FLOOD DEBRIS BUILD-UP LOADING AND ASSESSMENT OF ADEQUACY OF

ALDOT BRIDGE PILE BENTS DURING EXTREME FLOOD/SCOUR EVENTS

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Joslyn B. Daniels

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FLOOD DEBRIS BUILD-UP LOADING AND ASSESSMENT OF ADEQUACY OF

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Joslyn Blackburn Daniels

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Signature of Author

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Date

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VITA

Joslyn Tres Blackburn Daniels, daughter of Lynn Davis and Joan (Davis) Blackburn, was born October 30, 1980, in Montgomery, Alabama. She graduated High School from Lowndes Academy in May of 1998. She entered Auburn University in August of 1998 and graduated Auburn University with her Bachelor of Civil Engineering Degree in December of 2001. She then entered Graduate School at Auburn University in January of 2002. She married Jack Washington Daniels Jr., son of Mr. and Mrs. Jack Washington Daniels Sr. of Montgomery, Alabama on August 9, 2003 in Lowndesboro, Alabama.

THESIS ABSTRACT

FLOOD DEBRIS BUILD-UP LOADING AND ASSESSMENT OF ADEQUACY OF ALDOT BRIDGE PILE BENTS DURING EXTREME FLOOD/SCOUR EVENTS

Joslyn Blackburn Daniels

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A description of a flood debris build-up loading and an assessment of the adequacy of a chosen group of typical ALDOT bridge pile bents having various loading conditions and under various amounts of scour are presented in this thesis. Many of Alabama's existing bridges were not designed for scour, and this report is to aid in determination of the suitability and condition of these bridges when subjected to lateral flood water loadings (lateral to the bridge or in the plane of the bent). Pushover analyses were performed on numerous bridge pile bents having a range of loading and scour conditions present. The pushover analyses performed make up part of a screening tool that is presented in this report to evaluate the existing field bridges. Finally, conclusions and recommendations are made based on the research and analyses of the bridge pile bents having flood debris build-up loadings during extreme flood/scour events.

ACKNOWLEDGEMENTS

The author would like to thank the Alabama Department of Transportation (ALDOT) for funding this project. Also, the author would like to thank Dr. G. Ed Ramey for assistance with academic guidance and assistance in completing this thesis. Also, thanks are due to Dr. Dan A. Brown, for his contributions to the Phase I and Phase II reports to ALDOT on Stability of Highway Bridges Subject to Scour. The author would also like to acknowledge the advisory committee Dr. Barnes and Dr. Yoo. Thanks are in order to Jack Daniels Jr. for his support during the course of my graduate studies.

Style manual used:__The Chicago Manual of Style________________________________

Computer software used:____Microsoft Word, Microsoft Excel, GT STRUDL_________

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

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 was 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 of 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). In an extreme flooding and scour event, the possibility of considerable debris build-up at the bridge bents is very realistic. This in turn could result in sizeable lateral loadings on the bent piling which also have their unbraced length enlarged considerably due to scour. This could create a possible lack of strength or stability problem for the bent and in turn a bridge failure condition. Investigating this possibility is the impetus and purpose of this research.

1.2 OBJECTIVES

The objectives of this investigation are as follows:

1. To determine appropriate flood debris build-up model, resulting bridge bent loadings, mode of bent failure, and a failure load analysis procedure appropriate for analyzing pile bents in extreme flood/scour events.
2. Apply the debris build-up model and analysis procedure identified in (1) and determine the adequacy of some typical ALDOT pile bents over a range of scour levels.

1.3 WORK PLAN

A brief work plan to accomplish the research objectives cited above is given below:

1. Review the literature and AASHTO Design Specifications pertaining to river flood debris build-up and loadings on bridge piers and bents.
2. Develop bridge bent flood loading models in the transverse direction in extreme scour cases.
3. Identify the potential modes of failure of bridge bents for the bent models in two above.
4. Identify the appropriate analysis assumptions and procedures for assessing the adequacy or failure of bridge bents in (2) and (3) above.
5. Apply the debris build-up model and analysis procedure identified above, and analytically/numerically test the adequacy of some typical ALDOT pile bents over a range of scour levels.

6. Make recommendations on the easiest and the most appropriate way of including this loading and potential failure mode in the "Bridge Bent Screening Tool" being developed.

7. Prepare a final report on the research work.

1.4 SCOPE

This investigation was limited to a review of the literature and design specifications on flood debris build-up and bridge pile bent loadings during extreme flood events. Analytical/numerical analyses of some typical ALDOT pile bents subject to a range of flood build-up and scour levels were conducted to assess the adequacy of the pile bents. No laboratory or field testing was conducted to verify or refute the results of the analytical analyses.

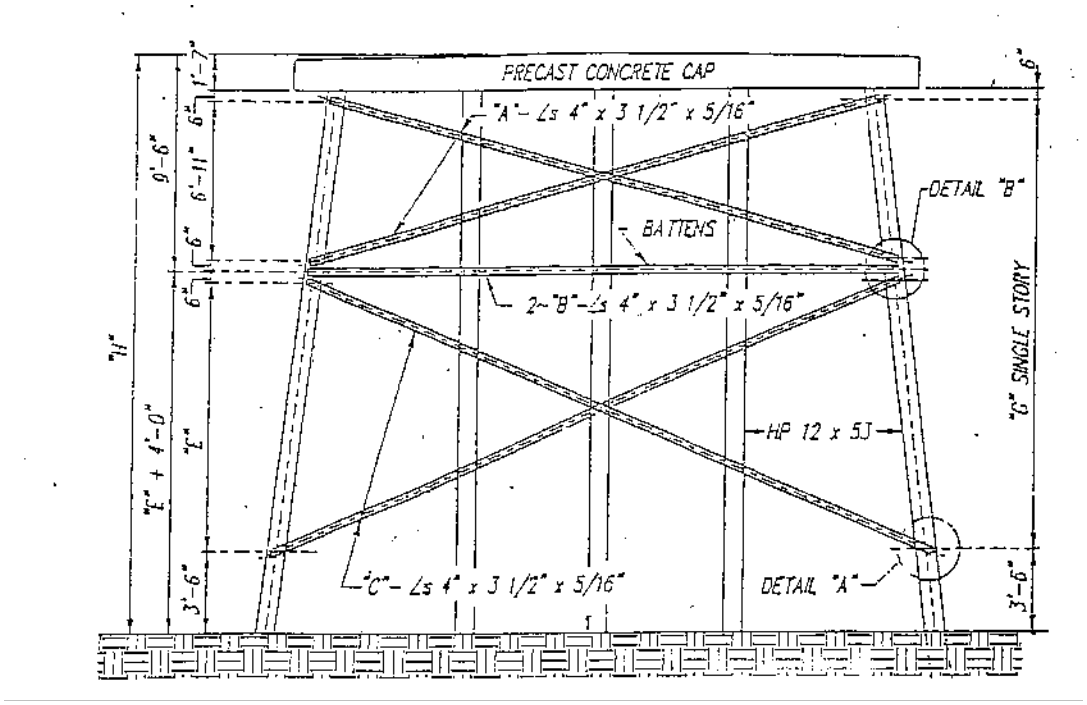
CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 BACKGROUND

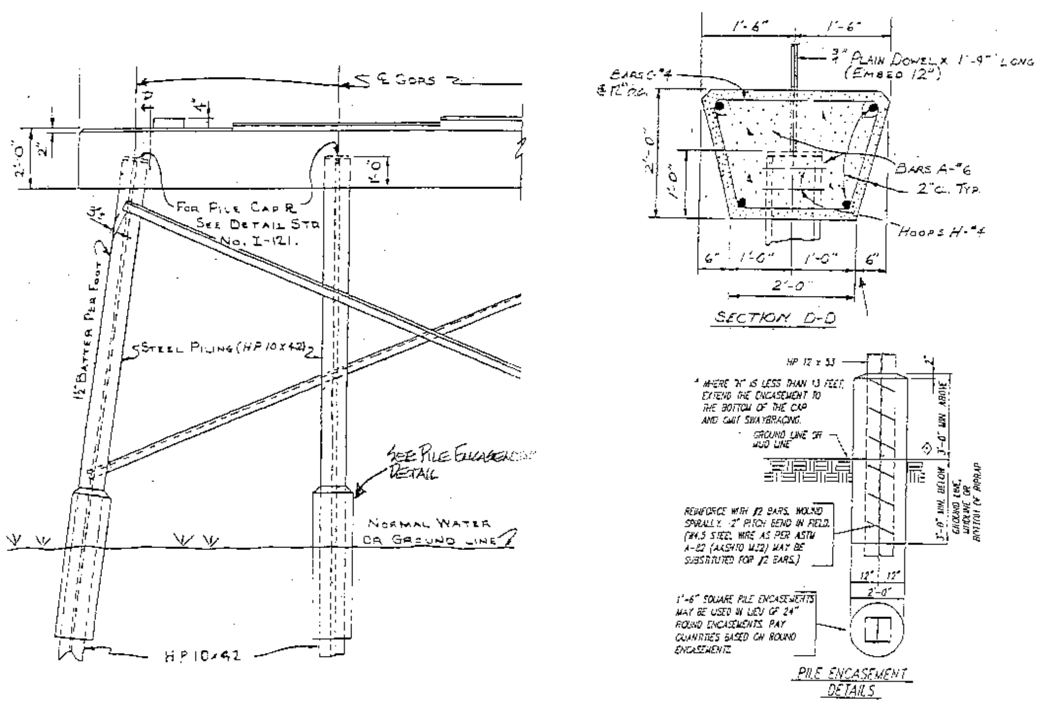
Scour is the movement of the stream bed from around the foundation, and this can significantly change the structural system, creating a situation that must be considered in the design (Barker and Puckett 1997). As noted in the introduction, scour has not been taken into account in the design of a great number of Alabama's bridges. This is cause for concern considering a majority of bridges that have failed in the United States and elsewhere have failed due to scour (AASHTO 1997).

The specific type of bridge substructure to be examined in this report is the pile bent pier. The pile bent pier has individual supporting piles in a row with the end piles typically being battered in the transverse directions (Tonias 1995). In Auburn University's Phase I Report to ALDOT it was found that bridges having HP10x42 and HP12x53 piles are of particular interest because these are the piles sizes commonly used by ALDOT (2003). Pile bent configurations having 3, 4, 5, and 6-piles are widely used by ALDOT. In the Phase I Report it was found the average bridge width was 32 feet, and the average span length was 36 feet (2003).

Pile bents are typically X-braced in the plane of the piles for lateral support, via one-story or two-story X-bracing as shown in Figure 2.1. For short bents, i.e. height $\leq$ 13 feet, ALDOT allows contractors to encase the piles from 3 feet below ground line up to the bent cap and omit the X-bracing as shown in Figure 2.2.

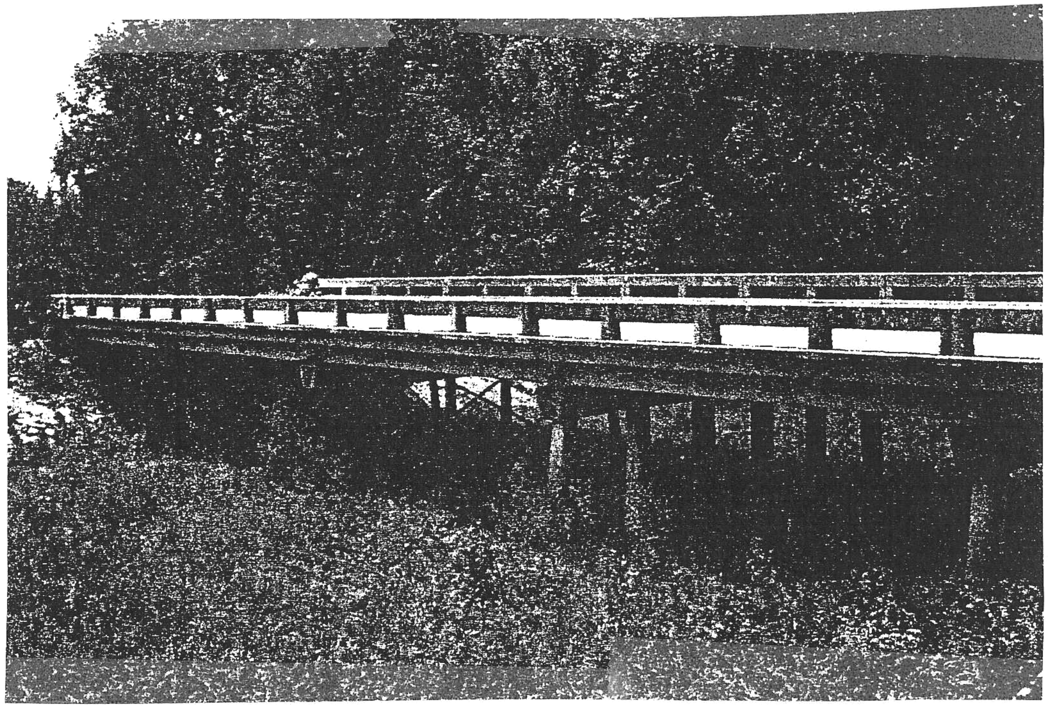


a. Two-Story X-Braced Bent



b. One-Story X-Braced Bent

Figure 2.1 Typical ALDOT X-Braced Pile Bents



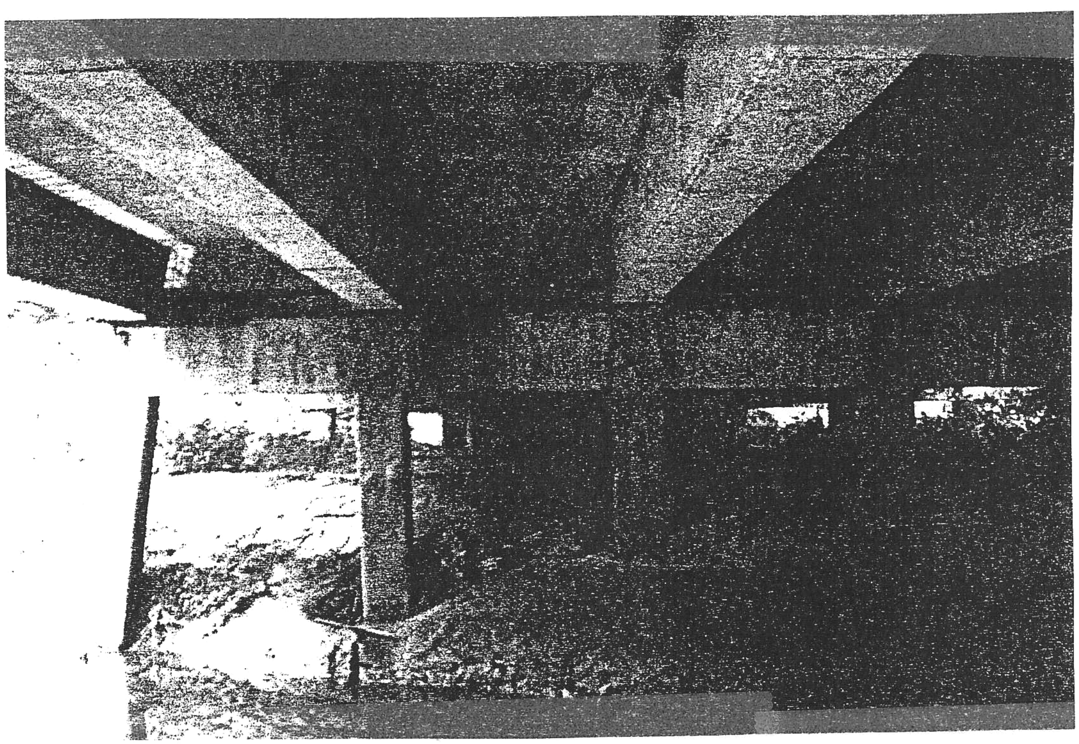


Figure 2.2 One-Story Bridge with Steel H-Pile Encased and Sway-Bracing Omitted

2.2 LITERATURE REVIEW

Pile bent piers are extremely popular in marine environments where multiple, simple span structures cross relatively shallow water channels (Tonias 1995). However, deterioration of exposed piles, impact from marine traffic, and accumulation of stream debris are all maintenance problems associated with pile bent piers (Tonias 1995).

Section 3.7.5 of AASHTO LRFD Bridge Design Specifications (1997) requires scour at bridge foundations to be investigated for two conditions. These two conditions are outlined in Section 2.6.4.4.2 titled *Bridge Scour* and are as follows:

> Condition 1: The design flood for scour: the streambed material in the scour prism above the total scour line shall be assumed to have been removed for design conditions. The design flood storm surge tide, or mixed population flood shall be the more severe of the 100-year event or an overtopping flood of lesser recurrence interval.
>
> Condition 2: The check flood for scour: the stability of bridge foundation shall be investigated for scour conditions resulting from a designated flood storm surge, tide or mixed population flood not to exceed the 500-year event or an overtopping flood of lesser recurrence interval. Excess reserve beyond that required for stability under this condition is not necessary. The Extreme Event limit state shall apply.

Also in Section 2.6.4.4.2 of AASHTO it states that if the site conditions, due to ice or debris jams, and low tailwater condition near stream confluences dictate the use of a more severe flood event for either the design or check flood for scour, the Engineer may use such flood event (1997). Spread footings on soil or erodible rock shall be located so that the bottom of footing is below scour depths determined for the check flood for scour. Spread footings on scour-resistant rock shall be designed and constructed to maintain the integrity of the supporting rock.

Many Alabama bridges were not designed for this condition of having a debris jam and a severe flood event. Maximum scour on some of Alabama's bridges is estimated to be up to 15 feet. The combination of scour and debris build-up could result in substantial lateral loading on the bent piling which also have their height and unbraced lengths enlarged considerably due to scour.

Flood debris build-up loading are considered to be channel forces. Channel forces are those loads imposed on a structure due to water course-related features. These forces include, but are not limited to stream flow, floating ice, and buoyancy (Tonias 1995). In Alabama, floating ice is very infrequent, thus it will not be taken into consideration. Buoyancy conditions would only take place in severe flooding conditions. Bridges with components (e.g., piers) which are submerged underwater can sometimes suffer from the effects of buoyancy; however, this generally is a problem only for very large structures (Tonias 1995). Buoyance can also impact pier footings and piles (Tonias 1995).

Floating logs, roots and other debris may accumulate at piers, and by blocking parts of the waterway, increase stream velocity and pressure load on the pier (AASHTO 1997). Such accumulation is a function of the availability of such debris and level of maintenance efforts by which it is removed (AASHTO 1997). Water flowing against and around the substructure as well as the possibility of debris build-up creates a lateral force directly on the substructure (Barker and Puckett 1997). Channel forces, similar to seismic forces, primarily affect substructure elements (Tonias 1995). Such water forces are most critical in flood conditions (Barker and Puckett 1997). According to Tonias (1995), excessive stream flow velocity, (V) in addition to increasing water pressure on the substructure proportional to V^2, can lead to adverse scour conditions which can undermine footings and threaten the integrity of the structure.

AASHTO specifications state that the pressure of flowing water acting in the longitudinal direction of substructures (this is usually transverse to the longitudinal direction of the bridge as shown in Figure 2.6) shall be taken as follows:

$$p = C_D V^2/1{,}000 \qquad (2.1)$$

where,

p = pressure of flowing water (KSF)

C_D = drag coefficient for piers as specified in Table 2.1 below

V = design velocity of water for the design flood in strength and service limit states and for the check flood in the extreme event limit state (FT/SEC)

Table 2.1 Drag Coefficients (AASHTO 1997)

AASHTO Specification	
Type	**C_D**
semi-circular nosed pier	0.7
square ended pier	1.4
debris lodged against the pier	1.4
wedged nosed pier with nose angle 90° or less	0.8

The relationship between water pressure and design velocity for C_D = 1.4 can be seen in the Figure 2.3.

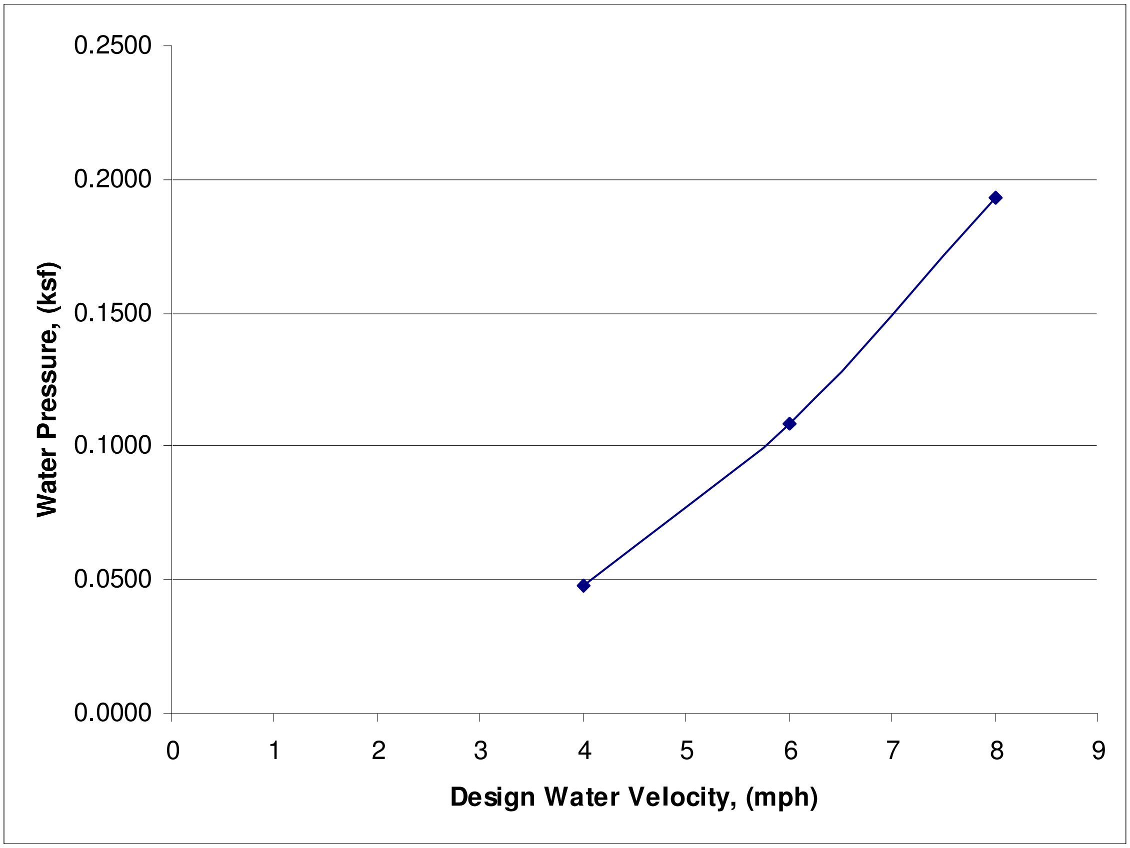


Figure 2.3 Relationship Between Water Pressure and
Design Water Velocity for $C_D = 1.4$

As noted above, the longitudinal direction refers to the major axis of the substructure unit, which is usually perpendicular to the longitudinal axis of the bridge. The drag coefficient, C_D presented in AASHTO was adopted from the *1983 Ontario Highway Bridge Design Code*. The transverse (to the bridge) drag force shall be taken as the product of stream water pressure as given by Equation 2.1, and the area of the debris raft projected on a vertical surface, as indicated in Equation 2.2 and Figure 2.4.

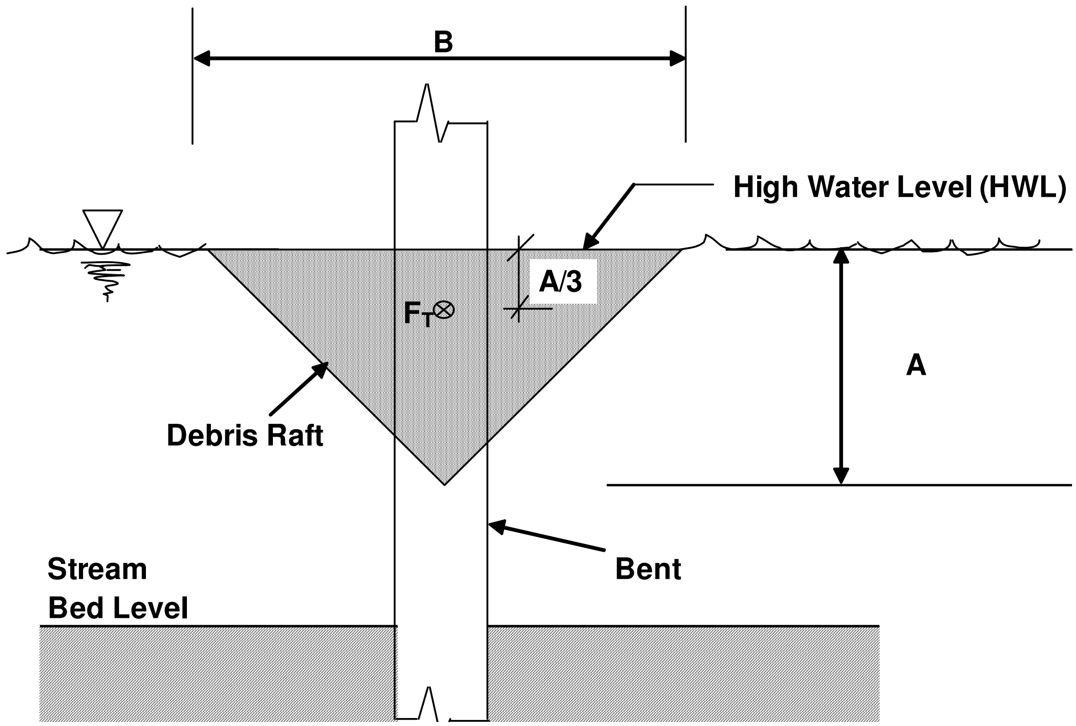


Figure 2.4 Debris Raft for Bent Design (AASHTO 1997)

F_t = p [shaded area in Fig. 2.4] (2.2)

A = ½ x water depth, but not greater than 10'

B= ½ x sum of adjacent span lengths, but not greater than 45'

F_t shall be assumed to act at the centroid of the shaded area. Thus F_t acts at a distance A/3 down for the water surface. In this study the water depth was taken to be at the top of the bent cap, and B was assumed to be 30 feet. These are considered to be conservative approximations. The linear relationships between F_T, for a range of values for A, and B for a stream with V_{design} = 6 mph are displayed in Figure 2.5

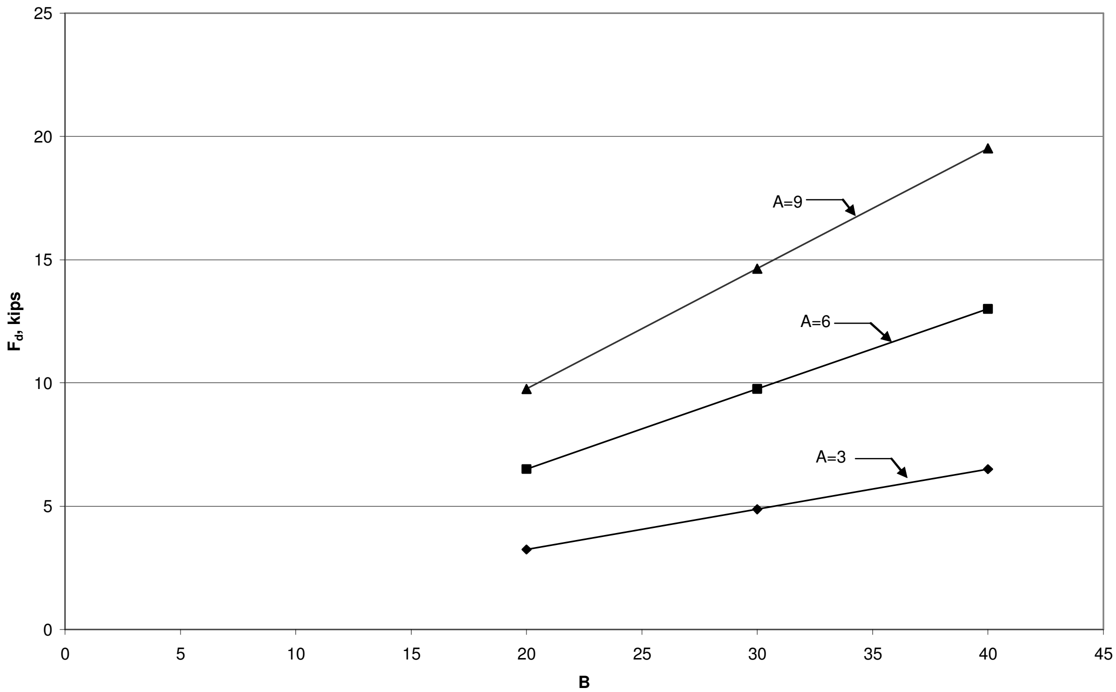


Figure 2.5 Debris Raft Force, $F_{T,}$ for Various Debris Raft Dimensions (B) and (A) with V_{design} = 6mph

A plan view of a typical pile bent supported bridge over water with a bent debris raft is shown in Figure 2.6, and section views of a typical bent showing longitudinal and transverse flood water loadings are shown in Figure 2.7.

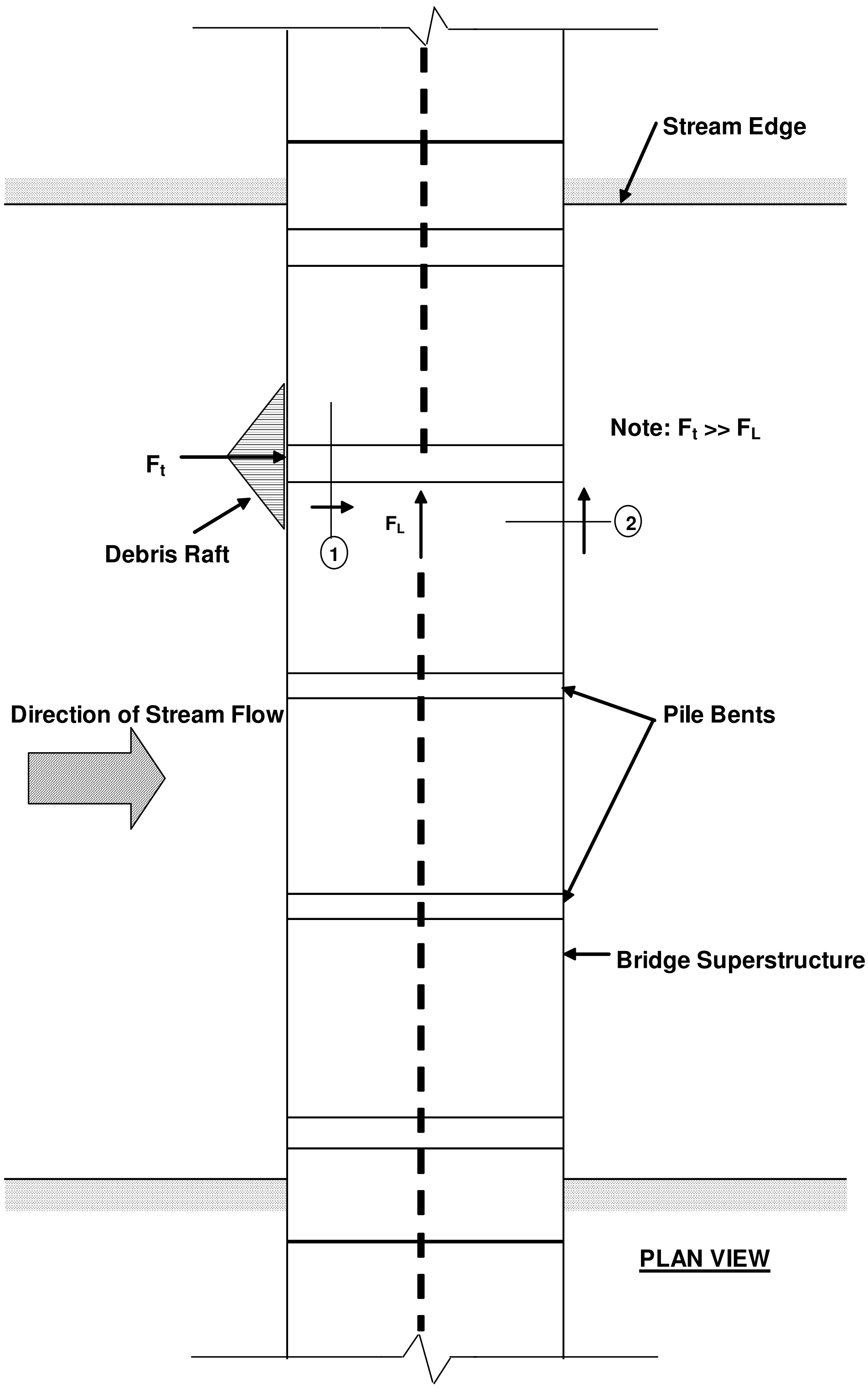
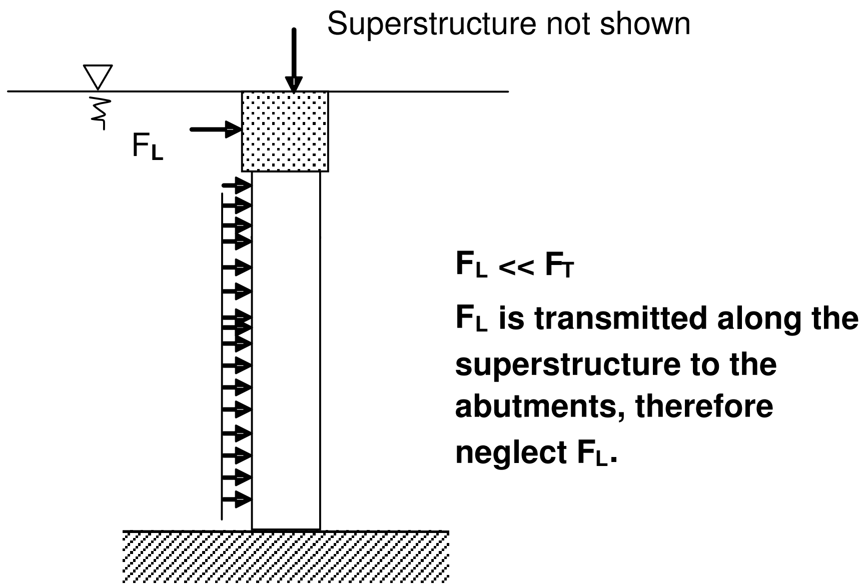
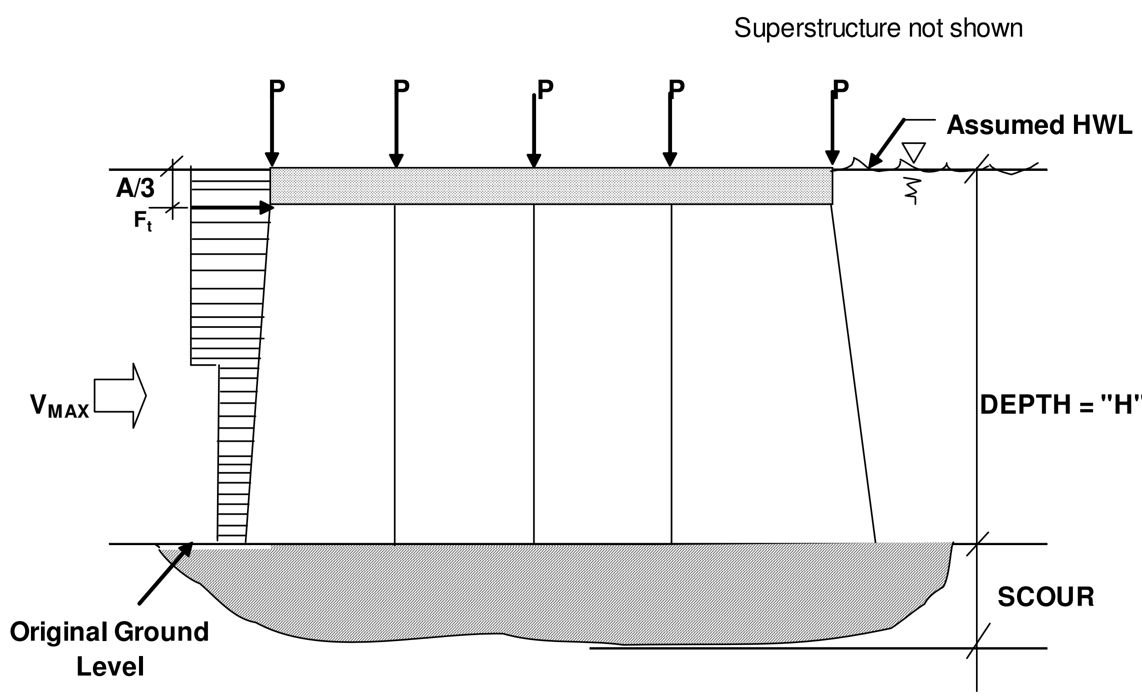


Figure 2.6 Typical Pile Bent Supported Bridge over a Stream



SECTION 1



SECTION 2

Figure 2.7 Sections Showing Longitudinal And Transverse Flood Water Loading on Bent (see Fig. 2.6)

As seen in Figure 2.6, bridge longitudinal forces may be considered. Longitudinal forces result from vehicles braking or accelerating while on a bridge (Tonias 1995). AASHTO specifies that 5 percent of the appropriate lane load along with the concentrated force for moment (for all travel lanes going in the same direction) be used as the resulting longitudinal force (AASHTO 1997). This force is applied 6' above the top of the deck surface (Tonias 1995). The effect of longitudinal forces on the superstructure is inconsequential, however, substructure elements are affected more significantly (Tonias 1995). In general, the more stiff or rigid the structure, the more severe the effects of longitudinal forces will be (Tonias 1995).

Also, as seen in Section 2 of Figure 2.6, superstructure gravity loads, i.e. the P-loads in Figure 2.6, are always acting on the bridge bents. In this study, P-loads of 100, 120, 140, and 160 kips were considered with one such load placed above each bent pile. These loads in conjunction with the debris raft load, F_t, probably constitute the governing design load on a bridge bent. In analyzing the performance of a bent for this load combination, the P-Δ effect should be considered. In this study, GTSTRUDL pushover analysis was utilized to consider both the geometric and material nonlinearity of this load combination to determine the adequacy of the bridge bents.

Typically bridge piers/bents are oriented with their longitudinal axis parallel to the direction of stream flow. However, sometimes the substructure may be oriented at an angle to the stream flow, as shown in Figure 2.8. AASHTO provides Equation 2.3 and Table 2.2 to determine the lateral pressure on the pier.

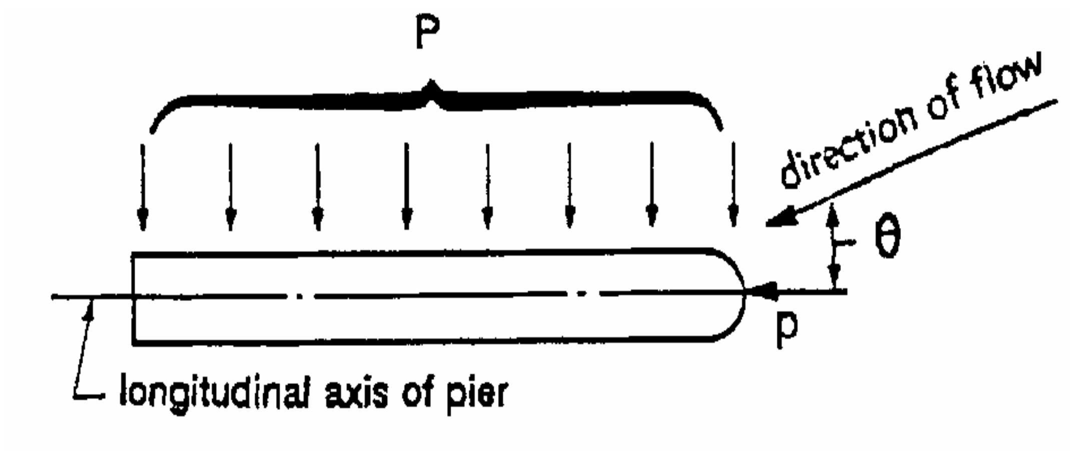


Figure 2.8 Plan View of Pier Showing Stream Flow Pressure (AASHTO 3.7.3.2-1)

The lateral drag force shall be taken as the product of the lateral stream pressure and the surface exposed thereto (AASHTO 1997). The greater the angle of the flow to the pier/bent the greater risk of possible bent failure. Potential modes of bent failure are discussed more in depth in Chapter 4.

$$p = C_L*V^2/1000 \qquad \text{EQN 2.3}$$

Where,

p = lateral pressure (KSF)

C_L = lateral drag coefficient specified in Table 2.2.

V = stream design flow velocity in (fps).

Table 2.2 Lateral Drag Coefficient (AASHTO 1997)

Angle, θ, between direction of flow and longitudinal axis of the pier	C_L
0°	0.0
5°	0.5
10°	0.7
20°	0.9
≥ 30°	1.0

The velocity, V, of the water in Equations 2.1 and 2.3 is typically estimated based on the conditions at the site. A range of different configurations of pile bent span lengths and water heights can result in a considerable number of values for A, B and thus thousands of different values for F_t. The value of F_t is found using Equation 2.2. Figures 2.9 – 2.11 simplify the process of evaluating F_t by using a range of values for A, B and V. Once the F_t force for a particular bent is found, one must determine if the bridge is safe for this loading. But what is the largest F_t force that a particular bent can handle and still be considered safe? In this report the answer to this question was analyzed using a nonlinear pushover analysis performed in GTSTRUDL. Using GTSTRUDL's pushover analysis, the F_t (force due to debris loads) that would "pushover" various pile bents were determined. In the pushover analysis different levels of scour and different loadings were placed on the pile bents to determine the effects of scour on the bridges.

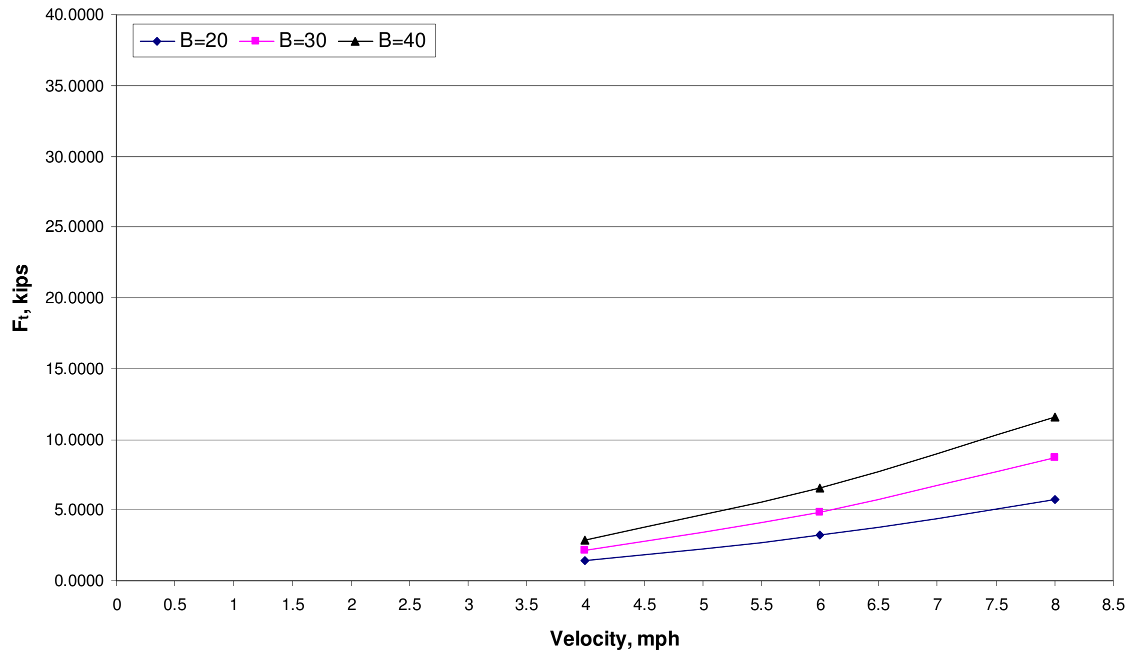


Figure 2.9 A=3, Velocity vs. F_t

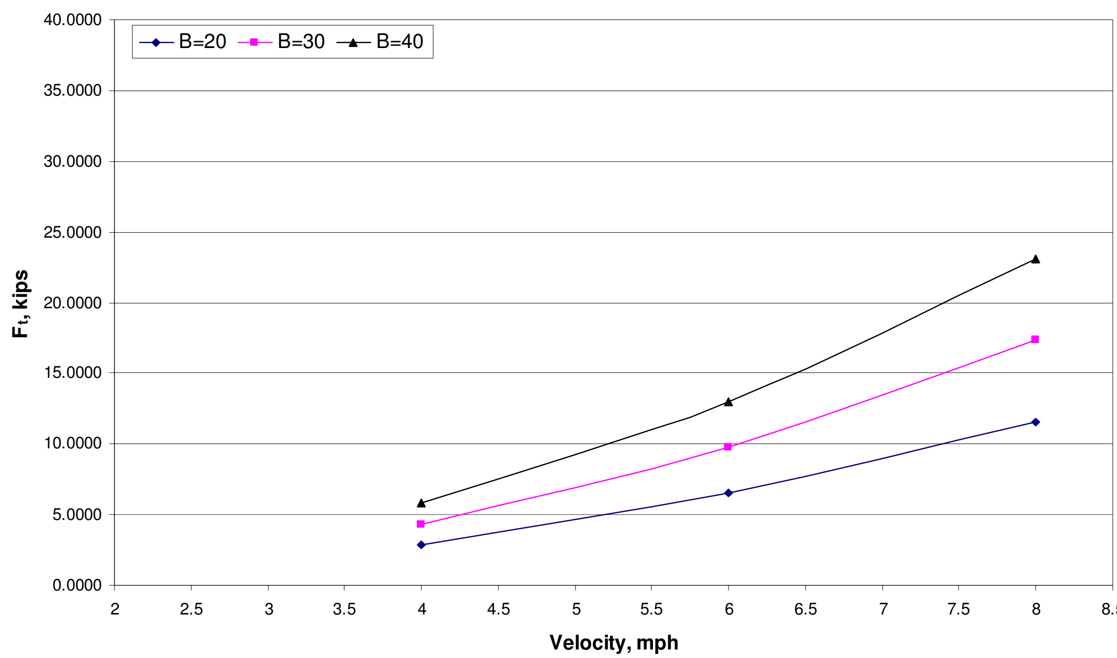


Figure 2.10 A=6, Velocity vs. F_t

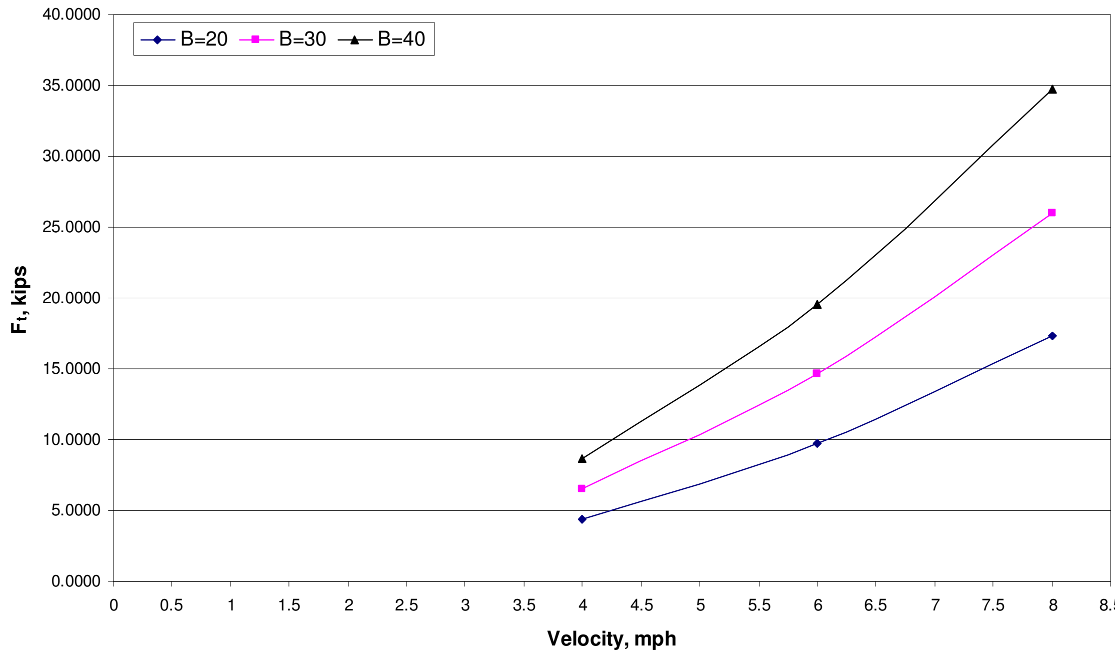


Figure 2.11 A=9, Velocity vs. F_t

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 ($P - \Delta$ effect) and/or material non-linearity under constant gravity loads and incrementally increasing lateral loads or vice versa.

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 2.12 (GTSTRUDL 2002). 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 stages of loading (see Figure 2.13a) (GTSTRUDL 2002). 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 2.13b) (GTSTRUDL 2002). 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.

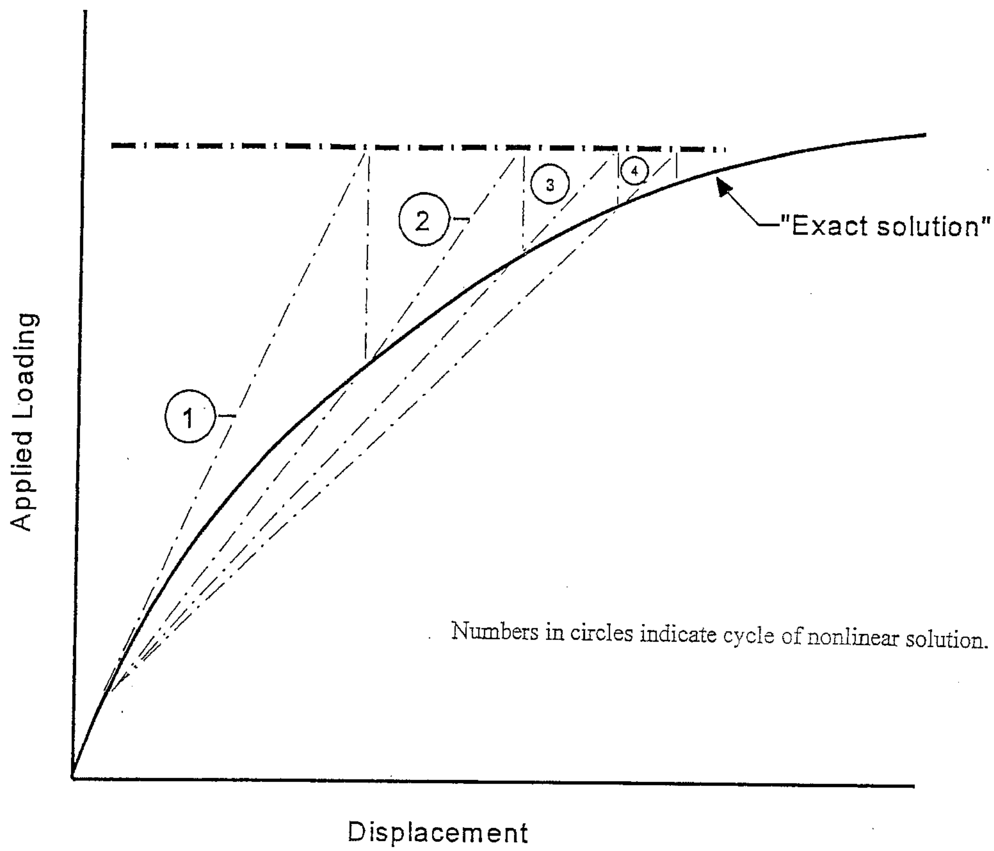
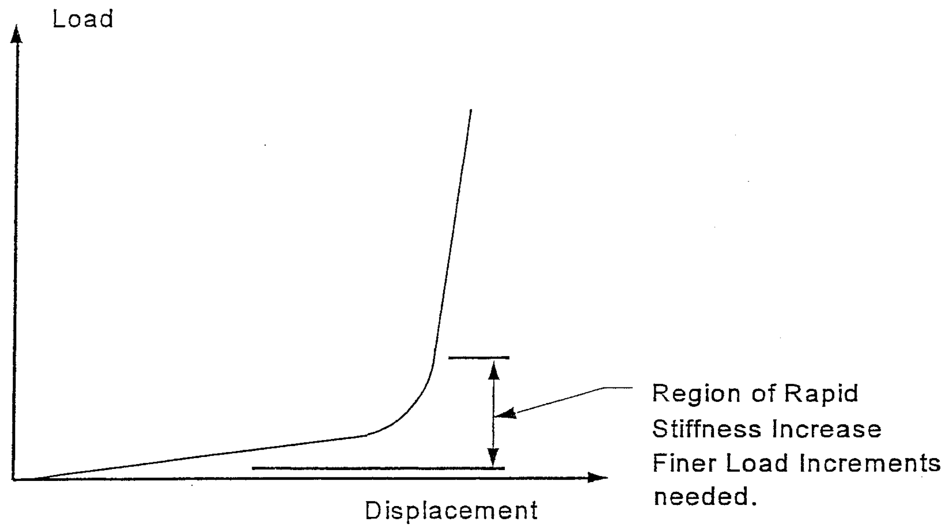
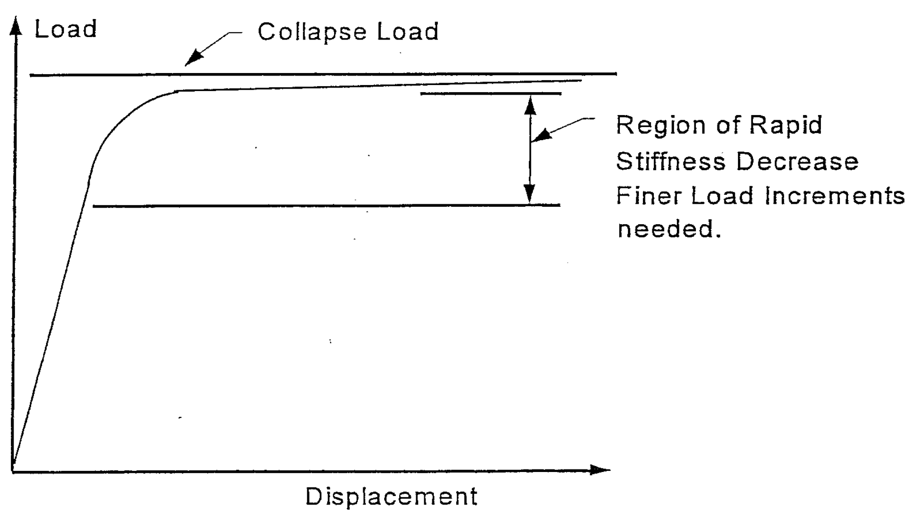


Figure 2.12 Direct Iteration Solution Procedure (GTSTRUDL 2002)



a) Typical Stress-Stiffening Response



b) Typical Instability Response

Figure 2.13 Examples of Nonlinear Response Requiring Load Incrementation (GTSTRUDL 2002)

Pushover analysis is described in GTSTRUDL Reference Manual, Vol. 3 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 (2002). 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.

FB-Pier recently added a pushover tab/analysis capability to their software. Thus, their software can now perform a nonlinear pushover analysis of a pile or pile bent in a soil setting. In the analysis procedure, two load cases are required – one for permanently applied loads and one for loads to be incremented.

The 5-pile bent shown in Figure 2.14 was analyzed via FB-Pier pushover analysis for scour values of S=0’, S=5’, S=10’, S=15’, and S=20’. In the analyses, the 1 kip horizontal force at the bent cap was held constant and the P_{loads} were incrementally increased until FB-Pier would not converge (this was viewed as the failure load). Note in this case, the piles were bending about their weak axis (Y – Y axis). Soil and other parameter values used in the FB-Pier modeling are given in Table 2.3. The resulting P – Δ_{top} curves generated in the analyses are shown in Figure 2.15.

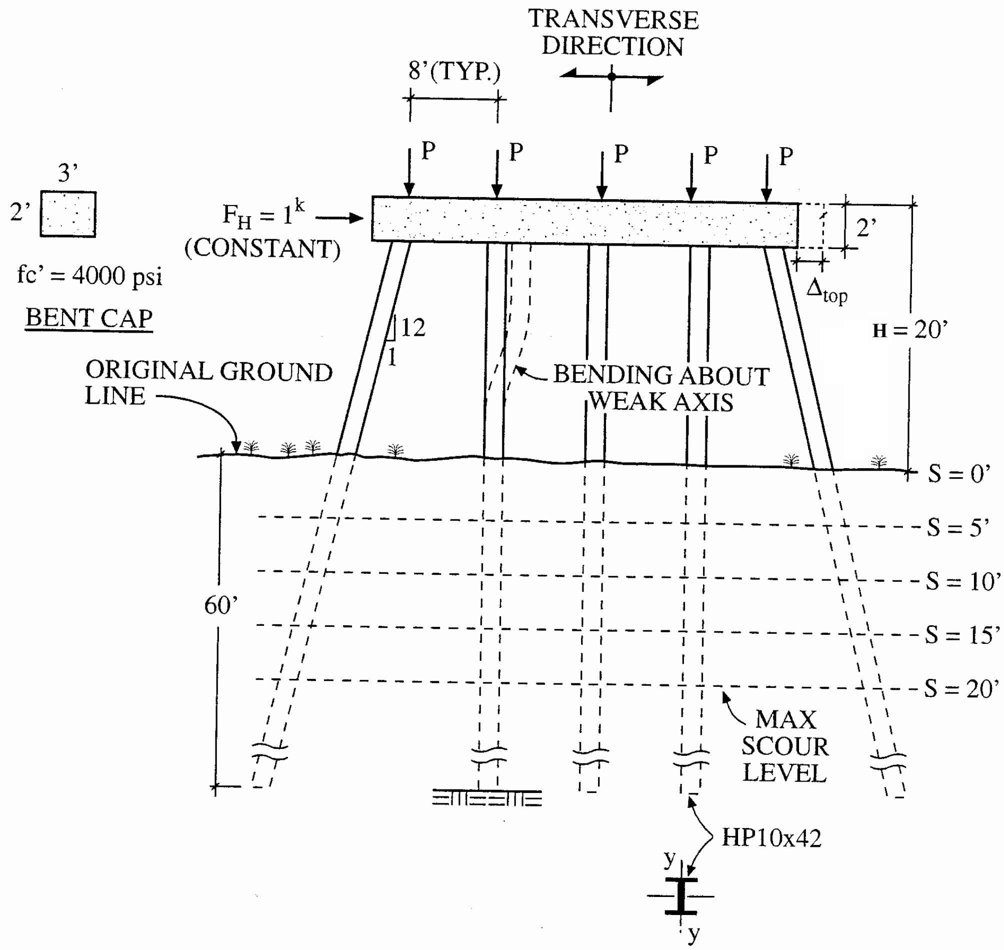


Figure 2.14 Pile Bent Analyzed to Determine P-Δ_{top} Curve in Transverse Direction

Table 2.3 Soil and Other Parameter Values Used in FB-Pier Modeling of Problems Shown in Figure 2.14

Pile: HP10x42	
Pile length: 80 ft	
Initial pile length above ground: 20 ft.	
Sand (Reese):	Unit weight = 120 pcf
	Internal friction angle = 35
	Subgrade modulus = 150lb./in.^3
	Poisson's ratio = 0.3
	Shear modulus = 3.5 ksi
	Vertical failure shear = 1152 psf
	Torsional shear stress = 1152 psf
Tip:	Shear modulus = 3.5 ksi
	Poisson's ratio = 0.35
	Axial bearing failure = 640 kips
Scour depth (ft.):	0, 5, 10, 15, 20

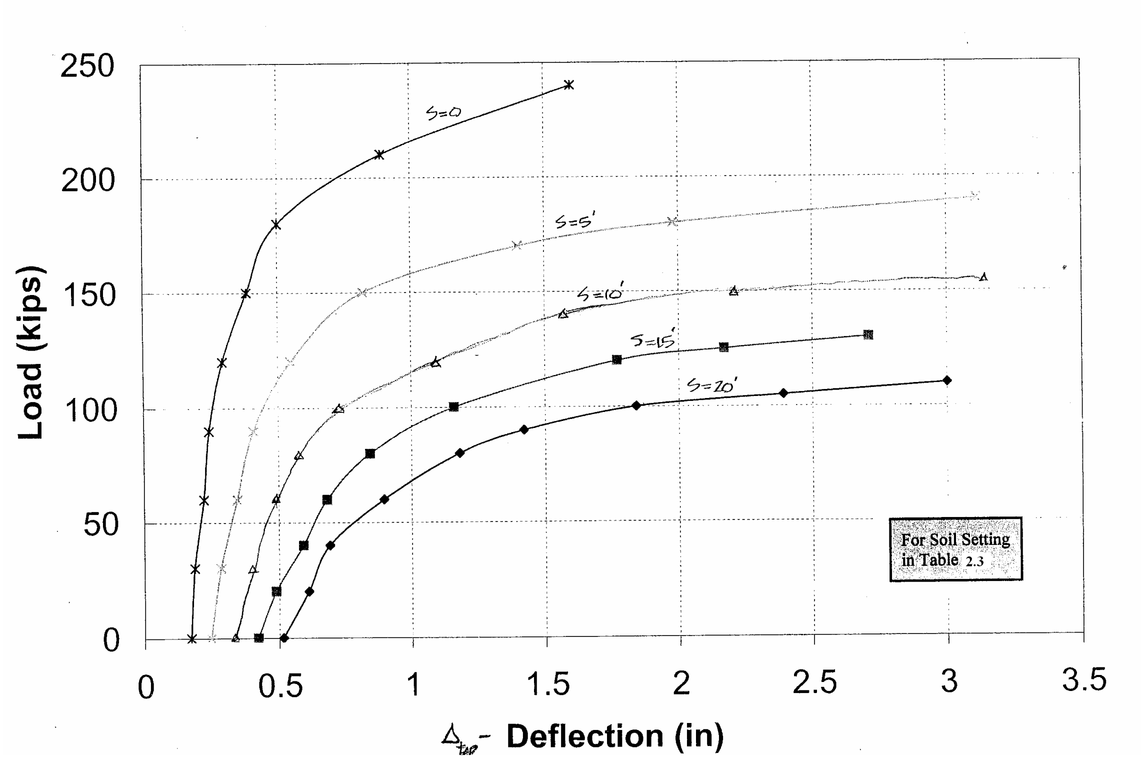


Figure 2.15 P-Δ_{top} Curves in Transverse Direction for HP10x42 Pile Bent in Figure 2.14 (Brown and Ramey 2003)

To determine the sensitivity of pile bent P – Δ_{top} curve in the transverse direction to the end pile batter, the pile bent shown in Figure 2.14 was re-analyzed using FB-Pier, for end pile batters of 1 in 12 or 0.083, 1½ in 12 or 0.125, and 2 in 12 or 0.167. The same soil setting and conditions as identified in Table 2.3 were used in the analyses, and the results are shown in Figures 2.16 - 2.18. These figures illustrate some of the capabilities and values of pushover analyses.

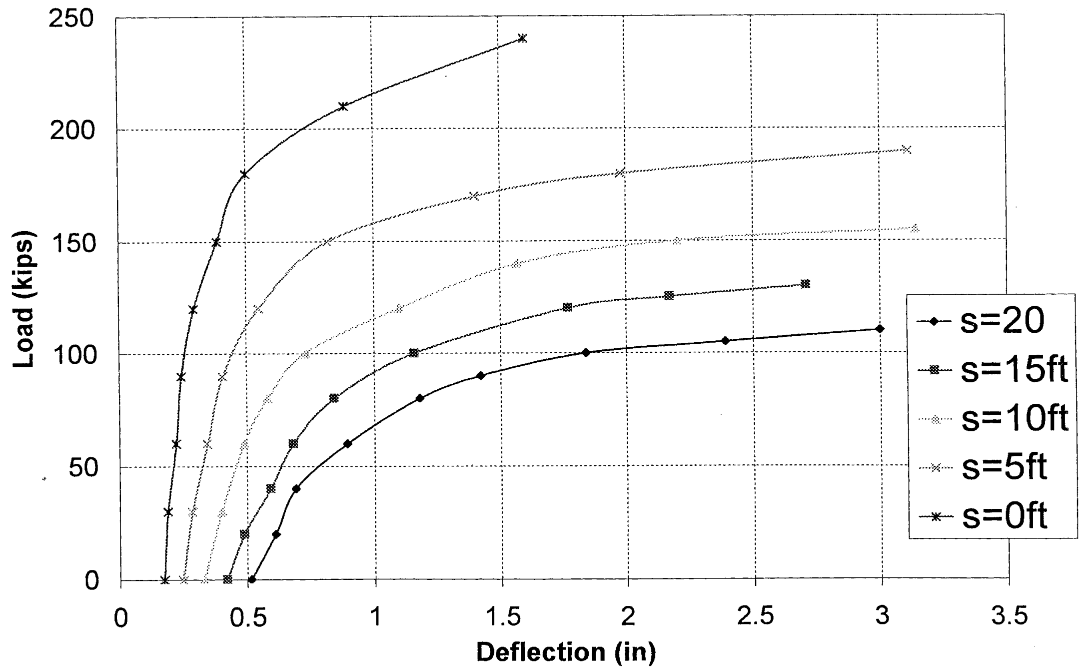


Figure 2.16 P-Δ_{top} Curves in Transverse Direction for Pile Bent in Figure 2.14 for Batter = 0.083 (Brown and Ramey 2003)

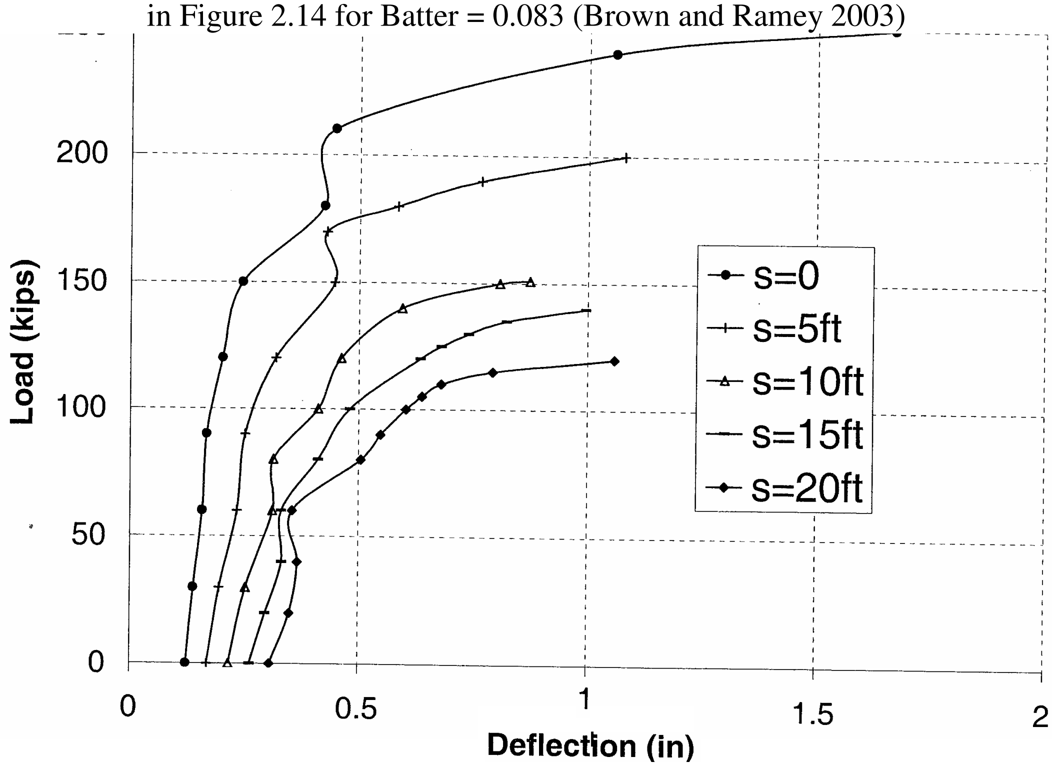


Figure 2.17 P-Δ_{top} Curves in Transverse Direction for Pile Bent in Figure 2.14 for Batter = 0.125 (Brown and Ramey 2003)

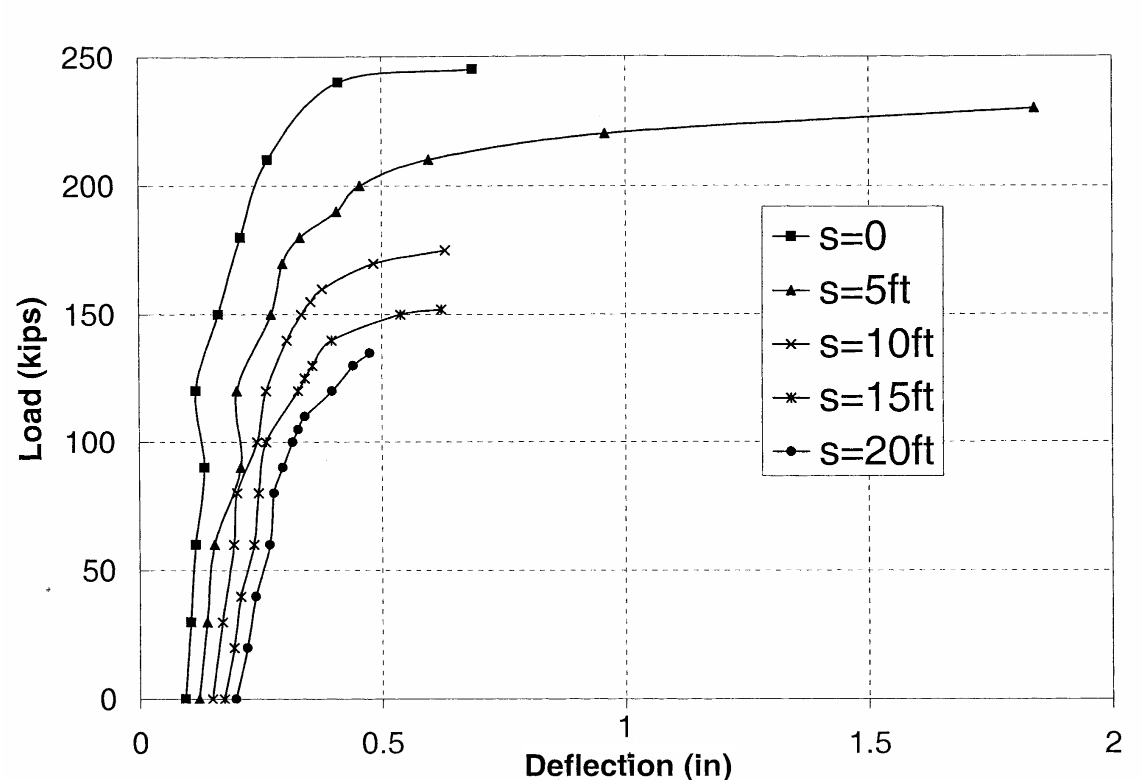


Figure 2.18 P-Δ_{top} Curves in Transverse Direction for Pile Bent
in Figure 2.14 for Batter = 0.167 (Brown and Ramey 2003)

In a preceding separate study for ALDOT, it was found that the most appropriate and sound way to analyze bridge pile bents was using GTSTRUDL's pushover analysis capabilities. Thus, in this study only GTSTRUDL was used to analyze bridge pile bents.

CHAPTER 3: DESCRIPTION OF BRIDGE PILE BENT DEBRIS BUILD-UP AND LOADING MODEL FOR EXTREME FLOOD/SCOUR EVENTS

3.1 GENERAL

Each bridge over water that is supported by pile bents and may be susceptible to an extreme flood/scour event should be checked to make sure that the bent is able to withstand a combined transverse debris raft force, F_t, gravity loads applied by the bridge superstructure, and an extreme level of scour. This transverse load, F_t, can be used to check the bent for a pushover failure from combined gravity and flood water lateral loads in conjunction with the extreme scour of the bent site. The loading model used to assess the adequacy of bridge pile bents when debris build-up is in place was taken from AASHTO C.3.7.3.1 (1997). The debris raft model is shown in Figure 3.1.

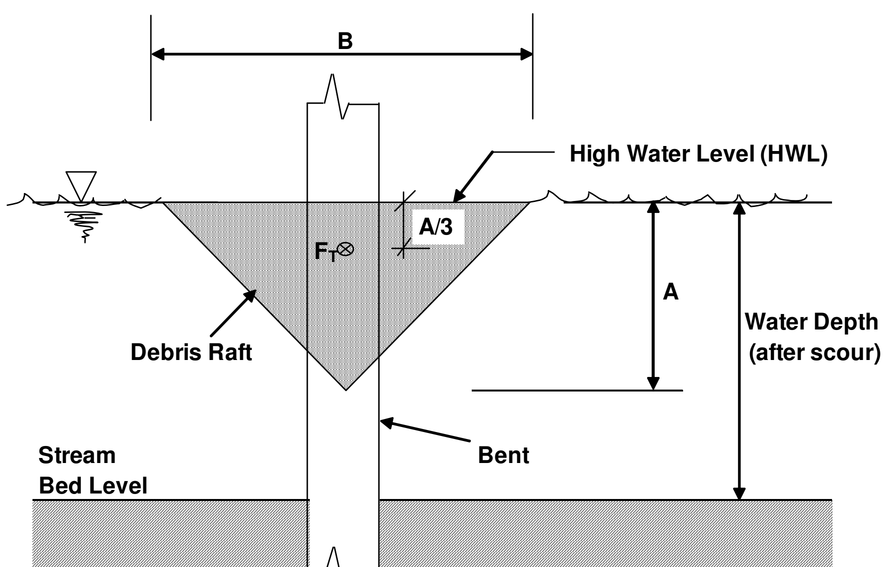


Figure 3.1 Debris Raft for Pier Design (AASHTO 1997)

3.2 DESCRIPTION OF DEBRIS BUILD-UP MODEL

In Figure 3.1, F_t is the flood water force applied to the bridge pile bent due to debris build-up. As discussed in Chapter 2, this force is based on the pressure of the flowing water in kips per square foot, the size of the debris raft in square feet, and C_D, the drag coefficient, which is equal to 1.4 for debris lodged against a pier. F_t is applied at a distance of A/3 down from the water surface as shown in Figure 3.1. The equations to find F_t are given in the AASHTO Specifications and are as follows (1997):

$$p = C_D \times (V^2/1000) \quad \text{where V is in fps and p is in ksf} \qquad (3.1)$$

$$F_t = p \times (1/2 \times A \times B) \qquad (3.2)$$

A = ½ x water depth, but not greater than 10'

B= ½ x sum of adjacent span lengths, but not greater than 45'

As covered earlier, a GTSTRUDL pushover analysis was the method employed to find the pushover values of F_t for different bent sizes and conditions. The GTSTRUDL pushover analysis determines the largest F_t force that a bent can handle before pushing-over, and also calculates the corresponding deflection. Pushover curves with deflection versus the pushover force, F_t, for pile bridge bents commonly used by ALDOT can be found in the Appendices of this report. These curves may be used to find the pushover force, F_t, for a particular bent and loading condition. Once the appropriate F_t for a particular bent is found it may be used in conjunction with the screening tool presented in Chapter 6 of this report to check and see if a failure by pushover is possible or imminent. The debris raft model presented in Sections C3.7.3.1 of the AASHTO was used to decide where the transverse load, F_t, was to be placed on the GTSTRUDL model of the pile bents. The model gives guidelines for where a debris load is likely to impact a bent.

According to the model the debris raft force, F_t, is likely to be applied a distance A/3 from the high water level (HWL). In this study the high water level was always taken at the top of the bent cap. This level was selected because bridge elevations are typically selected so that the HWL does not impinge on the bridge superstructure.

In the debris raft model shown in Figure 3.1, the only value needed to perform a pushover analysis in GTSTRUDL was the value of A. The value of B was not needed to perform the GTSTRUDL analysis because the span length has no effect upon the location of F_t on the bent. The B value does affect the magnitude of F_t, but most spans are short, and a value of B equal to 30 feet was taken for all bridges in determining the force F_t. The location of the force F_t is dependent only on the value of A. As seen in Figure 3.1 the location of F_t is located at a distance of A/3 down from the HWL. Figure 3.2 shows the applied bent force, F_t, for various values of A and B for an assumed V_{design} = 6 mph. To examine a range of values, A was taken as either equal to 3', 6', or 9'. A may not be taken larger than 10' as per AASHTO C3.7.3.1, thus, this range of values was chosen to exhibit the complete combination of possible conditions. It was found that the pushover load when modeling the debris raft with a value of A between A=3', 6', or 9' is somewhat dependent on the amount of scour. If a bent has zero scour the differences between pushover loads for values of A between A=3', 6' or 9' vary slightly. For example, in Figure 3.3 below, pushover load F_t varies by about 7 kips between the two extreme cases of A=3' and A=9'. However, if the bridge has a large scour such as scour equal to 15', the differences between pushover loads for various values of A barely differ at all as can be seen in Figure 3.4.

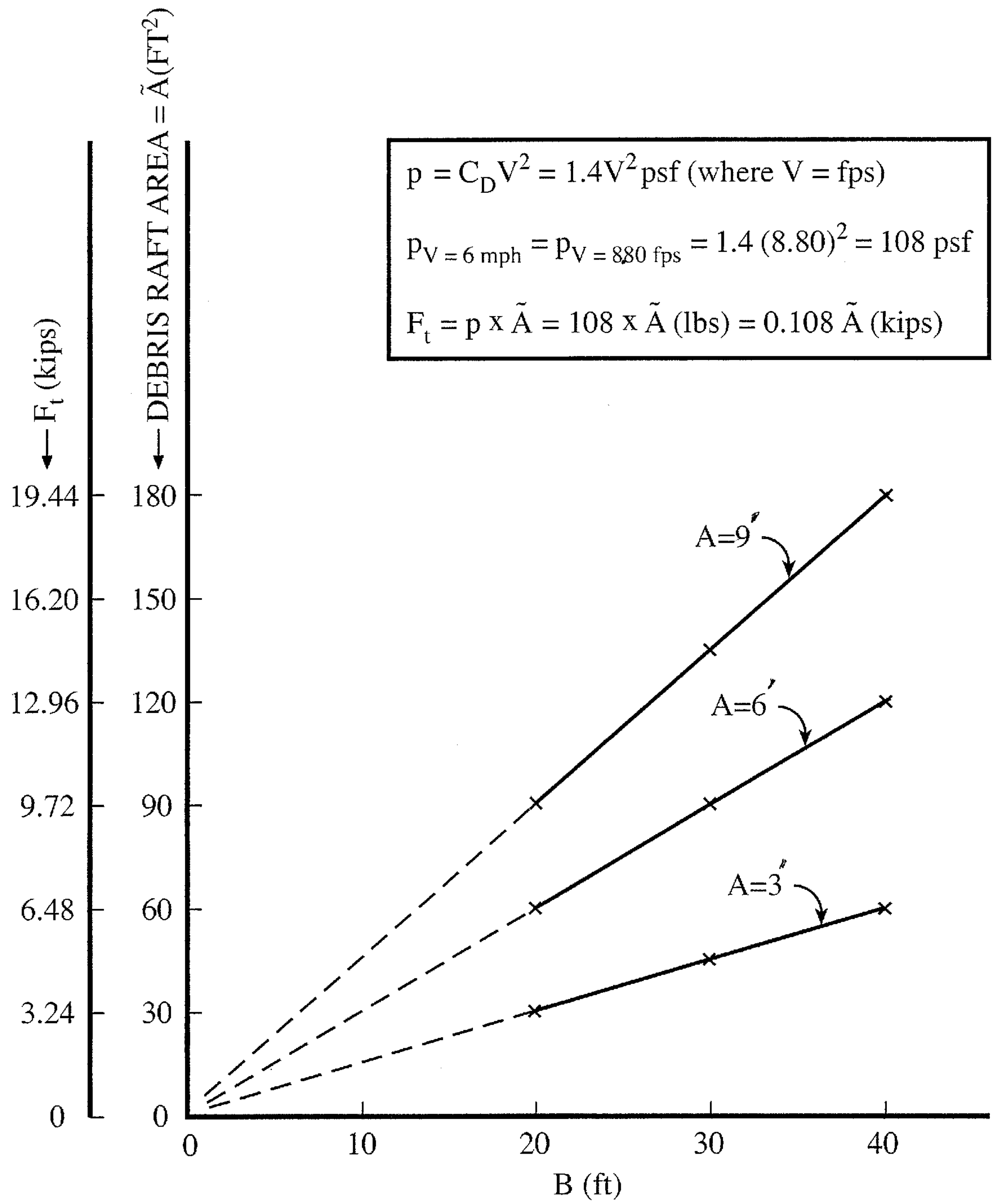


Figure 3.2 Bent F_t Force for Various Debris Raft Dimensions for V_{Design} = 6mph

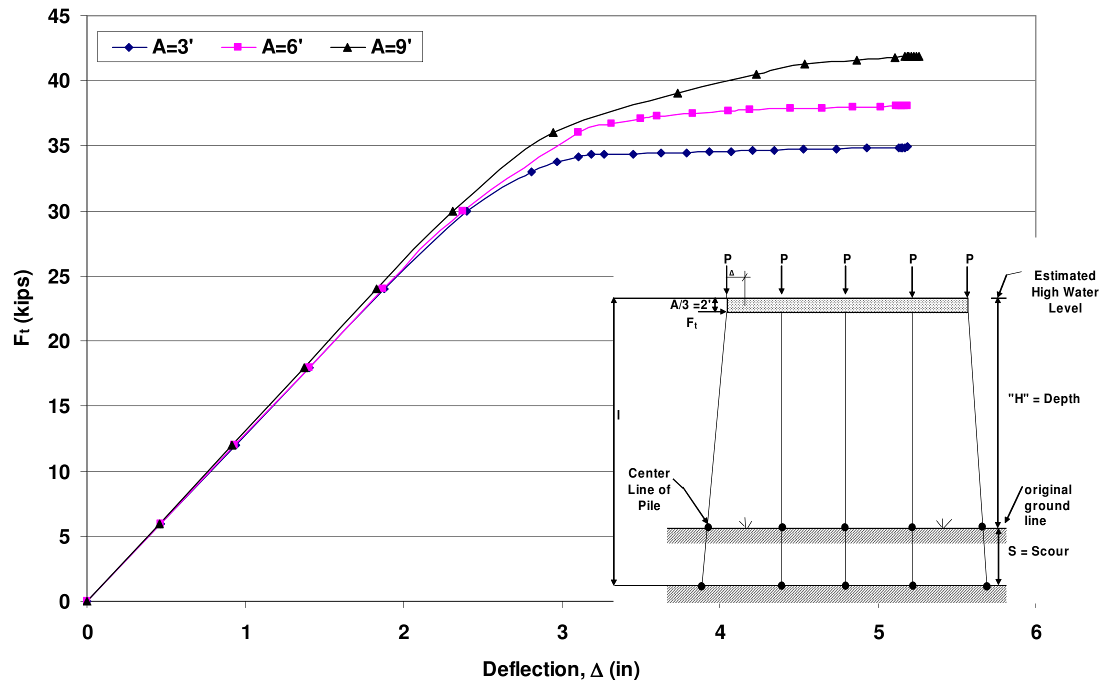


Figure 3.3 HP10x42 Unbraced 5-Pile Bent with H=13', S=0', and P=100kips Pushover Analysis Results

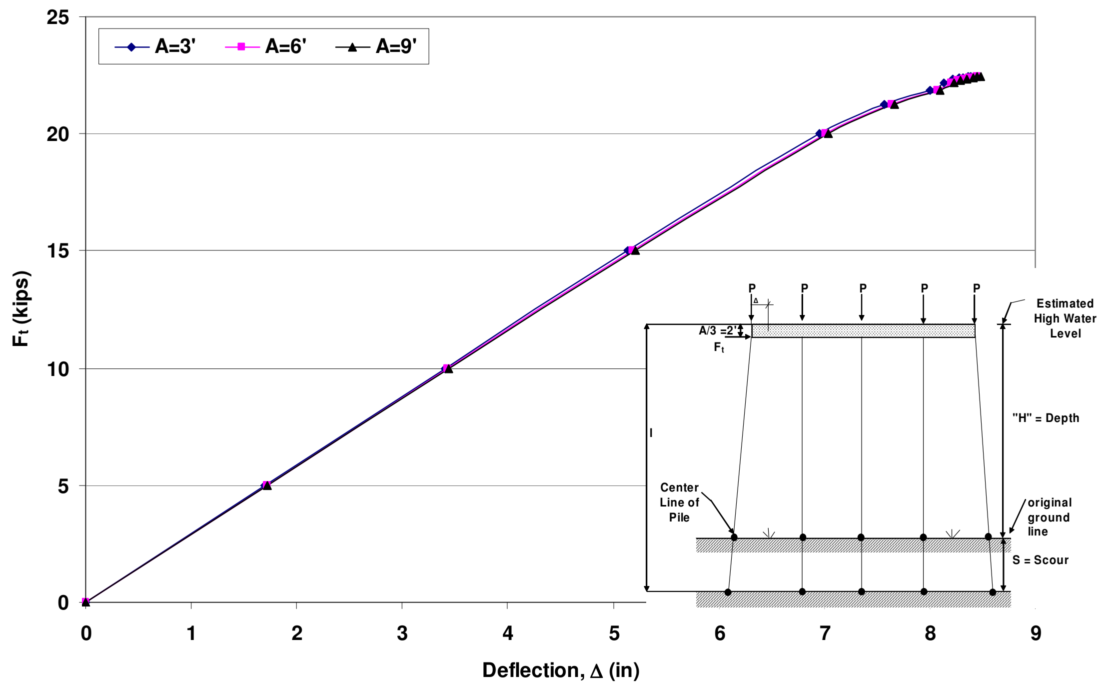


Figure 3.4 HP10x42 Unbraced 5-Pile Bent with H=13', S=15', and P=100kips Pushover Analysis Results

In Chapter 5, A was always taken equal to 6 feet, to simplify the results and to reduce the quantity of pushover curves. If studying a bent with low scours, and the depth of the debris raft is characterized as something other than A=6', then the differences discussed above should be taken into account.

3.3 DESCRIPTION OF LOADING MODEL

Based on the Phase I report submitted to ALDOT by Ramey and Brown (2003), a sampling of the most common pile bents and loading configurations were selected to be studied in greater depth. Bents having 3, 4, 5 and 6-piles were examined. Concentrated gravity P_{loads} of 100 kips, 120 kips, 140 kips and 160 kips were applied to the bents and centered above each of the piles. This range of P_{loads} between 100 kips and 160 kips represents a conservative range of values. These values were determined by using information provided in the Phase I report (Brown and Ramey 2003). Bents having HP10x42 and HP12x53 piles were examined. If the height of the bent is small, i.e., $H \leq 13$ft., the bent may be unbraced, but have the piling encased in concrete. Alternately, if $H \leq 13$ft. the bent piling may be unencased, but be X-braced. If $13\text{ft} < H \leq 19$ft. the bent will always be X-braced, and if $20\text{ft} < H \leq 25$ft the bent will have vertically stacked X-bracing (two-stories). The 3, 4, and 5-pile X-braced bents are single X-braced (either one-story or two-story bracing); however, the 6-pile bents may have side-by-side X-bracing or double X-bracing.

In this study, in the GTSTRUDL Pushover Analysis, the horizontal, F_t, force is the force being incremented and simulating the presence of a flood water loading condition and a debris raft buildup. An example of a typical bent loading condition may be seen in Figure 3.5.

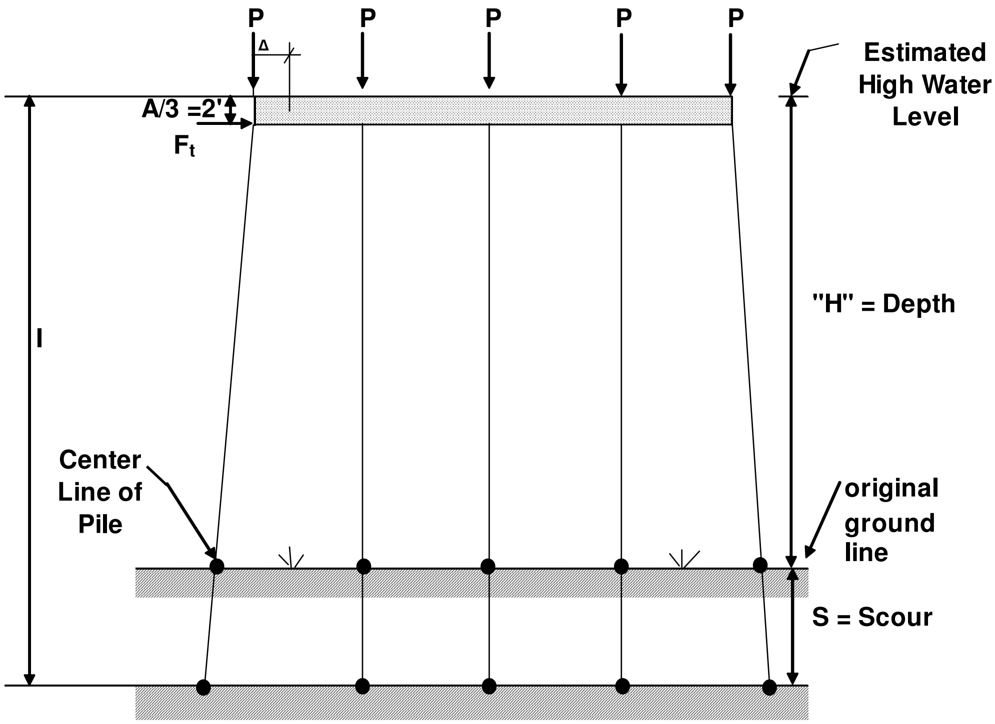


Figure 3.5 Typical Unbraced Bent and Typical Loading Conditions

The black dots at the bottom of the piles in Figure 3.5 represent pinned connections. Pinned connections at the ground line were used after determining that this would be the best method for modeling the end conditions. Two other bent pile end conditions were considered, those being fixed and fixed with an added 5' of exposed pile length. This added 5' of length to the end of the pile was determined by a preceding separate study. It is realized that in actual site conditions the actual fixity condition may be something in between pinned and fixed conditions. This presents some amount of inaccuracy into this study, and should be taken into account if it is known that the fixity conditions are something other than pinned. In conclusion of this study, it was determined that pinned connections would be the most conservative approach to take; thus, all pushover analyses were performed using pinned end conditions.

On X-braced bents there are dots where the X-bracing connects to the bent piles. A picture of a typical X-braced bent may be found below in Figure 3.6. The black dots connecting the X-bracing to the bent piles simply represent locations where the X-bracing is connected to the piles in the bent, and do not represent hinges or pins.

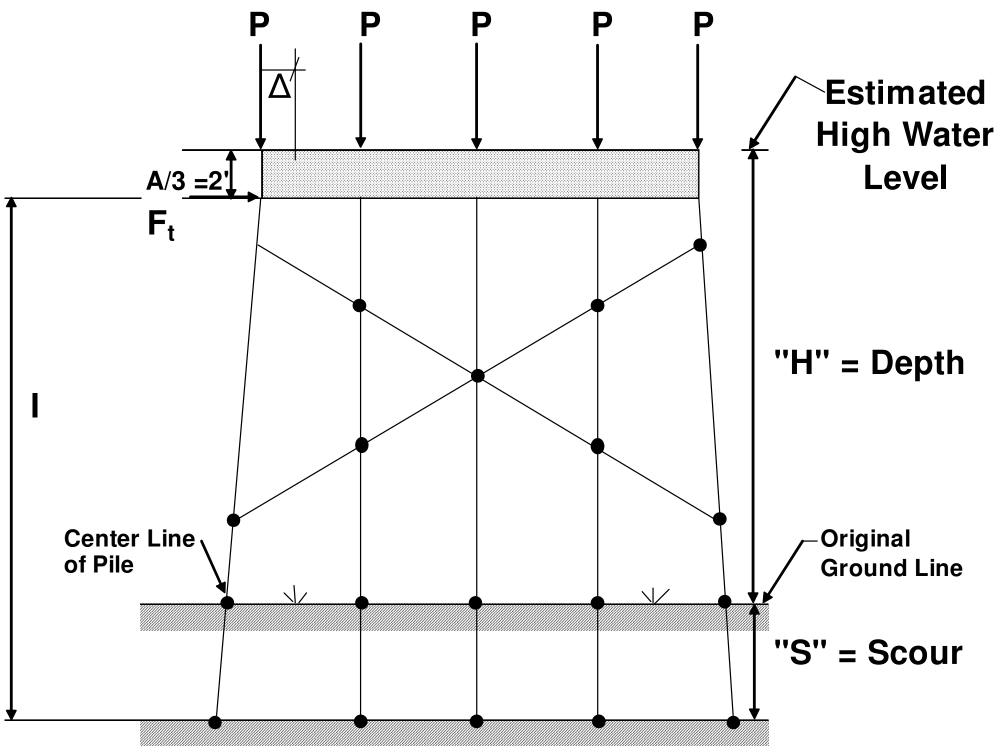


Figure 3.6 Typical X-braced Bent and Typical Loading Conditions

On the F_t versus deflection pushover curves presented in the Appendices A and B, drawings of the bent and the particular loading condition are given on each graph for clarity on the bent geometry, bracing condition, and loading condition represented by the P-Δ curves of that figure.

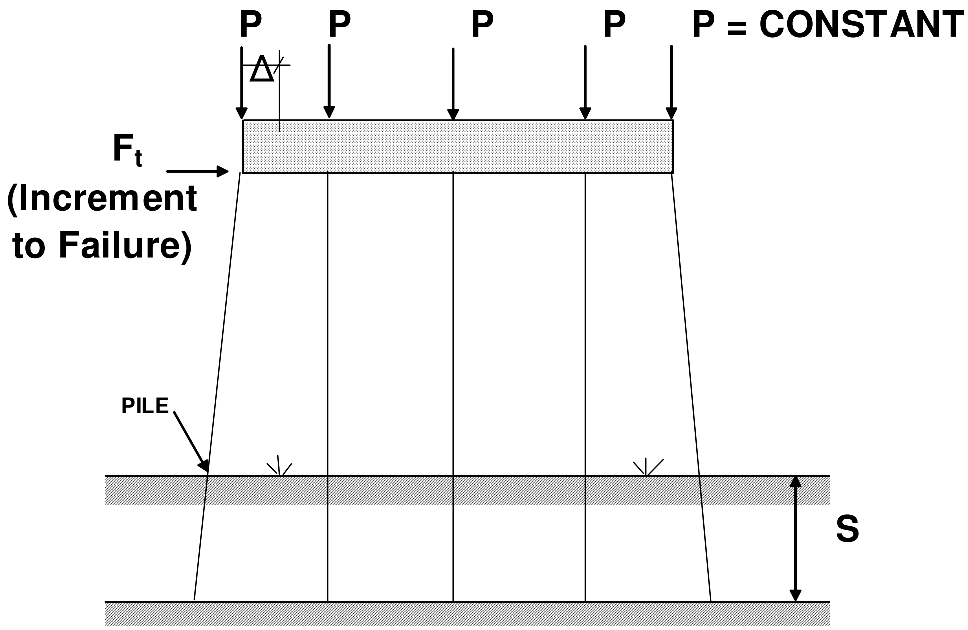
CHAPTER 4: POTENTIAL MODES OF PILE BENT FAILURE DURING FLOOD DEBRIS BUILD-UP AND SCOUR EVENTS

4.1 GENERAL

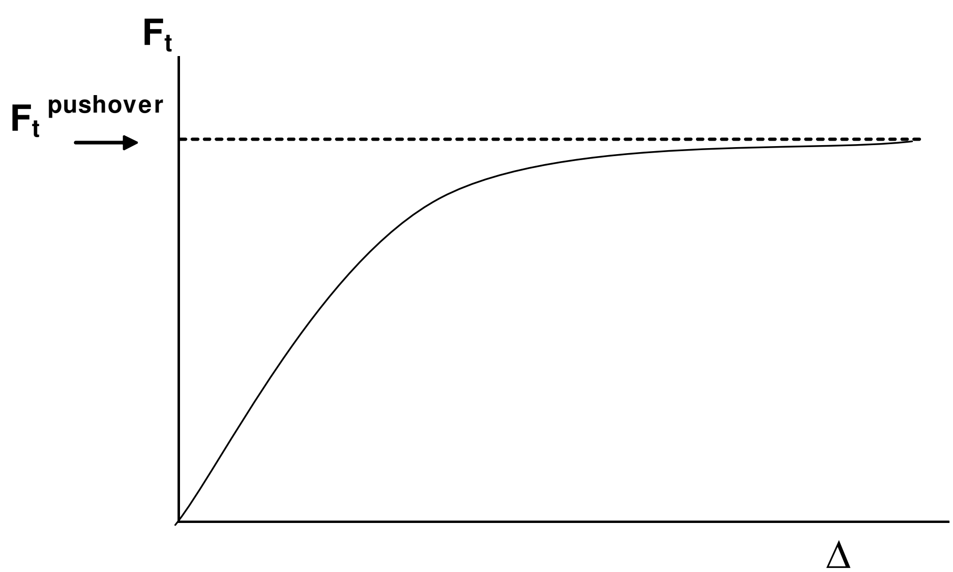
Extreme flood/scour event loadings, in conjunction with ever present gravity P-loads on a bridge pile bent can be a controlling load condition if the bent transverse load, F_t, and scour, S, are large (see Figure 4.1). Even for bents which are X-braced in the transverse direction, a significant P-Δ effect and a bent pushover failure may be possible in the region from the new ground line (NGL) to approximately 4 feet above the original ground line (OGL) as indicated in Figure 4.2. Additionally, for extreme flood/scour events, bent pile "kick-out" failures may occur if the level of scour approaches that of the original level of pile embedment as indicated in Figure 4.3. Each of these potential failure modes is discussed in the sections below.

4.2 PILE BENT PUSHOVER FAILURE

It is possible for a pile bent to fail due to pushover, and the presence of scour and a debris load in a flood condition make a failure due to pushover more probable. To determine the maximum applied bent flood water load, F_t, the current ALDOT 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. It should be performed prior to applying the “screening tool” to assess the adequacy of a bridge bent during an extreme flood/scour event.



a. Gravity + Flood Water Loaded Pile Bent



b. Bent Pushover Curve

Figure 4.1 Typical Nonlinear Pile Bent Pushover Curve

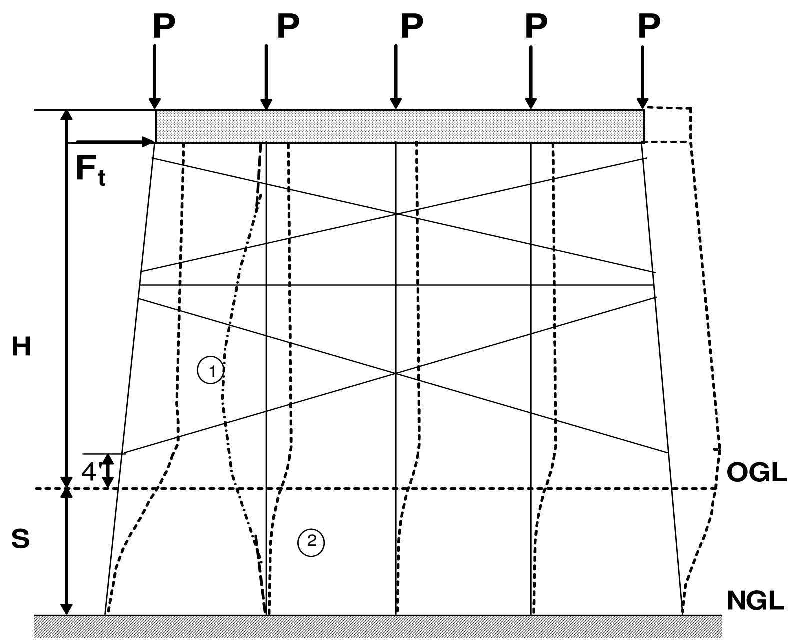


Figure 4.2 X-Braced Pile Bent Sidesway Buckling or Pushover Failure Load

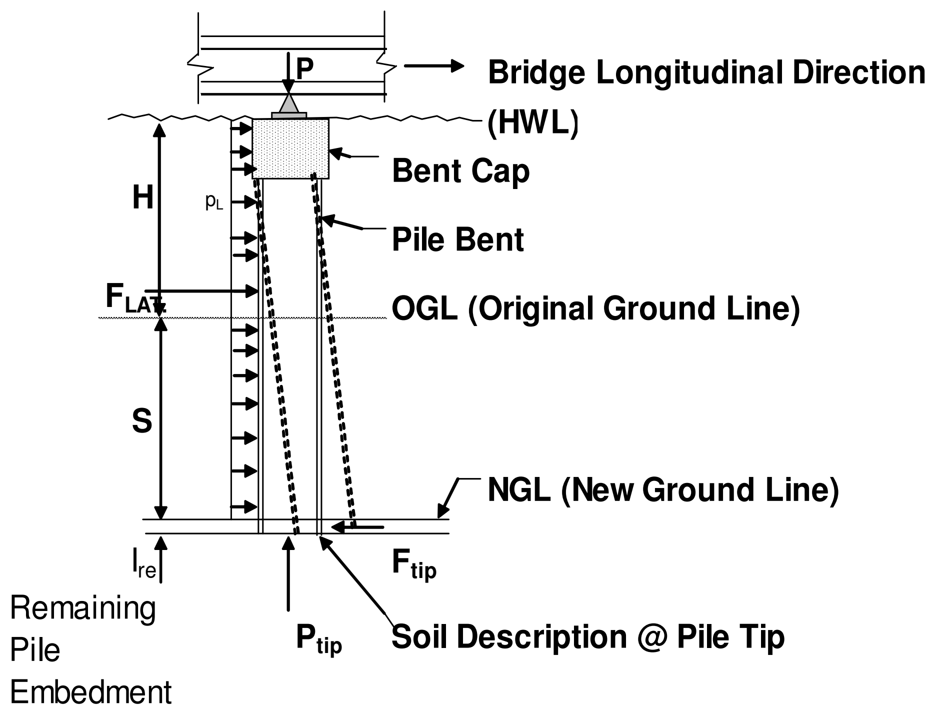


Figure 4.3 Evaluation of Bent Pile "Kick-Out" Load from Extreme Flood/Scour Event

The parameters below are identified and/or defined in Figures 4.4 and 4.5, and the guidelines and procedure for determining F_t are presented in Figure 4.5. The variations in the F_t force over a wide range of debris raft dimension A and B are shown in Figure 4.6.

Estimated flood high water level (HWL)

Max flow depth after scour = HWL –OGL + S

Is a formation of a debris raft possible ? π^{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), which is assumed to be at the top of the bent cap.

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, a lateral (lateral to the bridge or in the plane of the bent) flood water loading, F_t, applied near the top of the bent, and an extreme flood level of scour, S, nonlinear analyses (considering geometric and material nonlinearity) of the bent were performed in this study using the pushover analysis subprogram in GTSTRUDL. This subprogram basically models the pile bent as shown in Figure 4.1a (or an X-braced pile bent) 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. In this study, the latter loading variation was implemented. The program modifies the bent stiffness matrix after each load increment, via working with the deformed geometry and member stress-strain, and thus E values, for each load increment. In this manner the bent load-lateral deflection curve, i.e., pushover curve is generated (see Figure 4.1b) as is the bent F_t pushover load for a given bent and P-load level.

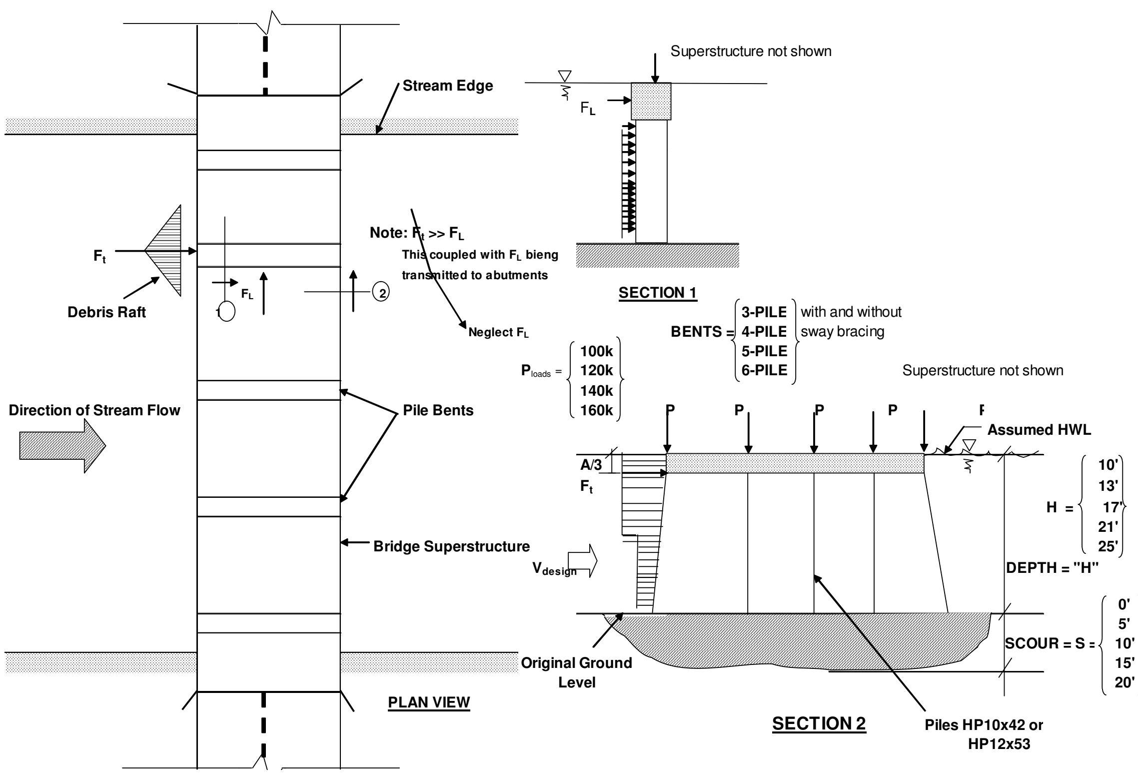
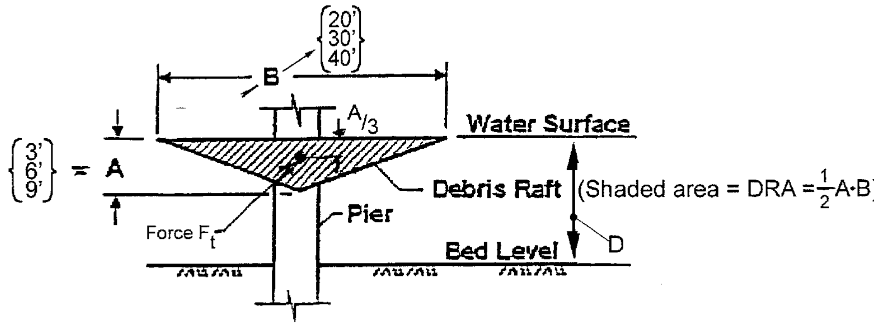


Figure 4.4 Typical Pile Bent Support Bridge Over Stream



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

$$F_t = p\ x\ DRA$$

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

Figure 4.5 Debris Raft and Flood Water Load for Checking Adequacy of Pile Bent During Major Flood Event (AASHTO 1997)

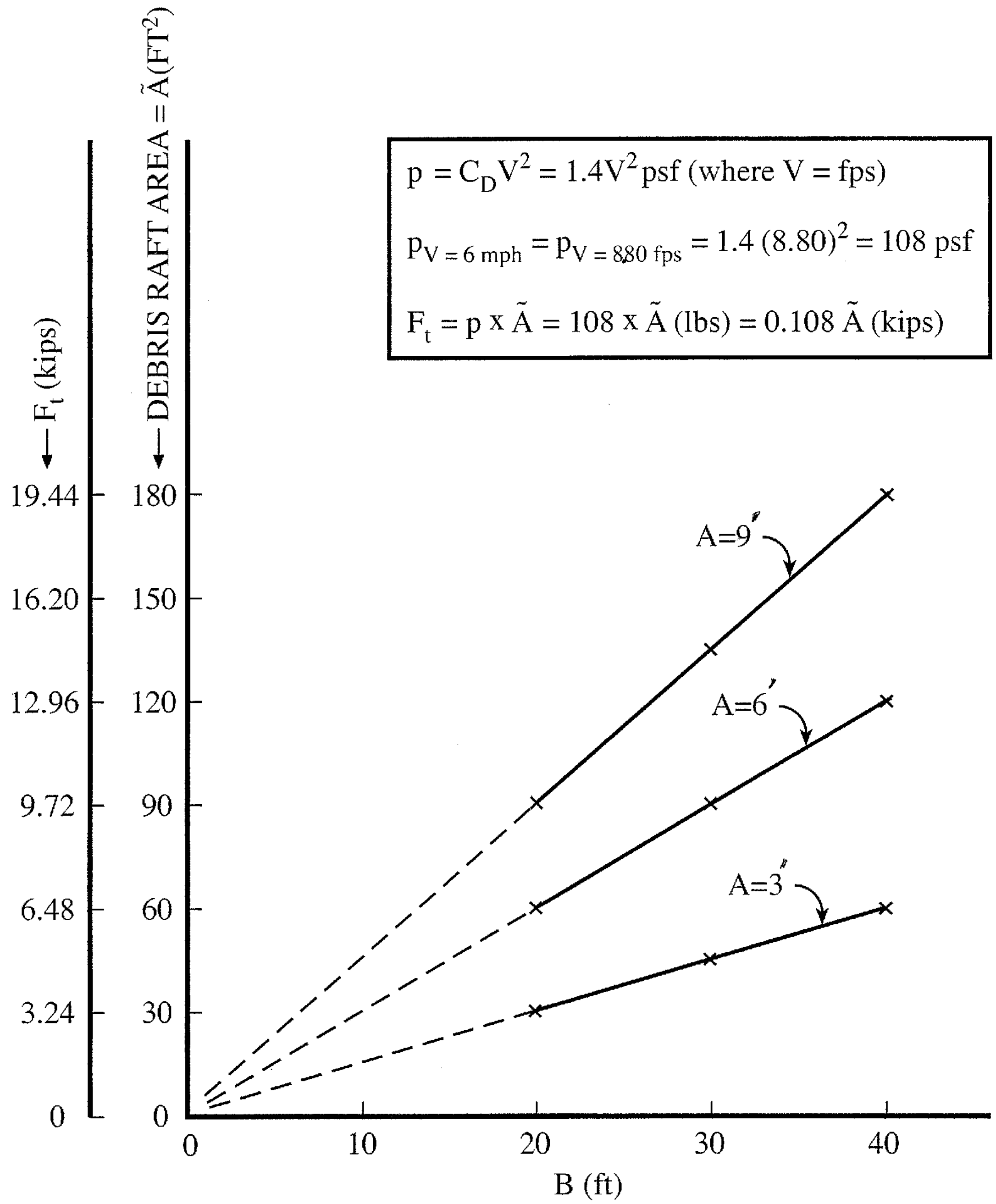


Figure 4.6 Bent F_t Force for Various Debris Raft Dimensions for V_{Design} = 6mph

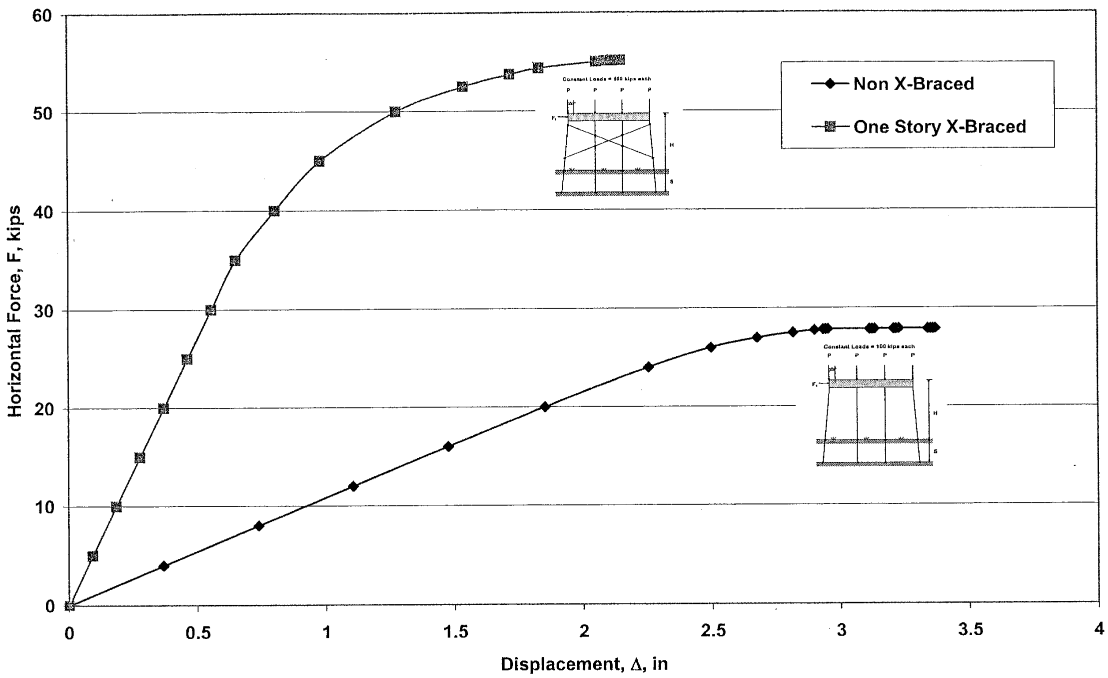


Figure 4.7 GTSTRUDL Pushover Analysis Results for HP10x42 4 Pile Bents, Bents Pinned at Ground, H=13ft, S=0ft

Typical GTSTRUDL bridge pile bent pushover curves for an X-braced and unbraced bent are shown in Figure 4.7. 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, geometry 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.

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, and maximum anticipated level of scour, S, should be checked to make sure that this F_t load is not greater than the bent F_t pushover load under the same gravity loading and scour conditions. Since, the pushover analysis is a nonlinear analysis which considers both the geometric and material nonlinearities present, it implicitly checks for possible buckling of the bent as well as failure due to inadequate strength or stiffness.

4.3 PILE BENT "KICK-OUT" FAILURE

Failure of a pile bent due to kick-out is also possible, especially when large amounts of scour exist in an extreme flood event. This situation is exasperated when the flow of water is at an angle to the pile bent. To determine the maximum applied bent "kick-out" flood water force, F_{tip}, ALDOT's current bridge/bent information database may need to be expanded to include the additional parameter values listed below.

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

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 (See Figures 4.8 and 4.9). It should be performed prior to applying the "screening tool" to assess the adequacy of a bridge bent during an extreme flood/scour event.

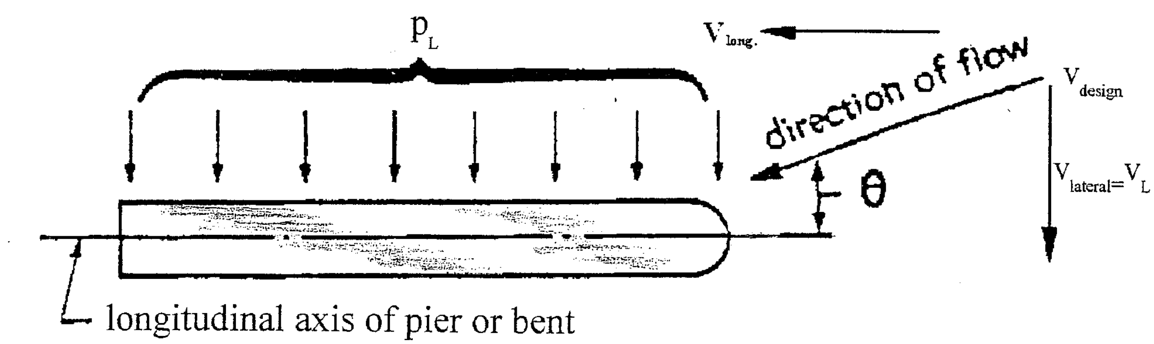


Figure 4.8 Plan View of Pier Showing Stream Flow and Lateral Pressure (AASHTO 1997)

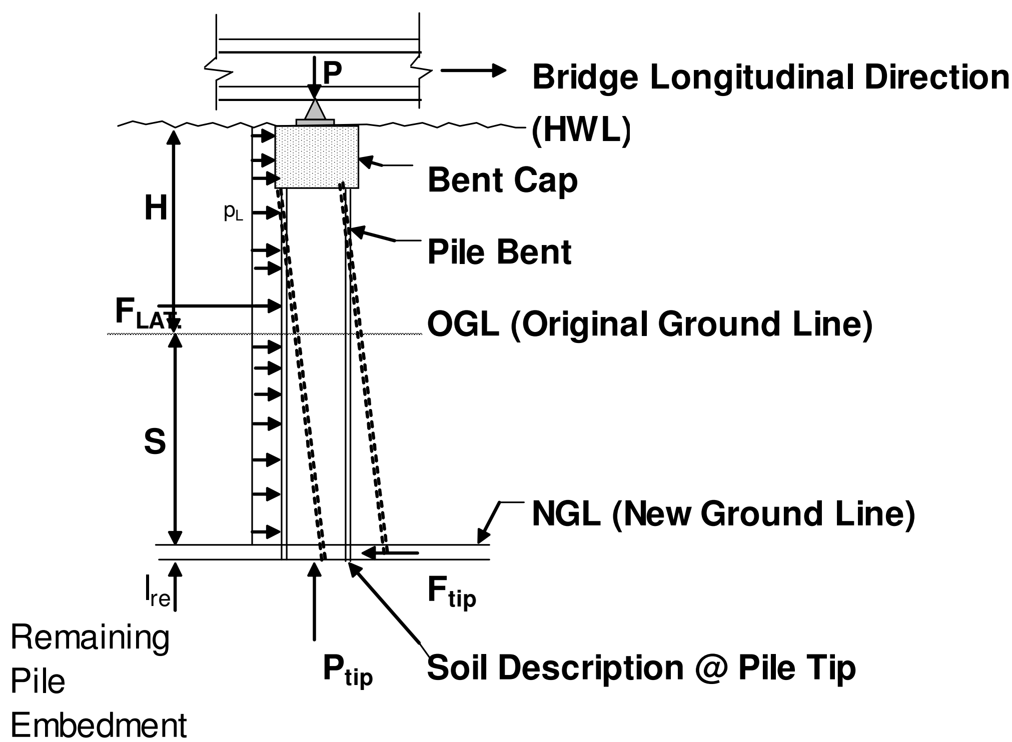


Figure 4.9 Evaluation of Bent Pile "Kick-Out" Load from Extreme Flood/Scour Event

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 that 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 (see Figures 4.8 and 4.9) 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 physics would indicate that the V_{Design} should be broken up into $V_{Lateral}$ and $V_{Longitudinal}$ as shown in Figure 4.8. 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,

$$p_L = C_{DL}\ V_L^2$$

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 indicated in Figure 4.8. 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 lateral pressure, p_L, shown in Figure 4.8 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 Probable Angle, Θ = 20°	Estimated Upper Bound Angle, Θ = 30°
V_{Design}	6.0 mph = 8.8 fps	6.0 mph = 8.8 fps
C_{DL}	2.0	2.0
$V_L = V_{Design} \sin \Theta$	3.0 fps	4.4 fps
$p_L = C_{DL}\ V_L^2$	18.1 psf	38.7 psf

The lateral drag force on a bent pile (lateral to the longitudinal axis of the bent) will be the lateral pressure, p_L, times the projected area of the pile on a vertical plane perpendicular to V_L, and will be as shown in Figure 4.9.

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

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

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

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

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

Values for F_{Tip} for HP10x42 and HP12x43 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.

To determine a possible pile "kick-out" failure, one need only determine the applied F_{Tip} (see Figure 4.9), which are given in Table 4.4 for various design parameter values. Then, check to make sure that the remaining pile tip embedment after scour, l_{re} exceeds the required values shown in Table 4.5 for the existing tip soil setting, i.e.

$$l_{re} > l_{re}^{required}$$

Estimated values of $l_{re}^{required}$ for various soil types at the pile tip and pile $F_t^{applied}$ values are given in Table 4.5. It is assumed that if a bent pile is safe from "kick-out", then the bent is safe from "kick-out".

Table 4.4 Applied F_{Tip} values for HP10x42 and HP12x53 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°	
	HP10x42 Pile	HP12x53 Pile	HP10x42 Pile	HP12x53 Pile
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

Table 4.5 Estimated Pile Embedment Required After Scour for Various Tip Geological Settings to Have Adequate Lateral $F_{t\ Capacity}$ for the Magnitudes of $F_t^{applied}$ Shown in Table 4.5

Tip Soil Type	$l_{re}^{required}$ (ft)		
	100lb < $F_t^{Applied}$ < 400lbs	400lb < $F_t^{Applied}$ < 700lbs	700lb < $F_t^{Applied}$ < 1,000lbs
Firm/Hard Clay	1.0	1.5	2.0
Very Firm/Very Hard Clay	0.5	1.0	1.5
Weathered/Broken Limestone	0.3	0.5	0.7
Limestone	0.2	0.3	0.4

CHAPTER 5: ANALYSES OF ALDOT PILE BENTS SUBJECT TO SCOUR AND GRAVITY AND FLOOD WATER LOADINGS

5.1 GENERAL

The ALDOT commonly uses 3, 4, 5, and 6-pile bents, with the piles being HP10x42 or HP12x53, to support deck-girder bridge superstructures. If the height of the bents is small, i.e., $H \leq 13$ ft., the bents may be unbraced but have the piling encased in concrete. Alternately, if $H \leq 13$ ft. the bent piling may be unencased, but be X-braced. If 13 ft $< H \leq 19$ ft. the bents will always be X-braced, and if 20 ft $< H \leq 25$ ft the bents will have vertically stacked X-bracing (two-stories). The 3, 4, and 5- pile X-braced bents are single X-braced at each story level; however, the 6-pile bents may be single X-braced or double X-braced. If the bridge crosses a stream, the bents may be subjected to large scours during extreme flood events. This scour "loading", in combination with gravity dead and live P-loads acting on the bent cap immediately above each bent pile, and a lateral (lateral to the bridge or in the plane of the pile bent) F_t flood water loading acting at or near the top of the bent can cause a pushover failure of a bent during an extreme flood/scour event. Bent pushover loads for the bents and conditions described above, where the bent height may be 10 ft $\leq H \leq$ 25 ft, the level of scour be 0 ft $\leq S \leq$ 20 ft, and gravity P-loads being 100 kips $\leq P \leq$ 160 kips were performed using GTSTRUDL Pushover Analysis, and the results are presented in the sections below.

5.2 3-PILE HP10x42 BENT WITHOUT X-BRACING

The 3-pile HP10x42 bent without X-bracing is the most volatile of all pile bent configurations. Results of the pushover analyses for the 3-pile HP10x42 bent without X-bracing can be found in Figures A.1 – A.8. The pushover force for a HP10x42 3-pile bent with no scour (S=0'), a P_{load} of 100 kips, A=6', and a height of 10 feet (H=10') was found to be 21.23 kips. The pushover force for the same bent having the same parameters with H=13' was found to be 13.79 kips. This small increase in height from the 10' bent to the 13' bent results in a 35% decrease in the pile bent capacity to resist pushover (S=0', P=100 kips). Also to be noted is the large decrease in pushover capacity when S=5'. For example, when H=13' the pushover force was found to be half of the force needed to pushover the bent when no scour occurs on the bent (P=100 kips). The H=10' bent was found to have a pushover force, F_t = 2.29 kips when P=120 kips and S=10'; when H=13', P=120 kips and S=10' the pile bent was found to be unstable. Both the 10' tall bents as well as the 13' tall bents were found to be unstable in all instances when S=15' and S=20'. As anticipated, when increasing the P_{load} from P=100 kips, to P=120 kips, to P=140 kips, and finally to P=160 kips, reductions in the force causing pushover were found. Table 5.1 summarizing the results is shown below.

Table 5.1 Pushover Capacities of a HP10x42 3-Pile Bent without X-Bracing With H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.1-A.8

5.3 3-PILE ONE-STORY HP10x42 X-BRACED BENT

Adding X-bracing to the 3-pile H=13' and H=17' bent greatly increases the pushover capacity of the 3-pile bent. When H=13', the 3-pile one-story HP10x42 X-braced bent with P=100 kips and S=0' has an increase in pushover capacity of 212% over its non X-braced counterpart. The pushover force for an HP10x42 3-pile X-braced bent with no scour (S=0'), a P_{load} of 100 kips, A=6', and a height of 13 feet (H=13') was found to be 43.03 kips, and in the same loading conditions with H=17' the pushover force was found to be 41.5 kips. The H=17' bent has pushover capacities just under the H=13' bent as expected. The H=13' bent has a pushover capacity of 1.15 kips when the P-load = 100 kips and S=15'; whereas the H=17' bent with the same parameter values was found to be unstable. Both the H=13' bent and the H=17' bent were found to be unstable at all instances when S=20'. Table 5.2 displays the pushover analyses results for the H=13' and H=17' 3-pile X-braced bent, and the results are displayed graphically in Figures A.9-A.16.

Table 5.2 Pushover Capacities of a HP10x42 3-Pile
X-Braced Bent with H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.9-A.16

One alarming detail about these particular types of bents is the substantial loss in pushover capacity after just 5 feet of scour is imposed on the bent. For example, when H=13' and P = 100 kips, a 27.07 kip reduction in bent pushover capacity is found when going from S=0' to S=5'. This is a 67% reduction in capacity, and similarly when H=17' a 65% reduction occurs when just 5 feet of scour is imposed on the bent and P=100 kips. Figures A.9 - A.16 display the various pushover analysis results for the 3-pile one-story HP10x42 X-braced bents with H=13' and H=17'.

5.4 3-PILE TWO-STORY HP10x42 X-BRACED BENT

The two-story 3-pile X-braced bent with H=21' and H=25' performs not too unlike the one-story X-braced H=13' and H=17' pile bents. The H=21' and the H=25' pile bents have a slightly higher pushover capacity than the H=13' and H=17' pile bents. Both the H=21' bent and the H=25' bent are found to be unstable in all instances when S=15' and S=20'. Also to be noted, the same deficient behavior occurs when only 5 feet of scour is added to the two-story 3-pile X-braced bent. With H=25' and when P=100 kips there is a 67 % reduction in capacity when only 5 feet of scour is imposed. Table 5.3 displays the various data for the two-story 3-pile X-braced bent pushover loads, and Figures A.17– A.24 display the corresponding pushover graphs.

Table 5.3 Pushover Capacities of a HP10x42 3-Pile Two-Story X-Braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.17-A.24

5.5 4-PILE HP10x42 BENT, WITHOUT X-BRACING

A 76% improvement was found in the 4-pile HP10x42 bent with H=10' and P = 100 kips without X-bracing over the 3-pile HP10x42 bent with H=10' and P = 100 kips without X-bracing; Also, a considerable 119% improvement was found in the 4-pile HP10x42 pile bent with H=13' and P = 100 kips without X-bracing over the 3-pile HP10x42 pile bent with H=13' and P = 100 kips without X-bracing. Also, another notable improvement over the 3-pile non X-braced bent was that the 4-pile non X-braced bent did not lose half of its capacity when only 5 feet of scour was introduced. In fact, a small 25% loss was found when introducing 5 feet of scour with H=10'and P=100 kips, and a smaller 15% loss was found when 5 feet of scour was imposed on the H=13' bent with P=100 kips. There were no 4-pile non X-braced bents found to be unstable due to pushover loads. Table 5.4 displays the numerical results of the 4-pile non X-braced bent, and Figures A.25-A.32 display the graphical $F_t - \Delta$ curves for the 4-pile non X-braced bent.

Table 5.4 Pushover Capacities of a HP10x42 4-Pile Bent without X-Bracing With H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.25-A.32

5.6 4-PILE ONE-STORY HP10x42 X-BRACED BENT

The 4-pile one-story HP10x42 X-braced pile bent showed slight improvement over the 3-pile one-story HP10x42 X-braced pile bent, with H=13' and P=100 kips the pushover force increased 11.96 kips, and the same bent with H=17' the pushover force increased 7.8 kips. However, when 5 feet of scour was imposed on the 4-pile one-story HP10x42 X-braced pile bent with H=13' and H=17' and with P=100 kips, there was found to be a 49% decrease in pushover capacity. The only 4-pile X-braced bent found to be unstable was one with H=17', P=160 kips and S=20'. On the whole the 4-pile one-story HP10x42 X-braced pile bent with H=13' outperformed the 4-pile one-story HP10x42 X-braced pile bent with H=17' when P=100 kips always by an average of 5.5 kips and when P=120 kips, 140 kips and 160 kips by an average of 3.2 kips. One other point of interest is that the 4-pile HP10x42 X-braced bent with H=13' and P=100 kips outperformed the 4-pile HP10x42 bent without X-bracing with H=13' and P=100 kips by 80%. This large increase illustrates the positive effect X-bracing has on these pile bents. However, when S=10' the 4-pile HP10x42 one-story X-braced bent has lower pushover capacities than the 4-pile HP10x42 bent without X-bracing. For example, when S=10' and P = 100 kips the HP10x42 4-pile bent without X-bracing with H=13' had a pushover capacity of 21.66 kips, its counterpart with X-bracing had a pushover capacity of 20.77 kips. This is a 0.88 kip difference in between the two bents, and can almost said to be negligible. This small difference between the non X-braced bent and the X-braced bent occurs for the 5-pile and 6-pile bents as well. It is possible, that this occurrence may be attributed to the fact that when S=10' the X-bracing frames into mid-height of the bent. This may cause the bents to be slightly less stable than its non X-braced counterpart. All of the numerical pushover capacities for the 4-pile, one-story, X-braced bents with H=13' and 17' may be found in Table 5.5 and the corresponding $F_t - \Delta$ pushover curves are shown in Figures are A.33-A.40.

Table 5.5 Pushover Capacities of a HP10x42 4 Pile One-Story X-Braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.33-A.40

5.7 4-PILE TWO-STORY HP10x42 X-BRACED BENT

The 4-pile two-story HP10x42 X-braced bent with H=21' and P=100 kips showed improvement over the 3-pile two-story HP10x42 X-braced bent with H=21'and P=100 kips with an increase in pushover capacity of 16%; and the 4-pile two-story HP10x42 X-braced bent with H=25' and P=100 kips showed a slightly smaller improvement with an 8% increase in pushover capacity over the 3-pile two-story HP10x42 X-braced bent with H=25'and P=100 kips. Also of note when comparing the 4-pile X-braced two-story HP10x42 bent to the 3-pile X-braced HP10x42 bent when H=21', the 3-pile X-braced bent was first found to be unstable when P=160 kips and S=10' also it was found to be unstable when S=15' and 20' for all instances. Conversely, in the 4-pile X-braced two-story HP10x42 bent with H=21' was not found to be unstable until P=160 kips and S=15' and was found to be stable when S=20' for P=100 kips and 120 kips and then again unstable with S=20' and P=140 kips and 160 kips. When H=25' the 3-pile X-braced two-story HP10x42 bent was first found to be unstable when P=140 kips and S=10' (for all load cases and scours over those values, it was found to be unstable as well) and in the 4-pile two-story HP10x42 X-braced bent it was first found to be unstable when P=140 kips and S=15'. The 4-pile bent was then stable again for S=20' with P=100 kips and P=120 kips and then was found to be unstable again when S=20' with P=140 kips and 160 kips.

