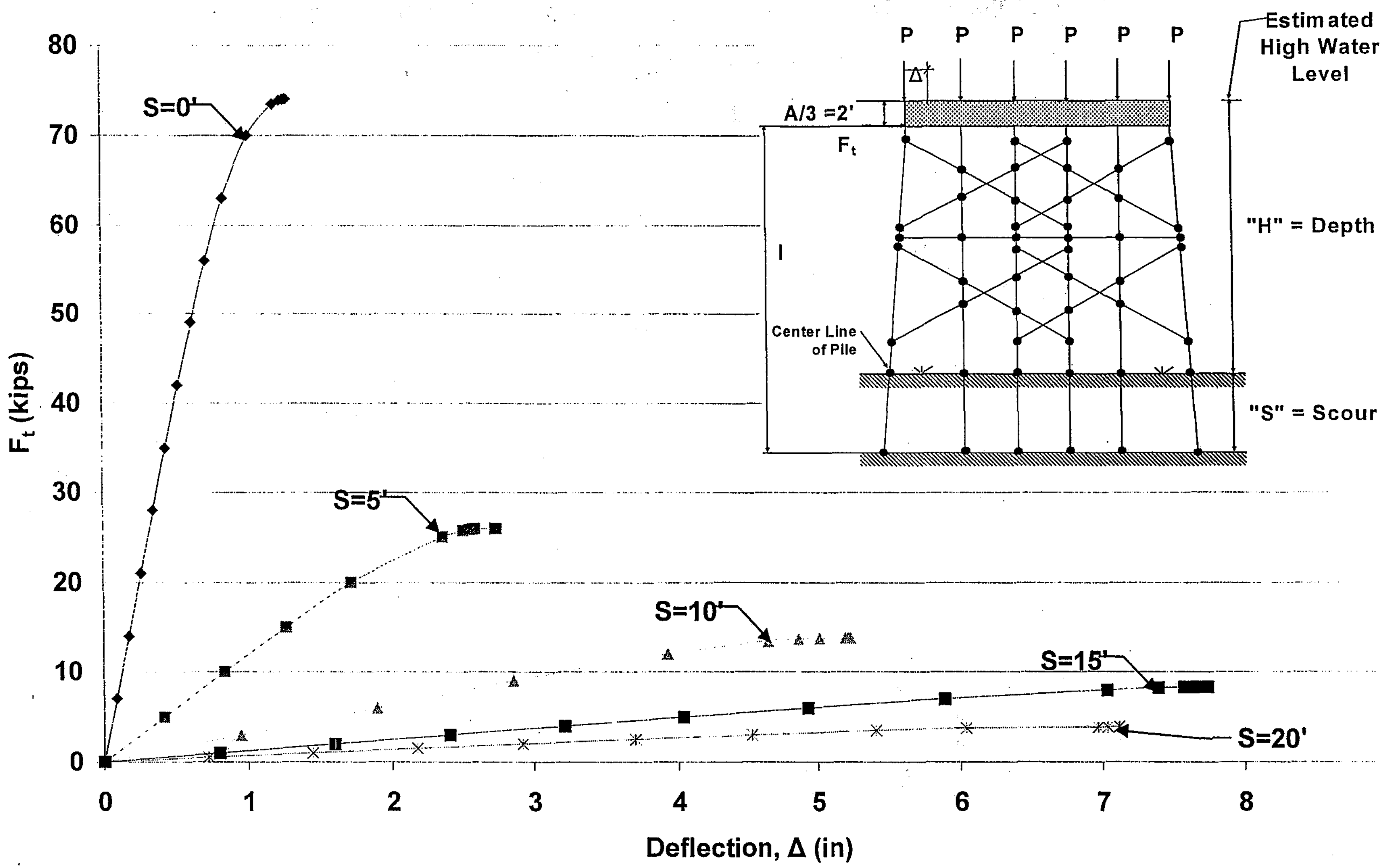


Figure A.108 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

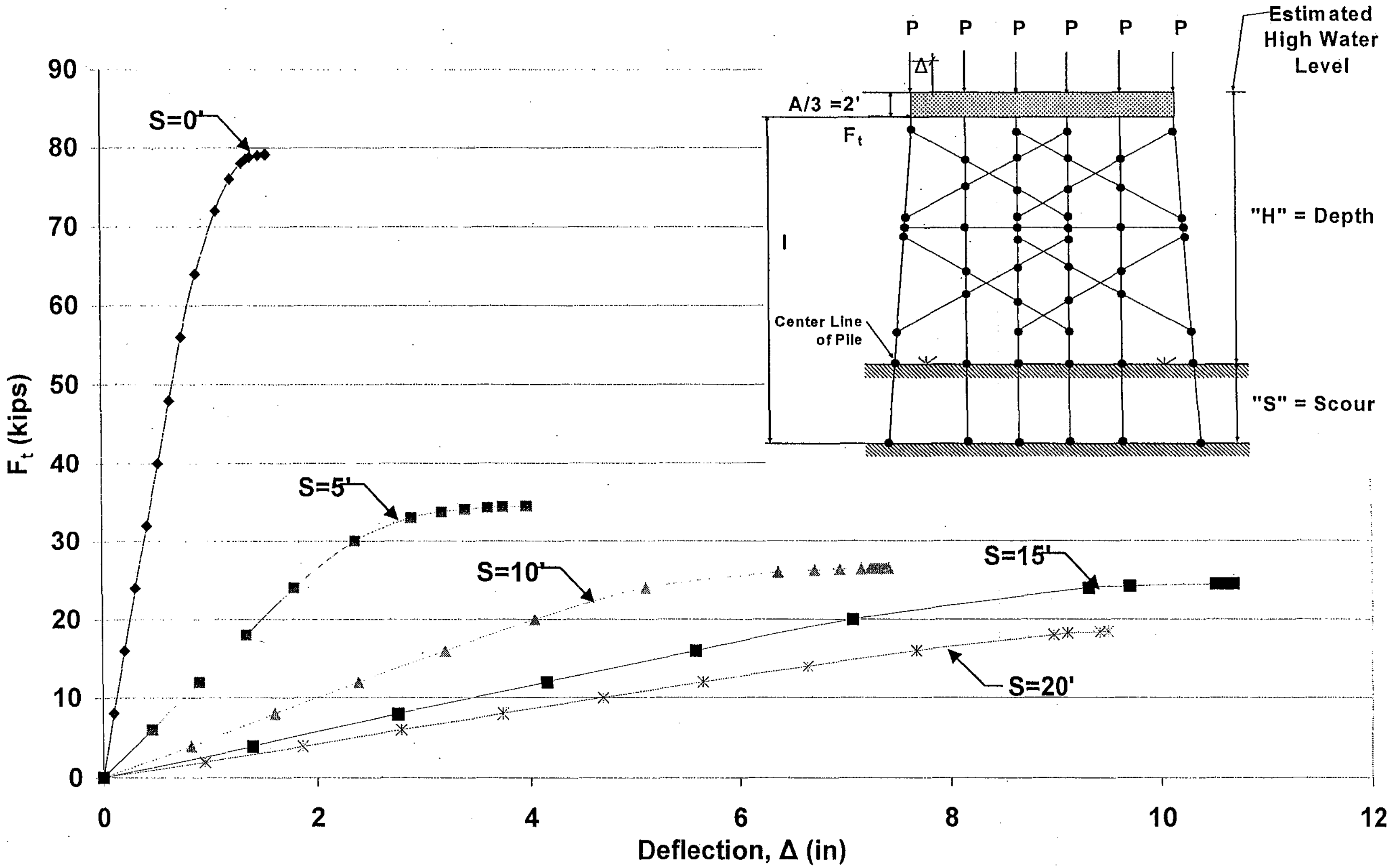


Figure A.109 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

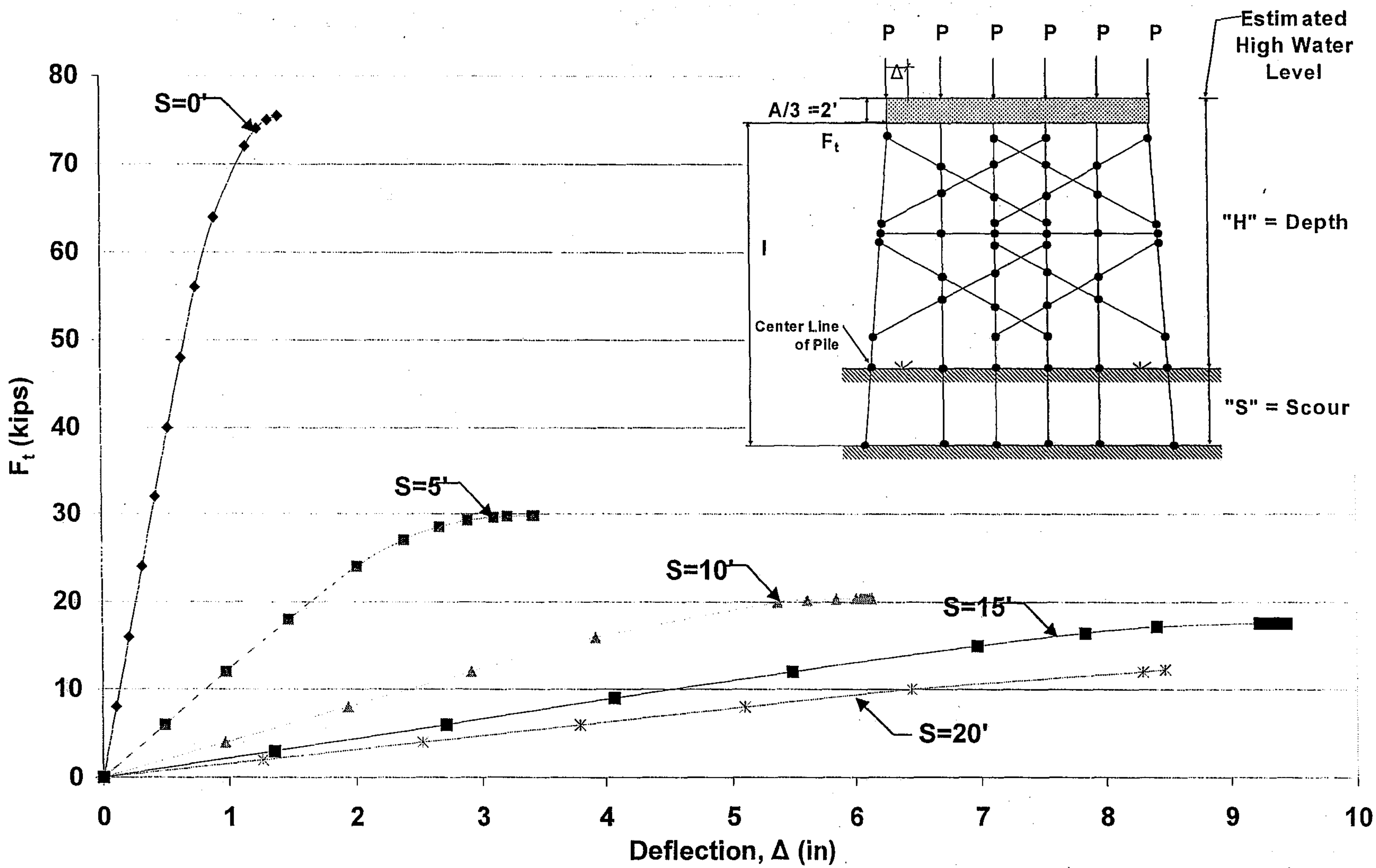


Figure A.110 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

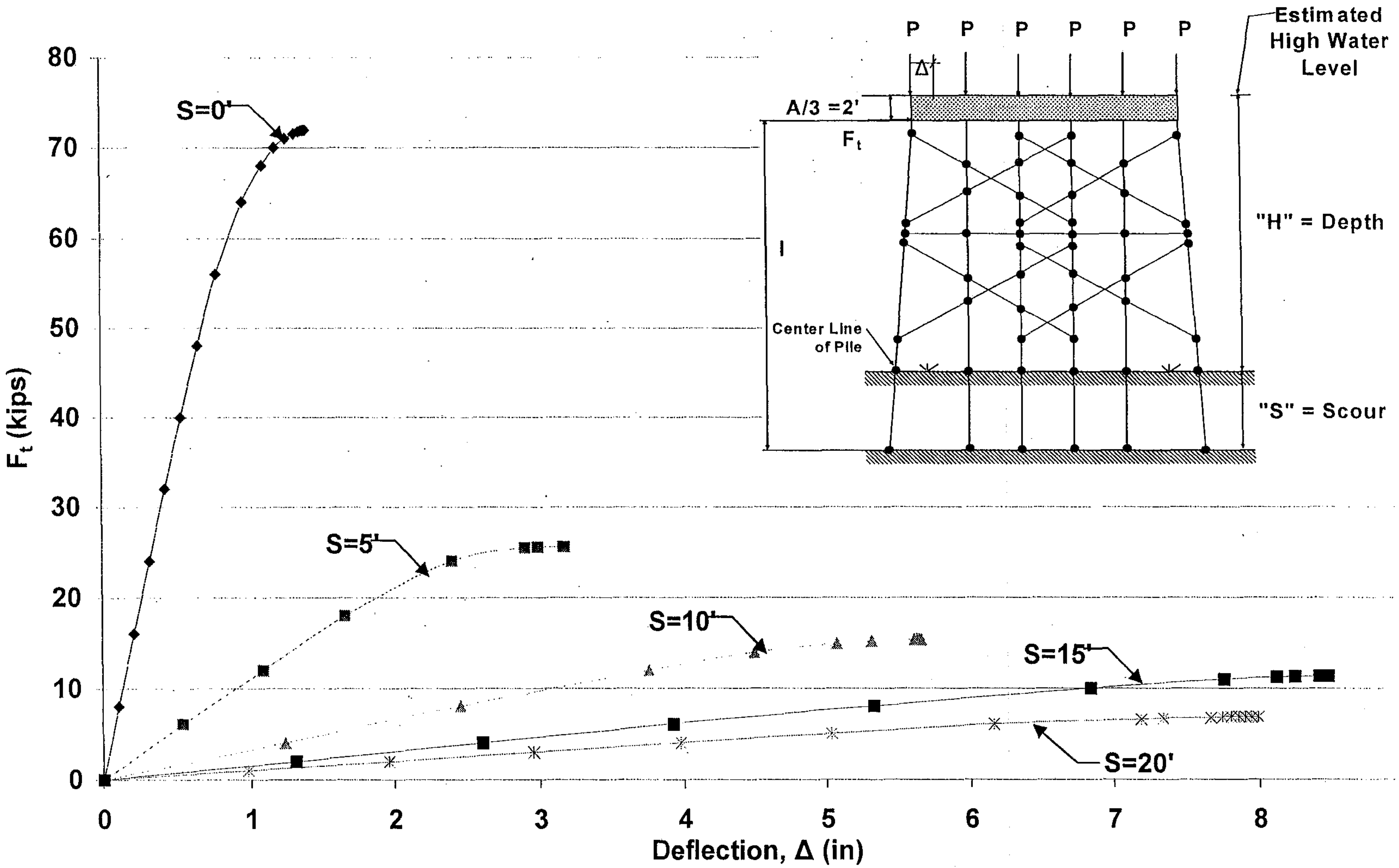


Figure A.111 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

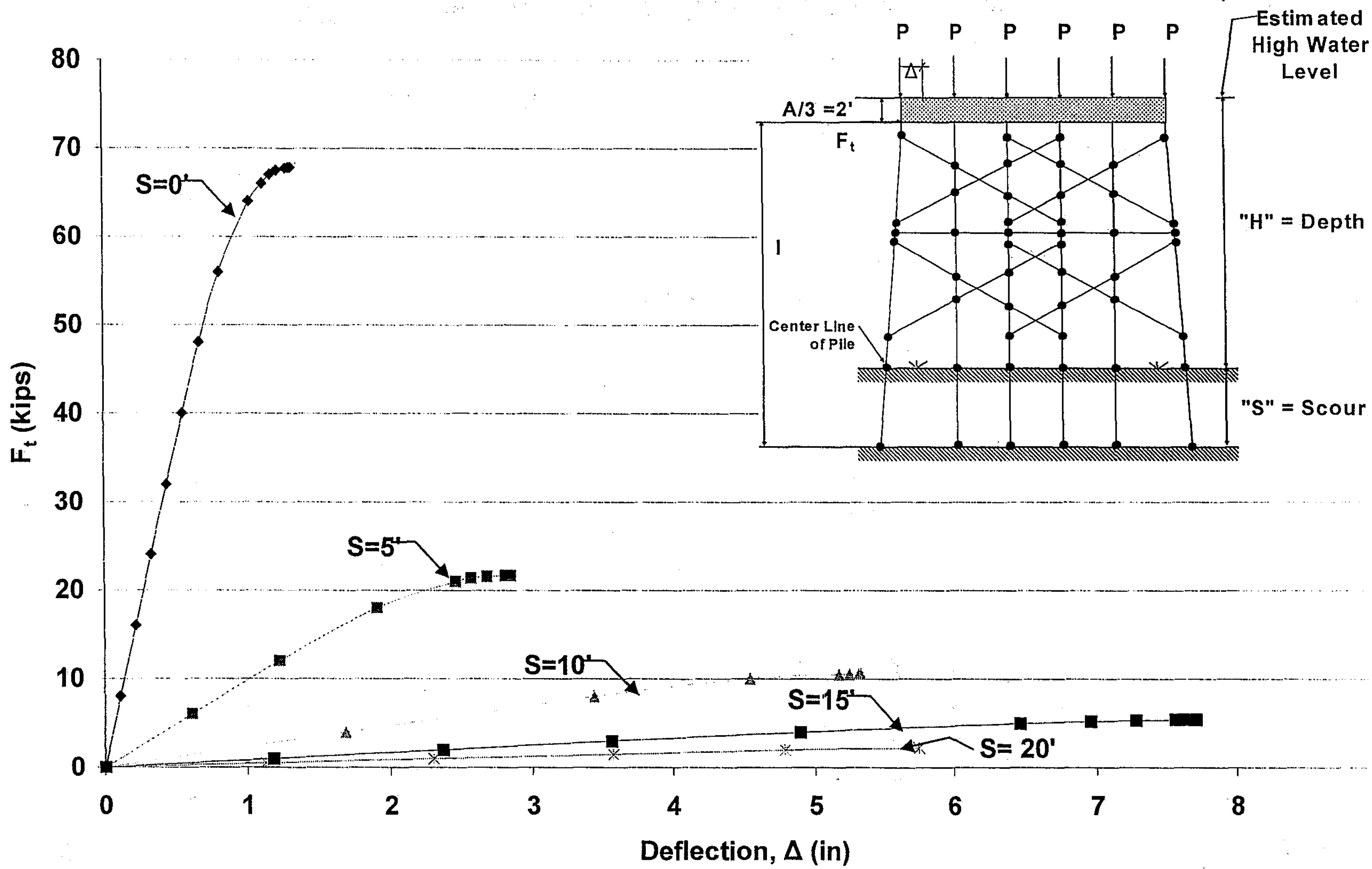


Figure A.112 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

APPENDIX B

Pushover Analysis Results for HP12x53 Pile Bents of Various Geometrical Configurations, P-Loadings, and Scour Levels

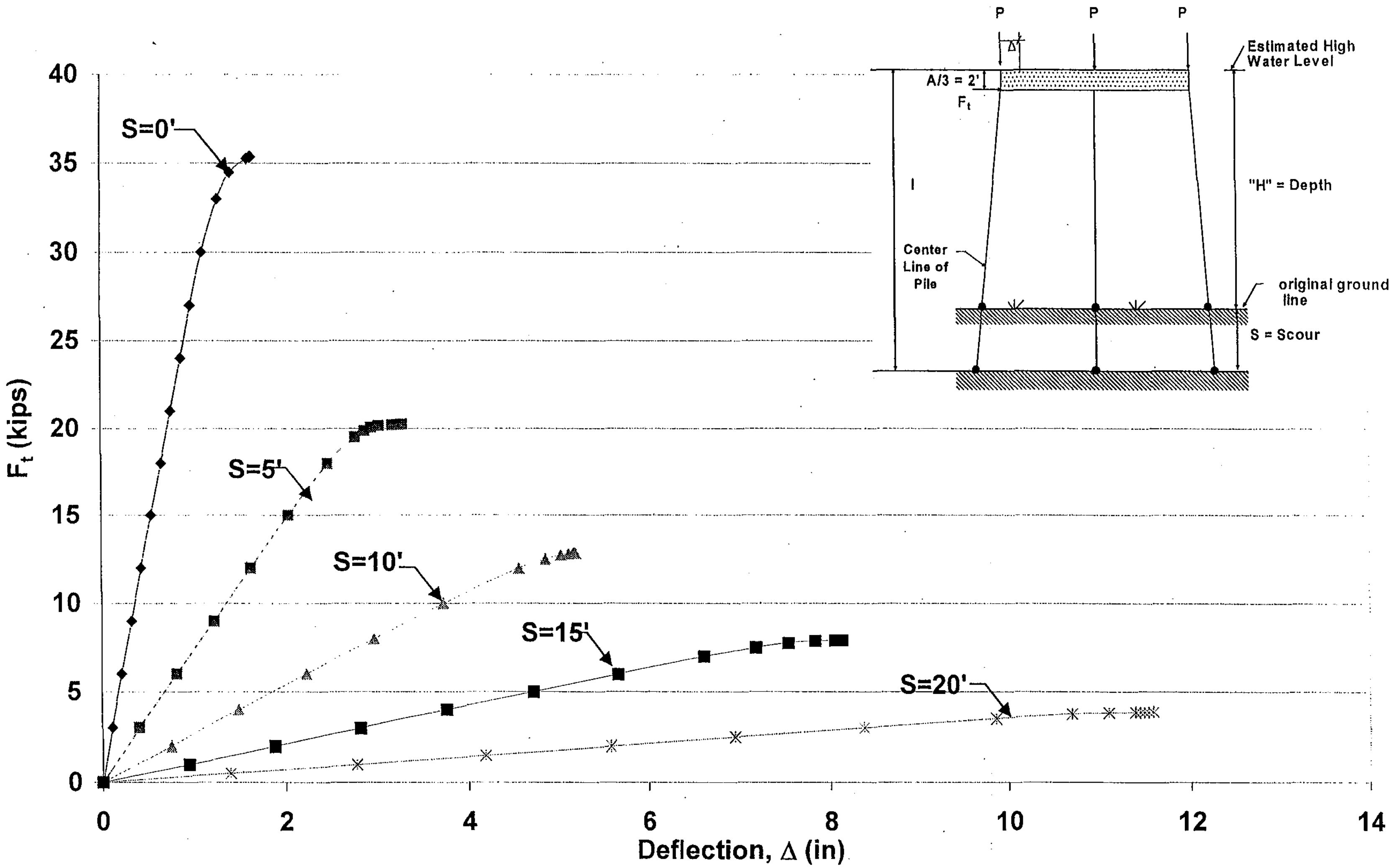


Figure B.1 HP12x53 Unbraced 3-PileBent with H=10', P=100kips and A=6' Pushover Analysis Results

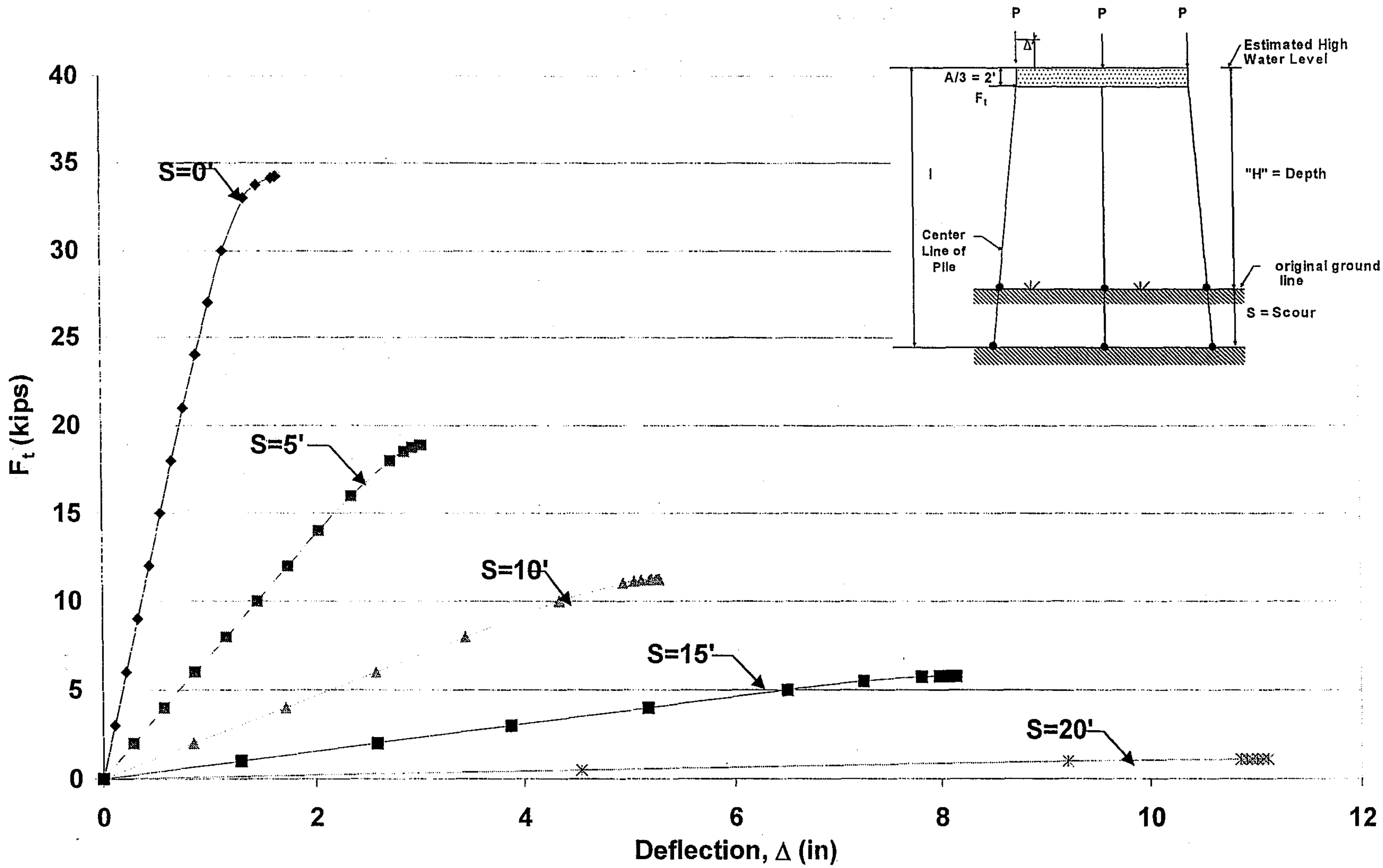


Figure B.2 HP12x53 Unbraced 3-Pile Bent with H=10', P=120kips and A=6', Pushover Analysis Results

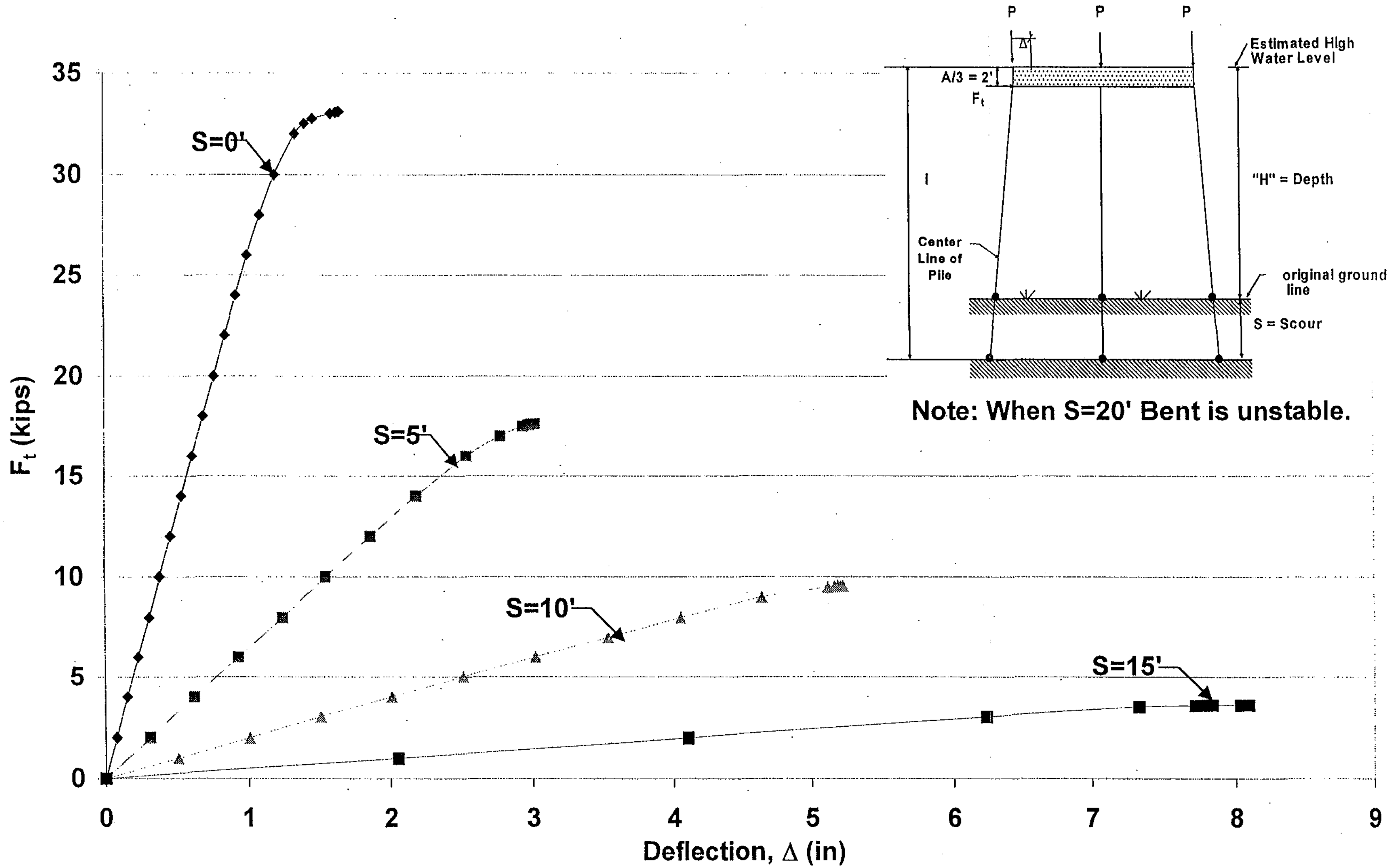


Figure B.3 HP12x53 Unbraced 3-Pile Bent with H=10', P=140kips and A=6' Pushover Analysis Results

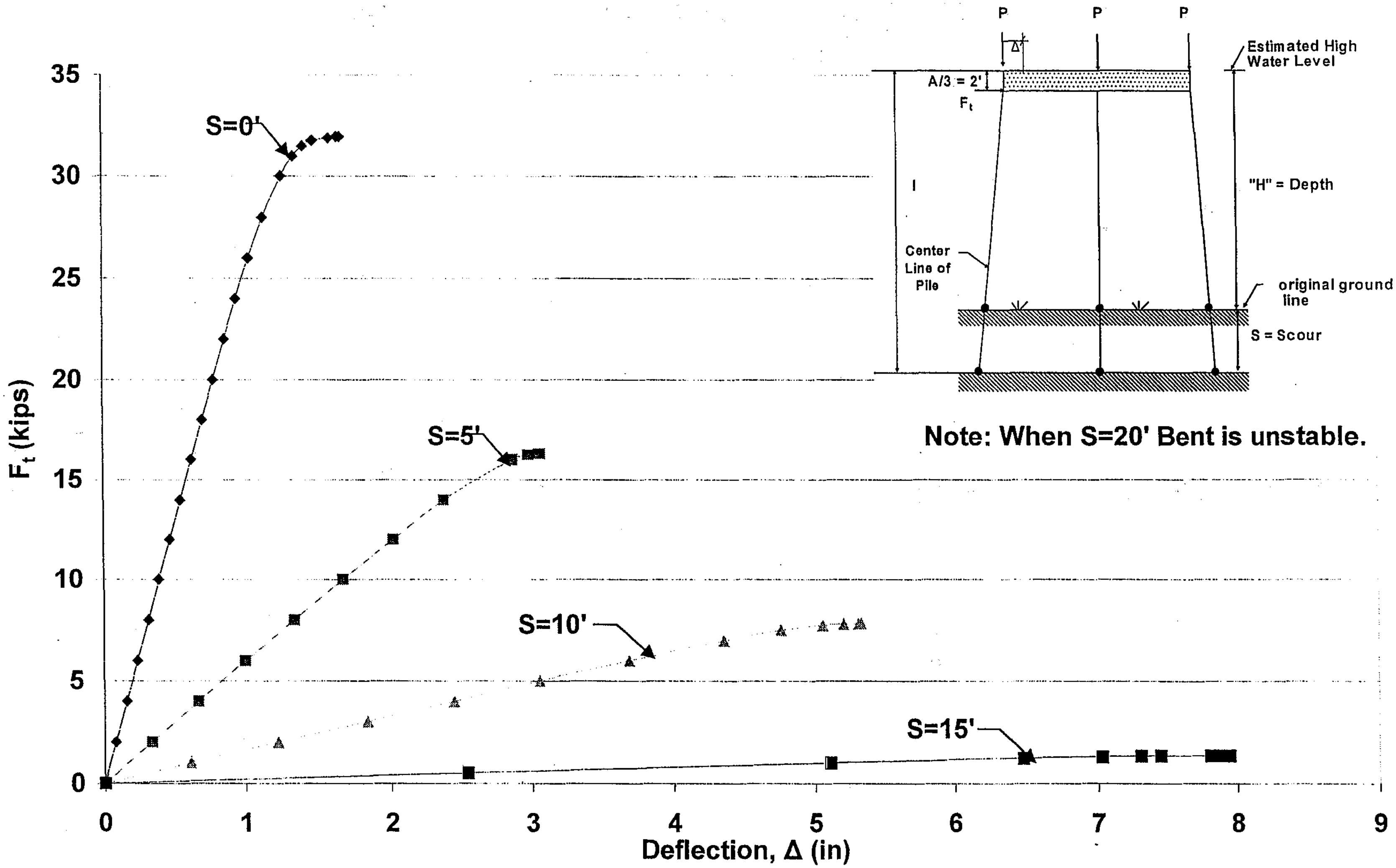


Figure B.4 HP12x53 Unbraced 3-Pile Bent with H=10', P=160kips and A=6' Pushover Analysis Results

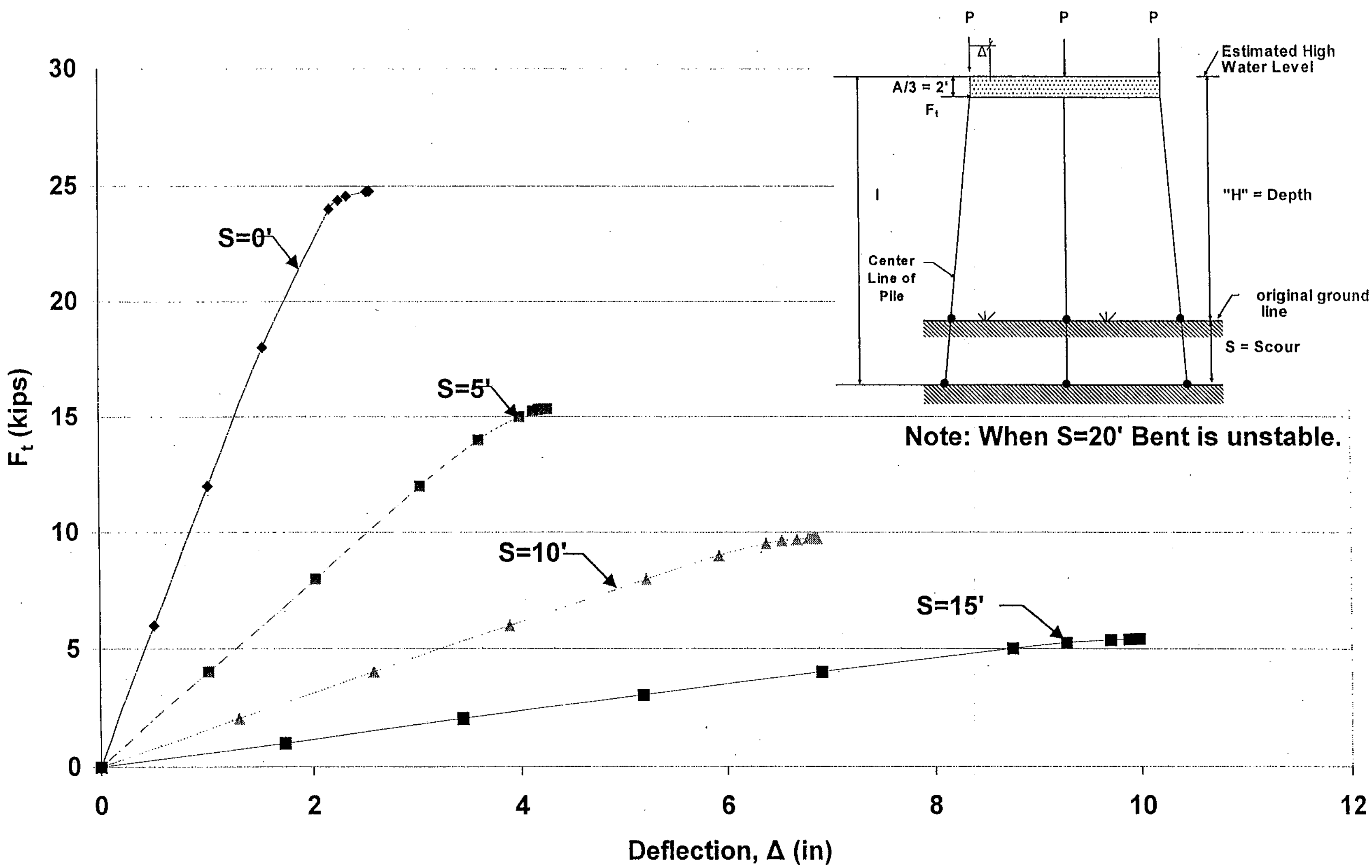


Figure B.5 HP12x53 Unbraced 3-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

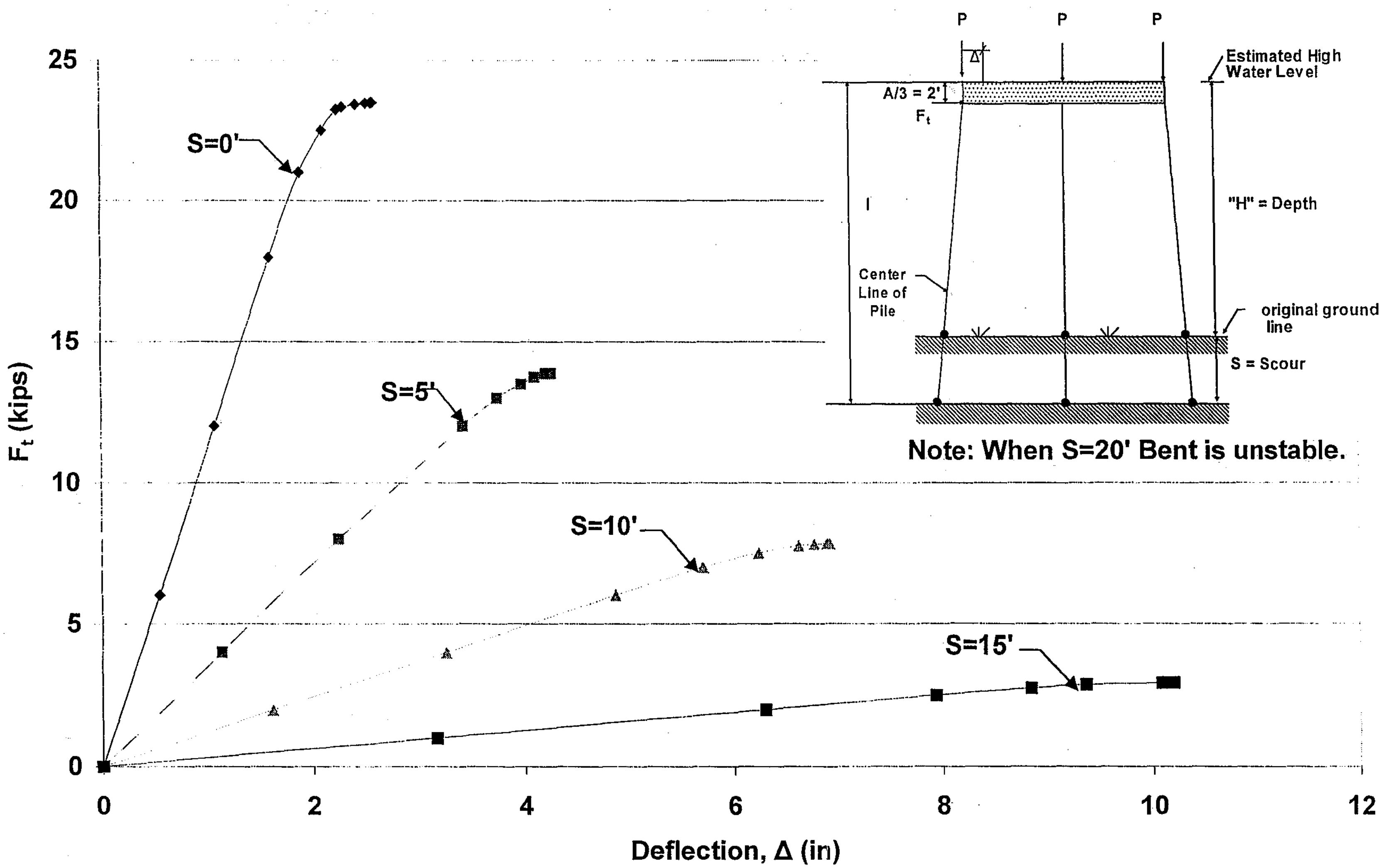


Figure B.6 HP12x53 Unbraced 3-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

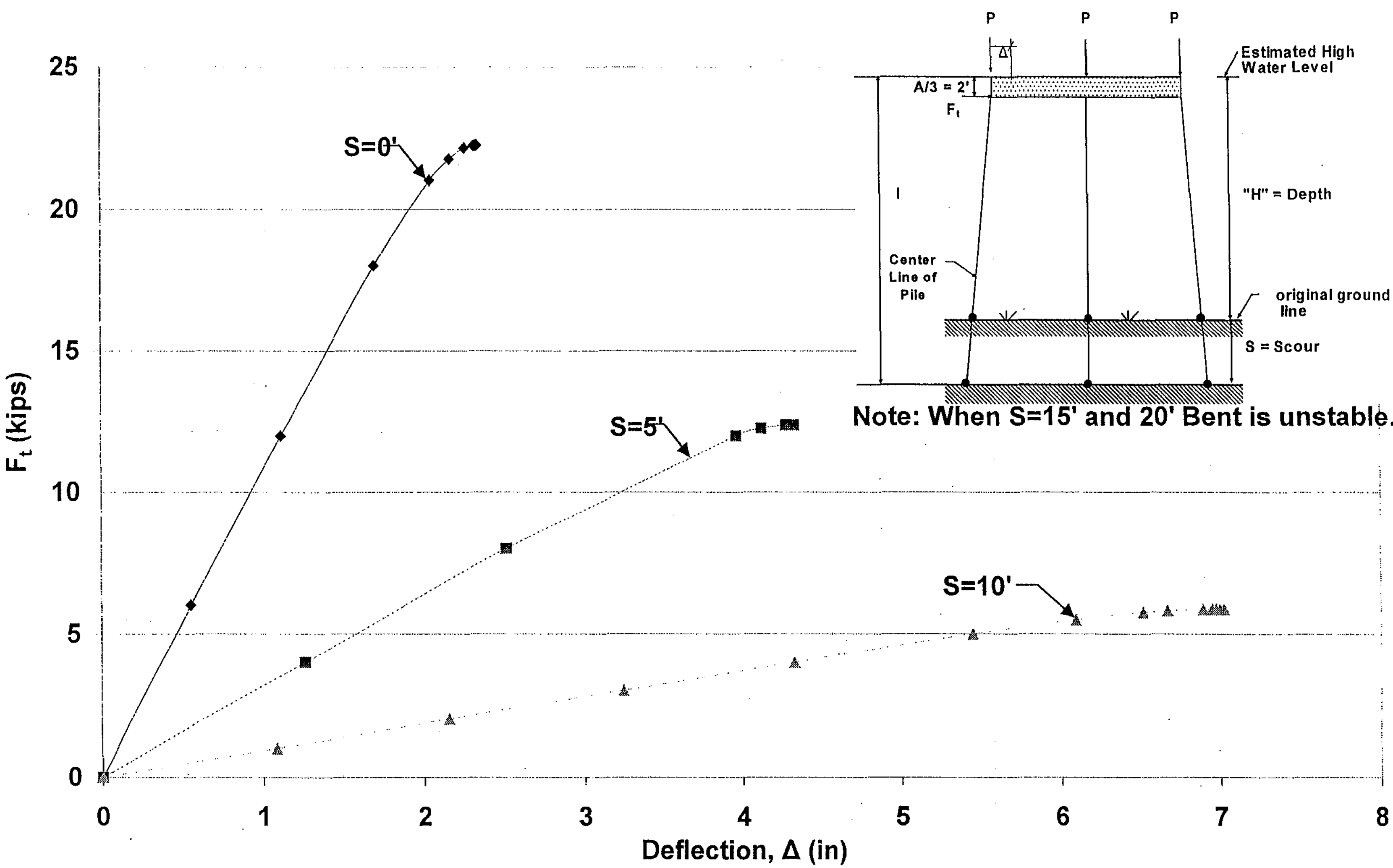


Figure B.7 HP12x53 Unbraced 3-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

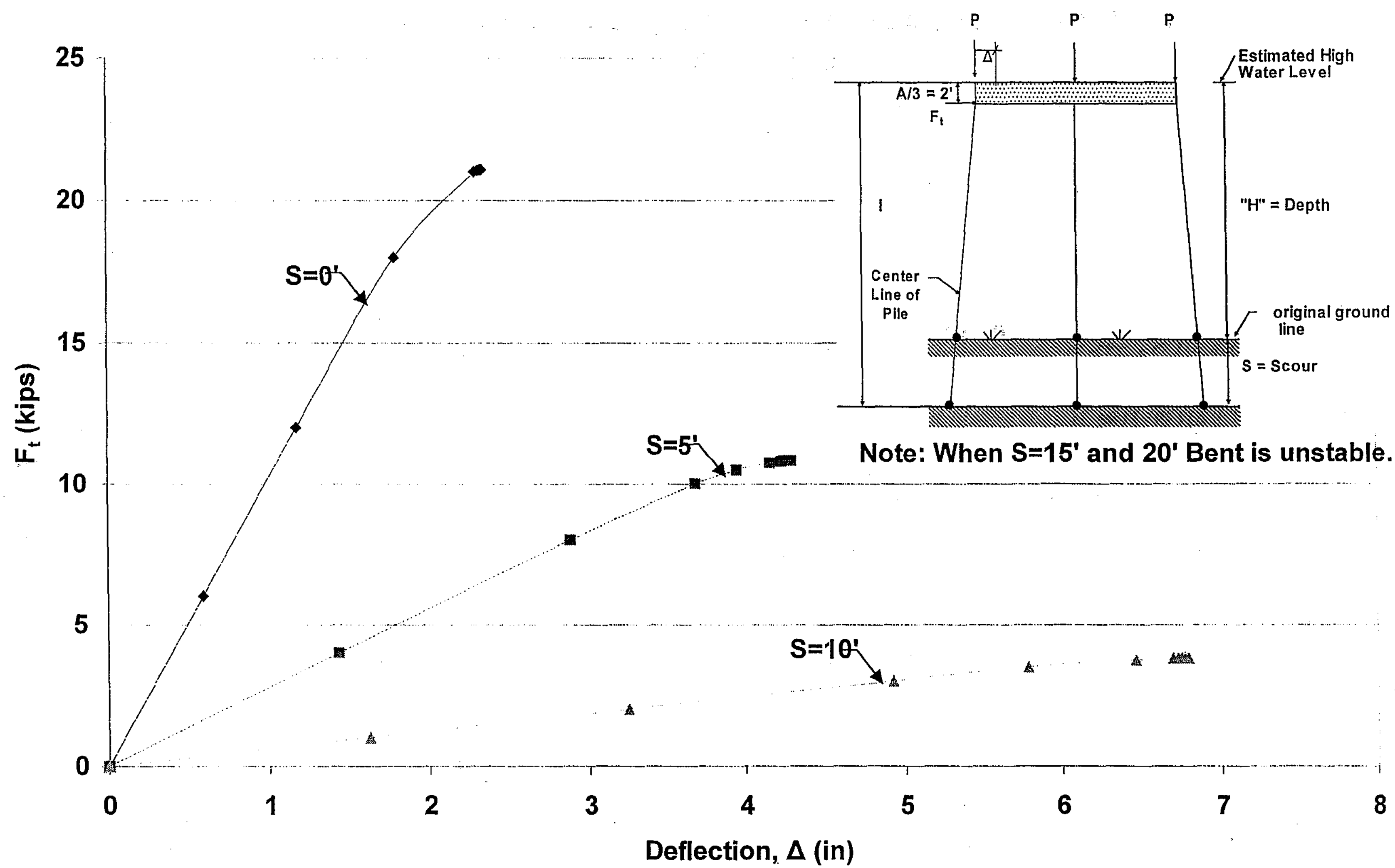


Figure B.8 HP12x53 Unbraced 3-Pile with H=13', P=160kips and A=6'
Pushover Analysis Results

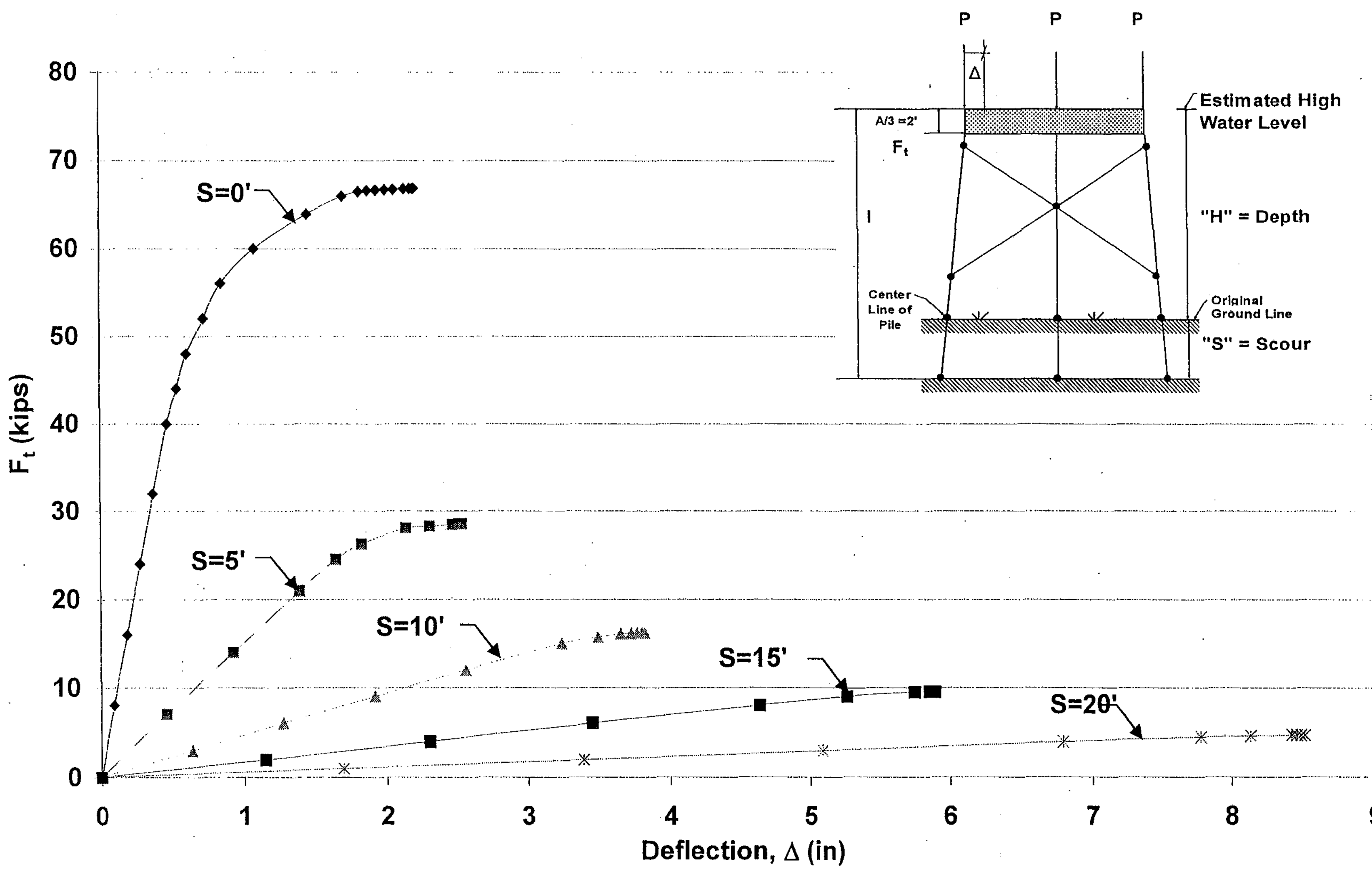


Figure B.9 HP12x53 X-Braced 3-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

