STABILITY OF HIGHWAY BRIDGES SUBJECT TO SCOUR

Except where reference is made to the work of others, the work described in this thesis is my own or was done in collaboration with my advisory committee. This thesis does not include proprietary or classified information.

James Nickolas Walker

Certificate of Approval:

Mary L. Hughes
Assistant Professor
Civil Engineering

G. Ed Ramey, Chair
Professor Emeritus
Civil Engineering

Robert W. Barnes
Associate Professor
Civil Engineering

George T. Flowers
Interim Dean
Graduate School

STABILITY OF HIGHWAY BRIDGES SUBJECT TO SCOUR

James Nickolas Walker

A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Masters of Science

Auburn, Alabama
December 19, 2008

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James Nickolas Walker

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Signature of Author

____

Date of Graduation

THESIS ABSTRACT

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James Nickolas Walker

Master of Science, December 19, 2008
(B.C.E., Auburn University, 2006)

238 Typed Pages

Directed by G. Ed Ramey

A common design/construction procedure for highway bridges in Alabama is the use of steel HP piles driven into 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 encased in concrete from the bent cap down to three feet below ground level and sometimes the piles are X-braced in the plane of the piles for lateral support.

The objectives of the Phase I research work were to identify the primary parameters of importance in assessing the adequacy of bridge pile bents for extreme scour events, and to identify the best approach to follow in developing a simple "screening tool", to check the adequacy. The objective of the Phase II research work was to develop a simple "screening tool" and a user's guide

explaining the proper use of the tool, for use in evaluating the structural stability of simple pile bent-supported bridges in an extreme scour event. The objectives of this Phase III research work were to expand, refine, and automate the "screening tool" developed in Phase II work. This thesis presents the expansions, refinements, and Tier-2 screenings added to the original "screening tool". The computer automation of the refined/2nd edition "screening tool" presented in this thesis is presented and discussed in a sister Phase III thesis.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Ramey for giving me this chance to work with him on this project and earn my Masters Degree. I am grateful for all his guidance and help throughout the project. I would also like to thank Nicole Donnee and Dr. Hughes for their help and cooperation on the project.

This thesis was prepared under cooperative agreement between the Alabama Department of Transportation (ALDOT) and the Highway Research Center (HRC) at Auburn University. I would like to thank the ALDOT and HRC for their sponsorship and support of the work.

I am also thankful for the assistance and guidance of several ALDOT engineers during the execution of the research work. Specifically, thanks are due to George Conner, Eric Christie, Randall Mullins, and Robert Fulton of the ALDOT.

Lastly, I would like to thank my family and friends for their support; most importantly my mother Julie for her encouragement and inspiration, and also Stephanie for her patience and encouragement.

Style used: Chicago Manual Style

Computer software used: Microsoft Word, Microsoft Excel, Microsoft Paint, GTSTRUDL

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CHAPTER 1: INTRODUCTION

1.1 Statement of Problem

The Alabama Department of Transportation (ALDOT) is currently performing an assessment of the scour susceptibility of its bridges, and a part of this assessment requires an evaluation of the structural stability of these bridges for an estimated flood/scour event. Because of the large number of bridges in the state subject to flood/scour events, and because structural stability analyses of each bridge represent a considerable effort in time and money, there is a compelling need to develop a simple "screening tool" which can be used, along with the scour analyses, to efficiently assess the susceptibility of these bridges to scour.

Phases I and II of the research toward this end have already been completed. It was determined in Phase I that it was indeed technically feasible to develop such a "screening tool", the primary parameters on which the scour susceptibility depend were identified, and it was verified that these parameters were in ALDOT's databases or could be estimated. In Phase II, a "screening tool" (ST) was developed to assess the adequacy of bridge pile bents for an estimated flood/scour event, and a Users Guide was developed to assist engineers in using the "screening tool".

1.2 Research Objectives

The objectives of this Phase III research were to enhance, simplify, expand the scope of applicability of the "ST" (screening tool), to develop and incorporate Tier-2 screenings for bents that do not pass safely through the "ST", and to automate the "ST" developed in Phase II. More specifically, the objectives of the Phase III work were as follows:

1. Work with ALDOT maintenance engineers performing bridge pile bent evaluations for adequacy during estimated extreme flood/scour events and identify how the "screening tool" can be simplified, enhanced, and expanded in scope of applicability to make it more user-friendly and helpful to ALDOT engineers.

2. Work with ALDOT engineers to determine if there are minimal changes that can be made in the "screening tool" that would allow significant expansion of the scope of applicability of the "screening tool". If there are, then make these changes.

3. Determine, where feasible, follow-up assessment procedures for those bents that do not pass through the "screening tool" with an evaluation of "the bent is safe from plunging (buckling, push-over)". More specifically, identify the appropriate follow-up checking procedures for those bents where the "screening tool" indicates that the "bent should be looked at more closely for possible plunging (buckling, push-over) failure". This will constitute a second tier of screening.

4. Work with ALDOT engineers to automate the “screening tool” as it currently exists. As simplifications, enhancements, and expansions of the “screening tool” are identified and made, it should be very easy to incorporate these into the automated version of the “screening tool”.

1.3 Work Plan

A brief work plan followed to accomplish the research objectives cited above is given in the work tasks below.

1. Work with ALDOT engineers in the bridge maintenance section to identify problem areas with the “screening tool” (ST) and areas where the ST is difficult to apply and/or where parameters needed by the ST are not readily available, and make appropriate modification in the ST to overcome these problems and render the ST more user-friendly and helpful.

2. Work with ALDOT engineers to identify bounding cases for other bents used by the ALDOT for which the ST may be applicable in order that these bounding cases may be used to assess the adequacy of these other bents. Also, for these other bents, determine what changes or additional analyses must be made to extend the scope of application of the ST. If the changes in the ST can reasonably be made, then make these changes.

3. Identify what additional checking, analyses, and input data are needed

for bents for which the ST indicates “check more closely for possible pile/bent plunging failure”.

4. Identify what additional checking, analyses, and input data are needed for bents for which the ST indicates “check more closely for possible pile/bent buckling failure”.

5. Identify what additional checking, analyses, and input data are needed for bents for which the ST indicates “check more closely for possible bent push-over failure”.

6. Develop a second tier “screening tool” which includes the checks identified in Work Tasks 3, 4 and 5 above. Discuss with ALDOT engineers whether this second tier of screening should be incorporated into the present ST so that there is just one ST, or make a second ST which is used only for those bents which do not safely pass through the present ST.

7. Prepare and conduct a training program on the second tier “screening tool” described in Task 6 above.

8. Work with ALDOT engineers to automate the ST for simple computer evaluation of the adequacy of bridge pile bents for estimated extreme flood/scour events. The automated ST will be a stand-alone computer

program system wherein ALDOT engineers input bridge/site parameter values and the program executes the ST evaluations and outputs intermediate and final results in a format appropriate for filing for record in the bridge's file folder for future reference if needed. The automated computer program should allow the user to change one or more input parameter values and generate a new evaluation without having to re-input the other bridge/site parameters.

9. Prepare and conduct a training program on the automated ST described in Task 8 above.

10. Prepare Phase III Final Report.

CHAPTER 2: ADDITIONAL "ST" LOAD AND SCOUR CONDITIONS, LOAD LEVELS, SENSITIVITY OF PUSHOVER LOAD TO BENT CAP STIFFNESS, AND EFFECTS OF CONTINUOUS-SPAN SUPERSTRUCTURES

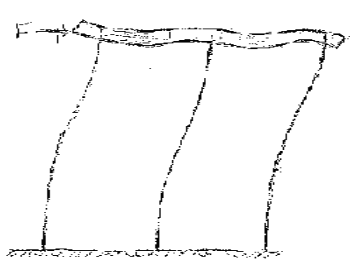
2.1 General

A number of "what if" questions regarding using the Phase II Screening Tool surfaced after submittal of the Phase II Report. Most of these questions pertained to the effect of other loading conditions, scour conditions, height of application of the pushover load, use of continuous superstructures, etc. on the possible pushover failure of a bridge pile bent during an extreme flood/scour event. Answering most of these questions required additional bent pushover analyses, and these are presented and discussed in the sections below.

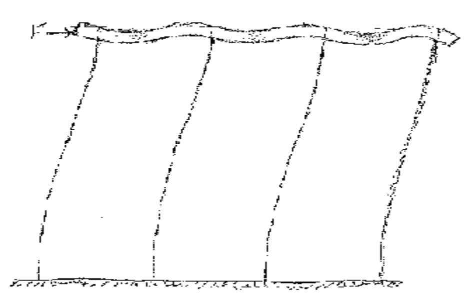
Also, during this interval, ALDOT personnel discovered that there are some sites in Alabama where the estimated maximum scour may be in excess of 20 ft and possibly as large as 25 ft, and thus the pushover analyses needed to be extended to a scour level of 25 ft. Lastly, for completeness, ALDOT personnel wanted to extend the pushover load tables to include 5-pile and 6-pile bents as well as 3-pile and 4-pile bents. The pushover analyses results of these extensions are presented in the following sections.

2.2 Sensitivity of Pushover Load to Bent Cap Size/Stiffness

Bent caps for all pile bents are either cast-in-place or precast concrete and thus a fair degree of uncertainty occurs about the appropriate value of bending stiffness, I, to use for the cap in a pushover analysis of pile bents. Since many pushover analyses of different bent sizes, bracing conditions, loadings, scour levels, etc., were to be performed, it was decided to conduct a limited sensitivity investigation on the sensitivity of a bent's pushover load to its cap size/stiffness. Only 3-pile and 4-pile bents of HP_{10x42} piles that were unbraced, such as the ones shown with qualitative deflection curves in Fig. 2.1, were considered for a rather short and a tall bent height. Values of I_{gross} for the caps of steel pile bents are typically in the range of 25,000 $in^4 \leq I_{gross} \leq$ 50,000. A wide range of I values were used in the analyses, with gross moments of inertia (I_{gross}) ranging from 10,000 in^4 to 2,000,000 in^4. The I = 2,000,000 in^4 value was taken to represent an infinitely stiff cap. The resulting bent pushover loads, F_t, are shown in table form in Table 2.1 and graphically in Fig. 2.2.



a. 3-Pile Bent



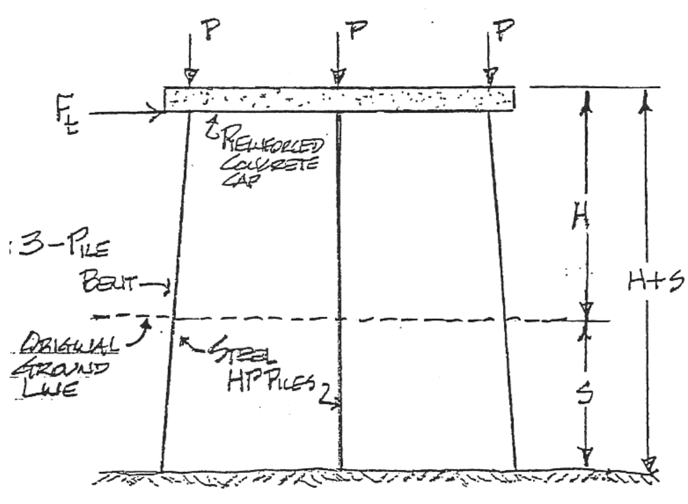
b. 4-Pile Bent

Fig. 2.1. Qualitative Lateral Load Induced Bent Deformations

Table 2.1. F_t for Unbraced 3-Pile and 4-Pile Bridge Bents for Varying Values of Bent Cap I_{gross} - HP_{10x42} Piles and $P=100^k$

I_{gross} (in^4)	3-Pile Bent		4-Pile Bent	
	F_t (kips)		F_t (kips)	
	H+S=10'	H+S=20'	H+S=10'	H+S=30'
10,000	19.52	4.25	28.40	7.44
25,000	19.59	4.30	31.62	11.13
50,000	19.61	4.31	34.06	12.47
100,000	19.62	4.32	35.92	13.06
150,000	19.63	4.33	36.75	13.38
200,000	19.63	4.33	37.26	13.49
2,000,000	19.64	4.34	38.61	13.80

Pile Bent Parameters:



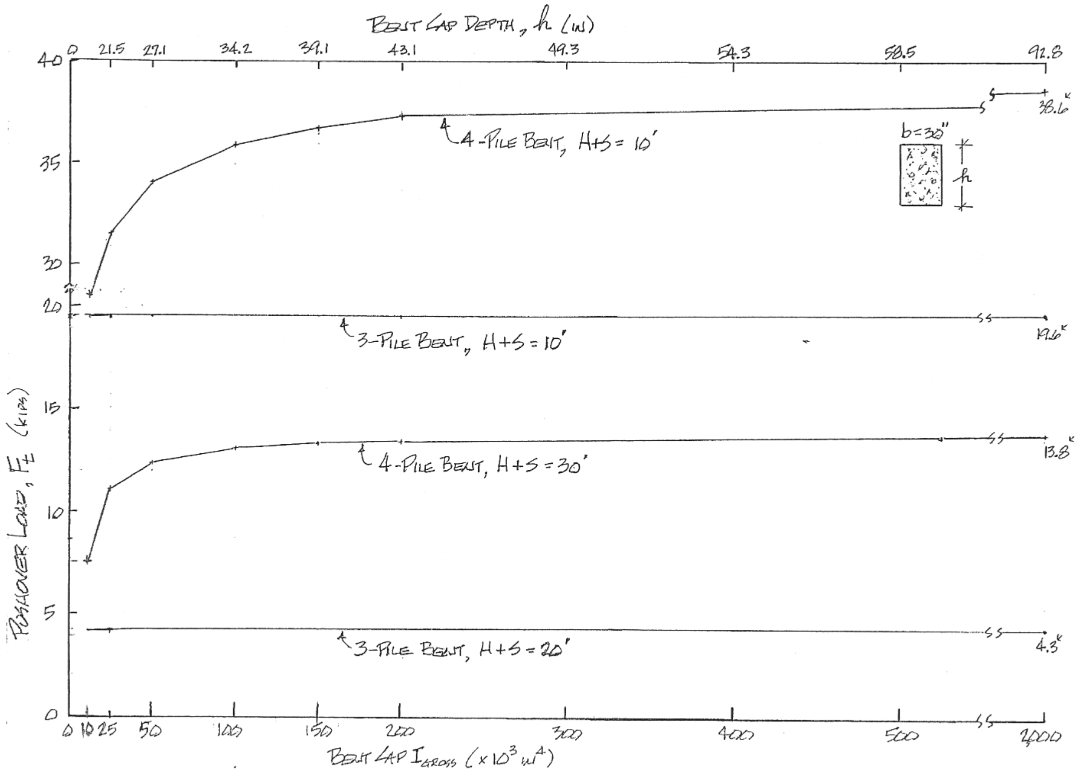


Fig. 2.2. Pushover Load vs. Bent Cap I_{gross} for Unbraced 3- and 4-Pile Bents (HP_{10x42} Piles) and P = 100^k

It can be seen in Table 2.1 and Fig. 2.2 that for the 3-pile bent, the pushover load is essentially independent of the bent cap size/stiffness. For the 4-pile bent the pushover load is sensitive to the cap stiffness at values of $I_{gross} \leq$ 100,000 in^4. However, even in these cases, the pushover load only decreases by about 19% when I decreases from I = 2,000,000 → 25,000 in^4, which is a 99% decrease in I. These results are consistent with the observation that for steel HP pile bents bending in the plane of the bent, i.e., about the weak axis of the HP piles, the very small value of I_{pile} relative to the I_{cap} of the concrete cap and the large exposed pile length after scour relative to the length of cap between piles, renders the bending stiffness of the piles to be vastly smaller than that of the cap (see Figs. 2.1 and 2.3). Thus, the flexibility of the bent piles is the controlling bent pushover parameter and the bent pushover load is essentially independent of the cap size/stiffness (within a reasonable range of I values). It is also important to note that the plastic hinges form in the steel HP piles because they have a much smaller plastic moment than that of the bent cap. This also contributes to the pushover failure being independent of the bent cap stiffness.

It should be noted that for X-braced bents (see Fig. 2.4) that the bracing system maintains the relative geometrical integrity (with or without the HB-1 brace shown in Fig. 2.4) of the bent in the region of the X-bracing and the bent sidesways in the region below the X-brace as shown in Fig. 2.4. In this case, the pushover load is even more independent of the bent cap I_{gross}.

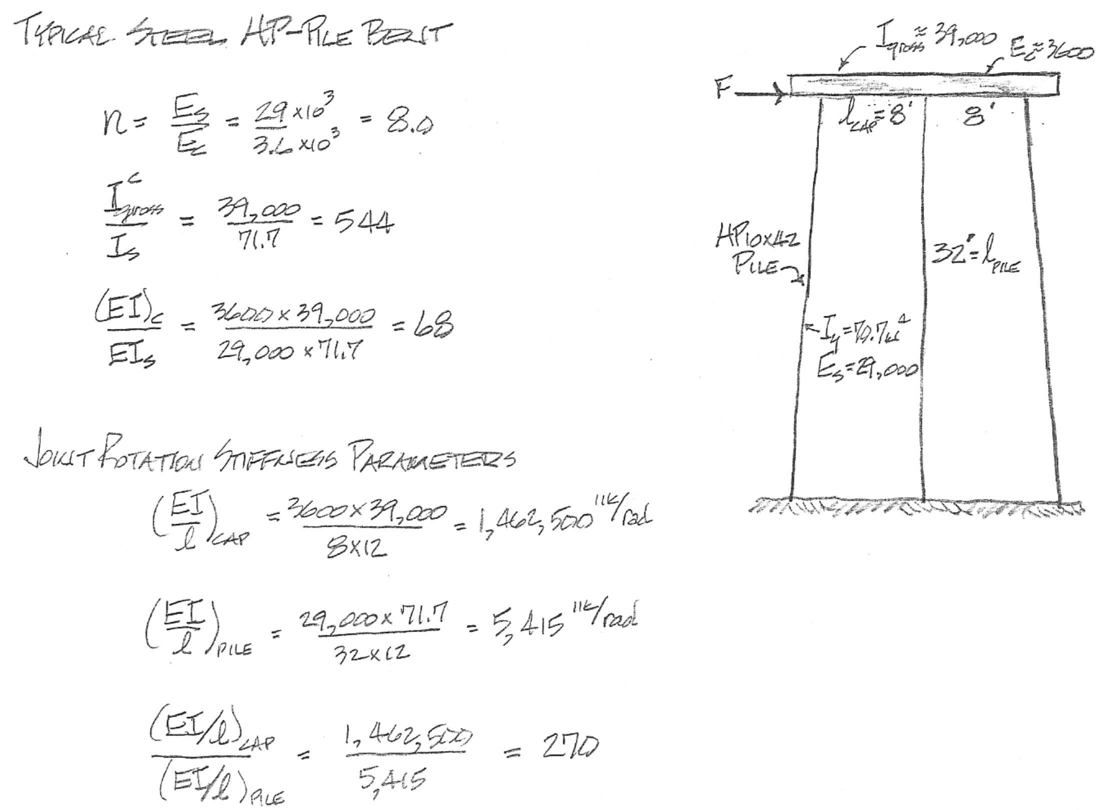


Fig. 2.3. Stiffness and Relative Stiffness Parameters for Typical 3-Pile Bent

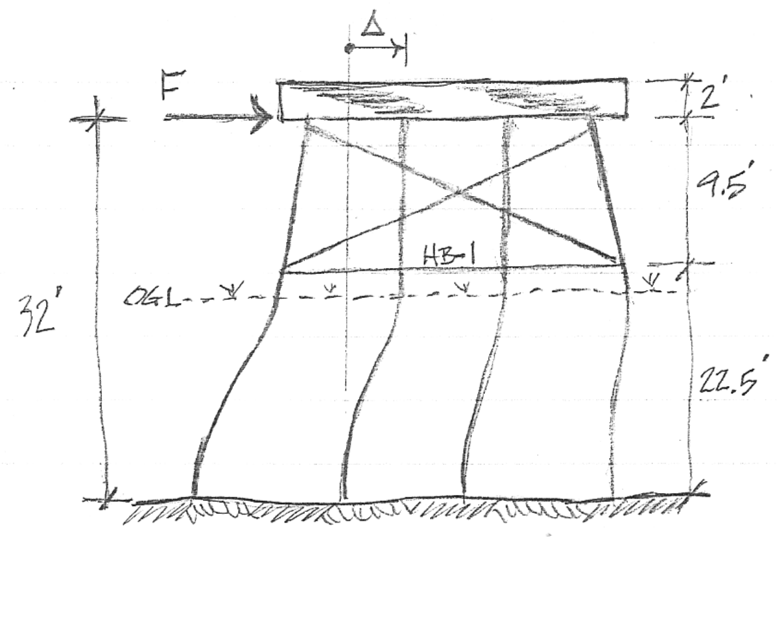


Fig. 2.4. X-Braced Bent Qualitative Lateral Load-Deformation Behavior

2.3 Additional Axial Pile Load Due to Flood Water Loading

In checking bent pile plunging or buckling failures we need to give some consideration to the additional pile axial load (ΔP) caused by flood water loading, F_{fw}, as shown in Fig. 2.5. We can see from Fig. 2.5 that ΔP will be largest for the downstream batter pile for the tallest and narrowest pile bent (3-pile bent).

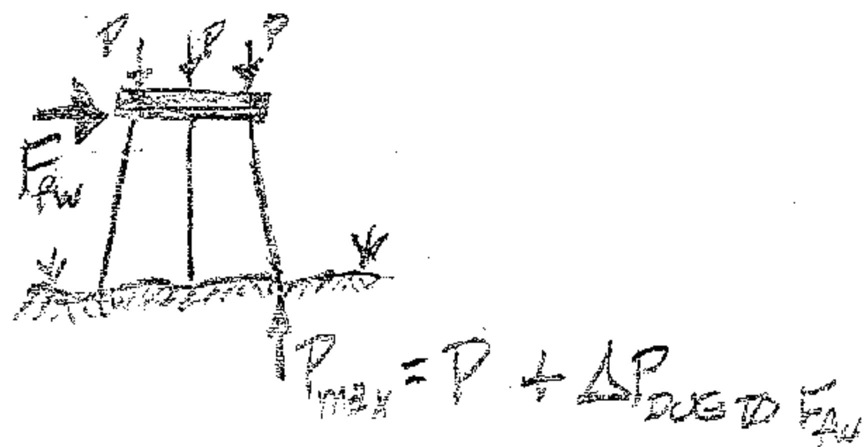


Fig. 2.5. Maximum Pile Load for Checking Pile Plunging and Buckling

However we need to determine the magnitude of ΔP for other bent sizes to determine whether we need to consider the ΔP force in the analyses of those bents. ALDOT Pile Bent Standards indicate the maximum pile bent height above the original ground line (OGL) to be 25 ft. Using this value for bent height, "H", a maximum scour of S = 20 ft, a girder/pile spacing (at the bent cap) of 8 ft, and a maximum flood water loading of $F_{fw} = 9.72^k$, the ΔP_{max} values of 3-, 4-, 5-pile bents are shown in Fig. 2.6. Thus the additional axial pile load on the downstream bent pile due to the maximum flood water load, F_{fw}, is fairly insignificant, except for the 3-pile bent. This additional axial load would contribute to trying to "plunge" or buckle the downstream pile; however, this pile would get some "lean-on" support from the other piles in the bent. It should be noted that the $\Sigma\Delta P_{\text{due to } F_{fw}} = 0$ at a bent and thus the fairly small value of ΔP_{max} due to the F_{fw} loading can be and will be neglected.

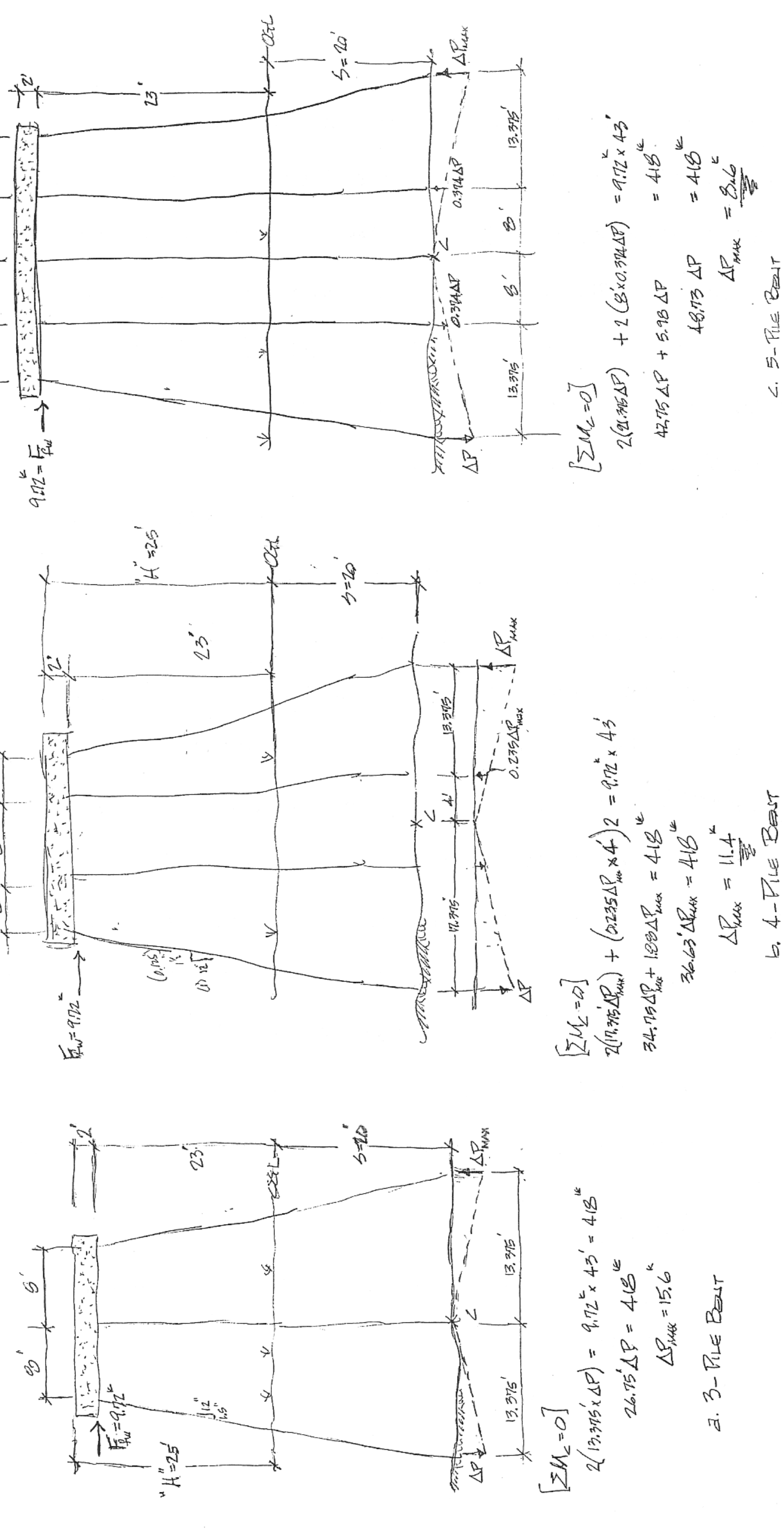


Fig. 2.6. Maximum Additional Axial Pile Load, ΔP_{max}, Due to F_{fw} Load

2.4 Effect of Continuous-Span Superstructures on Bridge/Bent Pushover

The flexural stiffness of a typical bridge deck/curb system bending in a horizontal plane is quite stiff, especially relative to the lateral flexural stiffness of a typical 3-pile or 4-pile bent, as can be seen in Figs. 2.7 and 2.8. Therefore, we can treat the bridge deck as rigid when working with horizontal flood water loadings on a debris raft, i.e., lateral loads in the plane of the deck, and thus all of the deflections due to these loads result from the lateral deflection of the supporting pile bents.

For simply-supported 2-span bridges, an accurate modeling for estimating lateral flood water load, F_t, vs deflection behavior of the bridge, and for estimating the load applied to the pile bent would be as shown in Fig. 2.9. For multi-span SS bridges, an accurate modelling would be as shown in Fig. 2.10, and the F_t load would be distributed over all the bents of the bridge. However, most of the F_t load goes to the bents near the F_t load, and a worst case scenario would be to assume the adjacent bents act as abutments in the 2-span bridge of Fig. 2.9. Thus in this case, $F_B = F_t$ as it was for the 2-SS span bridge of Fig. 2.9. This is indicated in Fig. 2.10. For a multi-span bridge composed of 2-continuous span segments as shown in Fig. 2.11, we can do the same thing as was done in Fig. 2.10. This is indicated in Fig. 2.11.

Bent forces for the simplified modellings shown in Figs. 2.8-2.11 are shown in Fig. 2.12. Note that the resulting bent forces for this approach can be generalized as

$$F_{\text{Bent Max}}^{\text{Applied}} = \frac{1}{N} \times F_t$$

where N = No. of continuous spans in the rigid segments

Thus, for a 4-span continuous segment,

$$F_{\text{Bent Max}}^{\text{Applied}} = \frac{1}{4} \times F_t = \frac{F_t}{4}$$

It should be noted that if the debris raft forms on a bent where the superstructure is continuous, then the F_t force would be applied at this location and the maximum bent force would be half of that occurring when F_t is applied at a bent where the superstructure does not have continuity. This can be seen by comparing the $F_{\text{Bent Max}}$ forces in Figs. 2.12b and 2.13.

Therefore for,

SS Bridge: $F_{\text{Bent Max Applied}} = F_t = 12.2^k$ (Includes a F.S. = 1.25 against bent pushover failure)

If $F_{\text{Capacity}}^{\text{Pushover}} \geq 12.2^k$ the bent is OK for pushover

2-Span Cont: $F_{\text{Bent Max Applied}} = \frac{F_t}{2} = 6.1^k$ (Includes a F.S. = 1.25)

If $F_{\text{Capacity}}^{\text{Pushover}} \geq 6.1^k$ the bent is OK for pushover

3-Span Cont: $F_{\text{Bent Max Applied}} = \frac{F_t}{3} = \frac{12.2}{3} = 4.1^k$ (Includes a F.S. = 1.25)

If $F_{\text{Capacity}}^{\text{Pushover}} \geq 4.1^k$ the bent is OK for pushover

4-Span Cont: $F_{\text{Bent Max Applied}} = \dfrac{F_t}{4} = \dfrac{12.2}{4} = 3.1^k$ (Includes a F.S.
(and larger) = 1.25)

If $F^{\text{Pushover}}_{\text{Capacity}} \geq 3.1^k$ the bent is OK for pushover

5-Span Cont: $F_{\text{Bent Max Applied}} = \dfrac{F_t}{5} = \dfrac{12.2}{5} = 2.5^k$ (Includes a F.S.
(and larger) = 1.25)

If $F^{\text{Pushover}}_{\text{Capacity}} \geq 2.5^k$ the bent is OK for pushover

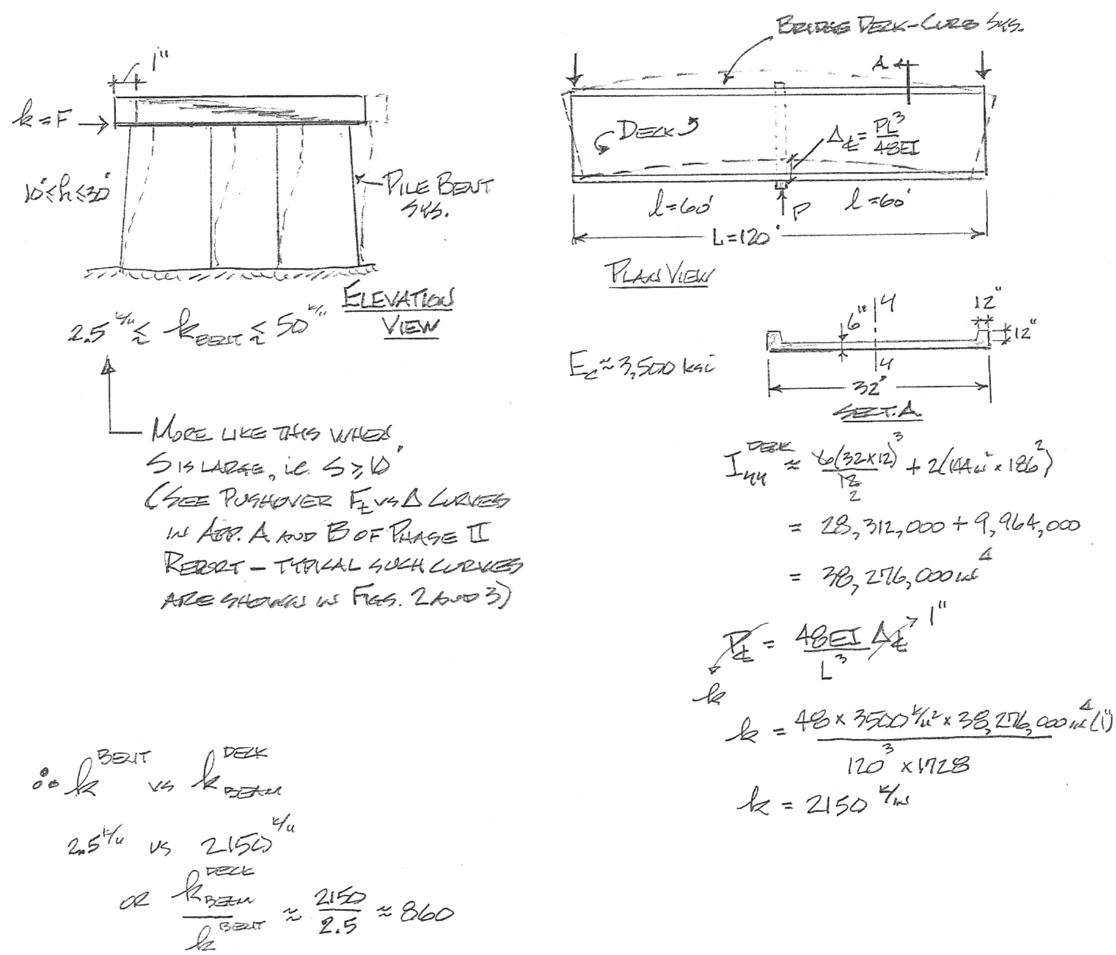
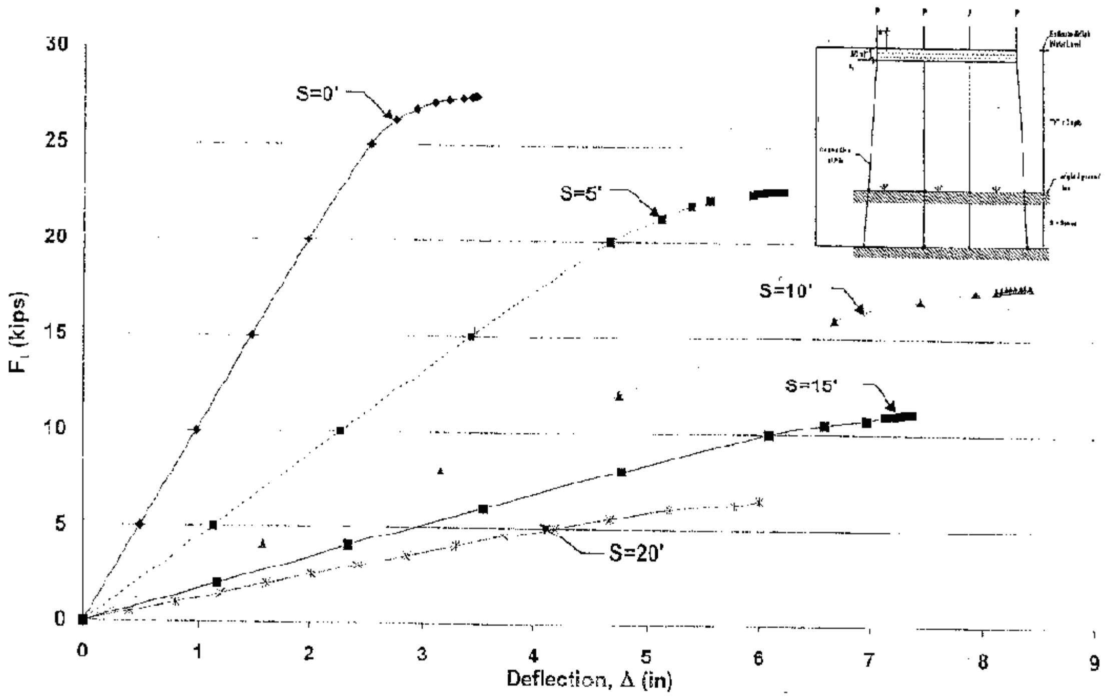
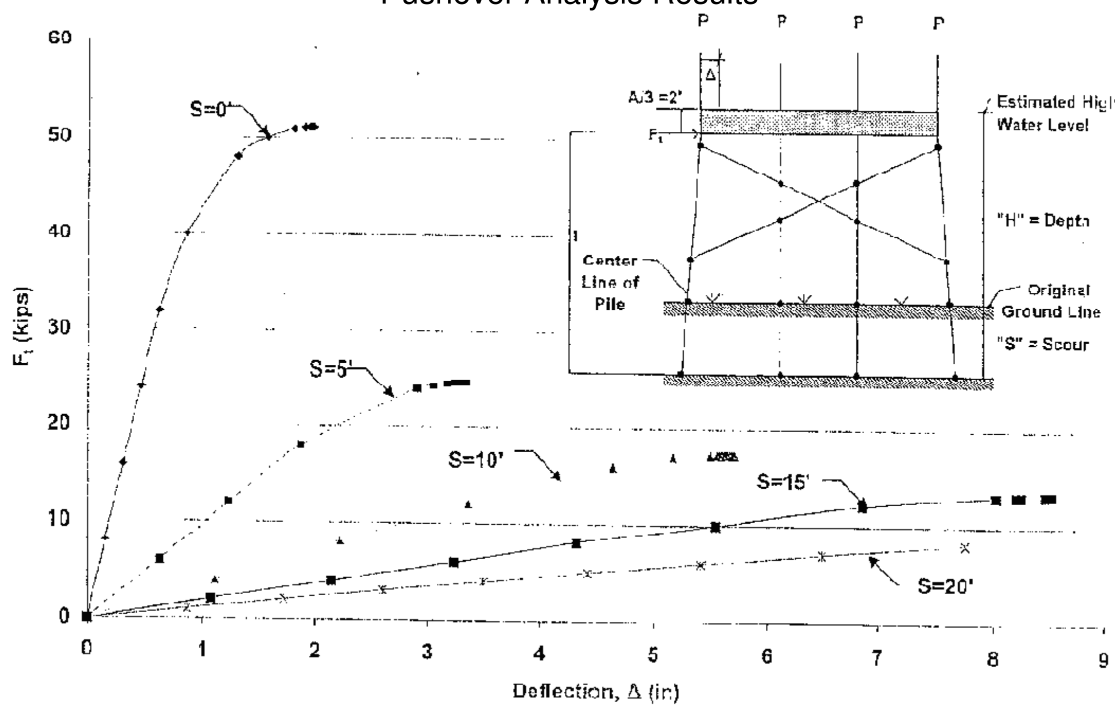


Fig. 2.7. Lateral Flexural Stiffness of Bridge Deck System vs. Support Pile Bent System



a) HP_{10x42} Unbraced 4-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results



b) HP_{10x42} X-Braced 4-Pile Bent with H=13', P=120kips and A=6' Pushover Analysis Results

Fig. 2.8. Typical Pushover/Lateral Stiffness Curves for Unbraced and X-Braced Pile Bents (from Phase II Report)

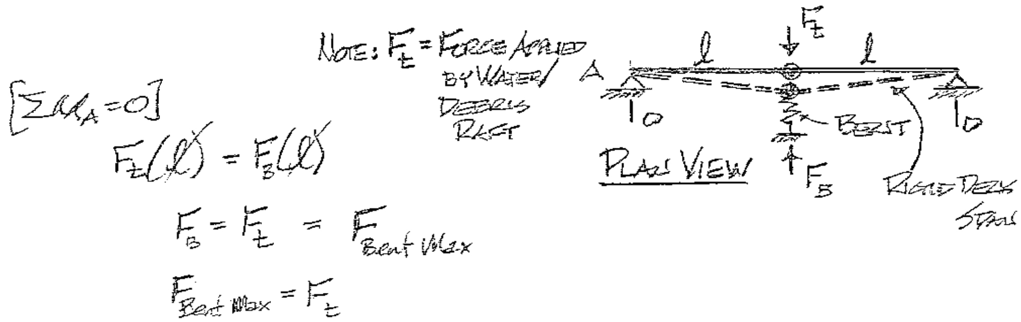


Fig. 2.9. 2-Span SS Bridge

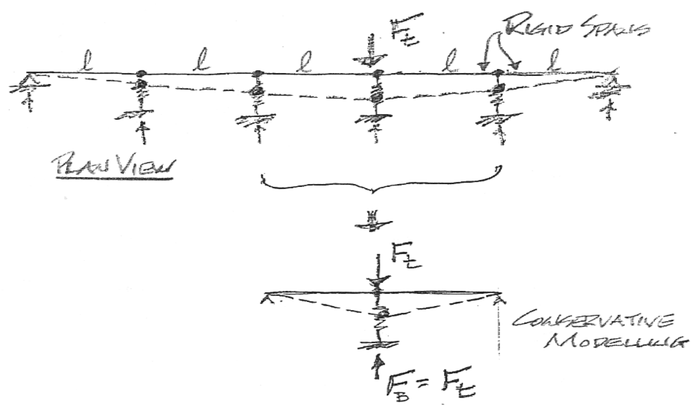


Fig. 2.10. Multi-Span Bridge with Many Rigid SS Spans

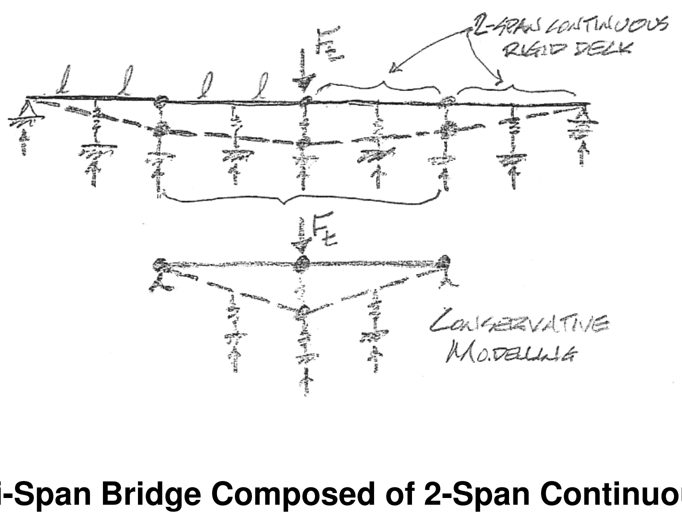
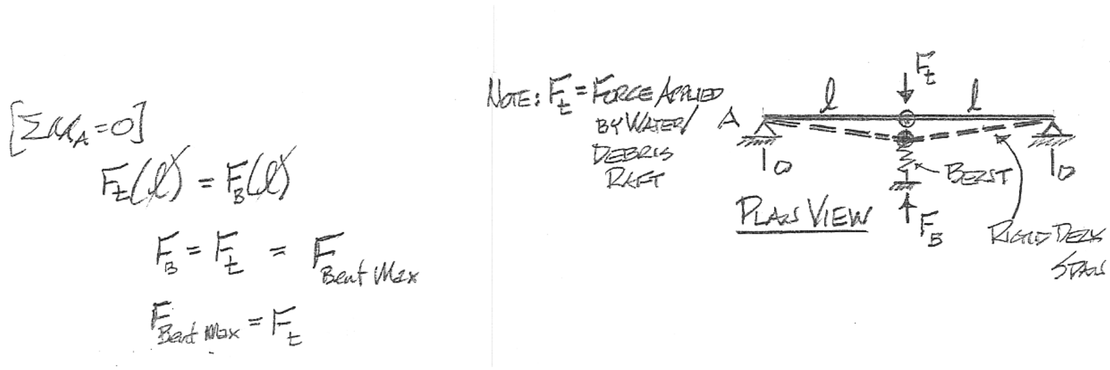
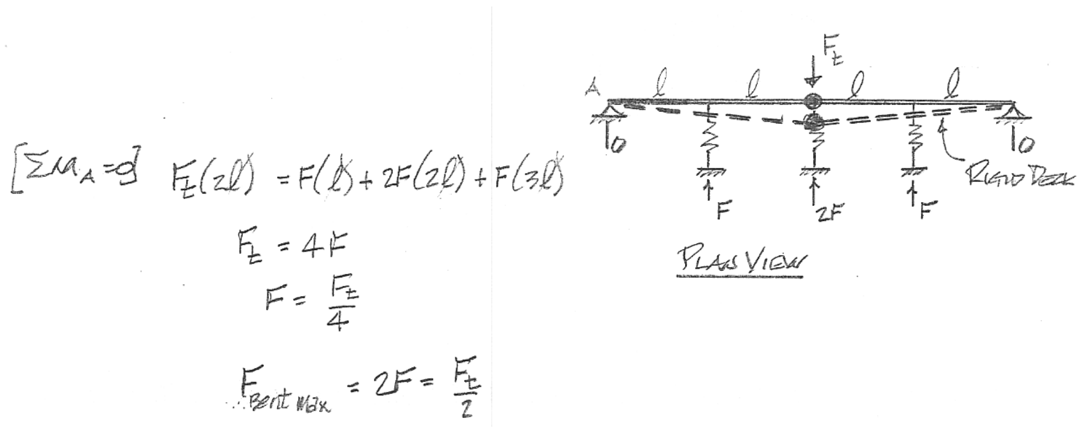


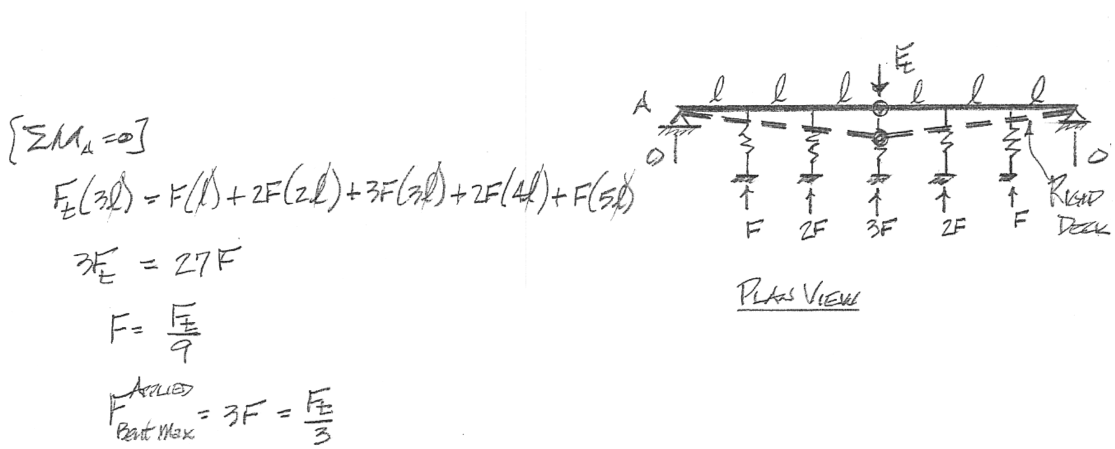
Fig. 2.11. Multi-Span Bridge Composed of 2-Span Continuous Segments



a) SS-Spans or 1-Rigid Span Segments



b) 2-Span Continuous Segments



c) 3-Span Continuous Segments

Fig. 2.12. Maximum Bent Forces for Continuous Span Bridges

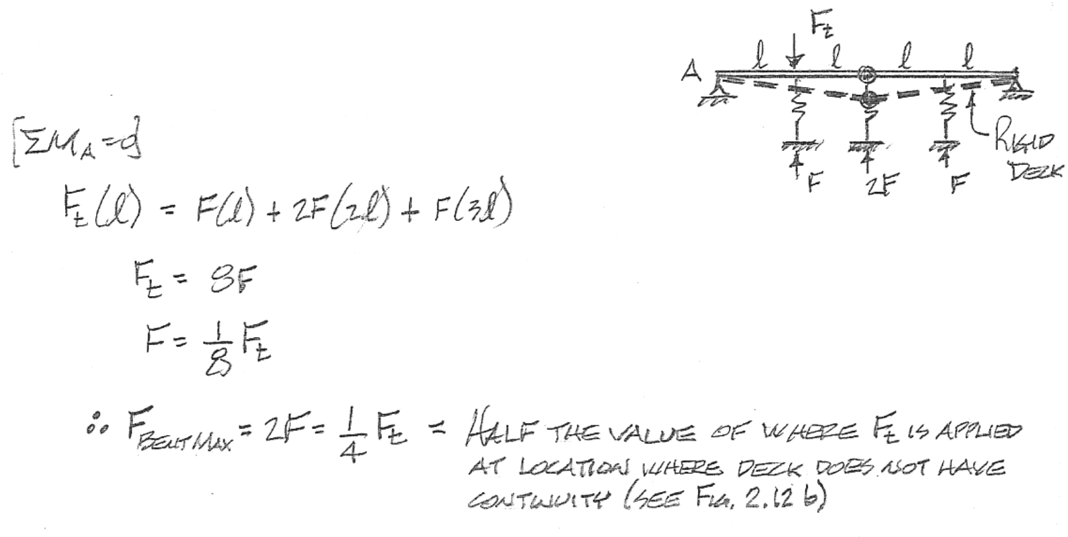


Fig. 2.13. $F_{Bent\ Max}$ on 2-Span Continuous Bridge when F_t is Applied at Bent Where Superstructure has Continuity

2.5 Effect of Continuous-Span Superstructures on Bent Pile Buckling

For continuous superstructures, or those made continuous for LL, a pile or bent cannot buckle in a sidesway mode unless the entire continuous segment does. This would require an unrealistically large loading and thus the piles/bents in continuous spans, or those made continuous for LL, cannot buckle in a sidesway mode. For such continuous superstructure bridges, P_{CR} and $P_{max\ allowed}$ would be as shown in Fig. 2.14 and Table 2.2 for non X-braced bents (see Fig. 2.2 in Phase II Report). Note in Fig. 2.14 that ℓ_{max} for ALDOT pile bents and maximum anticipated scour levels is 44 ft. Thus, from Table 2.2 if,

$P_{max\ applied} \leq 118^k$ for an HP_{10x42} pile

$P_{max\ applied} \leq 209^k$ for an HP_{12x53} pile then the pile/bent will be safe from buckling and doesn't need to be checked further for buckling. If $P_{max\ applied}$ is larger than the above values, the pile/bent may still be safe depending on the bent height and level of maximum scour at the site. In this case, the bent should be checked for buckling in the manner outlined in the "screening tool".