When comparing the 4-pile two-story X-braced HP10x42 pile bent with H=21' to the 4-pile two-story X-braced HP10x42 pile bent with H=25', the H=21' bent on average has a pushover capacity about 3 kips higher than the H=25' bent. Also, yet again there was over a 50% drop in F_t when adding only 5 feet of scour in both the H=21' and H=25' 4-pile two-story X-braced bents when P=100 kips. The numerical pushover force capacities and the corresponding $F_t - \Delta$ pushover curves for the 4-pile two-story X-braced bents can be found in Table 5.6 and Figures A.41-A.48 respectively.

Table 5.6 Pushover Capacities of a HP10x42 4-Pile Two-Story X-Braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.41-A.48

5.8 5-PILE HP10x42 BENT WITHOUT X-BRACING

The 5-pile HP10x42 non-X-braced bent with H=10' and P=100 kips showed an increase in pushover capacity over the 4-pile HP10x42 non-X-braced bent with H=10' and P=100 kips by 22%. This is an increase in pushover capacity, however, this increase is not as large as the 76% increase previously found in the pushover capacity of the 4-pile HP10x42 non-X-braced bent with H=10' over the 3-pile HP10x42 non-X-braced bent with H=10'. Again the 5-pile HP10x42 bent without X-bracing with H=13' and P=100 kips showed an increase in pushover capacity over the 4-pile HP10x42 without X-bracing with H=13' and P=100 kips by 26%. This increase in pushover capacity is not as large as the 119% increase the same 4-pile HP10x42 non-X-braced bent with H=13' showed over the 3-pile HP10x42 non-X-braced bent with H=13'. These results indicate that the progression of increases in pushover capacities with increased number of piles is slowly starting to level off, however the pushover capacities still continue to gradually rise with increase in the number of piles. On average the pushover capacity of the 5-pile HP10x42 bent without X-bracing and with H=10' was 4.4 kips higher than the 5-pile HP10x42 bent without X-bracing and with H=13'. The numerical data for the 5-pile HP10x42 non-X-braced bent with H=10' and H=13' is displayed in Table 5.7, and the graphical representations of deflection versus F_t for the 5-pile HP10x42 with H=10' and H=13' may be found in Figures A.49-A.56.

Table 5.7 Pushover Capacities of a HP10x42 5-Pile
One-Story Bent without X-Bracing with H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.49-A.56

5.9 5-PILE ONE-STORY HP10x42 X-BRACED BENT

As expected, the 5-pile one-story HP10x42 X-braced pile bent with H=13' and H=17' showed improvement over the 4-pile one-story HP10x42 X-braced pile bent with H=13' and H=17'. Both the H=13' and the H=17' 5-pile one-story X-braced bents exhibited a 17% increase in pushover capacity. Similar to the 3 and 4-pile bents, the 5-pile one-story HP10x42 X-braced pile bent with H=13' and H=17' and P=100 kips still performed poorly when 5 feet of scour was imposed on the bent. When H=13' the pushover force was reduced from 63.95 kips to 34.76 kips when P=100 kips and 5 feet of scour was imposed on the 5-pile one-story HP10x42 X-braced bent; this is a 45% decrease in capacity. Likewise when H=17' there was a 26% decrease in capacity in the 5-pile X-braced HP10x42 bent when 5' of scour was imposed and P=100 kips. Figures A.57-A.64 and Table 5.8 display the results from the pushover analysis of the 5-pile one-story HP10x42 X-braced bent.

Table 5.8 Pushover Capacities of an HP10x42 5-Pile One-Story X-Braced Bent with H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.57-A.64

5.10 5-PILE TWO-STORY HP10x42 X-BRACED BENT

The 5-pile two-story HP10x42 X-braced bent performed slightly better than the 4-pile two-story HP10x42 X-braced bent. On average the 5-pile two-story HP10x42 X-braced bent with H=21' outperforms the 4-pile two-story HP10x42 X-braced bent with H=21' by 6.2 kips, and likewise the 5-pile two-story HP10x42 X-braced bent with H=25' outperforms the 4-pile two-story HP10x42 X-braced bent with H=25' by 5.1 kips. The only 5-pile two-story HP10x42 X-braced bent to be found unstable was when H=25' and P=160 kips. Again, there was a notable drop in pushover capacity when only 5 feet of scour was introduced to both the H=21' and H=25' 5-pile two-story HP10x42 X-braced bents with P=100 kips. The capacity was reduced by half. The numerical pushover force capacities and the corresponding $F_t - \Delta$ pushover curves for the 5-pile two-story X-braced bents with H=21' and H=25' can be found in Table 5.9 and Figures A.65-A.72 respectively.

Table 5.9 Pushover Capacities of a HP10x42 5-Pile Two-Story
X-Braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.65-A.72

5.11 6-PILE HP10x42 BENT, WITHOUT X-BRACING

The 6-pile HP10x42 pile bent without X-bracing showed a small improvement over the 5-pile HP10x42 pile bent without X-bracing. The 6-pile HP10x42 bent without X-bracing with H=10' and P=100 kips showed 11% increase over the same 5-pile HP10x42 bent. The 6-pile HP10x42 bent without X-bracing with H=13' and P=100 kips showed a smaller 5% increase in pushover capacity over the 5-pile HP10x42 pile bent without X-bracing with H=13' and P=100 kips. There are smaller increases in the pushover capacity as scour is imposed on the bents, but not the significant loss of 50% as seen in the X-braced bents. For example, in the 6-pile non X-braced bent with H=13', P=100 kips and with S = 0' the F_t = 38.07 kips and on the same pile bent only with S = 5' the F_t = 34.99 kips. This is only an 8% decrease in pushover capacity when 5' of scour is imposed on the bent. The 6-pile HP10x42 pile bent without X-bracing with H=10' outperformed the 6-pile HP10x42 pile bent without X-bracing with H=13' by an average of 5.02 kips. None of the 6-pile HP10x42 pile bents without X-bracing were found to be unstable. The numerical data for the 6-pile HP10x42 non-X-braced bent with H=10' and H=13' is displayed in Table 5.10, and the graphical representations of deflection versus F_t for the 6-pile HP10x42 with H=10' and H=13' may be found in Figures A.73-A.80.

Table 5.10 Pushover Capacities of a HP10x42 6-Pile One-Story Bent without X-Bracing with H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures A.73-A.80

5.12 6-PILE ONE-STORY HP10x42 SINGLE X-BRACED BENT

The 6-pile one-story HP10x42 single X-braced bent performed slightly better than the 5-pile one-story HP10x42 X-braced bent. The pushover load, F_t, for the 6-pile one-story HP10x42 single X-braced bent with H=13' and P=100 kips equals 69.18 kips; this is only 5.59 kips stronger than the same 5-pile one-story HP10x42 X-braced bent. The 6-pile one-story HP10x42 single X-braced bent with H=17'and P=100 kips only outperformed the 5-pile one-story HP10x42 X-braced bent with H=17' and P=100 kips by 4.84 kips. Again, in the 6-pile one-story HP10x42 single X-braced bent significant losses in pushover capacity were found when only 5' of scour was imposed on the bent. Both the 6-pile one-story HP10x42 single X-braced bent with H=13' and H=17' showed a 46% decrease in pushover capacity when P=100 kips and moving from S=0' to S=5'.

This decrease of 46% in pushover capacity is almost the same decrease found in the 5-pile one-story HP10x42 X-braced bent with H=13'. The 6-pile one-story HP10x42 single X-braced bent with H=13' performed slightly better than the 6-pile one-story HP10x42 single X-braced bent with H=17'; when P=160 kips and S=20' the 6-pile one-story HP10x42 single X-braced bent with H=13' only had a pushover force 2.6 kips higher than the 6-pile one-story HP10x42 single X-braced bent with H=17'. The numerical data for the 6-pile one-story HP10x42 single X-braced bent with H=13' and H=17' is displayed in Table 5.11, and the graphical representations of deflection versus F_t for the 6-pile one-story HP10x42 single X-braced bent with H=13' and H=17' may be found in Figures A.81-A.88.

Table 5.11 Pushover Capacities of an HP10x42 6-Pile One-Story Single X-Braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips			
			P = 100k	P = 120k	P = 140k	P = 160k
ONE-STORY	13 SINGLE	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 SINGLE	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

* See Figures A.81-A.88

5.13 6-PILE ONE-STORY HP10x42 DOUBLE X-BRACED BENT

The 6-pile one-story HP10x42 double X-braced bents significantly outperformed the 6-pile one-story HP10x42 single X-braced bents. When H=13’, P=100 kips and S=0’ the 6-pile one-story HP10x42 double X-braced bent outperformed the 6-pile one-story HP10x42 single X-braced bent by 15.38 kips and when H=17’, P=100 kips and S=0’ the 6-pile one-story HP10x42 double X-braced bent outperformed the 6-pile one-story HP10x42 single X-braced bent by 14.9 kips. This is an increase in pushover capacity by 22% and 24% respectively. In spite of this increase in capacity when compared to the single X-braced bent, the double X-braced bent is still experiencing a large drop in pushover capacity when only 5 feet of scour is imposed on the bent. For example when H=13’ and P=100 kips the 6-pile one-story HP10x42 double X-braced bent experiences a 54% decrease in pushover capacity when going from S=0’ to S=5’. This is evidence that double X-bracing does not show sizeable improvements over single X-bracing as far as scour is concerned.

As expected when H=13’ the 6-pile one-story HP10x42 double X-braced bent outperformed the 6-pile one-story HP10x42 double X-braced bent with H=17’. The differences between the H=13’ and H=17’ 6-pile one-story HP10x42 double X-braced bents were small when P=100 kips and S=0, but grew slightly larger as the scour and the P-loads were increased. Numerical pushover capacities for the 6-pile one-story double X-braced bents may be found in Table 5.12 and the corresponding $F_t - \Delta$ pushover curves are shown in Figures are A.89-A.96.

Table 5.12 Pushover Capacities of an HP10x42 6-Pile One-Story Double X-Braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
ONE-STORY	13 DOUBLE	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 DOUBLE	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

* See Figures A.89-A.96

5.14 6-PILE TWO-STORY HP10x42 SINGLE X-BRACED BENT

Numerical pushover capacities for the 6-pile two-story HP10x42 single X-braced bent may be found in Table 5.13 and the corresponding $F_t - \Delta$ pushover curves are shown in Figures are A.97-A.104. The 6-pile two-story HP10x42 single X-braced bent only slightly outperformed the 5-pile two-story HP10x42 single X-braced bent. The pushover load, F_t, for the 6-pile two-story HP10x42 single X-braced bent with H=21' and P=100 kips equals 68.25 kips; This is only 5.3 kips stronger than the 5-pile two-story HP10x42 X-braced bent with H=21' and P=100 kips. The 6-pile two-story HP10x42 single X-braced bent with H=25'and P=100 kips only outperformed the 5-pile two-story HP10x42 X-braced bent with H=25' and P=100 kips by 4.6 kips. With H=25', P=160 kips and S=20' the 6-pile two-story HP10x42 single X-braced bent was found to be unstable. This was also the case when H=25', P=160 kips and S=20' in the 5-pile two-story HP10x42 X-braced bent. Once again a significant decrease in pushover capacity when only 5' of scour is imposed on the bent occurs. The expected decrease in capacity with height also occurs.

Table 5.13 Pushover Capacities of an HP10x42 6-Pile Two-Story Single X-Braced Pile Bent H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
TWO-STORY	21 SINGLE	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 SINGLE	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

* See Figures A.97-A.104

5.15 6-PILE TWO-STORY HP10x42 DOUBLE X-BRACED BENT

The 6-pile two-story HP10x42 double X-braced bent outperformed the 6-pile two-story HP10x42 single X-braced bent when H=21', P=100 kips and S=0' by a 25% increase in pushover capacity and the when H=25', P=100 kips and S=0' by a 30% increase in pushover capacity. Another improvement of the 6-pile two-story HP10x42 double X-braced bent over the 6-pile two-story HP10x42 single X-braced bent is that none of the 6-pile two-story HP10x42 double X-braced bents were found to be unstable. In fact, when P=160 kips and S=20' the H=25' 6-pile two-story HP10x42 double X-braced bent was able to withstand 2.25 kips before reaching its pushover capacity. Large decreases in pushover capacity where noted again when only 5' of scour was imposed on the bent. For instance, when H=21', P=100 kips and S=0' the pushover capacity of the 6-pile two-story HP10x42 double X-braced bent was 85.81 kips then when 5' of scour is imposed on this bent the pushover capacity decreases to 38.56 kips. This is a 55% decrease in capacity. Table 5.14 displays the numerical data for the 6-pile two-story HP10x42 double X-braced bents and the corresponding F_t versus deflection curves may be found in Figures A.105-A.112.

Table 5.14 Pushover Capacities of an HP10x42 6-Pile Two-Story Double X-Braced Bent H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
TWO-STORY	21 DOUBLE	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 DOUBLE	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

* See Figures A.105-A.112

5.16 3-PILE HP12x53 BENT WITHOUT X-BRACING

The HP12x53 3-pile bent without X-bracing showed marked improvement over the 3-pile HP10x42 pile bent without X-bracing. When H=10' the HP12x53 3-pile bent was only found to be unstable in two cases, when S=20' and P=140 and 160 kips. When H=13' the HP12x53 3-pile bent was found to be less unstable in fewer cases than the HP10x53 3-pile bent with H=13'. Table 5.15 displays the numerical results for pushover capacities of the 3-pile HP12x53-pile bent without X-bracing. The HP12x53 3-pile bent without X-bracing with H=10' naturally was able to withstand pushover loads larger than the HP12x53 3-pile bent without X-bracing and with H=13'. The HP12x53 3-pile bent without X-bracing with H=10', P=100 kips and S=0' had 10.57 kips more pushover capacity than the same bent with H=13'. This is a 30% decrease in pushover capacity due to differences in height. This is similar to the 35% decrease found in the same situation with HP10x52 piles instead of HP12x53 piles. Figures B.1 -B.8 display the F_t versus deflection curve results for the HP12x53 3-pile bent with out X-bracing.

Table 5.15 Pushover Capacities of a HP12x53 3-Pile Bent without X-bracing with H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.1-B.8

5.17 3-PILE ONE-STORY HP12x53 X-BRACED BENT

The HP12x53 3-pile one-story X-braced bent with H=13', P= 100 kips and S=0' performed a great deal better (170%) than the HP12x53 3-pile bent without X-bracing and with H=13' and under the same parameters. Also, the HP12x53 3-pile one-story X-braced bent with H=13', P=100 kips and S=0'outperformed the HP10x42 3-pile one-story X-braced bent with H=13' and under the same parameters by 56%; the HP12x53 3-pile one-story X-braced bent with H=17', P=100 kips and S=0'outperformed the HP10x42 3-pile one-story X-braced bent with H=17' and under the same parameters by 53%. The HP12x53 3-pile one-story X-braced bent with H=13' was found to be unstable only when S=20'and P=140 and 160 kips; the HP12x53 3-pile one-story X-braced bent with H=17' was found to be unstable only when S=20' and P=120, 140, and 160 kips. As seen in the HP10x42 results, and now here again in the HP12x53 results when only 5 feet of scour is added to the cross braced bent (P-load = 100 kips) the pile bent lost over half of its pushover capacity. In fact, the HP12x53 3-pile one-story X-braced pile bent with H=13' and H=17' lost slightly more of its pushover capacity than the HP10x42 3-pile one-story X-braced pile bent when 5 feet of scour was added. The HP12x53 3-pile one-story X-braced pile bent with H=13' saw a 57% decrease in pushover capacity when P=100 kips and scour was increased from S=0' to S=5', and the HP12x53 3-pile one-story X-braced bent with H=17' decreased 58% when P=100 kips and scour was increased from S=0' to S=5'. Table 5.16 displays the complete pushover force results for the HP12x53 3-pile X-braced bent with H=13' and H=17' and Figures B.9-B.16 display the corresponding F_t versus deflection curves results.

Table 5.16 Pushover Capacities of a HP12x53 3-Pile
X-braced Bent with H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, Ft, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.9-B.16

5.18 3-PILE TWO-STORY HP12x53 X-BRACED BENT

The 3-pile two-story HP12x53 X-braced bent with H=21'and H=25', P=100 kips and S=0' improved 51% in pushover capacity over the 3-pile two-story HP10x42 X-braced bent with H=21' and H=25' and the same parameters. Again, a large loss in capacity was found when only 5' of scour was imposed on the bent. For example, a 57% decrease in pushover capacity was found when H=21', the 3-pile two-story HP12x53 X-braced bent with P=100 kips and scour being increased from S=0' to S=5'. Both the H=21' and H=25' 3-pile two-story HP12x53 X-braced bent were found to be unstable when S=20' and P = 120 kips, 140 kips, and 160 kips. This is a large improvement over the 3-pile two-story HP10x42 X-braced bent. The complete numerical pushover force capacity results for the HP12x53 3-pile two-story X-braced bent with H=21'and H=25' are displayed in Table 5.17 and Figures B.17-B.24 display the corresponding F_t versus deflection curves results.

Table 5.17 Pushover Capacities of a HP12x53 3-Pile Two-Story X-braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.17-B.24

5.19 4-PILE HP12x53 BENT, WITHOUT X-BRACING

The 4-pile HP12x53 bent without X-bracing with S=0' and P=100 kips outperformed the 4-pile HP10x42 bent without X-bracing by 53% when H=10' and by 50% when H=13'. Also, as expected the 4-pile HP12x53 bent without X-bracing with

S=0’ and P=100 kips exceeded the pushover capacities of the 3-pile HP12x53 bent without X-bracing with S=0’ and P=100 kips by 61% when H=10’ and by a large 83% when H=13’. Also, none of the 4-pile HP12x53 non-X-braced bents were found to be unstable. In fact, in the worst case (H=13’, S=20’ and P=160 kips) of the 4-pile HP12x53 bent without X-bracing the pushover capacity is 12.75 kips. This is much larger than the pushover capacity of the 4-pile HP10x42 non-X-braced bent in the same conditions of a mere 2.53 kips. When 5’ of scour is imposed onto the 4-pile HP12x53 bent without X-bracing with H=10’ and P=100 kips a 27% reduction is found and when H=13’, P = 100 kips ,and 5’ of scour is imposed onto the 4-pile HP12x53 bent without X-bracing a 15% reduction in pushover capacity is found. Although 27% and 15% seem like significant losses in capacity they still do not compare to the large losses in capacity found in similar X-braced bents. Table 5.18 displays the complete pushover force results for the HP12x53 4-pile bent without X-bracing with H=10’ and H=13’ and Figures B.25-B.32 display the corresponding F_t versus deflection curve results.

Table 5.18 Pushover Capacities of a HP12x53 4-Pile Bent
Without X-bracing with H=10’ and H=13’

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.25-B.32

5.20 4-PILE ONE-STORY HP12x53 X-BRACED BENT

The 4-pile one-story HP12x53 X-braced bent also showed significant improvement over its non X-braced counterpart. In fact the 4-pile one-story HP12x53 X-braced bent with H=13’, P=100 kips and S=0’ improved 84% over the 4-pile HP12x53 bent without X-bracing, however, when P=160 kips and S=20’ the 4-pile one-story HP12x53 X-braced bent only improved a small 13% over the non X-braced 4-pile HP12x53 bent. Also of note when S=10’ and P=100 kips, the 4-pile one-story HP12x53 X-braced bent had a pushover capacity of 34.37 kips and with the same parameters the HP12x53 4-pile non X-braced bent exceeded the pushover capacity of the X-braced bent with a pushover capacity of 36.68 kips. This type of occurrence happens for all P loads (P=100, 120, 140 and 160 kips) when S=10’ and three times (when P= 120, 140, and 160 kips) when S=15’. If the differences in pushover capacities of the 4-pile one-story HP12x53 X-braced bent are taken with the pushover capacities of the 4-pile non-X-braced bent, the 4-pile one-story HP12x53 X-braced bent still outperforms the 4-pile HP12x53 non-X-braced bent by an average of 8.78 kips. One possible reason that the X-braced may have slightly lower pushover capacities than the non-X-braced is that when S=10’ the X-bracing comes in at around mid-height of the bent, this may be causing the bent to be less stable at resisting lateral pushover loadings.

When comparing the 4-pile one-story HP12x53 X-braced bent with the 4-pile one-story HP10x42 X-braced bent, the 4-pile one-story HP12x53 X-braced bent outperforms the 4-pile one-story HP10x42 X-braced bent in all cases. Also, the 4-pile one-story HP12x53 X-braced bent is not found to be unstable in any case. The numerical data for the 4-pile HP12x53 one-story X-braced bent with H=13’ and H=17’ is displayed in Table 5.19, and the graphical representations of deflection versus F_t for the 4-pile HP10x42 with H=13' and H=17' may be found in Figures B.33-B.40.

Table 5.19 Pushover Capacities of a HP12x53 4 Pile One-Story X-braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.33-B.40

5.21 4-PILE TWO-STORY HP12x53 X-BRACED BENT

The 4-pile two-story HP12x53 X-braced bent outperforms the 4-pile two-story HP10x42 X-braced bent in all cases. For example, when H=21' the 4-pile two-story HP12x53 X-braced bent on average has a pushover capacity 17.74 kips greater than the 4-pile two-story HP10x42 X-braced bent, and the 4-pile two-story HP12x53 X-braced bent with H=25' on average has a pushover capacity 16.73 kips greater than the 4-pile two-story HP10x42 X-braced bent. None of the 4-pile two-story HP12x53 X-braced bents were found to be unstable. Again, the 4-pile two-story HP12x53 X-braced bent looses much of its pushover capacity when only 5' of scour is imposed on the bent. A decrease in pushover capacity of 50% and 51% were found when P=100 kips and the scour was increased from S=0' to S=5' for the 4-pile two-story HP12x53 X-braced bent with H=21' and H=25' respectively. Decreases in pushover capacity are for the most part constant when increasing the P-load from 100 kips to 160 kips and as the scour is increased. The average drop in pushover capacity as scour is increased from S=0' to S=20' and when the concentrated load, P, is increased from P=100 kips to P=160 kips is 11.5 kips. The numerical data related to the 4-pile two-story HP12x53 X-braced bent with H=21' and H=25' may be found in Table 5.20, as can the corresponding F_t versus deflection curves in Figures B.41 – B.48.

Table 5.20 Pushover Capacities of a HP12x53 4-Pile
Two-Story X-braced Bent with H=21' and H=25'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.41-B48

5.22 5-PILE HP12x53 BENT WITHOUT X-BRACING

The 5-pile HP12x53 bent without X-bracing showed an increase in pushover capacity over the 5-pile HP10x42 bent without X-bracing. When comparing the worst case (S=20' and P=160 kips) the 5-pile HP12x53 bent without X-bracing with H=10' was a vast 227% higher in pushover capacity than the same bent only with HP10x42 piles, and when H=13' the 5-pile HP12x53 bent without X-bracing surpassed the 5-pile HP10x42 bent without X-bracing by a even larger 270%. Other large increases in the capacity of the 5-pile HP12x53 bent without X-bracing were found when comparing it to the 4-pile HP12x53 bent without X-bracing. For example, taking the worst case the 5-pile HP12x53 bent without X-bracing with H=10’ outperformed the 4-pile HP12x53 bent without X-bracing by 53%, and when H=13’ the 5-pile HP12x53 bent without X-bracing outperformed the 4-pile HP12x53 bent without X-bracing by 60%. None of the 5-pile HP12x53 bents without X-bracing were found to be unstable. On average the 5-pile HP12x53 bent without X-bracing with H=10’, S=0’ and with the P load increasing from 100 kips to 160 kips is around 13.2 kips greater than the same bent with H=13’; this number reduces as the scours increase. The numerical data related to the 5-pile HP12x53 bent without X-bracing and with H=10’ and H=13’ may be found in Table 5.21, as can the corresponding F_t versus deflection curves in Figures B.49 – B.56.

Table 5.21 Pushover Capacities of a HP12x53 5-Pile
Bent without X-bracing with H=10’ and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.49-B.56

5.23 5-PILE ONE-STORY HP12x53 X-BRACED BENT

A 51% and 56% increase in pushover capacity was found when comparing the 5-pile one-story HP12x53 X-braced bent with P=100 kips and S=0’ to the 5-pile one-story

HP10x42 bent with H=13' and 17' and the same parameters respectively. When comparing the 5-pile one-story HP12x53 X-braced bent to the 4-pile one-story HP12x53 X-braced bent with H=13' on average the 5-pile one-story HP12x53 X-braced bent had a larger pushover capacity of 10.34 kips; when H=17' the 5-pile one-story HP12x53 X-braced bent had a pushover capacity on average 9.25 kips higher than the 4-pile one-story HP12x53 X-braced bent. Again, large decreases in pushover capacities were found when scour was imposed on the bents. Taking a closer look, the 5-pile one-story HP12x53 X-braced bent with H=13' and when S is increased from S=0' to S=5' and the P-load is increased from 100 kips to 160 kips the average decrease in capacity is 39.86 kips. This number tends to decrease as the scour increases; for instance, when S=5' and then increases to S=10' as the P-loads increase the average drop in pushover capacity decreases to 11.50 kips. This drop in sensitivity to scour happens again when S=10' increases to S=15' as the P-loads increase the pushover capacity decreases to an average of 2.84 kips. The numbers are almost identical for the 5-pile one-story HP12x53 X-braced bent with H=17'. This occurrence simply indicates that when large scours are present on pile bents and are increased to even larger scours the pile bents develop a reduced sensitivity to these large scours and pushover capacities are reduced with addition of even more scour. All of the numerical data for the 5-pile one-story HP12x53 X-braced bent with H=13' and H=17' are displayed in Table 5.22 below and the corresponding F_t versus deflection curves may be found in Figures B.57 – B.64.

Table 5.22 Pushover Capacities of an HP12x53 5-Pile One-Story X-braced Pile Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.57-B.64

5.24 5-PILE TWO-STORY HP12x53 X-BRACED BENT

The 5-pile two-story HP12x53 X-braced bent with H=21', P=100 kips and S=0' had an increase of 59% in pushover capacity over the 5-pile two-story HP10x42 X-braced bent with H=21' and the same parameters. An even greater increase in pushover capacity of 69% was found in the 5-pile two-story HP12x53 X-braced bent with H=25', P=100 kips and S=0' over the 5-pile two-story HP10x42 X-braced bent with H=25' and the same parameters. Unlike the 5-pile two-story HP10x42 X-braced bent with H=25', none of the 5-pile two-story HP12x53 X-braced bents with H=25' were found to be unstable. When comparing the 5-pile two-story HP12x53 X-braced bent with the 4-pile two-story HP12x53 X-braced bent with H=21', P=100 kips and S=0' the 5-pile two-story HP12x53 X-braced bent had a pushover capacity greater than the 4-pile two-story HP12x53 X-braced bent by 13.44 kips. When comparing the worst case values (S=20'and P=160 kips) on those same bents the 5-pile two-story HP12x53 X-braced bent had a pushover capacity of 8.82 kips higher than the 4-pile two-story HP12x53 X-braced bent. The values are almost identical when comparing the 5-pile two-story HP12x53 X-braced bent with H=25' to the 4-pile two-story HP12x53 X-braced bent with H=25'. The same occurrence with scour happens again with the 5-pile two-story HP12x53 X-braced bents. The capacity of the bent is almost cut in half when P=100 kips and scour is increased from S=0' to S=5' then that number decreases when S=5' grows into S=10' and so on. The numerical data for the 5-pile two-story HP12x53 X-braced bent with H=21' and H=25' are displayed in Table 5.23 below and the corresponding F_t versus deflection curves may be found in Figures B.65 – B72.

Table 5.23 Pushover Capacities of a HP12x53 5-Pile Two-Story
X-braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.65-B.72

5.25 6-PILE HP12x53 BENT, WITHOUT X-BRACING

The HP12x53 bent without X-bracing is able to withstand much greater pushover loads than the HP10x42 bent without X-bracing. For example, taking the worst case, when S=20' and P=160 kips the HP12x53 6-pile bent without X-bracing and with H=10' has a pushover capacity of 24.80 kips. This is an 18.3 kip increase over the HP10x42 bent without X-bracing with H=10' and the same parameters. A comparable gain in capacity was obtained when considering the worst case(S=20' and P=160 kips) in the HP12x53 bent without X-bracing with H=13' when it surpassed the HP10x42 bent without X-bracing by 15.5 kips. When comparing the HP12x53 6-pile bent without X-bracing to the HP12x53 5-pile bent without X-bracing, initially the HP12x53 6-pile bent without X-bracing is stronger, but as the scours and vertical P-loads increase the 6-pile and 5-pile HP12x53 bents become closer in pushover capacity. For example the HP12x53 6-pile bent without X-bracing with H=13', P=100 kips and S=0' has a pushover capacity of 61 kips this is 5.05 kips greater than the HP12x53 5-pile bent without X-bracing having the same parameters. However, when P=160 kips and S=20' the HP12x53 6-pile bent without X-bracing with H=13' has a pushover capacity of 20 kips. This is 0.38 kips less than the HP12x53 5-pile bent without X-bracing having the same parameters. A similar nearing of values as the scours and vertical P-loads also takes place in the HP12x53 6-pile bent without X-bracing with H=10'. The numerical data for the 6-pile HP12x53 bent without X-bracing with H=10' and H=13' are displayed in Table 5.24 below and the corresponding F_t versus deflection curves may be found in Figures B.73 – B.80.

Table 5.24 Pushover Capacities of a HP12x53 6-Pile Bent without X-bracing with H=10' and H=13'

Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
		P = 100k	P = 120k	P = 140k	P = 160k
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

* See Figures B.73-B.80

5.26 6-PILE ONE-STORY HP12x53 SINGLE X-BRACED BENT

The 6-pile one-story HP12x53 single X-braced bent has much larger pushover capacities than the 6-pile one-story HP10x42 single X-braced bent. The 6-pile one-story HP12x53 single X-braced bent with H=13' and H=17' had on average a greater pushover capacity of 22 kips than its HP10x42 counterpart. When comparing the 6-pile one-story HP12x53 single X-braced bent with the 5-pile one-story HP12x53 single X-braced bent, the 6-pile bent outperformed the 5-pile bent in almost all cases. With S=0' and P=100 kips the 6-pile one-story HP12x53 single X-braced bent with H=17' has a pushover capacity of 88.89 kips. This is 6.22 kips higher than the same bent only with 5-piles. This difference, however, diminishes as the scours and the vertical P-loads are increased. When S=20' and P=160 kips the difference in the 6-pile one-story HP12x53 single X-braced bent to the 5-pile one-story HP12x53 single X-braced bent with H=17' is a trivial 0.07 kips. When comparing the worst case (S=20' to P=160 kips) for the 6-pile one-story HP12x53 single X-braced bent with H=13' to the 5-pile one-story HP12x53 single

X-braced bent with H=13', the 5-pile one-story HP12x53 single X-braced bent has a larger pushover capacity than the 6-pile one-story HP12x53 single X-braced bent by 0.23 kips. The cases when the 5-pile bents pushover capacity exceeds that of its 6-pile counterpart are few, and the differences are minute. The numerical data for the 6-pile HP12x53 one-story single X-braced bent with H=13' and H=17' are displayed in Table 5.25 below and the corresponding F_t versus deflection curves may be found in Figures B.81 – B.88.

Table 5.25 Pushover Capacities of an HP12x53 6-Pile One-Story Single X-braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
ONE-STORY	13 SINGLE	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 SINGLE	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

* See Figures B.81-B.88

5.27 6-PILE ONE-STORY HP12x53 DOUBLE X-BRACED BENT

The 6-pile one-story HP12x53 double X-braced bent outperforms the 6-pile one-story HP12x53 single X-braced bent in all cases. When P=100 kips and S=0' the double X-braced bent outperformed its single X-braced counterpart by 26 kips when H=13' and 31 kips better when H=17'. This is evidence that the double X-bracing adds more stability to the bents over the single X-bracing adds to the bents. Also, the HP12x53 6-pile one-story double X-braced bents outperformed the 6-pile HP10x42 one-story double

X-braced bents. For example, the HP10x42 6-pile one-story double X-braced bent with H=17' in the worst case has a pushover capacity of 4.34 kips. The 6-pile one-story HP12x53 double X-braced bent with H=17' in the worst case has a pushover capacity a little over 5 times that of its HP10x42 counterpart. This is a large difference. The double X-braced bent still experiences a large drop in pushover capacity when only 5' of scour is imposed on the bent. When H=13' the 6-pile one-story HP12x53 double X-braced bent experiences a massive 66.51 kip drop in capacity when P=100 kips and moving from S=0' to S=5'. A similar extreme drop in capacity is also found in the H=17', 6-pile one-story HP12x53 double X-braced bent. The typical small decrease in capacity is found when the height is increased from H=13' to H=17'. Figures B.89-B.96 display the F_t versus deflection curves for the HP12x53 6-pile one-story double X-braced bents with H=13' and H=17' and the corresponding pushover capacities are displayed in Table 5.26.

Table 5.26 Pushover Capacities of an HP12x53 6-Pile One-Story Double X-braced Bent H=13' and H=17'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
ONE-STORY	13 DOUBLE	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 DOUBLE	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

* See Figures B.89-B.96

5.28 6-PILE TWO-STORY HP12x53 SINGLE X-BRACED BENT

Numerical pushover capacities for the 6-pile two-story HP12x53 single X-braced bent may be found in Table 5.27 and the corresponding $F_t - \Delta$ pushover curves are shown in Figures are B.97-B.104. The 6-pile two-story HP12x53 single X-braced bent outperformed the 5-pile two-story HP12x53 single X-braced bent in all cases. The 6-pile two-story HP12x53 single X-braced bent with H=21', P=100 kips and S=0' had a pushover load 8.95 kips greater than its 5-pile counterpart. However, this number decreased as the scours and P-loads increased, and this difference between the 6-pile bent and its 5-pile counterpart was not as large when H=25'. When H=25', P=100 kips and S=0' the 6-pile two-story HP12x53 single X-braced bent only performed 3.37 kips better than its 5-pile counterpart. Larger differences in capacities are found when comparing the 6-pile two-story HP12x53 single X-braced bent to the 6-pile two-story HP10x42 single X-braced bent. When comparing the 6-pile two-story HP12x53 single X-braced bent with H=21', P=100 kips and S=0', the 6-pile two-story HP12x53 single X-braced bent outperformed its HP10x42 counterpart by a large 40.87 kips. In a similar manner, the 6-pile two-story HP12x53 single X-braced bent with H=25' had a pushover load 35.45 kips greater than the 6-pile two-story HP10x42 single X-braced bent. Again, both the H=21' and the H=25' 6-pile two-story HP12x53 single X-braced bents experienced large drops in capacity when only 5' of scour was imposed on the bents. When P=100 kips and scour was increased from S=0' to S=5' both the H=21' and the H=25' 6-pile two-story HP12x53 single X-braced bents experienced a 44% drop in capacity.

Table 5.27 Pushover Capacities of the 6-Pile Two-Story HP12x53 Single X-braced Bent with H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips *			
			P = 100k	P = 120k	P = 140k	P = 160k
TWO-STORY	21 SINGLE	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 SINGLE	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

* See Figures B.97-B.104

5.29 6-PILE TWO-STORY HP12x53 DOUBLE X-BRACED BENT

An increase in capacity was found when H=21' and H=25' for the 6-pile two-story HP12x53 double X-braced bents over the 6-pile two-story HP12x53 single X-braced bents the same height. However, the increase in capacity was greater in the H=25' bents over the H=21' bents. For example, when H=21', the 6-pile two-story HP12x53 double X-braced bent had an increase in pushover capacity over the 6-pile two-story HP12x53 single X-braced bent by 19%. A larger 26% increase was found when H=25' for the 6-pile two-story HP12x53 double X-braced bent over the 6-pile two-story HP12x53 single X-braced bent with H=25'. All of the 6-pile two-story HP12x53 double X-braced bents had pushover capacities greater than the 6-pile two-story HP10x42 double X-braced bents. Both the H=21' and the H=25' 6-pile two-story HP12x53 double X-braced bents on average had a pushover capacity of 26 kips greater than it HP10x42 counterpart. Yet again, the 6-pile two-story HP12x53 double X-braced bents had large decreases in capacity when only 5' of scour was imposed on the bent. When P=100 kips the 6-pile two-story HP12x53 double X-braced bent with H=21' and scour of S=0' was increased to S=5' a 52% decrease in capacity was found. A similar 54% decrease in capacity was found in the H=25' 6-pile two-story HP12x53 double X-braced bent with P=100 kips and an increase of scour from S=0' to S=5' occurred. Figures B.105-B.112 display the appropriate F_t versus deflection curves for the HP12x53 6-pile two-story double X-braced pile bent with H=21' and H=25' and the corresponding numerical data are displayed in Table 5.28.

Table 5.28 Pushover Capacities of an HP12x53 6-Pile Two-Story Double X-braced Pile Bent H=21' and H=25'

	Height, H (ft)	Scour, S (ft)	Pushover Force, F_t, in kips * P = 100k	P = 120k	P = 140k	P = 160k
TWO-STORY	21 DOUBLE	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 DOUBLE	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

* See Figures B.105-B.112

5.30 SUMMARY OF PUSHOVER CAPACITIES FOR PILE BENTS OF VARYING PILE SIZE, NUMBERS AND CONFIGURATIONS

Table 5.29 summarizes the pushover capacities of HP10x42 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 top of the piles (i.e., at the bottom of the pile cap) and the pile concrete encasement is neglected. Table 5.30 summarizes the pushover capacities of HP10x42 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. Table5.31 summarizes the pushover capacities of HP10x42 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 5.32-5.34 are sister tables to those above for bents with HP12x53 piles.

Assuming that the flood water debris raft dimensions and design flood water velocity values previously assumed to compute $F_{t\ max\ applied}$ 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 x 1.25 = 12.15 kips

Using this value of $F_{t\ max\ design}$, Tables 5.29-5.34 can be modified to reflect whether the bent is safe for combined flood water pushover loads, gravity loads, and level of scour. The modified tables are shown as Tables 5.35-5.40, 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 is probably inadequate for safety against pushover and should be looked at more closely. One can note in Tables 5.38-5.40, which are for the HP12x53 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 HP12x53 pile bents, only the 3-pile bents are of significant concern for adequacy for pushover capacity.

Table 5.29 Pushover Capacities of HP10x42 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	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 5.30 Pushover Capacities of HP10x42 3, 4, 5-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, (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 5.31 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, (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 5.32 Pushover Capacities of HP12x53 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 5.33 Pushover Capacities of HP12x53 3, 4, 5-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, (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 5.34 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_t, (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
6	SINGLE X PER STORY	ONE-STORY	13	5	60.94	55.79	50.93	46.20
6	SINGLE X PER STORY	ONE-STORY	13	10	48.07	42.29	37.06	31.96
6	SINGLE X PER STORY	ONE-STORY	13	15	45.77	39.21	32.97	27.13
6	SINGLE X PER STORY	ONE-STORY	13	20	45.21	38.94	31.41	24.33
6	SINGLE X PER STORY	ONE-STORY	17	0	95.11	89.40	84.28	79.72
6	SINGLE X PER STORY	ONE-STORY	17	5	55.85	50.31	45.23	40.62
6	SINGLE X PER STORY	ONE-STORY	17	10	44.97	38.87	33.34	28.11
6	SINGLE X PER STORY	ONE-STORY	17	15	43.48	36.47	29.59	23.48
6	SINGLE X PER STORY	ONE-STORY	17	20	42.75	35.20	27.31	20.19
6	SINGLE X PER STORY	TWO-STORY	21	0	109.13	101.77	94.52	87.84
6	SINGLE X PER STORY	TWO-STORY	21	5	60.29	54.22	48.58	43.48
6	SINGLE X PER STORY	TWO-STORY	21	10	46.12	39.84	34.11	28.83
6	SINGLE X PER STORY	TWO-STORY	21	15	42.47	35.19	28.53	22.37
6	SINGLE X PER STORY	TWO-STORY	21	20	41.28	32.80	24.88	17.63
6	SINGLE X PER STORY	TWO-STORY	25	0	96.43	89.77	83.63	78.27
6	SINGLE X PER STORY	TWO-STORY	25	5	54.41	48.46	43.00	38.13
6	SINGLE X PER STORY	TWO-STORY	25	10	42.09	35.69	29.82	24.52
6	SINGLE X PER STORY	TWO-STORY	25	15	39.43	31.45	24.44	18.15
6	SINGLE X PER STORY	TWO-STORY	25	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
6	DOUBLE X PER STORY	ONE-STORY	13	5	63.77	59.11	54.78	50.51
6	DOUBLE X PER STORY	ONE-STORY	13	10	49.00	43.59	38.59	33.81
6	DOUBLE X PER STORY	ONE-STORY	13	15	46.83	40.10	34.15	28.67
6	DOUBLE X PER STORY	ONE-STORY	13	20	46.44	39.36	32.40	25.79
6	DOUBLE X PER STORY	ONE-STORY	17	0	126.39	121.45	116.72	112.06
6	DOUBLE X PER STORY	ONE-STORY	17	5	59.51	54.09	49.36	45.18
6	DOUBLE X PER STORY	ONE-STORY	17	10	47.24	40.89	35.11	29.95
6	DOUBLE X PER STORY	ONE-STORY	17	15	44.78	37.49	31.17	25.44
6	DOUBLE X PER STORY	ONE-STORY	17	20	43.89	36.38	29.33	22.61
6	DOUBLE X PER STORY	TWO-STORY	21	0	134.38	128.97	123.95	119.63
6	DOUBLE X PER STORY	TWO-STORY	21	5	64.41	59.68	55.17	50.93
6	DOUBLE X PER STORY	TWO-STORY	21	10	48.54	43.00	37.85	33.07
6	DOUBLE X PER STORY	TWO-STORY	21	15	44.98	38.10	32.23	26.90
6	DOUBLE X PER STORY	TWO-STORY	21	20	43.80	36.12	29.13	22.63
6	DOUBLE X PER STORY	TWO-STORY	25	0	130.44	124.92	119.66	114.98
6	DOUBLE X PER STORY	TWO-STORY	25	5	60.07	54.60	50.13	46.09
6	DOUBLE X PER STORY	TWO-STORY	25	10	46.52	39.98	34.41	29.67
6	DOUBLE X PER STORY	TWO-STORY	25	15	42.83	35.72	29.56	23.99
6	DOUBLE X PER STORY	TWO-STORY	25	20	41.44	33.70	26.63	19.91

Table 5.35 Pushover Capacities of HP10x42 3, 4, 5, 6-Pile Bents without X-Bracing - Modified Table Showing, Adequacy to Resist $F_{tmaxdesign}$ = 12.15 kips

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	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 5.36 Pushover Capacities of HP10x42 3, 4, 5-Pile Bents with X-Bracing - Modified Table Showing, Adequacy to Resist $F_{tmaxdesign}$ = 12.15 kips

No. of Piles in Bent	No. of Stories 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	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 5.37 Pushover Capacities of HP10x42 6-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{tmaxdesign}$ = 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, (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 5.38 Pushover Capacities of HP12x53 3, 4, 5, 6-Pile Bents without X-Bracing - Modified Table Showing, Adequacy to Resist $F_{tmaxdesign}$ = 12.15 kips

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 5.39 Pushover Capacities of HP12x53 3, 4, 5-Pile Bents with X-Bracing - Modified Table Showing, Adequacy to Resist $F_{tmaxdesign}$ = 12.15 kips

No. of Piles in Bent	No. of Stories 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	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 5.40 Pushover Capacities of HP12x53 6-Pile Bents with X-Bracing - Modified Table Showing Adequacy to Resist $F_{tmaxdesign}$ = 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, (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

CHAPTER 6: SCREENING TEST AND PROCEDURE TO ASSESS ADEQUACY OF BRIDGE PILE BENTS FOR EXTREME FLOOD/SCOUR EVENTS

6.1 GENERAL

The Alabama Department of Transportation (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. 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 are more 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 bridges in Alabama, it is feasible to pursue the development of such a screening tool. This study provides the pile bent pushover evaluation component of the screening tool.

6.2 ASSESSING BENT ADEQUACY VIA A SCREENING TOOL

The screening tool is a comprehensive flow chart of questions developed to assess the adequacy of ALDOT's existing bridges. First, the screening tool asks some preliminary questions to discard those bridges for which the screening tool is not applicable or required. Then, more detailed subsequent questions follow, to bring a focus to the particular problem/problems for that particular bridge. A plan to evaluate the adequacy of ALDOT bridge pile bents for an extreme flood/scour event is shown in macro flow chart form in Figure 6.1. The check for bent pushover, which is the focus of this study, is Step 4 in this macro flow chart.

Some assumptions explicitly or implicitly included in checking the adequacy of bridge pile bents during an extreme flood/scour event for a failure due to pushover are as follows:

1. For a bent pushover failure, the total gravity load on the bent plus the flood water loading on the bent plus the level of scour must be considered.
2. The bridge bents are limited to single row pile bents with 3, 4, 5, or 6 unbraced or X-braced HP10x42 or HP12x53 steel piles.
3. For bents with concrete encased HP10x42 or HP12x53 piles, the contribution of the concrete encasement is neglected and the bent is treated as an uncased and unbraced steel pile bent.
4. The pile tops are embedded 1 foot 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.
5. Pile bent caps are adequate in strength and stiffness and will not be the cause of bent failure.

6. 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.

7. The bridge soil setting, to include total depth of 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.

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

9. A pile and/or bent is considered safe from failure if $P_{Failure} > 1.25P_{Max\ Applied}$.

After checking that the assumptions for the screening tool are satisfied by a specific bridge pile bent under consideration, then the screening tool may be utilized. Figure 6.2 shows the entire screening tool in flow chart form. In order to work through the Flow Chart one must Start at Step 1, the preliminary evaluation, and then work through to Steps 2 and 3, a determination of whether the bridge is safe from pile tip "kick-out" or plunging failures, and from pile buckling failures respectively. Finally, if the pile/bent satisfies the requirements in Steps 1, 2, and 3 the bent is checked for possible pushover failure in Step 4.

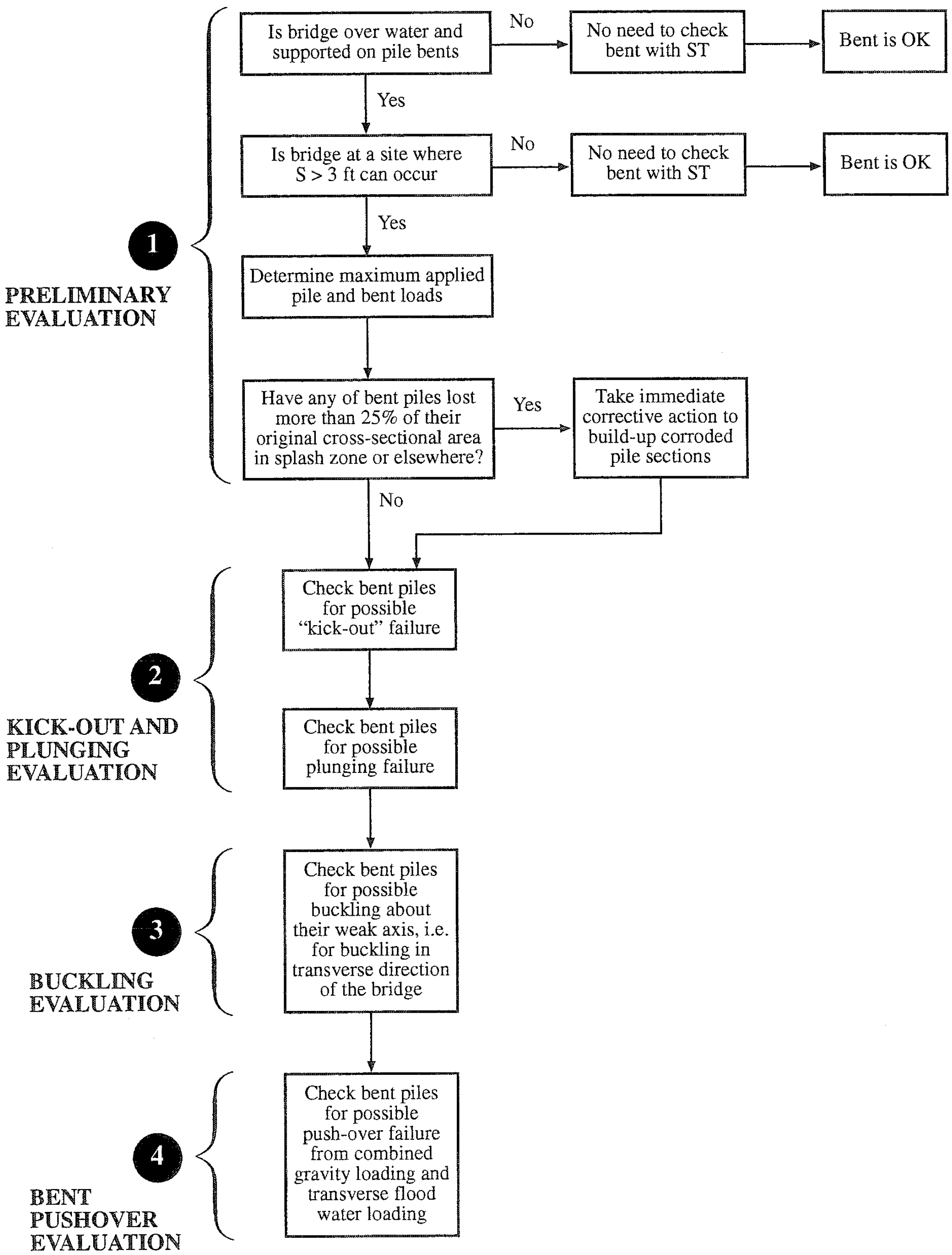


Fig. 6.1. Screening Tool (ST) Macro Flowchart

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Figure 6.2 may be found in pocket on back cover.

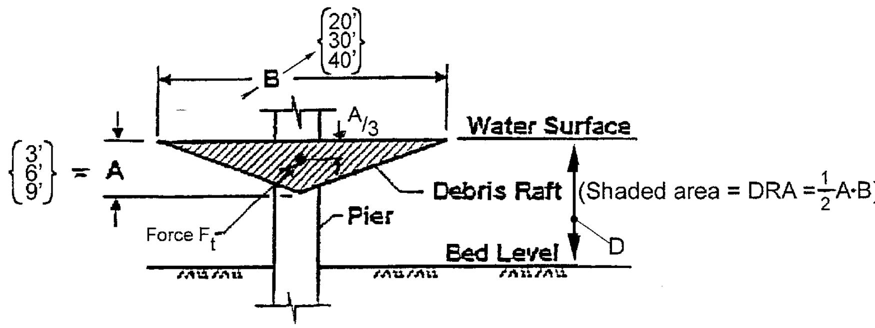
STEP 4: BENT PUSHOVER EVALUATION

The evaluation process in Step 4, the section on bent pushover evaluation, was determined by the research in this report. The bent pushover analyses were performed using GTSTRUDL, and the resulting pushover curves are presented in Appendixes A and B.

The first question, "Is there a source or history of stream flood debris from which a bent debris raft could be built?" in Step 4 may seem like a trivial question; however, it is essential that when performing the evaluation one be able to assemble information about the particular water body and determine if the build-up of a debris raft is possible or imminent. If there are no chances for a debris raft build-up on the bridge bents, then the possibility of failure due to pushover may be dismissed and the bents and bridge may be assigned a safe or adequate rating regarding pushover loading and/or failure. If build-up of a debris raft is possible the maximum force due to a transverse or debris load, $F_{t\ max\ applied}$ must be determined. An explanation of how to determine $F_{t\ max\ applied}$ may be found in Figure 6.3. The force, $F_{t\ max\ applied,}$ is applied to the bent at a distance A/3 down from the high water level (HWL), in this work the HWL is assumed to be at the top of the bent cap. The value of $P^{bent}_{max\ applied}$, found in Step 1 of the screening tool needs to be used to find the P-load applied to the bent cap above each pile. This P-load is found by the following equation:

$$P = P^{bent}_{max\ applied} \ / \ \text{No. of Piles in Bent} \qquad \text{Equation 6.1}$$

Once the appropriate P-load is determined from Equation 6.1, this value may be used to decide which F_t versus $\Delta_{horiz.}$ curve in the Appendices A and B would be most appropriate to use in determining the pushover load for a particular bent, scour, and loading condition. Once $F_{t\ pushover\ load}$ is determined from the appropriate graph this number should be taken and compared to $1.25 \times F_{t\ max\ applied}$. If $F_{t\ pushover\ load}$ is greater than $1.25 \times F_{t\ max\ applied}$ then the bent is considered adequate for an extreme scour/flood event and can be assigned a safe or adequate rating. If $F_{t\ pushover\ load}$ is less than $1.25 \times F_{t\ max\ applied}$ then it should be checked to see if $F_{t\ pushover\ load}$ is less than or equal to $F_{t\ max\ applied}$. If it is, then the pile/bent would probably have a pushover failure in an extreme flood/scour event and corrective action should be taken immediately. If $1.25 \times F_{t\ max\ applied} > F_{t\ pushover\ load} > F_{t\ max\ applied}$ then the bent should be examined more closely for a possible pushover failure during an extreme scour/flood event.



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

$$F_t = p \ x \ DRA$$

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

Figure 6.3 Debris Raft And Flood Water Load For
Checking Adequacy Of Pile Bent During Major Flood Event (AASHTO 1997)

Alternatively, rather than calculating $F_{t\ max\ applied}$ from Figure 6.3 and utilizing the F_t-$\Delta_{horiz.}$ pushover curves in the Appendices A and B, for relatively short bridges with L ≤ 40 feet, one could assume the debris raft dimensions indicated in Chapter 5 and thus use Tables 5.35-5.40 to assess the adequacy of the bridge under investigation for pushover. In using these tables, as indicated in Section 5.30 in Chapter 5, all of the 6 and 5-pile bents and almost all of the 4-pile bents are safe from pushover when the bent piles are HP12x53 piles.

CHAPTER 7: CONCLUSIONS AND RECOMENDATIONS

7.1 GENERAL

Sizeable lateral loadings on bridge pile bents can occur during an extreme flood event due to a debris raft build-up. Bent piles which experience these lateral loadings during extreme flood events can especially be vulnerable when their unbraced length is increased due to scour. This study examined these extreme conditions. To do this a review of all the available literature and design specifications on flood debris build-up and bridge pile bent loadings during extreme flood events was examined and analyzed. Based on the literature available, analytical and numerical analysis of a range of HP10x42 and HP12x53 typical ALDOT pile bents with a range of flood debris build-up and scour levels were conducted to assess the adequacy of the pile bents. A wide range of scour levels, pile bent configurations and loading conditions were examined. The range of pile bents examined was based on the most commonly used pile bents used by the ALDOT. This was determined from information presented in the Phase I report "Stability of Highway Bridges Subject to Scour" presented to ALDOT. No laboratory or field testing was conducted to verify or refute the results of the analytical analysis performed.

7.2 CONCLUSIONS

Several conclusions and observations can be taken from this investigation and they are listed below:

1. The addition of scour to any pile bent significantly reduces the pushover capacity of the bent. The larger the scour the smaller the force needed to pushover the bent. In most cases, when only 5 feet of scour is present on X-braced pile bents, a reduction in capacity of 50% and higher is likely and possible. Although there may be larger initial reductions in capacity in X-braced bents over non-X-braced bents when only 5’ of scour is imposed, overall the X-braced bents have higher pushover capacities than their non-X-braced bent counterparts.
2. The greater the number of piles used in a pile bent the higher the pushover capacity of that bent. All of the results presented in this report verify that bents with higher number of piles are able to withstand larger pushover loadings.
3. Shorter pile bents have higher pushover capacity than the same bent that is taller. If the pile bent must be tall due to its environment, X-bracing significantly increases its pushover capacity.
4. In the bents having 6 piles, the bents having double X-bracing consistently outperform those 6-pile bents only having single X-bracing.
5. HP12x53 pile bents consistently were able to withstand more load than the HP10x42 pile bents and have higher pushover capacities than the HP10x42 pile bents. Because of the HP12x53’s higher pushover capacity it is able to withstand higher lateral (lateral to the bridge or in the plane of the bent) flood water loads and also has improved ability to resist larger amounts of scour.

6. All of the 6 and 5-pile bents utilizing HP12x53 piles considered in this investigation were adequate/safe for pushover loadings, and almost all of the 4-pile bents of HP12x53 piles were adequate/safe.
7. If the bent pile base fixity conditions present at a site can be characterized as something other than pinned end conditions, this should be taken into account.
8. If it is possible for a debris raft to form on a bent, and the water level characterizes the value of A as something other than A = 6', then when comparing a bent that is comparable to one presented in the Appendices of this report appropriate adjustments may be made to account for the differences in A discussed in Chapter 3 of this report.

7.3 RECOMMENDATIONS

Presented below are the recommendations that may be drawn from the observations and conclusions of this study.

1. It is recommended that additional analytical testing be done to include additional bent configurations, water heights (HWL), and loading conditions.
2. It is recommended that ALDOT adopt Step 4 of the Screening Tool (the bent pushover evaluation step) presented in this study as a simple way to asses the suitability and condition of the field bridges that correspond to the bridges presented in this report. If field conditions match those assumed in this report (A = 6', V = 6 mph, and B = 30') Tables 5.35 -5.40

may be used to quickly determine if a certain bridge is at risk to a pushover failure. The figures presented in the Appendices and Tables 5.29-5.34 in conjunction with the Screening Tool may be used if the field conditions do not specifically match the assumed conditions mentioned above to determine if a bridge is at risk for a failure due to pushover. If the field bridges are characterized by the Screening Tool as able to have a pushover failure or a failure due to pushover is possible, then corrective action needs to be taken in order to secure the bridge and counteract the effects of scour.

3. It is recommended that the “screening tool” described in Figures 6.1 and 6.2 which includes Step 4: “Checking for bridge pile bent pushover failure” which is the emphasis of this report, be automated via an appropriate user-friendly computer program/system.

4. It is recommended that information currently available in ALDOT’s Bridge Information Database be examined in conjunction with the pushover analysis procedure identified in Step 4 of the “Screening Tool” to assess prior adequacy or scour level of each pile bent supported bridge over water in Alabama.

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APPENDIX A

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

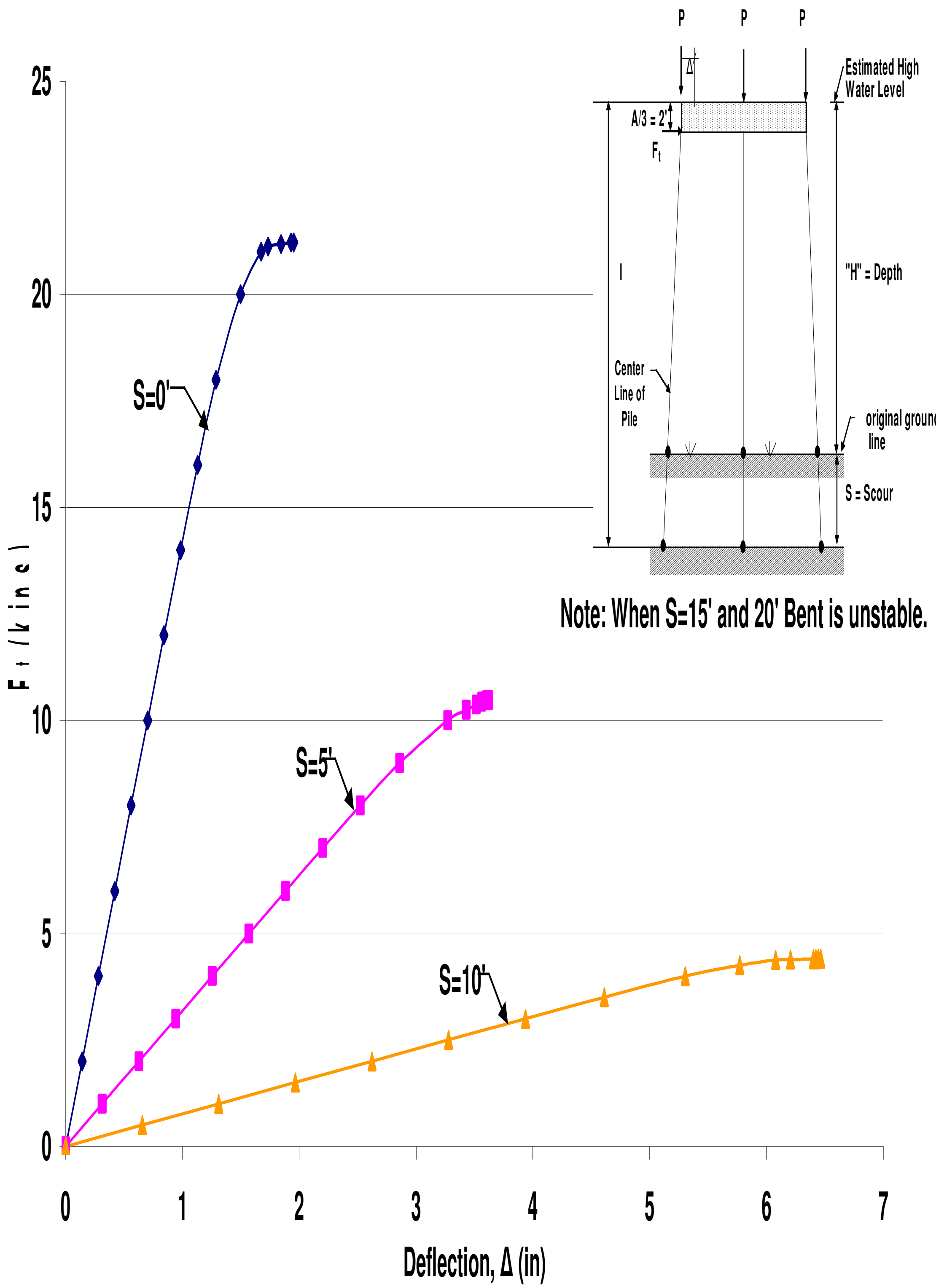


Figure A.1 HP10x42 Unbraced 3-Pile Bent with H=10', P=100kips, and A=6'
Pushover Analysis Results

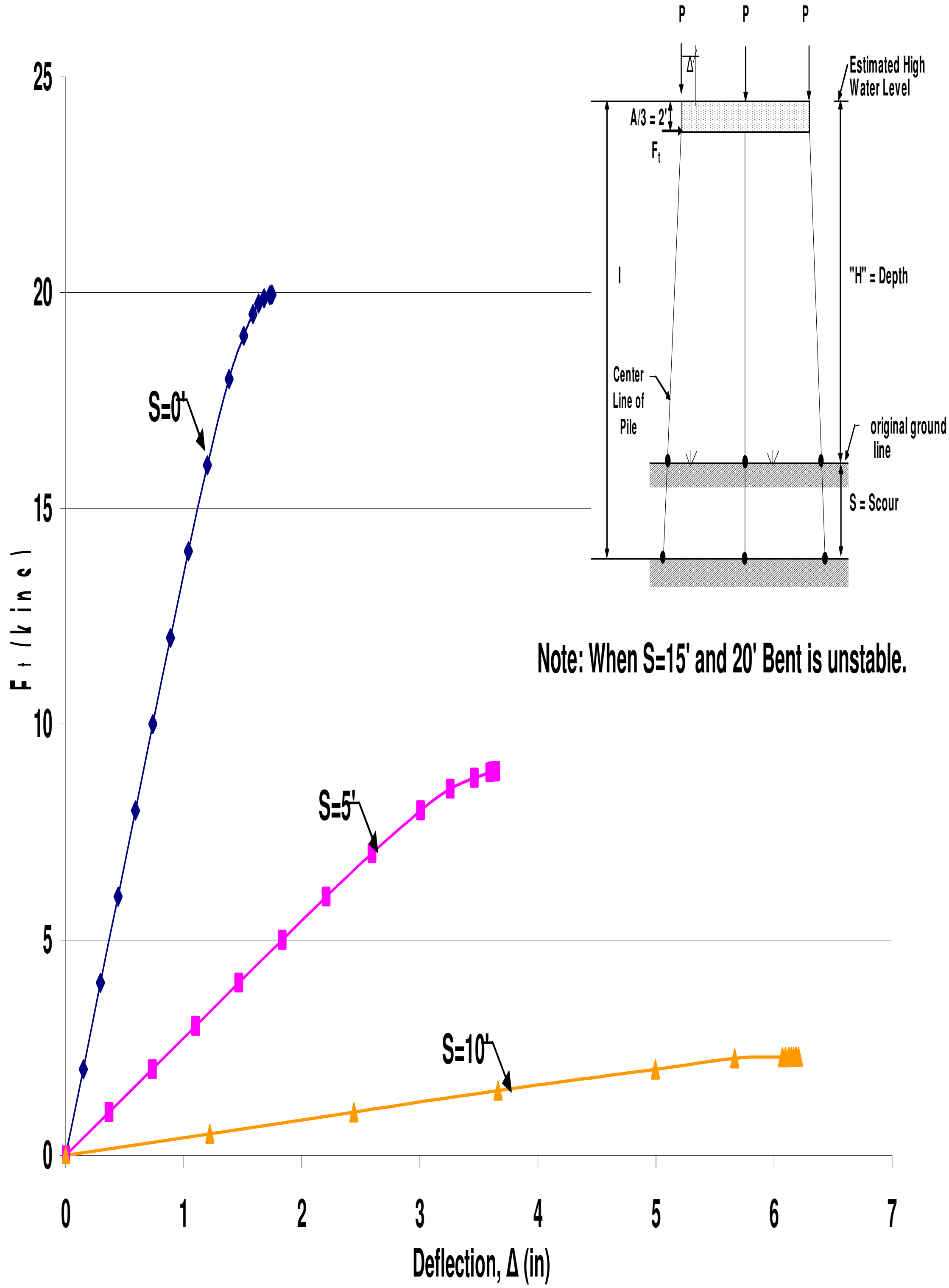


Figure A.2 HP10x42 Unbraced 3-Pile Bent with H=10', P=120kips, and A=6'
Pushover Analysis Results

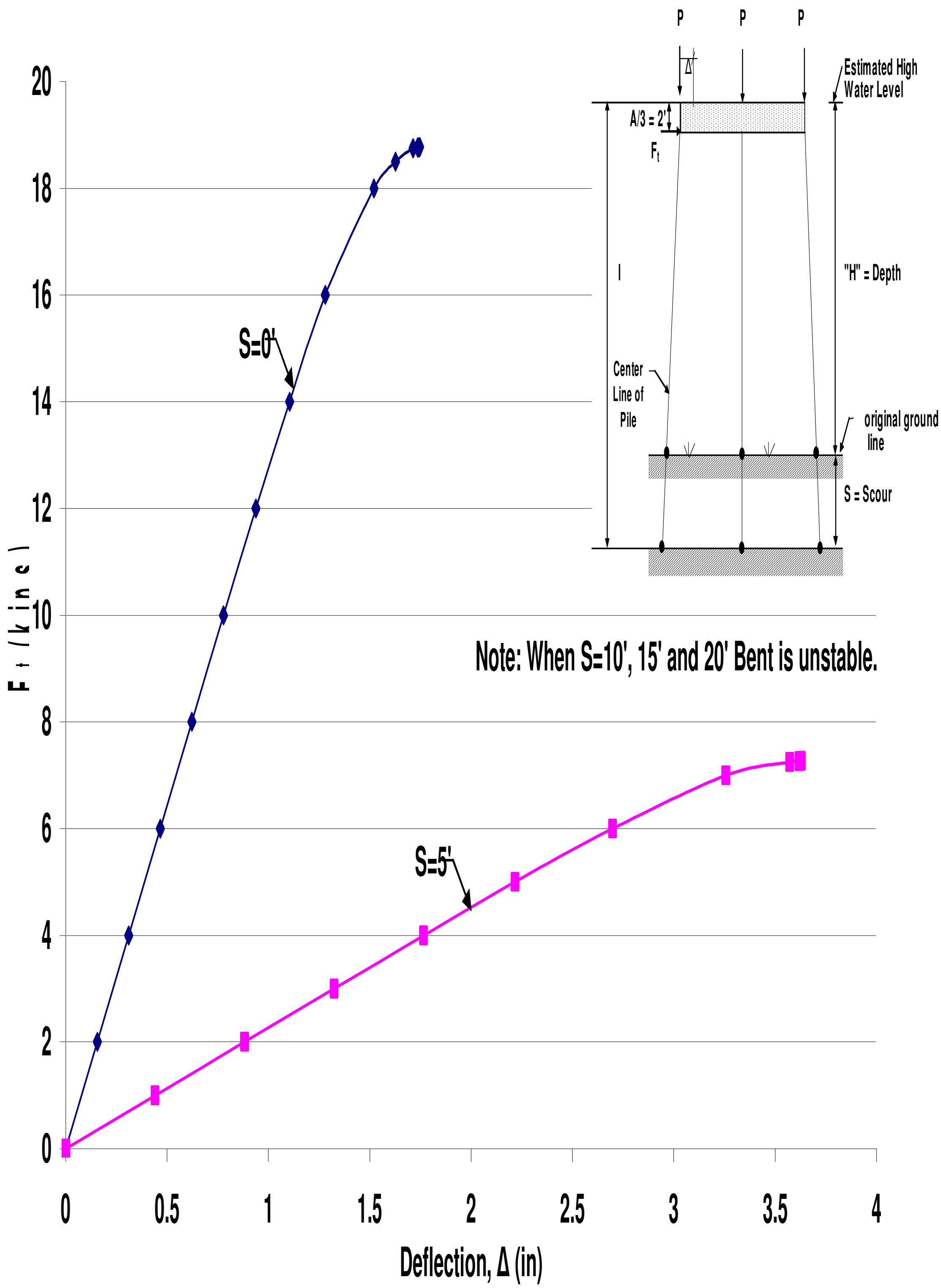


Figure A.3 HP10x42 Unbraced 3-PileBent with H=10', P=140kips, and A=6'
Pushover Analysis Results

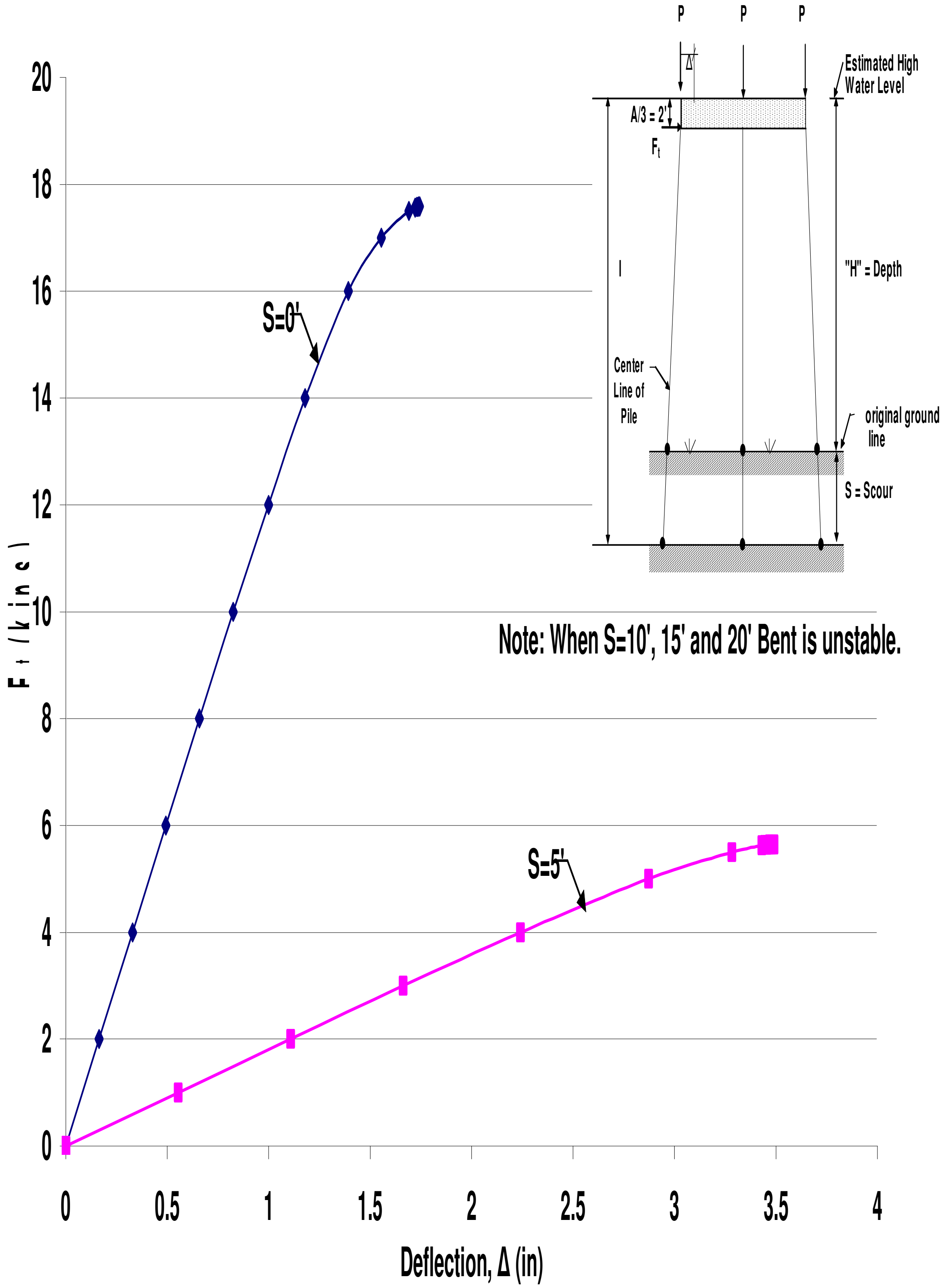


Figure A.4 HP10x42 Unbraced 3-Pile Bent with H=10', P=160kips, and A=6'
Pushover Analysis Results

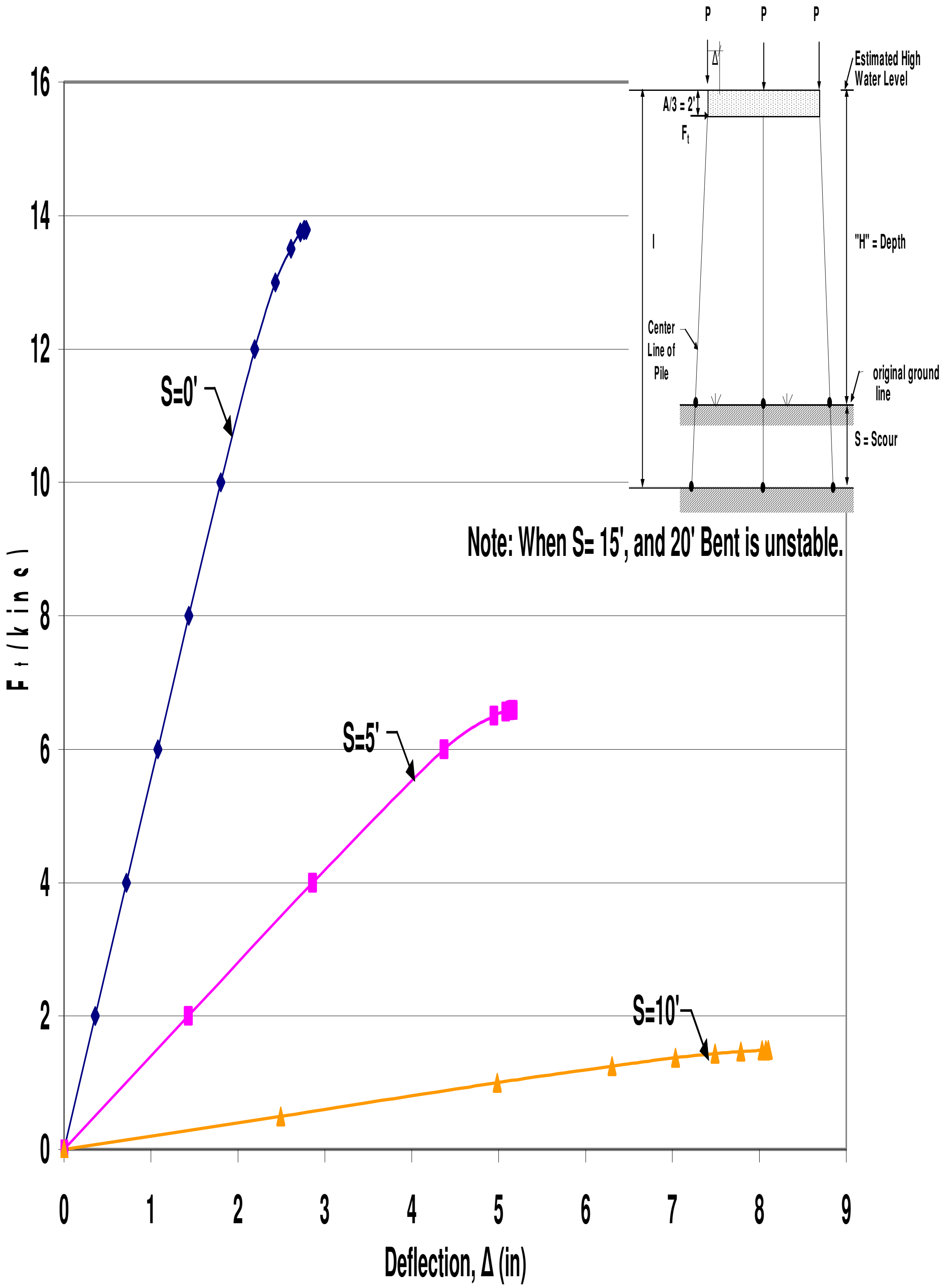


Figure A.5 HP10x42 Unbraced 3-Pile Bent with H=13', P=100kips, and A=6'
Pushover Analysis Results

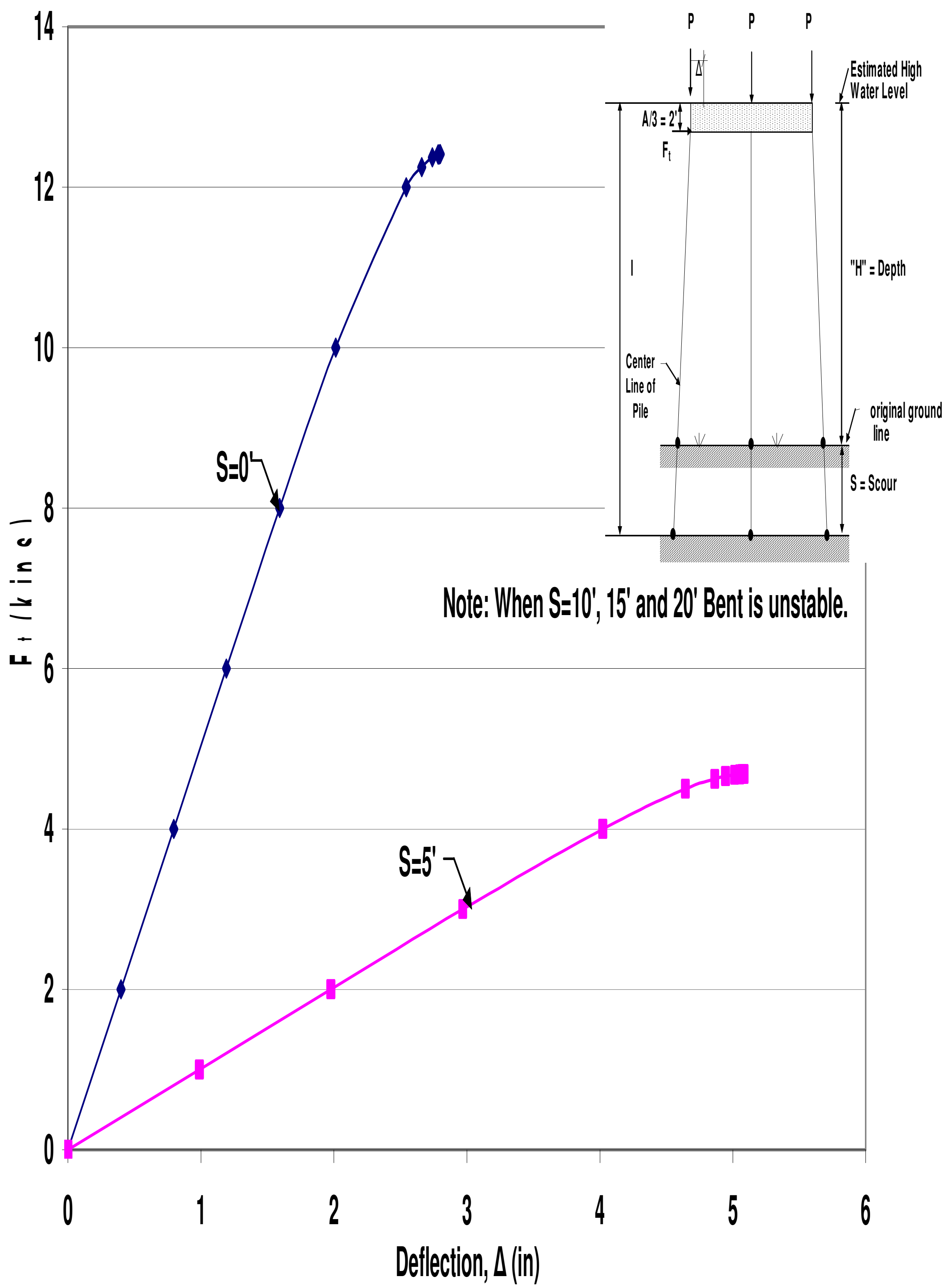


Figure A.6 HP10x42 Unbraced 3-Pile Bent with H=13', P=120kips, and A=6'
Pushover Analysis Results

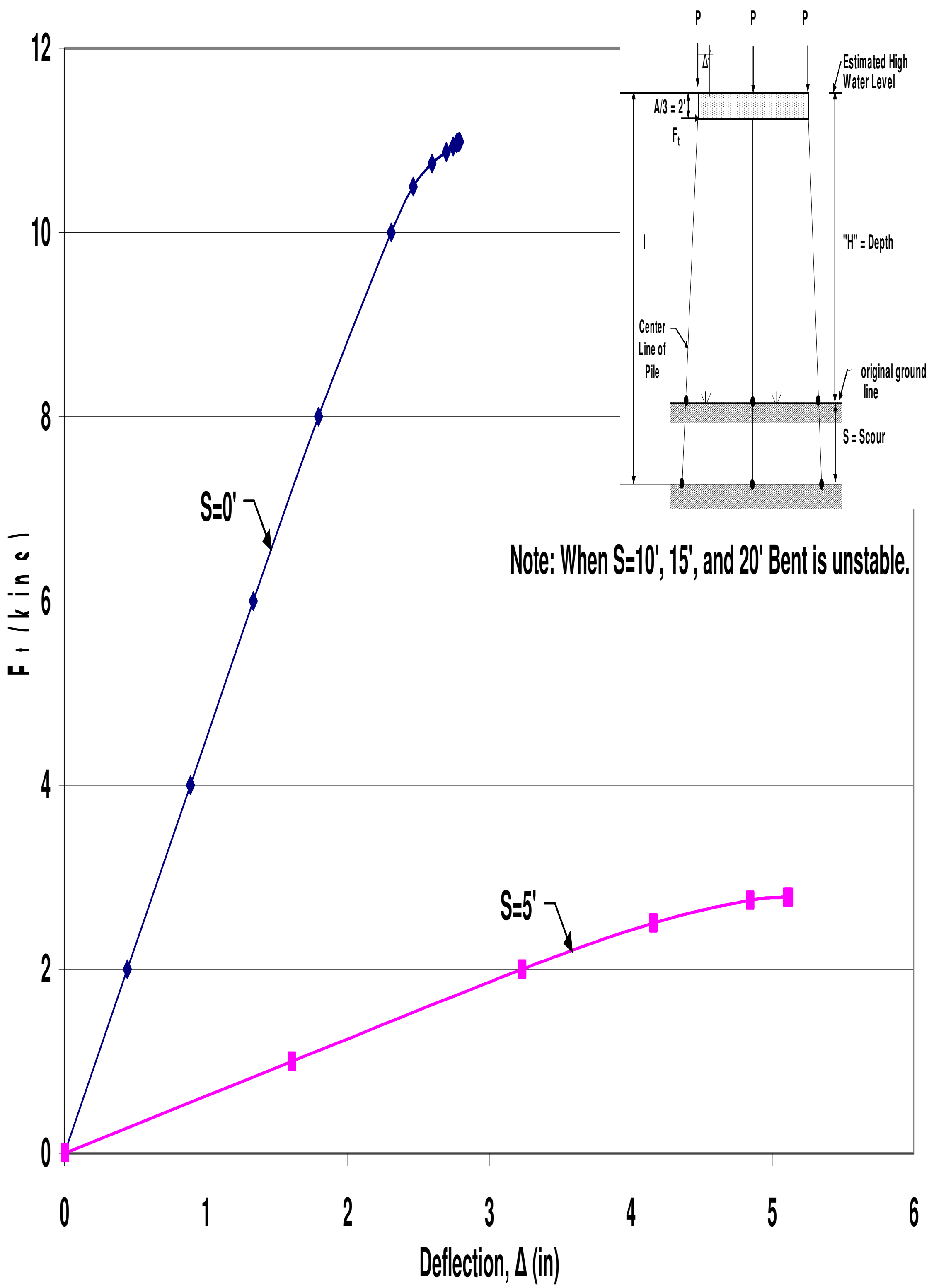


Figure A.7 HP10x42 Unbraced 3-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

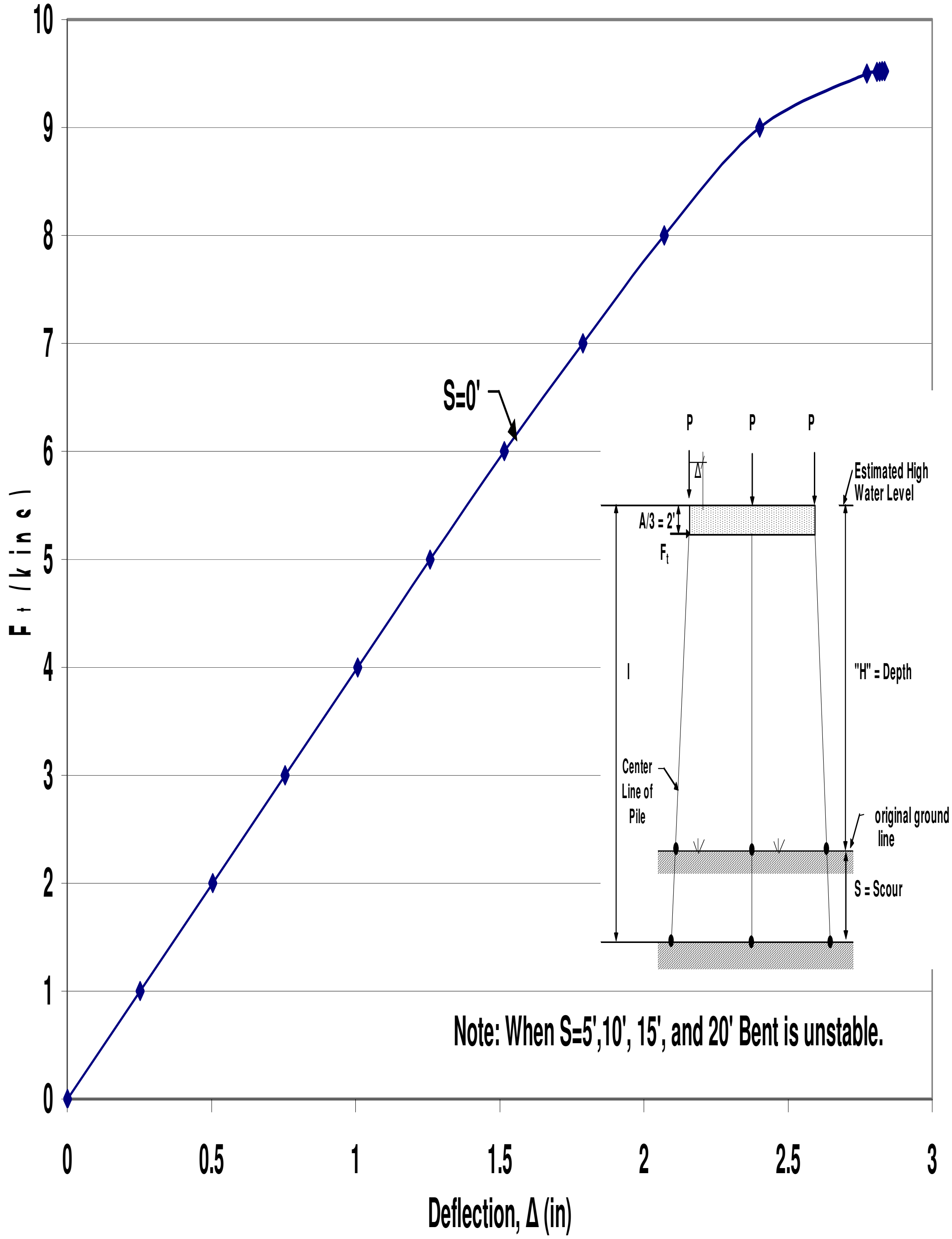


Figure A.8 HP10x42 Unbraced 3-Pile Bent with H=13', P=160 kips and A=6' Pushover Analysis Results

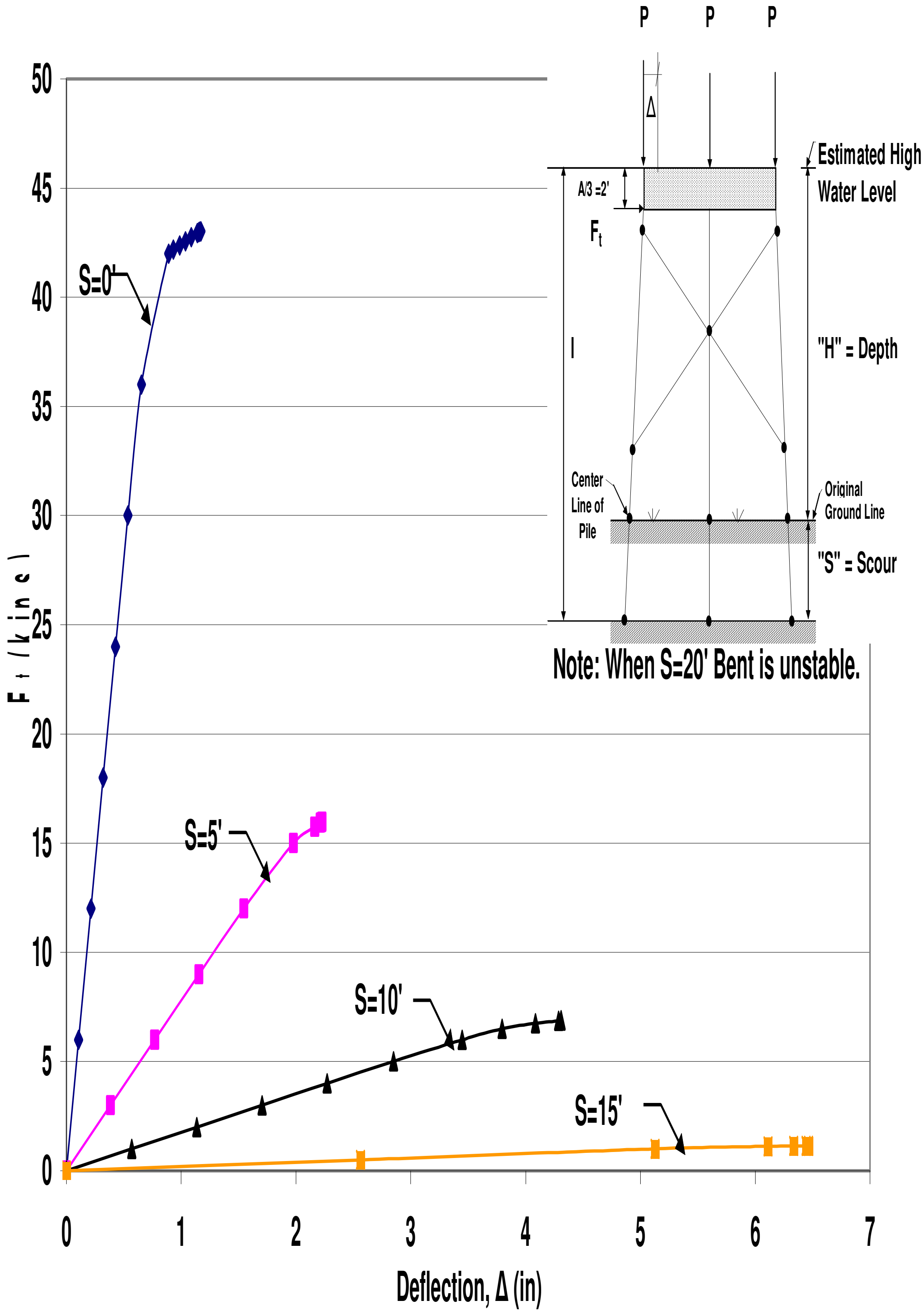


Figure A.9 HP10x42 X-Braced 3-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

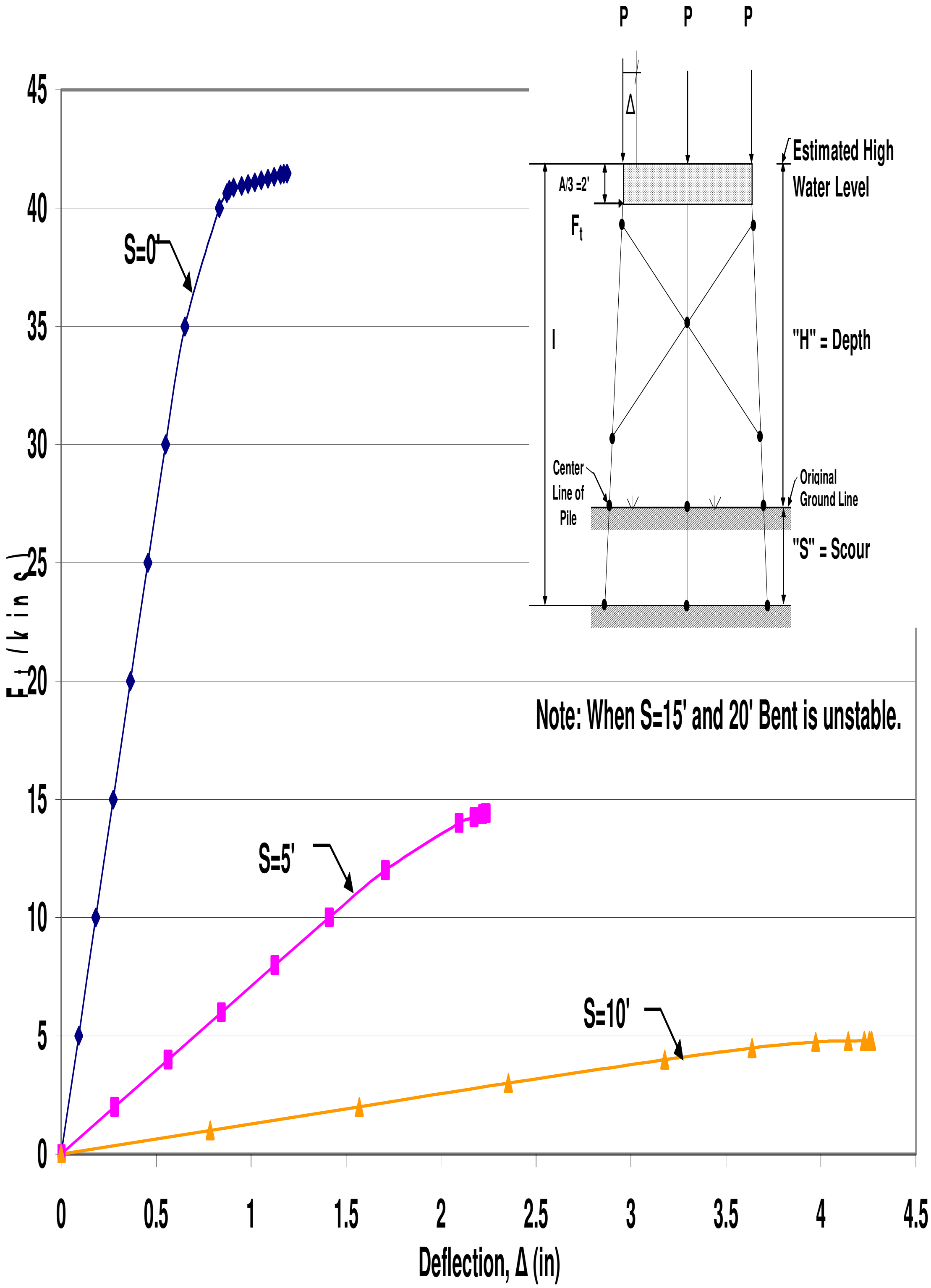


Figure A.10 HP10x42 X-Braced 3-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

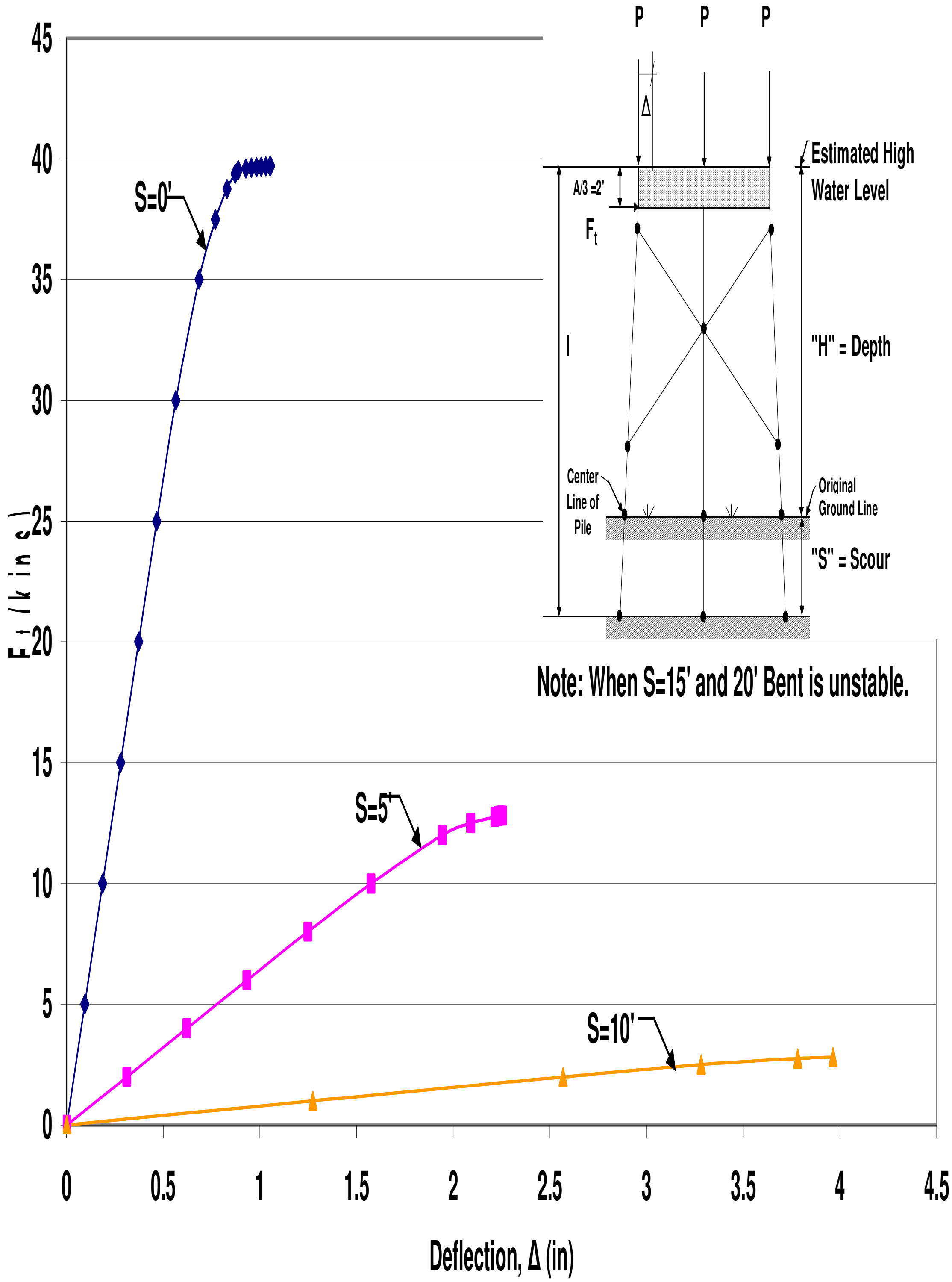


Figure A.11 HP10x42 X-Braced 3-Pile Bent with H=13', P=140kips and A=6'

Pushover Analysis Results

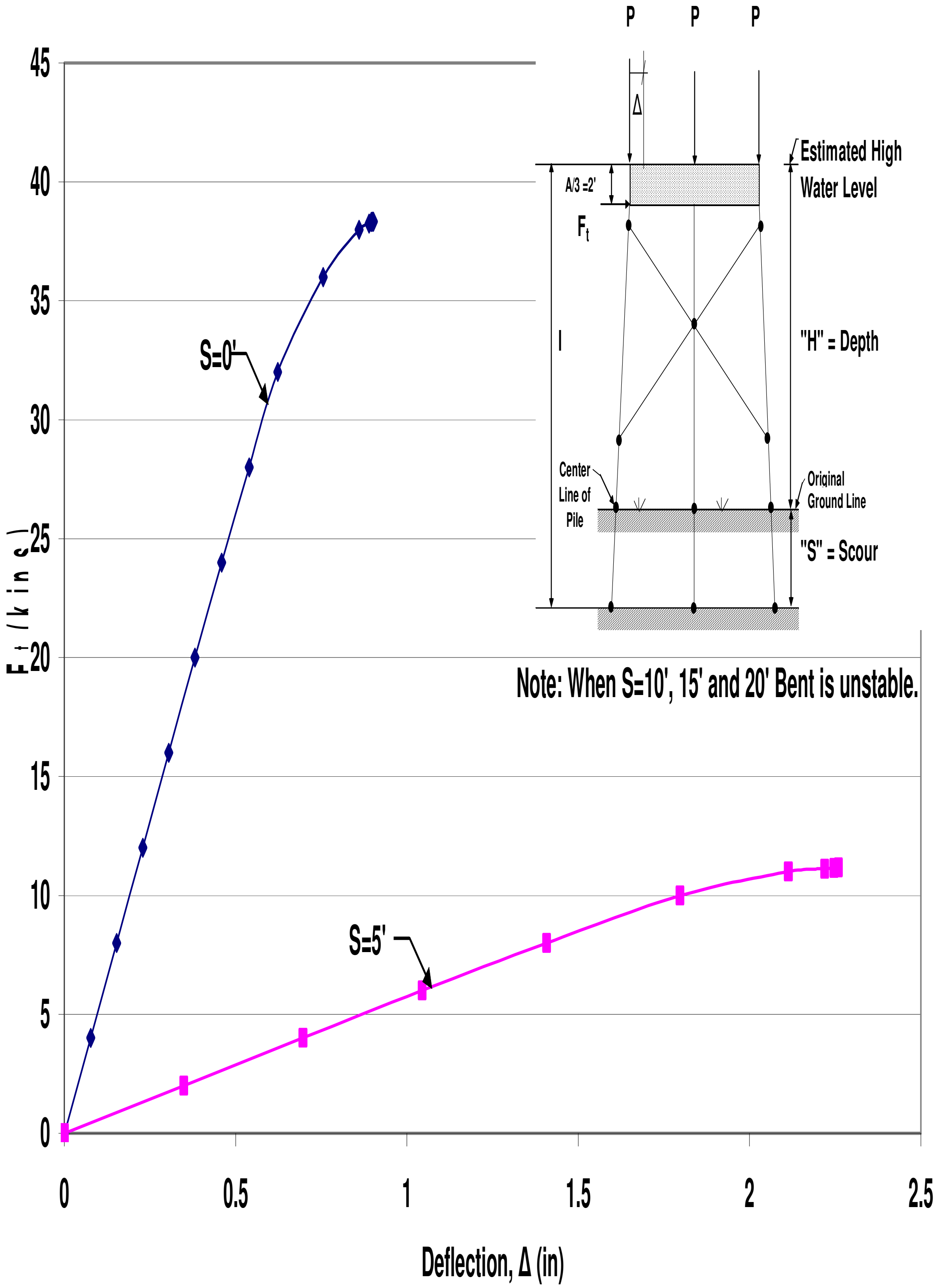


Figure A.12 HP10x42 X-Braced 3-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

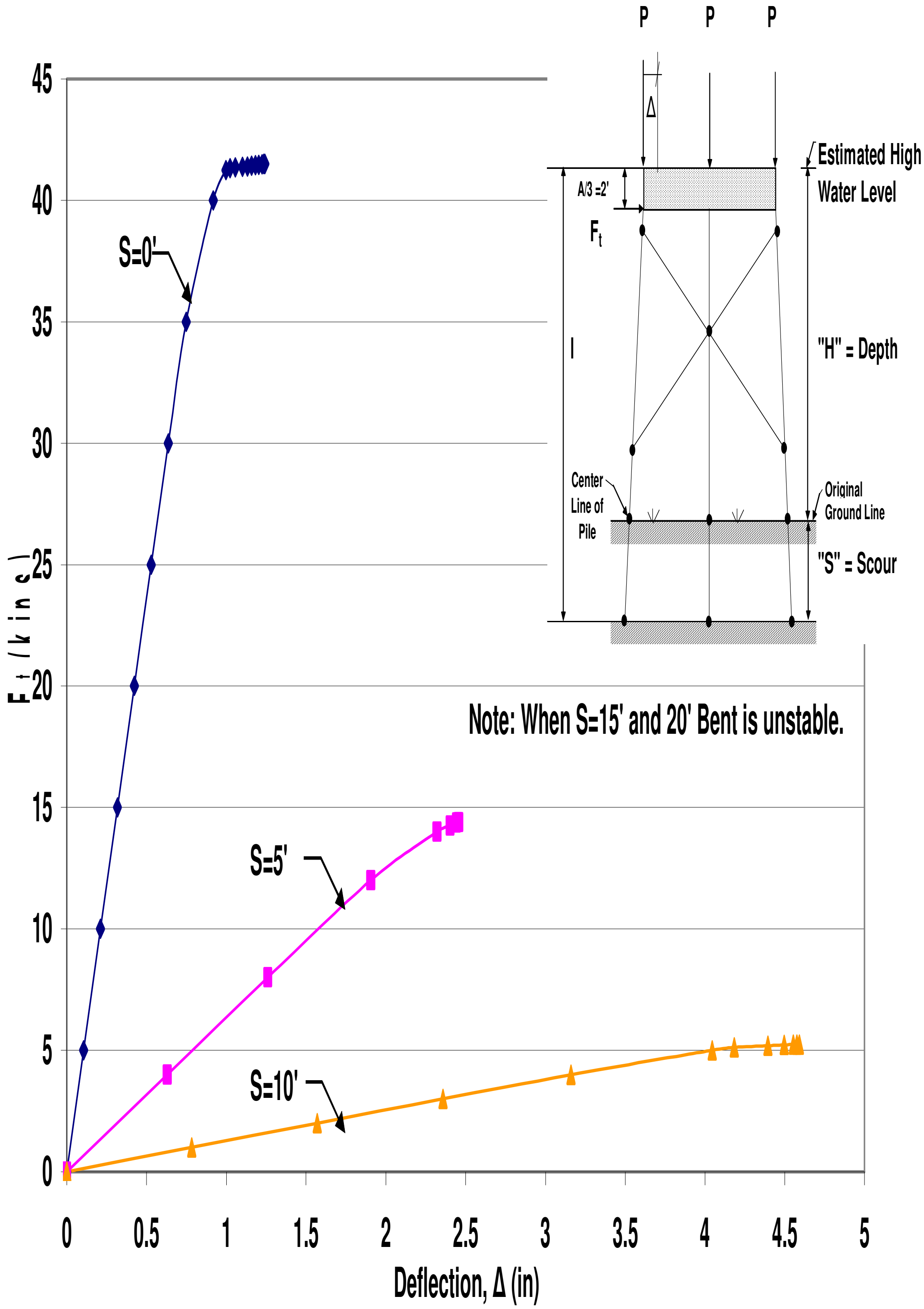


Figure A.13 HP10x42 X-Braced 3-Pile Bent with H=17', P=100kips and A=6'
Pushover Analysis Results

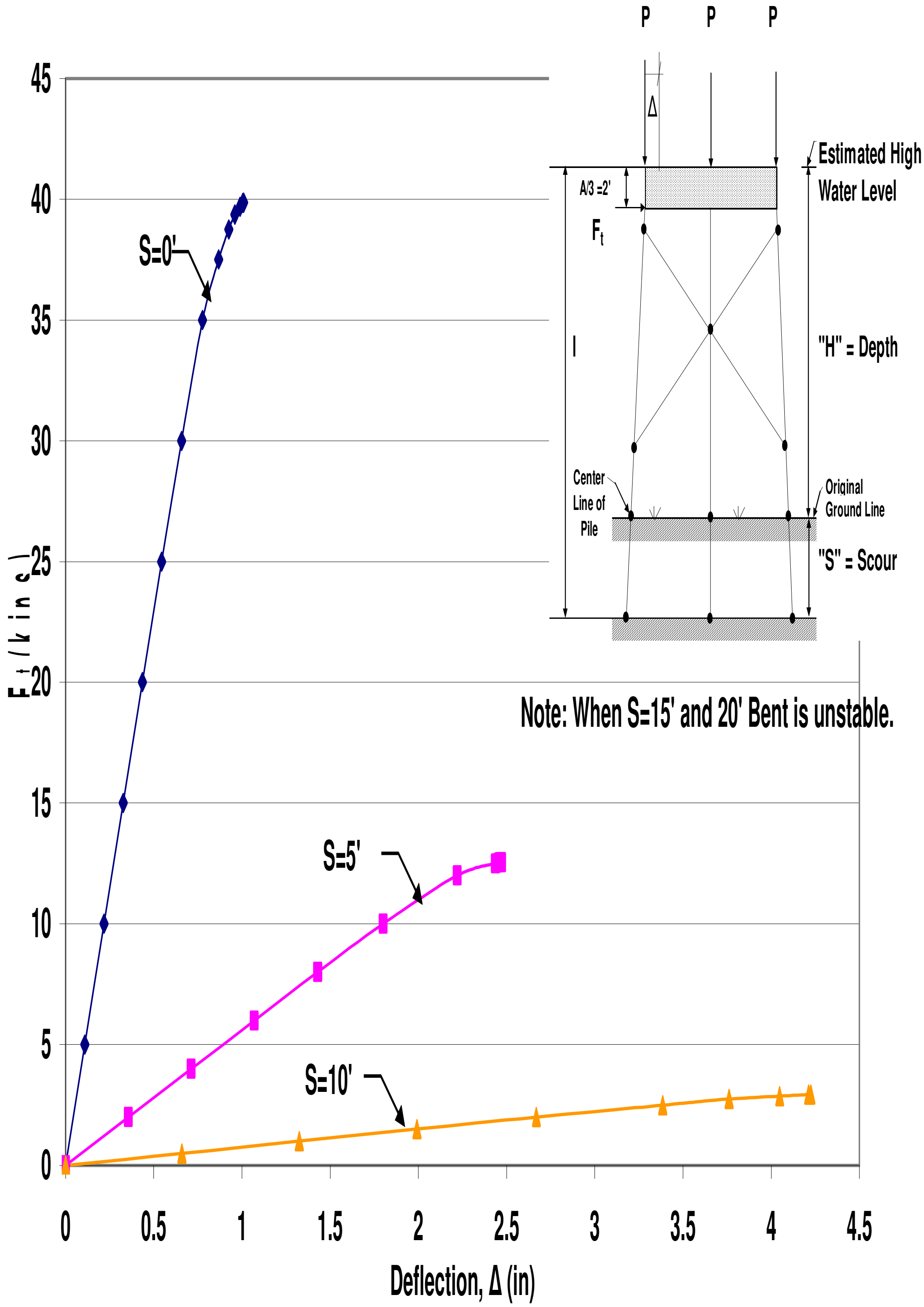


Figure A.14 HP10x42 X-Braced 3-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

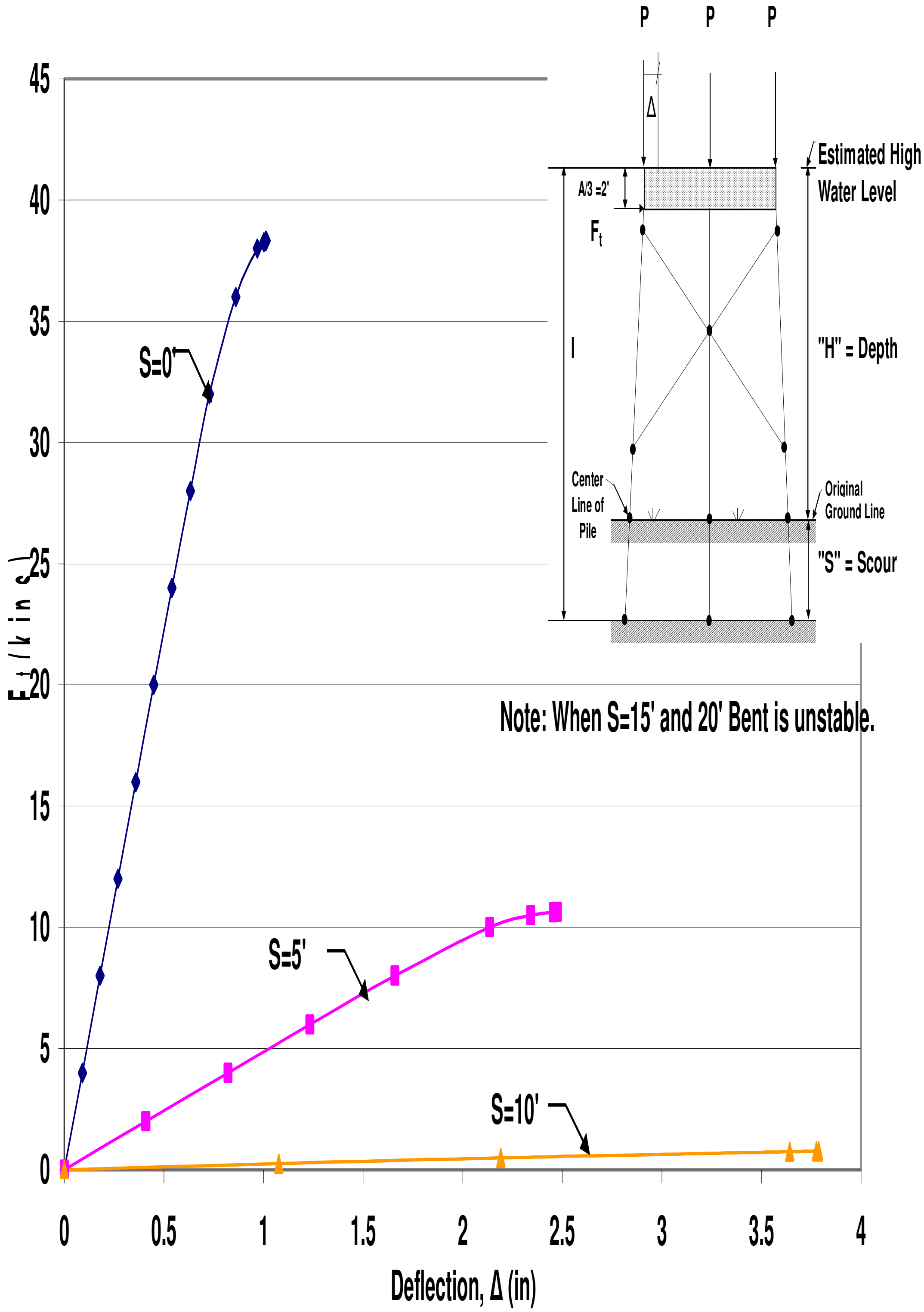


Figure A.15 HP10x42 X-Braced 3-Pile Bent with H=17', P=140kips and A=6'
Pushover Analysis Results

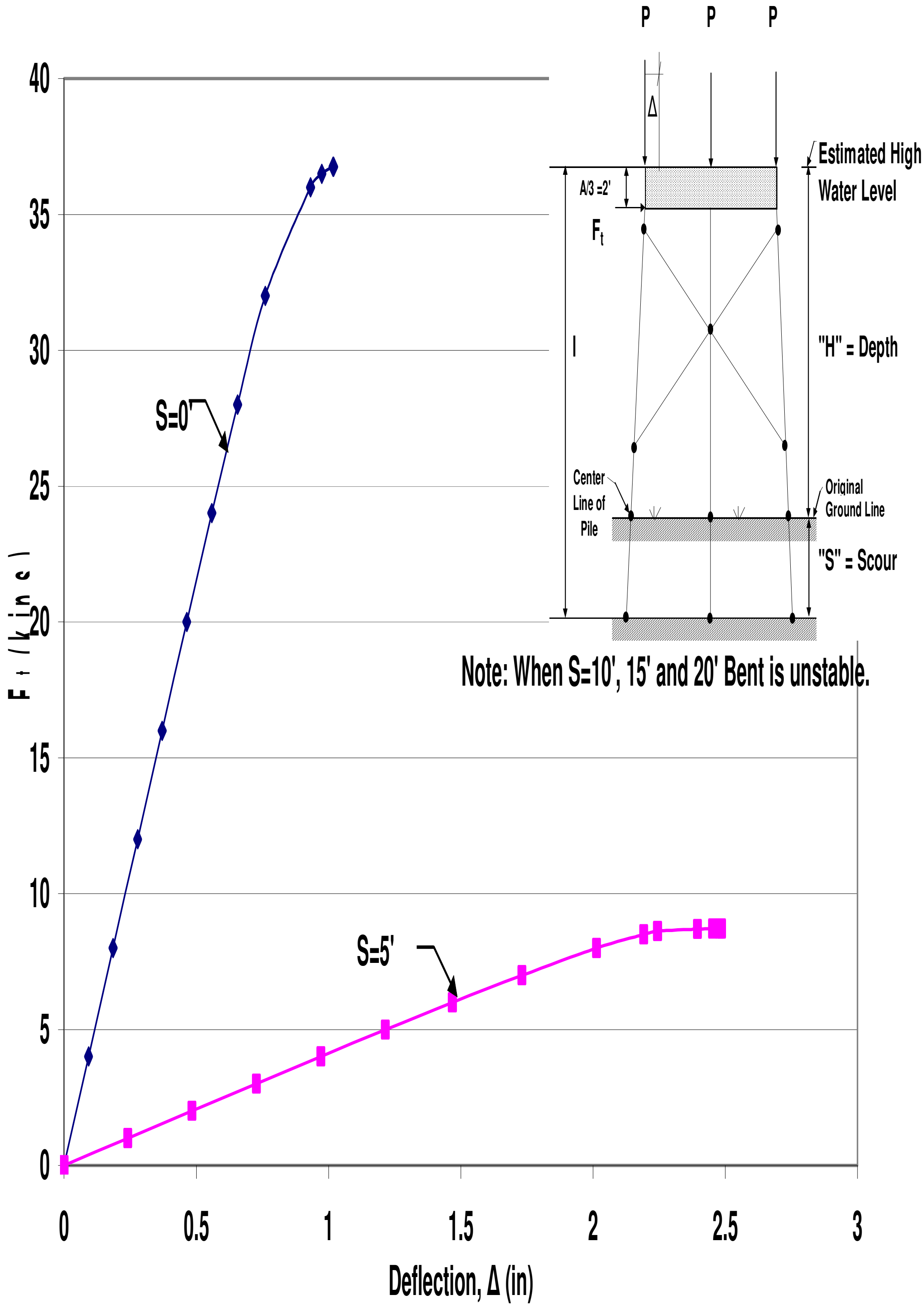


Figure A.16 HP10x42 X-Braced 3-Pile Bent with H=17', P=160kips and A=6'
Pushover Analysis Results

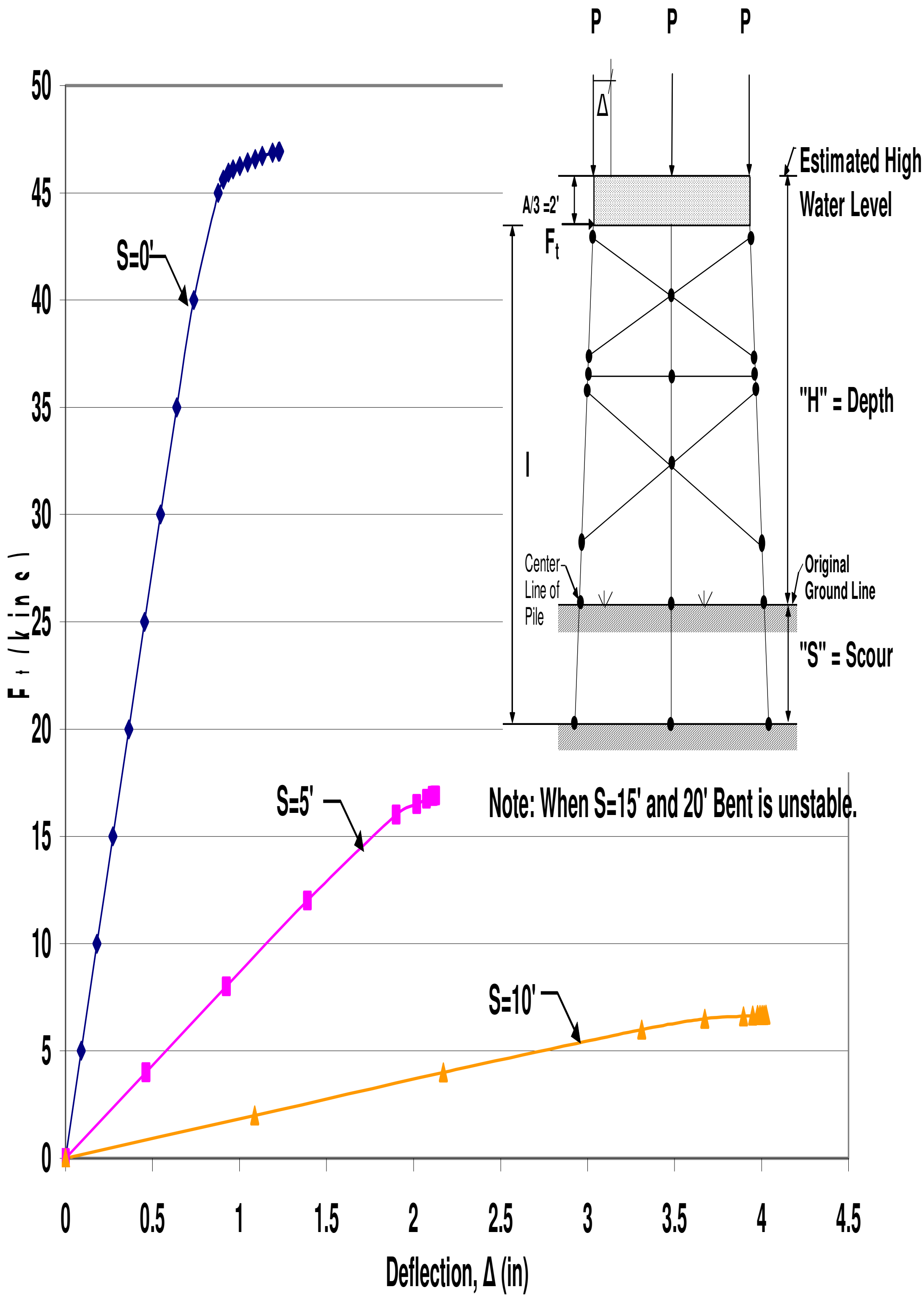


Figure A.17 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=100kips, and A=6' Pushover Analysis Results

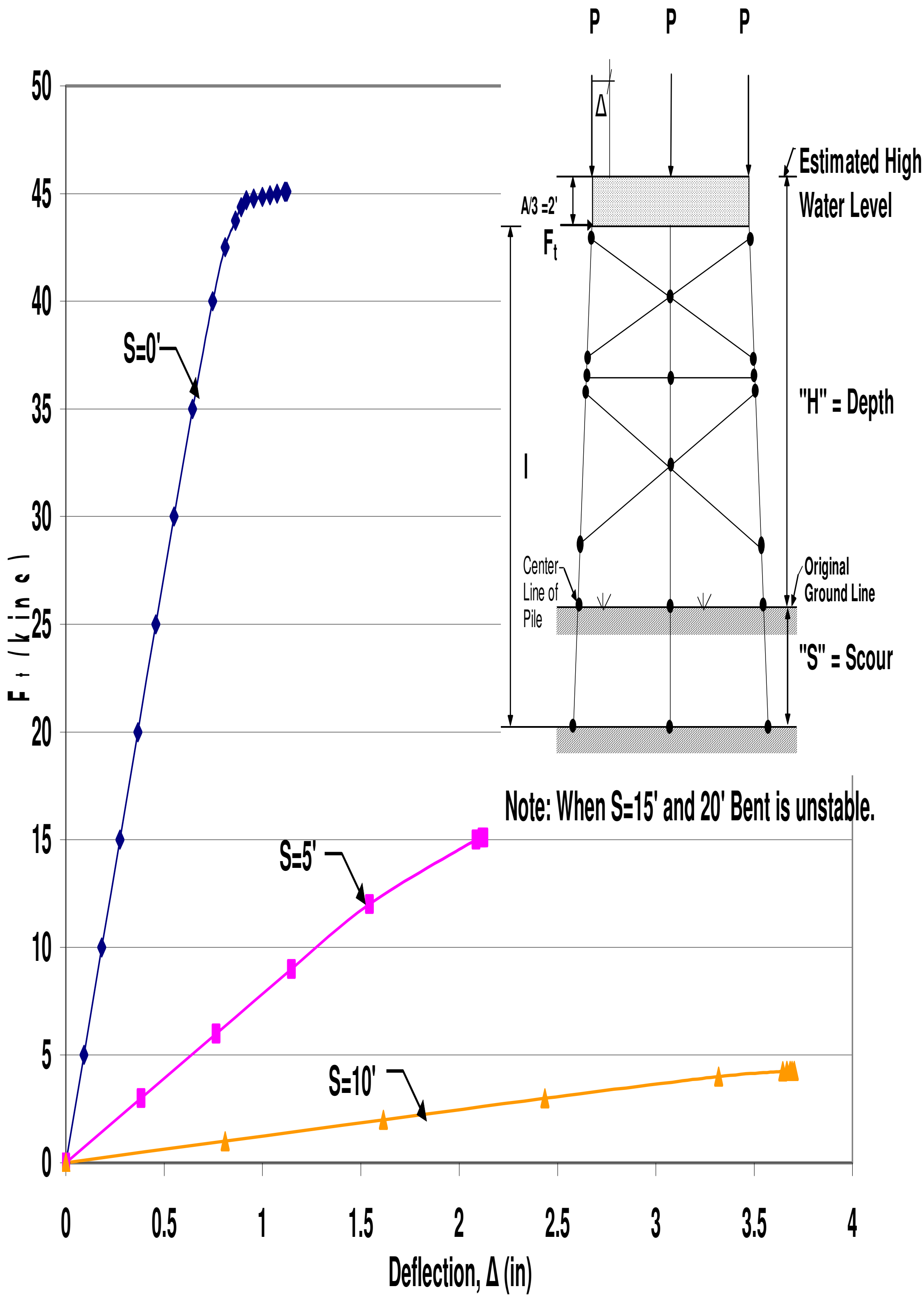


Figure A.18 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=120kips, and A=6' Pushover Analysis Results