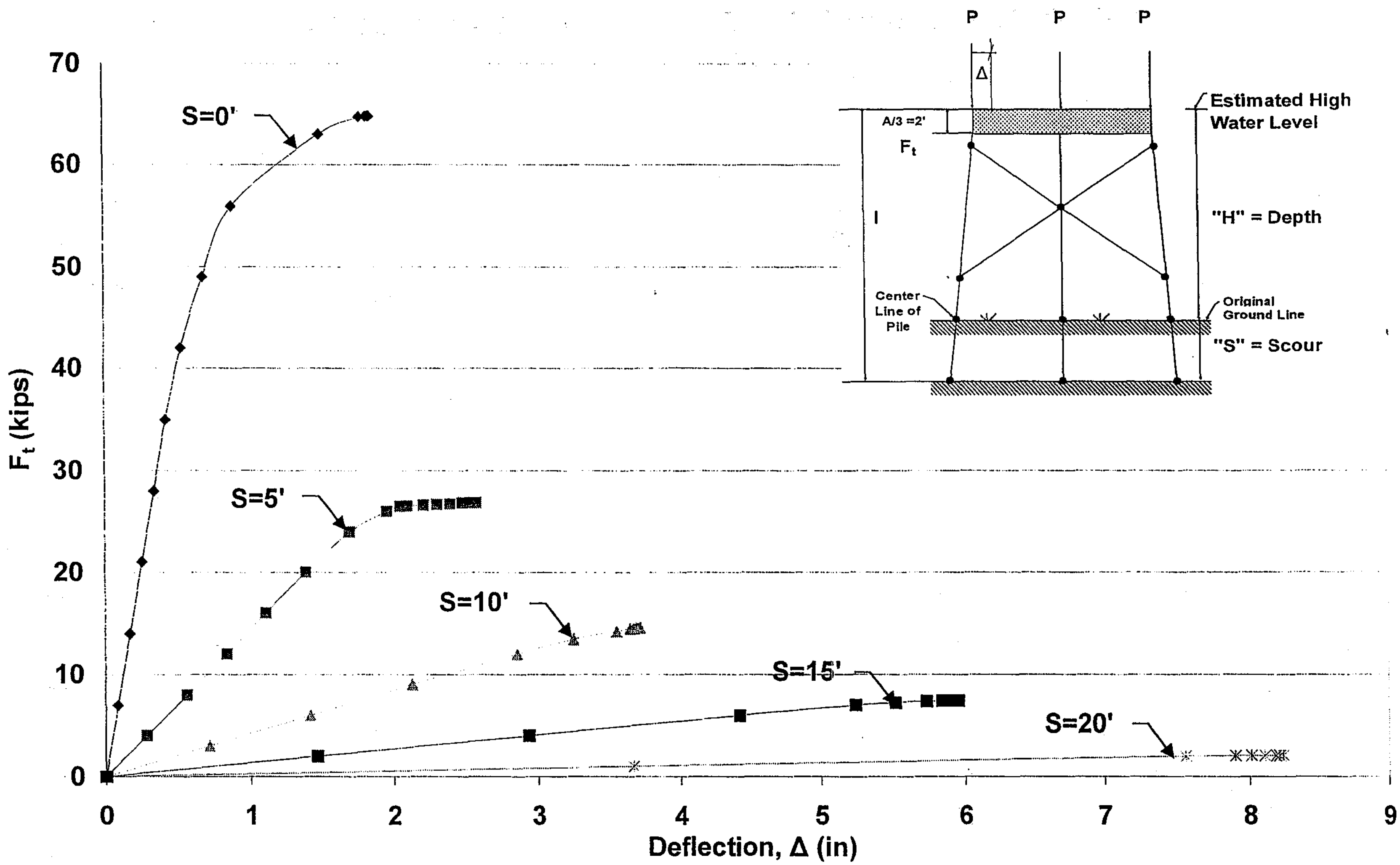


Figure B.10 HP12x53 X-Braced 3-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

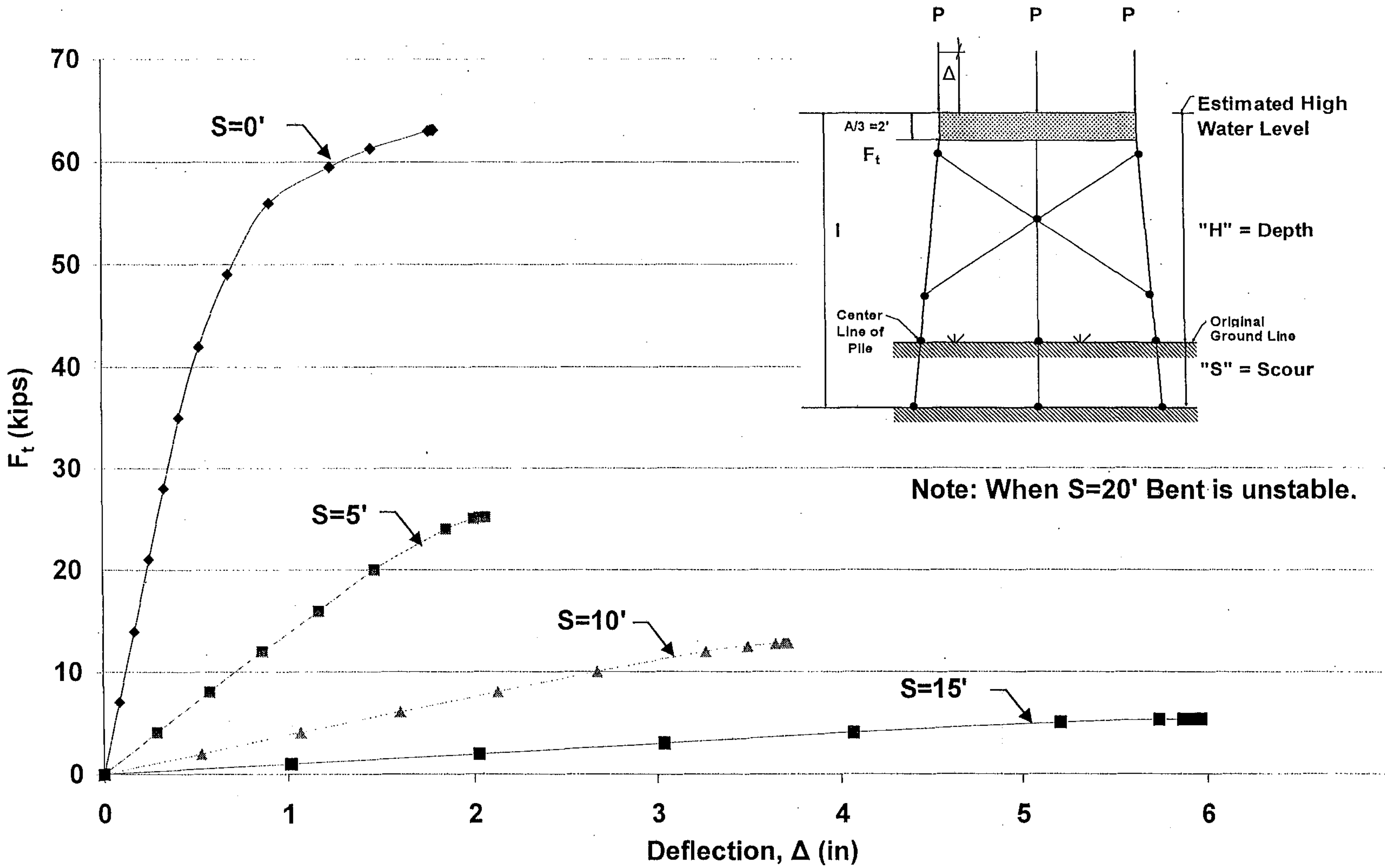


Figure B.11 HP12x53 X-Braced 3-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

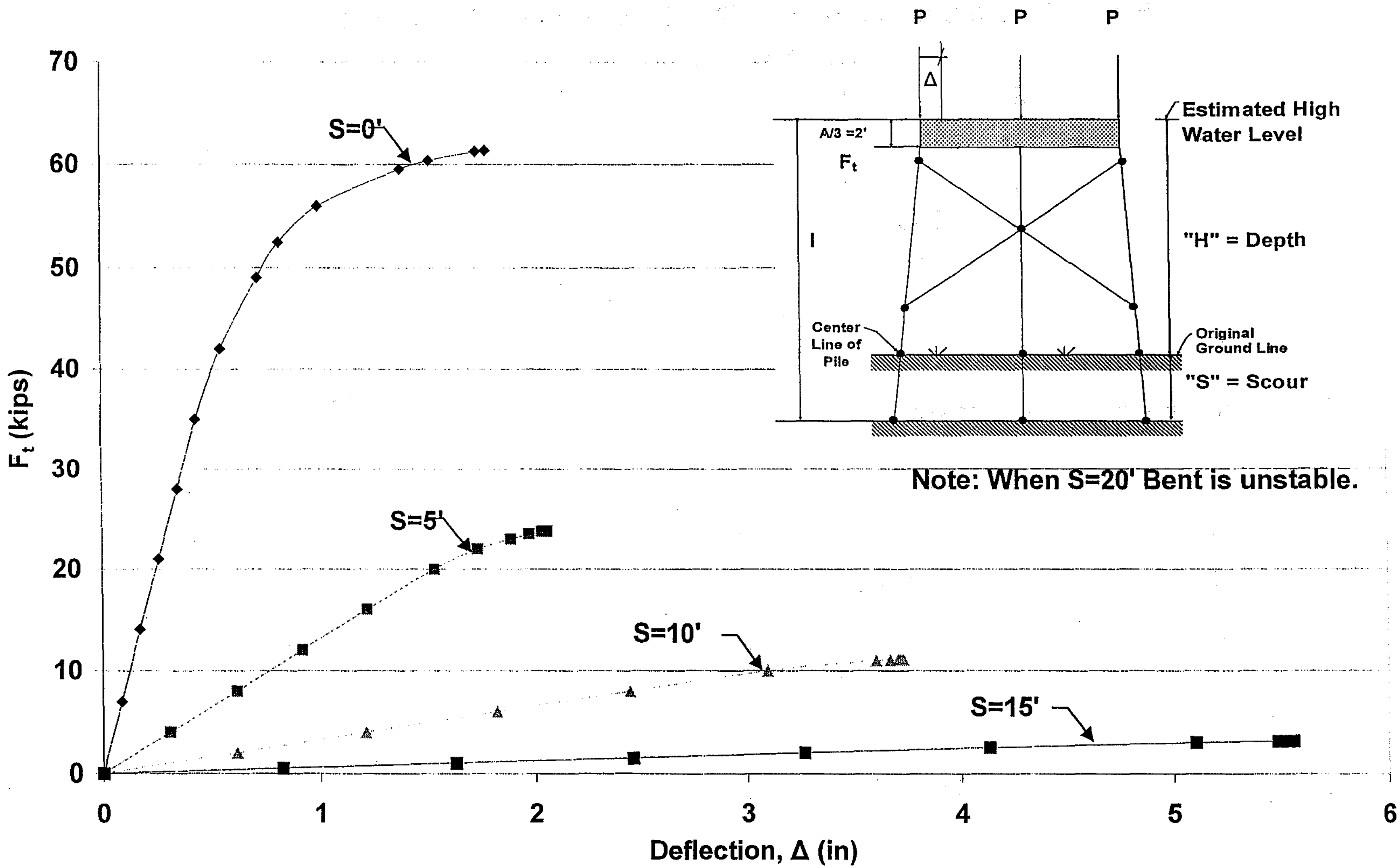


Figure B.12 HP12x53 X-Braced 3-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

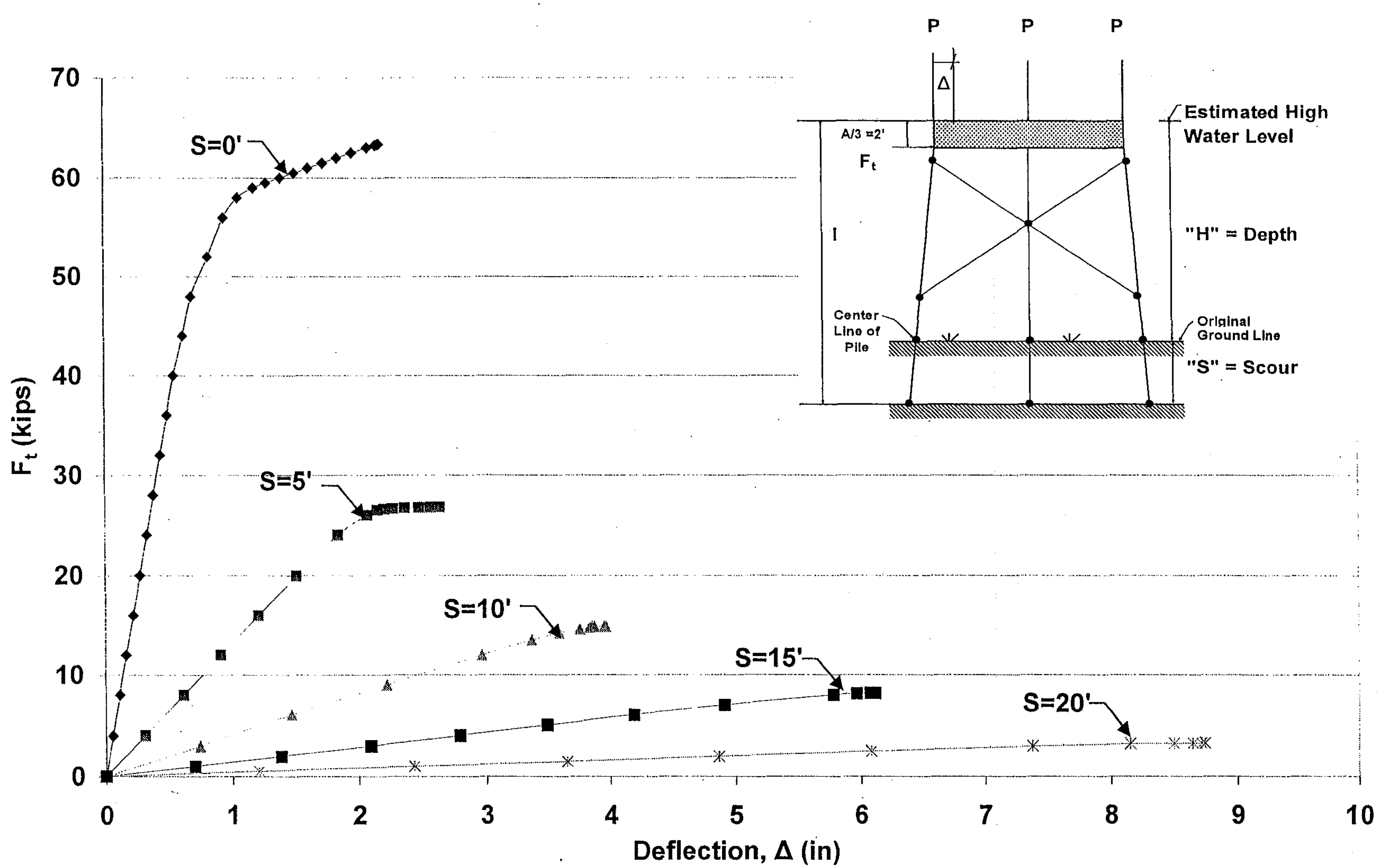


Figure B.13 HP12x53 X-Braced 3-Pile Bent with H=17', P=100 kips and A=6'
Pushover Analysis Results

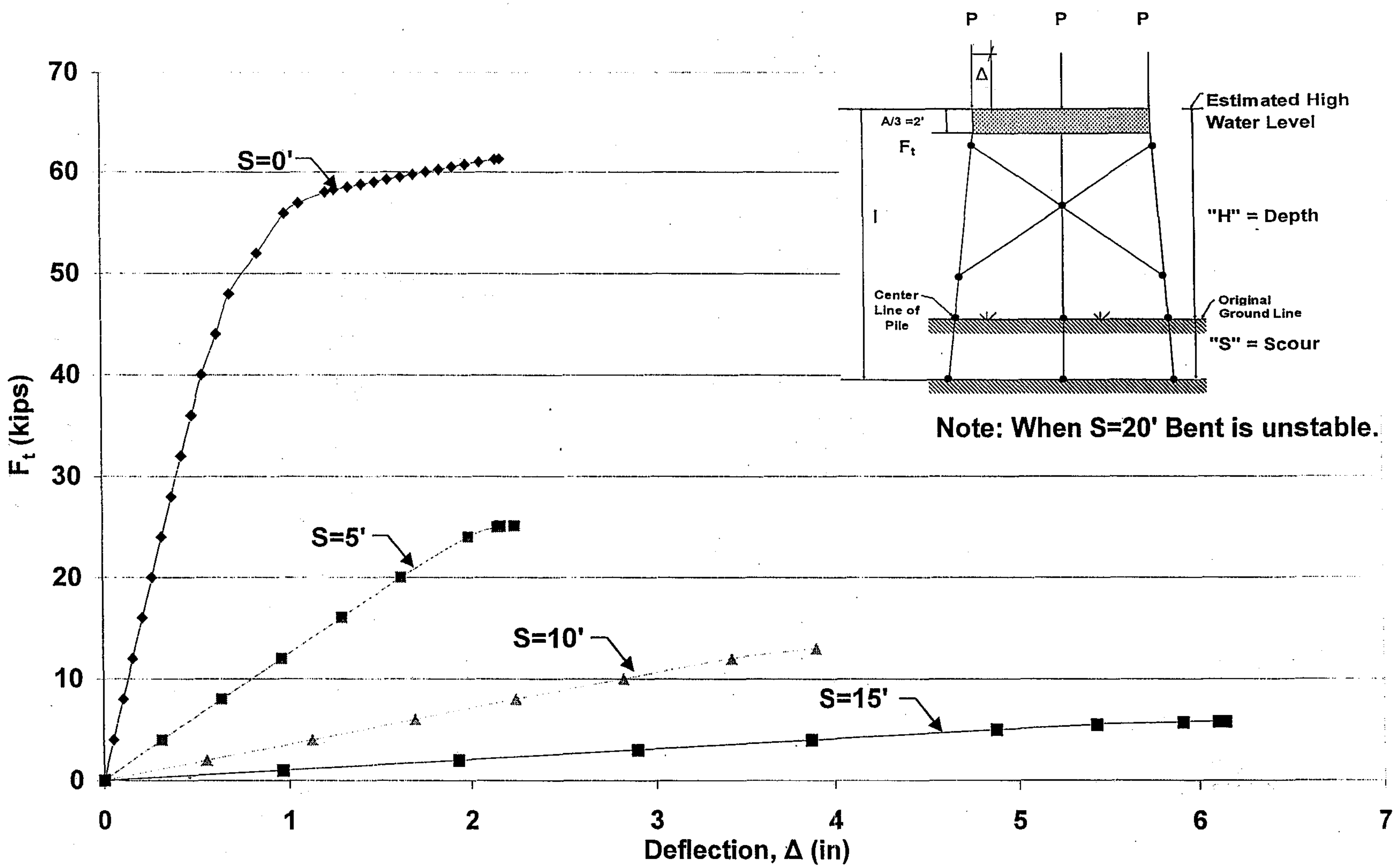


Figure B.14 HP12x53 X-Braced 3-Pile Bent with H=17', P=120 kips and A=6' Pushover Analysis Results

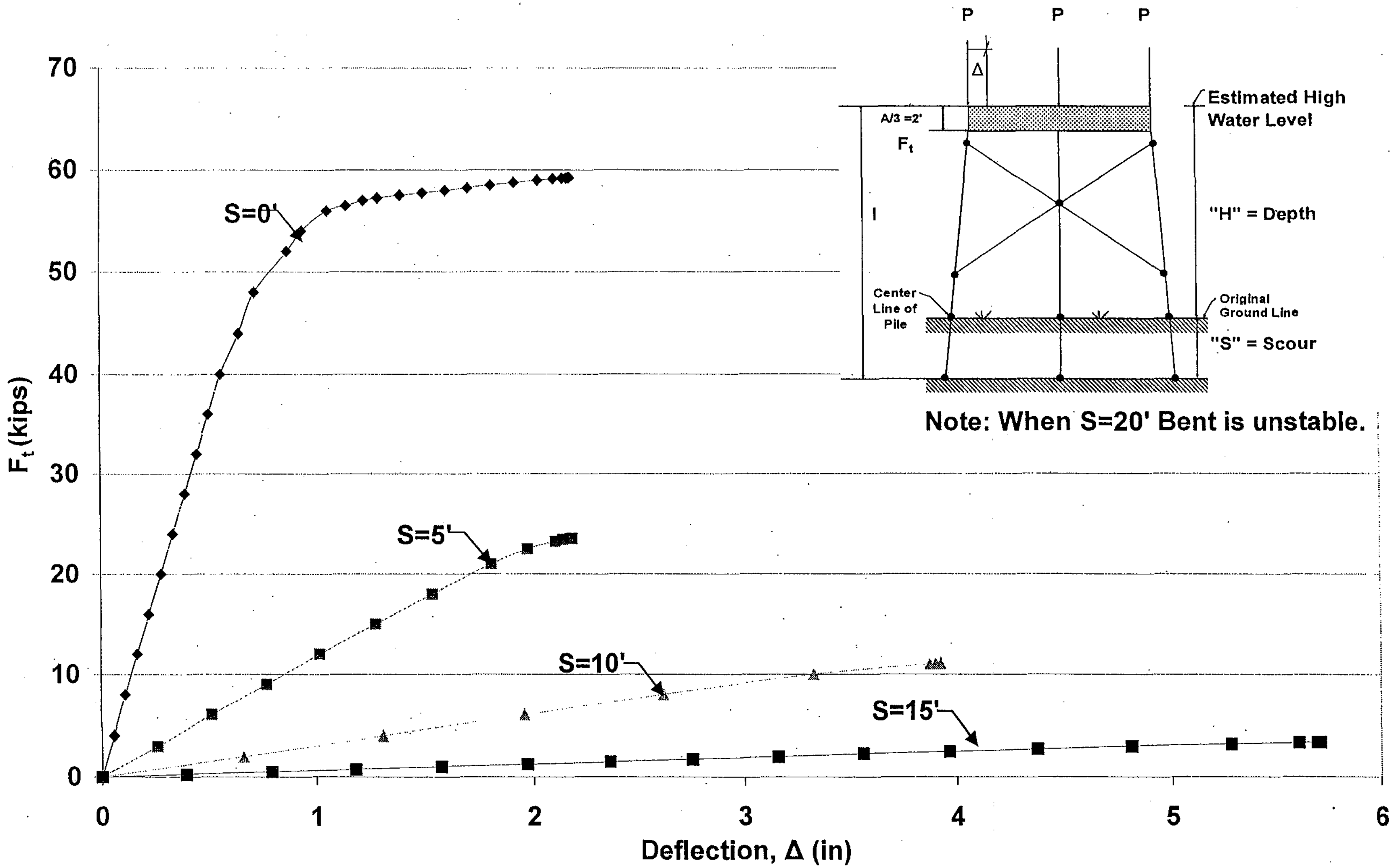


Figure B.15 HP12x53 X-Braced 3-Pile Bent with H=17', P=140 kips and A=6' Pushover Analysis Results

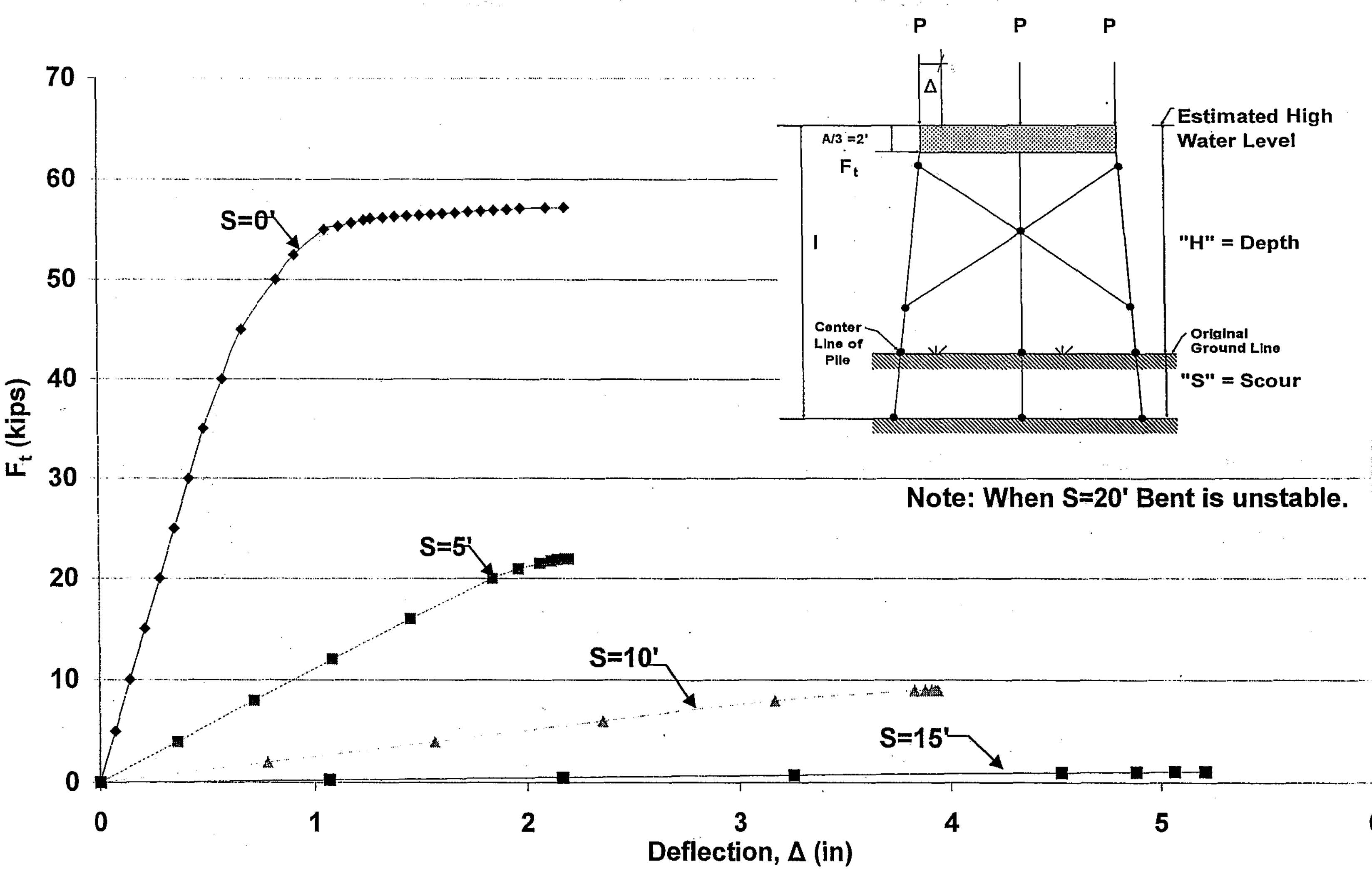


Figure B.16 HP12x53 X-Braced 3-Pile Bent with H=17', P=160 kips and A=6'
Pushover Analysis Results

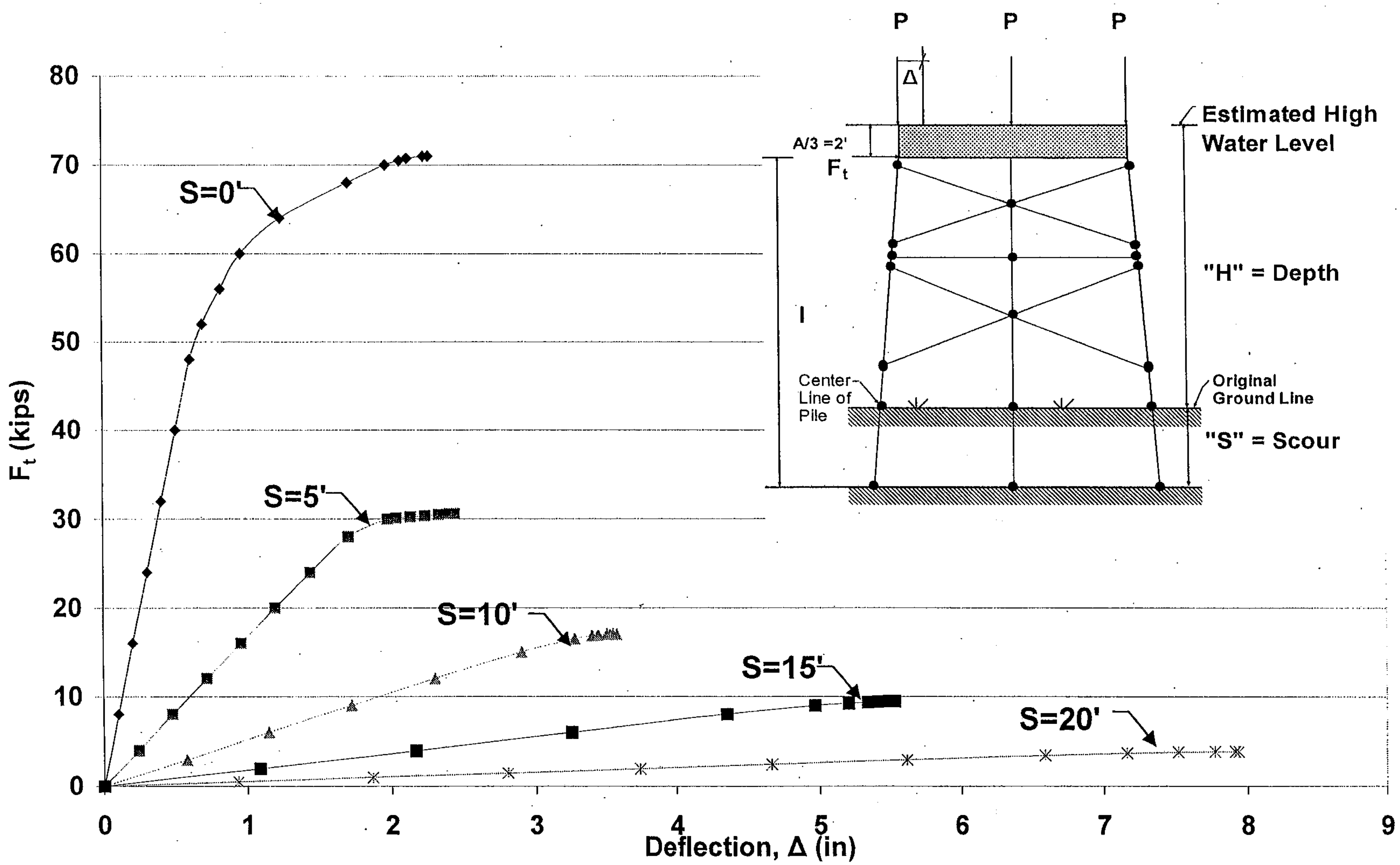


Figure B.17 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=100kips and A=6' Pushover Analysis Results

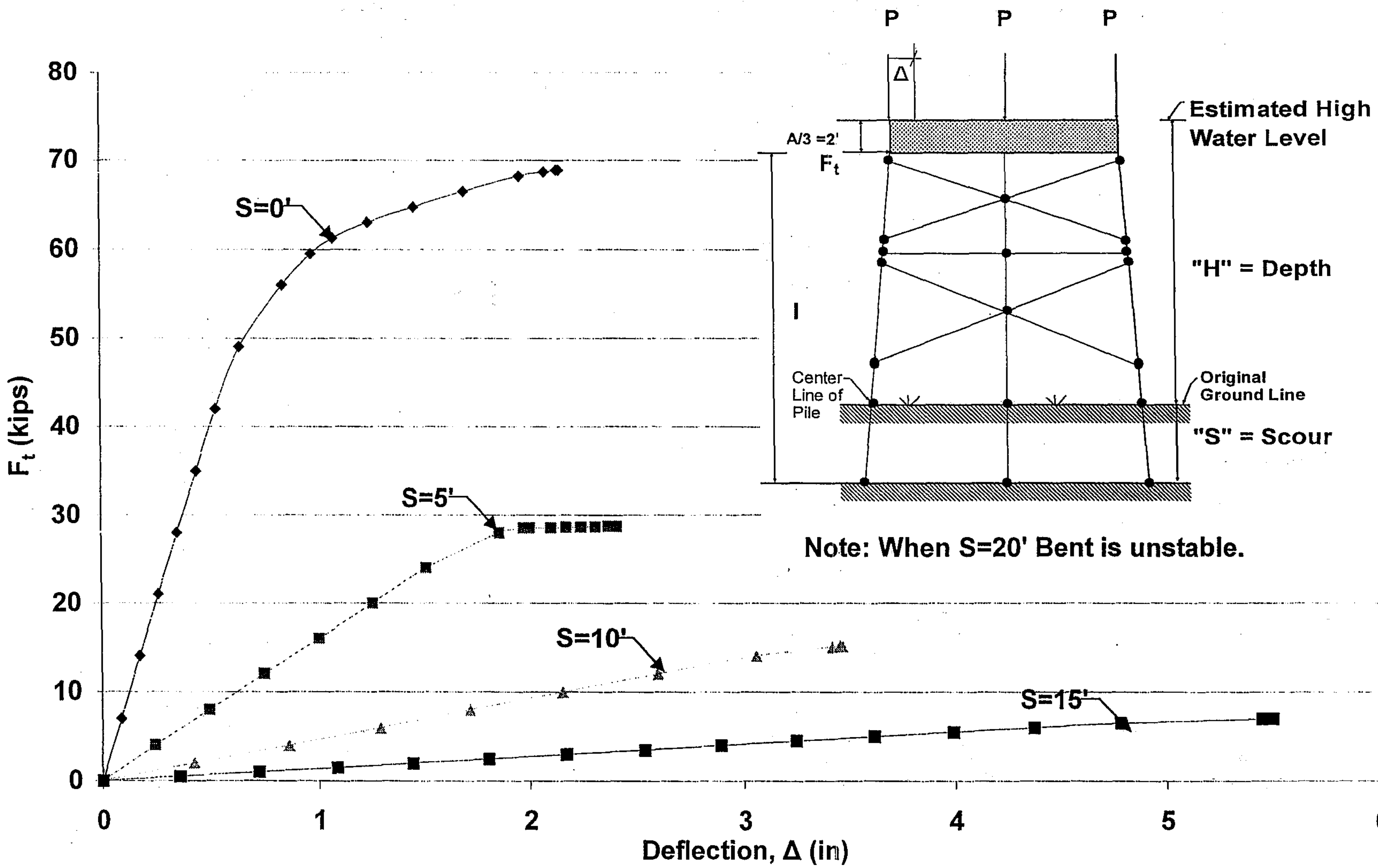


Figure B.18 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=120kips and A=6'
Pushover Analysis Results

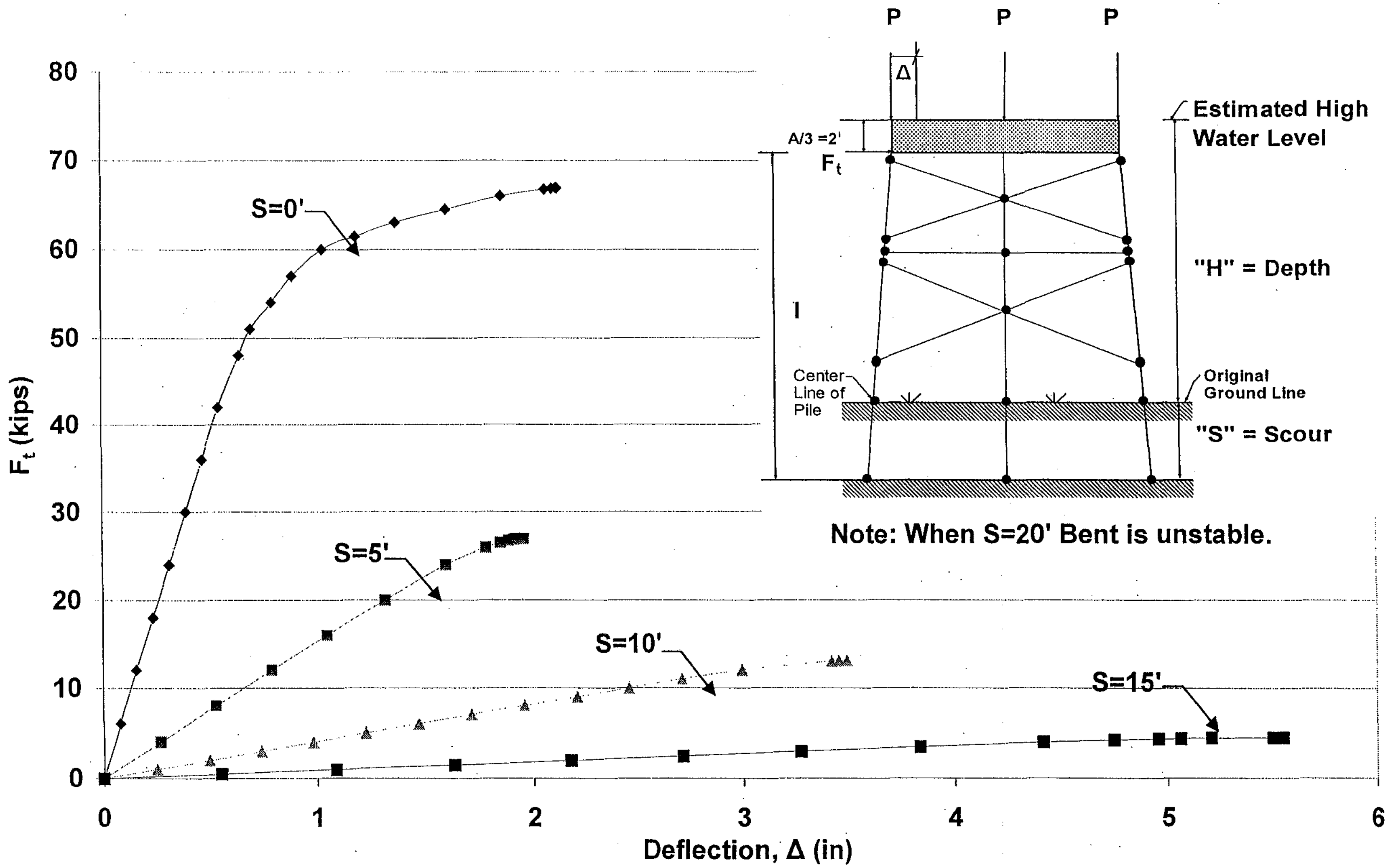


Figure B.19 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=140kips and A=6' Pushover Analysis Results

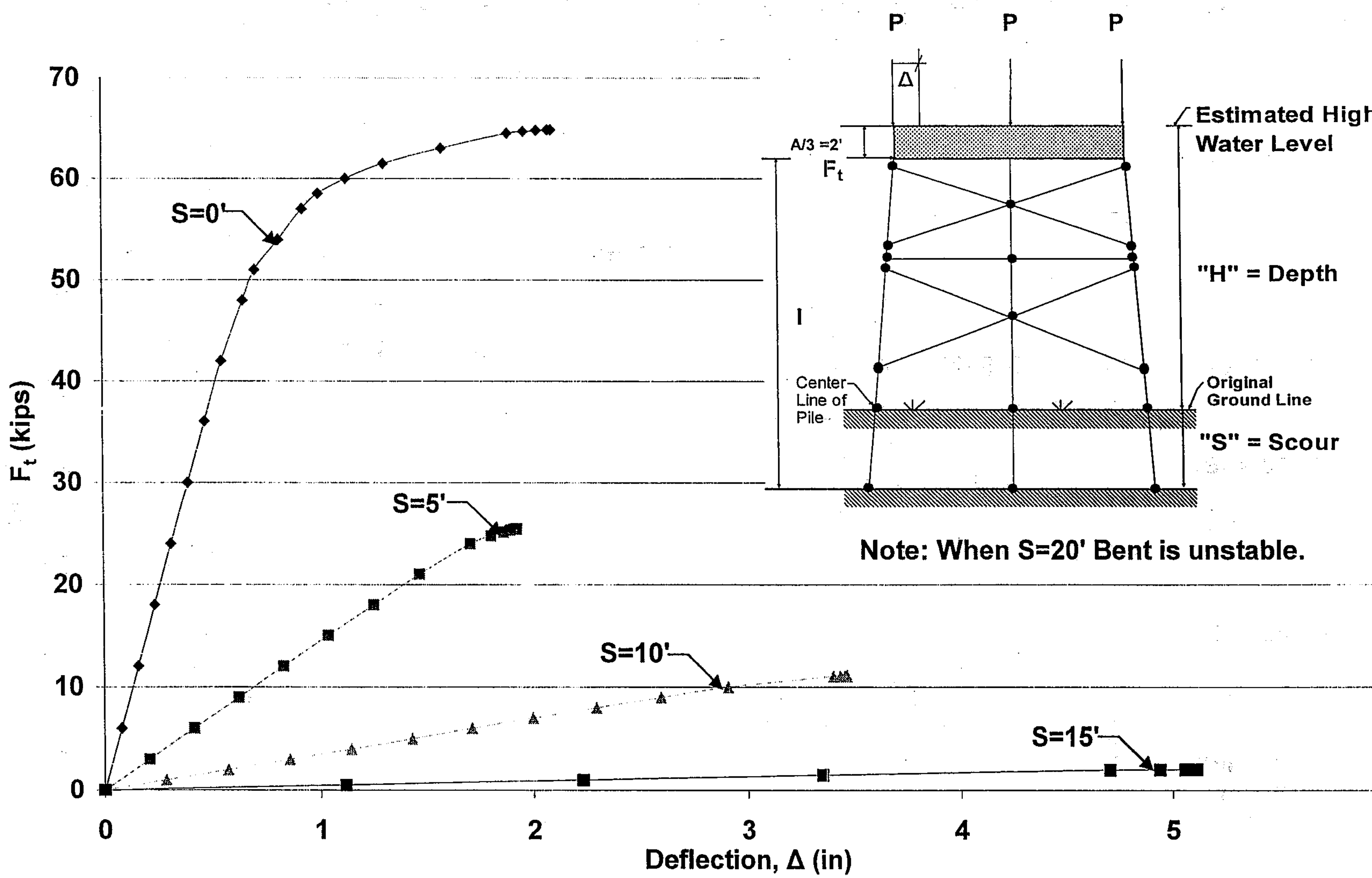


Figure B.20 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=160kips and A=6' Pushover Analysis Results

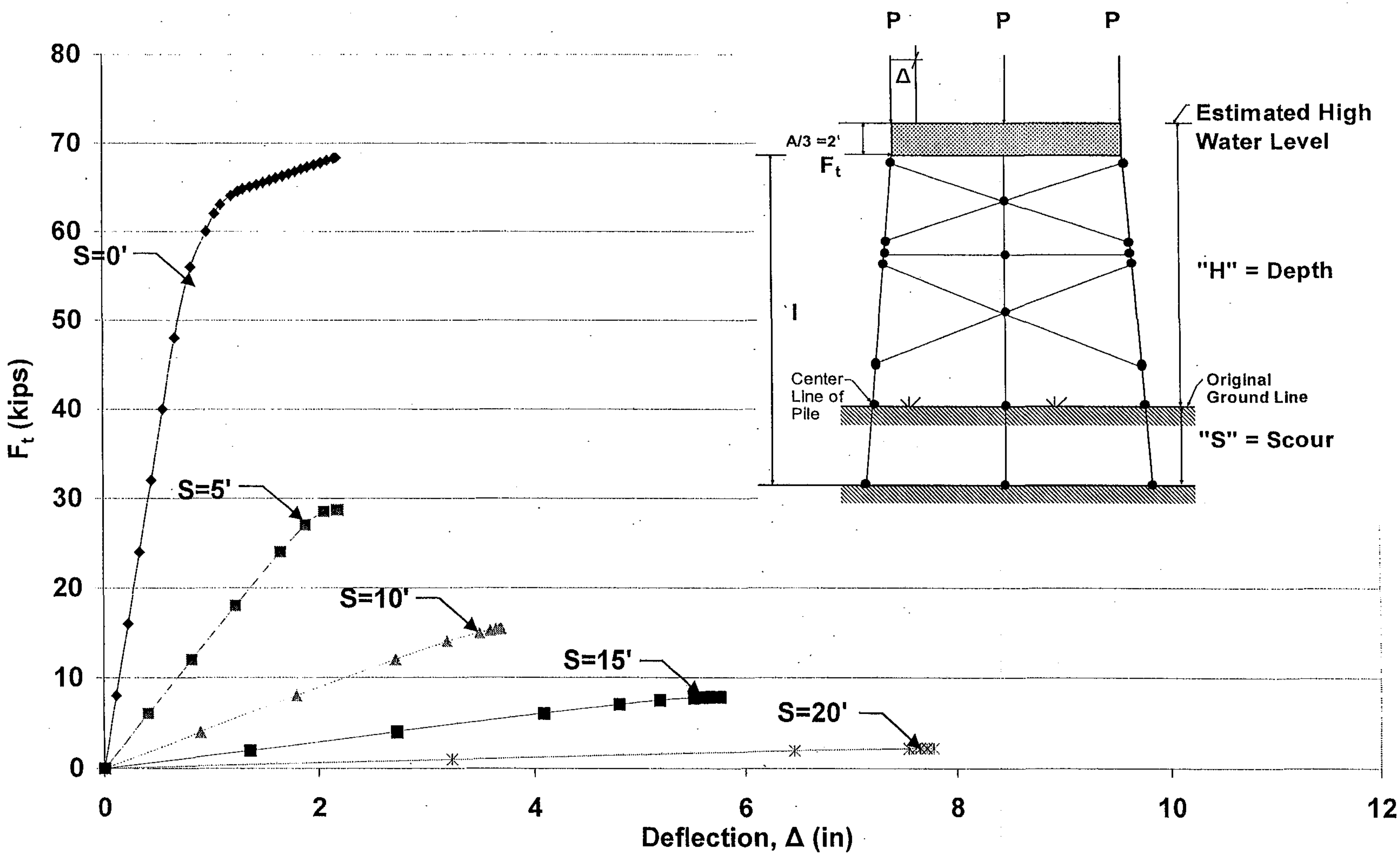


Figure B.21 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=100kips and A=6' Pushover Analysis Results

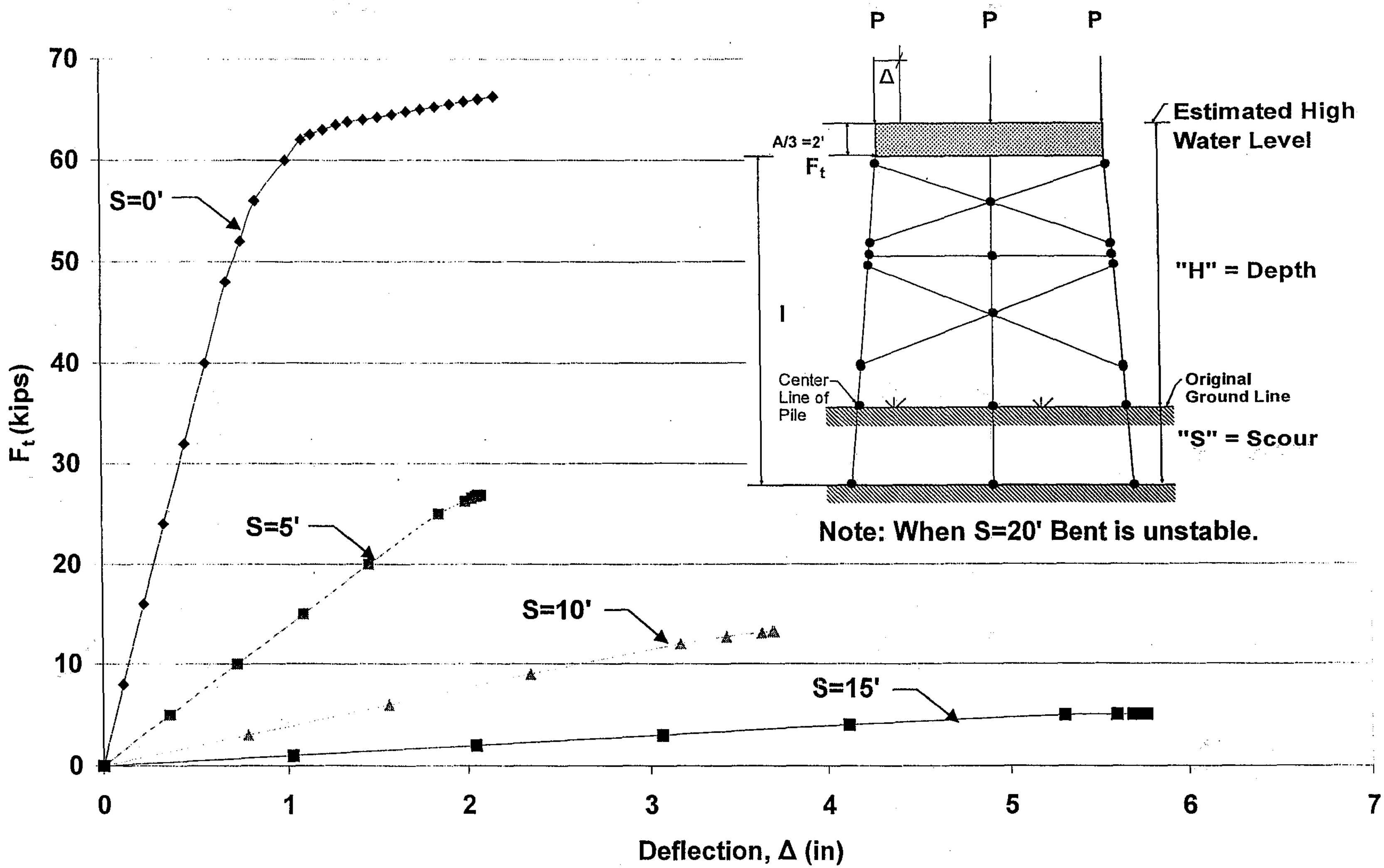


Figure B.22 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=120kips and A=6' Pushover Analysis Results

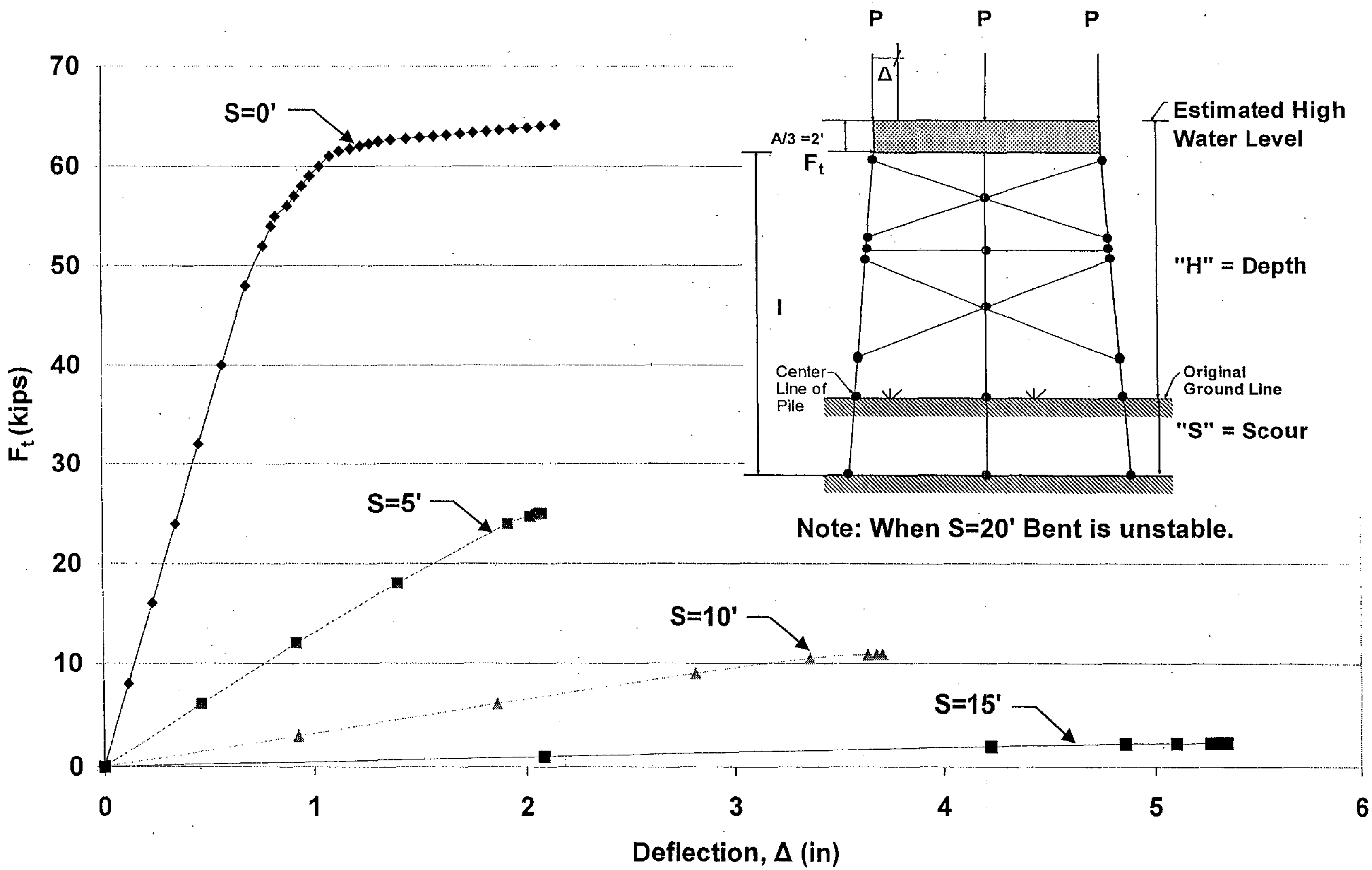


Figure B.23 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=140kips and A=6' Pushover Analysis Results