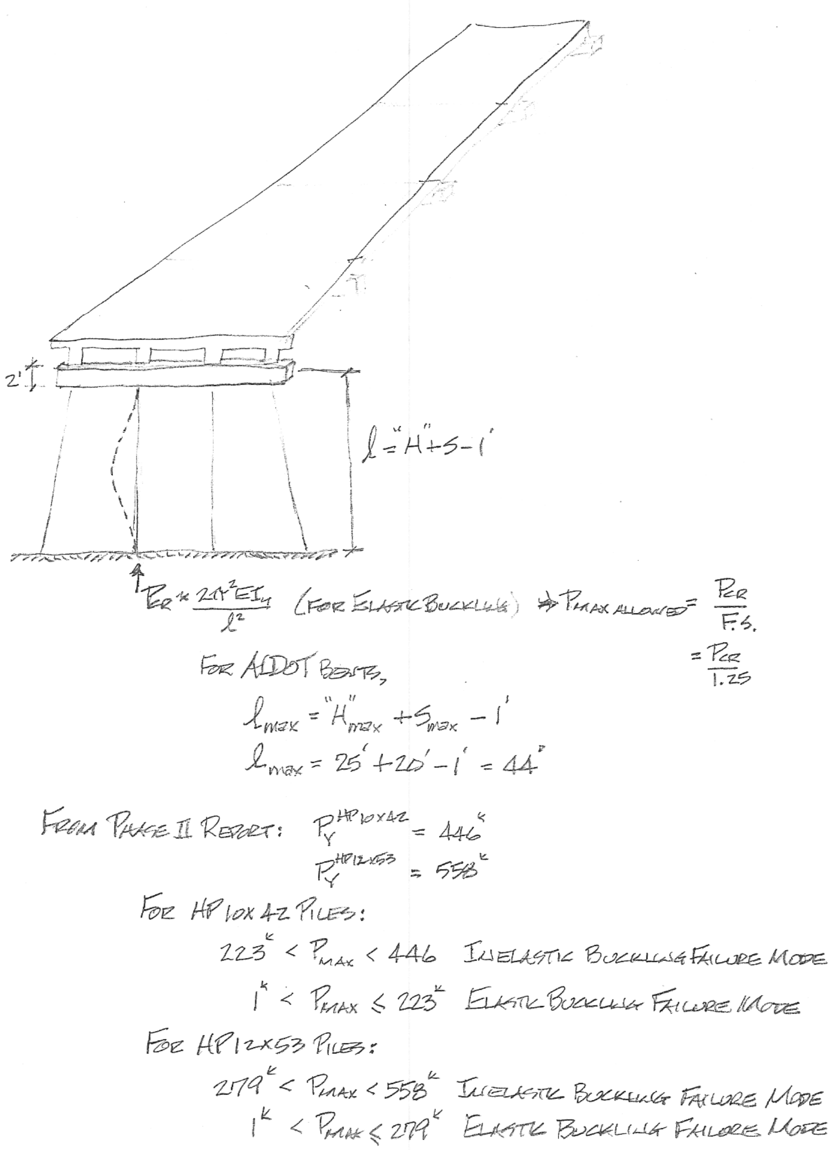


Fig. 2.14. Pile Buckling Modes and Equations for Bents Supporting Continuous Bridges

Table 2.2. P_{CR} and $P_{MAX\ ALLOWED}$ for Bent Piles Supporting Continuous-Span Bridge

	HP_{10x42}		HP_{12x53}	
l (ft)	P_{CR} (k)	$P^*_{MAX\ ALLOWED}$ (k)	P_{CR} (k)	$P^*_{MAX\ ALLOWED}$ (k)
20	375[a]	300[a]	496[a]	397[a]
25	330[a]	264[a]	460[a]	368[a]
30	290[a]	232[a]	420[a]	336[a]
35	230[a]	184[a]	365[a]	292[a]
44	147[b]	118[b]	261[b]	209[b]

* Includes a F.S. = 1.25
[a] Controlled by Pile Inelastic Buckling
[b] Controlled by Pile Elastic Buckling

2.6 Pushover Loads for Additional P-load and Scour

In the Tier 1 Screening Tool, i.e., the Phase II work, possible pile/bent failures via,

1. pile "kick-out"
2. pile plunging
3. pile buckling
4. bent pushover

were checked for ranges of bent sizes, pile sizes, scour levels, etc. In checking possible pile "kick-out" failure the criterion used was simply the remaining pile depth of embedment after an extreme flood/scour event. In checking possible pile plunging and pile buckling, $P^{Pile}_{Max\ Applied}$ was determined for the particular bridge/pile bent and this was compared with the pile $P^{Pile}_{Capacity}$ in plunging and $P^{Pile}_{Capacity}$ in buckling. However, in checking possible pile bent pushover, $P^{Bent}_{Max\ Applied}$ was determined for the particular bridge/pile bent and this load was assumed to be uniformly distributed to the bent piles as P-loads of $\dfrac{P^{Bent}_{Max\ Applied}}{\text{No. of Bent Piles}}$.

Using levels of uniformly distributed P-loads (one on the bent cap above each pile) of P = {100, 120, 140, 160^k}, pushover analyses were performed on the same range of bent sizes, pile sizes, scour levels, etc. as used in checking the other possible failure modes to determine the lateral pushover capacity, F_t. Thus, tables of bent pushover capacities were determined and these loads could then be compared with the maximum flood water load that could be applied of $F_{Max\ Applied} = 12.2^k$ (includes a F.S. = 1.25) to a bent via hydrodynamic flood water pressure acting on an assumed debris raft developed at the top of the pile bent. For a particular bent, if the pushover capacity, F_t, was greater than the $F_{Max\ Applied}$, then the bent was viewed as being safe from pushover failure.

It was felt at the time of development of the pushover capacity tables that the P-load range of {100, 120, 140, 160^k} would be such that any bent would be subjected to maximum loads in this range. Later, the ALDOT determined that the upper limit of $P=160^k$ was adequate for any of their bents, but that the lower limit of $P=100^k$ was too large for some of their smaller bridges. They indicated that a P-load level of $P=80^k$ should be added to the tables of bent pushover capacities. The ALDOT also noted that only the smaller pile bents had pushover capacities, F_t, low enough to be of concern for a possible pushover failure.

Additionally, it was initially felt that a scour level of S=20 ft would be the maximum possible scour at a bridge site in Alabama. However, ALDOT personnel have since found sites where maximum scour levels as high as 22 and 23 ft are estimated. To allow use of the "ST" at these sites, a maximum scour of 25 ft was added to all of the pushover analyses and tables of pushover capacities. Thus, all pushover capacity tables were expanded to include scour levels of S={0, 5, 10, 15, 20, 25 ft}.

About this same time, it was noted that a roadway live load (LL) positioned such that the upstream lane of a bridge was loaded and the downstream lane was not loaded could possibly result in a more severe load condition for pushover capacity than when all lanes were fully loaded (even though the total gravity load on the bent for this load condition would be smaller). This loading condition consisting of an unsymmetric LL distribution is described and discussed more fully in Section 2.7. To address the situations described above, additional pushover analyses with lower uniformly distributed P-loads of P = {60^k, 80^k} were performed. The P=60^k level was added in light of checking the loading case in which LL is not applied to the downstream traffic lane, and also because this loading allowed interpolation of results for uniform P-loads somewhat less than 80^k. Initially, in the new pushover analyses conducted for the Phase III work, only the smaller 3-pile and 4-pile bents were analyzed as these were the ones for which it was determined that pushover failure may likely occur in an extreme flood/scour event. However, for completeness, ALDOT desired that pushover results for the 5-pile and 6-pile bents analyses also be included, and this has been done.

Results of additional pushover analyses for 3- and 4-pile single-story bents for P-loads of 60^k and 80^k and scour of 25 ft have been added to those of the earlier analyses for larger P-loads and lower scour levels and these are shown in Tables 2.3-2.6. Also, these tables have been expanded to include 5- and 6-pile bents. One can note in these tables that there is a very dramatic reduction in pushover capacity after 5 ft of scour. For the 3-pile bents, the reduction continues after the first 5 ft of scour but at a reduced rate. For the 4-pile bents, the reduction tends to level out to approximately zero in the scour range of 5 ft $< S \leq$ 10 ft, and then the pushover capacity begins to decrease again at a significant rate. The leveling out tends to be more dramatic for the smaller P-load levels.

To better illustrate the effect of the P-load level on a bent's pushover capacity, the data of Tables 2.3-2.6 are shown plotted on Pushover Force vs. H+S curves in Figs. 2.15-2.18. Note in these tables and figures that bents with the lower P-loads of 60^k and 80^k do have a significantly larger pushover capacity.

To better understand the initial drop in pushover capacity, F_t, with scour (or H+S), followed by a leveling off of F_t, and then followed by significant drops in F_t with increases in scour (or H+S) shown in Figs. 2.15 and 2.16, bent F_t vs Δ curves contained in earlier reports were revisited and additional GTSTRUDL analyses using different bent end pile batters and cap stiffnesses were performed. Using the F_t vs Δ curves shown in Fig. 2.19 taken from Phase II - Part II and plotting the resulting pushover capacity vs H+S curves as shown in Fig. 2.20, bent behavior similar to that reflected in Figs. 2.15 and 2.16 is seen. Using the 5-pile bent, we then investigated its F_t vs S (or H+S) behavior as we varied the batter of the bent end piles and the bending stiffness of the bent cap. The resulting F_t vs S (or H+S) curves for these variations are shown in Fig. 2.21. Note in this figure that when the batter of the end piles is taken away, the pushover force decreased, as expected, as scour is increased, regardless of the stiffness of the bent cap. It can be observed that the behavior without batter is similar to the behavior with batter after the bent reaches a certain plateau point. This point is approximately ten feet of scour for the 5-pile bent of Fig. 2.21. When the stiffness of the bent cap is increased there is a significant increase in pushover force for the first ten feet of scour; however, after ten feet of scour, the increase in pushover force becomes significantly less. It can be concluded that the batter in the end piles causes the stiffness of the bent cap to increase the pushover capacity of the bent, but at a certain scour level, the bent becomes much more flexible and the failure is due to the lack of flexural strength in the piles.

It should be noted when the bents are X-braced, they act primarily as vertical trusses when subjected to F_t lateral loads prior to the occurrence of any scour. However, after about 4-5 ft of scour, the smaller flexural stiffness and strength of the piles bending about their weak axis begins to dominate and they act as very flexible bending frames, and thus the dramatic drop in bent pushover force when H+S > 17 ft as indicated in Figs. 2.17 and 2.18.

Results of additional pushover analyses for 3, 4, 5, and 6-pile bents that are 2-story and X-braced for P-loads of 60^k and 80^k and scours of 25 ft have been added to those generated in earlier analyses for larger P-loads and lower scour levels, and these are shown in Tables 2.7 and 2.8. Again, it can be noted in these tables that the lower P-loaded bents have a significantly larger pushover capacity than those with larger P-loads.

Lastly, additional pushover analyses for 1-story and 2-story 6-pile bents having double X-bracing across the width of the bent were performed for the additional P-loads of 60^k and 80^k and for scours of 25 ft, and the results of these analyses are presented in Tables 2.9a and b.

All pushover analyses were performed using GTSTRUDL. Example input files for various bent configurations can be viewed in Appendix A.

Table 2.3a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	10	0	10	21.6	20.6	19.6	20.0	18.8	17.6
		5	15	12.9	11.5	10.1	8.9	7.3	5.6
		10	20	8.2	6.3	4.3	2.3	unstable	unstable
		15	25	4.9	2.3	unstable	unstable	unstable	unstable
		20	30	2.0	unstable	unstable	unstable	unstable	unstable
		25	35	unstable	unstable	unstable	unstable	unstable	unstable
	13	0	13	15.6	14.4	13.2	12.4	11.0	9.5
		5	18	9.8	8.2	6.4	4.7	2.8	unstable
		10	23	6.1	3.9	1.5	unstable	unstable	unstable
		15	28	3.1	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable	unstable
		25	38	unstable	unstable	unstable	unstable	unstable	unstable
4	10	0	10	38.3	35.7	33.5	34.8	32.3	29.9
		5	15	31.8	28.9	26.1	24.8	21.8	18.9
		10	20	30.8	27.2	24.3	22.0	18.5	15.1
		15	25	24.8	21.6	18.2	14.8	11.6	8.4
		20	30	19.0	15.5	12.3	9.0	6.3	3.8
		25	35	13.6	10.5	7.8	5.3	3.3	1.8
	13	0	13	33.6	30.6	27.9	27.5	24.8	22.0
		5	18	30.7	27.6	24.6	22.7	19.3	16.0
		10	23	27.8	23.8	20.8	17.8	14.3	10.9
		15	28	21.3	17.8	14.5	11.1	8.0	5.3
		20	33	15.6	12.3	9.3	6.5	4.1	2.5
		25	38	11.0	8.3	6.0	4.0	2.5	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.3b. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	10	0	10	33.8	32.8	32.0	34.2	33.1	32.0
		5	15	21.6	20.4	19.3	18.9	17.6	16.3
		10	20	15.4	14.0	12.5	11.2	9.6	7.8
		15	25	11.5	9.7	7.7	5.8	3.6	1.4
		20	30	8.5	6.3	3.8	1.1	unstable	unstable
		25	35	6.1	3.2	unstable	unstable	unstable	unstable
	13	0	13	25.3	24.3	23.3	23.5	22.2	21.1
		5	18	17.5	16.2	14.9	13.9	12.4	10.9
		10	23	12.9	11.2	9.5	7.8	5.9	3.8
		15	28	9.6	7.5	5.3	2.9	unstable	unstable
		20	33	7.0	4.4	unstable	unstable	unstable	unstable
		25	38	4.7	unstable	unstable	unstable	unstable	unstable
4	10	0	10	56.6	53.4	50.7	54.4	52.3	50.1
		5	15	45.4	41.6	38.8	38.7	36.2	33.7
		10	20	41.1	37.8	35.0	34.0	31.0	27.8
		15	25	40.7	37.4	33.8	31.4	28.1	24.4
		20	30	33.3	29.6	26.6	23.4	19.9	16.5
		25	35	27.3	23.8	20.4	17.0	13.6	10.5
	13	0	13	47.3	44.3	41.7	42.8	40.5	38.1
		5	18	42.4	39.0	36.1	35.3	32.4	29.6
		10	23	41.0	37.4	35.0	33.1	29.6	26.3
		15	28	36.7	32.6	29.0	26.9	23.1	19.5
		20	33	29.2	26.2	22.7	19.3	16.0	12.8
		25	38	23.5	20.3	16.8	13.5	10.5	7.8

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.4a. Pushover Load, F_t, for Unbraced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	10	0	10	48.1	43.8	40.6	38.2	35.8	33.4
		5	15	42.6	37.6	33.4	29.6	26.3	23.0
		10	20	44.0	38.6	34.7	29.6	24.9	20.3
		15	25	36.5	31.9	27.0	22.6	18.1	13.9
		20	30	28.5	24.0	19.5	15.0	11.3	7.8
		25	35	21.3	17.0	13.3	9.9	6.9	4.3
	13	0	13	44.6	39.1	34.9	31.5	28.7	25.8
		5	18	41.9	37.7	32.9	28.8	24.7	20.8
		10	23	41.3	35.6	30.8	25.6	21.2	16.8
		15	28	31.7	27.0	22.4	18.0	13.6	9.8
		20	33	24.0	19.5	15.5	11.8	8.4	5.5
		25	38	17.6	13.9	10.5	7.5	5.0	3.0
6	10	0	10	53.1	48.2	45.2	42.7	40.0	37.3
		5	15	46.4	39.8	34.6	30.6	26.9	23.1
		10	20	47.4	41.0	35.0	28.8	23.5	17.9
		15	25	41.0	34.7	28.2	22.4	17.0	12.0
		20	30	31.6	26.1	20.6	15.5	10.7	6.5
		25	35	24.0	19.0	14.5	10.1	6.5	4.0
	13	0	13	46.4	40.7	37.1	33.8	30.4	27.1
		5	18	45.3	38.6	33.7	28.8	24.1	19.6
		10	23	46.0	38.1	32.4	25.7	19.7	14.3
		15	28	35.1	29.0	23.6	18.2	13.0	8.3
		20	33	27.0	21.5	16.5	12.0	8.0	4.5
		25	38	20.3	15.5	11.5	7.8	5.0	3.0

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.4b. Pushover Load, F_t, for Unbraced 5-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
5	10	0	10	70.7	64.4	60.5	58.1	56.1	54.1
		5	15	60.0	52.8	49.0	44.6	41.2	38.5
		10	20	55.6	51.5	46.3	41.8	37.7	33.9
		15	25	59.7	55.2	49.4	43.4	39.1	33.8
		20	30	49.0	43.2	39.1	34.0	29.6	25.2
		25	35	39.9	35.3	30.9	26.3	21.8	17.5
	13	0	13	60.4	55.4	51.3	47.9	45.2	42.8
		5	18	57.2	51.7	46.7	42.5	38.4	35.0
		10	23	58.4	52.2	47.9	43.2	38.6	34.4
		15	28	53.8	48.1	42.5	38.0	32.8	28.2
		20	33	42.7	38.5	33.8	29.4	24.9	20.5
		25	38	35.0	31.0	26.0	22.0	17.5	13.8
6	10	0	10	77.6	71.0	68.7	66.2	63.9	61.8
		5	15	61.7	56.0	51.4	47.5	44.4	41.3
		10	20	61.2	54.3	48.2	42.9	38.2	33.9
		15	25	67.0	58.6	51.0	44.9	38.5	31.8
		20	30	55.0	48.0	41.9	35.4	29.4	23.9
		25	35	44.3	38.4	32.9	27.6	22.3	17.2
	13	0	13	66.6	60.7	55.9	52.5	49.9	47.1
		5	18	62.4	55.6	49.1	43.8	39.5	35.9
		10	23	60.6	55.3	49.5	43.2	38.4	33.0
		15	28	60.1	52.8	46.0	39.8	33.0	26.9
		20	33	48.1	41.9	36.0	30.5	25.0	20.0
		25	38	39.2	34.0	28.5	23.0	18.0	13.5

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.5a. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	13	0	13	46.7	44.5	42.5	41.5	39.7	38.3
		5	18	19.1	17.1	15.5	14.4	12.8	11.2
		10	23	10.6	8.5	6.3	4.0	2.8	unstable
		15	28	5.9	3.3	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable	unstable
		25	38	unstable	unstable	unstable	unstable	unstable	unstable
	17	0	17	44.9	42.9	41.2	39.9	38.3	36.8
		5	22	17.8	15.9	13.9	12.6	10.6	8.7
		10	27	9.6	7.1	4.8	2.9	1.0	unstable
		15	32	4.9	2.0	unstable	unstable	unstable	unstable
		20	37	unstable	unstable	unstable	unstable	unstable	unstable
		25	42	unstable	unstable	unstable	unstable	unstable	unstable
4	13	0	13	62.8	58.6	55.1	51.2	48.2	45.3
		5	18	35.1	31.4	28.1	24.7	22.0	19.3
		10	23	28.7	24.6	21.0	17.3	14.0	10.9
		15	28	25.9	21.7	17.4	13.1	9.4	5.8
		20	33	19.7	15.4	11.3	8.0	5.0	1.8
		25	38	13.3	10.0	7.0	4.1	2.0	unstable
	17	0	17	58.4	53.7	49.8	45.5	42.6	40.2
		5	22	32.7	28.7	25.1	21.4	18.3	15.5
		10	27	27.0	22.4	18.2	14.3	10.7	7.4
		15	32	23.3	18.6	14.0	9.7	5.8	2.1
		20	37	17.0	12.4	9.0	5.0	2.1	unstable
		25	42	11.0	8.0	5.0	3.0	unstable	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.5b. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Bent Cap with $I_{gross} = 41,470\ in^4$ for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	13	0	13	67.7	65.9	64.0	64.8	63.1	61.4
		5	18	32.0	30.0	28.0	26.9	25.2	23.8
		10	23	19.8	17.7	15.9	14.5	12.8	11.1
		15	28	13.5	11.3	9.1	7.5	5.3	3.1
		20	33	9.5	6.9	4.3	2.1	unstable	unstable
		25	38	6.4	unstable	unstable	unstable	unstable	unstable
	17	0	17	66.8	64.9	62.9	61.3	59.2	57.2
		5	22	30.6	28.4	26.5	25.1	23.5	22.0
		10	27	18.8	16.6	14.6	13.0	11.1	9.1
		15	32	12.7	10.2	7.8	5.8	3.4	1.1
		20	37	8.6	5.8	2.9	unstable	unstable	unstable
		25	42	5.5	2.2	unstable	unstable	unstable	unstable
4	13	0	13	91.9	88.3	84.5	80.0	76.7	73.7
		5	18	53.3	49.3	45.7	41.9	38.8	35.9
		10	23	42.5	38.4	34.8	31.0	27.8	24.7
		15	28	38.9	34.9	30.9	26.6	22.9	19.4
		20	33	35.4	30.8	26.7	22.2	18.2	14.4
		25	38	28.2	24.1	19.9	15.6	12.0	9.0
	17	0	17	85.1	82.3	79.4	76.3	72.7	69.0
		5	22	50.9	46.4	42.4	38.2	34.9	31.8
		10	27	40.8	36.4	32.3	28.1	24.6	21.3
		15	32	37.4	32.8	28.1	23.5	19.7	15.9
		20	37	32.5	27.9	23.3	18.7	14.6	10.7
		25	42	25.6	21.1	16.6	12.5	9.0	6.0

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.6a. Pushover Load, F_t, for Single Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
5	13	0	13	74.8	69.0	64.4	60.2	56.3	52.5
		5	18	44.6	39.6	35.1	31.0	27.2	23.5
		10	23	40.0	34.2	28.9	24.0	19.5	15.3
		15	28	40.6	33.9	28.2	22.3	16.7	11.7
		20	33	31.8	26.1	20.6	15.4	10.6	6.4
		25	38	23.0	18.0	13.6	9.6	6.0	3.5
	17	0	17	69.0	63.0	57.8	53.3	49.3	45.7
		5	22	41.7	36.0	31.2	26.9	22.8	18.9
		10	27	38.3	32.0	26.2	20.9	16.0	11.6
		15	32	37.5	30.6	24.4	18.3	12.8	7.7
		20	37	28.8	22.8	17.1	12.0	7.4	3.6
		25	42	20.3	15.4	11.1	7.3	4.5	2.0
6	13	0	13	82.3	75.6	70.0	65.1	60.5	56.0
		5	18	49.4	43.1	37.7	32.7	28.1	23.7
		10	23	43.9	36.8	30.2	24.4	19.0	14.0
		15	28	46.5	37.5	30.2	22.8	15.8	9.8
		20	33	36.9	29.9	23.0	16.6	10.7	5.4
		25	38	27.4	21.3	15.8	10.6	6.3	3.0
	17	0	17	76.1	68.7	62.6	57.3	52.6	48.5
		5	22	46.0	39.3	33.5	28.4	23.6	19.1
		10	27	42.2	34.4	27.2	21.0	15.2	10.0
		15	32	43.4	34.6	26.5	18.8	12.0	6.0
		20	37	34.0	26.6	19.8	13.3	7.5	3.0
		25	42	24.7	18.8	13.2	8.4	5.0	2.0

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.6b. Pushover Load, F_t, for Single Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	13	0	13	107.2	102.1	97.1	92.3	88.2	84.4
		5	18	66.9	61.4	56.4	52.1	47.9	44.0
		10	23	57.5	50.9	45.2	40.6	36.2	31.8
		15	28	54.1	49.0	43.4	38.1	32.9	27.9
		20	33	55.0	48.6	42.1	36.3	30.4	24.8
		25	38	44.0	38.5	33.0	27.5	22.3	17.3
	17	0	17	99.0	95.2	91.1	84.8	80.1	76.0
		5	22	63.4	57.5	52.4	47.6	43.2	39.1
		10	27	55.2	48.2	42.2	37.2	32.5	28.1
		15	32	54.6	47.6	41.4	35.4	29.6	24.4
		20	37	51.8	44.7	38.1	32.0	26.0	20.3
		25	42	41.1	35.3	29.5	23.9	18.6	13.6
6	13	0	13	118.8	111.7	105.5	99.9	95.0	90.6
		5	18	74.1	67.5	61.7	56.4	51.5	46.7
		10	23	64.1	55.4	48.6	42.8	37.5	32.3
		15	28	60.8	53.5	46.3	39.6	33.3	27.4
		20	33	63.5	54.8	46.8	39.3	31.7	24.6
		25	38	51.7	44.4	37.4	30.6	24.1	18.0
	17	0	17	108.4	103.0	96.6	90.7	85.5	80.8
		5	22	70.1	62.7	56.6	50.9	45.7	41.0
		10	27	61.6	52.5	45.5	39.3	33.7	28.4
		15	32	59.5	51.7	43.9	36.9	29.9	23.7
		20	37	60.8	51.8	43.2	35.5	27.6	20.4
		25	42	48.6	41.2	34.1	27.1	20.5	14.5

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

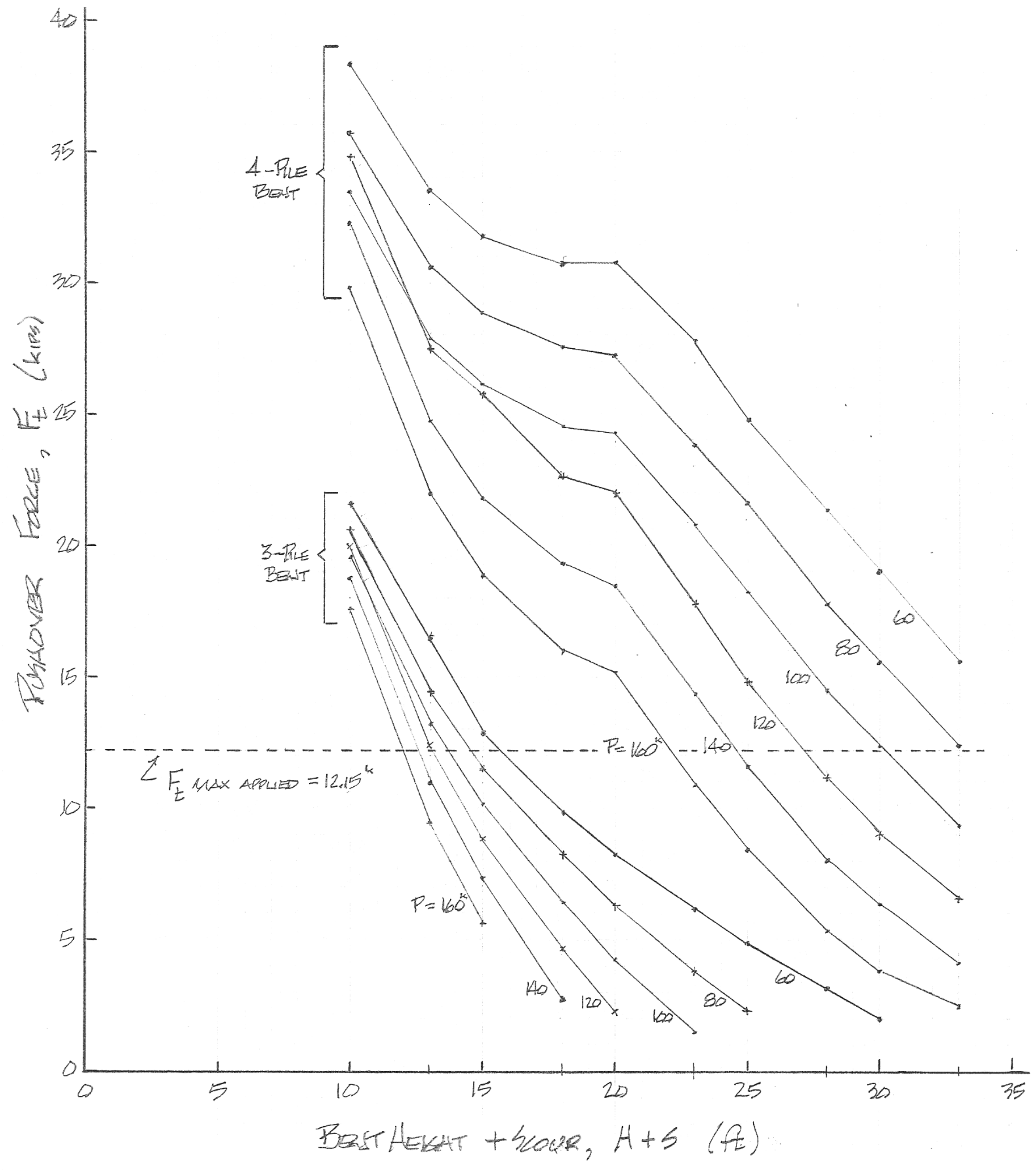


Fig. 2.15. Pushover Load vs. Bent Height Plus Scour for Unbraced 3- and 4-Pile Bents (HP_{10x42} Piles) with P-Loads of 60^k, 80^k, 100^k, 120^k, 140^k, and 160^k

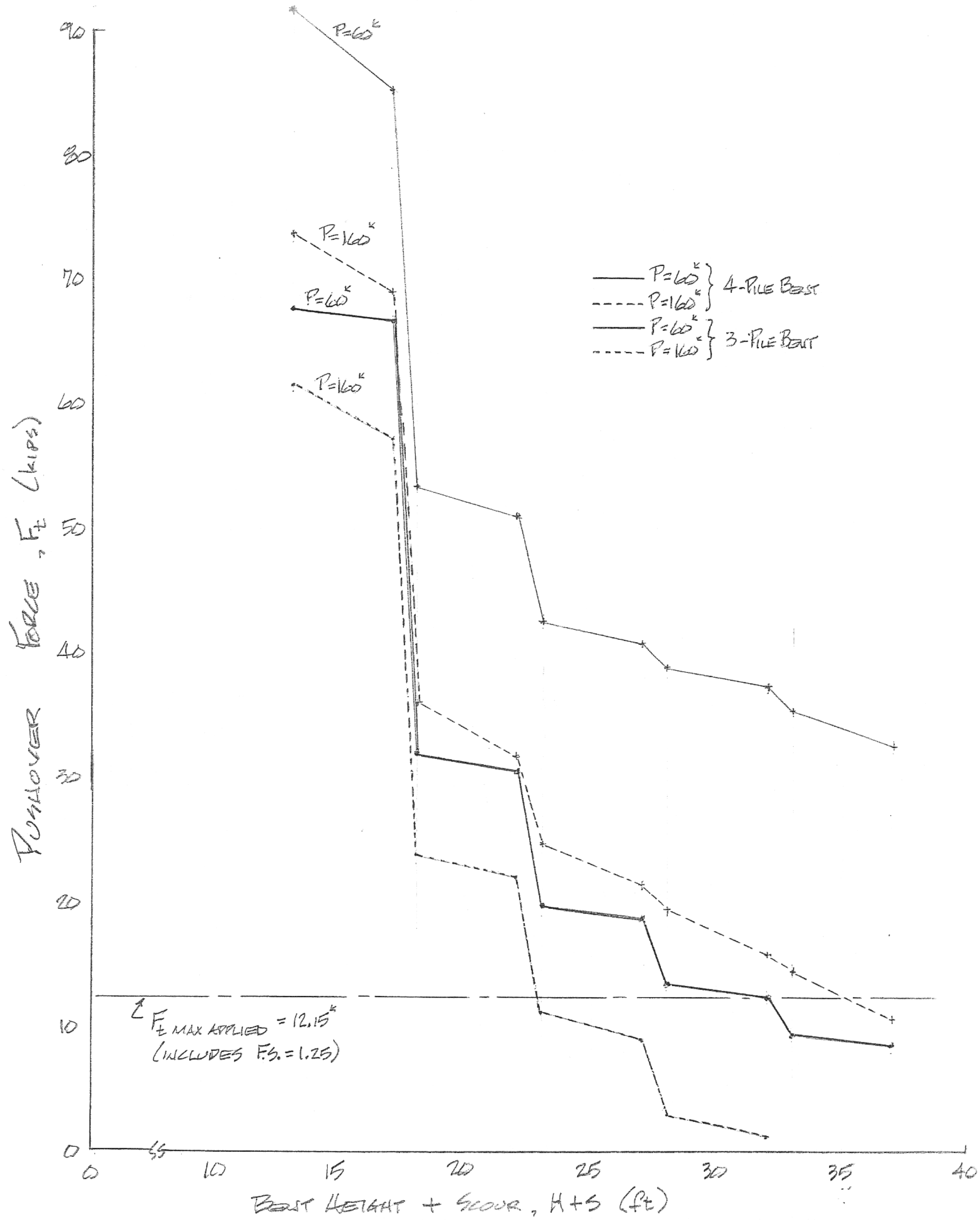


Fig. 2.16. Pushover Load vs. Bent Height Plus Scour for Unbraced 3- and 4-Pile Bents (HP_{12x53} Piles) with P-Loads of 60^k, 80^k, 100^k, 120^k, 140^k, and 160^k

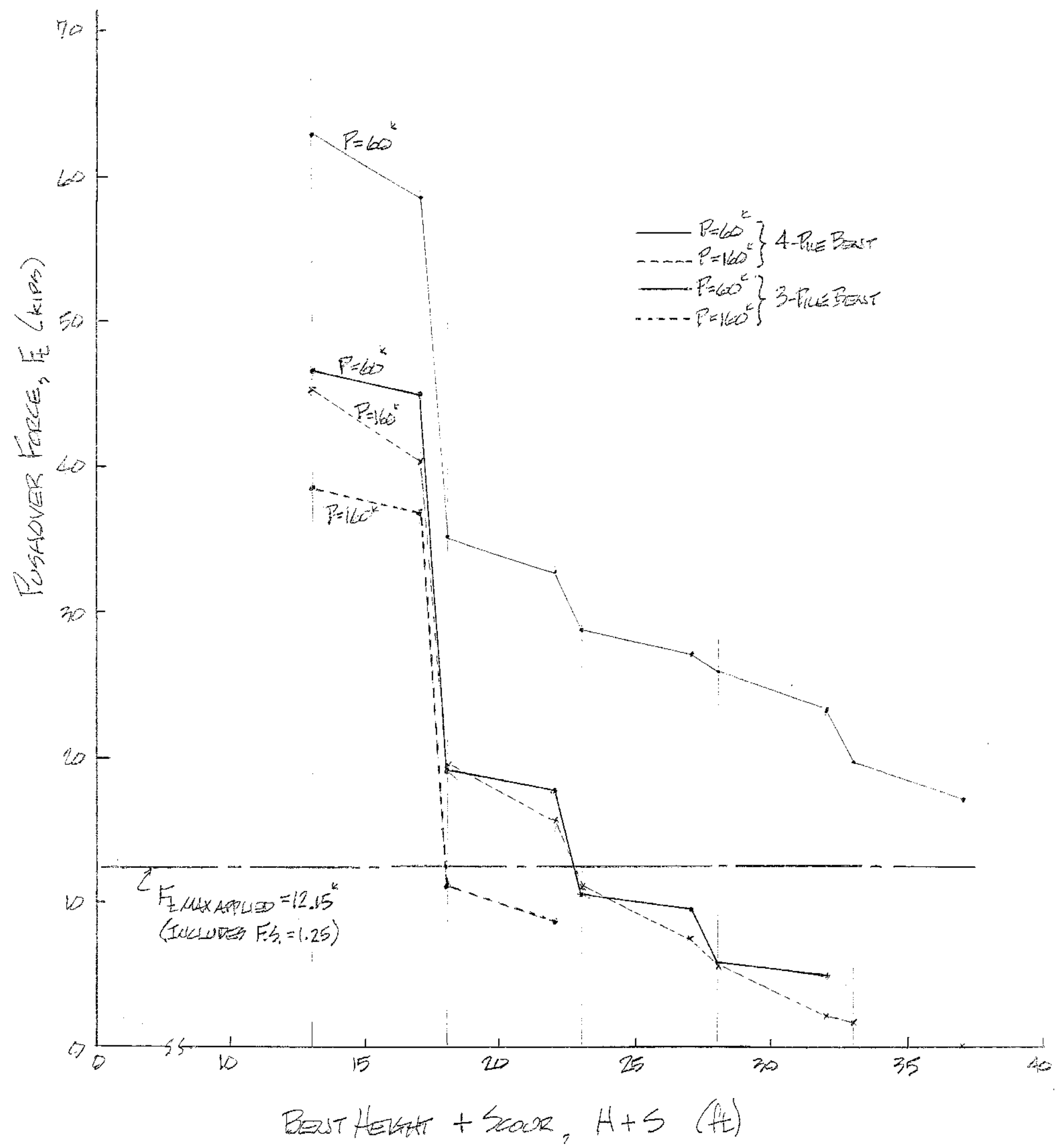


Fig. 2.17. Pushover Load vs. Bent Height Plus Scour for Single Story X-Braced 3- and 4-Pile Bents (HP_{10x42} Piles) with P-Loads of 60^k and 160^k