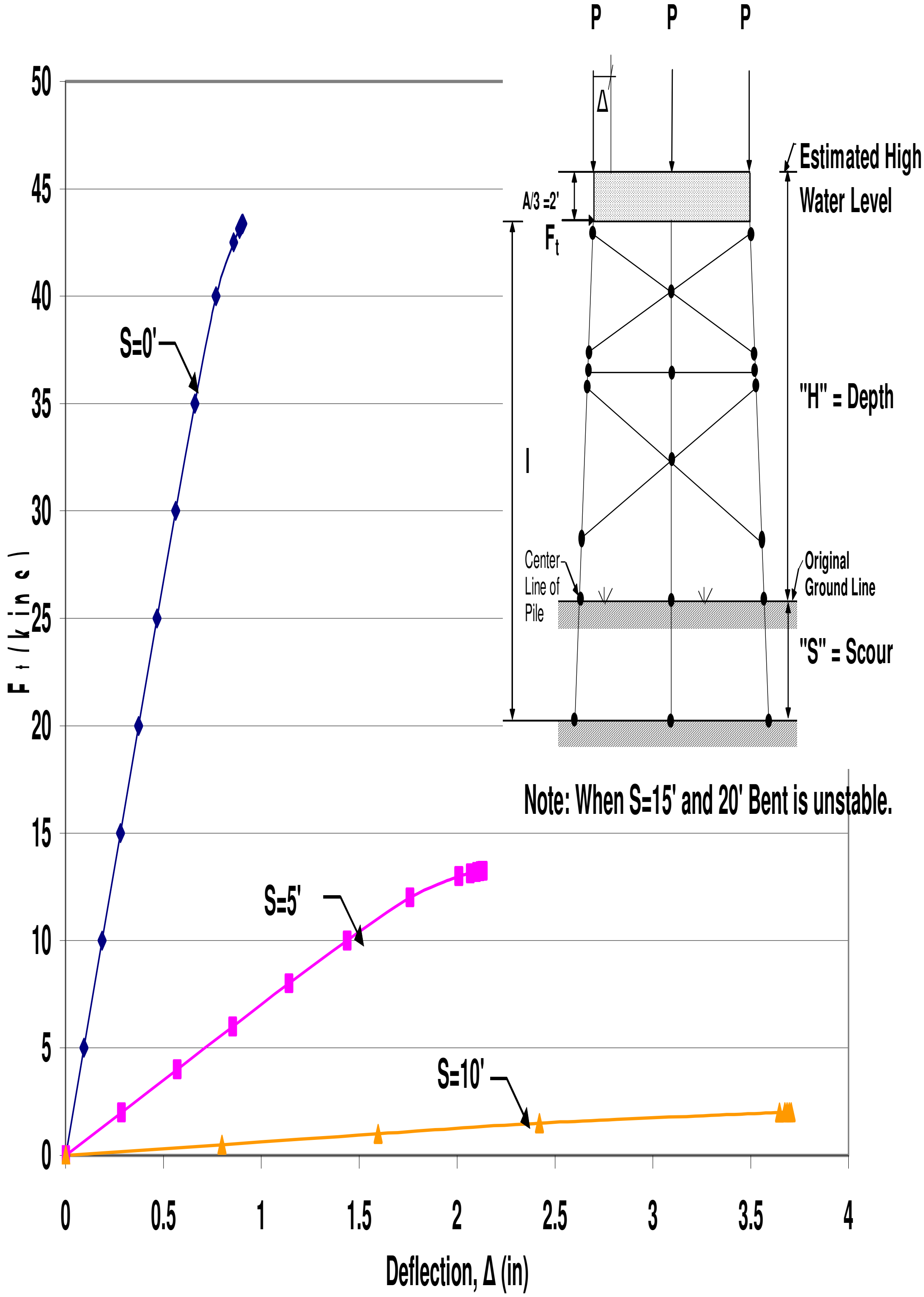


Figure A.19 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

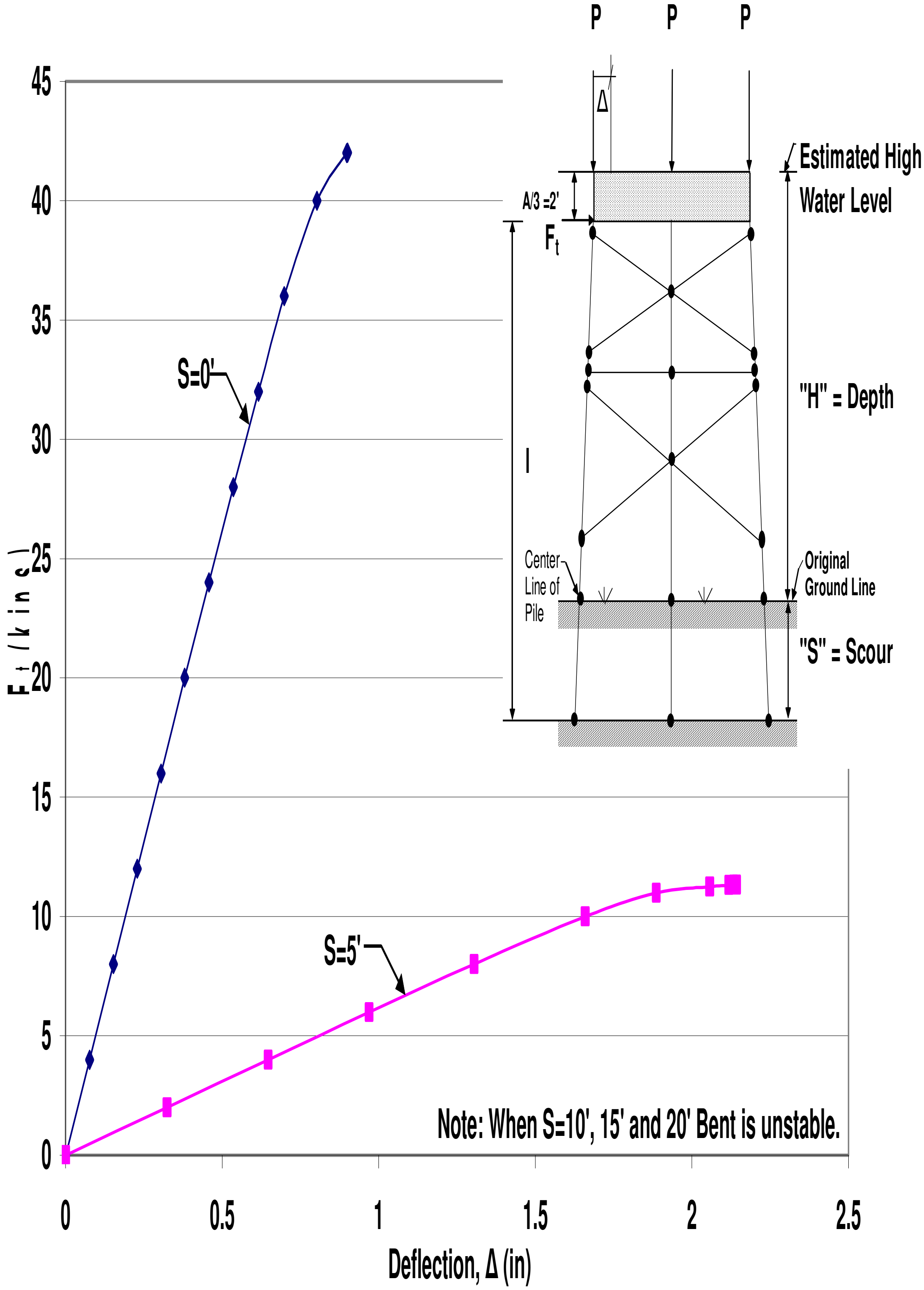


Figure A.20 HP10x42 Two-Story X-Braced 3-Pile Bent with H=21', P=160kips, and A=6' Pushover Analysis Results

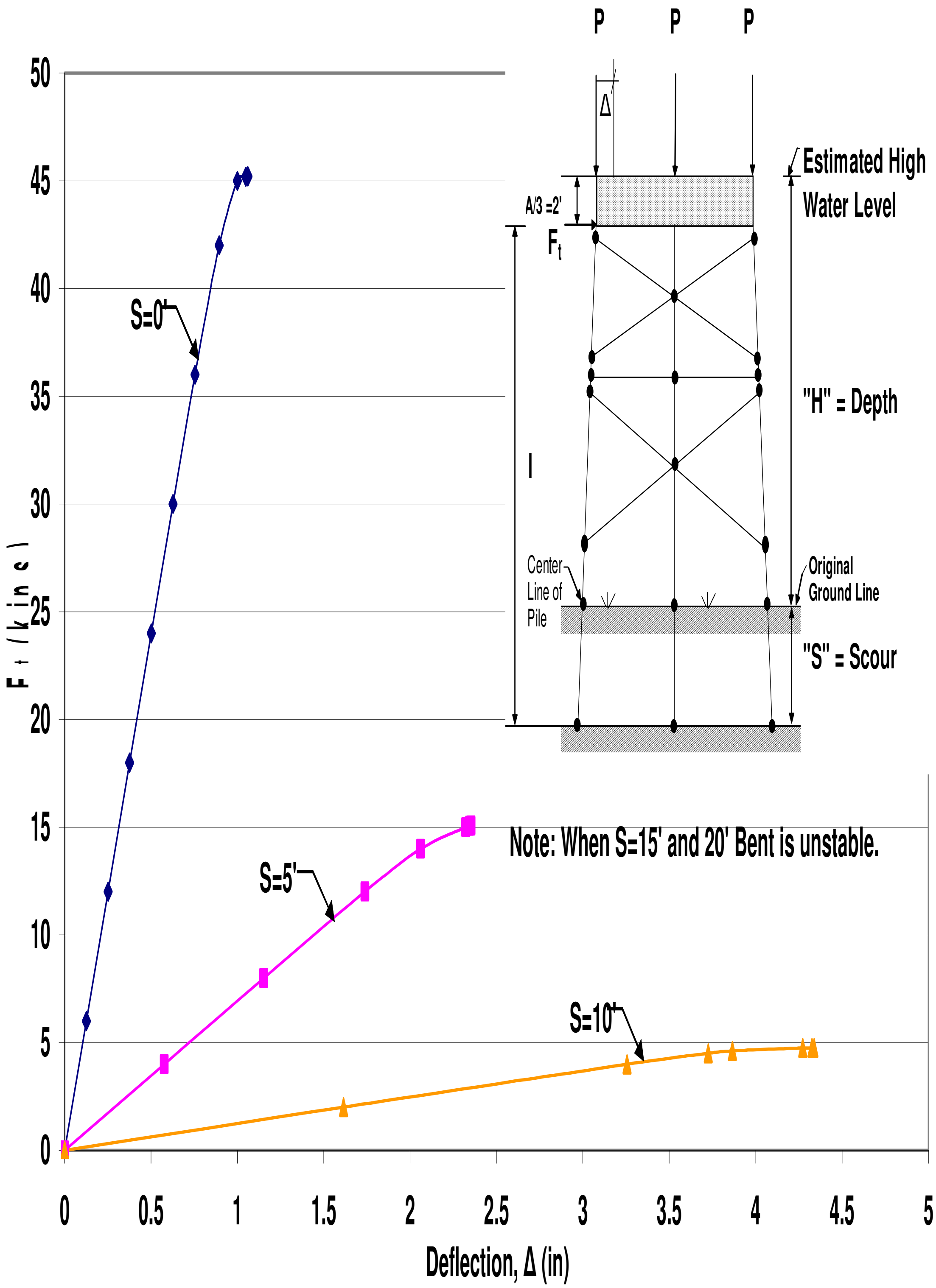


Figure A.21 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=100kips, and A=6' Pushover Analysis Results

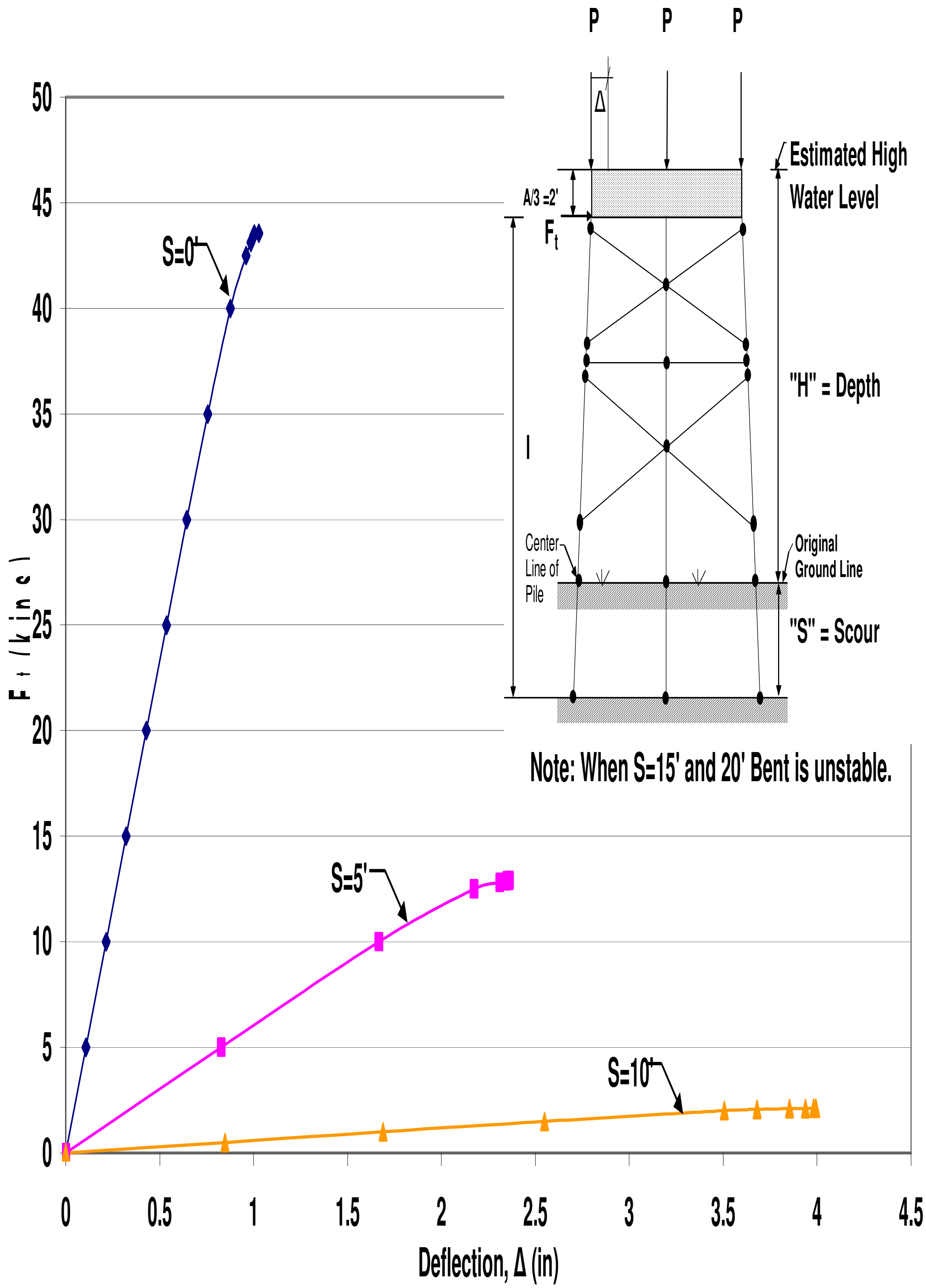


Figure A.22 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=120kips, and A=6' Pushover Analysis Results

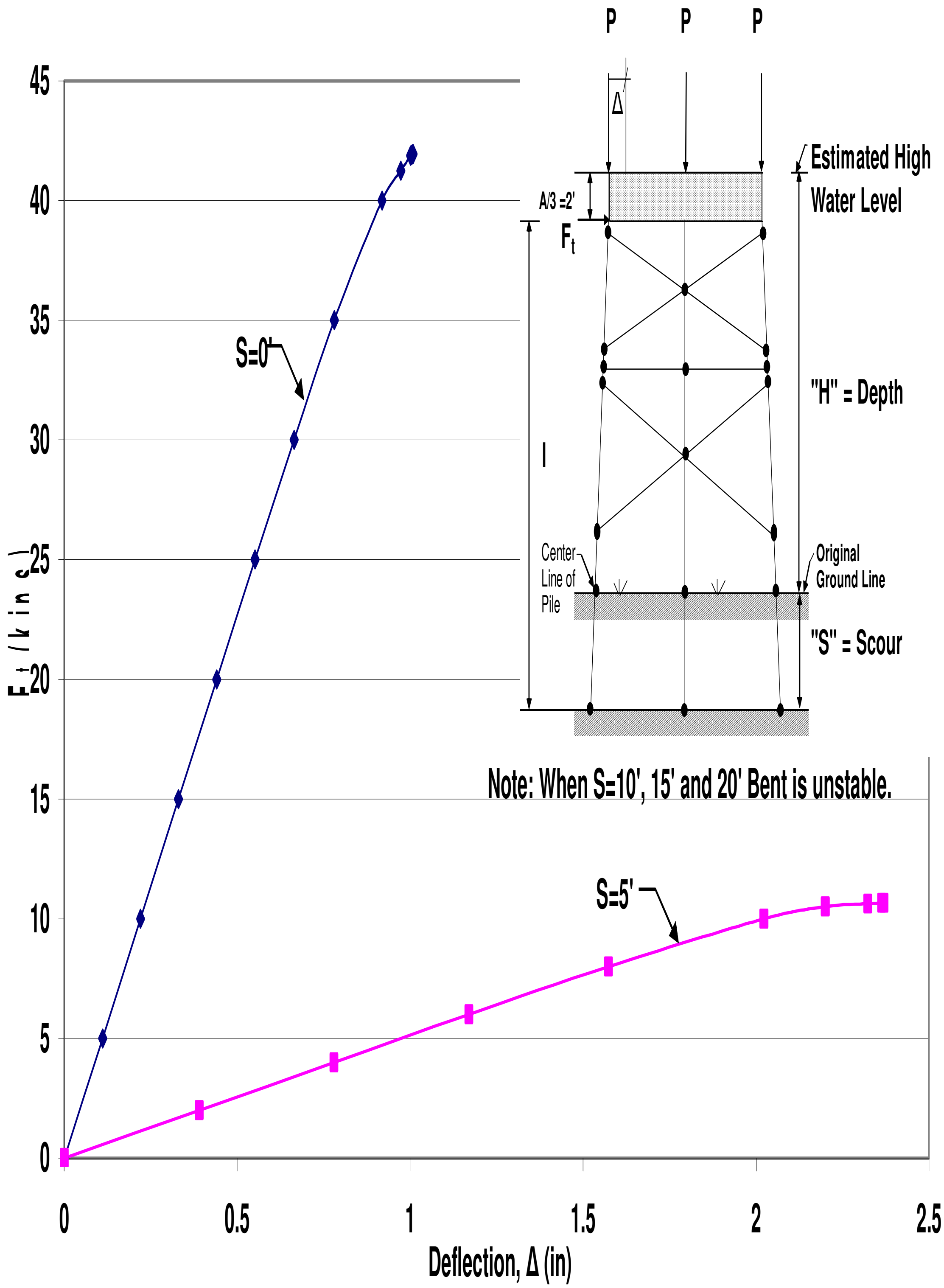


Figure A.23 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=140kips and A=6'
Pushover Analysis Results

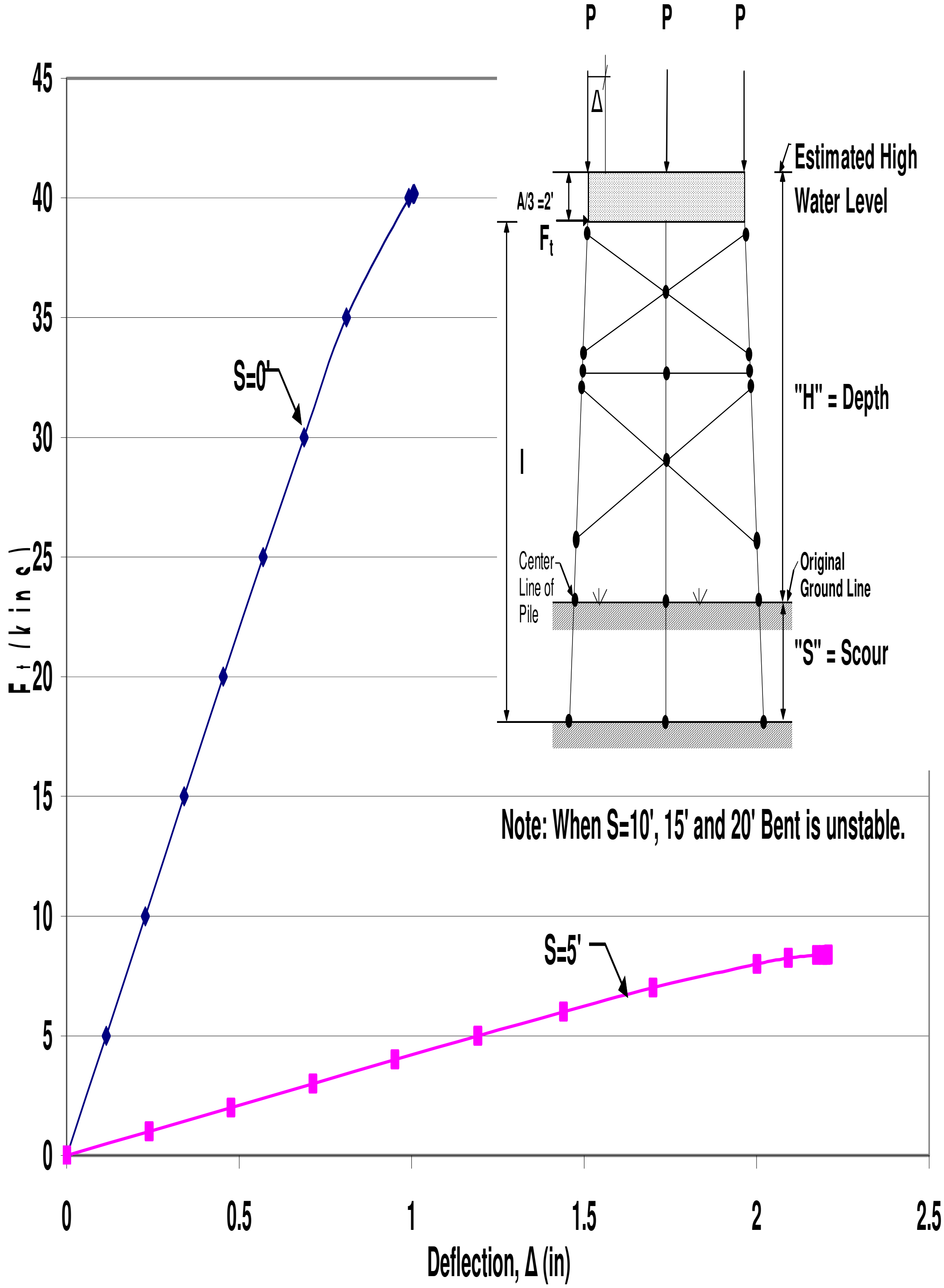


Figure A.24 HP10x42 Two-Story X-Braced 3-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

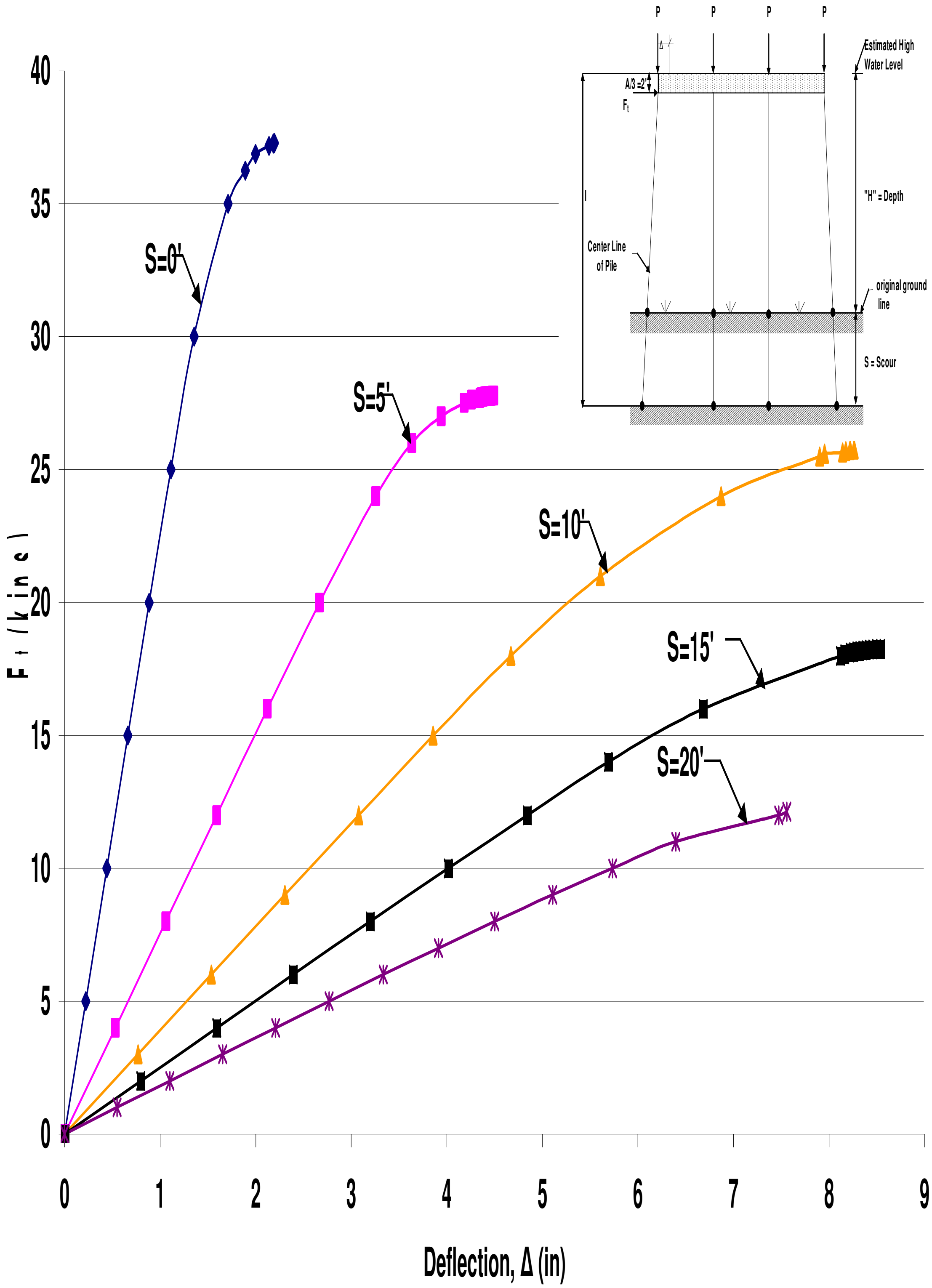


Figure A.25 HP10x42 Unbraced 4-Pile Bent with H=10', P=100kips, and A=6'
Pushover Analysis Results

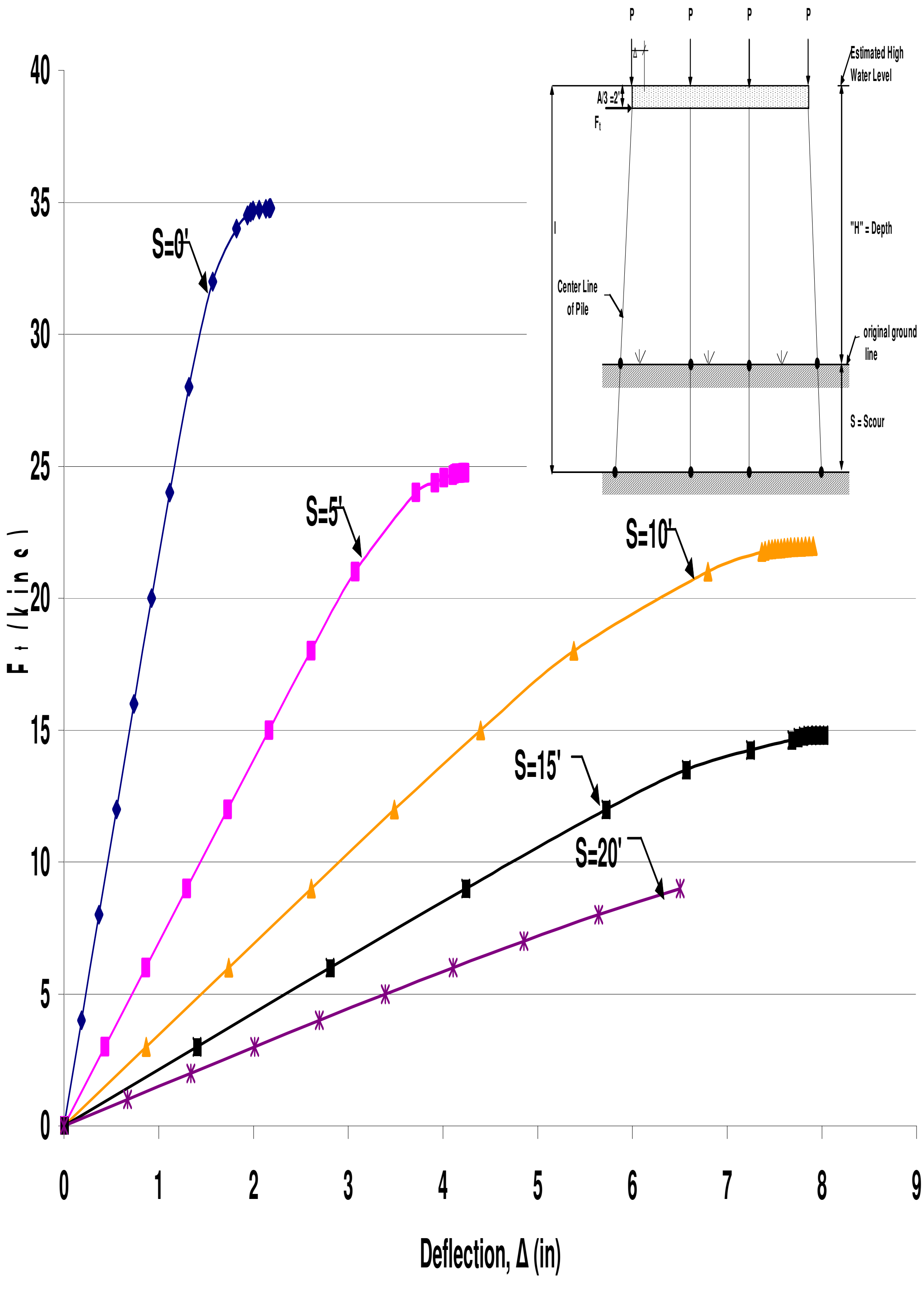


Figure A.26 HP10x42 Unbraced 4-Pile Bent with H=10', P=120kips, and A=6' Pushover Analysis Results

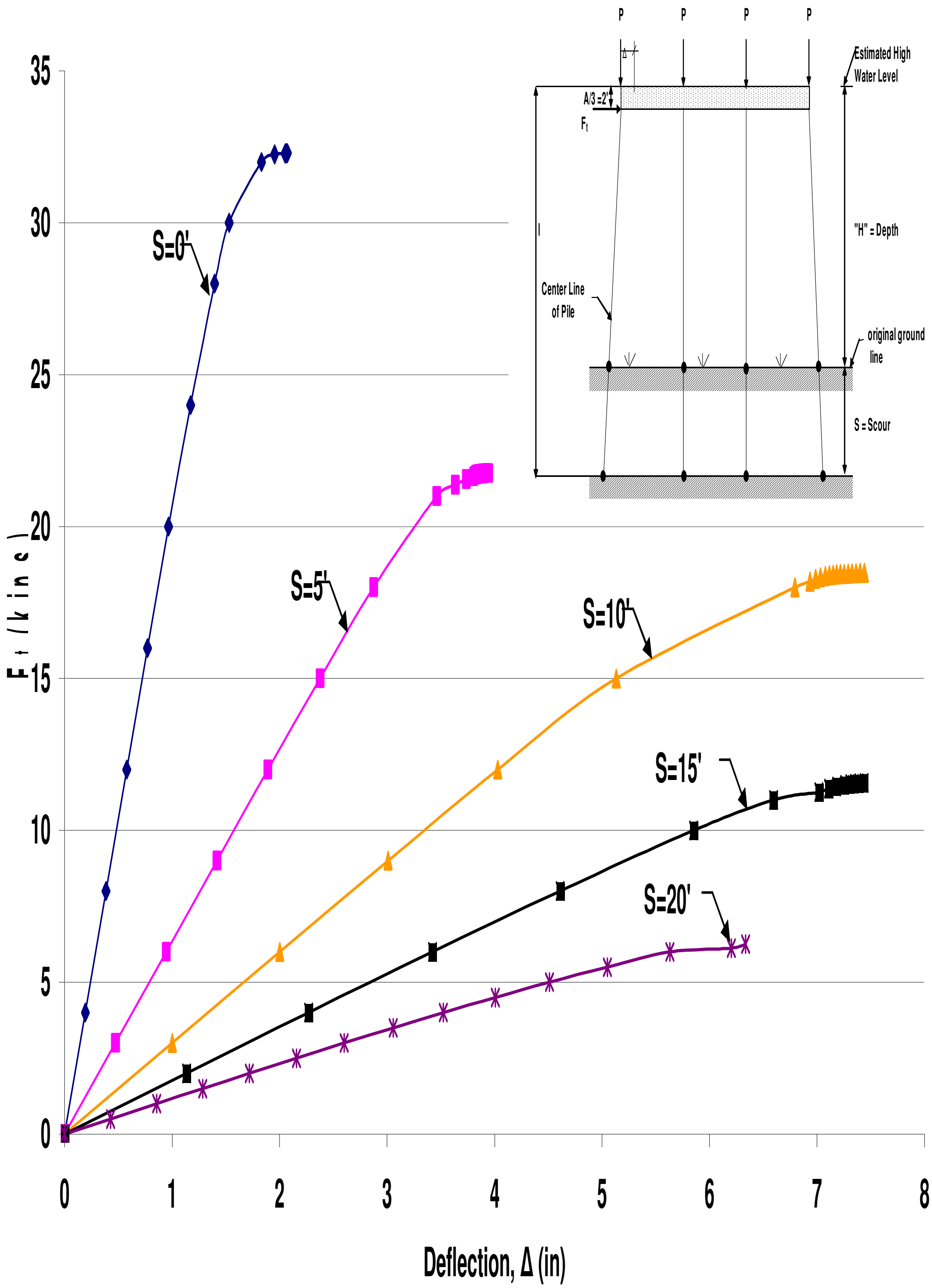


Figure A.27 HP10x42 Unbraced 4-Pile Bent with H=10', P=140kips, and A=6'

Pushover Analysis Results

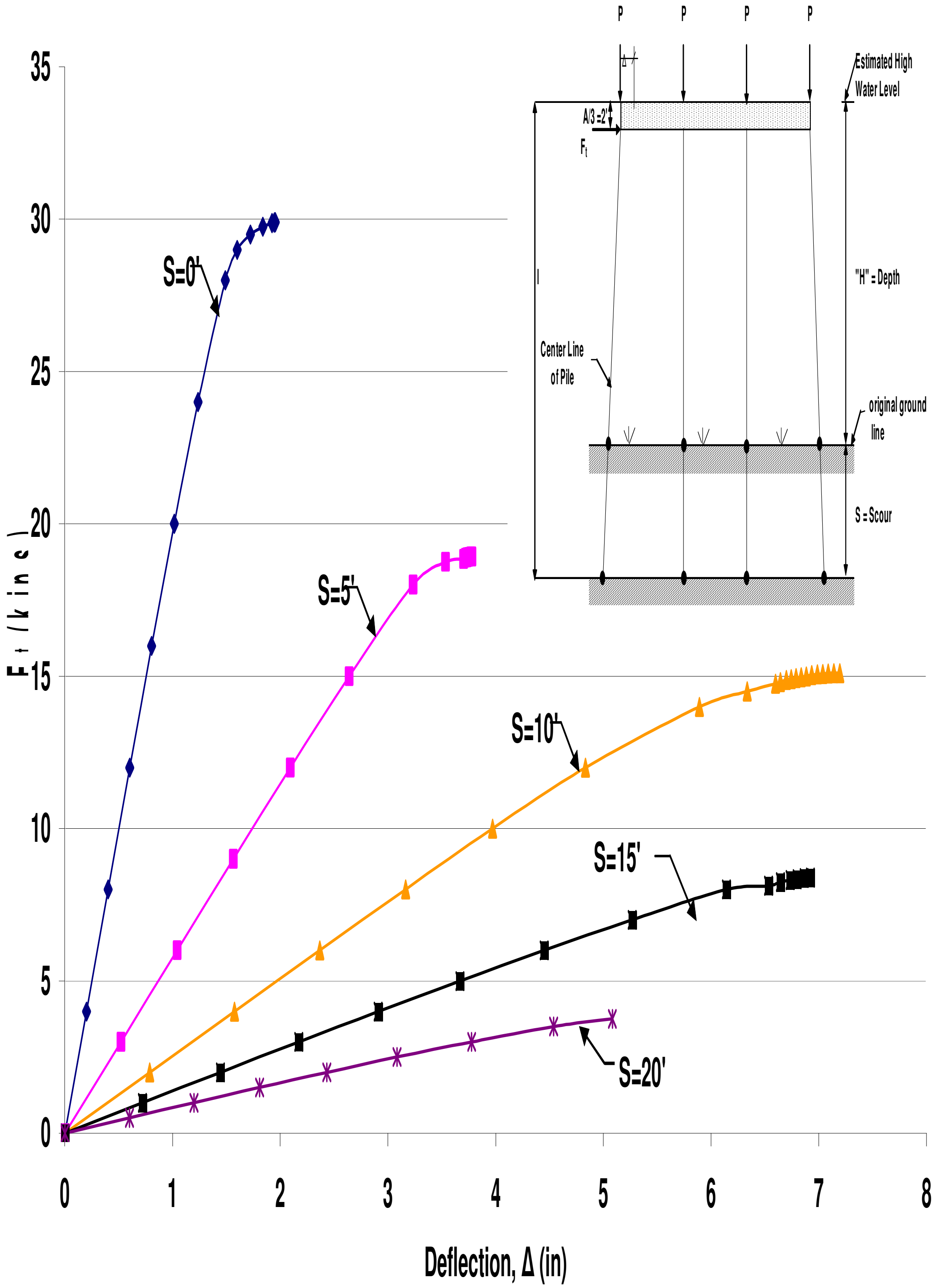


Figure A.28 HP10x42 Unbraced 4-Pile Bent with H=10', P=160kips, and A=6'

Pushover Analysis Results

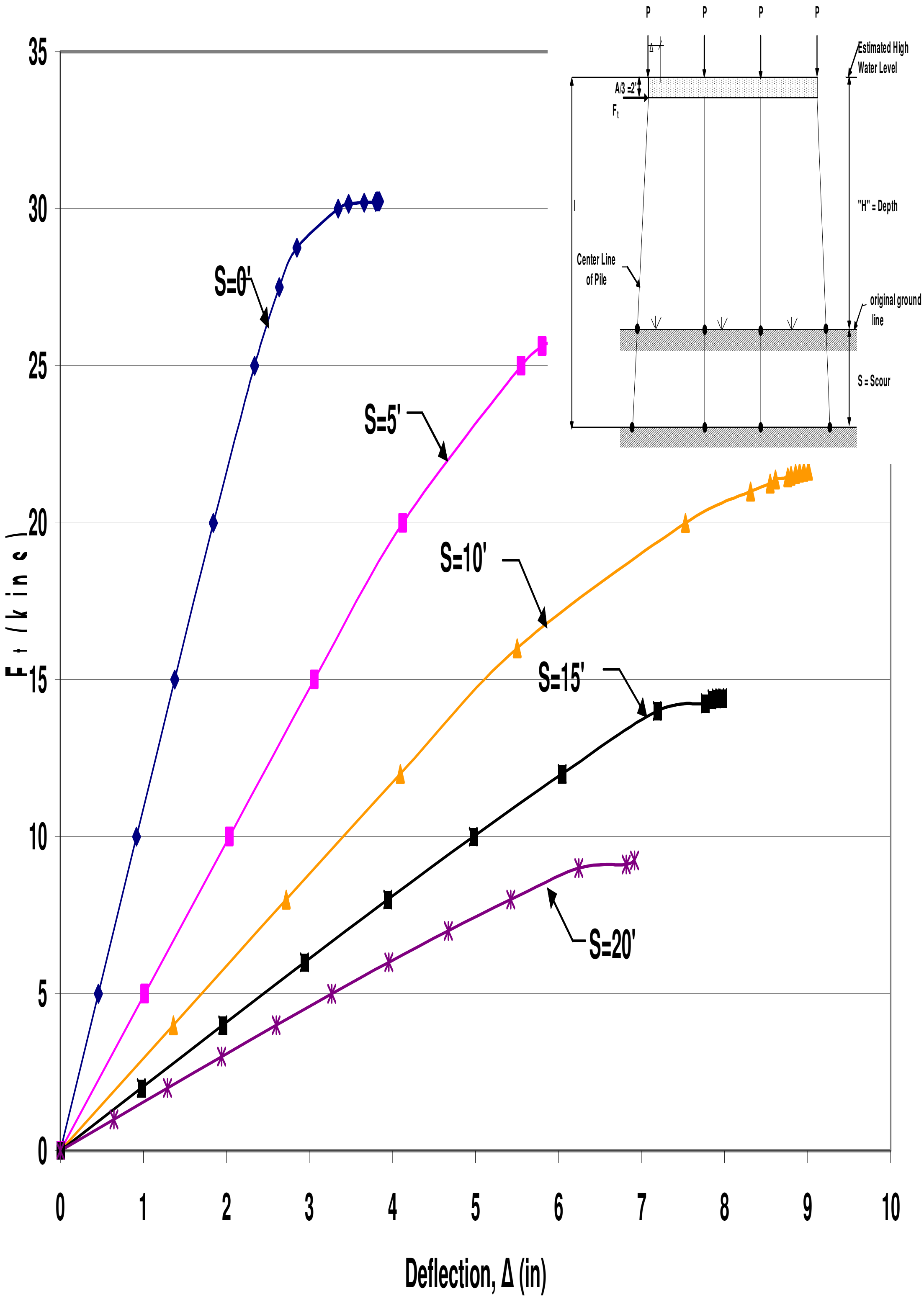


Figure A.29 HP10x42 Unbraced 4-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

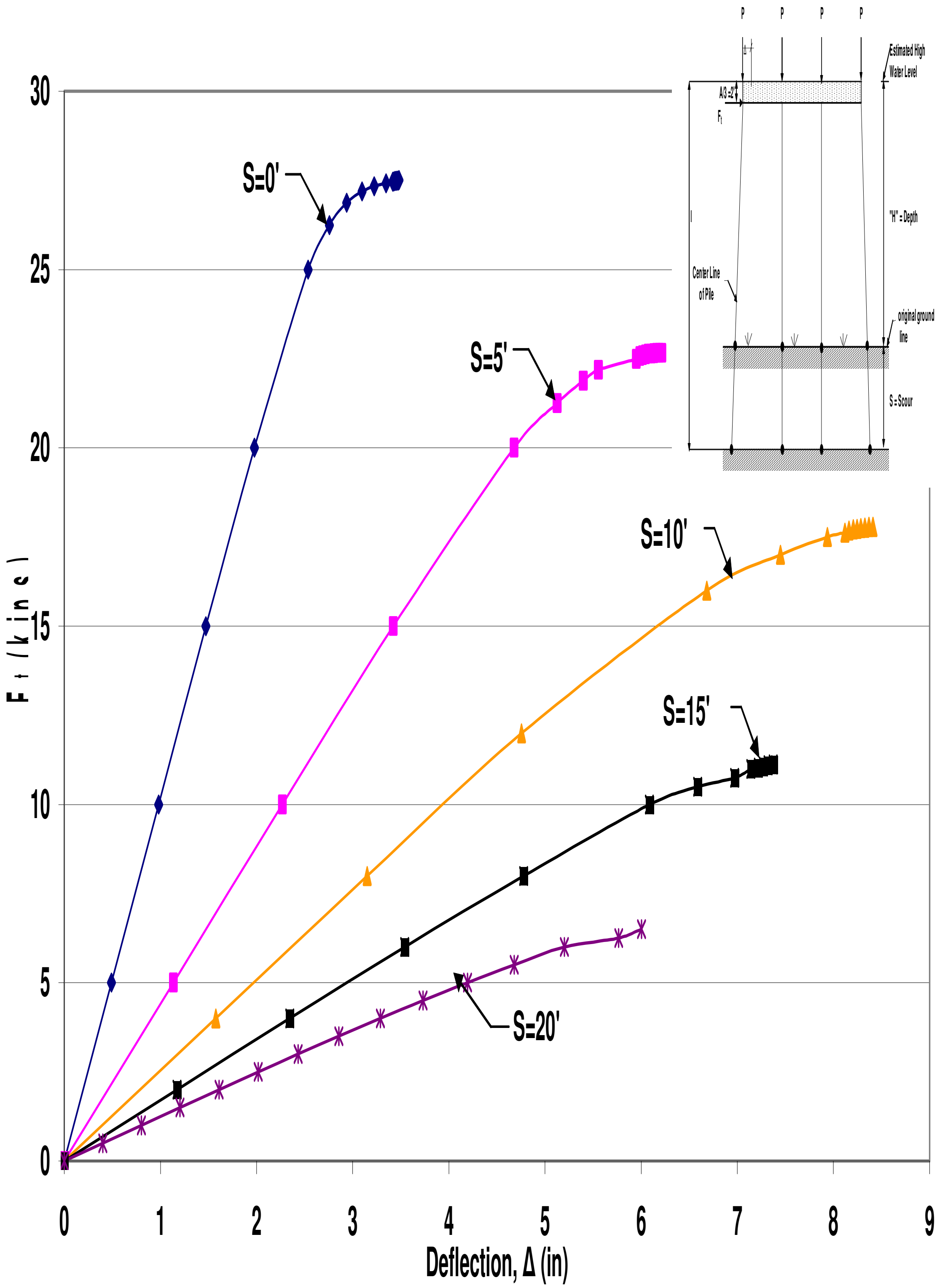


Figure A.30 HP10x42 Unbraced 4-Pile Bent with H=13', P=120kips and A=6'

Pushover Analysis Results

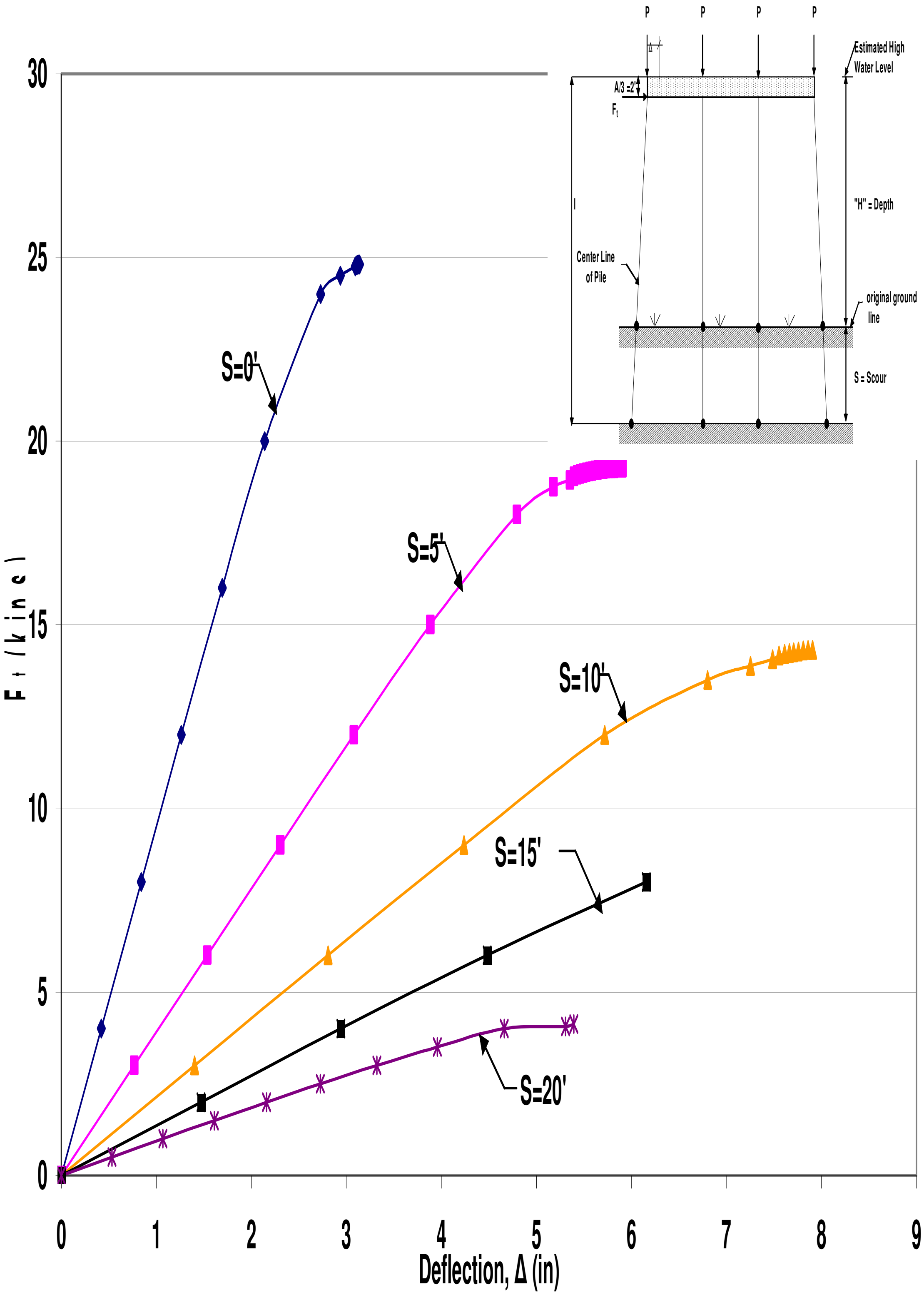


Figure A.31 HP10x42 Unbraced 4-Pile Bent with H=13', P=140kips and A=6'

Pushover Analysis Results

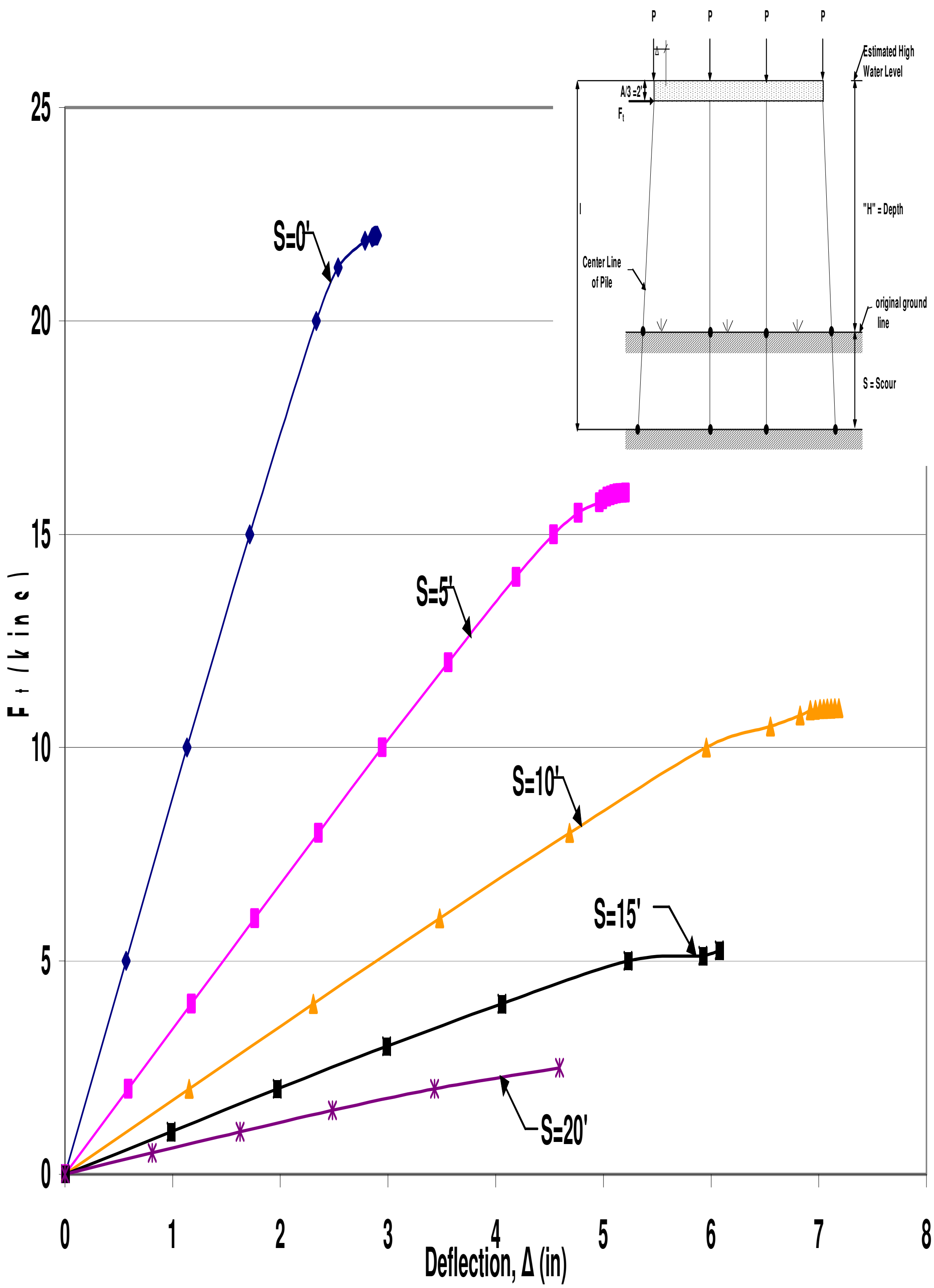


Figure A.32 Unbraced 4-Pile Bent with H=13', P=160kips and A=6'

Pushover Analysis Results

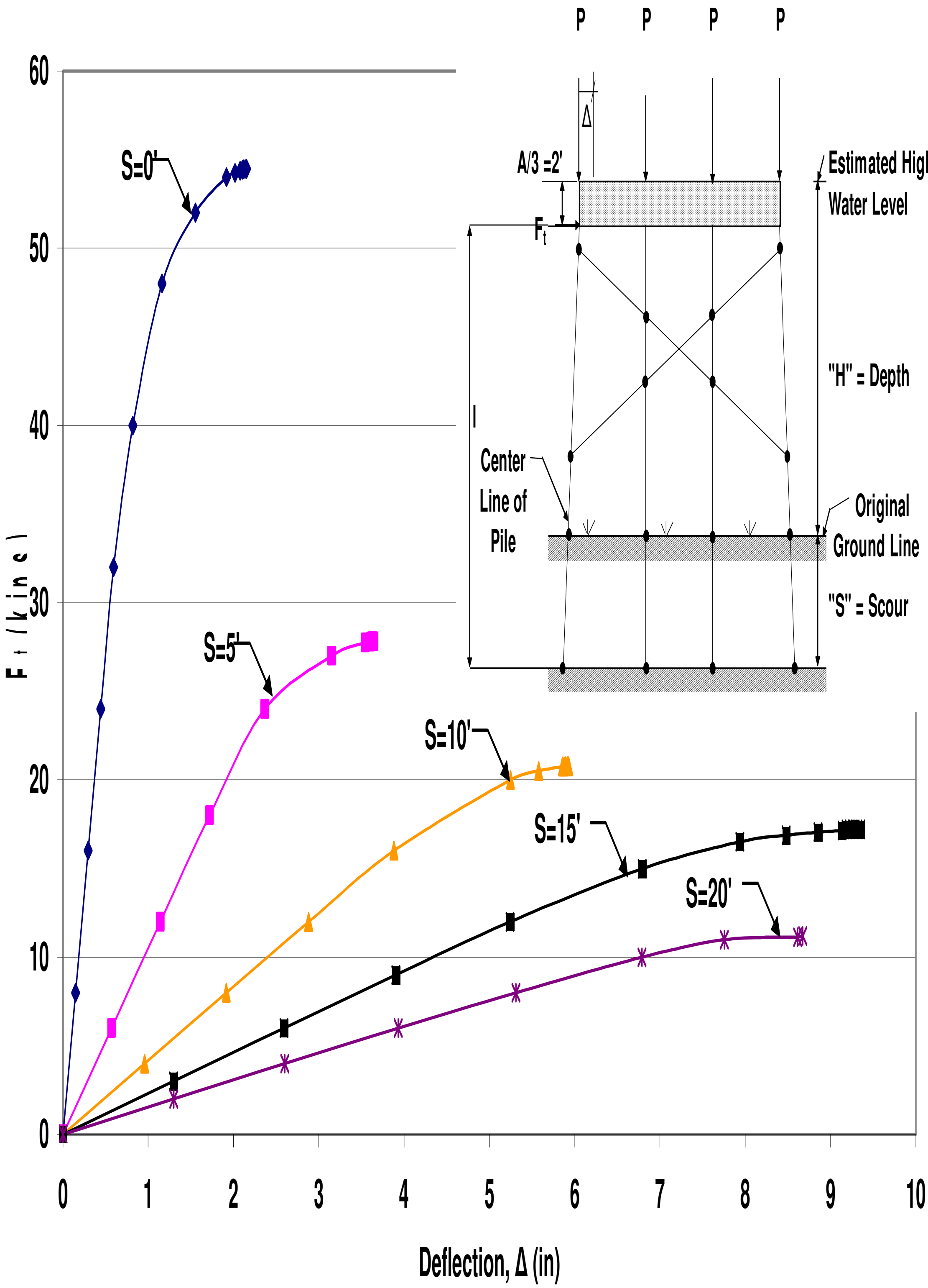


Figure A.33 HP10x42 X-Braced 4-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

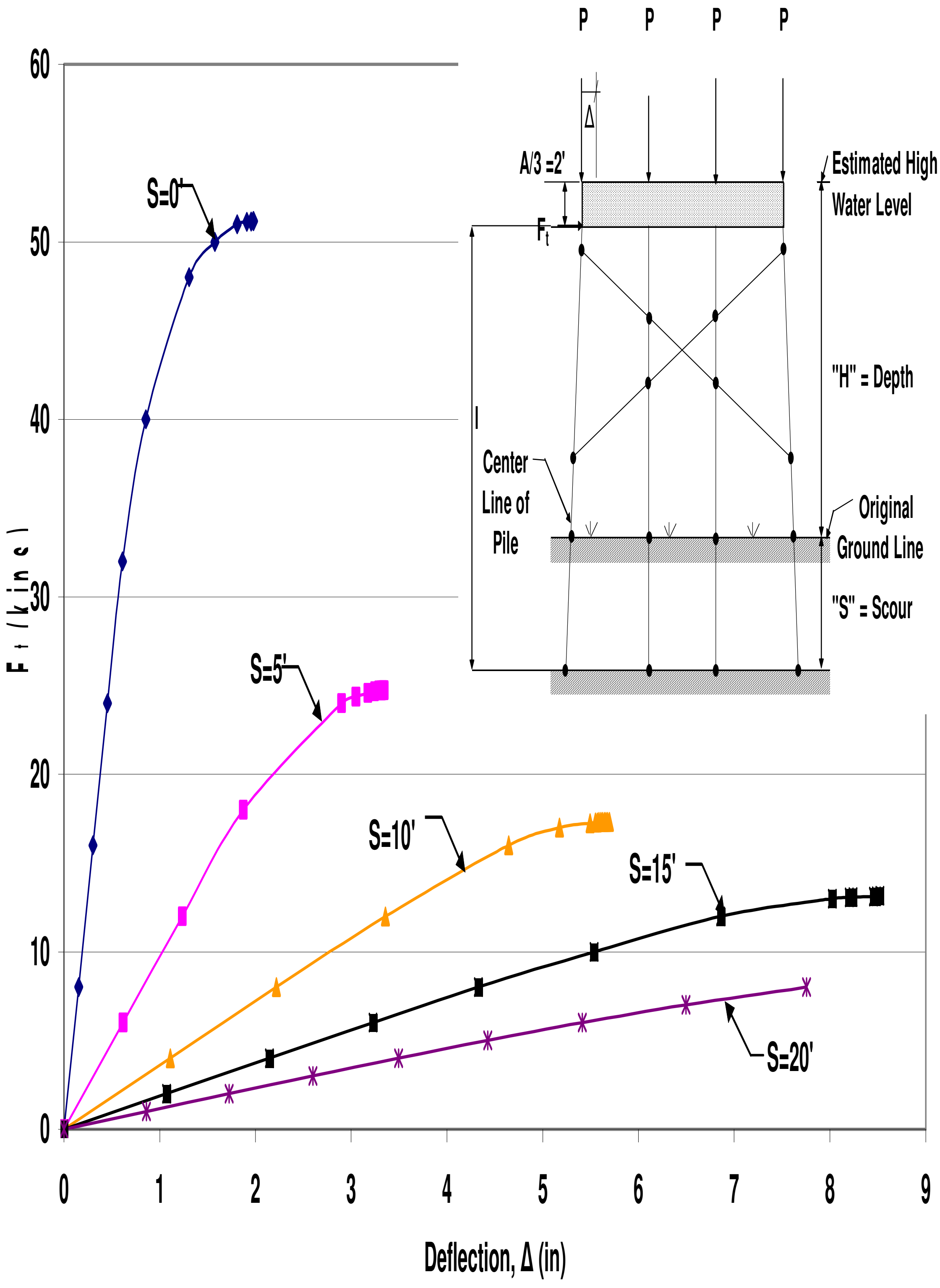


Figure A.34 HP10x42 X-Braced 4-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

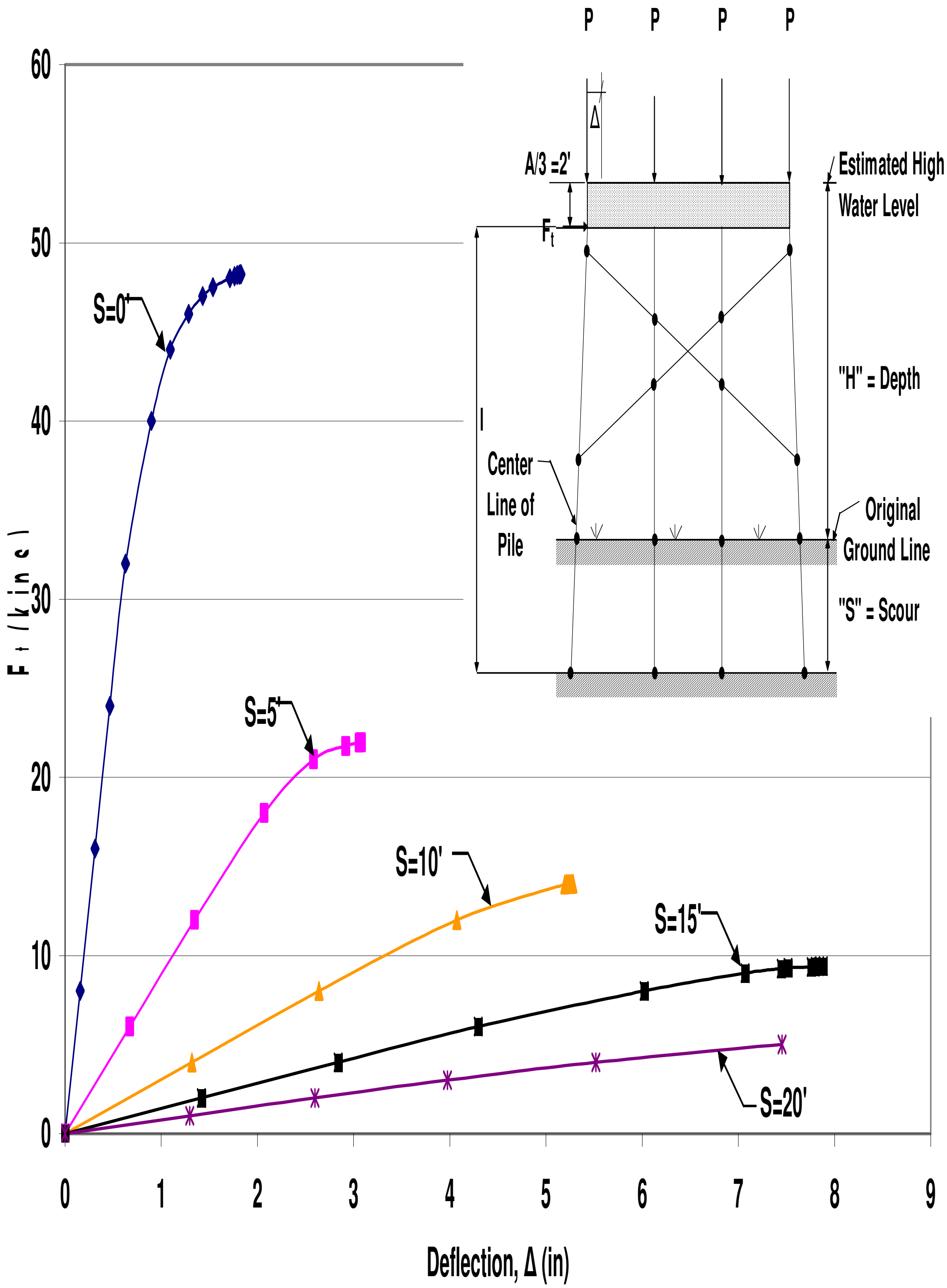


Figure A.35 HP10x42 X-Braced 4-Pile Bent with H=13', P=140kips, and A=6'
Pushover Analysis Results

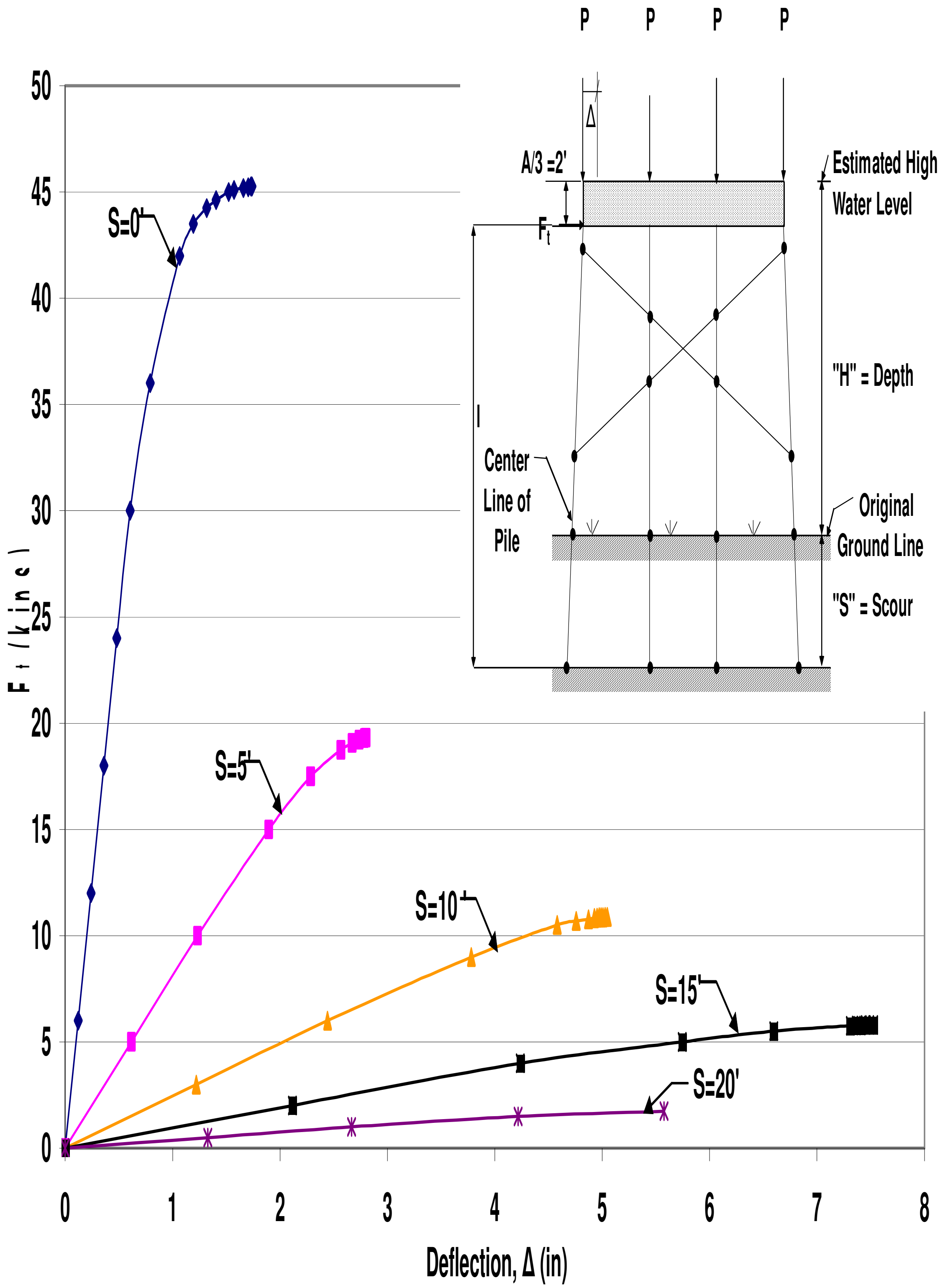


Figure A.36 HP10x42 X-Braced 4-Pile Bent with H=13', P=160 kips and A=6'
Pushover Analysis Results

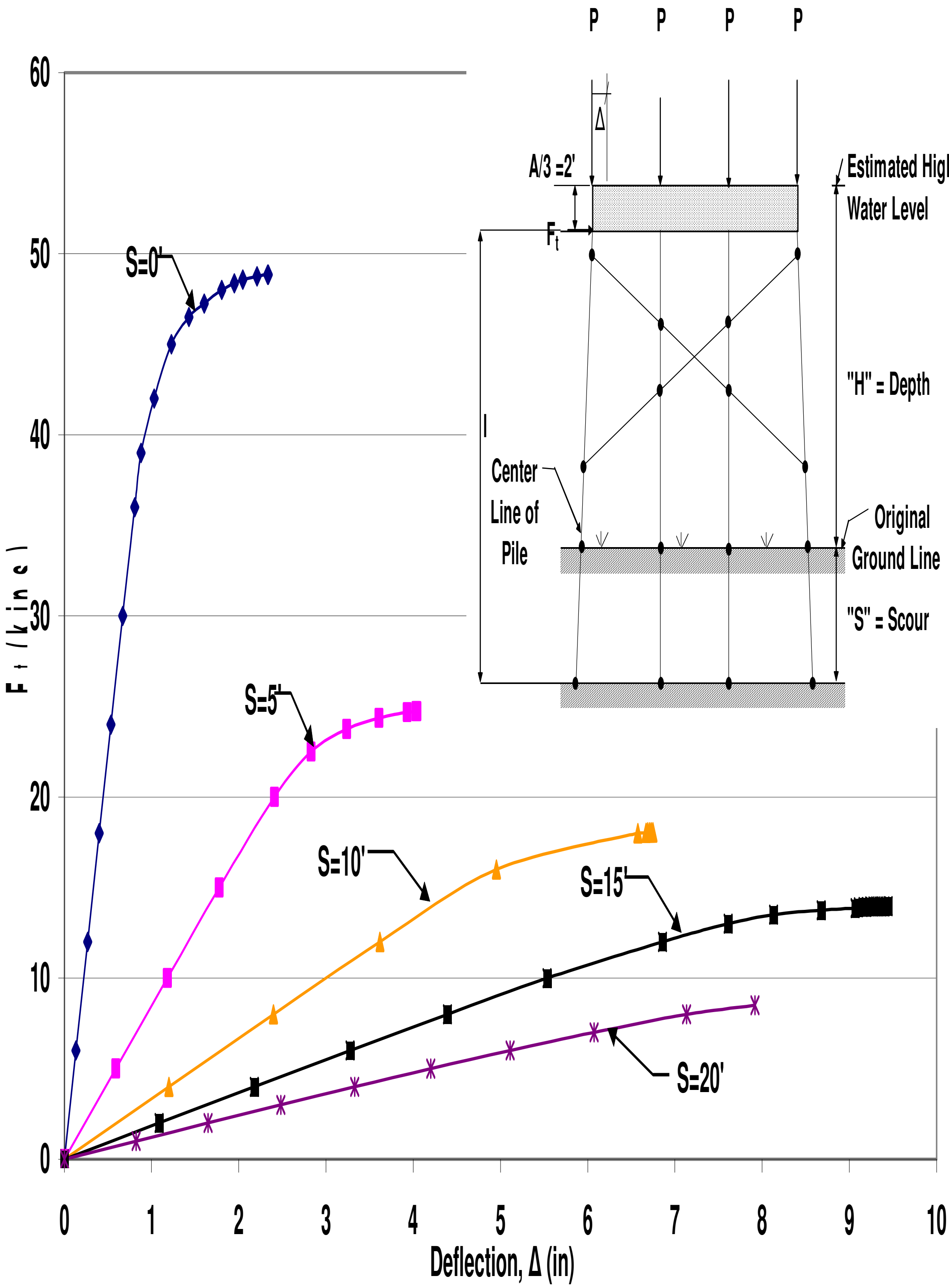


Figure A.37 HP10x42 X-Braced 4-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

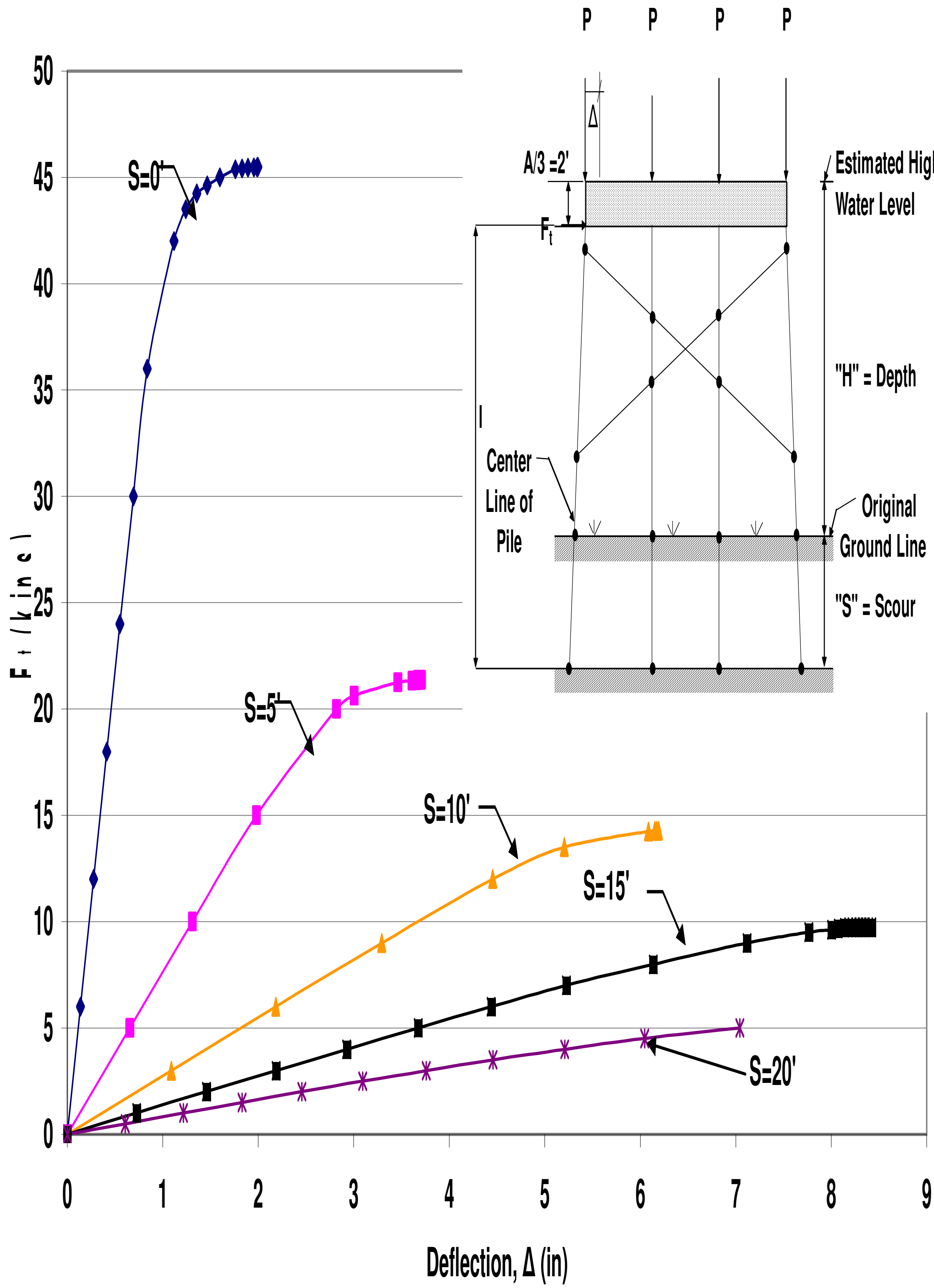


Figure A.38 HP10x42 X-Braced 4-Pile Bent with H=17',P=120kips, and A=6' Pushover Analysis Results

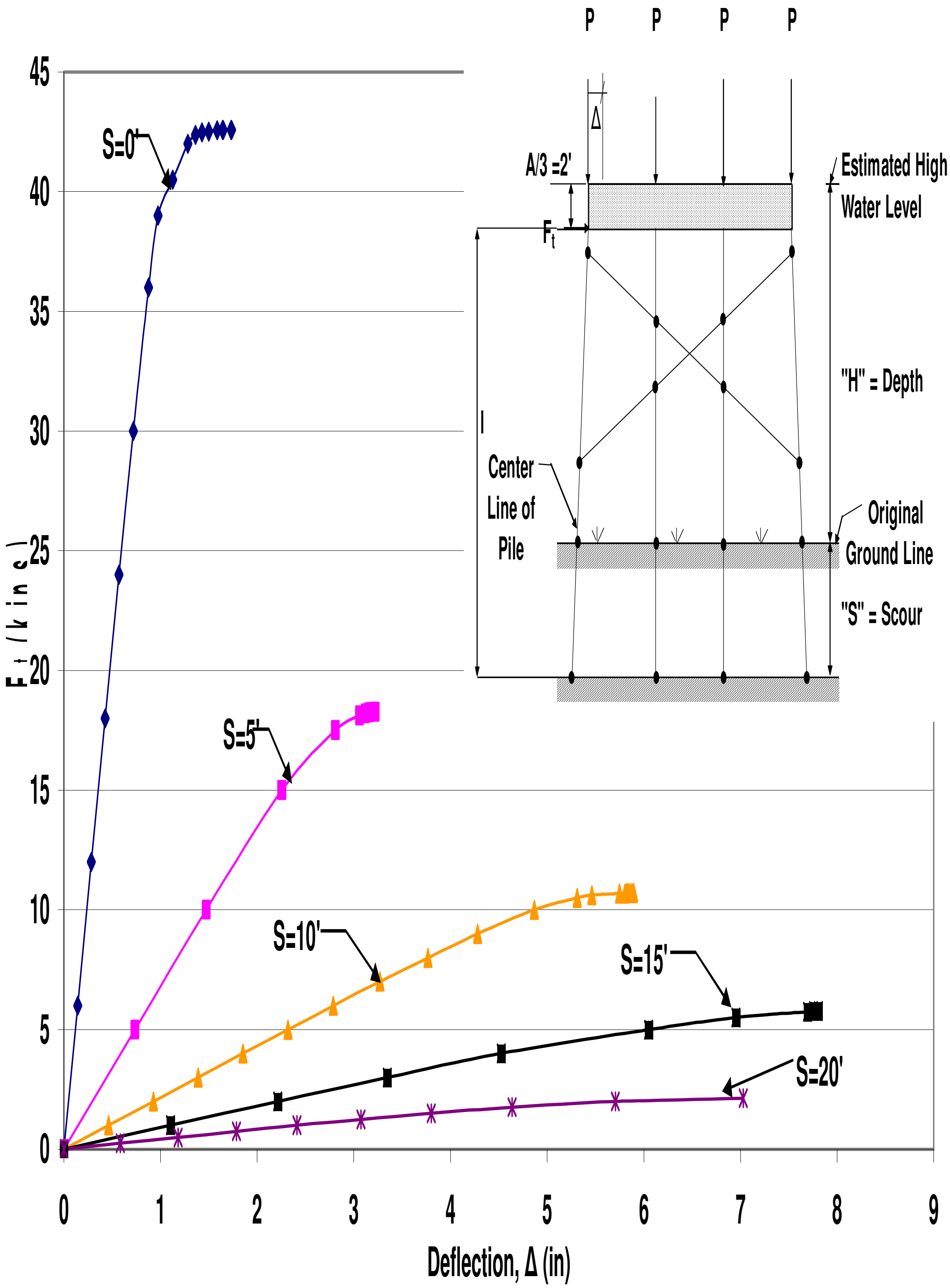


Figure A.39 HP10x42 X-Braced 4-Pile Bent with H=17', P=140kips and A=6'
Pushover Analysis Results

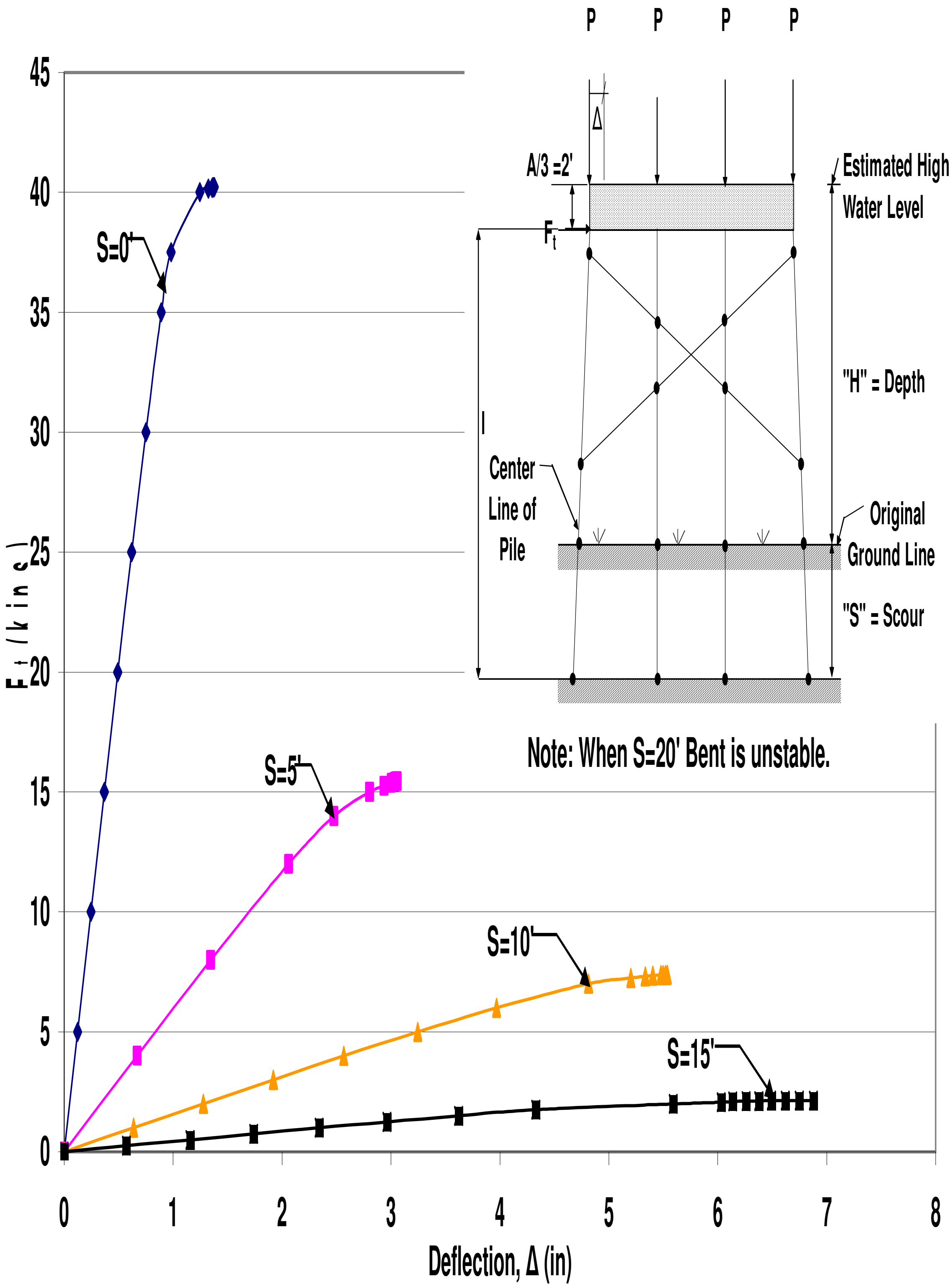


Figure A.40 HP10x42 X-Braced 4-Pile Bent with H=17', P=160kips, and A=6'
Pushover Analysis Results

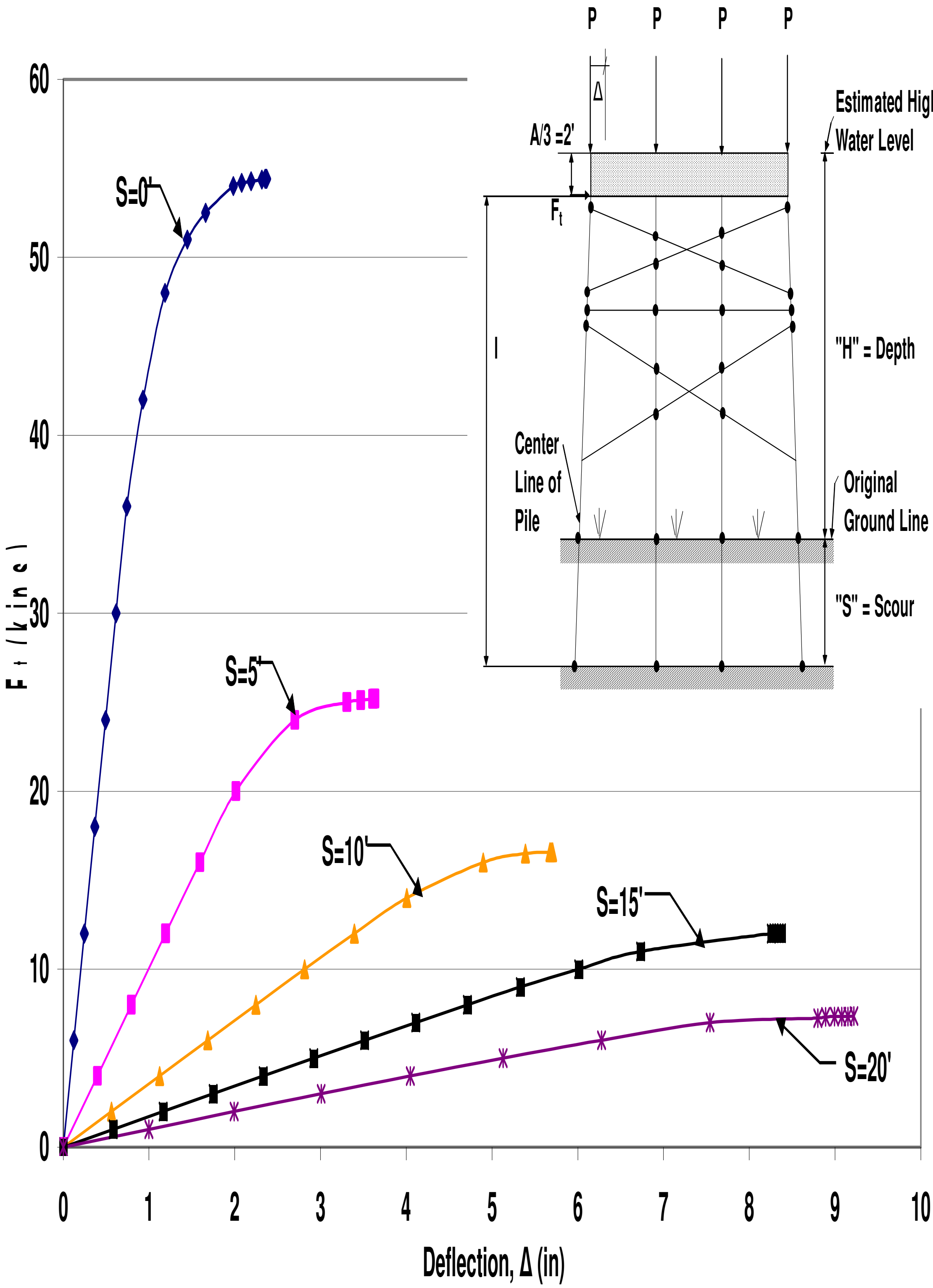


Figure A.41 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

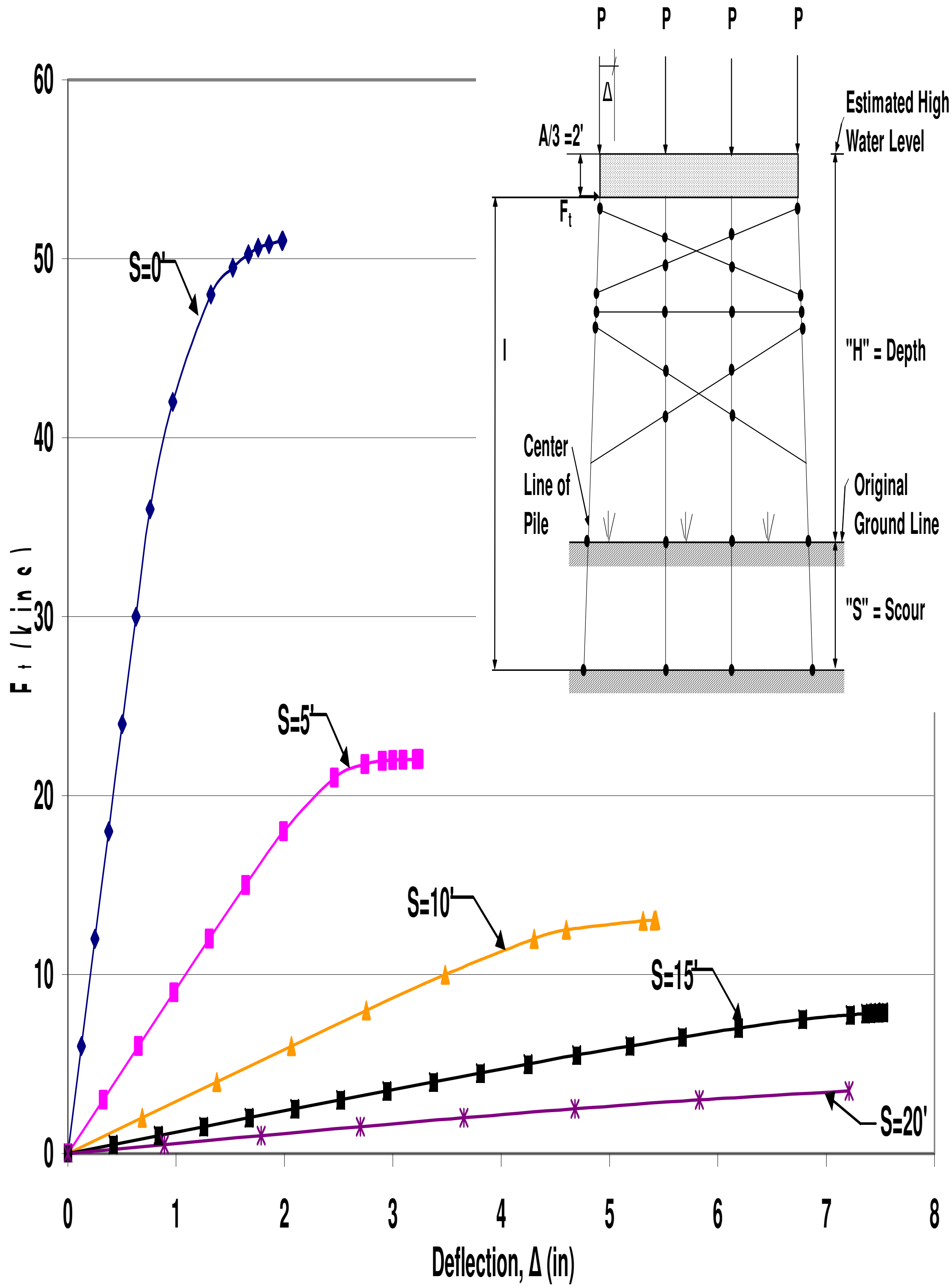


Figure A.42 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=120kips, and A=6'
Pushover Analysis Results

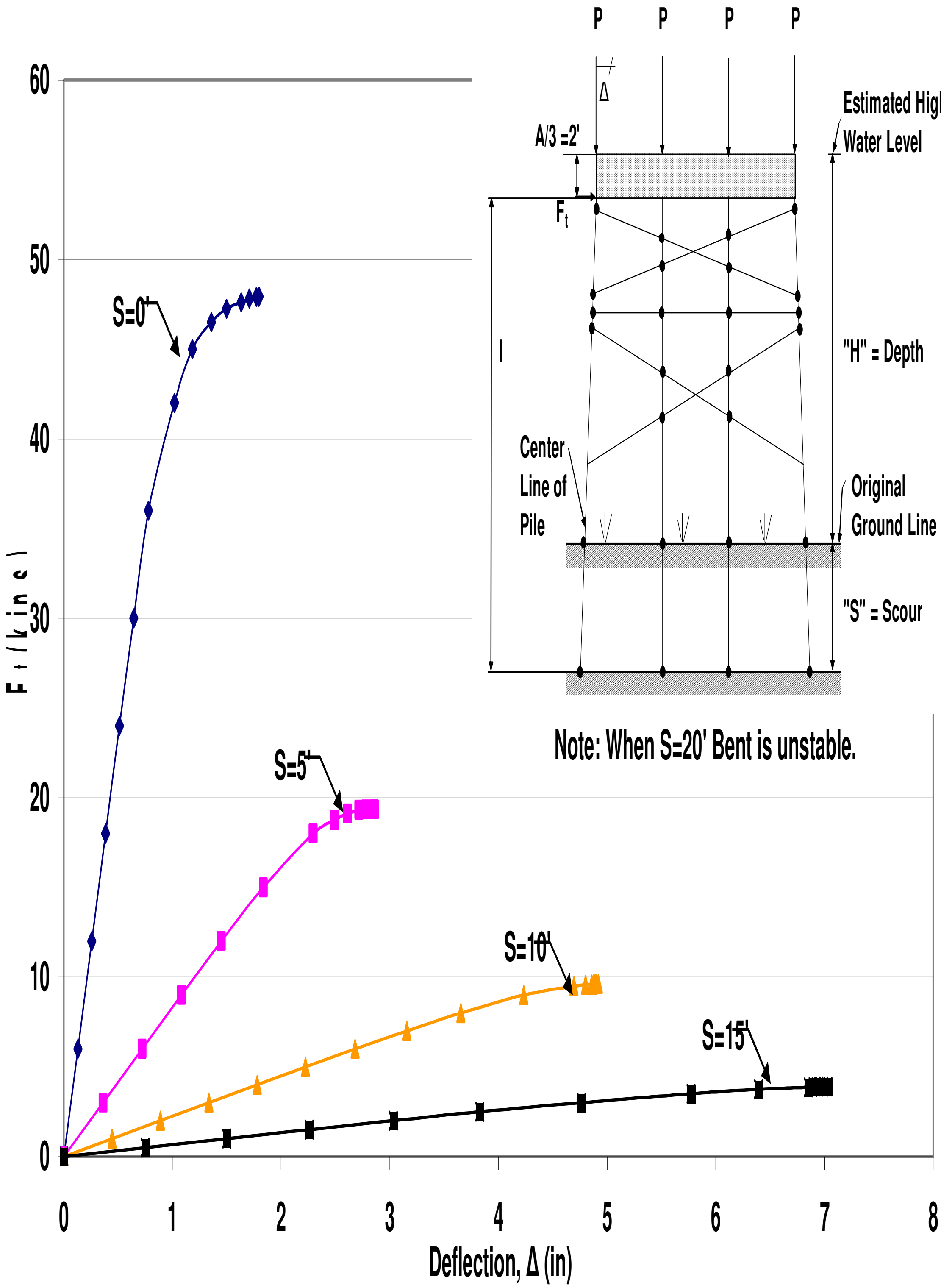


Figure A.43 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=140kips,and A=6' Pushover Analysis Results

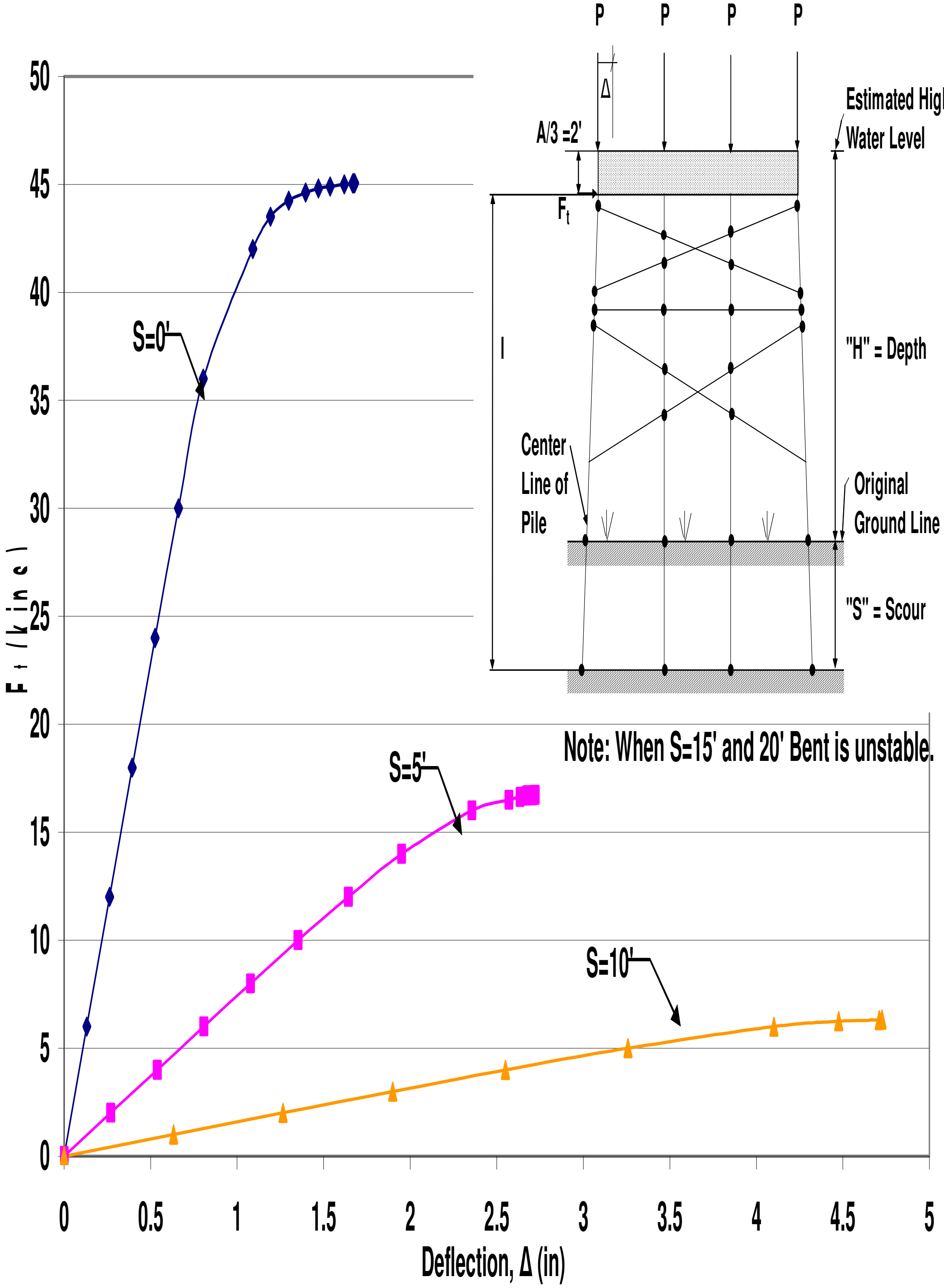


Figure A.44 HP10x42 Two-Story X-Braced 4-Pile Bent with H=21', P=160kips, and A=6' Pushover Analysis Results

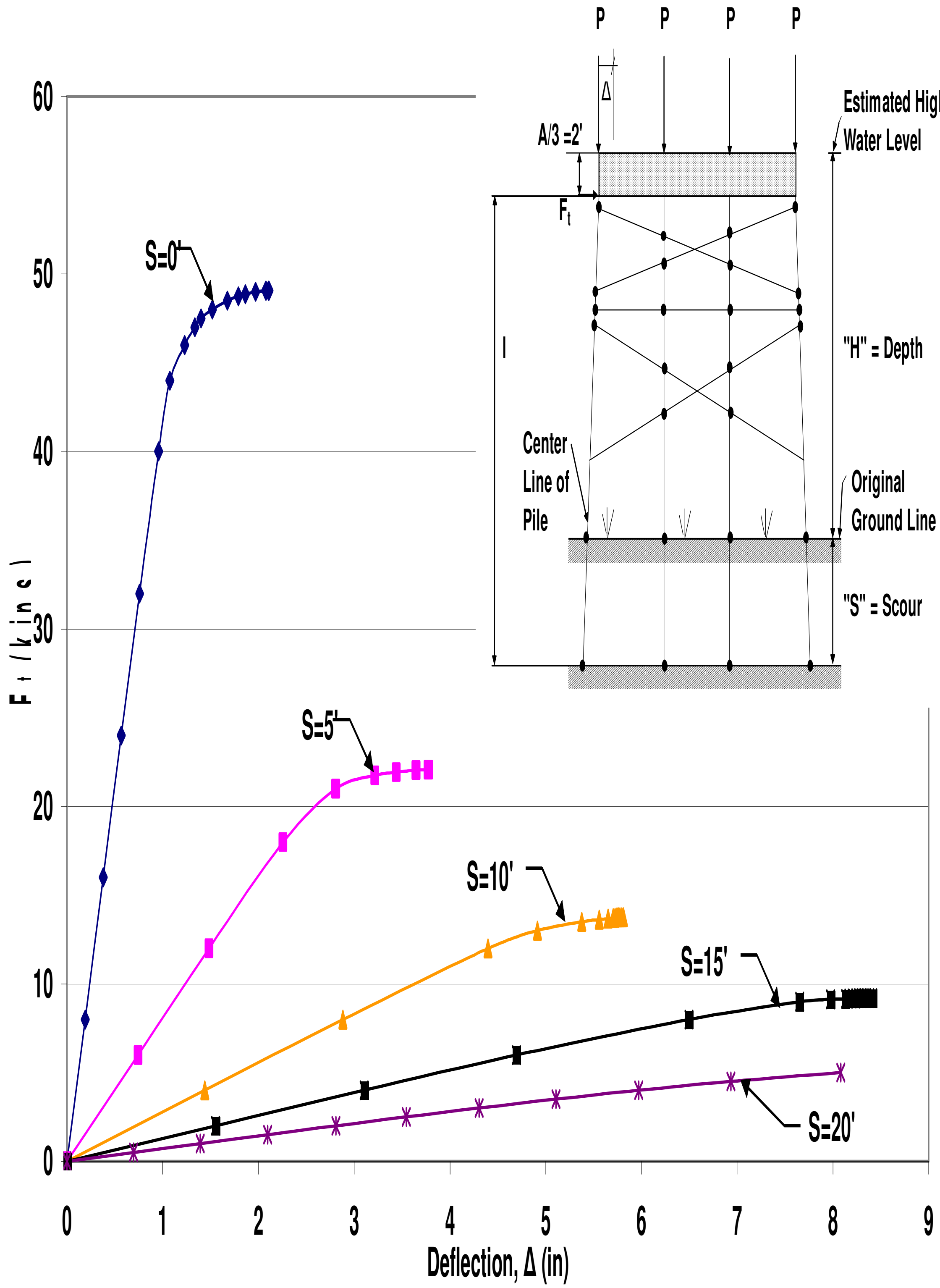


Figure A.45 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=100kips, and A=6' Pushover Analysis Results

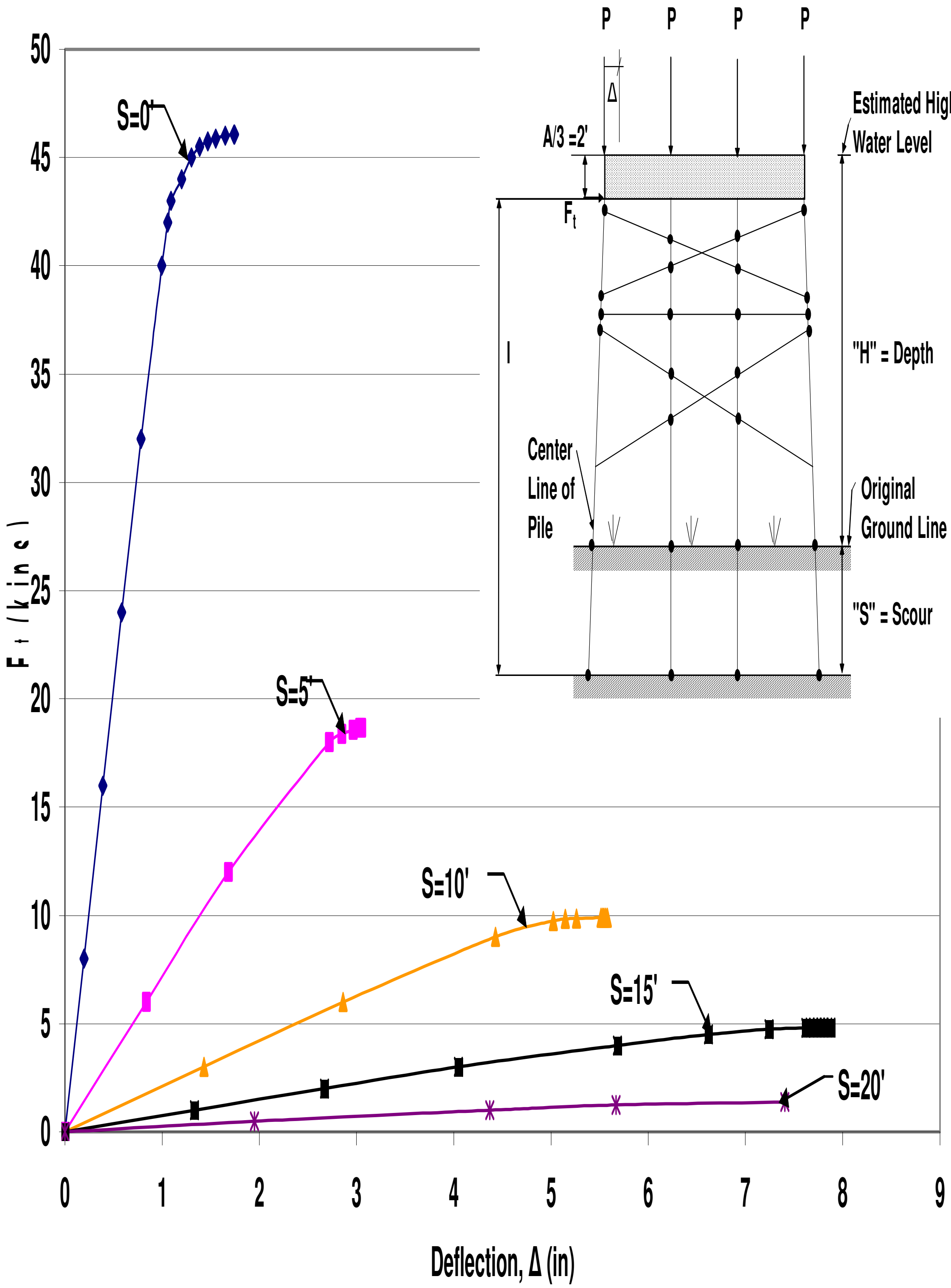


Figure A.46 HP10x42 Two-Story X-Braced 4-Pile bent with H=25',P=120kips, and A=6'
Pushover Analysis Results

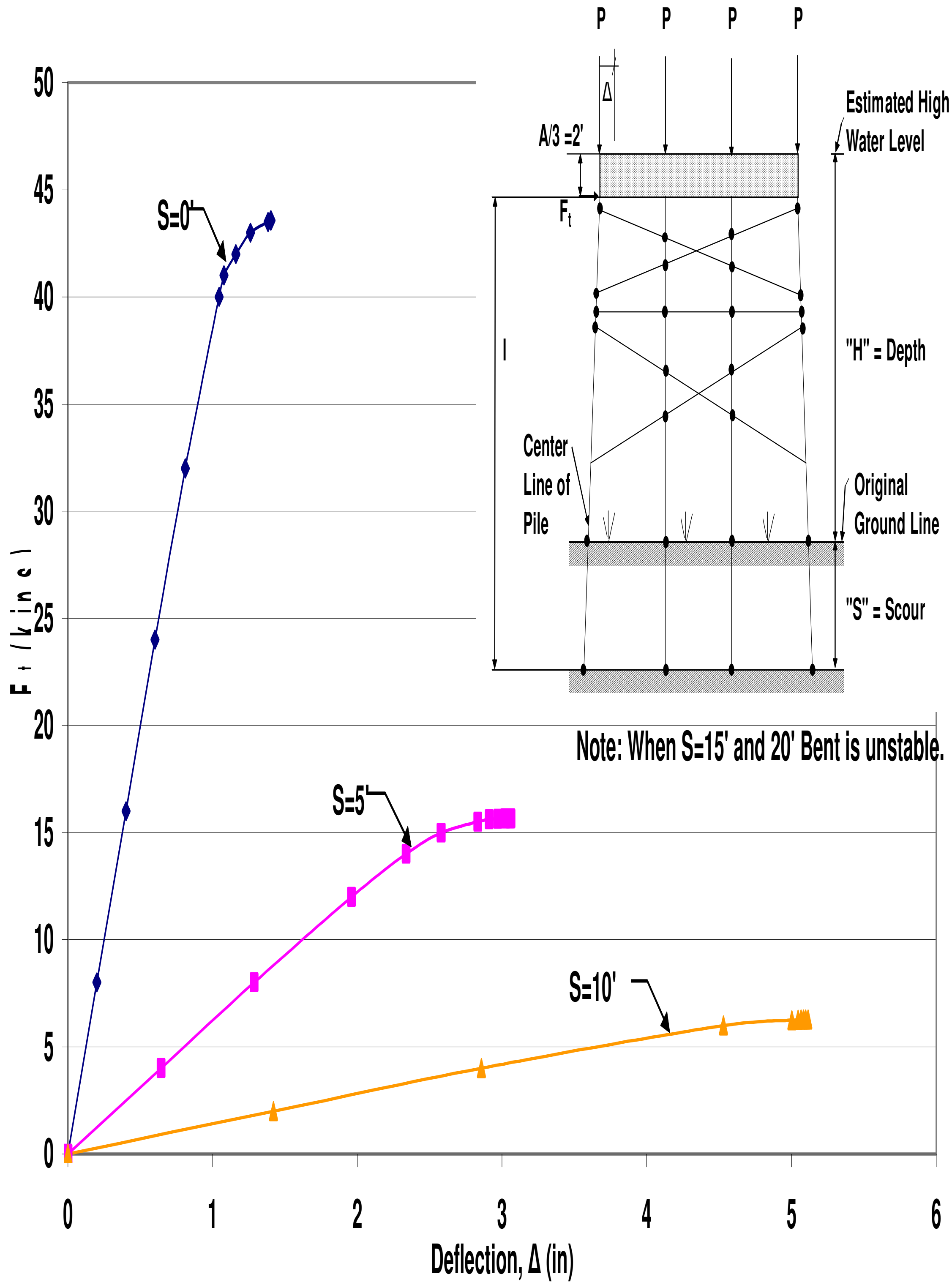


Figure A.47 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=140kips, and A=6' Pushover Analysis Results

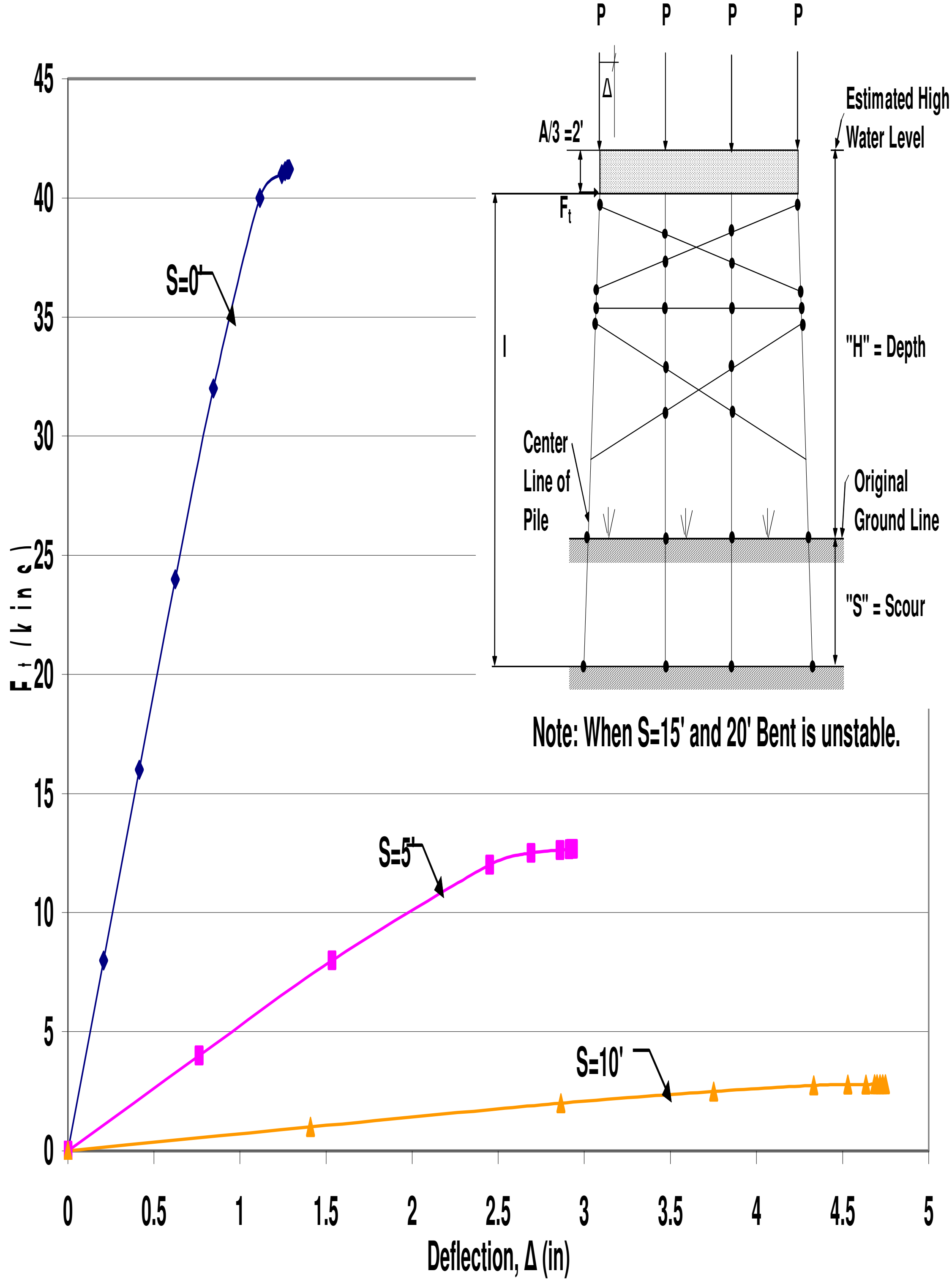


Figure A.48 HP10x42 Two-Story X-Braced 4-Pile Bent with H=25', P=160kips,and A=6' Pushover Analysis Results

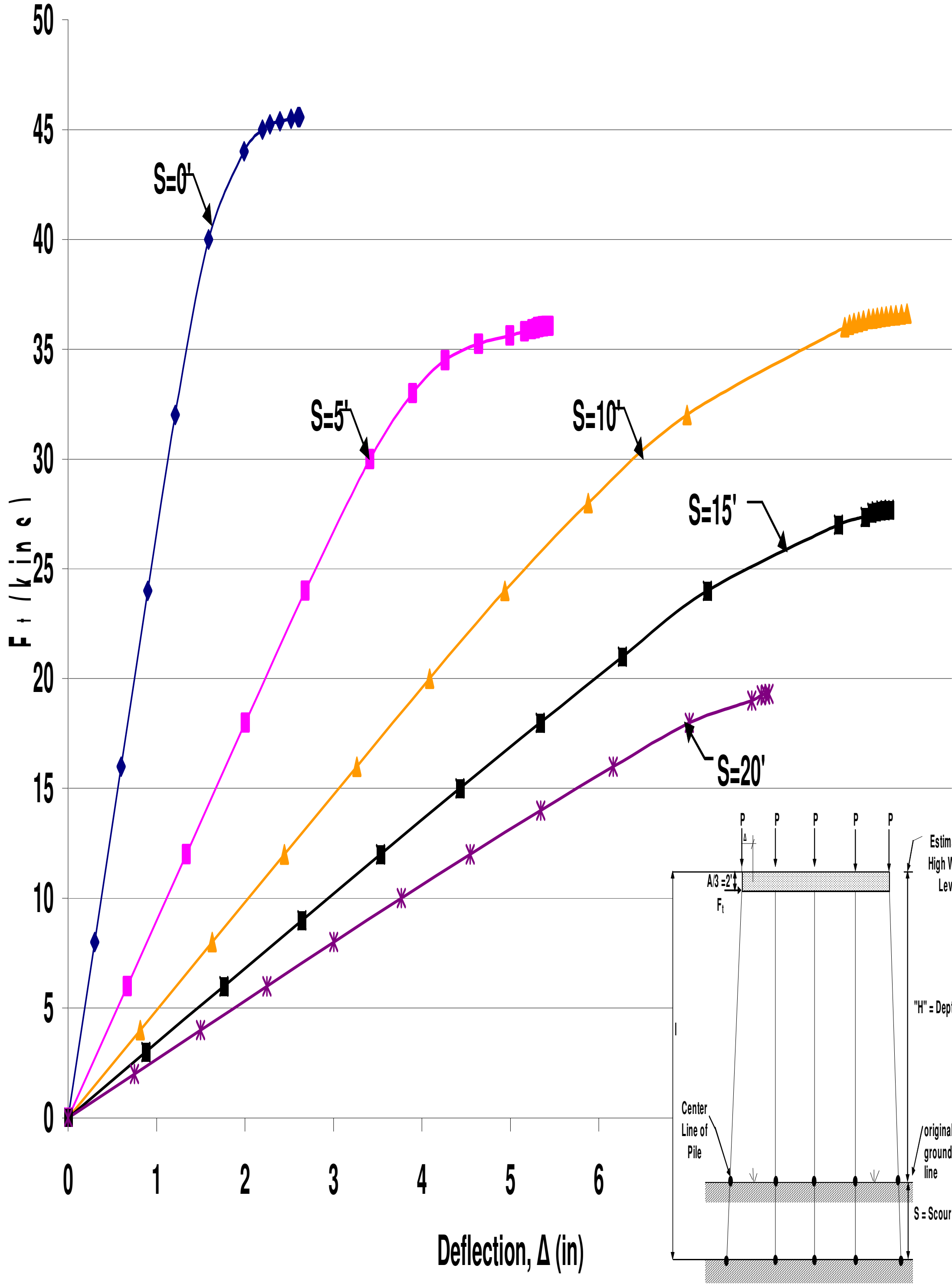


Figure A.49 HP10x42 Unbraced 5-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

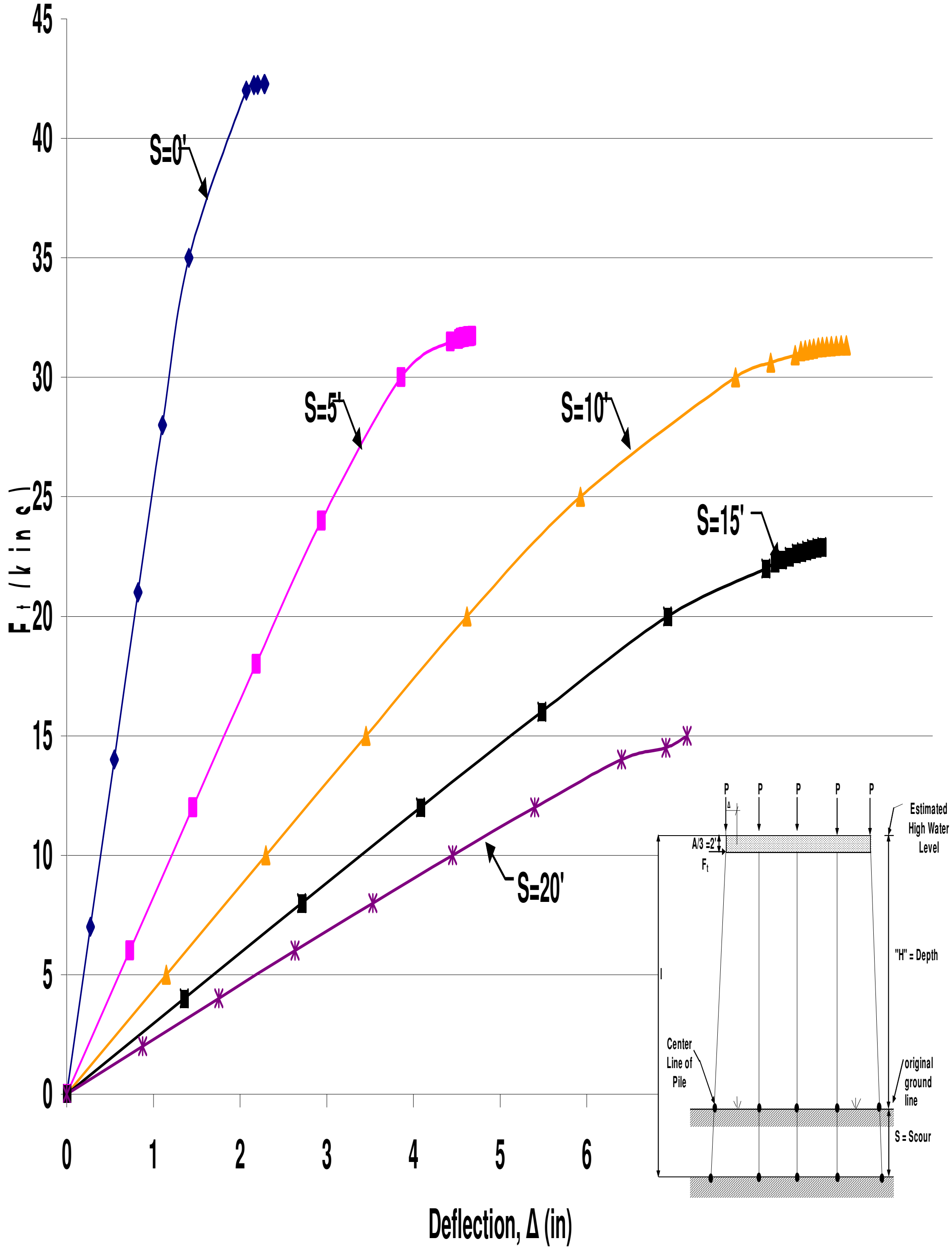


Figure A.50 HP10x42 Unbraced 5-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

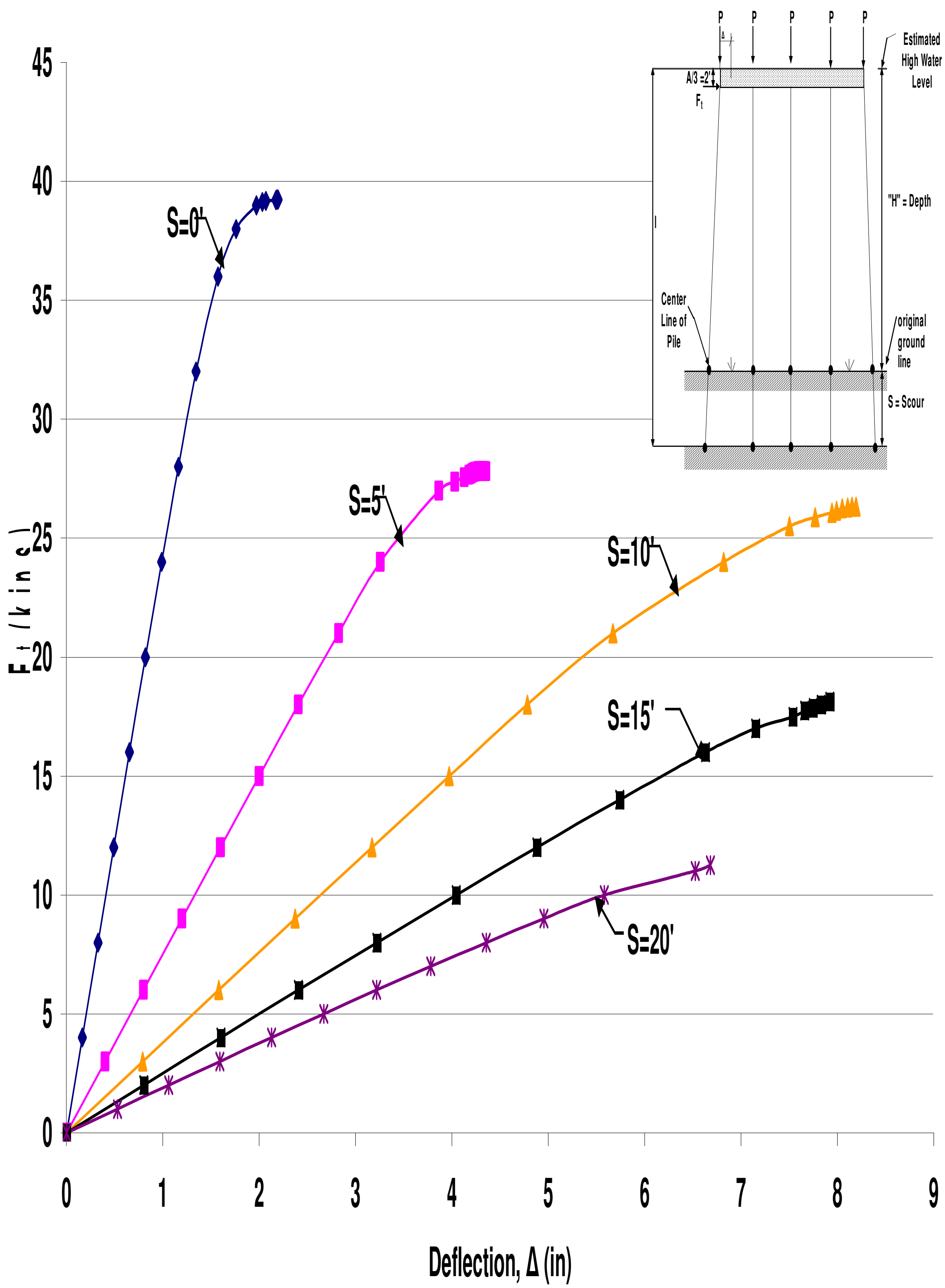


Figure A.51 HP10x42 Unbraced 5-Pile Bent with H=10', P=140kips and A=6'
Pushover Analysis Results

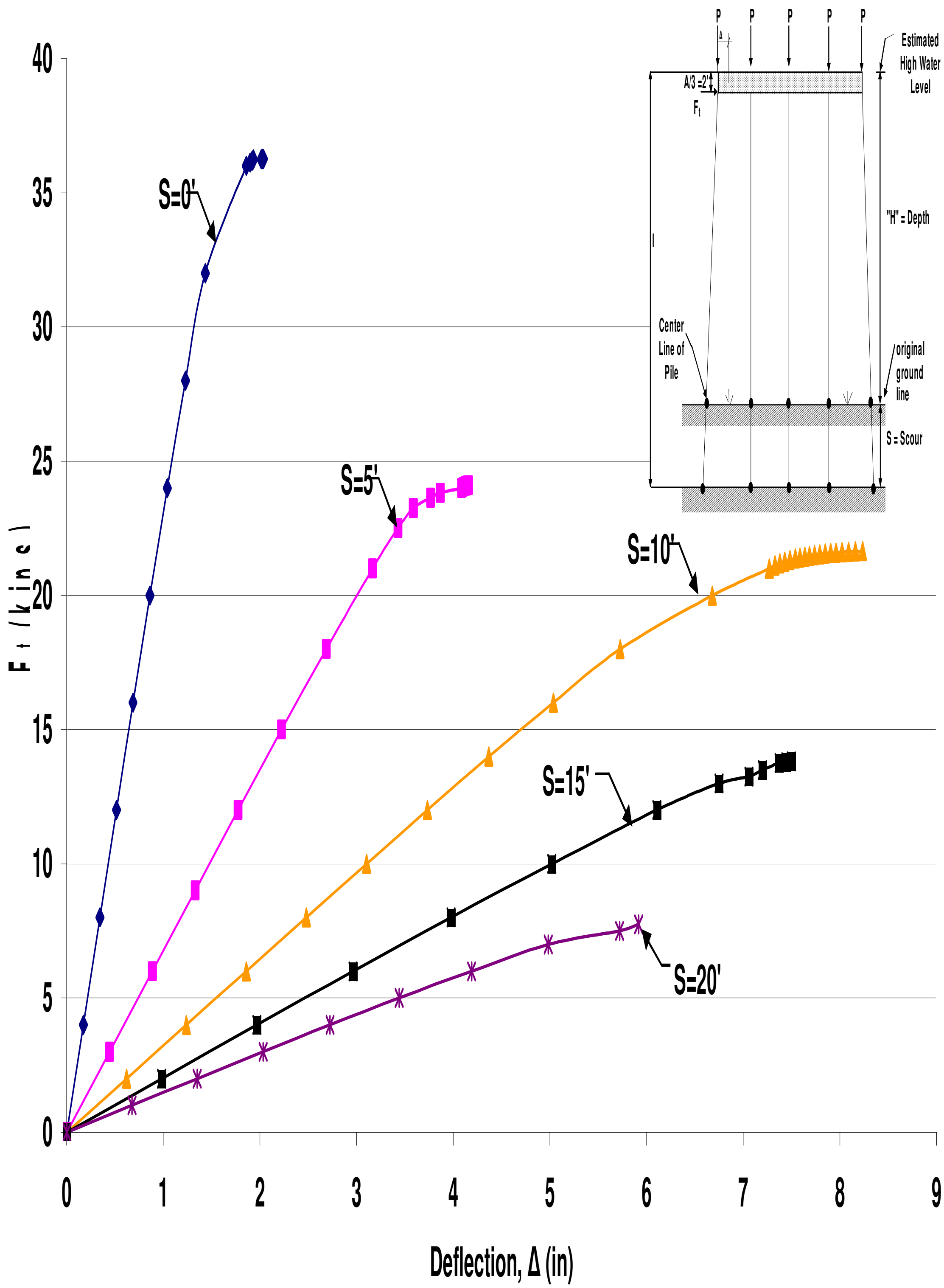


Figure A.52 HP10x42 Unbraced 5-Pile Bent with H=10', P=160kips and A=6' Pushover Analysis Results

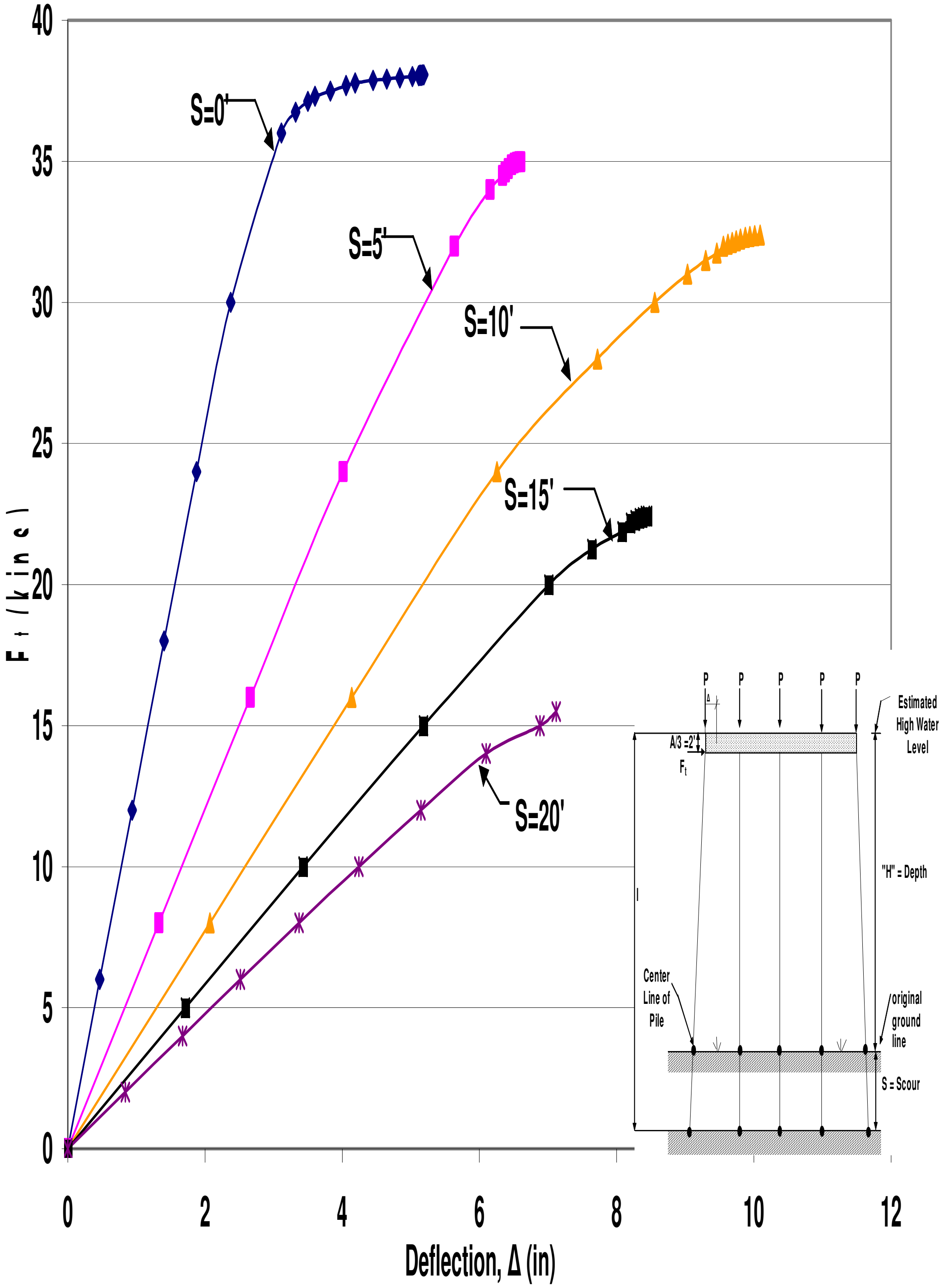


Figure A.53 HP10x42 Unbraced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