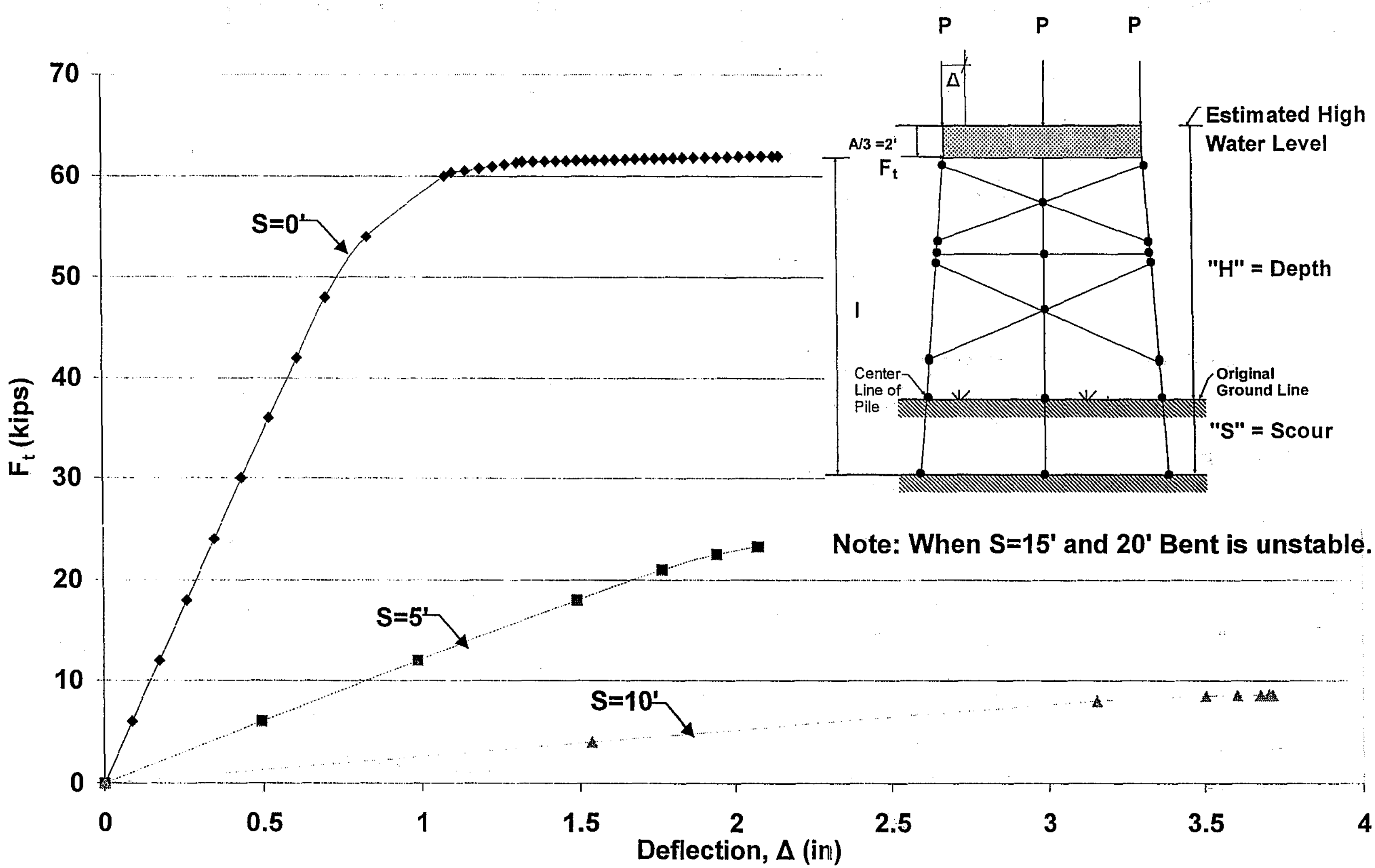


Figure B.24 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=160kips and A=6' Pushover Analysis Results

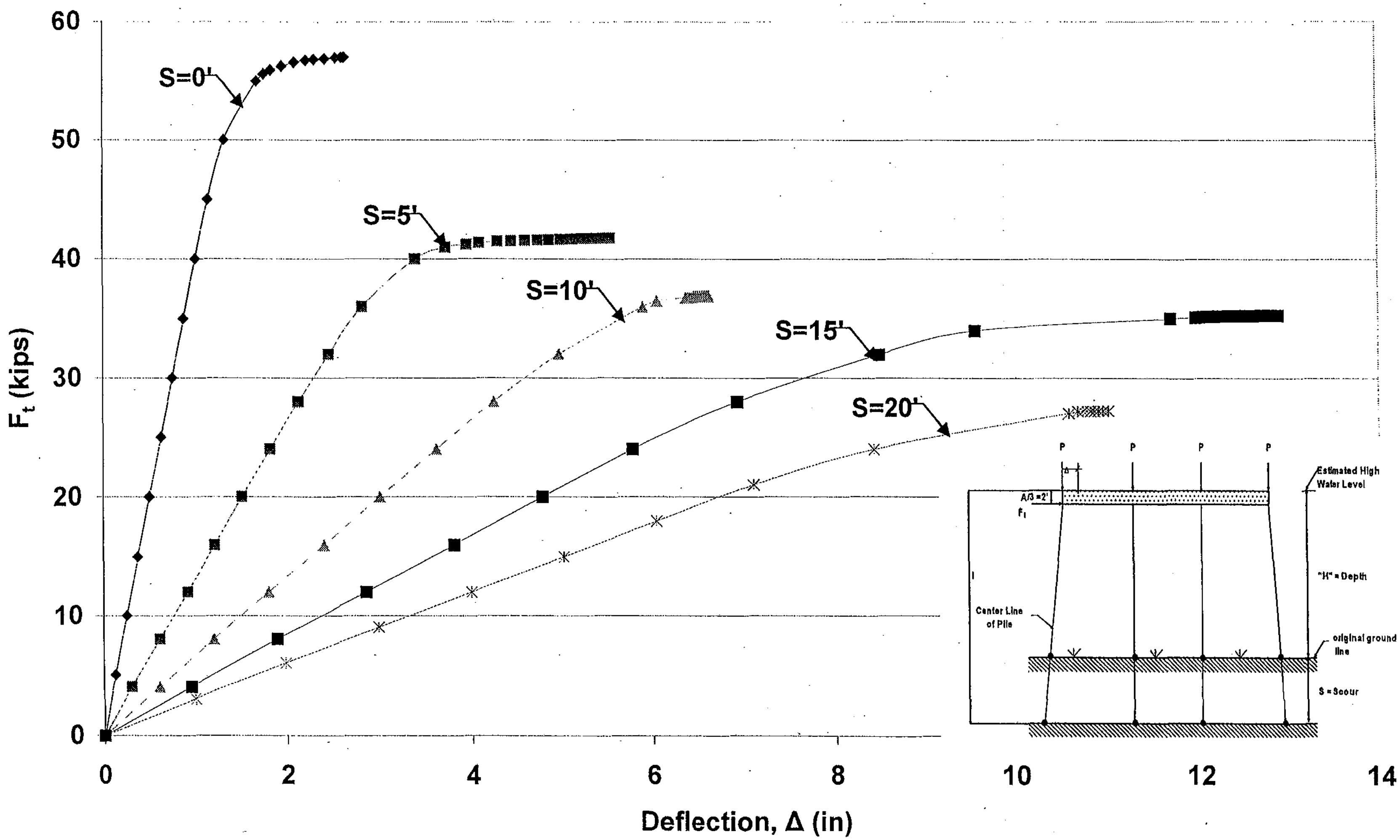


Figure B.25 HP12x53 Unbraced 4-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

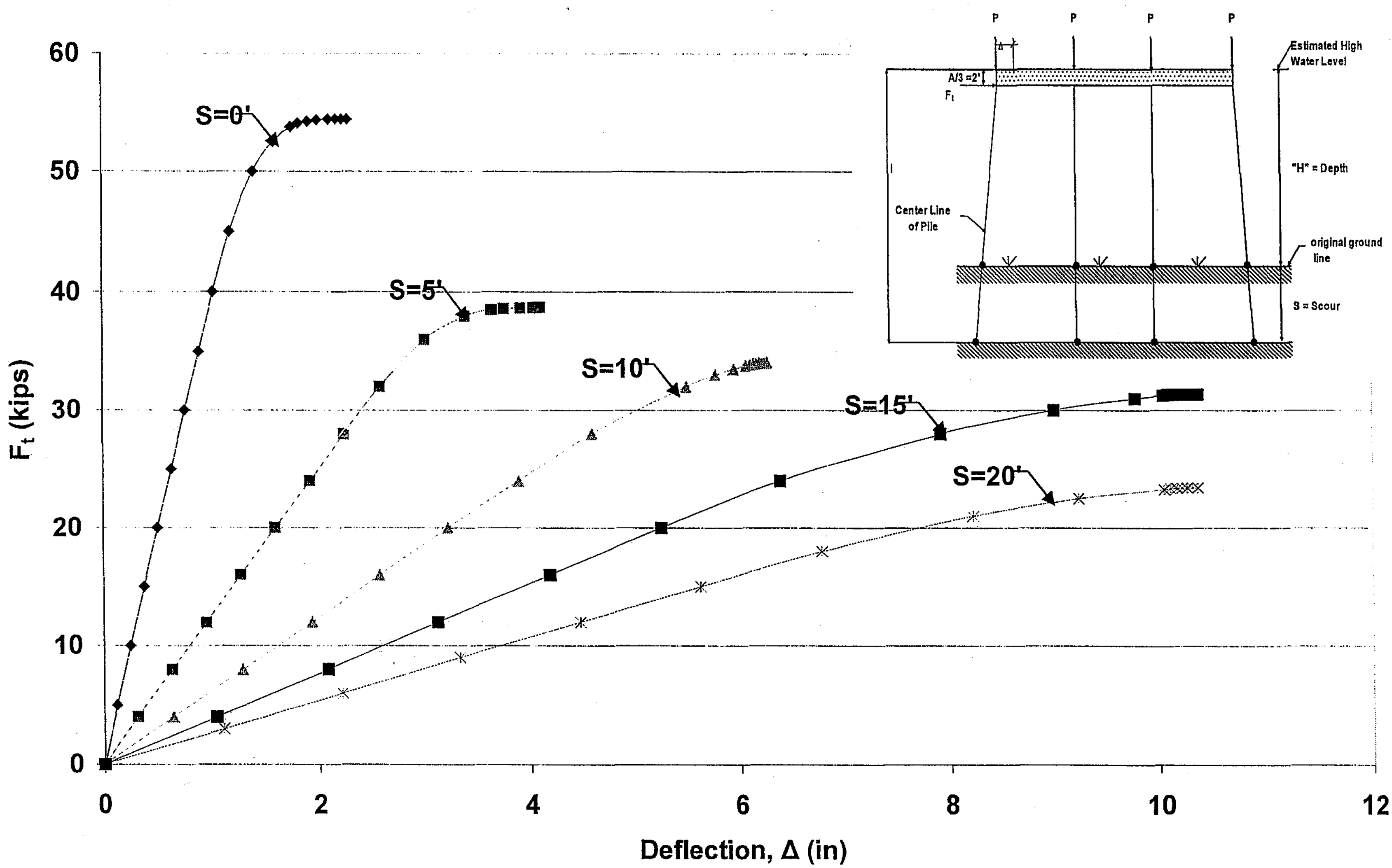


Figure B.26 HP12x53 Unbraced 4-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

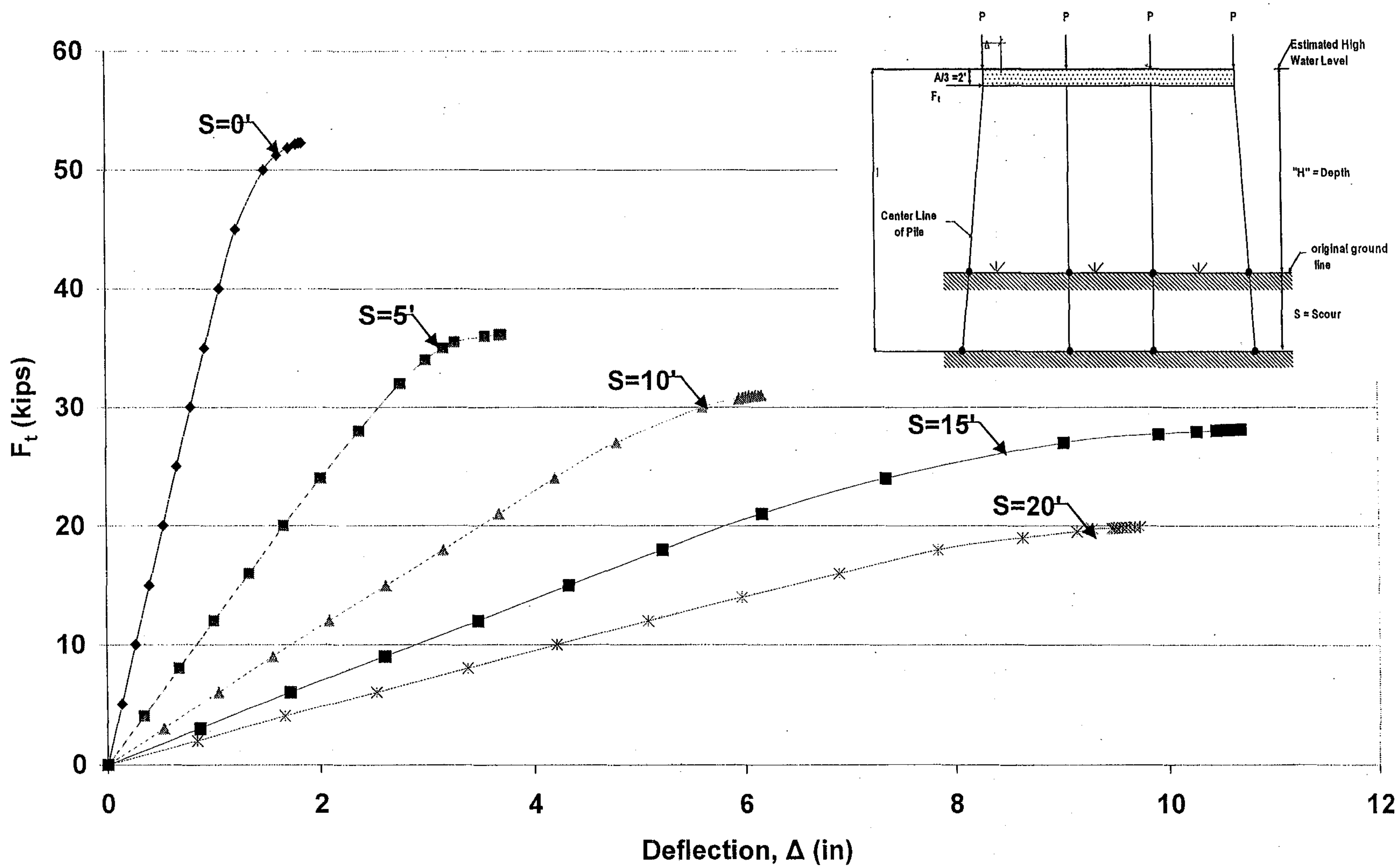


Figure B.27 HP12x53 Unbraced 4-Pile Bent with H=10', P=140kips and A=6' Pushover Analysis Results

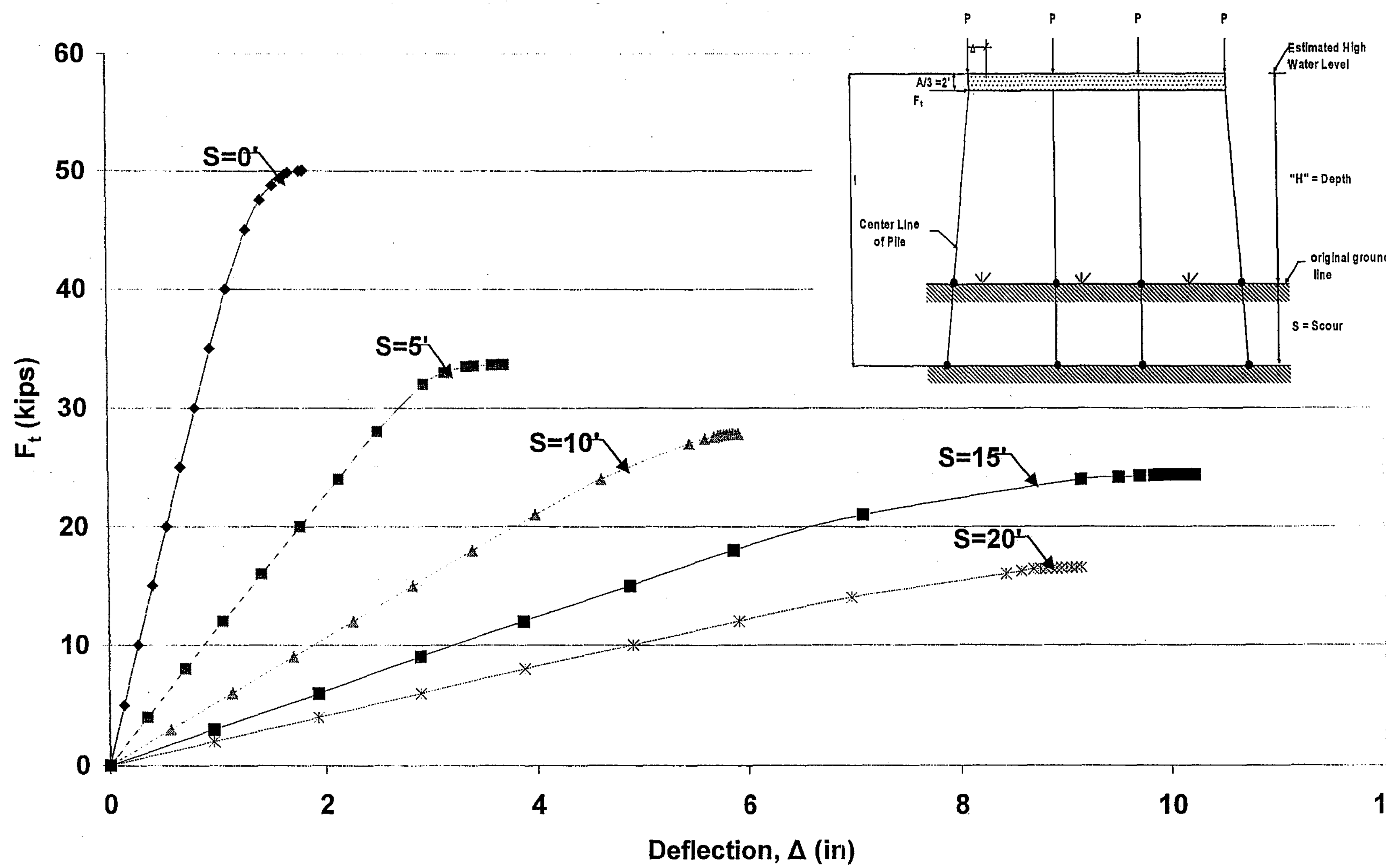


Figure B.28 HP12x53 Unbraced 4-Pile Bent with H=10', P=160kips and A=6' Pushover Analysis Results

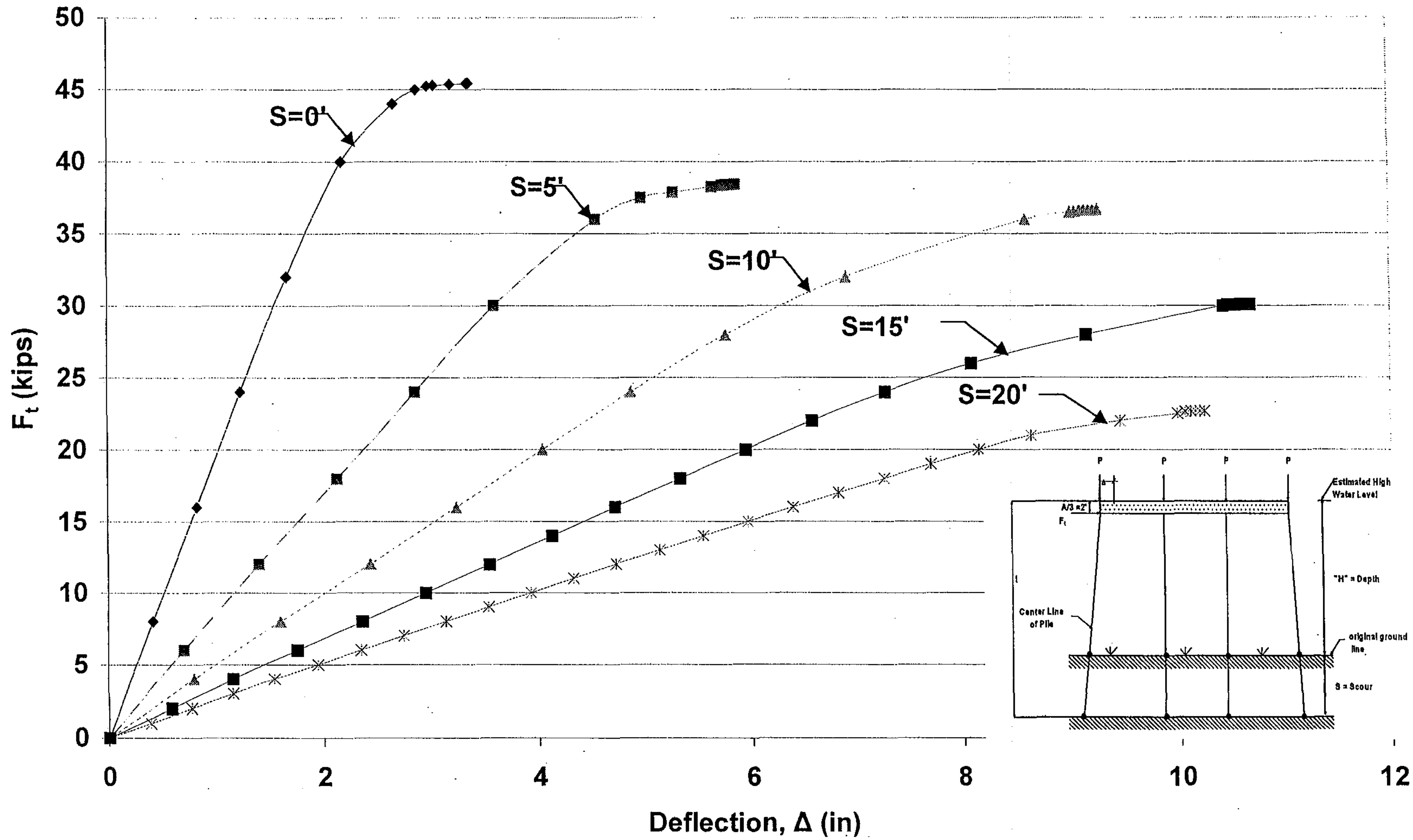


Figure B.29 HP12x53 Unbraced 4-Pile Bent with H=13', P=100kips, and A=6' Pushover Analysis Results

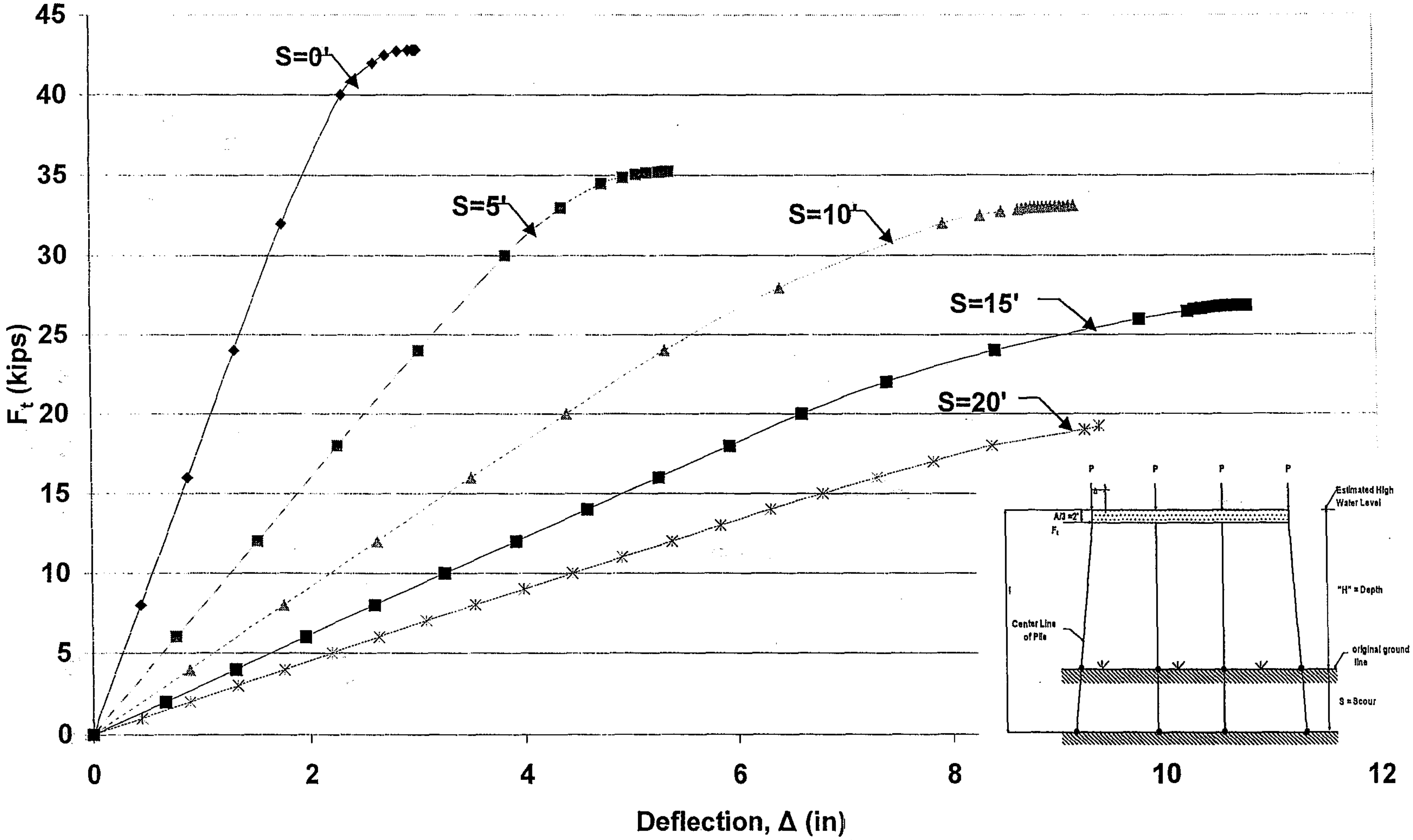


Figure B.30 HP12x53 Unbraced 4-Pile Bent with H=13', P=120kips, and A=6' Pushover Analysis Results

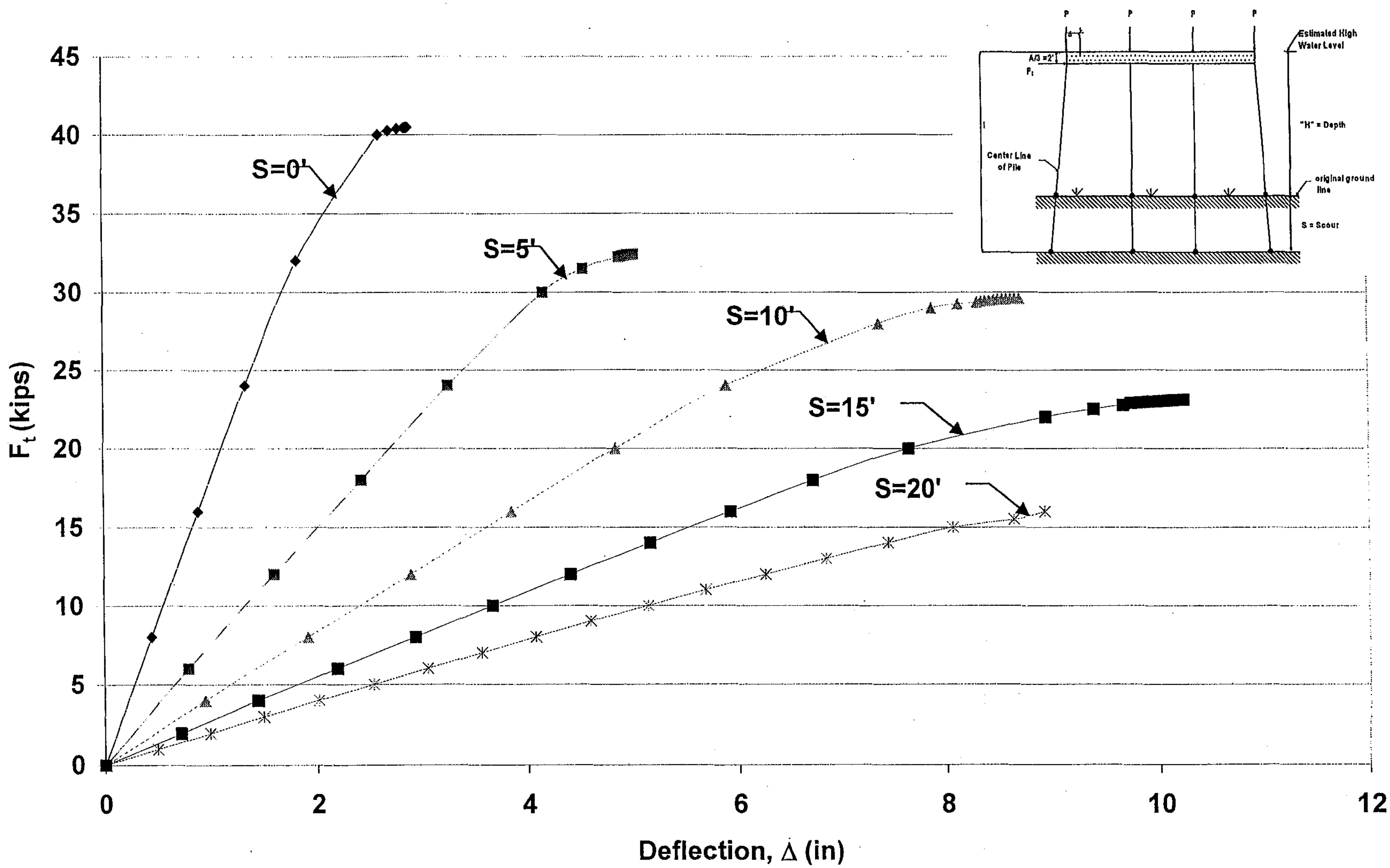


Figure B.31 HP12x53 Unbraced 4-Pile Bent with H=13', P=140kips, and A=6'
Pushover Analysis Results

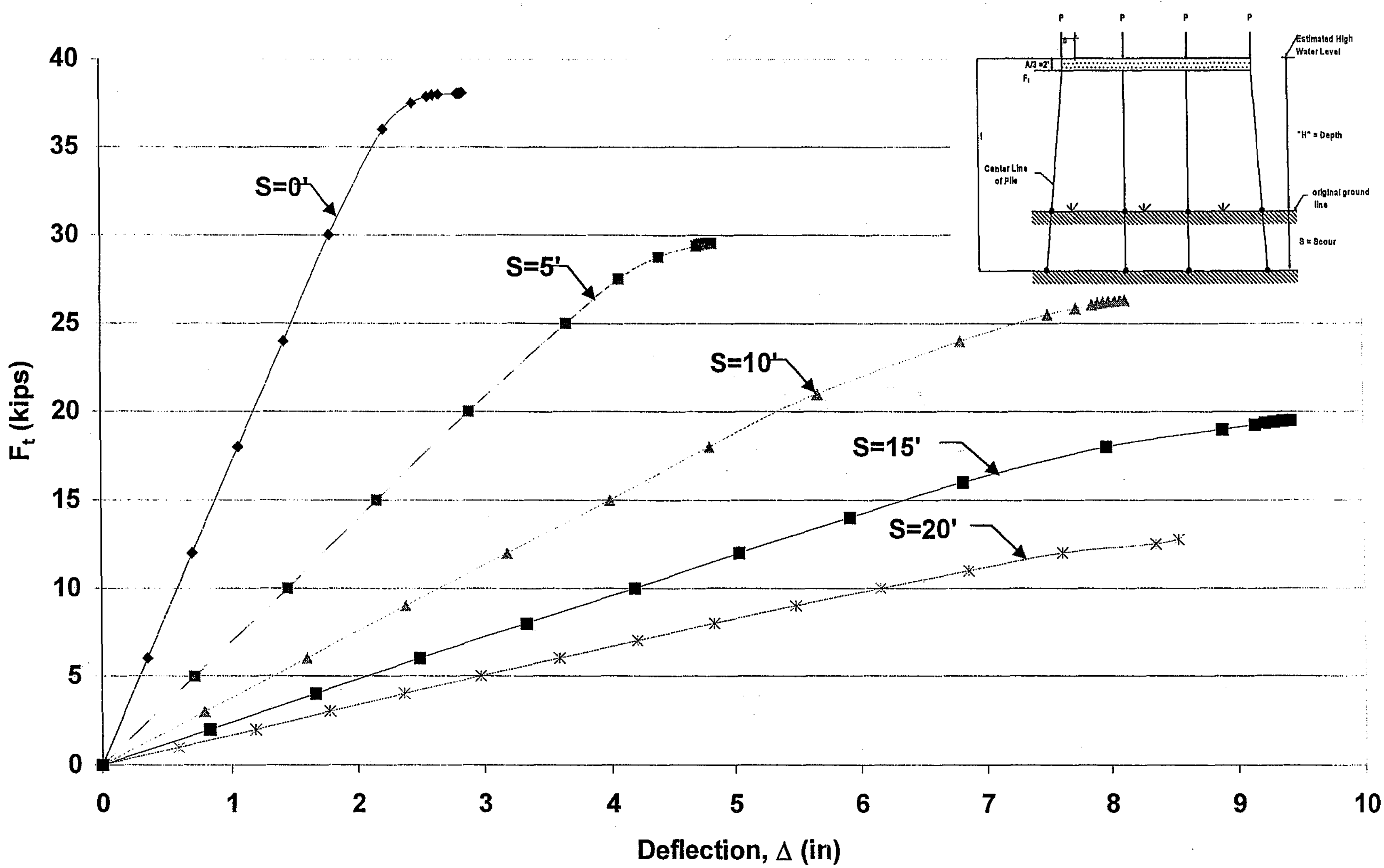


Figure B.32 HP12x53 Unbraced 4-Pile Bent with H=13', P=160kips, and A=6'
Pushover Analysis Results

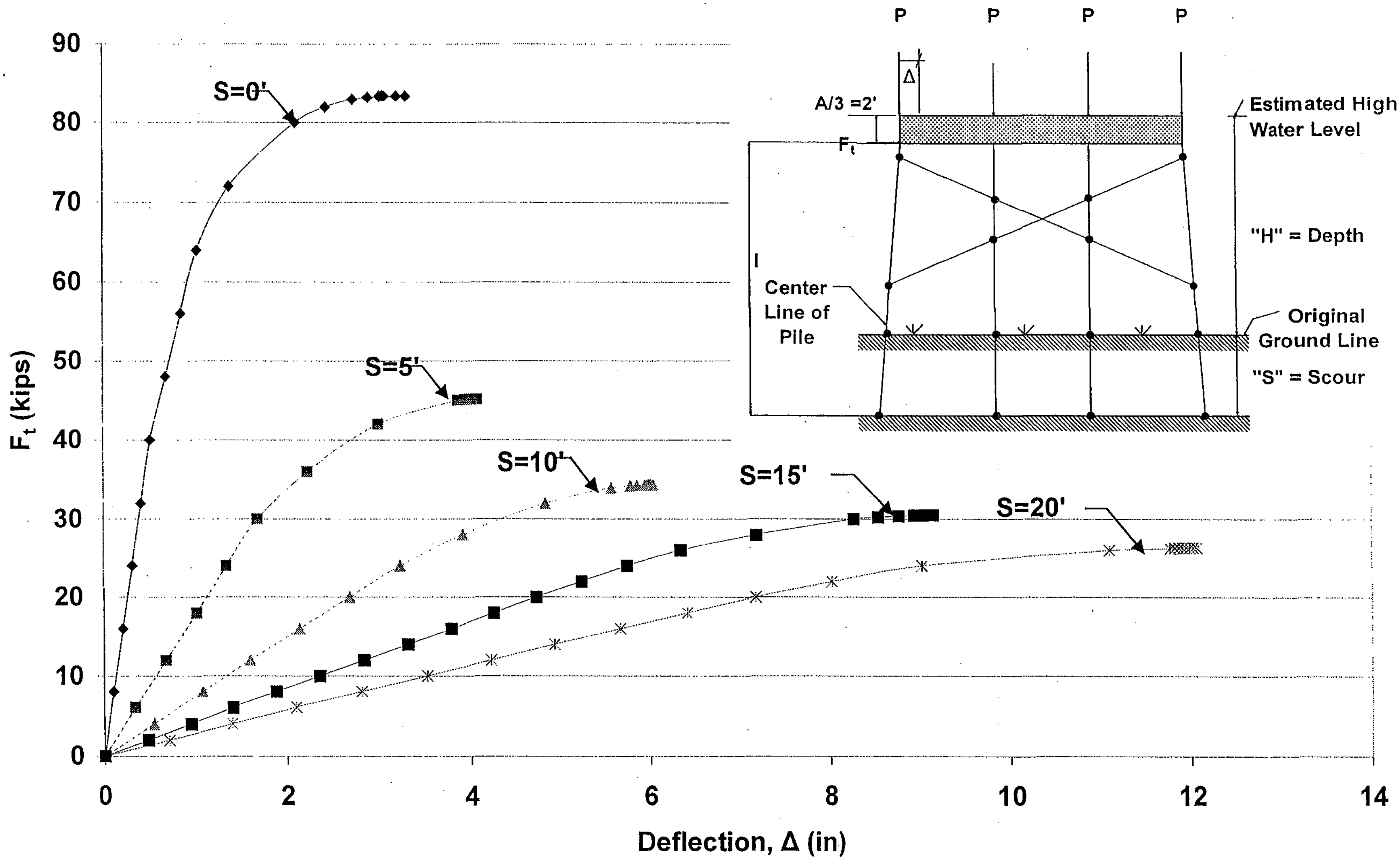


Figure B.33 HP12x53 X-Braced 4-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

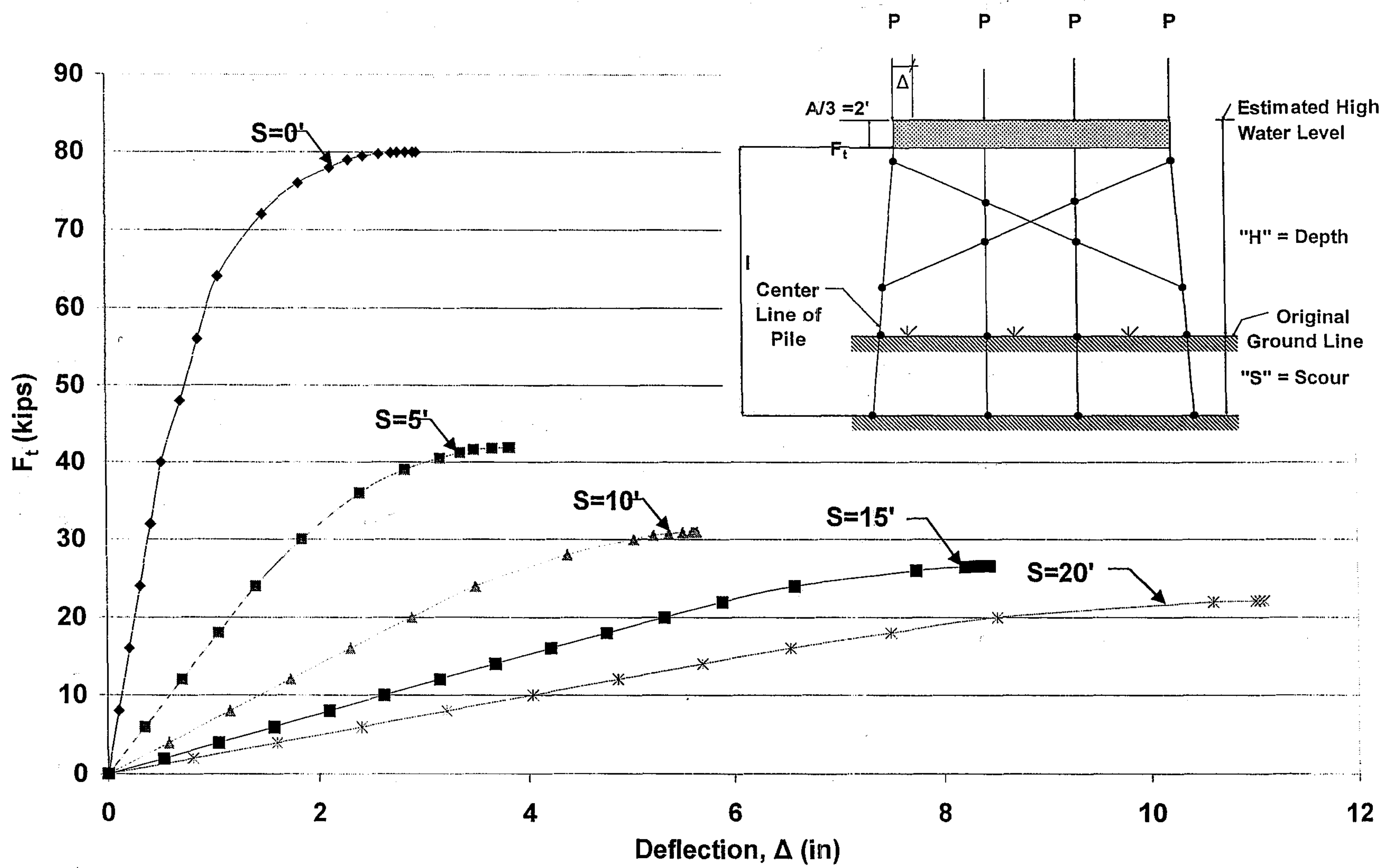


Figure B.34 HP12x53 X-Braced 4-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

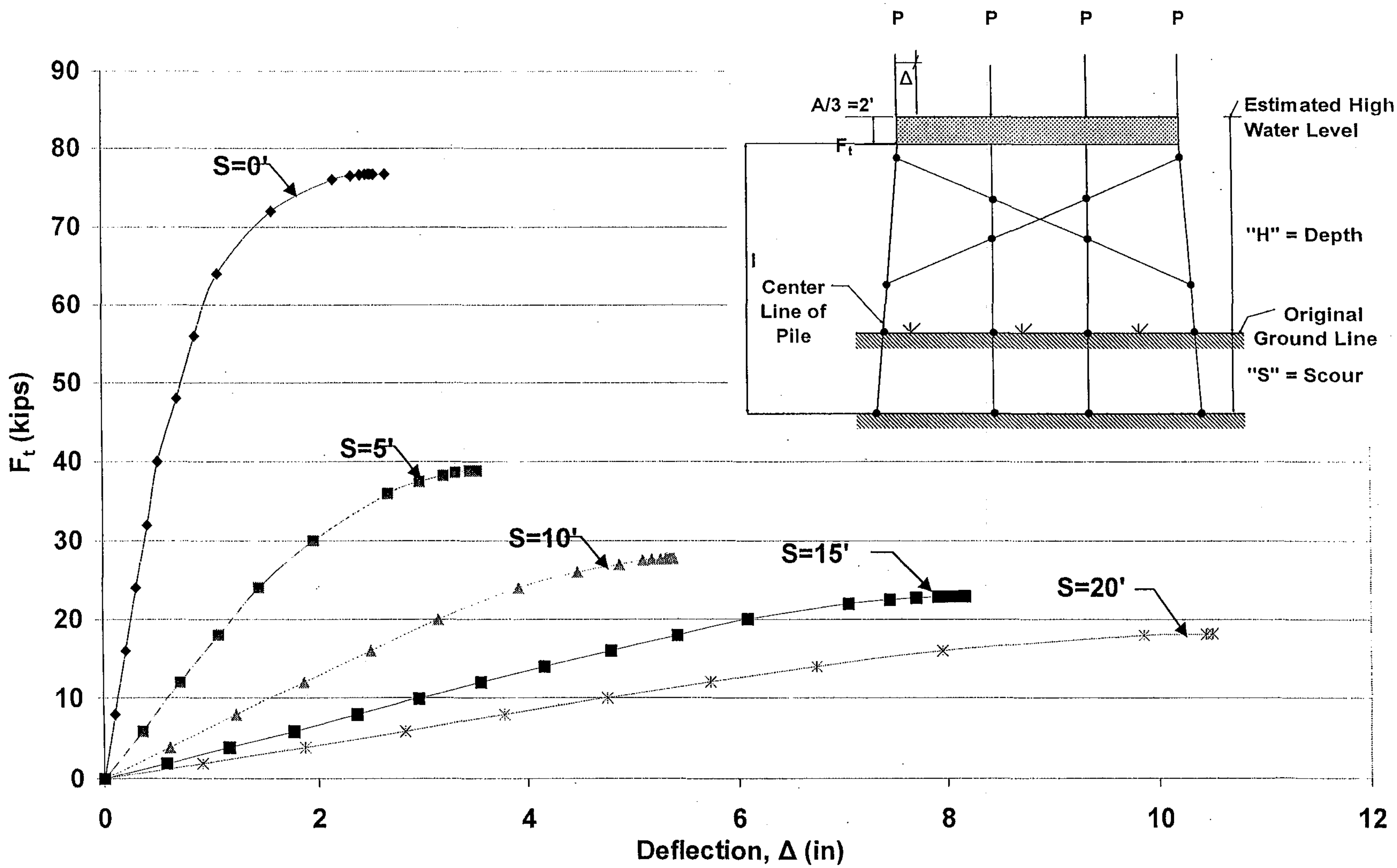


Figure B.35 HP12x53 X-Braced 4-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

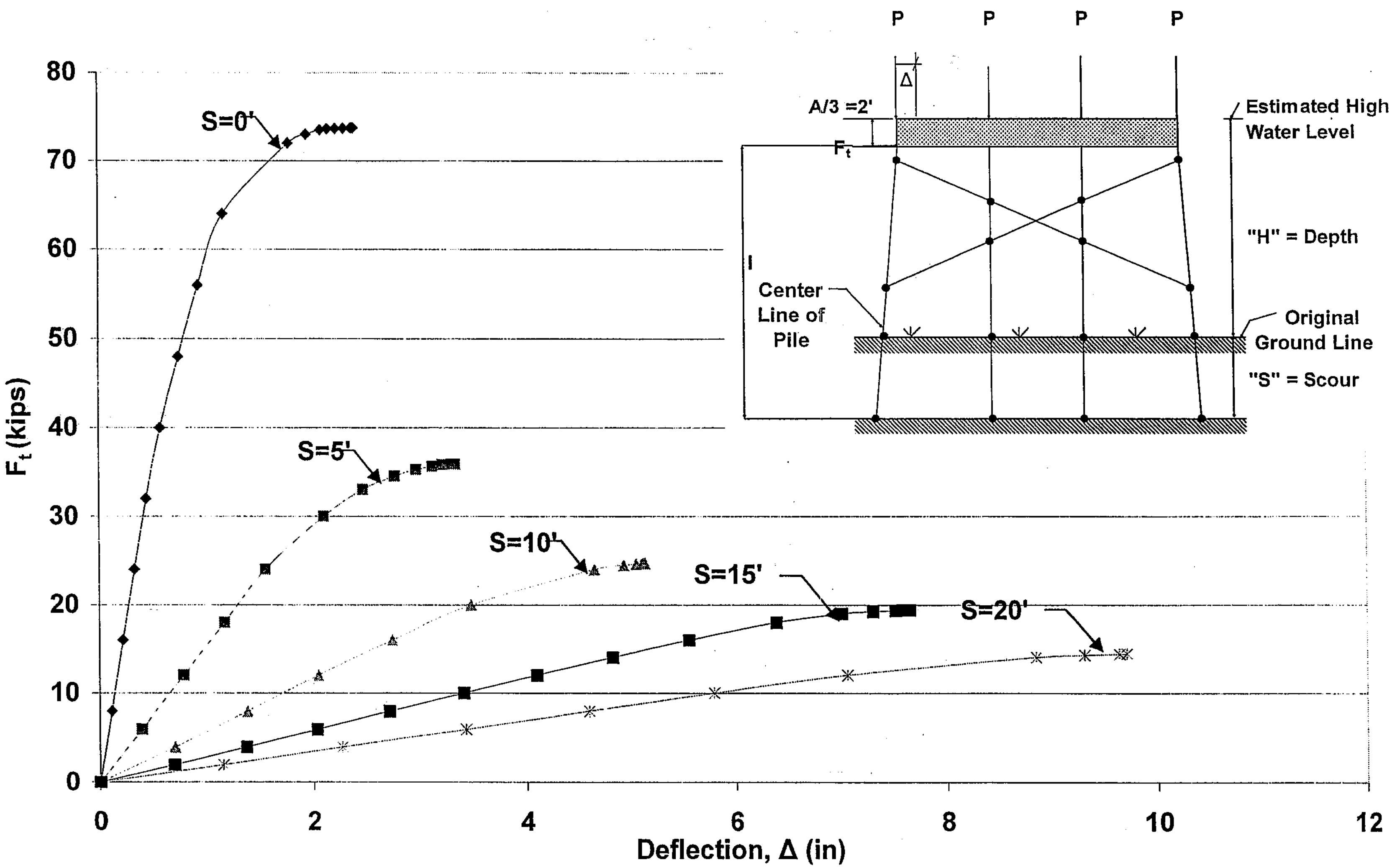


Figure B.36 HP12x53 X-Braced 4-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

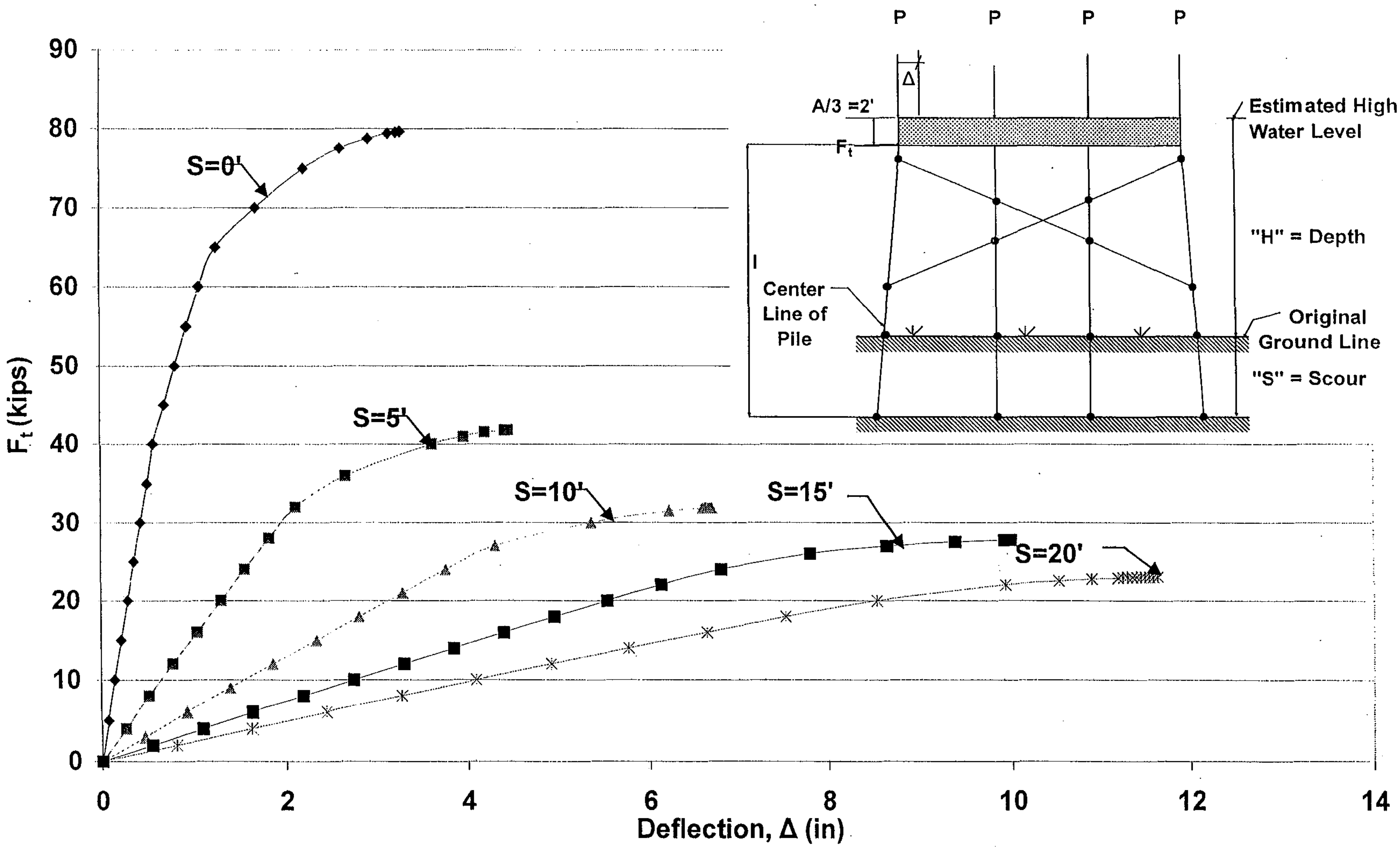


Figure B.37 HP12x53 X-Braced 4-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