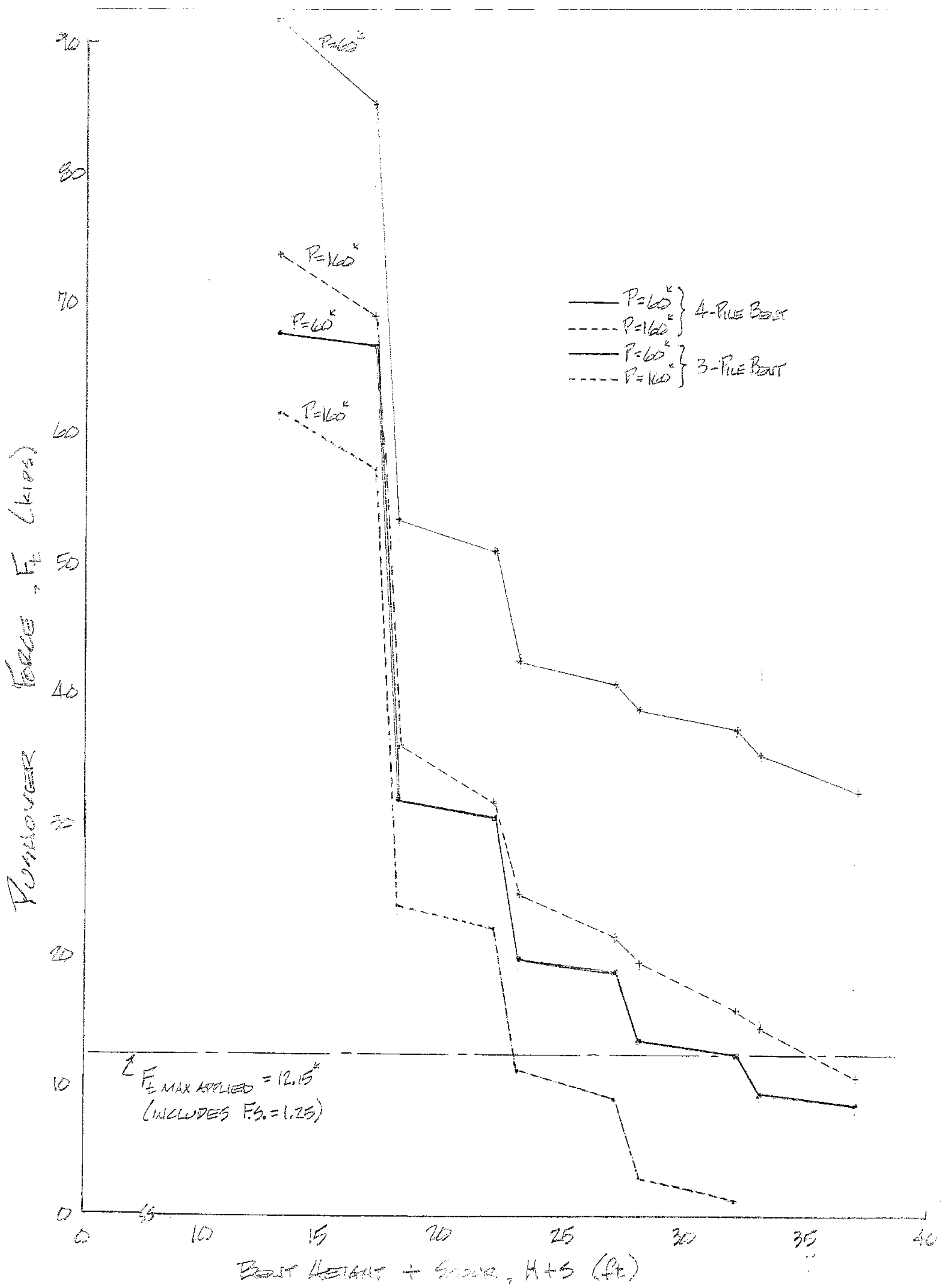
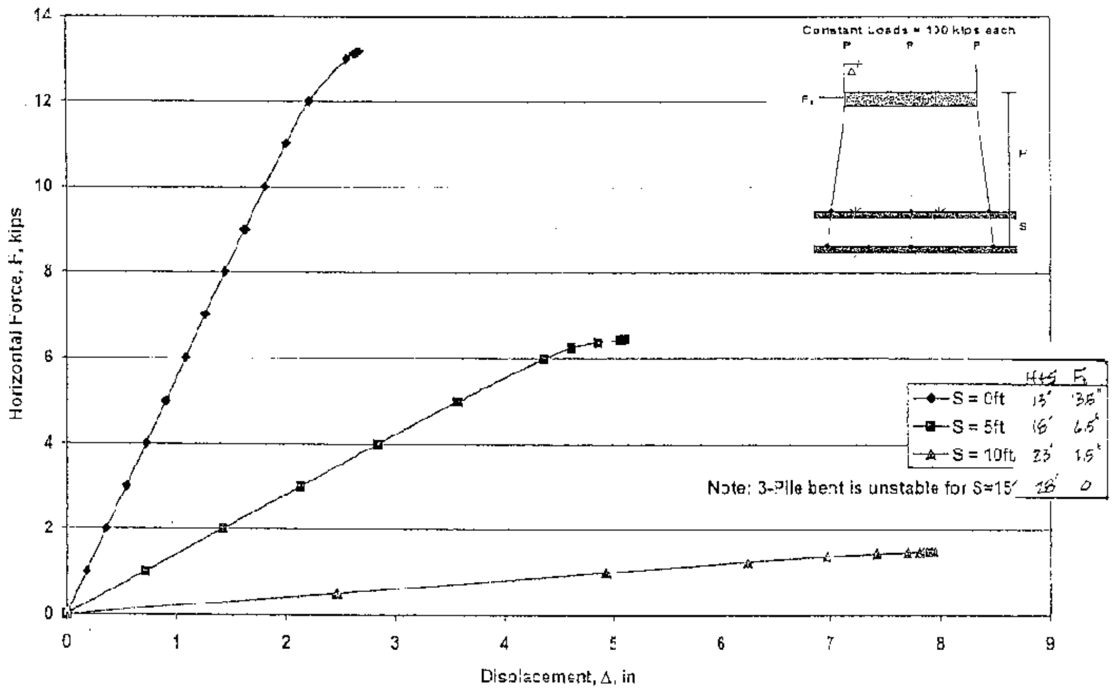
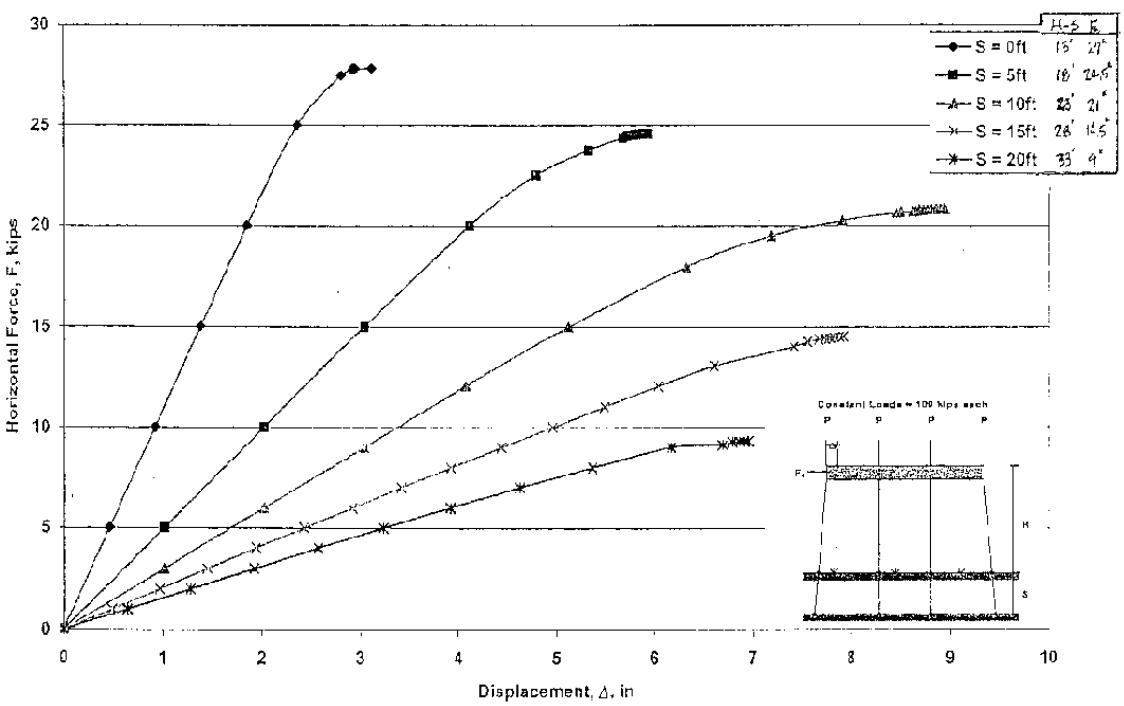


Fig. 2.18. Pushover Load vs. Bent Height Plus Scour for Single Story X-Braced 3- and 4-Pile Bents (HP_{12x53} Piles) with P-Loads of 60^k and 160^k

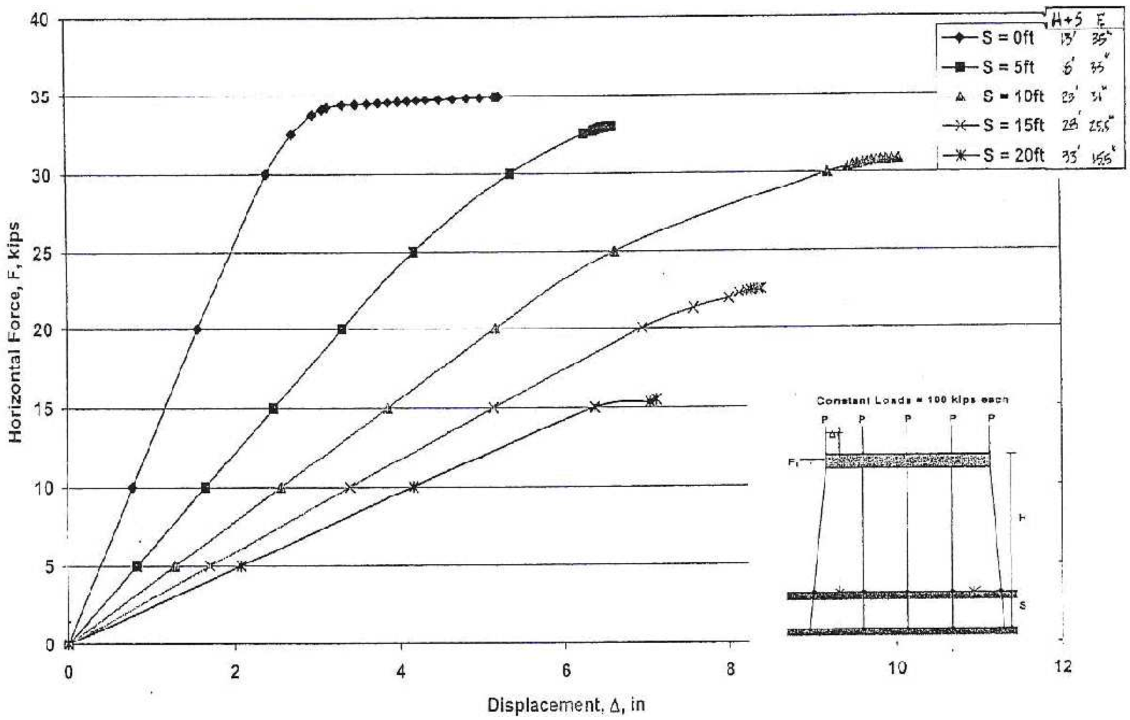


a) 3-Pile Bent

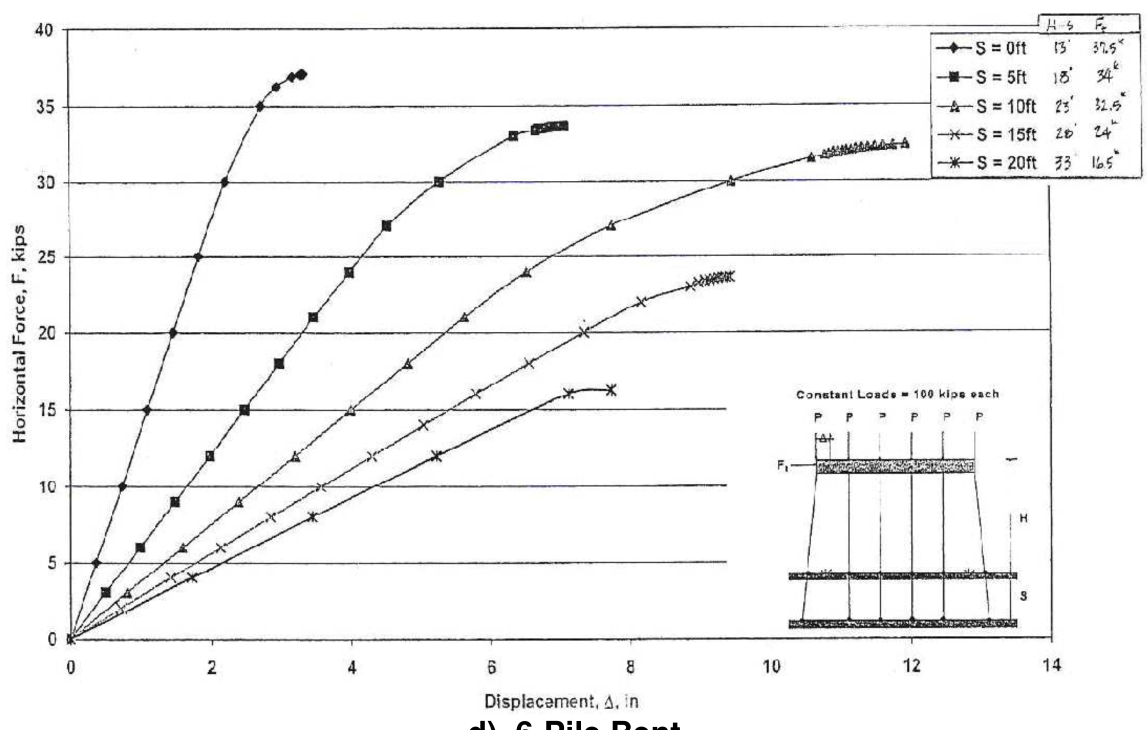


b) 4-Pile Bent

Fig. 2.19a. GTSTRUDL Pushover Analysis Results for 13 ft Tall Non X-Braced HP_{10x42} Pile Bents Subject to Scour



c) 5-Pile Bent



d) 6-Pile Bent

Fig. 2.19b. GTSTRUDL Pushover Analysis Results for 13 ft Tall Non X-Braced HP_{10x42} Pile Bents Subject to Scour (cont'd)

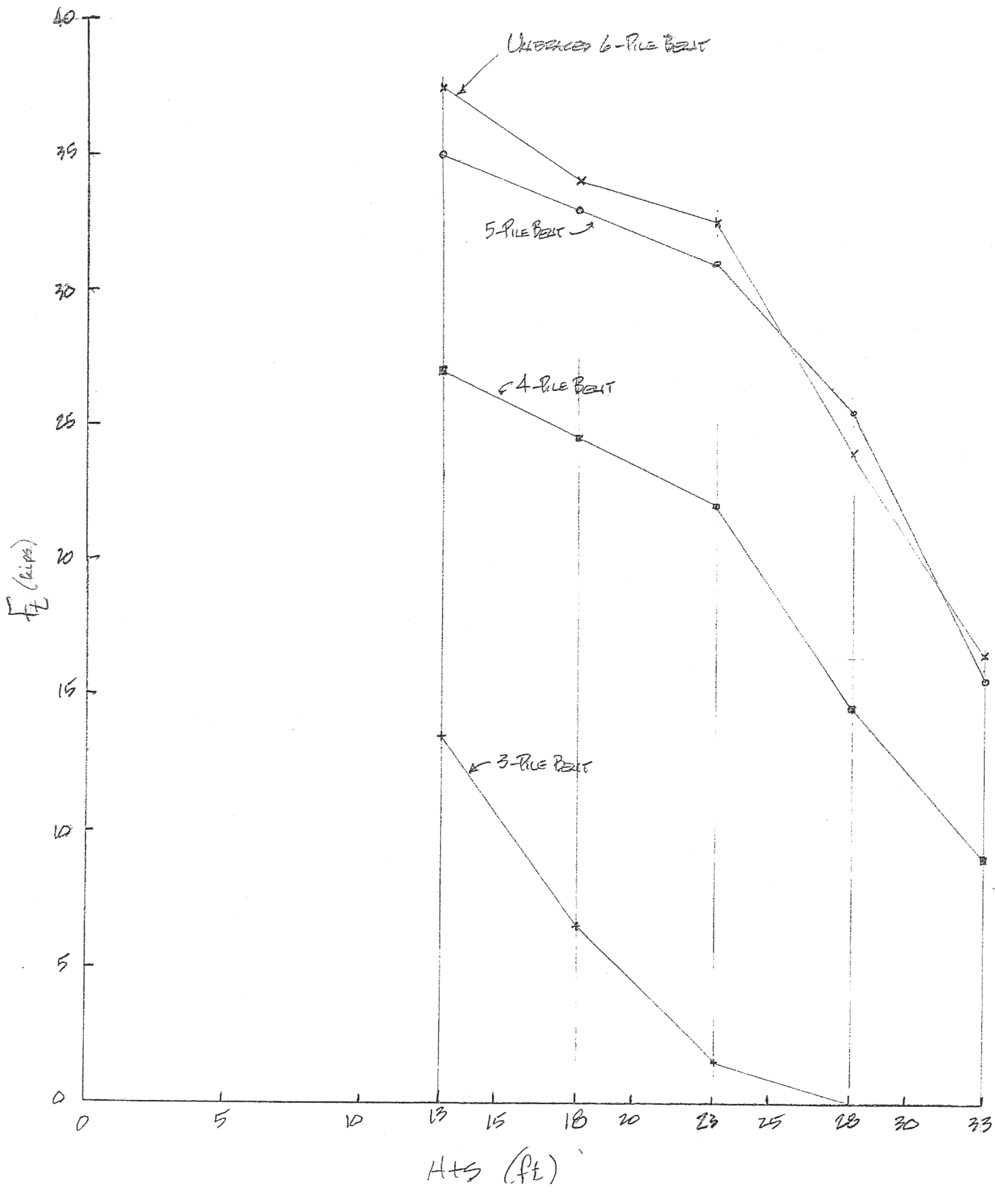


Fig. 2.20. Pushover Load (F_t) vs. Bent Height Plus Scour (H+S) for 13 ft Tall Unbraced Bents with 6, 5, 4, 3-Piles of HP_{10x42} and $P=100^k$

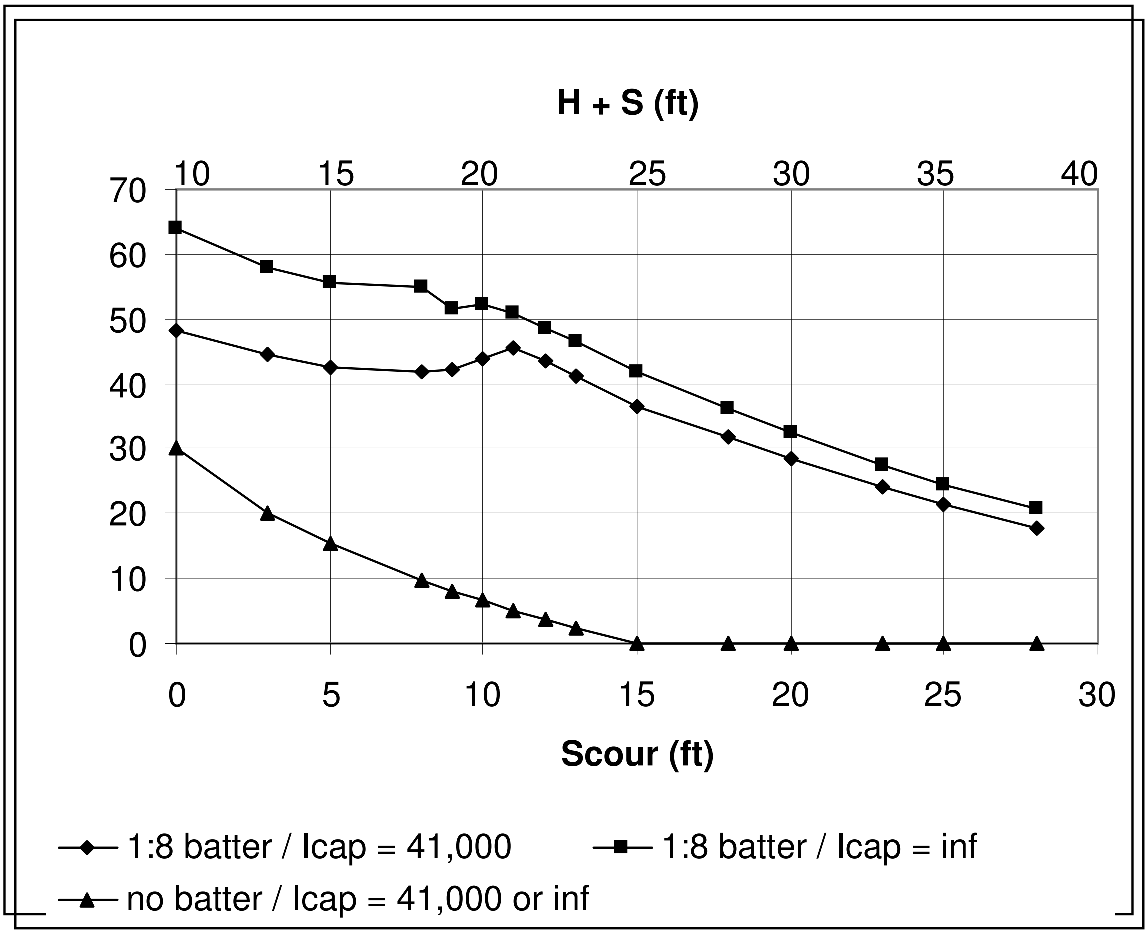


Fig. 2.21. Pushover Force vs. Scour (H+S) for 5-Pile bent with H=10', HP_{10x42} and P=60 kips

Table 2.7a. Pushover Load, F_t, for 2- Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	51.3	48.9	46.7	44.7	43.2	41.3
		5	26	20.6	18.4	16.5	14.5	12.3	10.4
		10	31	11.1	8.6	6.1	3.8	unstable	unstable
		15	36	5.8	2.8	unstable	unstable	unstable	unstable
		20	41	unstable	unstable	unstable	unstable	unstable	unstable
		25	46	unstable	unstable	unstable	unstable	unstable	unstable
	25	0	25	49.1	46.9	45.0	43.2	41.3	39.1
		5	30	19.1	16.8	14.5	12.1	9.8	7.6
		10	35	9.9	7.0	4.3	unstable	unstable	unstable
		15	40	4.6	unstable	unstable	unstable	unstable	unstable
		20	45	unstable	unstable	unstable	unstable	unstable	unstable
		25	50	unstable	unstable	unstable	unstable	unstable	unstable
4	21	0	21	63.3	58.9	55.1	51.6	48.5	45.6
		5	26	32.8	28.9	25.5	22.3	19.6	16.9
		10	31	25.0	20.6	16.8	13.2	9.7	6.4
		15	36	21.7	16.7	12.2	8.0	4.0	unstable
		20	41	16.8	12.0	7.4	4.0	unstable	unstable
		25	46	11.3	8.0	4.1	unstable	unstable	unstable
	25	0	25	58.3	53.5	49.7	46.6	44.1	41.7
		5	30	30.1	26.1	22.3	18.9	15.8	12.8
		10	35	23.2	18.1	13.9	10.0	6.4	2.8
		15	40	19.2	14.1	9.3	4.9	unstable	unstable
		20	45	14.4	9.4	5.0	unstable	unstable	unstable
		25	50	10.0	6.0	3.0	unstable	unstable	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.7b. Pushover Load, F_t, for 2- Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	21	0	21	76.0	73.8	71.6	69.4	67.1	64.9
		5	26	34.7	32.5	30.2	28.3	26.6	24.9
		10	31	21.2	18.9	16.7	14.6	12.4	10.2
		15	36	14.2	11.6	9.1	6.5	4.0	unstable
		20	41	9.6	6.6	3.6	unstable	unstable	unstable
		25	46	6.1	2.6	unstable	unstable	unstable	unstable
	25	0	25	73.4	71.4	69.3	67.1	64.9	62.6
		5	30	33.1	30.6	28.5	26.5	24.5	22.5
		10	35	19.9	17.4	15.1	12.7	10.2	7.8
		15	40	13.1	10.3	7.4	4.6	unstable	unstable
		20	45	8.6	5.2	unstable	unstable	unstable	unstable
		25	50	5.0	unstable	unstable	unstable	unstable	unstable
4	21	0	21	95.9	92.2	88.0	84.0	80.0	76.2
		5	26	51.6	47.5	43.8	40.3	37.0	33.9
		10	31	39.6	35.2	31.3	27.6	24.1	20.8
		15	36	35.4	30.6	25.8	21.6	17.8	14.1
		20	41	31.3	26.2	21.4	16.8	12.6	8.6
		25	46	25.4	20.6	16.1	11.6	7.5	4.0
	25	0	25	89.6	86.4	83.1	79.7	75.8	71.7
		5	30	48.8	44.3	40.2	36.3	32.9	29.8
		10	35	37.6	32.8	28.5	24.4	20.8	17.5
		15	40	34.0	27.9	22.7	18.5	14.4	10.5
		20	45	28.8	23.5	18.5	13.8	9.4	5.1
		25	50	23.1	18.0	13.3	8.8	5.0	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.8a. Pushover Load, F_t, for 2-Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	21	0	21	75.8	69.8	64.7	60.2	56.0	52.2
		5	26	42.4	37.3	32.8	28.6	24.6	21.0
		10	31	35.8	29.6	24.4	19.5	14.9	10.7
		15	36	35.3	28.5	21.9	15.8	10.3	5.3
		20	41	28.8	22.5	16.5	10.9	5.7	unstable
		25	46	21.0	15.5	10.5	6.5	3.0	unstable
	25	0	25	69.6	63.5	58.3	53.7	49.7	46.1
		5	30	38.4	32.8	28.0	23.5	19.5	15.8
		10	35	33.5	26.6	20.6	15.4	10.6	6.2
		15	40	32.0	24.7	17.8	11.6	6.2	unstable
		20	45	25.5	19.1	13.0	7.3	2.8	unstable
		25	50	18.3	13.0	8.0	4.5	unstable	unstable
6	21	0	21	84.5	76.9	70.2	64.4	59.0	54.2
		5	26	47.8	41.3	35.5	30.5	25.8	21.3
		10	31	41.1	33.1	26.6	20.6	15.2	10.2
		15	36	40.8	32.3	24.2	16.5	9.9	4.1
		20	41	34.8	26.5	18.9	12.0	5.6	unstable
		25	46	25.9	19.0	12.8	8.0	3.5	unstable
	25	0	25	76.9	69.2	62.6	57.1	52.3	48.1
		5	30	44.3	37.3	31.4	26.2	21.4	17.2
		10	35	38.8	30.5	23.5	17.1	11.3	6.1
		15	40	38.5	29.4	20.8	13.0	6.4	unstable
		20	45	31.7	23.4	15.8	8.8	3.1	unstable
		25	50	23.0	16.5	10.5	6.0	2.0	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.8b. Pushover Load, F_t, for 2-Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	21	0	21	114.7	108.8	102.9	97.0	91.3	86.0
		5	26	66.3	60.3	55.0	50.2	45.7	41.5
		10	31	54.3	47.5	42.2	37.2	32.5	28.1
		15	36	51.4	44.6	38.5	32.6	27.2	22.1
		20	41	50.3	42.8	36.5	29.7	23.4	17.6
		25	46	41.5	35.2	29.1	23.3	17.6	12.3
	25	0	25	108.9	102.5	96.3	90.3	84.8	78.6
		5	30	60.8	55.0	49.8	45.0	40.5	36.4
		10	35	51.2	43.6	37.7	32.5	27.7	23.2
		15	40	49.4	42.0	35.1	28.6	22.6	17.5
		20	45	46.7	39.2	32.2	25.2	18.8	13.2
		25	50	38.2	31.6	25.3	19.4	13.7	8.3
6	21	0	21	128.8	120.4	112.1	104.5	96.7	90.1
		5	26	75.0	67.6	60.8	54.7	49.0	43.9
		10	31	62.6	53.3	46.5	40.3	34.5	29.2
		15	36	59.4	50.6	42.6	35.4	28.8	22.6
		20	41	59.2	49.5	41.4	33.0	25.0	17.8
		25	46	50.0	41.8	33.8	26.3	19.4	12.9
	25	0	25	114.3	108.2	101.9	94.2	86.3	80.4
		5	30	69.6	62.3	55.8	49.7	44.2	39.2
		10	35	59.0	50.0	42.8	36.4	30.5	25.2
		15	40	57.4	48.1	40.0	32.0	24.9	18.6
		20	45	56.1	46.7	38.0	29.2	21.0	14.0
		25	50	46.8	38.5	30.5	23.0	16.1	9.4

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.9a. Pushover Load, F_t, Double X-Braced 1-Story and 2-Story 6-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Scour

No. Stories and Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
1-Story and 6-Piles	13	0	13	95.7	90.4	85.7	81.2	77.0	73.4
		5	18	50.8	44.9	39.8	34.9	30.6	26.8
		10	23	45.4	37.9	31.4	25.7	20.6	15.9
		15	28	46.3	37.7	30.4	23.6	17.3	11.3
		20	33	37.5	30.3	23.3	17.0	11.3	6.4
		25	38	27.3	21.2	15.8	11.0	7.0	4.0
	17	0	17	89.3	82.5	77.8	73.9	70.5	66.6
		5	22	49.1	41.7	35.5	30.5	26.3	22.4
		10	27	44.6	35.9	28.6	22.5	17.2	12.4
		15	32	43.5	35.3	27.6	20.5	14.0	7.9
		20	37	34.6	27.2	20.3	14.2	8.9	4.4
		25	42	24.7	18.9	13.8	9.4	6.0	3.0
2-Story and 6-Piles	21	0	21	98.1	92.7	88.0	83.4	79.1	75.6
		5	26	50.6	44.6	39.4	34.5	30.4	26.7
		10	31	44.1	36.3	29.8	24.0	19.0	14.3
		15	36	43.0	34.8	27.4	20.8	14.5	8.6
		20	41	36.7	29.0	21.8	15.2	9.3	4.1
		25	46	26.8	20.3	14.5	9.5	5.5	unstable
	25	0	25	91.4	85.0	80.7	76.8	73.2	69.2
		5	30	48.5	41.1	35.2	30.5	26.3	22.3
		10	35	42.8	34.1	27.0	20.9	15.8	10.9
		15	40	41.2	32.7	25.0	18.1	11.7	5.8
		20	45	33.9	26.2	18.9	12.6	7.0	2.3
		25	50	24.0	17.9	12.5	8.0	4.1	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.9b. Pushover Load, F_t, Double X-Braced 1-Story and 2-Story 6-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Scour

No. Stories and Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
1-Story and 6-Piles	13	0	13	143.5	137.5	132.3	127.5	123.5	119.7
		5	18	76.3	69.6	64.6	59.9	55.5	51.2
		10	23	65.3	56.4	49.6	44.1	39.0	34.2
		15	28	62.5	54.8	47.3	40.5	34.5	29.0
		20	33	63.4	54.8	46.9	39.7	32.7	26.0
		25	38	52.1	44.8	37.7	30.8	24.4	18.4
	17	0	17	139.3	134.0	128.4	123.3	118.5	113.6
		5	22	74.0	66.4	60.3	54.8	50.0	45.8
		10	27	64.2	55.2	47.8	41.4	35.5	30.3
		15	32	63.4	53.7	45.3	37.9	31.5	25.7
		20	37	60.5	52.1	44.3	36.8	29.6	22.8
		25	42	49.6	41.9	34.6	27.6	21.2	15.4
2-Story and 6-Piles	21	0	21	149.3	143.0	137.0	131.5	126.3	121.9
		5	26	76.9	70.8	65.7	61.0	56.5	52.1
		10	31	64.9	55.5	49.3	43.8	38.7	33.9
		15	36	62.2	53.1	45.5	38.7	32.8	27.5
		20	41	61.3	52.1	44.3	36.6	29.5	23.0
		25	46	51.6	43.9	36.4	29.3	22.7	16.4
	25	0	25	143.8	138.4	133.0	127.4	122.1	117.3
		5	30	74.6	67.4	61.4	55.9	51.2	47.1
		10	35	63.8	54.6	47.3	40.8	35.2	30.4
		15	40	61.4	51.9	43.4	36.3	30.2	24.6
		20	45	58.7	50.1	42.0	34.2	27.1	20.3
		25	50	49.1	41.0	33.5	26.3	19.7	13.7

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

2.7 Pushover Loads for Unsymmetric P-load Distribution

The Tier One Screening Tool (T1-ST) assumes a uniform and symmetric P-load distribution across the bent cap as shown in Fig. 2.24. However, this loading may not result in the smallest pushover load, F_t. A smaller but unsymmetrical P-load distribution on the bent resulting from the LL only being applied to the upstream traffic lane as shown in Fig. 2.24 may result in a smaller pushover load. From our earlier Phase II work, pushover failure is only a problem for 3-pile and 4-pile bents. Thus, for these bents, additional pushover analyses were performed for the nonsymmetric P-loading shown in Fig. 2.25.

For 3-pile and 4-pile bents, the P_{DL}, P_{LL}, and P_{total} load distributions shown in Figs. 2.22 and 2.23, respectively, were assumed. (See the Phase II Report or Chapter 3 of this report for calculating P_{DL}^{Bent} and P_{LL}^{Bent} for symmetrical and unsymmetrical loadings). From earlier Phase II work, it was noted that typical span DLs and LLs are such that the unsymmetrical P-loads for 3-pile and 4-pile bents can be taken as shown in Fig. 2.25. These, then, are the distributions and P-load values that were used in the pushover analyses of 3- and 4-pile bents in this Phase III work.

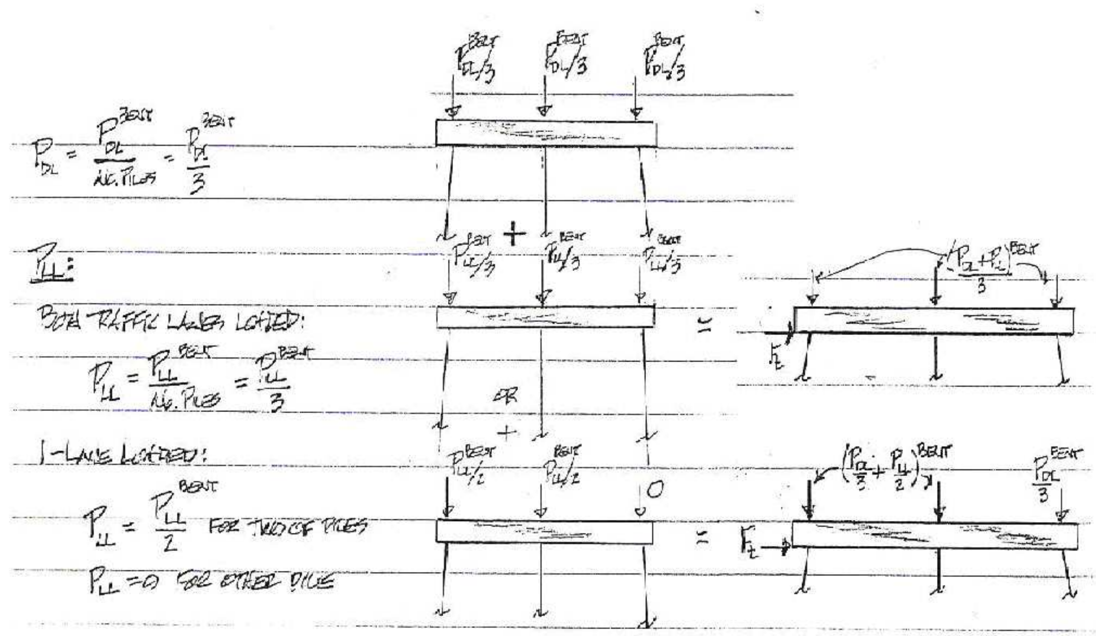


Fig. 2.22. 3-Pile Bent P-load Distributions

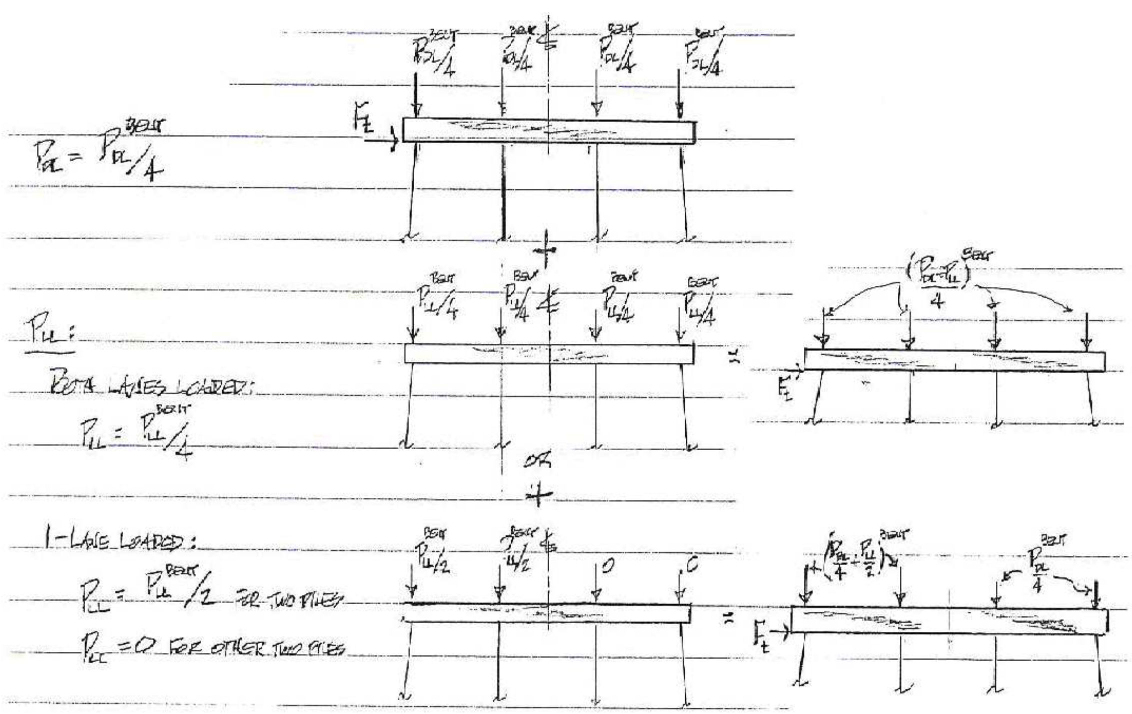


Fig. 2.23. 4-pile Bent P-load Distributions

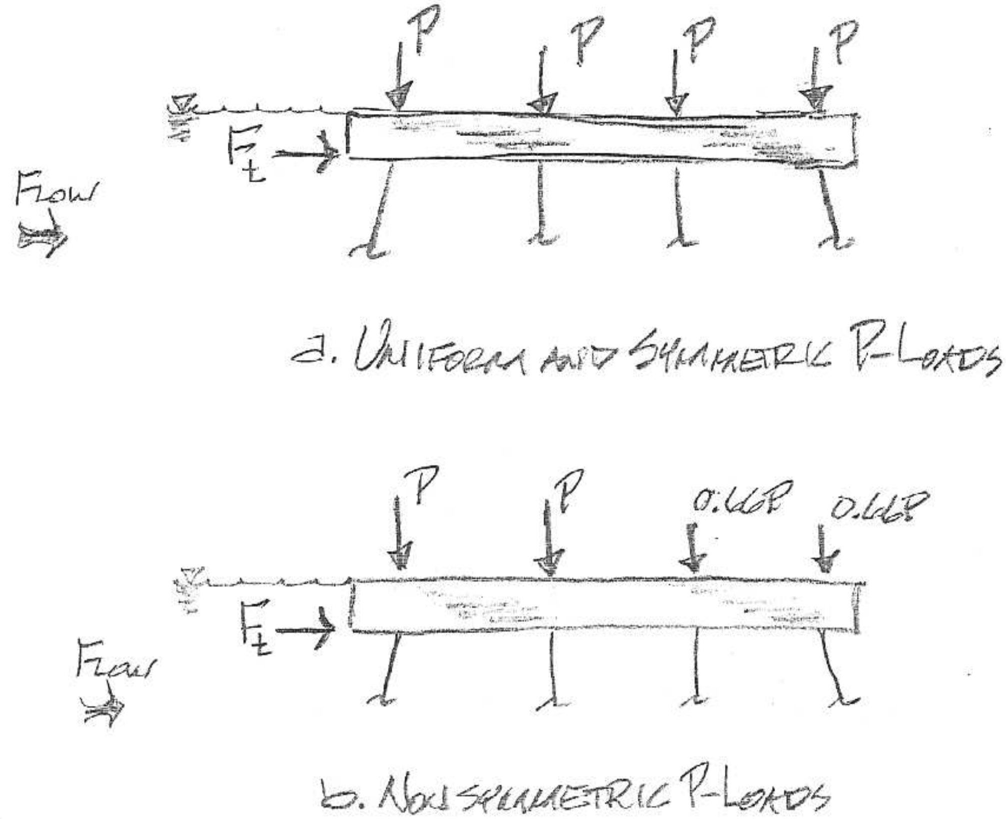


Fig. 2.24. Symmetric and Nonsymmetric P-load Distributions

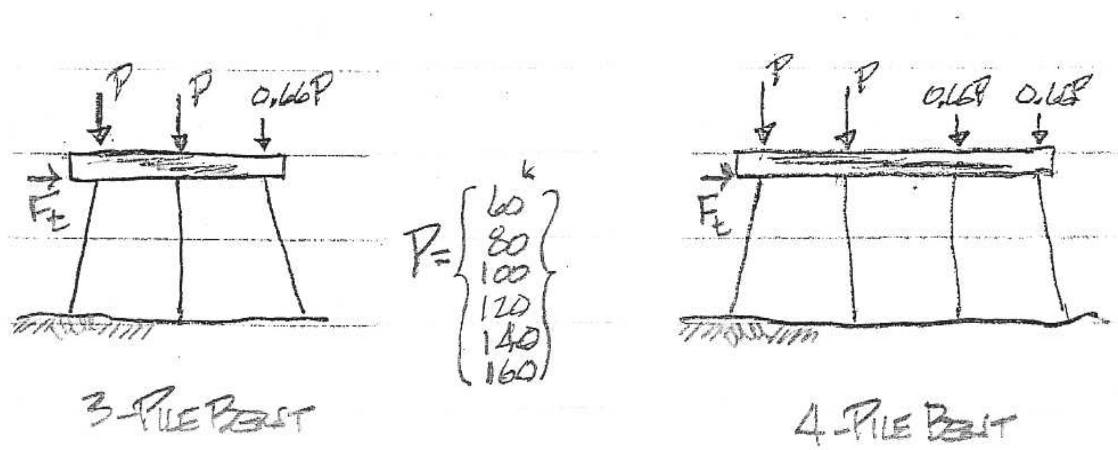


Fig. 2.25. Unsymmetric P-load Levels and Distributions Used in Phase III Work

Results of the bent pushover analyses with unsymmetric P-loading, resulting from applying LL only to the bridge upstream lane are presented in Tables 2.10a and 2.10b for single-story, unbraced, 3- and 4-pile bents, and in Tables 2.11a and 2.11b for single-story, X-braced, 3- and 4-pile bents. Again, to better illustrate the effect of P-load distribution on a bent's pushover capacity, a subset of the data of Tables 2.10a and 2.10b for unbraced bents are shown graphically in Figs. 2.26-2.27, and for braced bents in Figs. 2.28-2.29. As can be seen in all of these figures, the bent pushover load is a little smaller in every case with the unsymmetric P-load distribution. This is due to the sidesway caused by unsymmetric loading. Because the difference is so small, use of pushover analysis having a symmetric P-load distribution was felt to be justifiable.

Results of bent pushover analyses with unsymmetric P-loadings on 2-story X-braced 3- and 4-pile bents are presented in Tables 2.12a and 2.12b for HP_{10x42} and HP_{12x53} pile bents, respectively. By comparing the pushover loads in Table 2.7a and b with those in Tables 2.12a and b, one can again see that, in every case, the pushover load is a little smaller for the unsymmetric P-load distribution. Again, because of the small difference, restricting pushover analysis to those having a symmetric P-load distribution was felt to be justifiable.

Lastly, because of the small difference in pushover results for the unsymmetric P-load distribution relative to that for the symmetric P-load distribution, expansions of the pushover tables were not performed for S = 25ft and for 5-pile and 6-pile bents.