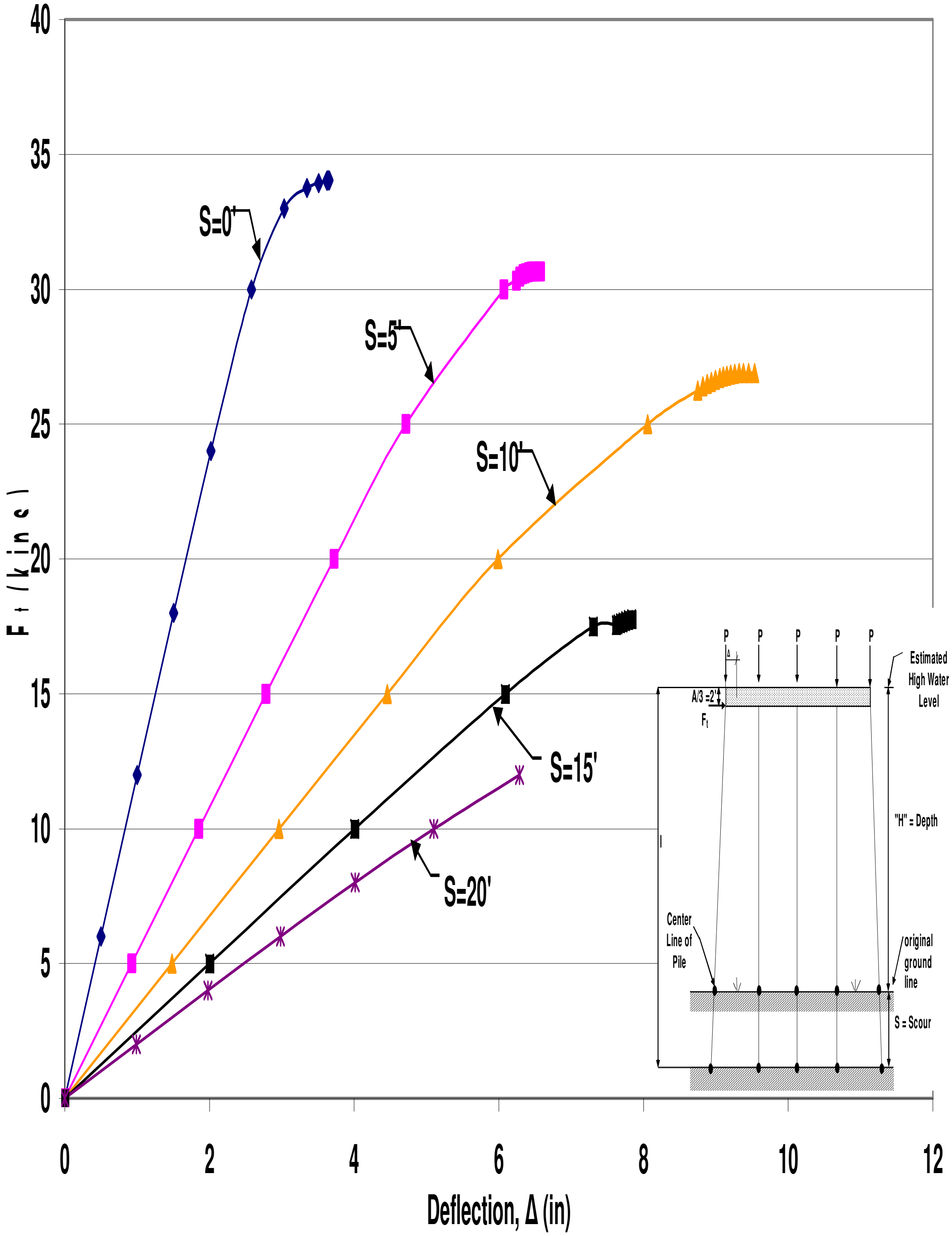


Figure A.54 HP10x42 Unbraced 5-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

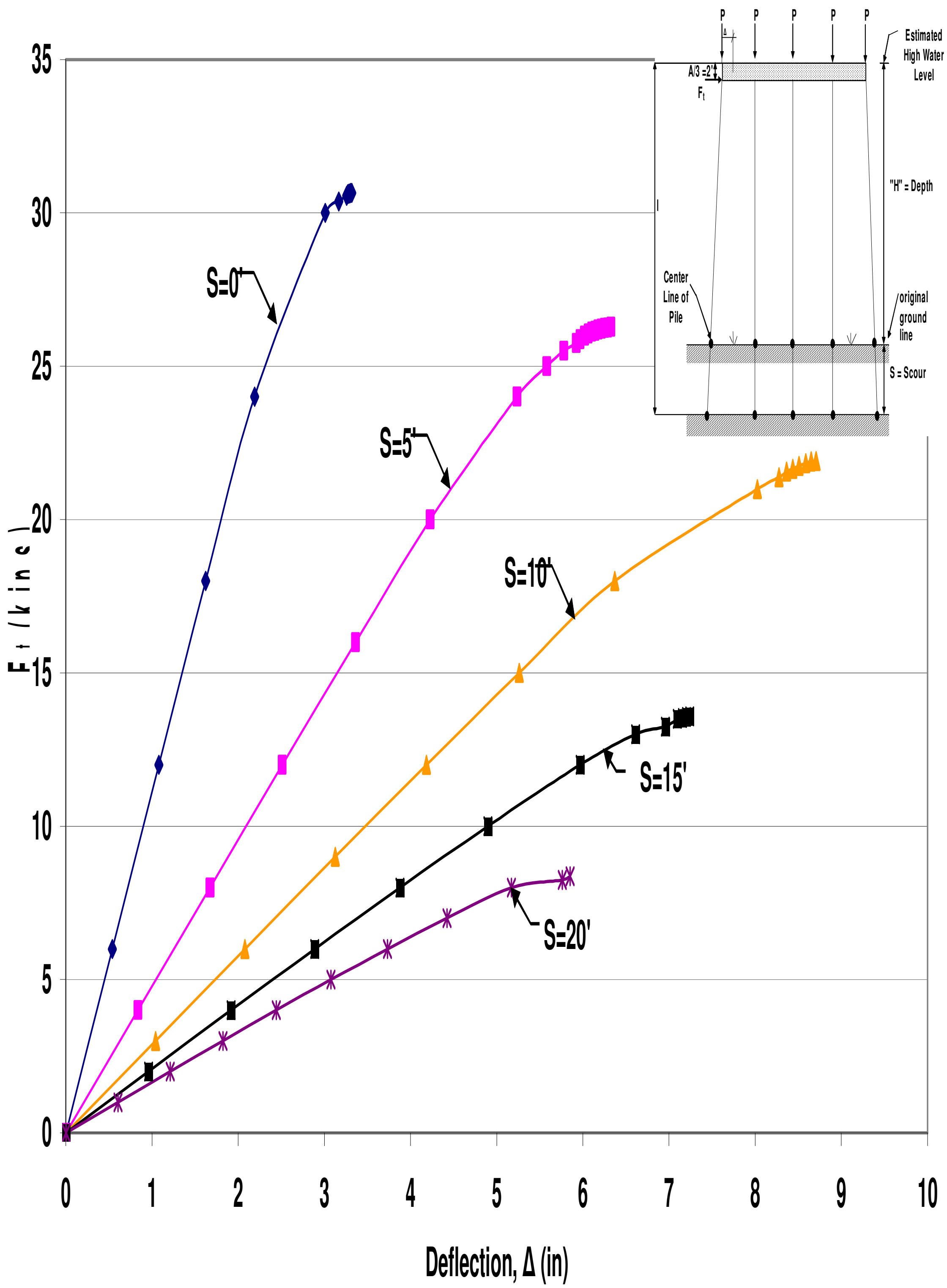


Figure A.55 HP10x42 Unbraced 5-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

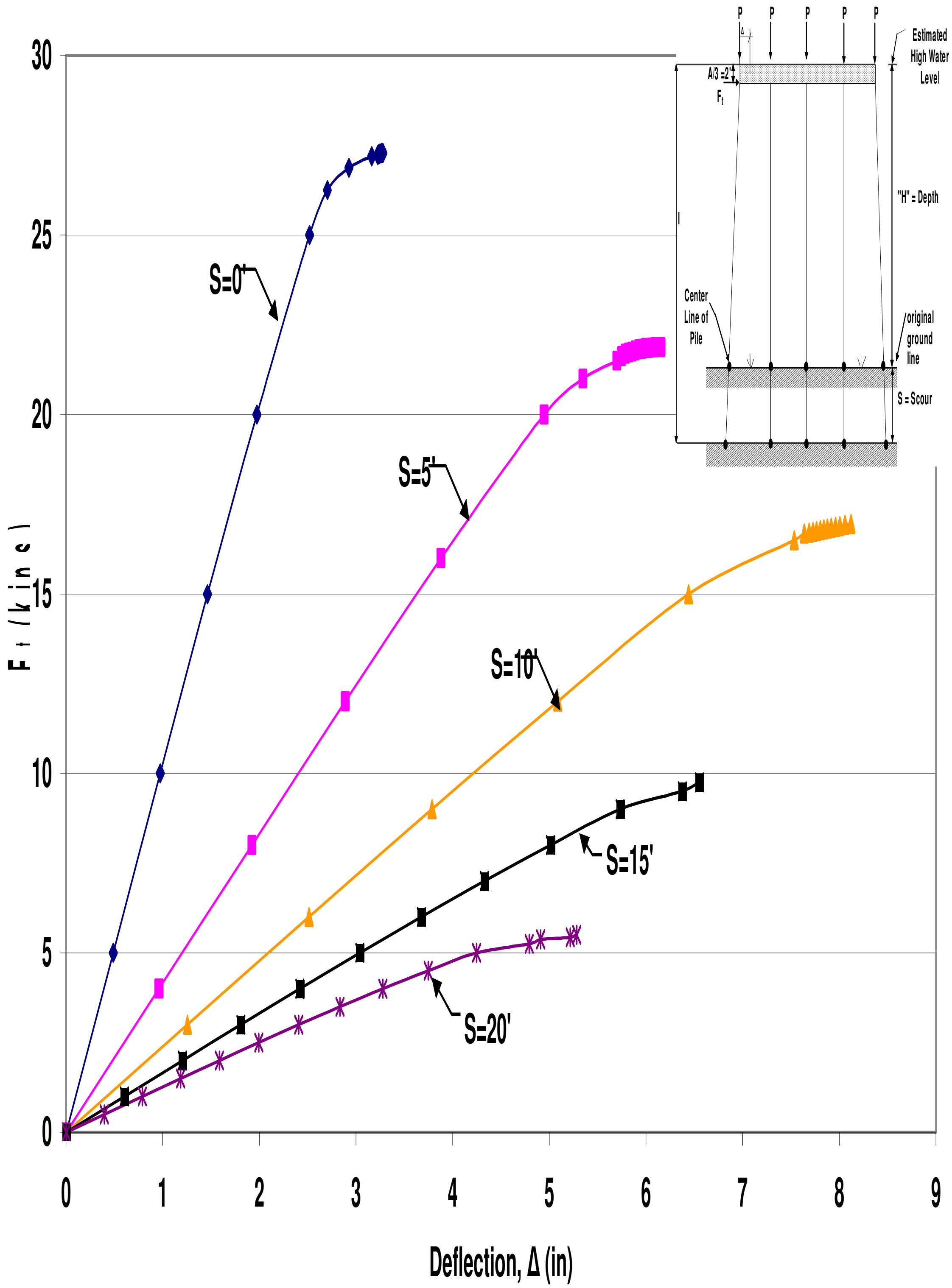


Figure A.56 HP10x42 Unbraced 5-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

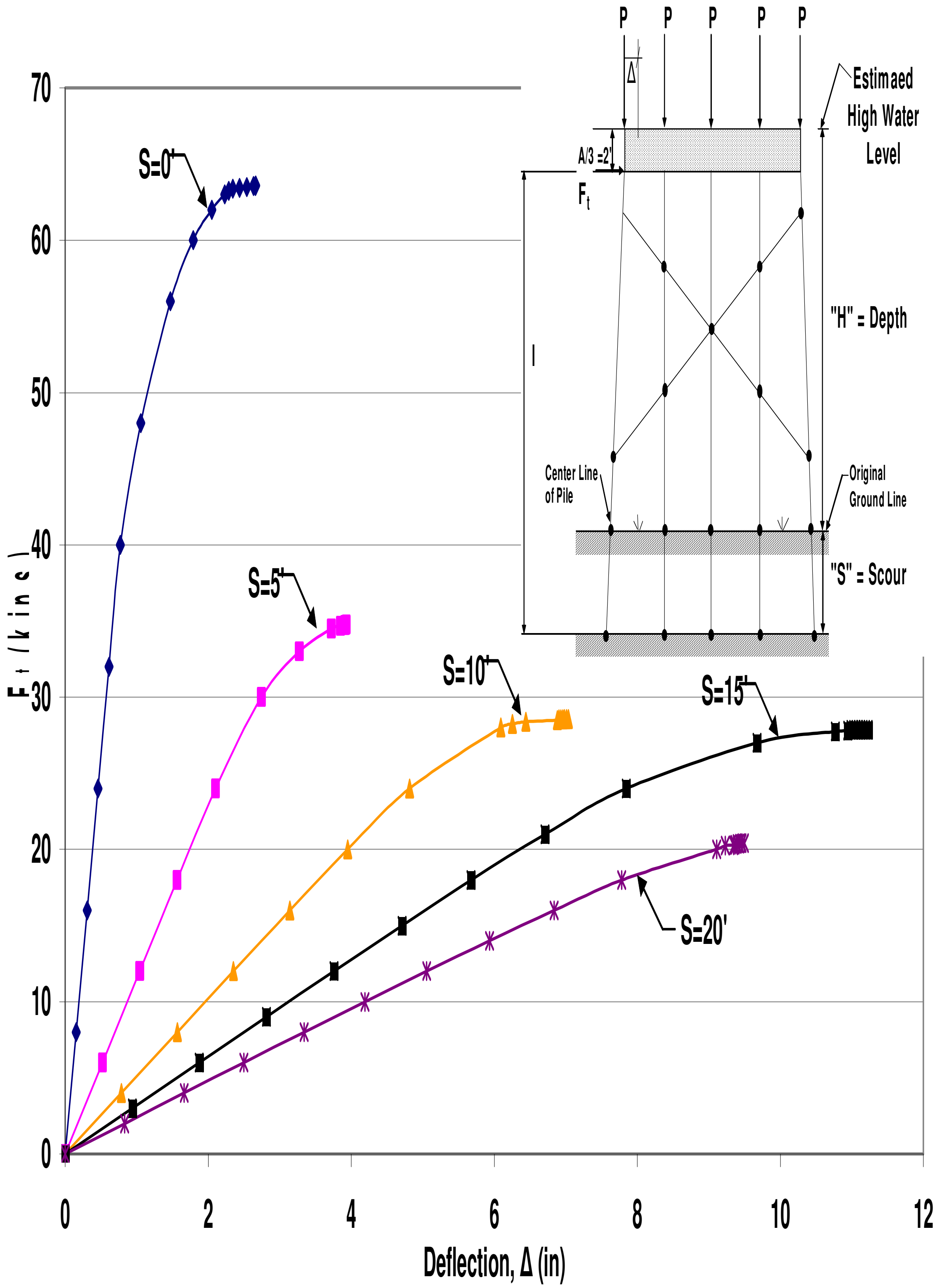


Figure A.57 HP10x42 X-Braced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

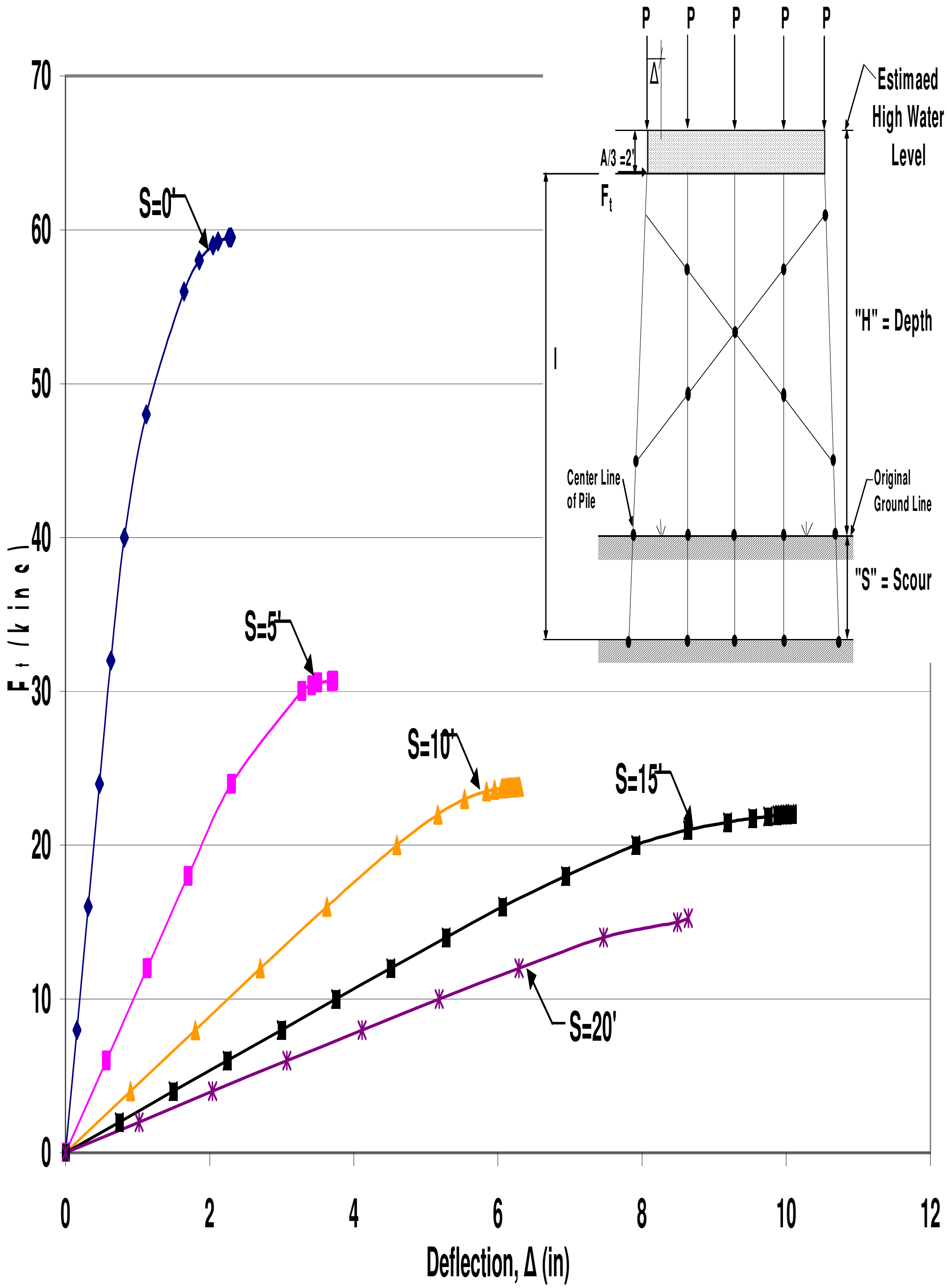


Figure A.58 HP10x42 X-Braced 5-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

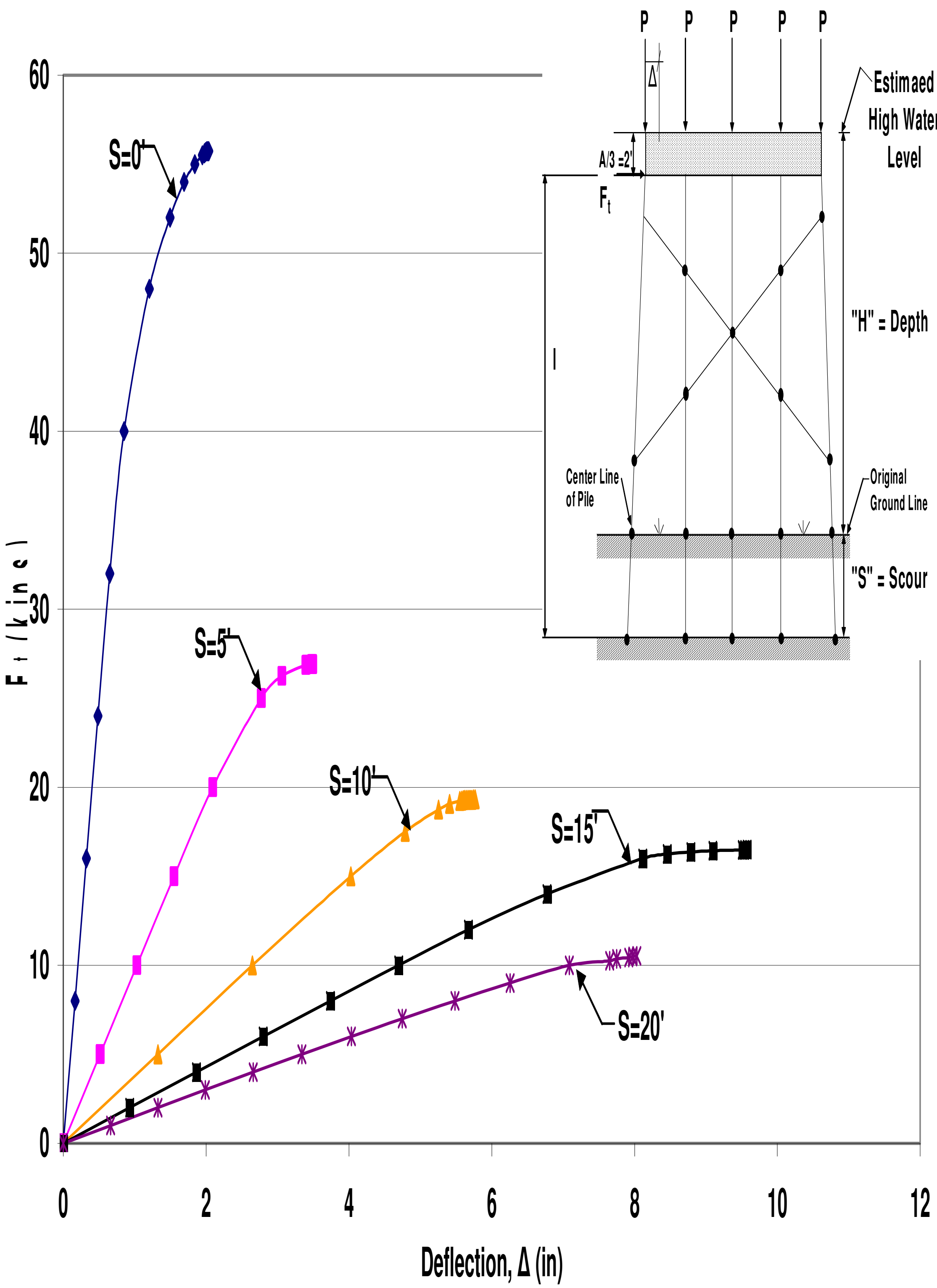


Figure A.59 HP10x42 X-Braced 5-Pile Bent with H=13',P=140kips and A=6' Pushover Analysis Results

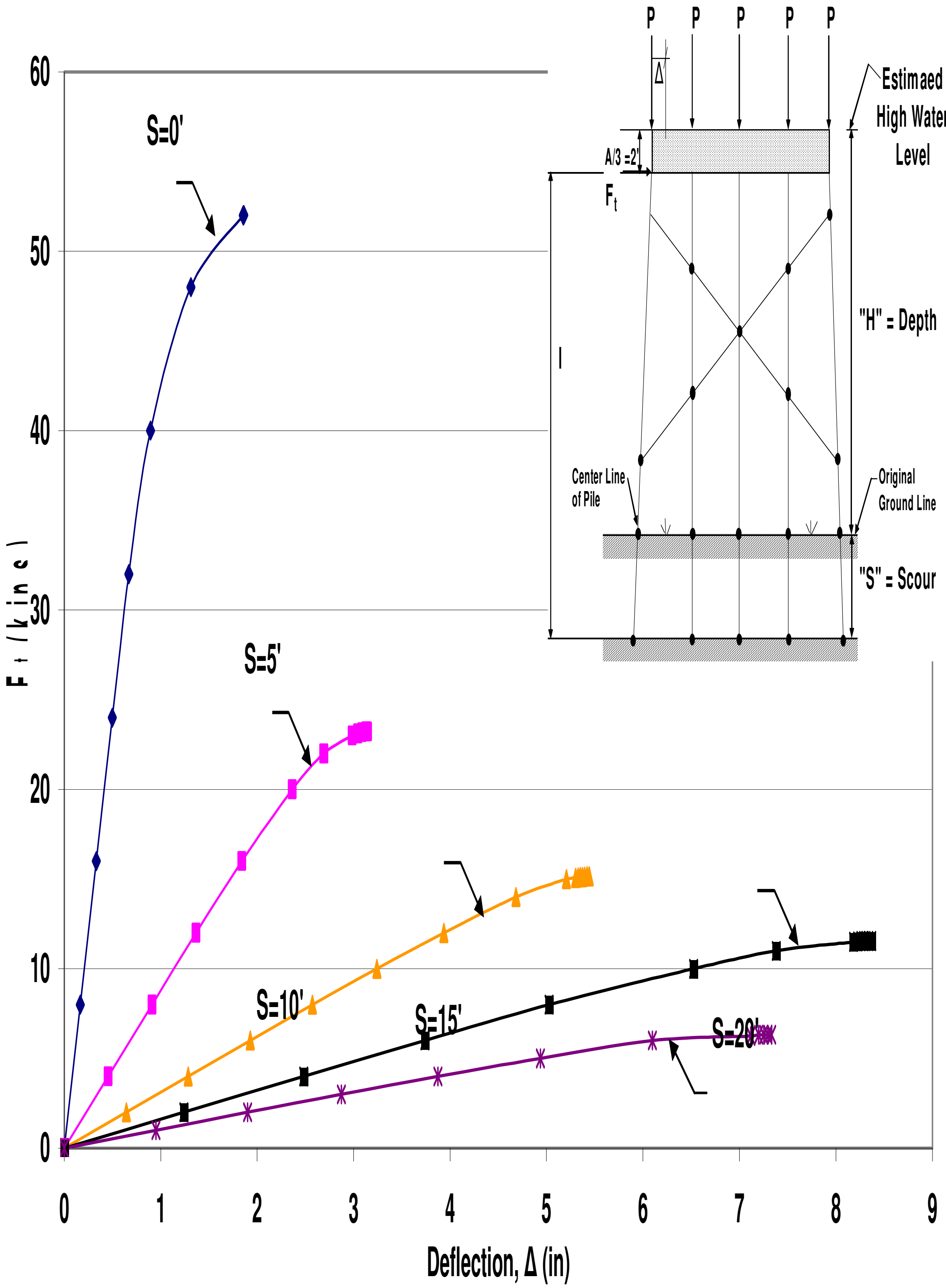


Figure A.60 HP10x42 X-Braced 5-Pile Bent with H=13',P=160kips and A=6'

Pushover Analysis Results

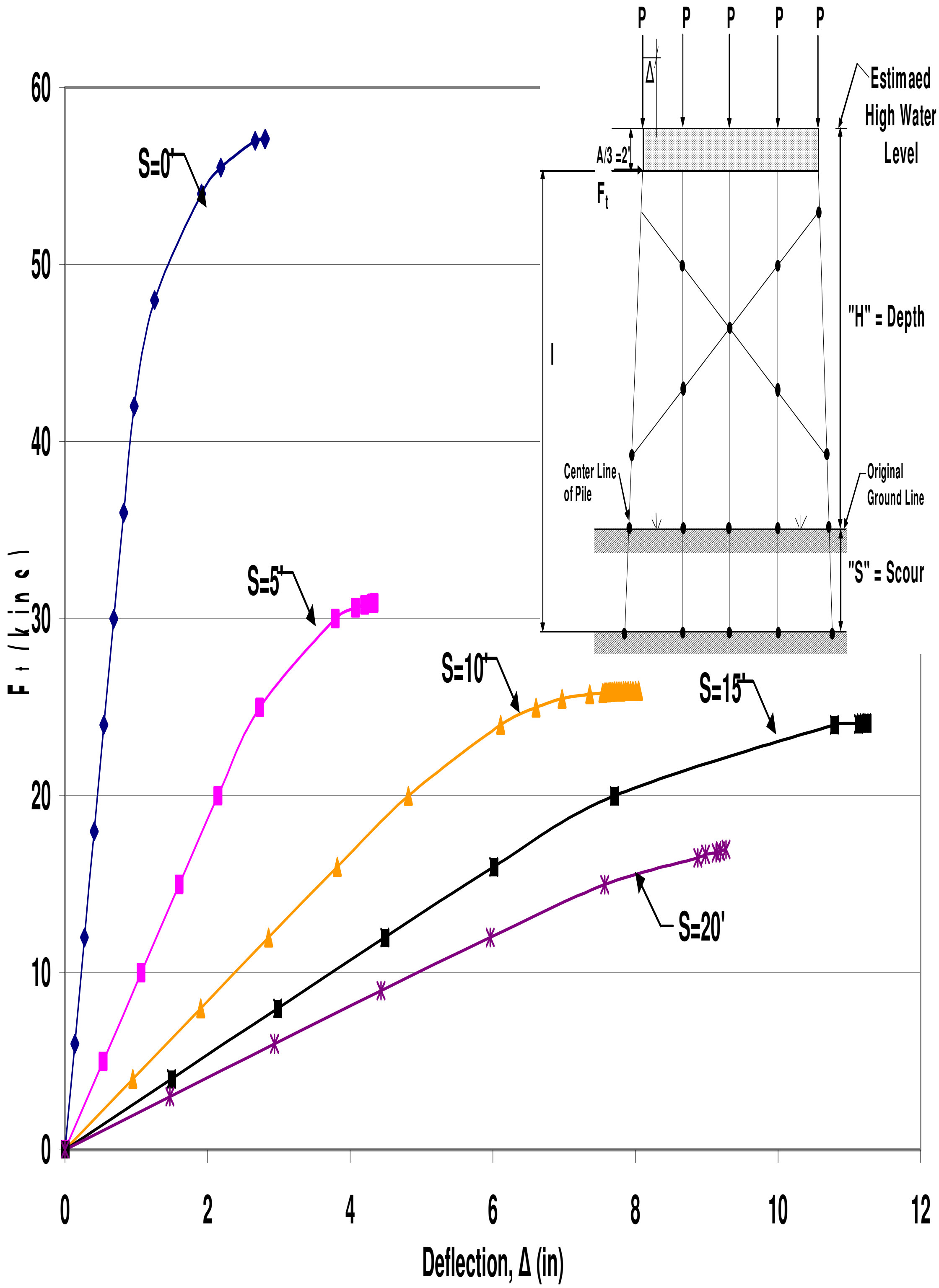


Figure A.61 HP10x42 X-Braced 5-Pile Bent with H=17',P=100kips and A=6'

Pushover Analysis Results

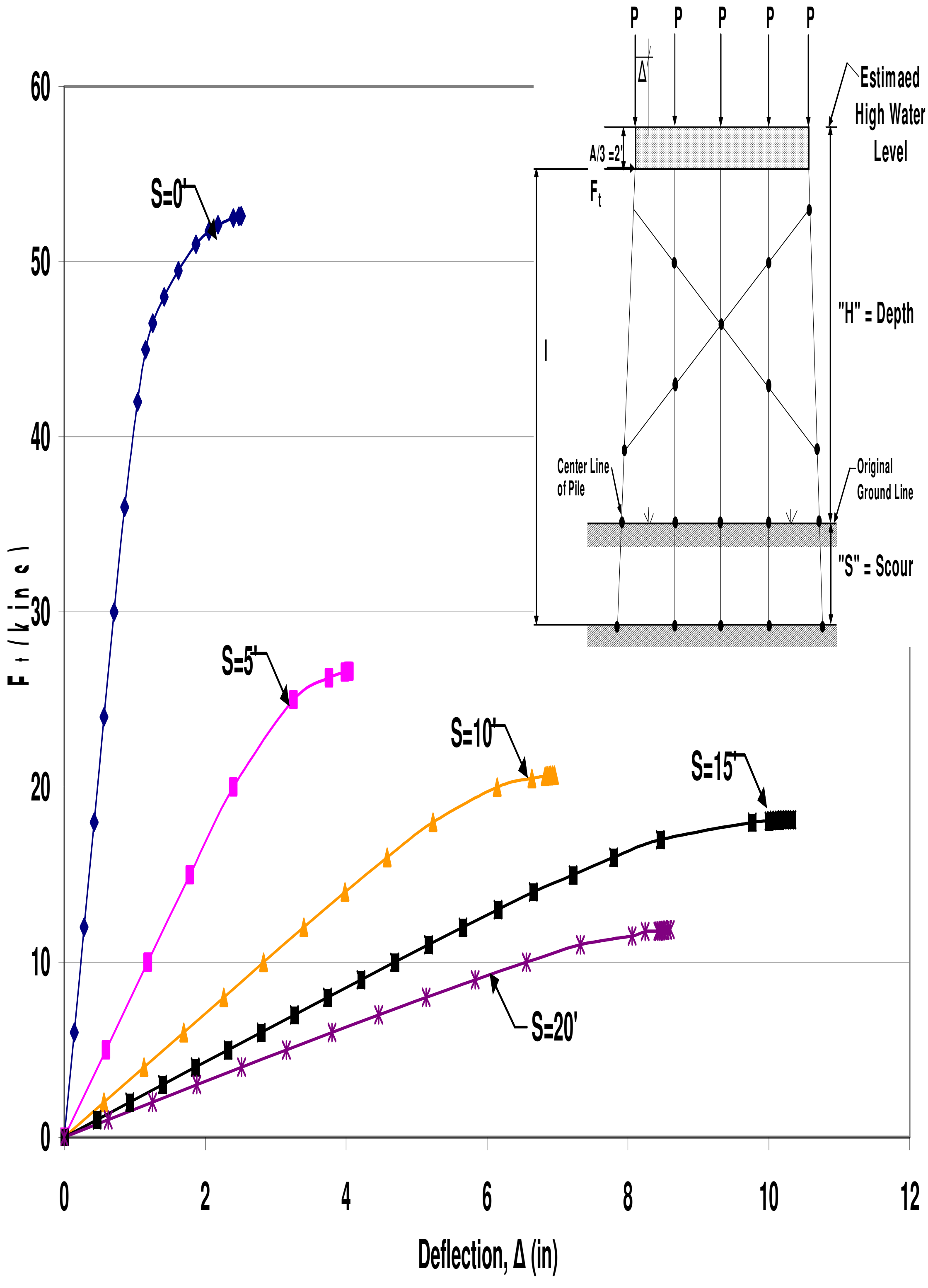


Figure A.62 HP10x42 X-Braced 5-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

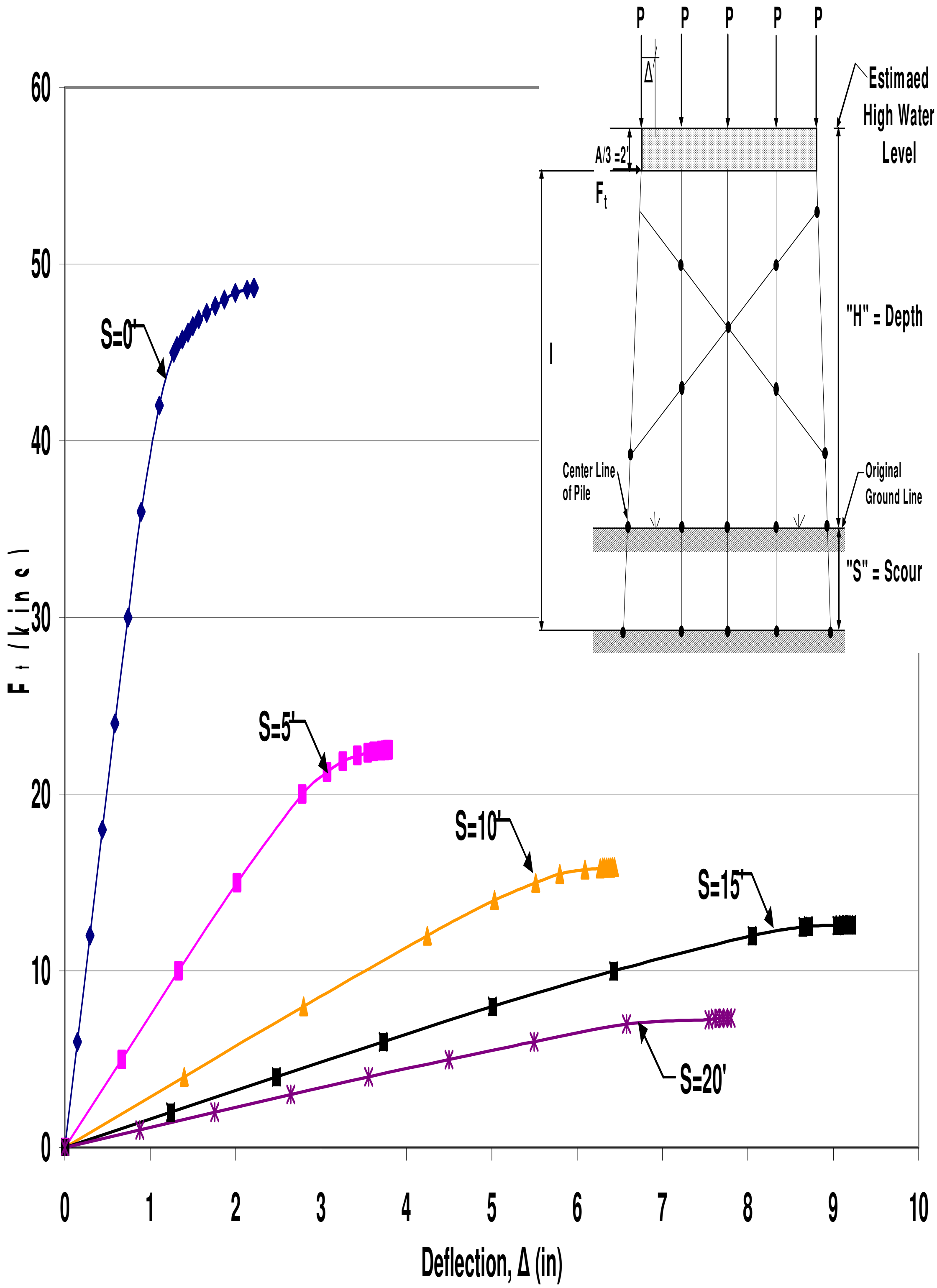


Figure A.63 HP10x42 X-Braced 5-Pile Bent with H=17', P=140kips and A=6'
Pushover Analysis Results

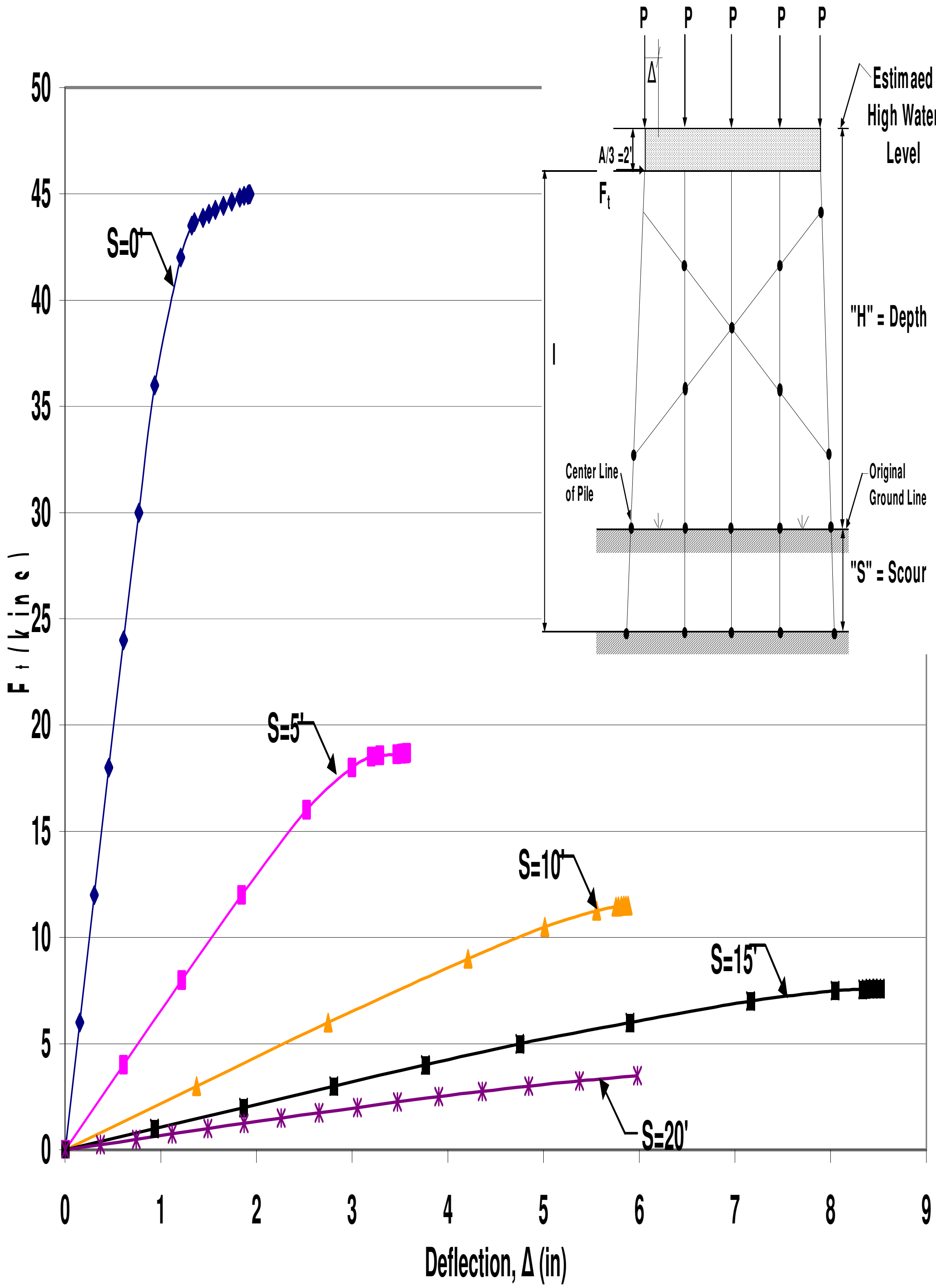


Figure A.64 HP10x42 X-Braced 5-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

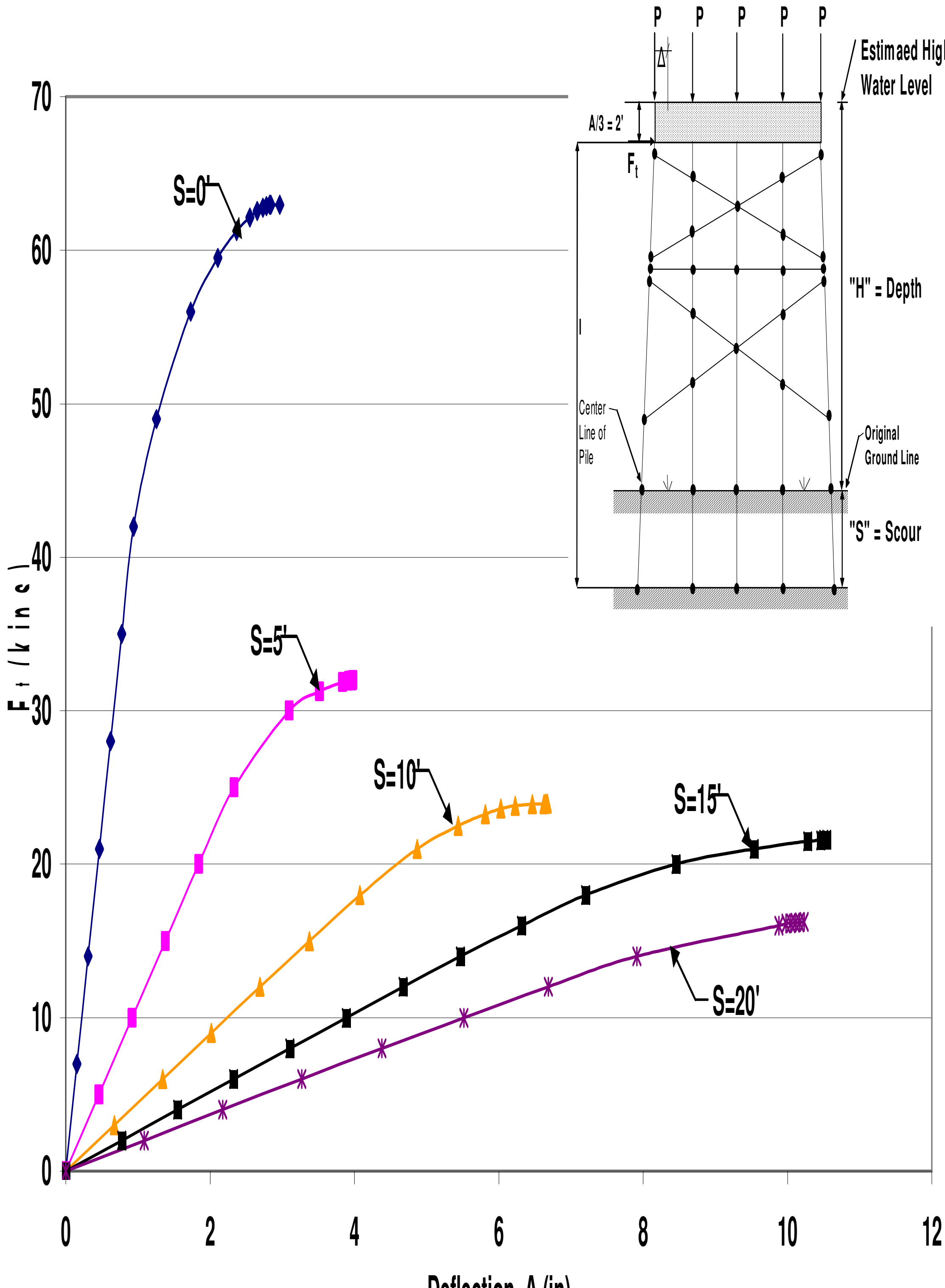


Figure A.65 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

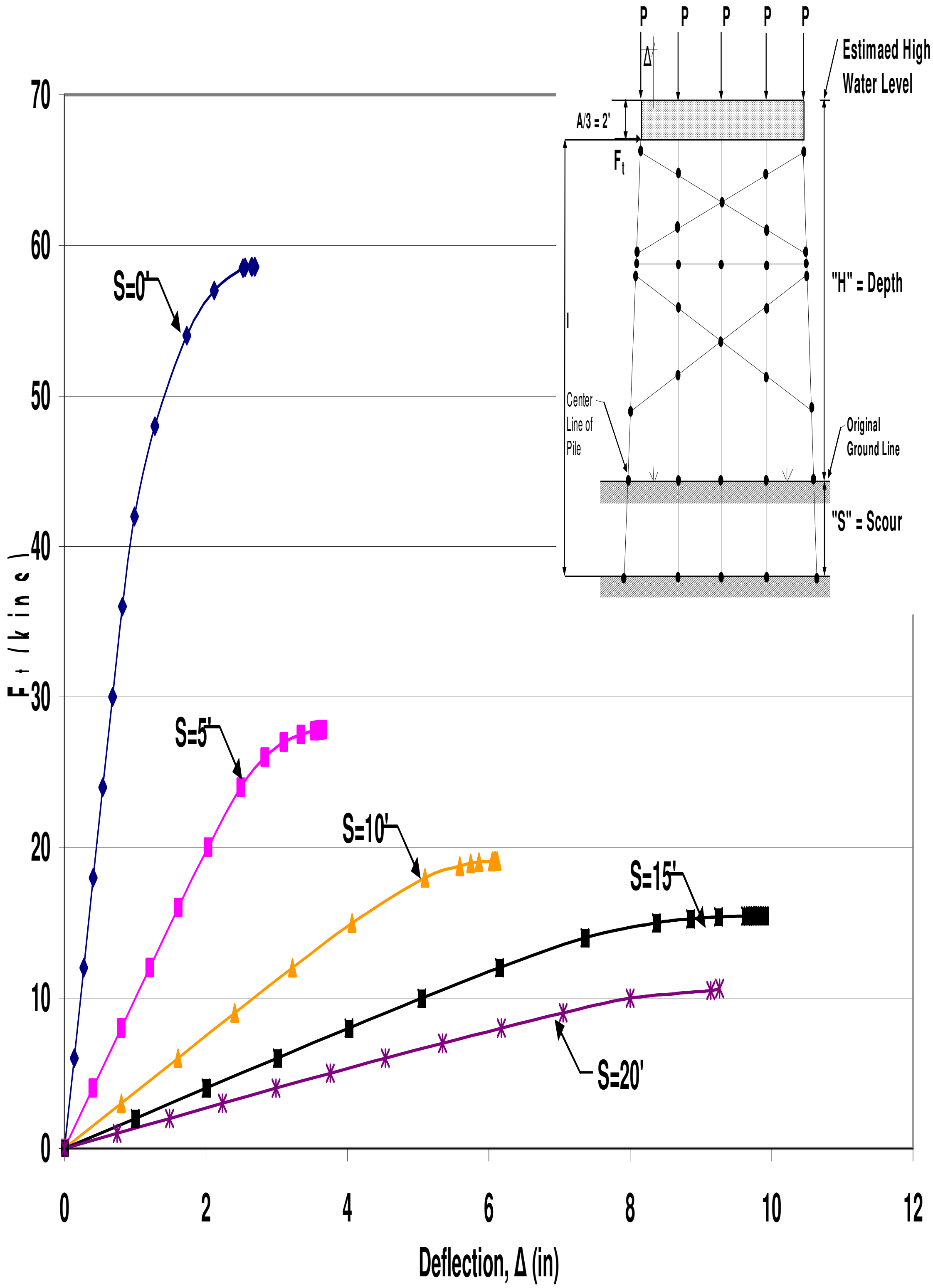


Figure A.66 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

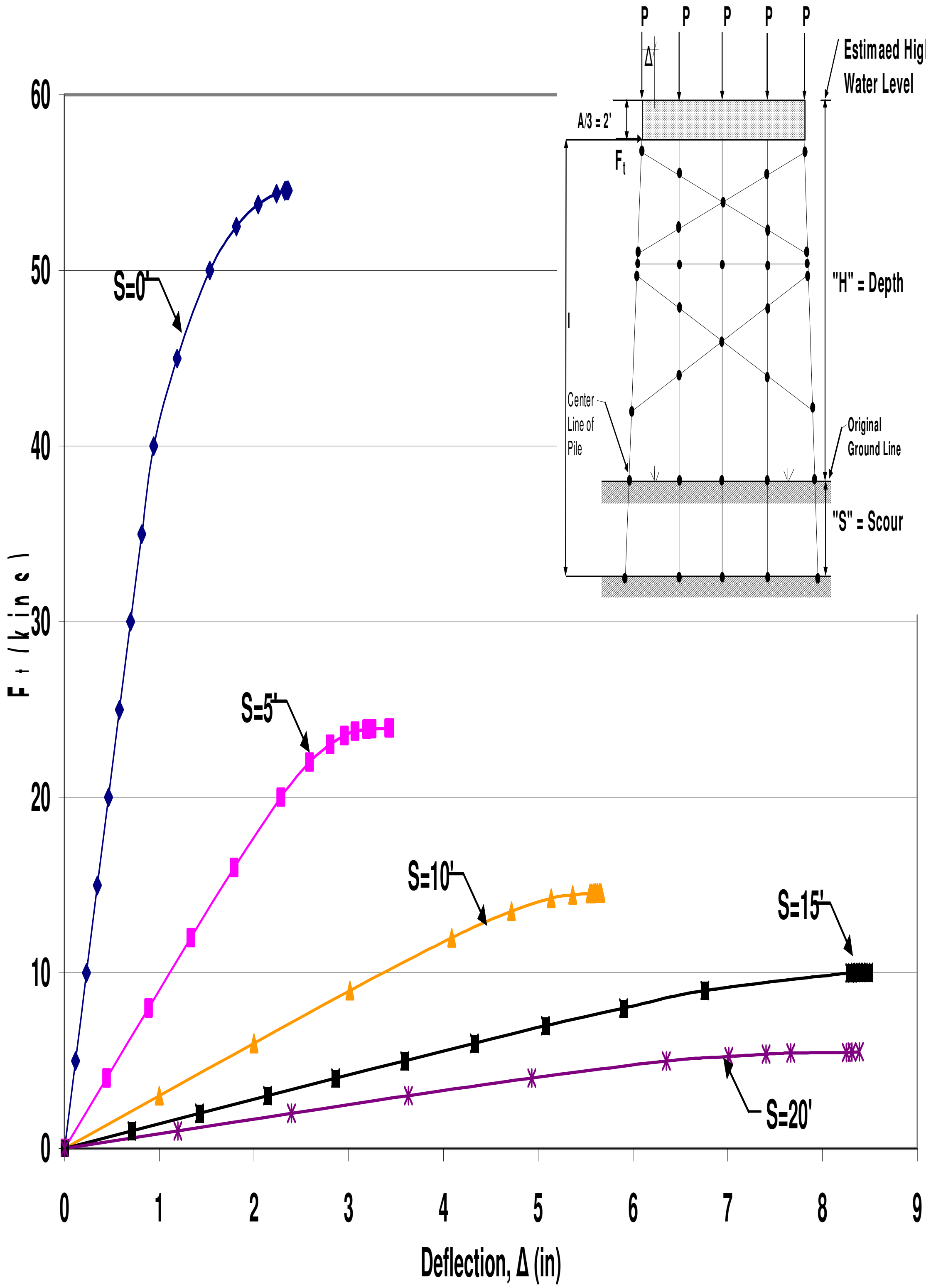


Figure A.67 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

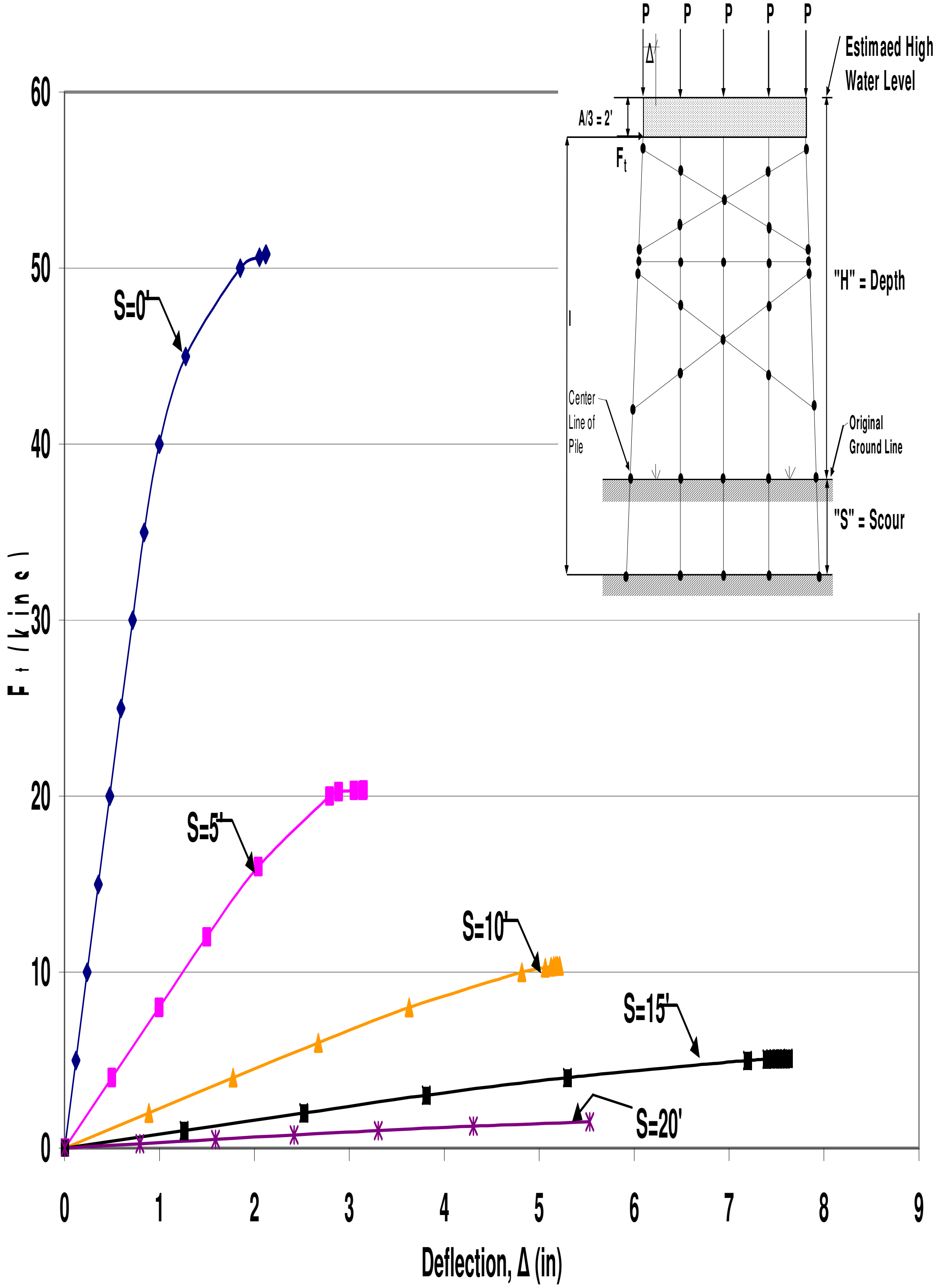


Figure A.68 HP10x42 Two-Story X-Braced 5-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

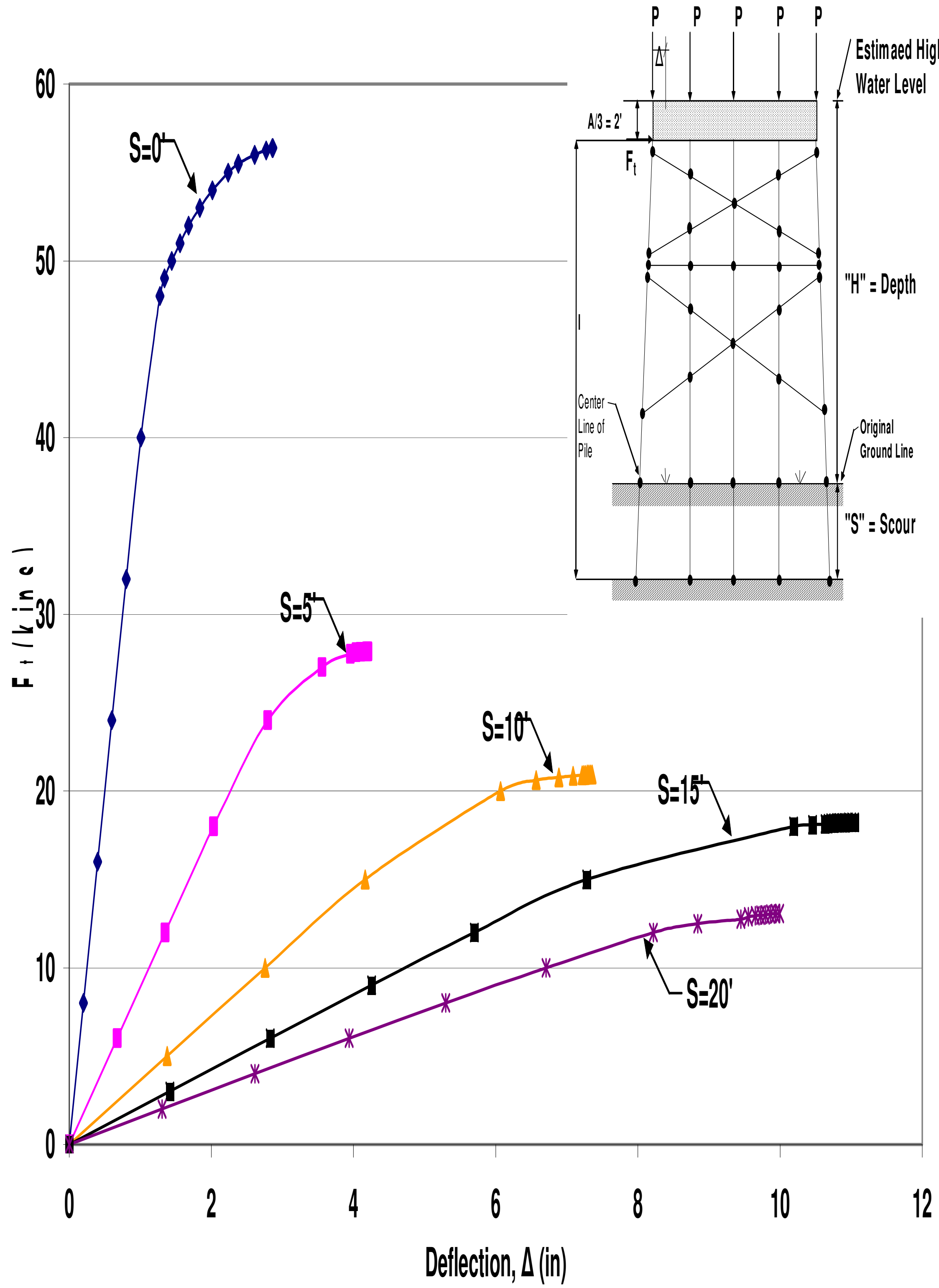


Figure A.69 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=100kips and A=6'
Pushover Analysis Results

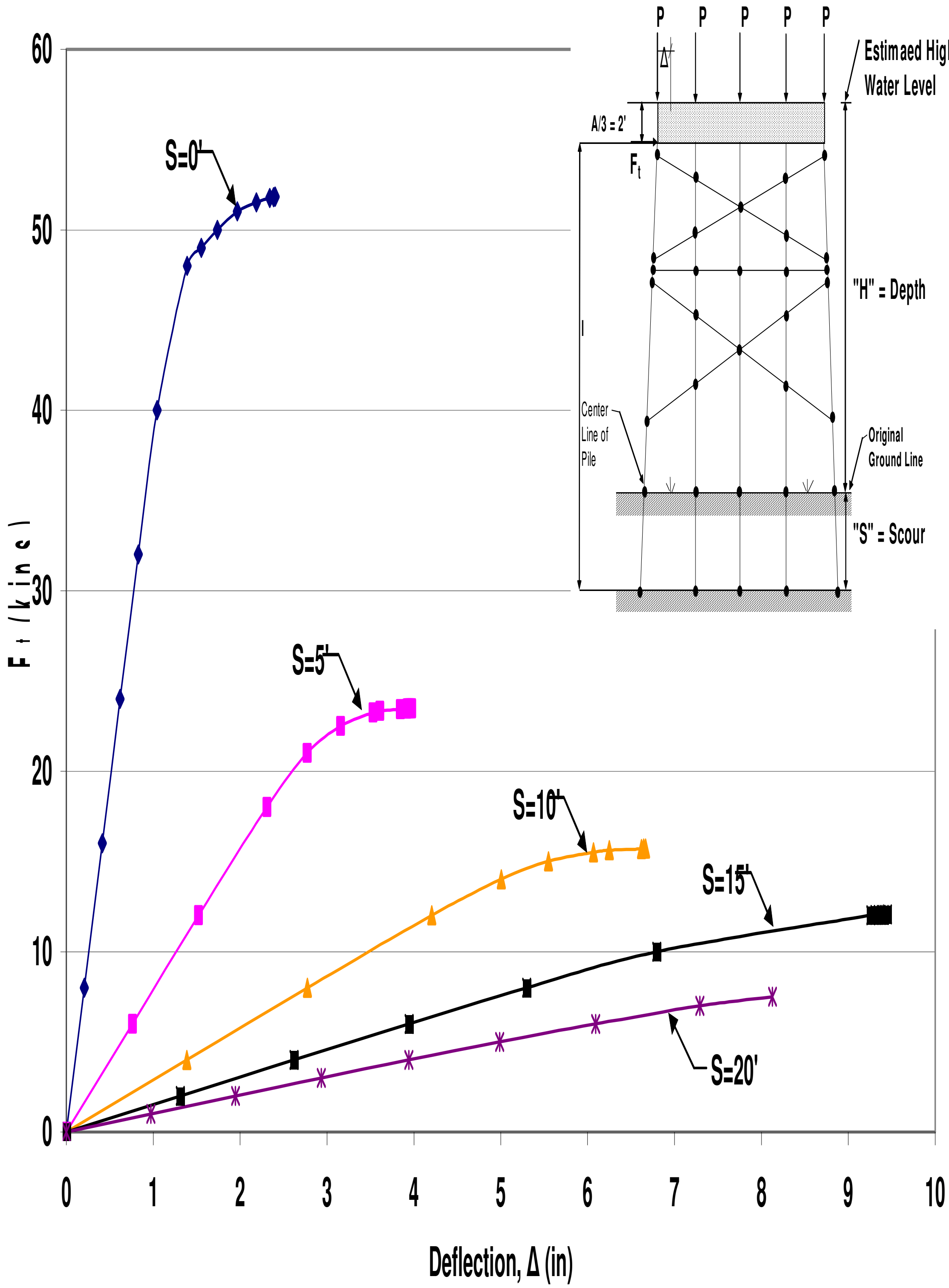


Figure A.70 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

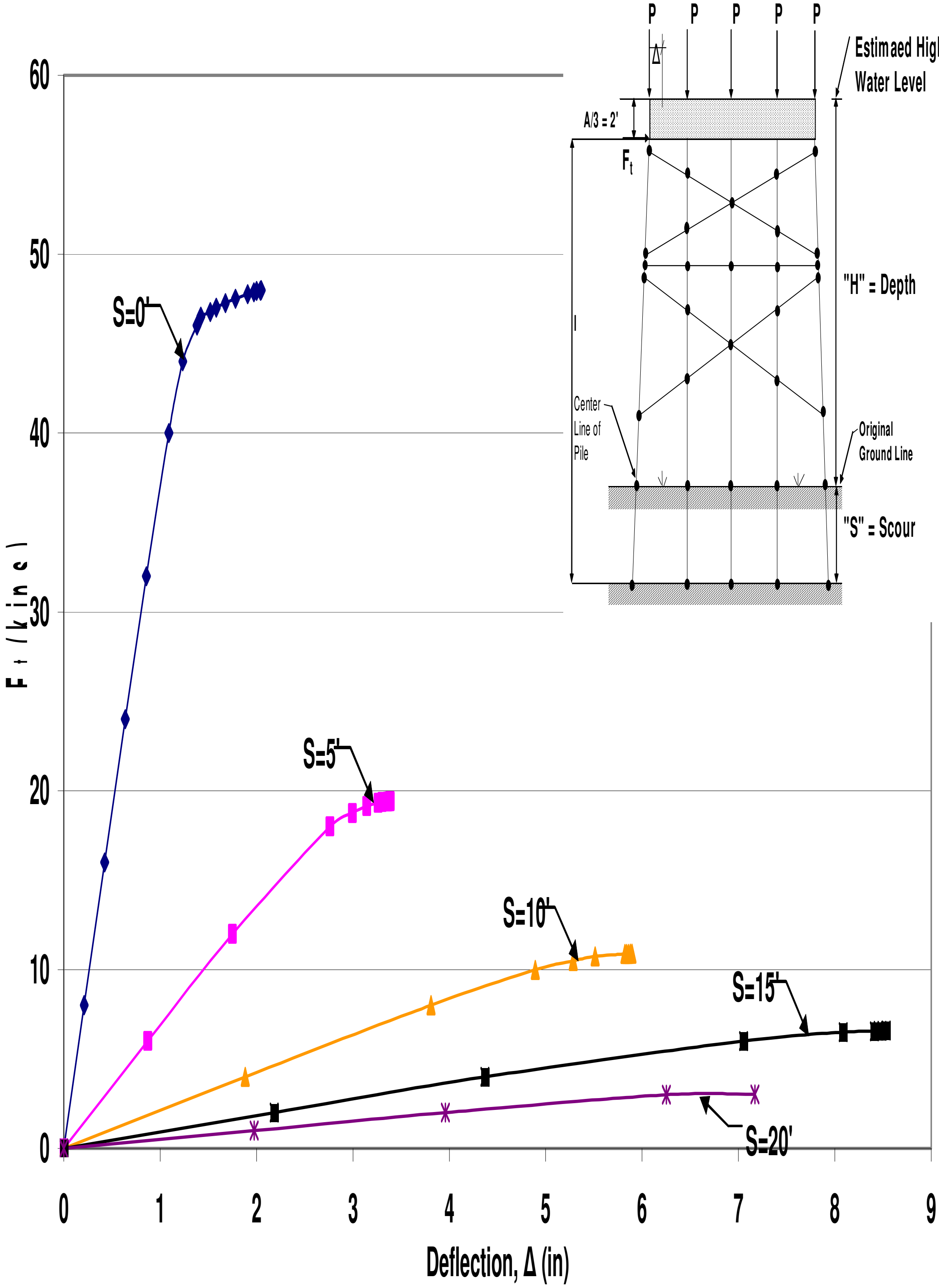


Figure A.71 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

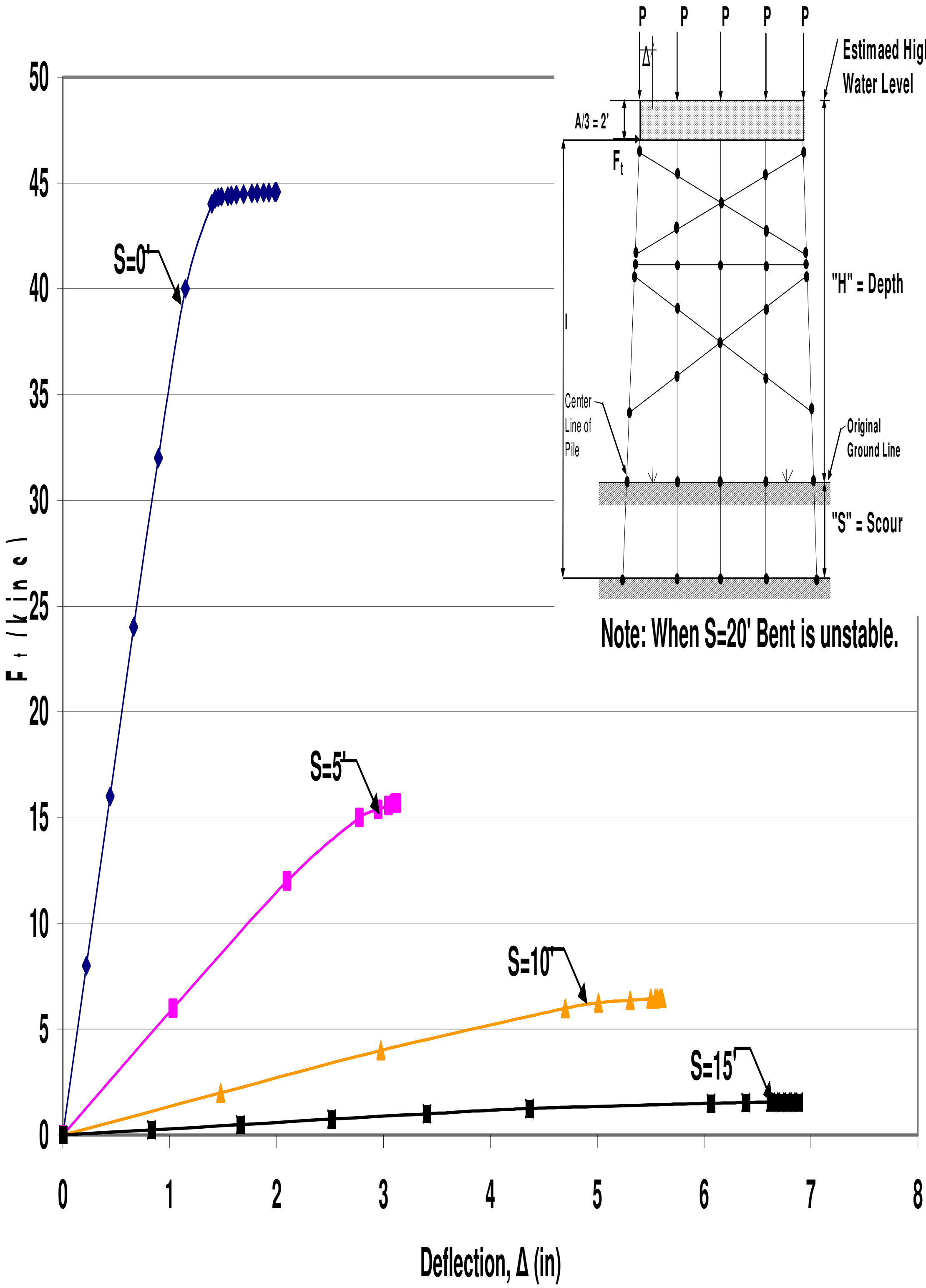


Figure A.72 HP10x42 Two-Story X-Braced 5-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

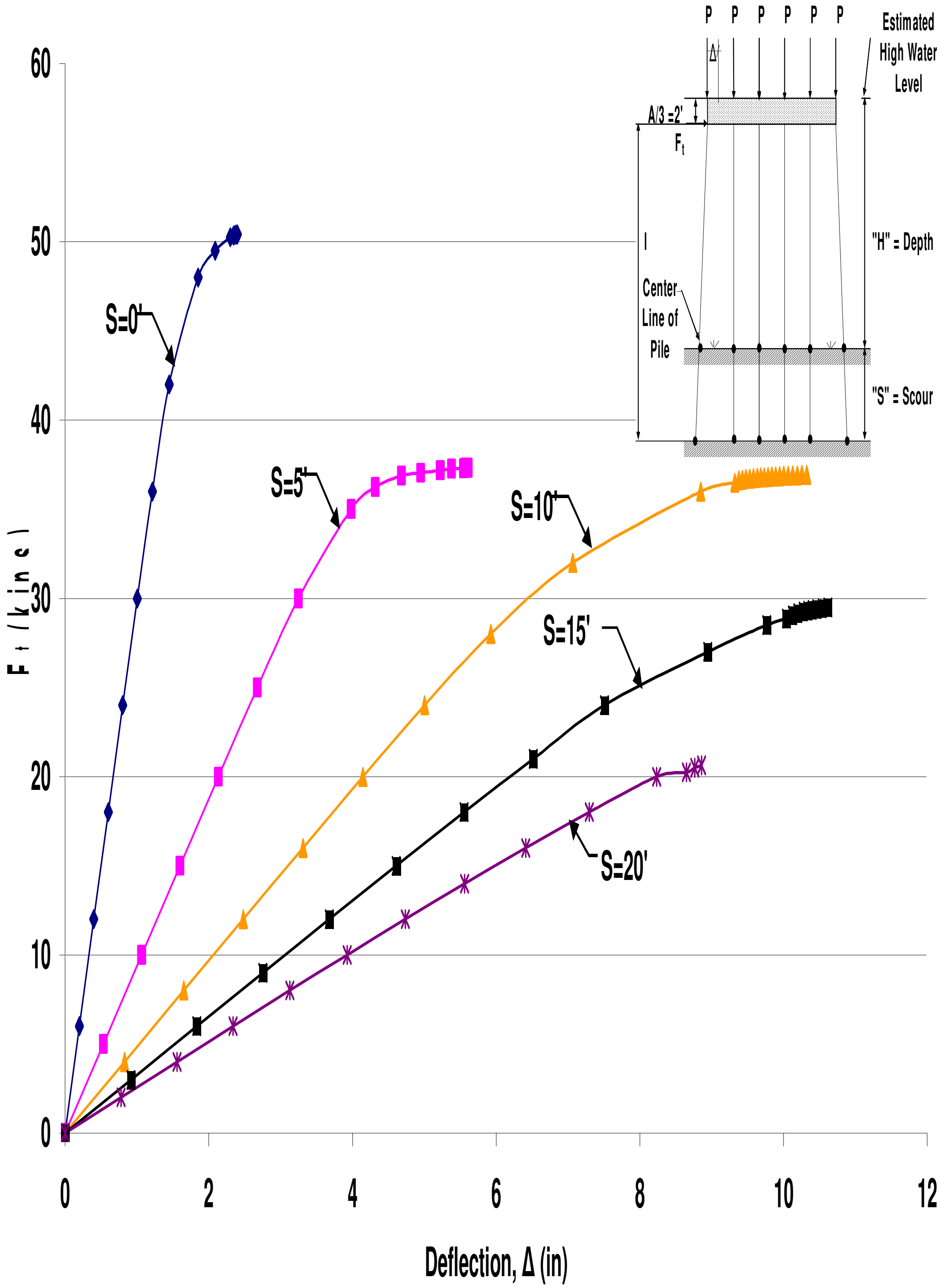


Figure A.73 HP10x42 Unbraced 6-Pile Bent with H=10', P=100kips and A=6' Pushover Anlaysis Results

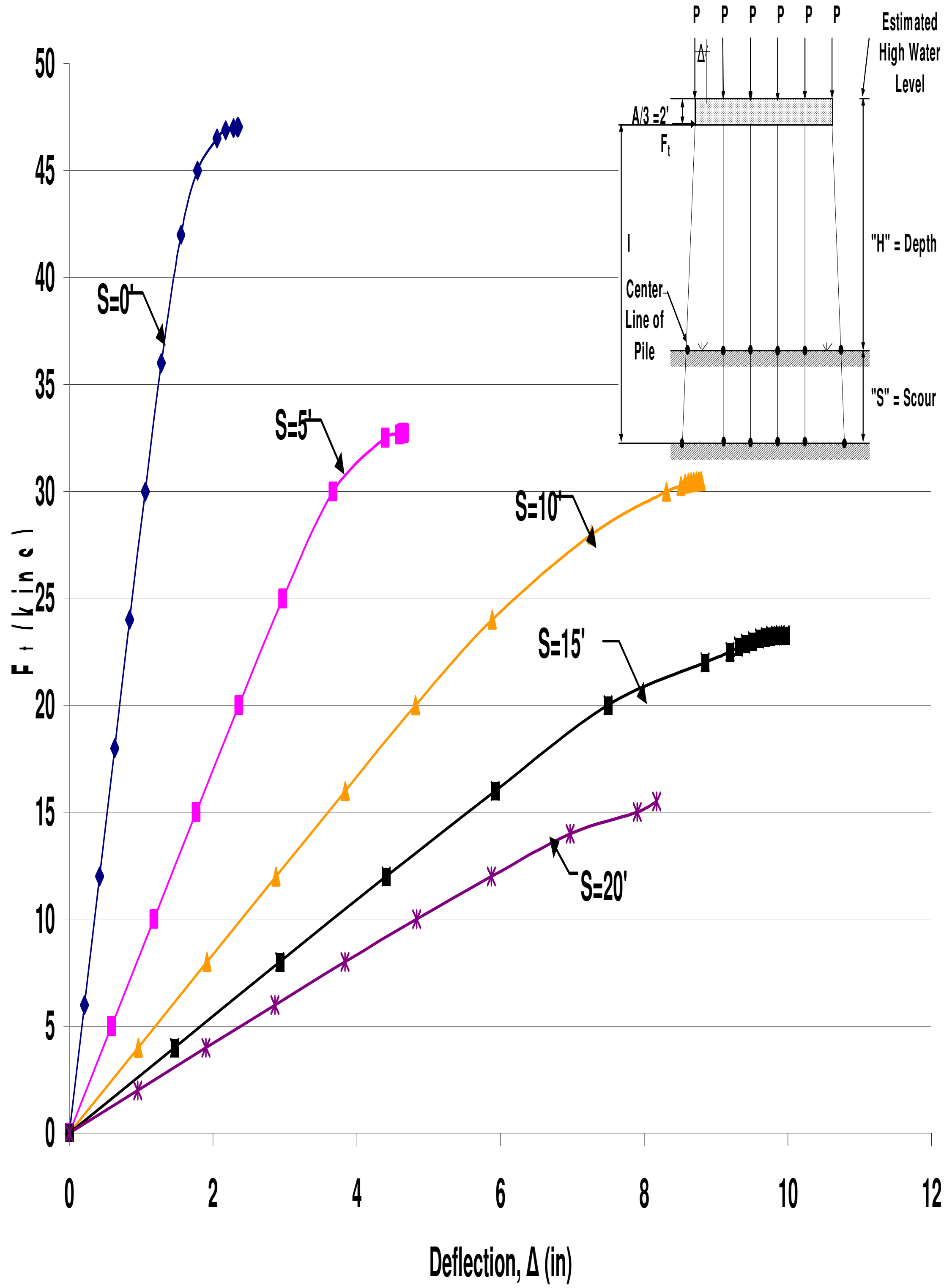


Figure A.74 HP10x42 Unbraced 6-Pile Bent with H=10', P=120kips and A=6'
Pushover Anlaysis Results

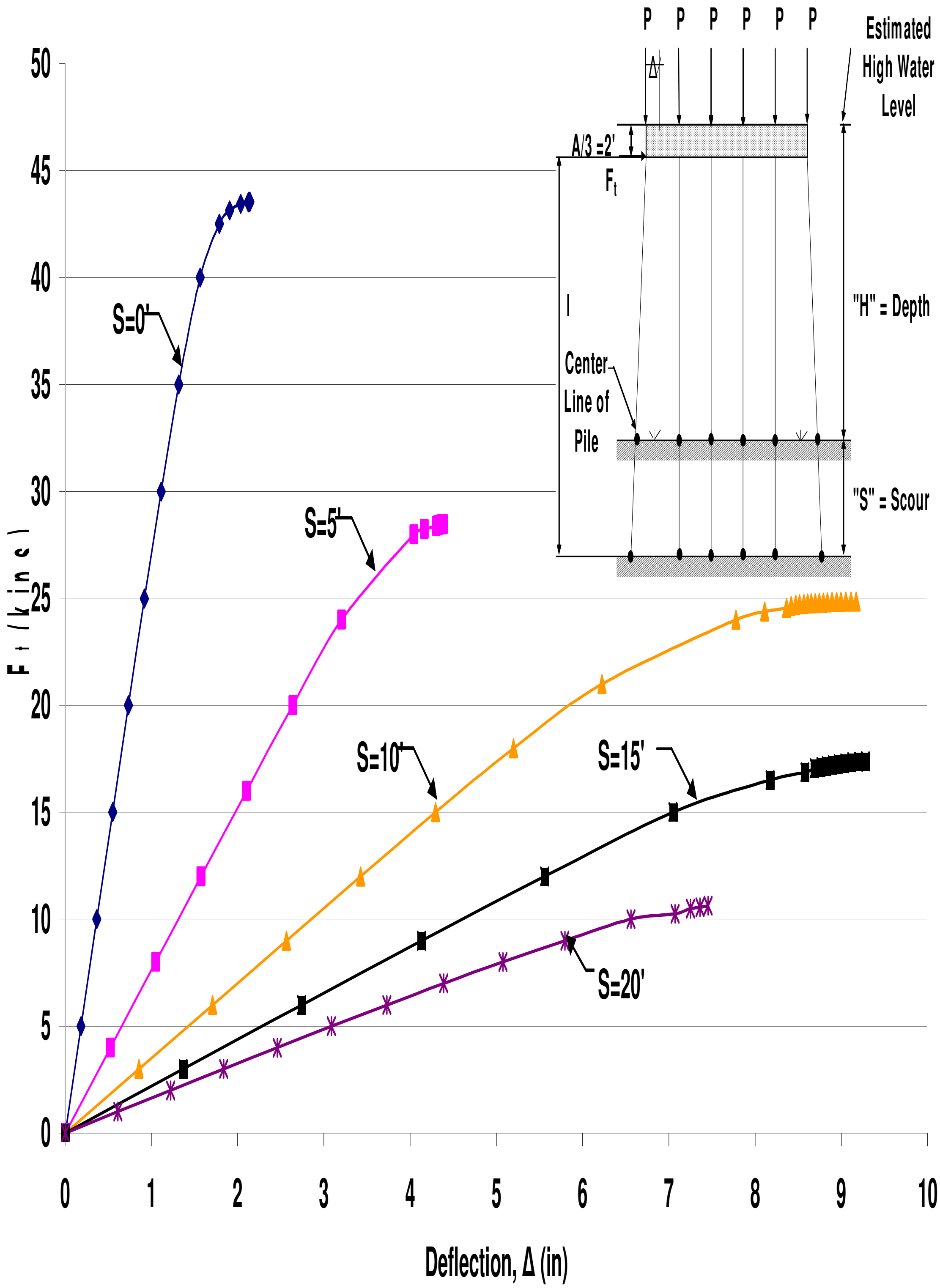


Figure A.75 HP10x42 Unbraced 6-Pile Bent with H=10', P=140kips and A=6' Pushover Anlaysis Results

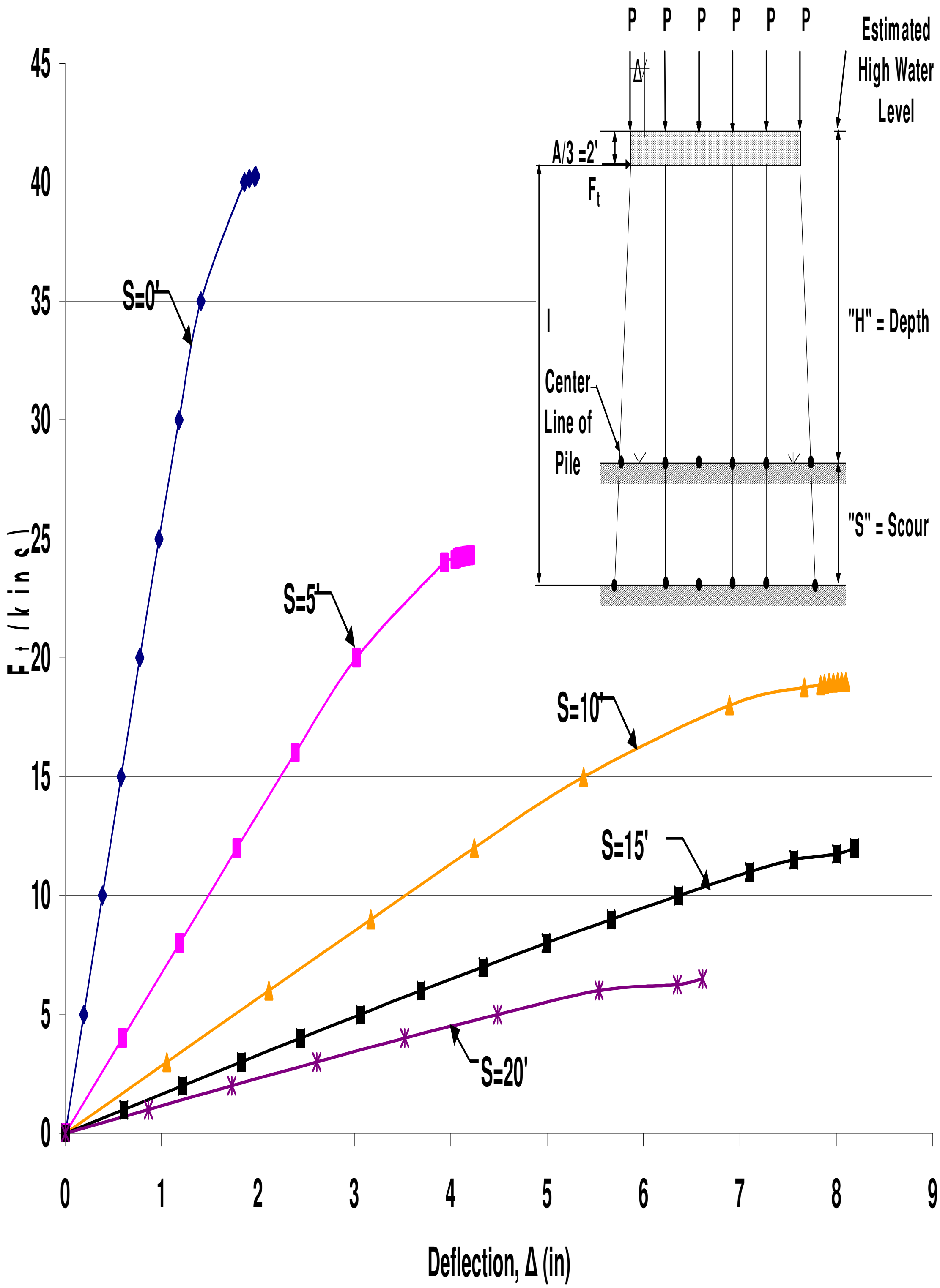


Figure A.76 HP10x42 Unbraced 6-Pile Bent with H=10', P=160kips and A=6'
Pushover Anlaysis Results

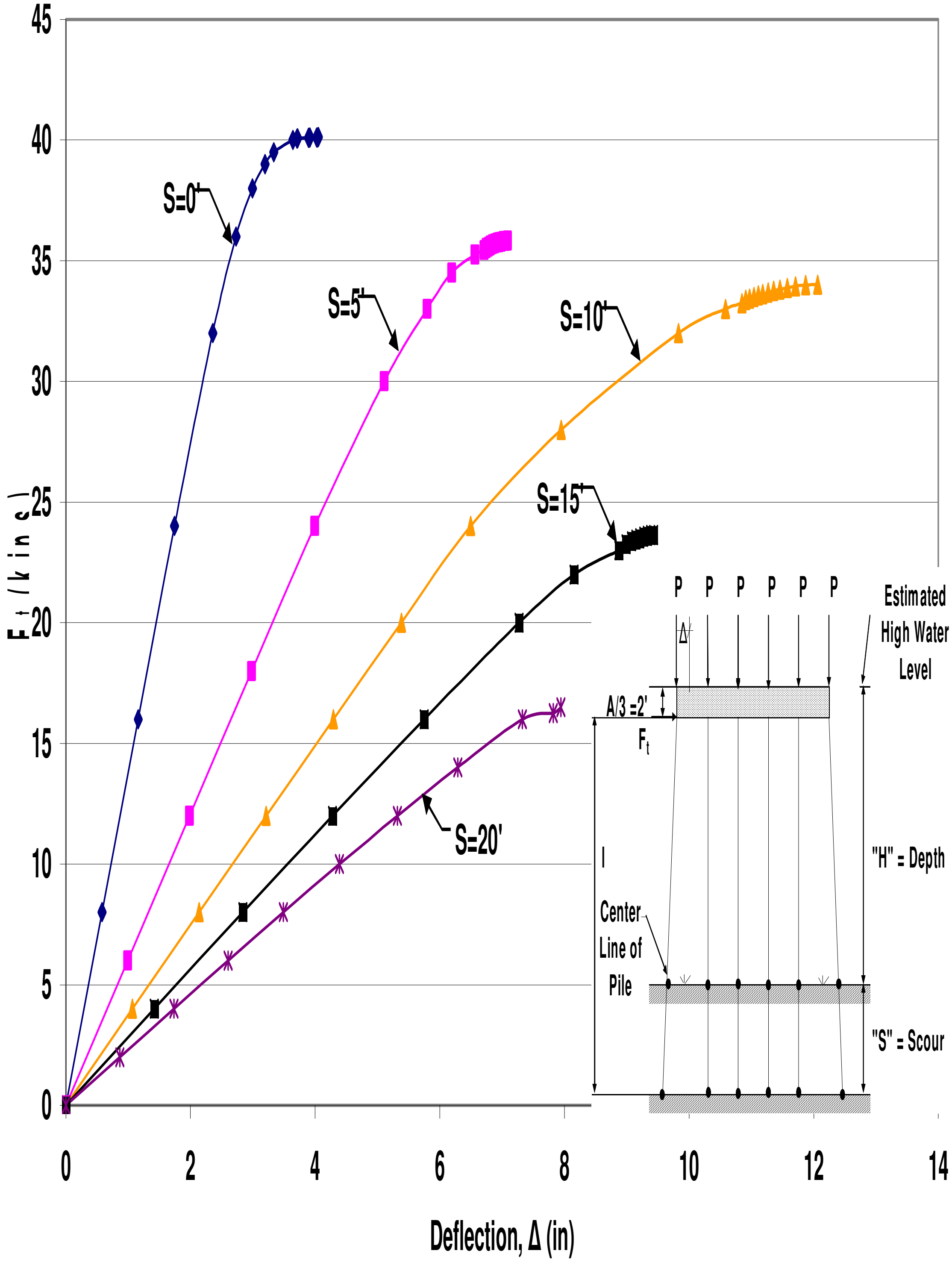


Figure A.77 HP10x42 Unbraced 6-Pile Bent with H=13',P=100kips and A=6'
Pushover Analysis Results

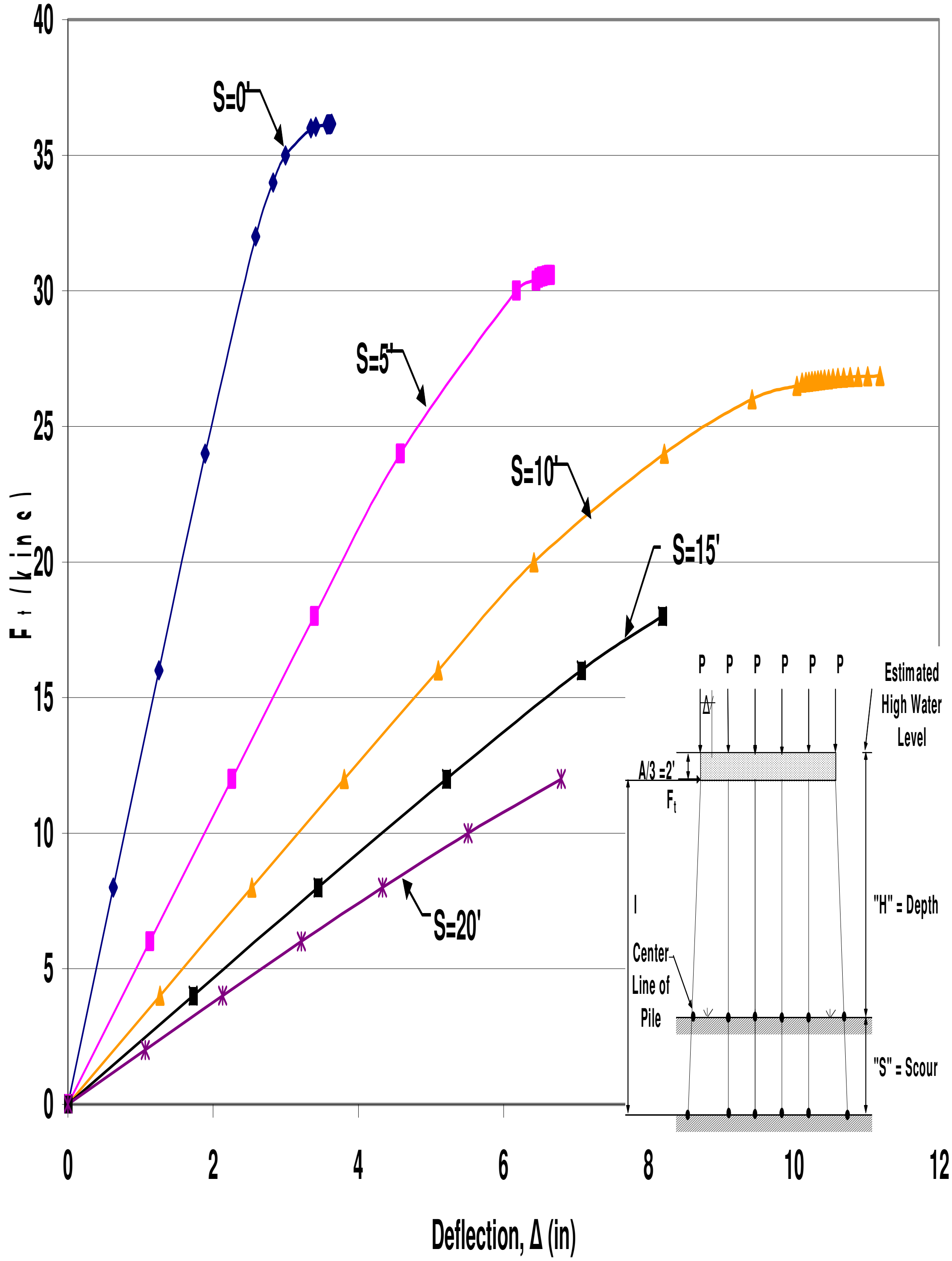


Figure A.78 HP10x42 Unbraced 6-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

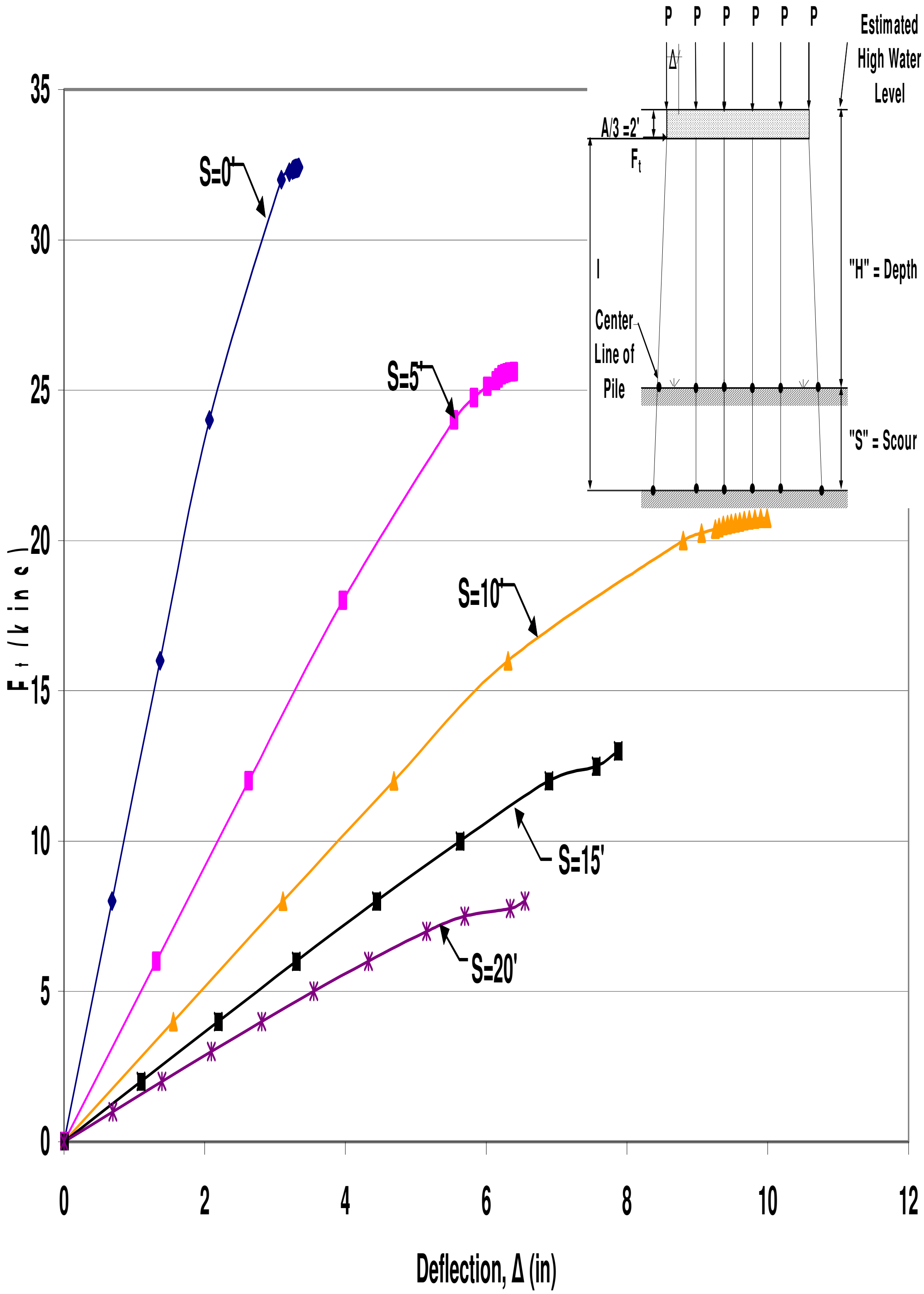


Figure A.79 HP10x42 Unbraced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

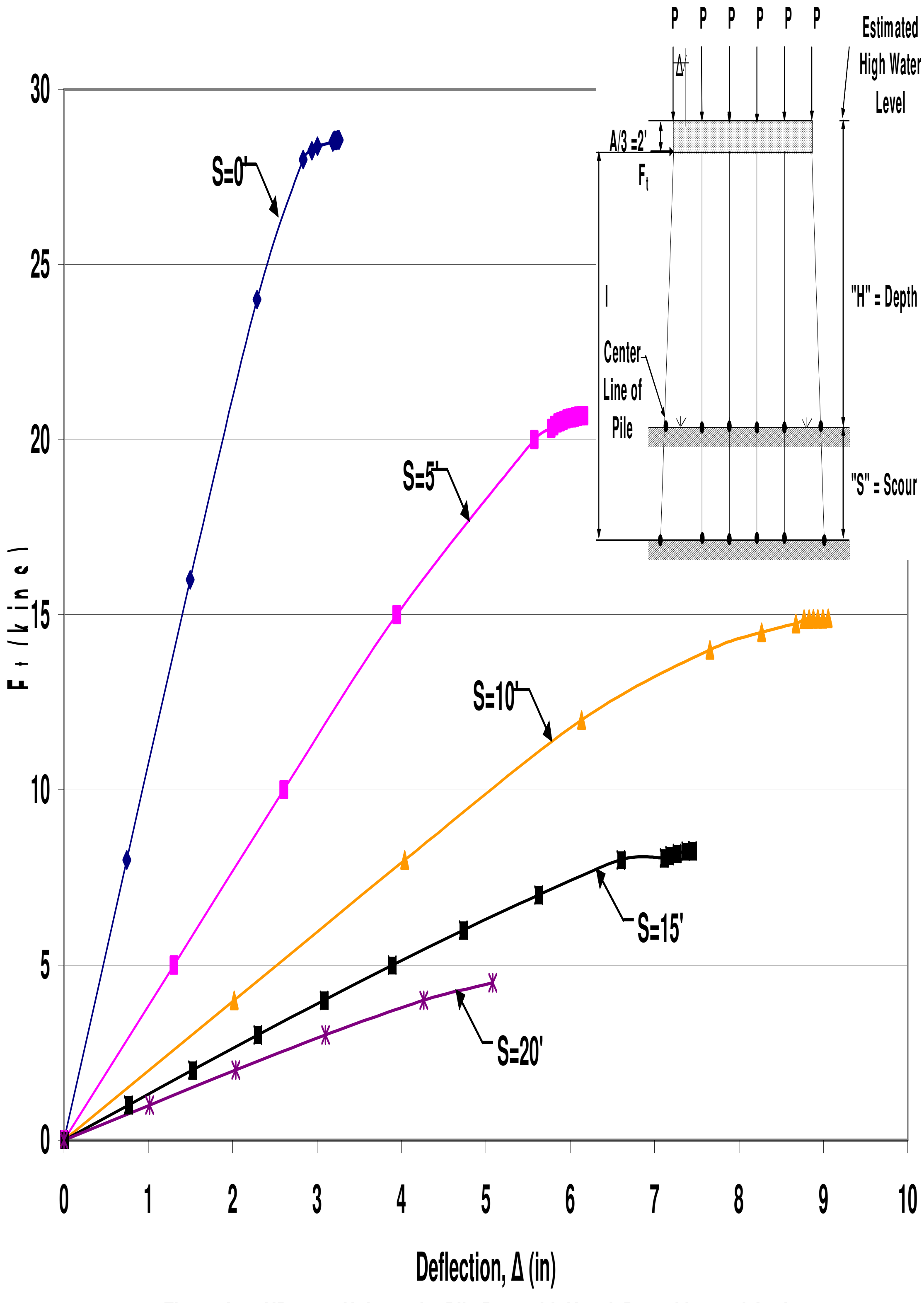


Figure A.80 HP10x42 Unbraced 6-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

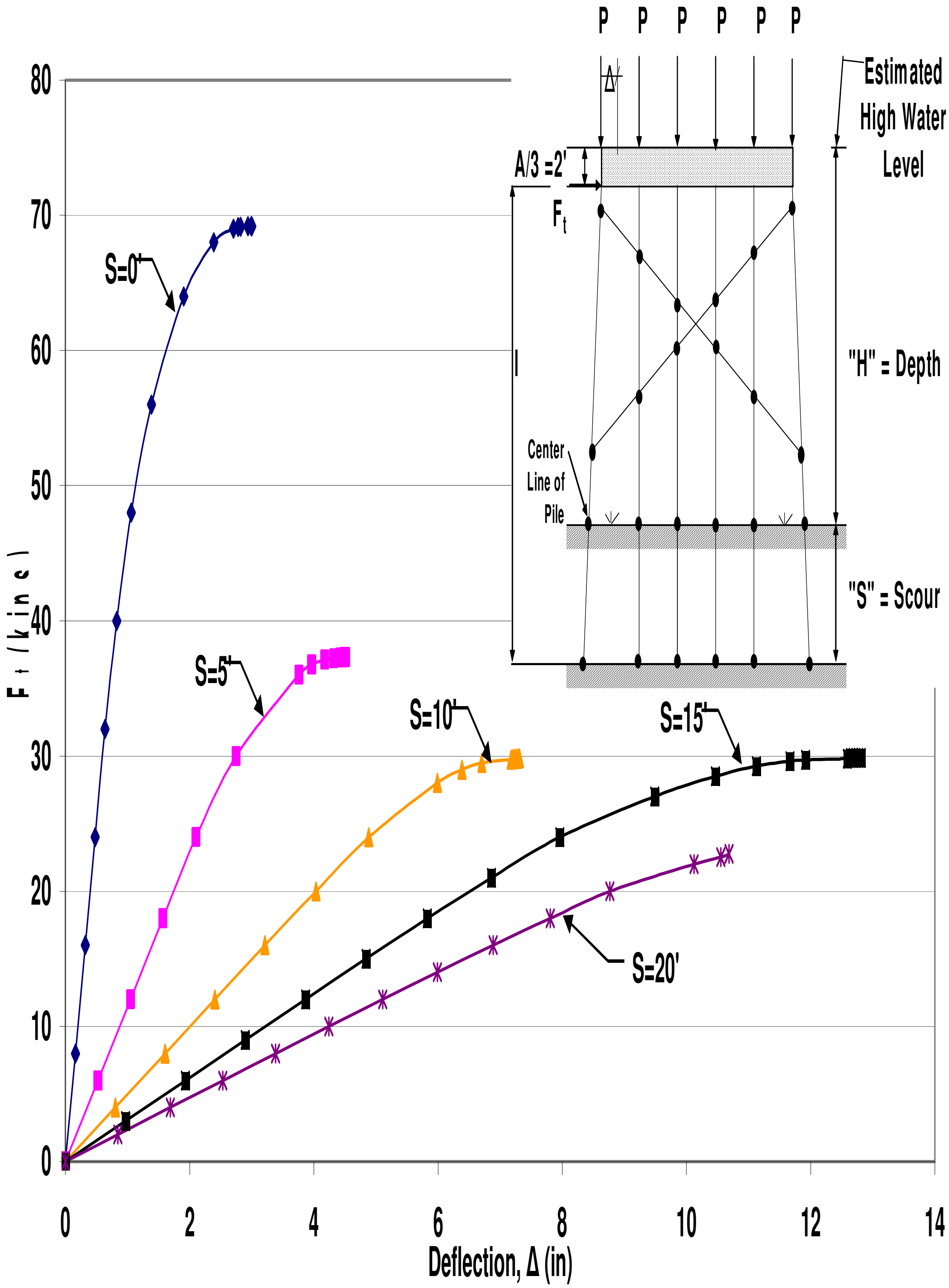


Figure A.81 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

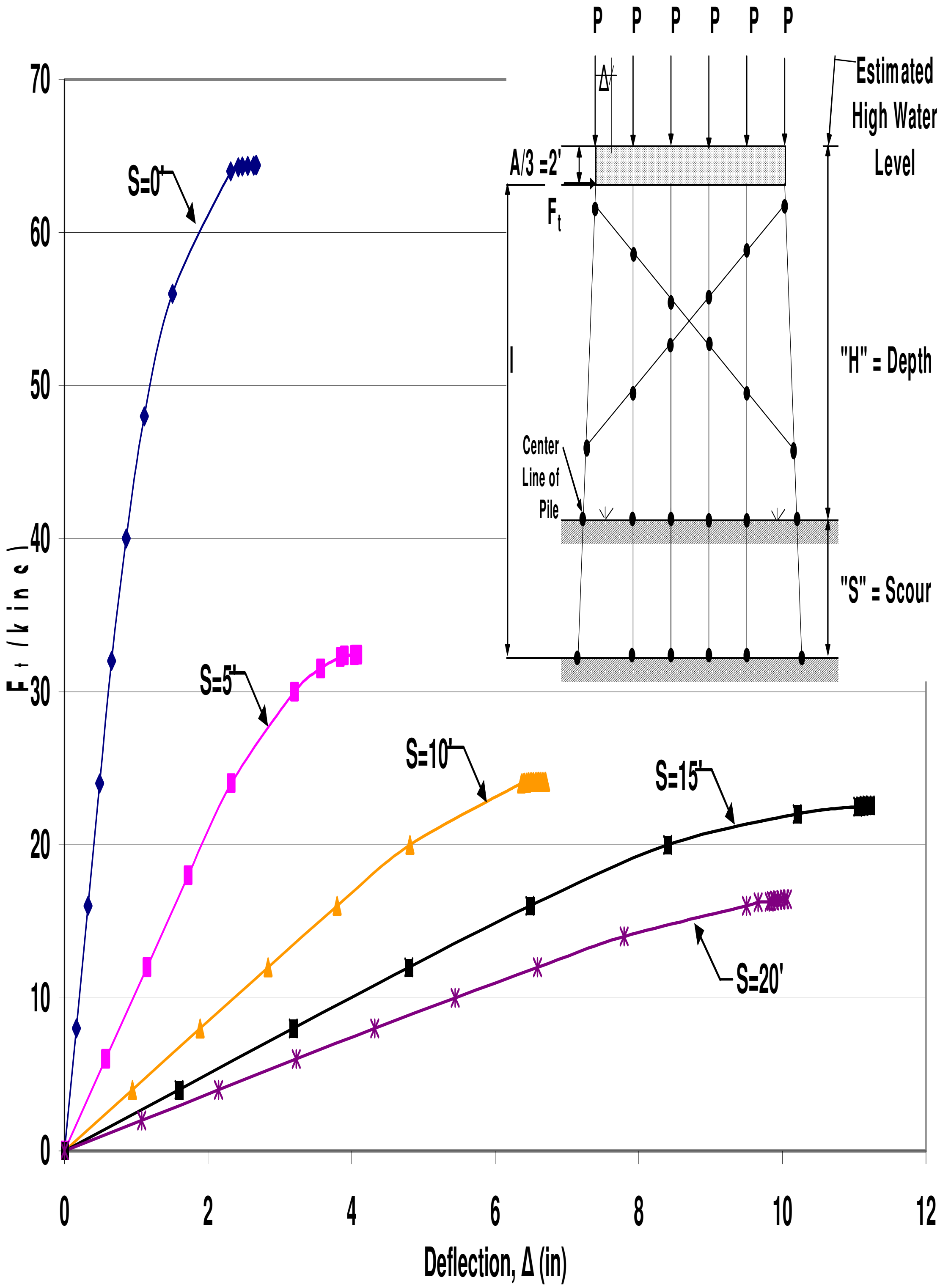


Figure A.82 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

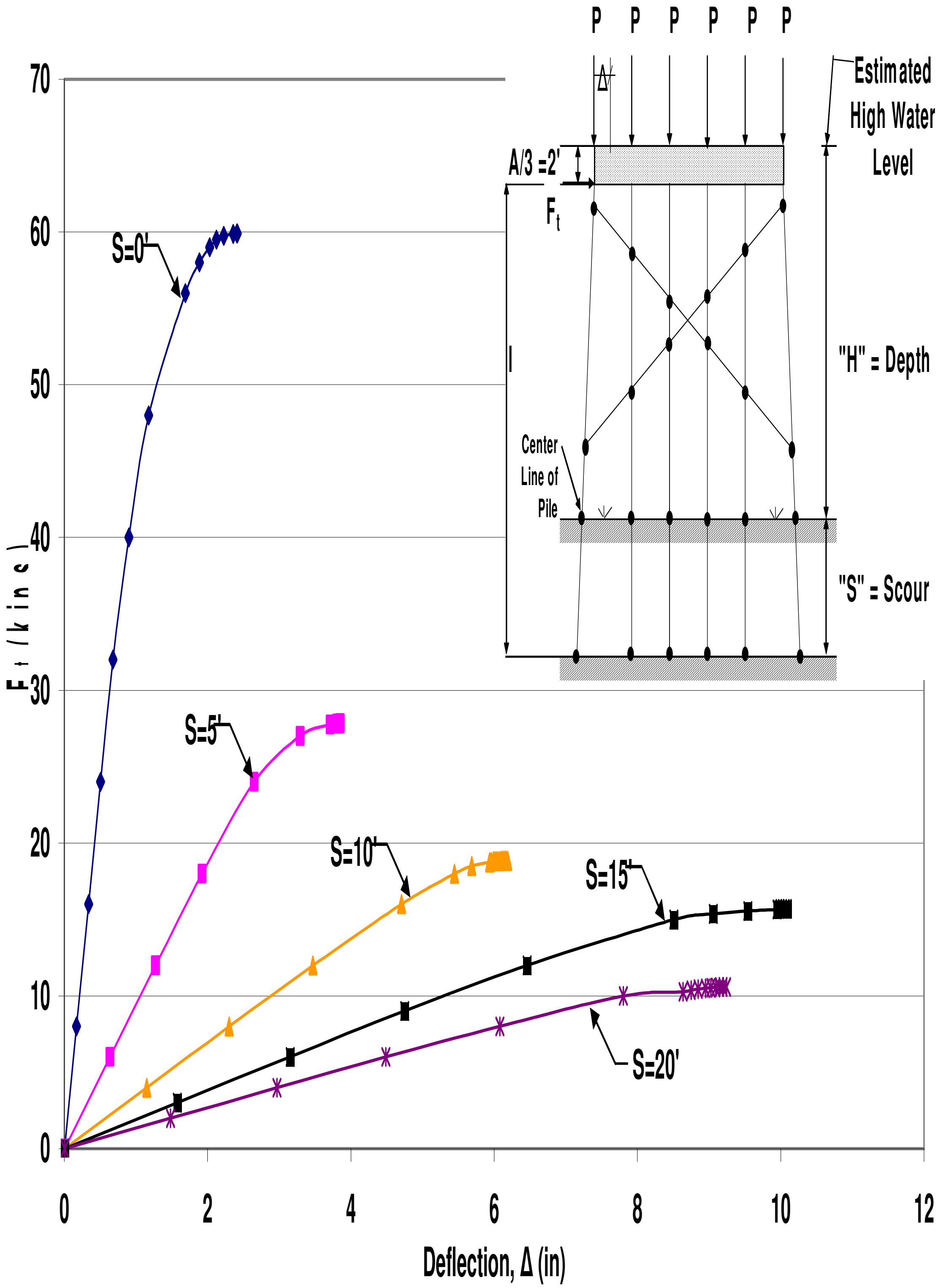


Figure A.83 HP10x42 Single X-Braced 6-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

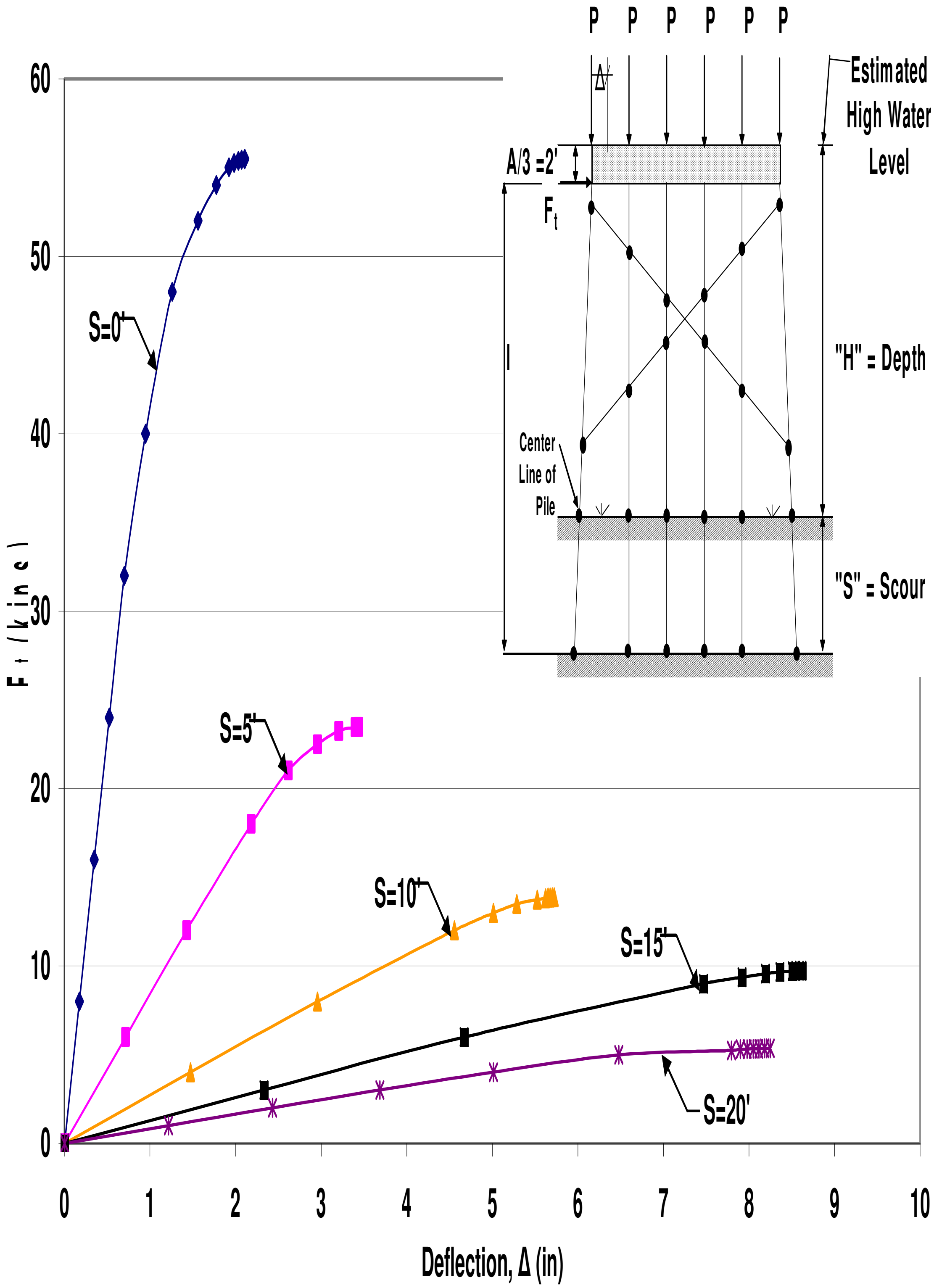


Figure A.84 HP10x42 Single X-Braced 6-Pile Bent with H=13',P=160kips and A=6' Pushover Analysis Results

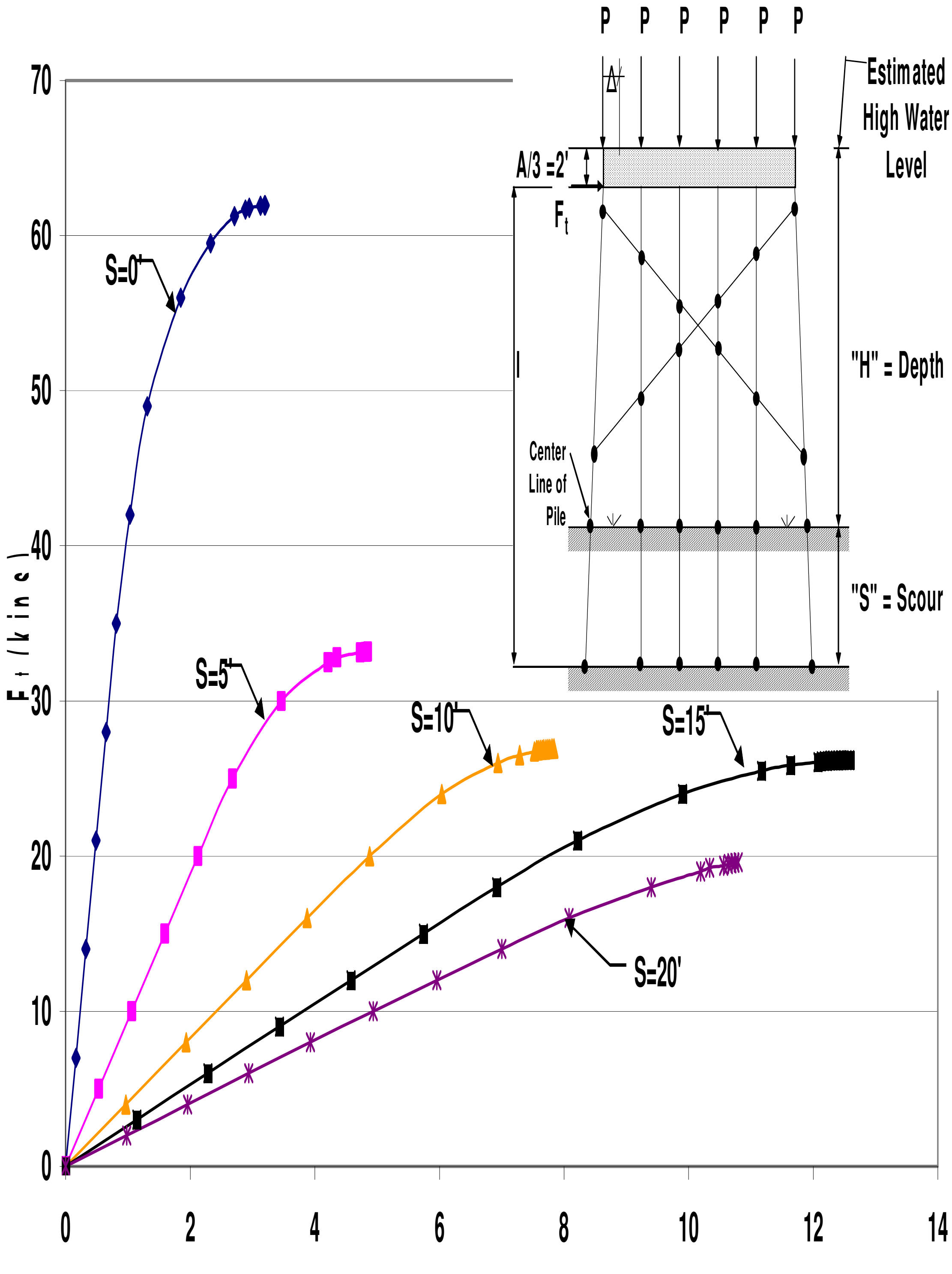


Figure A.85 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

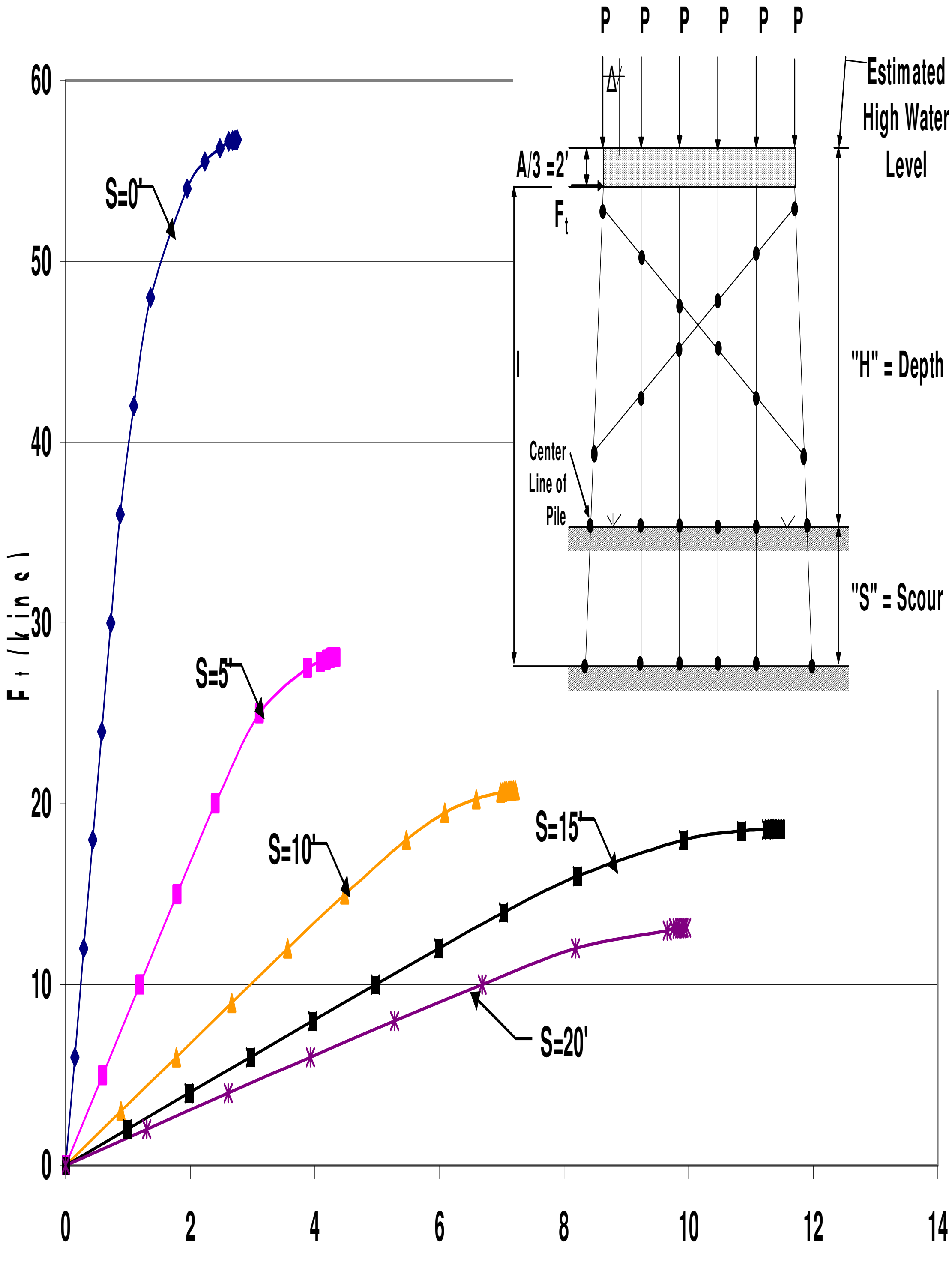


Figure A.86 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=120kips and A=6'

Pushover Analysis Results

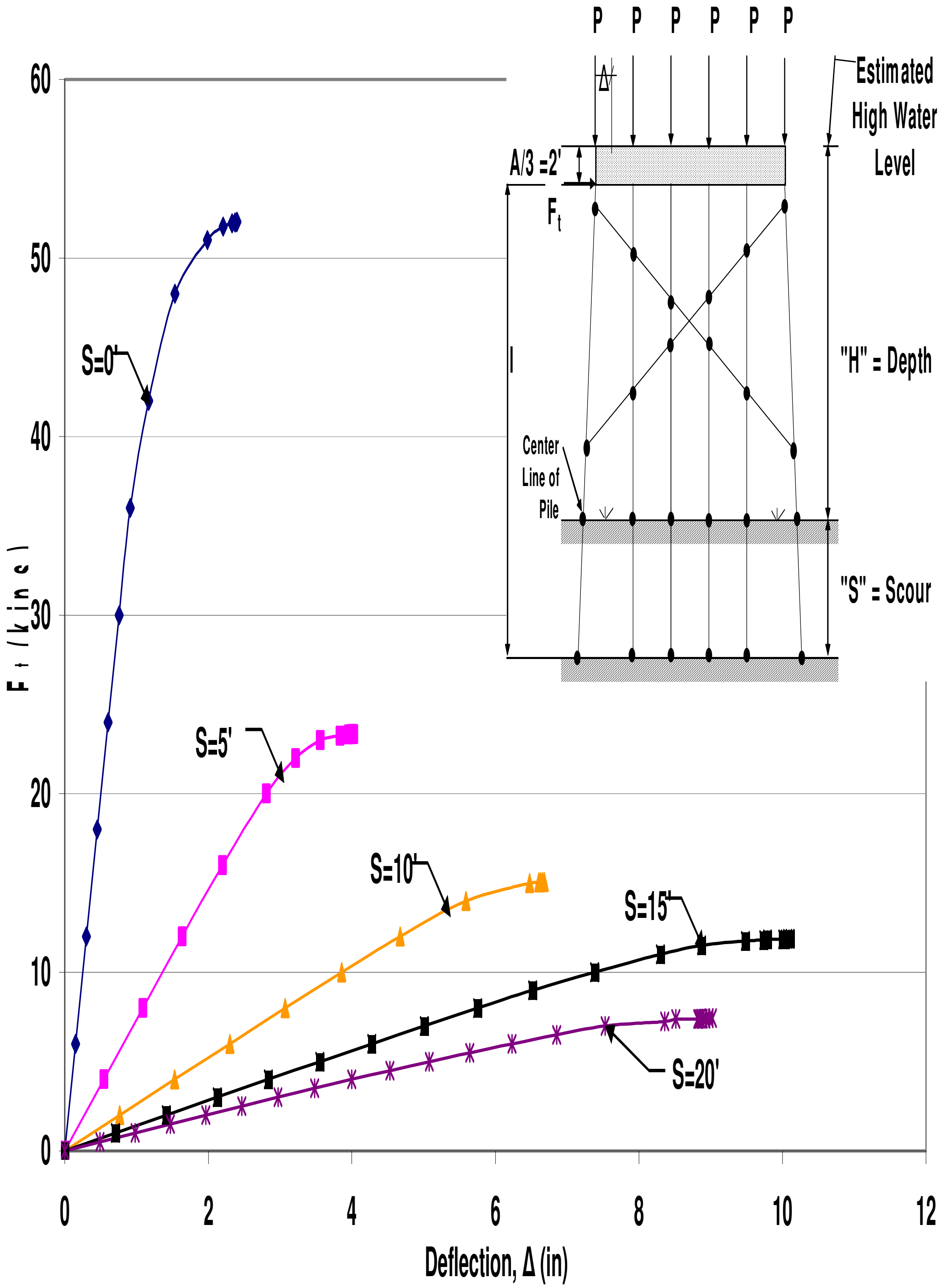


Figure A.87 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

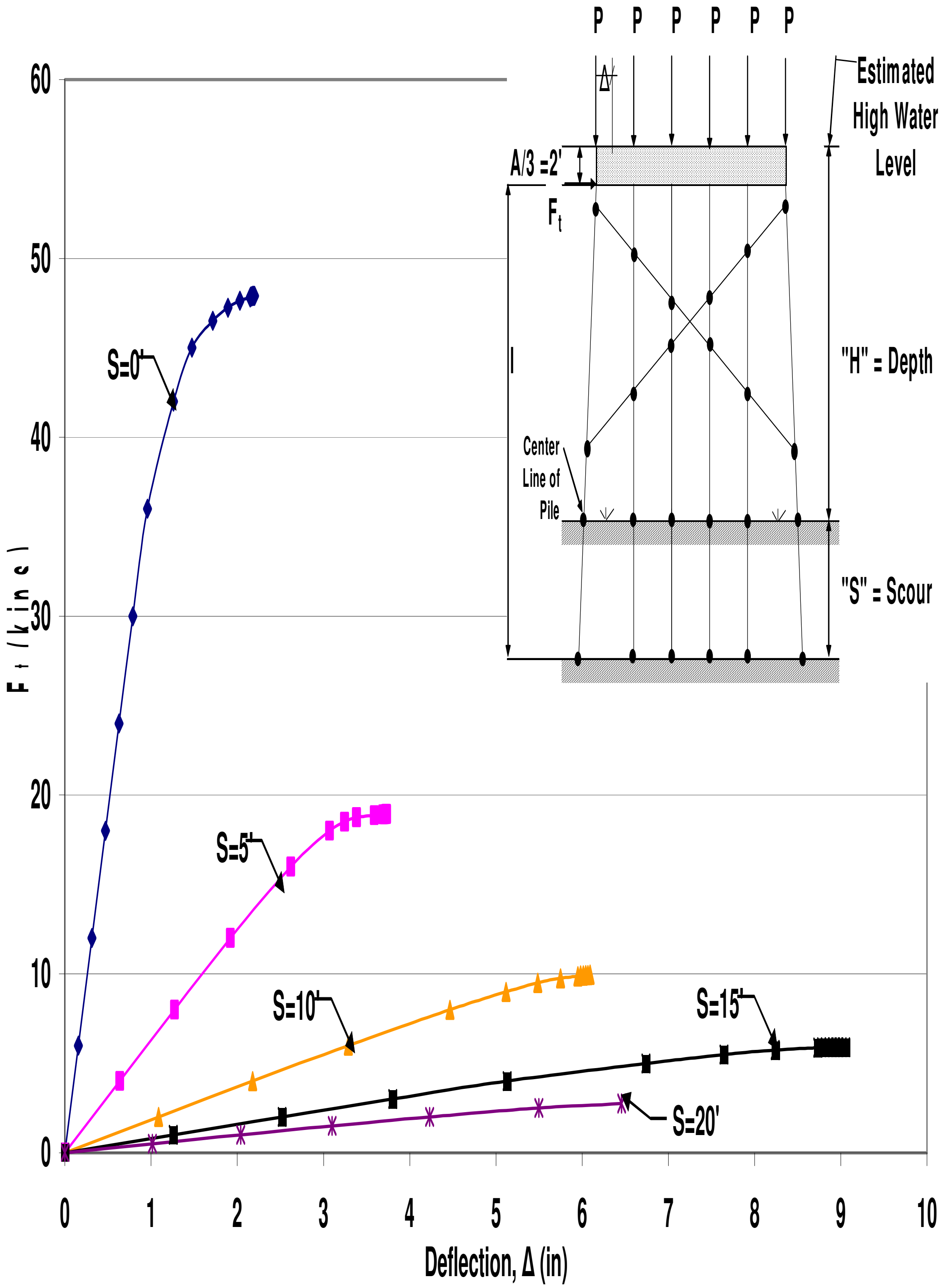


Figure A.88 HP10x42 Single X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