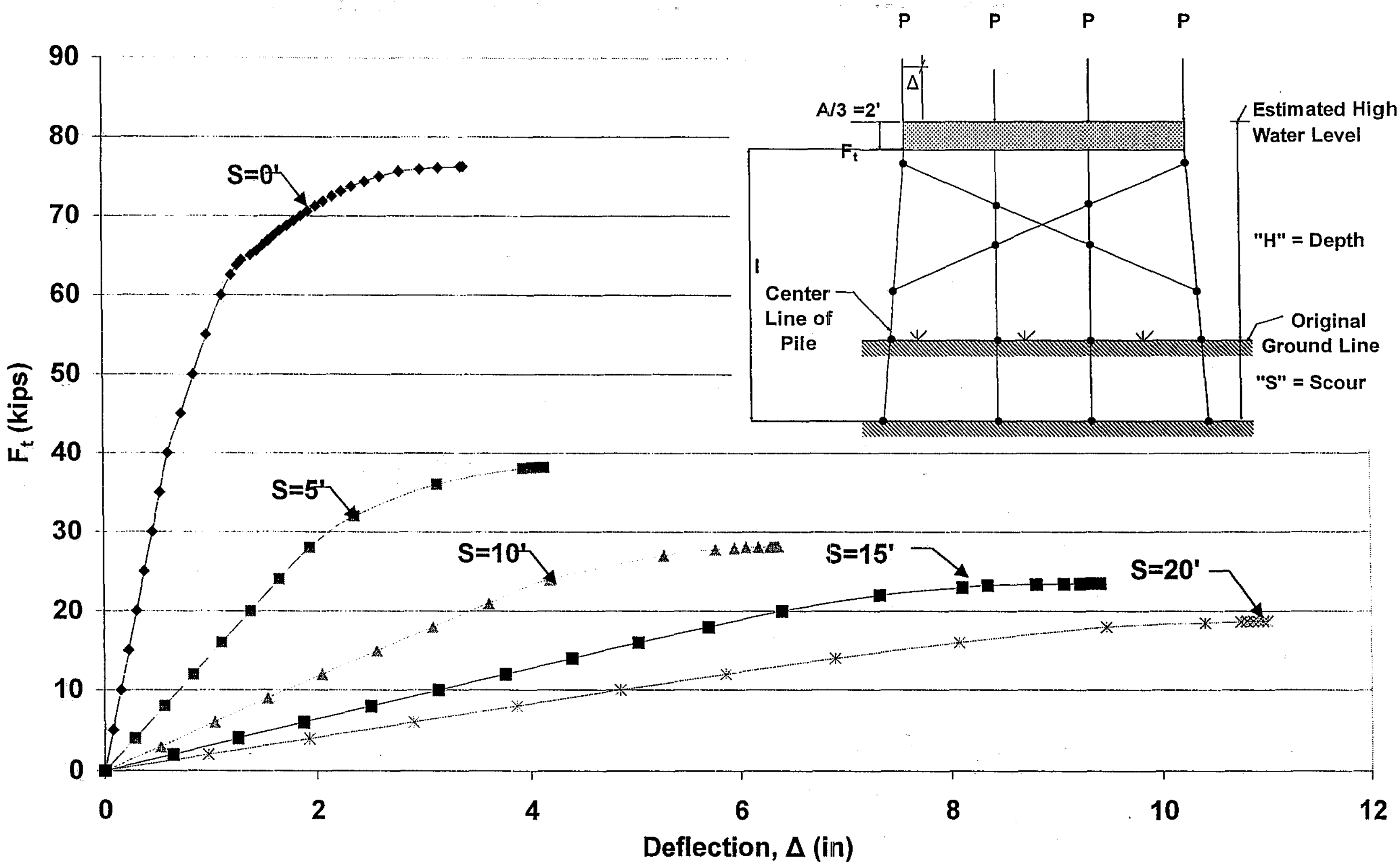


Figure B.38 HP12x53 X-Braced 4-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

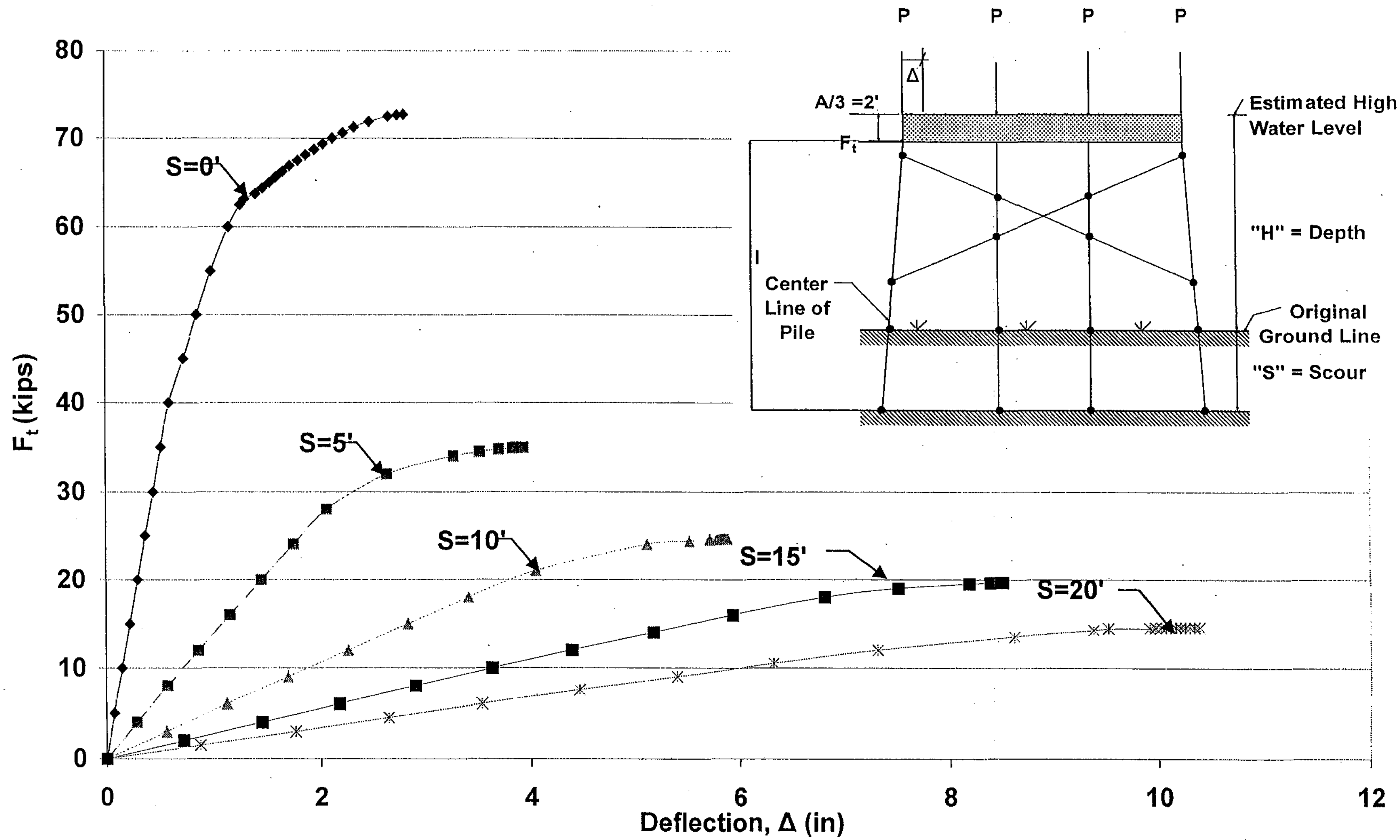


Figure B.39 HP12x53 X-Braced 4-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

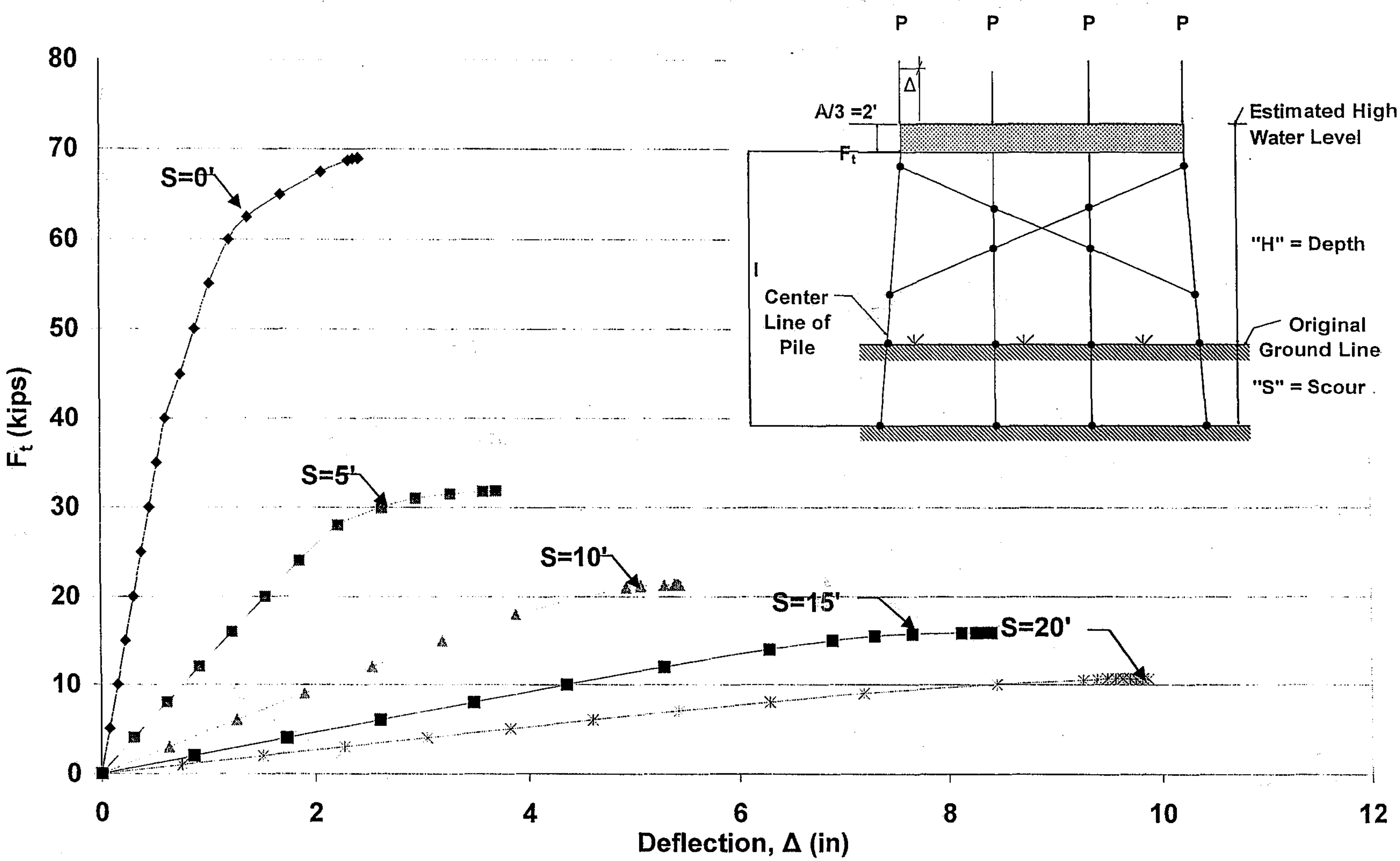


Figure B.40 HP12x53 X-Braced 4-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

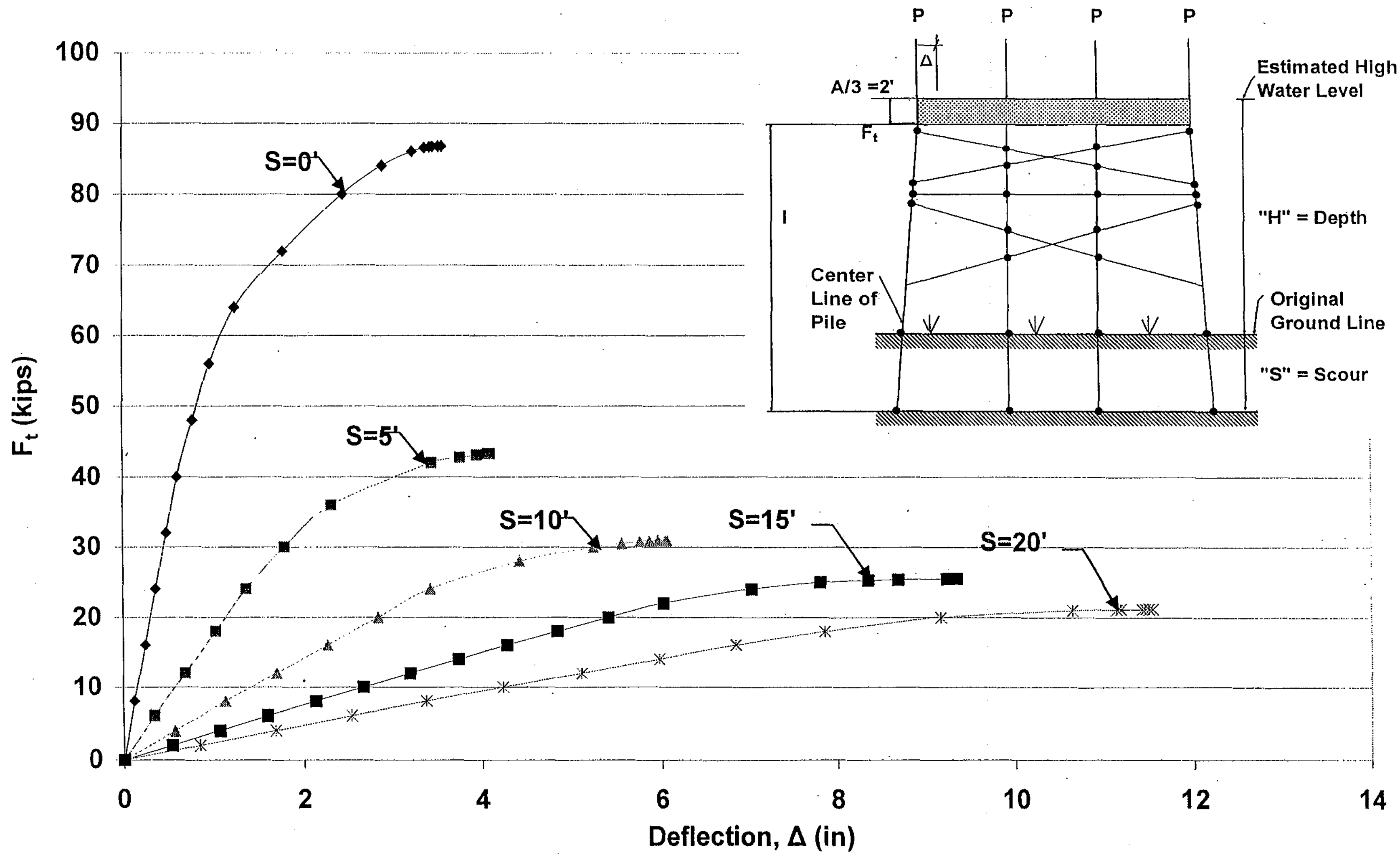


Figure B.41 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

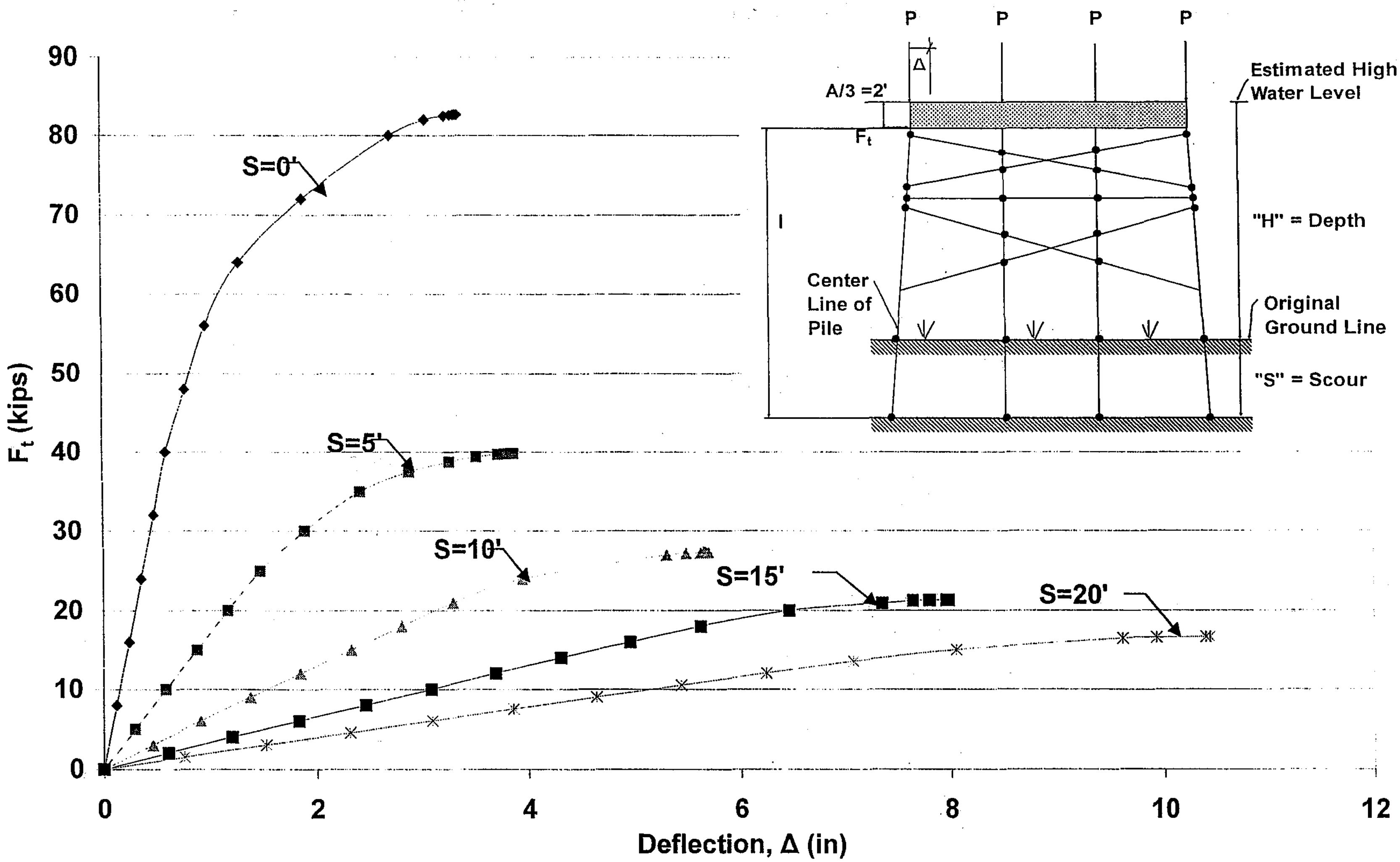


Figure B.42 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

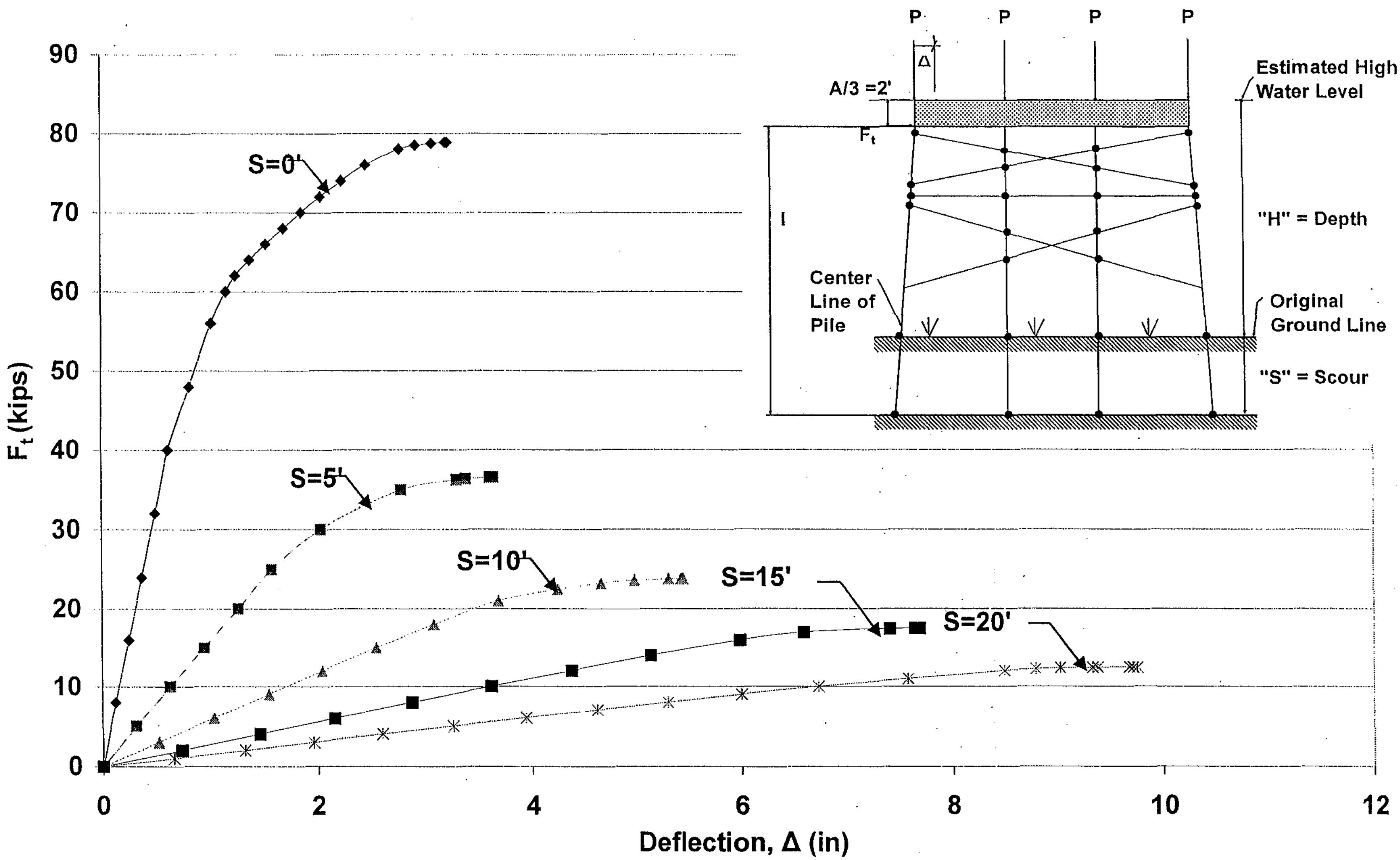


Figure B.43 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

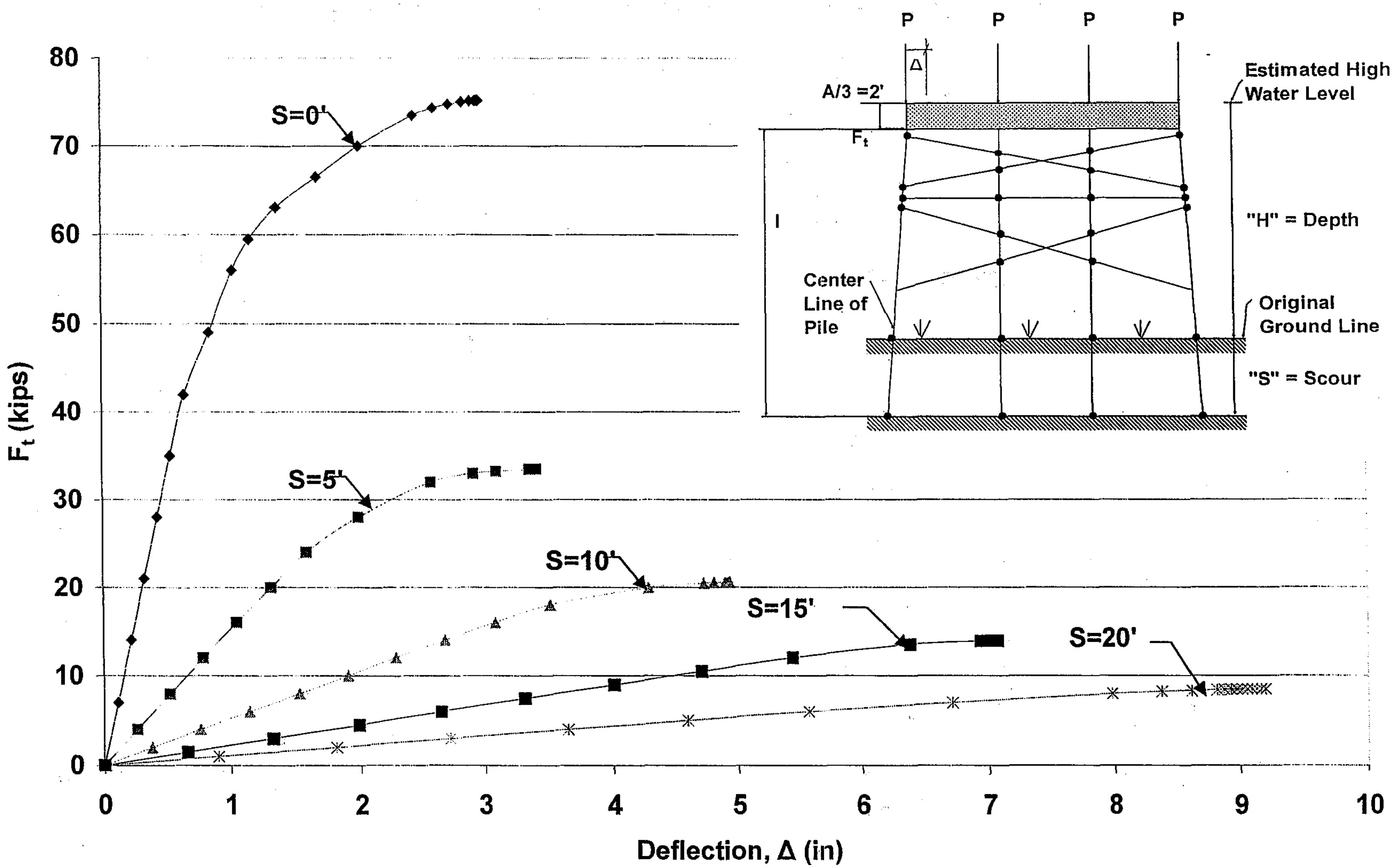


Figure B.44 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

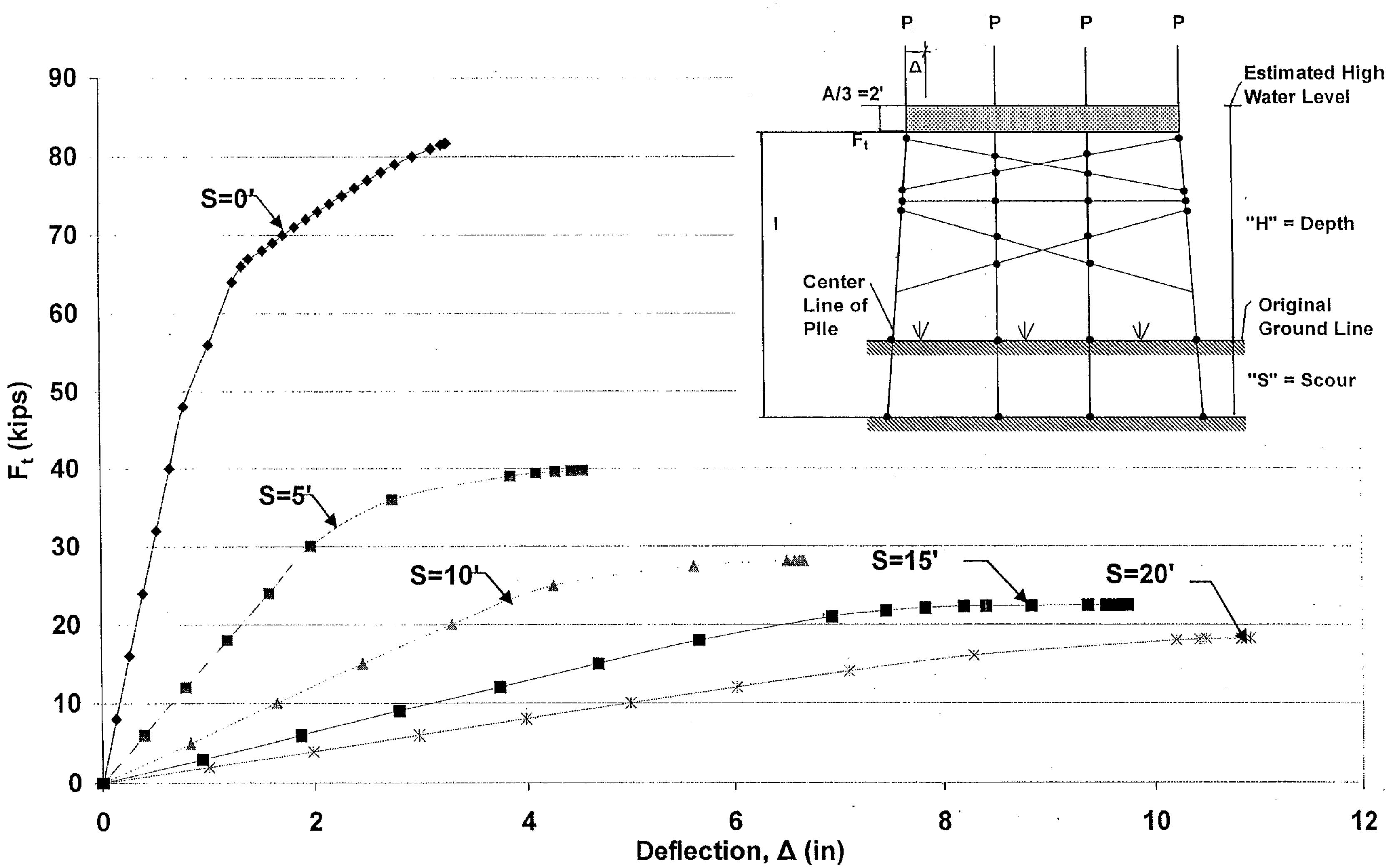


Figure B.45 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

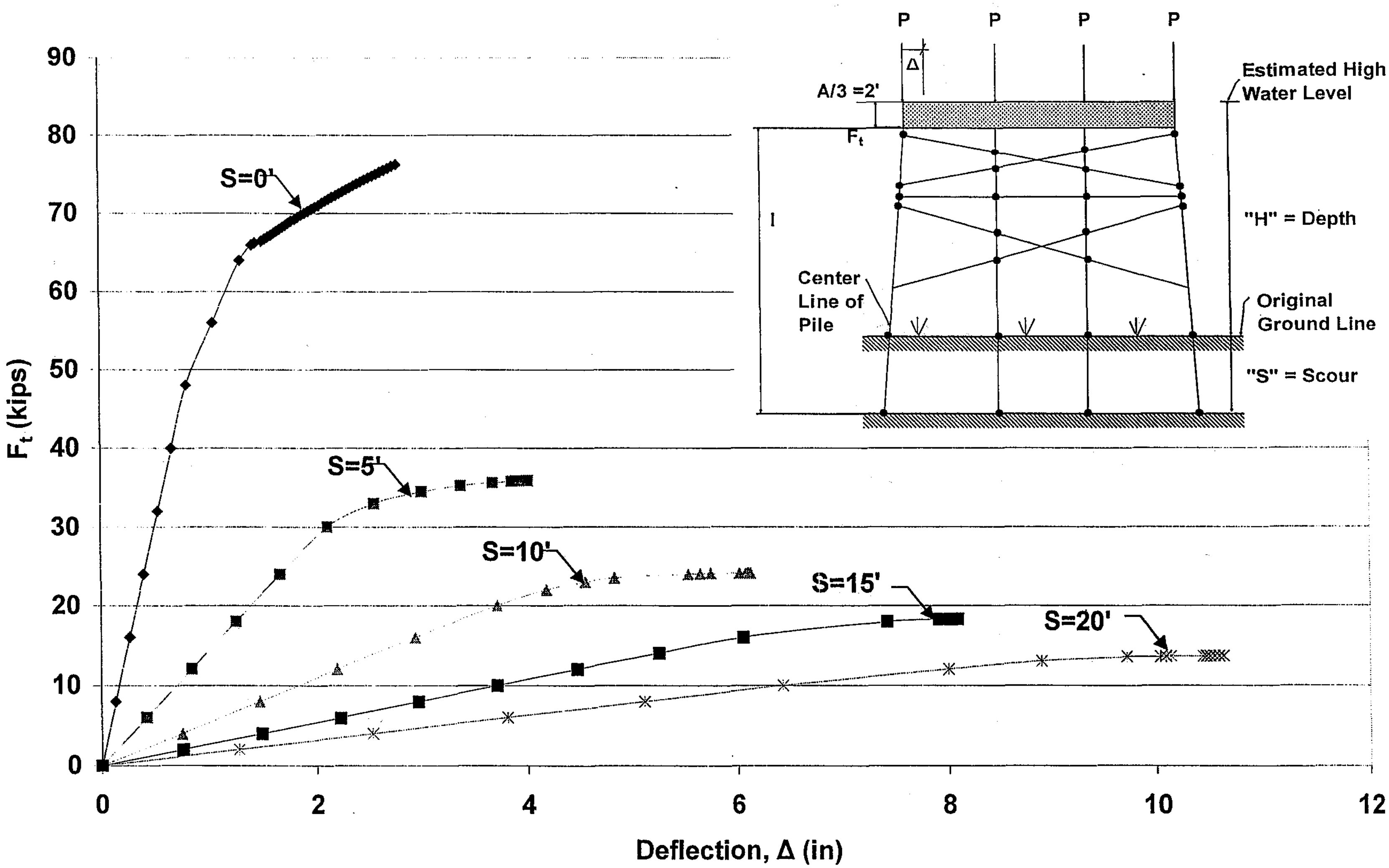


Figure B.46 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

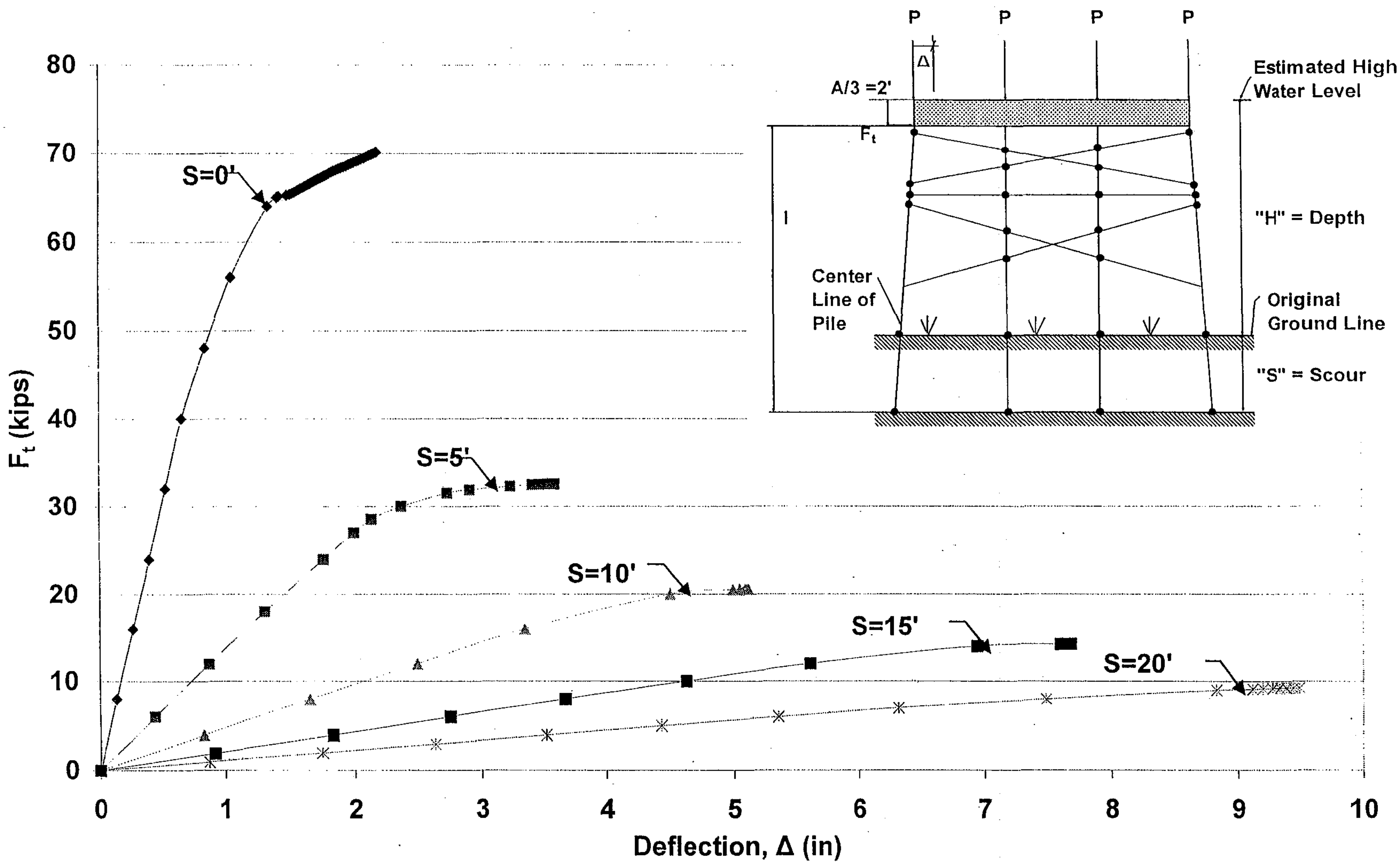


Figure B.47 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

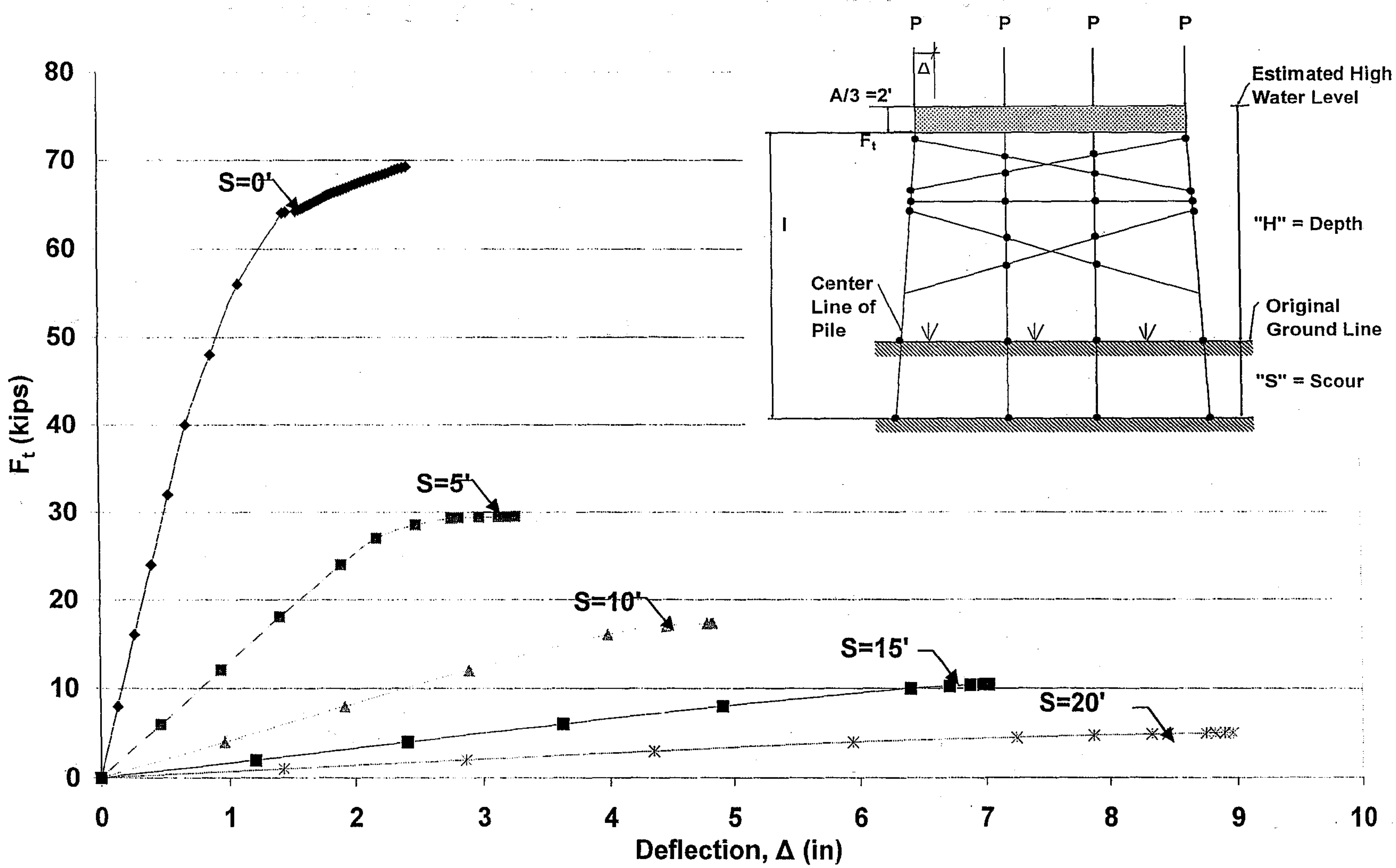


Figure B.48 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=160kips and A=6'
Pushover Analysis Results

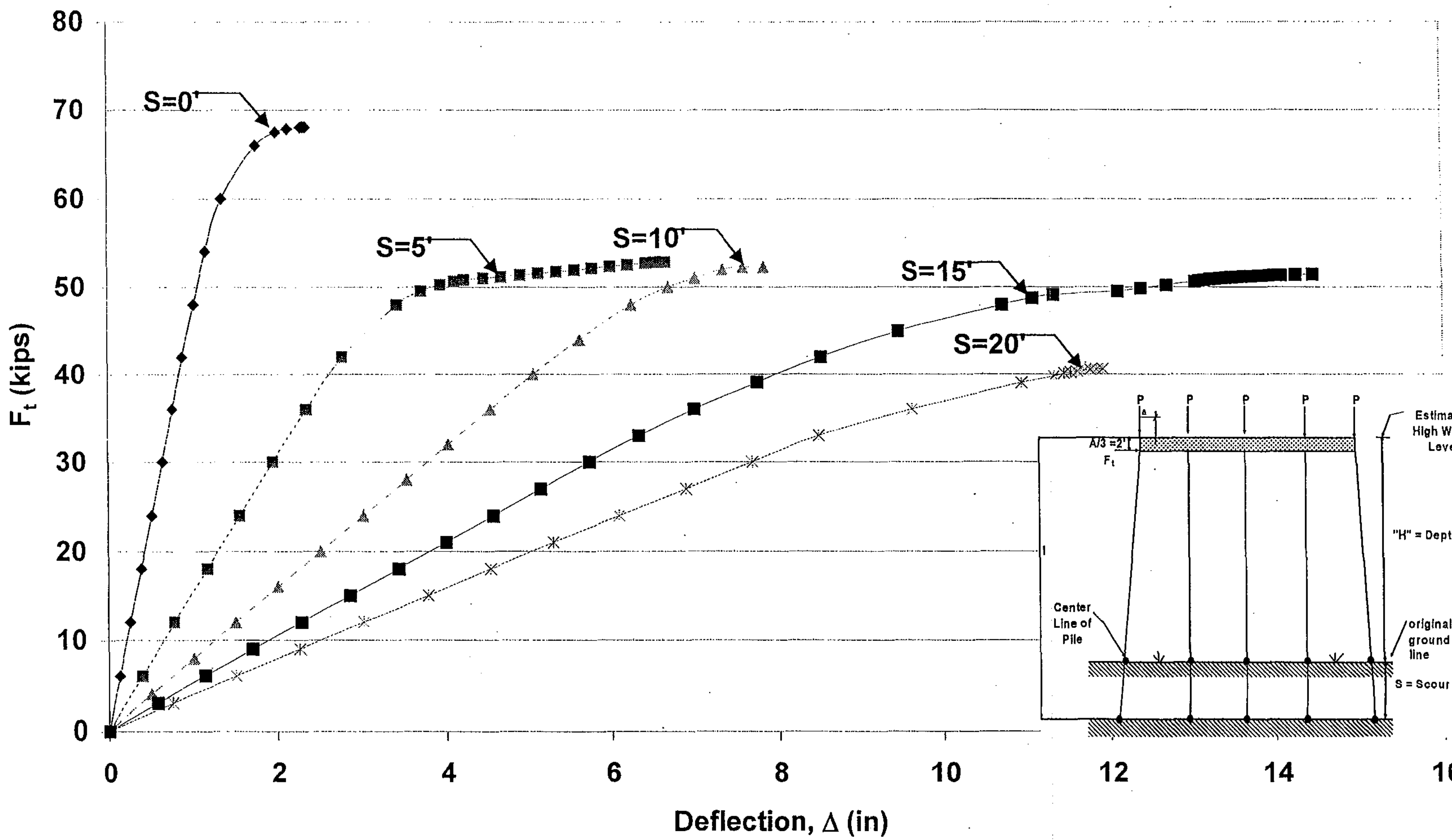


Figure B.49 HP12x53 Unbraced 5-Pile Bent with H=10',P=100kips and A=6' Pushover Analysis Results

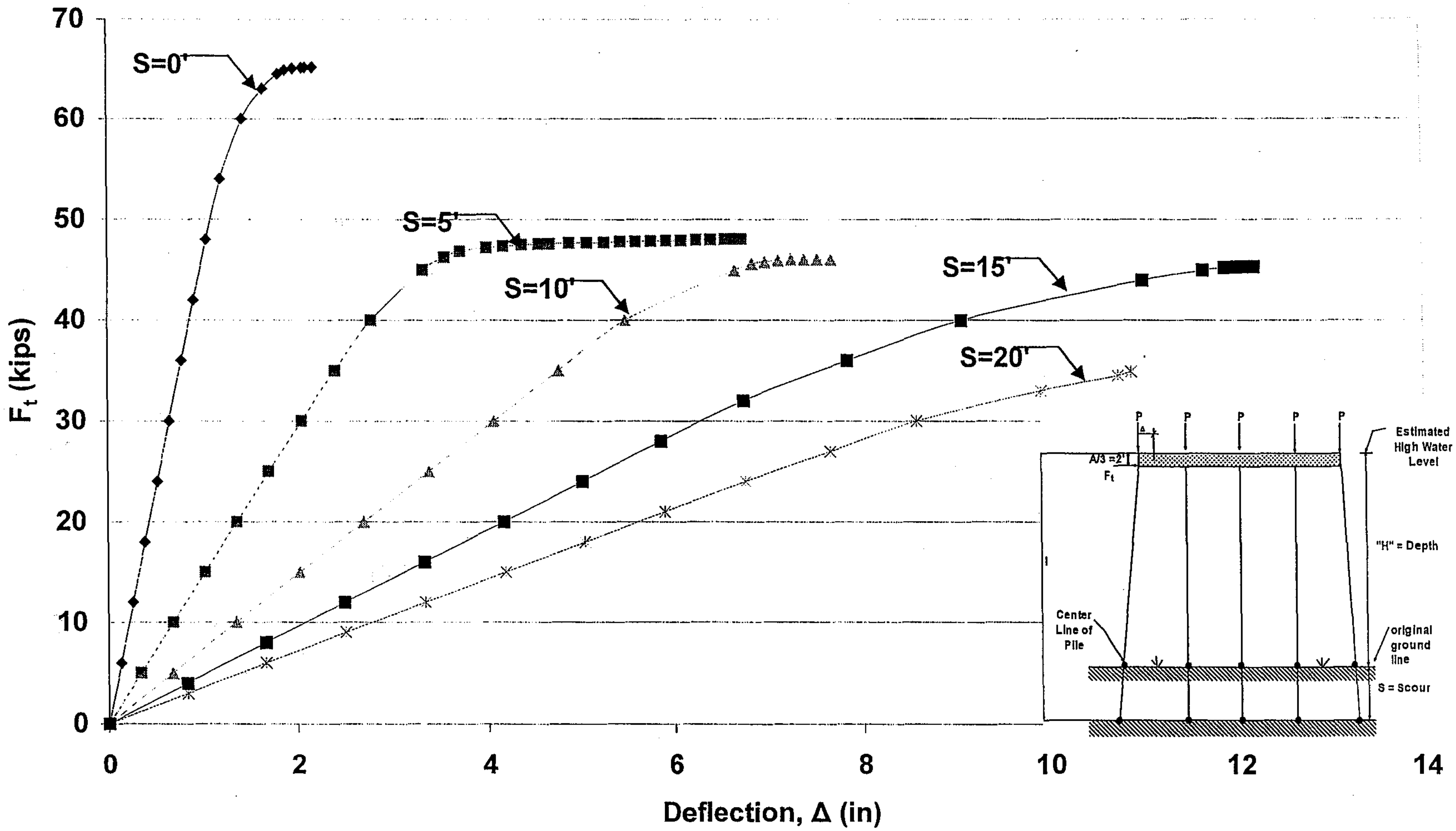


Figure B.50 HP12x53 Unbraced 5-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

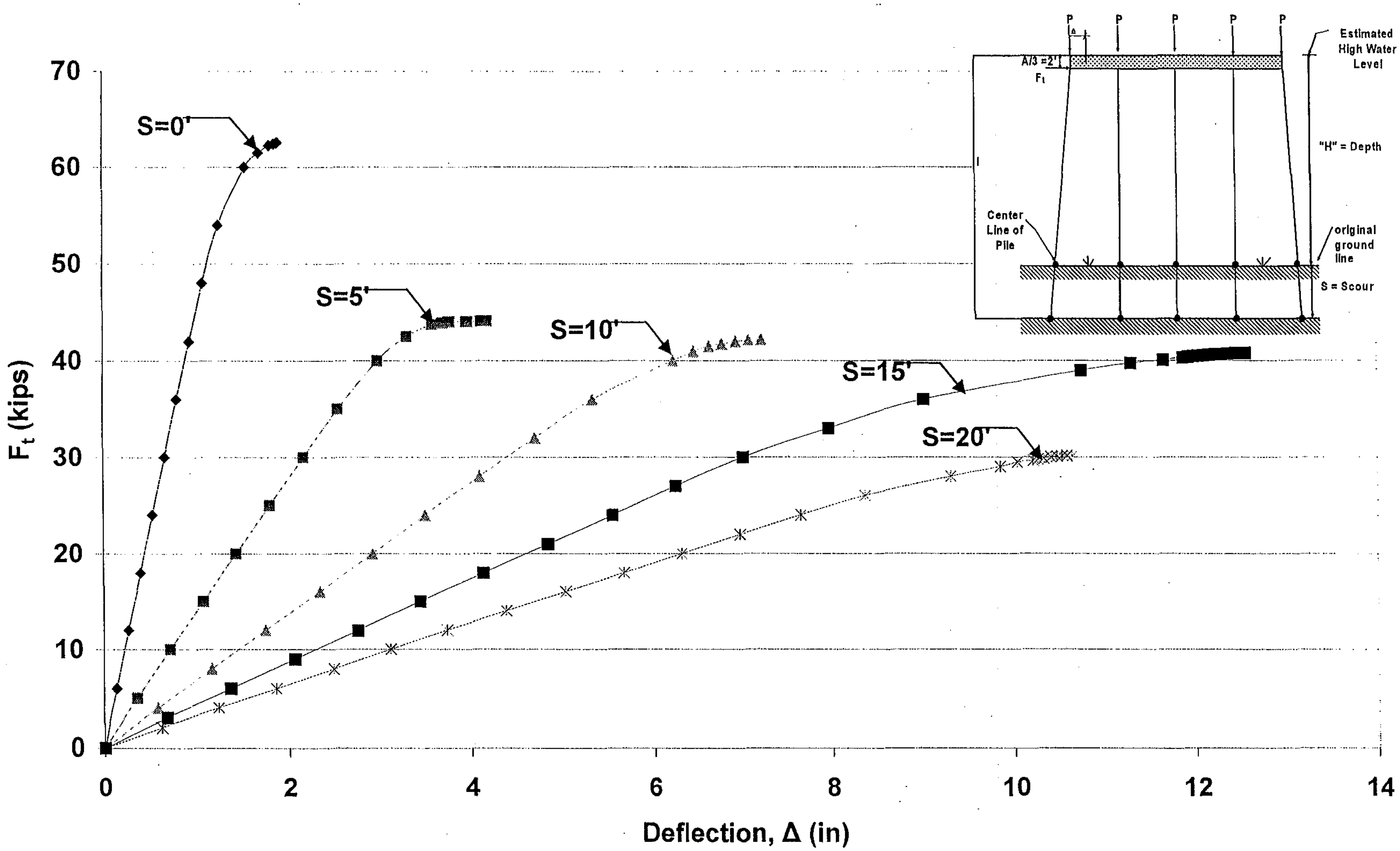


Figure B.51 HP12x53 Unbraced 5-Pile Bent with H=10', P=140kips and A=6' Pushover Analysis Results