Table 2.10a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Varying Values of 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	10	0	10	19.4	17.6	16.1	14.3	12.5
		5	15	10.8	8.8	6.8	4.7	2.4
		10	20	6.3	3.9	unstable	unstable	unstable
		15	25	3.2	unstable	unstable	unstable	unstable
		20	30	unstable	unstable	unstable	unstable	unstable
	13	0	13	13.5	11.6	9.8	7.8	5.7
		5	18	7.9	5.6	3.3	unstable	unstable
		10	23	4.4	unstable	unstable	unstable	unstable
		15	28	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable
4	10	0	10	36.8	33.4	30.4	27.6	25.0
		5	15	30.5	26.7	23.4	20.1	17.0
		10	20	29.7	25.5	21.6	18.4	14.5
		15	25	23.6	19.6	16.1	12.1	8.2
		20	30	17.5	13.6	9.8	6.0	2.3
	13	0	13	32.5	28.6	25.3	21.9	19.2
		5	18	28.8	25.5	22.1	18.6	15.1
		10	23	26.5	22.4	18.3	14.9	11.1
		15	28	19.8	16.0	12.1	8.3	4.5
		20	33	14.3	10.3	6.6	unstable	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.10b. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Varying Values of 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	10	0	10	31.6	29.9	28.3	26.7	25.1
		5	15	19.5	17.6	15.8	14.0	12.1
		10	20	13.4	11.3	9.3	7.1	4.8
		15	25	9.6	7.2	4.8	2.2	unstable
		20	30	6.8	4.0	unstable	unstable	unstable
	13	0	13	23.2	21.4	19.7	18.0	16.2
		5	18	15.5	13.4	11.5	9.5	7.4
		10	23	11.0	8.7	6.4	4.0	unstable
		15	28	7.8	5.2	2.6	unstable	unstable
		20	33	5.4	2.4	unstable	unstable	unstable
4	10	0	10	55.2	51.3	48.0	44.9	42.3
		5	15	43.7	40.2	36.3	33.0	29.7
		10	20	39.5	36.1	32.3	28.9	25.8
		15	25	39.0	35.4	31.7	27.7	23.5
		20	30	32.3	28.0	24.1	20.7	16.8
	13	0	13	45.7	42.1	38.9	35.9	33.0
		5	18	41.1	37.1	33.5	30.2	26.8
		10	23	40.0	35.6	31.8	28.8	25.1
		15	28	35.2	31.3	27.0	23.0	19.6
		20	33	27.9	24.2	20.5	16.5	12.8

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.11a. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Varying Values of 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k
3	13	0	13	45.1	42.2	39.7	37.0	34.7
		5	18	17.4	14.6	12.3	10.0	7.5
		10	23	8.8	6.1	3.4	unstable	unstable
		15	28	4.3	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable
	17	0	17	43.3	40.6	38.1	35.9	33.6
		5	22	16.1	13.4	11.0	8.3	5.7
		10	27	7.9	4.9	unstable	unstable	unstable
		15	32	3.4	unstable	unstable	unstable	unstable
		20	37	unstable	unstable	unstable	unstable	unstable
4	13	0	13	61.7	57.2	53.1	49.2	45.5
		5	18	34.0	29.8	25.9	22.2	18.6
		10	23	27.8	23.3	19.1	15.1	11.2
		15	28	25.4	20.2	15.9	11.5	7.1
		20	33	18.7	14.1	9.5	5.0	unstable
	17	0	17	57.8	52.4	48.0	43.9	40.1
		5	22	31.9	27.4	23.2	19.3	15.5
		10	27	26.4	21.4	16.7	12.3	8.1
		15	32	22.5	17.6	12.8	8.0	3.5
		20	37	16.1	11.1	6.5	2.1	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.11b. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Varying Values of 'H+S'

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	13	0	13	65.5	62.9	60.4	58.0	55.6
		5	18	30.2	27.6	25.1	22.5	20.2
		10	23	18.1	15.3	12.8	10.3	7.9
		15	28	11.8	9.0	6.3	3.5	unstable
		20	33	7.9	4.8	unstable	unstable	unstable
	17	0	17	64.5	61.9	59.2	56.4	53.6
		5	22	29.0	26.2	23.5	21.1	18.8
		10	27	17.2	14.2	11.6	9.0	6.3
		15	32	11.1	8.0	5.1	2.0	unstable
		20	37	7.1	3.8	unstable	unstable	unstable
4	13	0	13	90.1	86.0	81.9	77.6	73.6
		5	18	52.3	47.7	43.6	39.7	35.9
		10	23	41.8	37.1	32.8	28.7	24.9
		15	28	37.9	33.5	29.2	24.9	20.6
		20	33	34.6	29.6	24.8	20.6	16.2
	17	0	17	83.0	79.5	76.0	72.2	68.2
		5	22	50.1	45.1	40.6	36.4	32.4
		10	27	40.2	35.2	30.7	26.3	22.1
		15	32	37.2	31.8	27.0	22.1	17.5
		20	37	31.8	26.7	22.0	17.3	12.6

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

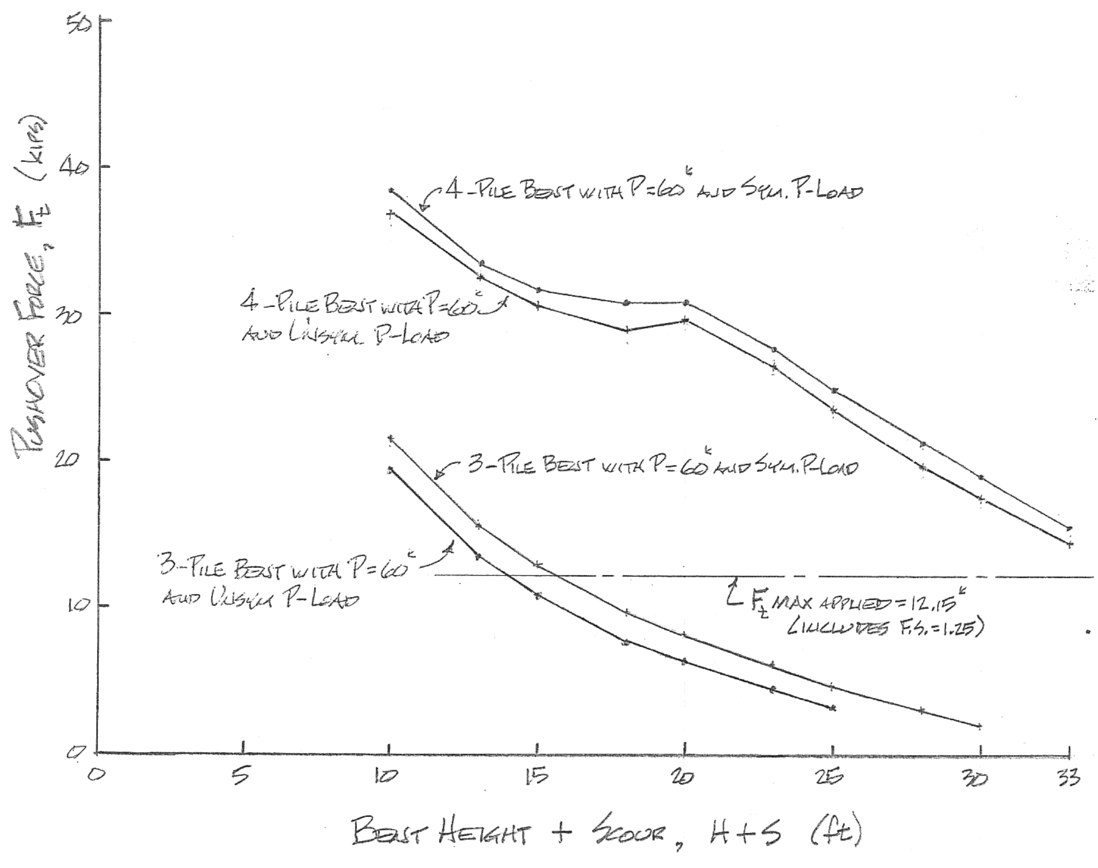


Fig. 2.26. Pushover Load vs. Bent Height Plus Scour for Unbraced 3- and 4-Pile Bents (HP_{10x42} Piles) with Sym. and Unsym. P-Loads

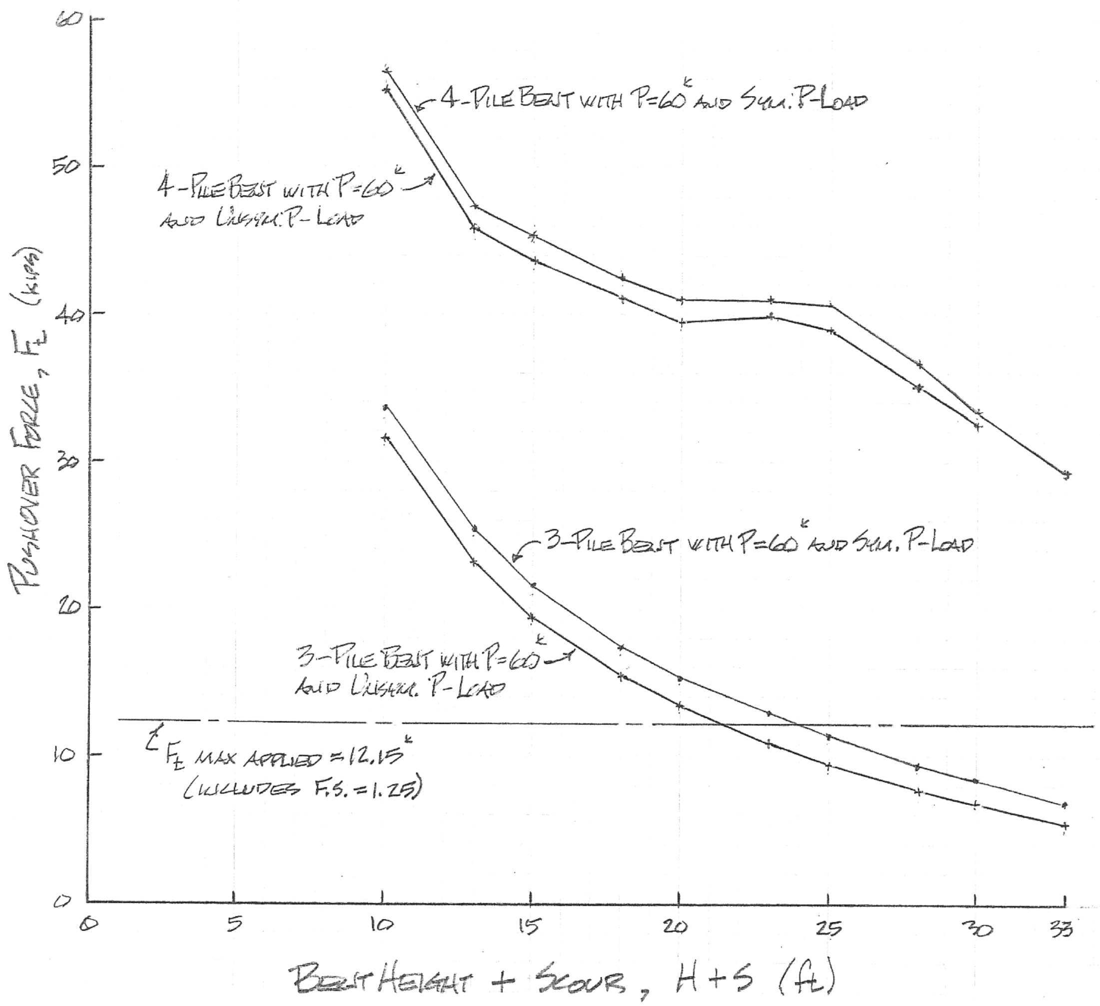


Fig. 2.27. Pushover Load vs. Bent Height Plus Scour for Unbraced 3- and 4-Pile Bents (HP_{12x53} Piles) with Sym. and Unsym. P-Loads

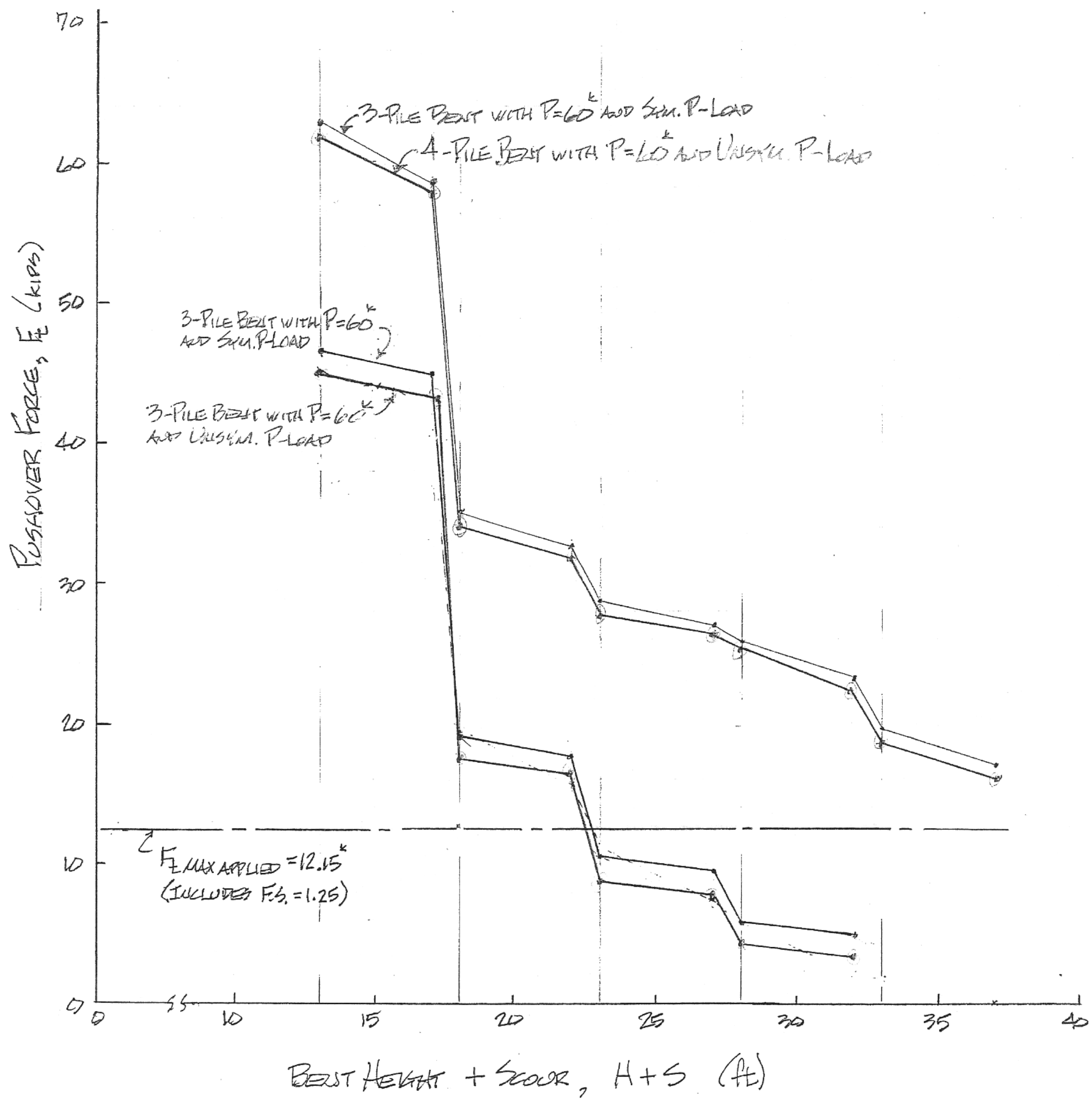


Fig. 2.28. Pushover Load vs. Bent Height Plus Scour for Single Story X-Braced 3- and 4-Pile Bents (HP_{10x42} Piles) with Sym. and Unsym. P-Loads

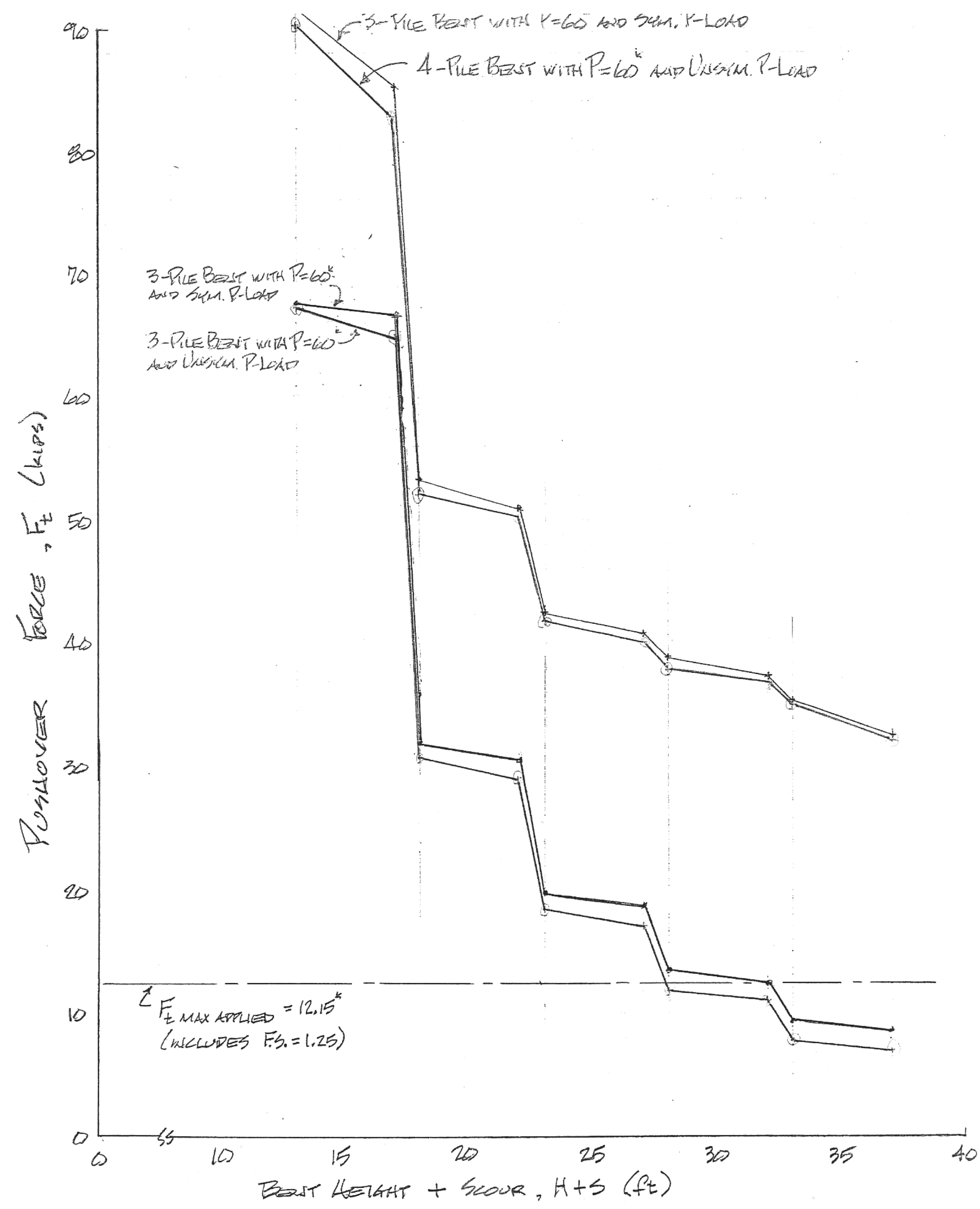


Fig. 2.29. Pushover Load vs. Bent Height Plus Scour for Single Story X-Braced 3- and 4-Pile Bents (HP_{12x53} Piles) with Sym. and Unsym. P-Loads

Table 2.12a. Pushover Load, F_t, for 2-Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Varying Values of 'H+S' and Unsymmetric P-Loadings

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	49.8	46.7	43.9	41.1	38.7	36.6
		5	26	19.0	16.1	13.5	10.9	8.2	5.6
		10	31	9.4	6.4	3.4	unstable	unstable	unstable
		15	36	4.3	unstable	unstable	unstable	unstable	unstable
		20	41	unstable	unstable	unstable	unstable	unstable	unstable
	25	0	25	47.6	44.7	42.1	39.7	37.2	34.8
		5	30	17.5	14.5	11.8	8.8	5.8	3.0
		10	35	8.3	5.0	unstable	unstable	unstable	unstable
		15	40	3.2	unstable	unstable	unstable	unstable	unstable
		20	45	unstable	unstable	unstable	unstable	unstable	unstable
4	21	0	21	62.3	57.5	53.3	49.2	45.4	41.9
		5	26	31.8	27.5	23.4	19.6	15.9	12.6
		10	31	24.5	19.5	15.1	10.9	6.9	3.1
		15	36	21.3	15.8	10.9	6.2	unstable	unstable
		20	41	16.1	11.1	6.1	unstable	unstable	unstable
	25	0	25	57.7	52.3	47.8	43.8	40.2	36.9
		5	30	29.4	24.7	20.6	16.5	12.6	9.2
		10	35	22.9	17.4	12.5	8.0	3.8	unstable
		15	40	19.0	13.3	8.3	3.4	unstable	unstable
		20	45	13.9	8.6	3.4	unstable	unstable	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.12b. Pushover Load, F_t, for 2-Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Varying Values of 'H+S' and Unsymmetric P-Loadings

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	73.9	70.9	68.1	65.2	62.2	59.3
		5	26	33.0	30.2	27.4	24.7	22.2	20.0
		10	31	19.6	16.5	13.8	11.1	8.4	5.7
		15	36	12.6	9.4	6.4	3.3	unstable	unstable
		20	41	8.1	4.7	unstable	unstable	unstable	unstable
	25	0	25	71.2	68.3	65.5	62.6	59.7	56.8
		5	30	31.5	28.4	25.6	22.9	20.4	17.9
		10	35	18.4	15.2	12.3	9.4	6.4	3.4
		15	40	11.6	8.2	4.9	unstable	unstable	unstable
		20	45	7.2	3.4	unstable	unstable	unstable	unstable
4	21	0	21	94.1	89.9	85.5	80.8	76.2	71.9
		5	26	50.8	46.0	41.9	37.8	33.8	30.2
		10	31	38.9	34.0	29.6	25.3	21.3	17.4
		15	36	35.1	29.7	24.7	19.8	15.3	11.2
		20	41	30.9	25.5	20.3	15.5	10.7	6.2
	25	0	25	87.4	83.5	79.6	75.9	71.5	67.1
		5	30	48.2	43.1	38.6	34.2	30.0	26.2
		10	35	37.2	31.9	27.2	22.6	18.2	14.1
		15	40	33.8	27.7	22.0	16.8	12.2	7.9
		20	45	28.4	22.8	17.6	12.5	7.6	2.9

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

2.8 Pushover Loads for Variable Scour Distribution

The Tier One Screening Tool assumes a uniform level of scour along the profile of the bent. However, localized scour at a bridge/pile bent site will not be uniform, but typically will vary from a maximum level at the upstream pile to a minimum level at the downstream pile as shown in Figs. 2.30 and 2.31. Thus, the piles with lower levels of scour can provide some “lean-on” buckling support and some “lean-on” plunging support to the piles for which scour is maximum. Also, the piles with lower levels of scour will provide additional pushover load capacity and thus, such bents (with variable scour) will have greater pushover capacity than if all piles in the bent experience S_{max}.

Based on pushover analysis results presented in Phase II Reports (Ramey), only 3-pile bents and a few 4-pile bents appear to be of concern regarding possible pushover failures. Hence, we initially only modeled and analyzed 3-pile and 4-pile bents for pushover loads using a variable scour distribution. In the analyses we assumed the scour distributions shown in Fig. 2.31.

An example application problem illustrating the effect of uniform and variable scour on the buckling load for a 3-pile bent is shown in Fig. 2.32. In looking at the results for that problem, the extremely negative effect of scour on bent buckling is obvious. The beneficial effect of a variable scour distribution which allows the piles at the locations of greatest scour to receive significant “lean-on” support from piles at less severely scoured locations is also obvious.

A variable distribution of scour such as that shown in Fig. 2.31 will also result in larger bent plunging failure loads and bent pushover loads, and these will be examined later.

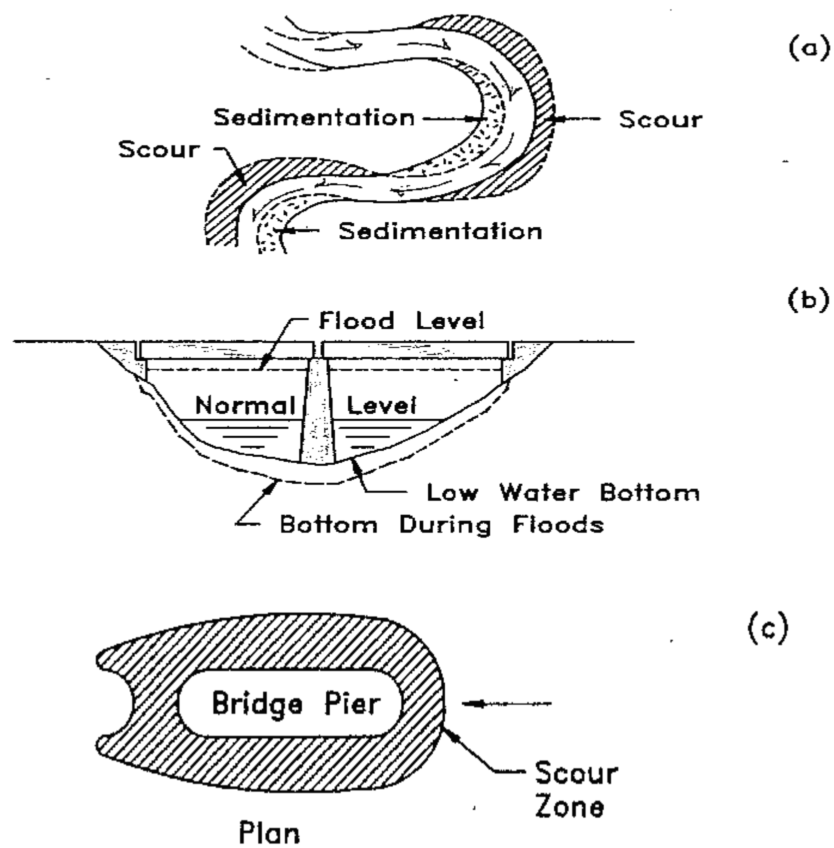


Fig. 2.30. Forms of Scour in Rivers: a) Lateral Shift of a Stream Caused by Bank Erosion and Deposition; b) Normal Bottom Scour During Floods; c) Accelerated Scour Caused By a Bridge Pier. [From Sowers, 1962]

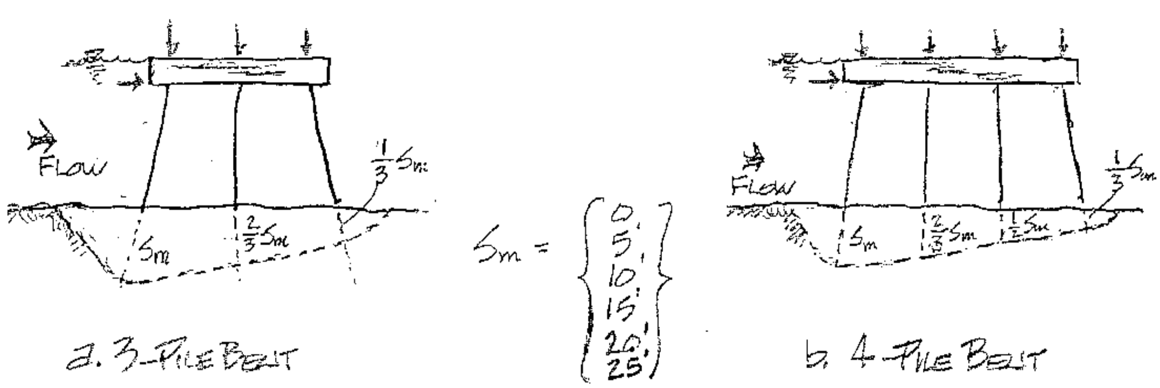


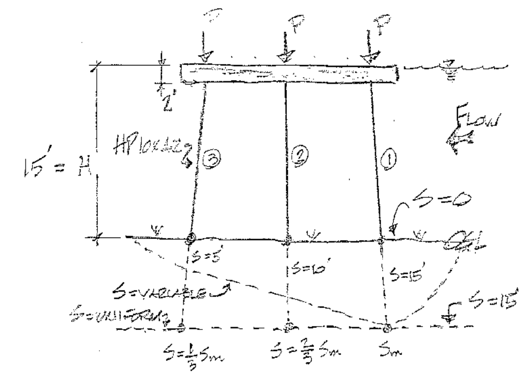
Fig. 2.31. Assumed Scour Distributions Profile

DETERMINE THE PILE AND BENT BUCKLING LOADS FOR THE 3-PILE BENT AT THE RIGHT FOR

$S = 0$

S = UNIFORM WITH $S = 15'$

S = VARIABLE WITH $S_m = 15'$



SOLNS:

SIDESWAY BUCKLING CONTROLS, $P_{CR} = \dfrac{0.5\pi^2 EI}{\ell^2}$

FOR CASE OF $S = 0$,

$$\ell = 15 - 2' = 13'$$

$$P_{CR} = \frac{0.5 \times \pi^2 \times 29{,}000 \times 70.7}{13^2 \times 144} = 415^k$$

$$P_{CR}^{BENT} = \sum P_{CR} = 415^k \times 3 = 1245^k$$

FOR CASE OF UNIFORM SCOUR = $S = 15'$,

$$\ell = H + S - 2' = 28'$$

$$P_{CR} = \frac{0.5 \times \pi^2 \times 29{,}000 \times 70.7}{28^2 \times 144} = 90^k$$

$$P_{CR}^{BENT} = \sum P_{CR} = 90 \times 3 = 270^k$$

FOR CASE OF VARIABLE SCOUR WITH $S_m = 15'$

$$P_{CR}^{①} = \frac{0.5 \times \pi^2 \times 29{,}000 \times 70.7}{28^2 \times 144} = 90^k$$

$$P_{CR}^{②} = \frac{0.5 \times \pi^2 \times 29{,}000 \times 70.7}{23^2 \times 144} = 133^k$$

$$P_{CR}^{③} = \frac{0.5 \times \pi^2 \times 29{,}000 \times 70.7}{18^2 \times 144} = 218^k$$

$$P_{CR}^{BENT} = \sum P_{CR} = 90 + 133 + 218 = 441^k \Rightarrow P_{CR}^{PILE\ AVG} = \frac{441}{3} = 147^k$$

Fig. 2.32. Example Problem Illustrating the Effect of Scour Distribution on Bent Buckling Loads

Results of the bent pushover analyses for variable scour distributions for unbraced and X-braced 3, 4, 5, and 6-pile bents are presented in Tables 2.13-2.16. It can be seen in these tables that when the bent consists of HP_{12x53} piles, the 4-pile bents are adequate for pushover, and in almost all cases so too are these bents when the piles are HP_{10x42}. However, this is not the case for the 3-pile bents. By comparing the pushover loads in Tables 2.13-2.16 with their "sister" tables having uniform scour, i.e., Tables 2.3 - 2.6, one can see the significantly larger bent pushover capacity when the scour is not uniform. This is graphically illustrated by plotting a subset of the unbraced and X-braced bent pushover load data vs. H+S in Tables 2.13-2.16, as shown in Figs. 2.33 and 2.34, respectively.

Results of bent pushover analyses for variable scour distributions for 2-story X-braced 3, 4, 5 and 6-pile bents with symmetric P-load distribution are shown in Tables 2.17 and 2.18. Comparing the pushover loads in these tables with their "sister" tables having uniform scour, i.e., Tables 2.7 and 2.8, one can again see a significantly larger pushover capacity when the scour is not uniform.

Table 2.13a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	0	10	21.6	20.6	19.6	20.0	18.8	17.6
		5	15	14.8	13.4	12.0	10.7	9.3	8.0
		10	20	10.3	8.7	7.2	5.7	4.5	3.3
		15	25	7.3	5.6	4.3	3.0	unstable	unstable
		20	30	5.1	3.7	2.3	unstable	unstable	unstable
		25	35	3.8	2.3	unstable	unstable	unstable	unstable
	13	0	13	15.6	14.4	13.2	12.4	11.0	9.5
		5	18	11.1	9.5	7.9	6.3	4.9	3.3
		10	23	7.8	6.0	4.3	2.8	unstable	unstable
		15	28	5.3	3.6	2.0	unstable	unstable	unstable
		20	33	3.7	2.0	unstable	unstable	unstable	unstable
		25	38	2.5	unstable	unstable	unstable	unstable	unstable
4	10	0	10	38.3	35.7	33.5	34.8	32.3	29.9
		5	15	33.1	30.5	27.7	25.2	22.8	20.4
		10	20	31.1	27.9	25.0	22.0	19.1	16.3
		15	25	30.3	26.9	24.1	20.0	16.9	13.8
		20	30	26.2	23.6	20.9	17.4	14.3	11.6
		25	35	23.9	21.0	17.9	15.0	12.2	9.4
	13	0	13	33.6	30.6	27.9	27.5	24.8	22.0
		5	18	31.0	28.1	25.3	22.5	19.8	17.1
		10	23	30.3	27.3	24.3	20.8	17.6	14.5
		15	28	28.1	24.3	21.5	18.0	15.0	12.0
		20	33	24.2	21.4	18.1	14.9	11.9	8.9
		25	38	21.2	17.8	14.6	11.5	8.5	5.8

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.13b Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{12X53} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	10	0	10	33.8	32.8	32.0	34.2	33.1	32.0
		5	15	24.5	23.3	22.1	20.9	19.7	18.5
		10	20	18.5	17.0	15.6	14.3	13.0	11.7
		15	25	14.4	12.8	11.3	9.8	8.4	7.2
		20	30	11.5	9.7	8.0	6.7	5.6	4.4
		25	35	9.2	7.3	5.9	4.8	3.5	2.3
	13	0	13	25.3	24.3	23.3	23.5	22.2	21.1
		5	18	19.4	18.0	16.7	15.3	14.0	12.7
		10	23	15.1	13.4	11.9	10.4	8.9	7.4
		15	28	11.9	10.2	8.4	6.8	5.5	4.1
		20	33	9.5	7.6	5.9	4.5	3.1	unstable
		25	38	7.6	5.7	4.2	2.7	unstable	unstable
4	10	0	10	56.6	53.4	50.7	54.4	52.3	50.1
		5	15	47.2	44.2	41.6	39.3	37.1	35.0
		10	20	43.9	40.3	37.7	34.7	31.9	29.2
		15	25	41.5	38.2	35.0	32.1	29.0	26.0
		20	30	40.7	36.9	34.3	31.1	25.0	23.7
		25	35	38.1	34.6	30.7	27.9	24.4	20.9
	13	0	13	47.3	44.3	41.7	42.8	40.5	38.1
		5	18	42.7	40.2	37.6	34.7	32.4	30.3
		10	23	41.5	38.2	35.2	32.5	29.5	26.6
		15	28	40.6	37.2	34.7	31.3	28.0	24.6
		20	33	38.6	33.9	31.4	28.6	25.2	21.4
		25	38	35.1	30.8	28.2	25.0	21.9	18.9

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.14a. Pushover Load, F_t, for Unbraced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	10	0	10	48.1	43.8	40.6	38.2	35.8	33.4
		5	15	44.3	38.9	34.8	31.2	28.0	24.7
		10	20	42.4	37.7	32.9	28.6	24.6	20.5
		15	25	42.6	36.2	32.1	27.2	22.5	17.9
		20	30	38.2	32.6	27.9	23.1	18.8	14.8
		25	35	32.5	28.2	23.8	19.8	16.0	12.2
	13	0	13	44.6	39.1	34.9	31.5	28.7	25.8
		5	18	42.3	37.4	33.0	28.9	25.1	21.5
		10	23	44.4	37.8	33.4	28.7	23.9	19.5
		15	28	39.2	33.8	29.5	24.6	20.2	16.0
		20	33	33.7	29.3	24.7	20.3	16.1	12.1
		25	38	28.3	23.9	19.6	15.3	11.5	8.1
6	10	0	10	53.1	48.2	45.2	42.7	40.0	37.3
		5	15	46.4	41.7	37.1	33.5	30.1	26.5
		10	20	46.2	39.6	34.1	29.1	24.5	20.0
		15	25	44.3	39.0	32.8	27.0	21.5	16.2
		20	30	42.3	36.4	30.4	24.2	18.7	13.4
		25	35	38.0	32.0	26.0	20.8	15.9	11.7
	13	0	13	46.4	40.7	37.1	33.8	30.4	27.1
		5	18	45.8	39.3	34.2	29.6	25.4	21.2
		10	23	48.5	40.0	34.0	27.9	22.7	17.6
		15	28	43.4	37.3	31.5	25.4	20.0	14.3
		20	33	38.6	33.1	27.1	21.7	16.2	11.5
		25	38	33.3	27.3	21.8	16.8	12.3	7.9

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.14b. Pushover Load, F_t, for Unbraced 5-Pile and 6-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	10	0	10	70.7	64.4	60.5	58.1	56.1	54.1
		5	15	59.8	54.9	50.7	47.3	44.4	41.9
		10	20	56.6	52.8	47.6	43.7	39.5	36.2
		15	25	55.9	51.9	47.1	42.1	37.4	33.0
		20	30	57.8	48.9	44.9	40.4	35.4	30.7
		25	35	52.4	46.5	41.4	36.7	31.6	26.9
	13	0	13	60.4	55.4	51.3	47.9	45.2	42.8
		5	18	58.5	53.1	47.8	43.7	39.6	36.7
		10	23	55.9	51.7	46.6	42.4	37.6	33.7
		15	28	59.3	50.0	46.3	41.9	37.0	32.1
		20	33	53.9	47.4	42.7	38.3	33.3	28.4
		25	38	47.7	42.6	38.3	33.3	28.7	24.7
6	10	0	10	77.6	71.0	68.7	66.2	63.9	61.8
		5	15	66.6	59.9	55.9	52.4	49.4	46.6
		10	20	60.2	55.9	51.0	46.2	42.1	38.4
		15	25	62.0	56.0	49.2	43.5	37.9	32.9
		20	30	63.1	53.8	47.9	40.5	35.5	30.0
		25	35	58.4	50.7	45.3	39.1	33.0	27.6
	13	0	13	66.6	60.7	55.9	52.5	49.9	47.1
		5	18	59.9	55.6	50.7	45.8	42.3	39.0
		10	23	61.7	55.4	48.9	43.8	38.6	33.9
		15	28	65.7	55.3	49.0	41.3	36.4	31.0
		20	33	59.2	51.5	46.2	40.1	34.1	28.8
		25	38	55.4	48.3	42.7	36.4	30.2	24.9

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.15a. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Symmetric Distribution of Varying Values of P-Load and 'H+S' for Variable Scour Distribution

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	13	0	13	46.7	44.5	42.5	41.5	39.7	38.3
		5	18	24.7	22.7	20.6	18.7	16.8	15.0
		10	23	15.4	13.0	11.0	9.8	8.6	7.3
		15	28	9.9	8.3	7.1	5.7	4.5	3.4
		20	33	7.1	5.8	4.4	3.2	unstable	unstable
		25	38	5.3	3.9	2.5	unstable	unstable	unstable
	17	0	17	44.9	42.9	41.2	39.9	38.3	36.8
		5	22	23.1	20.8	18.6	16.5	14.6	13.1
		10	27	13.9	11.6	10.1	8.7	7.2	5.8
		15	32	9.2	7.7	6.2	4.7	3.3	unstable
		20	37	6.7	5.1	3.6	2.1	unstable	unstable
		25	42	4.9	3.2	unstable	unstable	unstable	unstable
4	13	0	13	62.8	58.6	55.1	51.2	48.2	45.3
		5	18	40.7	37.0	33.7	30.6	27.5	24.7
		10	23	32.1	28.1	24.5	21.1	18.1	15.2
		15	28	27.6	23.3	19.4	16.0	13.0	10.3
		20	33	24.9	20.4	16.3	12.9	9.9	7.5
		25	38	22.0	17.8	14.1	10.7	7.9	5.5
	17	0	17	58.4	53.7	49.8	45.5	42.6	40.2
		5	22	38.5	34.7	31.3	28.2	25.1	22.3
		10	27	29.0	24.8	20.9	17.4	14.1	11.5
		15	32	25.1	20.1	16.1	12.6	9.7	7.4
		20	37	21.8	17.1	13.1	9.7	7.1	4.8
		25	42	19.2	14.8	11.0	7.8	5.2	2.9

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.15b. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and for Variable Scour and 'H+S' Distributions.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
3	13	0	13	67.7	65.9	64.0	64.8	63.1	61.4
		5	18	40.9	38.9	36.8	34.9	32.9	30.8
		10	23	27.4	25.2	23.0	20.9	18.9	17.2
		15	28	19.7	17.3	15.0	13.3	12.2	11.1
		20	33	14.6	12.2	10.8	9.6	8.5	7.2
		25	38	10.9	9.4	8.2	7.0	5.7	4.5
	17	0	17	66.8	64.9	62.9	61.3	59.2	57.2
		5	22	38.6	36.1	34.1	32.1	30.2	28.2
		10	27	26.1	23.6	21.1	18.8	17.0	15.7
		15	32	18.6	15.8	13.8	12.6	11.3	10.0
		20	37	13.4	11.5	10.2	8.9	7.5	6.2
		25	42	10.5	9.0	7.6	6.2	4.8	3.5
4	13	0	13	91.9	88.3	84.5	80.0	76.7	73.7
		5	18	60.7	57.5	54.1	50.9	47.8	44.8
		10	23	49.0	45.4	41.8	38.3	35.0	31.7
		15	28	42.4	38.2	34.2	30.6	27.1	24.0
		20	33	38.6	34.0	29.9	25.9	22.4	19.2
		25	38	35.4	31.3	26.8	22.8	19.1	16.0
	17	0	17	85.1	82.3	79.4	76.3	72.7	69.0
		5	22	57.3	53.5	49.5	45.9	42.5	39.3
		10	27	45.9	42.1	38.0	34.4	30.8	27.3
		15	32	39.6	35.4	30.9	26.9	23.2	19.9
		20	37	36.0	30.9	26.3	22.1	18.6	15.4
		25	42	32.7	27.5	23.0	19.0	15.6	12.4

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.16a. Pushover Load, F_t, for Single Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	13	0	13	74.8	69.0	64.4	60.2	56.3	52.5
		5	18	49.6	45.0	40.6	36.5	32.6	28.4
		10	23	40.7	35.3	30.4	25.8	21.5	17.4
		15	28	37.6	31.7	26.5	20.7	16.2	12.3
		20	33	35.1	29.4	23.2	17.6	13.2	9.5
		25	38	31.7	26.3	20.6	15.6	11.4	8.0
	17	0	17	69.0	63.0	57.8	53.3	49.3	45.7
		5	22	44.5	39.3	34.7	30.6	26.7	23.0
		10	27	37.2	31.4	26.2	21.2	17.0	13.3
		15	32	34.2	27.8	22.1	16.6	12.6	9.1
		20	37	31.1	25.3	19.3	14.3	10.1	6.9
		25	42	28.0	22.4	17.2	12.6	8.6	5.5
6	13	0	13	82.3	75.6	70.0	65.1	60.5	56.0
		5	18	56.3	50.6	45.2	40.1	35.3	30.4
		10	23	46.7	40.1	34.1	28.6	23.2	18.6
		15	28	43.1	35.3	28.6	22.3	17.1	13.0
		20	33	40.7	32.4	25.2	18.8	13.8	9.9
		25	38	38.0	30.6	23.3	16.9	12.0	8.0
	17	0	17	76.1	68.7	62.6	57.3	52.6	48.5
		5	22	50.7	44.5	39.0	33.8	29.1	24.9
		10	27	42.4	35.5	29.3	23.5	18.5	14.5
		15	32	39.2	31.3	24.4	18.2	13.5	9.5
		20	37	37.8	29.2	21.7	15.4	10.7	6.8
		25	42	35.3	26.9	19.5	13.7	9.1	5.3

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.16b. Pushover Load, F_t, for Single Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k	P=160^k
5	13	0	13	107.2	102.1	97.1	92.3	88.2	84.4
		5	18	74.4	69.0	64.5	60.5	56.5	52.5
		10	23	60.8	55.4	50.7	46.3	41.8	37.6
		15	28	54.4	48.8	43.5	38.3	33.4	28.9
		20	33	51.3	45.9	40.2	34.6	28.9	23.8
		25	38	49.6	42.6	37.5	31.3	25.5	20.8
	17	0	17	99.0	95.2	91.1	84.8	80.1	76.0
		5	22	69.7	69.2	59.4	54.7	50.4	46.2
		10	27	56.6	51.1	45.9	41.1	36.4	31.9
		15	32	50.4	44.6	39.1	33.8	28.6	23.9
		20	37	47.6	41.8	35.6	30.0	24.5	19.7
		25	42	44.9	38.9	33.1	27.1	21.7	17.2
6	13	0	13	118.8	111.7	105.5	99.9	95.0	90.6
		5	18	84.1	77.6	72.5	67.7	62.9	58.3
		10	23	69.7	63.0	57.2	51.7	46.3	41.2
		15	28	62.8	55.6	48.9	42.5	36.6	31.0
		20	33	60.1	52.3	44.1	37.5	31.0	25.4
		25	38	57.8	49.2	41.0	34.0	27.3	21.8
	17	0	17	108.4	103.0	96.6	90.7	85.5	80.8
		5	22	79.1	72.4	66.6	61.3	56.1	51.2
		10	27	64.6	57.8	51.6	45.8	40.3	35.0
		15	32	58.4	51.2	44.2	37.7	31.7	26.3
		20	37	56.0	47.7	40.0	33.2	26.8	21.4
		25	42	52.9	45.9	37.4	30.6	23.7	18.4

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

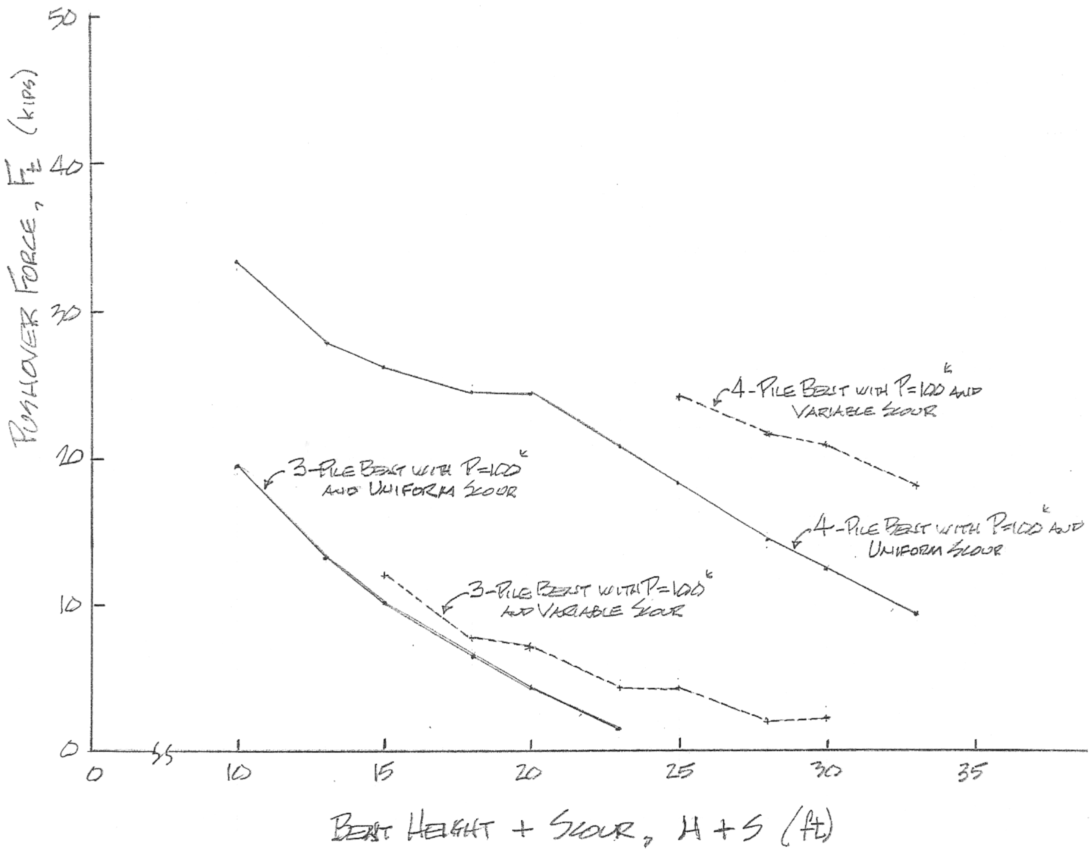


Fig. 2.33. Pushover Load vs. Bent Height Plus Scour for Unbraced 3-Pile and 4-Pile Bents (HP_{10x42} Piles) with Uniform and Variable Scour