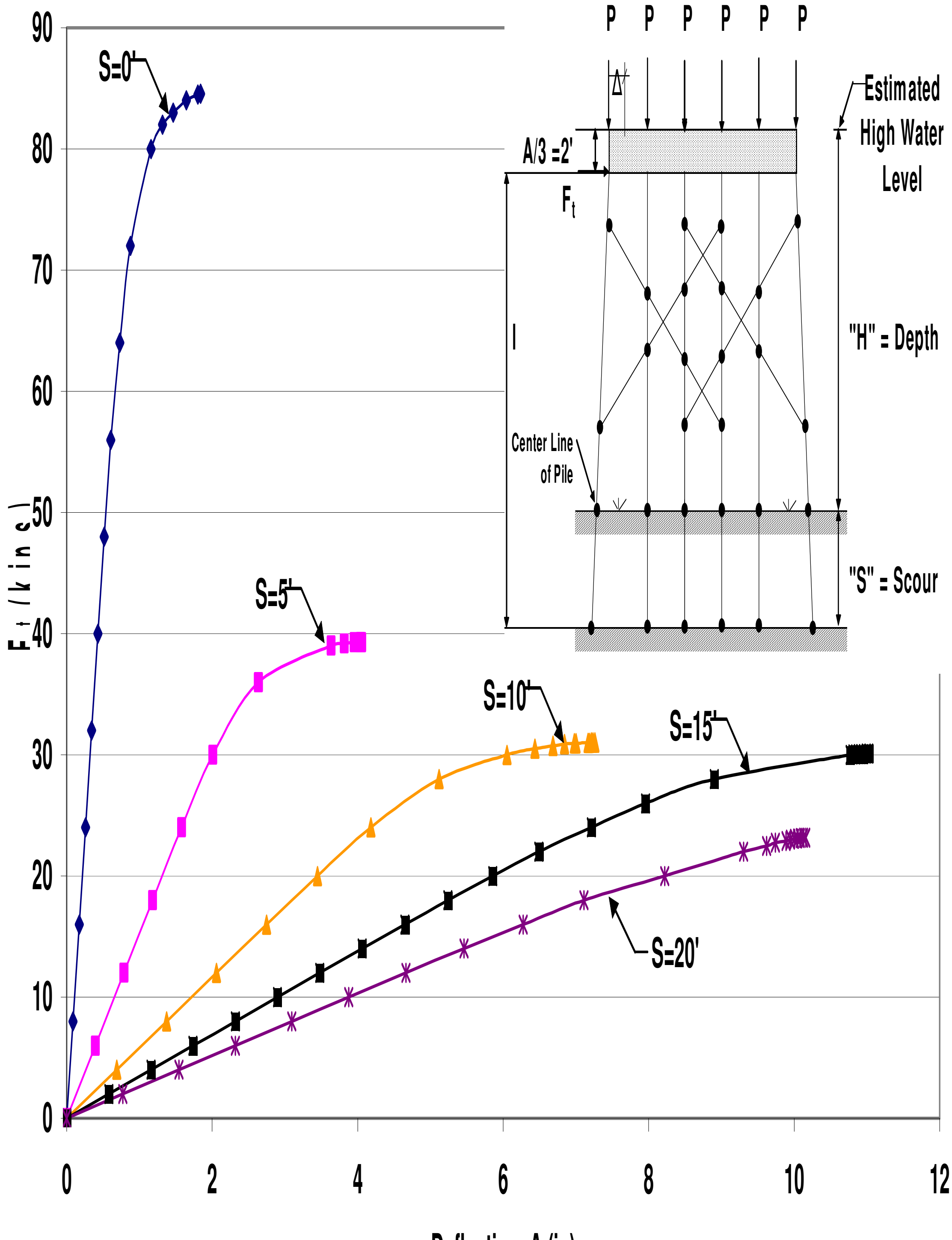


Figure A.89 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis

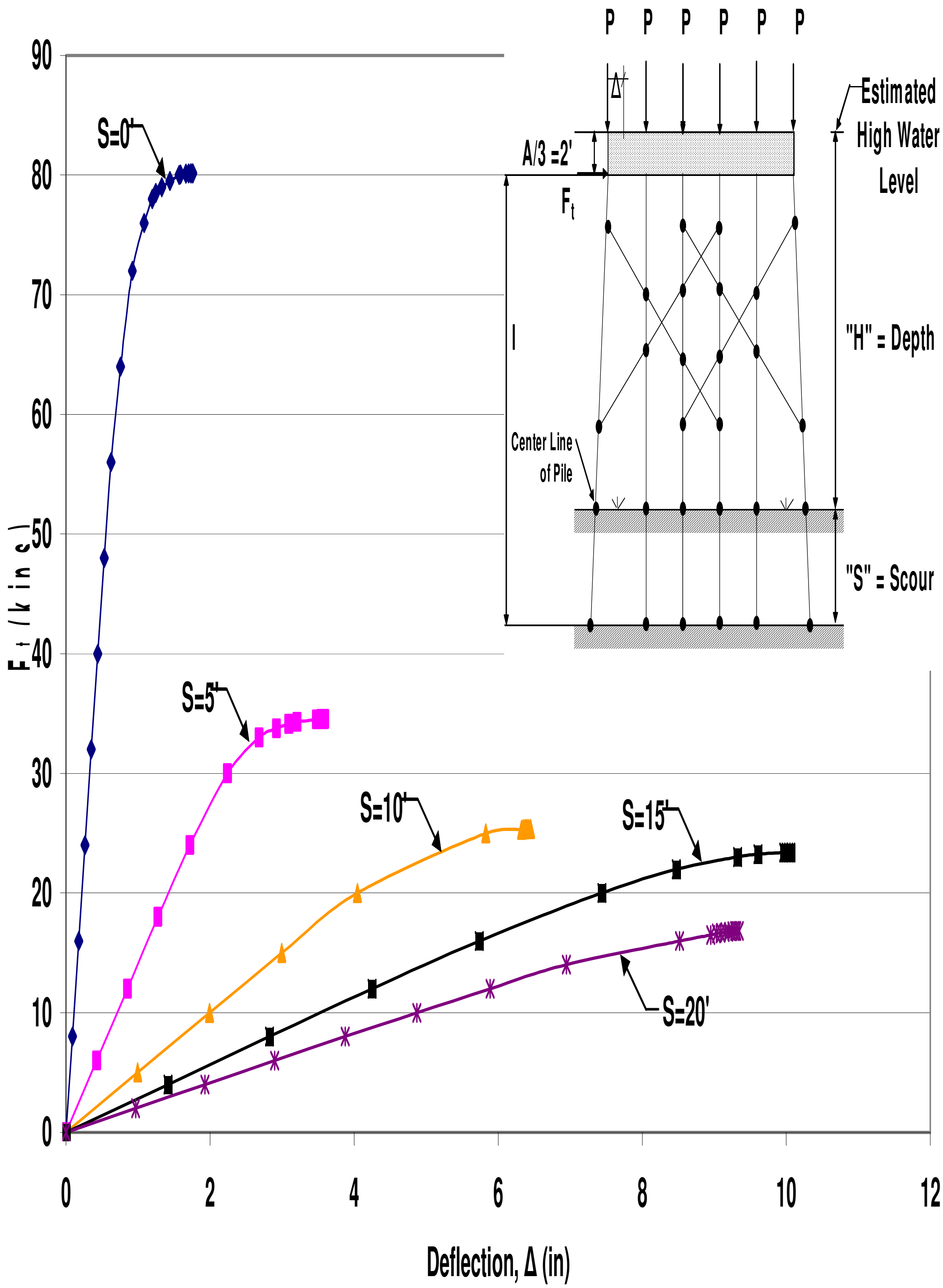
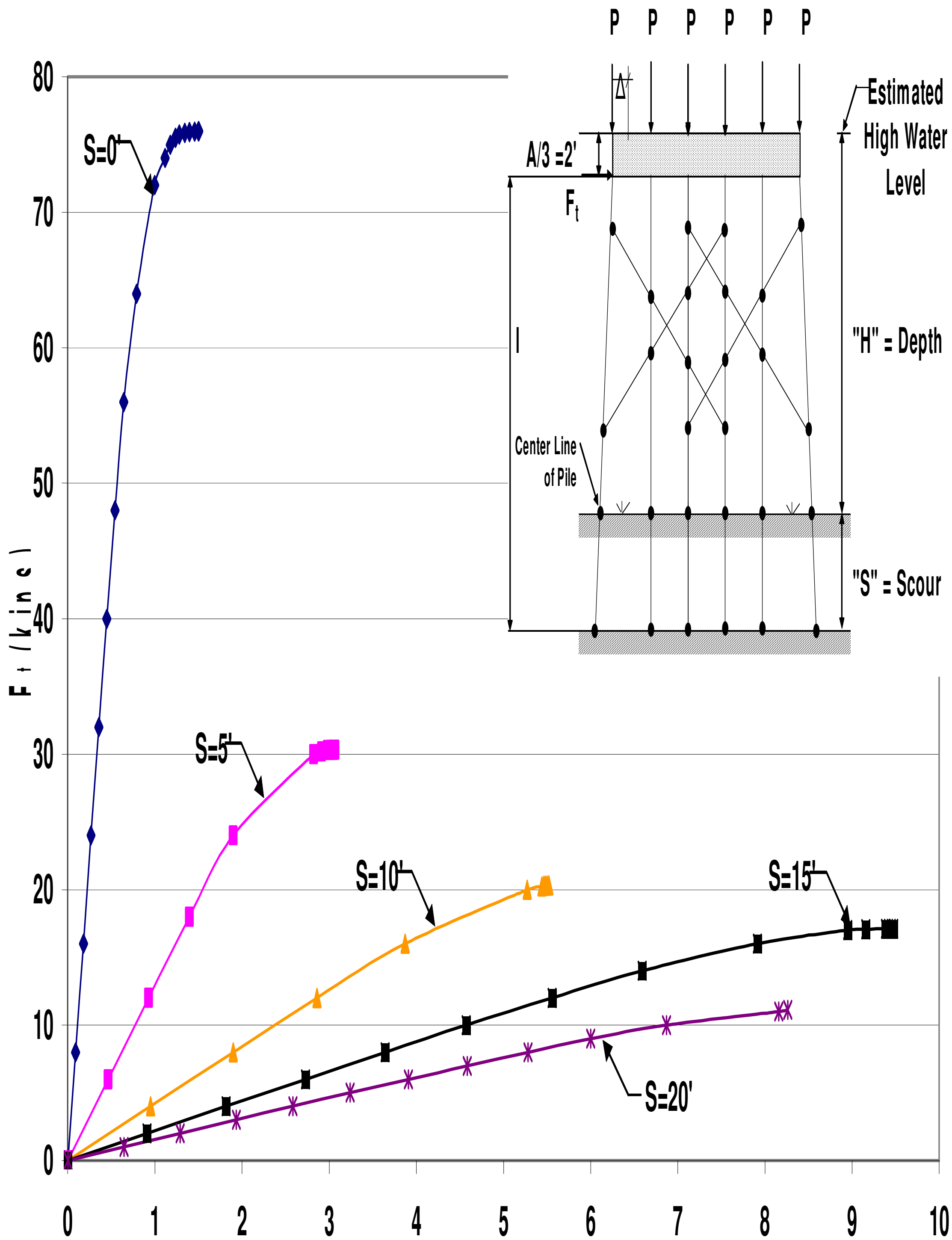


Figure A.90 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results



Deflection, Δ (in)

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

Pushover Analysis Results

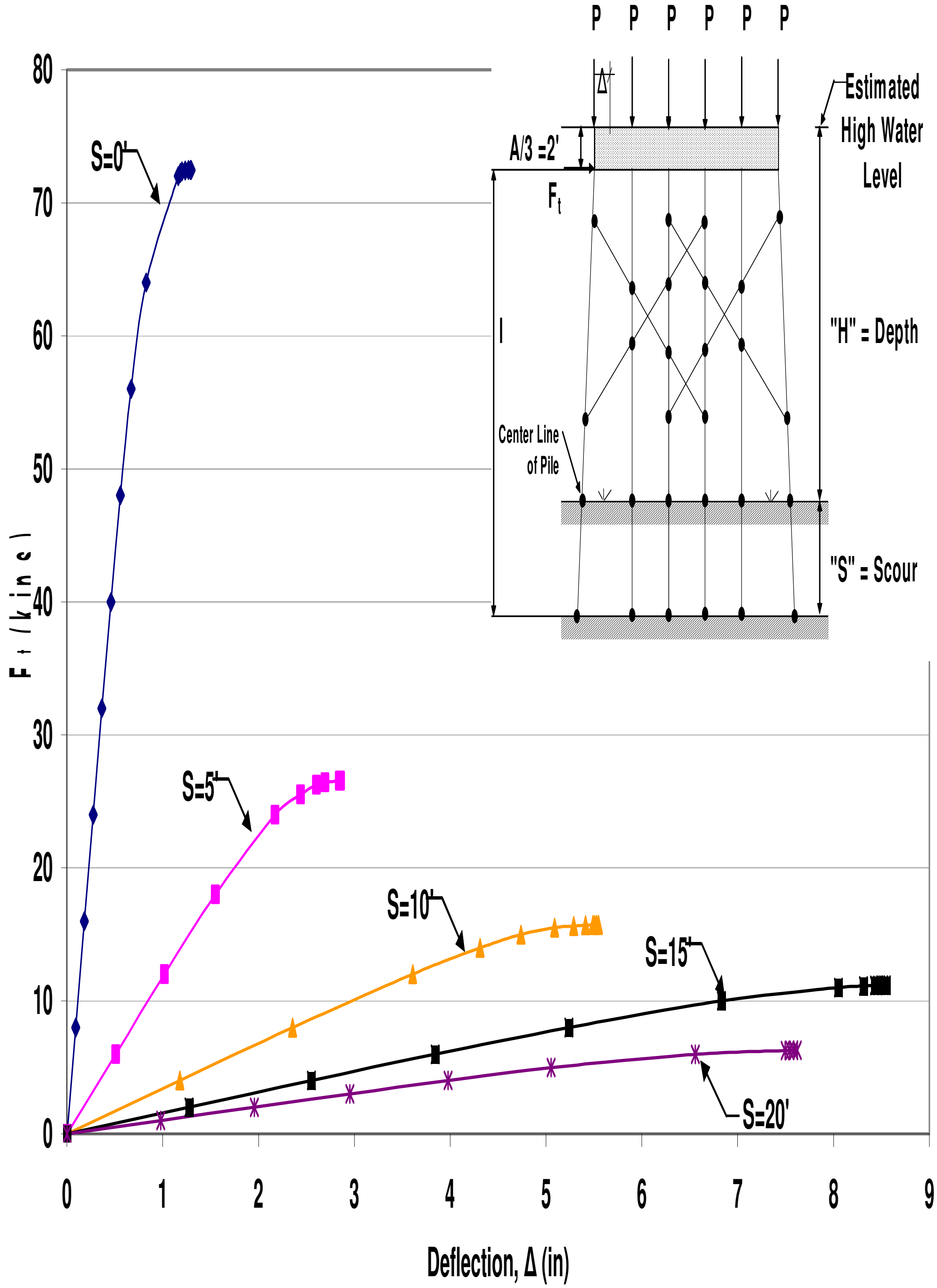


Figure A.92 HP10x42 Double X-Braced 6-Pile Bent with H=13', P=160kips and A=6'

Pushover Analysis Results

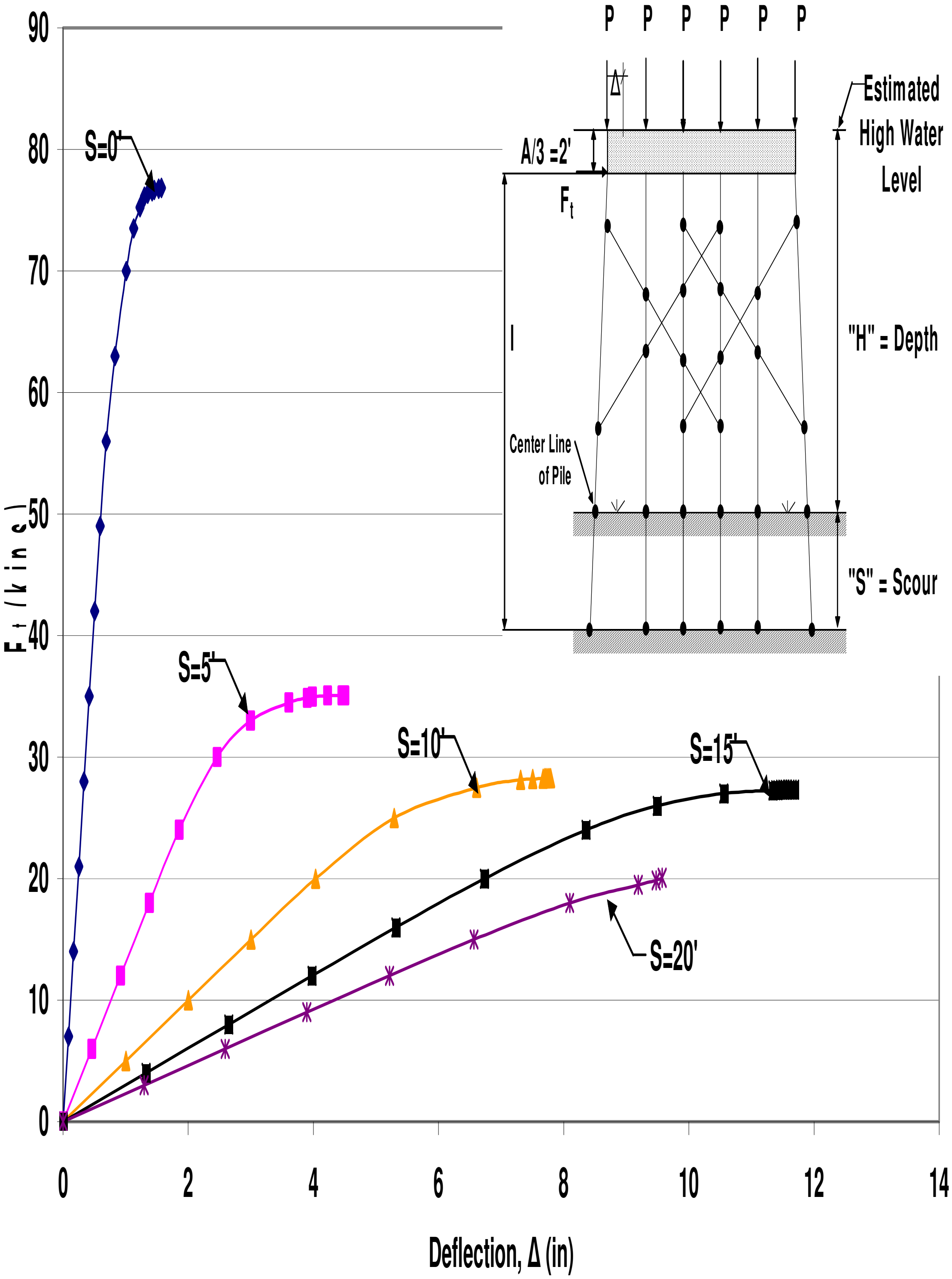


Figure A.93 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

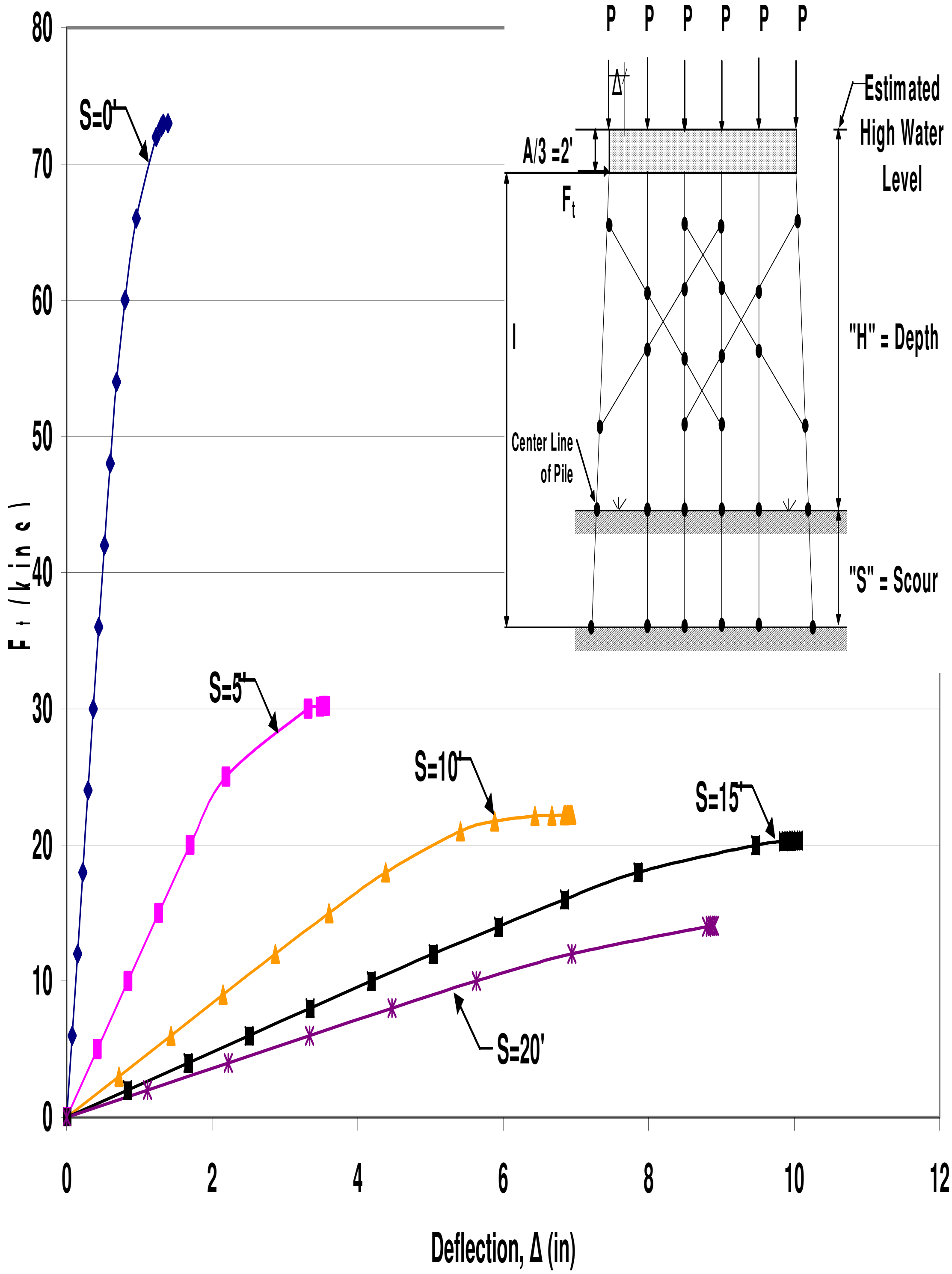


Figure A.94 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

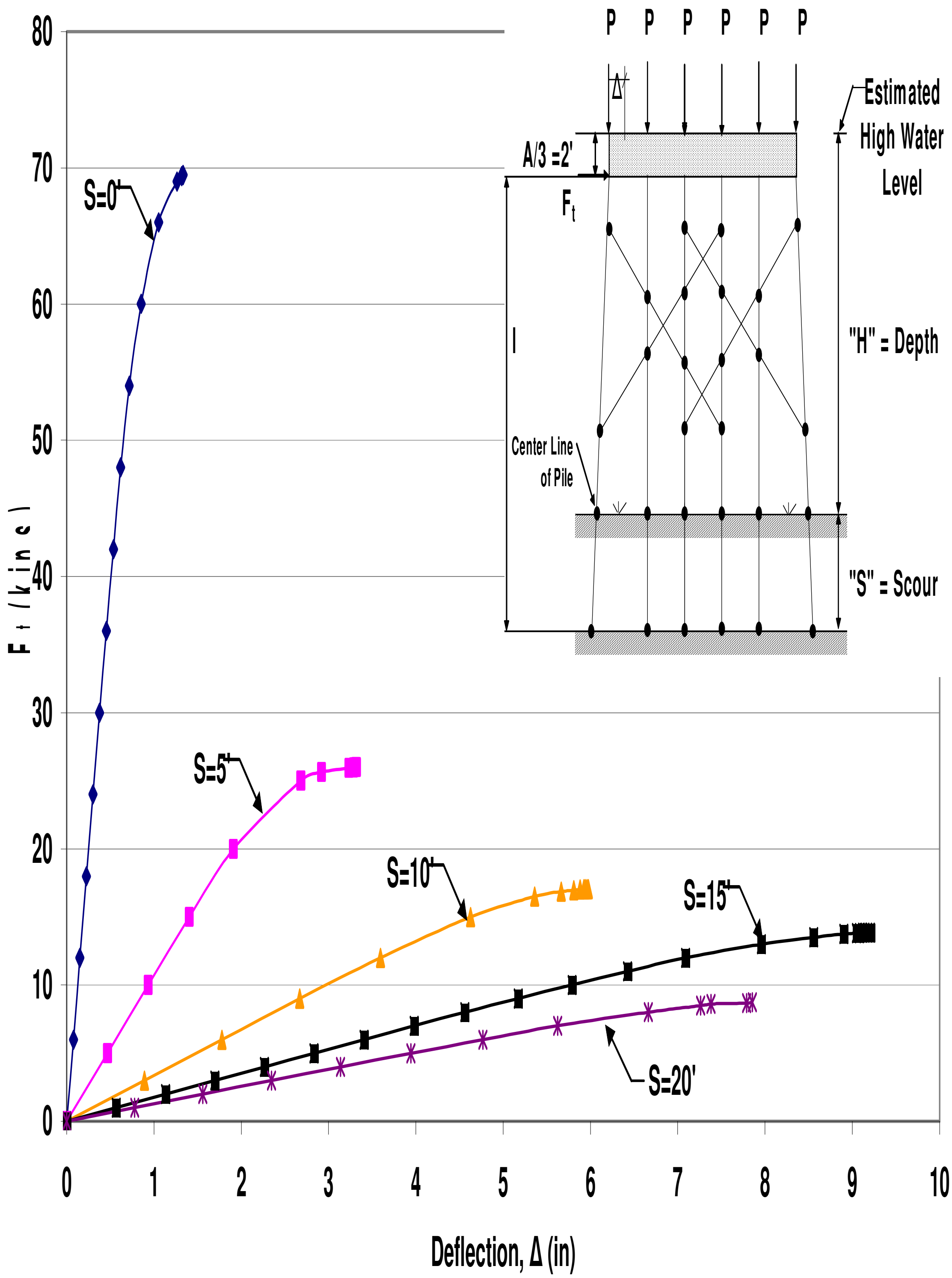


Figure A.95 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

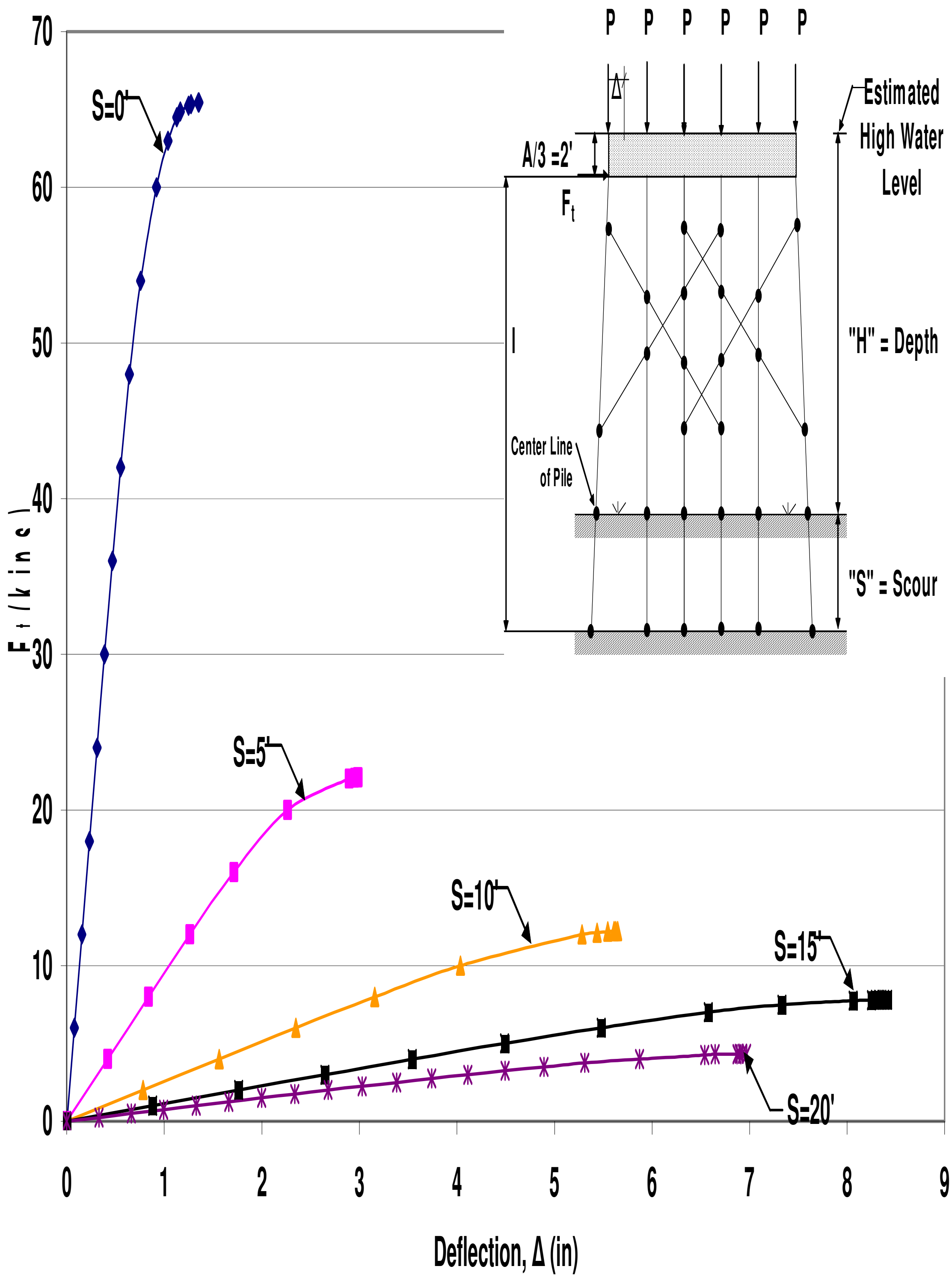


Figure A.96 HP10x42 Double X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

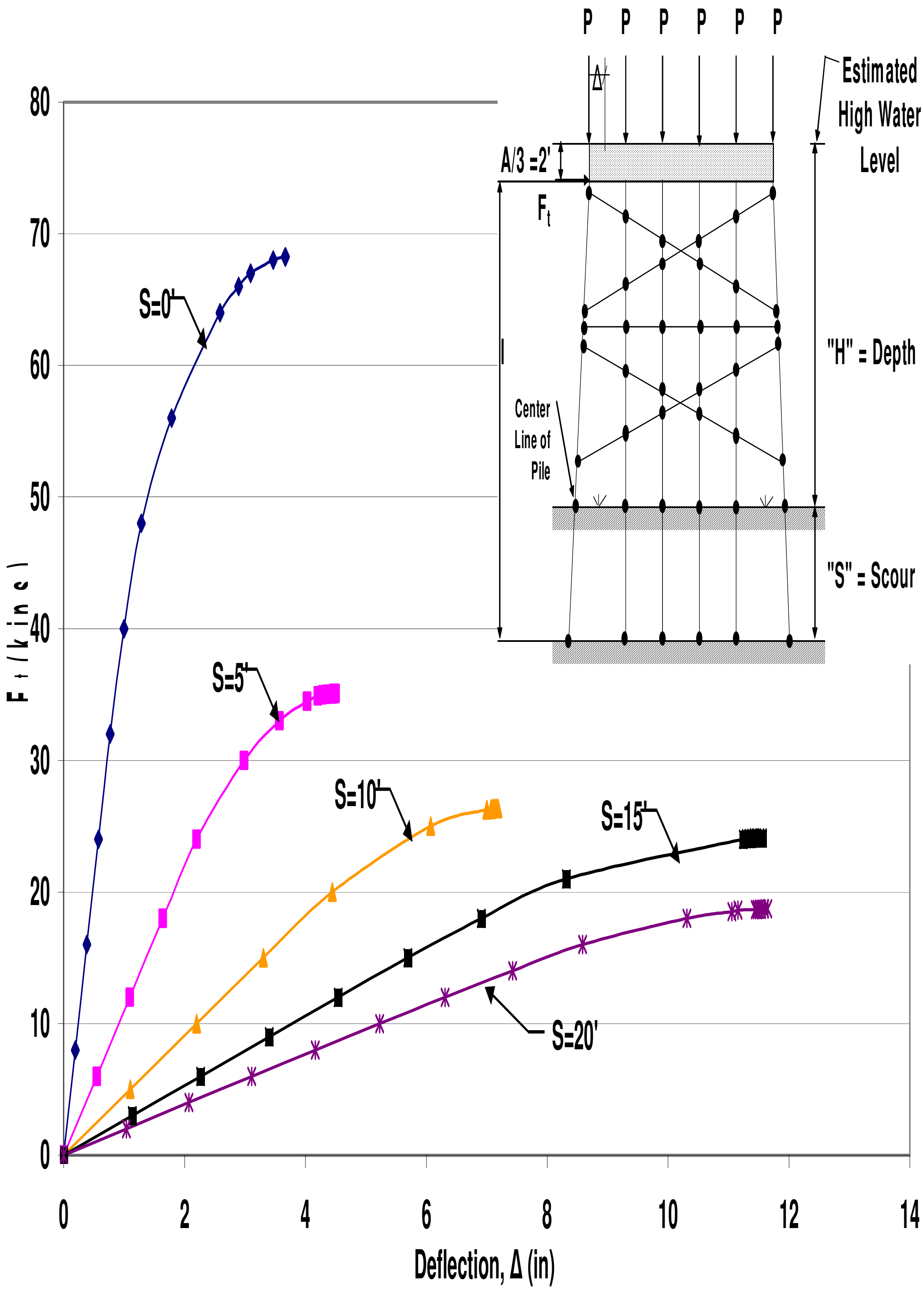


Figure A.97 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

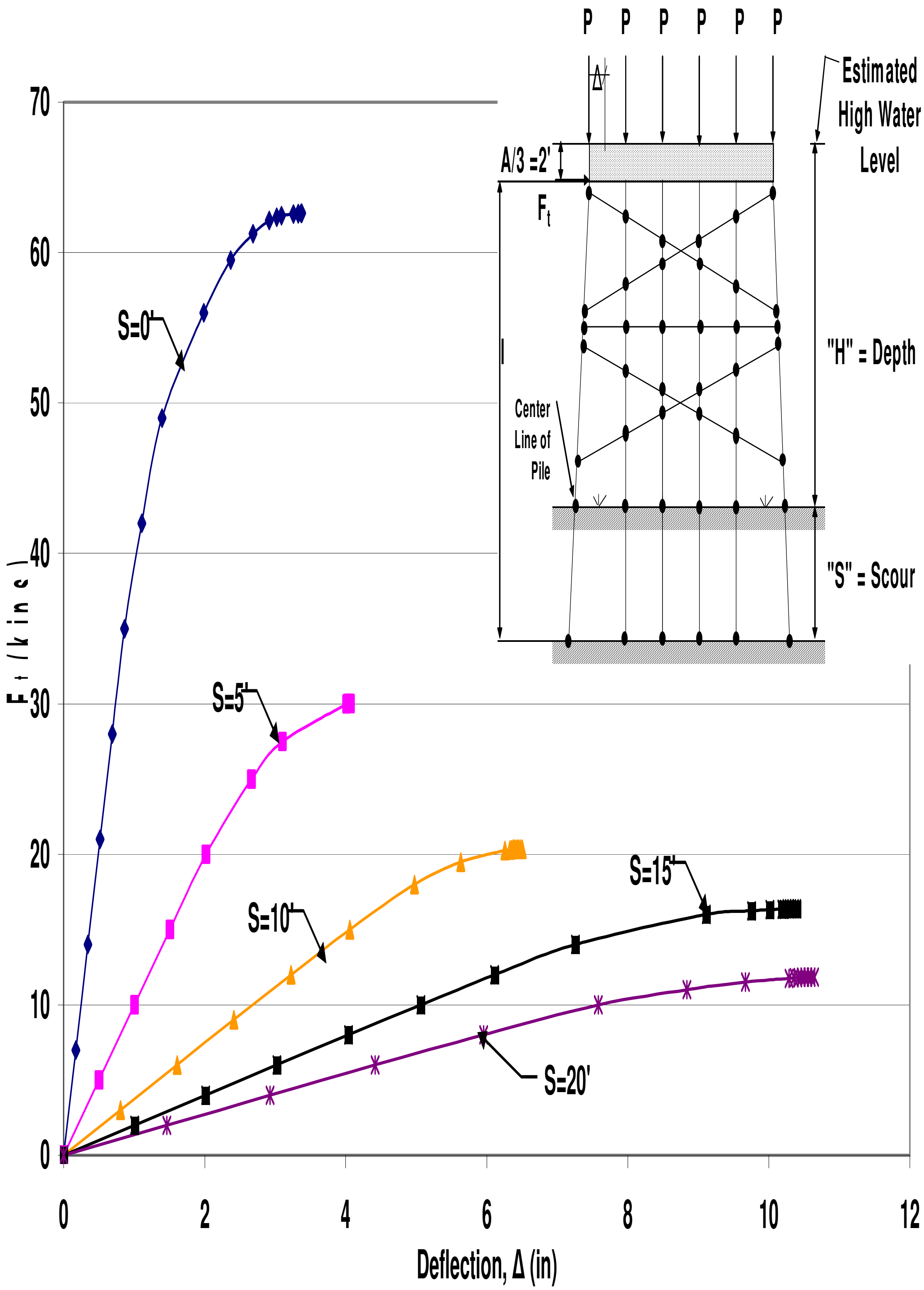


Figure A.98 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

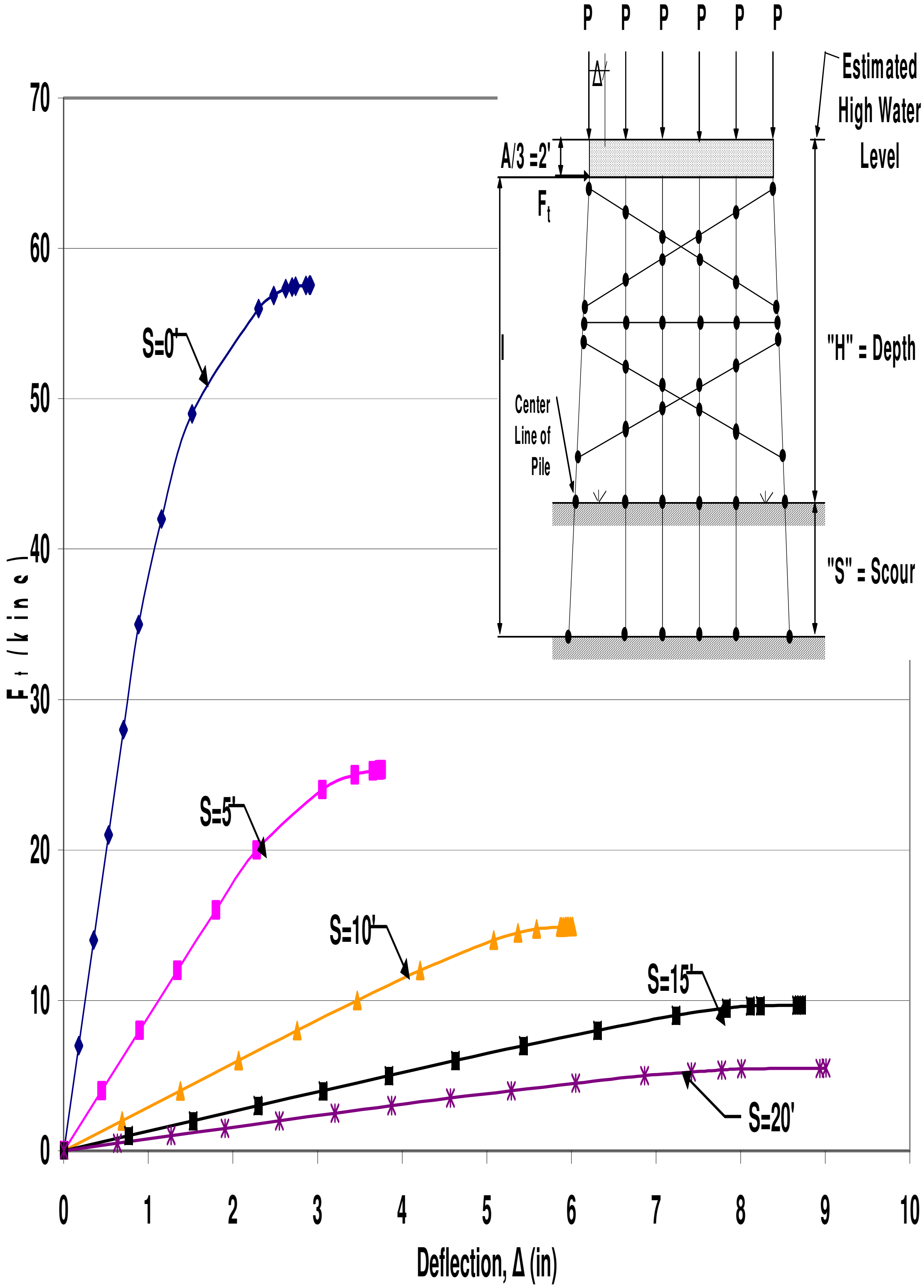


Figure A.99 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

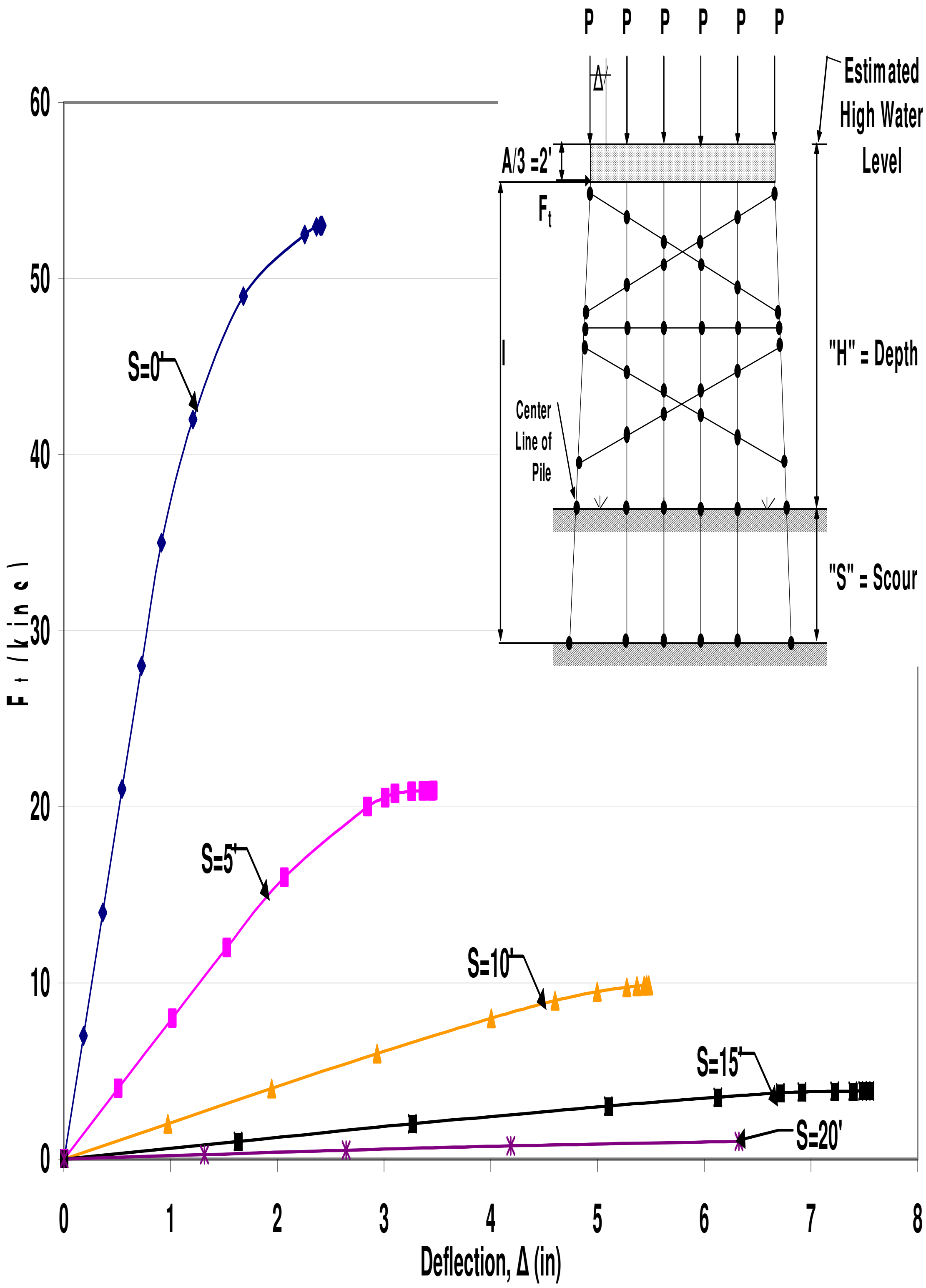


Figure A.100 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

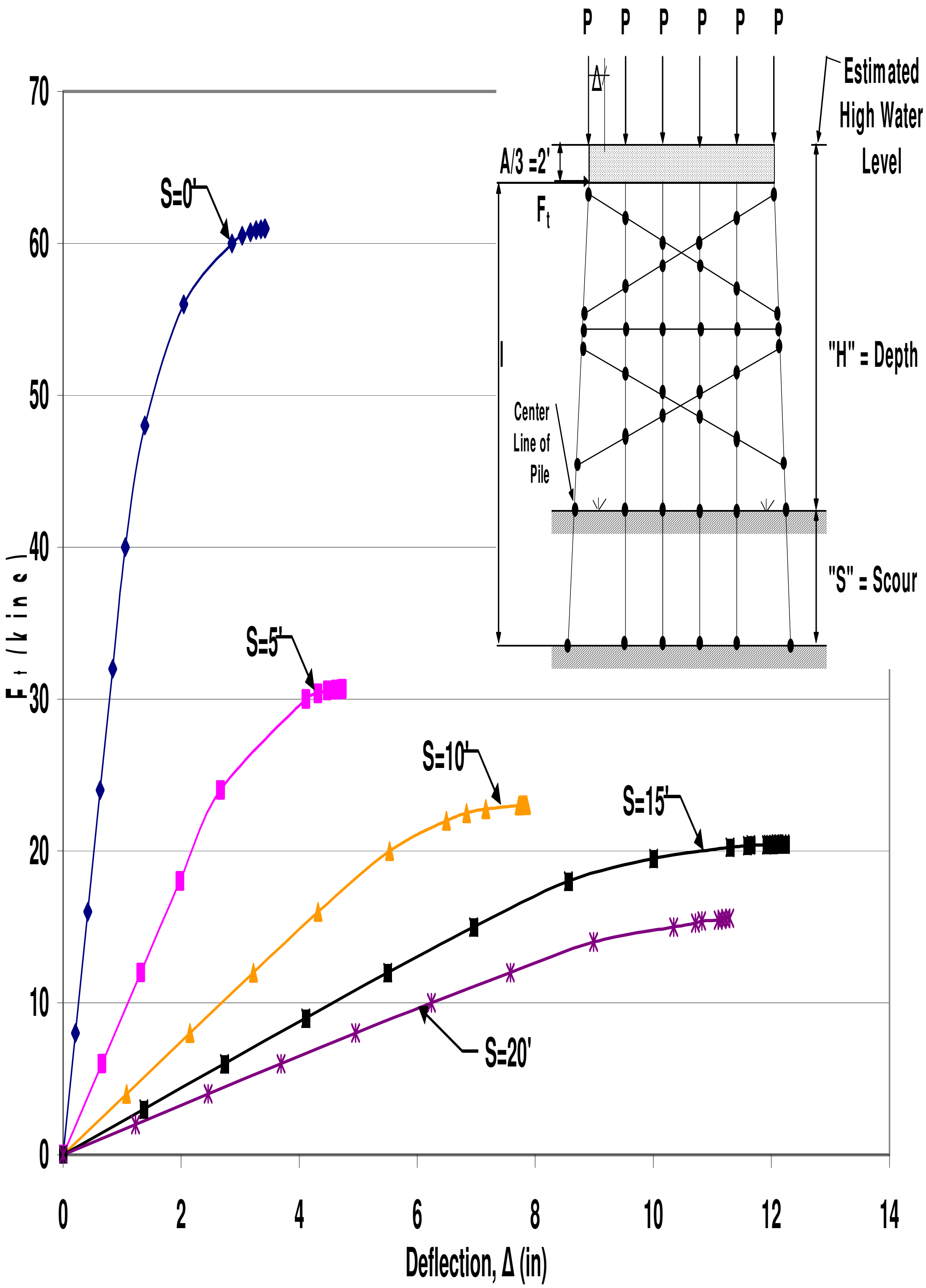


Figure A.101 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

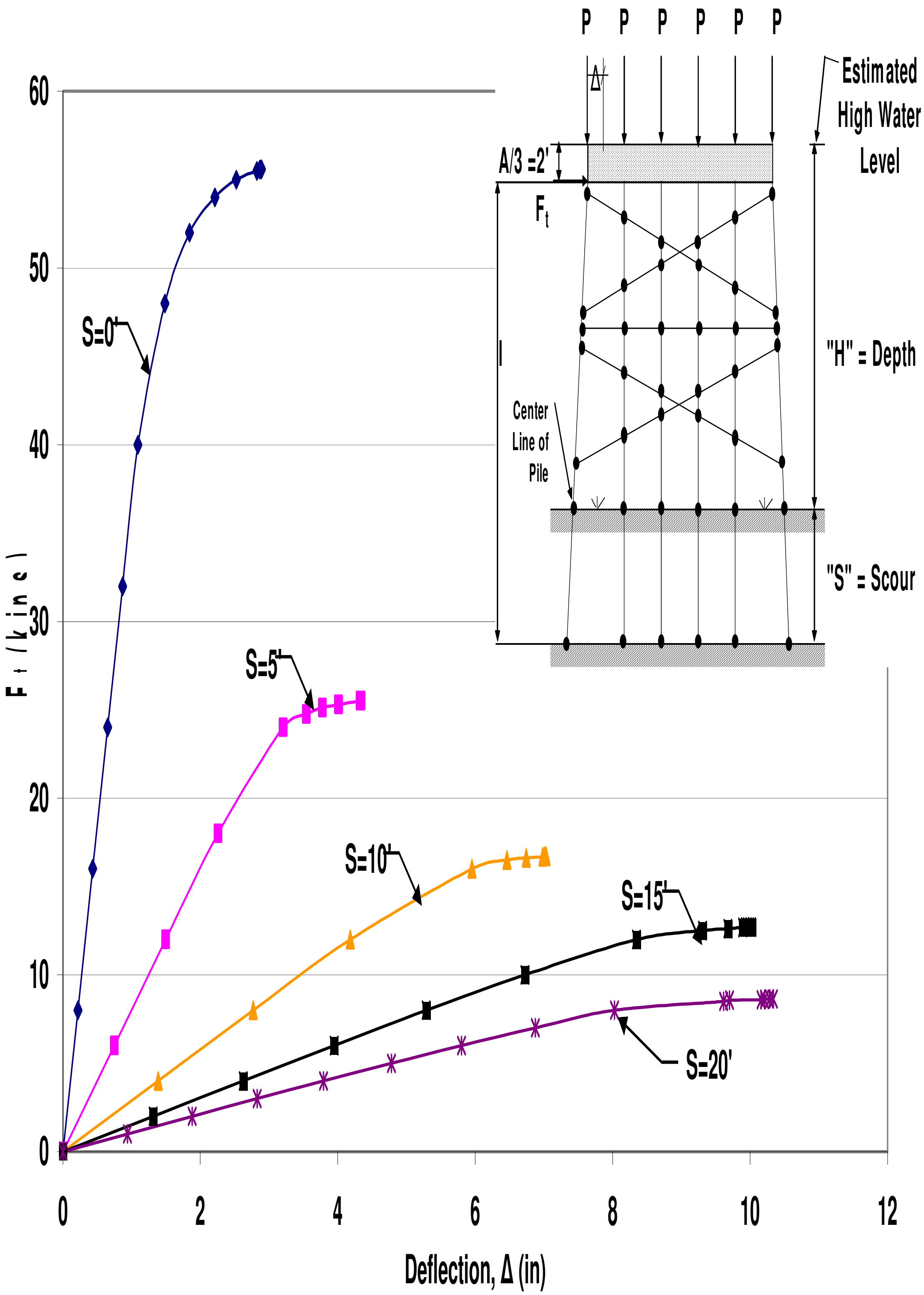


Figure A.102 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

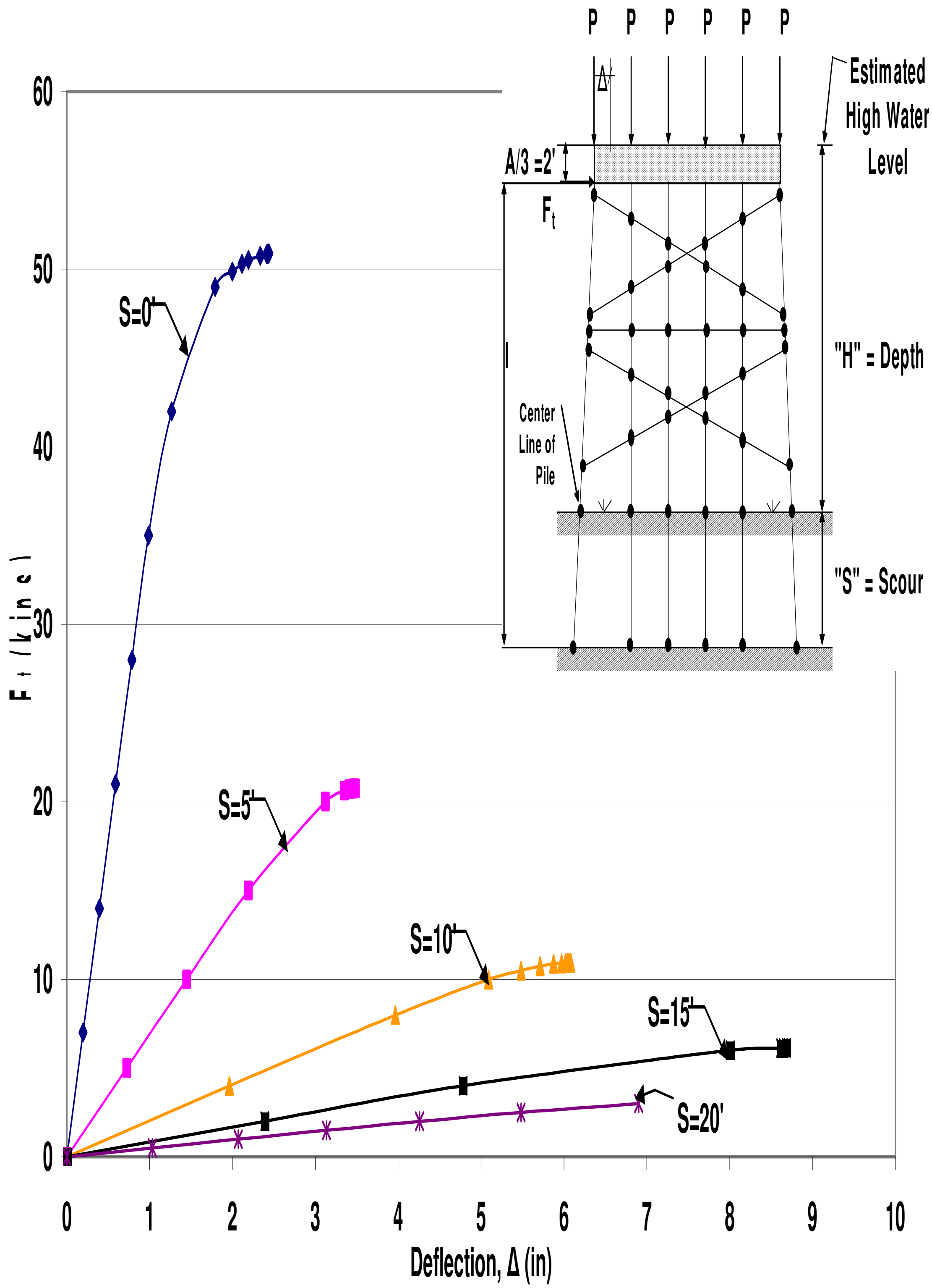


Figure A.103 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

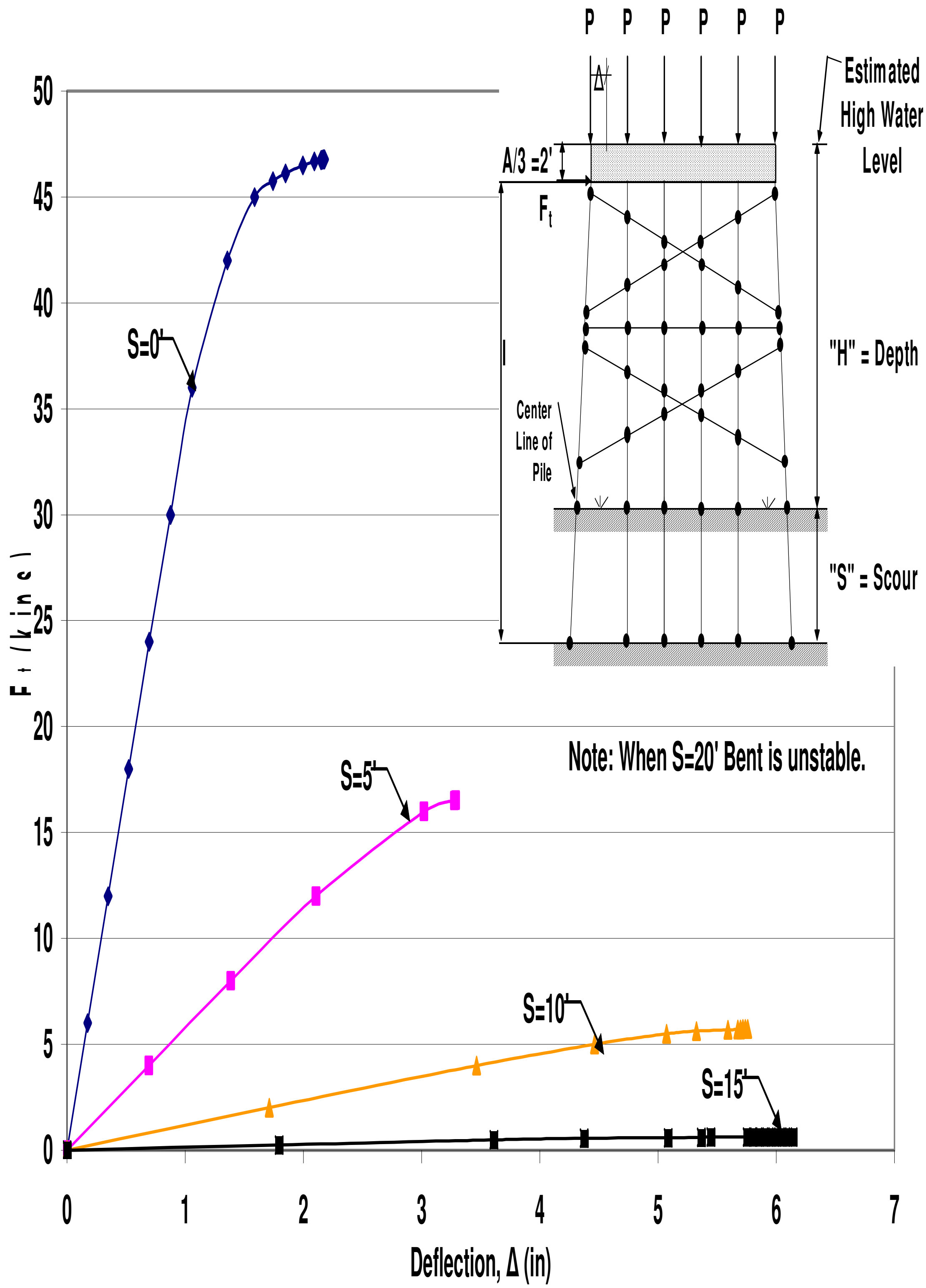


Figure A.104 HP10x42 Two-Story Single X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

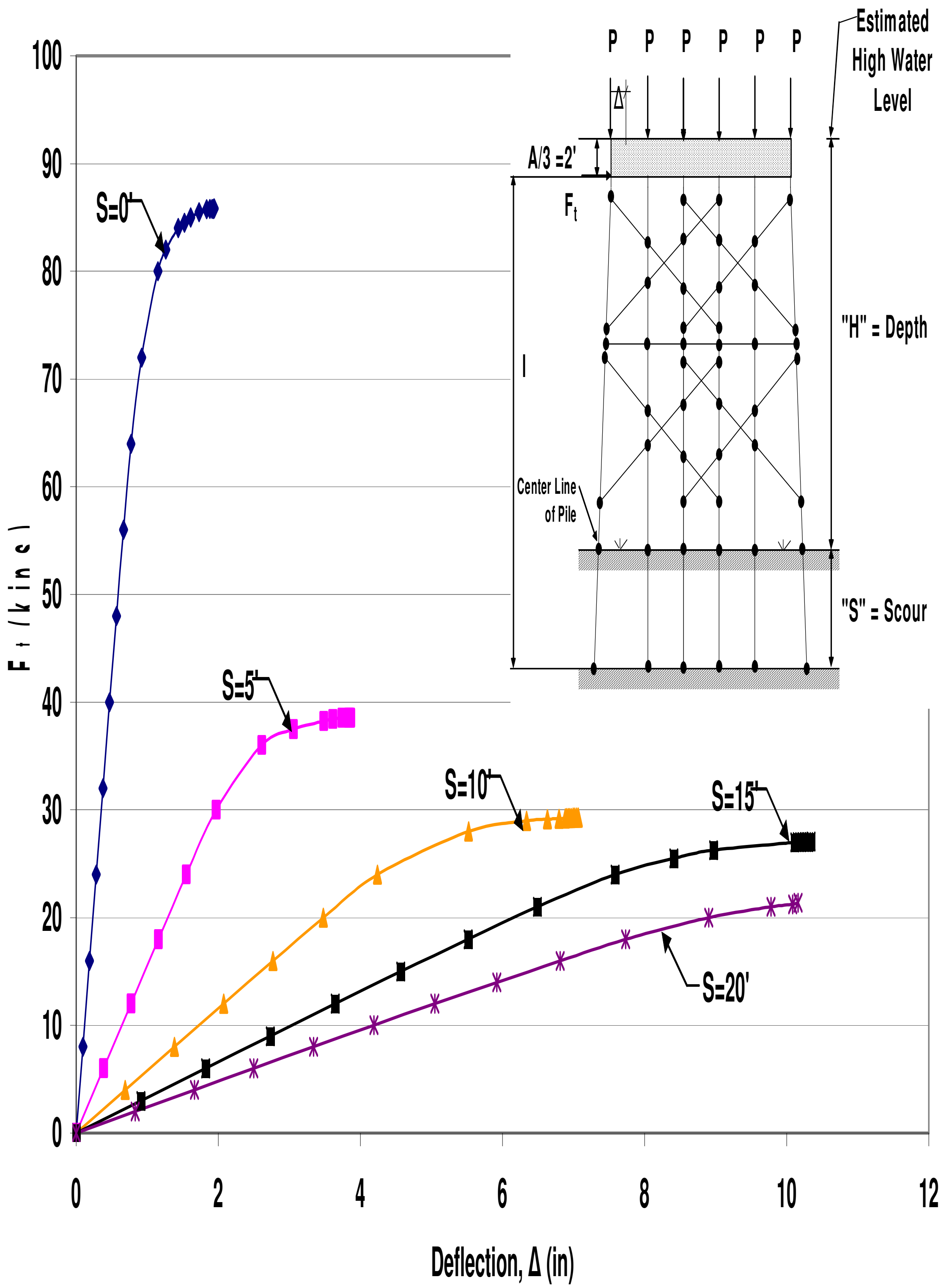


Figure A.105 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

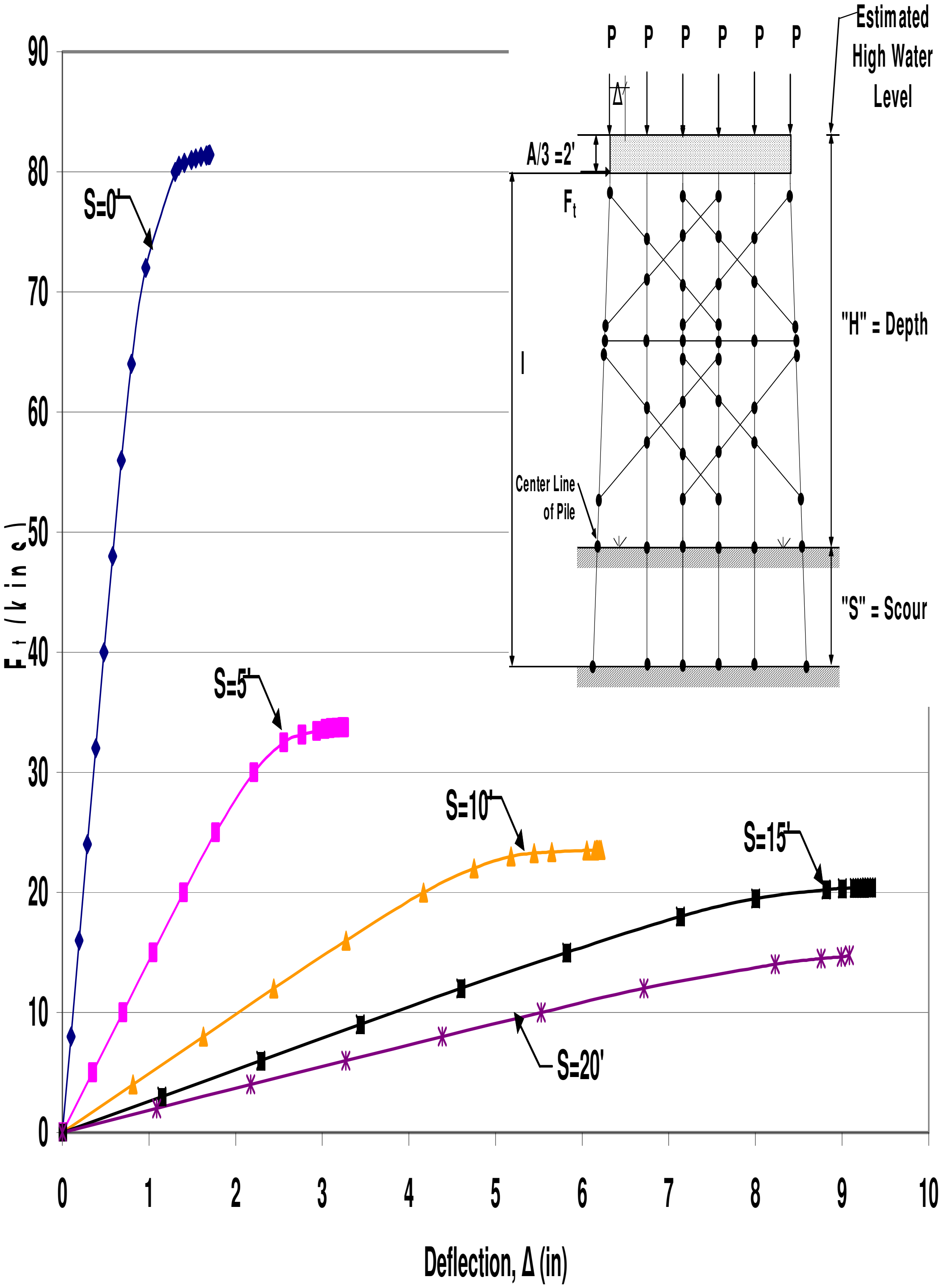


Figure A.106 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

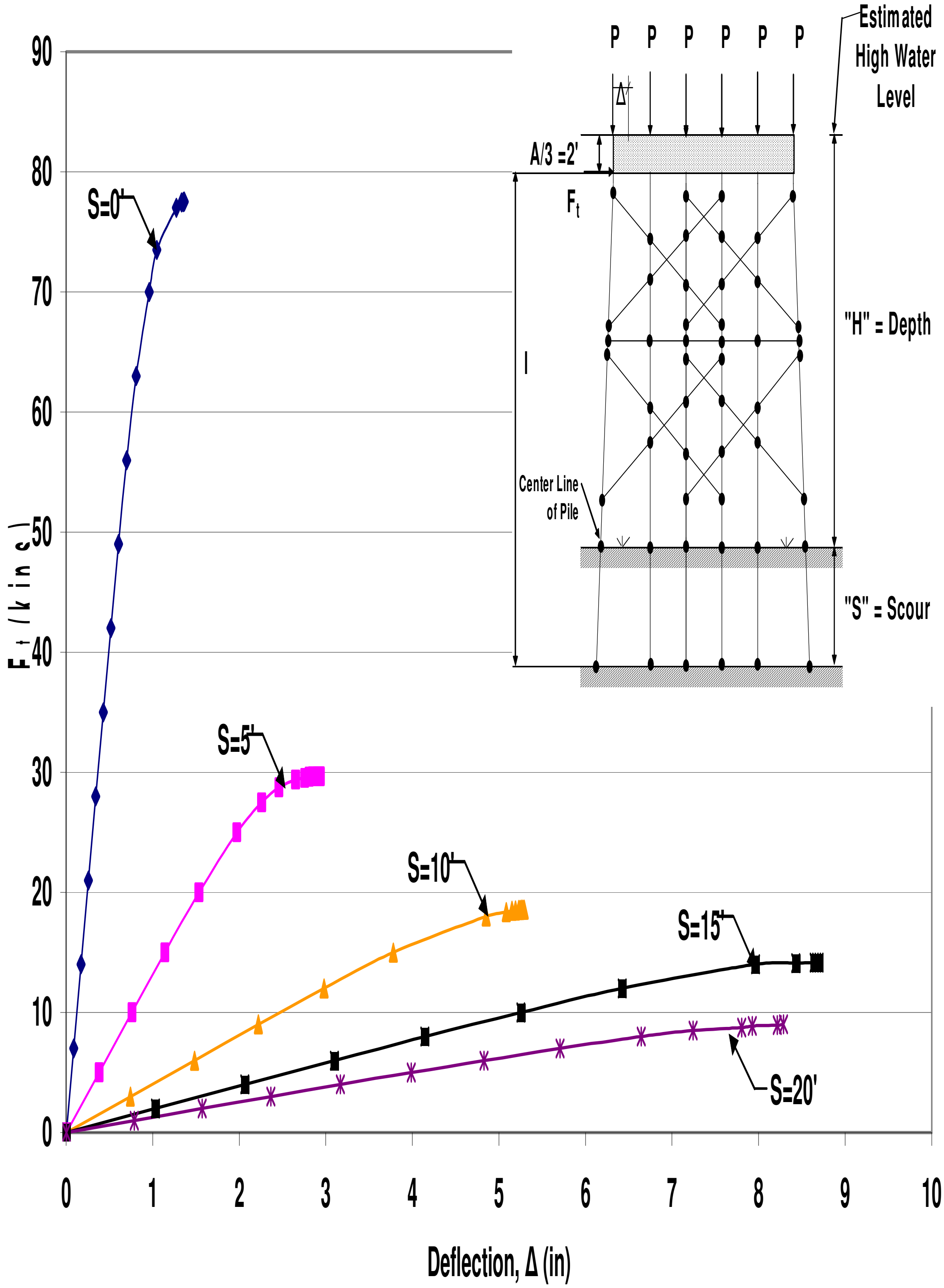


Figure A.107 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

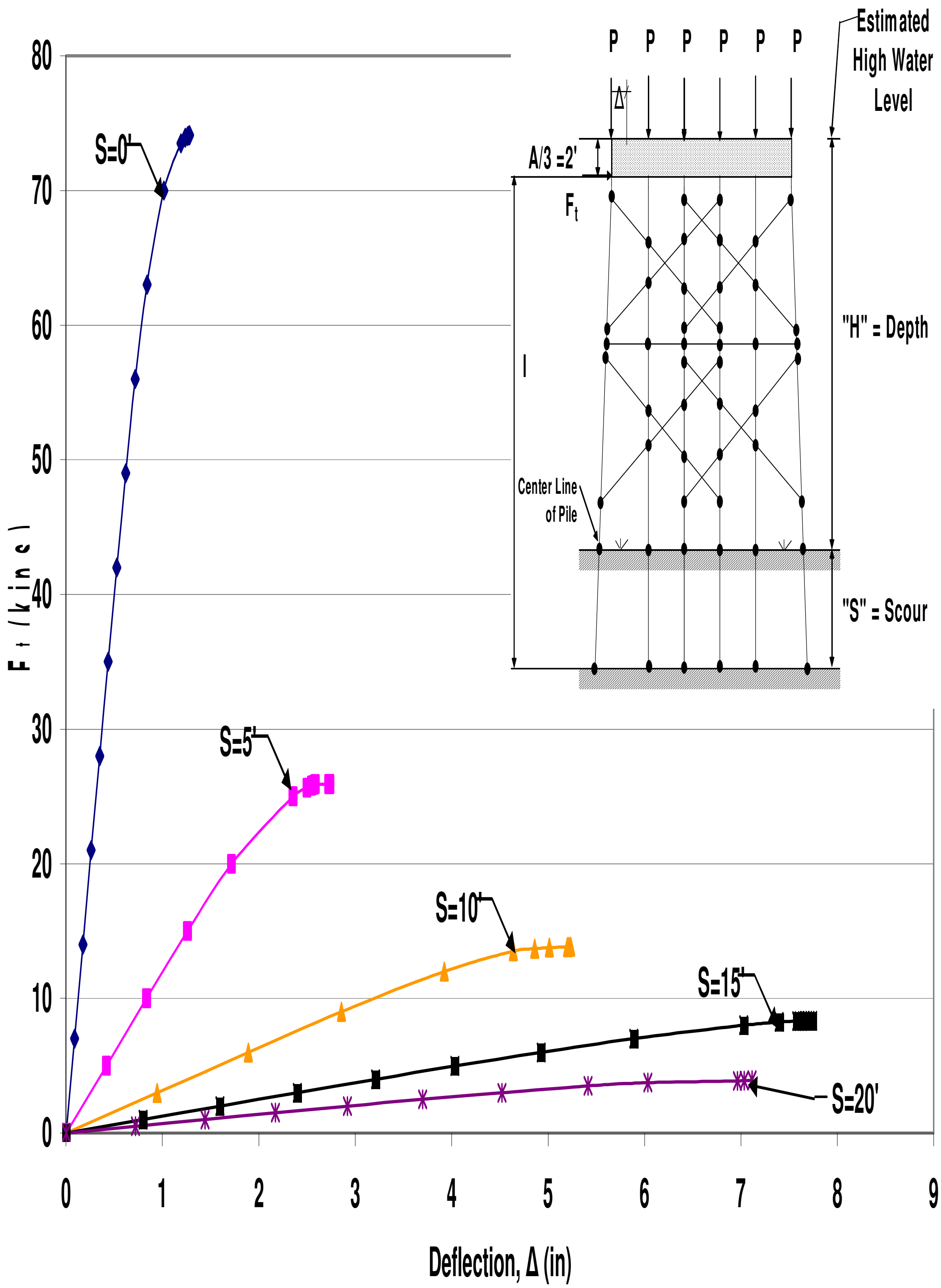


Figure A.108 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

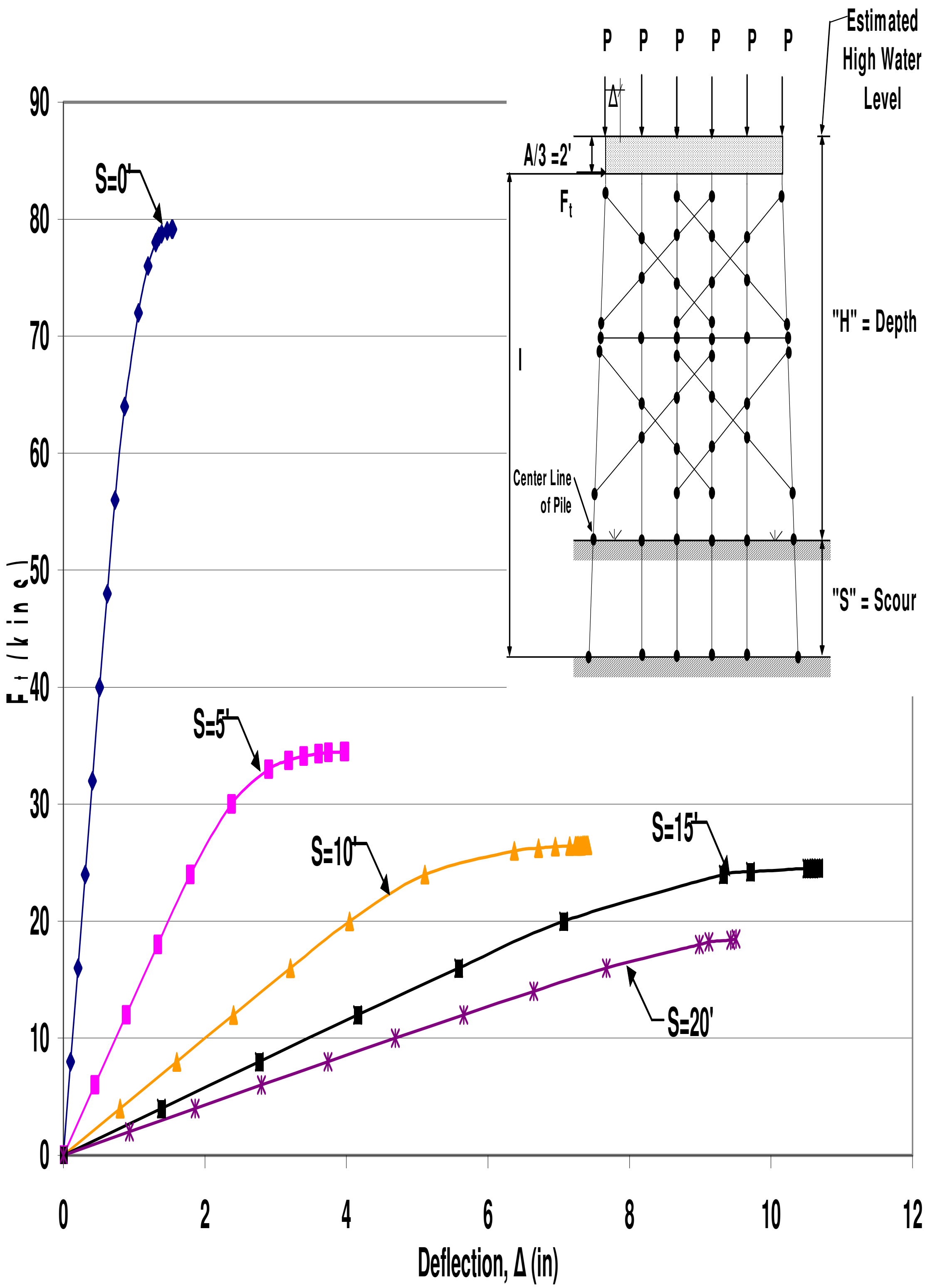


Figure A.109 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

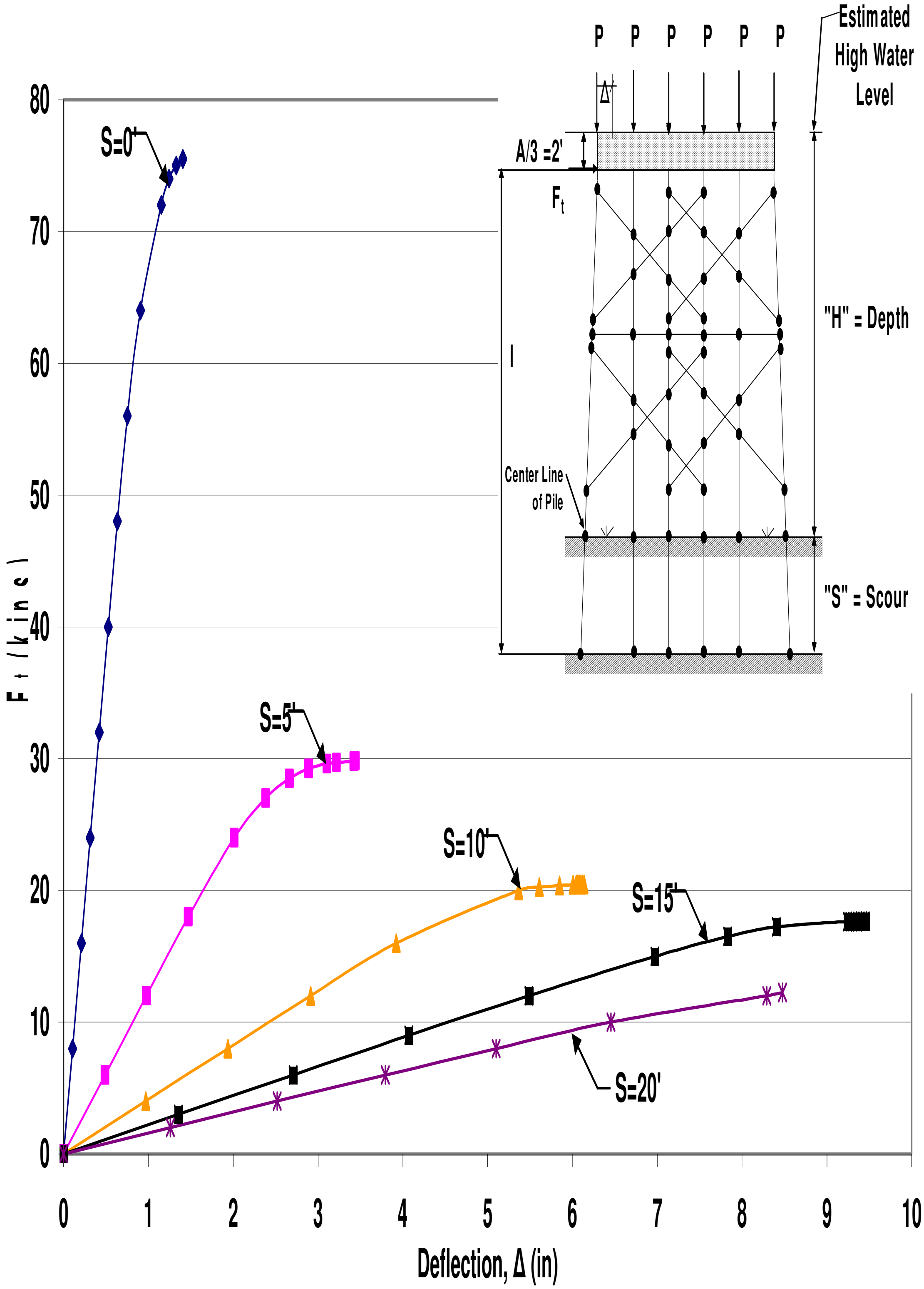


Figure A.110 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

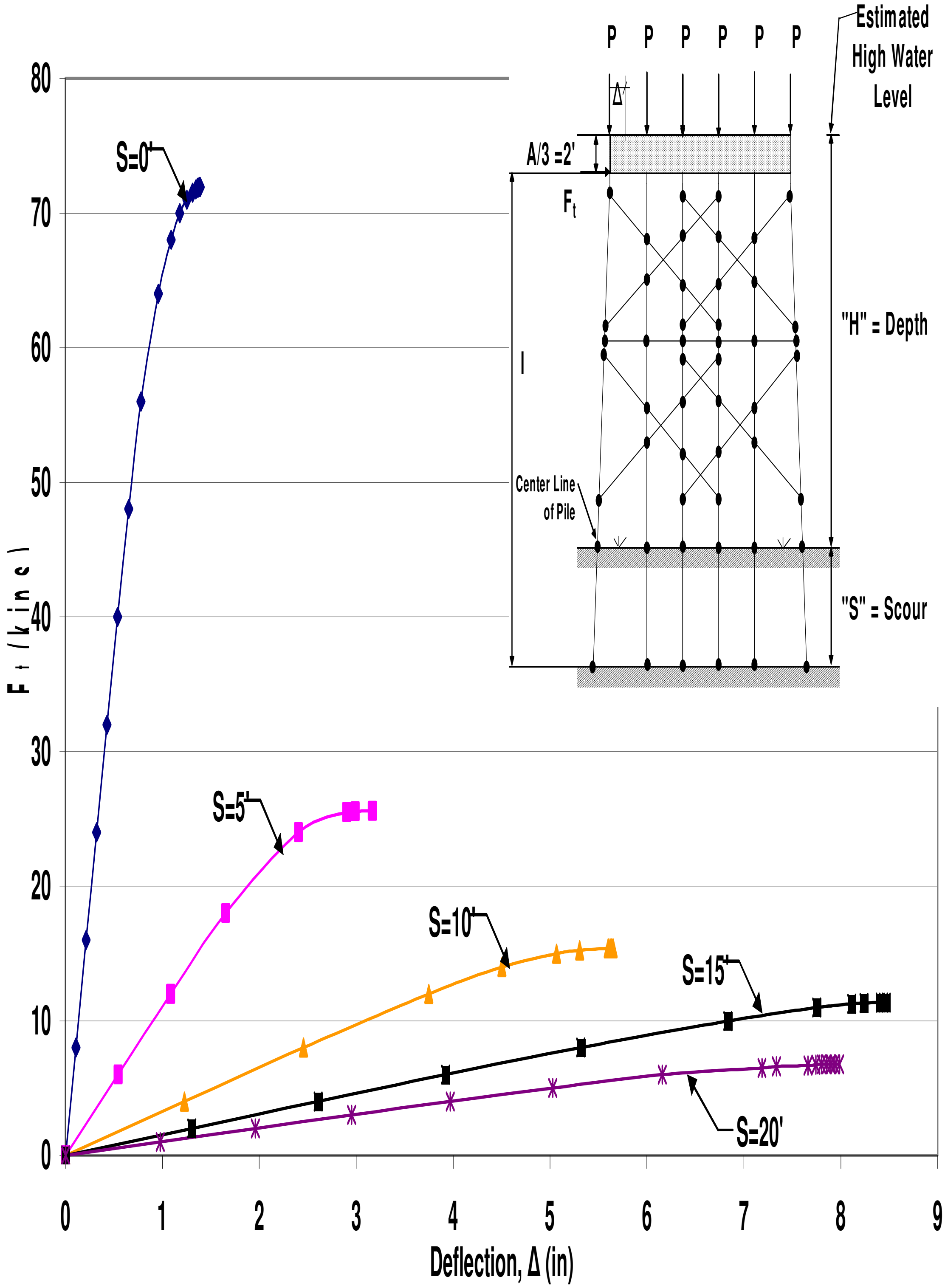


Figure A.111 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

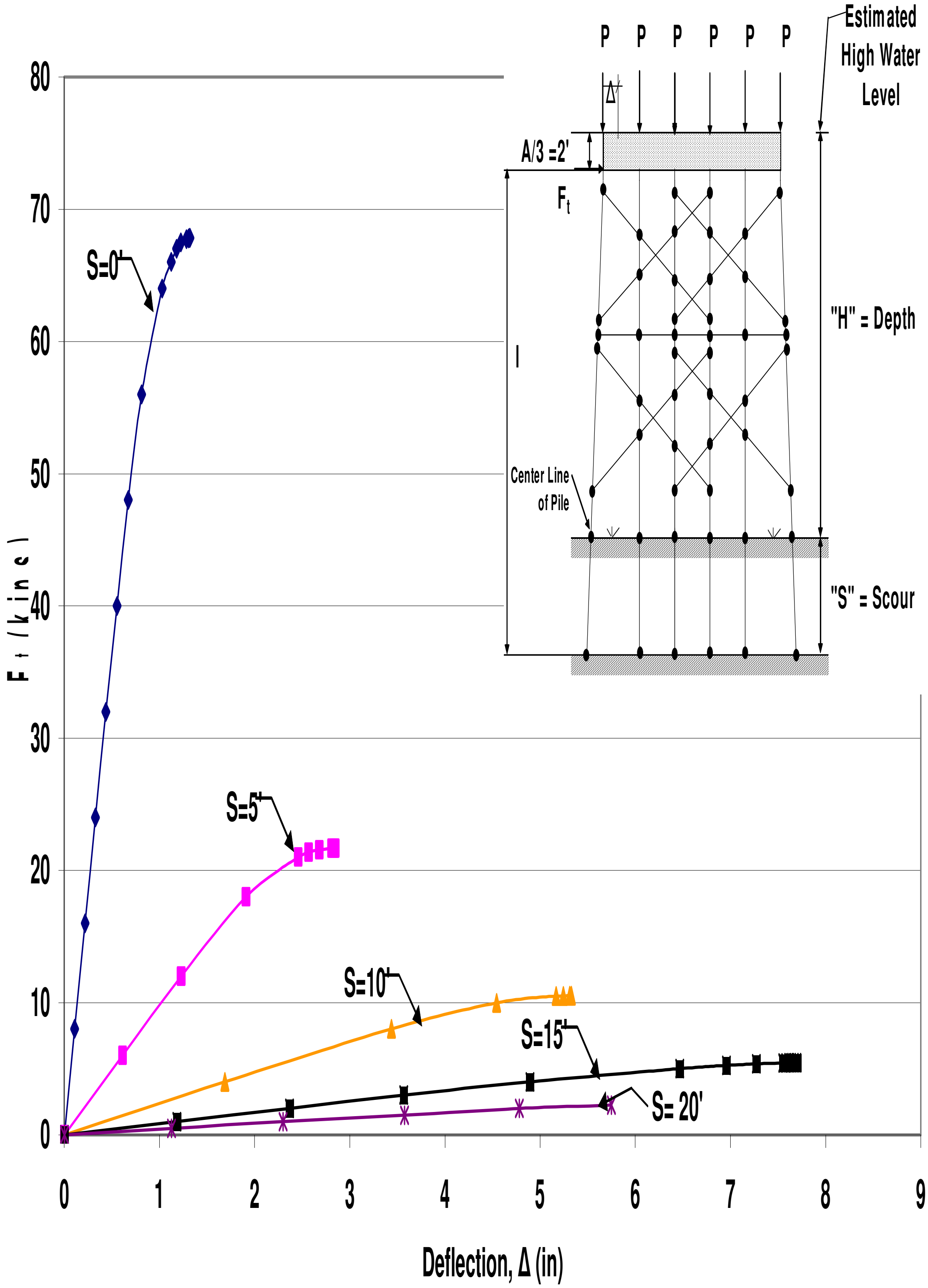


Figure A.112 HP10x42 Two-Story Double X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

APPENDIX B

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

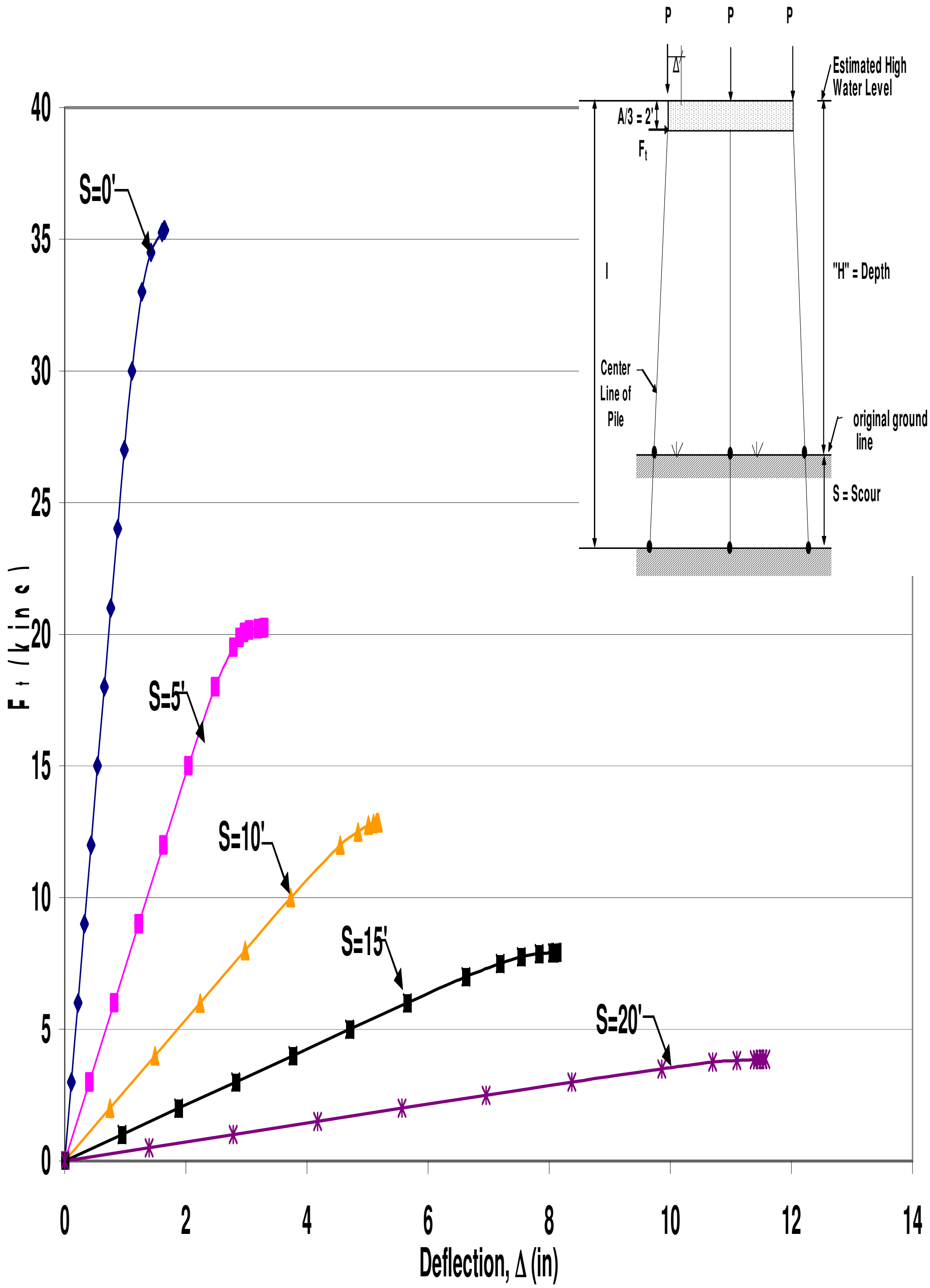


Figure B.1 HP12x53 Unbraced 3-PileBent with H=10', P=100kips and A=6'

Pushover Analysis Results

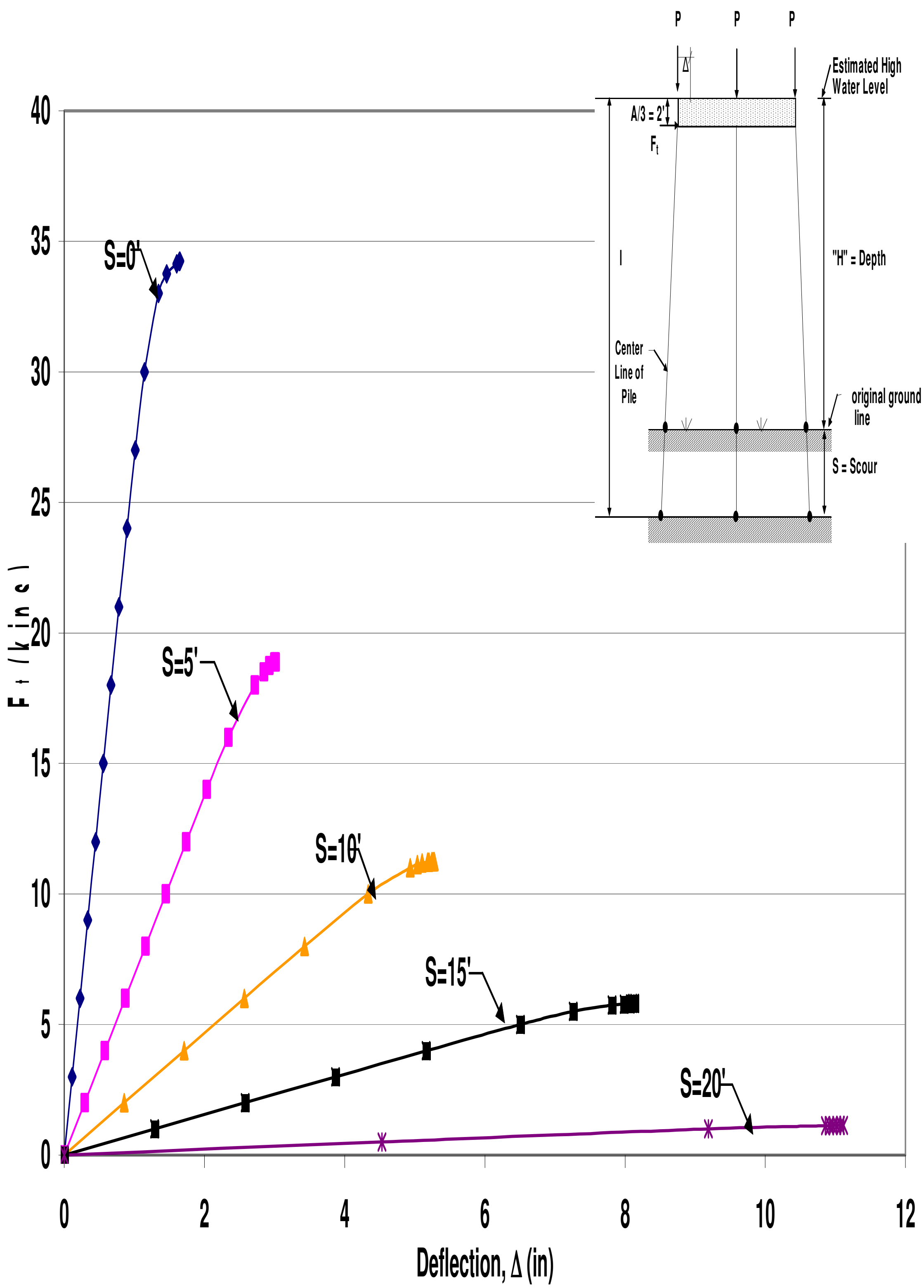


Figure B.2 HP12x53 Unbraced 3-Pile Bent with H=10', P=120kips and A=6', Pushover Analysis Results

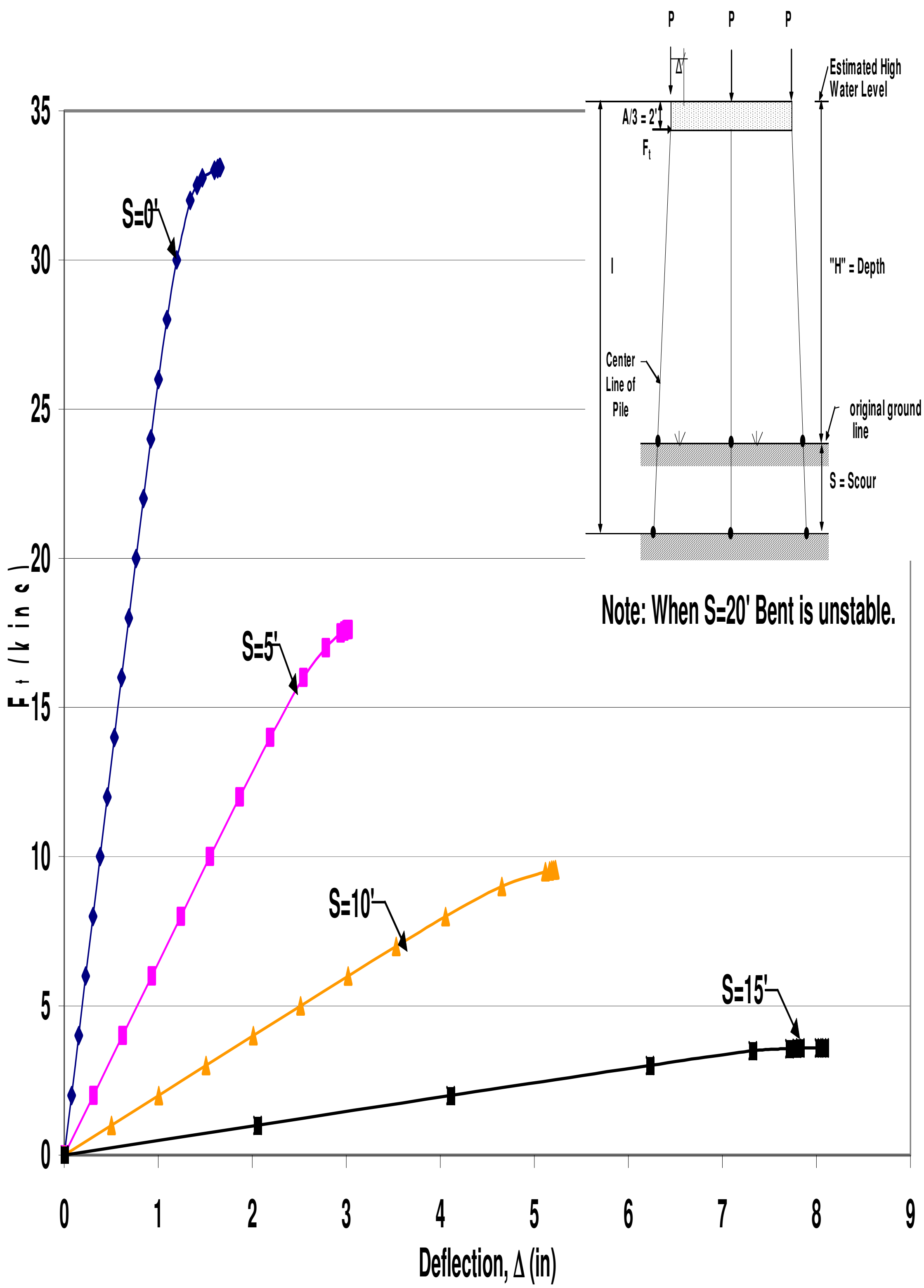


Figure B.3 HP12x53 Unbraced 3-Pile Bent with H=10', P=140kips and A=6'
Pushover Analysis Results

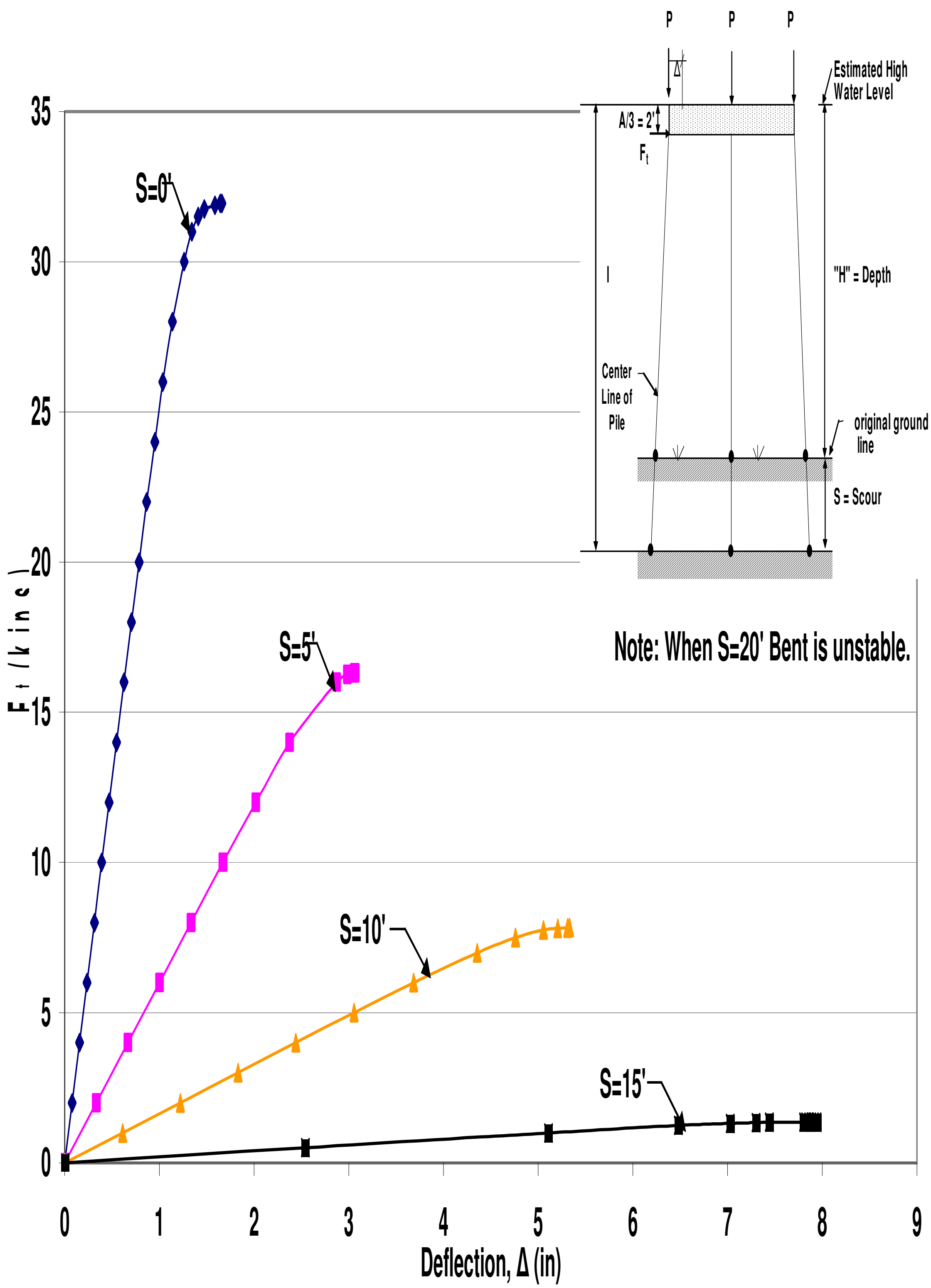


Figure B.4 HP12x53 Unbraced 3-Pile Bent with H=10', P=160kips and A=6'

Pushover Analysis Results

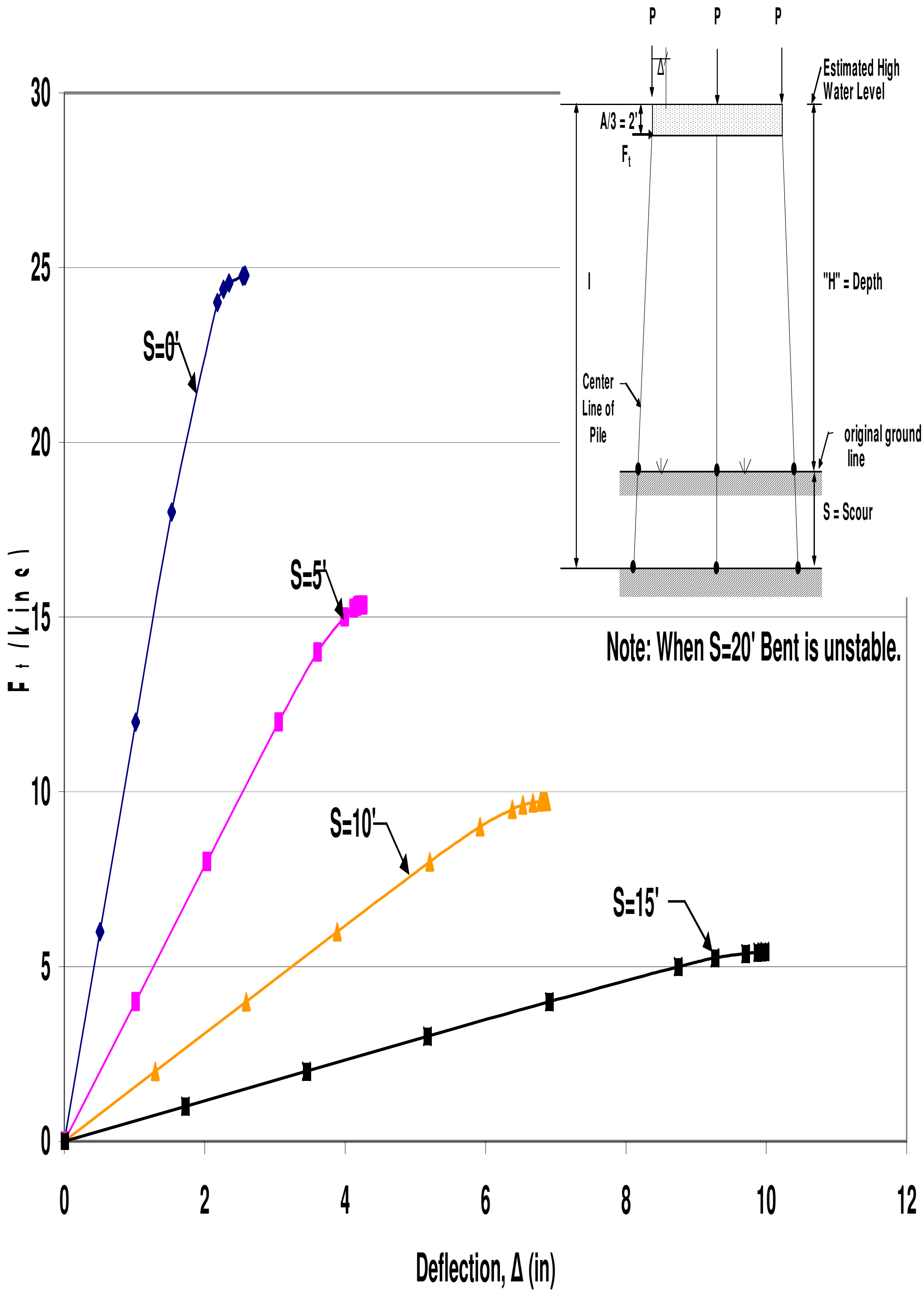


Figure B.5 HP12x53 Unbraced 3-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

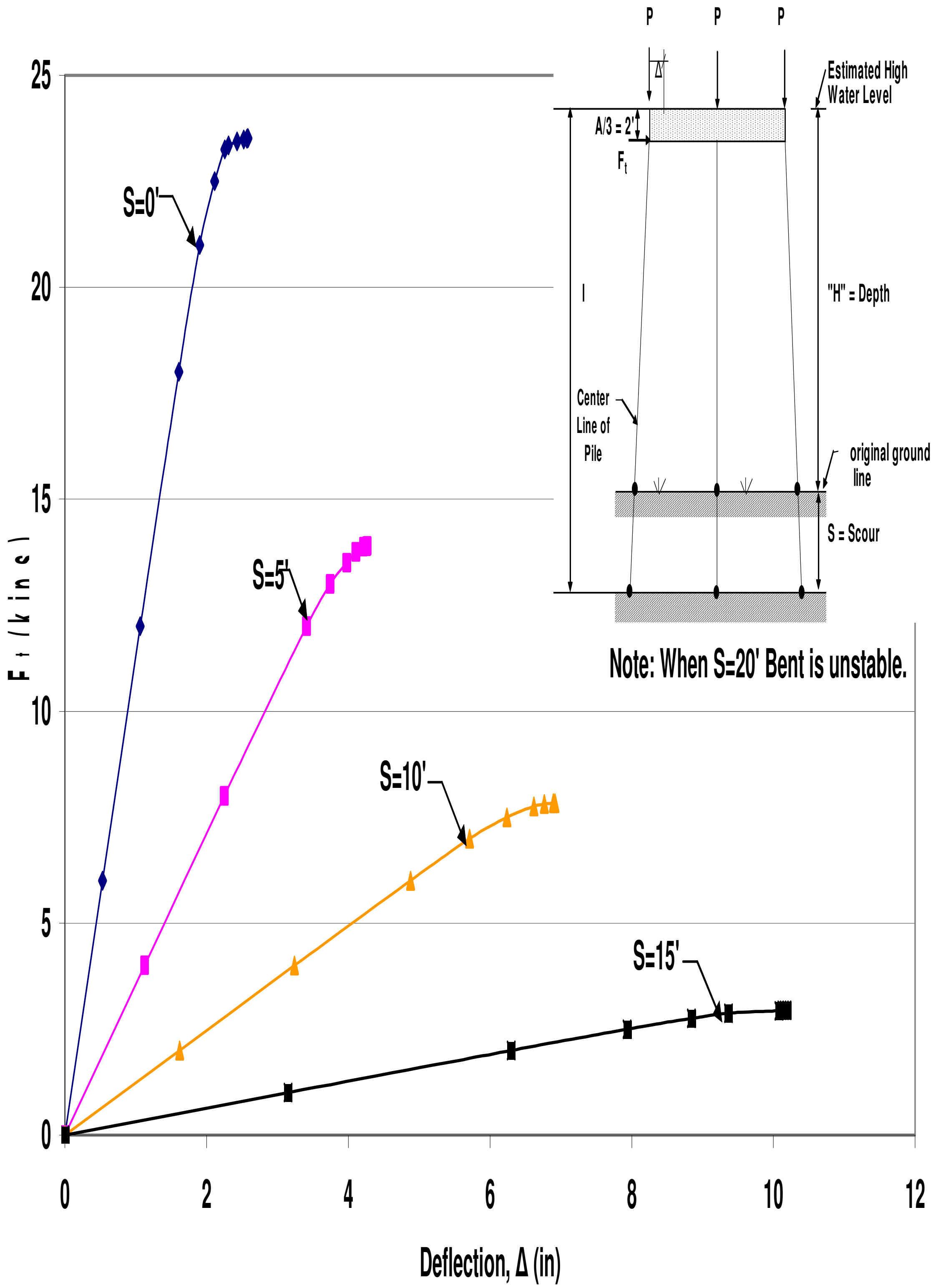


Figure B.6 HP12x53 Unbraced 3-Pile Bent with H=13', P=120kips and A=6'

Pushover Analysis Results

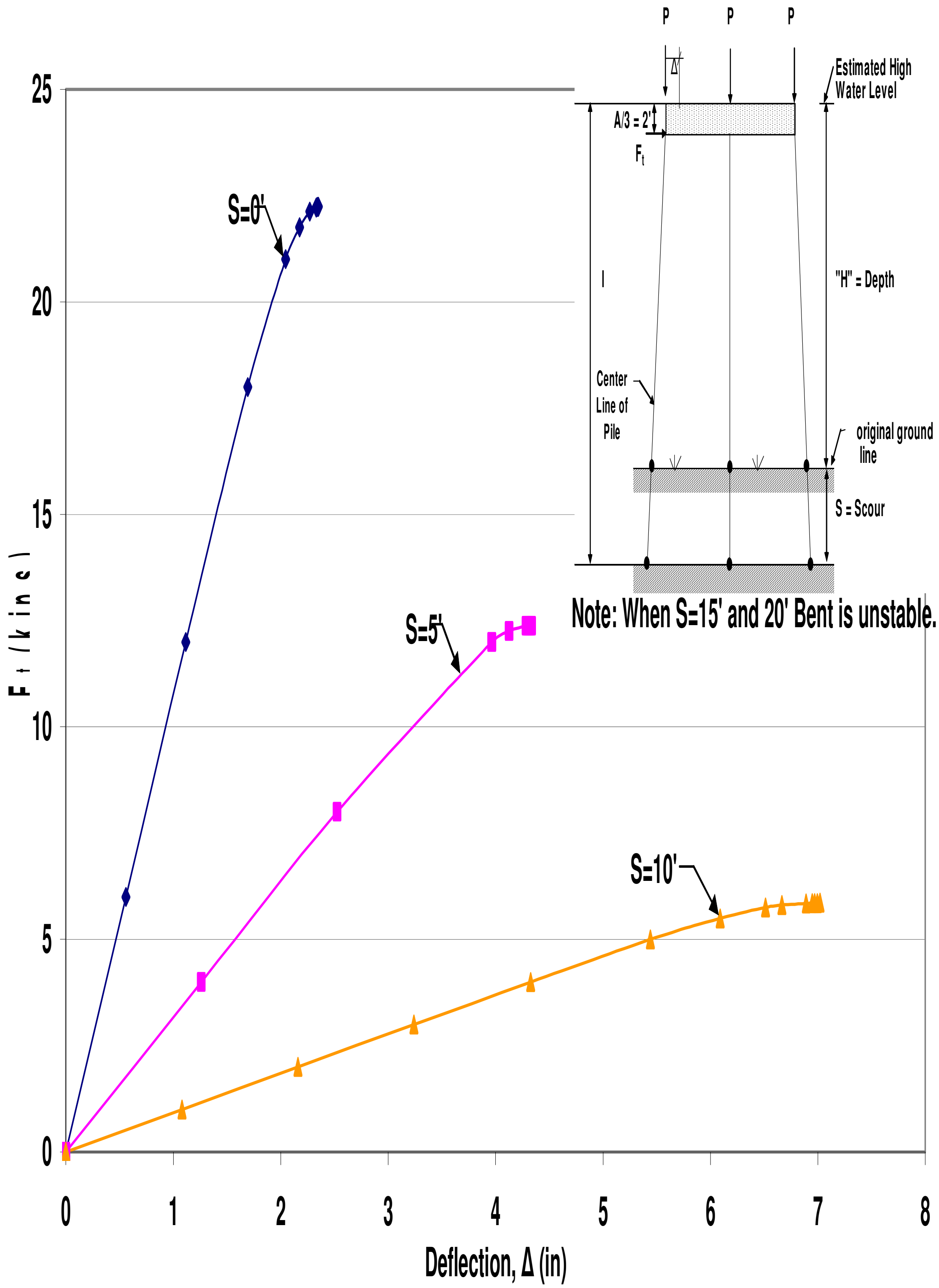


Figure B.7 HP12x53 Unbraced 3-Pile Bent with H=13', P=140kips and A=6'

Pushover Analysis Results

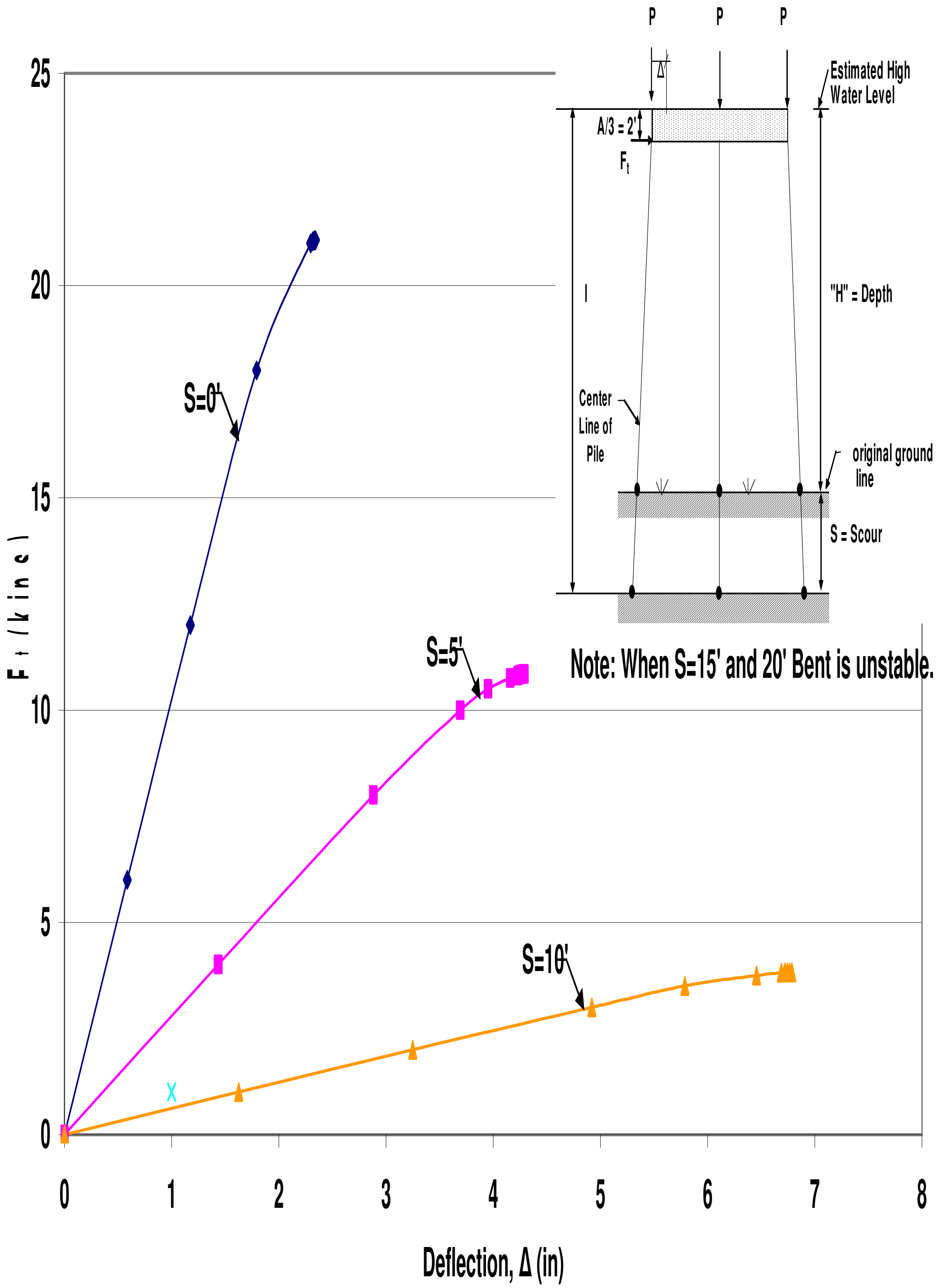


Figure B.8 HP12x53 Unbraced 3-Pile with H=13', P=160kips and A=6'
Pushover Analysis Results

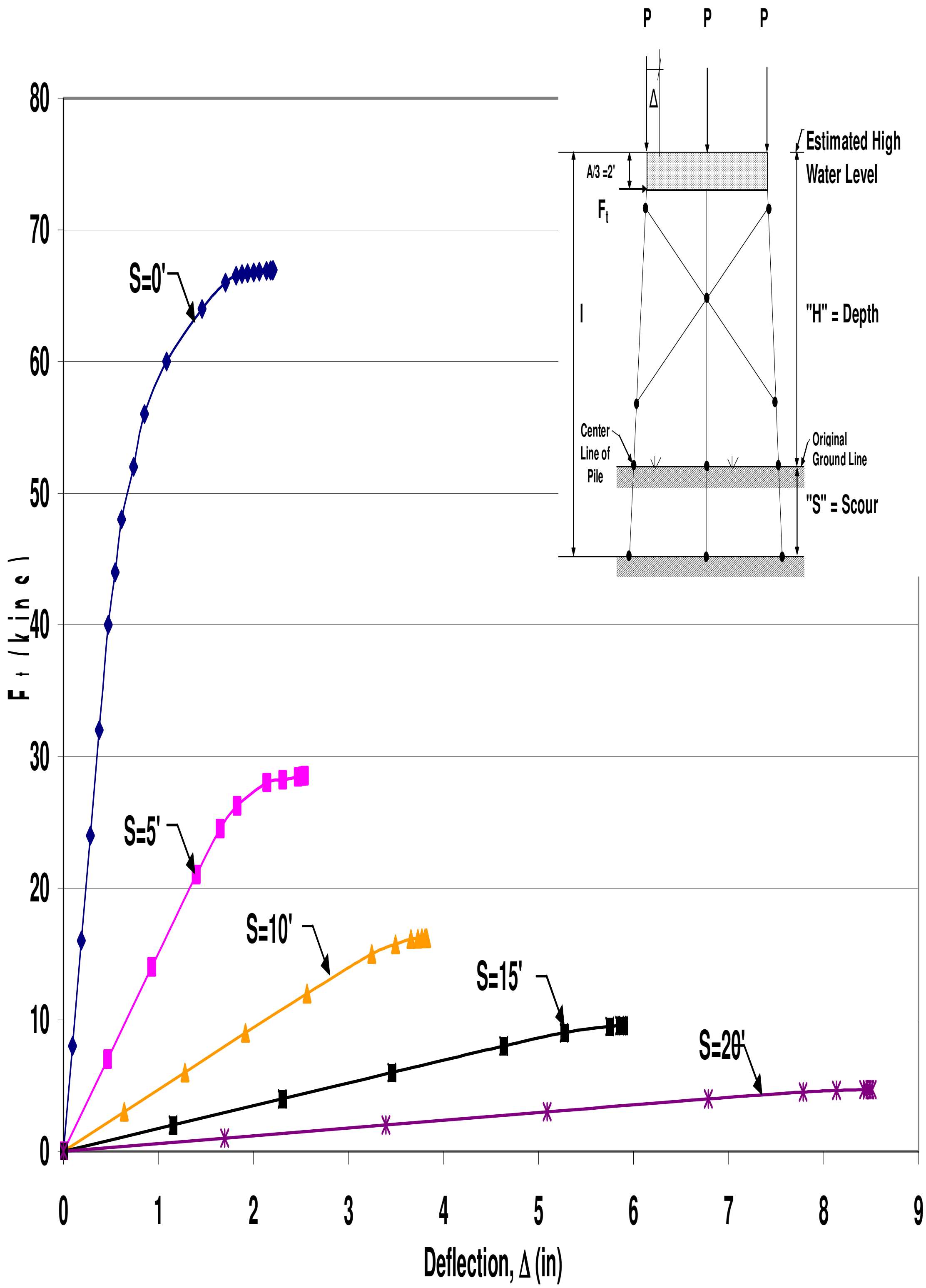


Figure B.9 HP12x53 X-Braced 3-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

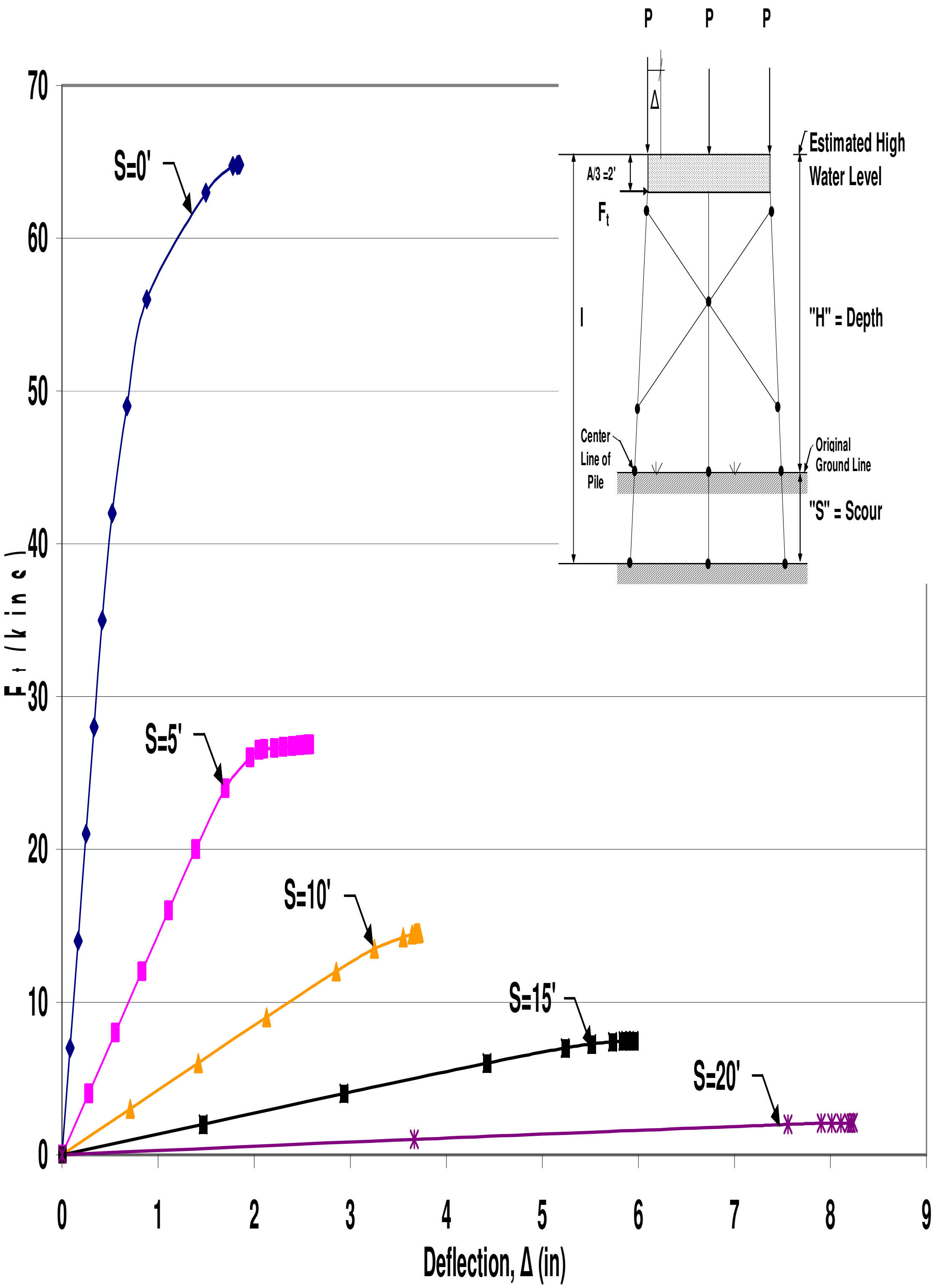


Figure B.10 HP12x53 X-Braced 3-Pile Bent with H=13', P=120kips and A=6'