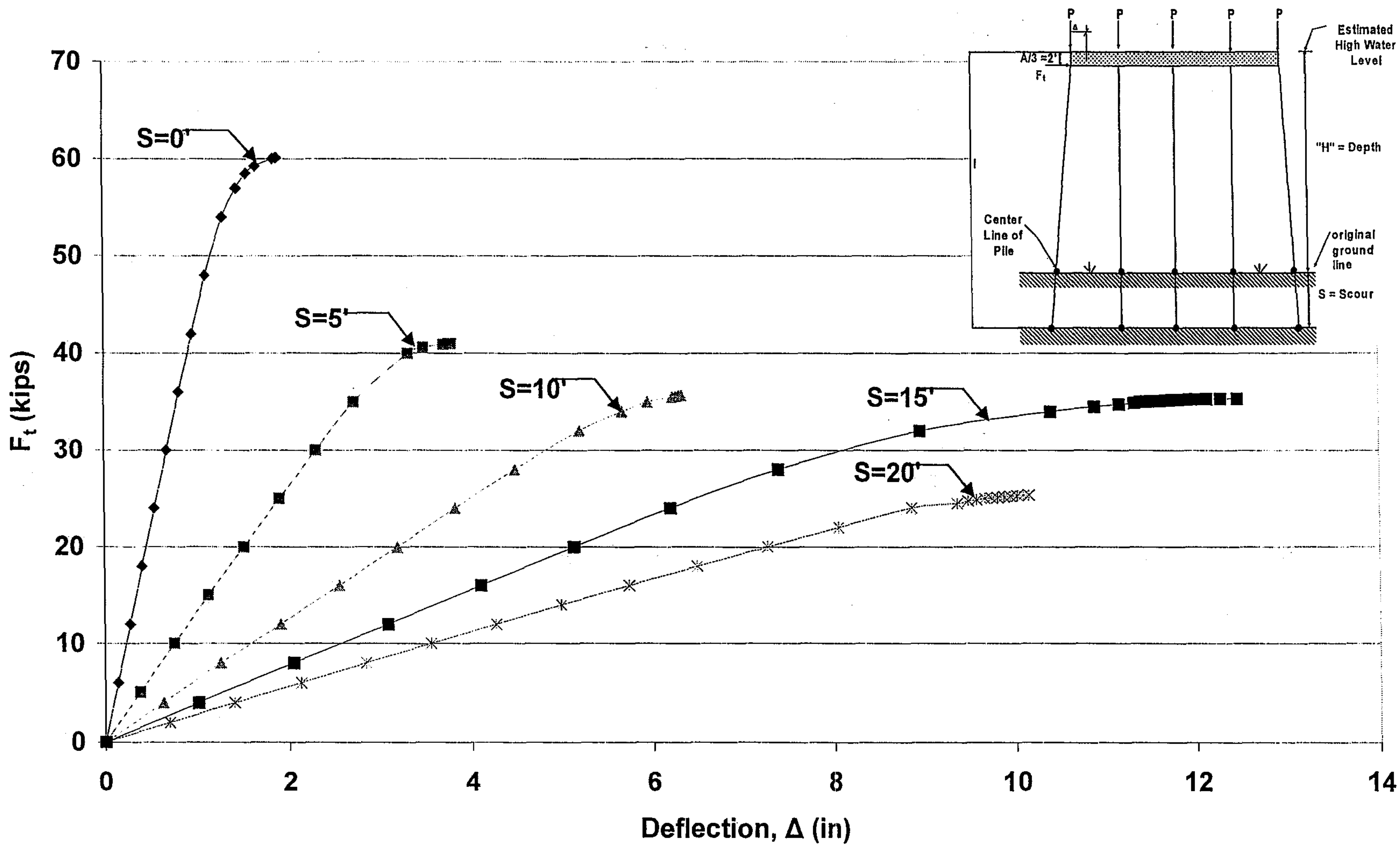


Figure B.52 HP12x53 Unbraced 5-Pile Bent with H=10', P=160kips and A=6'
Pushover Analysis Results

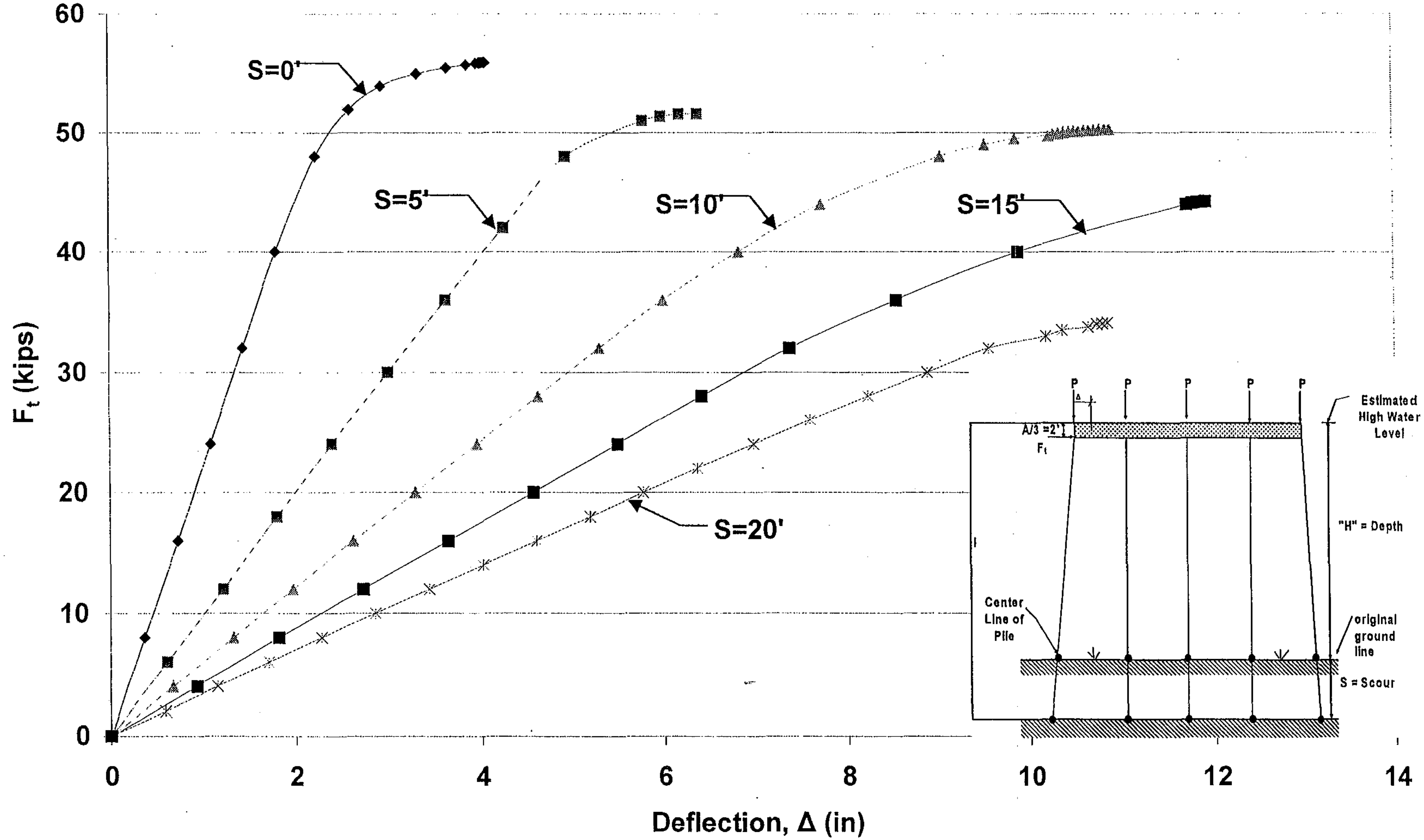


Figure B.53 HP12x53 Unbraced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

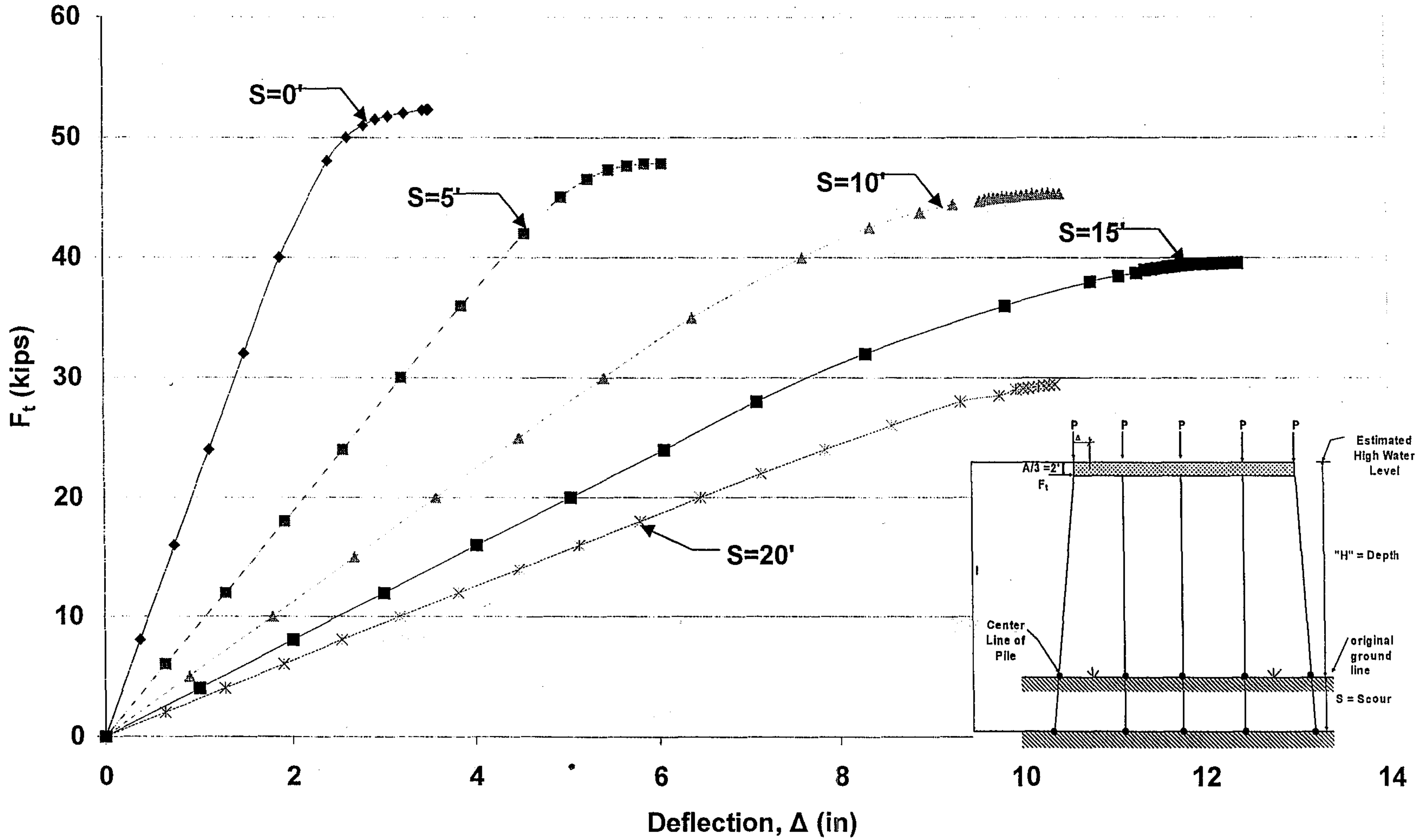


Figure B.54 HP12x53 Unbraced 5-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

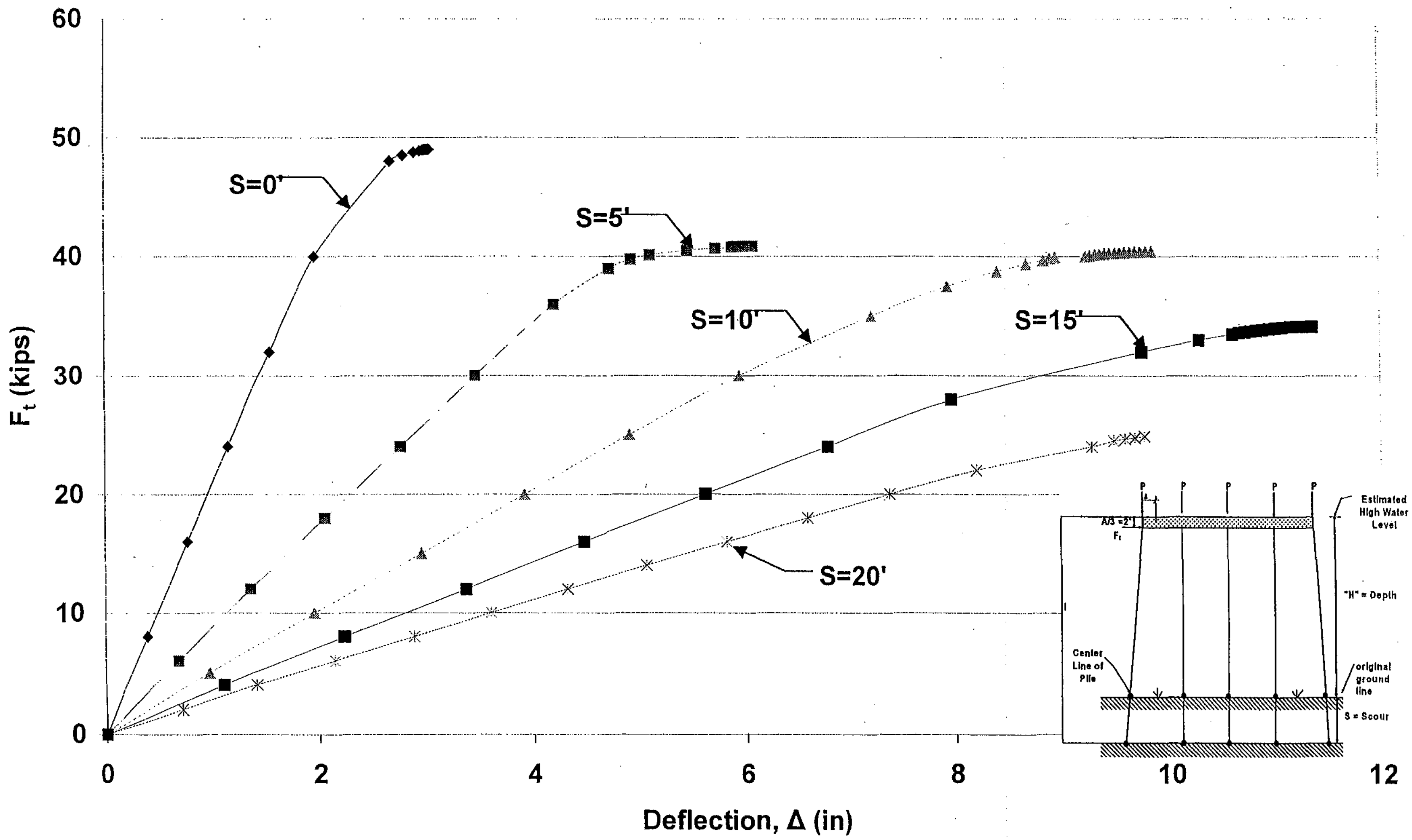


Figure B.55 HP12x53 Unbraced 5-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

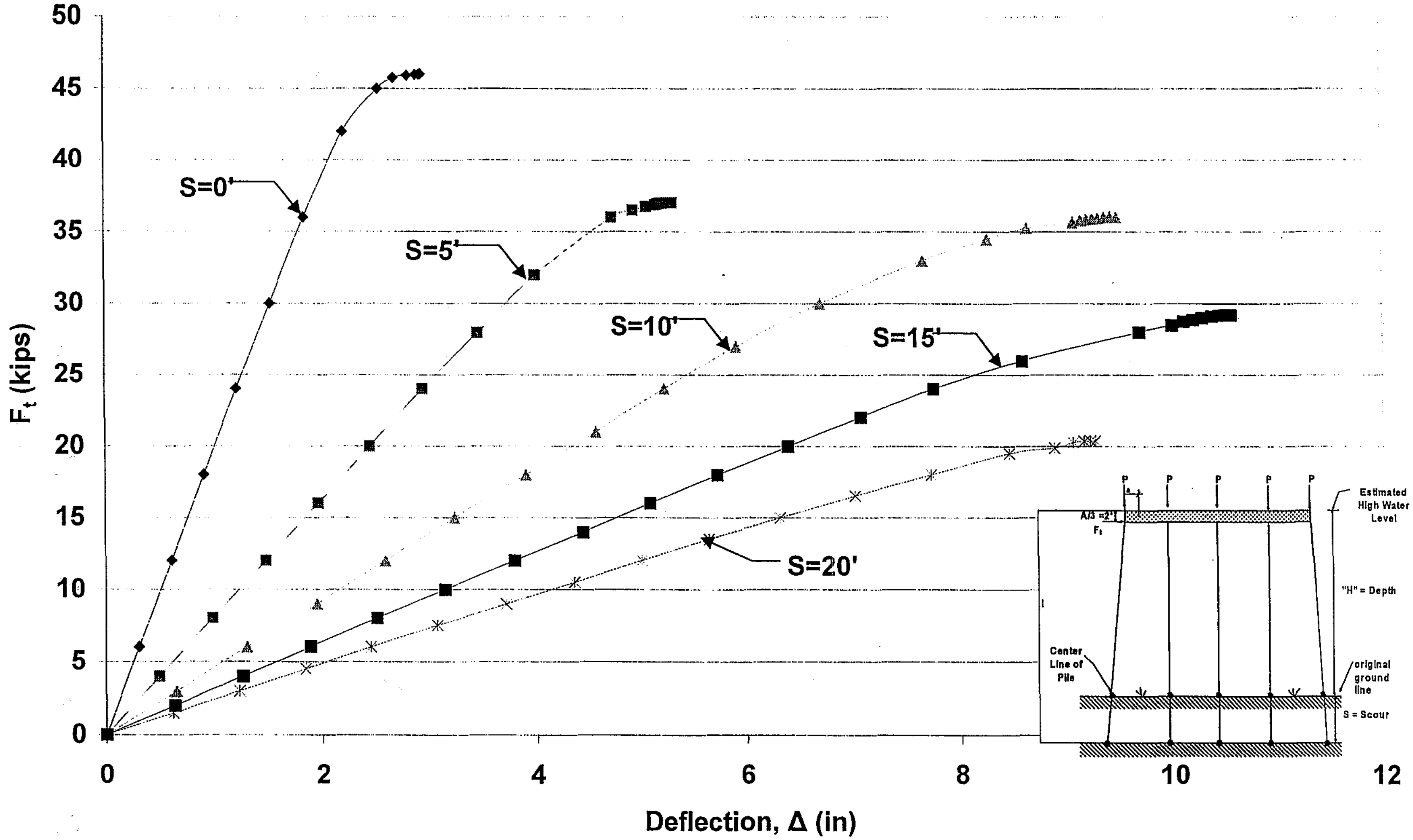


Figure B.56 HP12x53 Unbraced 5-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

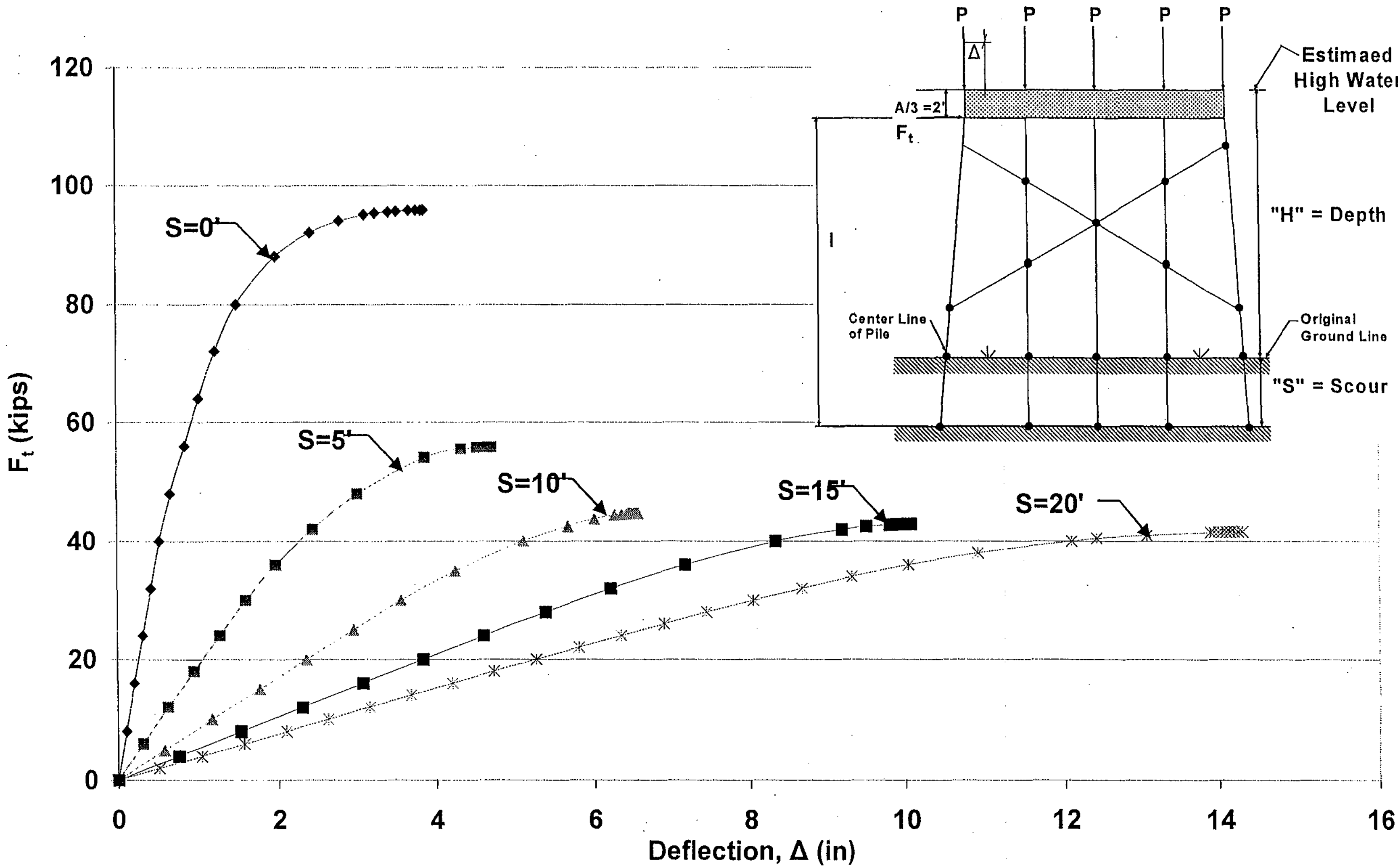


Figure B.57 HP12x53 X-Braced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

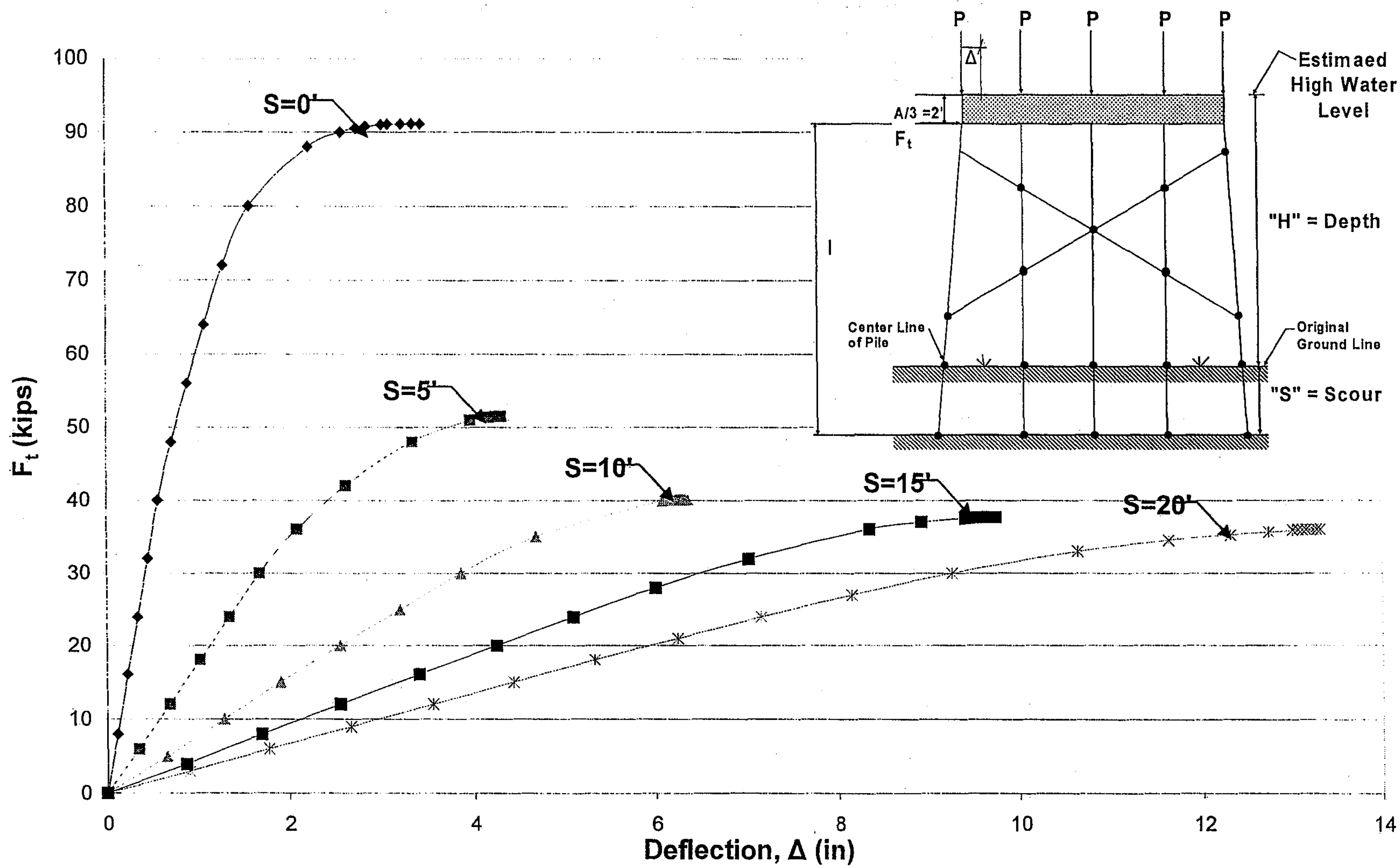


Figure B.58 HP12x53 X-Braced 5-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

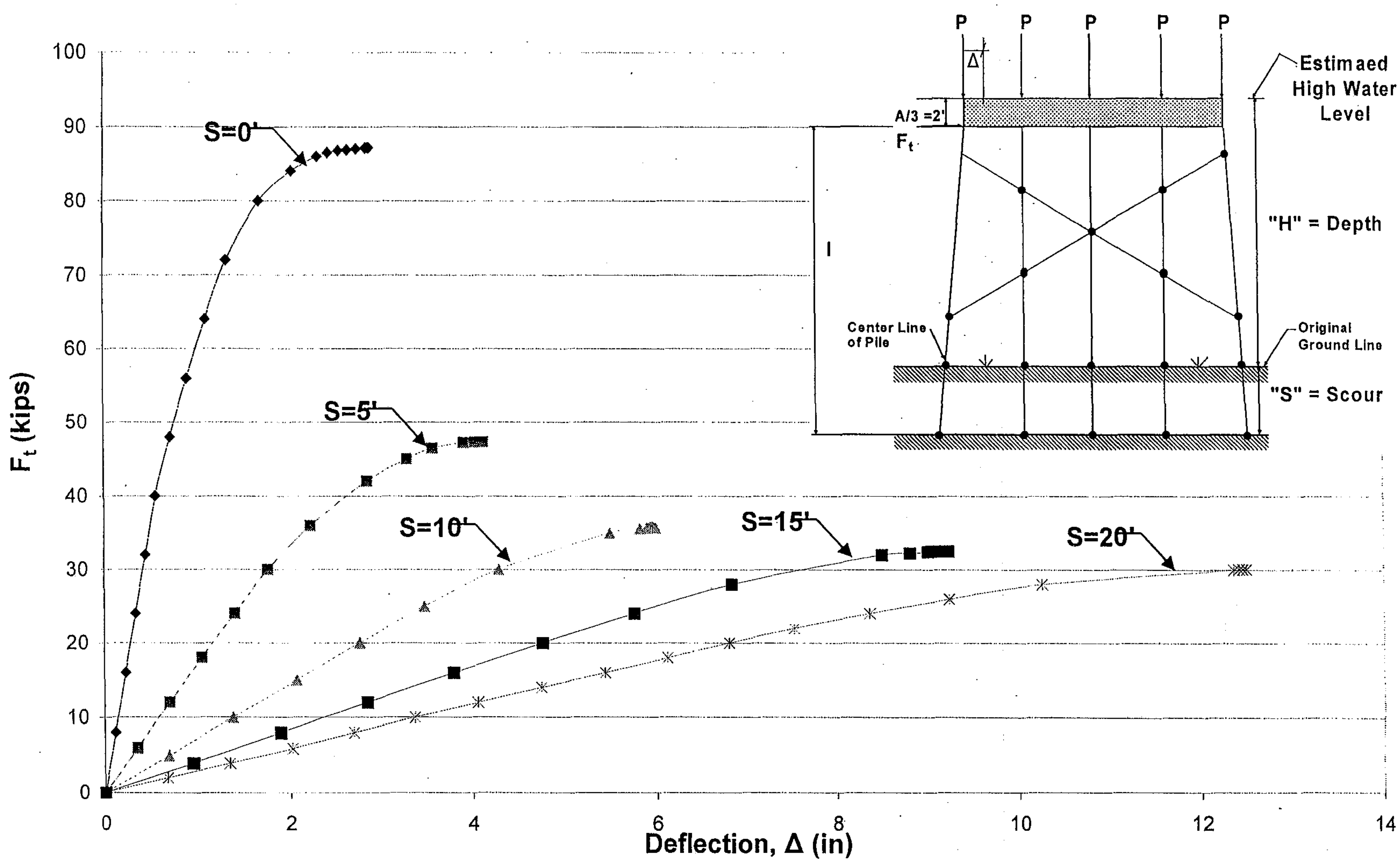


Figure B.59 HP12x53 X-Braced 5-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

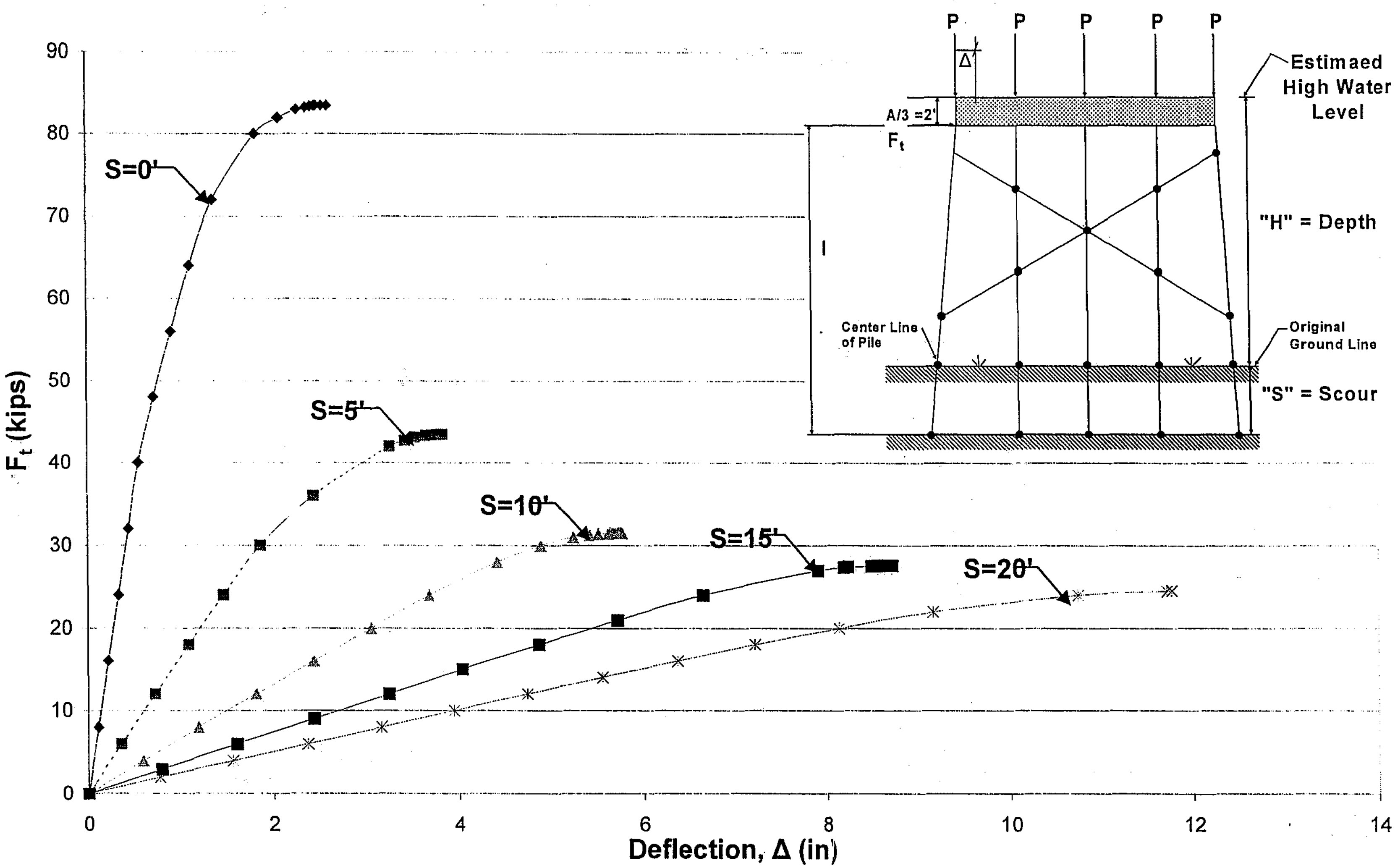


**Figure B.60 HP12x53 X-Braced 5-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results**

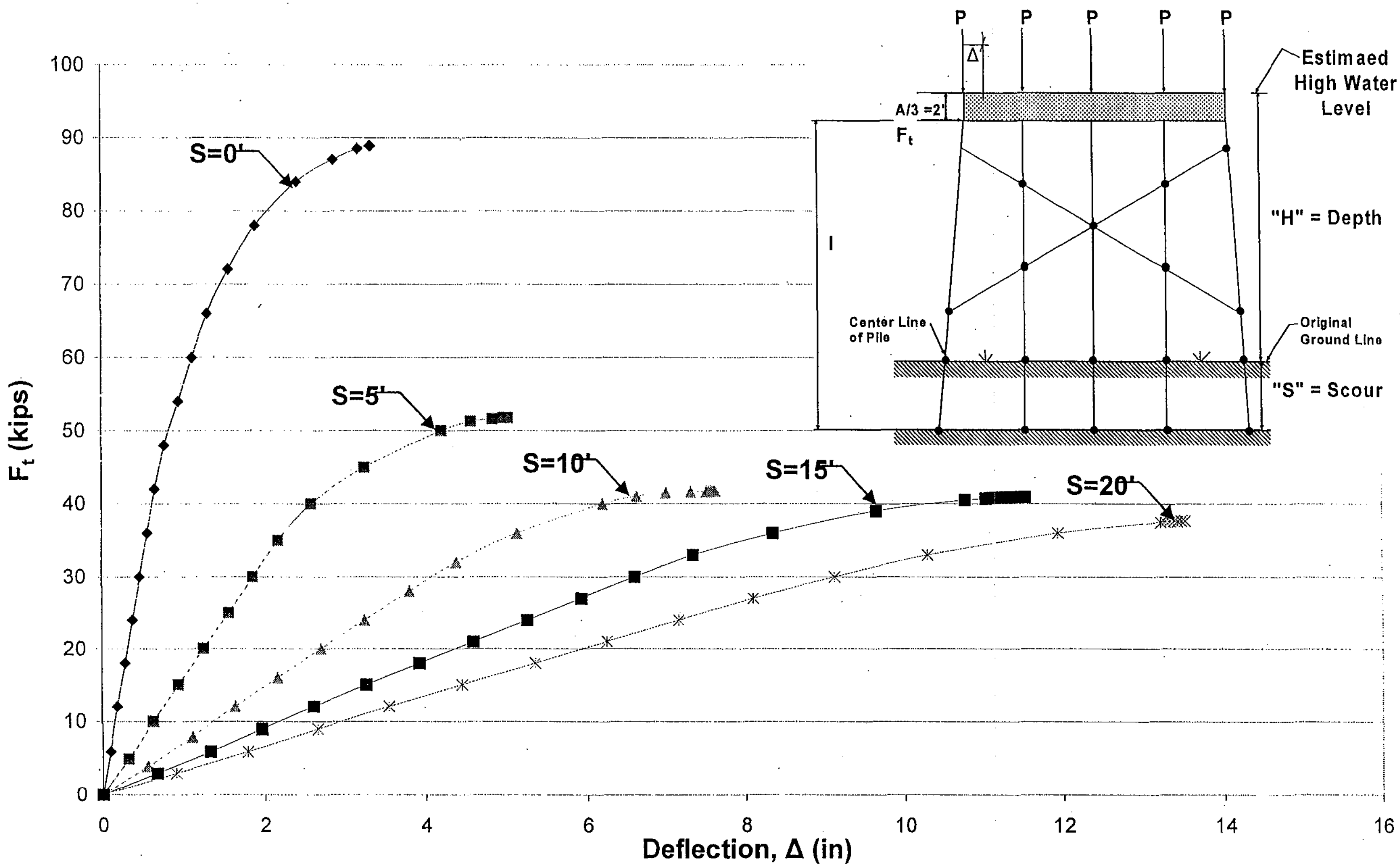


Figure B.61 HP12x53 X-Braced 5-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

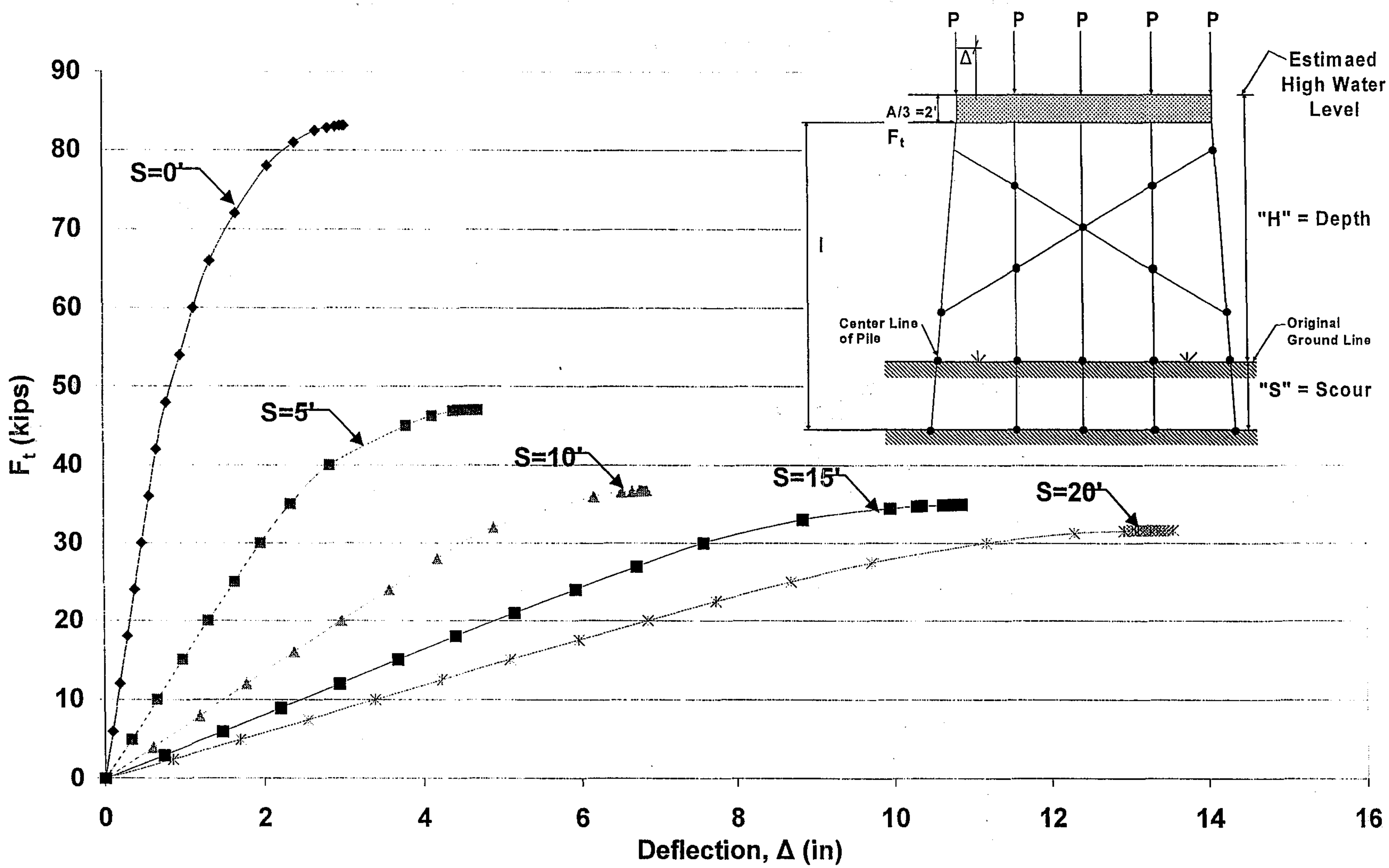


Figure B.62 HP12x53 X-Braced 5-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

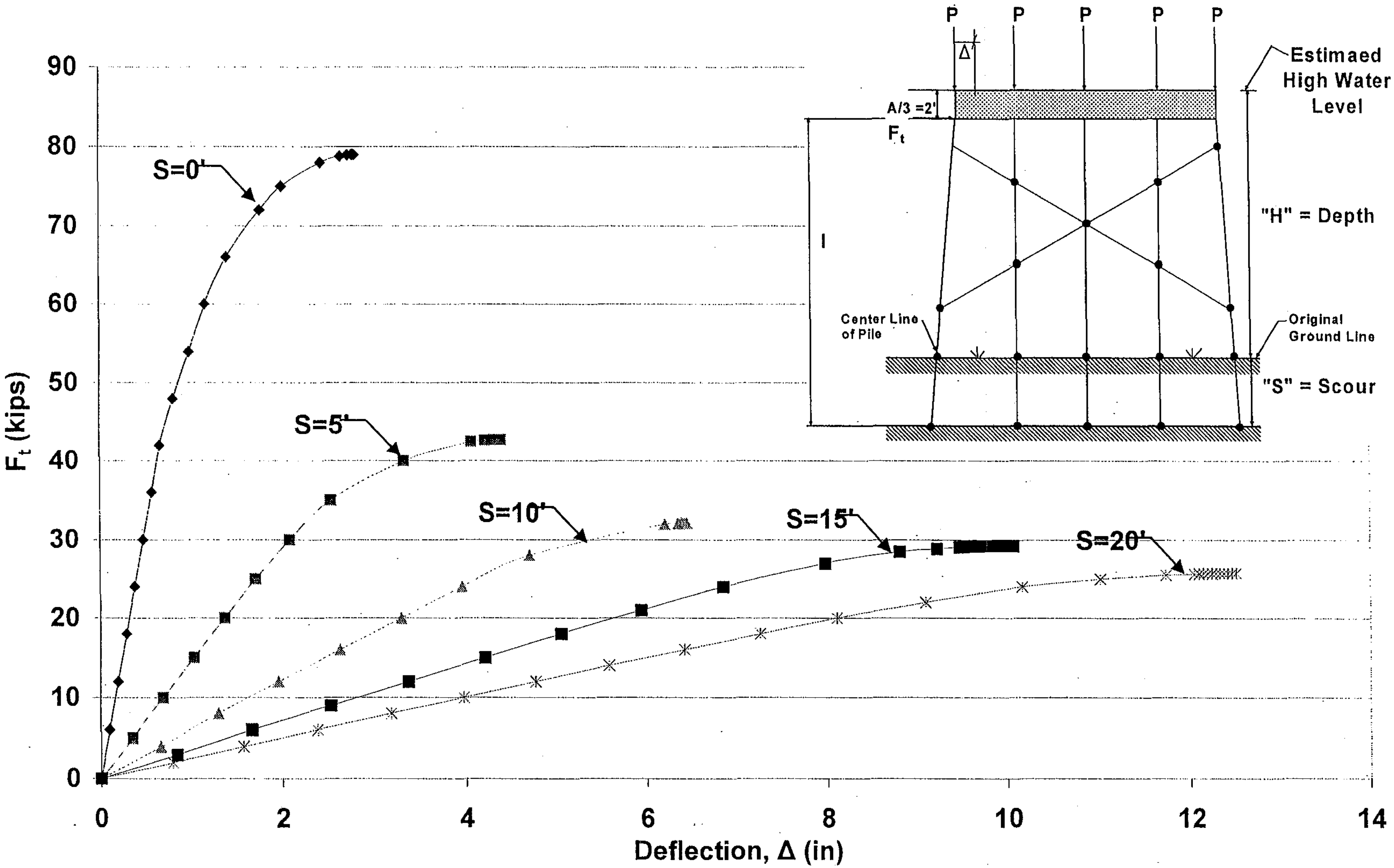


Figure B.63 HP12x53 X-Braced 5-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

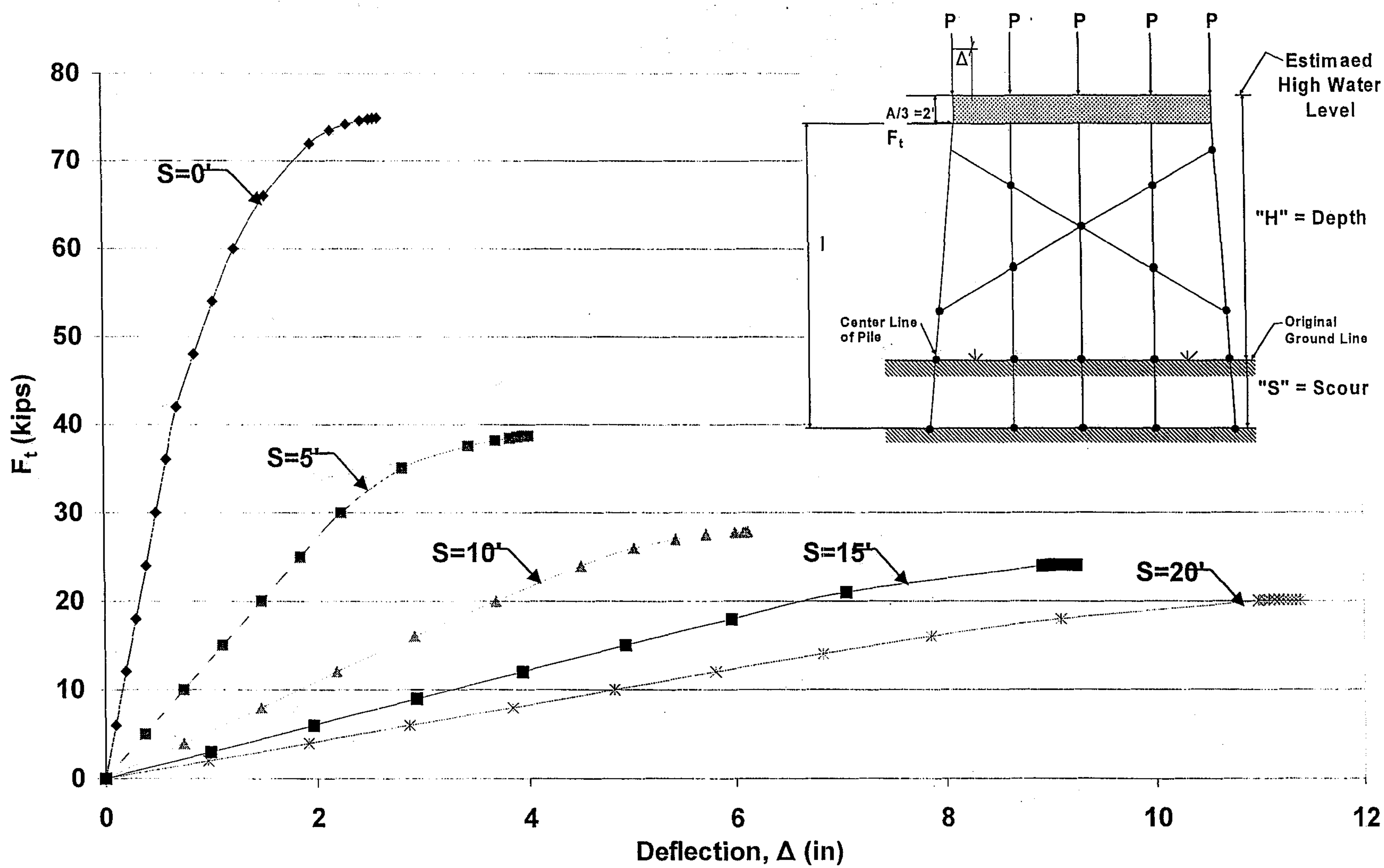


Figure B.64 HP12x53 X-Braced 5-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