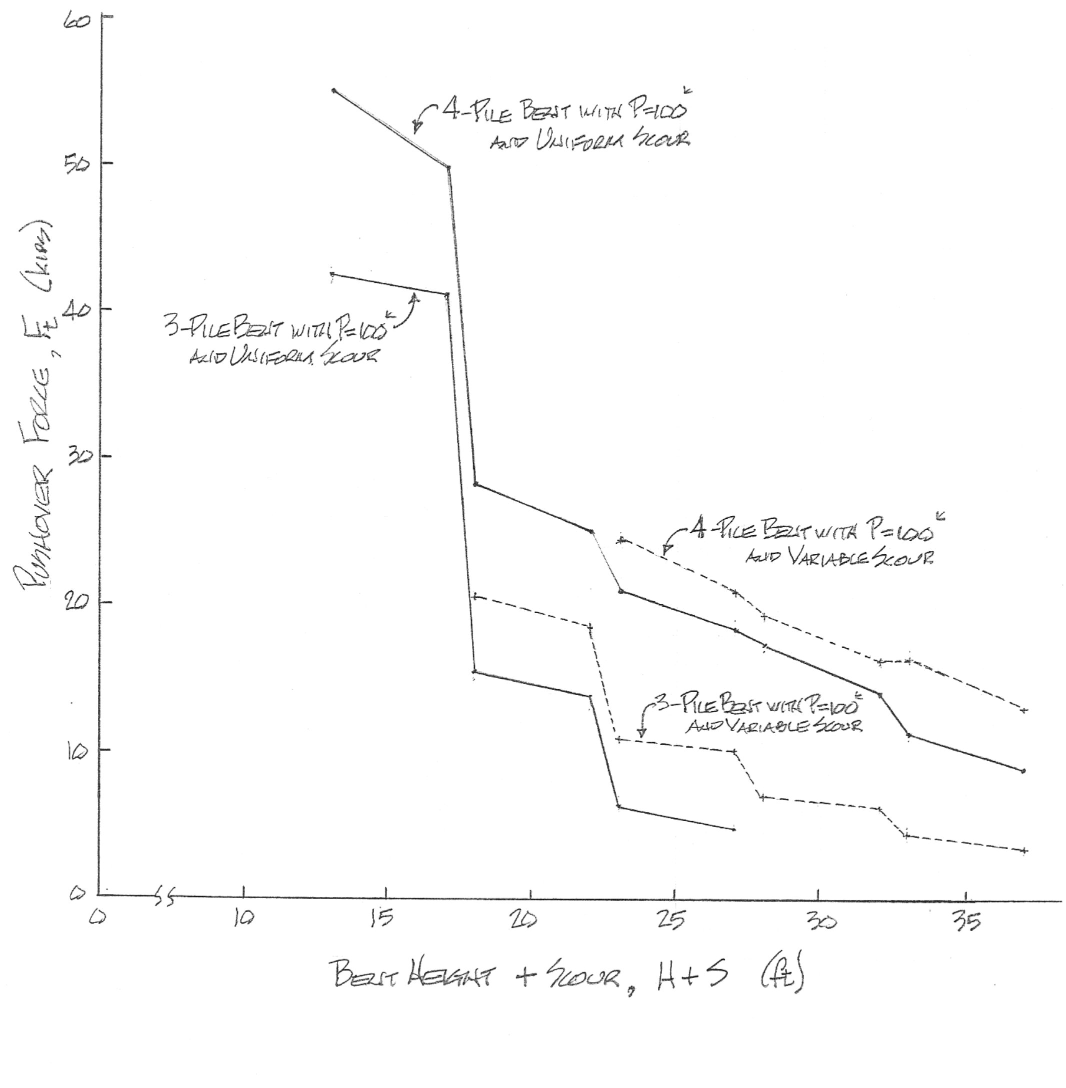


Fig. 2.34. Pushover Load vs. Bent Height Plus Scour for X-Braced 3-Pile and 4-Pile Bents (HP_{10x42} Piles) with Uniform and Variable Scour

Table 2.17a. Pushover Load, F_t, for 2-Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loadings and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	51.3	48.9	46.7	44.7	43.2	41.3
		5	26	26.7	24.4	22.1	19.9	17.7	15.9
		10	31	16.3	13.6	11.7	10.3	8.8	7.3
		15	36	10.4	8.7	7.3	5.7	4.4	3.0
		20	41	7.4	5.9	4.3	2.9	unstable	unstable
		25	46	5.5	3.8	2.3	unstable	unstable	unstable
	25	0	25	49.1	46.9	45.0	43.2	41.3	39.1
		5	30	24.6	22.0	19.6	17.1	15.3	13.5
		10	35	14.4	12.1	10.5	8.8	7.1	5.5
		15	40	9.6	7.9	6.1	4.5	2.9	unstable
		20	45	6.8	5.0	3.3	unstable	unstable	unstable
		25	50	4.9	3.0	unstable	unstable	unstable	unstable
4	21	0	21	63.3	58.9	55.1	51.6	48.5	45.6
		5	26	38.8	35.2	31.7	28.5	25.4	22.5
		10	31	29.1	25.1	21.4	18.0	15.0	12.3
		15	36	24.1	19.3	15.6	12.3	9.6	7.4
		20	41	20.8	15.8	12.1	8.9	6.5	4.4
		25	46	18.0	13.5	9.8	6.8	4.4	2.2
	25	0	25	58.3	53.5	49.7	46.6	44.1	41.7
		5	30	35.1	31.4	27.9	24.6	21.3	18.1
		10	35	26.0	21.8	18.0	14.4	11.5	9.3
		15	40	21.0	16.4	12.6	9.4	7.1	4.9
		20	45	17.7	13.3	9.5	6.7	4.3	2.1
		25	50	15.3	11.1	7.4	4.8	2.3	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.17b. Pushover Load, F_t, for 2-Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loadings and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	76.0	73.8	71.6	69.4	67.1	64.9
		5	26	44.5	41.9	39.5	37.1	35.0	32.7
		10	31	29.3	26.8	24.4	22.1	19.9	18.0
		15	36	20.8	18.1	15.7	14.1	12.8	11.5
		20	41	15.1	12.8	11.3	10.0	8.6	7.2
		25	46	11.4	9.8	8.4	7.0	5.5	4.2
	25	0	25	73.4	71.4	69.3	67.1	64.9	62.6
		5	30	41.2	38.9	36.6	34.4	32.3	29.9
		10	35	27.7	24.8	22.0	19.7	17.9	16.4
		15	40	19.3	16.3	14.5	13.1	11.6	10.1
		20	45	13.9	12.1	10.5	9.0	7.4	5.9
		25	50	10.9	9.2	7.6	6.0	4.4	2.9
4	21	0	21	95.9	92.2	88.0	84.0	80.0	76.2
		5	26	59.6	56.1	52.8	49.3	46.0	42.9
		10	31	46.8	42.9	39.2	35.6	32.2	28.7
		15	36	39.2	35.0	30.7	26.8	23.3	20.0
		20	41	34.9	30.4	25.3	21.3	17.9	14.9
		25	46	32.1	26.5	21.5	17.8	14.5	11.5
	25	0	25	89.6	86.4	83.1	79.7	75.8	71.7
		5	30	55.9	51.7	47.8	44.1	40.6	37.6
		10	35	43.3	39.1	35.4	31.4	27.7	24.2
		15	40	36.1	31.5	27.4	23.2	19.5	16.5
		20	45	31.6	26.7	22.0	18.2	14.7	11.9
		25	50	28.2	23.1	18.6	14.8	11.5	9.1

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.18a. Pushover Load, F_t, for 2-Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	21	0	21	75.8	69.8	64.7	60.2	56.0	52.2
		5	26	48.2	43.3	38.8	34.5	30.5	26.8
		10	31	37.5	32.0	26.9	22.3	18.2	14.8
		15	36	33.0	26.9	21.1	16.1	12.4	9.2
		20	41	30.5	23.9	17.8	13.0	9.2	6.3
		25	46	27.8	21.3	15.5	11.1	7.3	4.5
	25	0	25	69.6	63.5	58.3	53.7	49.7	46.1
		5	30	42.3	37.0	32.4	28.4	24.4	20.6
		10	35	33.2	27.2	22.0	17.5	13.6	10.6
		15	40	28.9	22.4	16.6	12.3	9.0	6.2
		20	45	26.2	19.4	13.8	9.6	6.5	3.7
		25	50	23.6	17.3	12.2	8.1	4.8	unstable
6	21	0	21	84.5	76.6	70.2	64.4	59.0	54.2
		5	26	55.9	49.6	43.9	38.6	33.8	28.8
		10	31	44.2	37.5	31.2	25.5	20.4	16.5
		15	36	39.4	31.8	24.7	18.8	14.3	10.6
		20	41	37.5	28.7	21.5	15.2	10.8	7.0
		25	46	35.4	26.6	19.3	13.1	8.6	4.8
	25	0	25	76.9	69.2	62.6	57.1	52.3	48.1
		5	30	49.2	42.9	37.2	32.2	27.6	23.3
		10	35	39.9	32.8	26.6	20.9	16.5	12.6
		15	40	35.4	27.6	20.6	15.2	10.9	7.3
		20	45	33.2	24.9	17.6	12.1	7.8	4.2
		25	50	31.7	23.0	15.7	10.3	5.9	2.2

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.18b. Pushover Load, F_t, for 2-Story X-Braced 5-Pile and 6-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
5	21	0	21	114.7	108.8	102.9	97.0	91.3	86.0
		5	26	73.6	68.3	63.6	59.0	54.5	50.3
		10	31	59.4	53.8	48.7	43.8	39.2	34.9
		15	36	51.6	45.6	39.8	34.5	29.5	25.0
		20	41	47.9	41.0	35.0	29.1	23.7	19.4
		25	46	44.4	38.1	31.6	25.7	20.1	16.0
	25	0	25	108.9	102.5	96.3	90.3	84.8	78.6
		5	30	68.7	63.0	57.8	53.2	48.6	44.4
		10	35	54.1	47.9	42.7	37.8	33.2	28.8
		15	40	46.6	40.3	34.2	28.7	23.7	19.8
		20	45	43.3	36.1	29.8	23.7	18.9	15.0
		25	50	40.2	33.2	26.6	20.6	16.1	12.1
6	21	0	21	128.8	120.4	112.1	104.5	97.6	90.1
		5	26	85.3	78.3	72.3	66.6	60.9	55.6
		10	31	69.7	62.9	56.5	50.5	44.6	39.2
		15	36	61.1	53.6	46.3	39.6	33.5	28.3
		20	41	58.3	49.2	41.6	34.1	27.5	22.1
		25	46	54.9	46.6	37.8	30.6	23.8	18.4
	25	0	25	114.3	108.2	101.9	94.2	86.3	80.4
		5	30	79.3	72.3	65.9	60.1	54.5	49.4
		10	35	63.7	56.8	50.1	44.0	38.2	32.8
		15	40	56.5	48.7	41.4	34.8	28.5	23.3
		20	45	53.0	44.1	36.4	29.3	23.0	18.2
		25	50	50.3	41.4	33.4	26.0	19.7	15.0

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.19a. Pushover Load, F_t, Double X-Braced 1-Story and 2-Story 6-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Stories & Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
1-Story and 6-Piles	13	0	13	95.7	90.4	85.7	81.2	77.0	73.4
		5	18	58.3	52.9	48.3	43.8	39.6	35.7
		10	23	46.7	39.9	34.4	29.9	25.8	22.0
		15	28	42.9	35.1	28.6	23.6	19.3	15.0
		20	33	40.2	32.3	25.7	20.3	15.5	11.2
		25	38	37.6	30.5	23.9	18.2	13.3	8.9
	17	0	17	89.3	82.5	77.8	73.9	70.5	66.6
		5	22	53.9	47.9	42.8	38.1	33.8	30.5
		10	27	42.9	36.1	30.5	25.6	21.6	18.2
		15	32	38.9	31.4	25.3	20.2	15.8	12.0
		20	37	37.1	29.4	23.1	17.4	12.5	8.5
		25	42	35.3	28.0	21.3	15.6	10.6	6.6
2-Story and 6-Piles	21	0	21	98.1	92.7	88.0	83.4	79.1	75.6
		5	26	58.6	53.4	48.7	44.2	40.0	36.1
		10	31	45.8	39.3	33.9	29.5	25.4	21.6
		15	36	41.1	33.6	27.4	22.6	18.2	14.2
		20	41	38.8	31.2	24.5	18.9	14.1	9.9
		25	46	36.7	29.2	22.3	16.6	11.5	7.3
	25	0	25	91.4	85.0	80.7	76.8	73.2	69.2
		5	30	54.2	48.3	43.2	38.5	34.6	31.2
		10	35	42.1	35.7	30.1	25.4	21.6	18.1
		15	40	37.7	30.2	24.4	19.3	15.1	11.4
		20	45	35.6	28.1	21.7	16.1	11.5	7.5
		25	50	33.9	26.7	20.0	14.2	9.2	5.2

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

Table 2.19b. Pushover Load, F_t, Double X-Braced 1-Story and 2-Story 6-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Variable Scour and 'H+S' Distributions

No. Stories & Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
1-Story and 6-Piles	13	0	13	143.5	137.5	132.3	127.5	123.5	119.7
		5	18	89.1	83.6	78.9	74.6	70.2	66.1
		10	23	69.9	63.3	57.8	52.9	48.5	44.3
		15	28	62.3	54.9	48.1	42.1	37.5	33.4
		20	33	59.6	51.5	43.8	37.3	32.0	27.3
		25	38	56.6	48.6	40.9	34.4	28.6	23.8
	17	0	17	139.3	134.0	128.4	123.3	118.5	113.6
		5	22	84.4	78.1	72.4	67.3	63.0	58.8
		10	27	66.0	58.7	53.1	48.0	43.3	39.0
		15	32	59.0	50.9	44.0	38.4	33.8	29.5
		20	37	55.3	47.0	40.0	33.7	28.8	24.2
		25	42	52.4	44.7	37.7	31.4	25.9	20.9
2-Story and 6-Piles	21	0	21	149.3	143.0	137.0	131.5	126.3	121.9
		5	26	90.0	84.9	80.3	75.9	71.4	67.3
		10	31	70.6	64.2	58.9	54.0	49.4	45.1
		15	36	61.7	54.3	47.7	42.4	37.9	33.7
		20	41	59.2	49.9	42.9	36.5	31.5	27.1
		25	46	56.0	47.5	40.0	33.5	27.9	23.3
	25	0	25	143.8	138.4	133.0	127.4	122.1	117.3
		5	30	86.3	79.9	74.5	69.6	65.2	60.8
		10	35	66.3	59.7	54.2	49.1	44.2	39.7
		15	40	58.4	50.6	44.2	38.9	34.1	29.7
		20	45	54.6	46.3	39.3	33.7	28.7	23.9
		25	50	52.2	43.9	36.7	30.6	25.3	20.4

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

2.9 Pushover Loads for Unsymmetric P-load and Variable Scour Distributions

Earlier pushover analyses indicated somewhat smaller bent pushover force for bents loaded unsymmetrically with LL, i.e., the case for which only the upstream lane of the bridge contained a traffic load. Also, earlier analyses indicated an increased bent capacity/pushover load when subjected to a variable scour distribution (rather than to a uniform scour at a level of S_{max}). Thus, it was of interest to determine which of these opposite effects (nonuniform P-load and nonuniform scour) would have the larger effect on a bent's pushover capacity. Pushover analyses of 3-pile and 4-pile bents were performed for a combination of these conditions for a range of P-loads including 60^k, 80^k, 100^k, 120^k, and 140^k.

The results of these analyses are presented in Tables 2.20a and b for unbraced bents with HP_{10x42} and HP_{12x53} piles, respectively, and in Tables 2.21a and b for braced bents with HP_{10x42} and HP_{12x53} piles, respectively. These tables indicate that for HP_{12x53} pile bents, all of the 4-pile bents are adequate for pushover, and almost all of the 3-pile bents are adequate as well. This is not the case for the HP_{10x42} pile bents. For these bents, almost all of the 4-pile bents are adequate, but most of the 3-pile bents are not adequate for pushover. A subset of the pushover loads of Tables 2.20a and 2.21a (for HP_{10x42} 3-pile bents) are shown in Fig. 2.35 for convenience in comparing the effects of nonuniform P-load and scour distributions versus uniform P-load and scour distributions on bent pushover loads. As can be seen in that figure, for unbraced bents, the effect is minimal; however, for X-braced bents, the nonuniform P-load and scour distributions yield significantly higher bent pushover capacities.

Results of pushover analyses for 2-story X-braced 3- and 4-pile bents with HP_{10x42} and HP_{12x53} piles for unsymmetric P-loads and variable scour distributions are presented in Tables 2.22a and b respectively. By comparing the pushover loads in Tables 2.22a and b with their "sister" pushover loads for symmetric P-loads and uniform scour in Tables 2.7 and 2.8 respectively, one can see significantly larger pushover capacities for the nonuniform P-load and scour situation. Thus, if one assumes uniform distributions of P-loads and scour, the analyses results will be conservative.

Table 2.20a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	10	0	10	NN	NN	NN	NN	NN
		5	15	12.8	10.7	8.7	6.7	4.6
		10	20	8.4	6.2	4.0	unstable	unstable
		15	25	5.5	3.0	unstable	unstable	unstable
		20	30	3.3	unstable	unstable	unstable	unstable
	13	0	13	13.5	11.6	9.8	7.8	5.7
		5	18	9.1	6.9	4.7	2.4	unstable
		10	23	5.9	3.4	unstable	unstable	unstable
		15	28	3.6	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable
4	10	0	10	NN	NN	NN	NN	NN
		5	15	NN	NN	NN	NN	NN
		10	20	NN	NN	NN	NN	NN
		15	25	29.5	25.4	21.6	18.4	14.5
		20	30	26.5	22.5	18.4	15.2	11.5
	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	29.3	25.3	22.1	18.6	14.7
		15	28	26.9	23.1	18.8	15.6	11.9
		20	33	23.2	19.3	15.9	12.2	8.6

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NN = Not needed, bent is adequate for uniform scour

Table 2.20b. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	10	0	10	NN	NN	NN	NN	NN
		5	15	NN	NN	NN	NN	NN
		10	20	16.6	14.4	12.3	10.3	8.3
		15	25	12.6	10.3	8.1	5.9	3.7
		20	30	9.7	7.3	5.0	2.7	unstable
	13	0	13	NN	NN	NN	NN	NN
		5	18	17.4	15.3	13.3	11.3	9.2
		10	23	13.2	10.8	8.7	6.5	4.2
		15	28	10.0	7.6	5.3	2.9	unstable
		20	33	7.7	5.2	2.7	unstable	unstable
4	10	0	10	NN	NN	NN	NN	NN
		5	15	NN	NN	NN	NN	NN
		10	20	NN	NN	NN	NN	NN
		15	25	NN	NN	NN	NN	NN
		20	30	NN	NN	NN	NN	NN
	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	NN	NN	NN	NN	NN
		15	28	NN	NN	NN	NN	NN
		20	33	NN	NN	NN	NN	NN

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NN = Not needed, bent is adequate for uniform scour

Table 2.21a. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	13	0	13	NN	NN	NN	NN	NN
		5	18	23.2	20.5	18.0	15.4	13.0
		10	23	14.1	11.2	8.4	6.0	4.1
		15	28	8.6	5.8	3.9	2.0	unstable
		20	33	5.3	3.3	unstable	unstable	unstable
	17	0	17	NN	NN	NN	NN	NN
		5	22	21.6	18.8	16.1	13.4	10.7
		10	27	12.8	9.6	7.1	5.1	3.1
		15	32	7.5	5.2	3.3	unstable	unstable
		20	37	4.9	2.8	unstable	unstable	unstable
4	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	31.4	27.3	23.4	19.5	15.8
		15	28	27.3	23.0	18.6	14.5	10.9
		20	33	25.0	20.3	15.7	11.5	7.7
	17	0	17	NN	NN	NN	NN	NN
		5	22	NN	NN	NN	NN	NN
		10	27	28.7	24.4	20.1	16.2	12.3
		15	32	24.9	20.2	15.7	11.4	7.5
		20	37	21.8	17.3	12.5	8.3	4.5

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NN = Not needed, bent is adequate for uniform scour

Table 2.21b. Pushover Load, F_t, for Single Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$
3	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	26.0	23.2	20.6	17.9	15.2
		15	28	18.4	15.4	12.7	9.9	7.7
		20	33	13.4	10.3	7.8	5.7	3.9
	17	0	17	NN	NN	NN	NN	NN
		5	22	NN	NN	NN	NN	NN
		10	27	24.9	21.8	18.9	16.0	13.2
		15	32	17.6	14.2	11.1	8.8	6.9
		20	37	12.4	9.3	7.2	5.2	3.2
4	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	NN	NN	NN	NN	NN
		15	28	NN	NN	NN	NN	NN
		20	33	NN	NN	NN	NN	NN
	17	0	17	NN	NN	NN	NN	NN
		5	22	NN	NN	NN	NN	NN
		10	27	NN	NN	NN	NN	NN
		15	32	NN	NN	NN	NN	NN
		20	37	NN	NN	NN	NN	NN

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NN = Not needed, bent is adequate for uniform scour

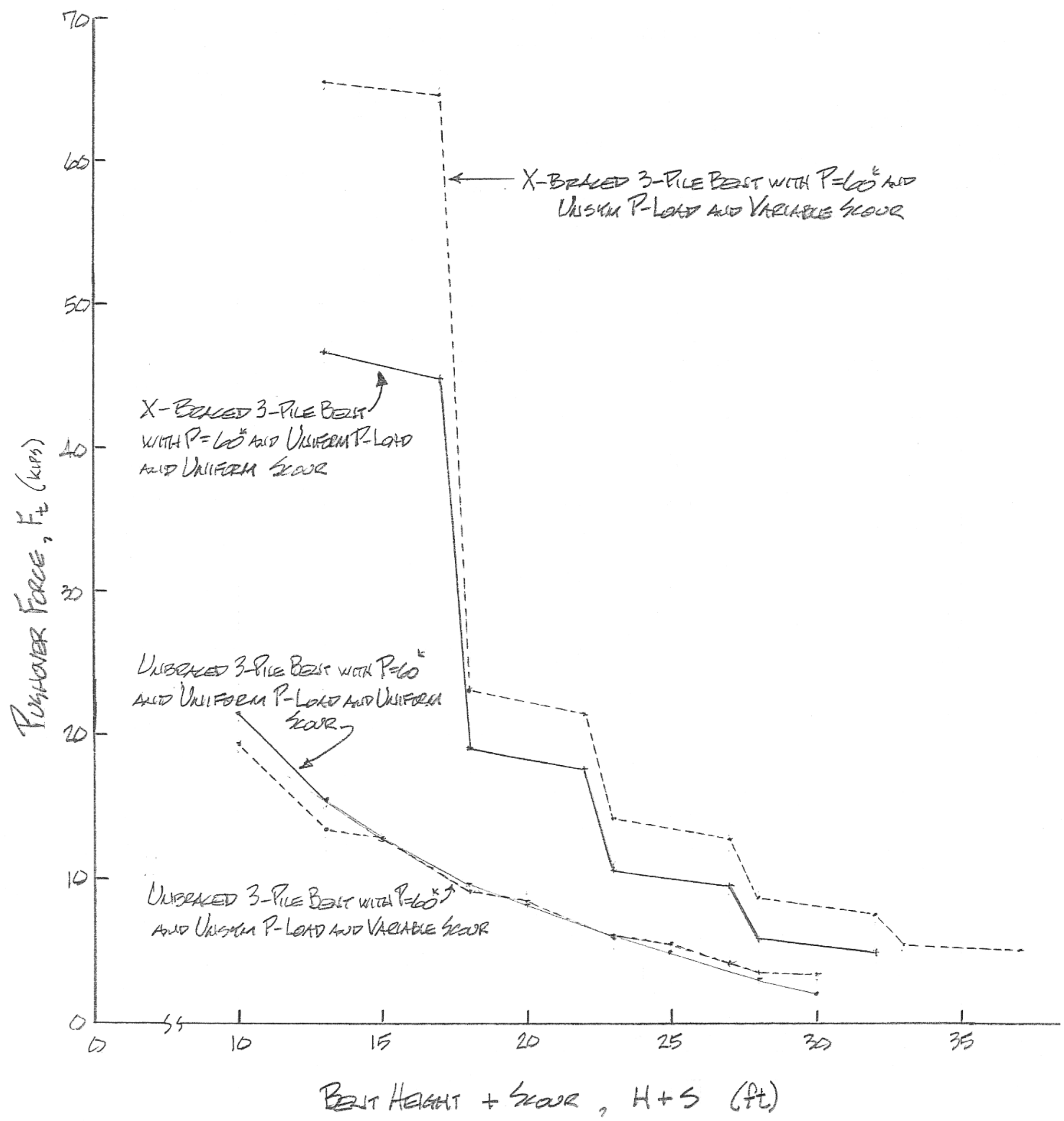


Fig. 2.35. Pushover Load vs. Bent Height Plus Scour for Unbraced and X-Braced 3-Pile Bents (HP_{10x42} Piles) with Uniform P-Load and Scour and with Unsym. P-Load and Variable Scour

Table 2.22a. Pushover Load, F_t, for 2- Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{10X42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	NA	NA	NA	NA	NA	NA
		5	26	25.2	22.4	19.6	16.8	14.1	11.4
		10	31	15.1	11.9	9.0	6.6	4.6	2.6
		15	36	9.0	6.3	4.3	2.2	unstable	unstable
		20	41	5.7	3.5	unstable	unstable	unstable	unstable
	25	0	25	NA	NA	NA	NA	NA	NA
		5	30	23.3	20.2	17.2	14.3	11.4	9.0
		10	35	13.4	10.1	7.7	5.4	3.2	unstable
		15	40	8.0	5.6	3.4	unstable	unstable	unstable
		20	45	5.2	2.8	unstable	unstable	unstable	unstable
4	21	0	21	NA	NA	NA	NA	NA	NA
		5	26	38.0	34.0	30.2	26.5	23.0	19.5
		10	31	28.6	24.4	20.4	16.4	12.7	9.2
		15	36	24.1	19.2	14.6	10.5	7.0	3.6
		20	41	21.1	15.8	11.0	7.2	3.5	unstable
	25	0	25	NA	NA	NA	NA	NA	NA
		5	30	34.6	30.3	26.3	22.6	19.1	15.6
		10	35	25.8	21.3	17.0	13.1	9.2	5.6
		15	40	21.3	16.2	11.7	7.7	3.9	unstable
		20	45	18.1	12.9	8.5	4.4	unstable	unstable

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NA = Not applicable, no scour present

Table 2.22b. Pushover Load, F_t, for 2- Story X-Braced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and for Variable Scour and 'H+S' Distributions

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	21	0	21	NA	NA	NA	NA	NA	NA
		5	26	43.2	40.3	37.3	34.5	31.7	28.8
		10	31	28.1	25.0	22.1	19.2	16.4	13.7
		15	36	19.7	16.4	13.4	10.6	8.4	6.5
		20	41	14.0	10.7	8.3	6.2	4.3	2.4
	25	0	25	NA	NA	NA	NA	NA	NA
		5	30	40.0	36.9	34.2	31.4	28.6	26.1
		10	35	26.6	23.3	20.0	16.8	14.0	11.7
		15	40	18.4	14.7	11.8	9.5	7.4	5.4
		20	45	12.8	9.8	7.6	5.5	3.4	unstable
4	21	0	21	NA	NA	NA	NA	NA	NA
		5	26	58.6	54.6	51.0	47.3	43.6	40.0
		10	31	46.1	42.0	38.0	34.1	30.4	26.7
		15	36	39.1	34.5	30.1	25.9	21.9	18.1
		20	41	34.9	30.1	25.4	20.7	16.4	12.6
	25	0	25	NA	NA	NA	NA	NA	NA
		5	30	55.4	50.8	46.6	42.5	38.6	34.8
		10	35	43.1	38.7	34.3	30.2	26.3	22.5
		15	40	36.2	31.4	26.9	22.4	18.2	14.3
		20	45	32.0	26.9	22.0	17.1	13.0	9.3

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

NA = Not applicable, no scour present

2.10 Bent Pushover Failure in Terms of Critical Scour Level

As with the original screening tool (ST), the use of linear interpolation of F_t values between values of F_t determined by GTSTRUDL analysis for bent height values after scour, i.e., (H+S) values, which are 5 ft apart, are quite accurate. Thus, we again performed linear interpolation on the $F_t^{capacity}$ vs. S (or H+S) data in Tables 2.3 - 2.9 to generate tables of critical uniform scour, S_{CR}, for different levels of P-loads. These tables can in turn be used to determine S_{CR} for a given bent geometry and level of P-load. As with the original ST, Tables 2.3 - 2.9 were used to interpolate values of S_{CR} corresponding to $F_t^{failure} = 12.15^k$ for each bent geometry configuration, height, and level of P-load. These values of S_{CR} are presented in Tables 2.23 - 2.24, and include a FS = 1.25 on the pushover load, $F_t^{capacity}$. If the resulting $S_{CR} > S_{max\ applied}$ at the site, then the bent is safe from pushover failure.

The above procedure was repeated for bents with nonuniform scour using the data in Tables 2.13 - 2.19. The resulting values of S_{cr} for nonuniform scour are presented in Tables 2.25 - 2.26, and again these values include a FS = 1.25 on the pushover load, $F_t^{capacity}$.

Table 2.23a. Critical Uniform Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	Bent Height (ft)	Critical Uniform Scour, S_{CR} (ft)[1,2]					
		P = 60^k	P = 80^k	P = 100^k	P = 120^k	P = 140^k	P = 160^k
3	10	5.9	4.6	3.9	3.5	2.9	2.3
	13	3.0	1.8	0.8	0.2	0	0
4	10	>25.0	23.4	20.0	17.3	14.6	12.2
	13	23.8	20.2	17.3	14.2	11.7	8.8
5	10	>25.0	>25.0	>25.0	22.8	19.3	16.4
	13	>25.0	>25.0	23.4	19.7	16.4	13.3
6	10	>25.0	>25.0	>25.0	23.1	18.9	14.9
	13	>25.0	>25.0	24.4	19.9	15.8	12.1

[1] Includes a FS=1.25 on the Pushover Force, F_t.
[2] If $S_{max\,applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

Table 2.23b. Critical Uniform Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	Bent Height (ft)	Critical Uniform Scour, S_{CR} (ft)[5,6]					
		P = 60^k	P = 80^k	P = 100^k	P = 120^k	P = 140^k	P = 160^k
3	10	14.2	12.2	10.4	9.4	8.4	7.4
	13	11.1	9.1	7.5	6.4	5.2	4.4
4	10	>25.0	>25.0	>25.0	>25.0	>25.0	23.6
	13	>25.0	>25.0	>25.0	>25.0	23.5	20.6
5	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
6	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0

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

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

Table 2.24a. Critical Uniform Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\,max\,design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	X-Bracing Configuration	No. Stories in Bent	Bent Height (ft)	Critical Uniform Scour, S_{CR} (ft)[3,4]					
				P = 60^k	P = 80^k	P = 100^k	P = 120^k	P = 140^k	P = 160^k
3	Single-X per Story	1-Story	13	9.1	7.9	6.8	6.1	5.3	4.8
			17	8.4	7.1	6.0	5.2	4.7	4.4
		2-Story	21	8.9	8.1	7.3	6.4	5.5	4.9
			25	7.5	6.9	6.4	5.3	4.8	4.4
4	Single-X per Story	1-Story	13	>25.0	23.0	19.3	15.9	12.0	9.3
			17	24.0	20.3	16.9	12.3	9.0	7.1
		2-Story	21	24.2	19.8	14.9	10.9	8.7	7.2
			25	22.6	17.0	11.8	8.7	6.9	5.3
5	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	22.8	18.6	14.2
			17	>25.0	>25.0	24.1	19.8	15.4	9.5
		2-Story	21	>25.0	>25.0	23.6	18.4	12.7	9.1
			25	>25.0	>25.0	20.9	14.9	9.3	6.9
6	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	23.7	18.5	12.1
			17	>25.0	>25.0	>25.0	21.2	14.6	8.8
		2-Story	21	>25.0	>25.0	>25.0	19.7	12.6	9.0
			25	>25.0	>25.0	23.4	15.7	9.4	7.0
6	Double-X per Story	1-Story	13	>25.0	>25.0	>25.0	24.0	19.1	13.9
			17	>25.0	>25.0	>25.0	22.1	16.7	10.1
		2-Story	21	>25.0	>25.0	>25.0	22.7	16.9	11.5
			25	>25.0	>25.0	>25.0	20.3	14.0	9.3

[3] Includes a FS=1.25 on the Pushover Force, F_t.
[4] If $S_{max\,applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

Table 2.24b. Critical Uniform Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\ max\ design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	X-Bracing Configuration	No. Stories in Bent	Bent Height (ft)	Critical Uniform Scour, S_{CR} (ft)[7,8]					
				$P = 60^k$	$P = 80^k$	$P = 100^k$	$P = 120^k$	$P = 140^k$	$P = 160^k$
3	Single-X per Story	1-Story	13	16.7	14.3	12.8	11.7	10.4	9.6
			17	15.7	13.5	11.8	10.6	9.6	8.8
		2-Story	21	15.5	14.3	13.2	11.8	10.5	9.6
			25	14.3	13.2	12.2	10.7	9.6	8.8
4	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	24.9	22.0
			17	>25.0	>25.0	>25.0	>25.0	22.2	18.6
		2-Story	21	>25.0	>25.0	>25.0	24.5	20.4	16.6
			25	>25.0	>25.0	>25.0	21.7	17.1	13.7
5	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	21.1
6	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	22.0
6	Double-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0

[7] Includes a FS=1.25 on the Pushover Force, F_t.
[8] If $S_{max\ applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

Table 2.25a. Critical Nonuniform Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	Bent Height (ft)	Critical Nonuniform Scour, S_{CR} (ft)[1,2]					
		$P = 60^k$	$P = 80^k$	$P = 100^k$	$P = 120^k$	$P = 140^k$	$P = 160^k$
3	10	7.9	6.3	4.9	4.2	3.5	2.8
	13	3.8	2.3	1.0	0	0	0
4	10	>25.0	>25.0	>25.0	>25.0	>25.0	18.8
	13	>25.0	>25.0	>25.0	>25.0	24.0	19.6
5	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	24.3	19.9
6	10	>25.0	>25.0	>25.0	>25.0	>25.0	23.7
	13	>25.0	>25.0	>25.0	>25.0	>25.0	18.8

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

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

Table 2.25b. Critical Nonuniform Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents without X-Bracing to Resist $F_{t\,max\,design} = 12.15^k$ (includes a FS = 1.25)

No. Piles in Bent	Bent Height (ft)	Critical Nonuniform Scour, S_{CR} (ft)[5,6]					
		$P = 60^k$	$P = 80^k$	$P = 100^k$	$P = 120^k$	$P = 140^k$	$P = 160^k$
3	10	18.9	16.0	14.0	12.4	10.9	9.7
	13	14.6	12.0	9.7	8.2	6.8	5.5
4	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
5	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
6	10	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0

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

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

Table 2.26a. Critical Nonuniform Scour, S_{CR}, of HP_{10x42} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\,max\,design}$ = 12.15^k (includes a FS = 1.25)

No. Piles in Bent	X-Bracing Configuration	No. Stories in Bent	Bent Height (ft)	Critical Nonuniform Scour, S_{CR} (ft)[3,4]					
				P = 60^k	P = 80^k	P = 100^k	P = 120^k	P = 140^k	P = 160^k
3	Single-X per Story	1-Story	13	13.0	10.9	9.4	8.7	7.8	6.9
			17	11.9	9.7	8.8	7.8	6.7	5.7
		2-Story	21	13.5	11.5	9.8	9.0	8.1	7.2
			25	12.3	10.0	9.1	8.0	6.9	5.8
4	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	21.7	16.4	13.1
			17	>25.0	>25.0	22.3	15.8	12.2	9.7
		2-Story	21	>25.0	>25.0	19.9	15.2	12.6	10.2
			25	>25.0	22.6	15.7	12.3	9.7	8.4
5	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	22.9	15.3
			17	>25.0	>25.0	>25.0	>25.0	15.9	11.4
		2-Story	21	>25.0	>25.0	>25.0	22.2	15.4	12.4
			25	>25.0	>25.0	>25.0	15.3	11.6	9.2
6	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	24.6	16.4
			17	>25.0	>25.0	>25.0	>25.0	17.4	12.4
		2-Story	21	>25.0	>25.0	>25.0	>25.0	18.1	13.7
			25	>25.0	>25.0	>25.0	19.9	13.9	10.4
6	Double-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	18.9
			17	>25.0	>25.0	>25.0	>25.0	20.9	14.9
		2-Story	21	>25.0	>25.0	>25.0	>25.0	23.8	17.4
			25	>25.0	>25.0	>25.0	>25.0	19.1	14.4

[3] Includes a FS=1.25 on the Pushover Force, F_t.
[4] If $S_{max\,applied}$ < S_{CR} at the site, the bent is safe from pushover failure.

Table 2.26b. Critical Nonuniform Scour, S_{CR}, of HP_{12x53} 3, 4, 5, 6-Pile Bents with X-Bracing to Resist $F_{t\,max\,design}$ = 12.15^k (includes a FS = 1.25)

No. Piles in Bent	X-Bracing Configuration	No. Stories in Bent	Bent Height (ft)	Critical Nonuniform Scour, S_{CR} (ft)[7,8]					
				P = 60^k	P = 80^k	P = 100^k	P = 120^k	P = 140^k	P = 160^k
3	Single-X per Story	1-Story	13	23.3	20.1	18.4	16.6	15.1	14.1
			17	22.2	19.2	17.3	15.6	14.3	13.1
		2-Story	21	24.0	21.0	19.0	17.4	15.8	14.5
			25	22.9	19.9	17.9	16.2	14.6	13.4
4	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	24.0
			25	>25.0	>25.0	>25.0	>25.0	24.0	19.7
5	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	24.9
6	Single-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
6	Double-X per Story	1-Story	13	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			17	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
		2-Story	21	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
			25	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0

[7] Includes a FS=1.25 on the Pushover Force, F_t.
[8] If $S_{max\,applied} < S_{CR}$ at the site, the bent is safe from pushover failure.

2.11 Check Upstream Bent Pile for Beam-Column Failure from Debris Raft Loading

In extreme flood/scour events, a debris raft and flood water loadings, F_t, on this raft may occur at a bridge support bent. The raft and loading may be applied to a pile bent as high as the bottom of the bent cap, and this would be the critical location in checking for bent pushover adequacy. This is where the loading was applied in all of the pushover analyses in the Phase II work. (See the HWL^1 and F_t^1 positions in Fig. 2.36.) However, the F_t loading could also be applied at a lower position on the bent and this would be the critical location in checking the upstream pile for failure as a beam-column. (See HWL^2 and F_t^2 positions in Fig. 2.36.)

Before checking the upstream pile for adequacy as a beam-column, consider it as a vertical beam with pinned-ends, as shown in Fig. 2.37. Note in Fig. 2.37 that the debris raft loading, F_t^2, which will henceforth be denoted as F_t, is assumed to be applied 7.5 ft down from the top of the pile and the distance from F_t to the new river bottom varies as shown. depending on the level of scour, S. This height was determined by acknowledging that the tallest unbraced bent is 13 ft. The worst case scenario for maximum applied moment due to F_t was found to be at a height of 7.5 ft from the top of the pile.

Using M_{max} in Fig. 2.37, which occurs at the location of the F_t loading for the maximum scour, i.e., $(H+S)_{max}$ condition, and assuming the pile is an HP_{10x42}, then for a maximum height unbraced bent,

$$\sigma_{max} = \frac{M_{max}}{S} = \frac{57.74^{'k} \times 12^{"/'}}{14.2\ in^3} = 48.8\ ksi\ \ (for\ S{=}25\ ft)$$

$$M_P = Z_y \times \sigma_y = 21.8\ in^3 \times 36\ ksi = 785^{"k} = 65.4^{'k}$$

Thus an HP_{10x42} pile would have significant local yielding at the M_{max} location, but it would be adequate for the beam-only loading. If the pile is an HP_{12x53}, then

$$\sigma_{max} = \frac{57.74^{'k} \times 12^{"/'}}{21.1\ in^3} = 32.8\ ksi\ \ (for\ S{=}25\ ft)$$

$$M_P = Z_y \times \sigma_y = 32.2\ in^3 \times 36\ ksi = 1159^{"k} = 96.6^{'k}$$

the pile would be adequate and would not experience any local yielding.

If a fixed-end condition is assumed for the pile, the resulting M_{max} and σ_{max} for an HP_{10x42} pile would be as shown in Fig. 2.38. For these end conditions, the pile would be adequate but would have some small local yielding at the M_{max} location. Actual end conditions for the bent pile would be somewhere between pinned and fixed, but probably closer to fixed.

For bents with X-bracing, which all taller bents should have, the horizontal strut, or bracing member, will serve to distribute the F_t force to all piles in the bent (see Fig. 2.39). Therefore these bents will be adequate for the lower F_t loading position. If there is no horizontal strut, the diagonal L 4"x3½"x5/16" brace will be sufficiently strong in compression to prevent the upstream pile from failing in bending (see Fig. 2.39).