Pushover Analysis Results

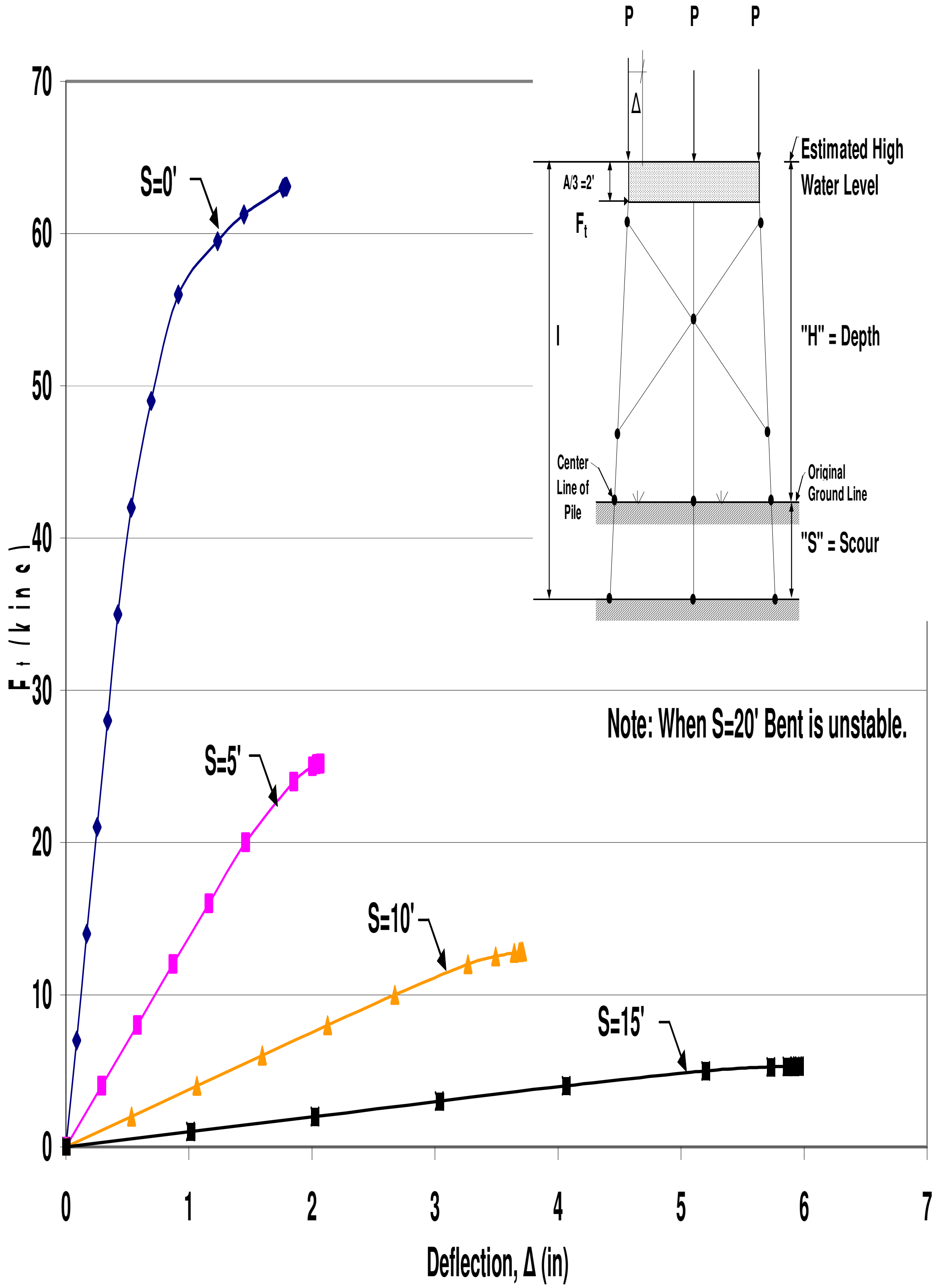


Figure B.11 HP12x53 X-Braced 3-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

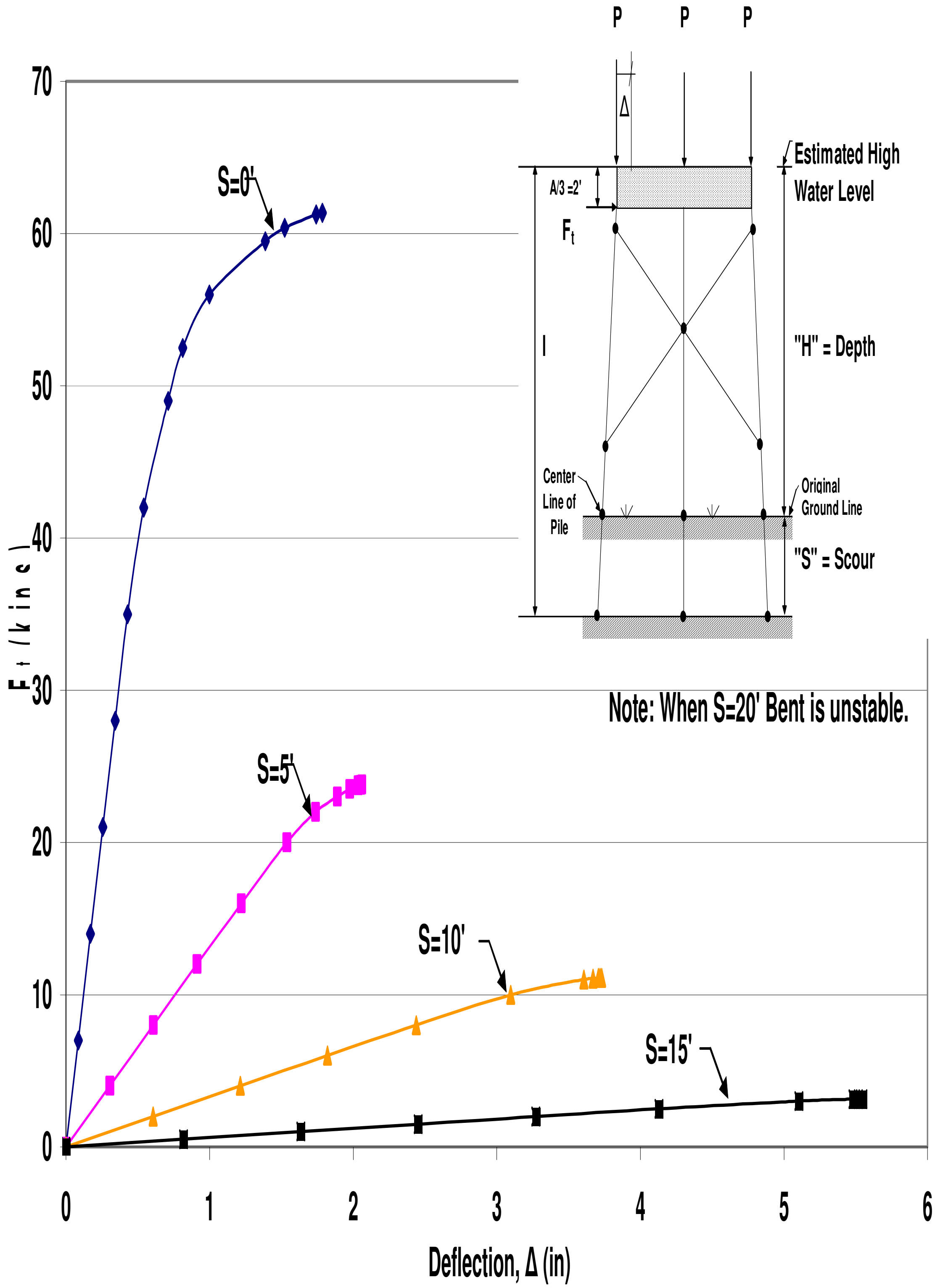


Figure B.12 HP12x53 X-Braced 3-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

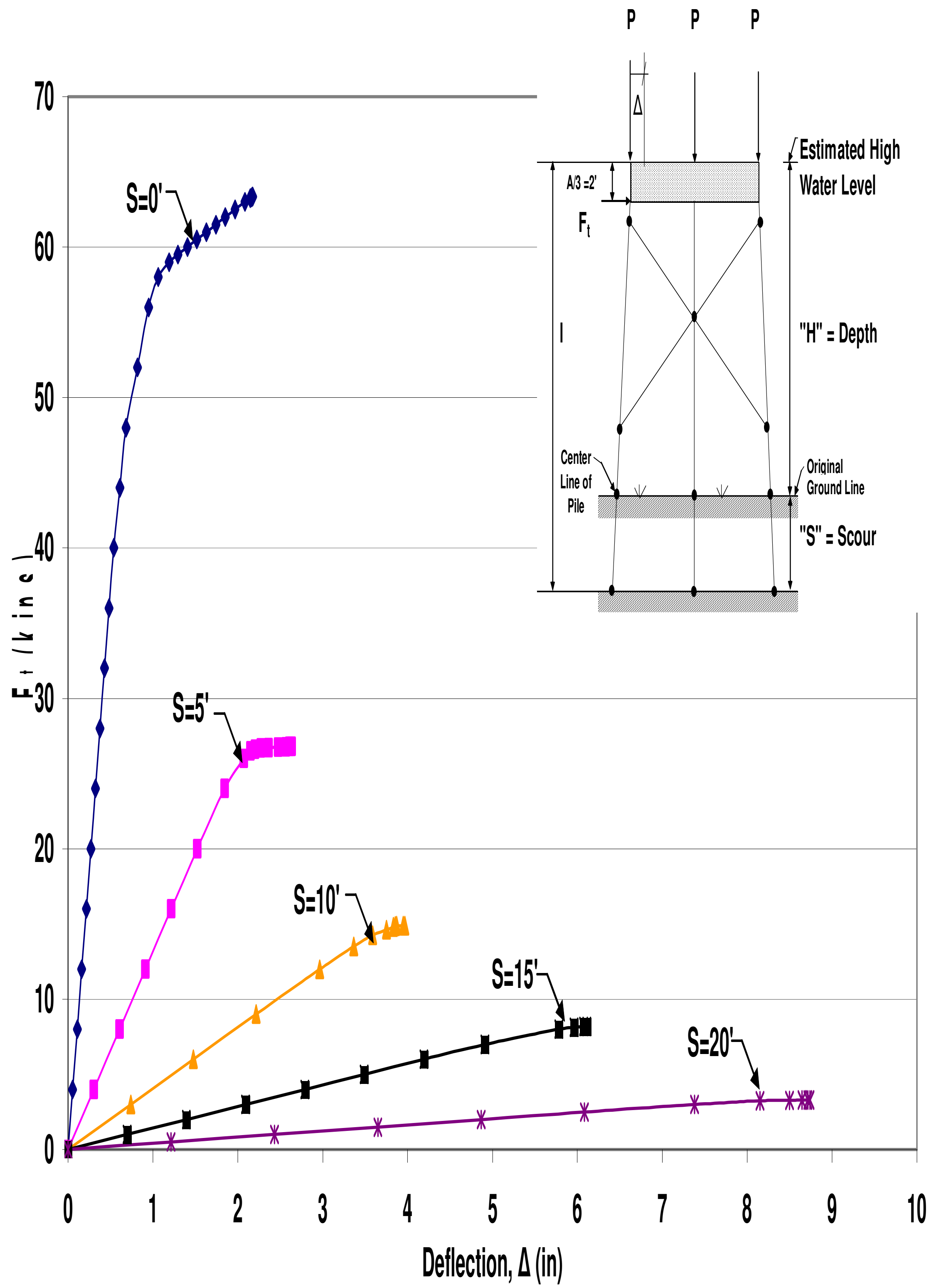


Figure B.13 HP12x53 X-Braced 3-Pile Bent with H=17', P=100 kips and A=6'
Pushover Analysis Results

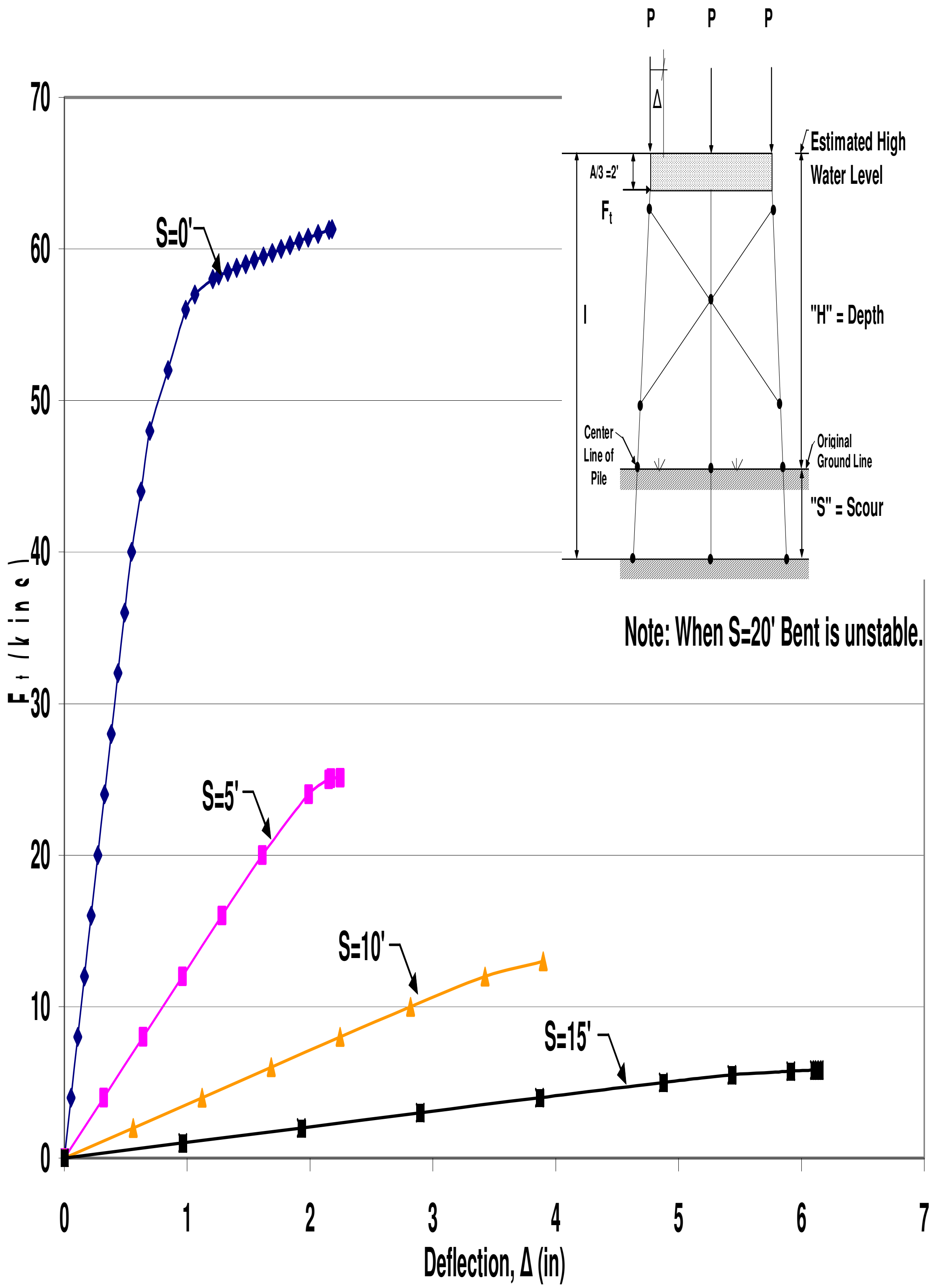


Figure B.14 HP12x53 X-Braced 3-Pile Bent with H=17', P=120 kips and A=6'

Pushover Analysis Results

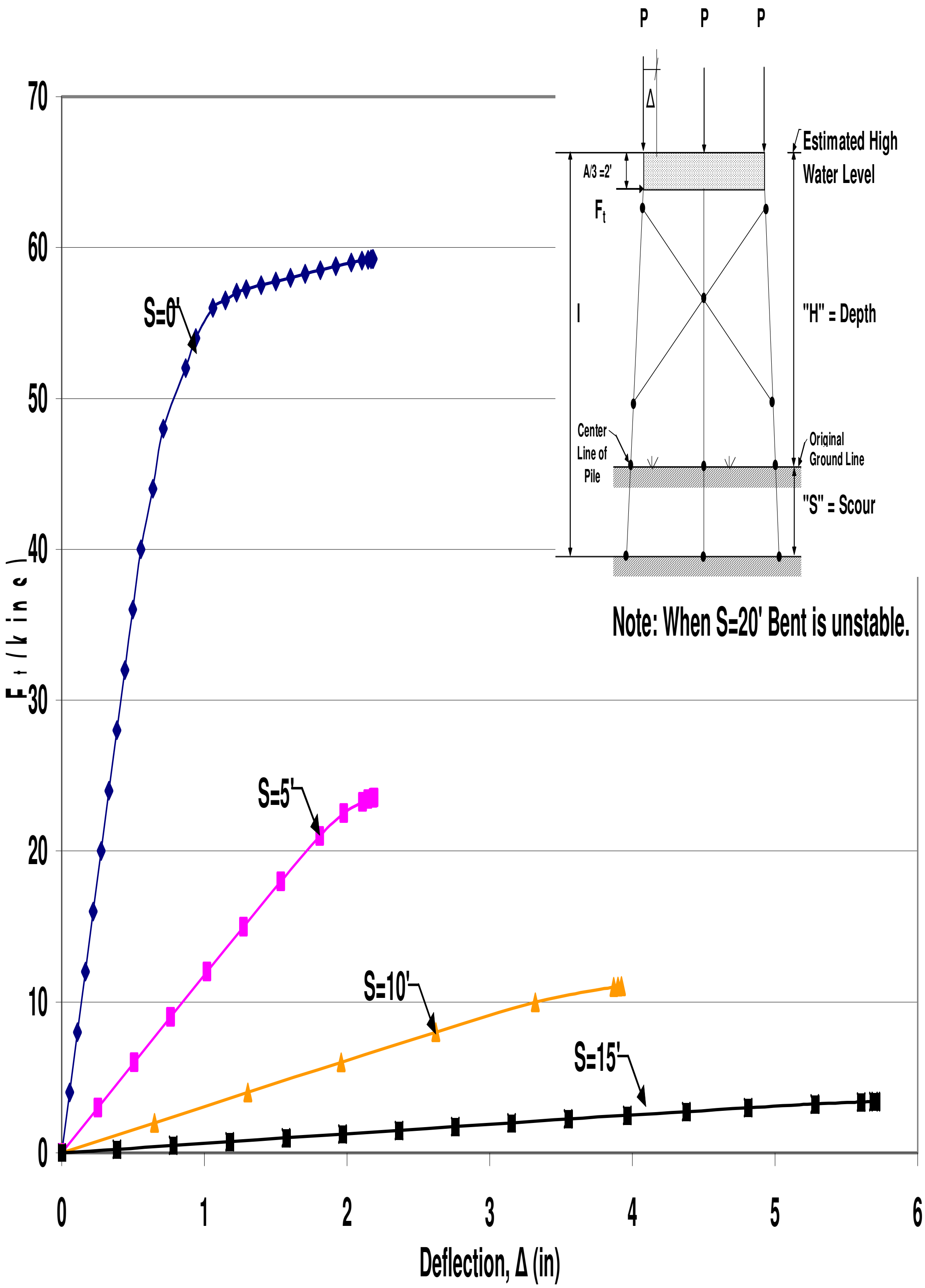


Figure B.15 HP12x53 X-Braced 3-Pile Bent with H=17', P=140 kips and A=6'

Pushover Analysis Results

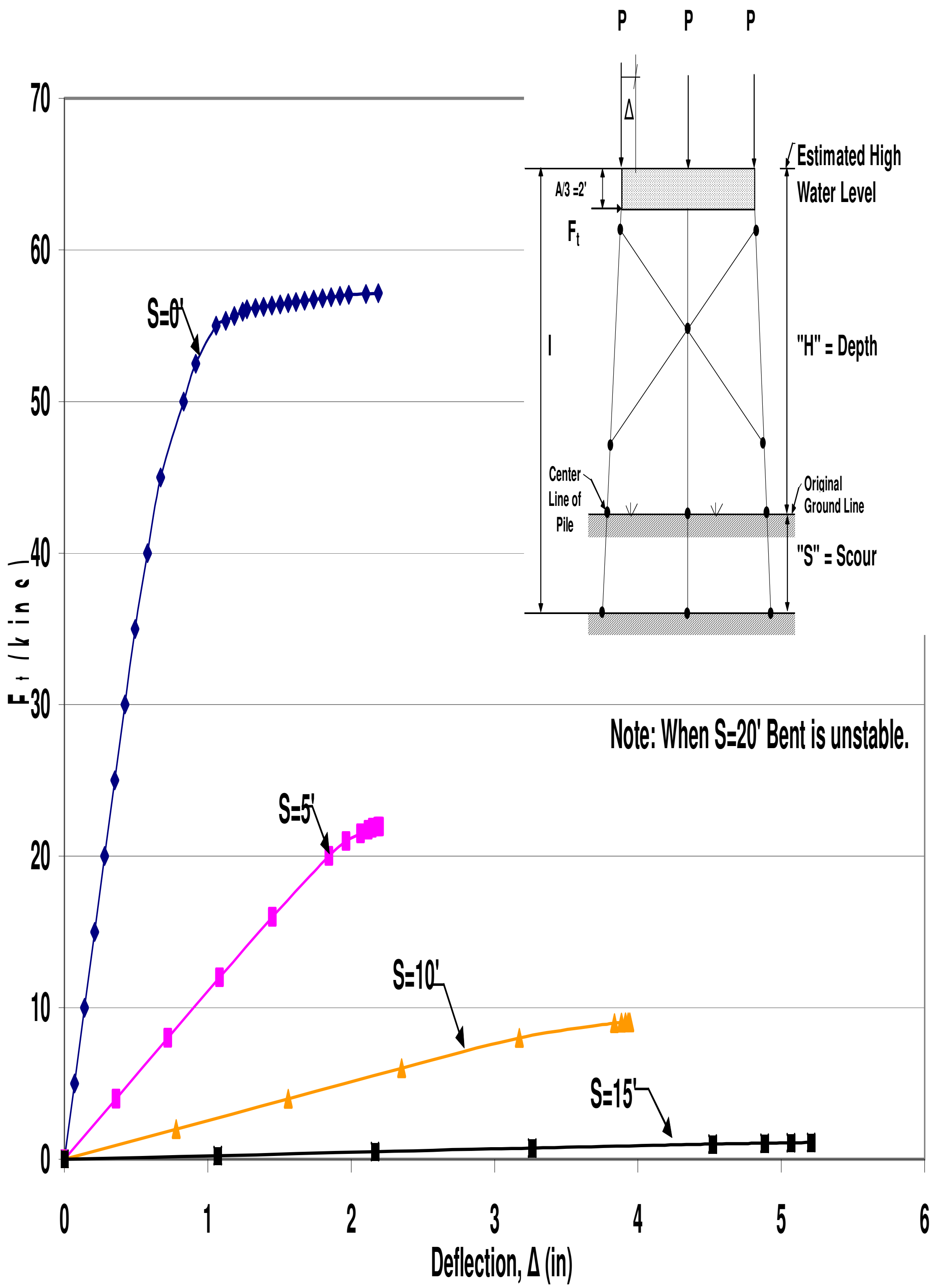


Figure B.16 HP12x53 X-Braced 3-Pile Bent with H=17', P=160 kips and A=6'

Pushover Analysis Results

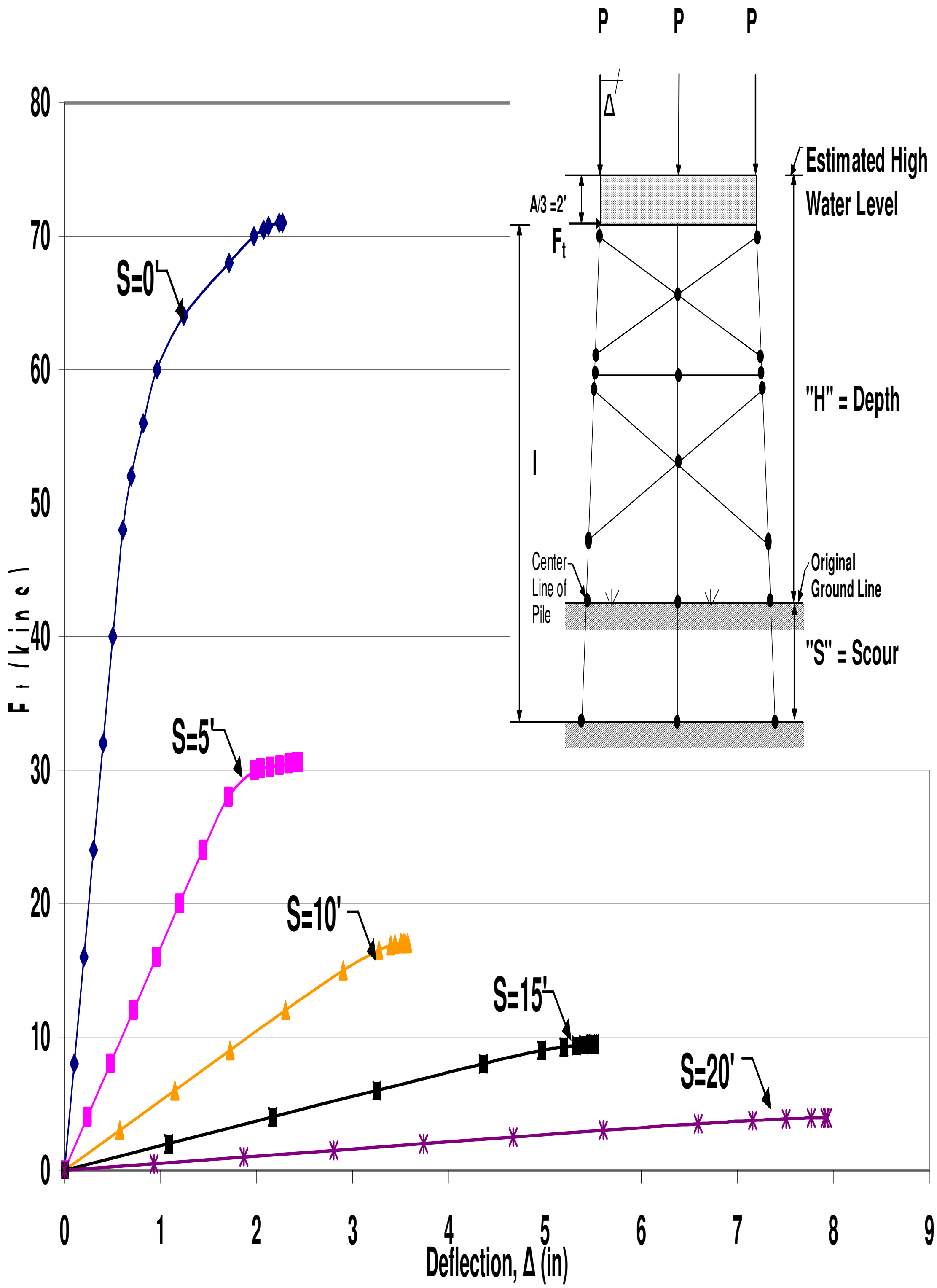


Figure B.17 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=100kips and A=6'
Pushover Analysis Results

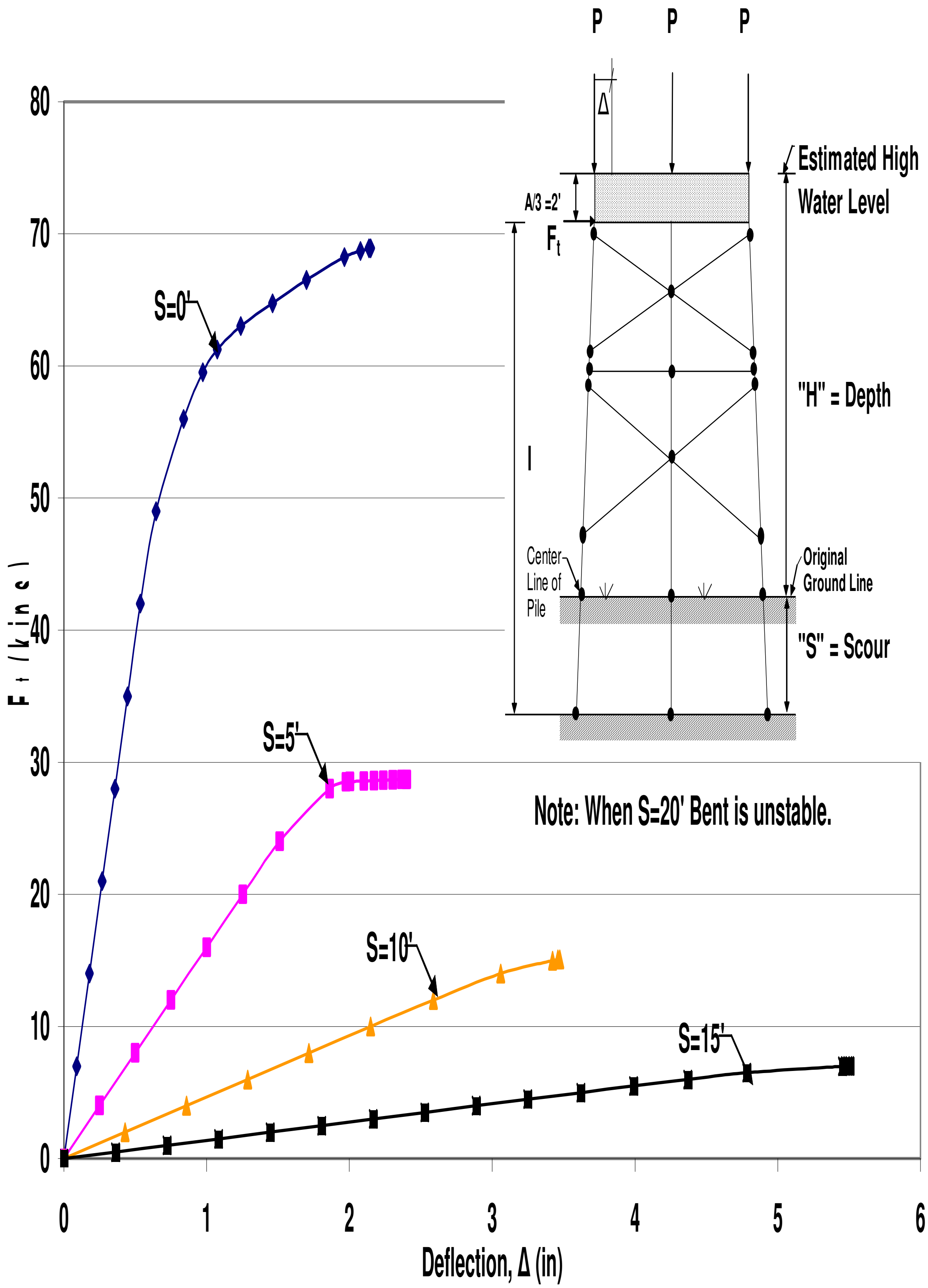


Figure B.18 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=120kips and A=6' Pushover Analysis Results

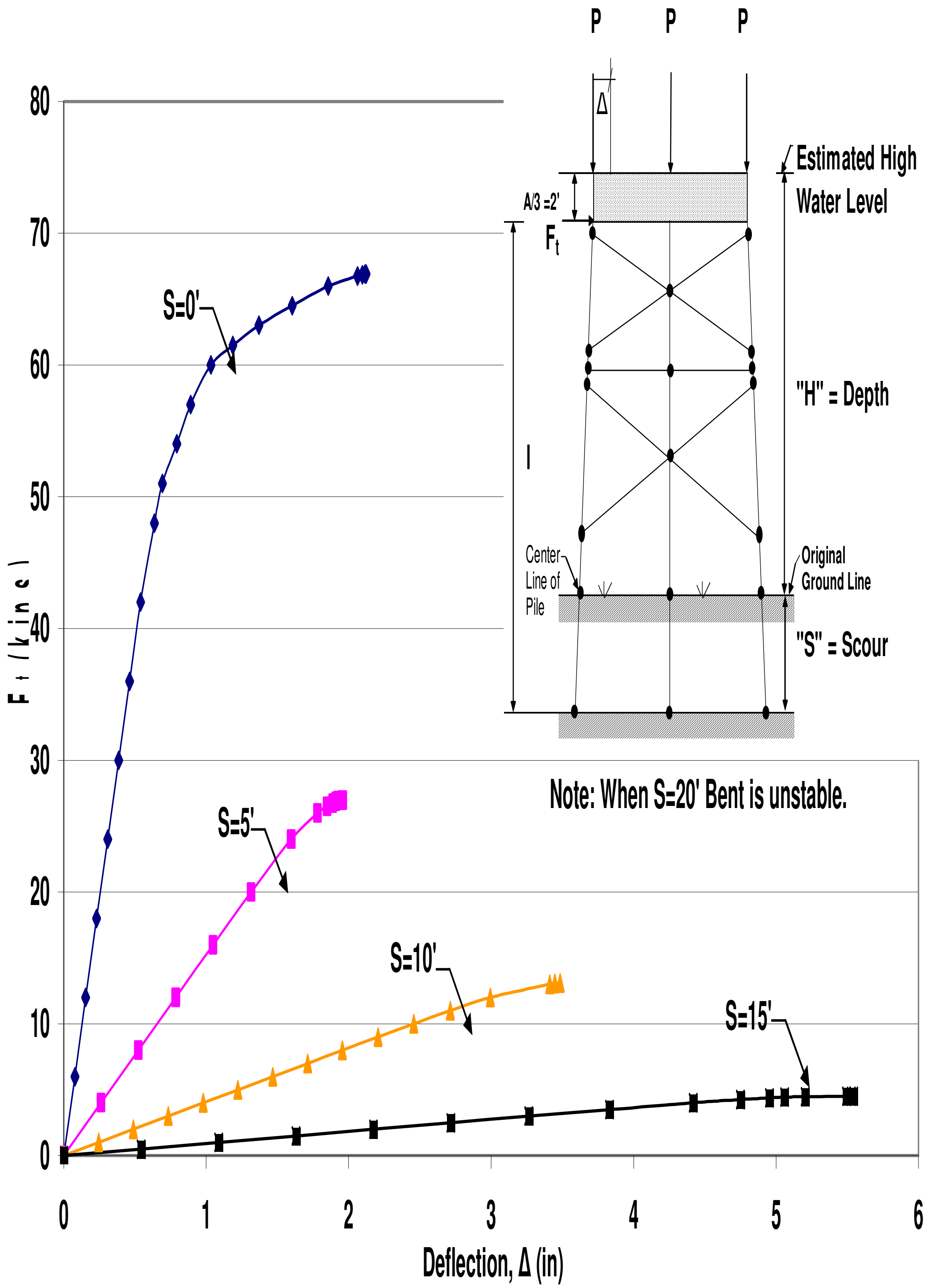


Figure B.19 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=140kips and A=6'
Pushover Analysis Results

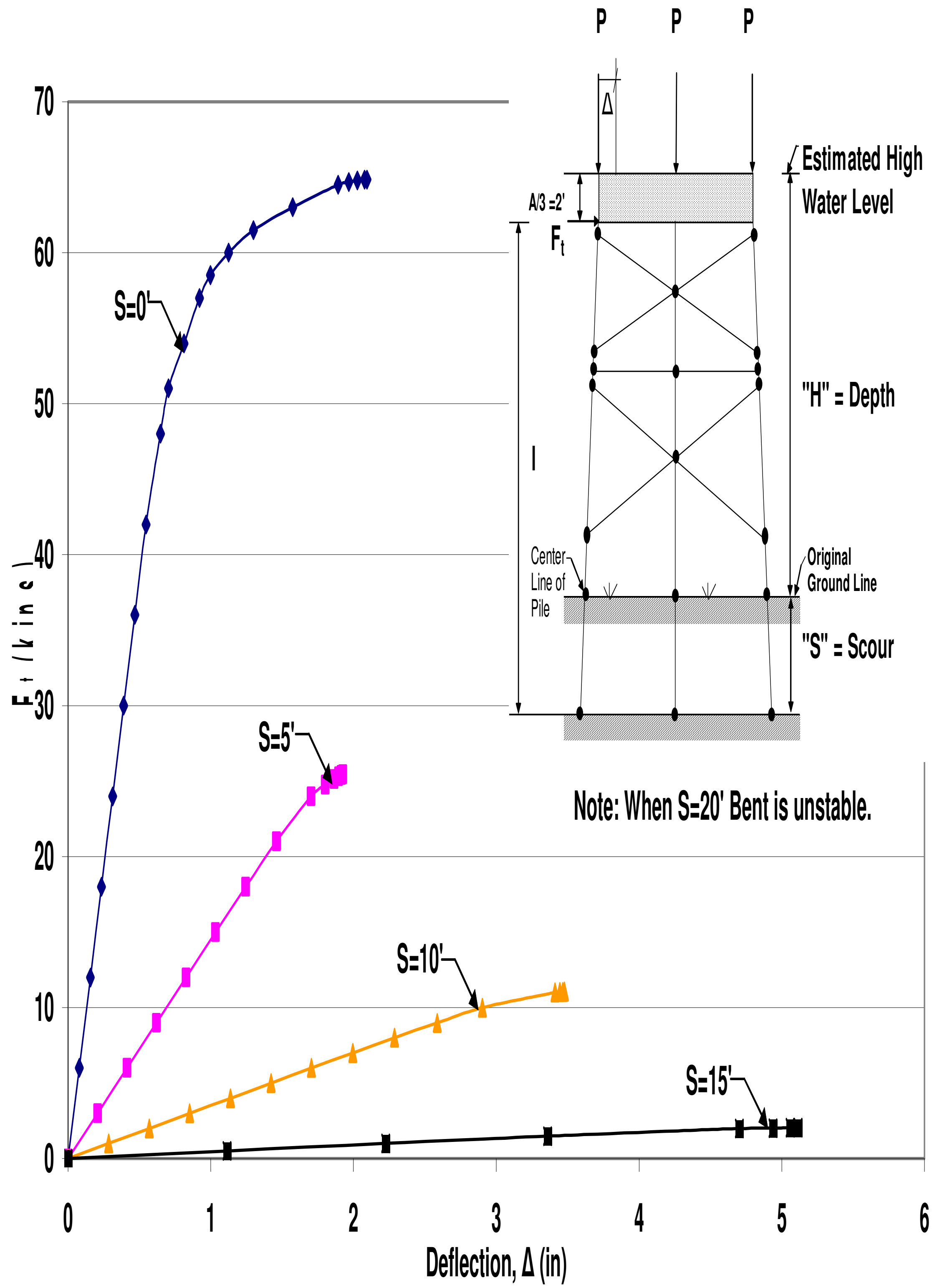


Figure B.20 HP12x53 Two-Story X-Braced 3-Pile Bent with H=21',P=160kips and A=6' Pushover Analysis Results

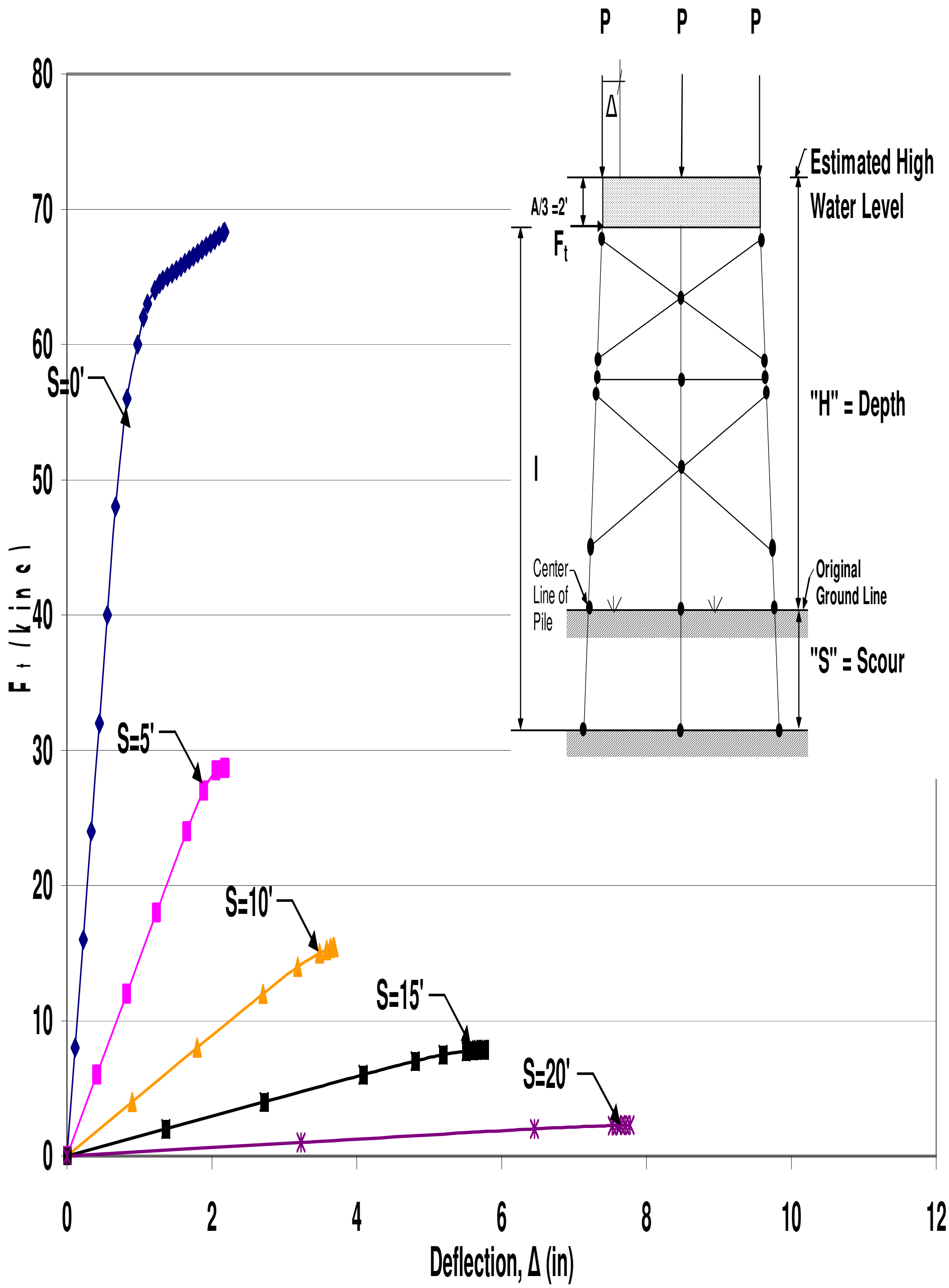


Figure B.21 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=100kips and A=6' Pushover Analysis Results

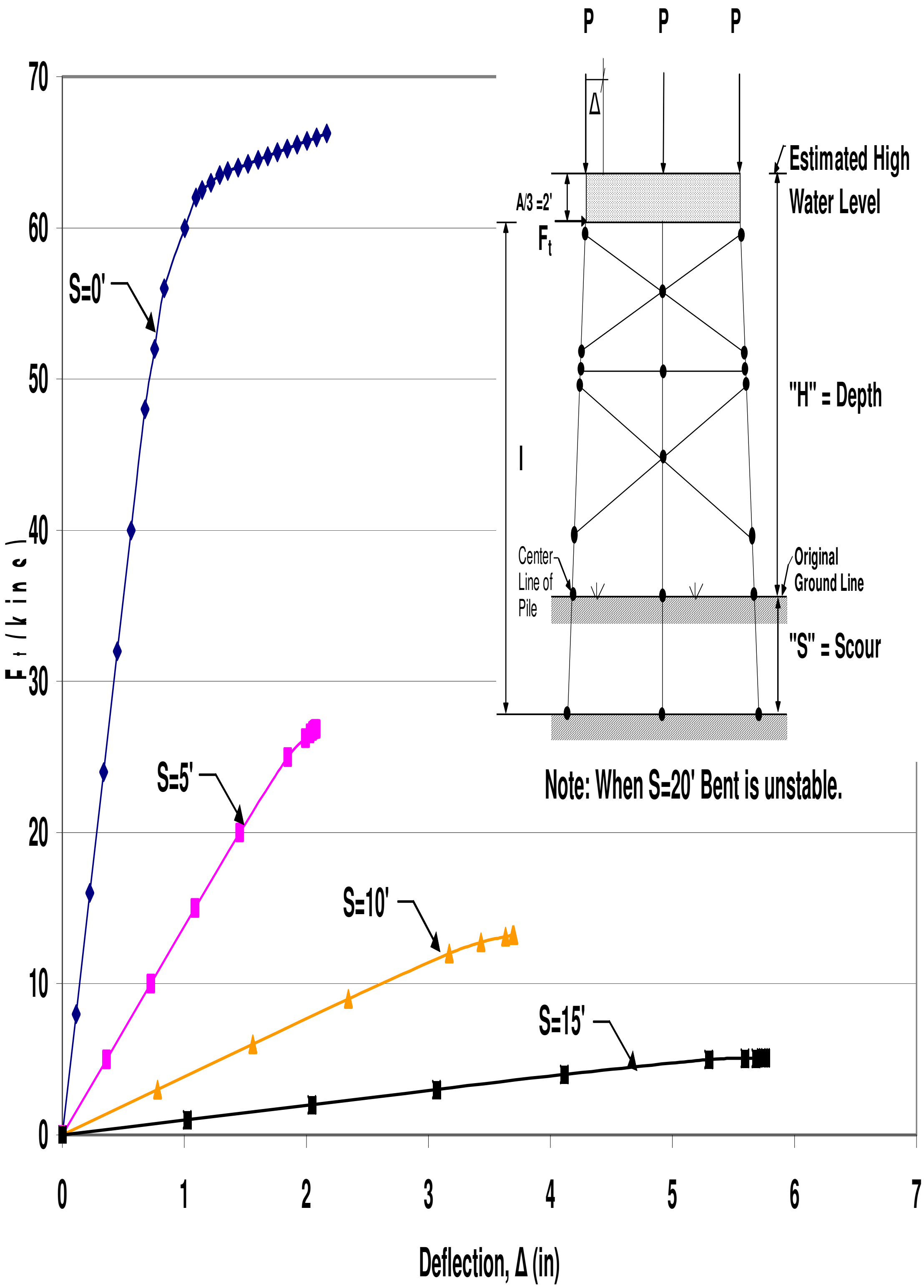


Figure B.22 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=120kips and A=6' Pushover Analysis Results

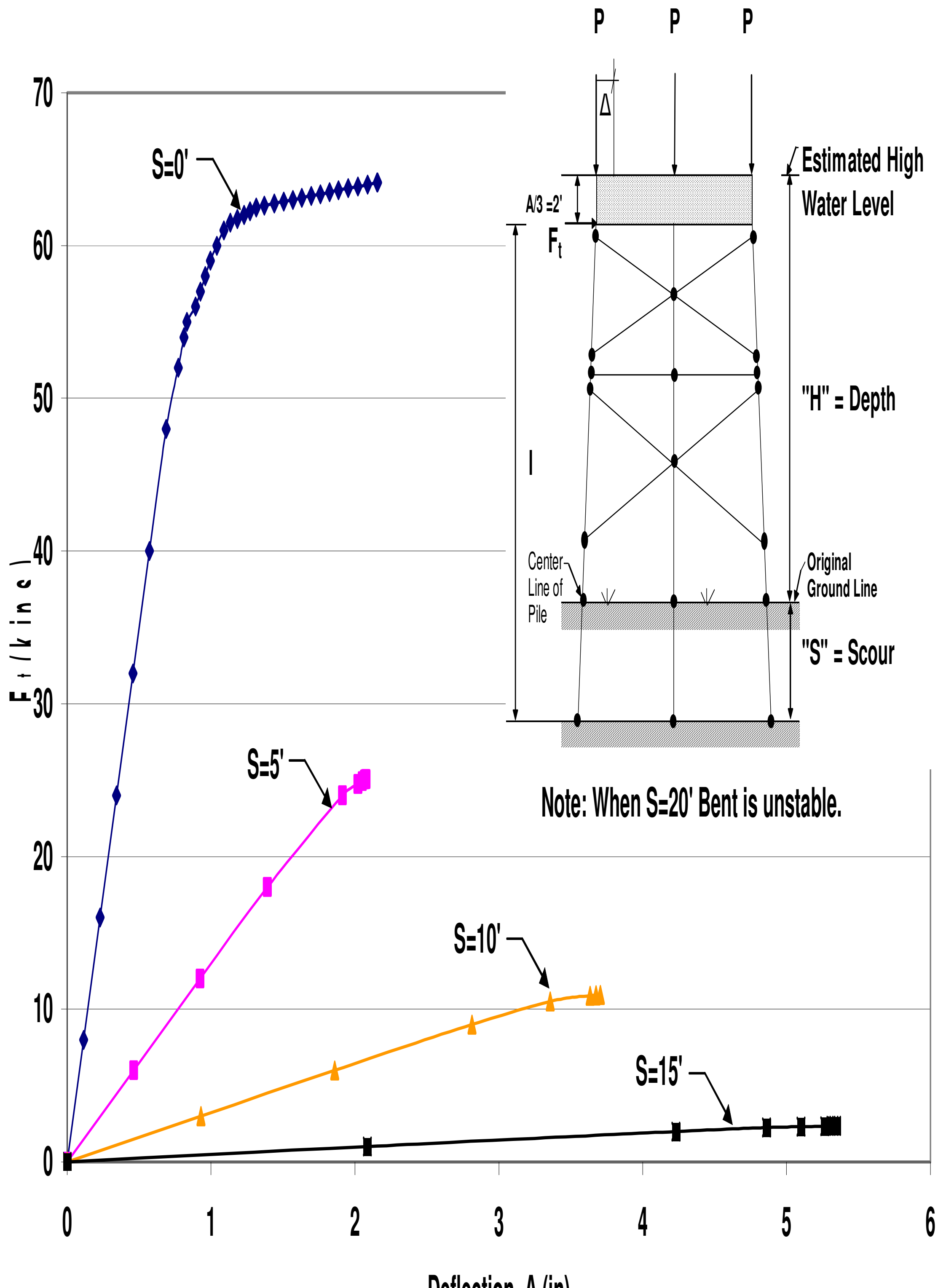


Figure B.23 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=140kips and A=6'
Pushover Analysis Results

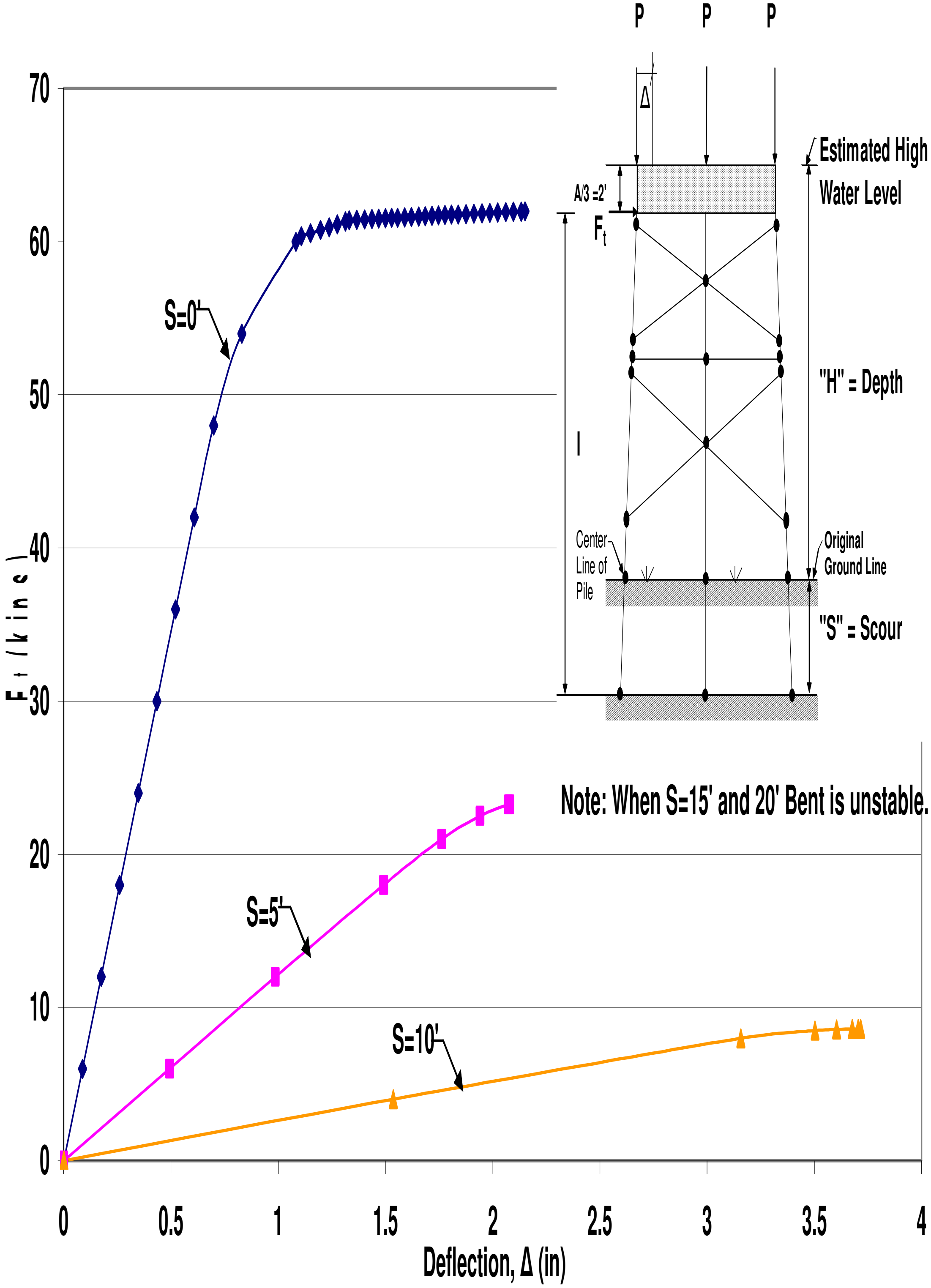


Figure B.24 HP12x53 Two-Story X-Braced 3-Pile Bent with H=25',P=160kips and A=6'
Pushover Analysis Results

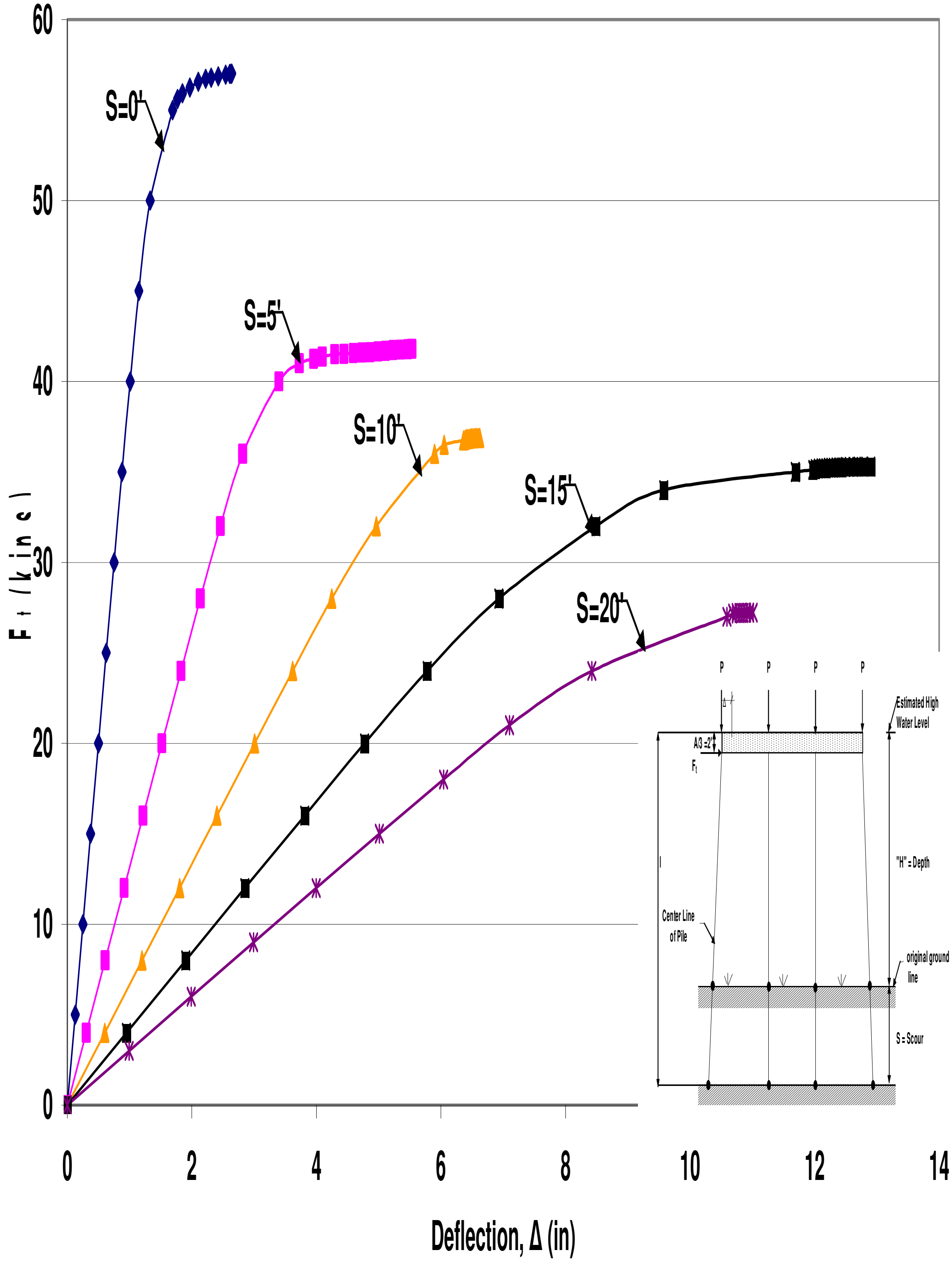


Figure B.25 HP12x53 Unbraced 4-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

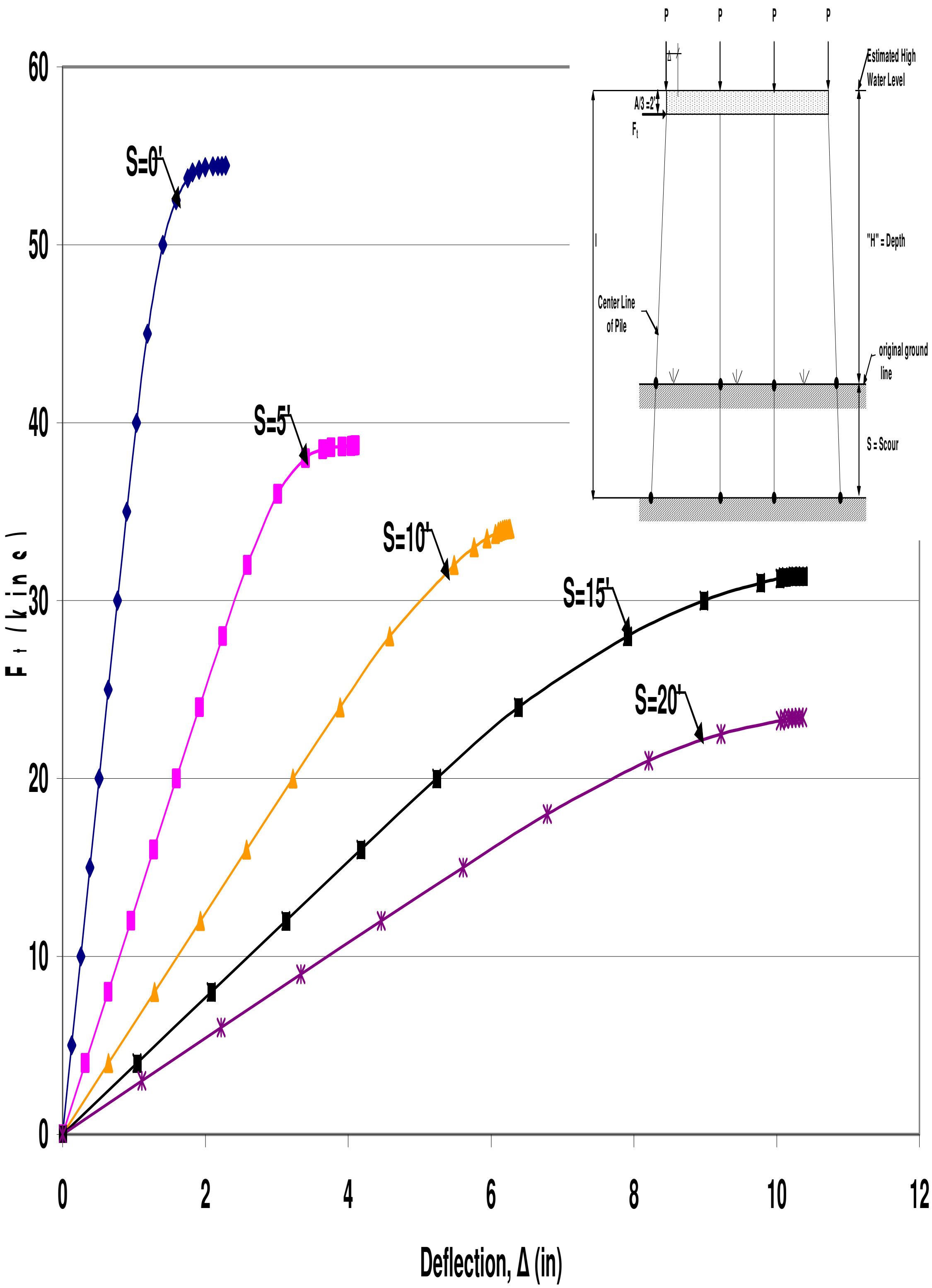


Figure B.26 HP12x53 Unbraced 4-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

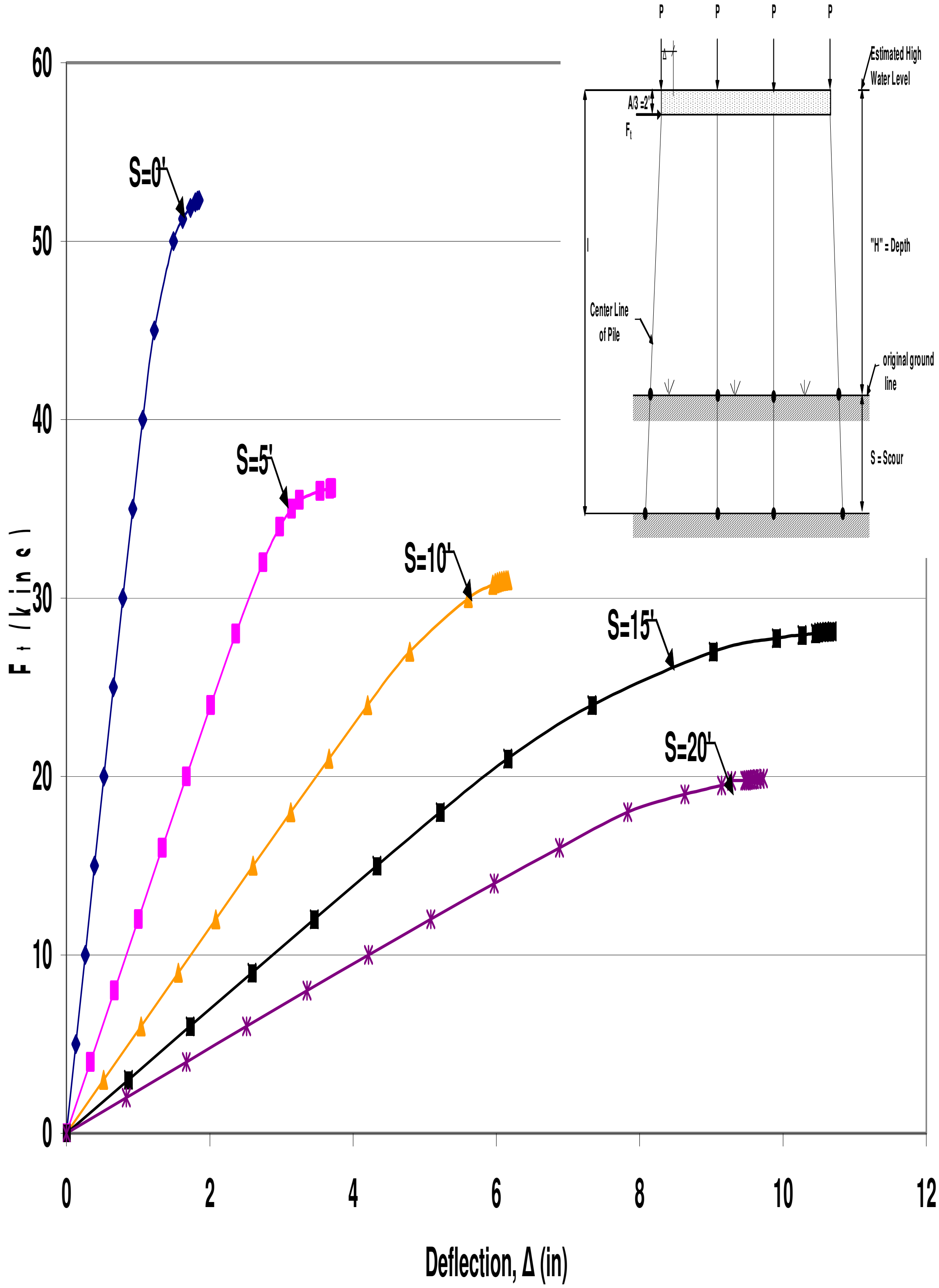


Figure B.27 HP12x53 Unbraced 4-Pile Bent with H=10', P=140kips and A=6'
Pushover Analysis Results

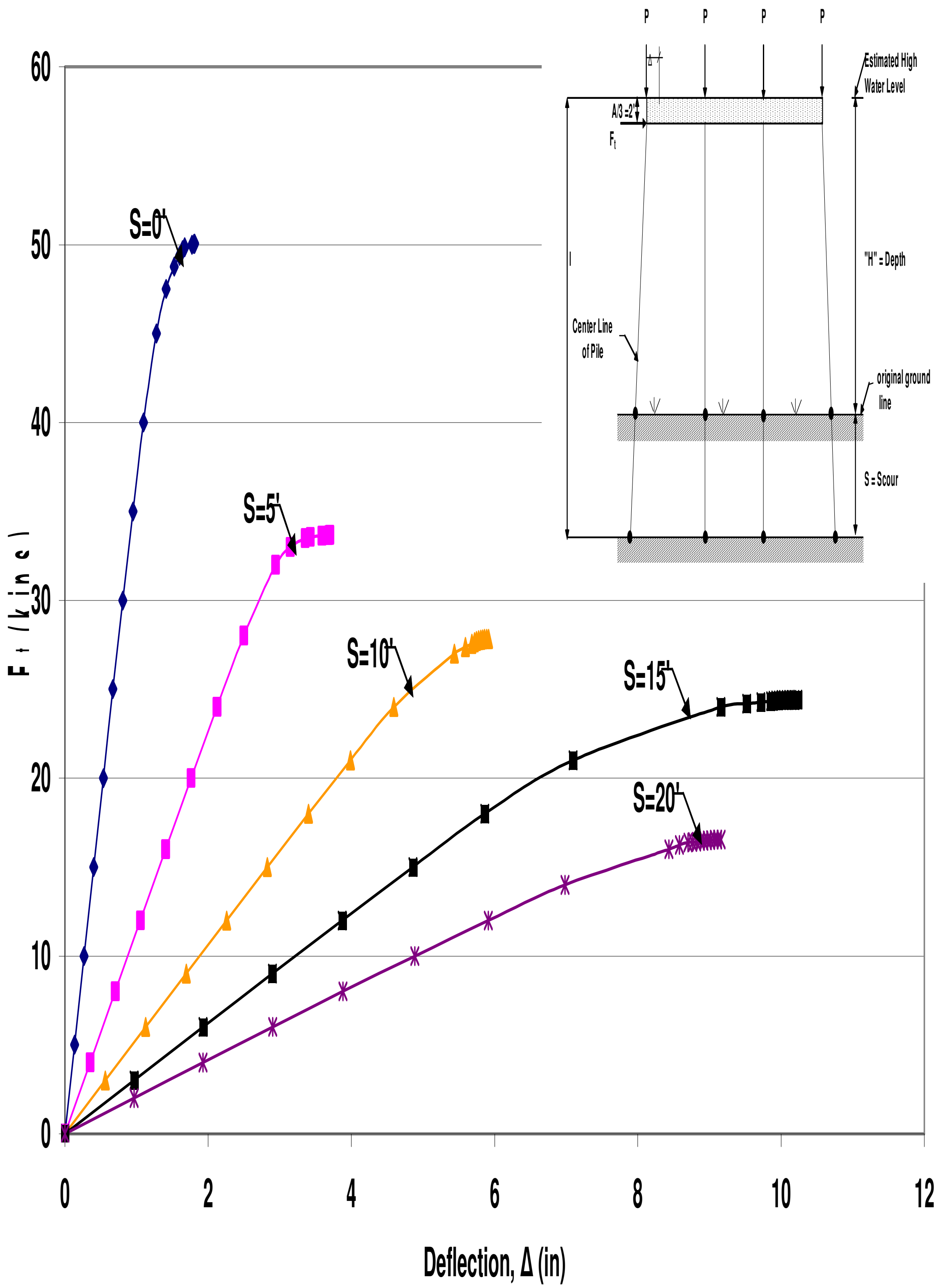


Figure B.28 HP12x53 Unbraced 4-Pile Bent with H=10', P=160kips and A=6'
Pushover Analysis Results

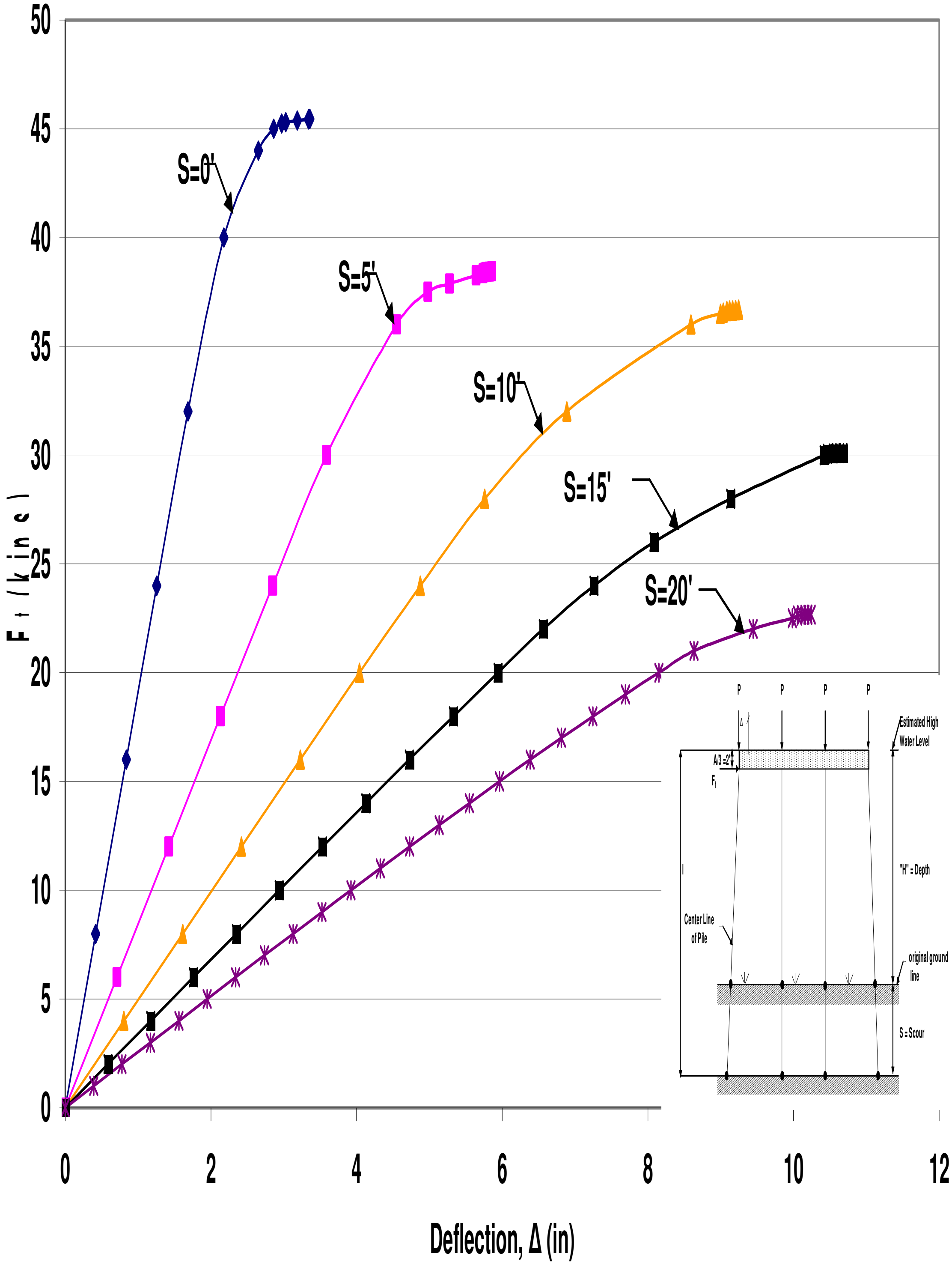


Figure B.29 HP12x53 Unbraced 4-Pile Bent with H=13', P=100kips, and A=6' Pushover Analysis Results

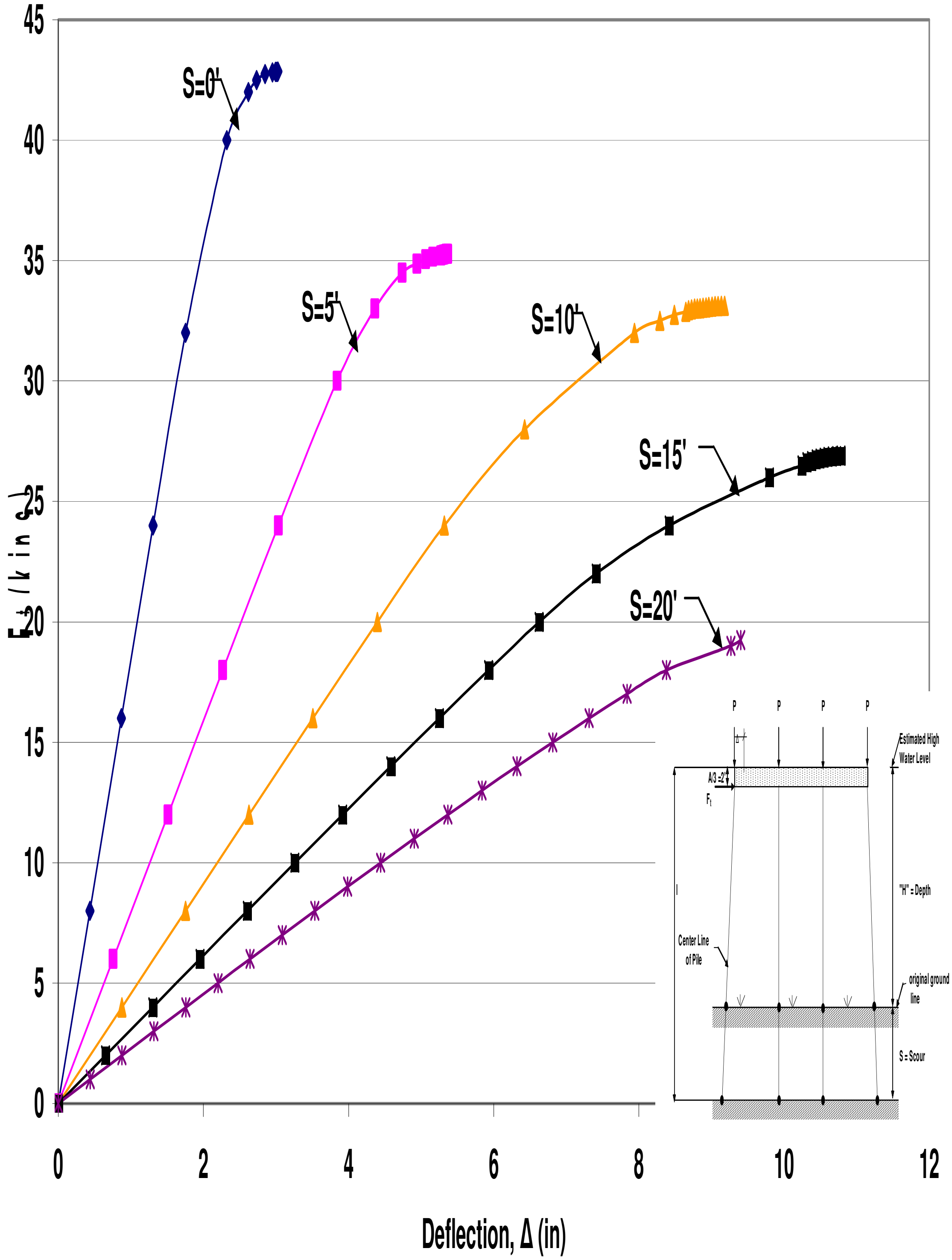


Figure B.30 HP12x53 Unbraced 4-Pile Bent with H=13', P=120kips, and A=6'
Pushover Analysis Results

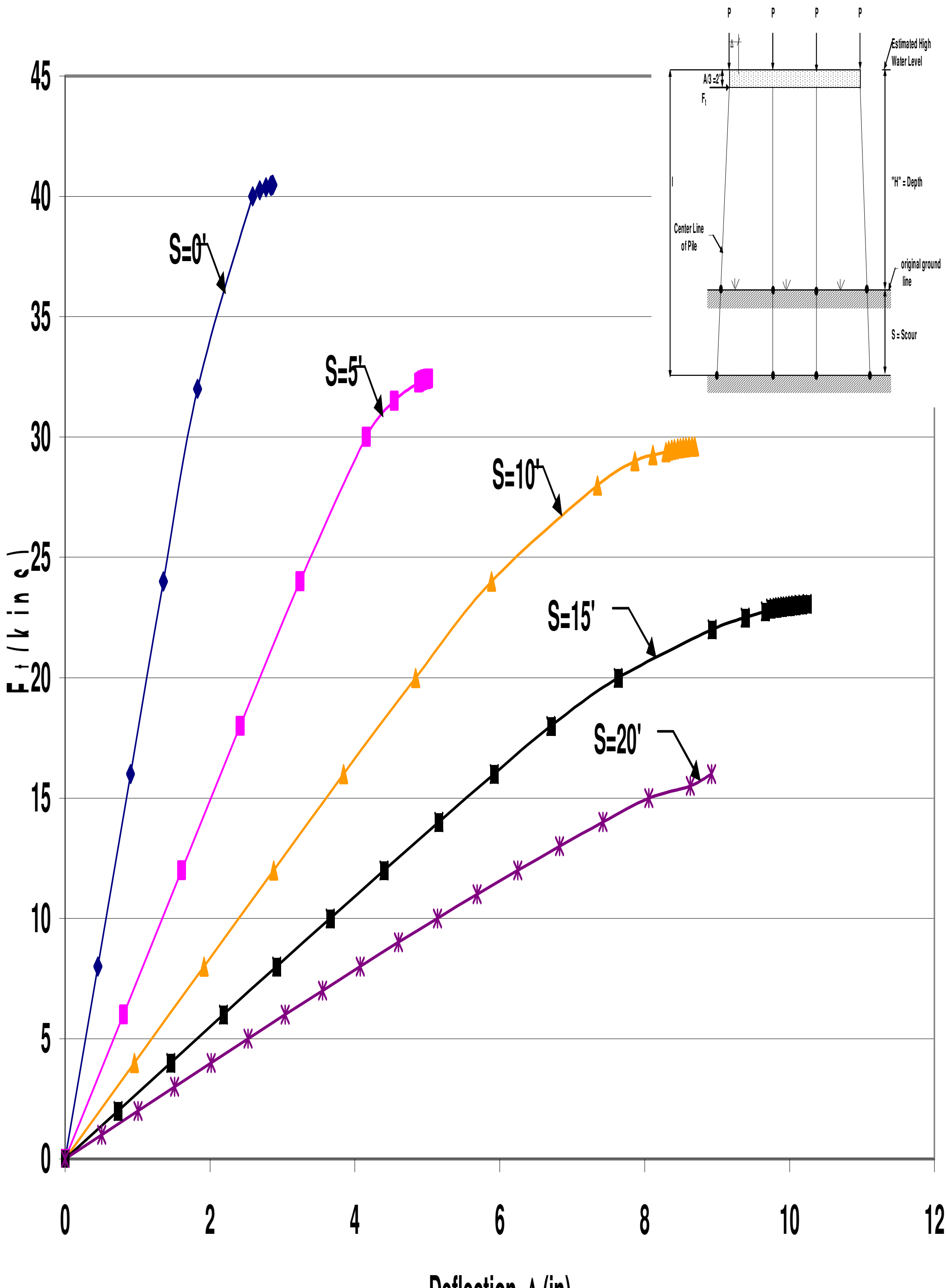


Figure B.31 HP12x53 Unbraced 4-Pile Bent with H=13', P=140kips, and A=6'
Pushover Analysis Results

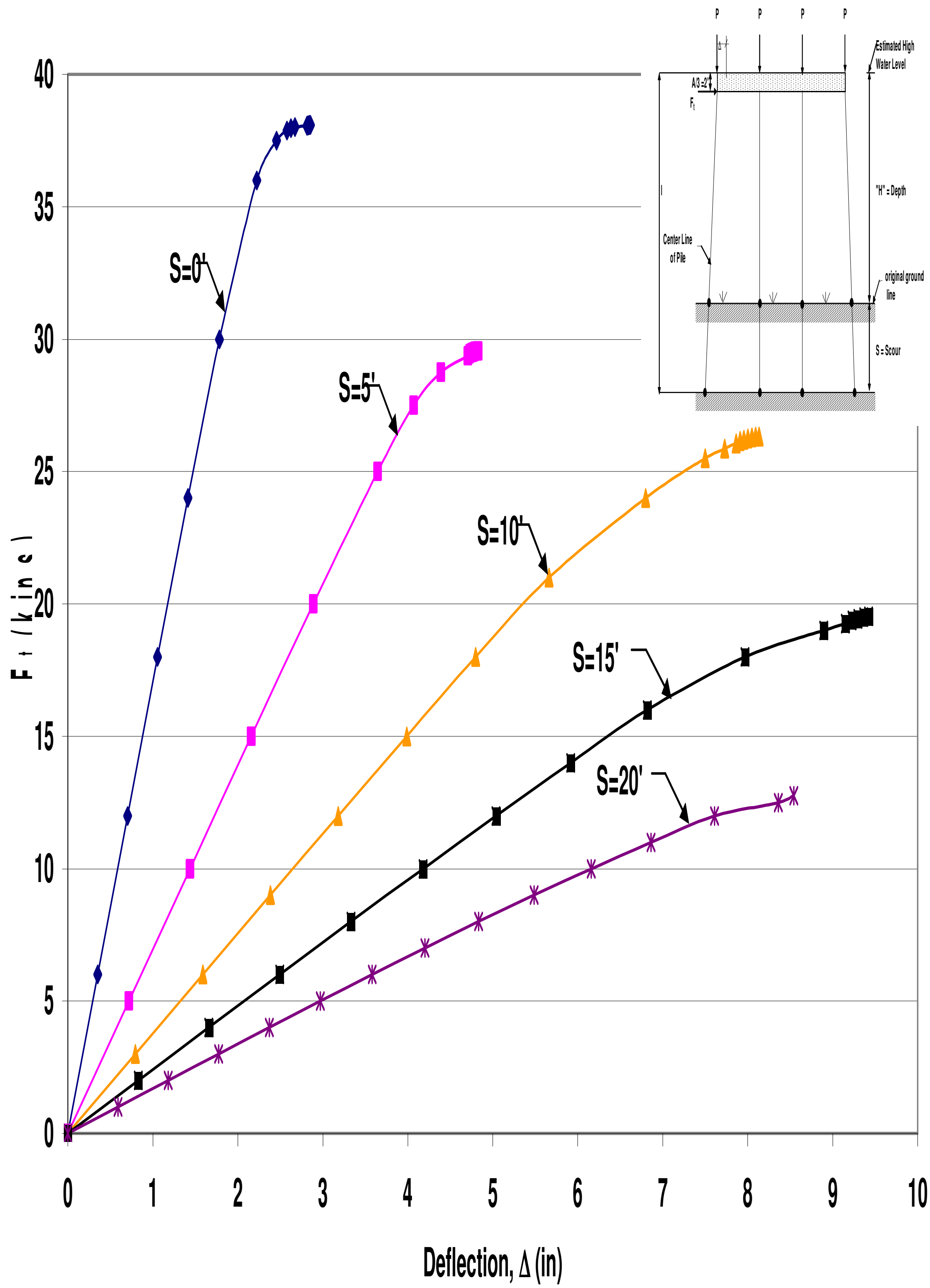


Figure B.32 HP12x53 Unbraced 4-Pile Bent with H=13', P=160kips, and A=6'

Pushover Analysis Results

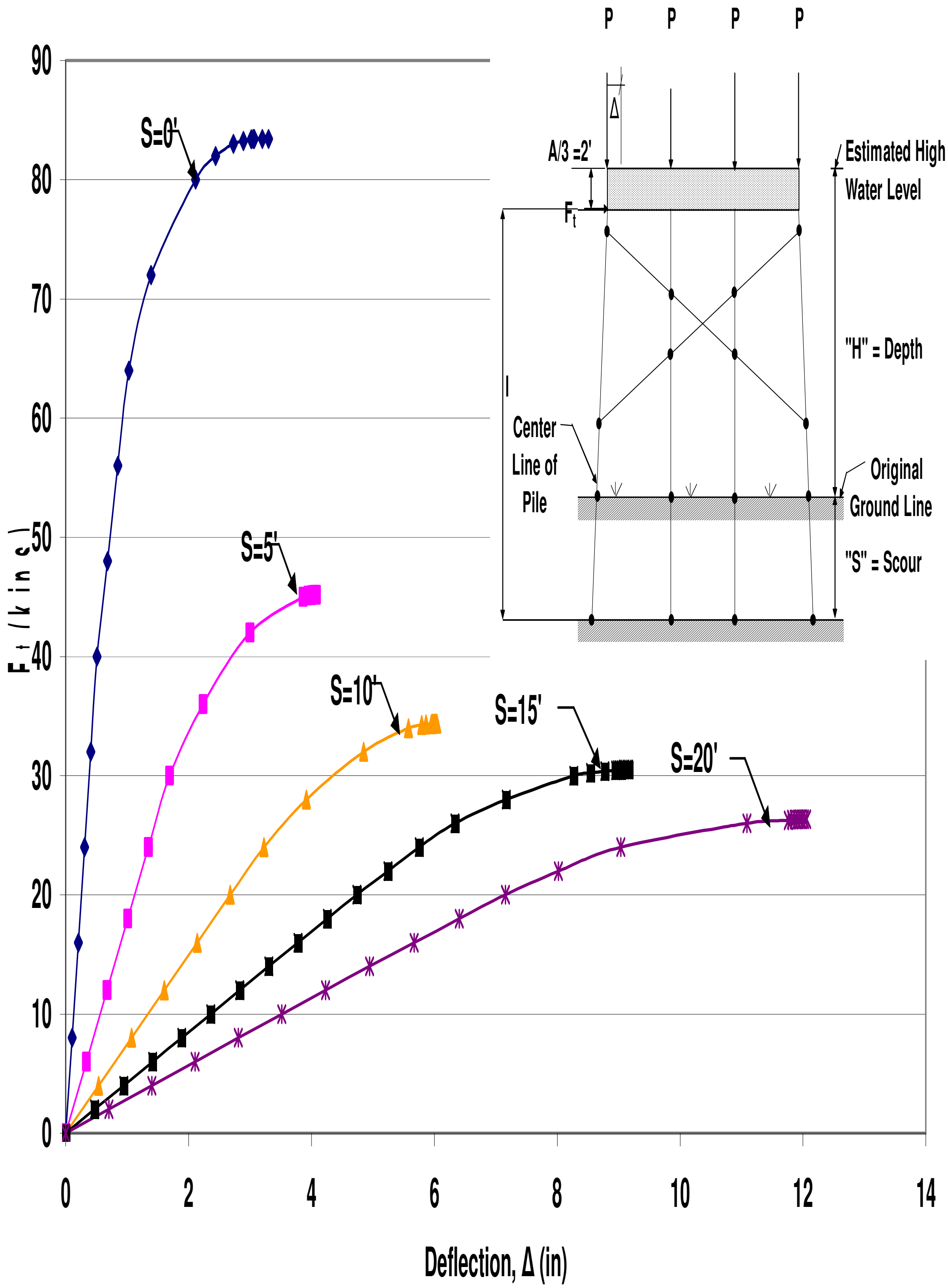


Figure B.33 HP12x53 X-Braced 4-Pile Bent with H=13', P=100kips and A=6'
Pushover Analysis Results

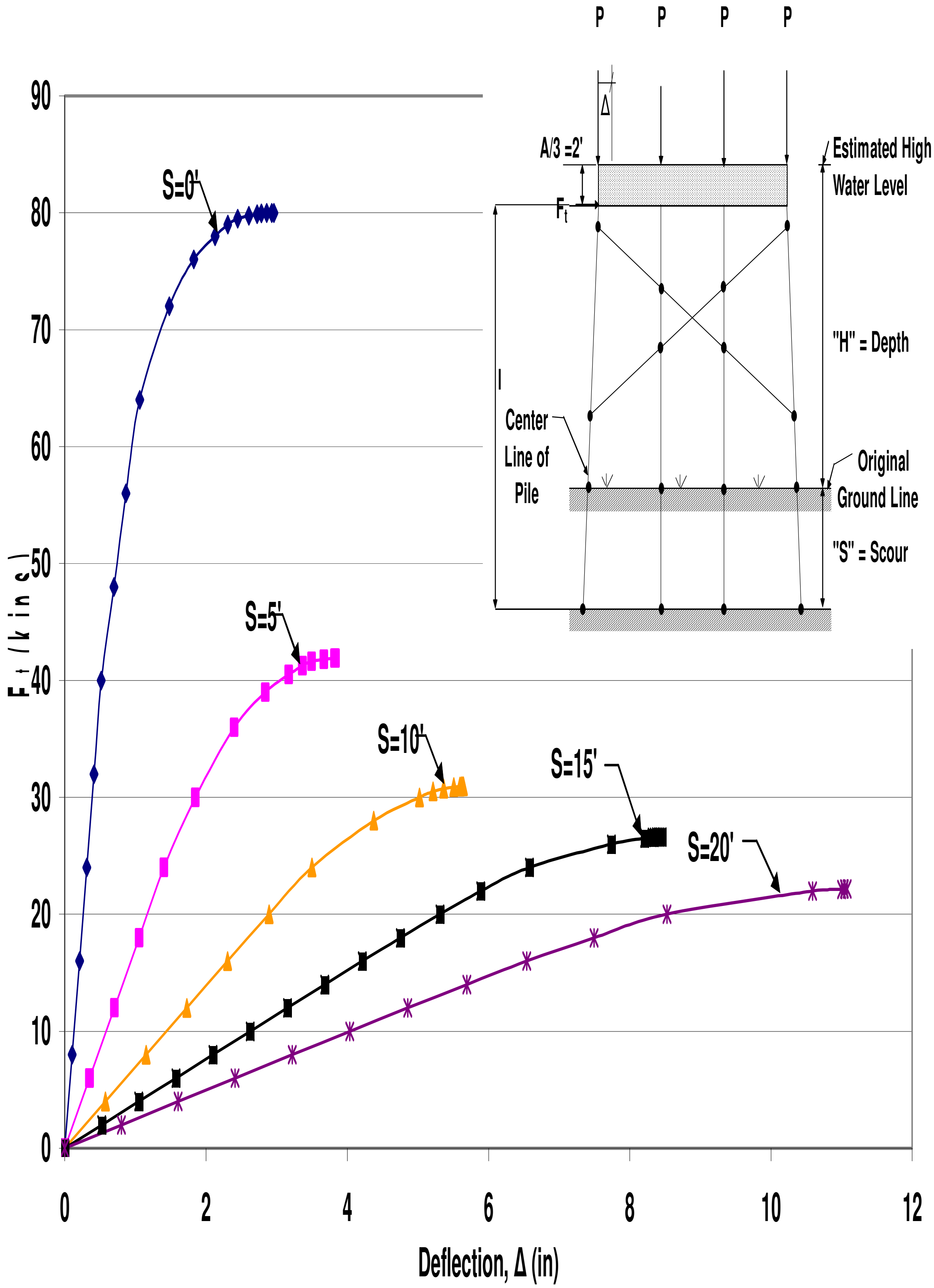


Figure B.34 HP12x53 X-Braced 4-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

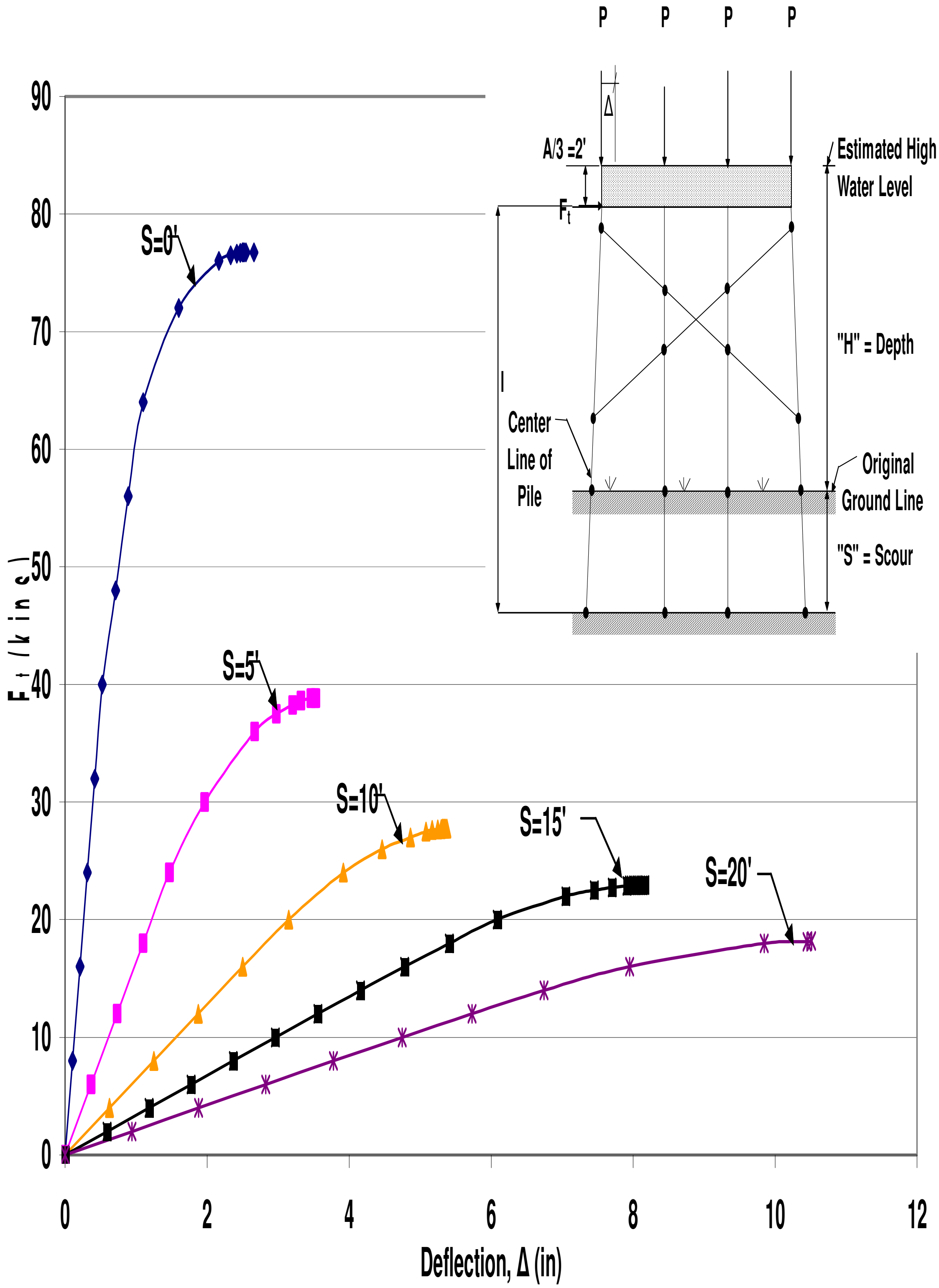


Figure B.35 HP12x53 X-Braced 4-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

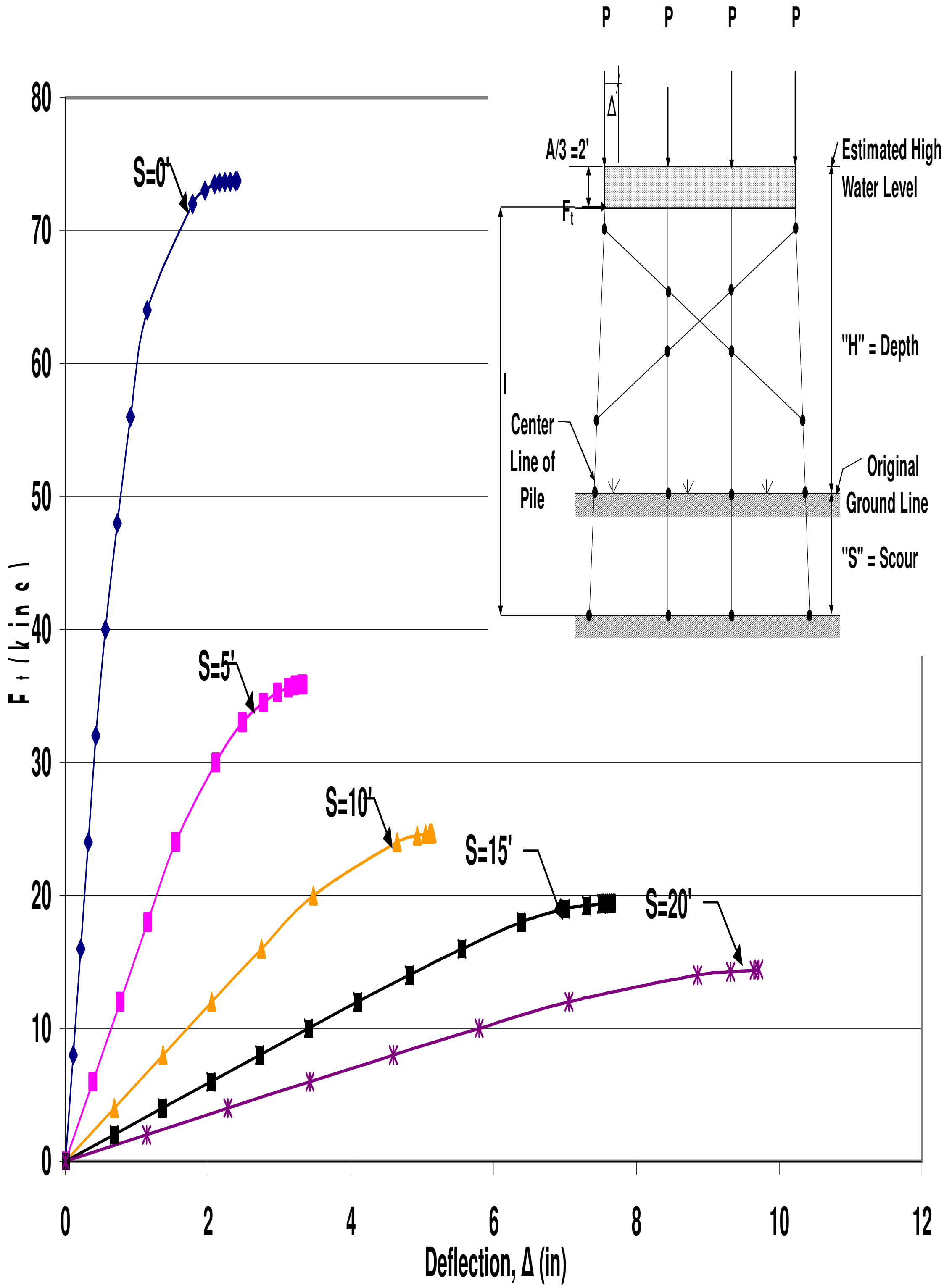


Figure B.36 HP12x53 X-Braced 4-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

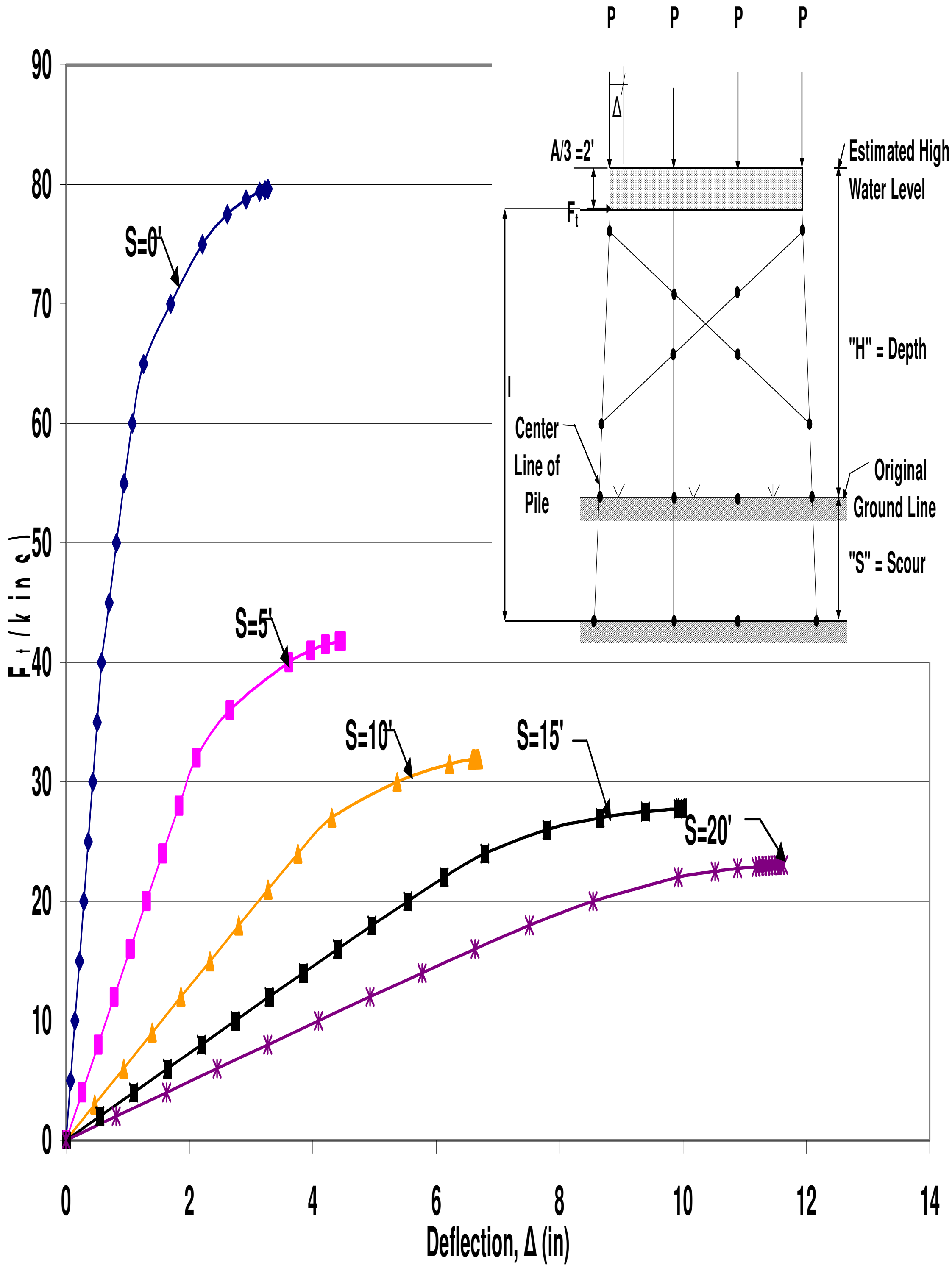


Figure B.37 HP12x53 X-Braced 4-Pile Bent with H=17', P=100kips and A=6'

Pushover Analysis Results

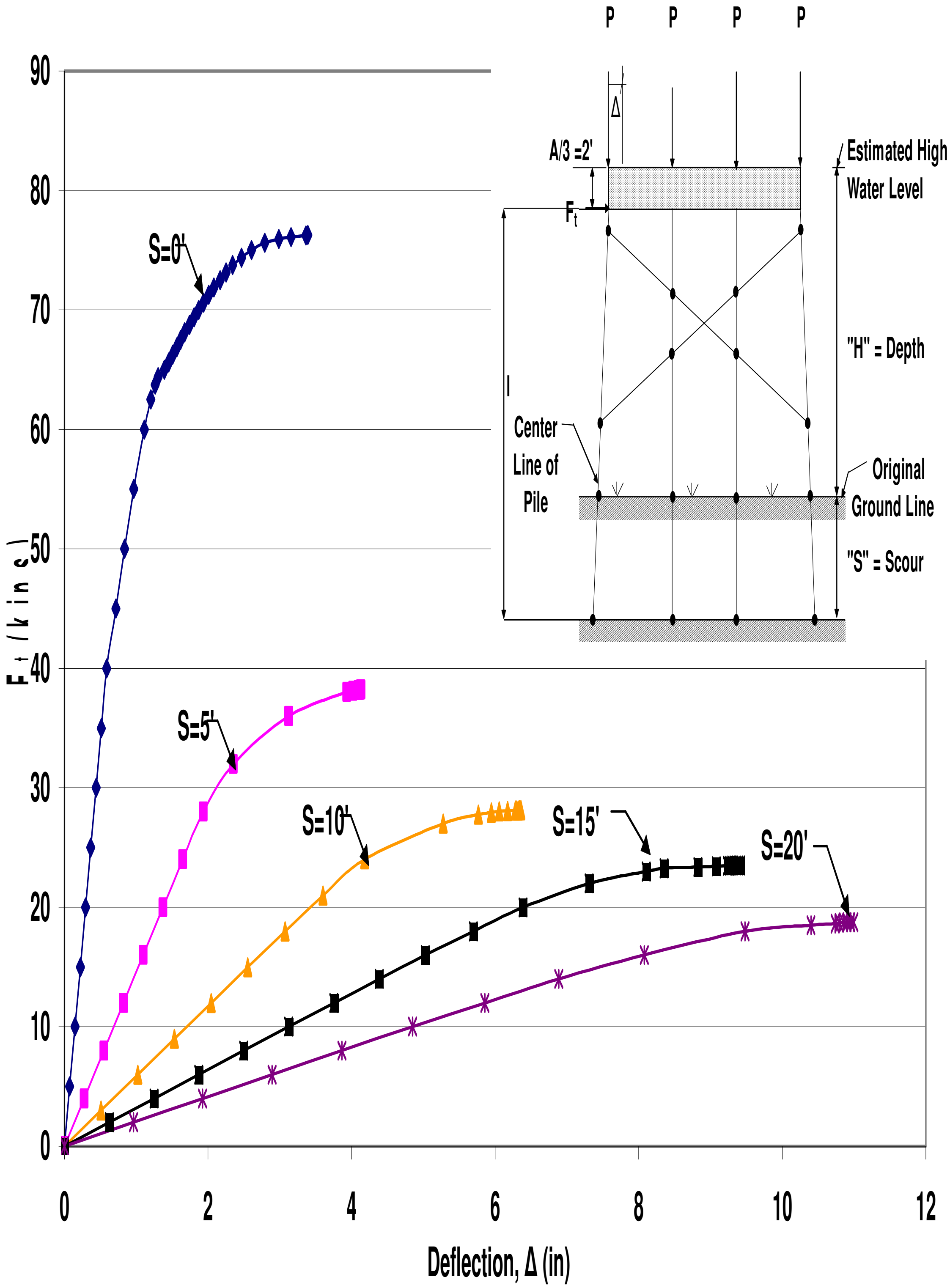


Figure B.38 HP12x53 X-Braced 4-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

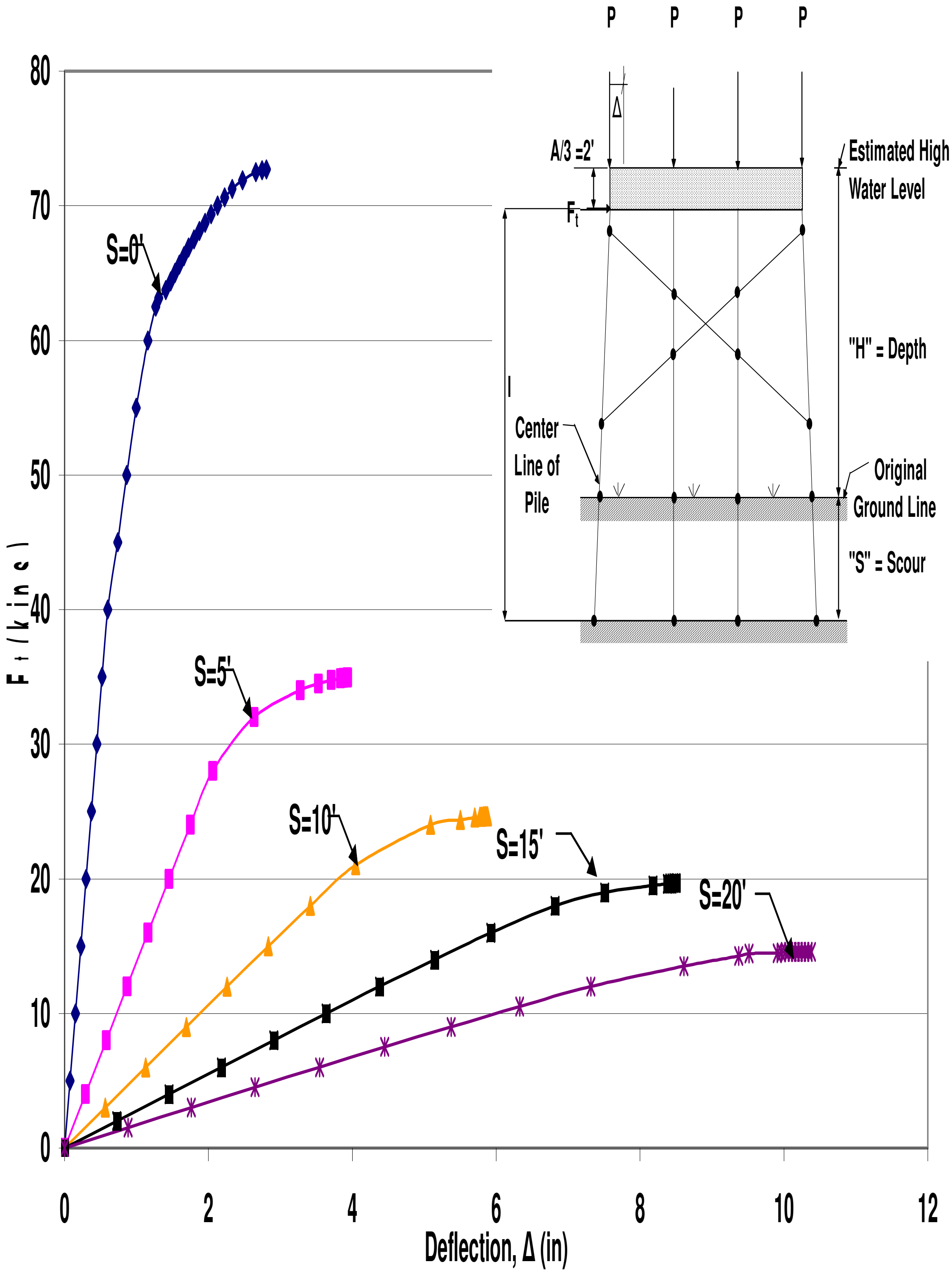


Figure B.39 HP12x53 X-Braced 4-Pile Bent with H=17', P=140kips and A=6'

Pushover Analysis Results

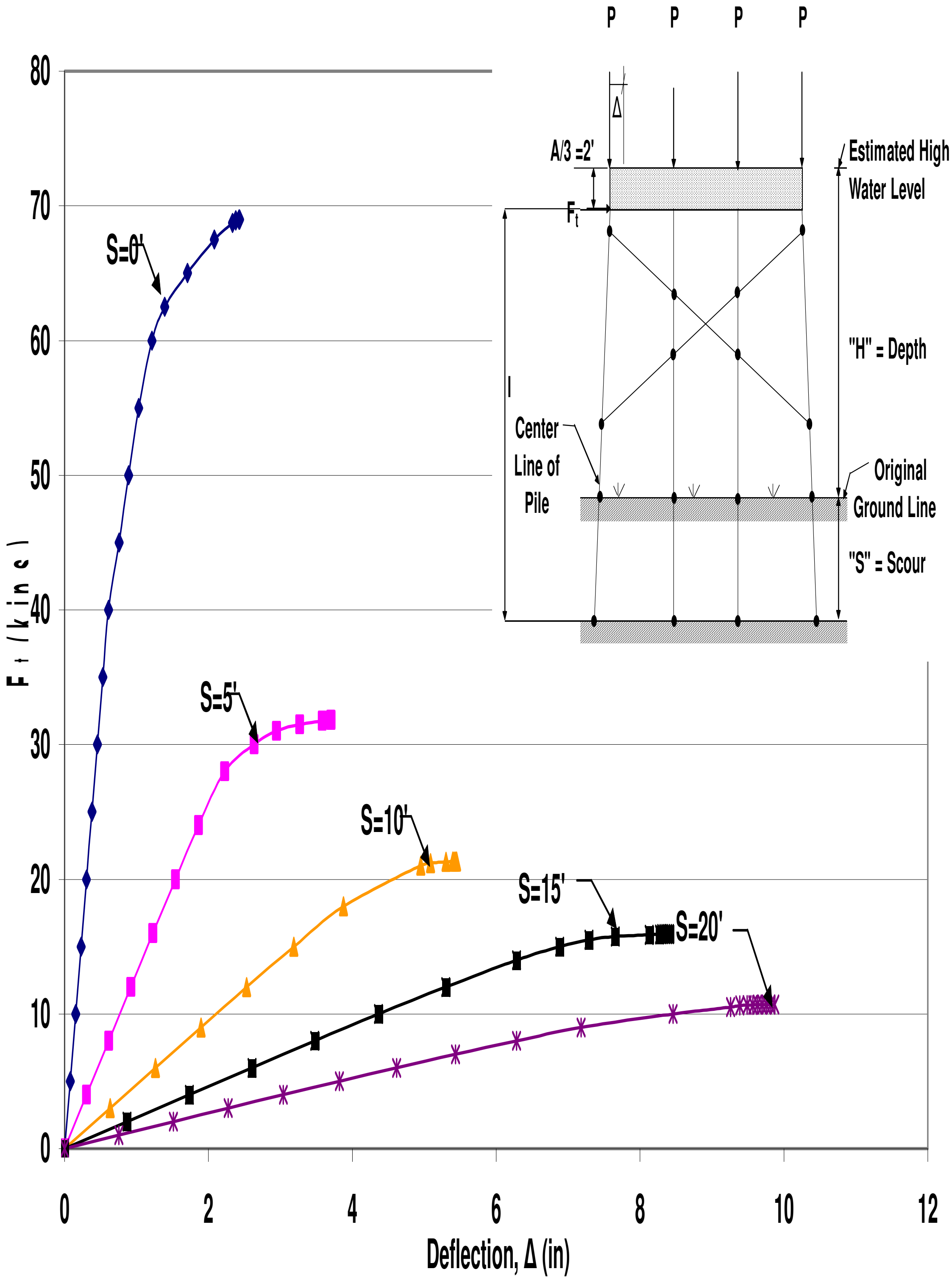


Figure B.40 HP12x53 X-Braced 4-Pile Bent with H=17', P=160kips and A=6'
Pushover Analysis Results

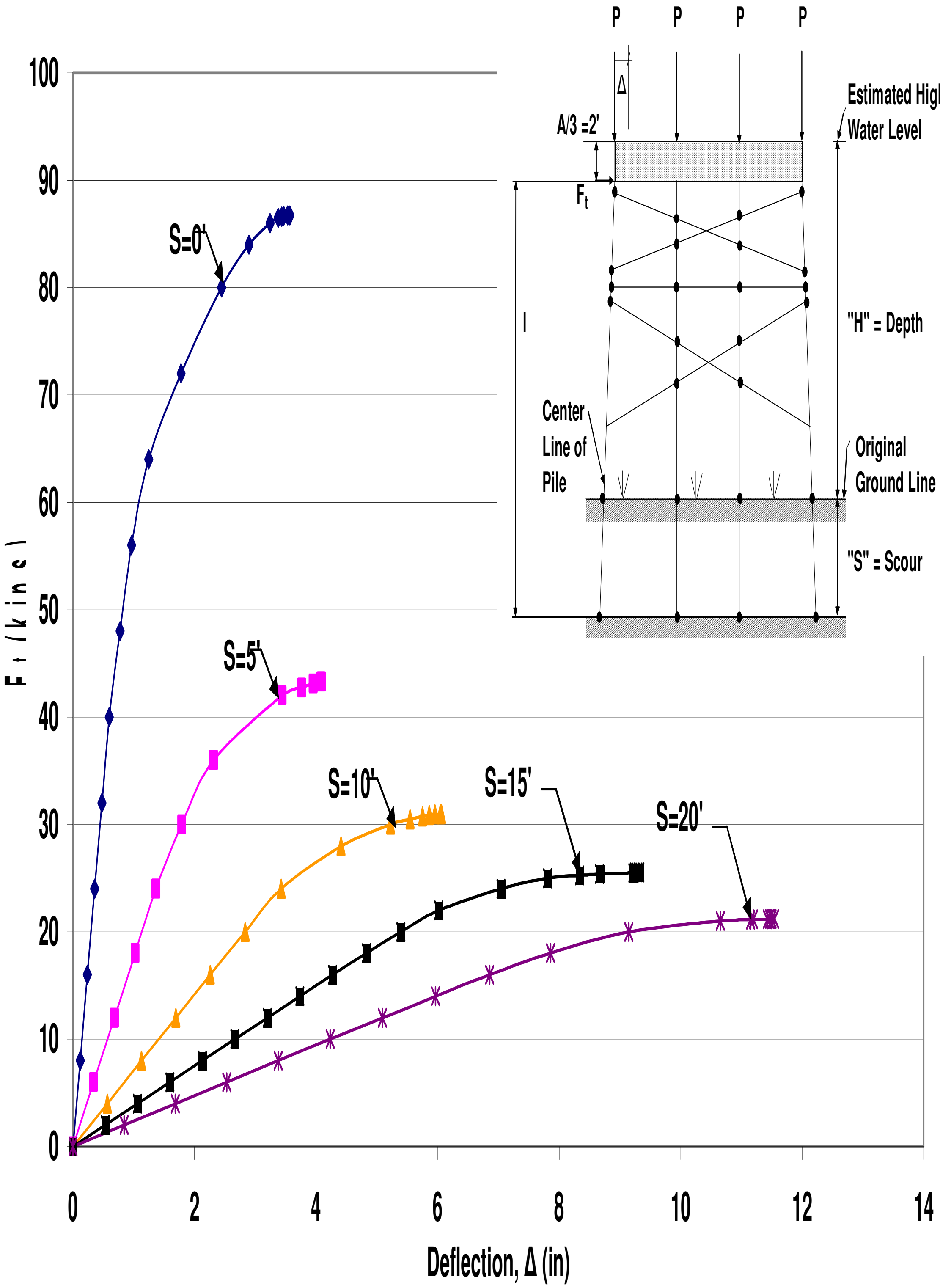


Figure B.41 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

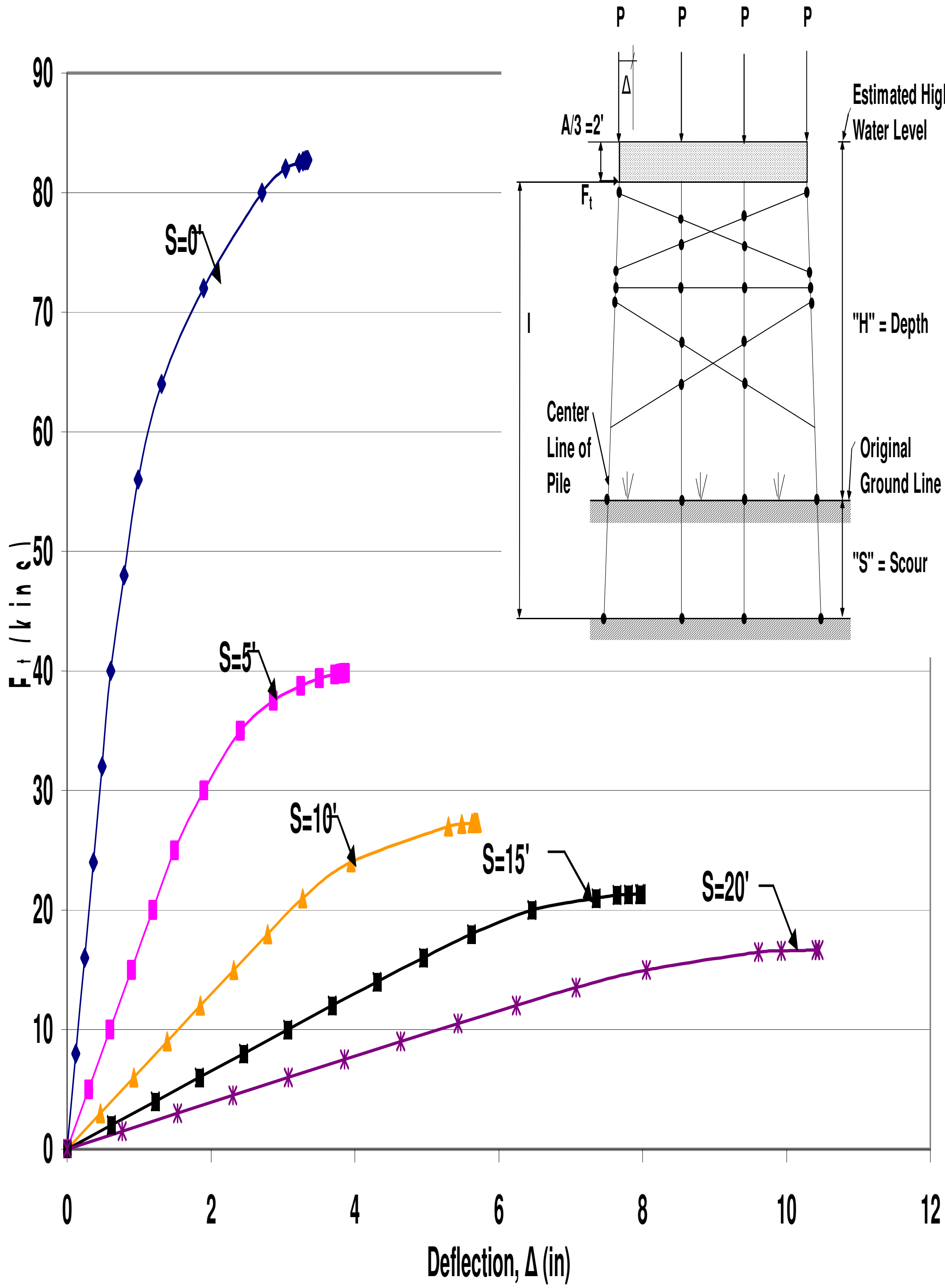


Figure B.42 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

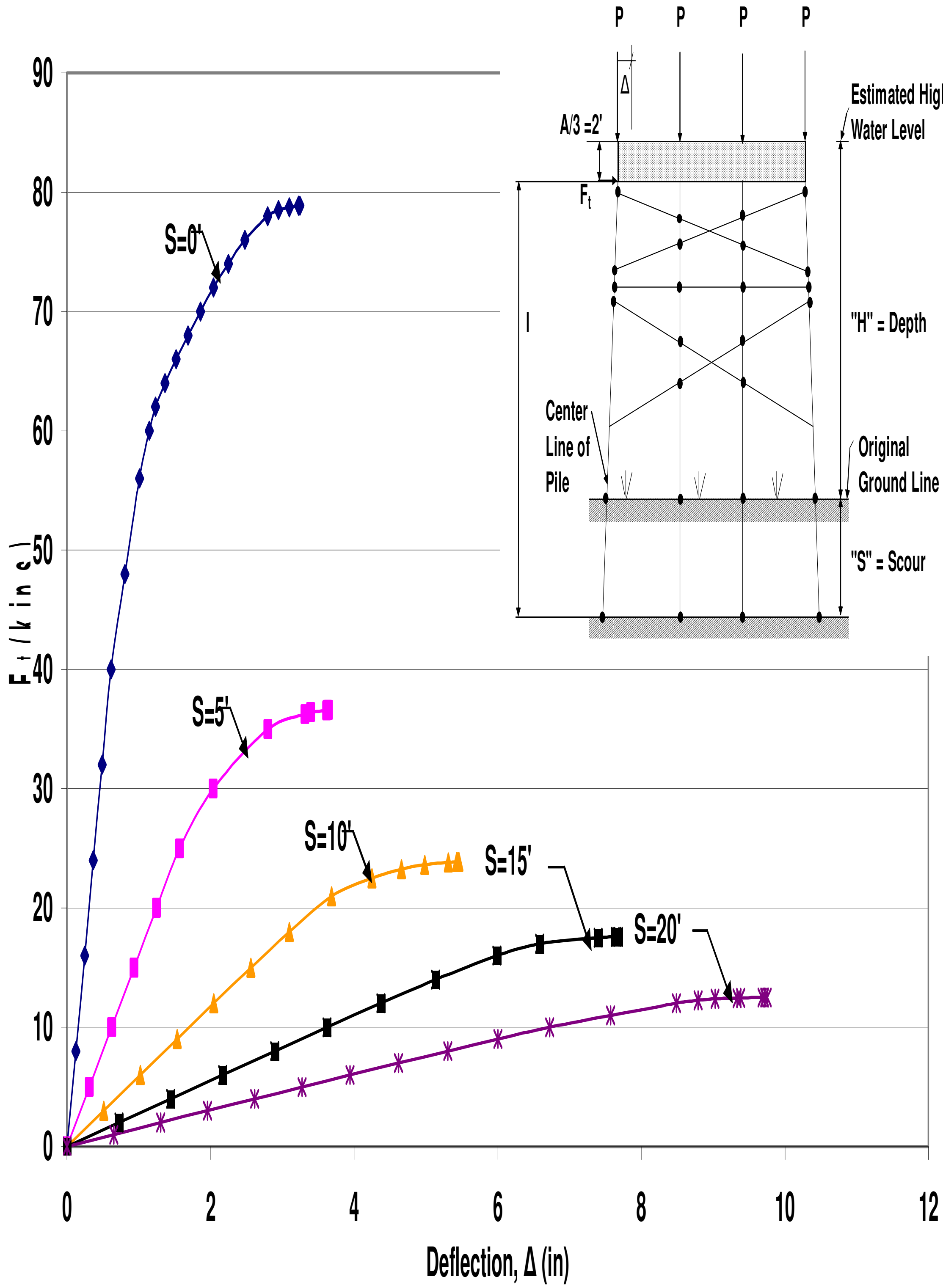


Figure B.43 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

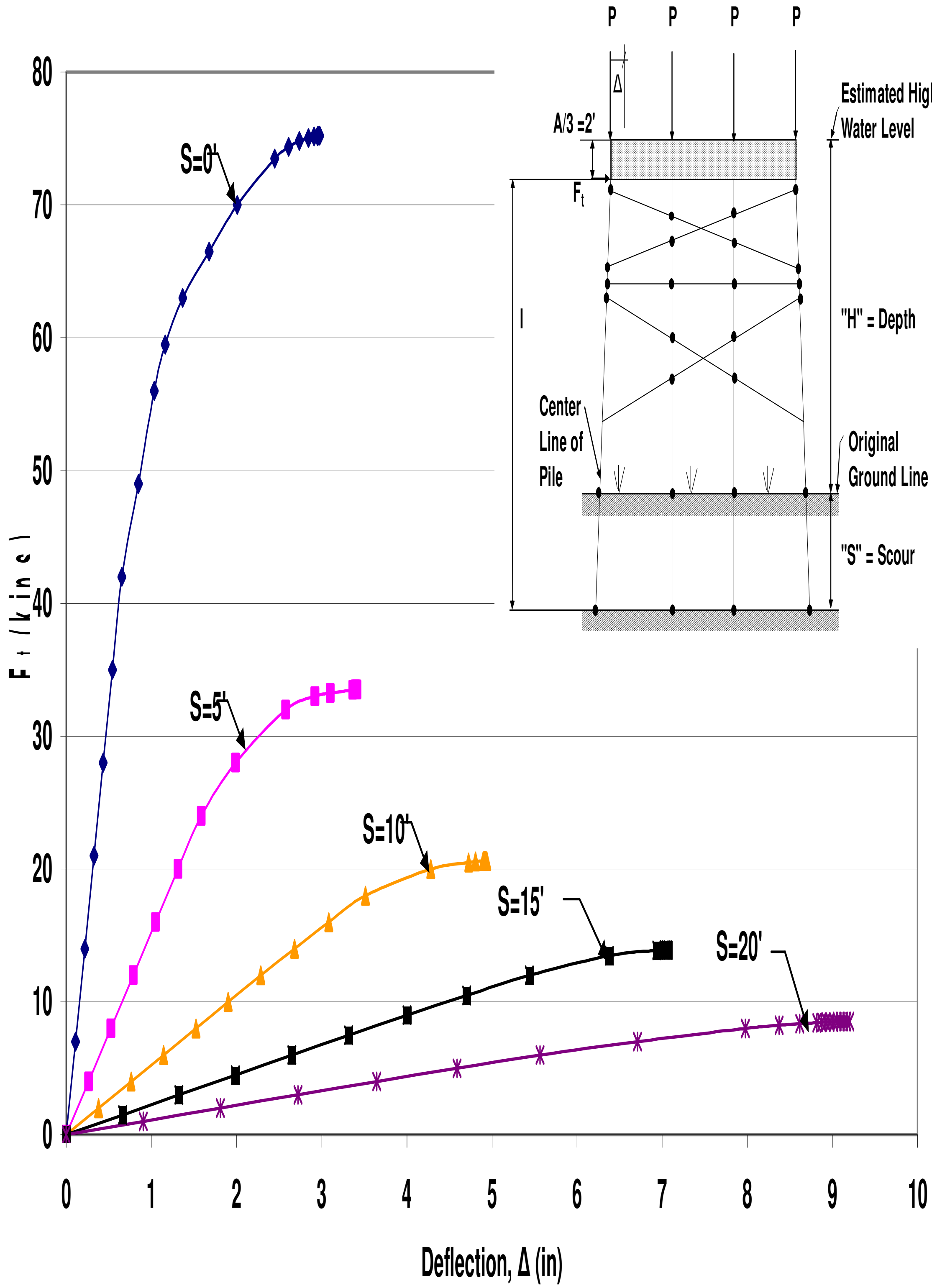


Figure B.44 HP12x53 Two-Story X-Braced 4-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