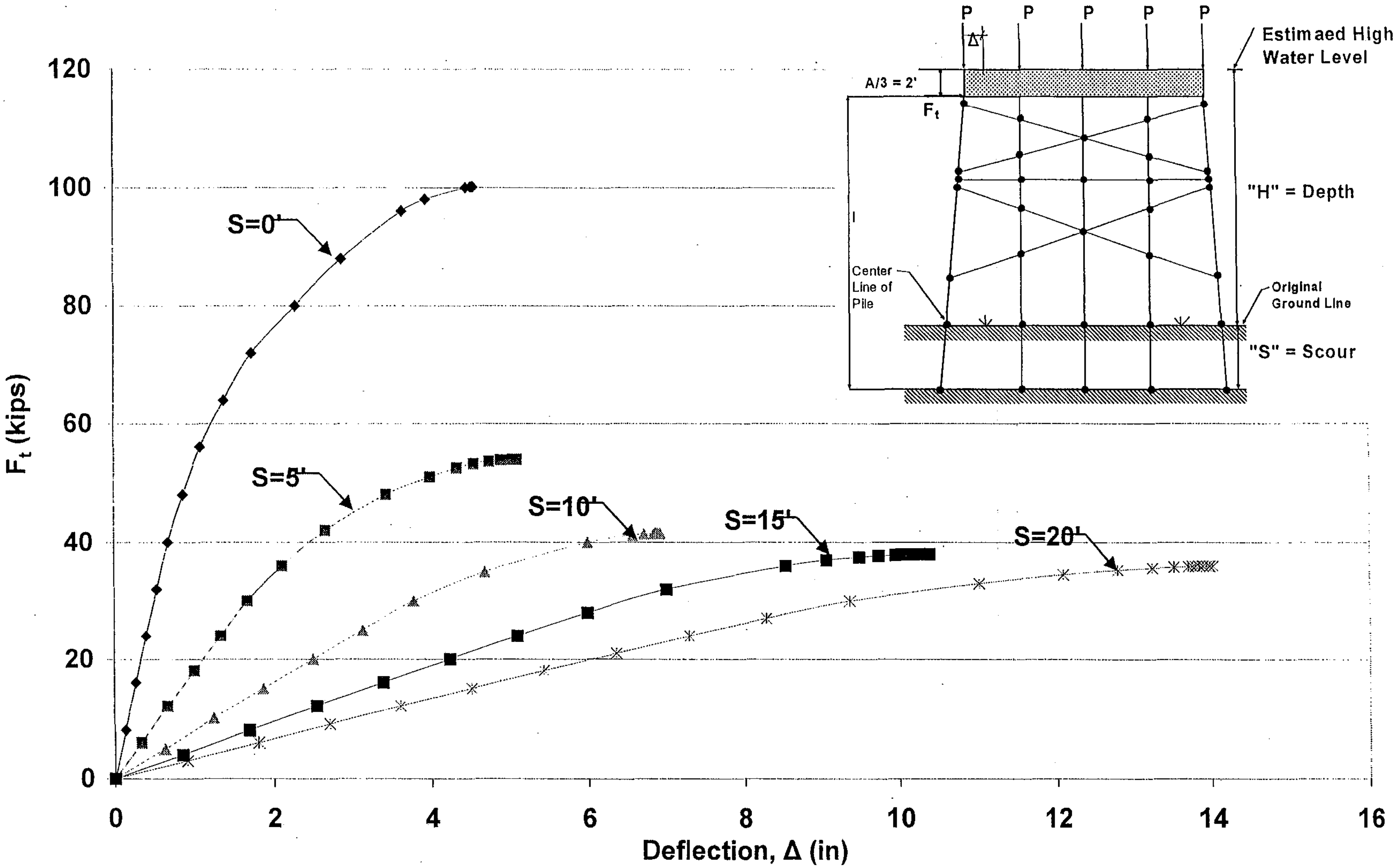


Figure B.65 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

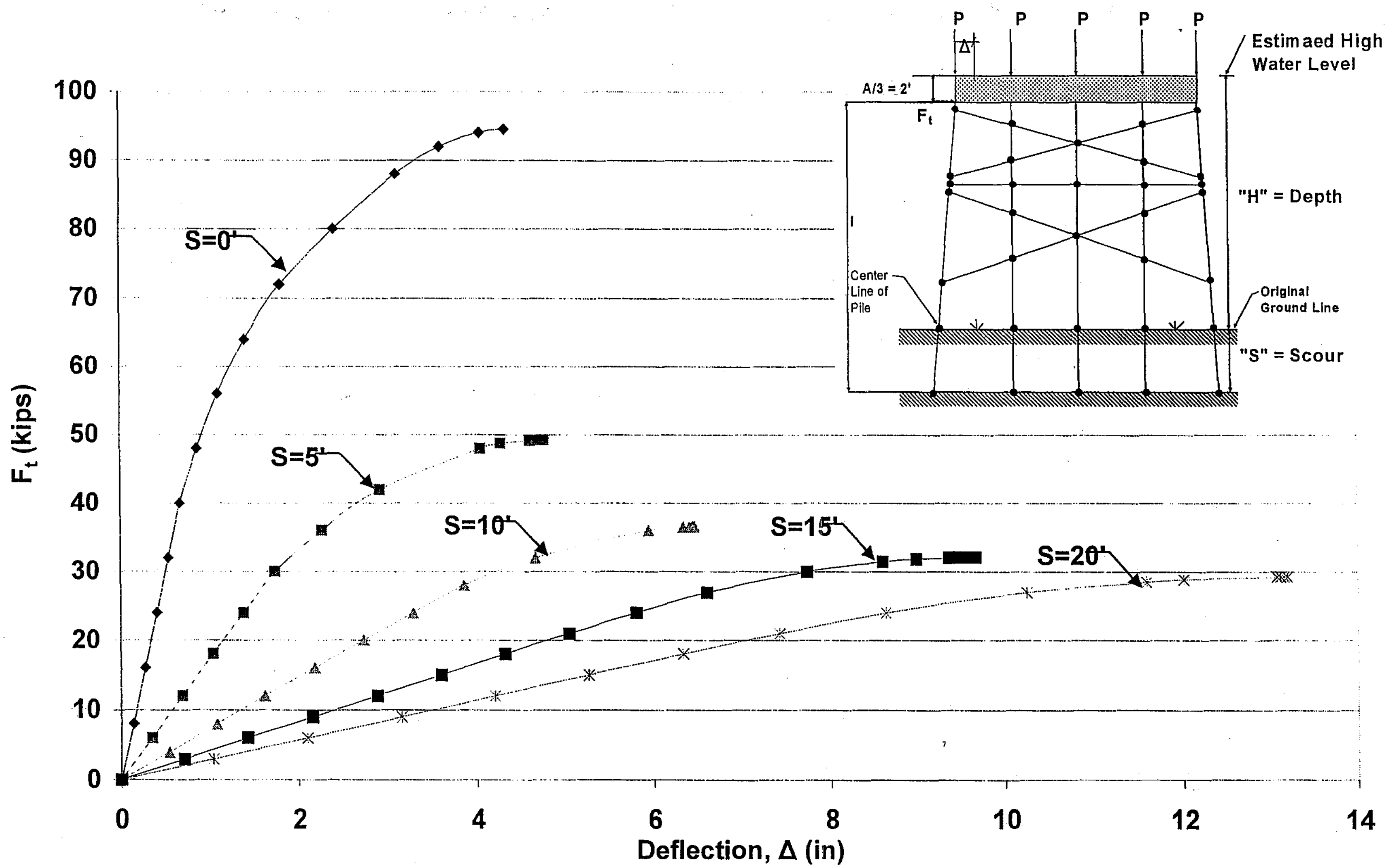


Figure B.66 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

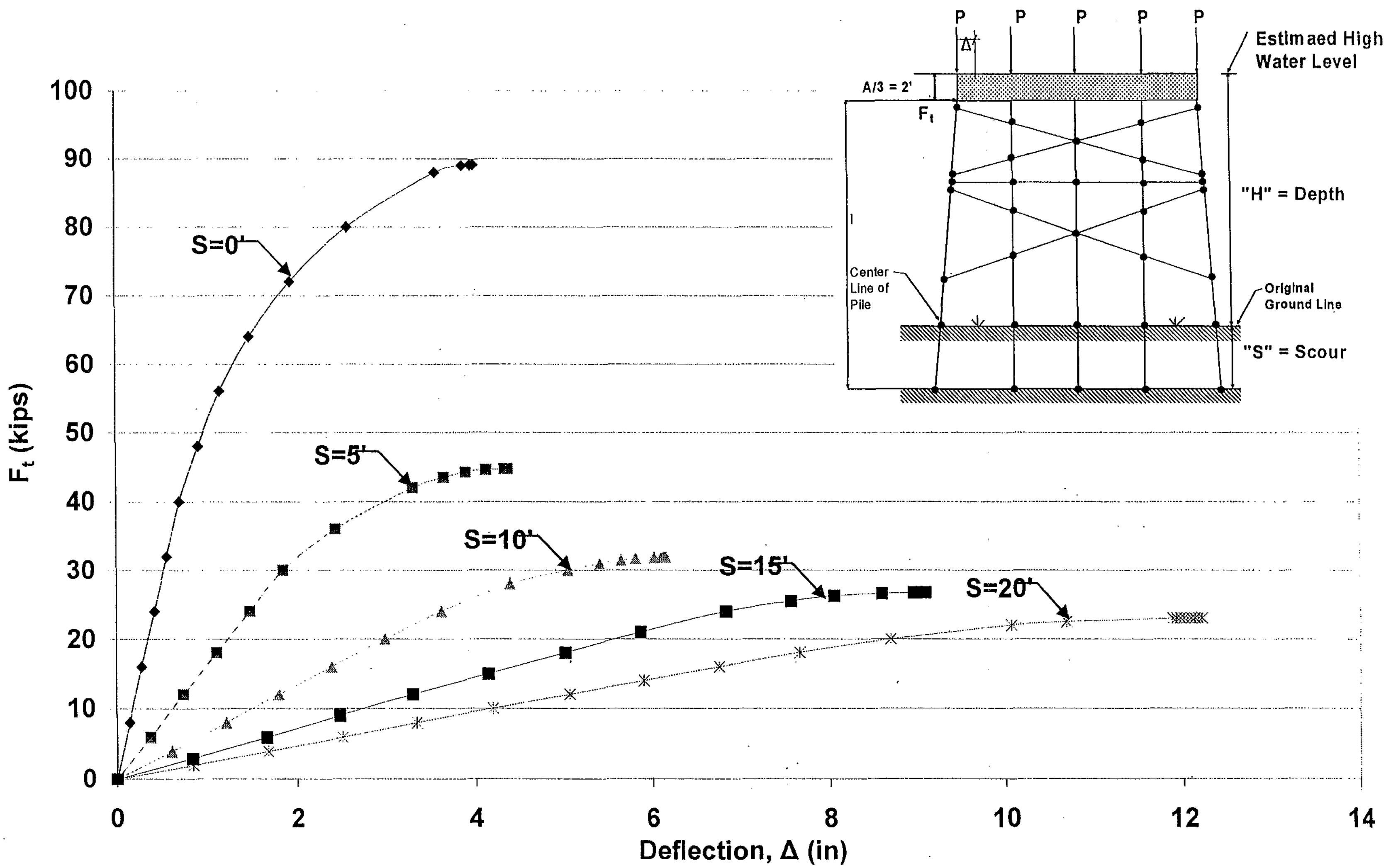


Figure B.67 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

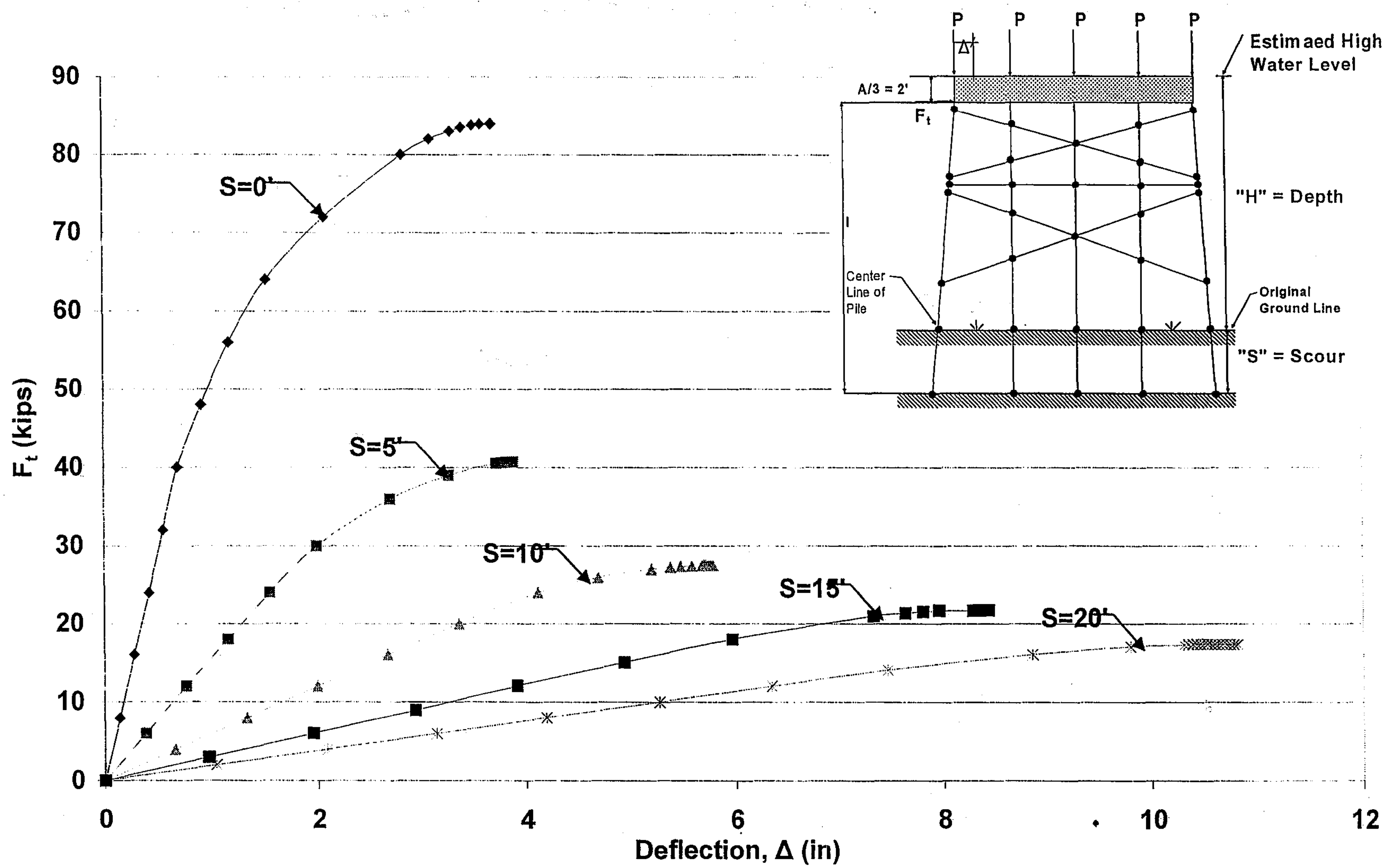


Figure B.68 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

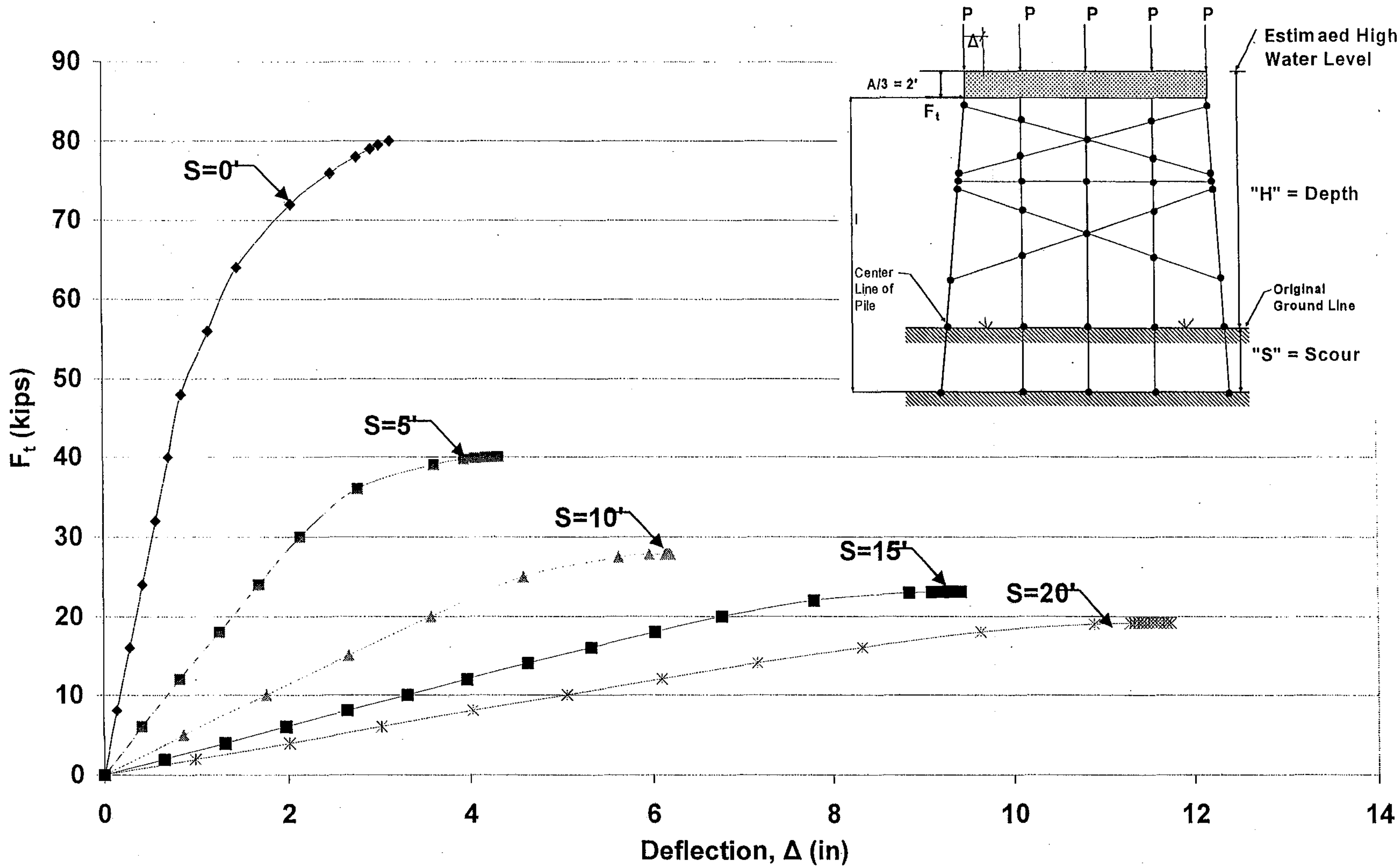


Figure B.71 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

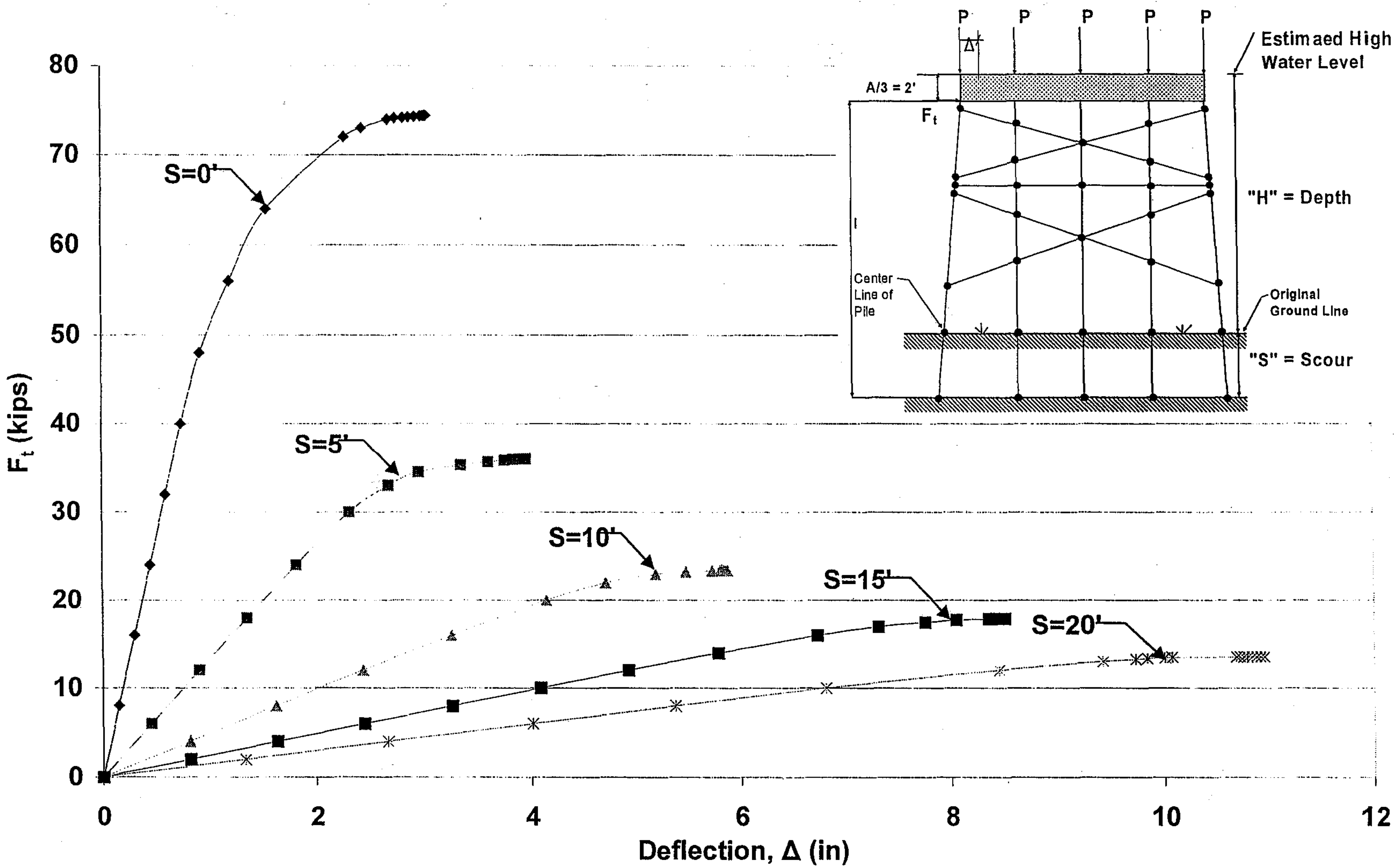


Figure B.72 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

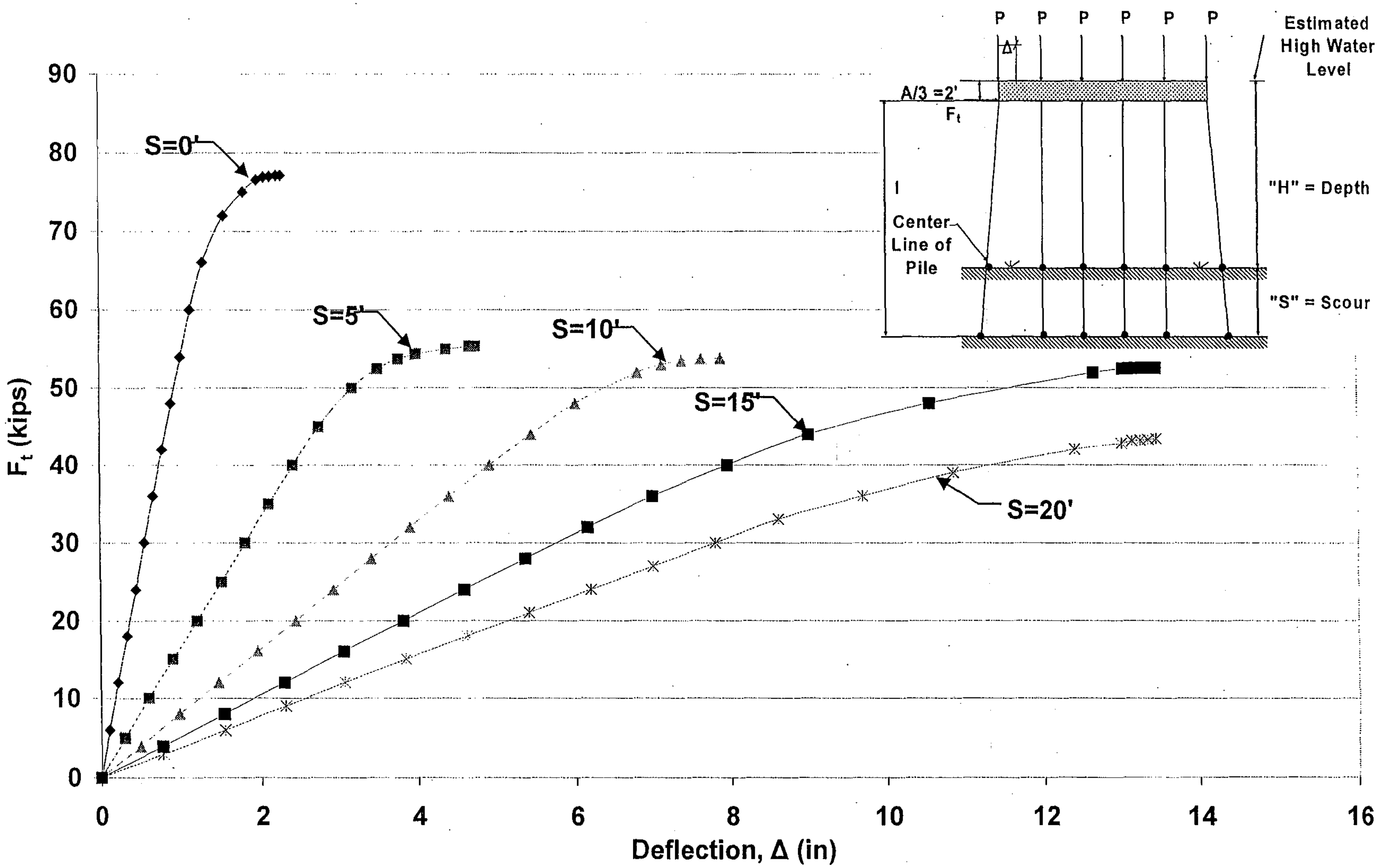


Figure B.73 HP12x53 Unbraced 6-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

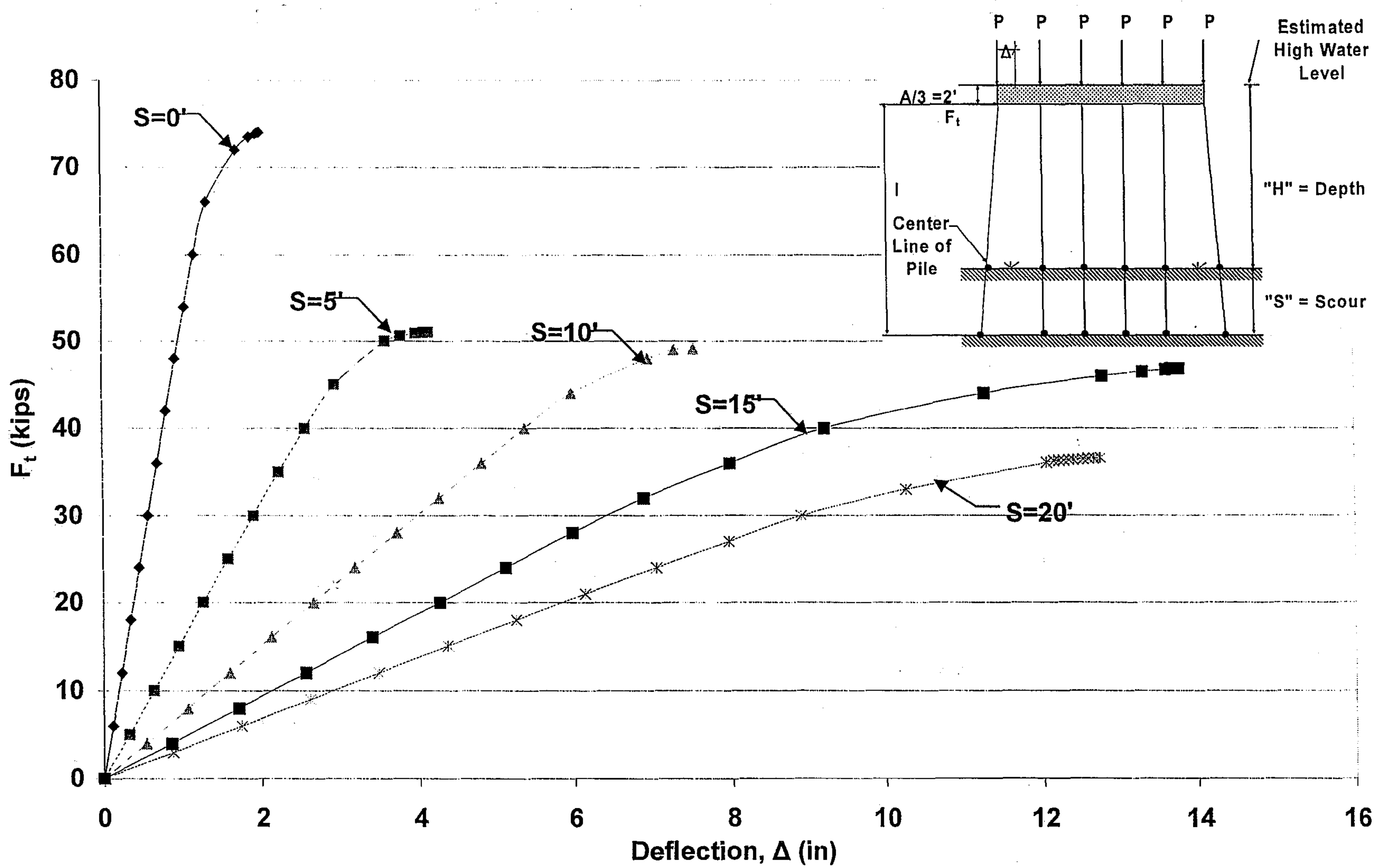


Figure B.74 HP12x53 Unbraced 6-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

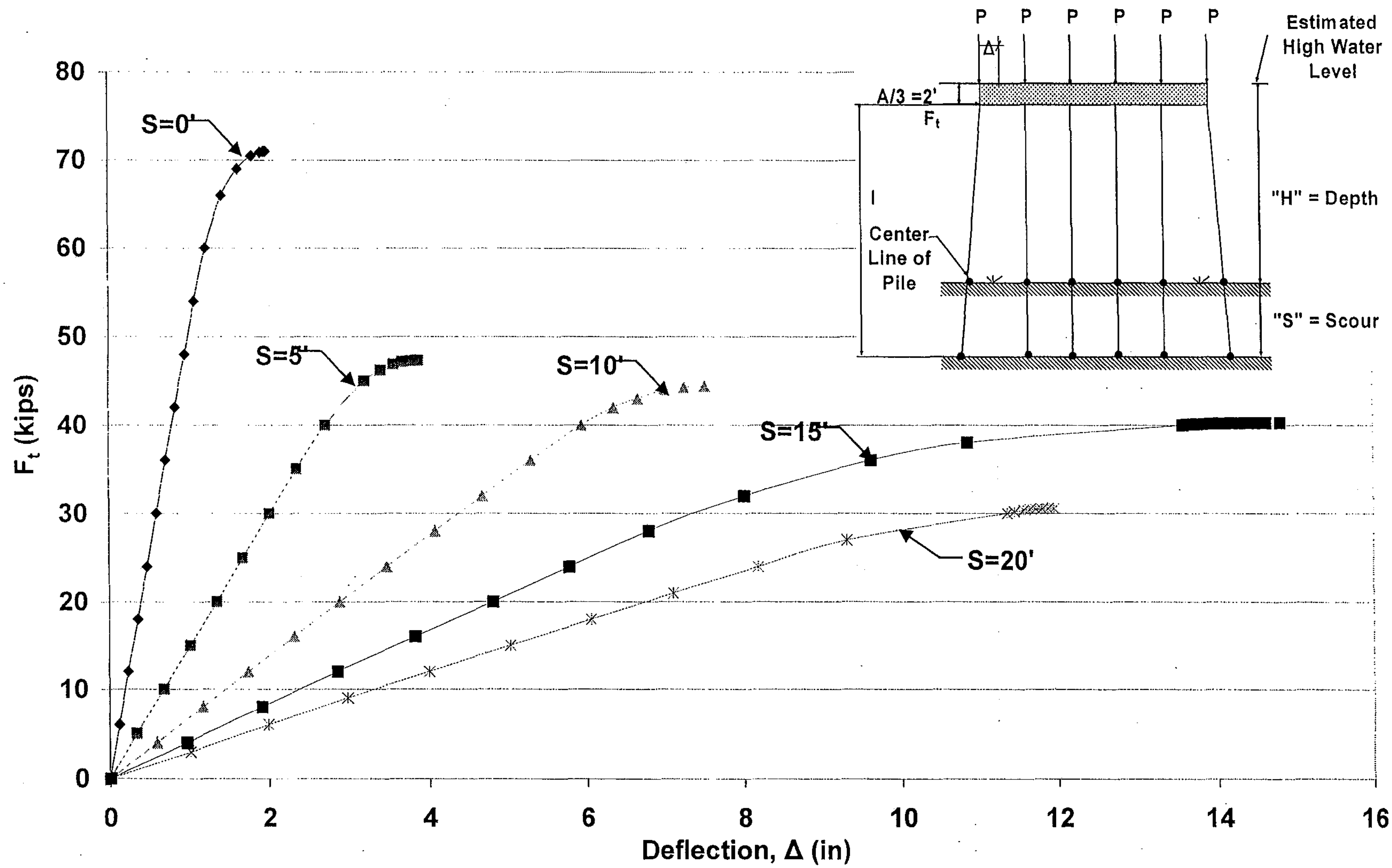


Figure B.75 HP12x53 Unbraced 6-Pile Bent with H=10', P=140kips and A=6' Pushover Analysis Results

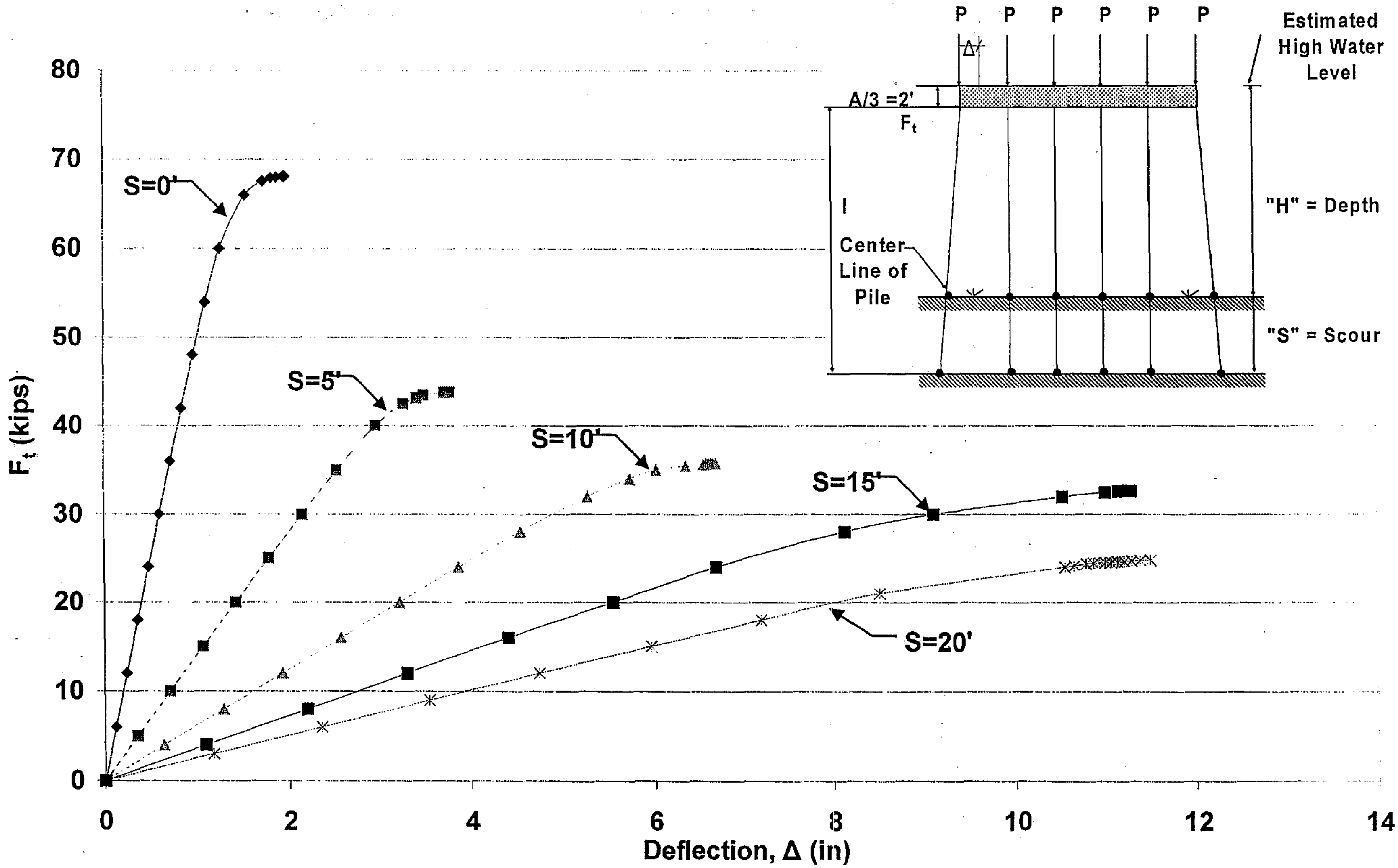


Figure B.76 HP12x53 Unbraced 6-Pile Bent with H=10', P=160kips and A=6'
Pushover Analysis Results

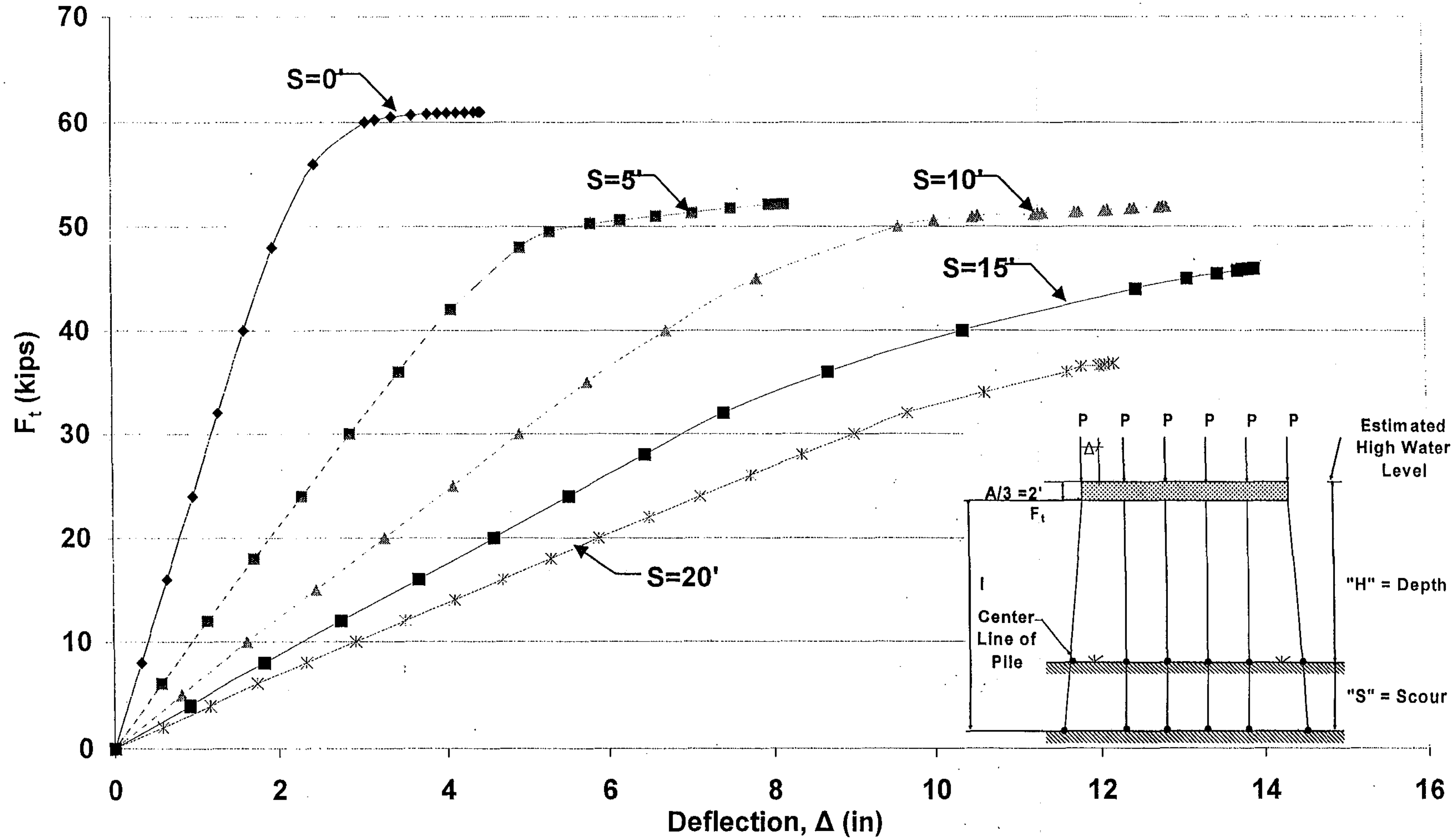


**Figure B.77 HP12x53 Unbraced 6-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results**

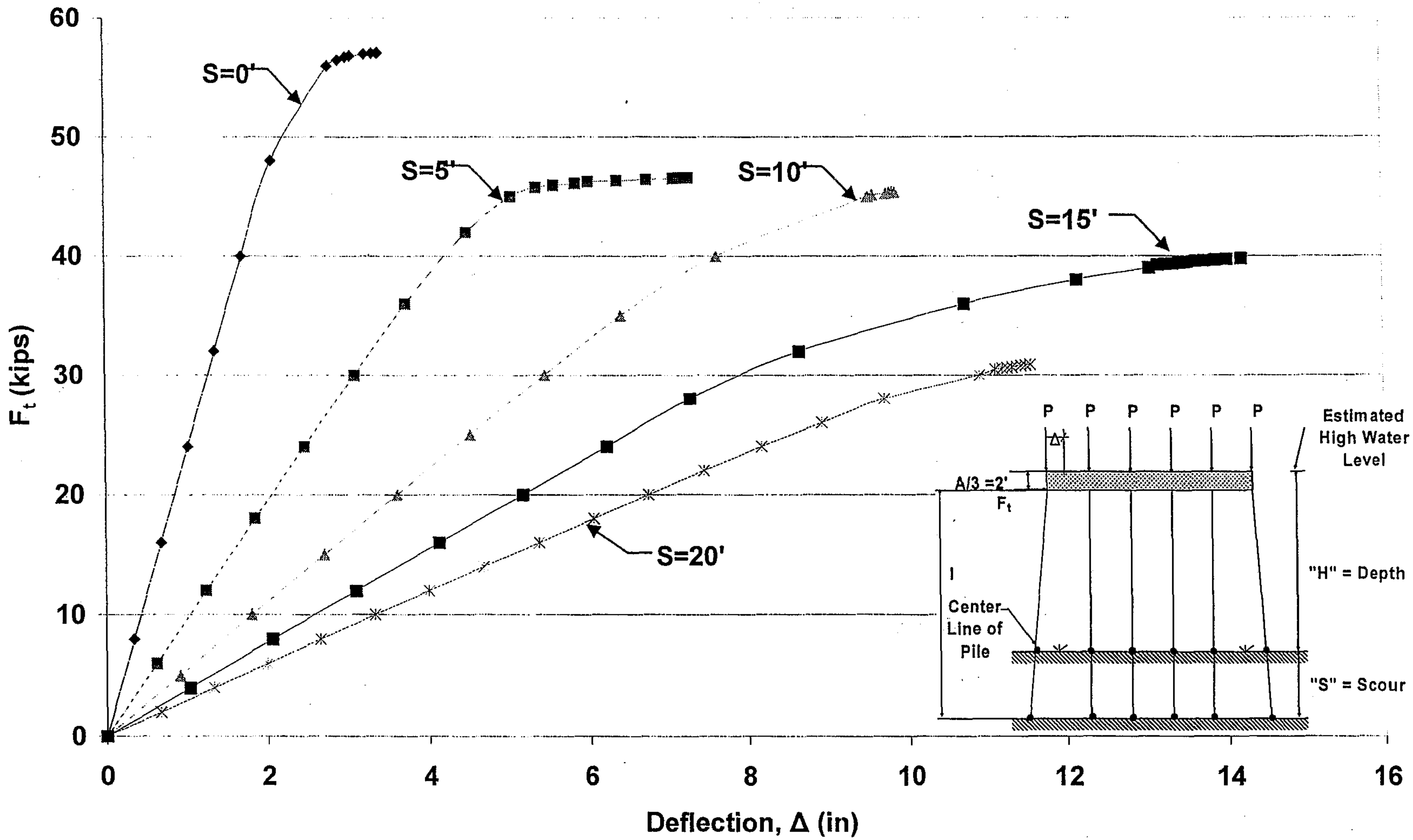


Figure B.78 HP12x53 Unbraced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

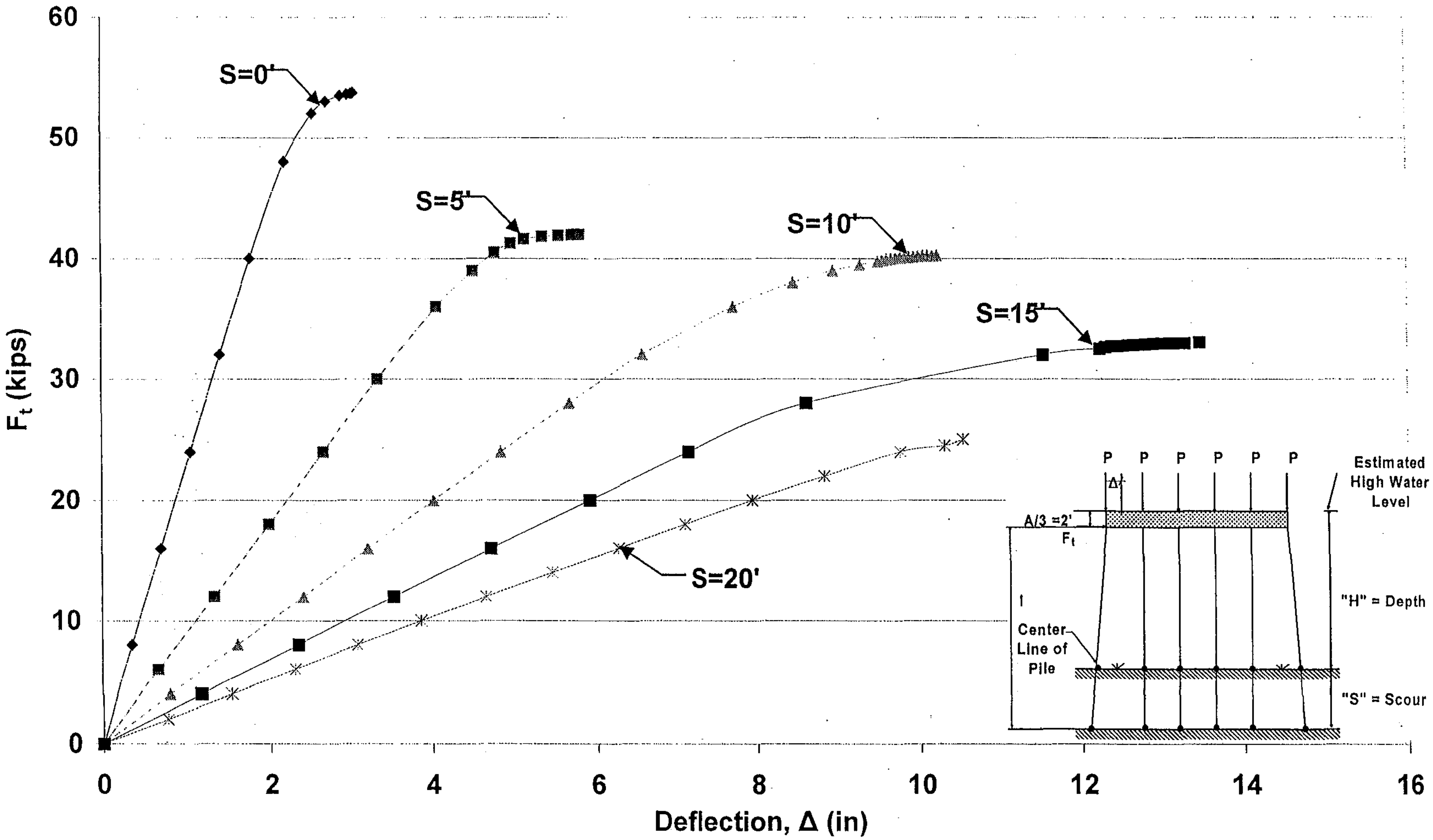


Figure B.79 HP12x53 Unbraced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

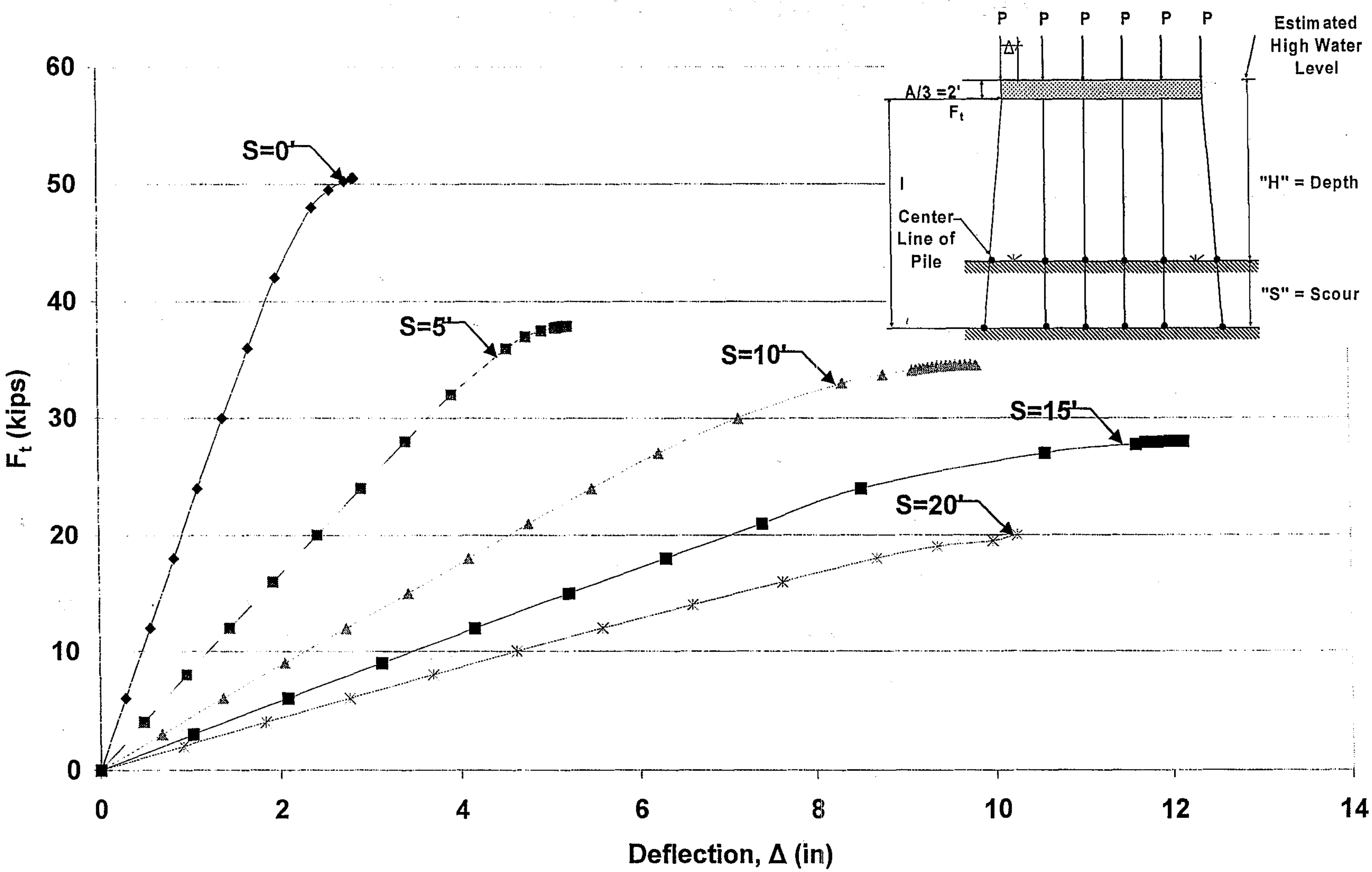


Figure B.80 HP12x53 Unbraced 6-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