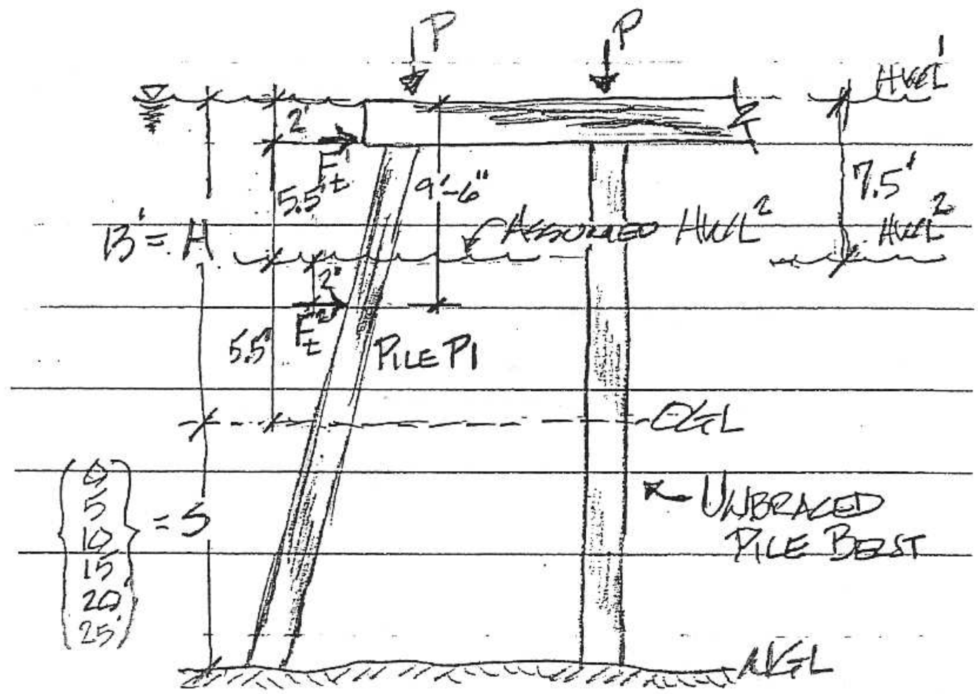


Fig. 2.36. Maximum Height Unbraced Bent Showing Two HWL and F_t Locations

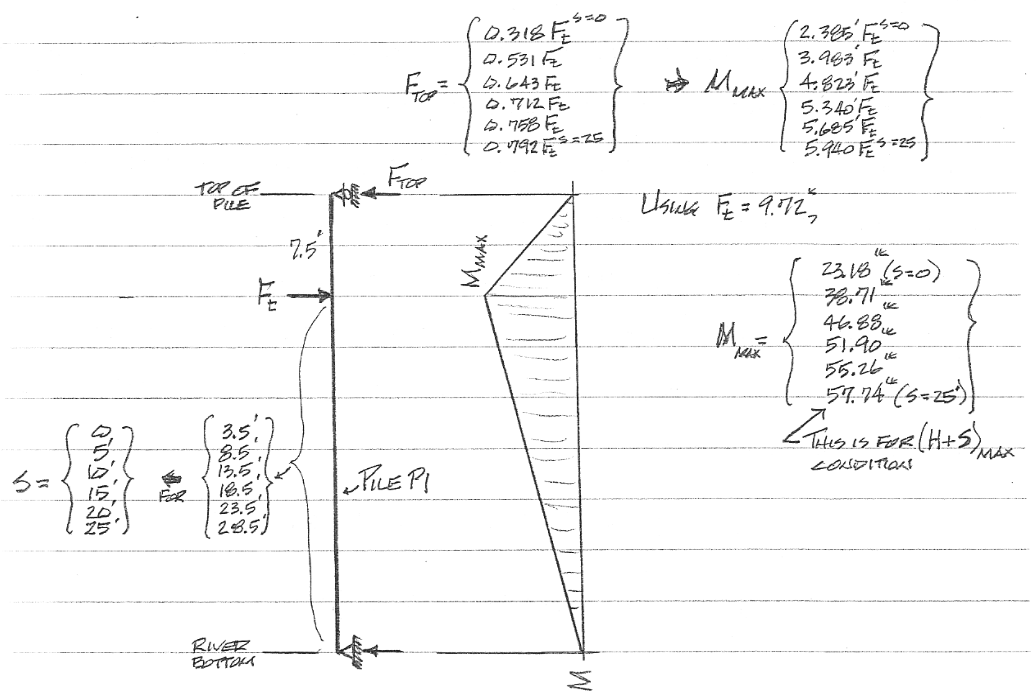
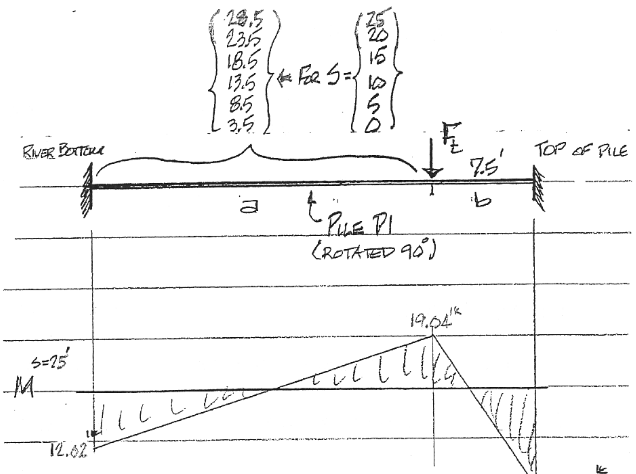


Fig. 2.37. Upstream Pile, P1, M_{max} Values for Pinned-End Condition



For $F_t = 9.72^k$

$$M_{top}^{S=0} = \frac{Pa^2b}{l^2} = F_t\left(\frac{3.5^2 \times 7.5}{11^2}\right) = 0.759 F_t \qquad M_{Top}^{S=0} = 7.38^{1k} \qquad M_{bottom}^{S=0} = F_t\left(\frac{3.5 \times 7.5^2}{11^2}\right) = 15.8^{1k}$$

$$M_{top}^{S=5} = F_t\left(\frac{8.5^2 \times 7.5}{16^2}\right) = 2.117 F_t \qquad M_{Top}^{S=5} = 20.58^{1k}$$

$$M_{top}^{S=10} = F_t\left(\frac{13.5^2 \times 7.5}{21^2}\right) = 3.100 F_t \qquad M_{Top}^{S=10} = 30.13^{1k}$$

$$M_{top}^{S=15} = F_t\left(\frac{18.5^2 \times 7.5}{26^2}\right) = 3.797 F_t \qquad M_{Top}^{S=15} = 36.91^{1k}$$

$$M_{top}^{S=20} = F_t\left(\frac{23.5^2 \times 7.5}{31^2}\right) = 4.310 F_t \qquad M_{Top}^{S=20} = 41.89^{1k}$$

$$M_{top}^{S=25} = F_t\left(\frac{28.5^2 \times 7.5}{36^2}\right) = 4.700 F_t \qquad M_{Top}^{S=25} = 45.69^{1k}$$

$$M_{bottom}^{S=25} = F_t\left(\frac{28.5 \times 7.5^2}{36^2}\right) = 1.237 F_t \qquad M_{bottom}^{S=25'} = 12.02^{1k}$$

$$M_{F_t\text{-}Load}^{S=25} = F_t\left(\frac{2 \times 28.5^2 \times 7.5^2}{36^3}\right) = 1.959 F_t \qquad M_{F_t\text{-}Load}^{S=25} = 19.04^{1k}$$

For HP10x42 Pile with Fixed Ends ⇒ $M_{MAX} = 45.69^{1k}$ ⇒ $\sigma_{MAX} = \frac{M_{MAX}}{S} = \frac{45.69 \times 12}{14.2} = 38.6\ ksi$

OK

$M_p = Z_y \times \sigma_y = 21.8 \times 36 = 785^{"k} = 65.4^{1k}$

For "H" = "H_{MAX}" & $S = S_{MAX}$ Conditions

Fig. 2.38. Upstream Pile, P1, M_{max} Values for Fixed-End Condition

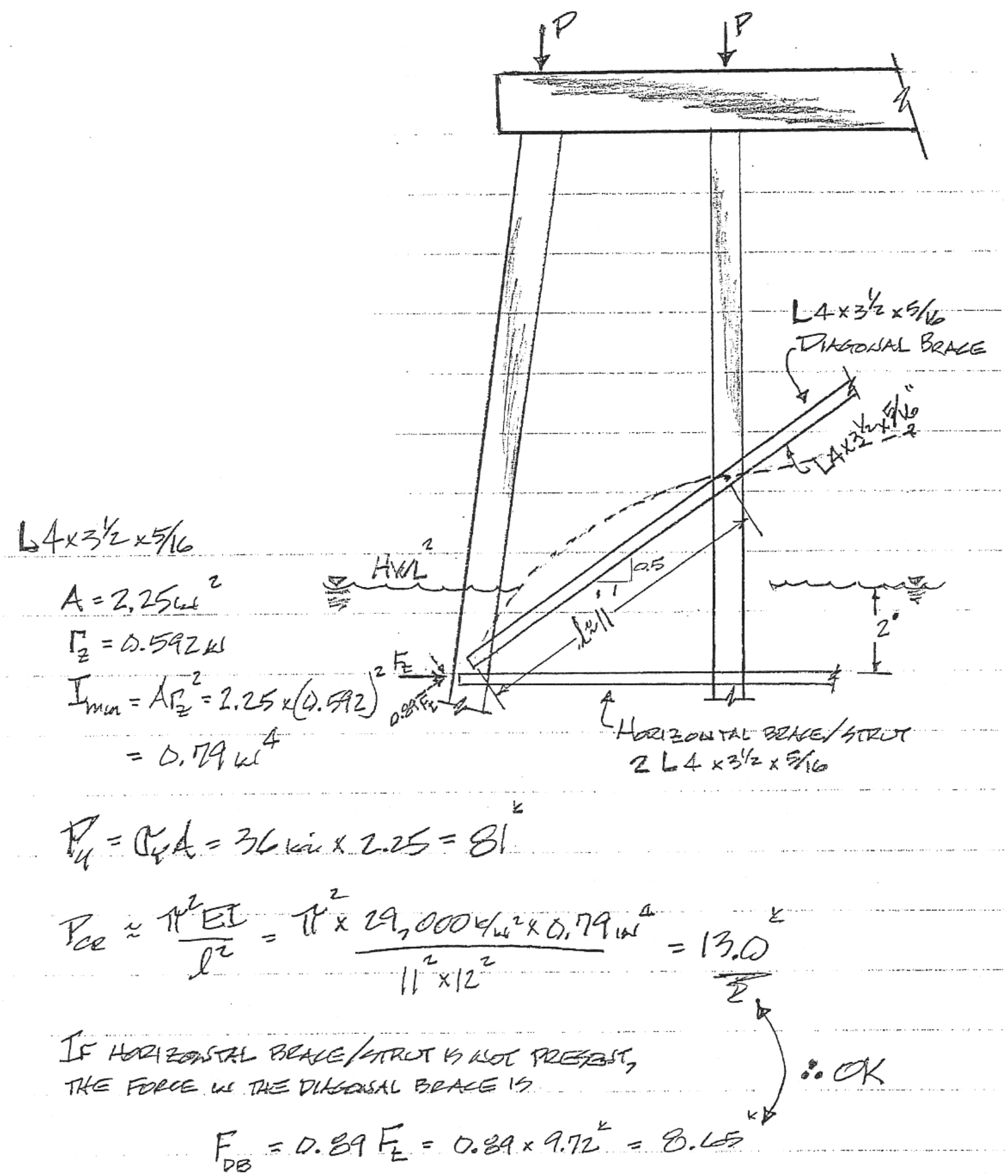


Fig. 2.39. X-Braced Bent with F_t-Load at Level of Horizontal Brace

The analyses above neglected the axial P-load on the upstream pile. We now need to consider this load and analyze the pile as a beam-column. To do this we will use the approximate straight-line interaction equation

$$\frac{P}{P_u} + \frac{M}{M_u} \leq 1.0 \tag{2.1a}$$

or,

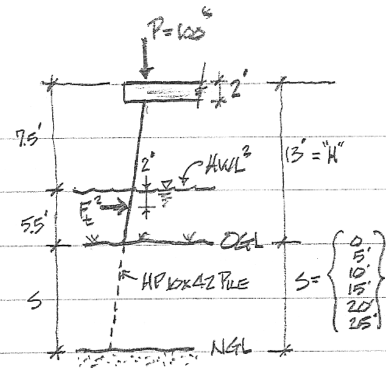
$$\frac{P}{P_{cr}} + \frac{M}{M_P} \leq 1.0 \tag{2.1b}$$

to determine its adequacy.

For our maximum height unbraced bent shown in Fig. 2.36 with $P=100^k$ and the HWL and F_t being at level 2 as shown in Fig. 2.40, and assuming the bent has full fixity at both ends, HP_{10x42} piles, and cannot buckle in a sidesway mode, a check of the adequacy of the upstream pile as a beam-column is as shown in Fig. 2.40. It should be noted that only the bent's upstream pile is acting primarily as a beam-column with a significant value of M/M_p. Thus, the other piles in the bent will provide lean-on buckling support for the upstream pile, i.e., for a sidesway buckling mode to occur all of the piles in the bent must be loaded to their sidesway buckling capacity. This will not be the case and thus the bent and the upstream pile will not sidesway. Note in Fig. 2.40 that the upstream pile would not be adequate for the low level position of the F_t load if the scour is extremely large, i.e., S > 20ft if the bent piles are HP_{10x42}. However, if the piles are HP_{12x53} or larger, the upstream pile is adequate for $S \leq 25$ ft.

Lateral Debris Raft Load = $F_L = 9.72^k$

Check Adequacy of Upstream Pile as a Beam-Col. for $S = 15', 20', 25'$.



Upstream Portion of Max Height Unbraced Bent

Interaction Eqn: $\frac{P}{P_{CR}} + \frac{M}{M_P} \leq 1.0$ for adequacy

$M_P = Z_y \times \sigma_y = 21.8\,\text{in}^3 \times 36\,\text{k/in}^2 / 12 = 65.4^{1k}$

$P_{CR} = \frac{2\pi^2 E I_y}{l^2}$

where $l = H + S - 2' = \begin{cases} 13+15-2 = 26' \\ 13+20-2 = 31' \\ 13+25-2 = 36' \end{cases}$

$P_{CR}^{S=15'} = \frac{2 \times \pi^2 \times 29{,}000\,\text{k/in}^2 \times 71.7\,\text{in}^4}{26^2 \times 144\,\text{in}^2} = 422^k$; $P_{CR}^{S=20'} = 297^k$; $P_{CR}^{S=25'} = 220^k$

From Fig. 2.33 ⇒ $M_{MAX}^{S=15'} = 36.9^{1k}$; $M_{MAX}^{S=20'} = 41.9^{1k}$; $M_{MAX}^{S=25'} = 45.7^{1k}$

Check S=15':

$\frac{P}{P_{CR}} + \frac{M_{MAX}}{M_P} = \frac{100^k}{422^k} + \frac{36.9^{1k}}{65.4^{1k}} = 0.237 + 0.564 = 0.801 < 1$ ⇒ ∴ Adequate

Check S=20':

$\frac{100}{297} + \frac{41.9}{65.4} = 0.337 + 0.641 = 0.978 < 1$ ⇒ Probably OK. The straight line interaction eqn does not consider secondary M's and is thus somewhat unconservative.

Check S=25':

$\frac{100}{220} + \frac{45.7}{65.4} = 0.455 + 0.699 = 1.154 > 1.0$ ⇒ ∴ Not Adequate

∴ S = 20' is the upper limit of adequacy of the upstream pile if the max HWL is as estimated above, i.e., is 7.5ft below the top of the bent cap and P ≤ 100k and pile is an HP10x42

Note for HP12x53 pile for S = 25' ⇒ $P_{CR} = 390^k$ & $M_p = 96.6^{1k}$,

∴ $\frac{P}{P_{CR}} + \frac{M_{MAX}}{M_P} = \frac{100^k}{390^k} + \frac{45.7^{1k}}{96.6^{1k}} = 0.256 + 0.473 = 0.729 < 1.0$

∴ Adequate

Fig. 2.40. Checking Upstream Pile of Maximum Height Unbraced Bent as a Beam-Column

As can be seen in Figs. 2.38 and 2.40 for unbraced bents, the larger the bent height, H, and scour, S, the longer the unsupported length, ℓ, of the upstream pile, and this means the smaller the pile buckling load, P_{cr}, and the larger the applied moment, M, leading to a larger value on the lefthand side of the interaction equation, Equation 2.1. Also, as indicated in Fig. 2.40, the relationship of the upstream pile unsupported length and the bent height and level of scour is

$$\ell = H + S - 2' \tag{2.2}$$

Thus, for a maximum height unbraced bent of H=13 ft, Eqn 2.2 can be used to determine the unsupported length of the upstream pile for different levels of scour, $M_{max\ applied}$ can be determined from the equation in Fig. 2.38 and P_{cr} can be determined from the equation in Fig. 2.40. With these values and a knowledge of M_p for the various HP piles, Eqn 2.1 can be used to determine the applied P-load level necessary for the left side of Eqn 2.1 to equal unity, thus indicating incipient failure, as indicated below.

For H=13' and S=20' $\quad \ell = H + S - 2' = 13+20-2 = 31'$

$$P_{cr} = \frac{2\pi^2 EI_y}{l^2} = \frac{2\pi^2 \times 29{,}000^{k/in^2} \times 71.7 in^4}{31^2 \times 144 in^2} = 297^k$$

$M_{max} = 41.9^{'k}$ (see Fig. 2.38)

$$M_p = \sigma_y \times Z = \frac{36ksi \times 21.8in^3}{12^{''/'}} = 65.4^{'k}$$

$$\therefore \frac{P}{P_{cr}} + \frac{M}{M_p} = 1.0 \rightarrow \frac{P}{297^k} + \frac{41.9^k}{65.4^k} = 1 \rightarrow P = \left(1 - \frac{41.9}{65.4}\right) 297^k$$

$$P = 0.359 \times 297^k = 107^k$$

$\therefore$ For the maximum height unbraced bent with HP_{10x42} piles and a maximum scour level of S_{max}=20 ft, if

$P_{applied} < 107^k$ the upstream pile is safe

$P_{applied} \geq 107^k$ the upstream is not safe

The procedure above was employed for different levels of scour, and the resulting $P_{failure}^{applied}$ loads are shown in Table 2.27. It should be noted in Table 2.27. that for S=0, 5ft, and 10ft, axial yielding of the pile (rather than buckling) controls and P_y was used in Eqn 2.1. Also, for S=15ft and 20ft, the P_{cr} values shown in Table 2.27 are for elastic buckling and adjusted values are also shown and recommended since inelastic buckling would occur for these levels of scour. An interaction diagram of axial $P_{failure}$ vs Scour using the data in Table 2.27 is shown in Fig. 2.41. Both the unadjusted and adjusted (for inelastic buckling) failure curves are shown on the figure as well as safe and unsafe combinations of applied pile axial load P and scour S.

Table 2.27 Upstream Pile Beam-Column Failure for Lower Elevation Debris Raft with F_t=9.72^k and H=13 ft Unbraced Bent with HP_{10x42} Piles

H (ft)	S (ft)	ℓ (ft)	$M_{max}^{applied}$ (ft-kips)	M_p (ft-kips)	P_{buckle} (kips)	P_{yield} (kips)	P_{cr} (kips)	$P_{failure}$ (kips)
13	0	11	15.8	65.4	2355	446	446	338
13	5	16	20.6	65.4	1113	446	446	306
13	10	21	30.1	65.4	646	446	446	241
13	15	26	36.9	65.4	422	446	422*	160
13	20	31	41.9	65.4	297	446	297*	100
13	25	36	45.7	65.4	220	446	220	66

*Somewhat high as they assume elastic buckling whereas inelastic buckling would occur at these scour levels

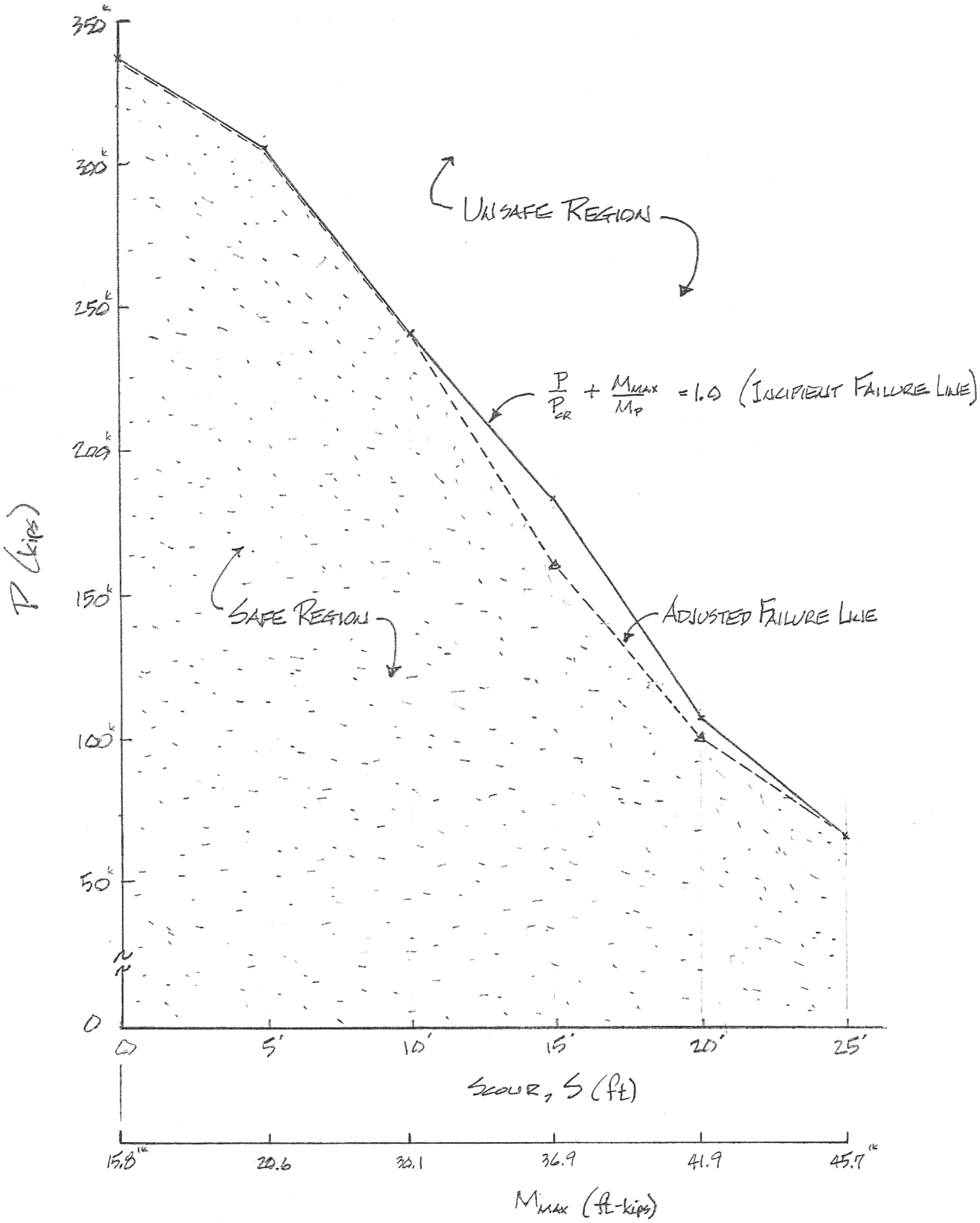


Fig. 2.41 Interaction Diagram of Axial $P_{failure}$ vs. S for the Upstream Pile for Unbraced Bents with H=13 ft and HP_{10x42} Piles

Two-story bents will always be X-braced with the bottom of the lower X-brace being located 3'-6" above the original ground line. Thus, if extreme scour of such a bent were to occur during high-water flood conditions, the HWL and flood debris raft would be located somewhere in the X-braced region of the bent. In this case, the upstream bent pile would not be subjected to significant bending/beam-column forces and stresses and need not be checked for a beam-column failure. Such bents should be checked for possible pushover failure, and the effect of height of HWL and debris raft location on such bents is discussed in Section 2.12.

In summary, for X-braced bents, both single-story X-braced and two-story X-braced, the upstream bent pile is adequate as a beam-column for debris raft lateral loading, F_t, at any elevation along the pile. For unbraced bents, the taller the bent, the more likely the upstream pile might not be adequate as a beam-column for a debris raft forming at a lower elevation below the bent cap. If the unbraced bent has HP_{12x53} or larger piles, then the upstream pile is adequate as a beam-column no matter where the debris raft forms. However, if the unbraced bent has HP_{10x42} piles, then the tallest such bent (prior to scour) should be one with H=13 ft, and for such a bent, the interaction diagram of Fig. 2.41 indicates the following for the upstream pile:

$P=160^k \rightarrow S_{failure} = 15' \rightarrow S_{safe} = 12'$ $P=140^k \rightarrow S_{failure} = 16.6' \rightarrow S_{safe} = 13.3'$

$P=120^k \rightarrow S_{failure} = 18.3' \rightarrow S_{safe} = 14.6'$ $P=100^k \rightarrow S_{failure} = 20' \rightarrow S_{safe} = 16'$

$P=80^k \rightarrow S_{failure} = 23' \rightarrow S_{safe} = 18.4'$ $P=60^k \rightarrow S_{failure} = 27' \rightarrow S_{safe} = 21.6'$

Thus, only unbraced pile bents need to be checked for adequacy of the upstream pile as a beam-column, and for these bents, only those with HP_{10x42} or smaller piles need to be checked. Also, only those unbraced bents with HP_{10x42} or smaller piles that have a height, H, and high water level, HWL, such that a debris raft could likely form at the lower elevation level need to be checked. The adequacy of the bent upstream pile as a beam-column, summarized above, are further summarized in more concise flowchart form in Fig. 2.42.

Is the bent X-braced?

No → Are the bent piles larger than HP_{10x42}?

Yes → Upstream pile is OK as a beam-column!

Are the bent piles larger than HP_{10x42}?

No → Is there a source or history of flood debris such that a debris raft could form?

Yes → Upstream pile is OK as a beam-column!

Is there a source or history of flood debris such that a debris raft could form?

No → Upstream pile is OK as a beam-column!

Yes → Are the bent height, H, and high water level, HWL, such that during an extreme flood event a debris raft could likely form 7 ft or more below the top of the bent cap?

Are the bent height, H, and high water level, HWL, such that during an extreme flood event a debris raft could likely form 7 ft or more below the top of the bent cap?

No → Upstream pile is OK as a beam-column!

Yes → Then for

$P = 160^k \rightarrow S_{failure}$ = 15' and S^{safe}_{max} = 12'

$P = 140^k \rightarrow S_{failure}$ = 16.6' and S^{safe}_{max} = 13.3'

$P = 120^k \rightarrow S_{failure}$ = 18.3' and S^{safe}_{max} = 14.6'

$P = 100^k \rightarrow S_{failure}$ = 20' and S^{safe}_{max} = 16'

$P = 80^k \rightarrow S_{failure}$ = 23' and S^{safe}_{max} = 18.4'

$P = 60^k \rightarrow S_{failure}$ = 27' and S^{safe}_{max} = 21.6'

at the site, and at the site is, $S_{max} > S^{safe}_{max}$?

No → Upstream pile is OK as a beam-column!

Yes → Bent upstream pile should be checked more closely for possible failure as a beam-column

Fig. 2.42 Checking Adequacy of Bent Upstream Pile as a Beam-Column

2.12 Effect of Height of Debris Raft Loading on Bent Pushover

In extreme flood/scour events, a debris raft may develop at a pile bent, and the resulting dominant flood water loading, F_t, on the bent may occur as high on the bent as the bottom of the pile cap and this was the position of F_t assumed in the Phase II work. However, the topology at some bridge locations may be such that tall bents are required to achieve an appropriate roadway elevation, but the high water level at the site may be significantly lower than the top of the bent cap. It was anticipated that this would be a less severe bent pushover load condition relative to that of the load located at the bottom of the bent cap, as was used in the Phase II work. GTSTRUDL pushover analyses were performed for the family of relatively tall two-story X-braced 3- and 4-pile bents of HP_{10x42} piles shown in Fig. 2.43. Each bent had a height, "H" of 21 ft and was subjected to P-loads of {P} = {60, 80, 100, 120, 140^k, 160^k} and scour levels of {S} = {0, 5', 10', 15', 20', 25'} and had the pushover force, F_t, applied at 2'-0 below the top of the cap, i.e., at the bottom of the bent cap, and at 9'-6" below the top of the cap, i.e., at the location of the bent horizontal strut, as shown in Fig. 2.43. The resulting pushover forces for the bents are shown in Table 2.28, and as evident from that table, the higher location of the F_t load did not prove to be the most severe load location. Rather, the lower location of F_t yielded pushover loads approximately 8% - 12% lower than the high location of F_t.

Essentially, the analyses results indicate that the vertical position of the flood water horizontal loading, F_t, doesn't significantly affect the bent pushover load, as the bent bracing system is effective in maintaining the relative geometrical relationships of the bent members in the region of X-bracing. Thus, almost all of the bending deformations of the bent occur in the lower unbraced region, and are essentially independent of where F_t is applied in the upper braced region, as shown in Fig. 2.44. This weak axis pile bending in the lower unbraced region is the primary cause of the lateral deflections at the top of the bent, and is the cause of the bent pushover failures. GTSTRUDL-generated deformation curves for 3- and 4-pile bents with the F_t loading located at the bottom of the bent cap and at the location of the horizontal strut are shown in Figs. 2.45 and 2.46.

An additional family of pushover analyses were conducted on an X-braced, 2-story, 3-pile bent with the lateral load applied at the level of the bent horizontal brace for the P-load and scour levels indicated in the figure at the bottom of Table 2.29. Five different combinations of axial and flexural stiffnesses of the horizontal brace were used in the analyses to gain an understanding of the importance of the horizontal brace stiffness on the bent pushover load. The results of these analyses are summarized in Table 2.29, and indicate that the bent pushover load is also essentially independent of the stiffness of the bent horizontal brace.

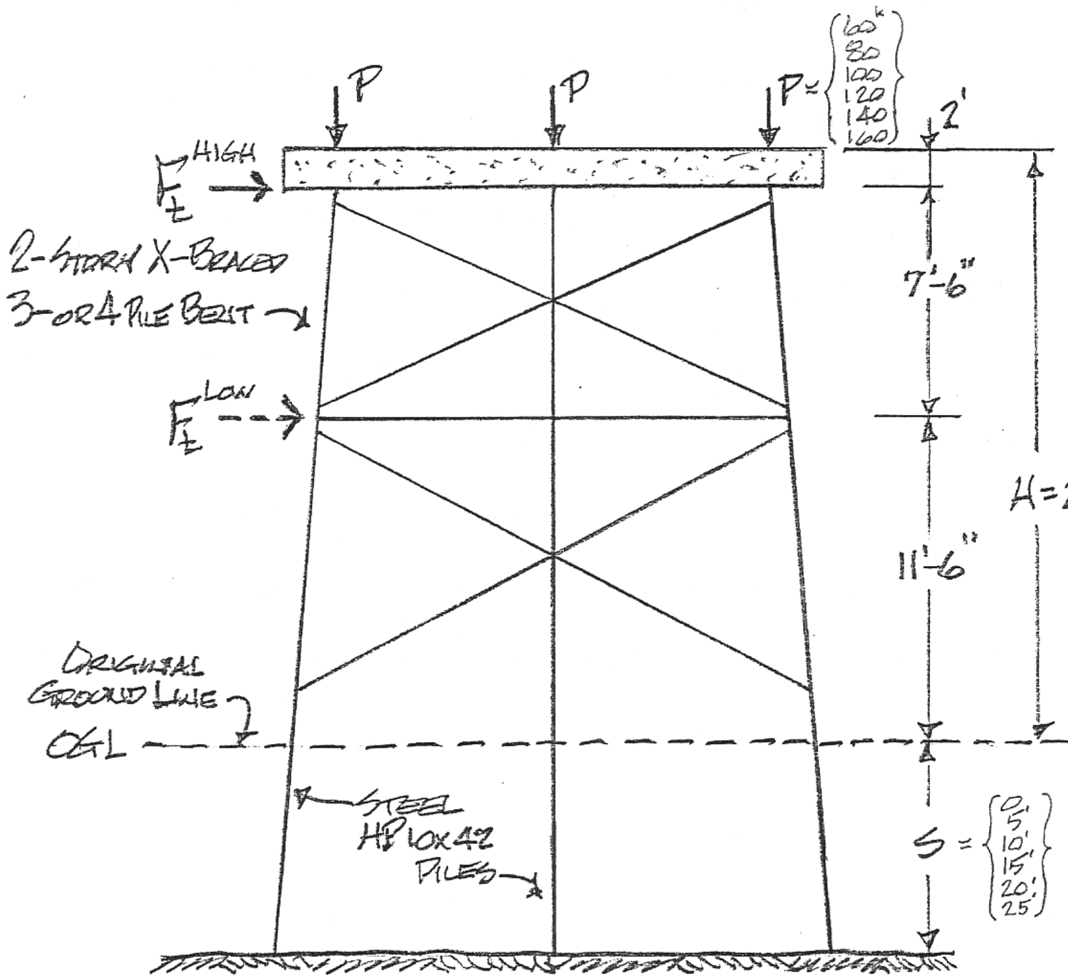


Fig. 2.43. Two-Story X-Braced 3-Pile Bent with Horizontal Flood Water Load, F_t, Applied at Bottom of Cap or Location of Horizontal Strut in GTSTRUDL Pushover Analyses

Table 2.28. Pushover Load, F_t, at High or Low Position for 2-Story X-Braced 3-Pile and 4-Pile Bridge Bents of Height H=21 ft with HP_{10x42} Piles and Concrete Bent Cap with I_{gross} = 41,470 in^4 for Symmetric P-Loads and Uniform Scour

No. Bent Piles	F_t Position	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k
3	High (Bottom of Cap)	0	21	45.1	48.9	46.7	44.7	43.2
		5	26	20.6	18.4	16.5	14.5	12.3
		10	31	11.1	8.6	6.1	3.8	UNS
		15	36	5.8	2.8	UNS	UNS	UNS
		20	41	UNS	UNS	UNS	UNS	UNS
	Low (Horiz. Strut)	0	21	45.1	43.0	40.9	39.2	37.8
		5	26	18.2	16.3	14.6	12.7	10.8
		10	31	9.8	7.6	5.4	3.3	UNS
		15	36	5.1	2.5	UNS	UNS	UNS
		20	41	UNS	UNS	UNS	UNS	UNS
4	High (Bottom of Cap)	0	21	63.3	58.9	55.1	51.6	48.5
		5	26	32.8	28.9	25.5	22.3	19.6
		10	31	25.0	20.6	16.8	13.2	9.7
		15	36	21.7	16.7	12.2	8.0	4.0
		20	41	16.8	12.0	7.4	4.0	UNS
	Low (Horiz. Strut)	0	21	57.4	53.7	50.3	47.2	44.3
		5	26	30.0	26.4	23.3	20.3	17.8
		10	31	23.0	18.9	15.3	12.1	8.9
		15	36	19.9	15.3	11.1	7.3	3.6
		20	41	15.4	11.0	6.8	3.5	UNS

H = Bent height from top of bent cap to original ground line

S = Scour depth, or original ground line minus new ground line

UNS = unstable

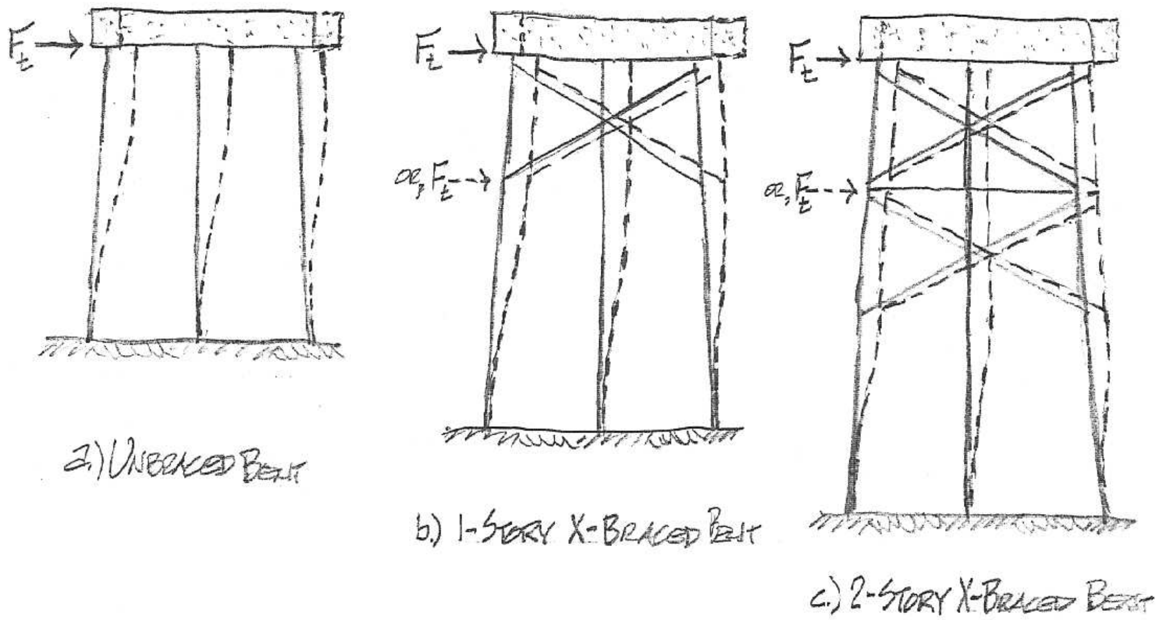
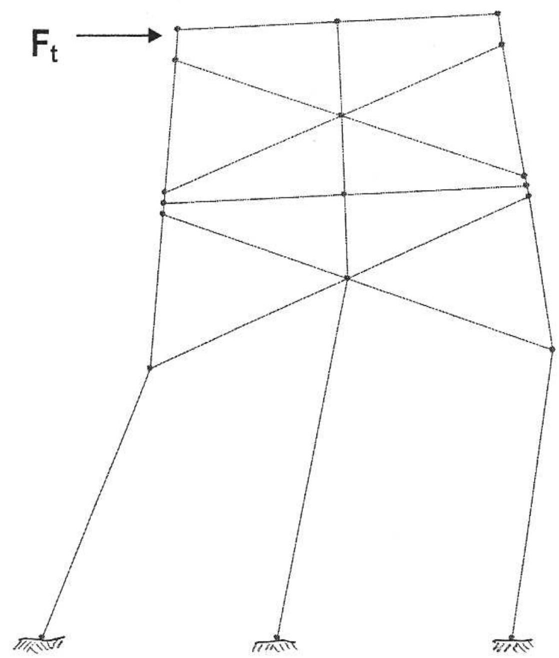
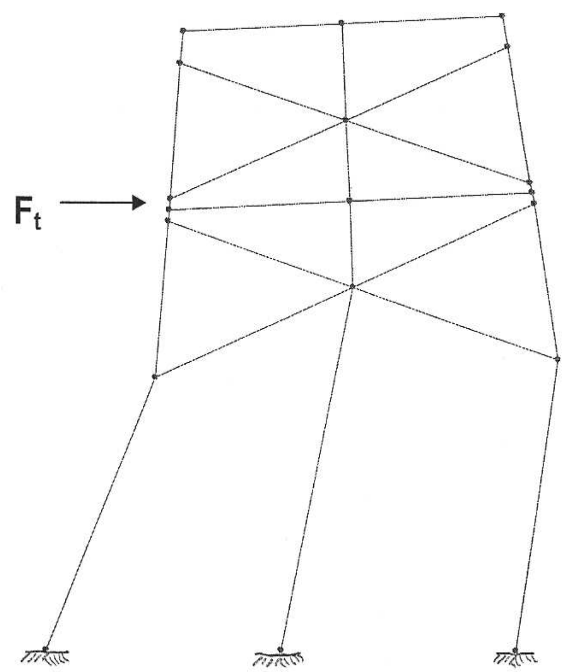


Fig. 2.44. Unbraced, 1-Story X-Braced, and 2-Story X-Braced Bent Deformations

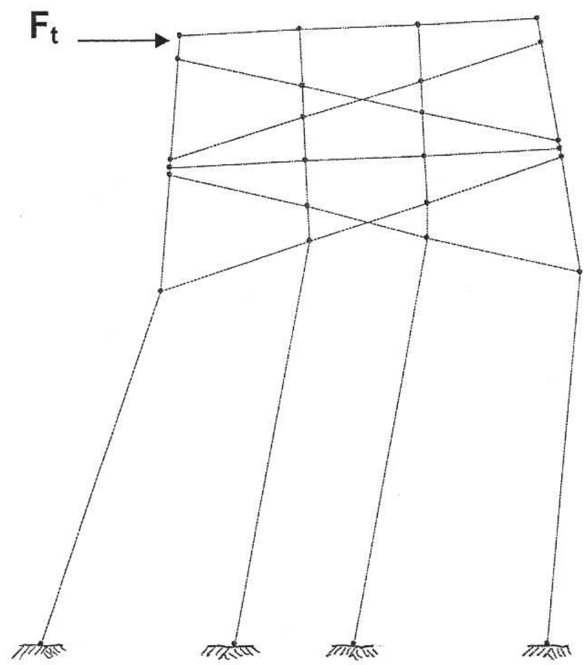


a. F_t loading at Bent Cap

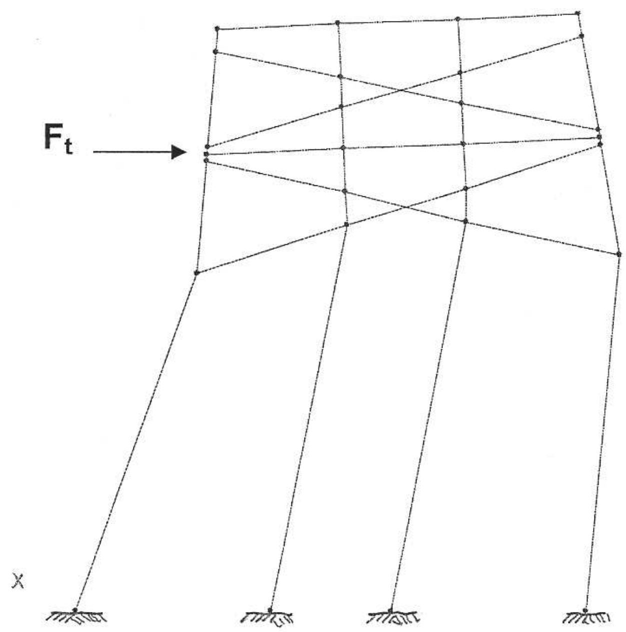


b. F_t loading at Horizontal Brace

Fig. 2.45. GTSTRUDL Generated Deformations of 3-Pile Bent from F_t Loadings



a. F_t loading at Bent Cap



b. F_t loading at Horizontal Brace

Fig. 2.46. GTSTRUDL Generated Deformations of 4-Pile Bent from F_t Loadings

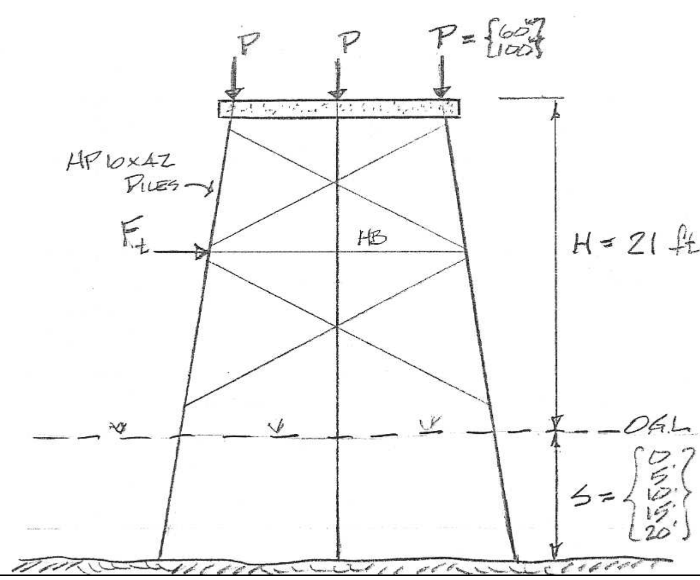
Table 2.29. Pushover Load, F_t, at Low Position for 2-Story X-Braced 3-Pile Bent of Height H=21 ft with HP_{10x42} Piles for Various Values of Horizontal Brace (HB) Stiffnesses

P-Load (kips)	No. of Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
					I = 0 A = 0	$I = I_{hb}$ $A = A_{hb}$	$I = I_{hb}$ $A = 2A_{hb}$	$I = I_{hb}$ $A = 40A_{hb}$	$I = 1000 I_{hb}$ $A = A_{hb}$
60	3	21	0	21	43.9	45.1	45.3	45.6	45.1
			5	26	17.6	18.2	18.2	18.2	18.2
			10	31	9.5	9.8	9.8	9.8	9.8
			15	36	UNS	UNS	UNS	UNS	UNS
			20	41	UNS	UNS	UNS	UNS	UNS
100	3	21	0	21	39.9	41.0	41.2	41.4	45.1
			5	26	14.1	14.6	14.6	14.6	14.6
			10	31	5.1	5.4	5.4	5.4	5.4
			15	36	UNS	UNS	UNS	UNS	UNS
			20	41	UNS	UNS	UNS	UNS	UNS

UNS = unstable
I, A = values of I and A used in GTSTRUDL Pushover Analyses

I_{hb}, A_{hb} = actual values of I and A of bent horizontal brace

Pile Bent Parameters:



2.13 Additional Expansions of Applicability of the Tier-1 Screening Tool

Guidelines for some additional expansions of applicability of the Phase II Report/Tier-1 Screening Tool are given below.

1. For pile bents with more than six HP steel piles in a row, do the following: Use the “ST” as written for checking for pile/bent kick-out, plunging, and buckling failures. Use the pushover load check for the 6-pile bent in the “ST” having the same HP pile size as the one being investigated to check the adequacy of bents with more than 6-piles in a bent.

2. For pile bents with HP steel piles larger than HP_{12x53} do the following: Use the “ST” as written for checking the adequacy for kick-out and plunging failures, and use the I_y of the bent pile in checking for possible buckling when using the buckling equation of section three in the “ST”. Use the pushover results for HP_{12x53} pile bents in checking the bent adequacy for pushover failure.

3. The current “ST” checks for pile/bent “kick-out” adequacy via checking to verify that depth of pile embedment in a firm soil after scour is equal to or greater than 3 ft. Upon reviewing this criterion further and recognizing the limited ability to accurately predict the S_{max} value at a bent site, it is recommended that the above criterion for “kick-out” adequacy be retained as is in the Tier-2 “ST”.

2.14 Closure

Bent pushover loads for lower levels of P-loads, i.e., $P=60^k$ and 80^k, and for a larger level of scour, i.e., S = 25 ft have been added in the refined "ST", and these have also been presented in terms of the critical scours, S_{CR}. Bent pushover loads for cases of unsymmetric P-load distribution having only the upstream bridge lane loaded with live load have been added in the refined "ST". Pushover loads for cases of variable scour where the scour decreases in the downstream direction, and cases of unsymmetric P-load distribution and variable scour have also been added in the refined "ST".

Checks have been made on the effect of additional pile axial load, ΔP, due to lateral flood water loading, and checks regarding the adequacy of upstream bent piles when subjected to a debris raft loading at the level of horizontal strut for two-story bents have been made and included in this chapter. Also, the effect of height of debris raft loading on bent pushover, as well as the effect of continuous-span superstructures on bent pushover and pile buckling have been evaluated. Interestingly, the height of the debris raft loading has very little effect on the bent pushover load, and, as expected, continuous-span superstructures offer greater resistance to bent pushover failure.

CHAPTER 3: DETERMINING BRIDGE/BENT MAXIMUM APPLIED LOADS

3.1 General

The maximum applied pile and bent gravity loads are primarily a function of:

- the span length
- the bridge width and girder spacing
- the superstructure support conditions, i.e., simply-supported or continuous-spans

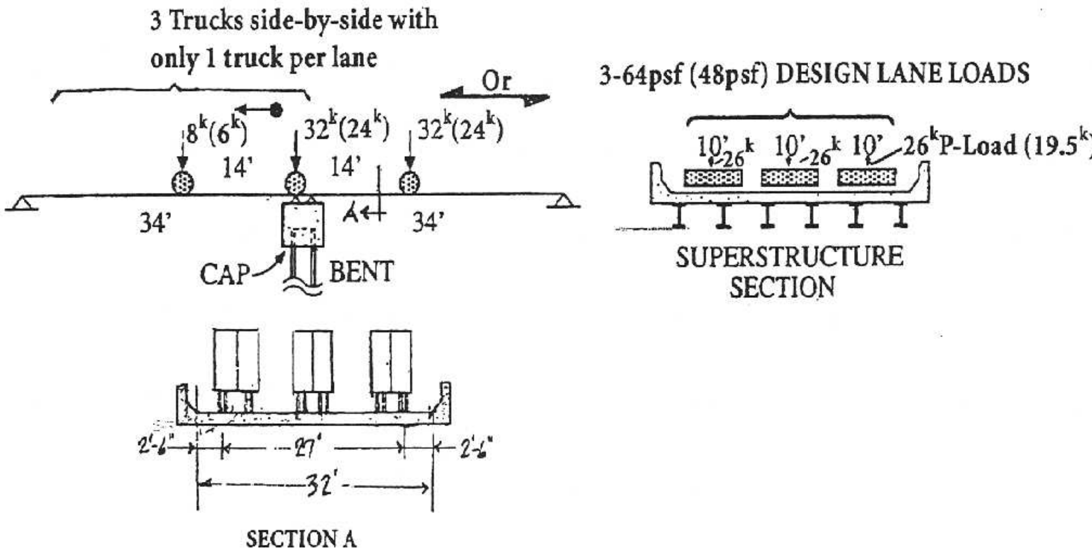
The procedures for determining maximum applied dead load (DL) are straightforward and rather easy to implement; however, the procedures for live load (LL) are more involved and not as easy to implement. In placing truck and lane loads in traffic lanes, the AASHTO design truck and lane loadings, seen in Fig. 3.1, are meant to cover a 10-ft. width. These loads are then placed in 12 ft. traffic lanes spaced across the bridge from curb-to-curb. If the curb-to-curb width is between 20 ft. and 30 ft., two design lanes are required, each of which is half the curb-to-curb distance. The number and spacing of design traffic lanes is based on the layout which creates the maximum stress. Table 3.1 shows the number of design lanes based on a bridge's curb-to-curb width, and Fig. 3.1

illustrates “truck lane loadings” and “design lane loading” on a 32 ft. curb-to-curb width bridge. The larger of these two loadings is the required design live loading.

It should be noted that the number of design traffic lanes and lane LL-loadings shown in Table 3.1 and Fig. 3.1 are appropriate for checking bent pile buckling or plunging, but are unrealistically conservative for the maximum high water level pushover loading unless the bridge actually has 3-traffic lanes. Otherwise, the LL-loading for the pushover loading check should be restricted to using the actual number of traffic lanes. Also, the most adverse LL-loading may occur with only the upstream lane loaded for the pushover loading condition, and this should be checked.