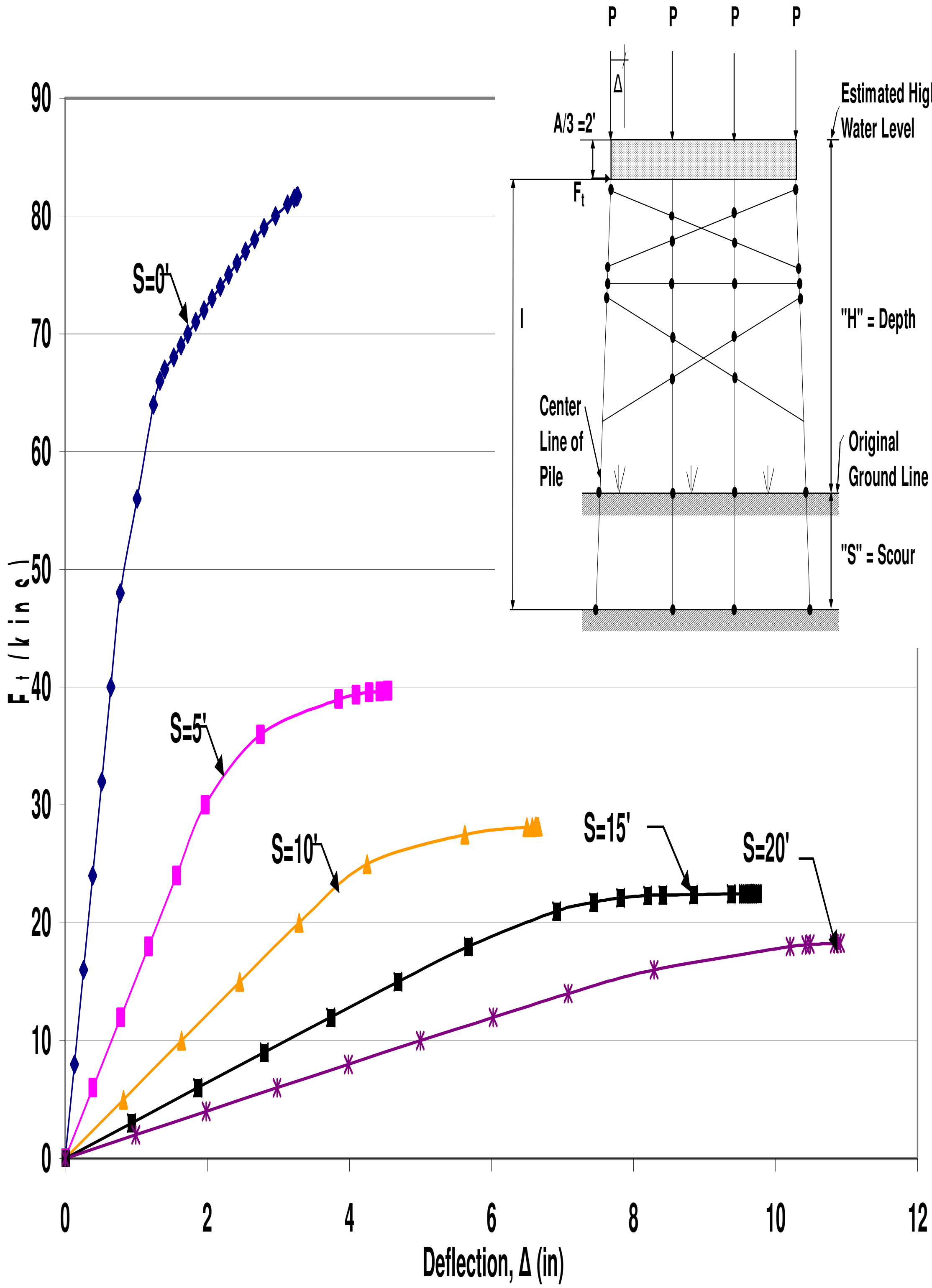


Figure B.45 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

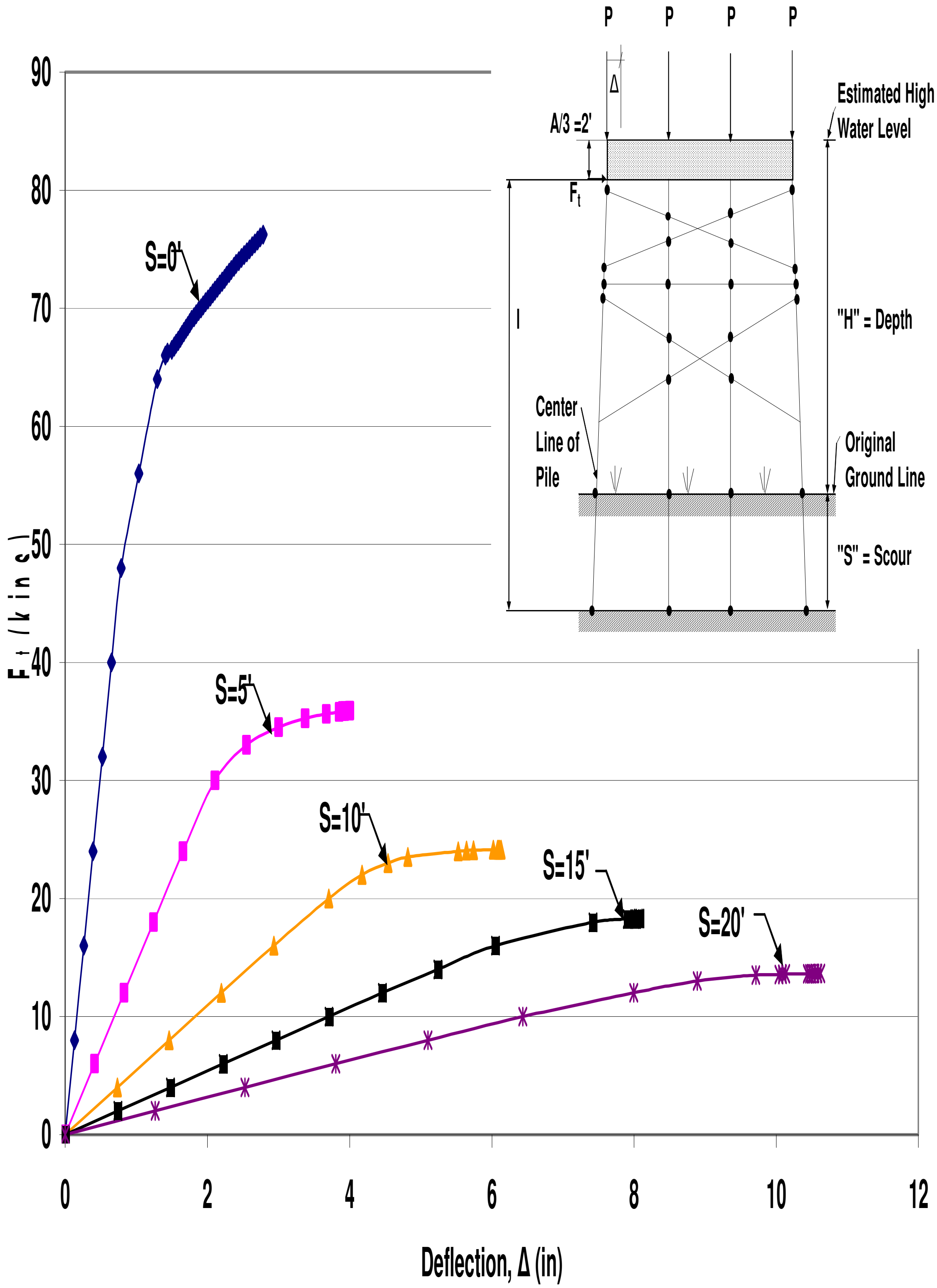


Figure B.46 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

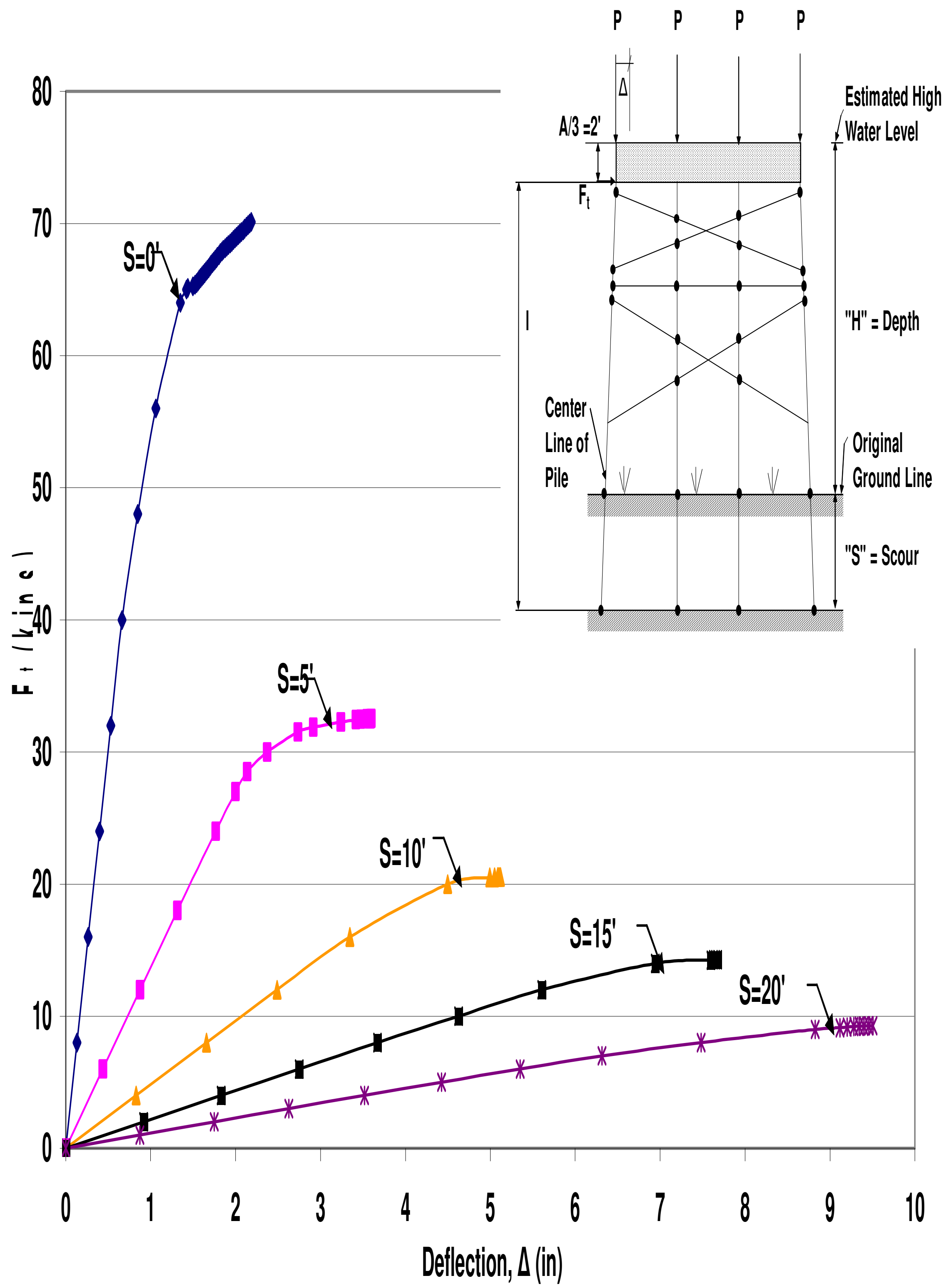


Figure B.47 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

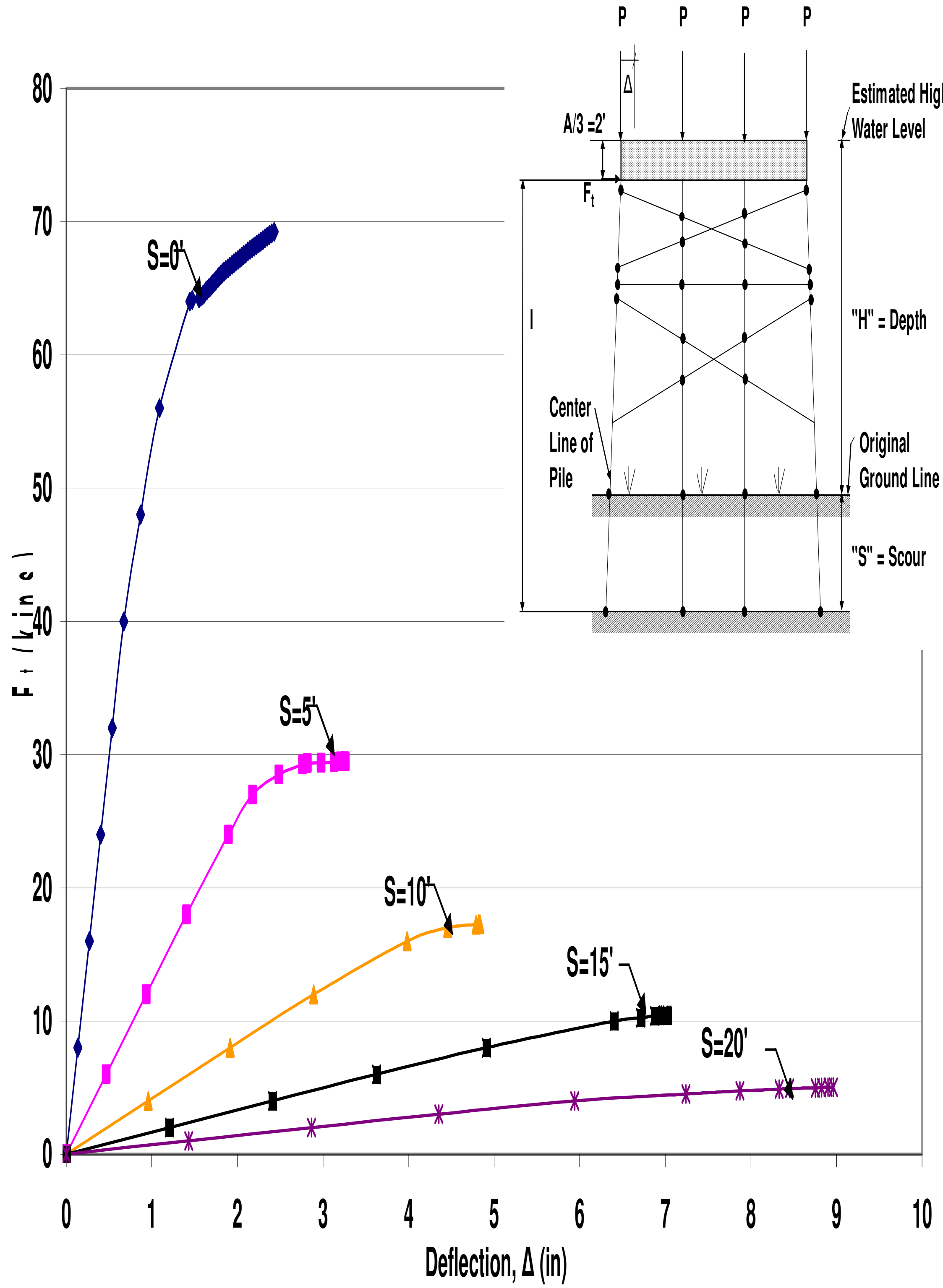


Figure B.48 HP12x53 Two-Story X-Braced 4-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

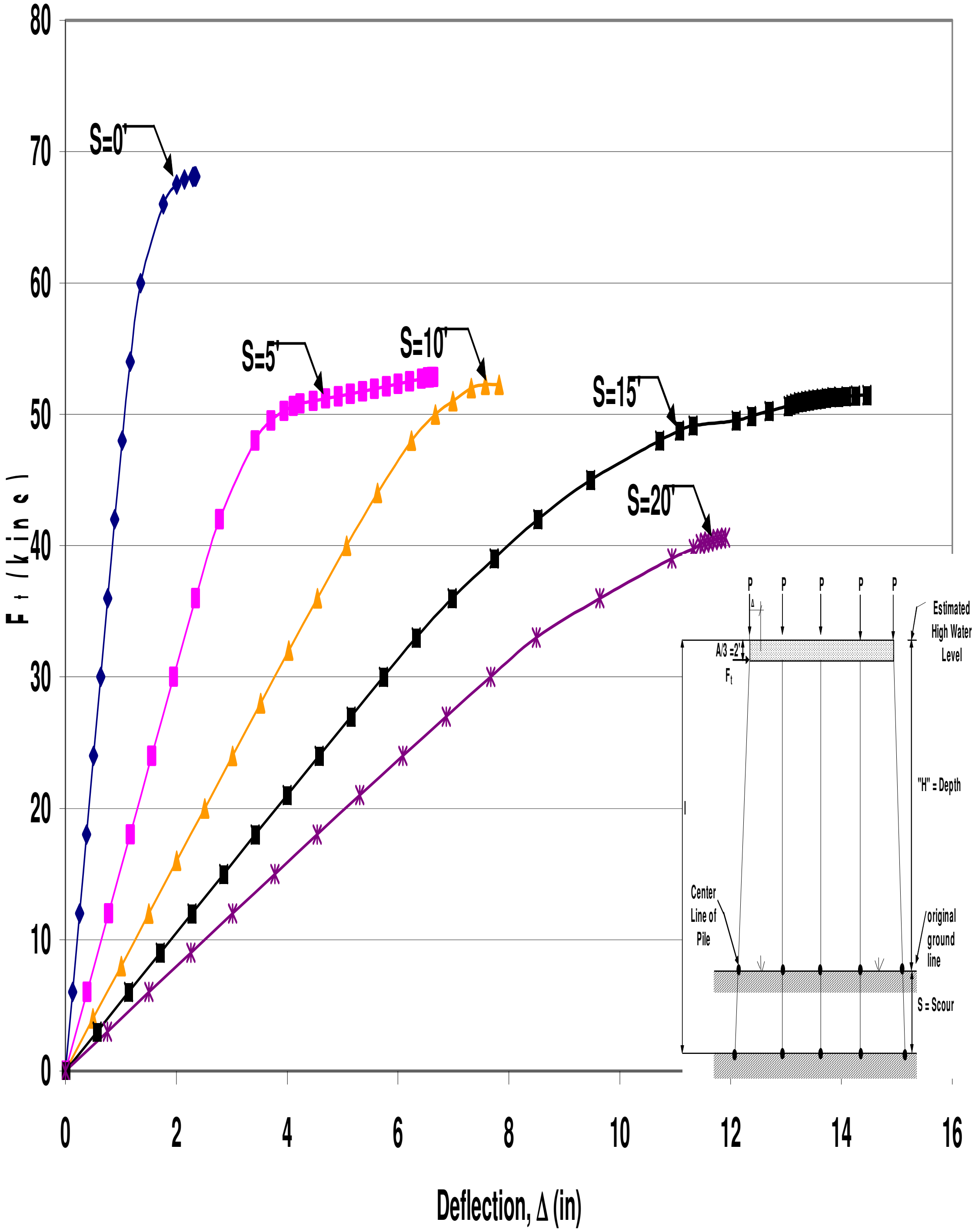


Figure B.49 HP12x53 Unbraced 5-Pile Bent with H=10',P=100kips and A=6'

Pushover Analysis Results

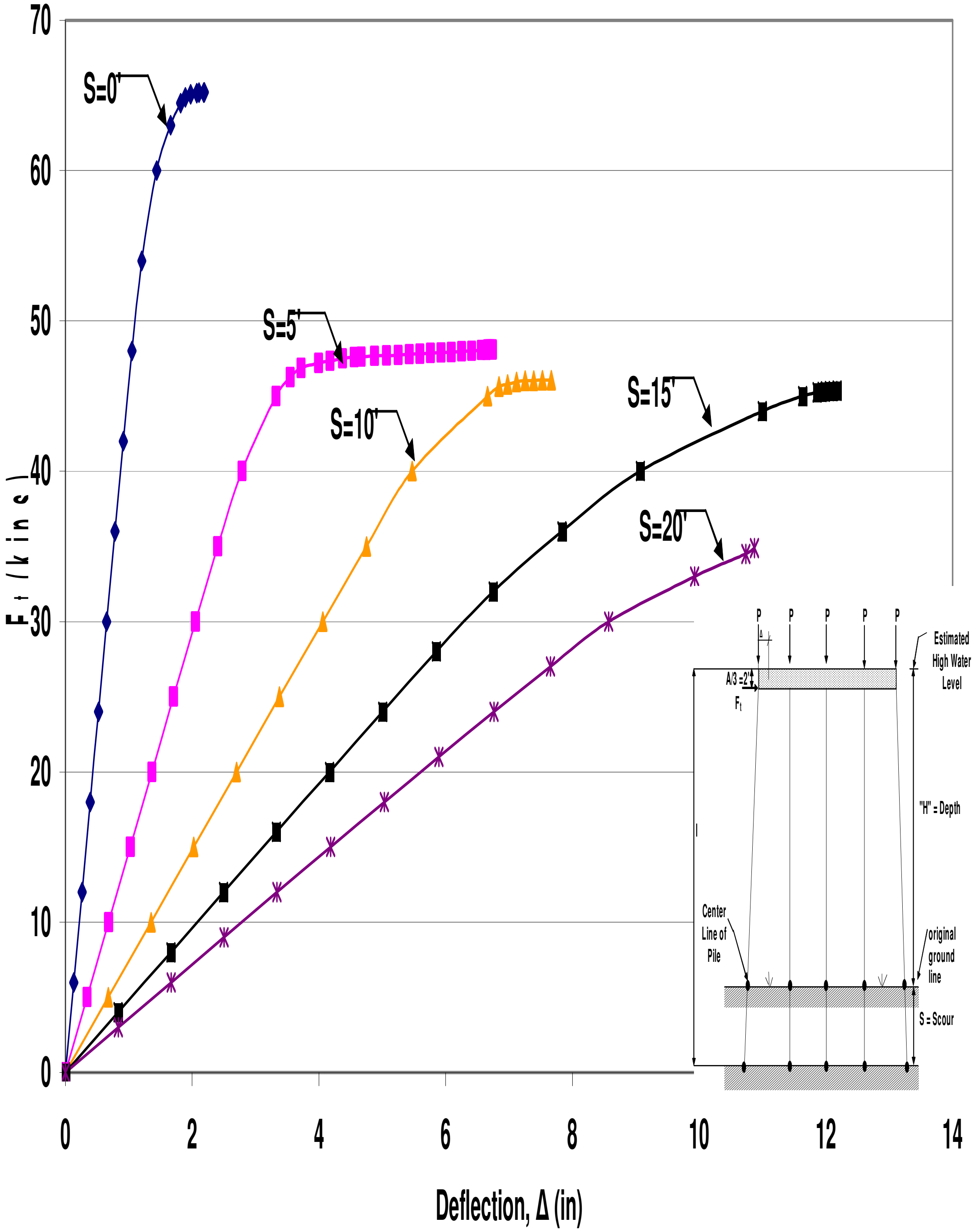


Figure B.50 HP12x53 Unbraced 5-Pile Bent with H=10', P=120kips and A=6'
Pushover Analysis Results

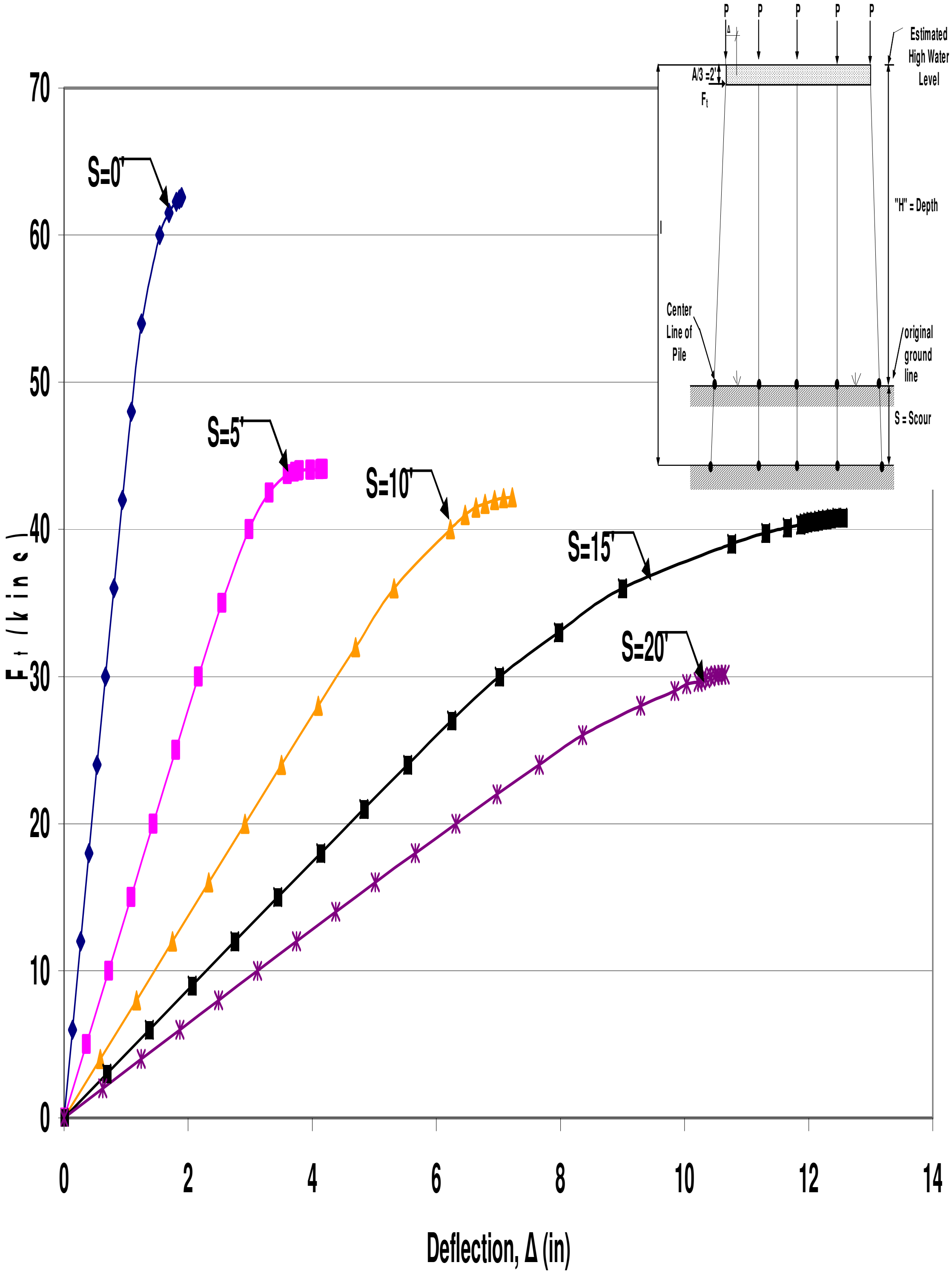


Figure B.51 HP12x53 Unbraced 5-Pile Bent with H=10', P=140kips and A=6'

Pushover Analysis Results

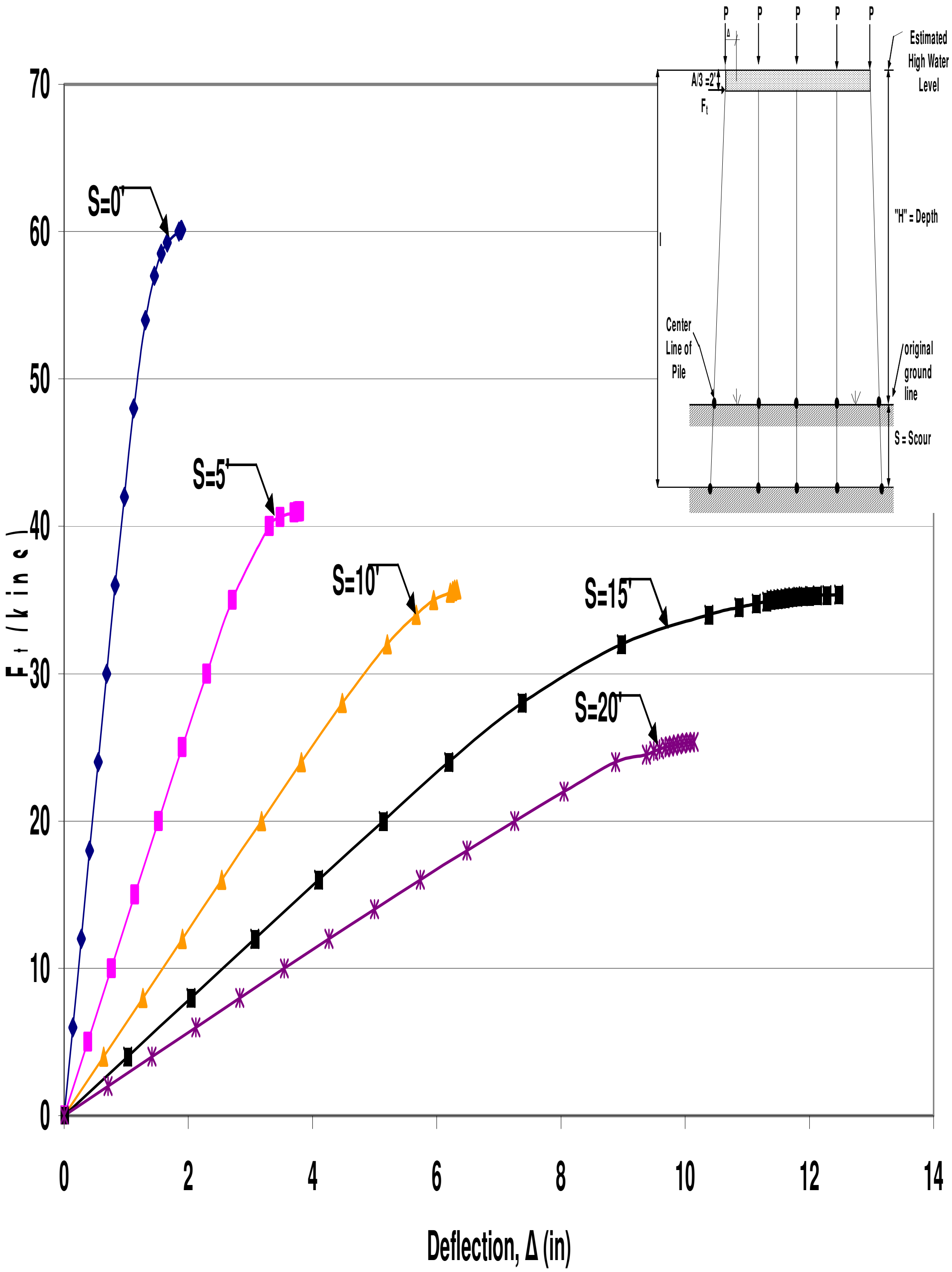


Figure B.52 HP12x53 Unbraced 5-Pile Bent with H=10', P=160kips and A=6'

Pushover Analysis Results

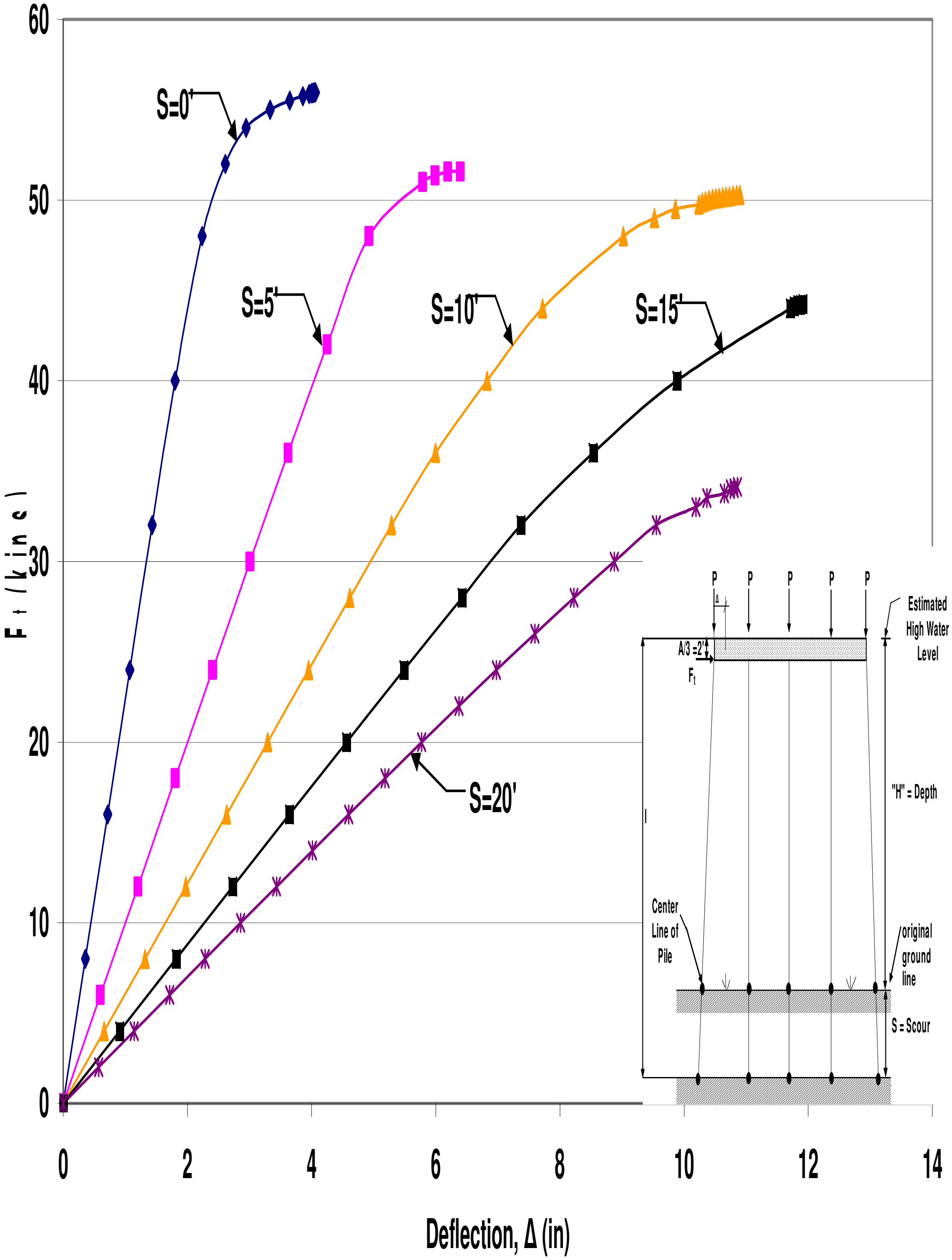


Figure B.53 HP12x53 Unbraced 5-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

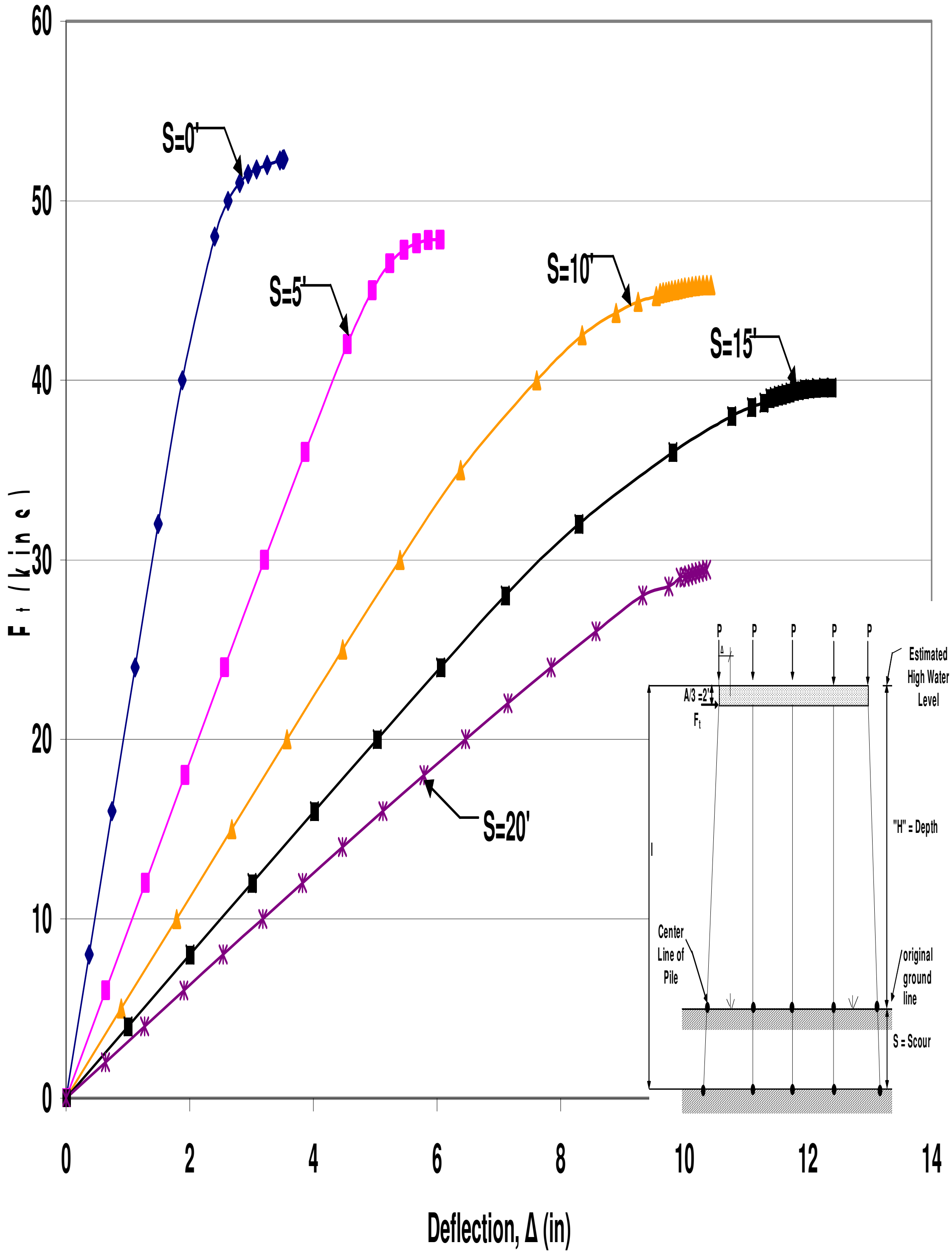


Figure B.54 HP12x53 Unbraced 5-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

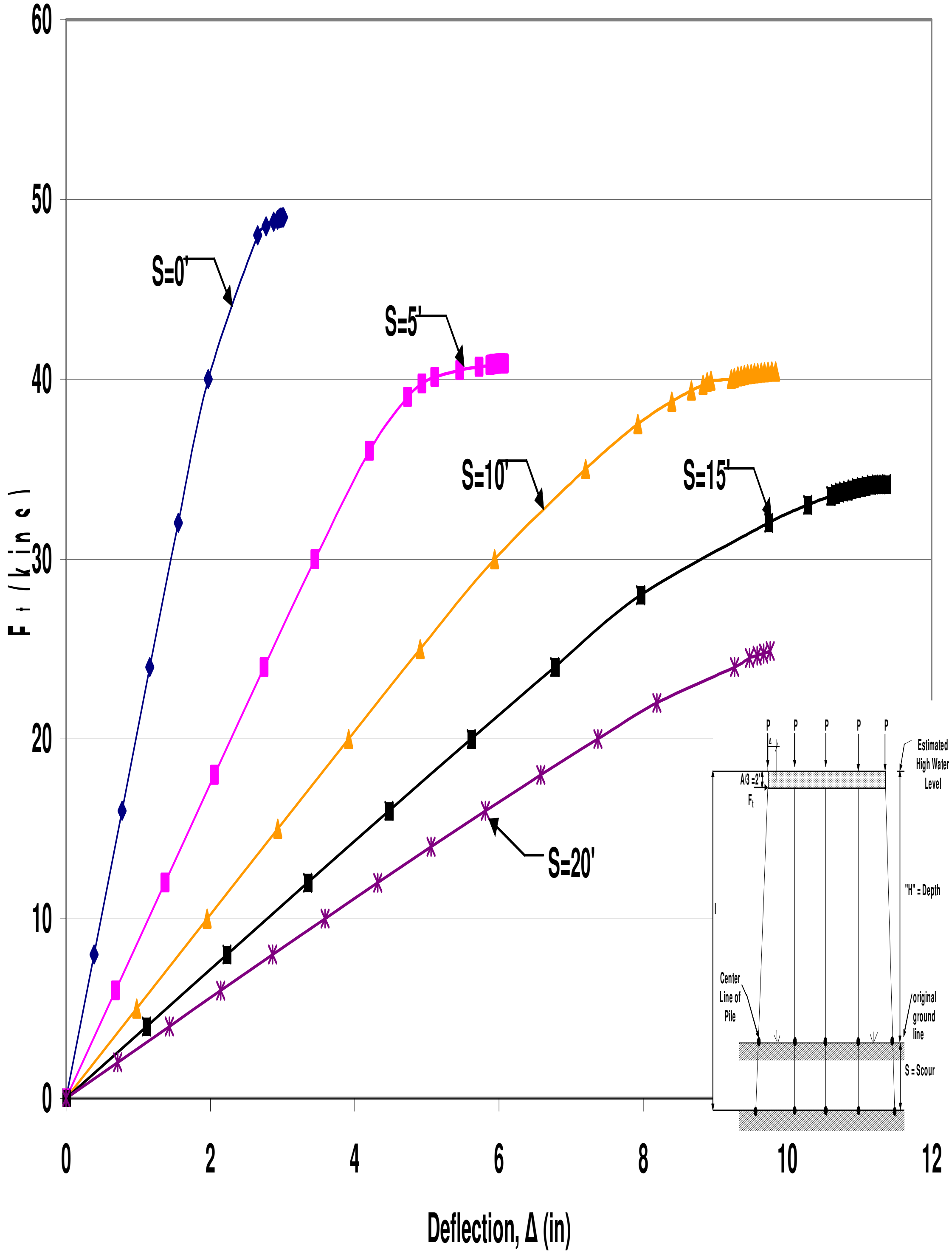


Figure B.55 HP12x53 Unbraced 5-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

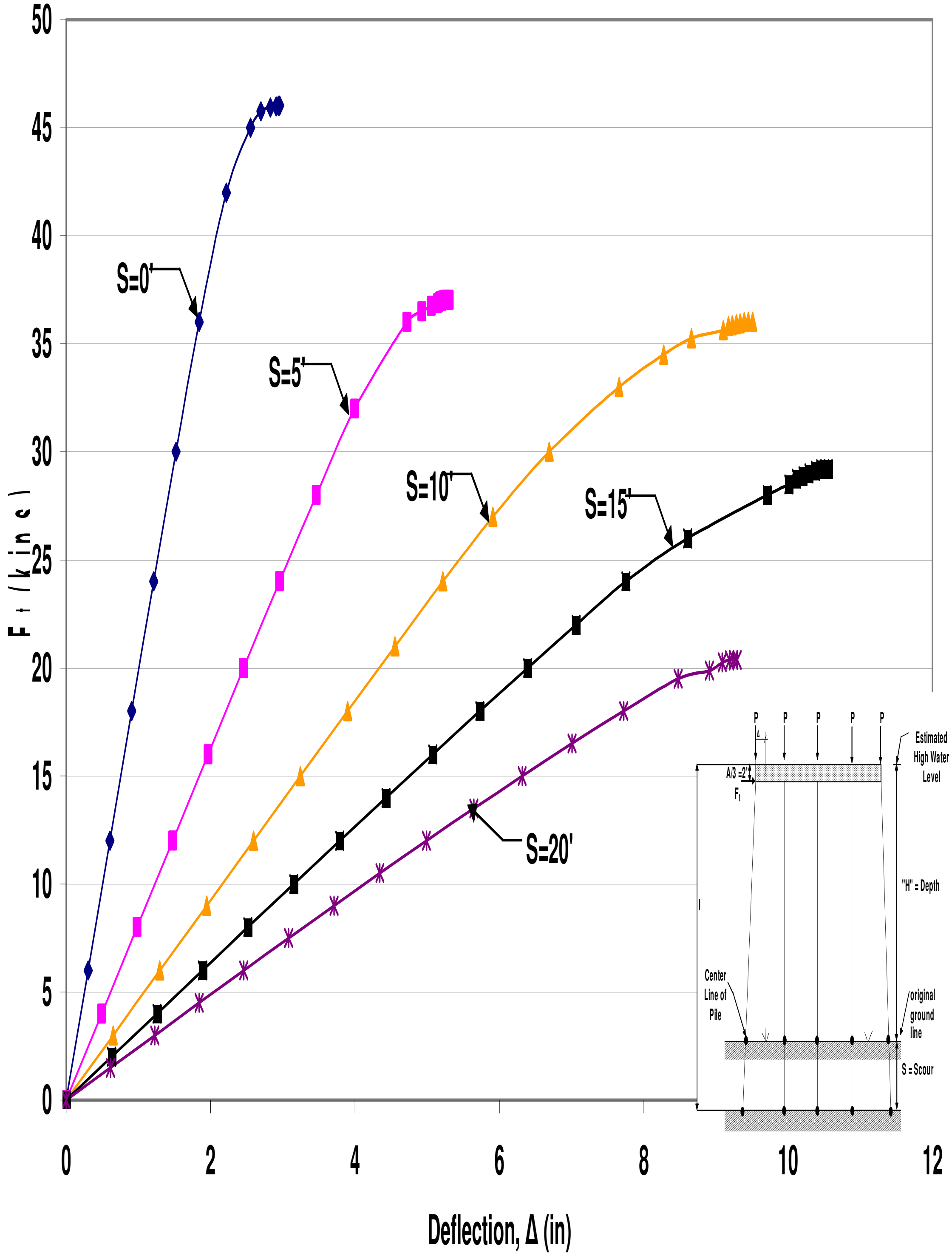


Figure B.56 HP12x53 Unbraced 5-Pile Bent with H=13', P=160kips and A=6'

Pushover Analysis Results

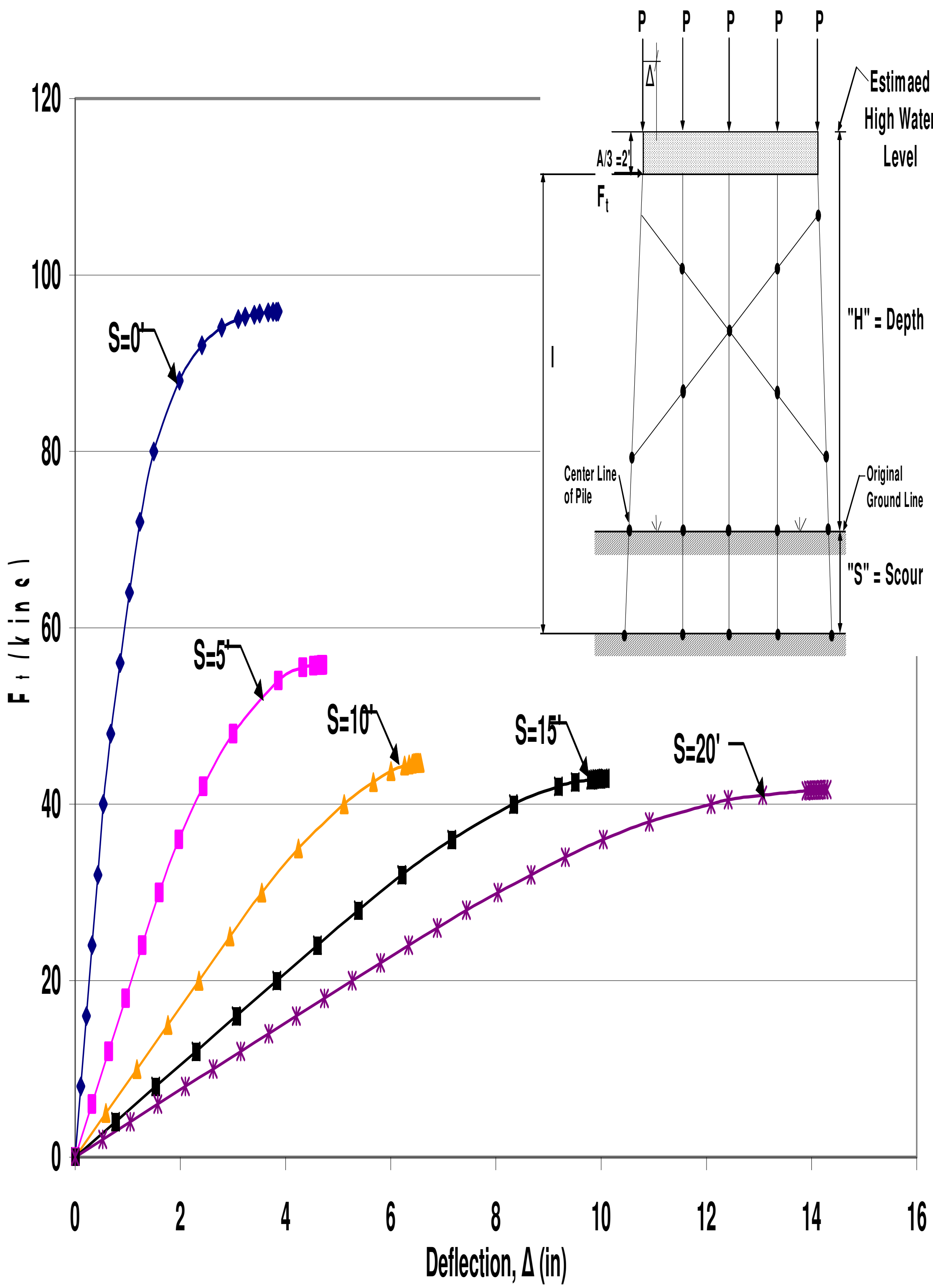


Figure B.57 HP12x53 X-Braced 5-Pile Bent with H=13', P=100kips and A=6'

Pushover Analysis Results

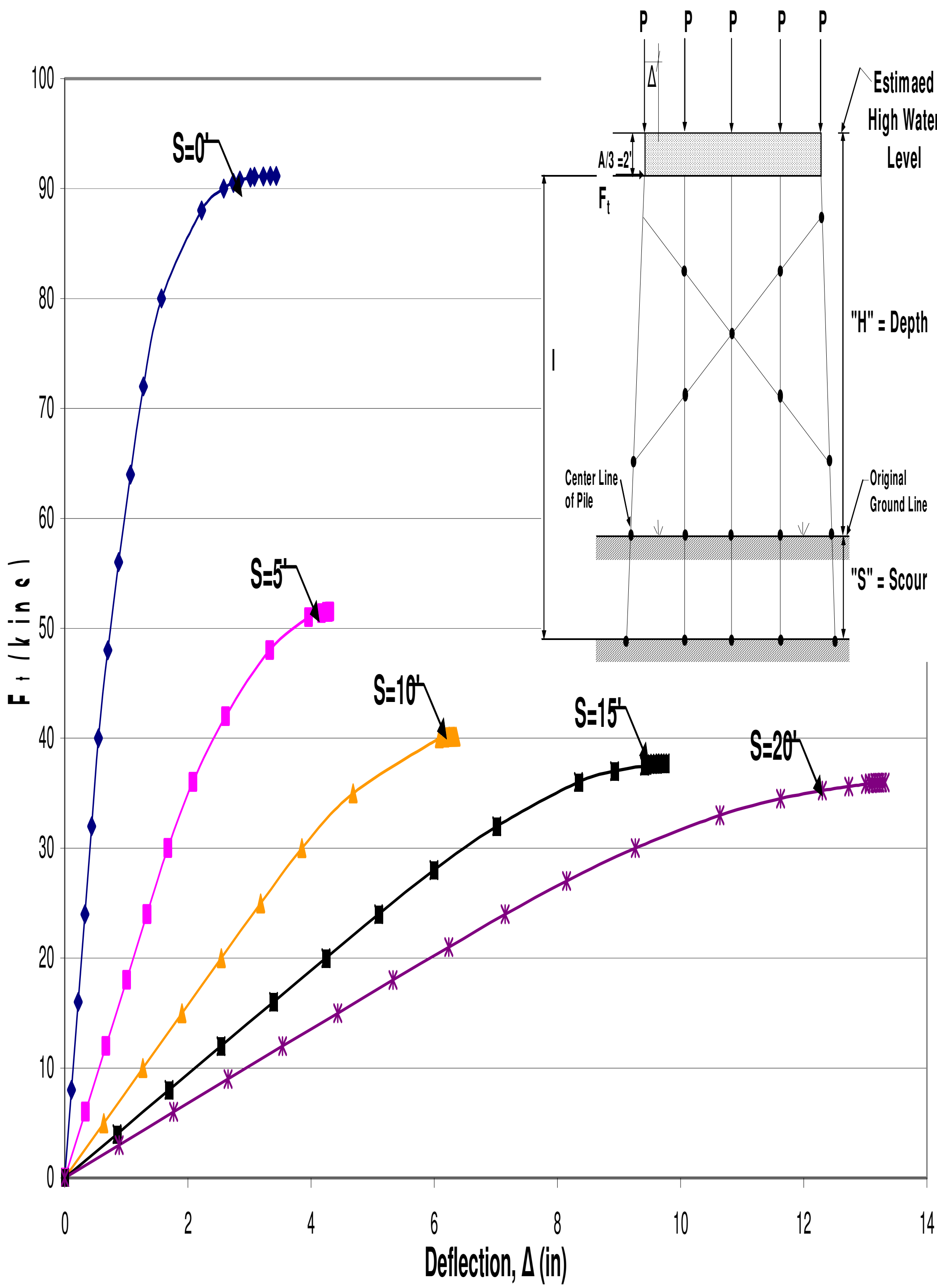


Figure B.58 HP12x53 X-Braced 5-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

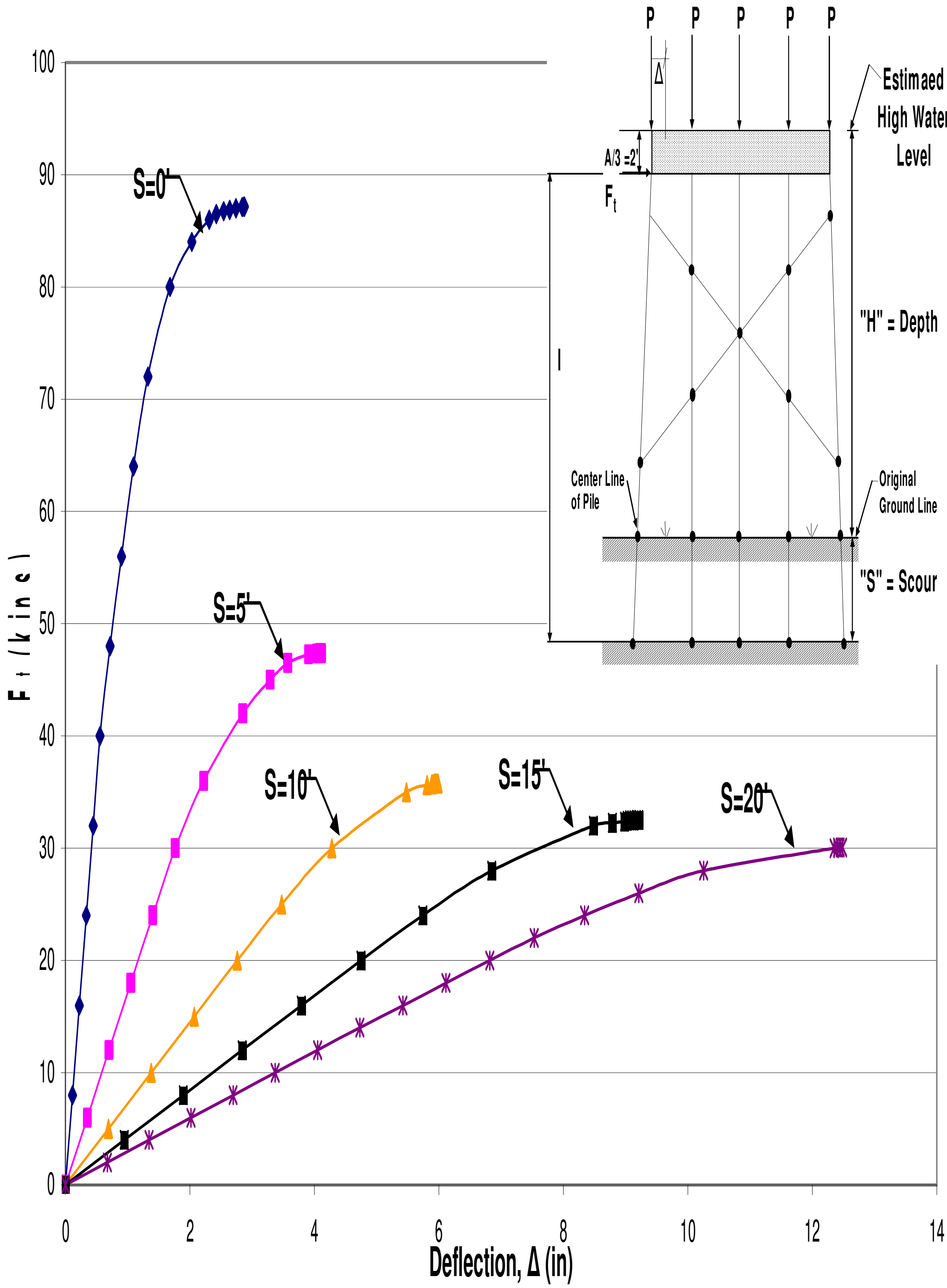


Figure B.59 HP12x53 X-Braced 5-Pile Bent with H=13', P=140kips and A=6' Pushover Analysis Results

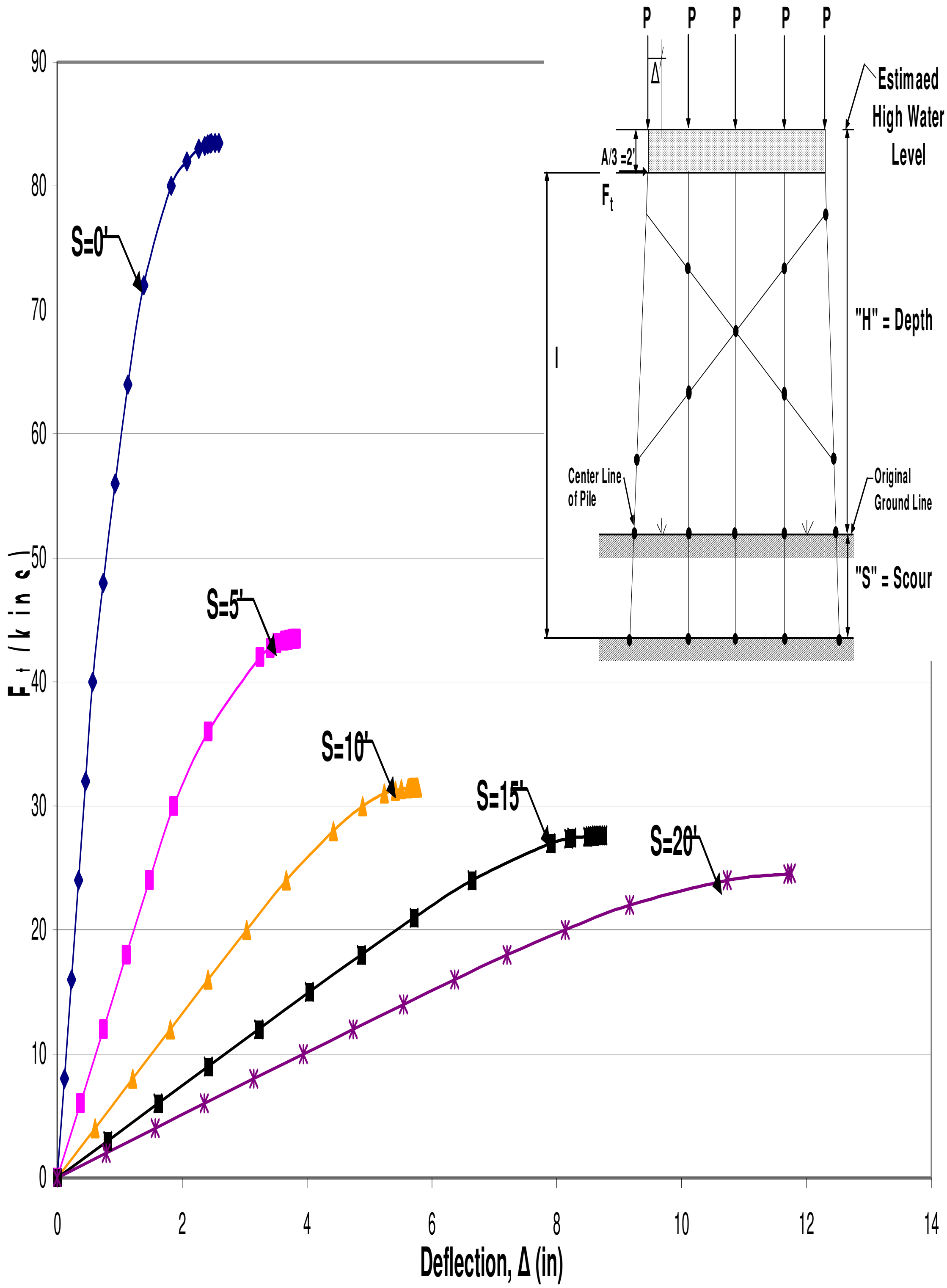


Figure B.60 HP12x53 X-Braced 5-Pile Bent with H=13', P=160kips and A=6'
Pushover Analysis Results

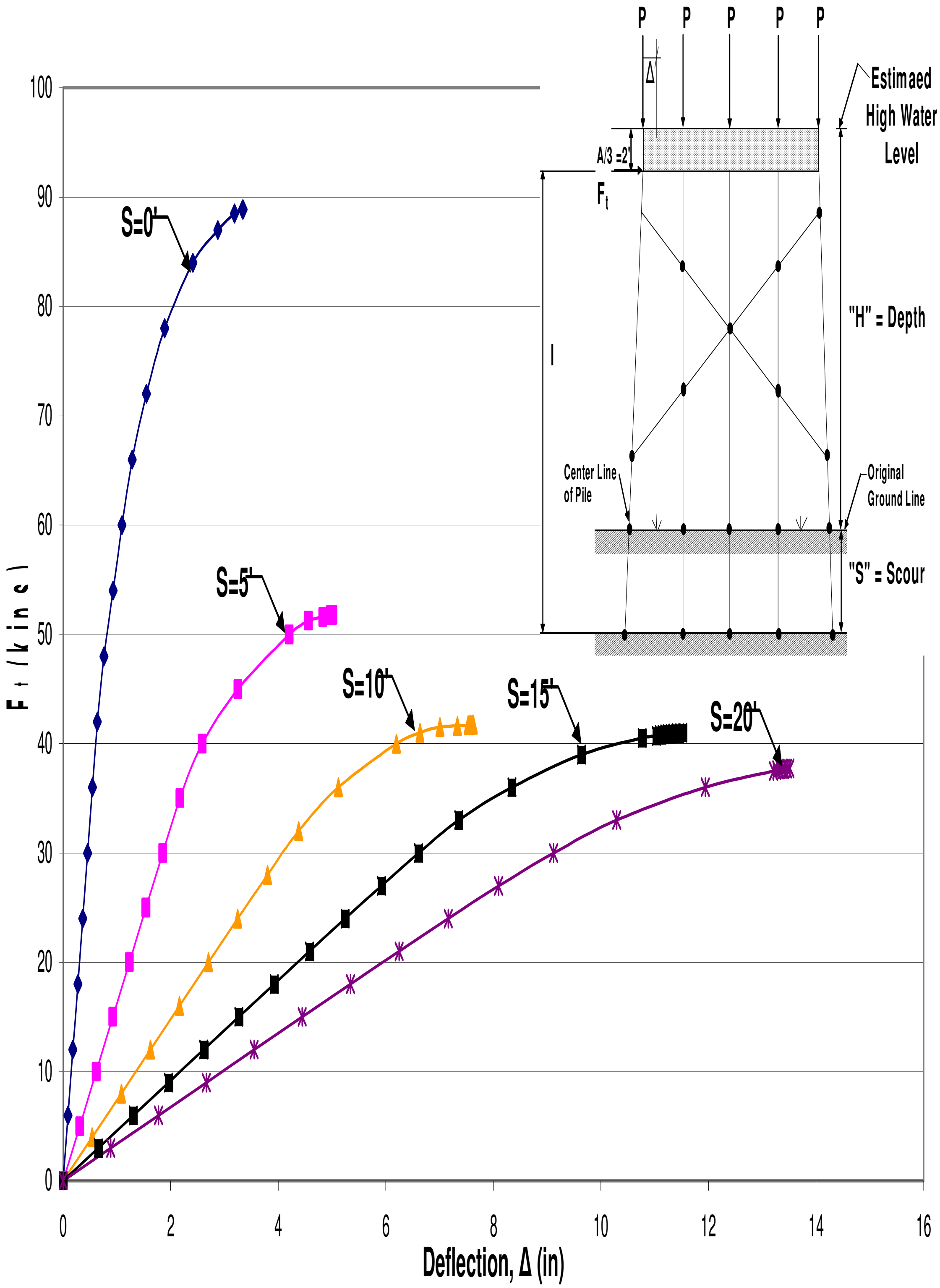


Figure B.61 HP12x53 X-Braced 5-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

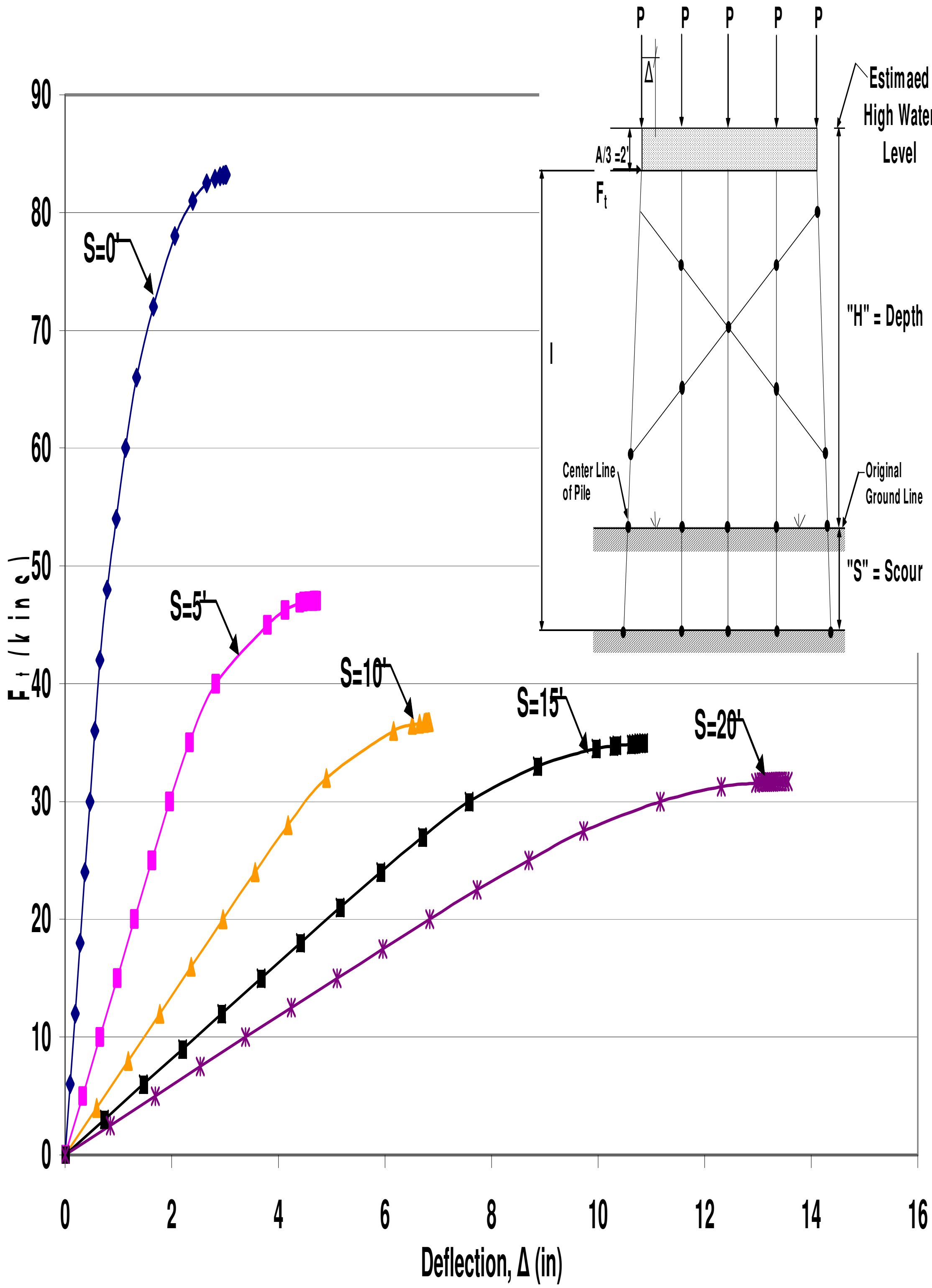


Figure B.62 HP12x53 X-Braced 5-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

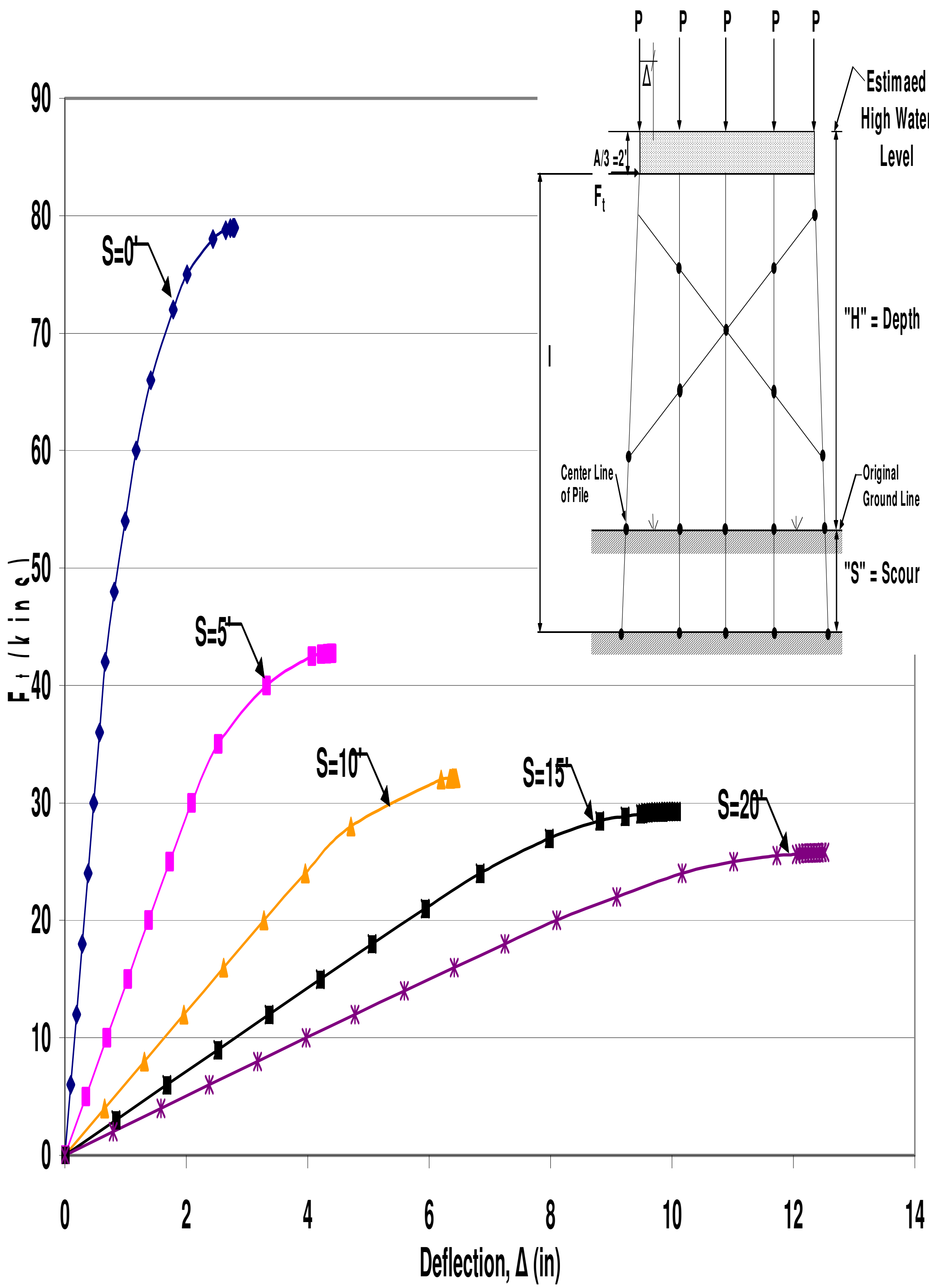


Figure B.63 HP12x53 X-Braced 5-Pile Bent with H=17', P=140kips and A=6'

Pushover Analysis Results

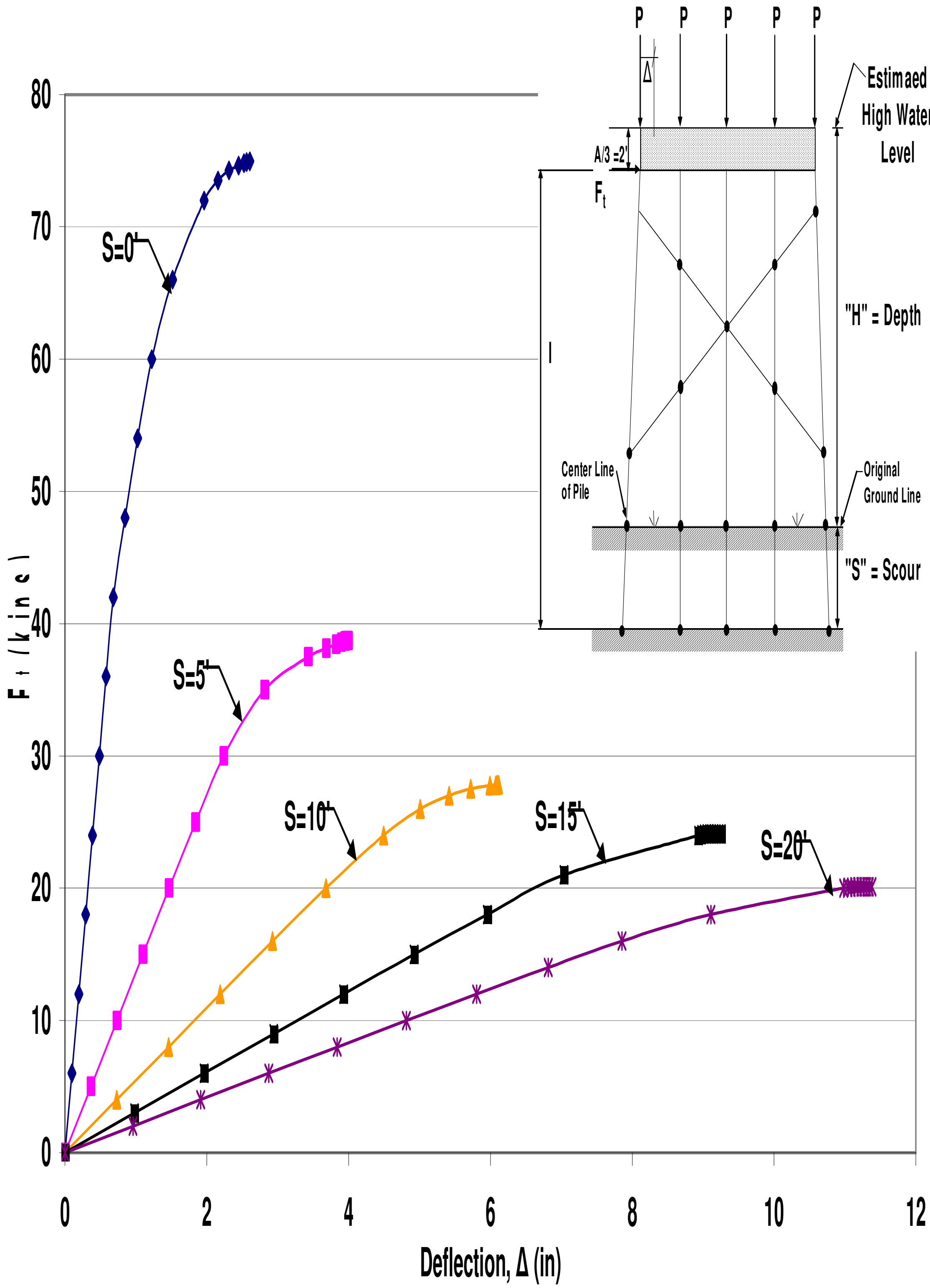


Figure B.64 HP12x53 X-Braced 5-Pile Bent with H=17', P=160kips and A=6'

Pushover Analysis Results

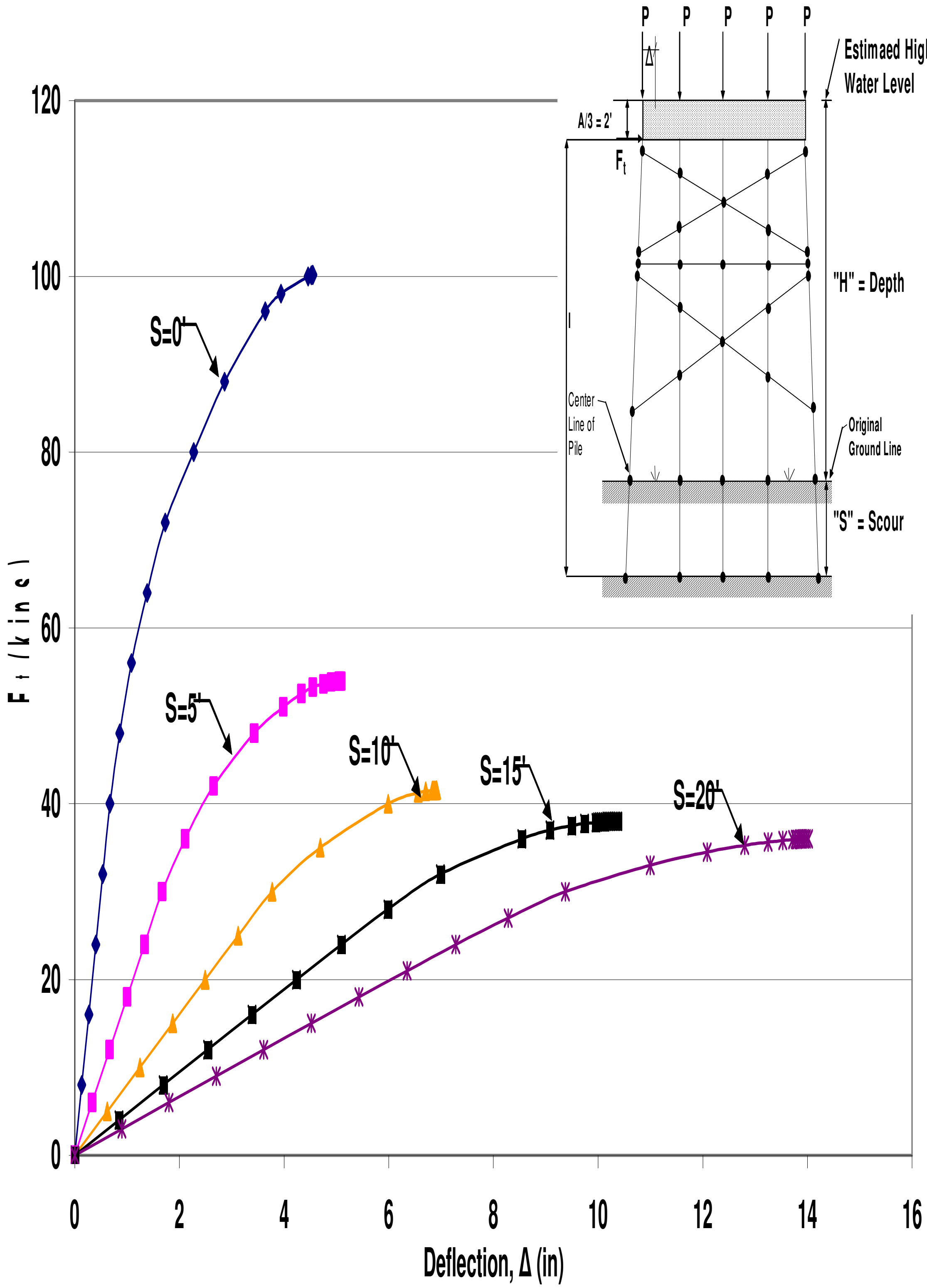


Figure B.65 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

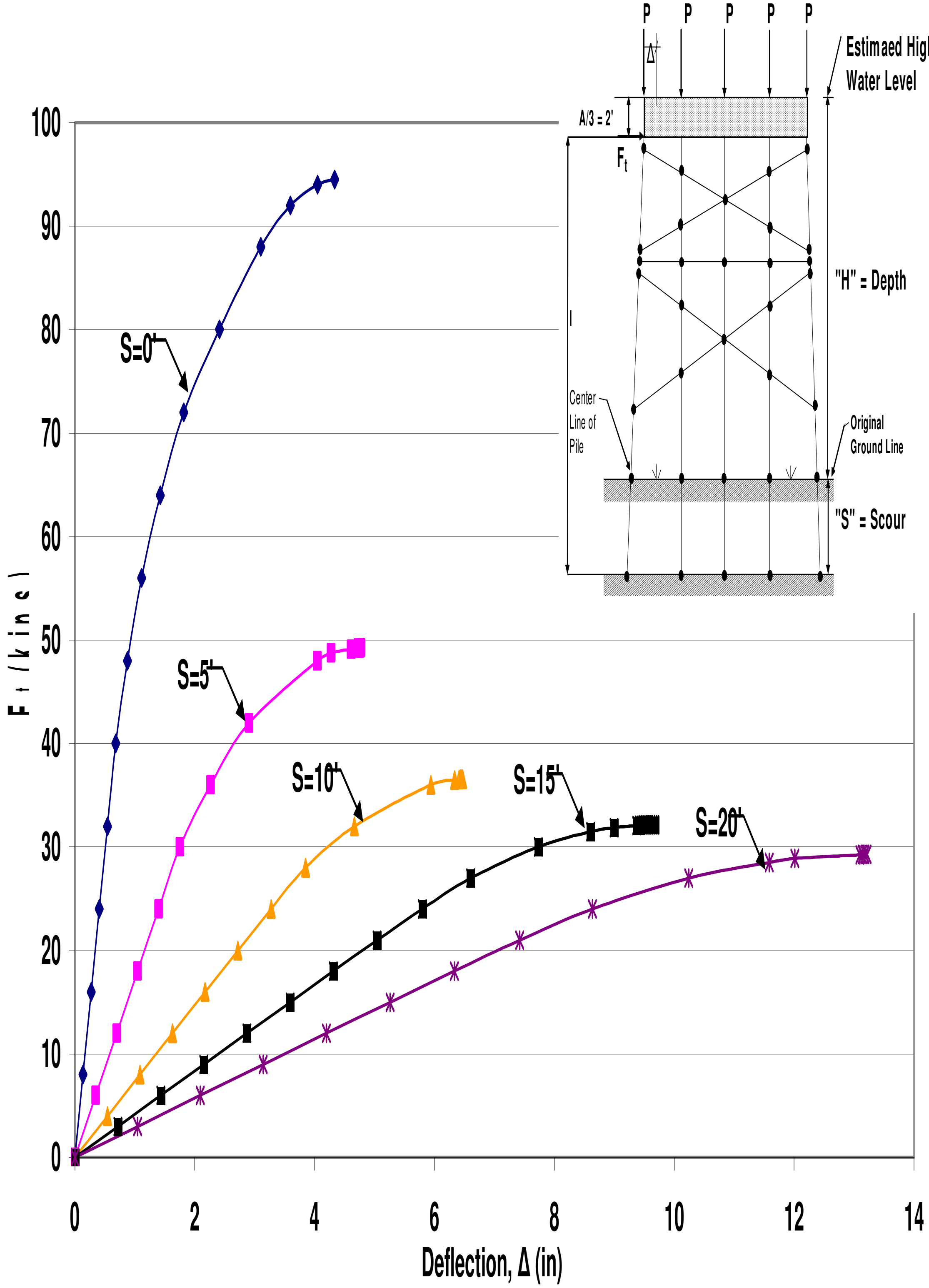


Figure B.66 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

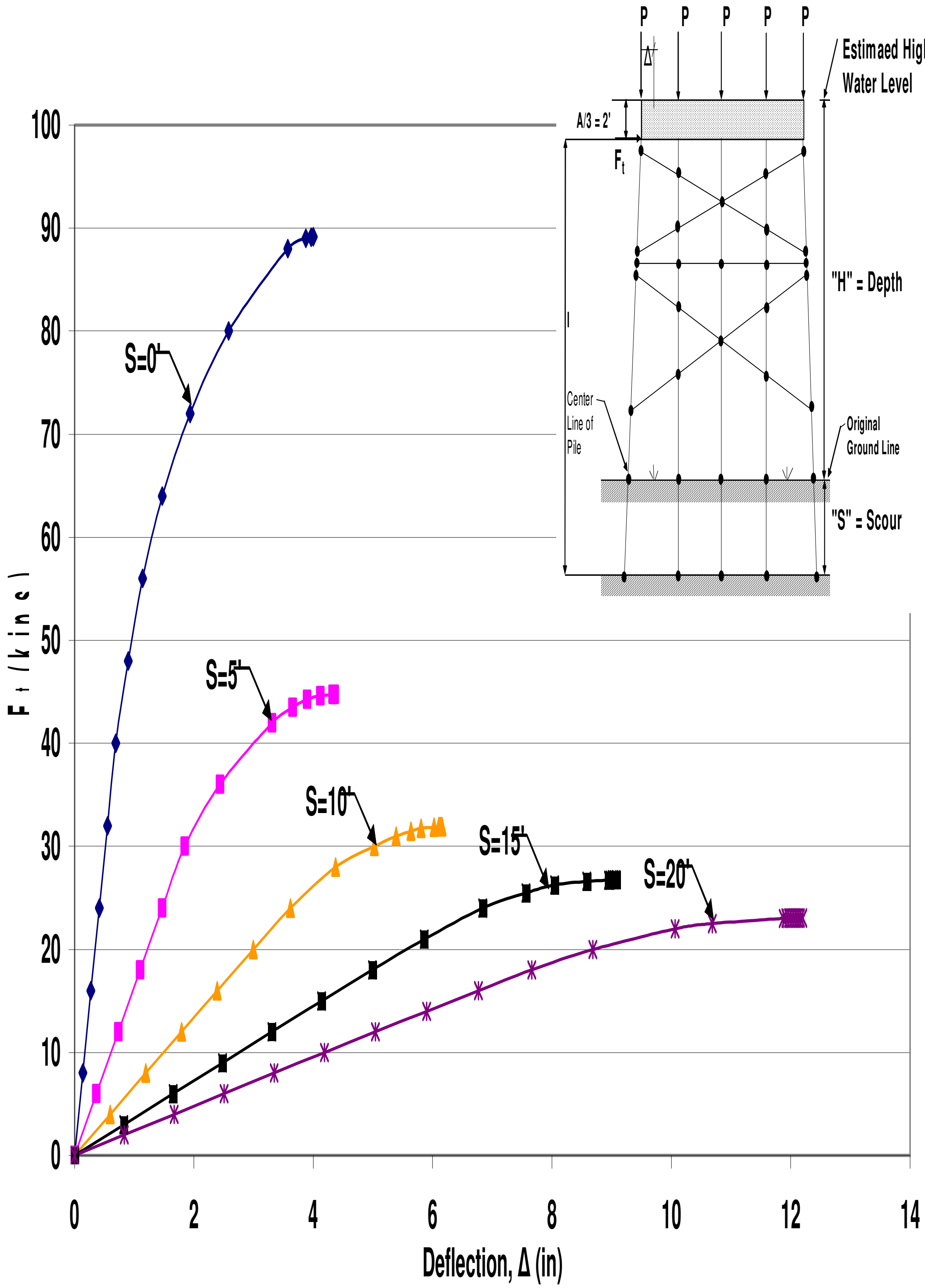


Figure B.67 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

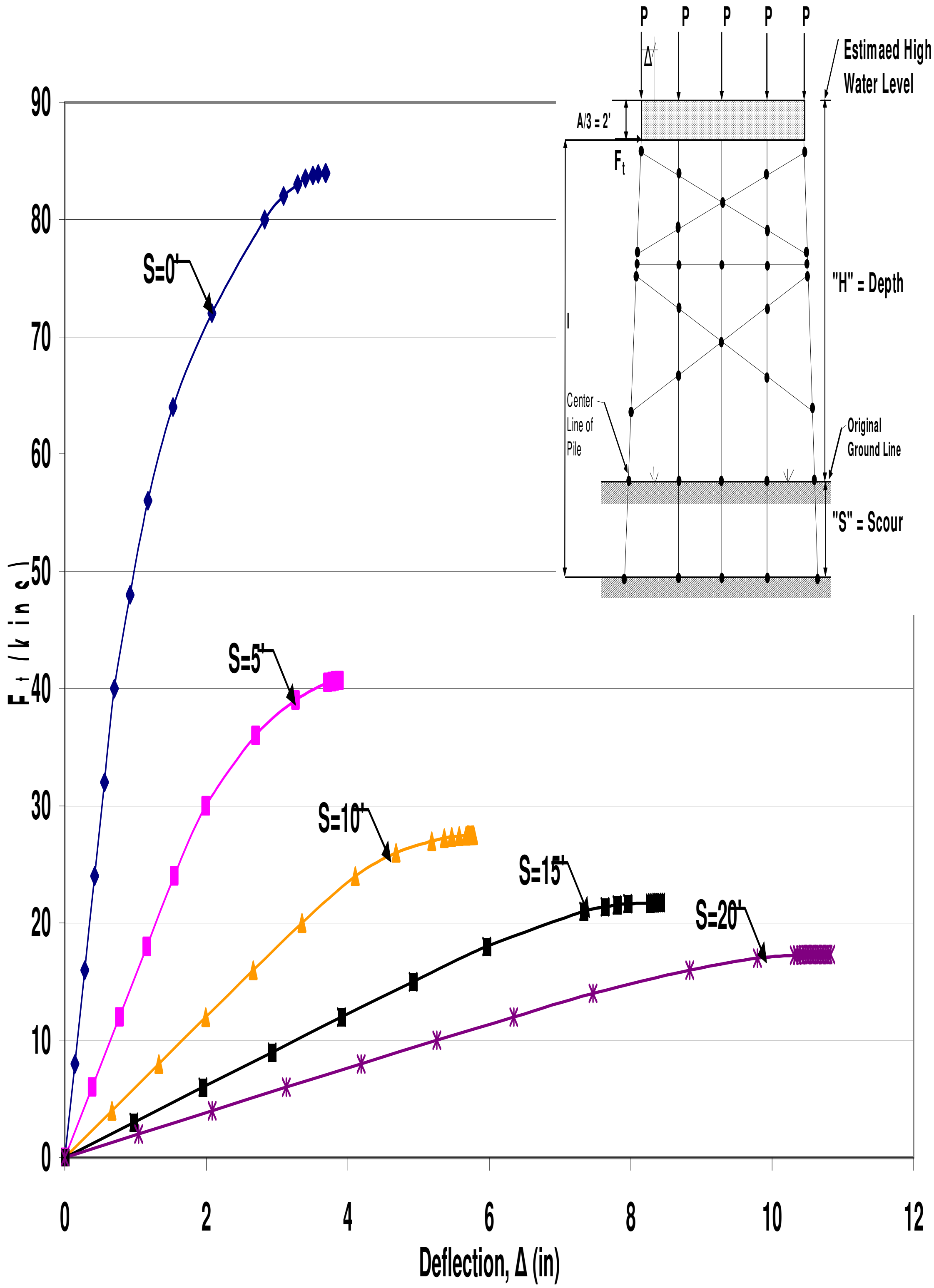


Figure B.68 HP12x53 Two-Story X-Braced 5-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

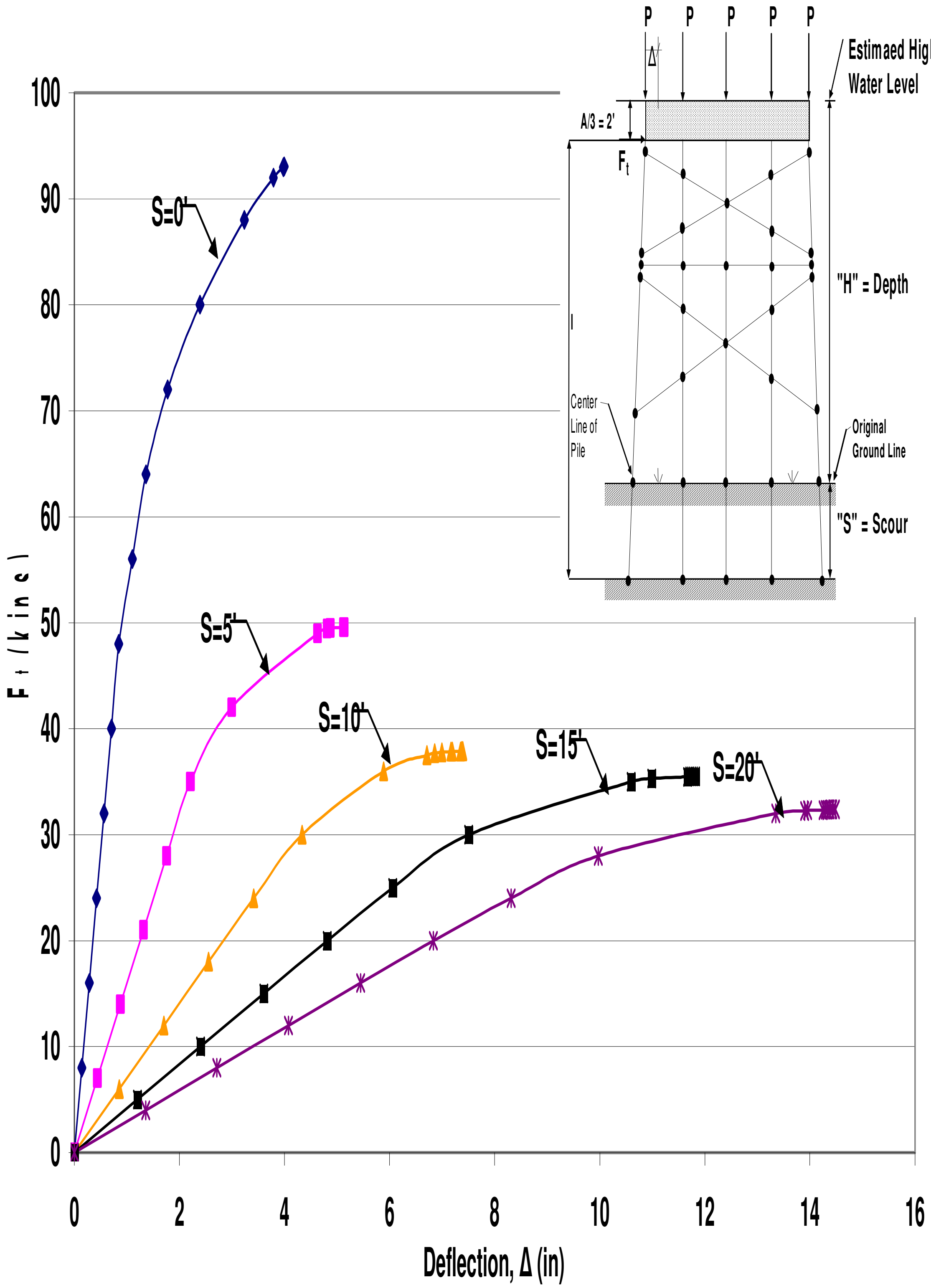


Figure B.69 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=100kips and A=6'
Pushover Analysis Results

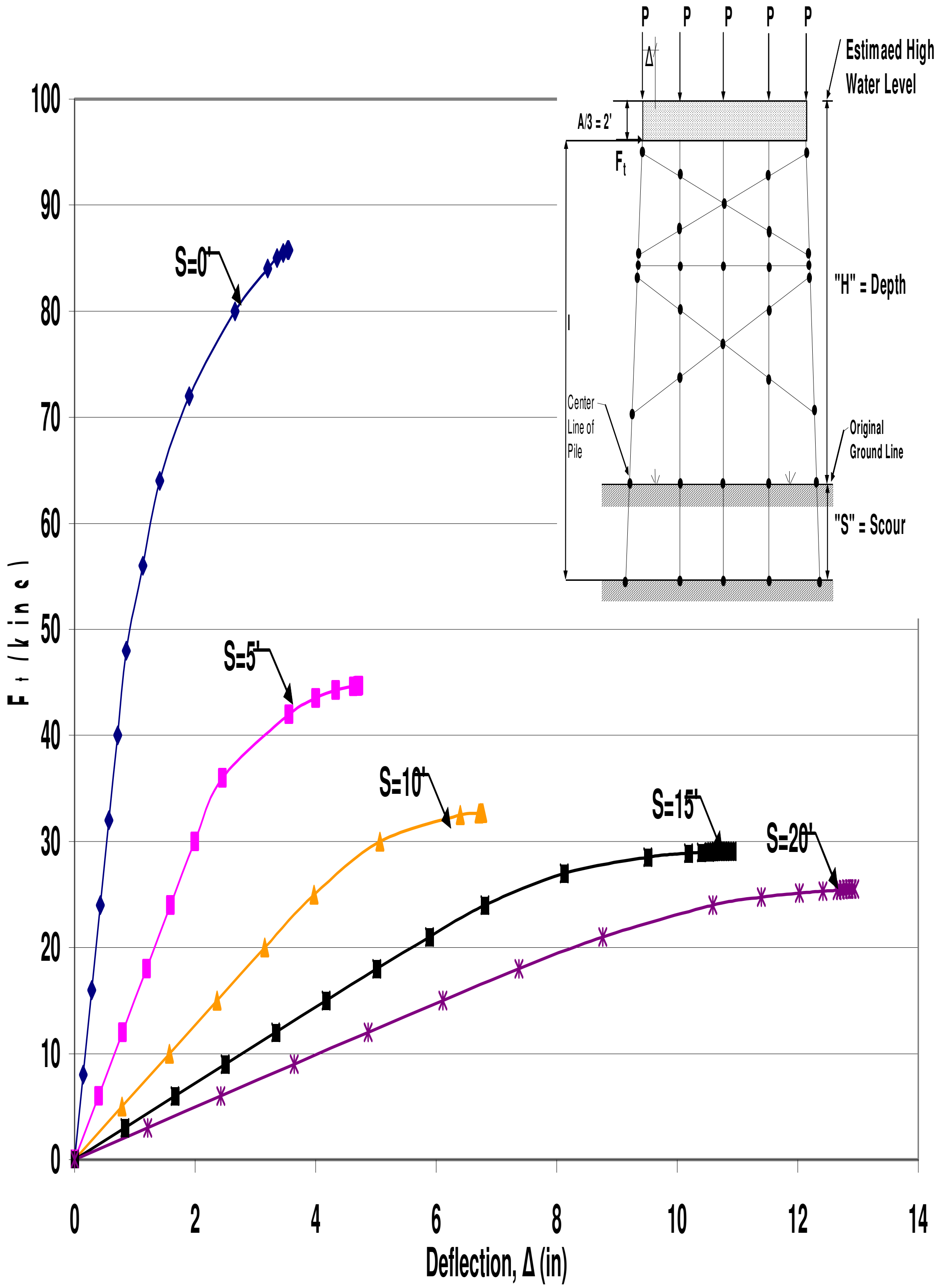


Figure B.70 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

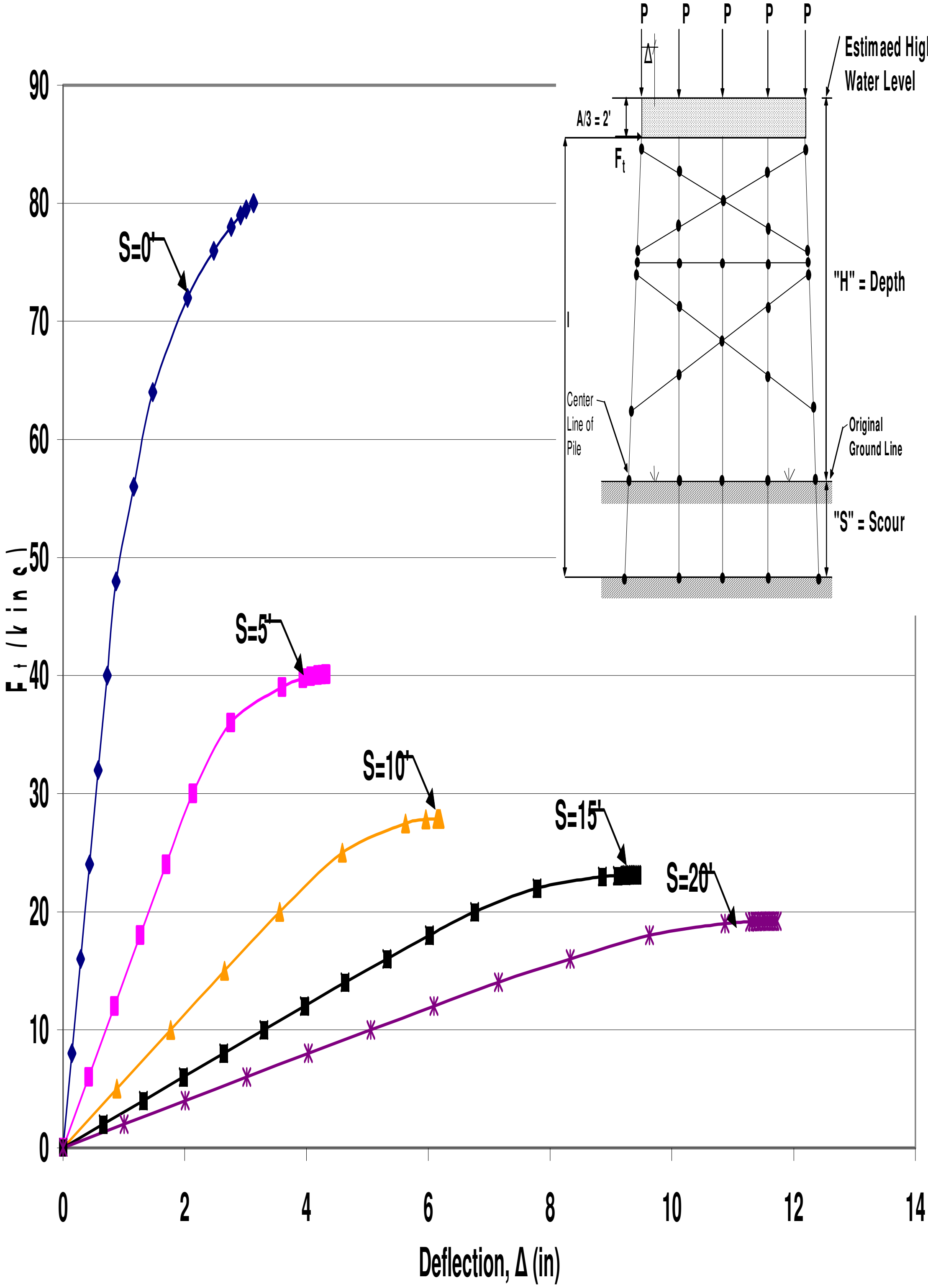


Figure B.71 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

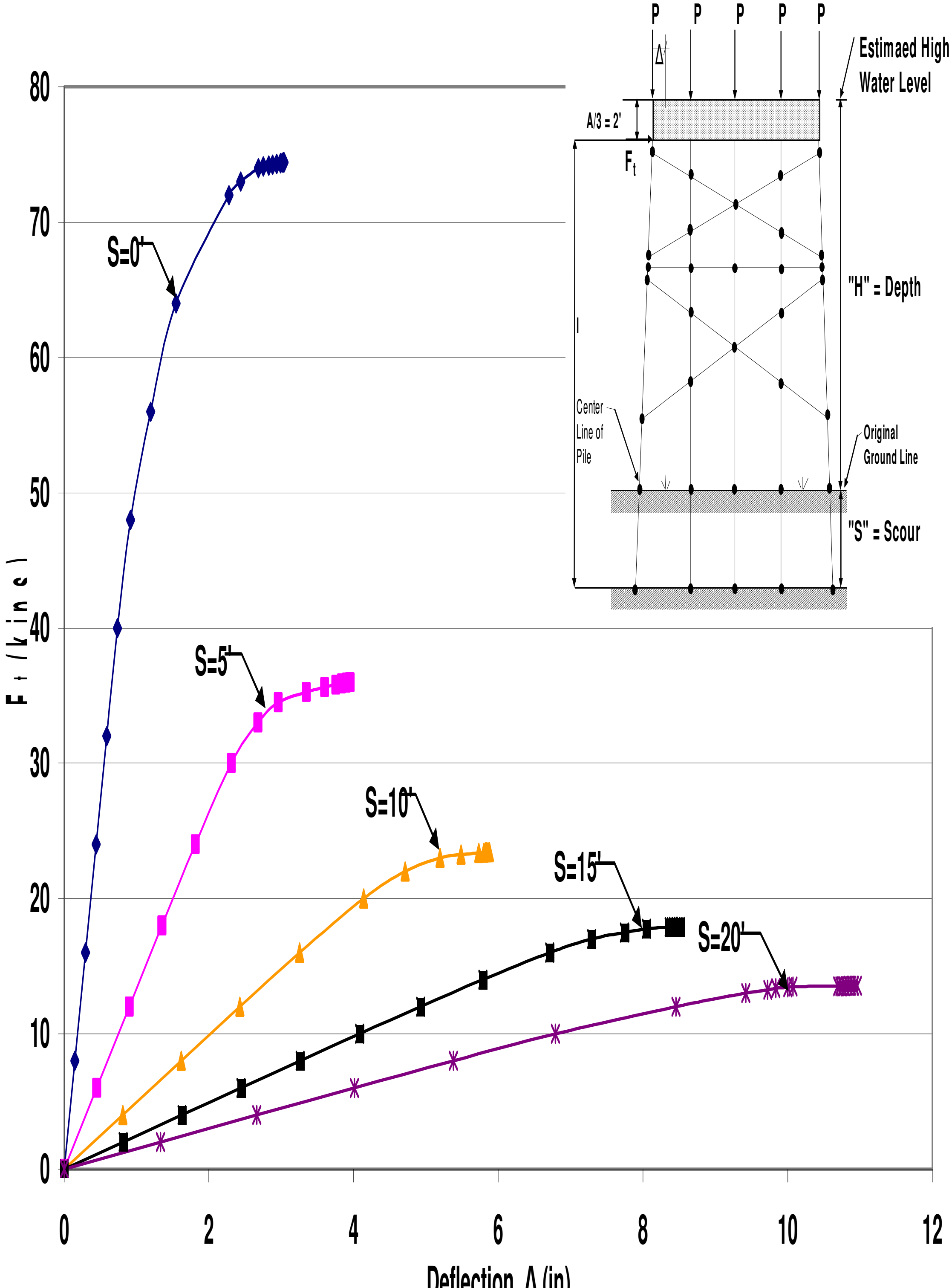


Figure B.72 HP12x53 Two-Story X-Braced 5-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

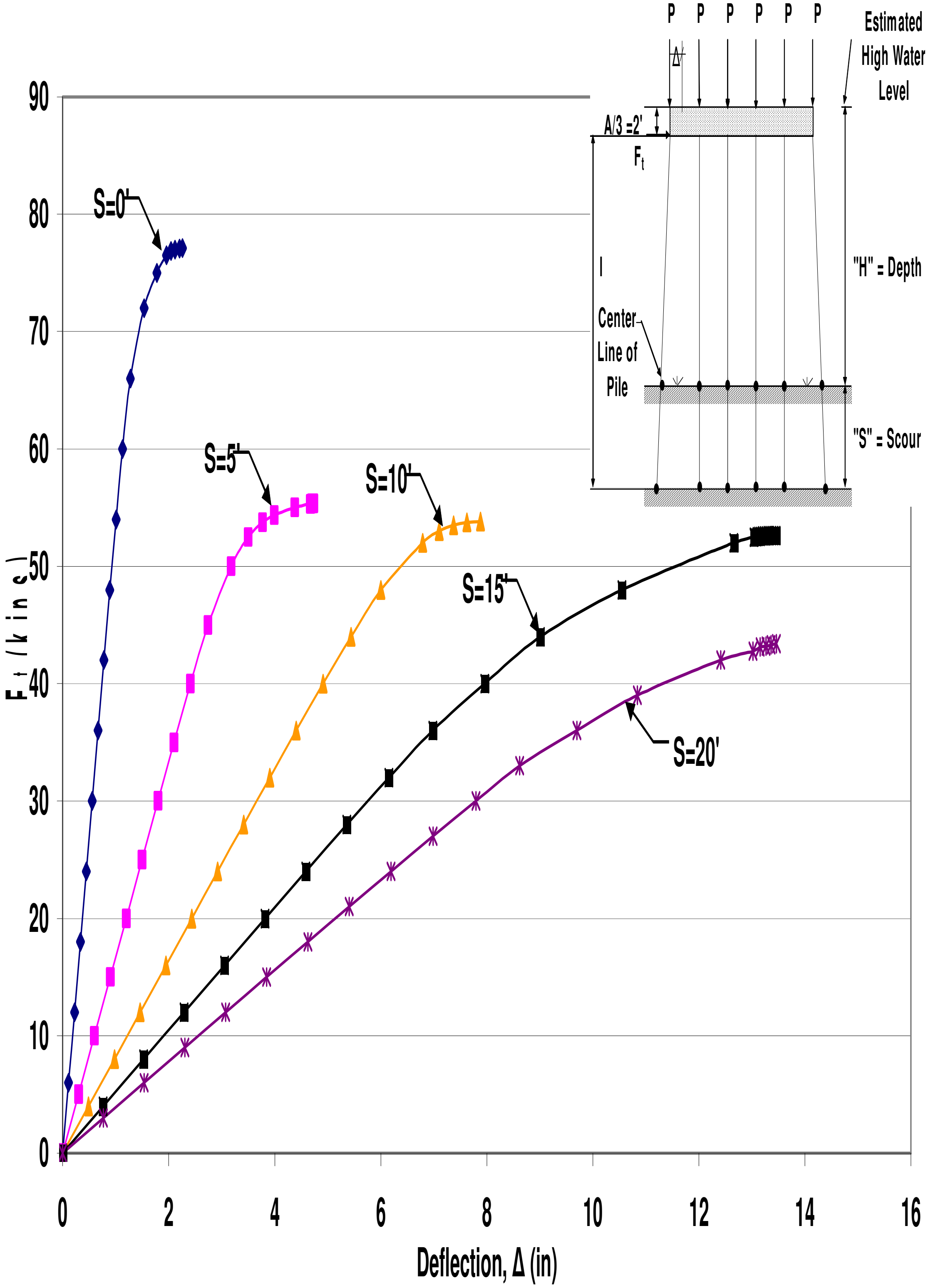


Figure B.73 HP12x53 Unbraced 6-Pile Bent with H=10', P=100kips and A=6' Pushover Analysis Results

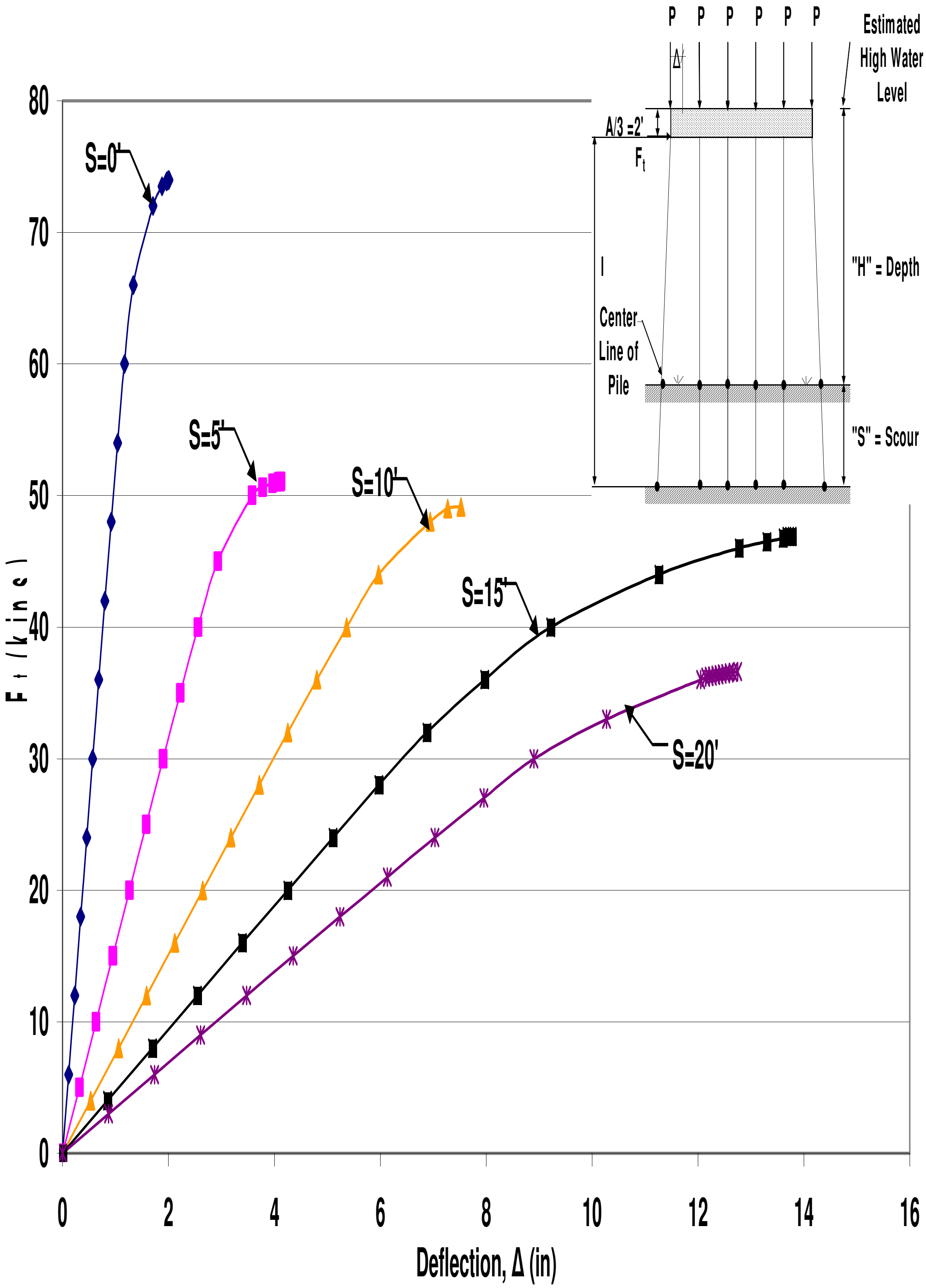


Figure B.74 HP12x53 Unbraced 6-Pile Bent with H=10', P=120kips and A=6' Pushover Analysis Results

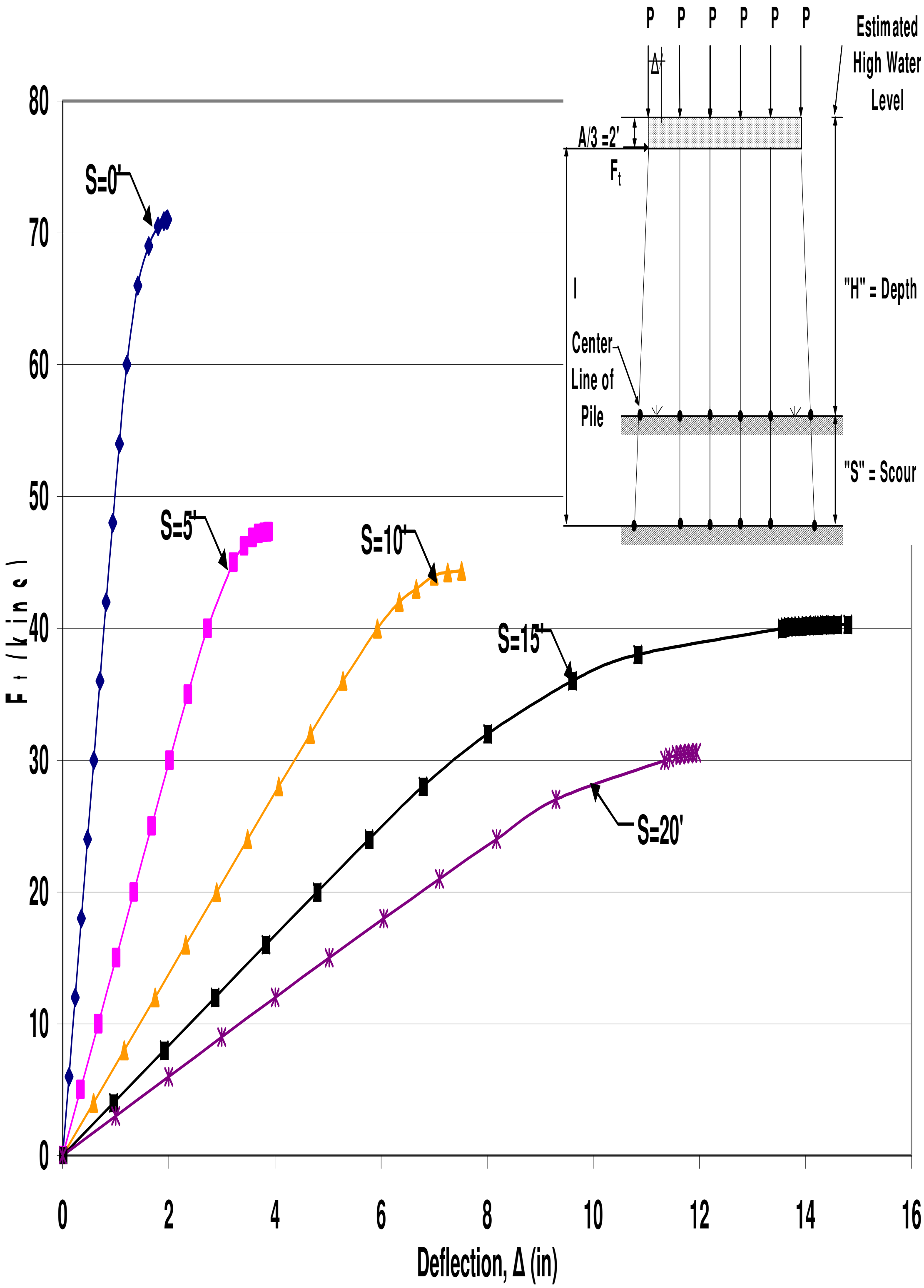


Figure B.75 HP12x53 Unbraced 6-Pile Bent with H=10', P=140kips and A=6'
Pushover Analysis Results

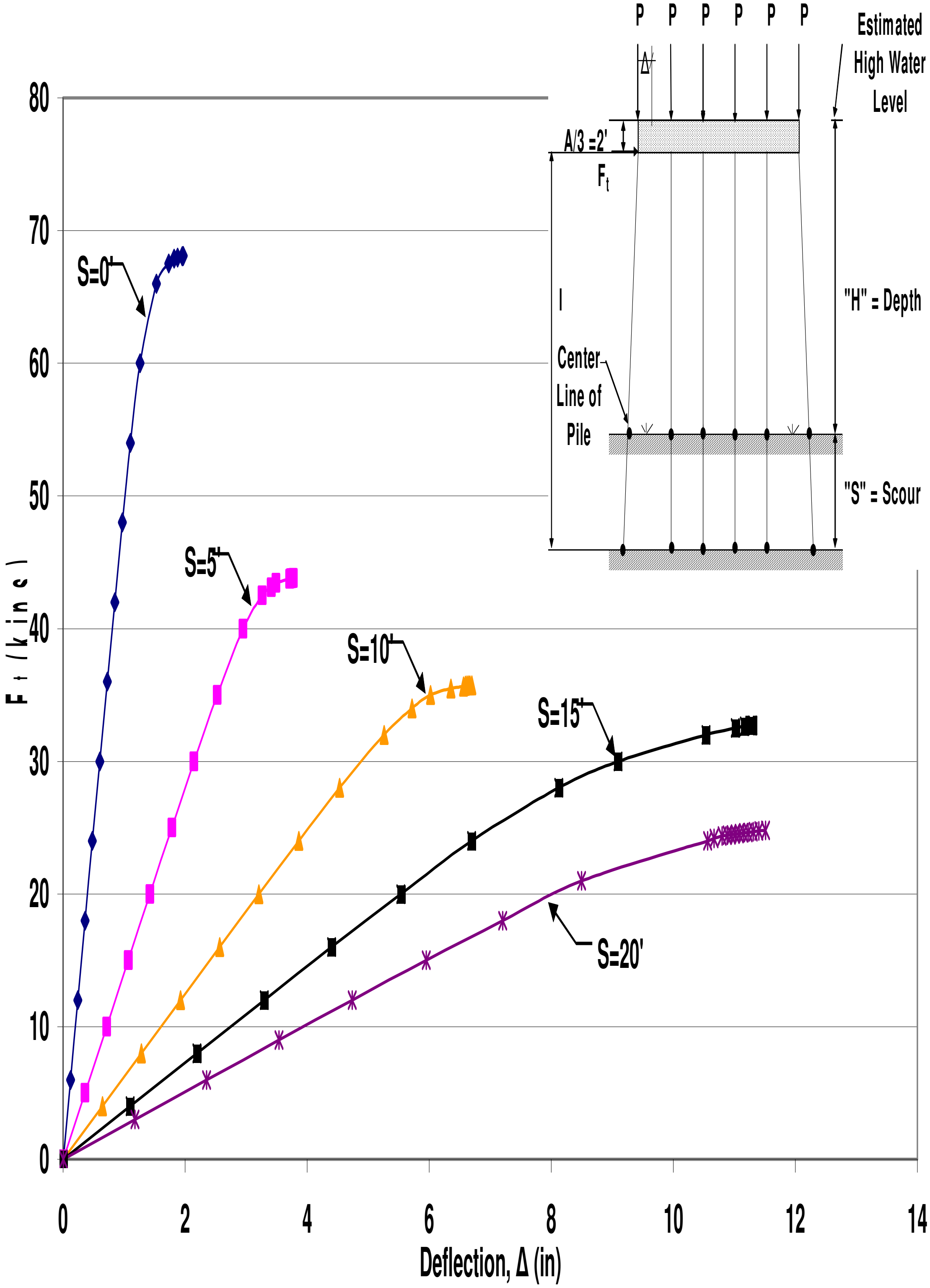


Figure B.76 HP12x53 Unbraced 6-Pile Bent with H=10', P=160kips and A=6' Pushover Analysis Results

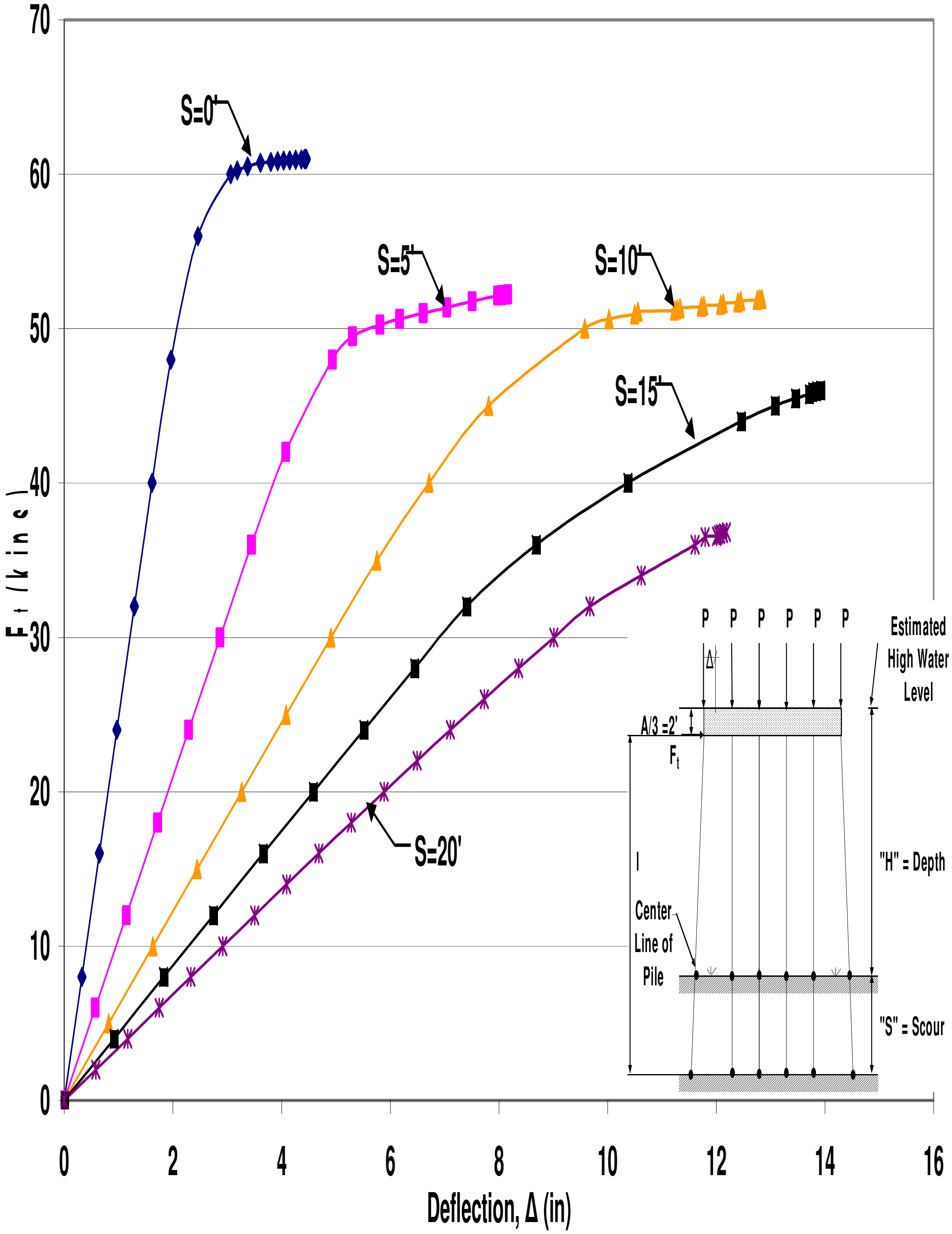


Figure B.77 HP12x53 Unbraced 6-Pile Bent with H=13', P=100kips and A=6'

Pushover Analysis Results

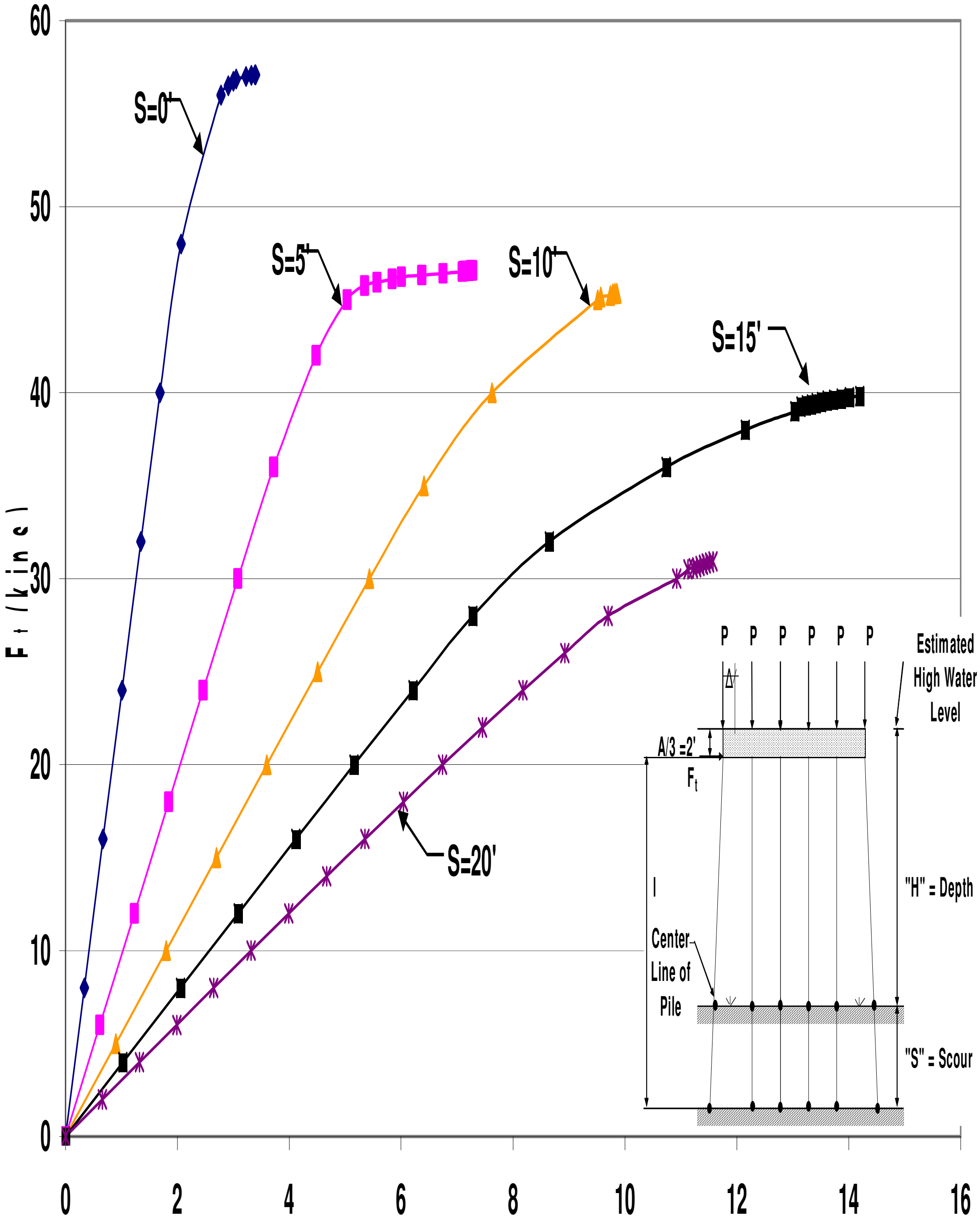


Figure B.78 HP12x53 Unbraced 6-Pile Bent with H=13', P=120kips and A=6'