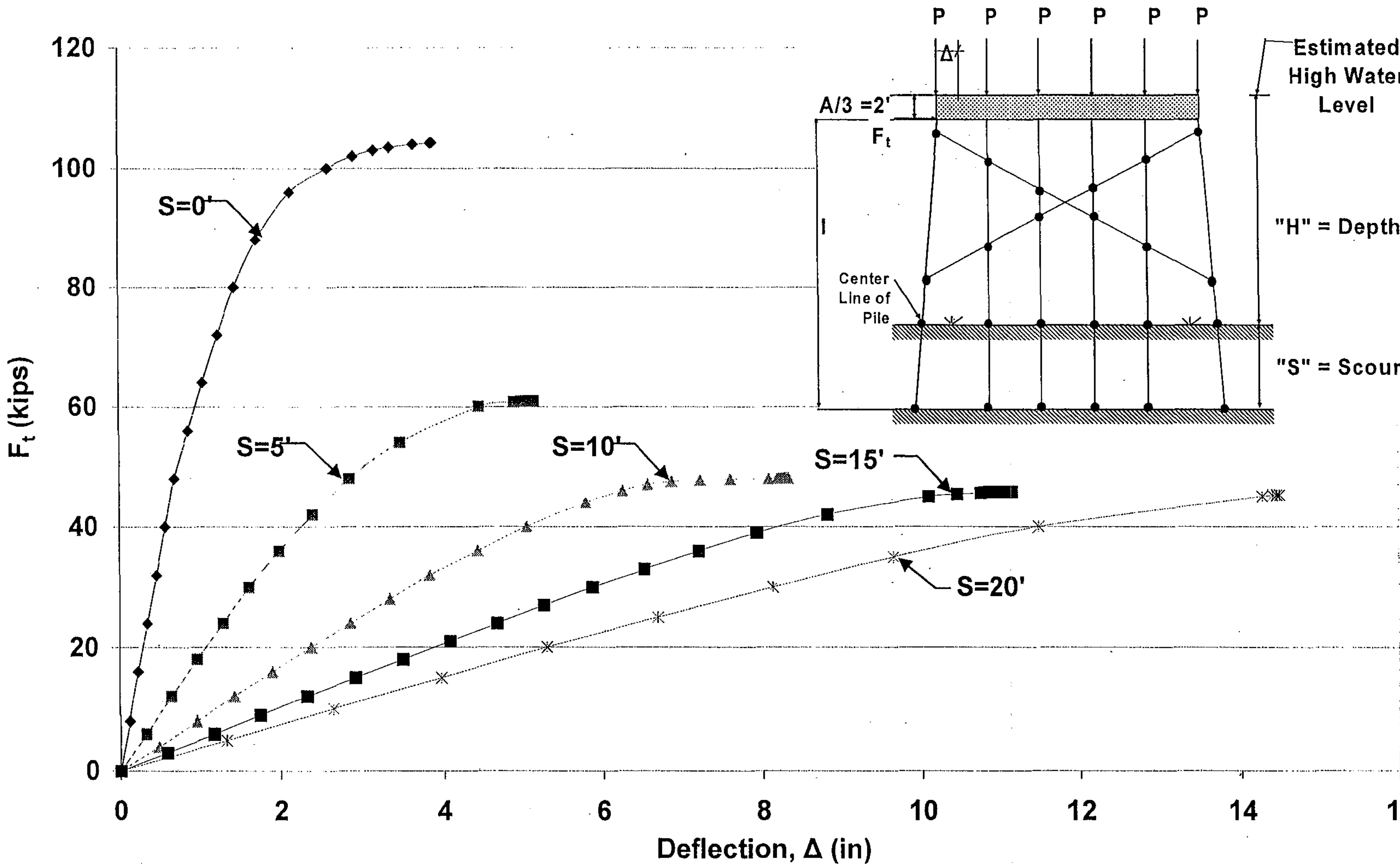


Figure B.81 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

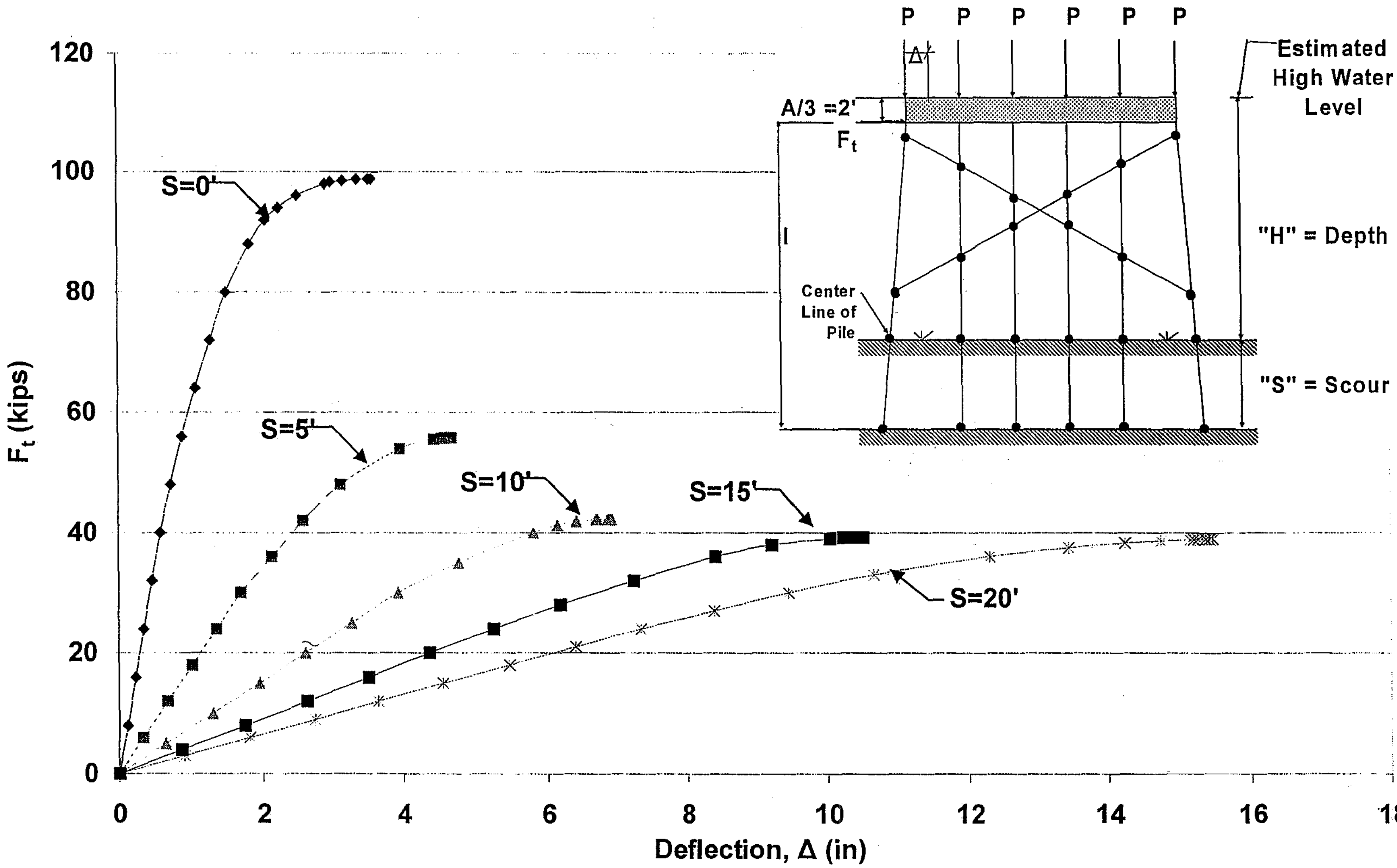


Figure B.82 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

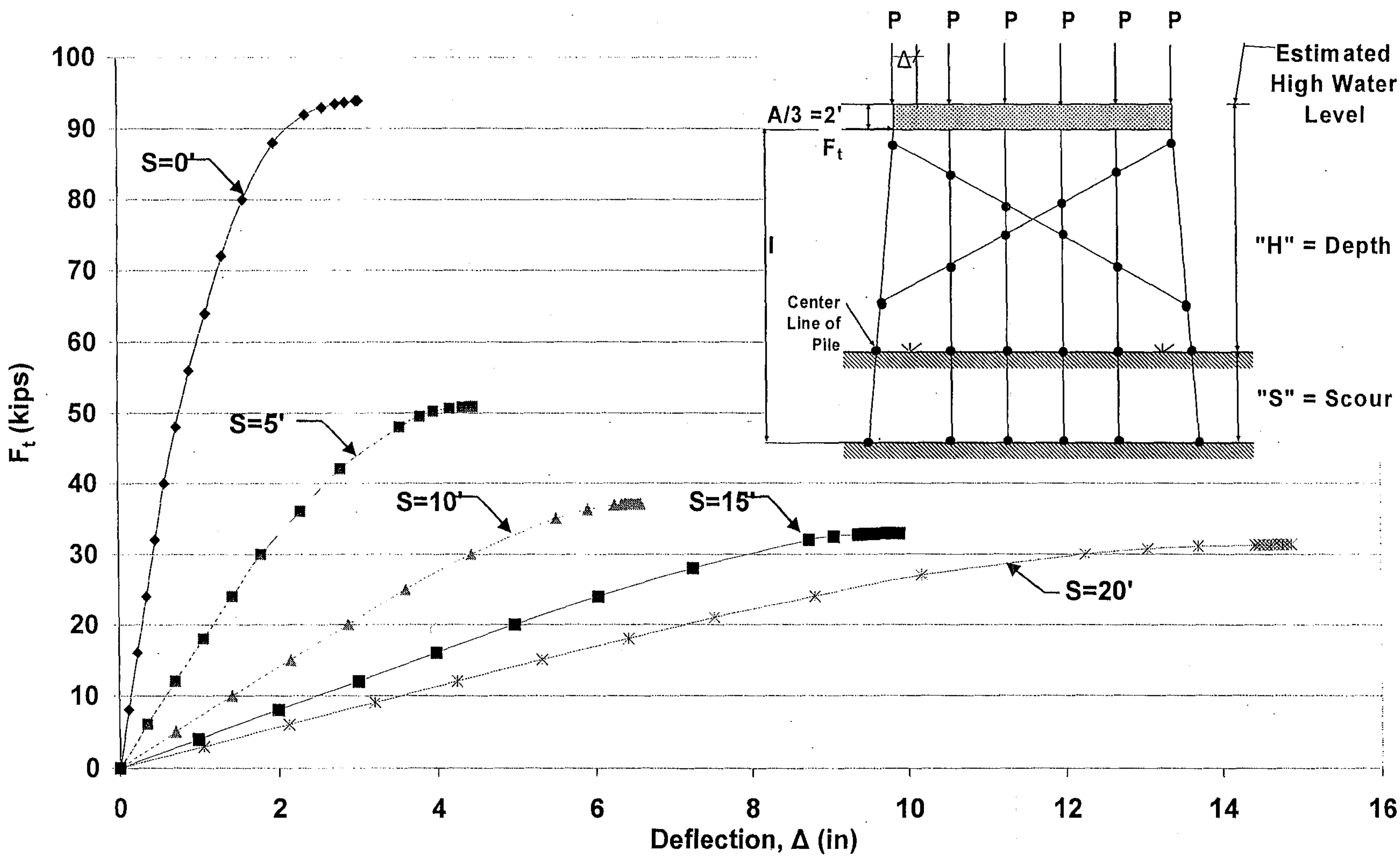


Figure B.83 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

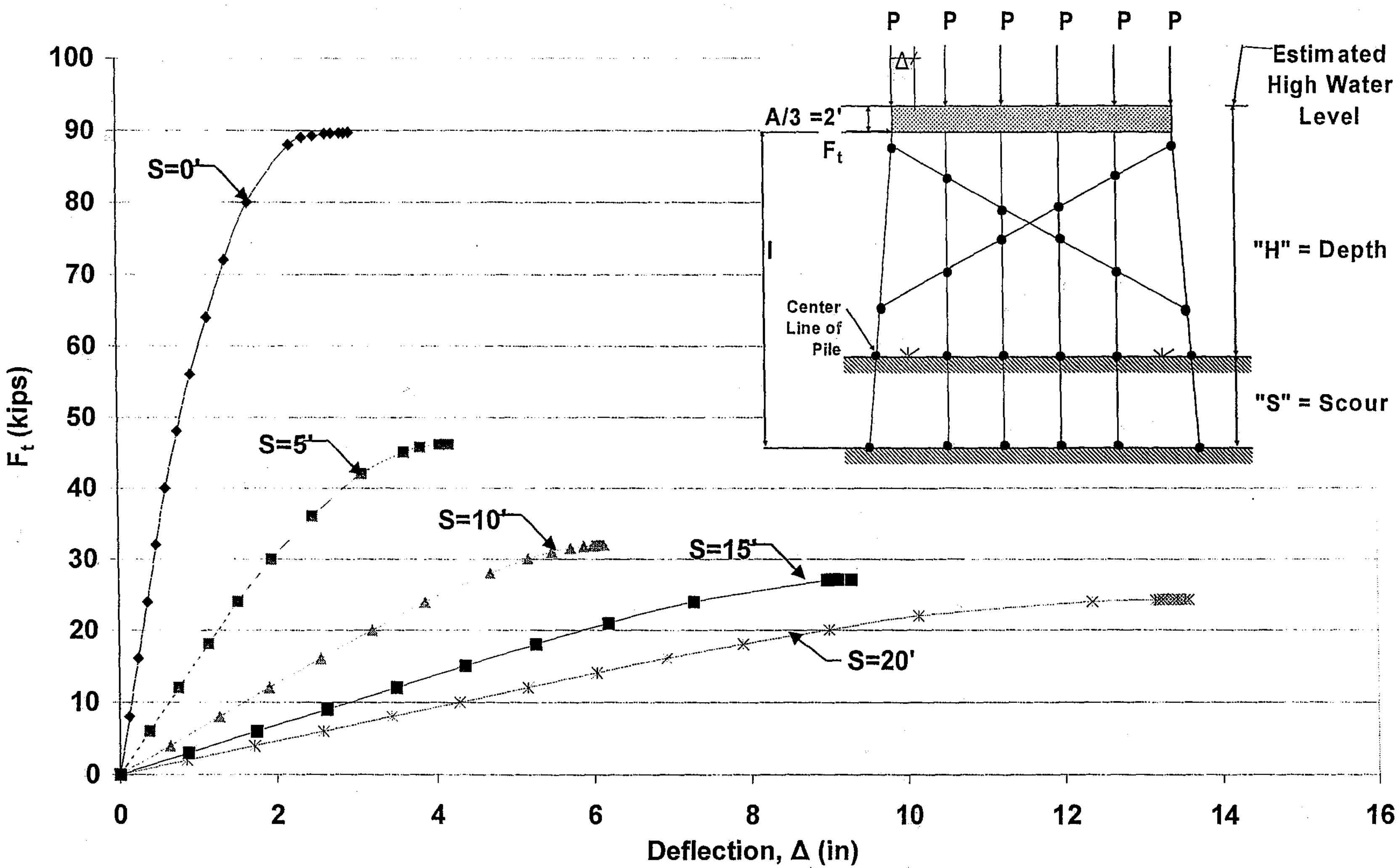


Figure B.84 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

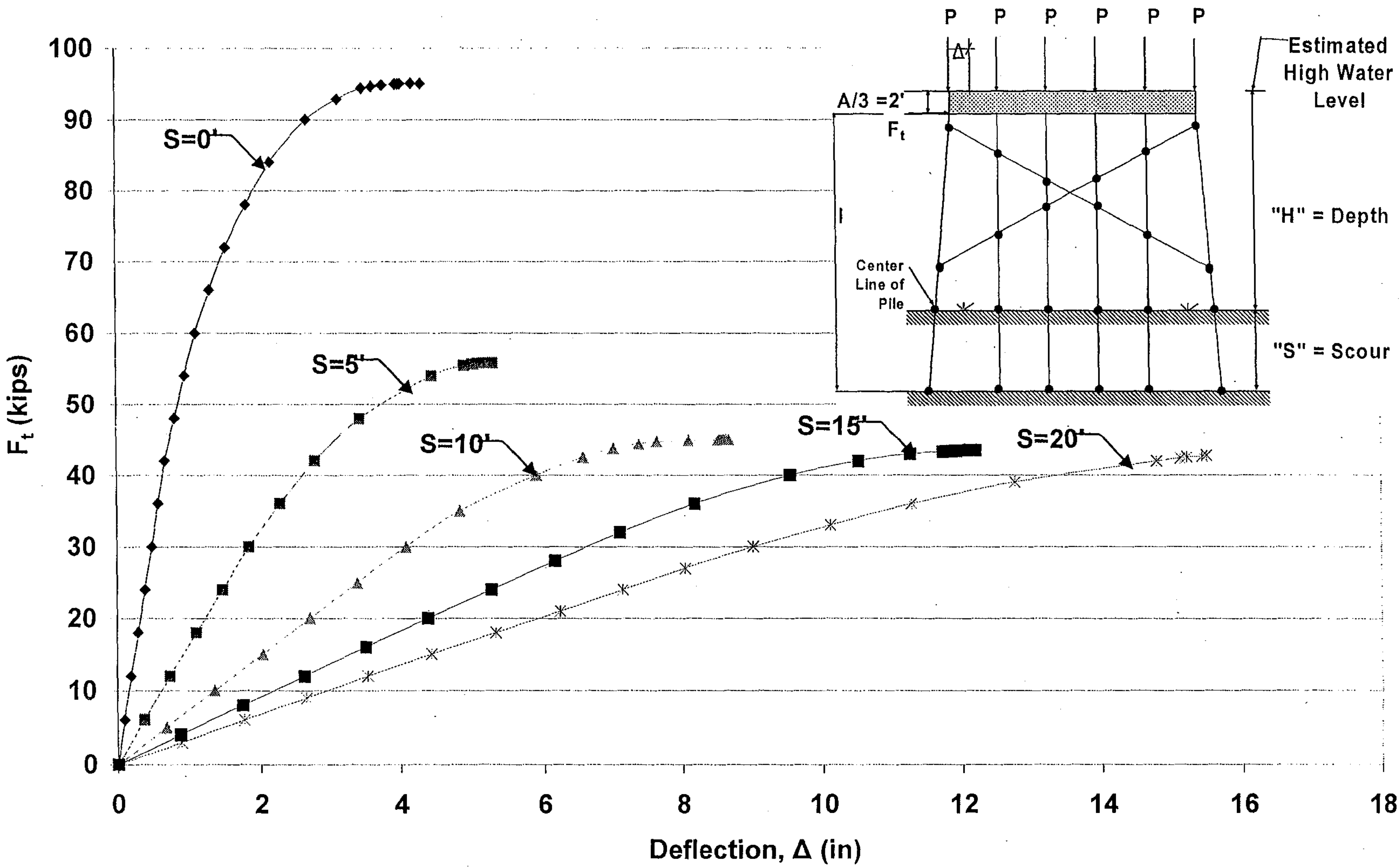


Figure B.85 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

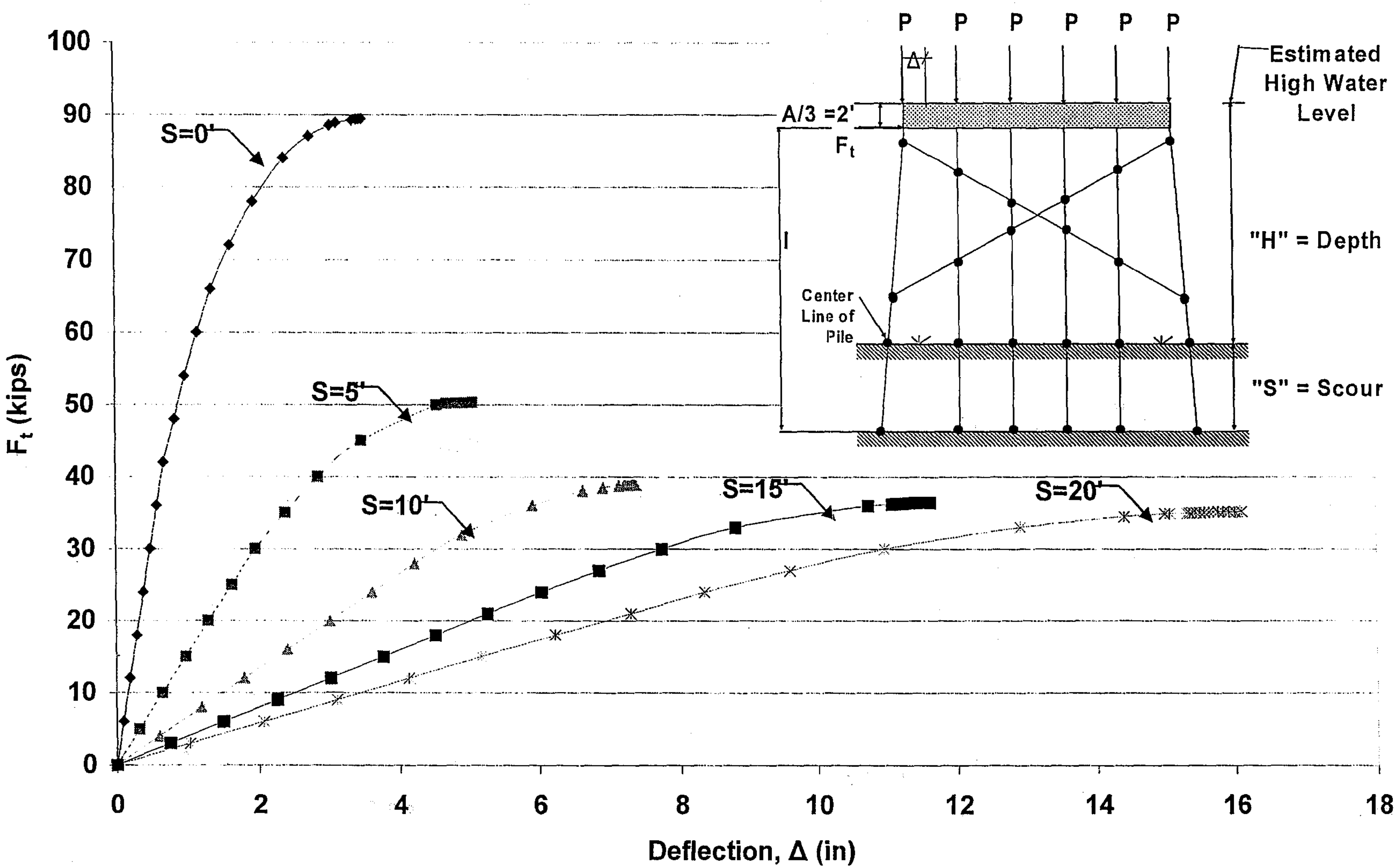


Figure B.86 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

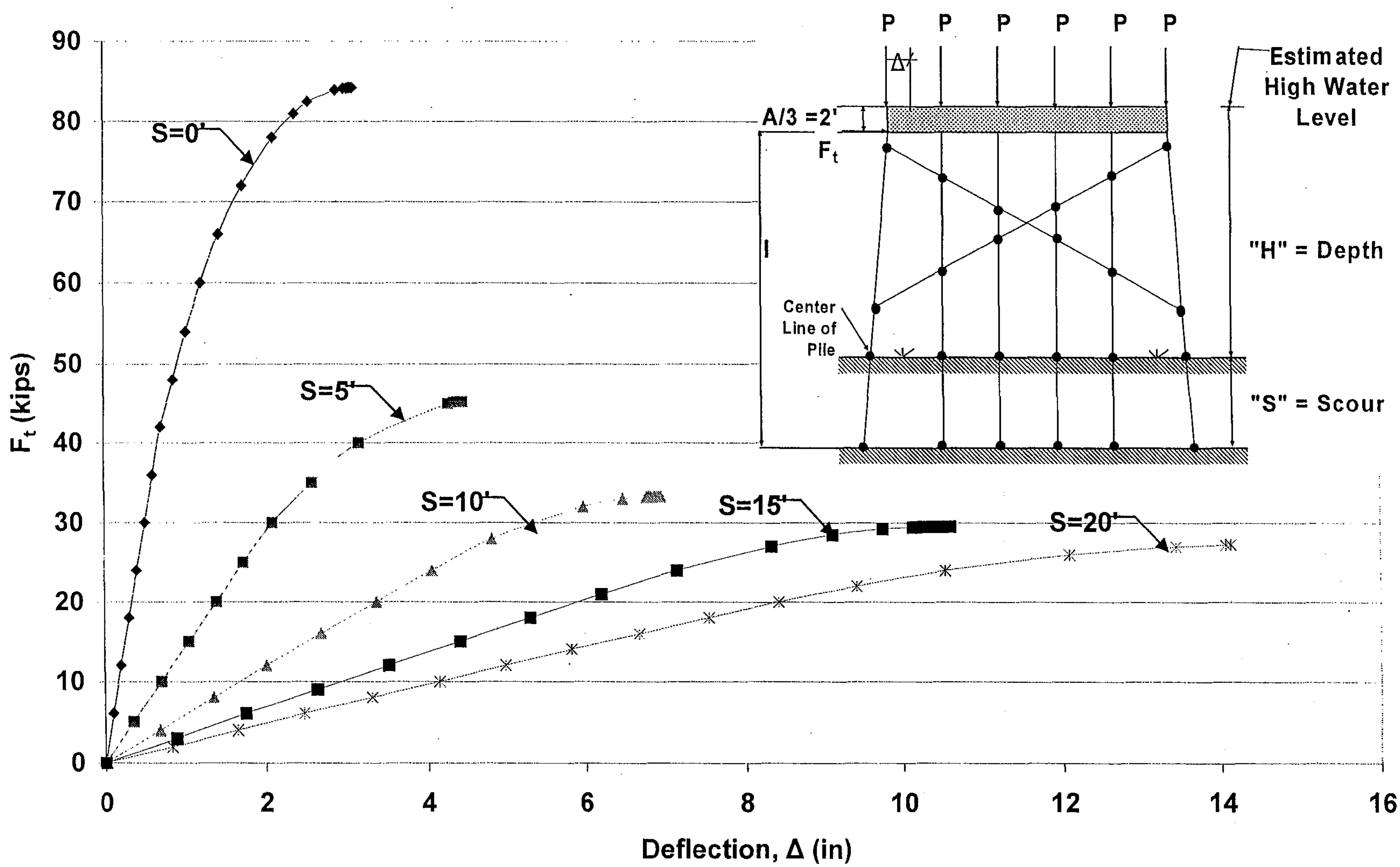


Figure B.87 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

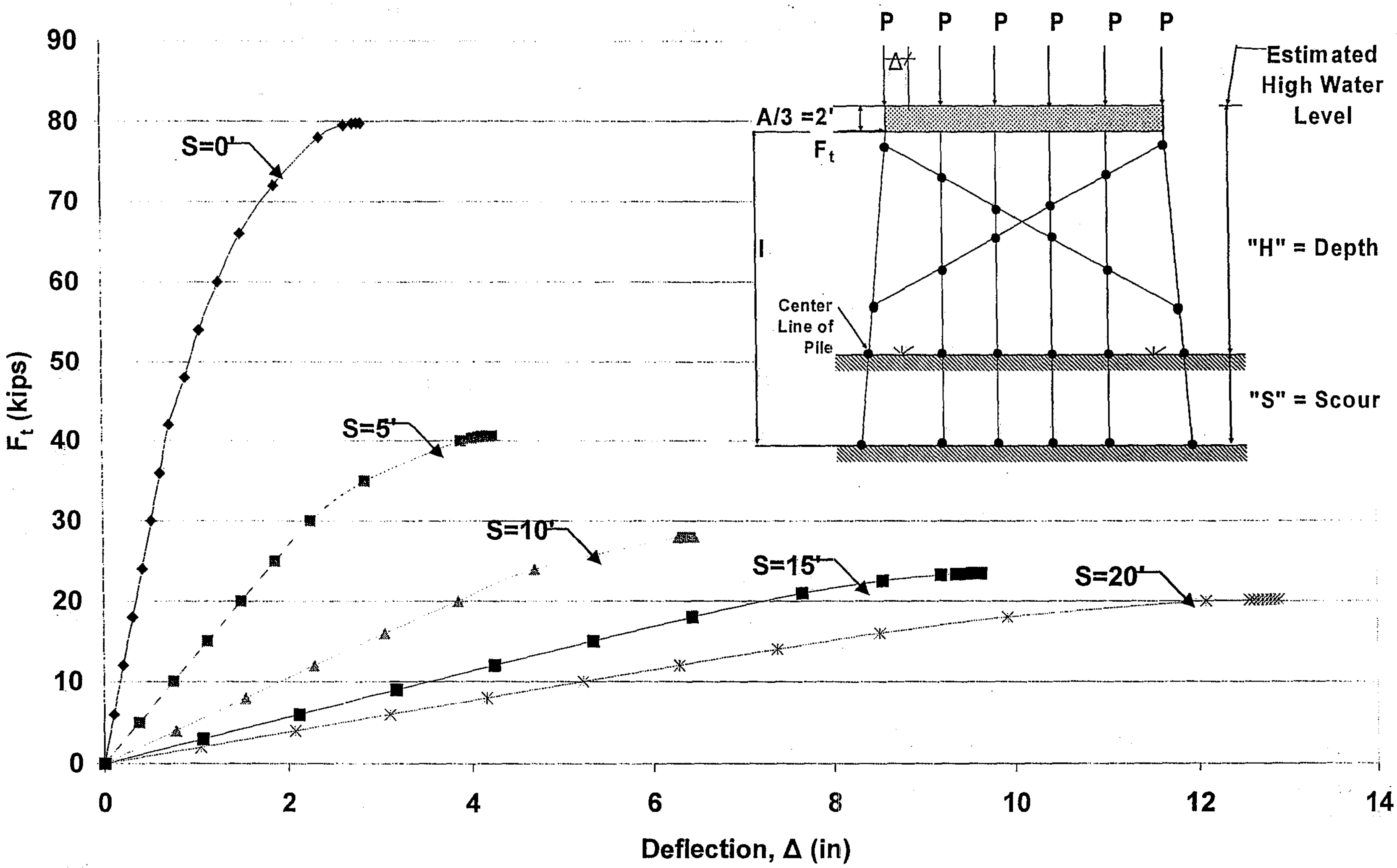


Figure B.88 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

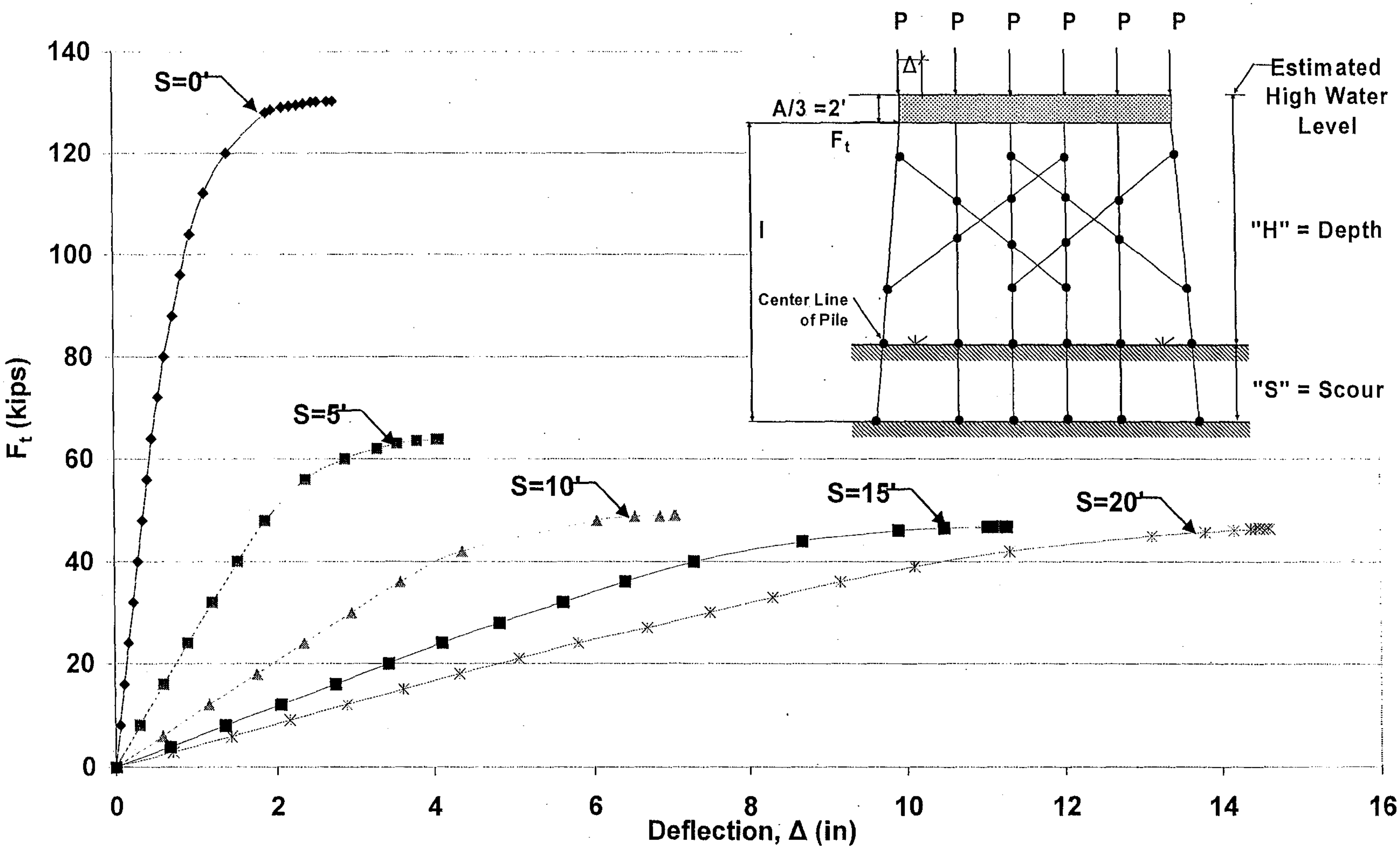


Figure B.89 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

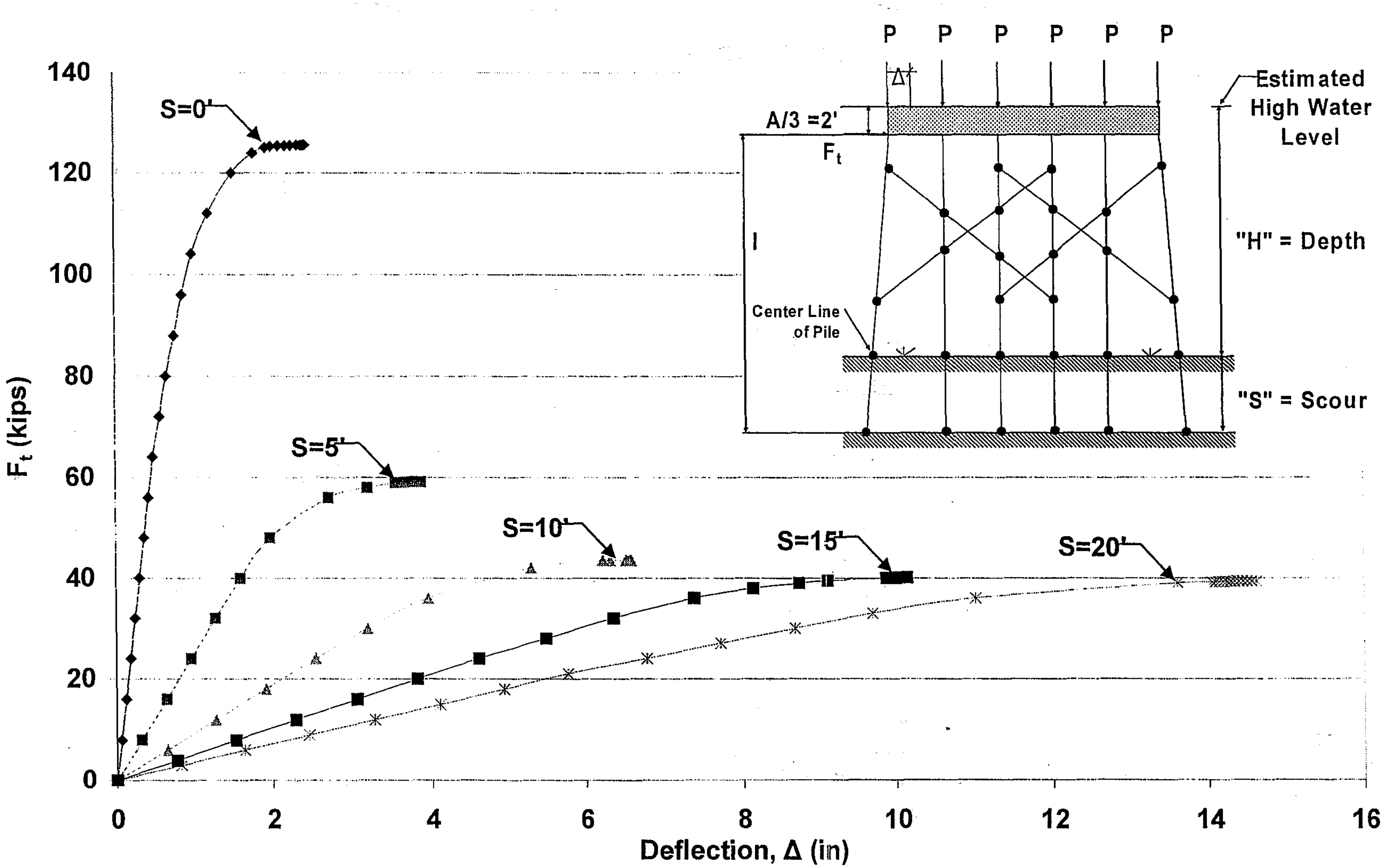


Figure B.90 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

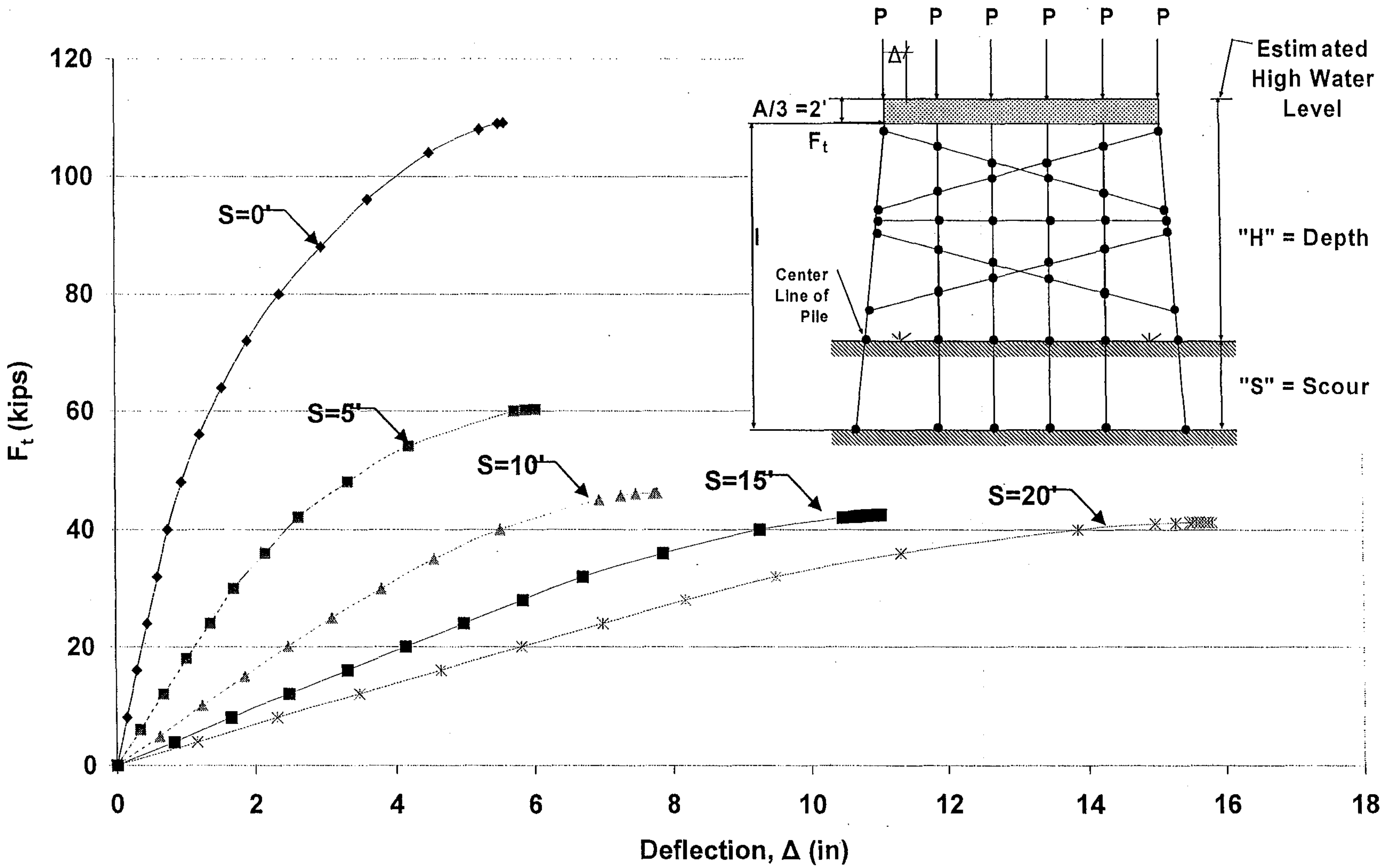


Figure B.97 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

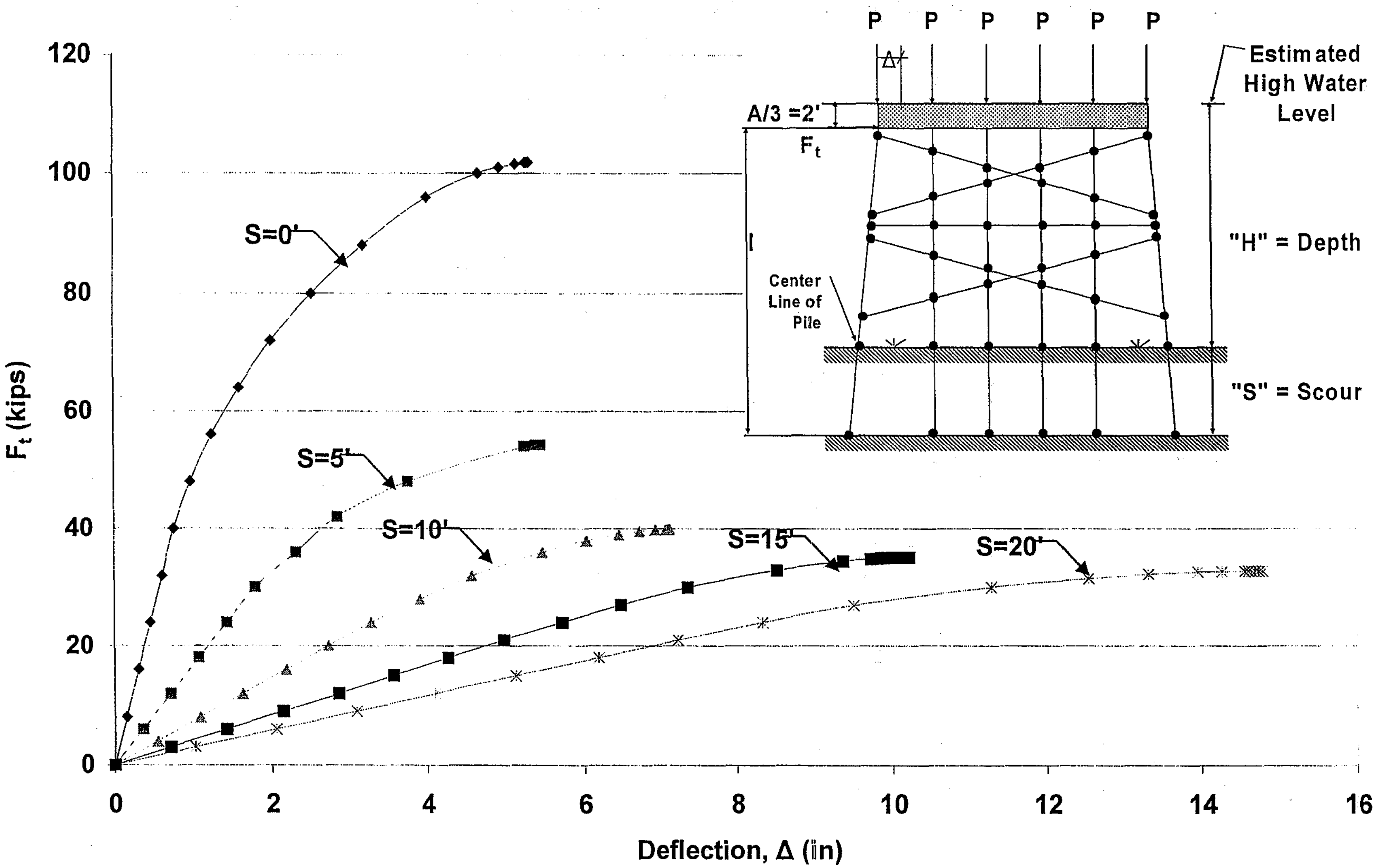


Figure B.98 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

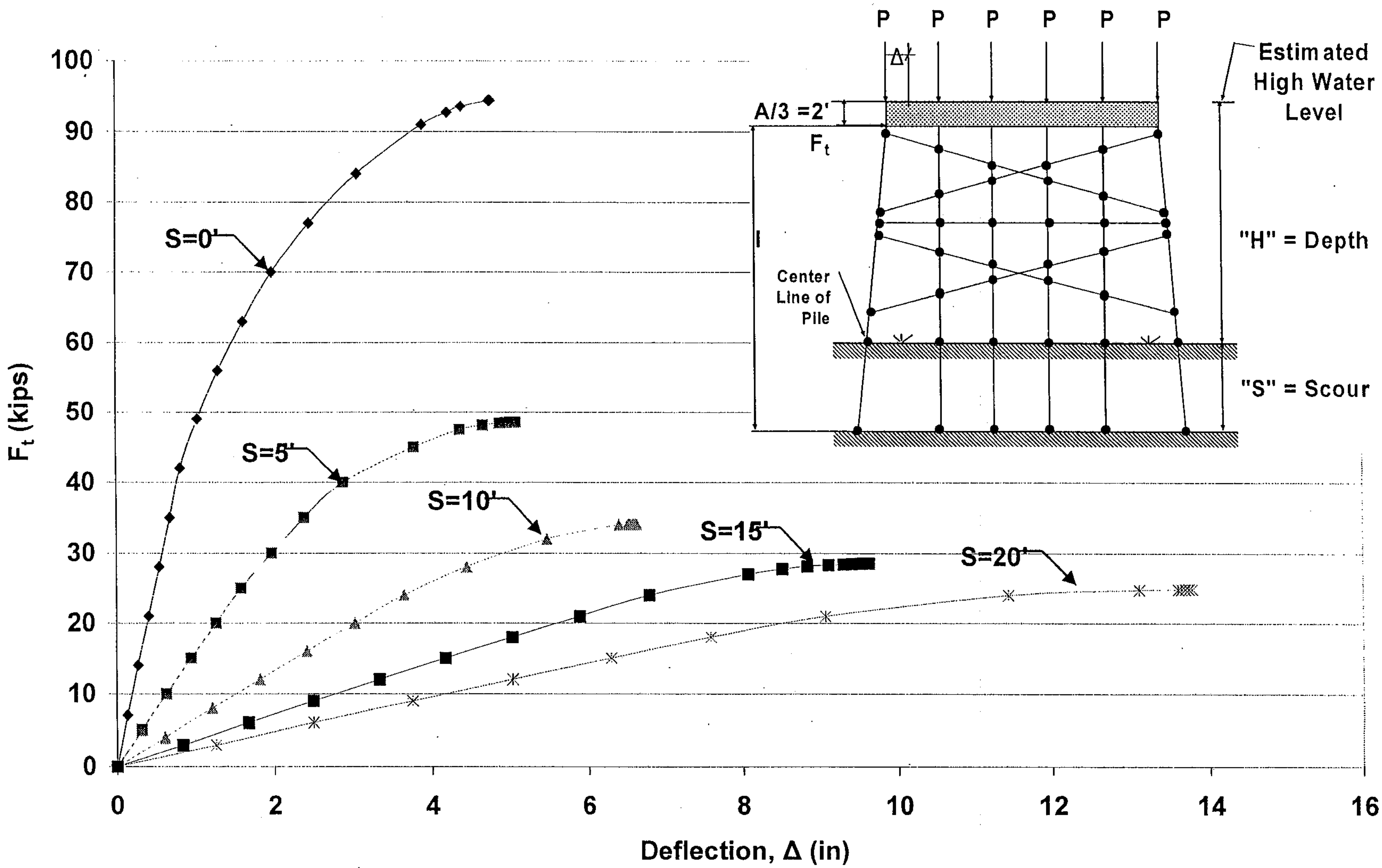


Figure B.99 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

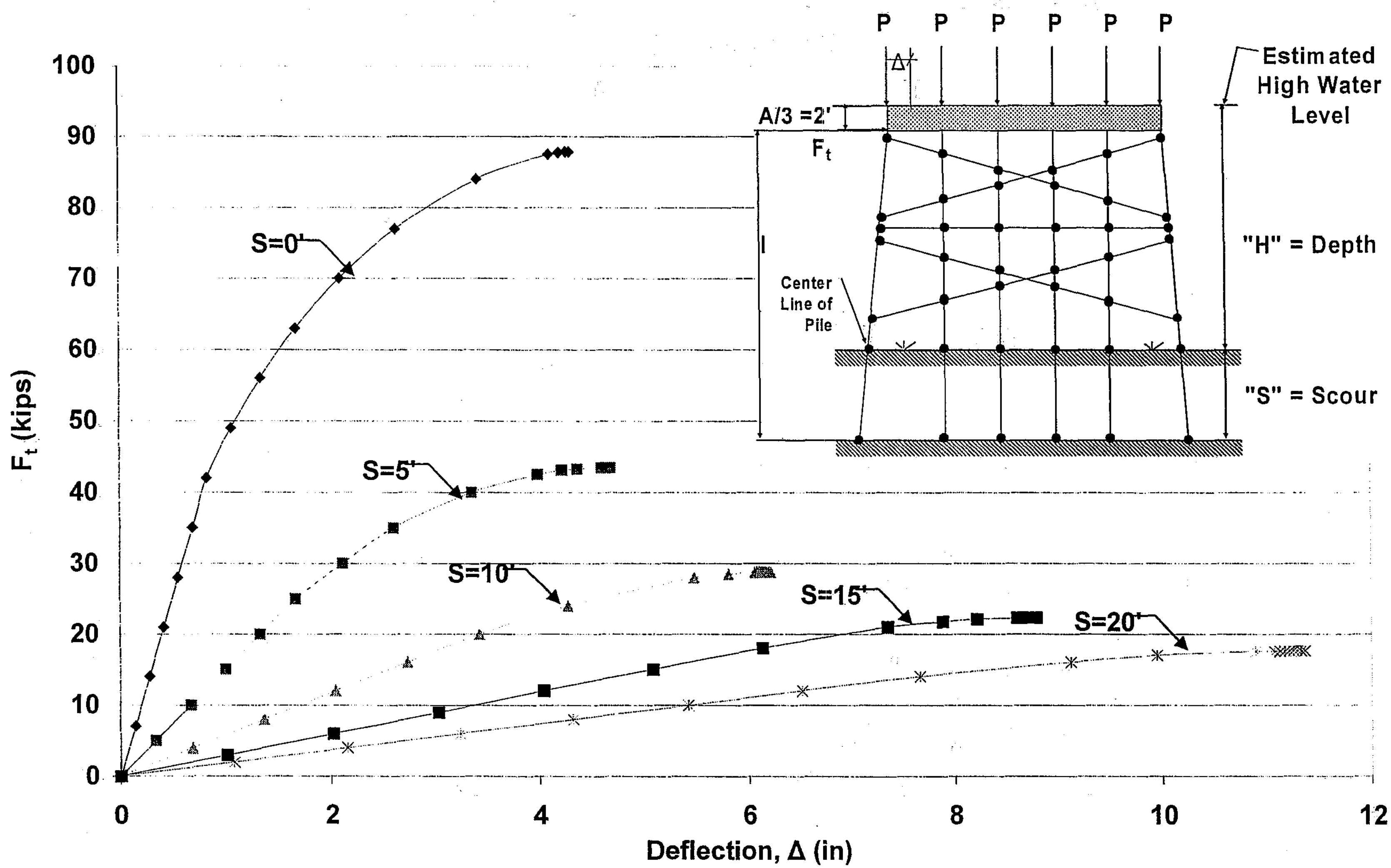


Figure B.100 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

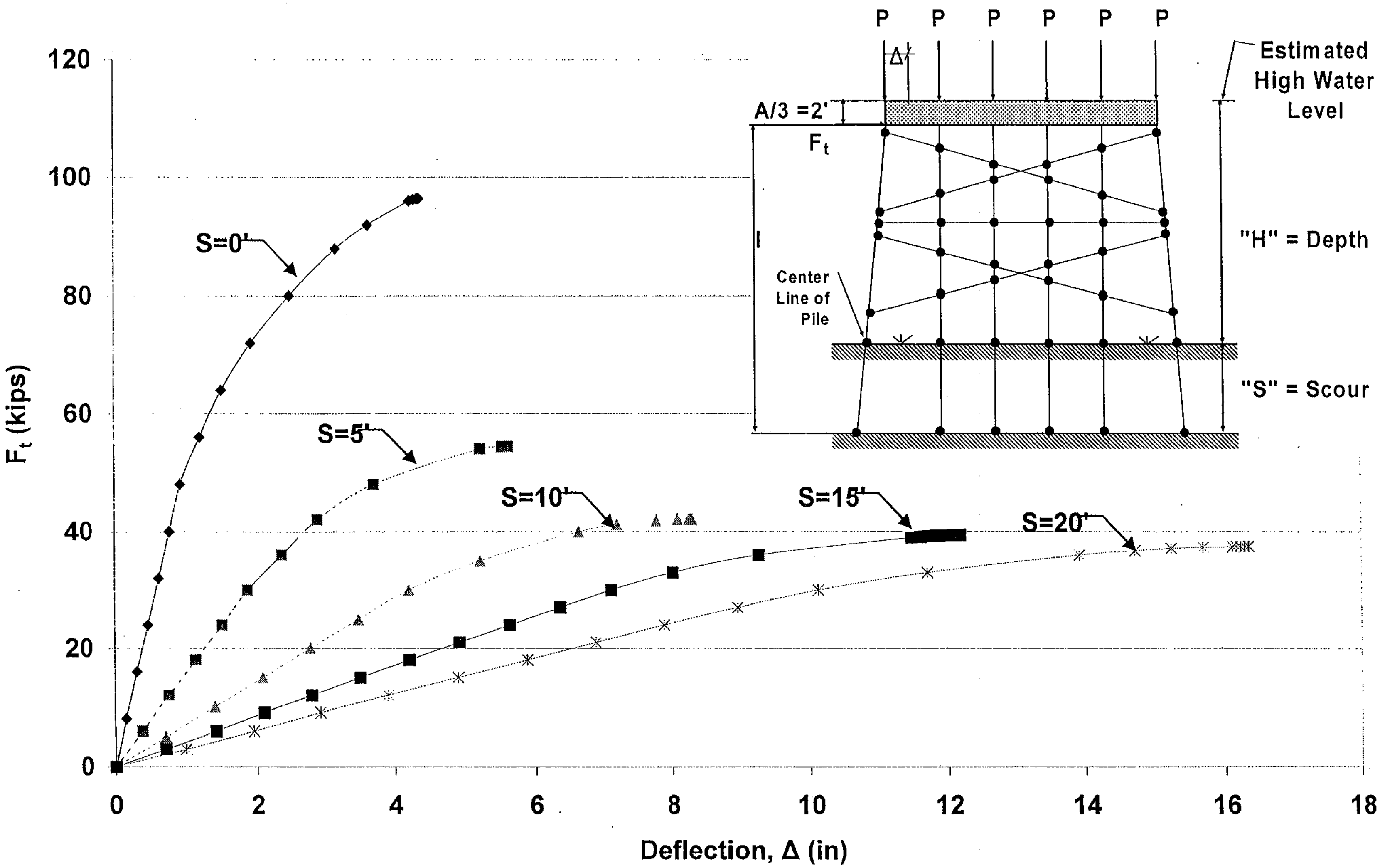


Figure B.101 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

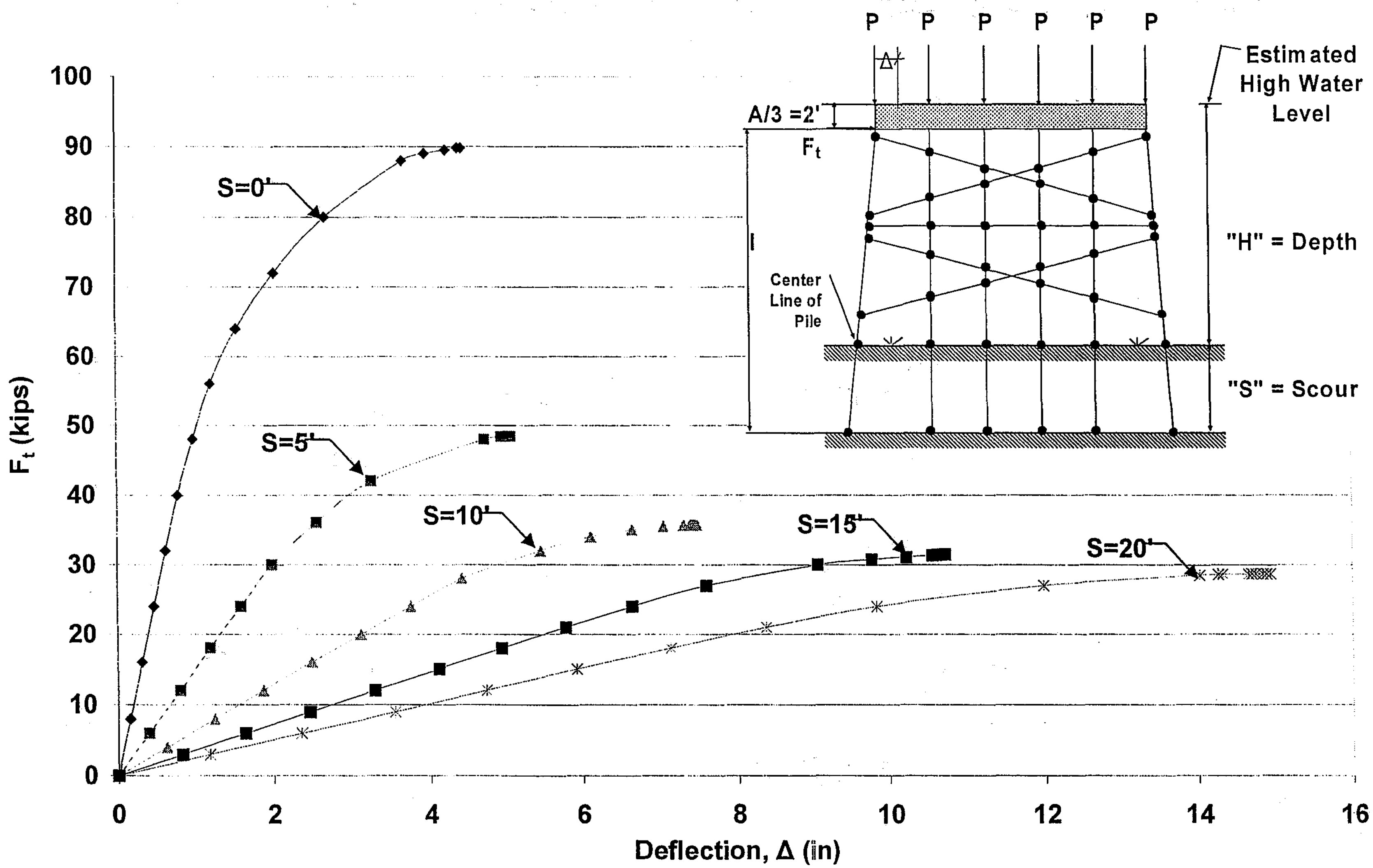


Figure B.102 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

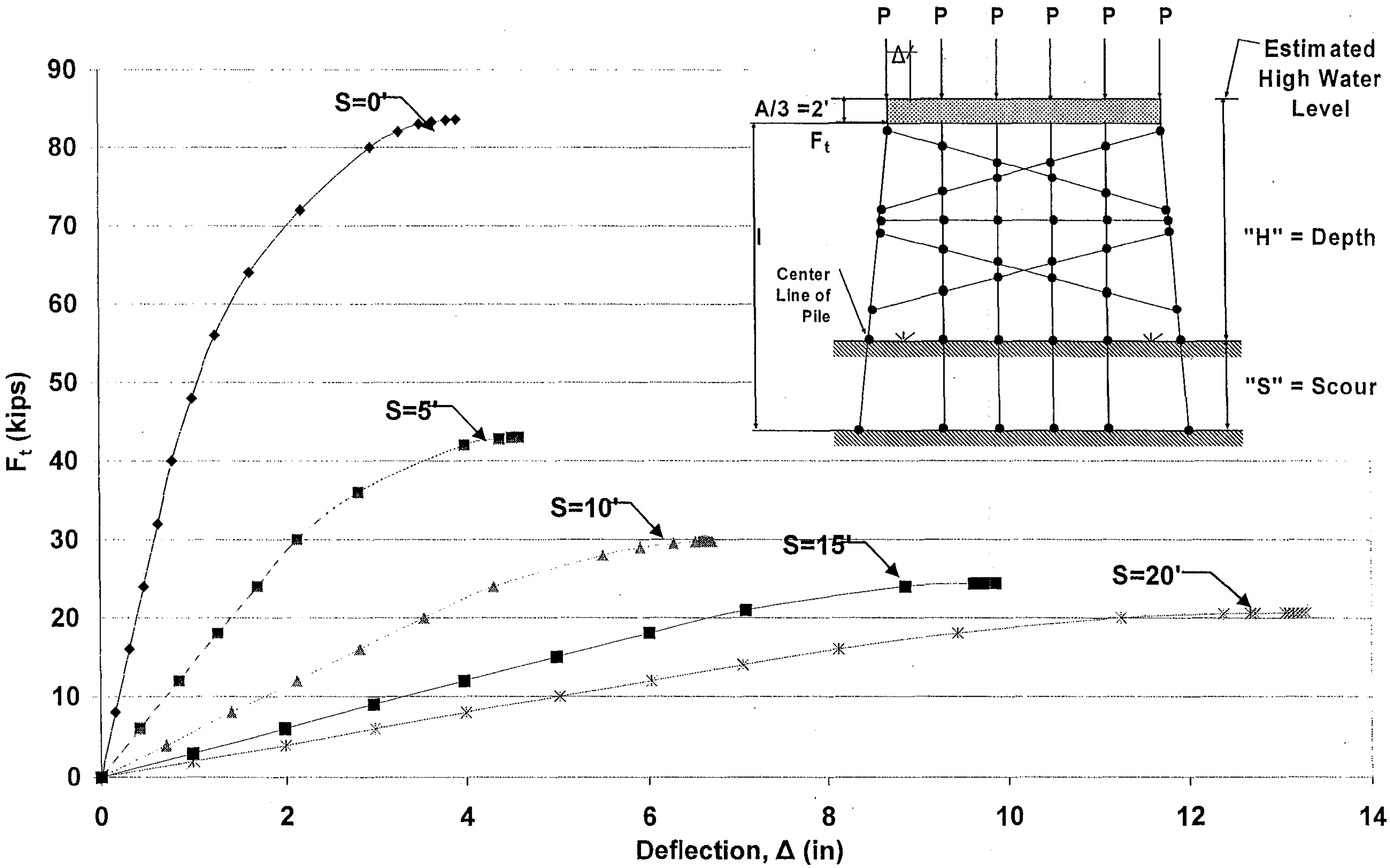


Figure B.103 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

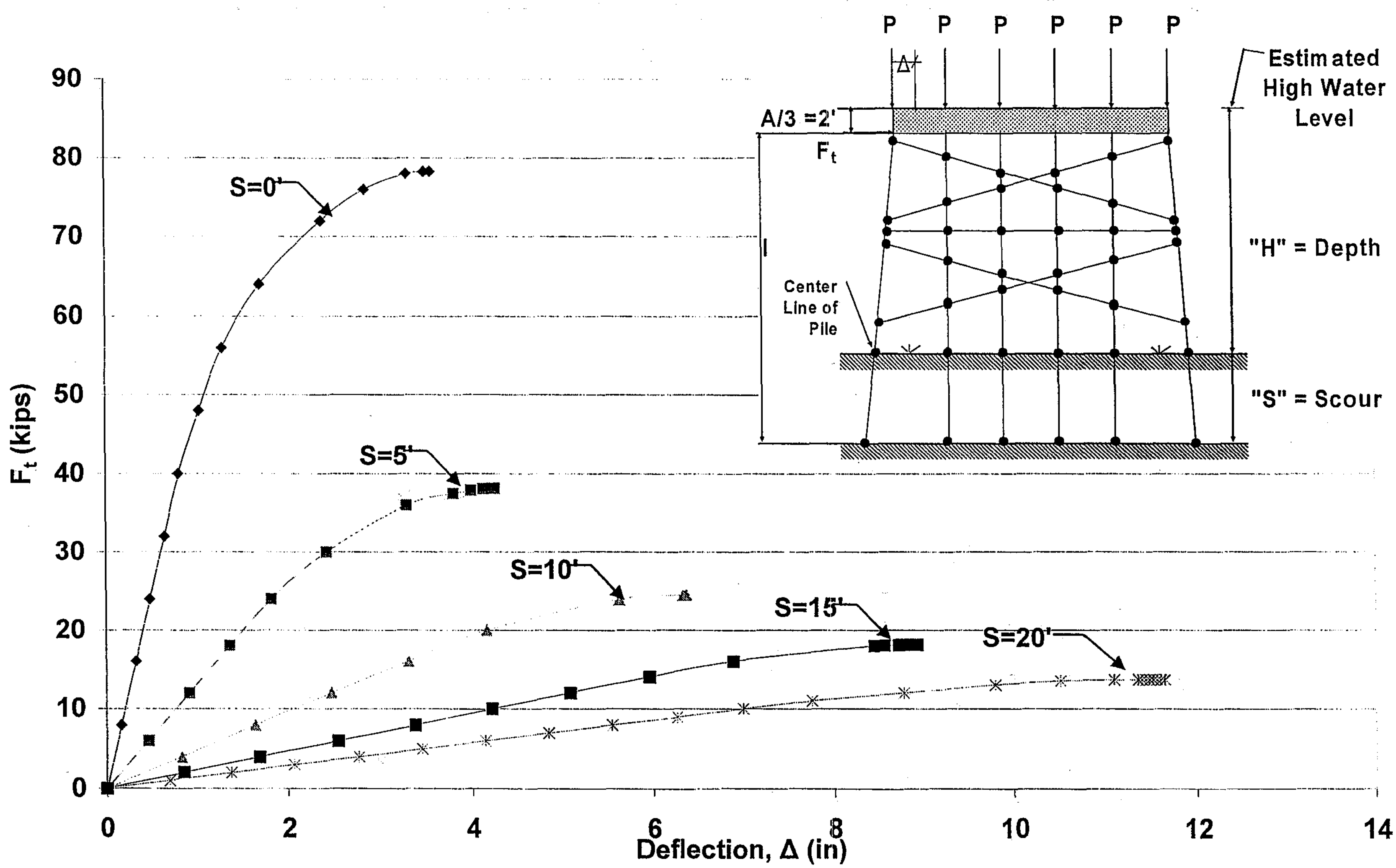


Figure B.104 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

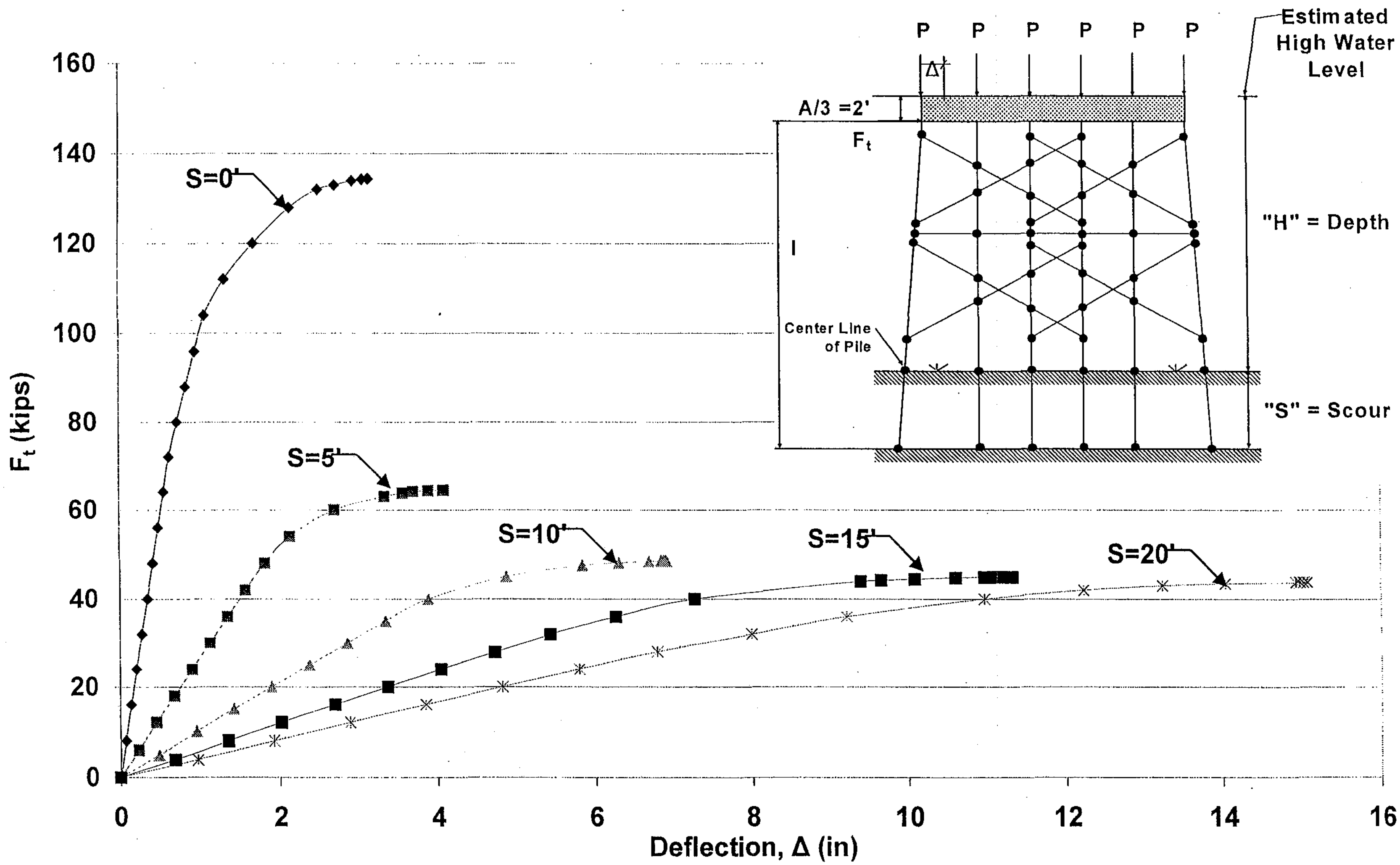


Figure B.105 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

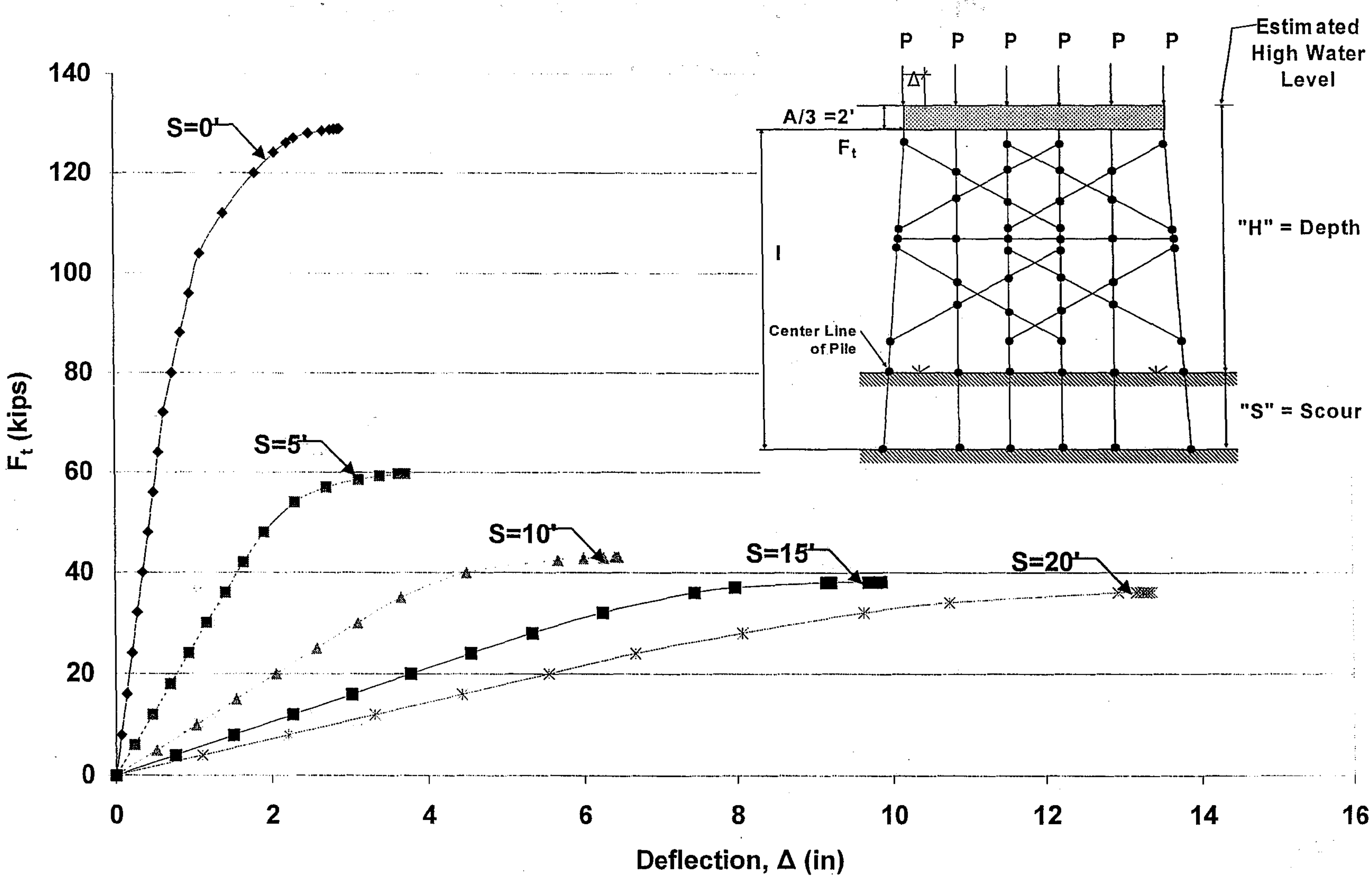


Figure B.106 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

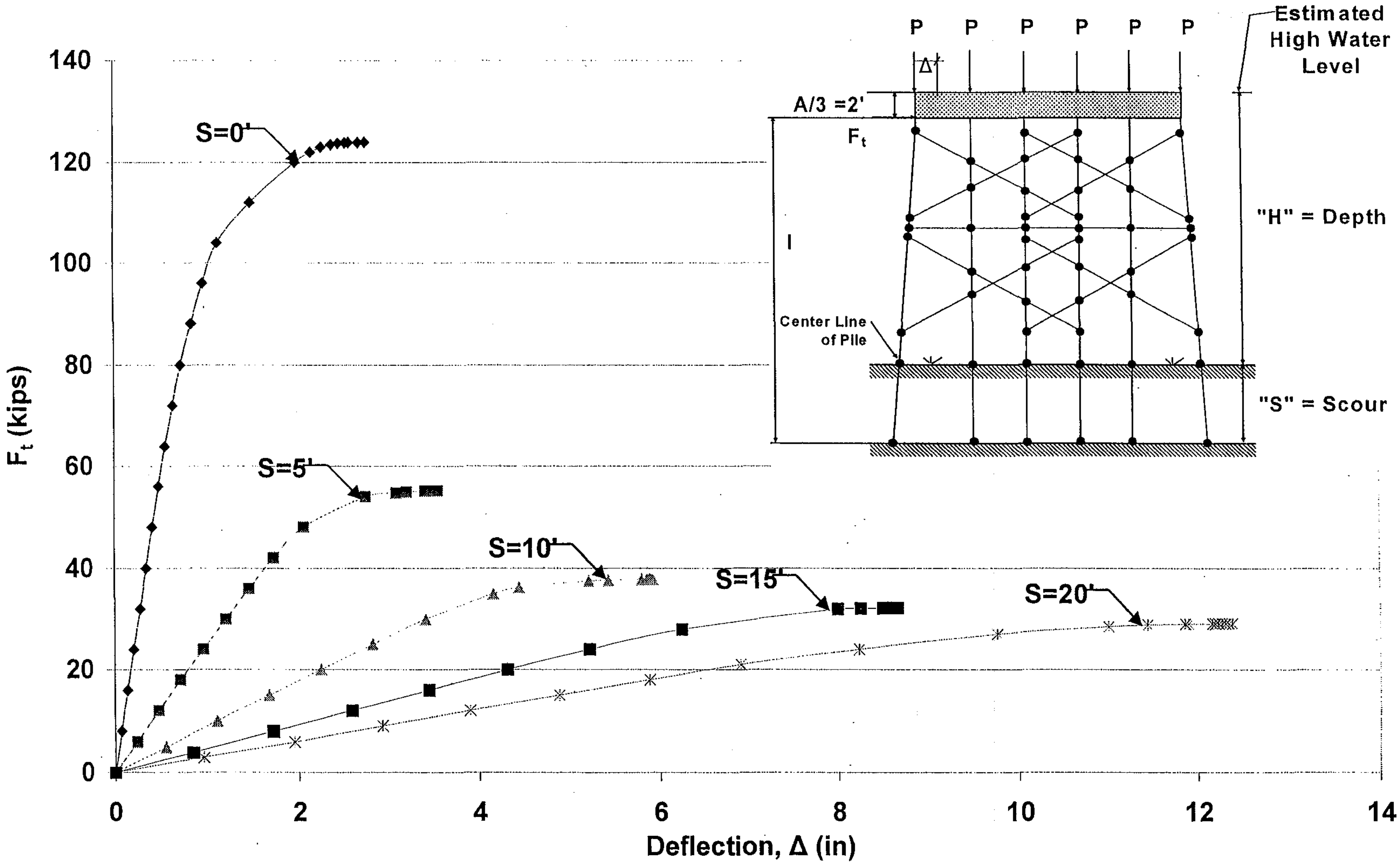


Figure B.107 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

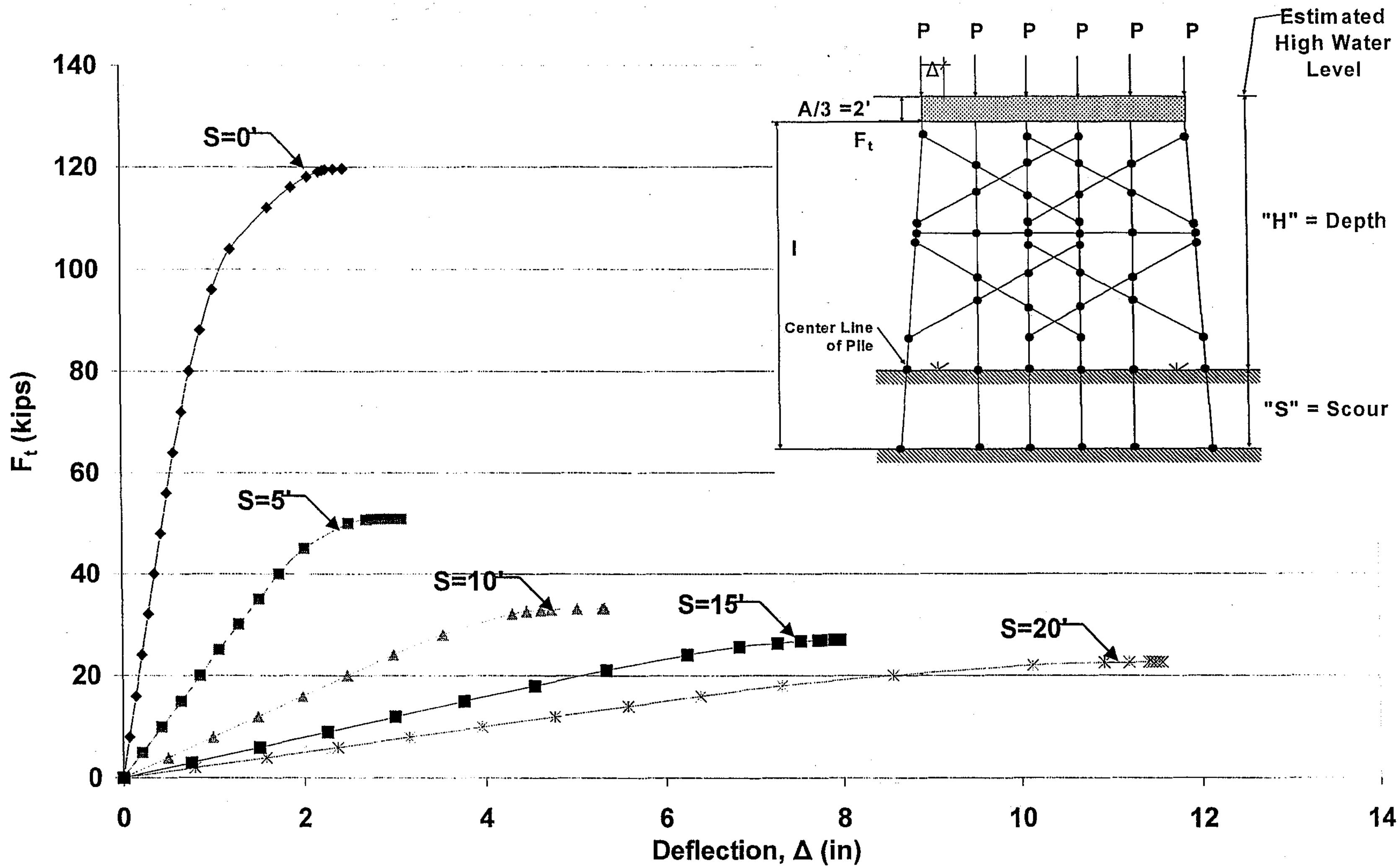


Figure B.108 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

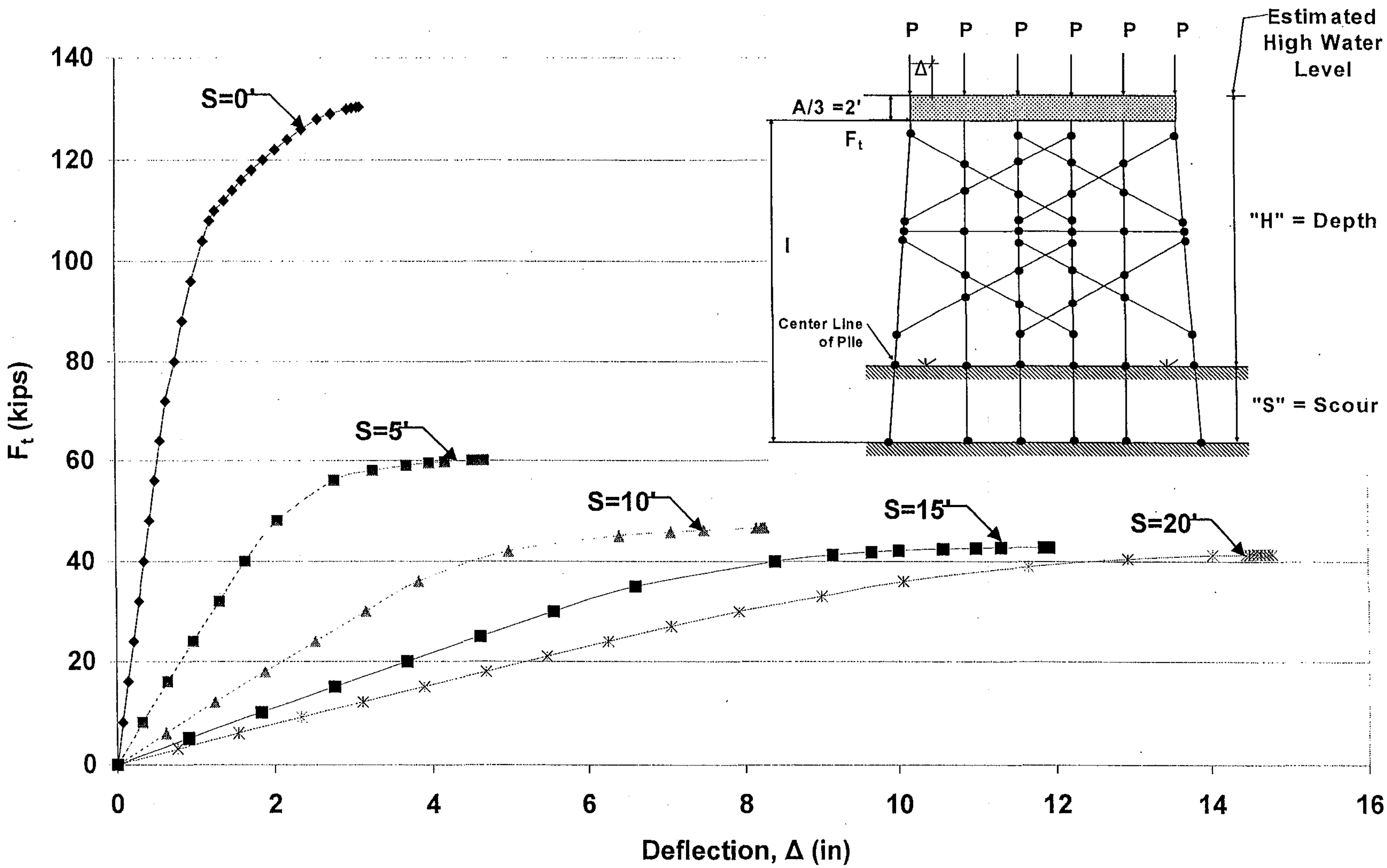


Figure B.109 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

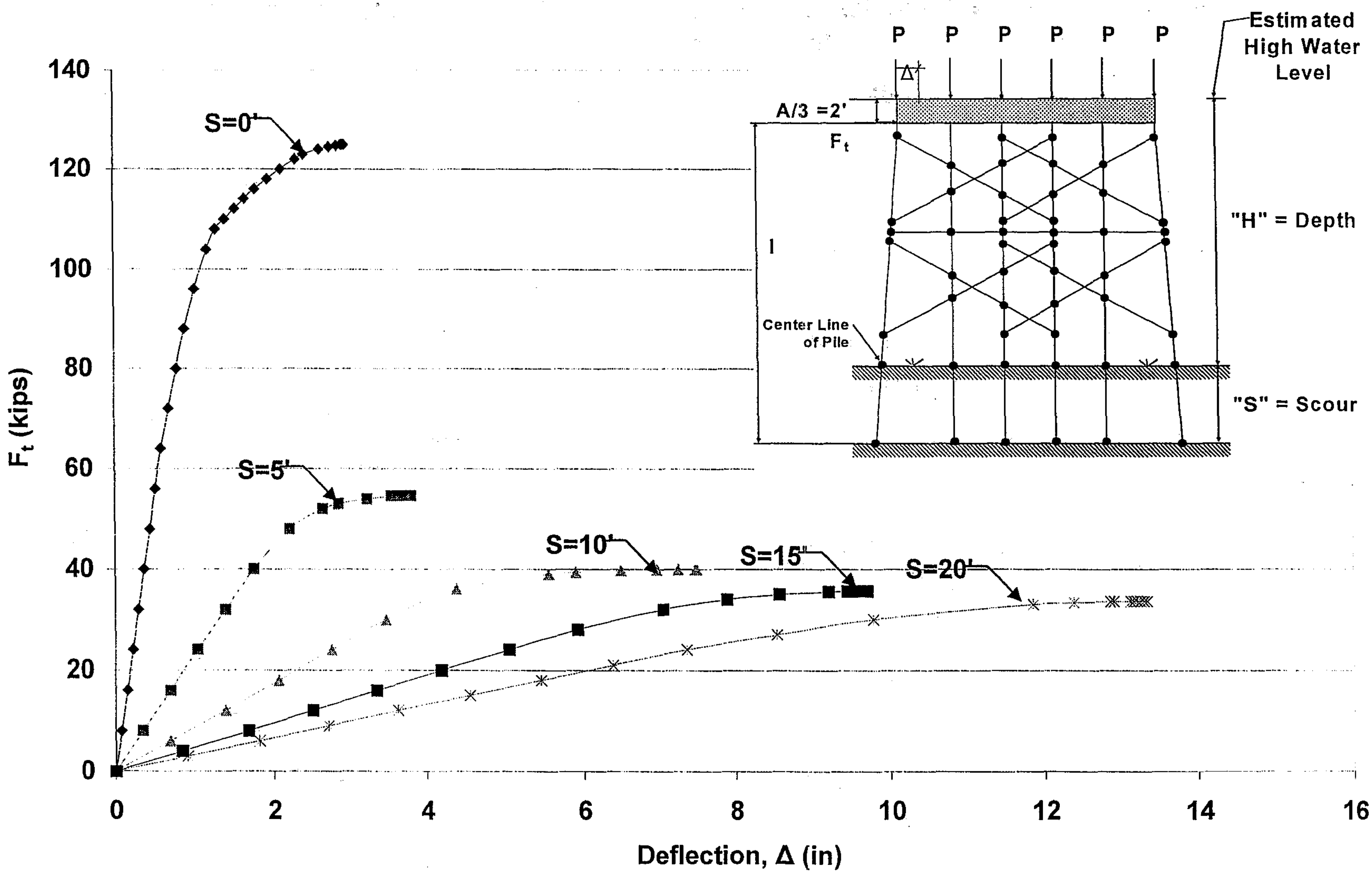


Figure B.110 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

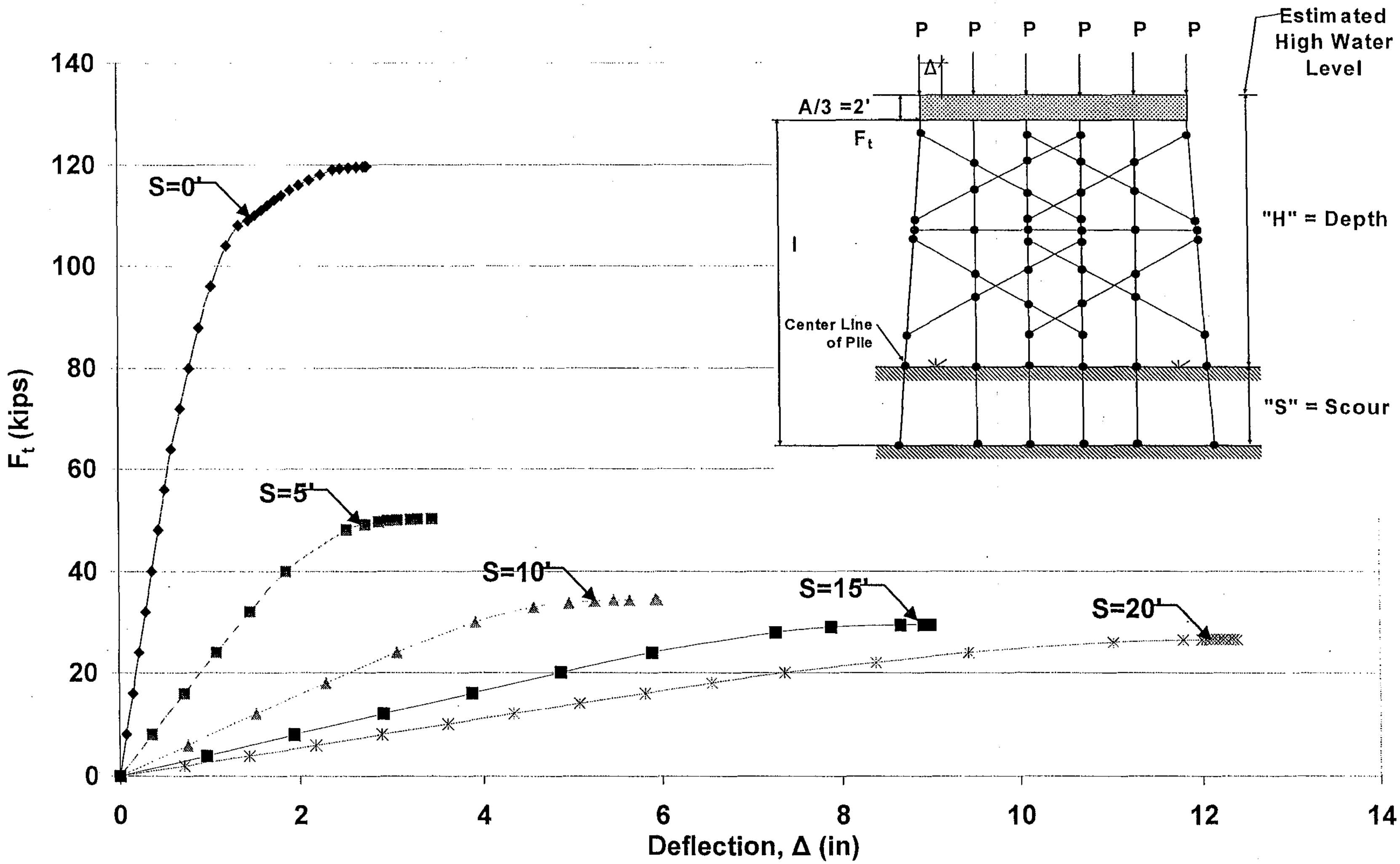


Figure B.111 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