Table 3.1 Design Traffic Lanes

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



a. Truck Lane Loading   b. Design Lane Loading

Fig. 3.1 Live Load to Determine $P^{LL}_{Bent\ Max\ Applied}$

3.2 Determining Maximum Applied Dead Load

Bridge girder maximum dead load reactions for various girder support conditions are summarized in Table 3.2 for a uniform dead load, ω_{DL}.

Table 3.2 Bridge Girder Maximum Reactions for SS and Equal Span Continuous Bridges Under Uniform Loads

Bridge/Girder Support Condition	R^{DL}_{Max}	R^{LL}_{Max}
SS	1.0 ω_{DL}	1.0 ω_{LL}
2-Span Continuous	1.25 ω_{DL}	1.25 ω_{LL}
3-Span Continuous	1.10 ω_{DL}	1.20 ω_{LL}
4-Span Continuous	1.15 ω_{DL}	1.22 ω_{LL}
5 -Span Continuous (or larger)	1.15 ω_{DL}	1.22 ω_{LL}

It should be noted that the tributary weight of the bent cap needs to be added to the appropriate girder reaction to determine the pile and bent design DL forces. If the bent cap size is known, that actual size is used in the "ST" to determine the cap weight to add to the bent load. If the cap size is unknown, the following is assumed to estimate its size and weight.

Girder/Pile spacing x (No. Piles – 1) + 4 ft

Bent Pile Cap Size = 2.5' x 2.5' x Cap Length

Bent Cap Weight = Cap Size (volume in ft^3) x 0.150 k/ft^3

Assume Cap Weight Is Equally Distributed To Piles. $\Longrightarrow$ $$P^{Cap}_{Pile} = \frac{\text{Cap Weight}}{\text{No. Bent Piles}}$$

Example problems illustrating the computation of $P^{DL}_{Max\ Applied}$ are given in Section 3.4.

3.3 Determining Maximum Applied Live Load

As with the original "ST", an impact factor of 1.1 is assumed in determining the maximum applied pile live load(LL). Also, as with the original "ST", a girder-line approach is taken to estimate the maximum vehicular LL (plus impact) on a bent pile, and the approach is illustrated with its application to a simply-supported superstructure, with span lengths of 34' and a girder spacing of 6', in Fig. 3.2. The loads shown in Fig. 3.2 apply to an HS20 loading and the loads shown in parenthesis pertain to an HS15 loading. $P^{LL}_{Max\ Applied}$ is the larger of those determined from the truck line load of Fig. 3.2(a) or the design lane loading of Fig. 3.2(b).

$P^{LL}_{Pile\,Max\,Applied}$ is determined from Fig 3.2 and 3.3 as follows:

a. Truck Line Load:

	SS Spans	2-Span Continuous
P^{LL}_{Pile} =	$\left[16^k + 16^k\left(\frac{20}{34}\right) + 4^k\left(\frac{20}{34}\right)\right]1.1$	$[2(3.12)+16+9.36]1.1$
	$=[16+9.41+2.35]1.1 = 30.5^k$	34.8^k

b. Design Lane Load:

	SS - Spans	2-Span Continuous
P^{LL}_{Pile} =	$\left[0.064\frac{k}{ft^2}x6'x34' + 26^k\right]1.1$	$[(0.064x6x34)1.25 + 26]1.1$
	= [13.1+26]1.1 = 43.0 Governs	$[16.32+26]1.1=46.6^k$ Governs

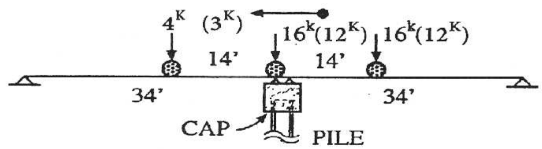
$\therefore P^{LL}_{Pile\,Max\,Applied} = 43.0^k$ for Simply Supported Bridge

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

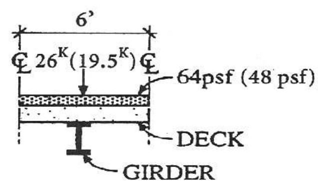
$\therefore P^{LL}_{Pile\,Max\,Applied} = 46.6^k$ for 3 or More Span Continuous or Continuous for LL

As can be seen from Table 3.2, for purposes of estimating the maximum $P^{LL}_{Pile\,Max}$ applied to a bent cap and pile, using the upper bound value of $P^{LL}_{Max} = 1.25 w_{LL} l$ would be appropriate for the “screening tool” for equal-span continuous bridges of any number of continuous spans. Note also that the uniform lane loading (rather than truck wheel loadings) controls by a sizeable margin for both the SS bridge and the continuous bridges.

Example problems illustrating the computation of $P^{LL}_{Pile\ Max}$ are given in Section 3.4.



a. Truck Line Load



b. Design Lane Loading

Fig. 3.2 Girder Line Loading to Determine $P^{LL}_{Pile\ Max\ Applied}$

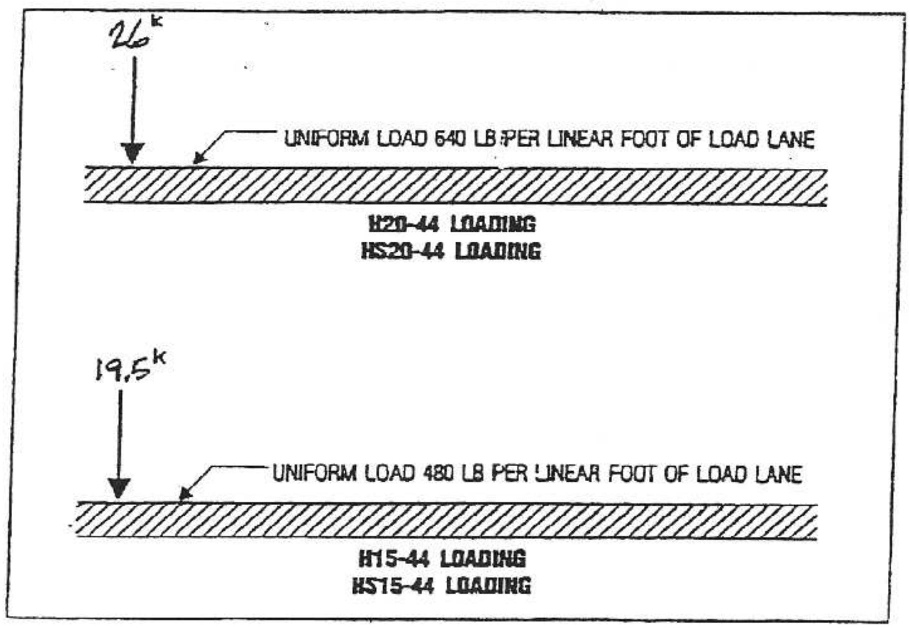


Fig. 3.3 AASHTO H and HS Lane Loading

3.4 Example $P^{Bent}_{Max\ Applied}$ Determinations

Two example problems illustrating the computation of $P^{Bent}_{Max\ Applied}$ for purposes of checking bridge bent pushover adequacy in extreme flood/scour events are presented below. Both examples illustrate calculations of loadings for the symmetric case of both bridge traffic lanes loaded with LL, and for the unsymmetric case of only the upstream traffic lane loaded. Example 1 pertains to a 4-pile bent bridge and Example 2 pertains to a 3-pile bent bridge.

Example 1: Refer to Figures 3.4 - 3.7

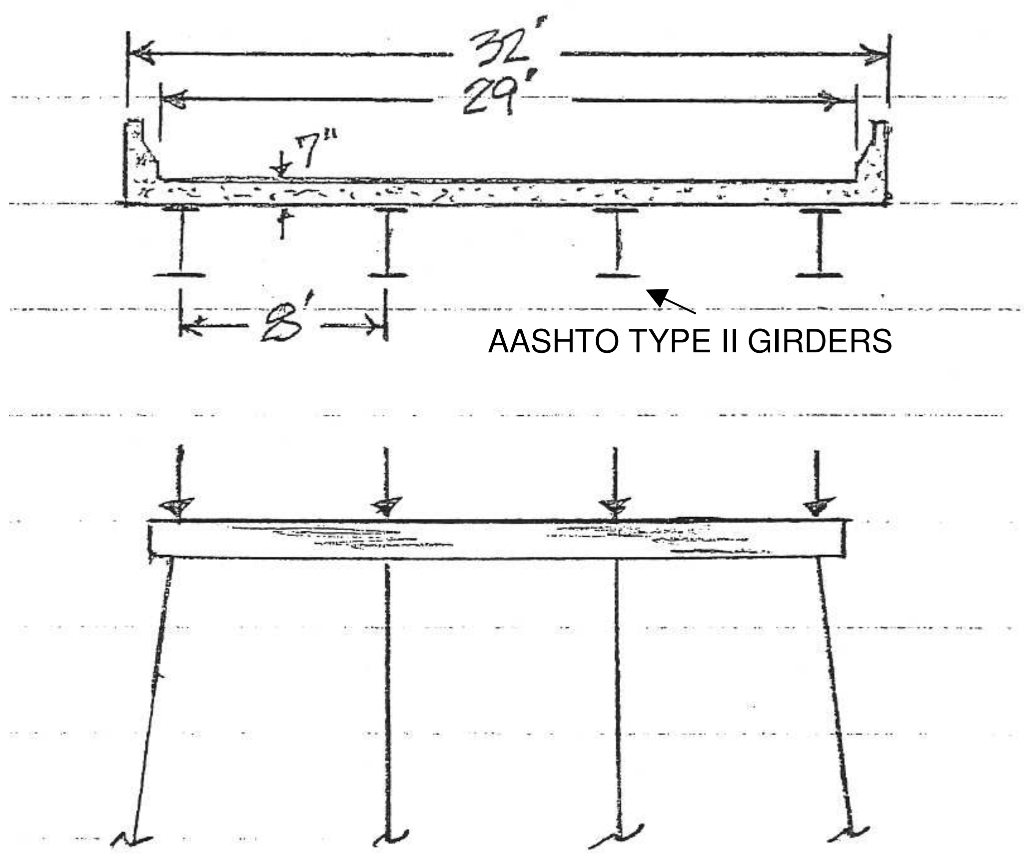


Fig. 3.4. 34' Span SS Bridge with 7" Deck, AASHTO Type II Girders (4 Girders at 8' Spacing), Jersey Barriers, 4-Pile Bents with 2.5' x 2.5' Caps

Determine $P_{Max\ Applied}^{Bent}$

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

$\frac{7'}{12}x32'x34'x0.150^{k}/ft.^{3}$ $= 95.2^{k}$

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

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

Diaph: $\frac{9'}{12}x$ *Girder Depth x Distance Between Exterior Girders x 0.150^{k} / ft.^{3} x No. Diaph/Span*

$\frac{9'}{12}x3.0'x24'x0.150^{k}/ft.^{3}x3$ $= 24.3^{k}$

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

$0.384^{k}/ft.x34'x4$ $= 52.2^{k}$

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

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

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

$2.5'x2.5'x28'x0.150^{k}/ft.^{3}$ $\underline{= 26.3^{k}}$

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

P_{DL} $= 231.3^{k}$

P_{LL} – Both Lanes Loaded (Case I Loading):

Design Lane Load: $\left[0.064^k / ft.^2 x10' x34' + 26.0^k\right]2x1.1$ $= 105.1^{\text{k}}$

Truck Lane Load: $\left[32^k + 32\left(\frac{20}{34}\right) + 8\left(\frac{20}{34}\right)\right]2x1.1$ $= 122.2^{\text{k}}$ ← Governs

P_{LL} $= 122.2^{\text{k}}$

$$\therefore P^{Bent}_{Max\ Applied} = \text{P}_{\text{DL}} + \text{P}_{\text{LL}} = 231.3^{\text{k}} + 122.2^{\text{k}} = 353.5^{\text{k}}$$

∴ P-load to be used above each pile in pushover analysis $= \dfrac{P^{Bent}_{Max\ Applied}}{No.\ of\ Piles} = \dfrac{353.5^k}{4 \text{ piles}} = 88.4^k \text{ per pile}$

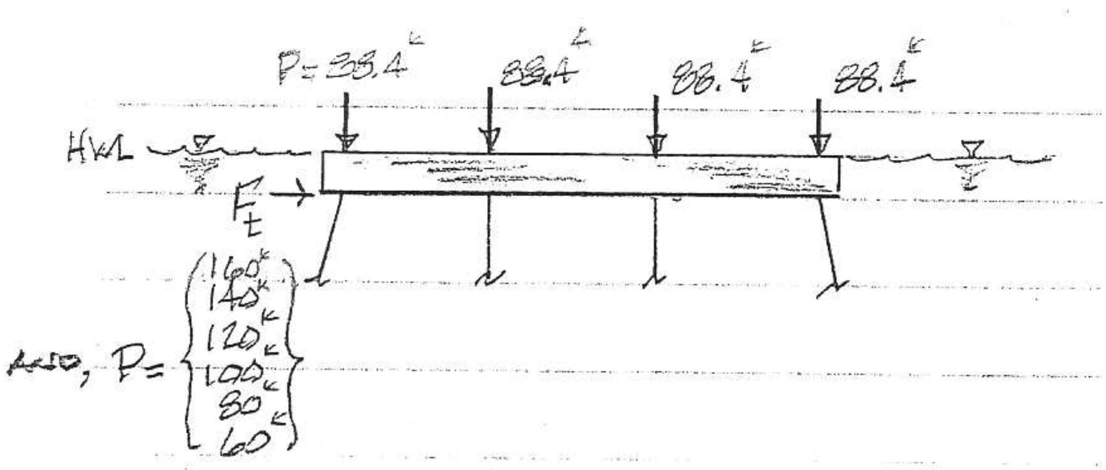


Fig. 3.5. Pushover Load Case I

P_{LL} – Only Up-Stream Lane Loaded (Case II Loading):

Design Lane Load: $\left[0.064^k / ft.^2 x10' x34' + 26.0^k\right]1x1.1$ $= 52.5^{\text{k}}$

Truck Lane Load: $\left[32^k + 32\left(\frac{20}{34}\right) + 8\left(\frac{20}{34}\right)\right]1x1.1$ $= 61.1^{\text{k}}$ ← Governs

P_{LL} $= 61.1^{\text{k}}$

$$P_{\text{DL Applied}}^{\text{Bent}} = \frac{P_{DL}}{\text{No. of Piles}} = \frac{231.3^k}{4} = 57.8^k \text{ per pile}$$

$$P_{\text{LL Applied}}^{\text{Bent}} = \frac{P_{LL}}{2} = \frac{61.1^k}{2} = 30.6^k \; ; \qquad P_{\text{LL Applied}}^{\text{Bent}} = 0 \quad \text{(other 2 piles)}$$

$$88.4^k \qquad\qquad 57.8^k$$

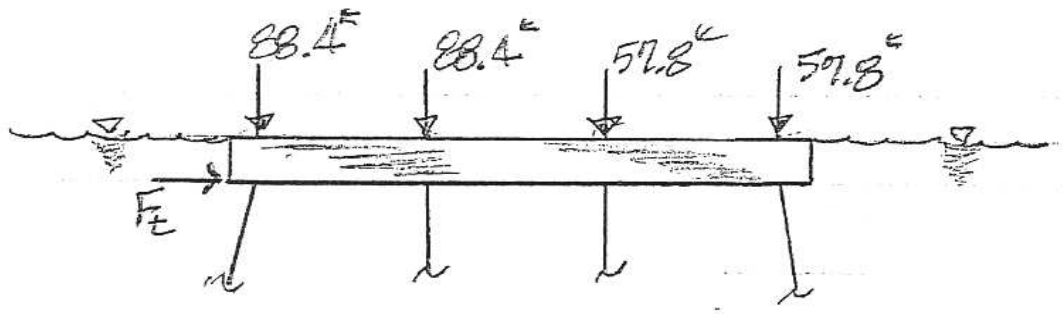


Fig. 3.6. Pushover Load Case II

Note, $\frac{88.4}{57.8} = 1.53$ or $\frac{1}{1.53} = 0.65$

Therefore, based on Example 1, in performing pushover analyses for Load Case II, use the following bent loadings.

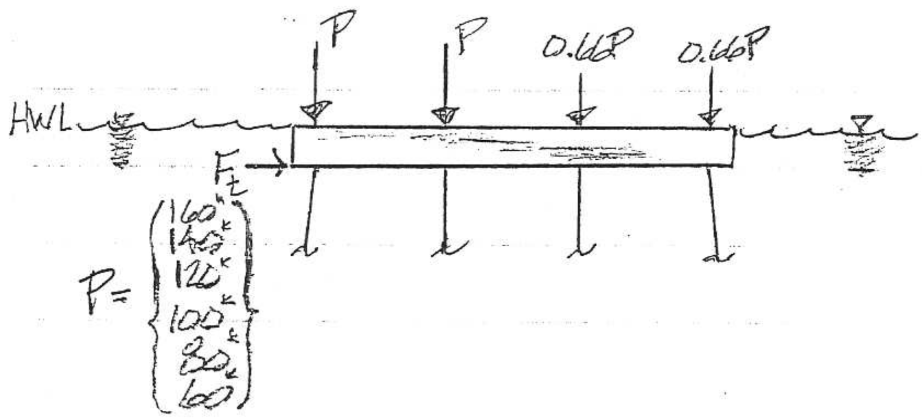


Fig. 3.7. Unsymmetric P-Loading for 4-Pile Bents

Example 2: Refer to Figures 3.8 - 3.11

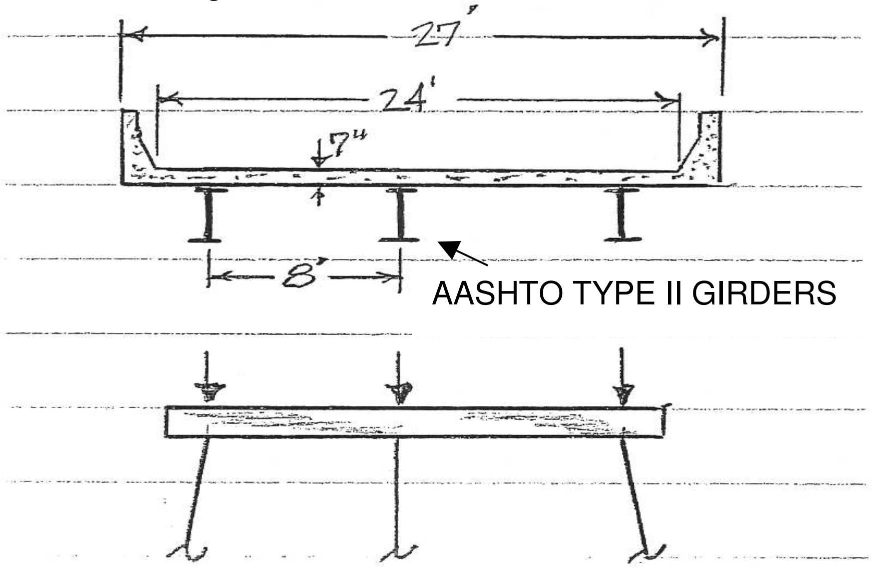


Fig. 3.8. 34' Span SS Bridge with 7" Deck, AASHTO Type II Girders (3 Girders at 8' Spacing), Jersey Barriers, 3-Pile Bents with 2.5' x 2.5' Caps

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

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

$$\frac{7'}{12}x27'x34'x0.150^k/ft.^3 \qquad = 80.3^k$$

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

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

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

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

$$\frac{9'}{12}x3.0'x16'x0.150^k/ft.^3x3 \qquad = 16.2^k$$

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

$0.384^k / ft. x 34' x 3$ = 39.2^k

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

$0.390^k / ft. x 34' x 2$ = 26.5^k

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

$2.5' x 2.5' x 20' x 0.150^k / ft.^3$ = 18.8^k

*If Cap Length is not available use

(Distance Between Exterior Girders + 4')

P_{DL} = 187.8^k

P_{LL} = Both Lanes Loaded (Case I Loading):

Design Lane Load: $\left[0.064^k / ft.^2 x 10' x 34' + 26.0^k\right] 2 x 1.1$ = 105.1^k

Truck Lane Load: $\left[32^k + 32\left(\frac{20}{34}\right) + 8\left(\frac{20}{34}\right)\right] 2 x 1.1$ = 122.2^k←Governs

P_{LL} = 122.2^k

$$\therefore P^{Bent}_{Max\ Applied} = P_{DL} + P_{LL} = 187.8^k + 122.2^k = 310.0^k$$

∴ P-load to be used above each pile in pushover analysis $= \frac{P^{Bent}_{Max\ Applied}}{No.\ of\ Piles} = \frac{310.0^k}{3\ \text{piles}} = 103.3^k$ per pile

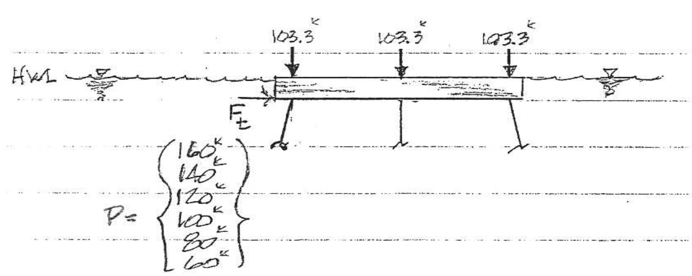


Fig. 3.9. Pushover Load Case I

P_{LL} – Only Up-Stream Lane Loaded (Case II Loading):

Design Lane Load: $\left[0.064^k / ft.^2 x10' x34' + 26.0^k\right]1x1.1$ = 52.5^k

Truck Lane Load: $\left[32^k + 32\left(\frac{20}{34}\right) + 8\left(\frac{20}{34}\right)\right]1x1.1$ = 61.1^k←Governs

P_{LL} = 61.1^k

$$P^{Bent}_{DL\ Applied} = \frac{P_{DL}}{\text{No. of Piles}} = \frac{187.8^k}{3} = 62.6^k \text{ per pile}$$

$$P^{Bent}_{LL\ Applied} = \frac{P_{LL}}{2} = \frac{61.1^k}{2} = 30.6^k \;;\qquad P^{Bent}_{LL\ Applied} = 0 \text{ (other 1 pile)}$$

93.2^k 62.6^k

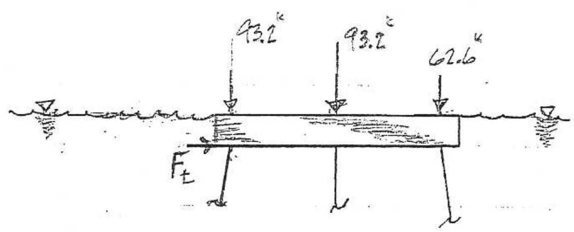


Fig. 3.10. Pushover Load Case II

Note, $\frac{93.2^k}{62.6^k} = 1.49$ or $\frac{1}{1.49} = 0.67$

Therefore, based on Example 1 and 2, in performing pushover analyses for Load Case II, use the following bent loadings.

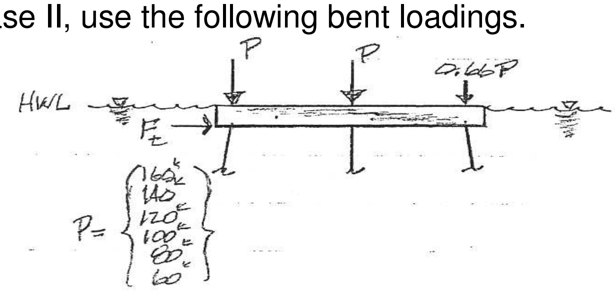


Fig. 3.11. Unsymmetric P-Loading for 3-Pile Bents

CHAPTER 4: REFINED "ST" AND TIER-2 SCREENING

4.1 General

The original "screening tool" developed to assess the adequacy of bridge pile bents for extreme flood/scour events screened only steel HP pile bents where the piles were HP_{10x42} or HP_{12x53}, and checked these bents for the following possible failure modes:

1. Bent pile tip "kick-out" failure (due to insufficient pile embedment after scour)
2. Bent pile plunging failure (due to insufficient pile end bearing or side friction capacity after scour)
3. Bent pile buckling failure (due to insufficient pile buckling capacity after scour)
4. Bent pushover failure (due to the combined effect of gravity P-loads and lateral flood water loads on the bent after scour)

In checking the many bent geometries and loading scenarios and piling bracing and support conditions, simplifying assumptions were made to estimate both the maximum applied loads on the bent/pile, and the load capacities of the bent/pile. In developing the "ST", upper or lower bound values as appropriate for the bent parameters were sometimes used, and in cases of uncertainty, which were many, conservative values were used.

After using the "ST" for about a year now, areas for improvements and refinements of the "ST" have been identified, as well as other possible critical load conditions and failure modes. These improvements in the basic "ST" have been incorporated in the refined/2nd-edition "ST" which is presented and discussed in the following section. This new edition still incorporates a conservative approach where uncertainties exist. Also included in this chapter is a section on 2nd-tier screening which should be performed to address the "blocks" in the original "ST" that instructed the user to "check more closely for possible failure". This 2nd-tier screening should result in additional bents being determined as adequate for extreme flood/scour events, and thus should further reduce the number of bents requiring a fully comprehensive analysis to assess the bent's adequacy.

4.2 Refined/2nd Edition "ST"

The refined/2nd edition "ST" is shown in flowchart form in Fig. 4.1. By comparison of this figure with the corresponding one for the original "ST", one can readily see that an additional failure-check module, i.e., Module 5, has been added to the refined/2nd edition "ST". This module provides for a check of the upstream bent pile for possible failure as a beam-column when simultaneously subjected to an axial P-load and a lateral flood water loading on a debris raft located with its top 7.5 ft below the top of the bent cap, i.e., with the F_t loading located 9.5 ft below the top of the bent cap. This check and module is discussed later in this section. Also, one can note in Fig. 4.1 that no changes were made in the Preliminary Evaluation Module, i.e., in Block 1. An enlarged drawing of Block 1 only is shown in Fig. 4.2 for convenience and readability.

In the “Kick-Out” and Plunging Evaluation Module (Block 2), slight refinements in the wording and sequence for indicating the adequacy of bent piles for “kick-out” were made at the very beginning of the Block. However, no changes of substance were made in checking for “kick-out”, nor are any follow-up screenings indicated for those bents where “check more closely for “kick-out” failure” is indicated by the “ST”. However, in this module, if a plunging failure is identified as being possible, the user is referred by the “ST” to second-tier screenings (Tier-2/2) to make assumptions regarding the bent pile-driving system when complete information on the system is not known, and/or to further refine the maximum load on the bent and pile in assessing the adequacy of the bent/pile for plunging. An enlarged drawing of Block 2 only is shown in Fig. 4.3 for convenience and readability.

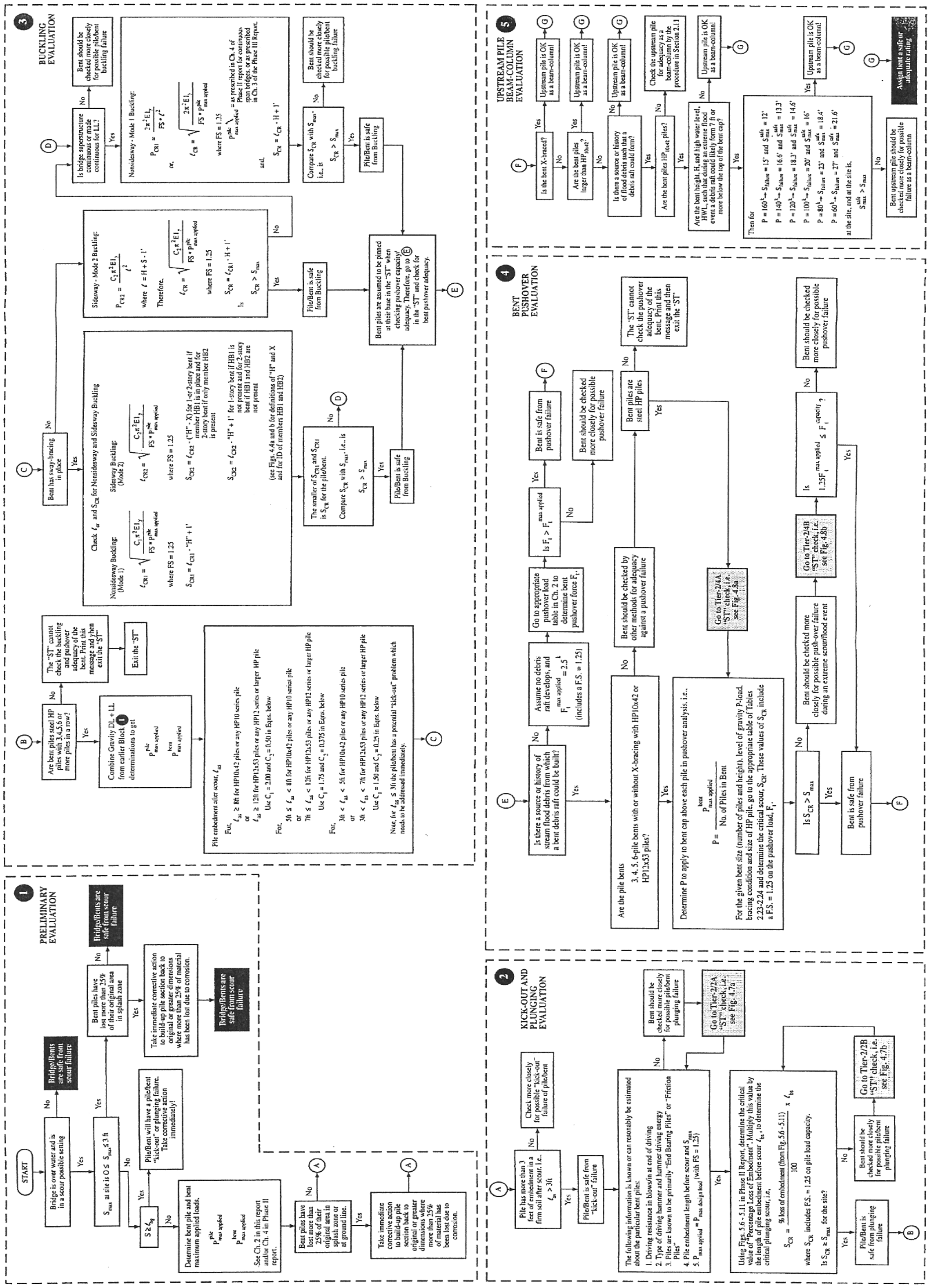


Fig. 4.1. Refined Screening Tool Flowchart for Assessing Pile Bent Adequacy During an Extreme Flood/Scour Event

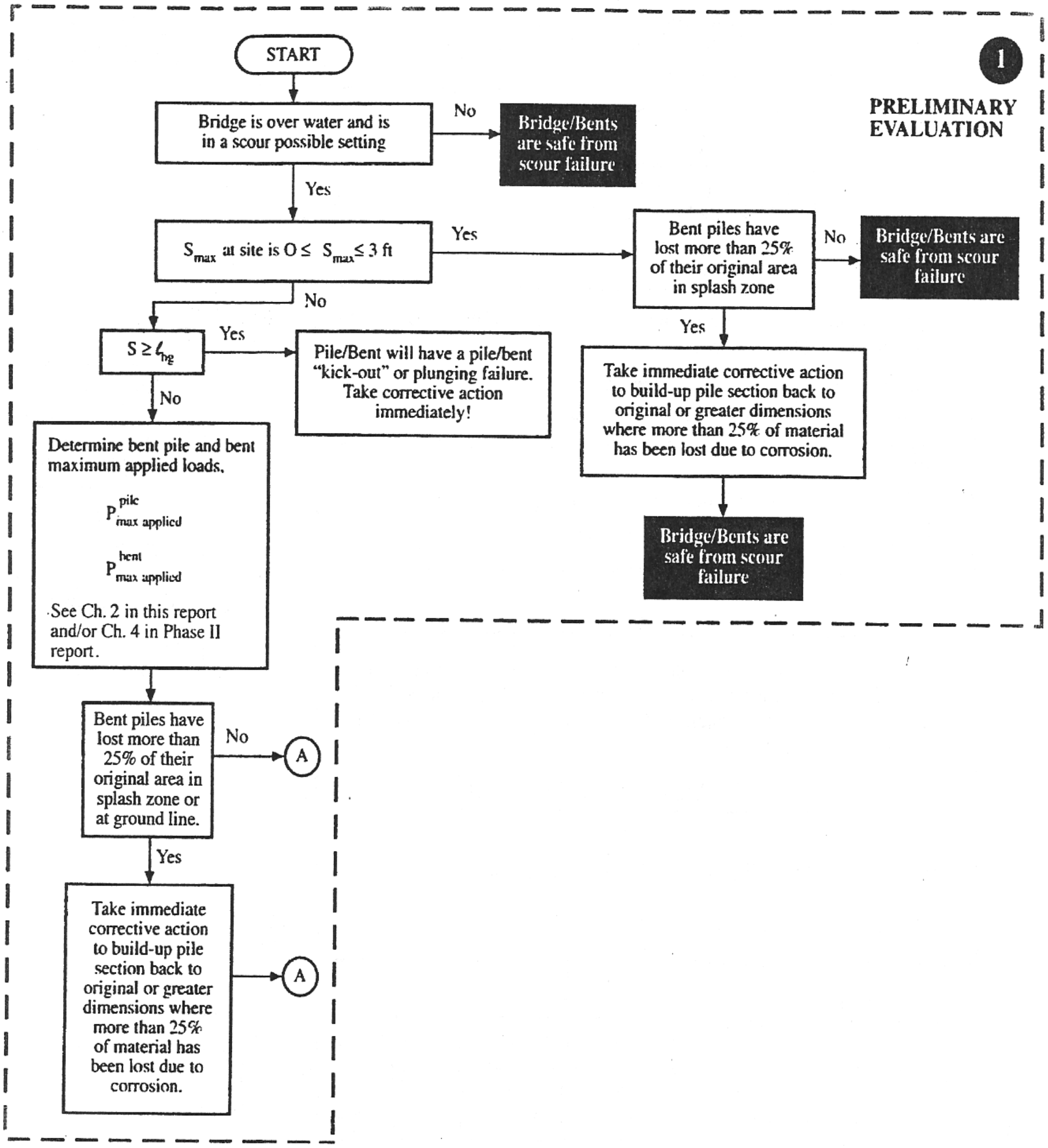


Fig. 4.2. Enlargement of Preliminary Evaluation Module

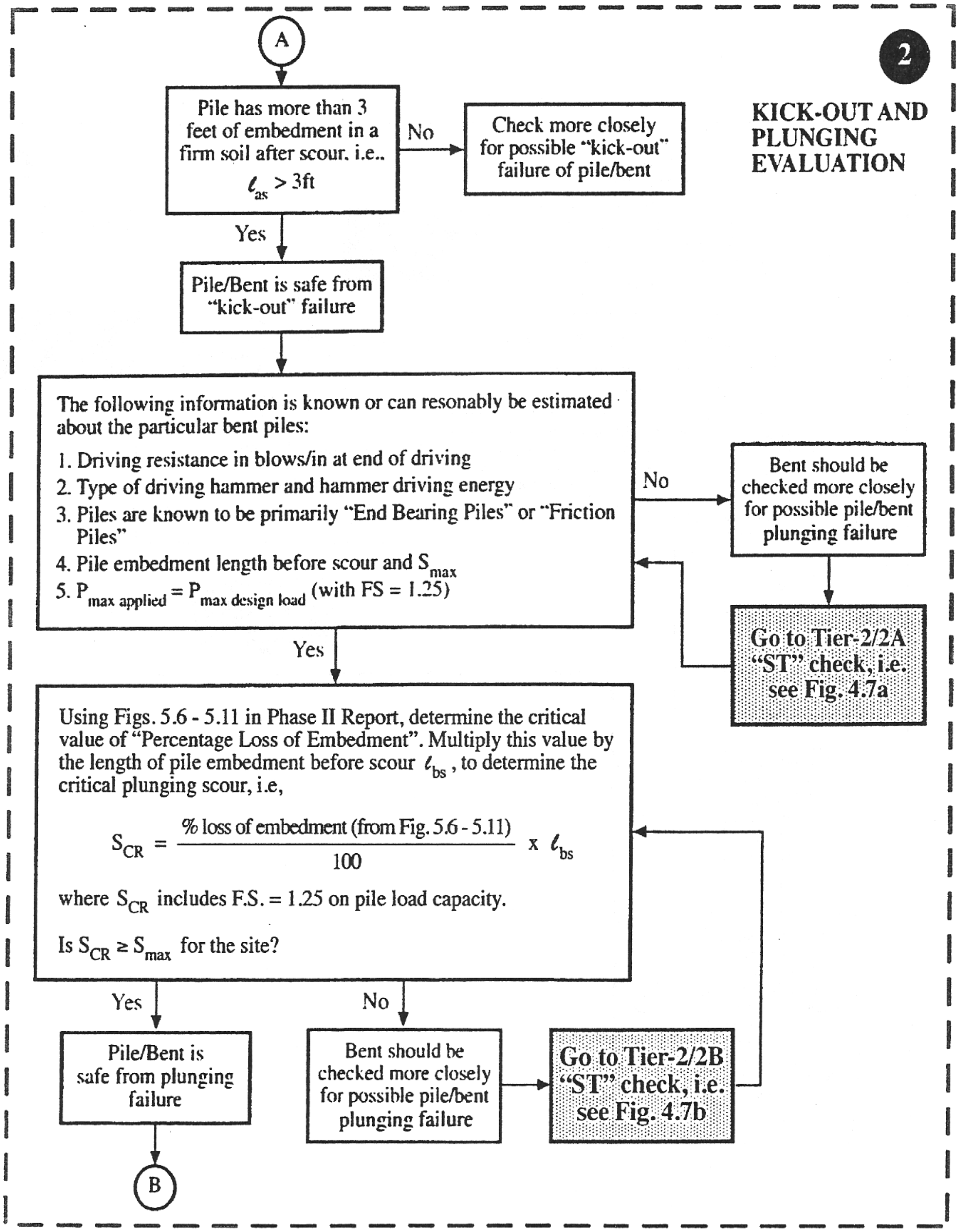


Fig. 4.3. Enlargement of Kick-Out and Plunging Evaluation Module

Block 3 of the Refined “ST”, the Buckling Evaluation Module, is shown in enlarged form in Fig. 4.4. The refinements allow bent buckling adequacy to be assessed for all steel HP pile bents with piles in a single row for any number and size of pile and any depth of embedment after scour in excess of 3 feet. As with the original “ST”, Figs. 4.5a and 4.5b provide labeled dimension values and member definitions including members HB1 and HB2 referred to in Fig. 4.4. Note that Block 3 has been slightly modified to use the parameter X (distance from top of bent cap to lowest horizontal brace) in determining the position of the lowest horizontal brace rather than the parameter “E” and 4 ft.

Block 4 of the Refined “ST”, the Bent Pushover Evaluation Module, is shown in enlarged form in Fig. 4.6. The refinements in this module are the most sweeping and significant of all. In refining the “ST” pushover load assessment during this Phase III work, the effects of additional P-load levels and distributions, scour levels and distributions, and height of pushover loading on bent pushover adequacy were performed via evaluation of bent pushover loads for these conditions using GTSTRUDL. These new pushover load evaluations are shown in tables and figures in Chapter 2. A user of the “ST” can continue to use the original “ST” in evaluating bent pushover adequacy and still be conservative. However, the additional pushover load tables generated in this Phase III work provide a more accurate assessment of pushover adequacy under a larger range of bridge/bent conditions.