Pushover Analysis Results

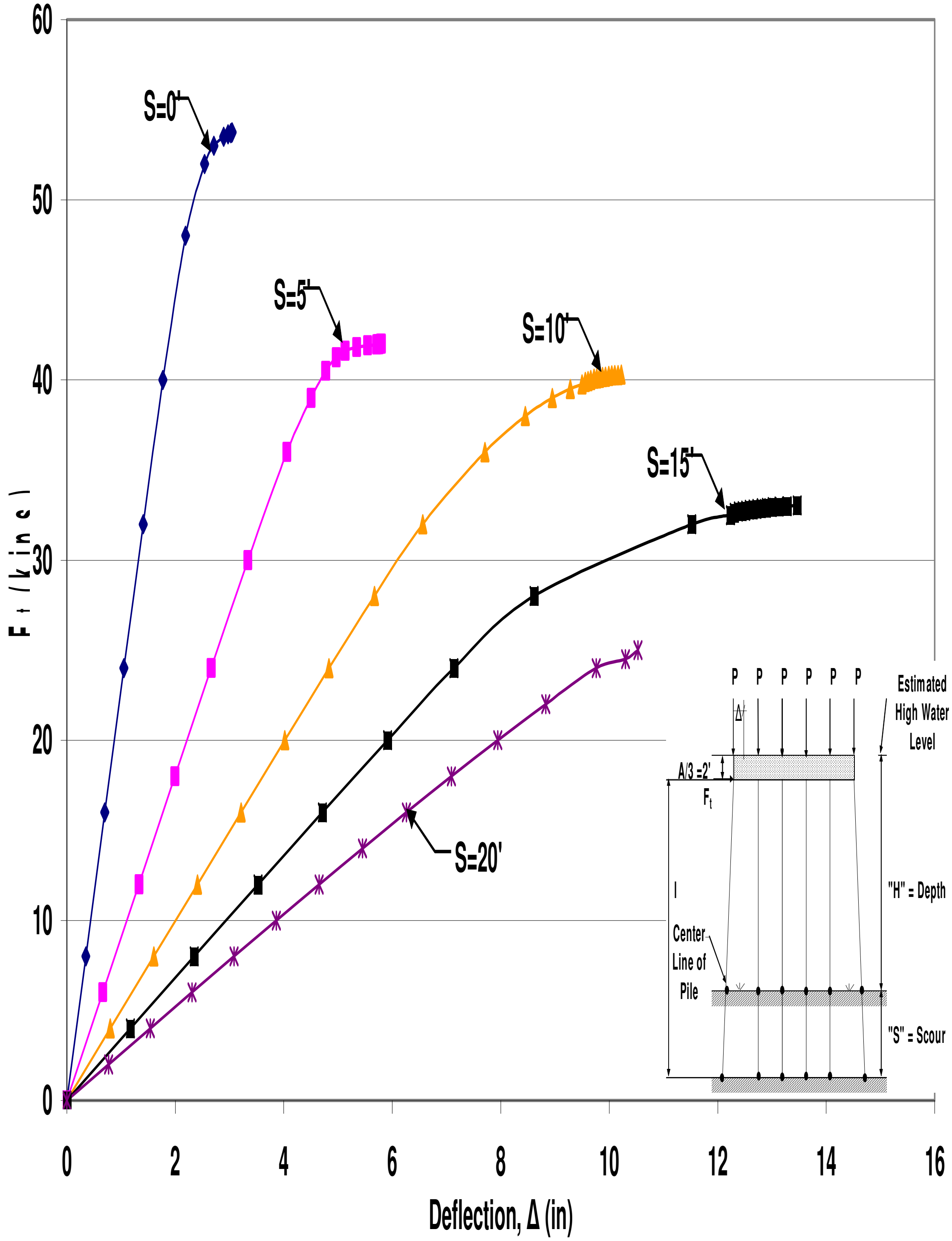


Figure B.79 HP12x53 Unbraced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

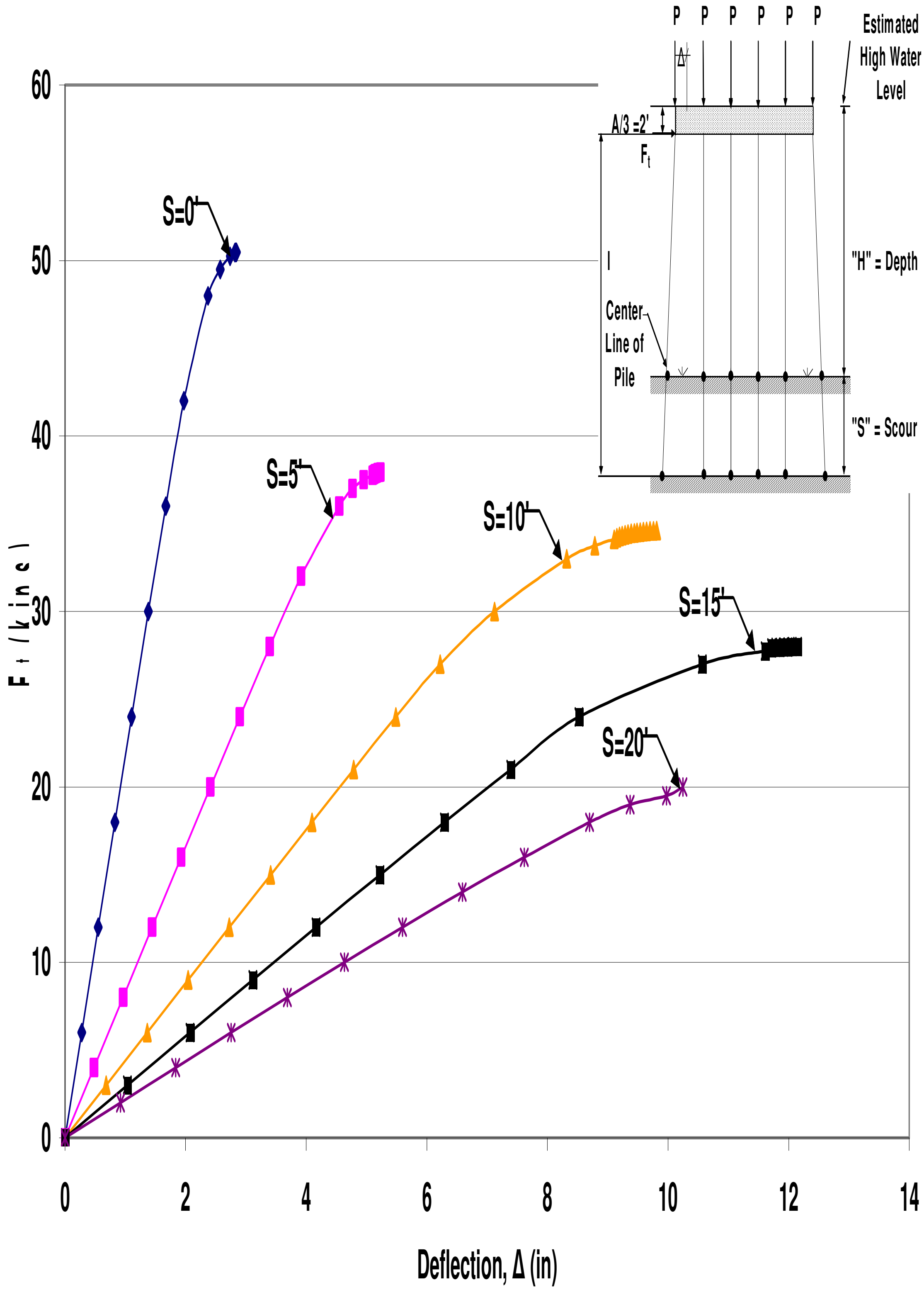


Figure B.80 HP12x53 Unbraced 6-Pile Bent with H=13', P=160kips and A=6'

Pushover Analysis Results

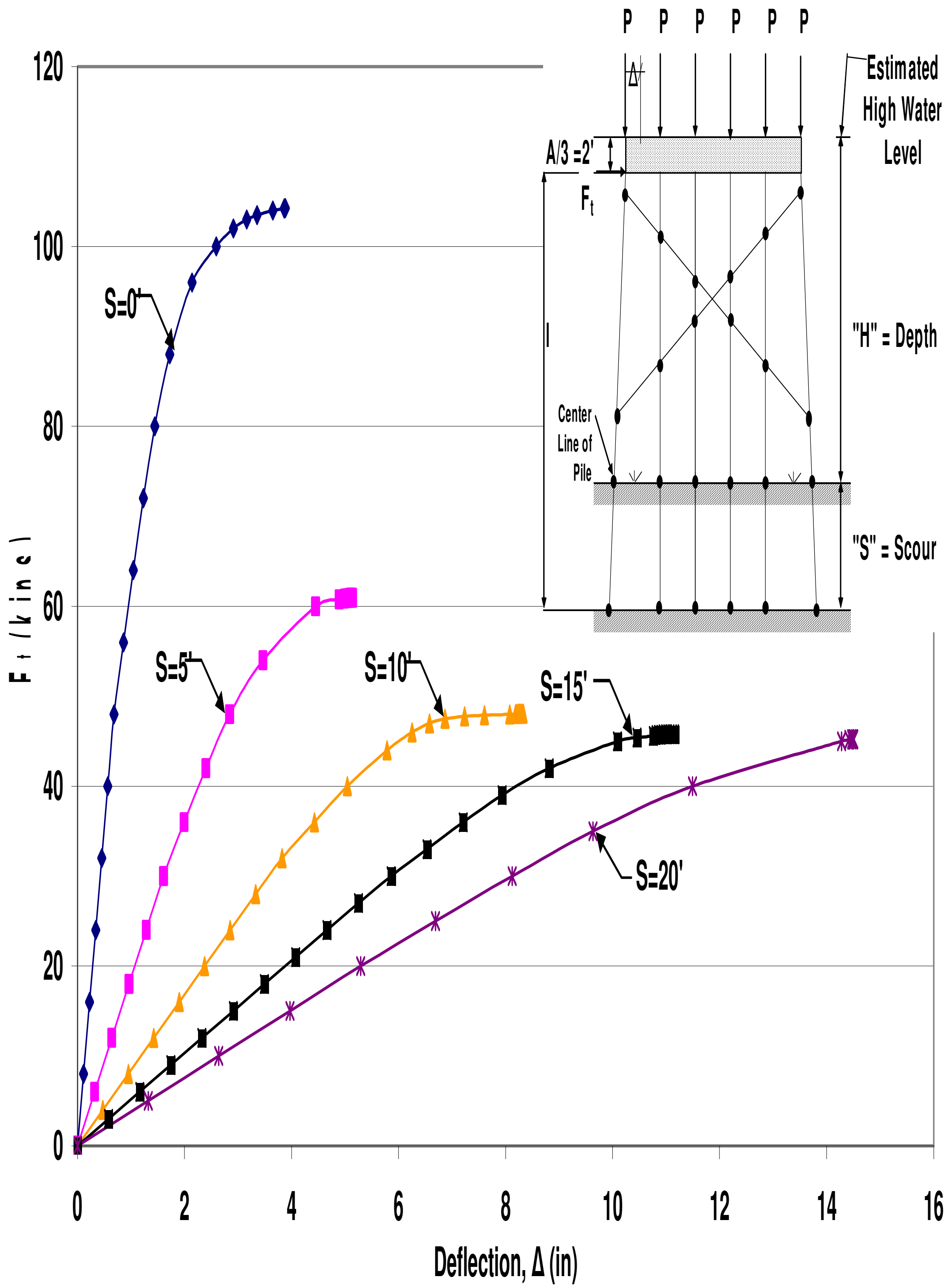


Figure B.81 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

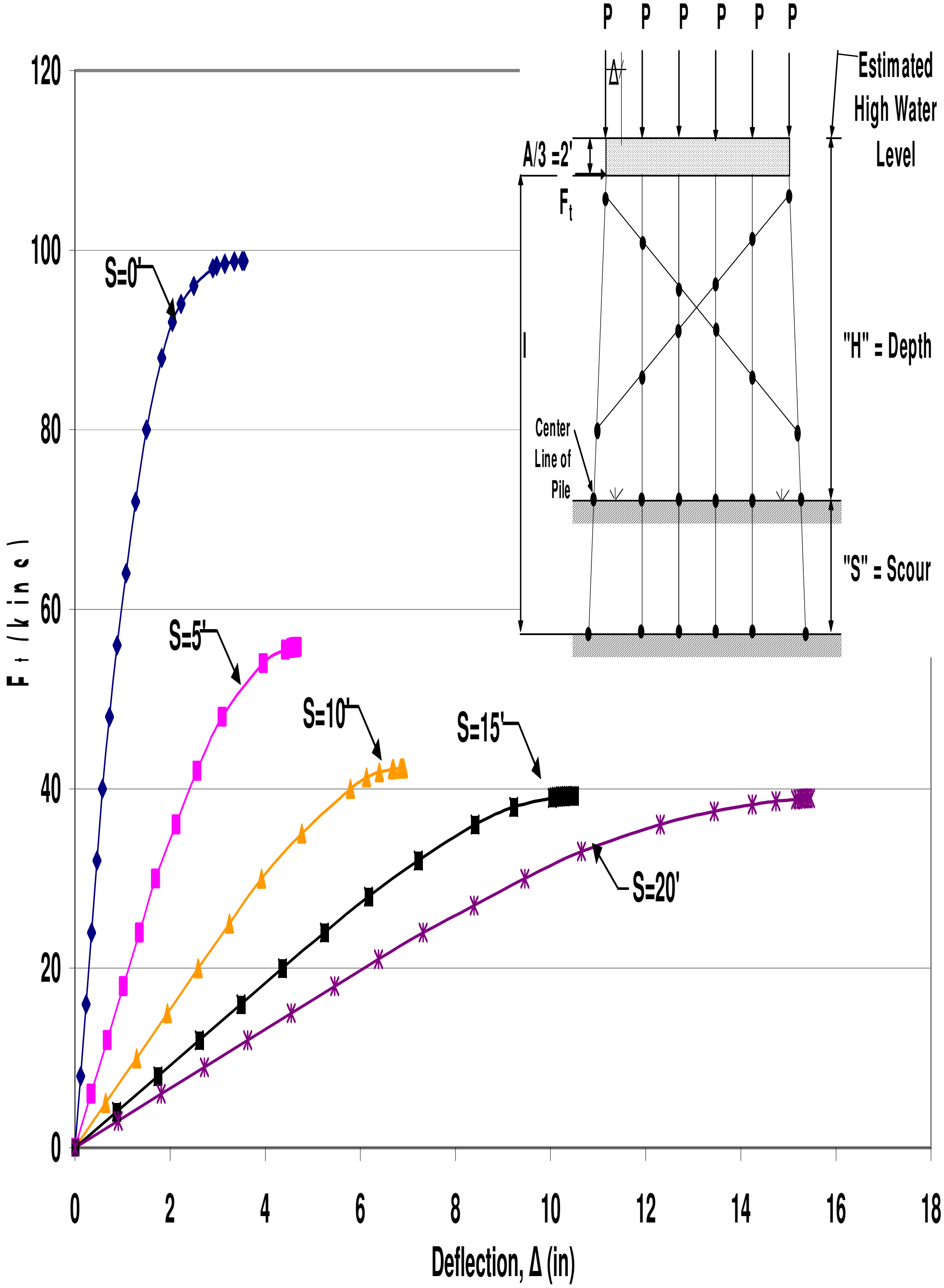


Figure B.82 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=120kips and A=6'
Pushover Analysis Results

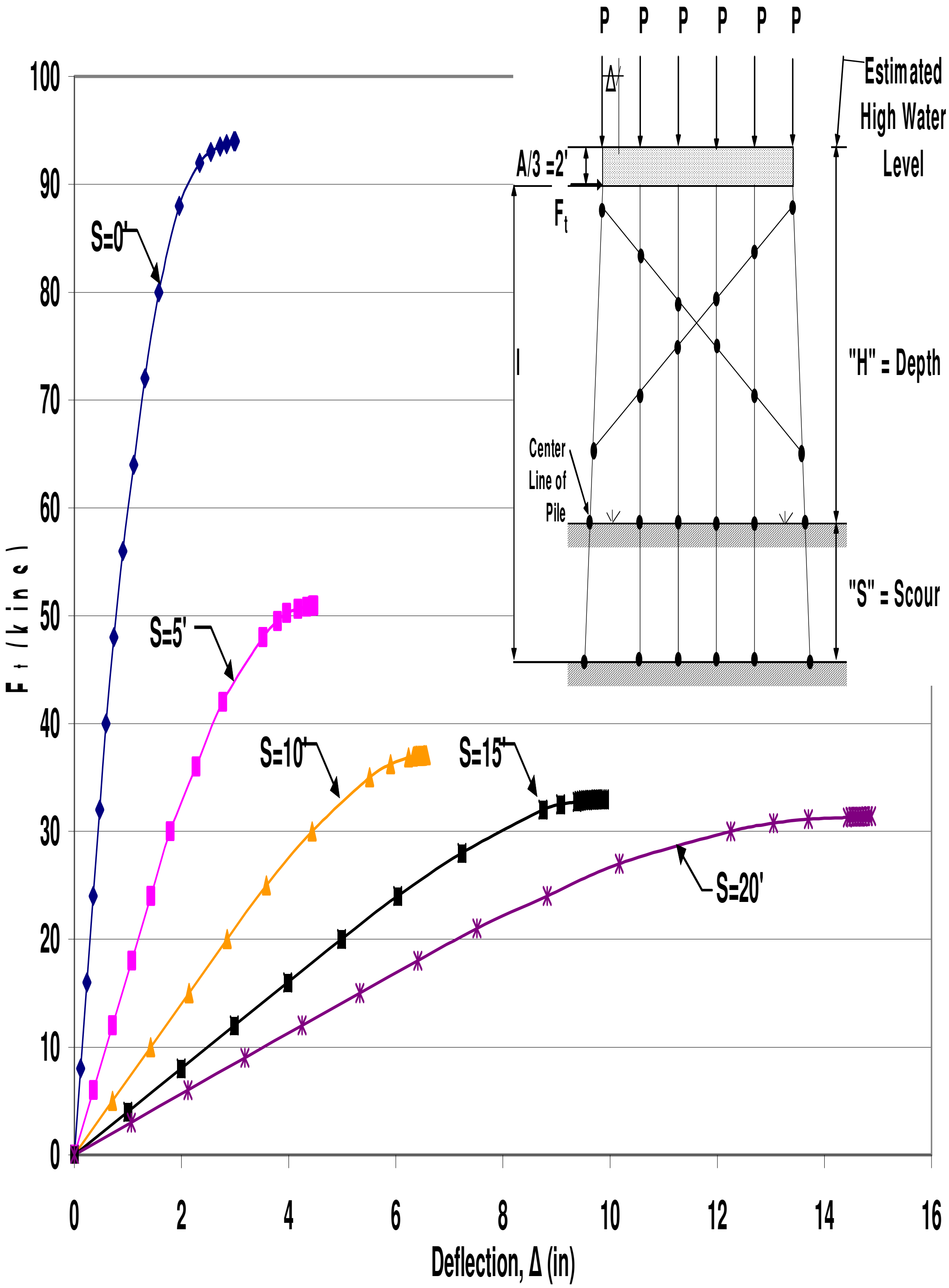


Figure B.83 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

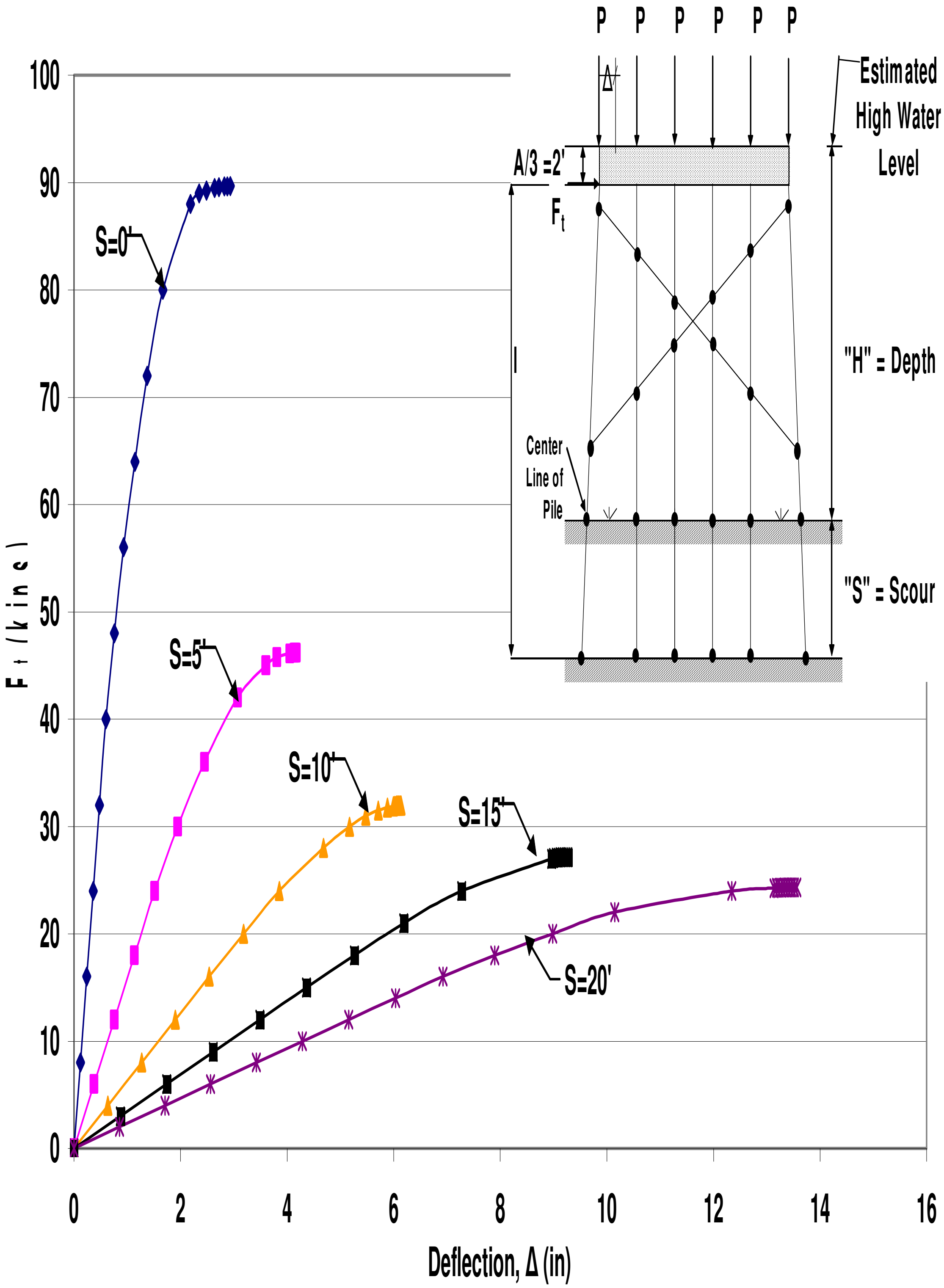


Figure B.84 HP12x53 Single X-Braced 6-Pile Bent with H=13', P=160kips and A=6' Pushover Analysis Results

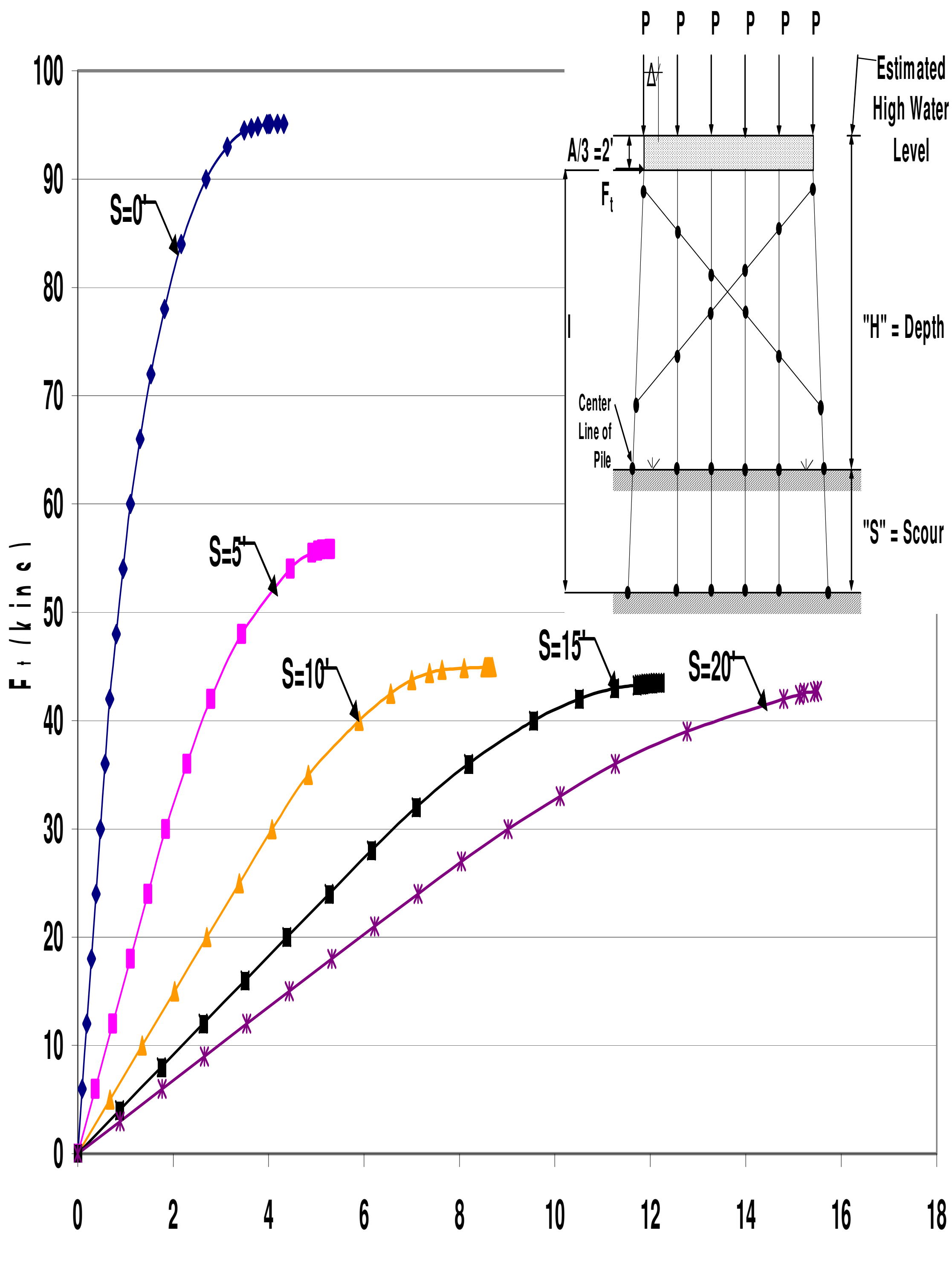


Figure B.85 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=100kips and A=6' Pushover Analysis Results

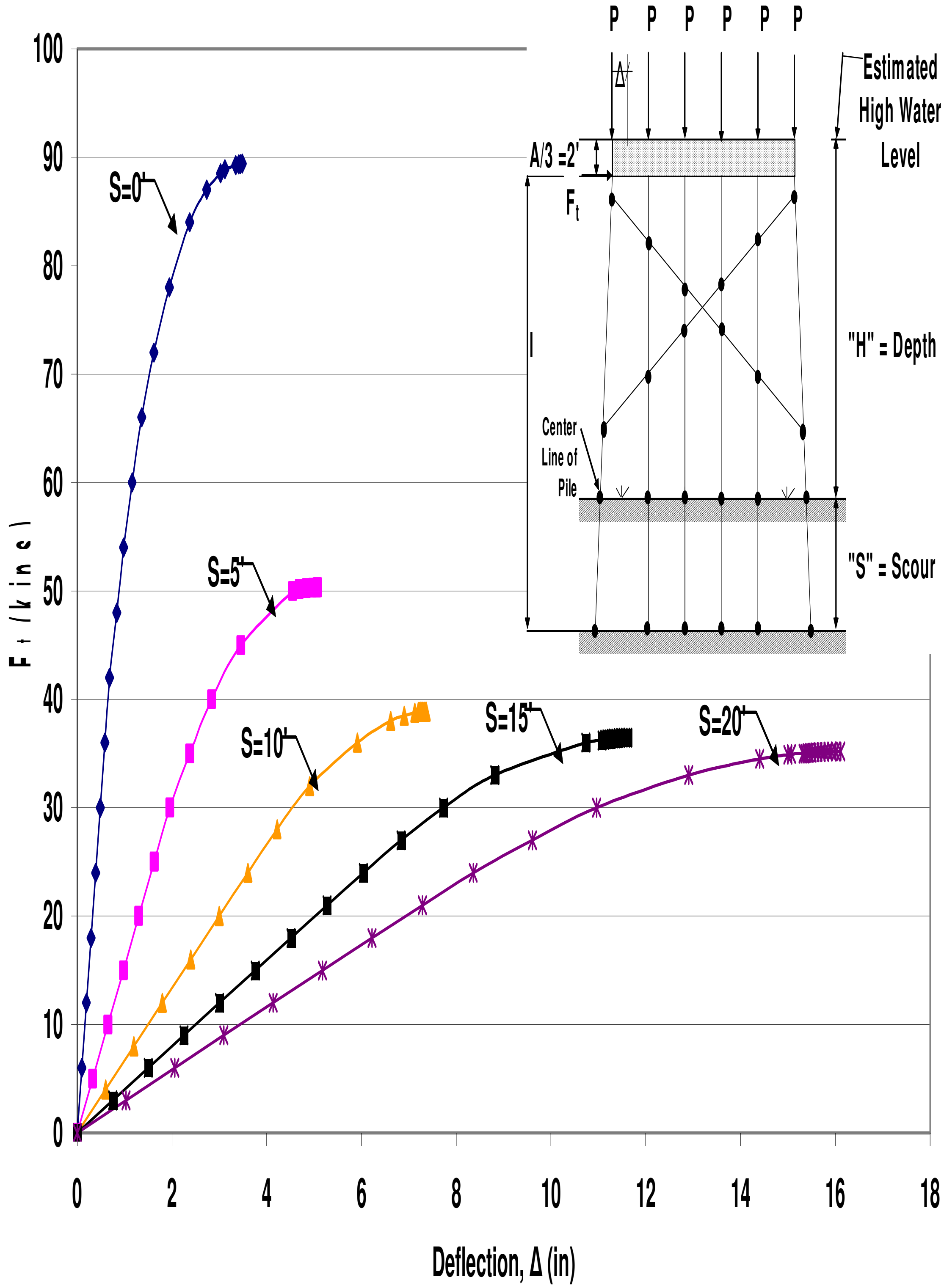


Figure B.86 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=120kips and A=6' Pushover Analysis Results

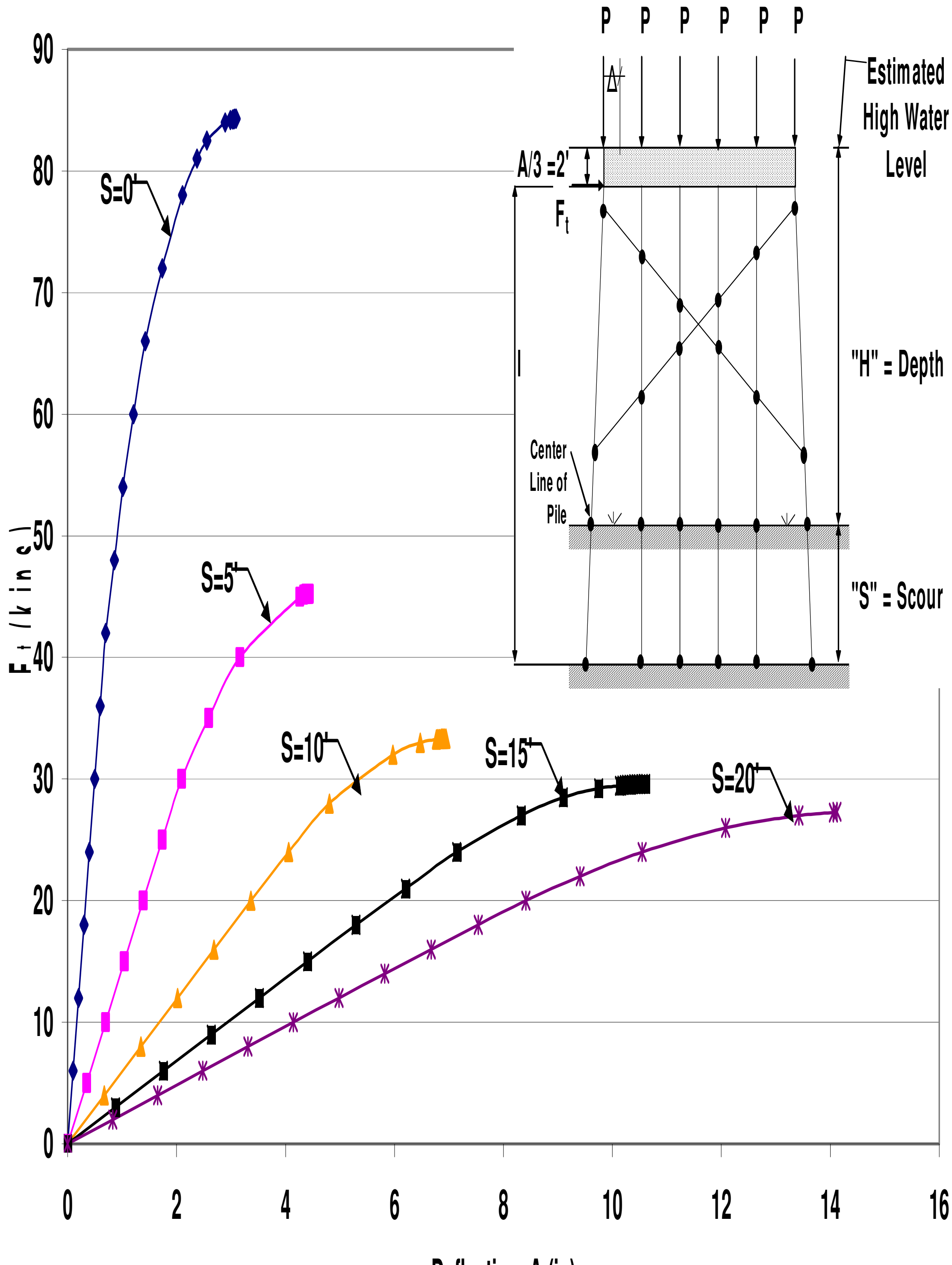


Figure B.87 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

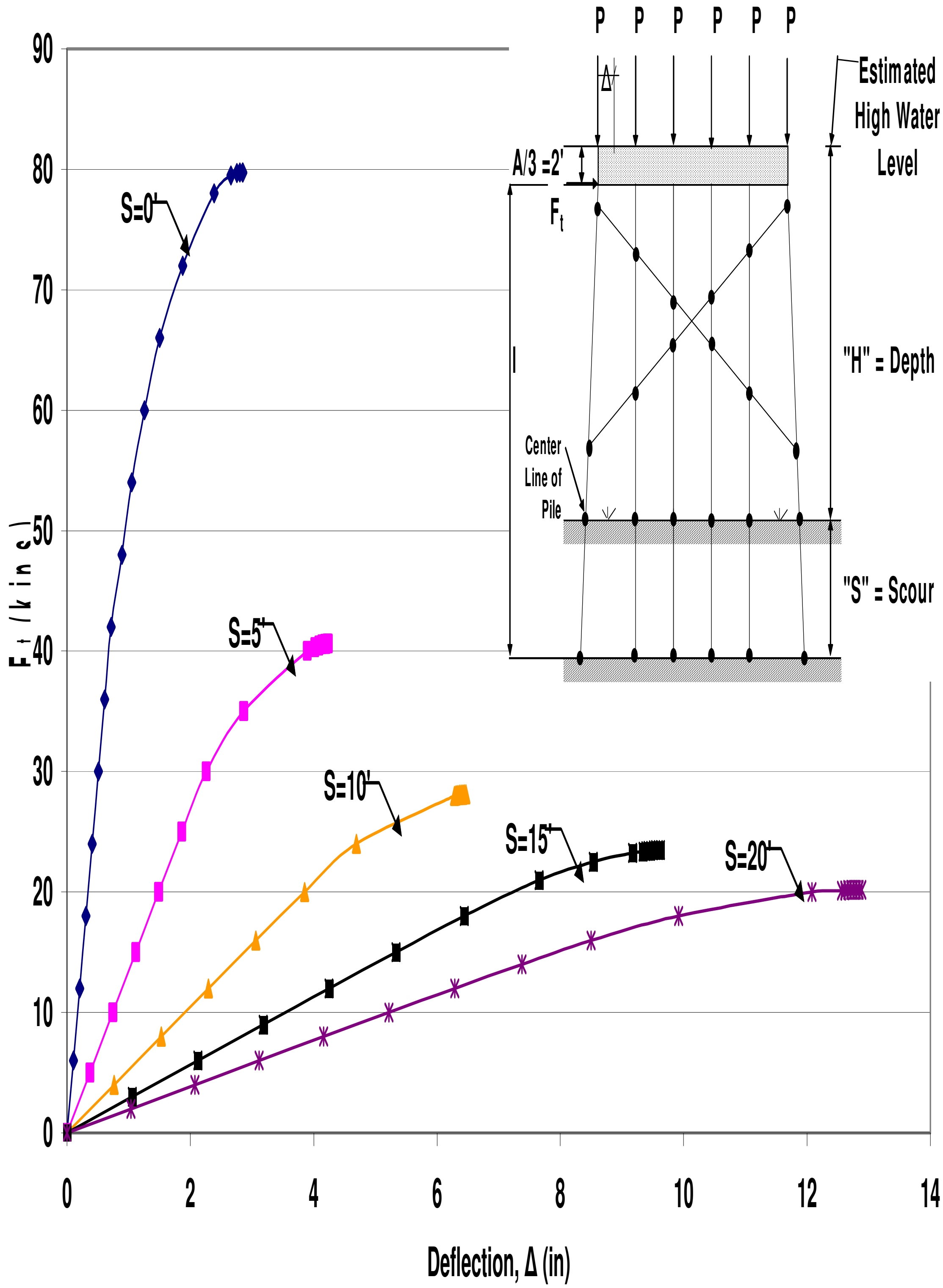


Figure B.88 HP12x53 Single X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

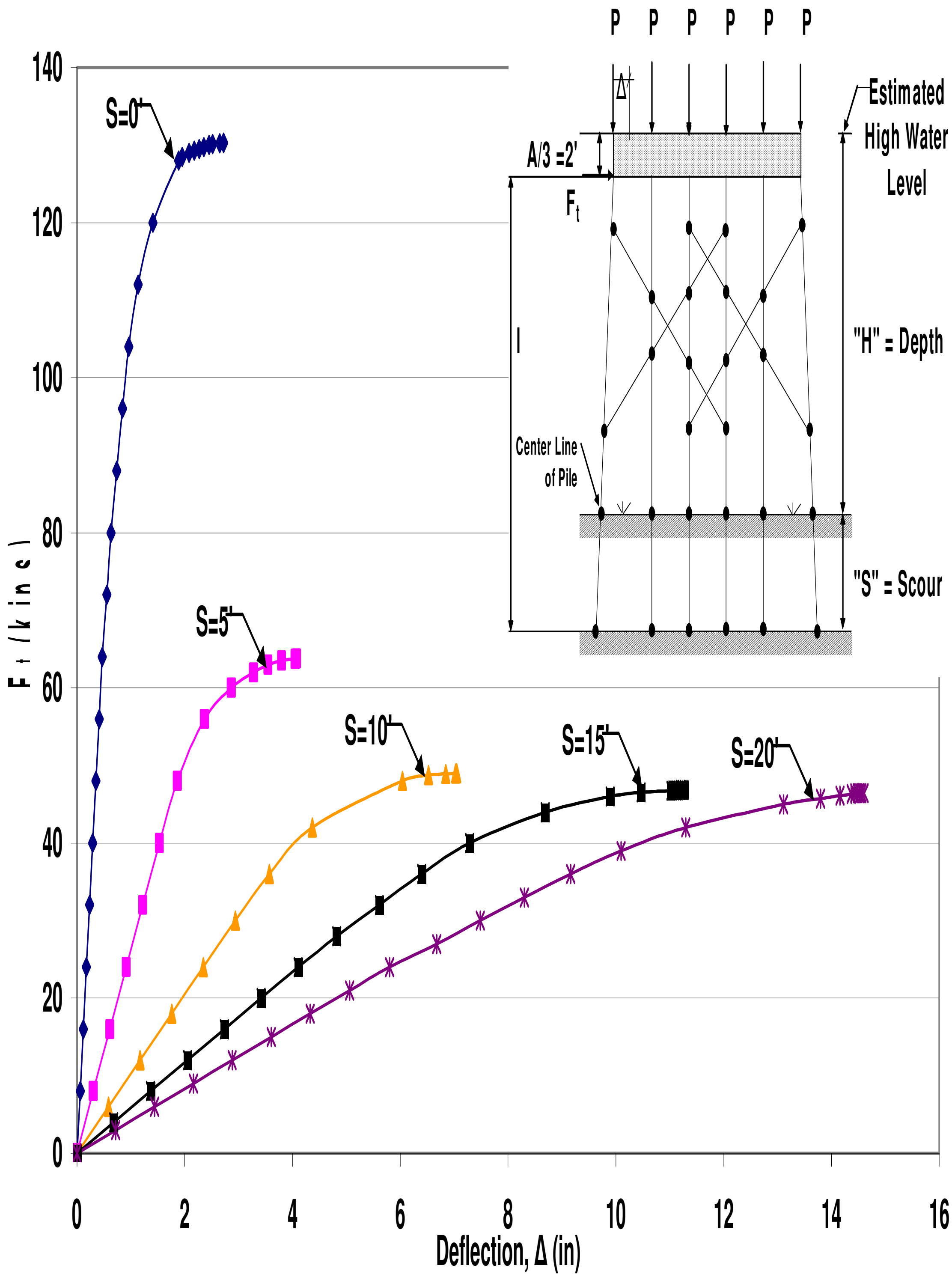


Figure B.89 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=100kips and A=6' Pushover Analysis Results

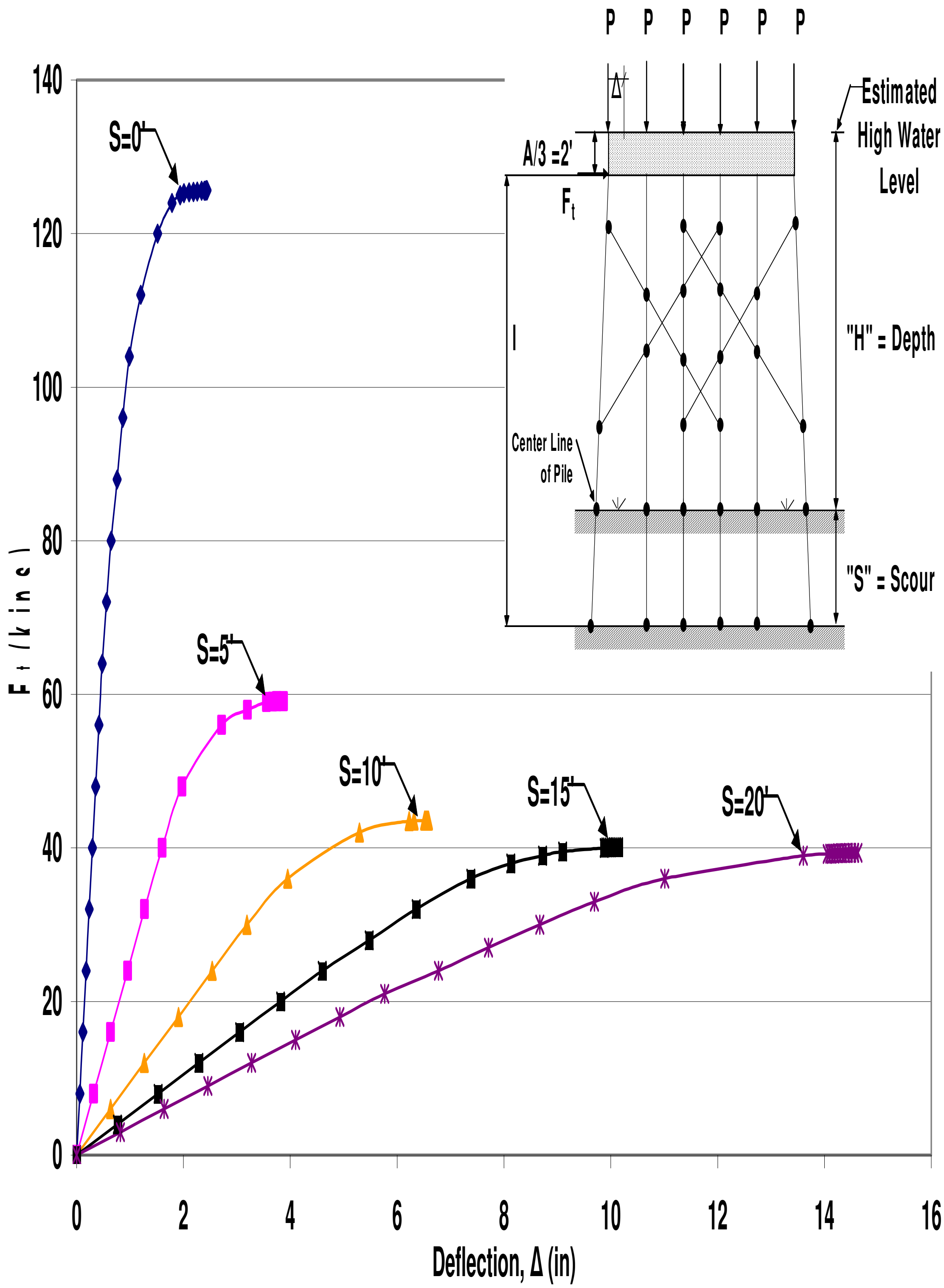


Figure B.90 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

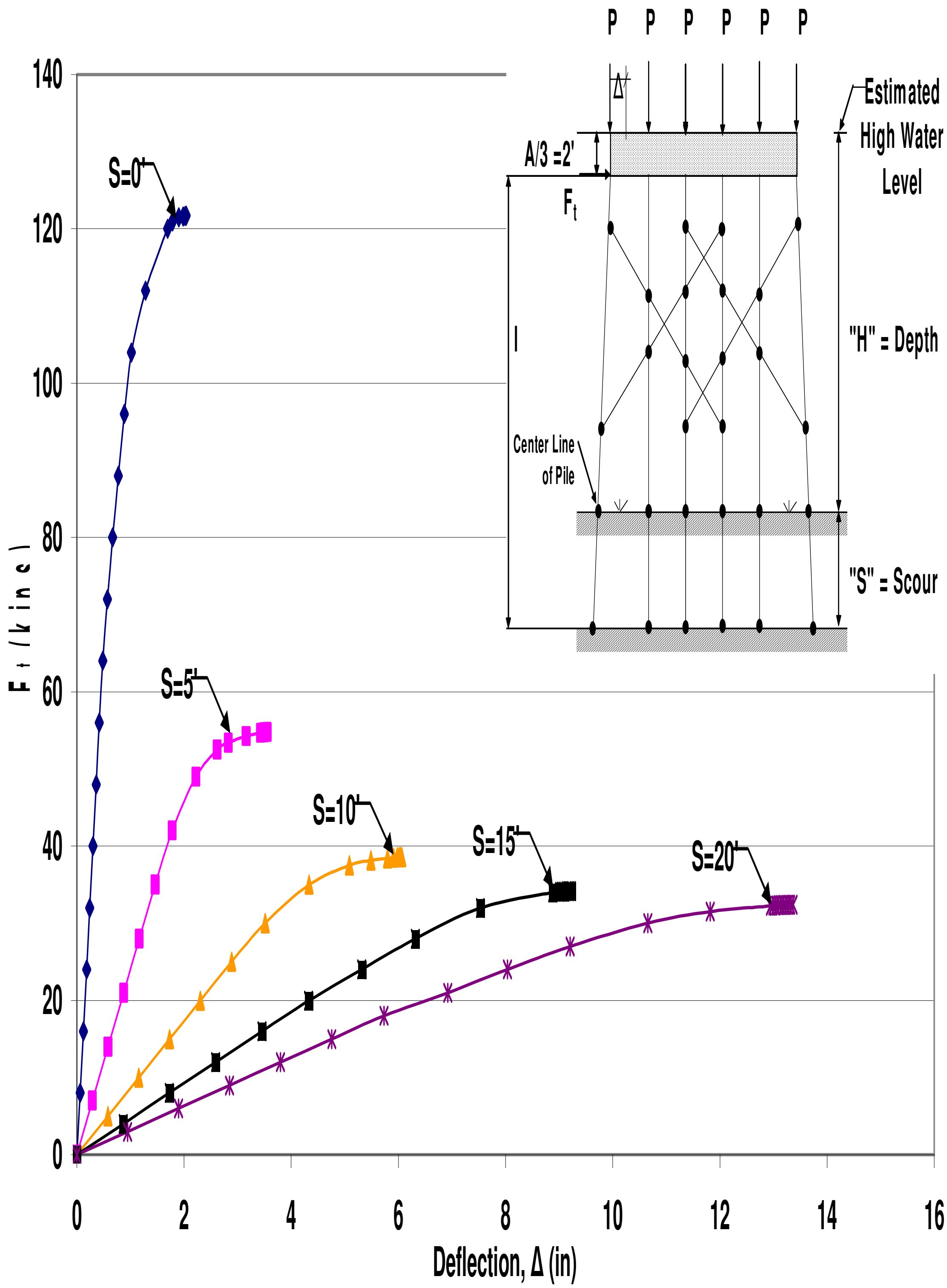


Figure B.91 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=140kips and A=6'
Pushover Analysis Results

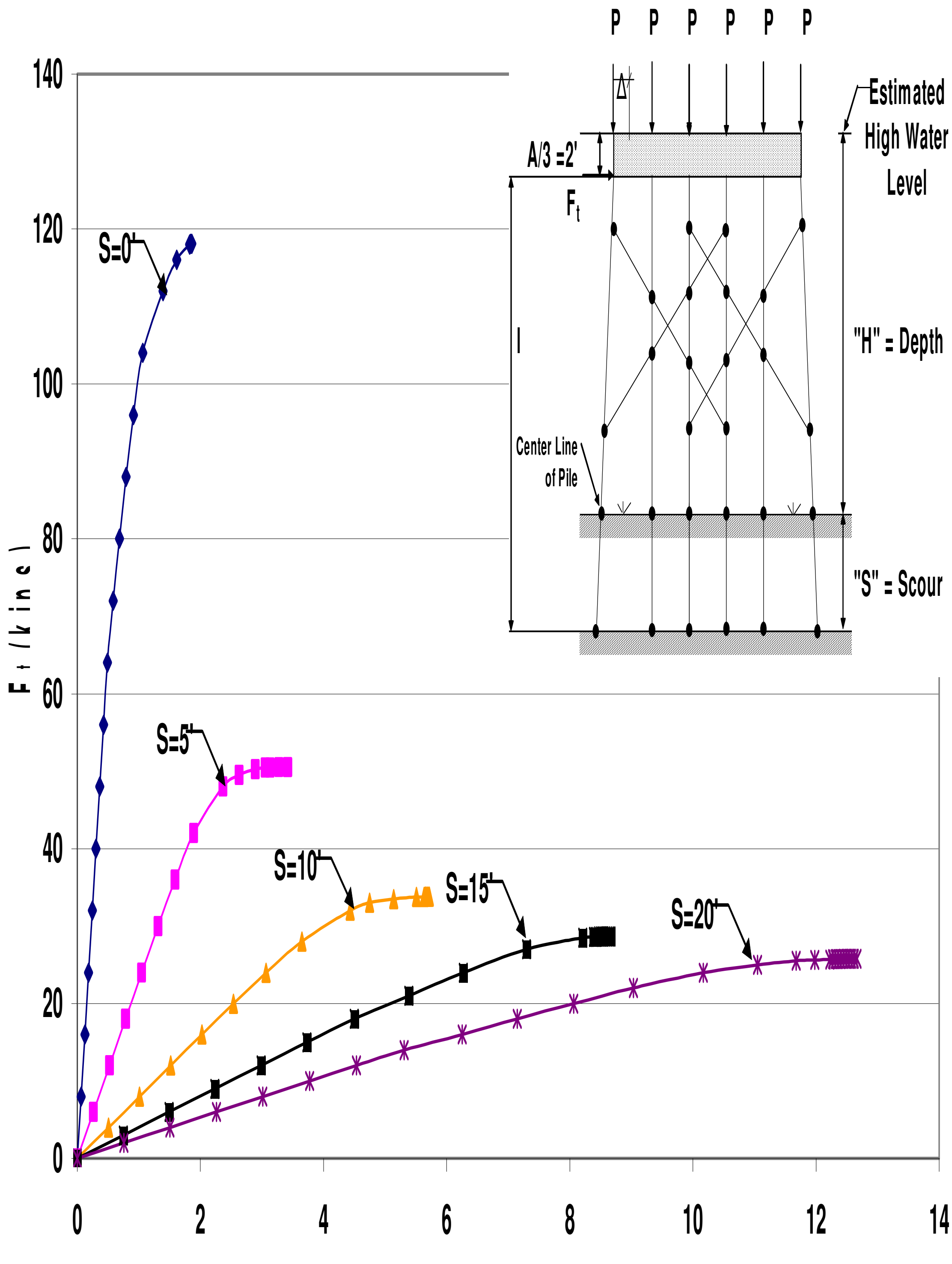


Figure B.92 HP12x53 Double X-Braced 6-Pile Bent with H=13', P=160kips and A=6'

Pushover Analysis Results

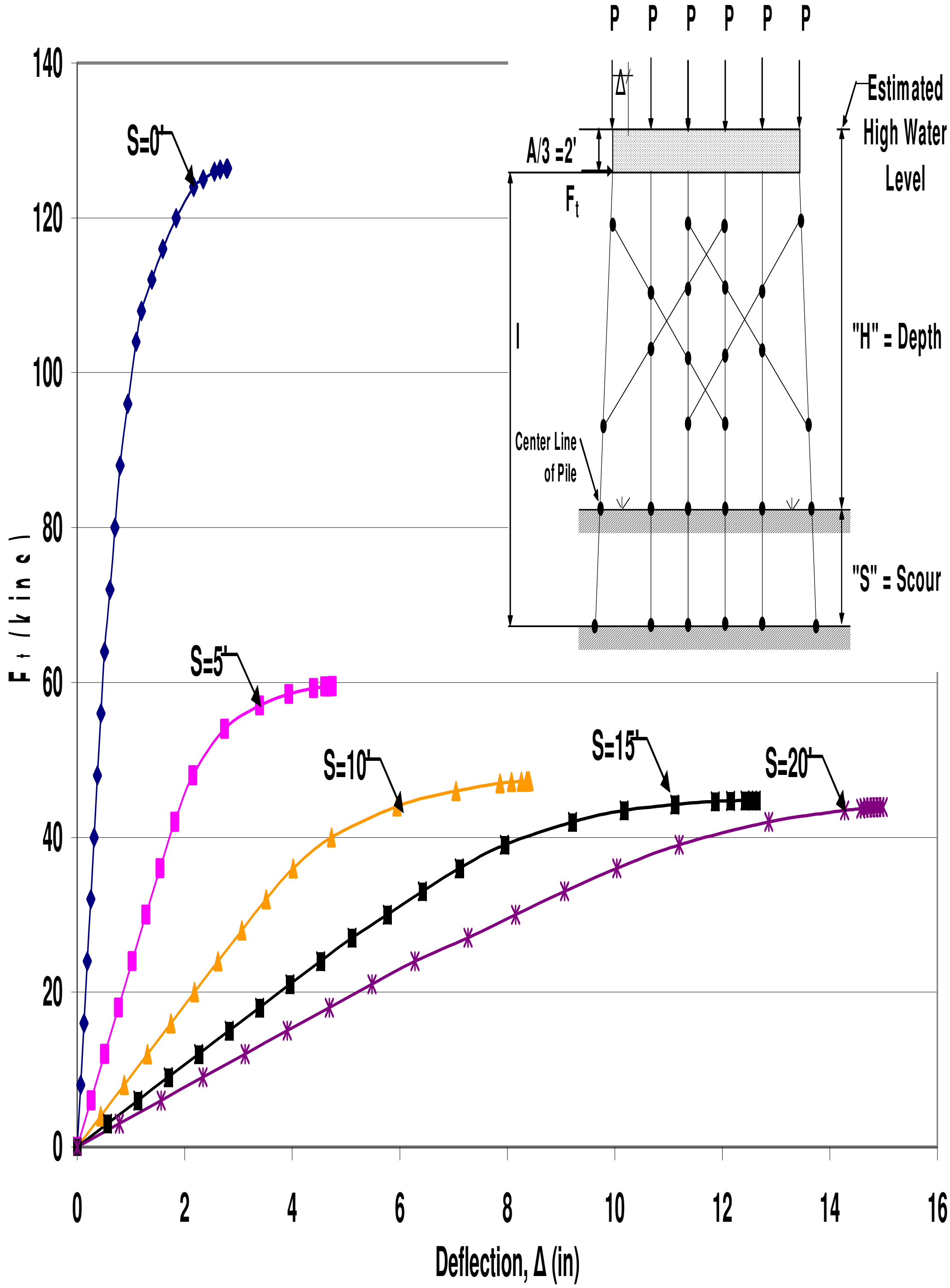


Figure B.93 HP12x53 Double X-Braced 6-Pile Bent with H=17', P=100kips and A=6'
Pushover Analysis Results

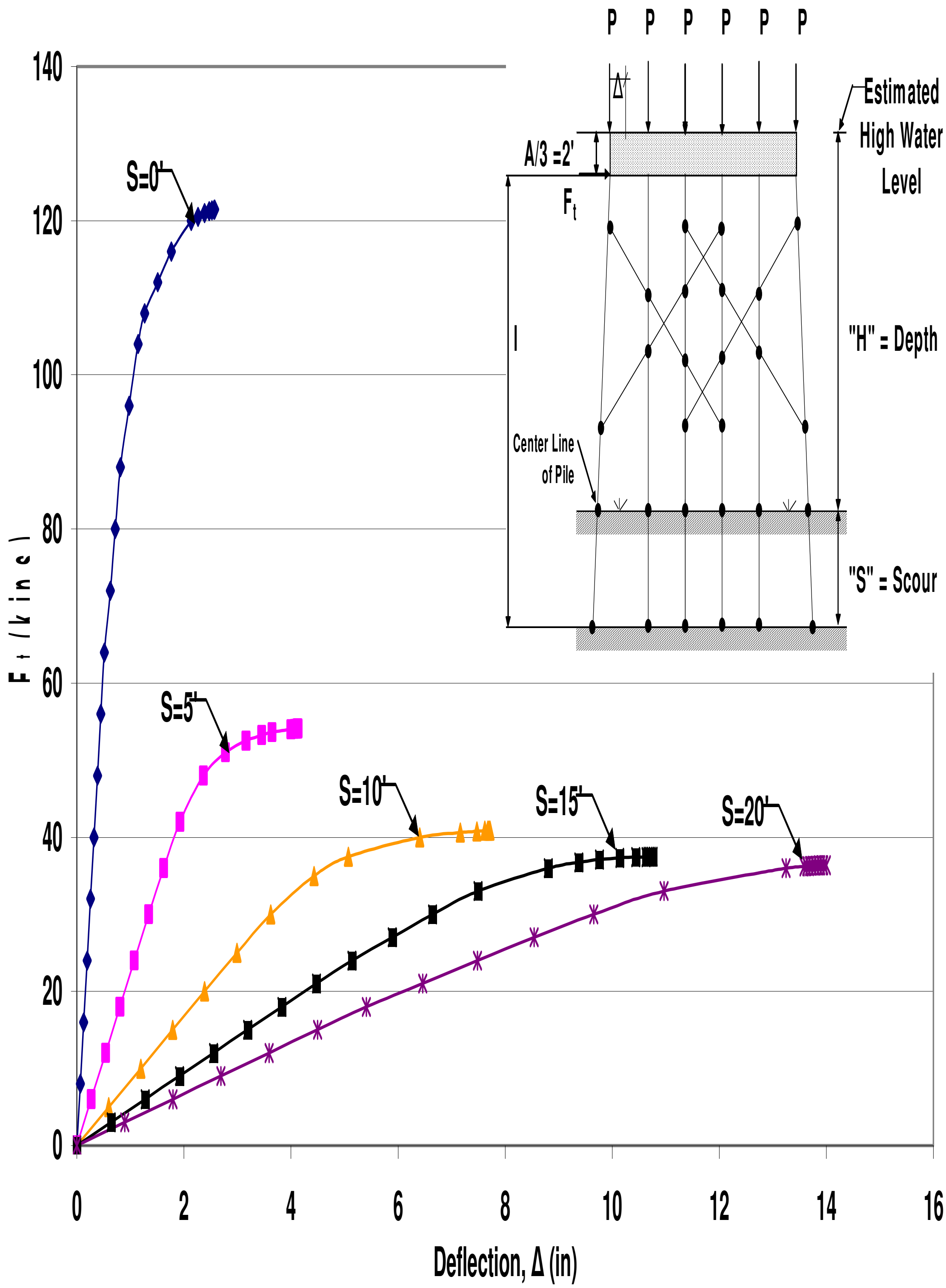


Figure B.94 HP12x53 Double X-Braced 6-Pile Bent with H=17', P=120kips and A=6'
Pushover Analysis Results

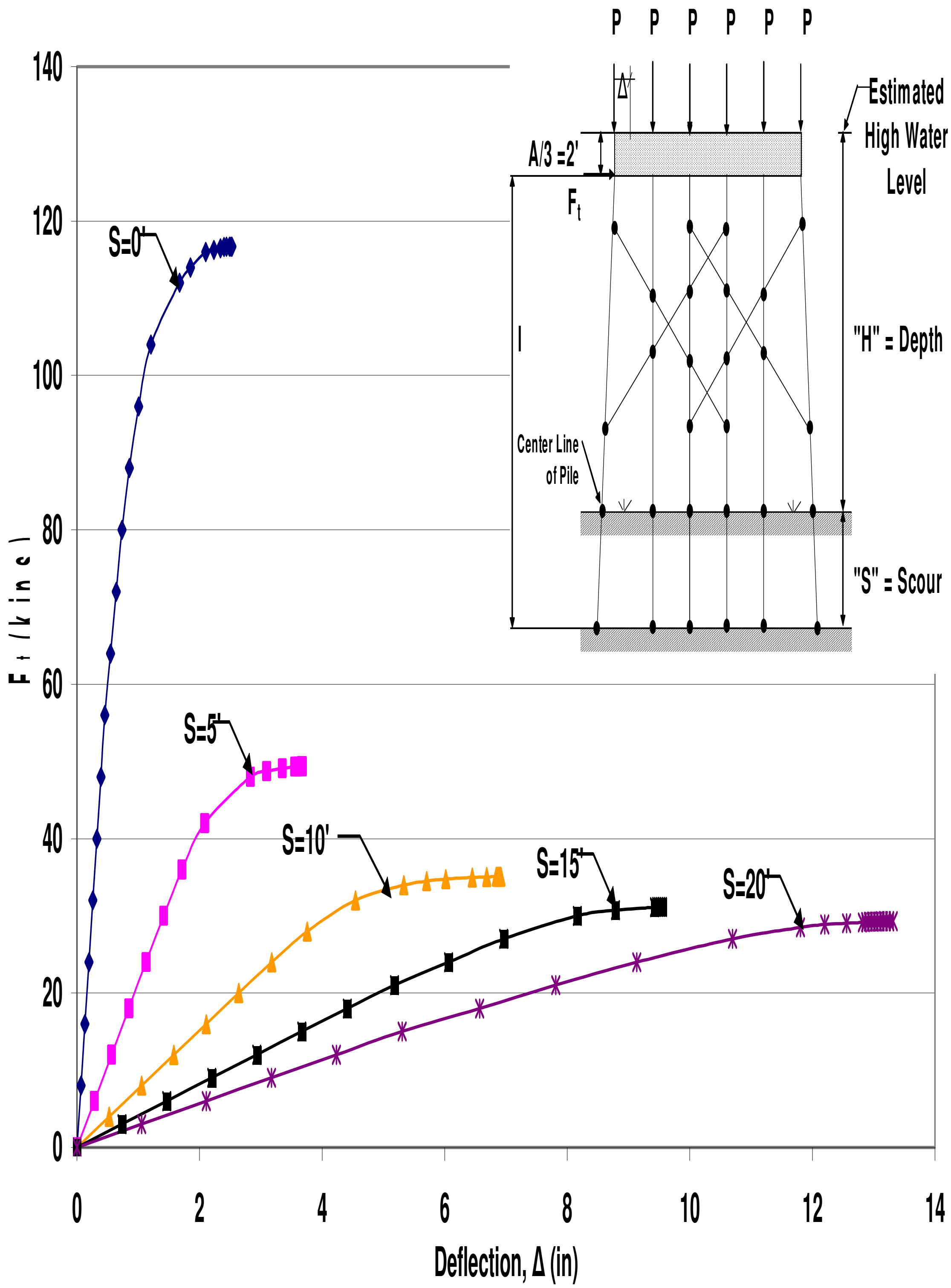


Figure B.95 HP12x53 Double X-Braced 6-Pile Bent with H=17', P=140kips and A=6' Pushover Analysis Results

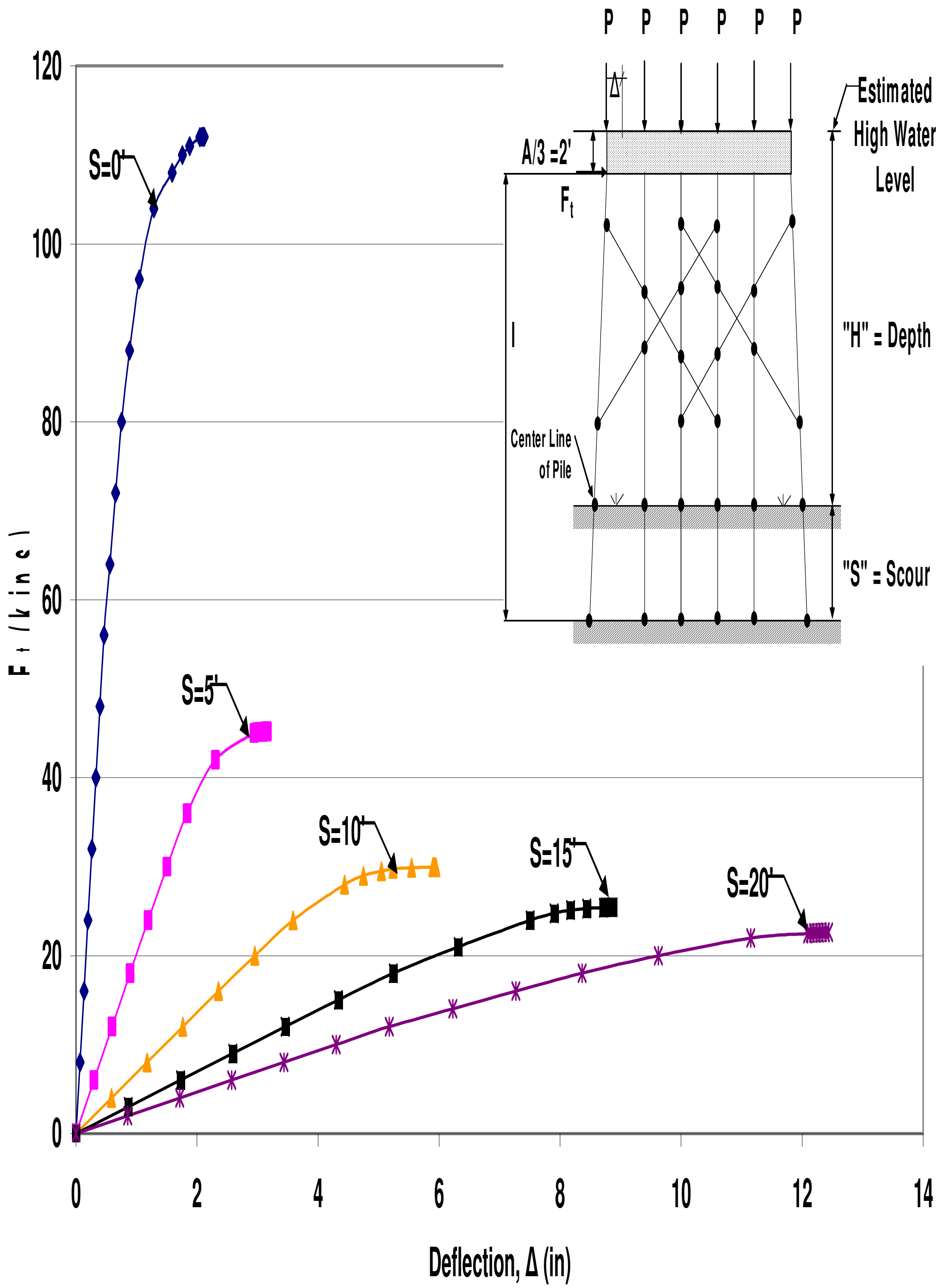


Figure B.96 HP12x53 Double X-Braced 6-Pile Bent with H=17', P=160kips and A=6' Pushover Analysis Results

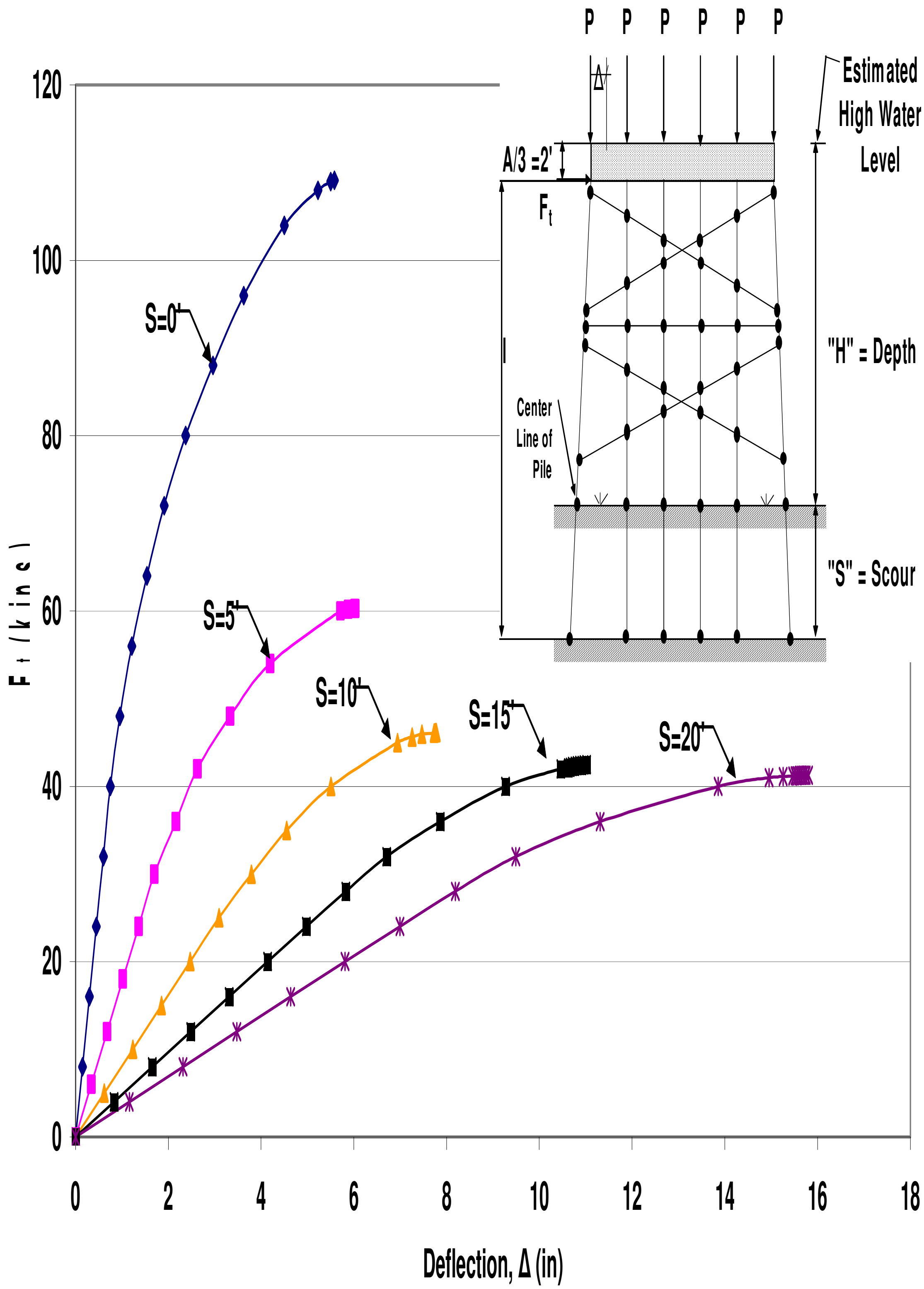


Figure B.97 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

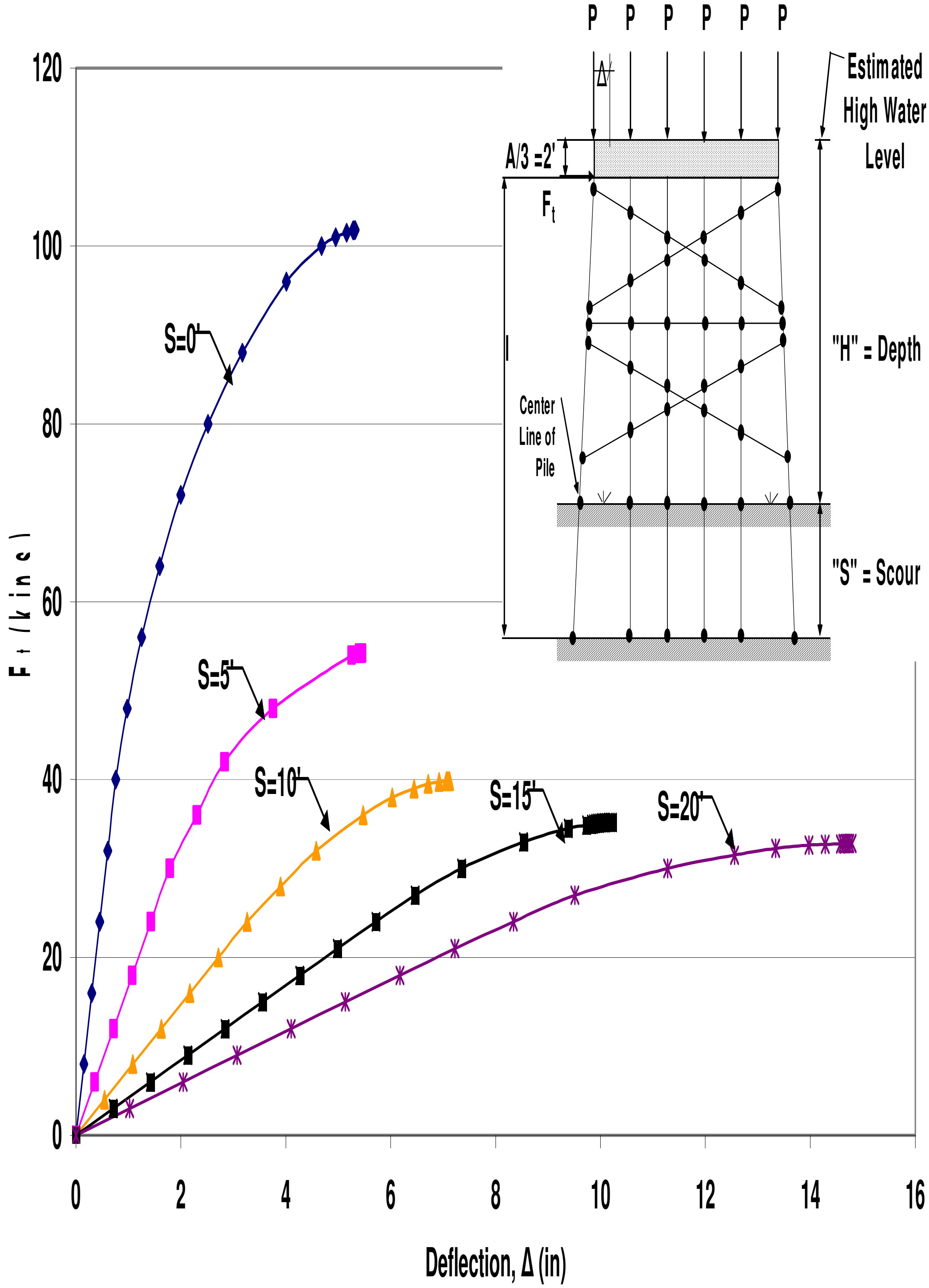


Figure B.98 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

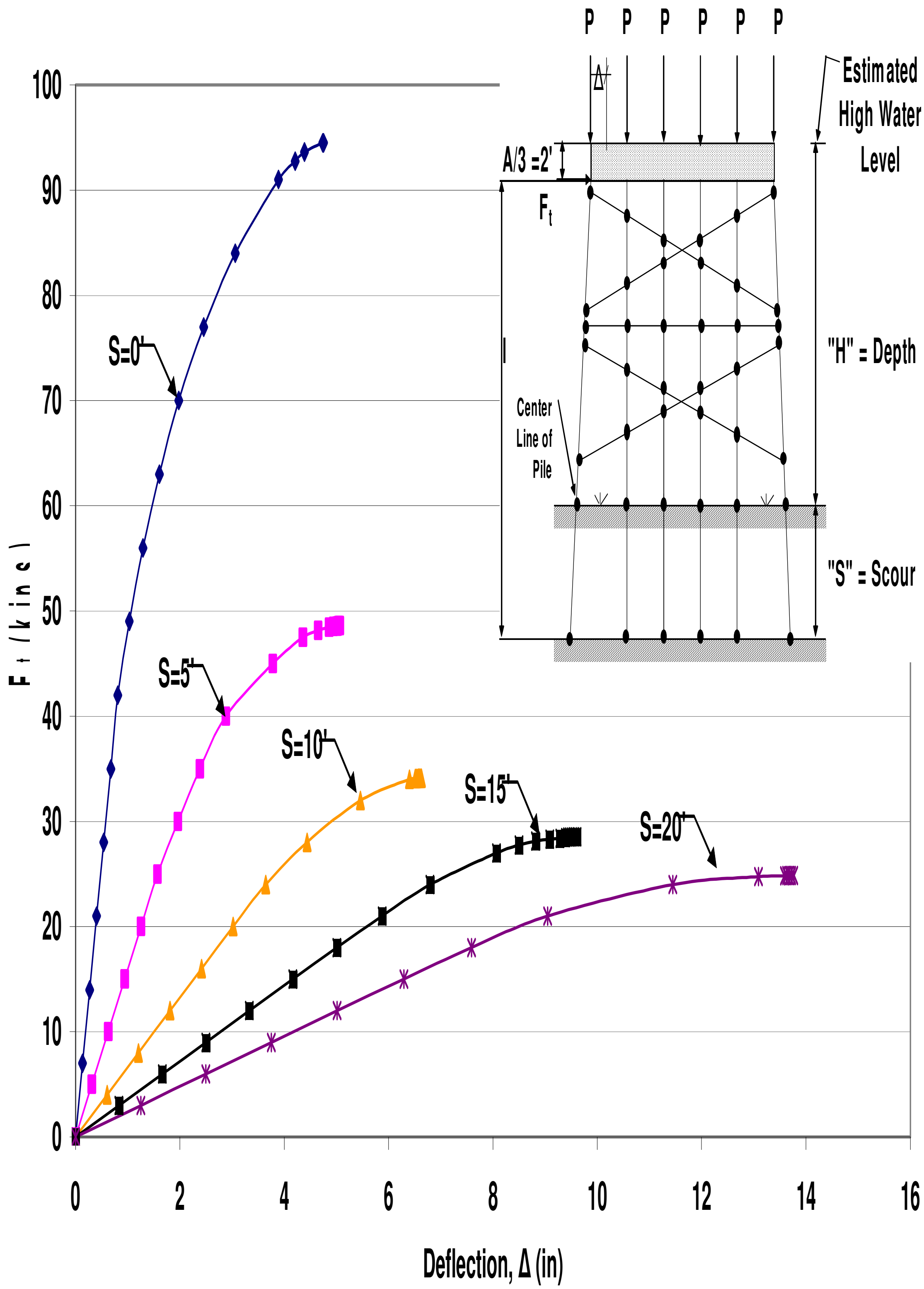


Figure B.99 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

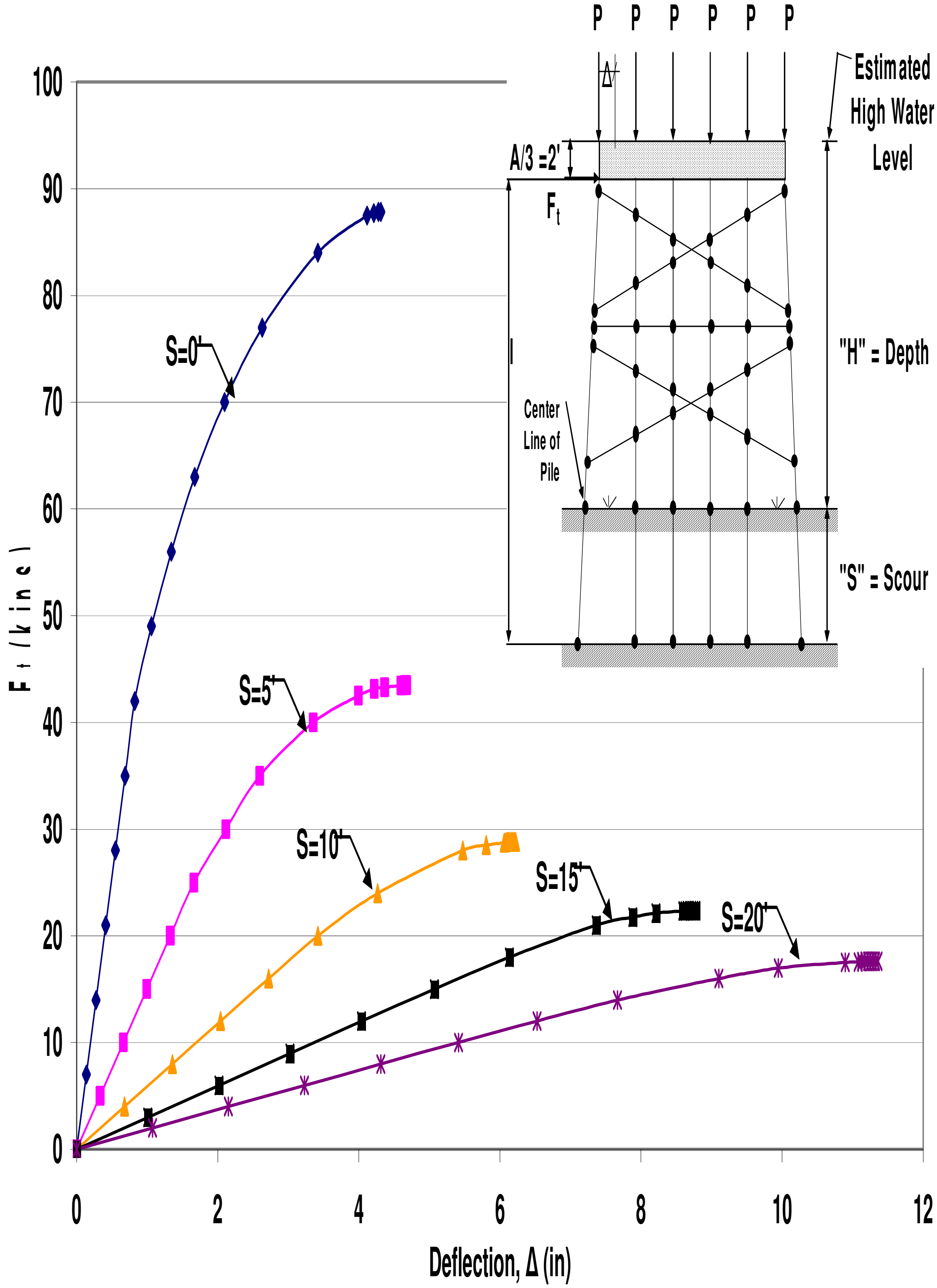


Figure B.100 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

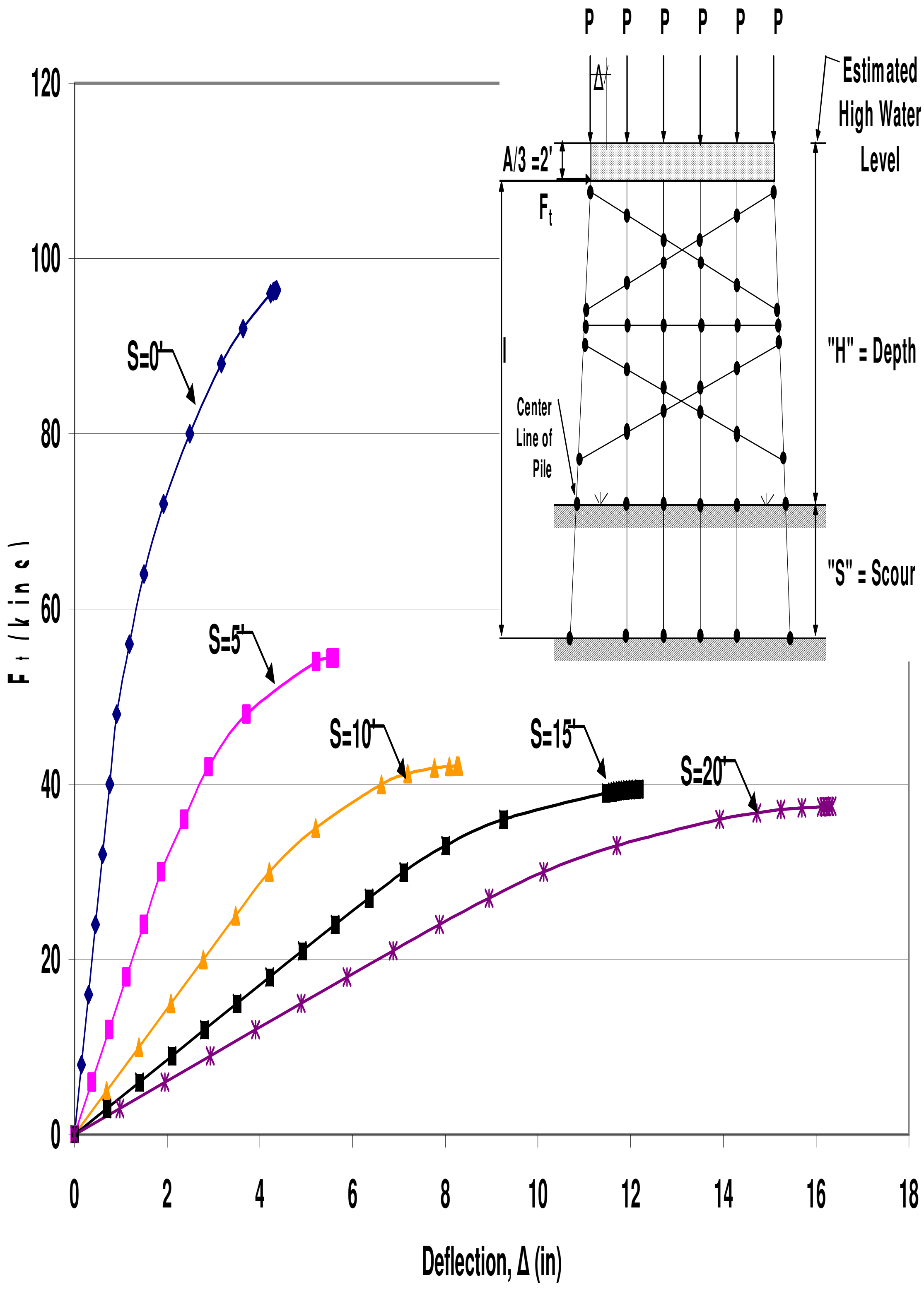


Figure B.101 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

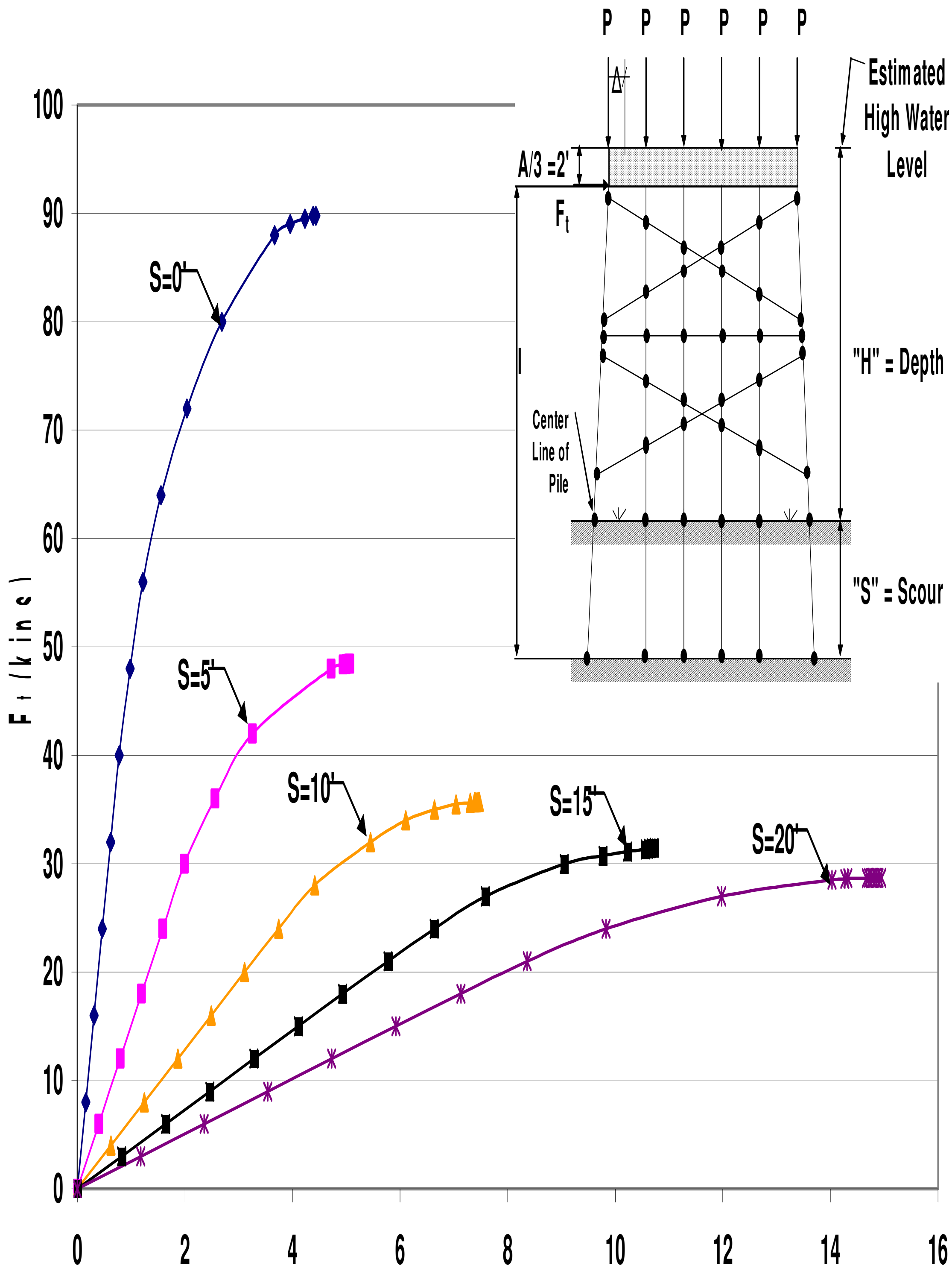


Figure B.102 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

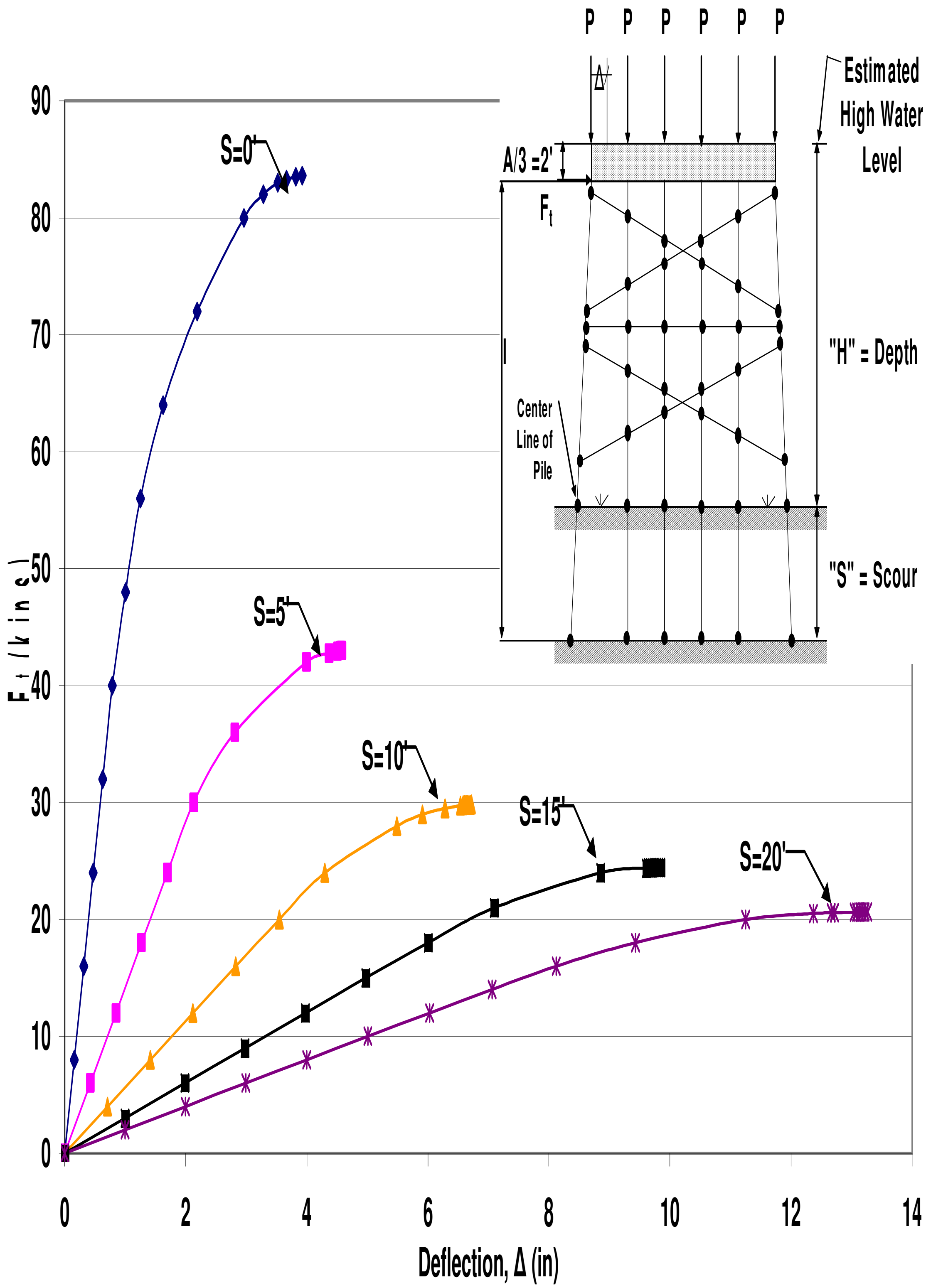


Figure B.103 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

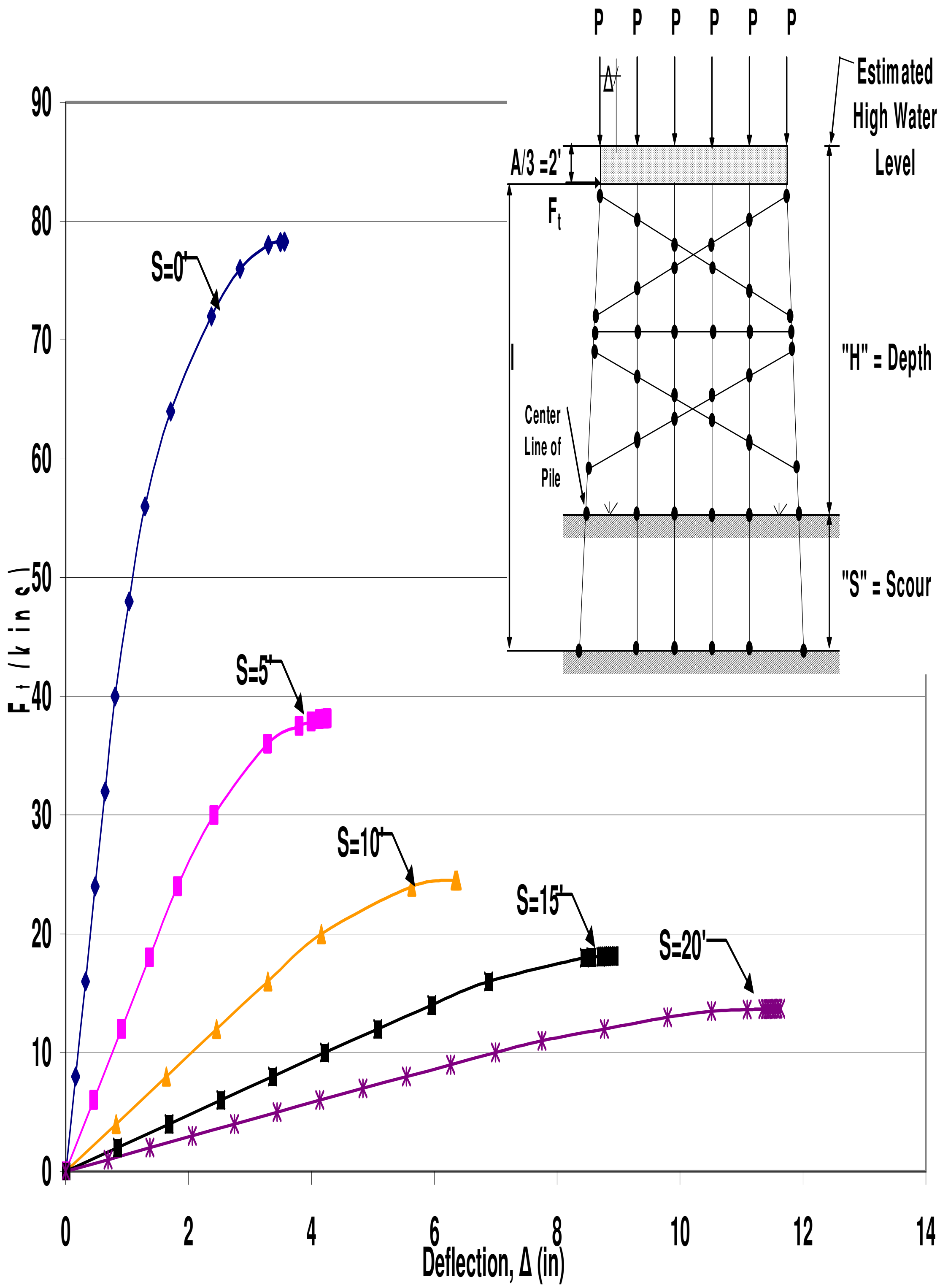


Figure B.104 HP12x53 Two-Story Single X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results

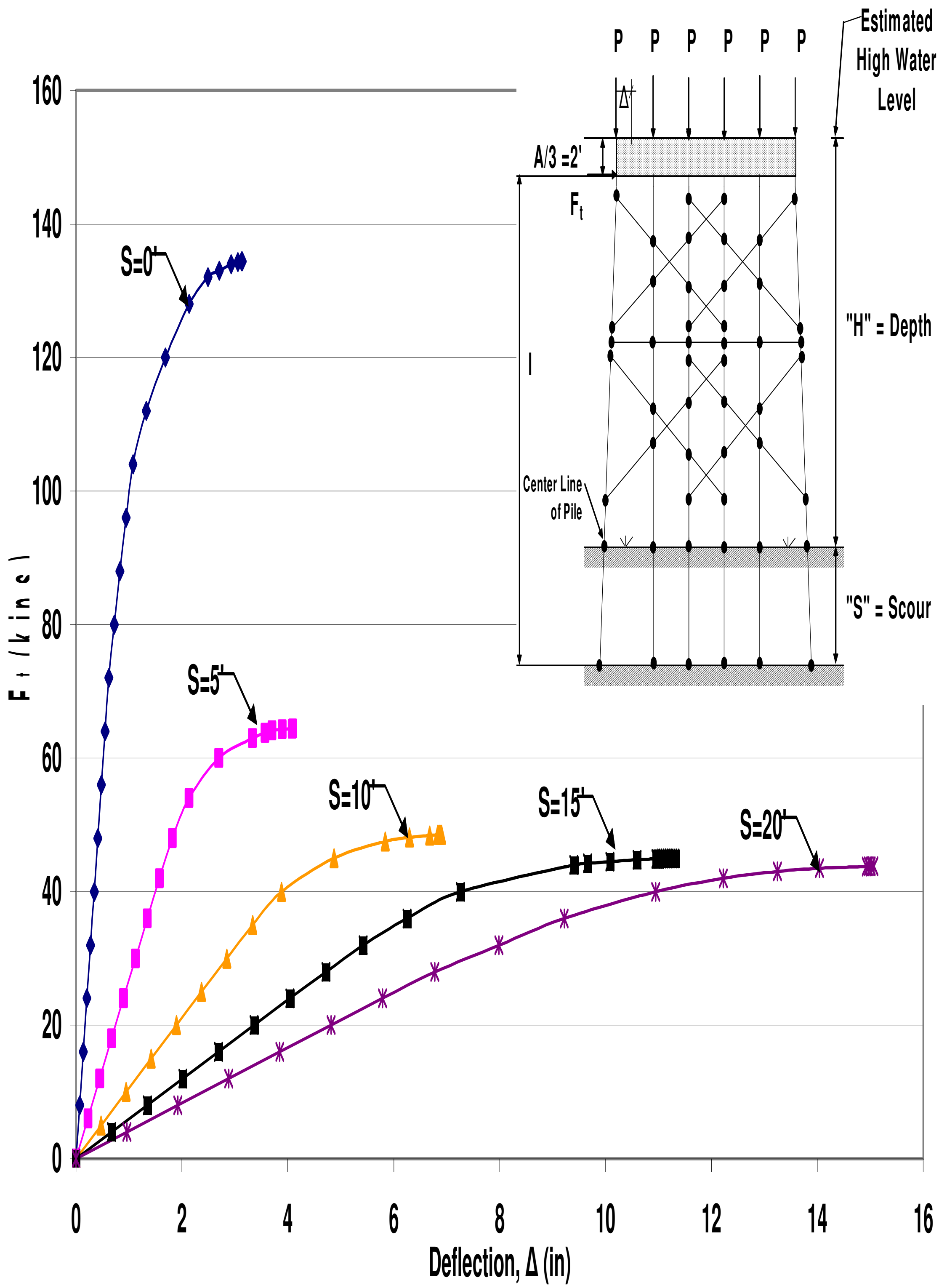


Figure B.105 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=100kips and A=6' Pushover Analysis Results

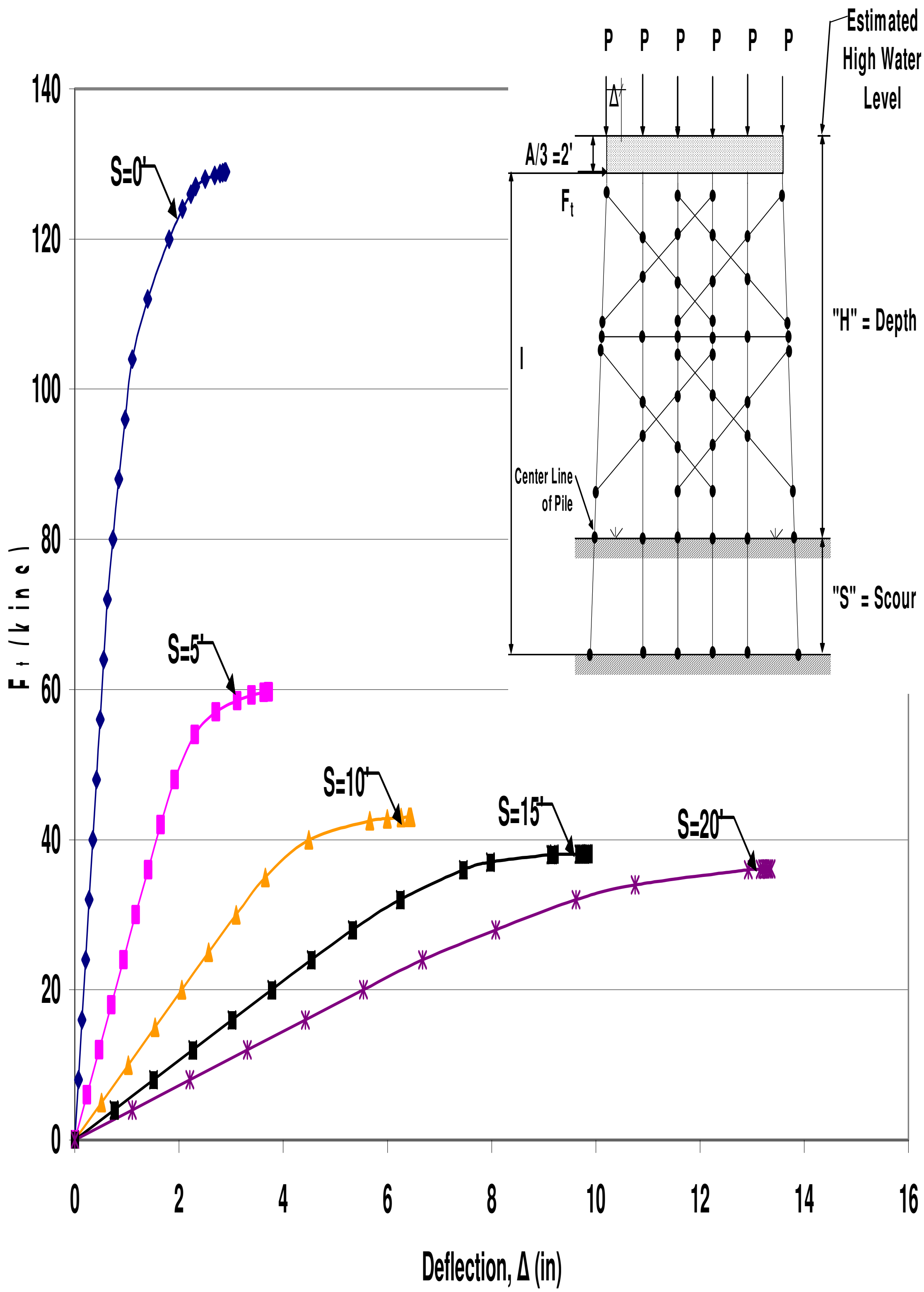


Figure B.106 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=120kips and A=6' Pushover Analysis Results

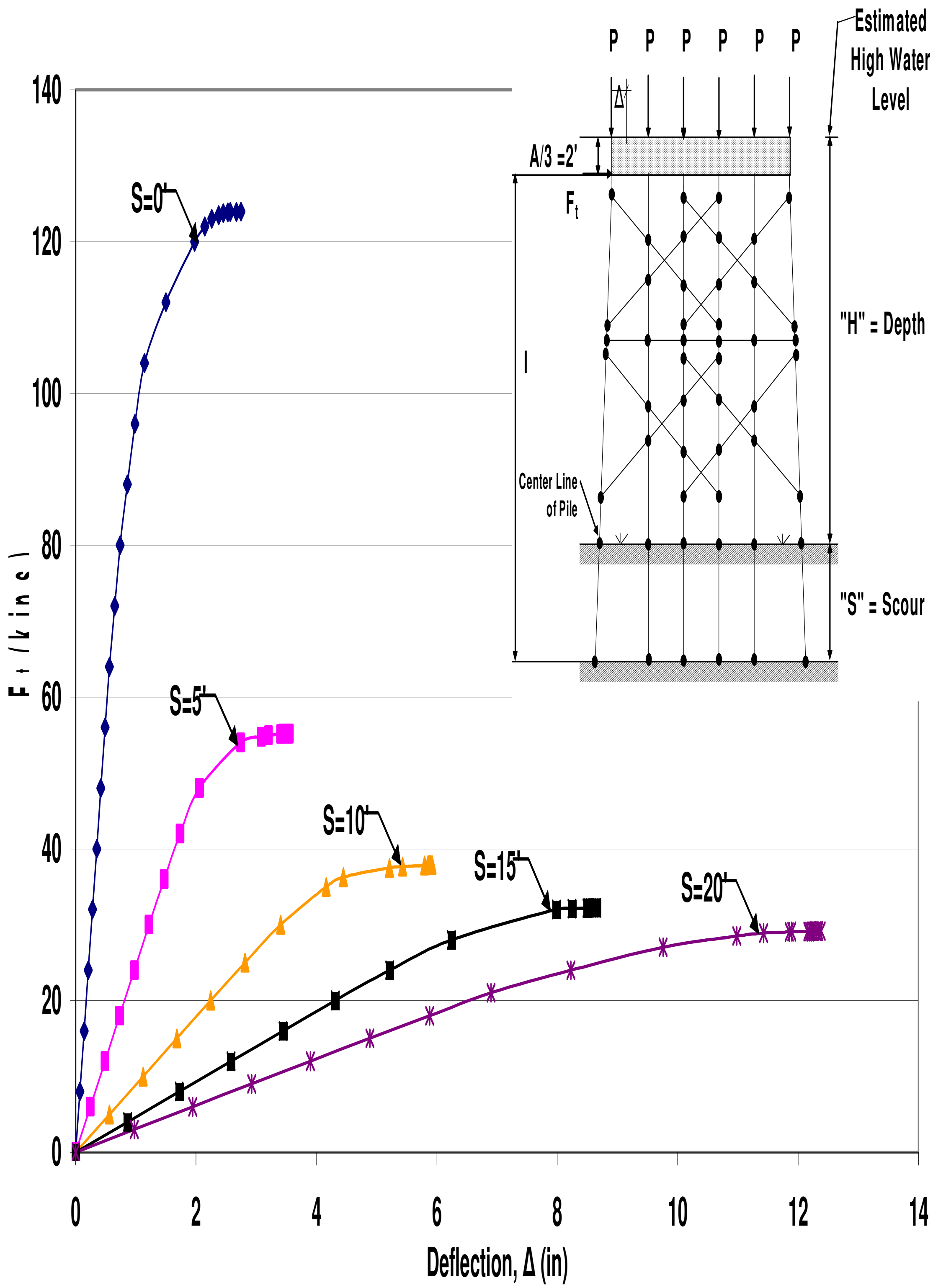


Figure B.107 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=140kips and A=6' Pushover Analysis Results

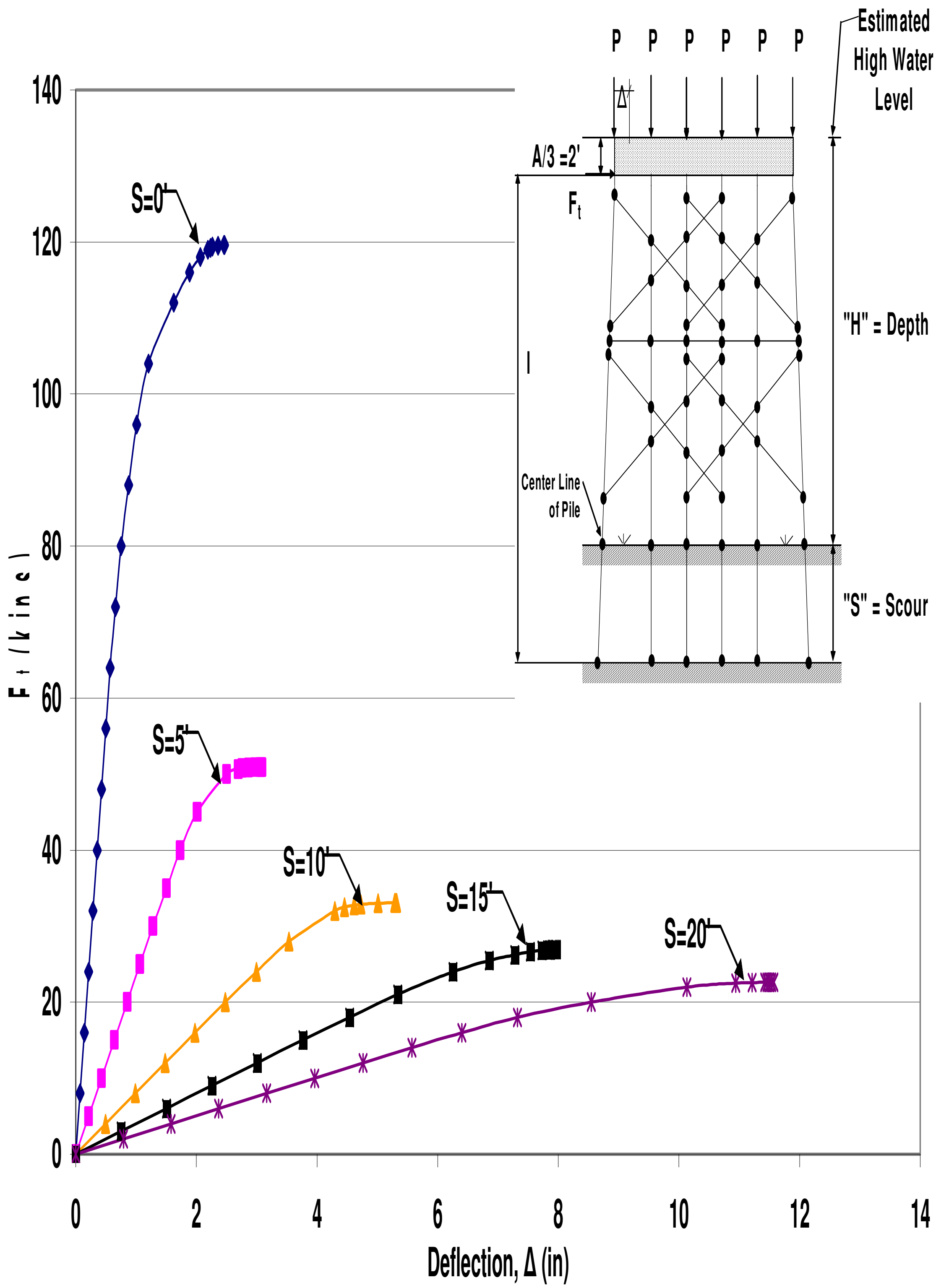


Figure B.108 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=21', P=160kips and A=6' Pushover Analysis Results

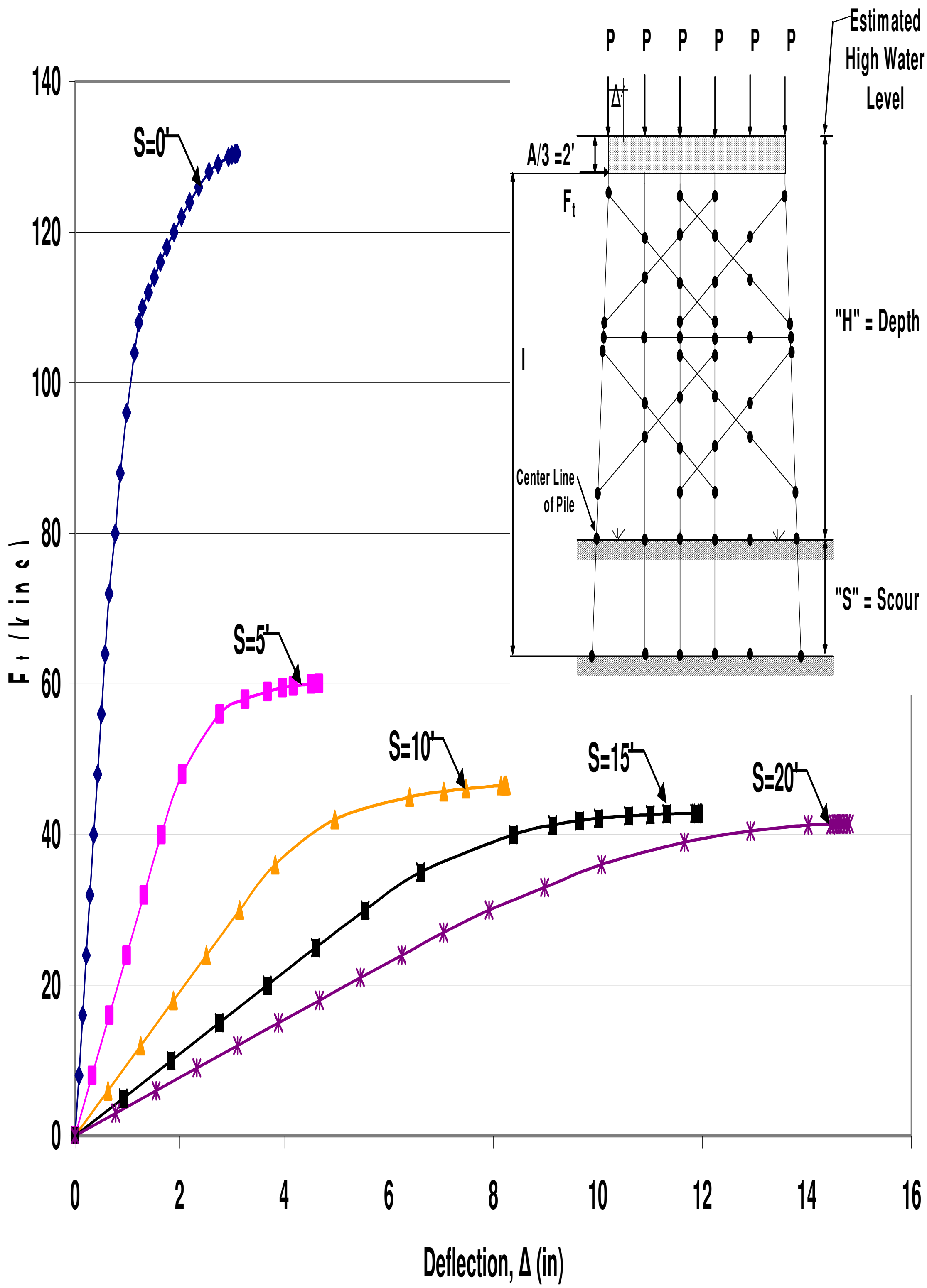


Figure B.109 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=100kips and A=6' Pushover Analysis Results

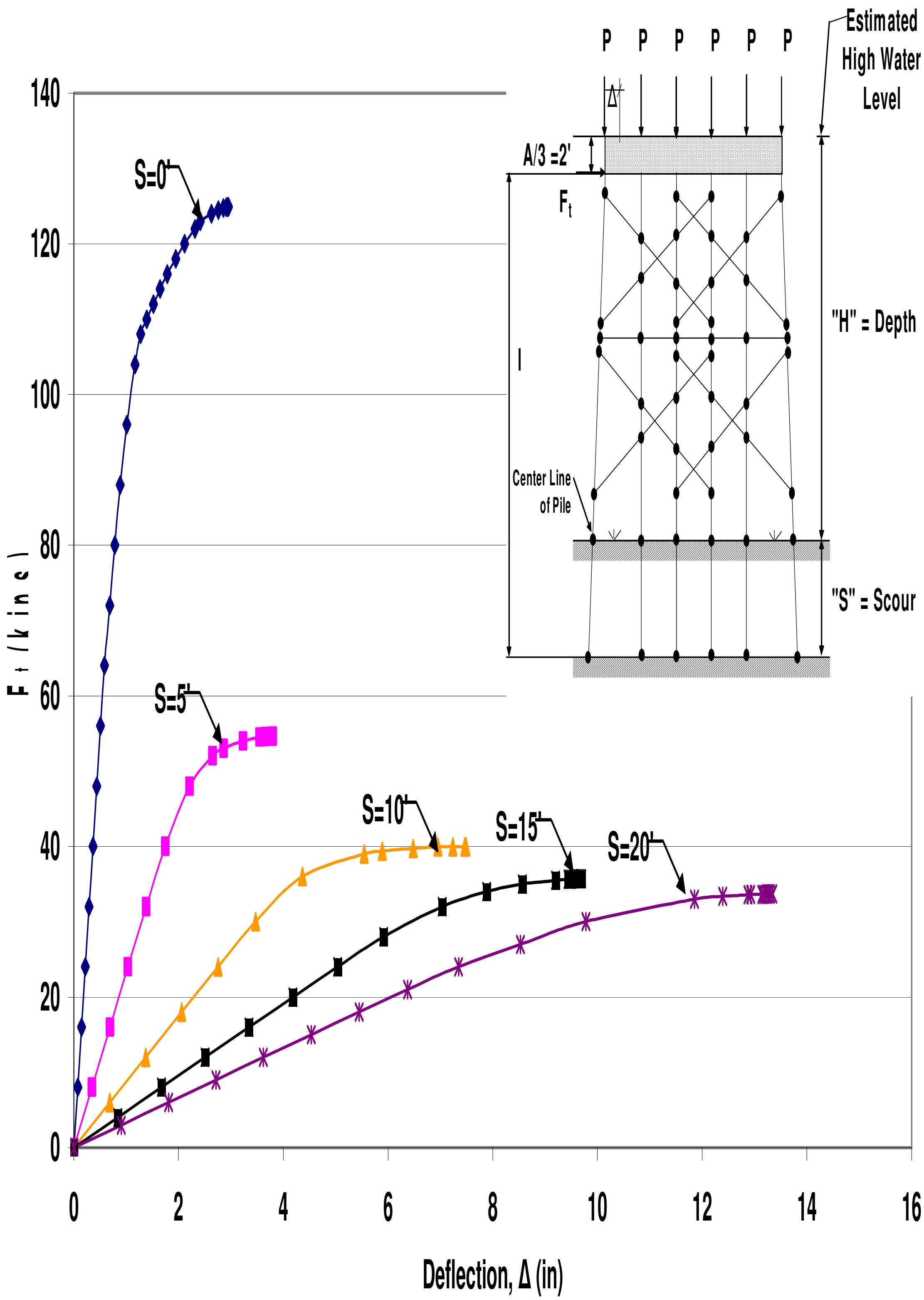


Figure B.110 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=120kips and A=6' Pushover Analysis Results

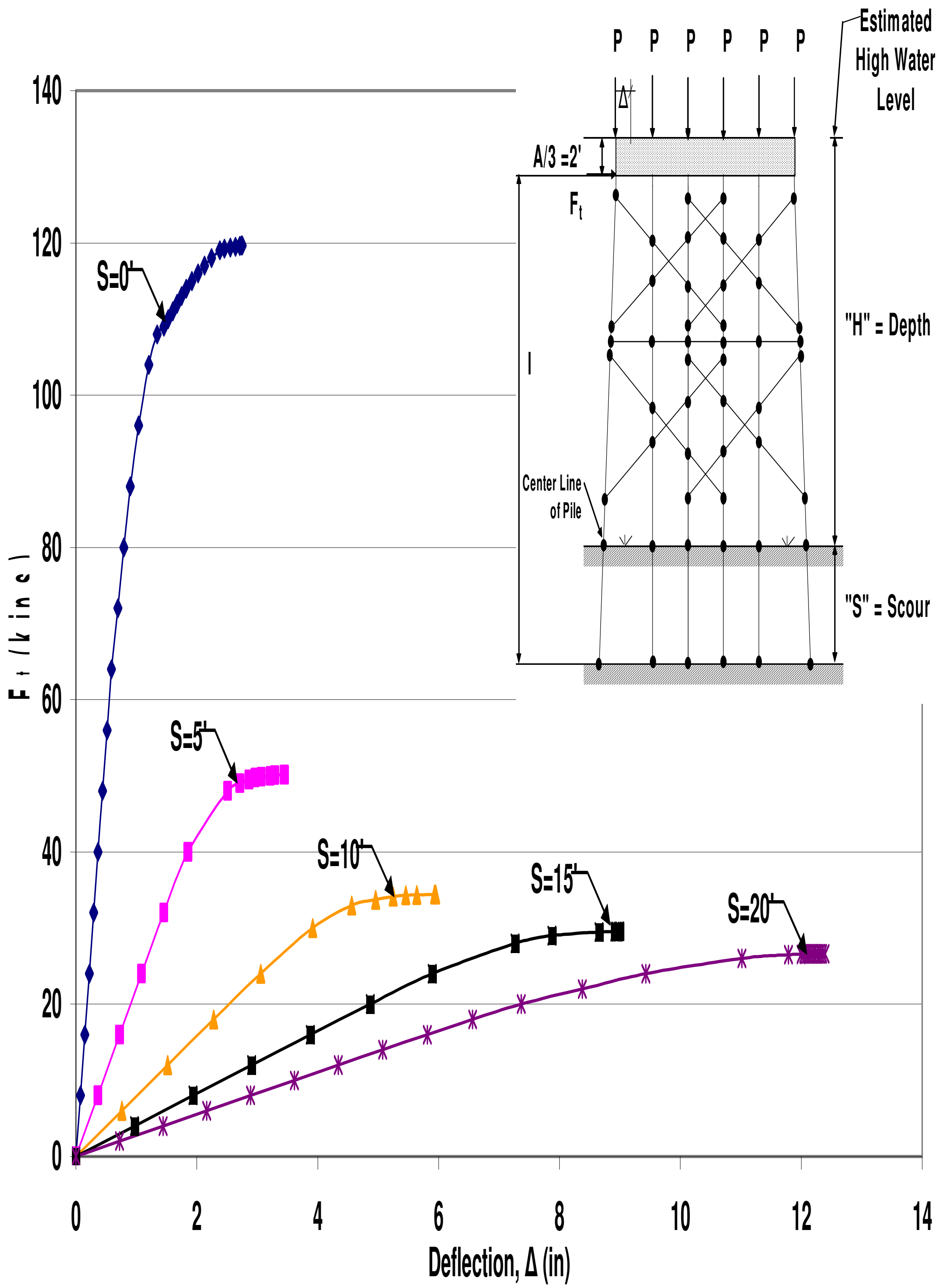


Figure B.111 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=140kips and A=6' Pushover Analysis Results

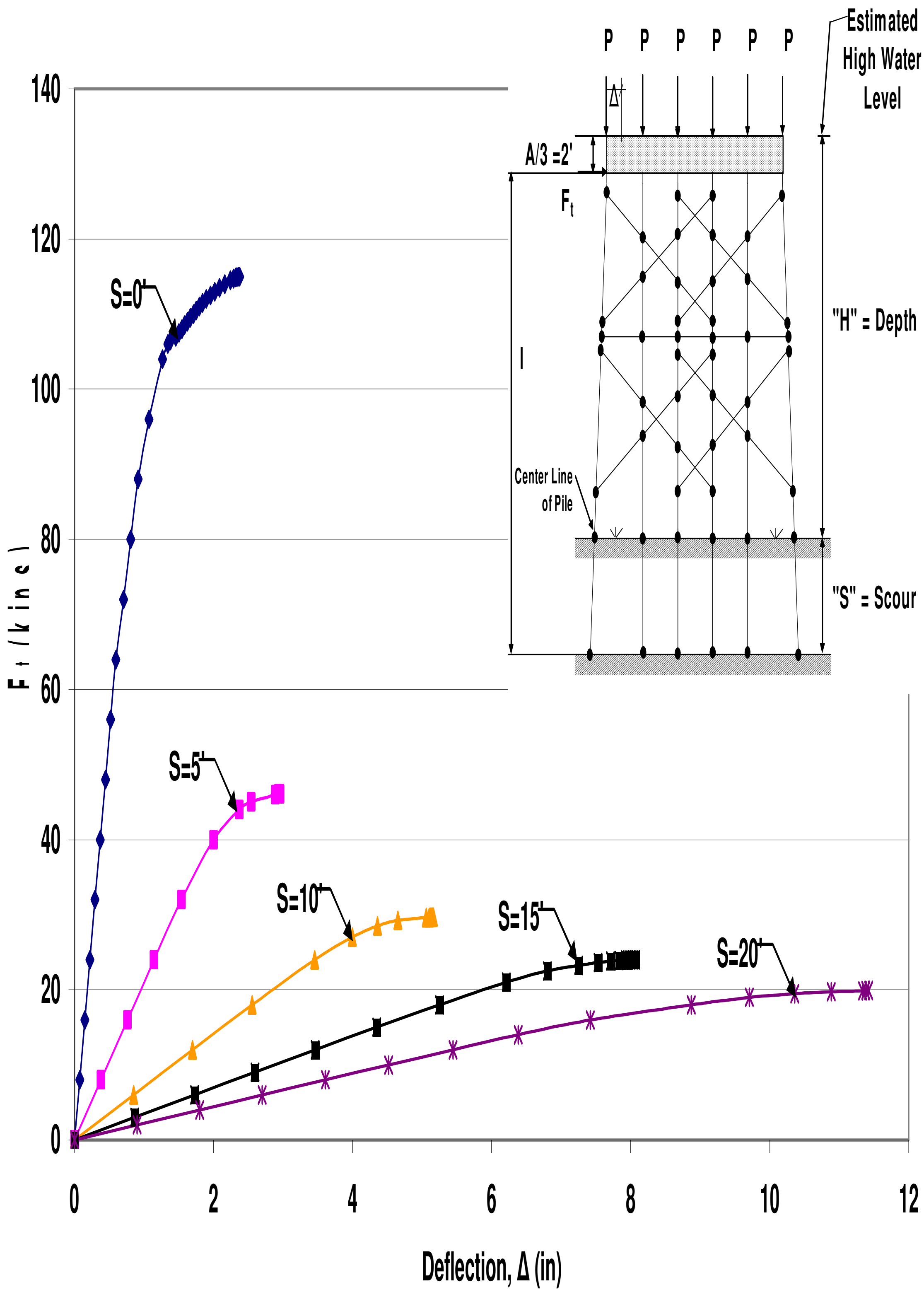


Figure B.112 HP12x53 Two-Story Double X-Braced 6-Pile Bent with H=25', P=160kips and A=6' Pushover Analysis Results