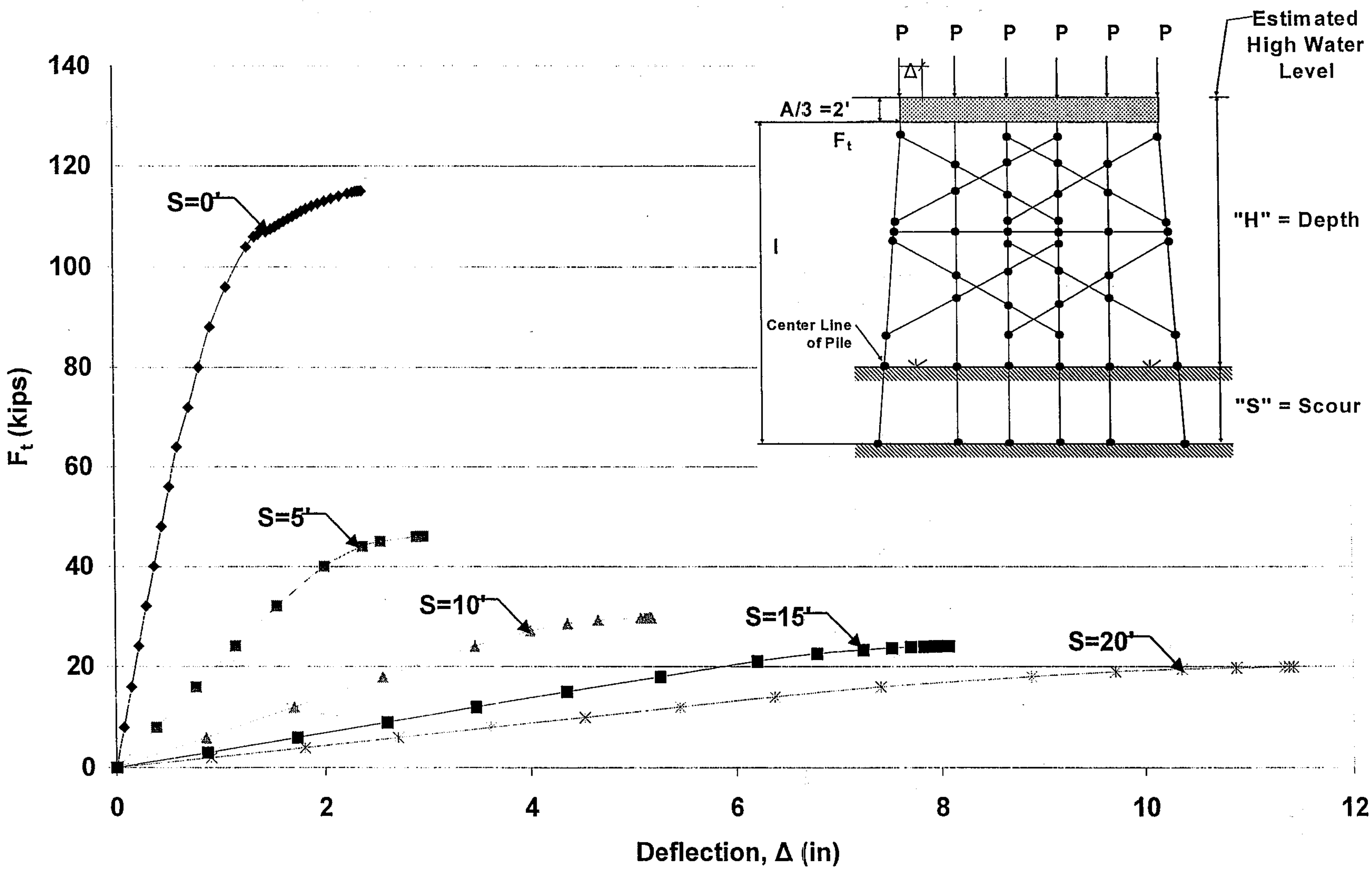


Figure B.112 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

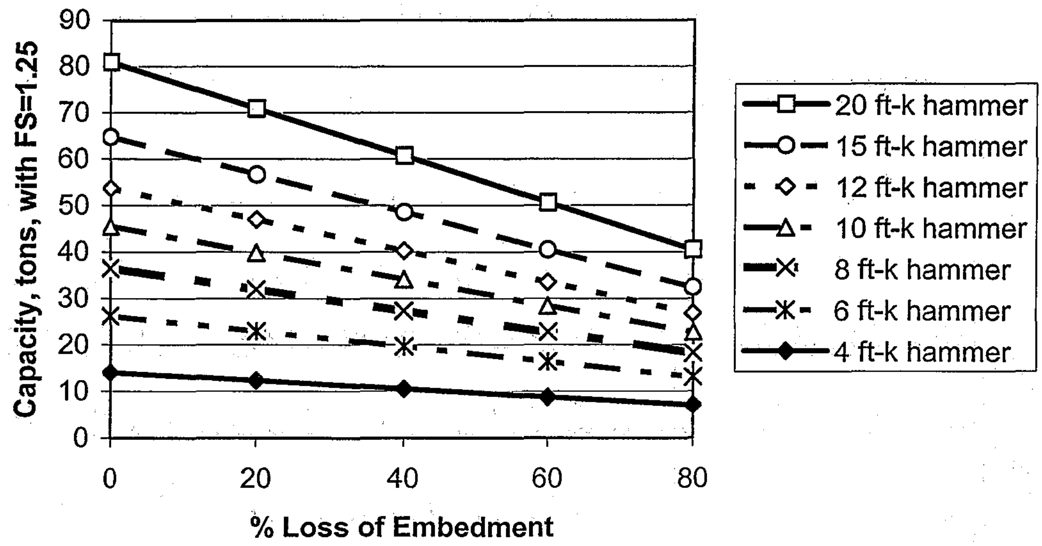
APPENDIX C

Pile Capacity Based on Modified Gates Formula For Four Final Driving Resistances Given in Inches Per 10 Blows and bpf

Table C.1. Pile Capacity in Tons with FS = 1.25 Based on Modified Gates Formula

Hammer Energy (ft-lb)	Final Driving Resistance in Inches per 10 blows (bpf)	Allowable Resistance (ton)	End Bearing Pile 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
4000	6 (20)	14	14	12	11	9	7	14	12	9	7	4
6000	6 (20)	26	26	23	20	16	13	26	22	17	12	8
8000	6 (20)	36	36	32	27	23	18	36	30	24	17	11
10000	6 (20)	46	46	40	34	28	23	46	38	30	22	14
12000	6 (20)	54	54	47	40	34	27	54	44	35	26	16
15000	6 (20)	65	65	57	49	40	32	65	53	42	31	19
20000	6 (20)	81	81	71	61	51	40	81	67	53	38	24
4000	4 (30)	22	22	19	16	14	11	22	18	14	10	7
6000	4 (30)	36	36	31	27	22	18	36	30	23	17	11
8000	4 (30)	48	48	42	36	30	24	48	39	31	23	14
10000	4 (30)	58	58	51	43	36	29	58	48	38	27	17
12000	4 (30)	67	67	59	50	42	34	67	55	44	32	20
15000	4 (30)	80	80	70	60	50	40	80	66	52	38	24
20000	4 (30)	98	98	86	74	61	49	98	81	64	47	30
4000	2 (60)	35	35	31	26	22	18	35	29	23	17	11
6000	2 (60)	52	52	46	39	33	26	52	43	34	25	16
8000	2 (60)	66	66	58	50	41	33	66	55	43	32	20
10000	2 (60)	79	79	69	59	49	39	79	65	51	37	24
12000	2 (60)	90	90	79	68	56	45	90	74	59	43	27
15000	2 (60)	106	106	92	79	66	53	106	87	69	50	32
20000	2 (60)	128	128	112	96	80	64	128	106	83	61	38
4000	1.25 (96)	44	44	39	33	28	22	44	37	29	21	13
6000	1.25 (96)	63	63	55	47	39	32	63	52	41	30	19
8000	1.25 (96)	79	79	69	59	49	40	79	65	51	38	24
10000	1.25 (96)	93	93	82	70	58	47	93	77	61	44	28
12000	1.25 (96)	106	106	93	79	66	53	106	87	69	50	32
15000	1.25 (96)	123	123	108	92	77	62	123	102	80	58	37
20000	1.25 (96)	148	148	130	111	93	74	148	122	96	70	45

a. End Bearing Piles, 6 inches per 10 blows Driving Resistance



b. End Bearing Piles, 4 inches per 10 blows Driving Resistance

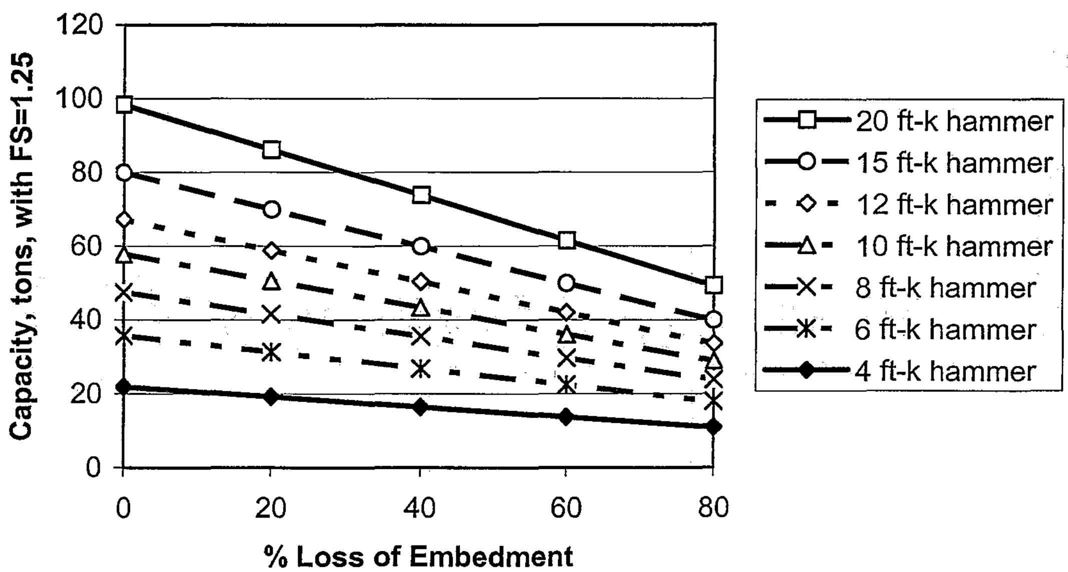
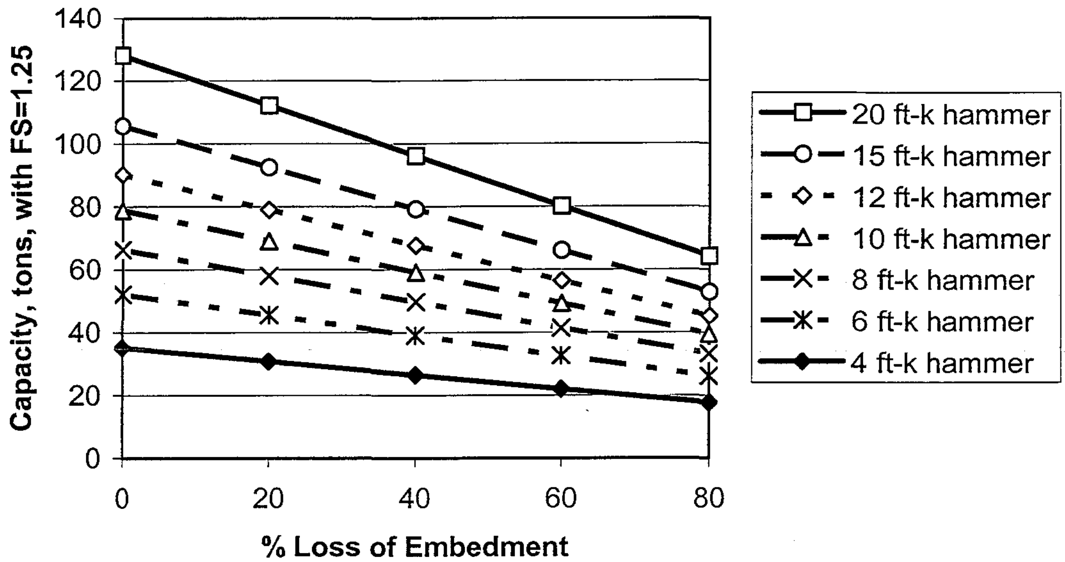


Figure C.1a - End Bearing Piles

c. End Bearing Piles, 2 inches per 10 blows Driving Resistance



d. End Bearing Piles, 1.25 inches per 10 blows Driving Resistance

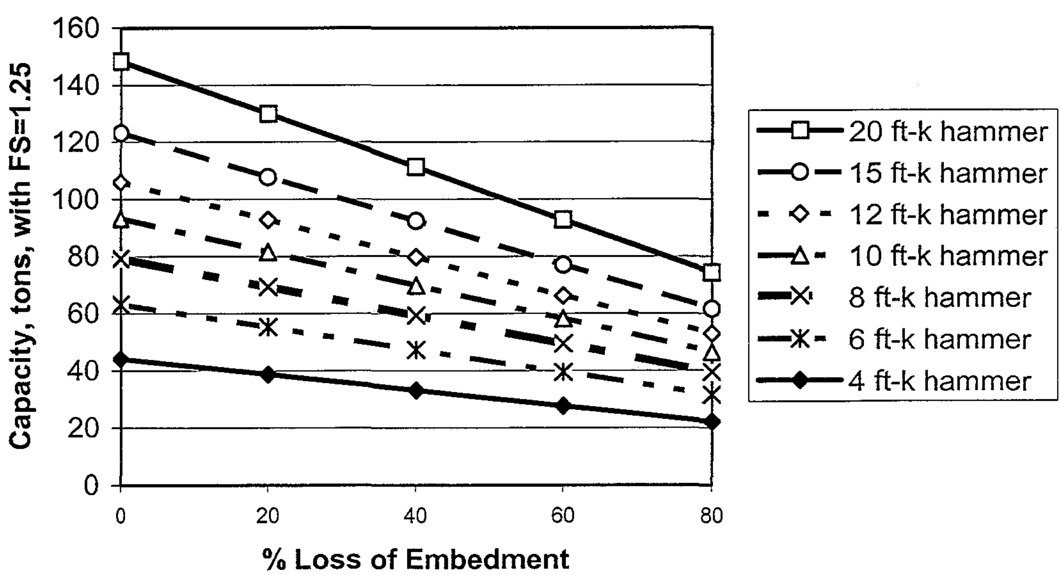
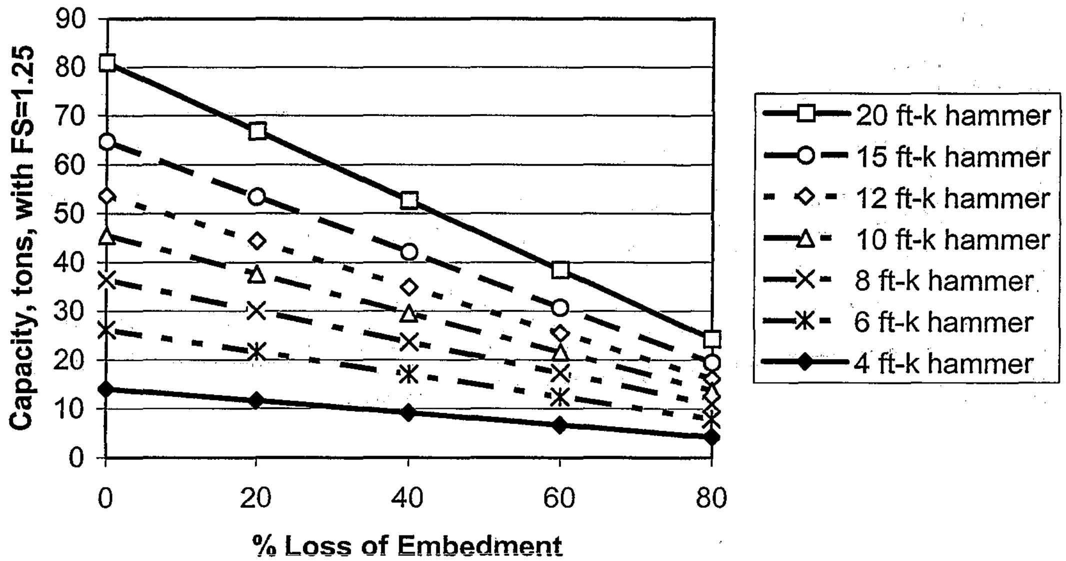


Figure C.1b - End Bearing Piles

a. Friction Piles, 6 inches per 10 blows Driving Resistance



b. Friction Piles, 4 inches per 10 blows Driving Resistance

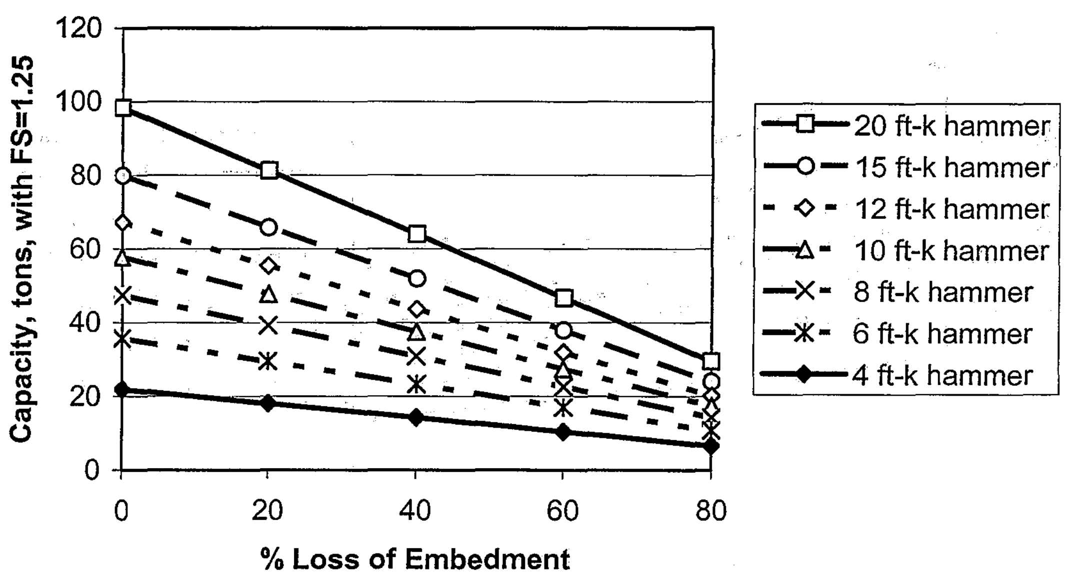


Figure C.2a – Friction Piles

c. Friction Piles, 2 inches per 10 blows Driving Resistance

d. Friction Piles, 1.25 inches per 10 blows Driving Resistance

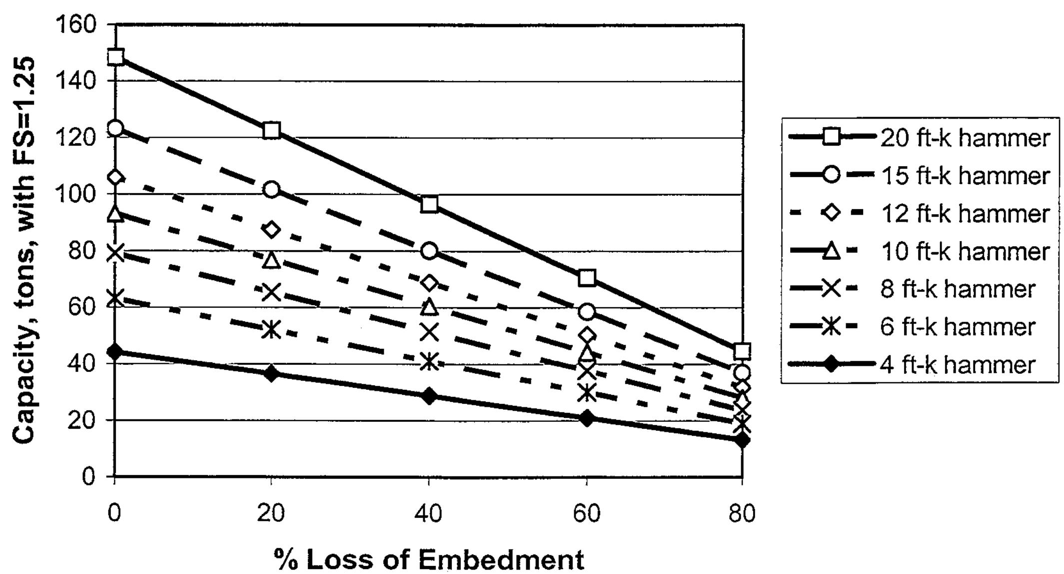


Figure C.2b – Friction Piles