As can be seen in Fig. 4.6, the refined Block 4 identifies at the beginning a condition of no bent debris raft forming and proceeds to show the pushover

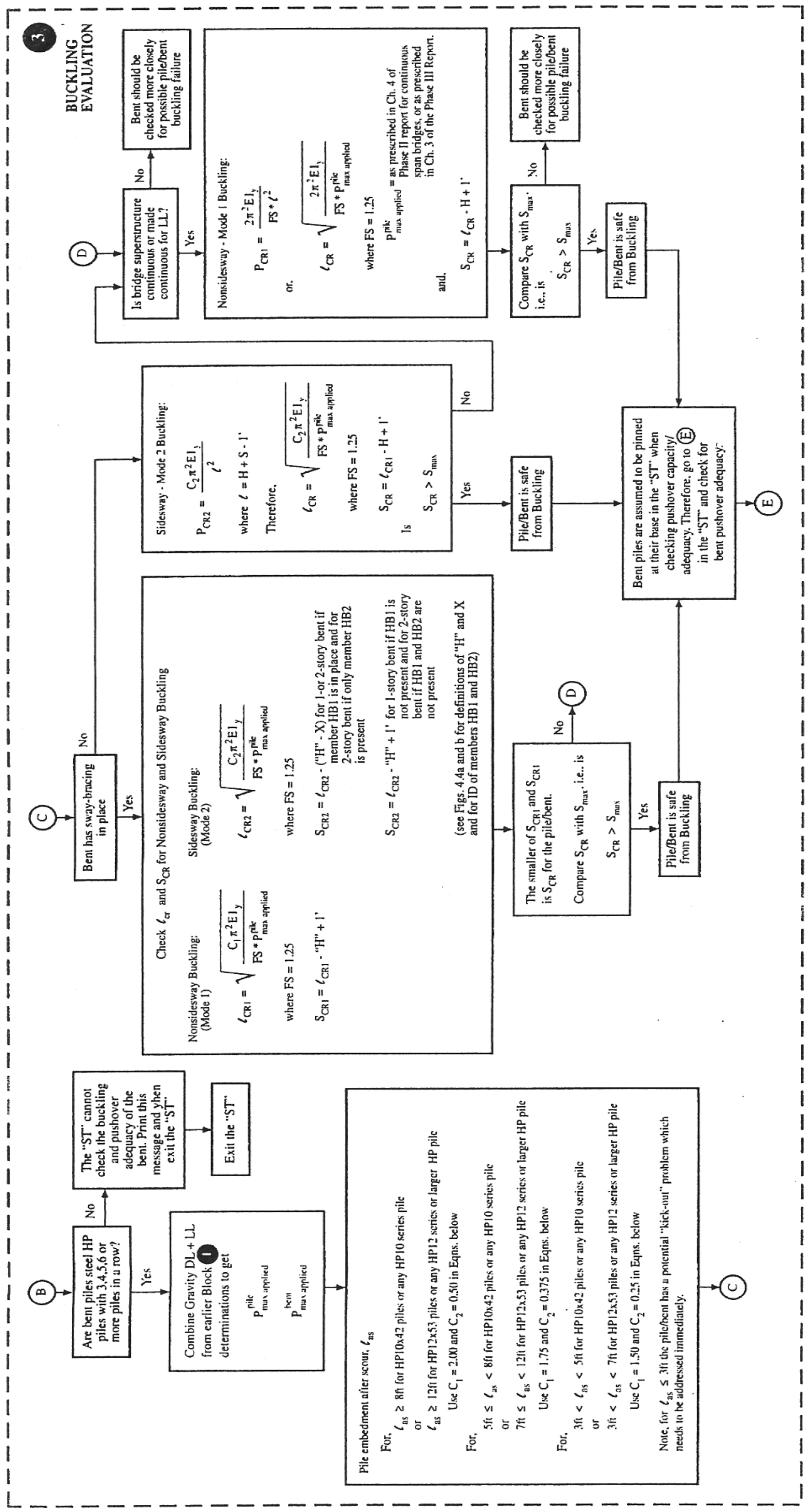
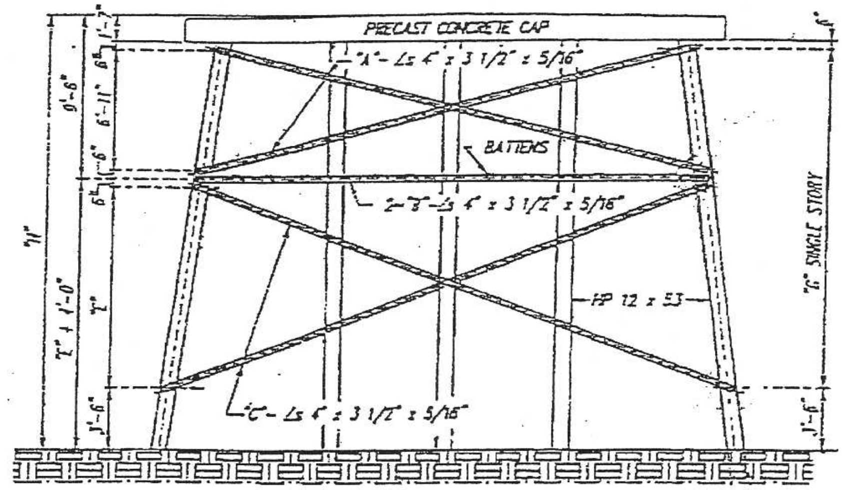


Fig. 4.4 Enlargement of Refined Buckling Evaluation Module



SWAYBRACING DETAILS

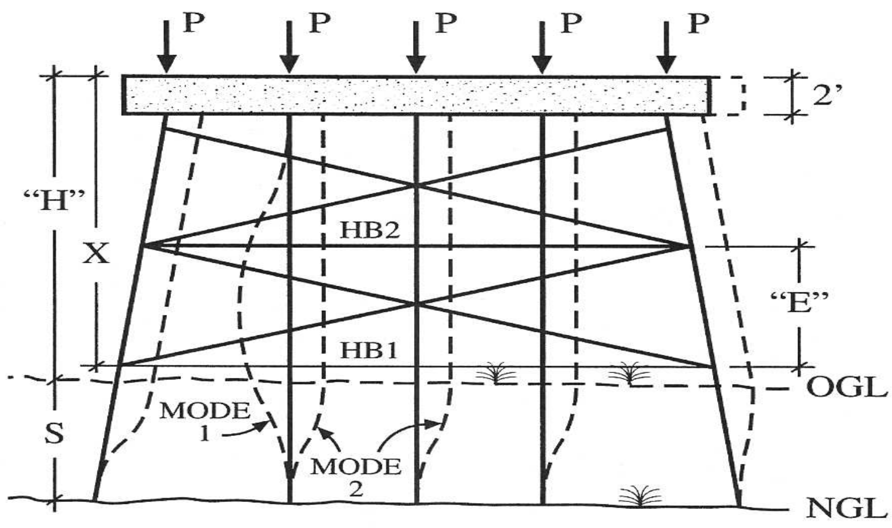
TWO STORY BENT SWAYBRACING TABLES					
"H"	"E"	"A"	"B"	"C"	WT. LBS.
20'-0"	6'-1"	29'-10"	30'-0"	31'-6"	1407
21'-0"	7'-1"	29'-10"	30'-0"	31'-10"	1412
22'-0"	8'-1"	29'-10"	30'-0"	32'-2"	1417
23'-0"	9'-1"	29'-10"	30'-0"	32'-7"	1423
24'-0"	10'-1"	29'-10"	30'-0"	33'-0"	1430
25'-0"	11'-1"	29'-10"	30'-0"	33'-5"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

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

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

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

Fig. 4.5a. Typical ALDOT X-Braced Pile Bent Geometry



X=Vertical Distance in Feet From Top of Bent Cap
To the Lowest Horizontal Brace (HB)

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

$$P_{CR1} \approx \frac{C_1 \pi^2 EI_y}{l_{CR1}^2} \qquad \text{where } l_{cr1} = S+\text{"H"}-1' \tag{4.1}$$

Buckling Mode 2 - Sidesway (lower portions of piles)

$$P_{CR2} \approx \frac{C_2 \pi^2 EI_y}{l_{CR2}^2} \tag{4.2}$$

Where:

l_{cr2} =S+("H"-X) for 1 or 2-story bent if member HB1 is present and for 2-story bent if only member HB2 is present

l_{cr2} =S+("H"-1') for 1-story bent if HB1 is not present and for 2-story bent if HB1 and HB2 are not present

Fig. 4.5b. Transverse Buckling Modes and Equations for X-Braced Bents

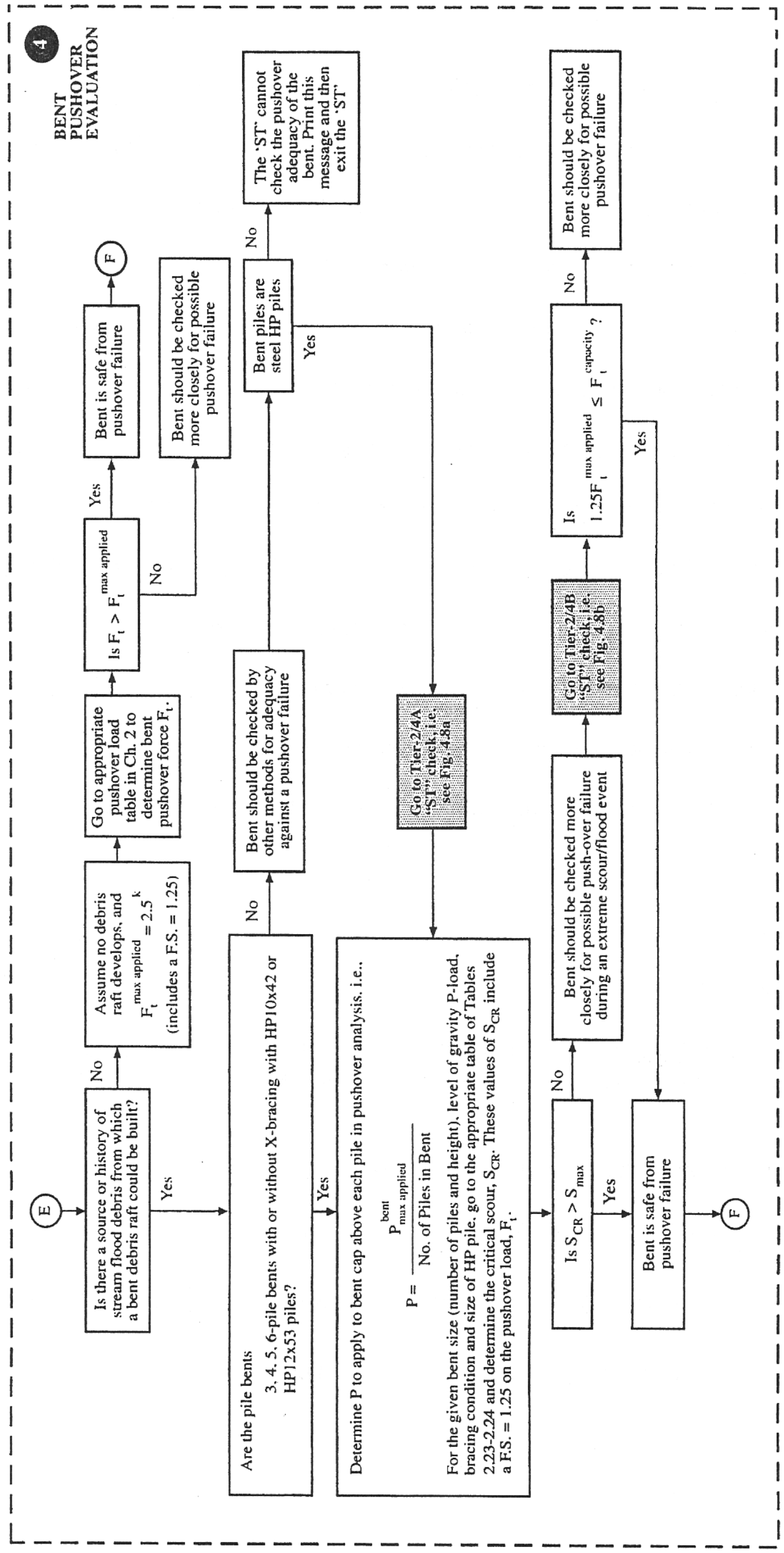


Fig. 4.6. Enlargement of the Bent Pushover Evaluation Module

check for this condition. Also, the refined Block 4 identifies two 2nd tier screenings (Tier-2/4A and Tier-2/4B) for bents that do not successfully pass through the original "ST". By executing these refinements, it is anticipated that many more bents will be determined to be adequate without requiring full-blown structural stability analyses.

As indicated earlier, Block 5 has been added to the refined/2nd edition "ST" and is shown in enlarged form in Fig. 4.7. This module involves a check for possible failure of the upstream pile as a beam-column due to a combined axial P-load and a lateral flood water loading, F_t, acting on a debris raft formed at an elevation of 9.5 ft below the top of the bent cap (see Fig. 2.36). It should be noted that if the debris raft forms at or near the top of the bent, then bent pushover failure would govern. If the bent is X-braced, the bracing will serve to distribute the force F_t to all of the piles in the bent and the piles and bent will be adequate for the lower position of the F_t load. Also, if the bent piles are HP piles larger than HP_{10x42}, then the upstream pile will be safe for the beam-column loading. Thus, the possibility of a beam-column failure of the upstream bent pile only occurs when the bent piles are

- HP_{10x42} or smaller
- Unbraced
- Loaded with the F_t loading at an elevation of 9 ft or more (debris raft forming at elevation 7 ft or more) below the top of the bent cap.

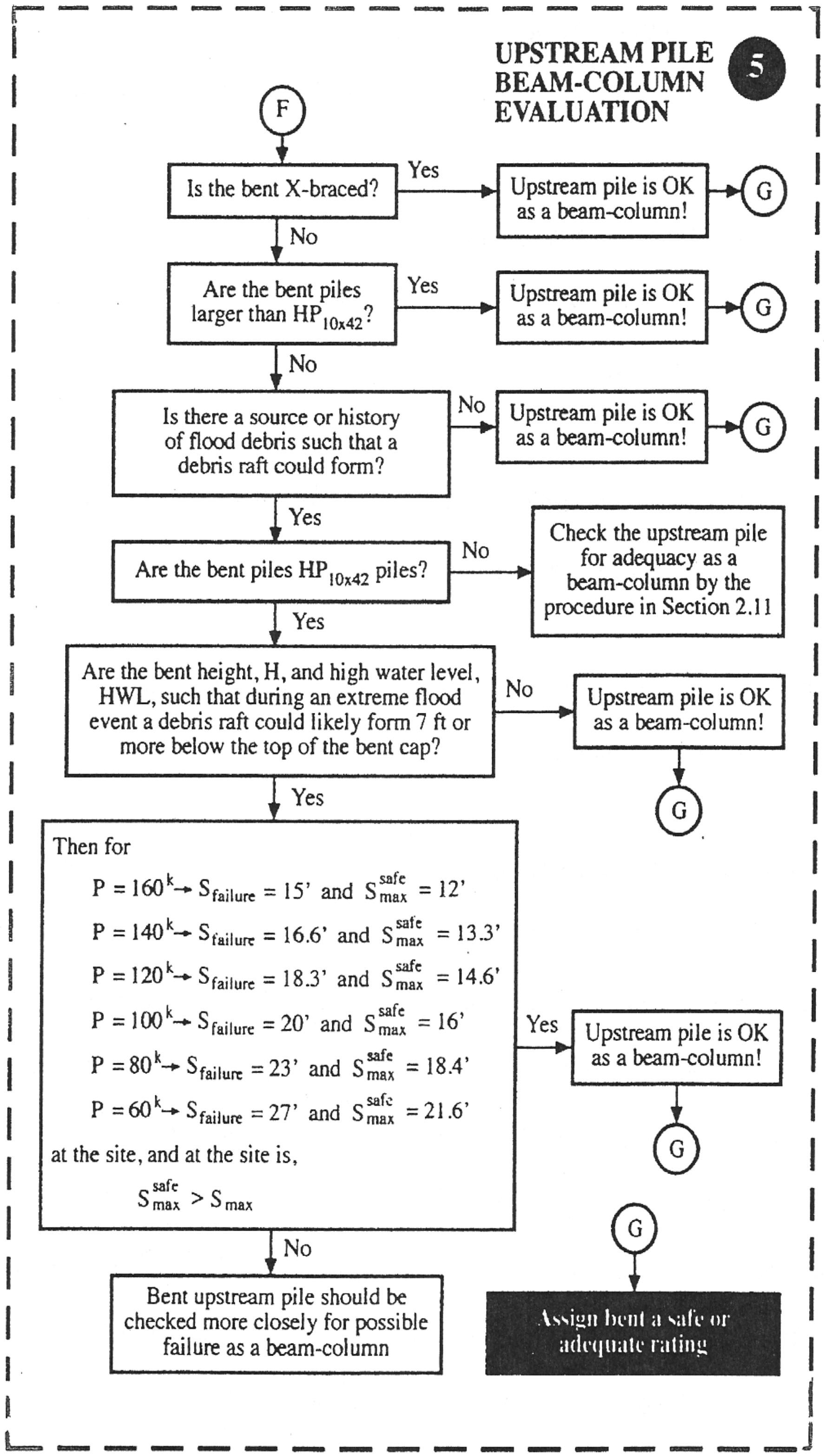


Fig. 4.7. Enlargement of Upstream Pile Beam-Column Evaluation Module

These conditions are included in Block 5 which, for conditions where a beam-column failure is possible, guides the user through a determination of the $S_{failure}$ level and then a conversion of this value to a S_{max}^{safe} by dividing $S_{failure}$ by a F.S.=1.25. In turn, S_{max}^{safe} is compared with the S_{max} anticipated at the site to determine the adequacy of the upstream bent pile as a beam-column.

4.3 Second Tier/Tier-2 Screening

As indicated in the previous section,

- there are no 2nd tier screening referrals in the Preliminary Evaluation Module, 1.
- there are two 2nd tier screening referrals each in Modules 2 and 4, and these are shown shaded in gray in the 2nd Edition "ST" flowcharts of Fig. 4.3 an 4.6.
- 2nd tier screenings initially identified for Module 3 were combined with 1st tier screenings of the original "ST" into a new refined Module 3 which is shown in Fig. 4.4.

Each of these 2nd tier screenings, as well as the new refined Module 3 (Buckling Module) are presented and discussed below.

4.3.1 Pile Plunging Evaluation 2nd Tier Screening

Second-tier pile/bent plunging screenings are recommended for the shaded/gray referral blocks in the "ST" Flowchart shown in Module 2 in Figs. 4.1 and 4.3. Second-tier screening for bents for which complete information about the bent pile-driving system are not known, i.e., Tier- 2/2A screening, is described in Fig. 4.8a. In this second-tier screening, the most conservative or most probable conservative values of the missing information are assumed, and the user is returned to continue executing the "ST".

Second-tier screening for bents that do not pass the $S_{cr} \geq S_{max}$ check in the pile plunging evaluation, i.e., Tier-2/2B screening, are described in Fig. 4.8b. In this second tier screening, a new and probably less conservative $P^{pile}_{max\ applied}$ is determined for the pile being investigated. It should be noted that after executing the Tier-2/2 screenings, the user should return to, and continue executing, the ST.

4.3.2 Pile Buckling Evaluation 2nd Tier Screening

Second-tier screenings were initially added to the buckling evaluation module, i.e., Block 3, to allow expanded screening for additional sizes of HP pile bents, numbers of HP piles, and depths of pile embedment after scour. However, this procedure was later changed to combining the 2nd tier and 1st tier screenings into just one buckling evaluation module, i.e., the refined Block 3 screening which is shown in Figs. 4.1 and 4.4. The refined buckling evaluation module allows bent buckling adequacy evaluation for all steel HP pile bents with any number of piles in a single row, and for any depth of pile embedment after scour in excess of 3 feet. It should be noted that if the depth of embedment after scour, ℓ_{as}, is less than or equal to 3 feet, then the "ST" will indicate a possible "kick-out" failure may occur. If the bent is determined to be adequate for buckling, then the refined 'ST' moves forward to checking the bent adequacy for pushover failure.

If lack of information regarding the bent pile driving system in Block 2 of the "ST" causes exit of the ST to Tier-2/2A ST check, do the following:

- If driving resistance at end of driving (EOD) is unknown, assume a Final Driving Resistance = 5 blows/inch.

- If type of driving hammer and hammer driving energy is unknown, assume a 6 ft-kip hammer driving energy.

- If it is unknown whether piles are primarily "End Bearing" or "Friction", assume the piles are primarily "Friction Piles".

- After making one or all of the assumptions above, return to the ST at the point/block of exit and continue executing the ST.

Fig. 4.8a. Tier-2/2A Screening for Pile Plunging Adequacy Assessment

In recognition of the facts that,

- the most heavily loaded pile in a bent will get "lean-on" plunging support from the adjacent piles in the bent
- for continuous span bridges, the most heavily loaded bent will get "lean-on" support from the adjacent supports/bents
- the loading of all possible Design Traffic Lanes (see Table 3.1 in Phase III-Screening Tool Users Guide) with LL when a bridge only has two actual traffic lanes is unreasonable for an extreme flood/scour event

it is recommended that $P^{pile}_{max\ applied}$ be redetermined as follows:

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

Return to the ST at the point/block shown in Fig. 4.1 and continue executing the ST.

Fig. 4.8b. Tier-2/2B Screening for Pile Plunging Adequacy Assessment

4.3.3 Bent Pushover Evaluation (Block 4) 2nd Tier Screening

Second-tier bent pushover screenings are recommended for the shaded/gray referral blocks in Block 4 of Fig. 4.1. The 2nd tier screening regarding the number and size of the bent piles, i.e. Tier-2/4A screening, is given in Fig. 4.9a. Second-tier screening for bents that do not pass the $S_{cr} > S_{max}$ check in the bent pushover evaluation, i.e., Tier-2/4B screening, is described in Fig. 4.9b. It should be noted in Fig. 4.8b that, for continuous bridges, the lateral flood water loading acting on a bent is reduced, and thus the pushover capacity of the bent can likewise be reduced and still be adequate. The bent pushover capacities for various continuous-span superstructures are given in Section 2.4 of this report.

4.4 Closure

In this Phase III work, improvements and refinements in the “ST” have been made and are included in the refined/2nd edition “ST” presented in Section 4.2. It should be noted in Section 4.2 that an additional possible mode of bent failure and a check for the same, i.e., failure of the upstream bent pile as a beam-column, has been added to the “ST”. This failure mode is only possible for unbraced bents with HP_{10x42} or smaller piles where the lateral flood water loading, F_t, can be applied at an elevation of 9 ft or more below the top of the bent cap. The author views this 2nd edition “ST” as being the basic “ST” that should be applied to all of ALDOT’s steel pile bent supported bridges that are exposed to extreme flood/scour events.

If the bent is not a 3, 4, 5, or 6-pile bent with or without X-bracing with HP_{10x42} or HP_{12x53} piles, do the following:

- Bents with more than 6 HP piles of any size in a row, whether braced or unbraced, have adequate pushover capacity for maximum scour levels anticipated anywhere in Alabama, and thus are safe for pushover.

- For bents with HP_{10x57} piles, check the bent pushover adequacy by treating it as a HP_{10x42} pile bent.

- For bents with $HP_{12x(63, 74, 84)}$ or larger HP piles, check the bent pushover adequacy by treating it as a HP_{12x53} pile bent.

- Bents with piles as large or larger (based on the pile $I_y$value), than HP_{12x53} with 5 or more piles have adequate bent pushover capacity for the maximum scour levels anticipated anywhere in Alabama, and thus are safe for pushover.

Fig. 4.9a Tier-2/4A Screening for Bent Pushover Adequacy Assessment

For bents not passing the $S_{cr} > S_{max}$ requirement for pushover adequacy, do the following:

a. Use the expanded bent pushover capacity tables and information in Chapter 2, i.e.,

- Pushover loads for nonuniform scour distribution
- Pushover load for debris raft at lower height level on the bent
- Reduced flood water loading due to no debris raft forming
- Reduced lateral load due to a continuous superstructure as appropriate to determine more refined values of both, the maximum applied lateral load on the bent, and the bent pushover capacity.

b. Check to see if,

$$F_t^{max\ applied} \times \underbrace{1.25}_{F.S.} \leq F_t^{capacity}$$

c. If $F_t^{max\ applied} \times 1.25 \leq F_t^{capacity}$, the bent is adequate for pushover.

If $F_t^{max\ applied} \times 1.25 > F_t^{capacity}$, the bent is not adequate and should be checked more closely for possible pushover failure.

Fig. 4.9b Tier-2/4B Screening for Bent Pushover Adequacy Assessment

For those bridges/bents with steel HP pile bents that failed to pass the original “ST” screening process because of pile size or number of piles in the bent, and for the steel HP pile bents that fail to pass the “ST” screening process for a lack of adequate capacity in the areas checked by the “ST”, the second tier, or Tier-2, screening process developed in this work should be applied. This Tier-2 screening process is presented in Section 4.3. Only those bridges with steel HP pile bents that did not check out to be adequate via the original “ST” should be subjected to this second tier or Tier-2 screening. Bents not checked via the “ST” to date, should be checked using the Phase III refined “ST”.

It is anticipated that the Tier-2 screening will find many of the bridges/bents that failed to pass the initial “ST” to be adequate. Those bridges/bents not found to be adequate via the follow-up Tier-2 screening should be analyzed more closely via a comprehensive structural stability analysis for the maximum flood/scour event that can occur at the bridge site.

CHAPTER 5: EXAMPLE APPLICATIONS OF THE TIER-2 "ST"

5.1 General

As indicated in Chapter 4, there are no 2^{nd} tier screening referrals in the original or refined "ST" in the Preliminary Evaluation Module (Module 1), and thus there are no Tier-2 screenings for this module. Also, in the Kick-Out and Plunging Evaluation Module (Module 2), there are no changes in the "ST" regarding the check for "kick-out" failure and there are no Tier-2 screenings for those piles/bents identified as possibly having a "kick-out" failure problem. However, for piles/bents identified in the refined "ST" as possibly having a pile plunging or a bent pushover failure problem, the refined "ST" refers the user to a 2^{nd} level of screening, i.e., Tier-2 screening, in checking for these possible failure modes. As indicated earlier, for pile buckling checks, 2^{nd} level screenings have been implicitly incorporated into the buckling evaluation module, and thus, there are no explicit Tier-2 screenings for buckling. It is anticipated that the Tier-2 screenings will be able to determine that many of the piles/bents sent to this 2^{nd} level of screening are adequate and do not need to be checked further.

The original "ST" Reports included example checks for failure via pile plunging, pile buckling, and bent pushover. In the following sections, example applications are given for the refined "ST", Tier-2 plunging and pushover failure checks, and for checking of the upstream pile for possible failure as a beam-column. These examples focus on the Tier-2 screening process. They are designed to assist a user starting at a point at which the original "ST" has indicated that "the piles/bent should be looked at more closely for a possible failure". The Tier-2 screening constitutes the first step, and in many cases the only step needed, in the "…bent should be looked at more closely…" process.

5.2 Bent/Site Conditions to Check for Need/Applicability of the "ST"

Just as with the original ST, the questions below should be answered at the very beginning to determine the need to apply the Refined ST, or to determine the applicability of the Refined ST to the bridge bent/site under investigation. In certain situations, the Refined ST refers the user to Tier-2 screenings. Also, it should be noted that Question 4 below expands the range of applicability of the Refined ST to all steel HP pile bents.

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

   If answer is No, the bridge bents do not need to be checked by the ST.

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

   If answer is Yes, the bridge bents do not need to be checked by the ST.

3. Is the bridge at a site where the maximum estimated scour, S_{max}, is greater than the pile embedment length, 1_{bg}, i.e., is $S_{\max} \ge 1_{bg}$?

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

4. Are the bridge pile bents 3, 4, 5, 6, 7, 8-pile (or more) bents with piles in a single row with or without X-bracing and with the piles being steel HP piles?

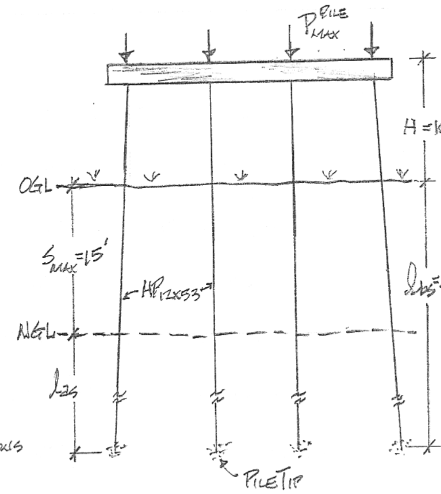
If the answer is No, the bridge bents cannot be checked by the ST.

5.3 Example Applications for Tier-2 Pile Plunging Failure Check

Given below are some example applications of the refined/2nd edition "ST" checks for possible pile/bent plunging and kick-out failures. It should be noted that the refined "ST" is the same as the original "ST" regarding checking for pile/bent "kick-out" failure, i.e., checking to make sure that the bent piles have more than 3 ft of embedment in a firm soil after scour to be safe from a kick-out failure. However, for the pile plunging check, the refined "ST" includes two Tier-2 pile-plunging checks, and these are emphasized in Examples 1 and 2 below.

EXAMPLE 1

CHECK THIS UNBRACED 4-PILE BENT FOR PLUNGING & "KICK-OUT."



GIVEN:

PILE TYPE/SIZE = HP12x53

$P^{PILE}_{MAX\ APPLIED} = 80^{k}$

$P^{PILE}_{NEEDED\ CAPACITY} = F.S. \times P^{PILE}_{MAX\ APPLIED}$

$= 1.25 \times 80^{k} = 100^{k} = 50$ TONS

$S_{MAX} = 15$ ft

$l_{bs} = 40'$

PILE DRIVING HAMMER ENERGY = 10 ft-k

$l_{as} = l_{bs} - S_{MAX} = 40 - 15 = 25$ ft

DRIVING RESISTANCE AT END OF DRIVING = UNKNOWN

PILES ARE PRIMARILY "END BEARING" OR "FRICTION" = UNKNOWN

PLUNGING & KICK-OUT CHECK:

NOTE, IF MOST HEAVILY LOADED PILE IN THE BENT IS ADEQUATE FOR PLUNGING, THEN THE BENT IS ADEQUATE FOR PLUNGING.

FOLLOWING THE "ST" MODULE ②,

$l_{as} = 25$ ⇒ ∴ $l_{as} > 3$ ft ⇒ ∴ PILE/BENT IS SAFE FROM "KICK-OUT"

DRIVING RESISTANCE AT EOD IS UNKNOWN.
PILES ARE PRIMARILY "END BEARING" OR "FRICTION" IS UNKNOWN.

∴ GO TO TIER-2/2A "ST" CHECK (SEE NEXT PAGE)

ASSUME DRIVING RESISTANCE AT EOD = 5 BLOWS/INCH

ASSUME PILES ARE "FRICTION PILES".

RETURN TO "ST" AND CONTINUE TO CHECK ADEQUACY.

USING FIG. 5.10 (SEE NEXT PAGE), FOR 50 TON CAPACITY (WITH FS INCLUDED) THE MAX % LOSS OF EMBEDMENT IS, 42%

OR $0.42 \times 40' = 16.8$ ft.

∴ $S_{MAX\ ACCEPTABLE} = 16.8$ ft $= S_{CR}$

∴ $S_{CR} > S_{MAX}$ ⇒ PILE/BENT IS ADEQUATE FOR PLUNGING

Fig. 5.1. Example Problem 1 for Kick-Out and Plunging

Ex. 1 Cont'd.

If lack of information regarding the bent pile driving system in Block ② of the ST causes exit of the ST to Tier-2/2A ST check, do the following:

- If driving resistance at end of driving (EOD) is unknown, assume a Final Driving Resistance = 5 blows/inch.
- If type of driving hammer and hammer driving energy is unknown, assume a 6 ft-kip hammer driving energy.
- If piles are primarily "End Bearing" or "Friction" is unknown, assume the piles are primarily "Friction Piles".
- After making one or all of the assumptions above, return to the ST at the point/block of exit and continue executing the ST.

Fig. 4.7a. Tier-2/2A Screening for Pile Plunging Adequacy Assessment

Fig. 5.2. Example Problem 1 for Kick-Out and Plunging (Continued)

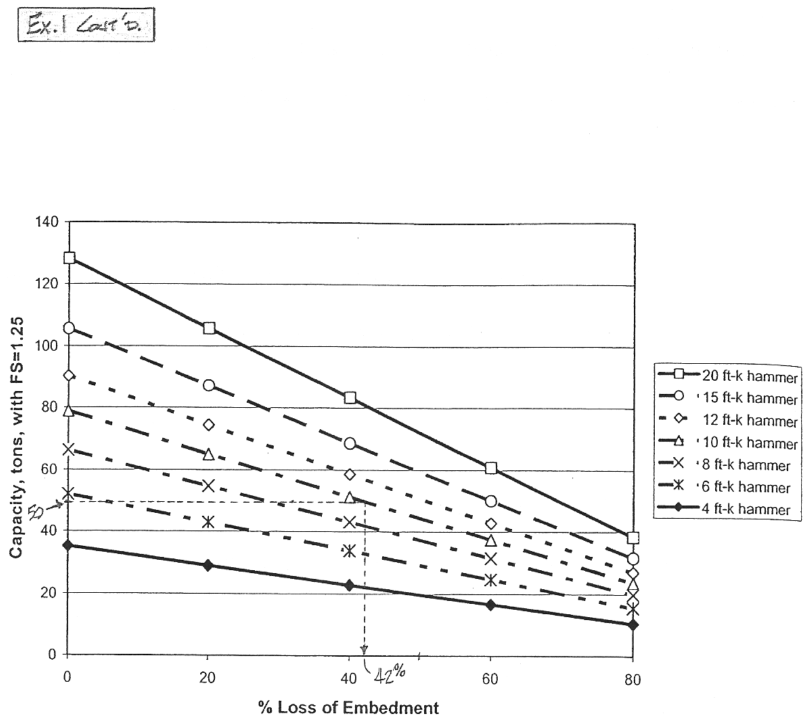
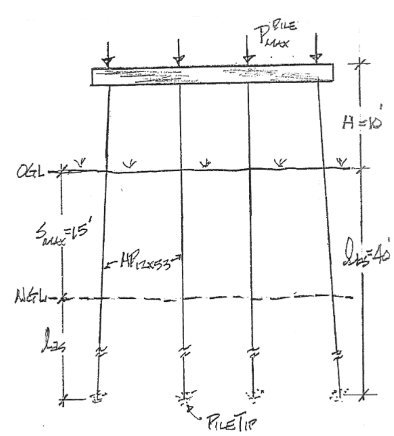


Figure 5.10. Friction Piles, 5 blows/inch Driving Resistance at End of Driving

Fig. 5.3. Example Problem 1 for Kick-Out and Plunging (Continued)

EXAMPLE 2

CHECK THIS UNBRACED 4-PILE BENT FOR PLUNGING.



GIVEN:

BENT GEOMETRY, DIMENSIONS, AND SETTING AS SHOWN AT THE RIGHT.

$P^{PILE}_{MAX\ APPLIED} = 64^k$

$P^{PILE}_{NEEDED\ CAPACITY} = F.S. \times P^{PILE}_{MAX\ APPLIED}$
$= 1.25 \times 64^k = 80^k = 40$ TONS

$S_{MAX} = 15$ ft

$l_{bs} = 40$ ft

$l_{as} = l_{bs} - S_{MAX} = 40' - 15' = 25$ ft

PILE DRIVING RESISTANCE AT END OF DRIVING (EOD) = UNKNOWN

TYPE OF DRIVING HAMMER AND HAMMER DRIVING ENERGY = UNKNOWN

PILES ARE "END BEARING" OR "FRICTION" = UNKNOWN

PLUNGING CHECK:

NOTE, IF THE MOST HEAVILY LOADED PILE IS ADEQUATE FOR PLUNGING, THEN THE BENT IS ADEQUATE FOR PLUNGING.

FOLLOWING THE "ST" PLUNGING EVALUATION MODULE, i.e., MODULE ②,

- DRIVING RESISTANCE AT EOD IS UNKNOWN ⇒ GO TO TIER-2/2A "ST" CHECK (SEE ATTACHED FIGS.)
  ASSUME FINAL DRIVING RESIST. = 5 BLOWS/IN
- DRIVING HAMMER/ENERGY IS UNKNOWN ⇒ GO TO TIER-2/2A "ST" CHECK (SEE ATTACHED FIG. A.?)
  ASSUME 6 ft-kip HAMMER ENERGY
- PRIMARY "END BEARING" OR "FRICTION" PILE IS UNKNOWN ⇒ GO TO TIER-2/2A "ST" CHECK
  ASSUME PRIMARY "FRICTION PILES"
- RETURN TO "ST"
- USE FIG 5.10 (IN PHASE II REPORT) FOR FRICTION PILES AND 5 BLOWS/IN AND 6 ft-k HAMMER (SEE ATTACHED FIG)

  FOR $P^{PILE}_{CAPACITY} = 40$ TONS (WITH F.S. = 1.25)

  % LOSS OF EMBEDMENT = 25 %

  $\therefore S_{MAX\ ACCEPTABLE} = 0.25 \times l_{bs} = 0.25 \times 40' = 10$ ft $= S_{CR}$

Fig. 5.4. Example Problem 2 for Plunging

EX. 2 CONT'D.

- IS $S_{CR} > S_{MAX}$? → 10' ≯ 15' → ∴ CHECK MORE CLOSELY

- GO TO TIER-2/2B "ST" CHECK (SEE ATTACHED FIG. 4.7b)

- FROM FIG. 4.7b, ASSUME THE BRIDGE WIDTH IS SUCH THAT $P_{MAX\ APPLIED}$ USING THE NUMBER OF ACTUAL LANES IS LESS THAN CALCULATED EARLIER USING THE NUMBER OF DESIGN LANES (SEE TABLE 3.1 ATTACHED), AND/OR THE BRIDGE IS CONTINUOUS RATHER THAN SS (SEE TABLE 3.2 ATTACHED), AND UPON REDETERMINATION,

$$P^{BENT}_{MAX\ APPLIED} = 268^{K} = 134 \text{ TONS (WITH A F.S.} = 1.25)$$

$$P^{PILE}_{MAX\ APPLIED} = \frac{268}{4} = 67^{K} = 33.5 \text{ TONS (WITH A F.S.} = 1.25)$$

- RETURN TO FIG. 5.10 (ATTACHED),

FOR $P^{PILE}_{CAPACITY} = 33.5$ TONS (WITH F.S. = 1.25)

% LOSS OF EMBEDMENT = 38%

$\therefore S_{MAX\ ACCEPTABLE} = 0.38 \times l_{bs} = 0.38 \times 40' = 15.2 \text{ ft} = S_{CR}$

- IS $S_{CR} > S_{MAX}$? → 15.2' > 15' → YES

∴ PILE/BENT IS ADEQUATE FOR PLUNGING

Fig. 5.5. Example Problem 2 for Plunging (Continued)

Ex. 2 Cont'd.

If lack of information regarding the bent pile driving system in Block ② of the ST causes exit of the ST to Tier-2/2A ST check, do the following:

→ • If driving resistance at end of driving (EOD) is unknown, assume a Final Driving Resistance = 5 blows/inch.

→ • If type of driving hammer and hammer driving energy is unknown, assume a 6 ft-kip hammer driving energy.

→ • If piles are primarily "End Bearing" or "Friction" is unknown, assume the piles are primarily "Friction Piles".

→ • After making one or all of the assumptions above, return to the ST at the point/block of exit and continue executing the ST.

Fig. 4.7a. Tier-2/2A Screening for Pile Plunging Adequacy Assessment

Fig. 5.6. Example Problem 2 for Plunging (Continued)

Ex. 2 Con't'd.

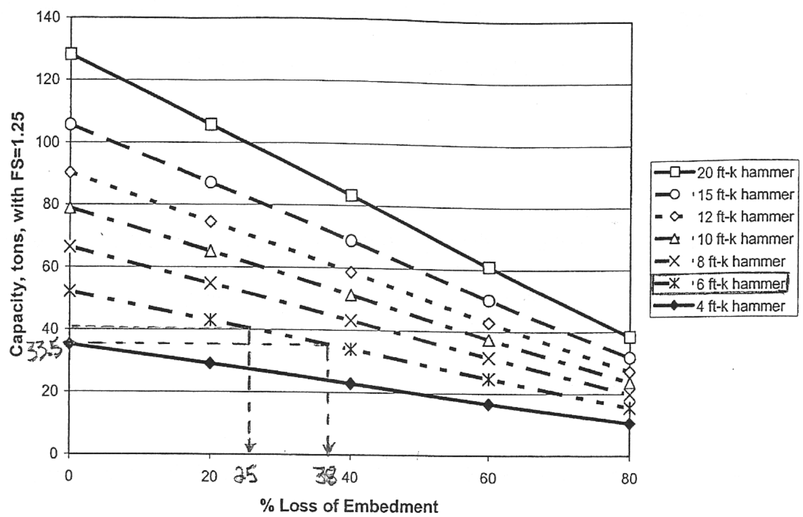


Figure 5.10. Friction Piles, 5 blows/inch Driving Resistance at End of Driving

Fig. 5.7. Example Problem 2 for Plunging (Continued)

Ex. 2 Cont'd.

In recognition of the facts that,

- the most heavily loaded pile in a bent will get "lean-on" plunging support from the adjacent piles in the bent
- for continuous span bridges, the most heavily loaded bent will get "lean-on" support from the adjacent supports/bents
- the loading of all possible Design Traffic Lanes (see Table 3.1 in Phase III-Screening Tool Users Guide) with LL when a bridge only has two actual traffic lanes is unreasonable for an extreme flood/scour event

it is recommended that $P^{pile}_{max\ applied}$ be redetermined as follows:

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

Return to the ST at the point/block shown in Fig. 4.6 and continue executing the ST.

Fig. 4.8b. Tier-2/2B Screening for Pile Plunging Adequacy Assessment

Fig. 5.8. Example Problem 2 for Plunging (Continued)

Ex. 2 Cont'd.

Table 3.1 Design Traffic Lanes (8)

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

Table 3.2 Bridge Girder Maximum Reactions for SS and Equal Span Continuous Bridges Under Uniform Loads

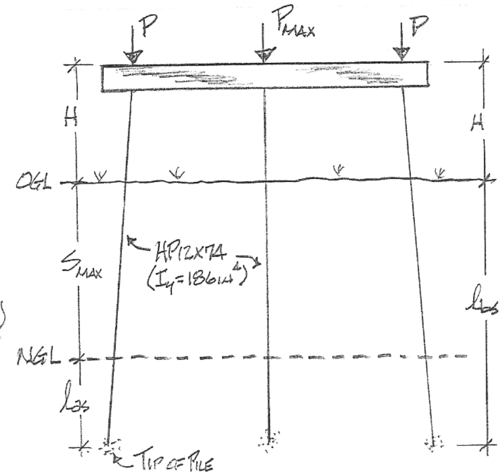
Bridge/Girder Support Condition	R^{DL}_{Max}	R^{LL}_{Max}
SS	$1.0\ \omega_{DL}\ell$	$1.0\ \omega_{LL}\ell$
2-Span Continuous	$1.25\ \omega_{DL}\ell$	$1.25\ \omega_{LL}\ell$
3-Span Continuous	$1.10\ \omega_{DL}\ell$	$1.20\ \omega_{LL}\ell$
4-Span Continuous	$1.15\ \omega_{DL}\ell$	$1.22\ \omega_{LL}\ell$
5 -Span Continuous (or larger)	$1.15\ \omega_{DL}\ell$	$1.22\ \omega_{LL}\ell$

Fig. 5.9. Example Problem 2 for Plunging (Continued)

5.4 Example Applications for Tier-2 Pile Buckling Failure Check

Applications of the refined “ST” buckling check are given in Examples 3, 4, and 5 below. The examples focus on using the expansions and refinements made in the refined “ST” buckling check module. As indicated earlier, 2nd-tier screening has been implicitly included in the refined buckling check module.

EXAMPLE 3



CHECK THIS UNBRACED 3-PILE BENT FOR BUCKLING ADEQUACY.

GIVENS:

Pile Type/Size = HP12X74 ($I_y = 186\,in^4$)

$P_{MAX}^{PILE} = 100^k$

$H = 10$ ft

$l_{bs} = 30$ ft

$S_{MAX} = 20$ ft

$l_{as} = 30' - 20' = 10$ ft

F.S. = 1.25

BUCKLING CHECK:

NOTE, IF MOST HEAVILY LOADED PILE IN THE BENT IS ADEQUATE FOR BUCKLING, THEN THE BENT IS ADEQUATE FOR BUCKLING.

FOLLOWING THE "ST" BUCKLING EVALUATION MODULE, i.e., MODULE ③,

BENT PILES ARE NOT HP10X42 OR HP12X53 PILES, BUT ARE HP12 SERIES PILES.

BENT PILES ARE STEEL HP PILES WITH 3 PILES IN A ROW.

$l_{as} = 10'$ → $7' < 10' < 12'$ FOR HP12 SERIES PILES,

∴ $C_1 = 1.75$ AND $C_2 = 0.375$

BENT HAS NO SWAY BRACING → ∴ SIDESWAY – MODE 2 BUCKLING CONTROLS

$$P_{cr2} = C_2 \pi^2 E I_y / l^2 \quad \text{WHERE } l = H + S + 1'$$

$$\therefore l_{cr} = \sqrt{\frac{C_2 \pi^2 E I_y}{FS \times P_{MAX}^{PILE}}} = \sqrt{\frac{0.375 \times \pi^2 \times 29{,}000 \times 186}{1.25 \times 100^k}}$$

$$l_{cr} = 400\text{ in} = 33.3\text{ ft}$$

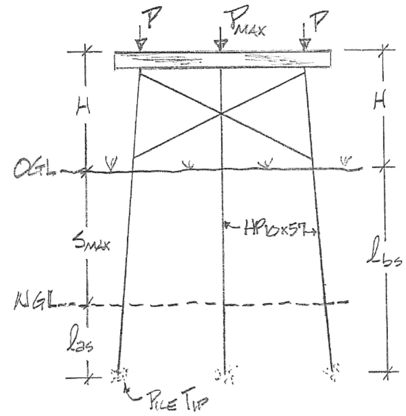
OR, $S_{cr} = l_{cr} - H + 1' = 33.3' - 10' + 1' = 24.3$ ft

$S_{cr} > S_{MAX}$ → ∴ PILE/BENT IS ADEQUATE FOR BUCKLING

Fig. 5.10. Example Problem 3 for Buckling

EXAMPLE 4

CHECK THIS X-BRACED 3-PILE BENT FOR BUCKLING ADEQUACY



GIVEN:

PILE TYPE/SIZE = HP10x57 ($I_y = 101\ in^4$)

$P_{MAX}^{PILE} = 80^k$

$l_{bs} = 22\ ft$

$H = 13\ ft$

$S_{MAX} = 15\ ft$

$l_{as} = 22 - 15 = 7\ ft$

F.S. = 1.25

BUCKLING CHECK:

NOTE, IF MOST HEAVILY LOADED PILE IN THE BENT IS ADEQUATE FOR BUCKLING, THEN THE BENT IS ADEQUATE FOR BUCKLING.

FOLLOWING THE "ST" BUCKLING EVALUATION MODULE, i.e., MODULE ③,

BENT PILES ARE NOT HP10x57 → NOT HP10x42 BUT ARE HP10 SERIES PILES.

BENT PILES ARE STEEL HP PILES WITH 3 PILES IN A ROW.

$l_{as} = 7' \Rightarrow 5' < 7' < 8'$ FOR HP10 SERIES PILES,

$\therefore C_1 = 1.75$ AND $C_2 = 0.375$

BENT HAS SWAY-BRACING $\Rightarrow \therefore$ CHECK NONSIDESWAY & SIDESWAY BUCKLING

$$l_{cr1} = \sqrt{\frac{C_1 \pi^2 E I_y}{F.S. \times P_{MAX}^{PILE}}} = \sqrt{\frac{1.75 \times \pi^2 \times 29{,}000 \times 101}{1.25 \times 80}} = 636'' = 53\ ft$$

$$l_{cr2} = \sqrt{\frac{C_2 \pi^2 E I_y}{F.S. \times P_{MAX}^{PILE}}} = \sqrt{\frac{0.375 \times \pi^2 \times 29{,}000 \times 101}{1.25 \times 80}} = 329'' = 27.4\ ft \leftarrow \text{CONTROLS}$$

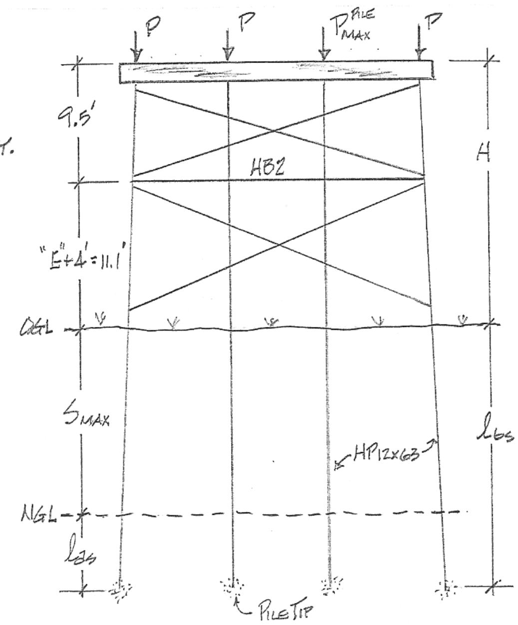
$$S_{cr2} = l_{cr2} - H + 1'$$
$$= 27.4' - 13 + 1 = 15.4\ ft$$

$S_{cr} > S_{MAX} \Rightarrow \therefore$ PILE/BENT IS ADEQUATE FOR BUCKLING

Fig. 5.11. Example Problem 4 for Buckling

EXAMPLE 5

CHECK THIS X-BRACE, 2-STORY, 4-PILE BENT FOR BUCKLING ADEQUACY.



GIVEN:

PILE TYPE/SIZE = HP12x63 (I_y=153 in^4)

$P^{PILE}_{MAX} = 80^k$

H = 21 ft

l_{bs} = 21.5 ft

S_{MAX} = 15 ft

l_{es} = 21.5' − 15' = 6.5 ft

F.S. = 1.25

BUCKLING CHECK:

NOTE, IF MOST HEAVILY LOADED PILE IN THE BENT IS ADEQUATE FOR BUCKLING, THEN THE BENT IS ADEQUATE

FOLLOWING THE "ST" BUCKLING EVALUATION MODULE, i.e., MODULE ③,

BENT PILES ARE NOT HP10x42 OR HP12x53 PILES, BUT ARE HP12 SERIES PILES WITH 4 HP PILES IN A ROW.

$l_{es} = 6.5'$ ⇒ 3' < 6.5' < 7' FOR HP 12 SERIES PILES,

∴ C_1 = 1.50 AND C_2 = 0.25

BENT HAS SWAY-BRACING ⇒ ∴ CHECK NONSIDESWAY & SIDESWAY BUCKLING

$$l_{cr1} = \sqrt{\frac{C_1 \pi^2 E I_y}{F.S. \times P^{PILE}_{MAX}}} = \sqrt{\frac{1.50 \times \pi^2 \times 29{,}000 \times 153}{1.25 \times 80}} = 810.5'' = 67.5 \text{ ft}$$

$$l_{cr2} = \sqrt{\frac{C_2 \pi^2 E I_y}{F.S. \times P^{PILE}_{MAX}}} = \sqrt{\frac{0.25 \times \pi^2 \times 29{,}000 \times 153}{1.25 \times 80}} = 331'' = 27.6 \text{ ft}$$

$S_{cr2} = l_{cr2} - (E'' + 4') = 27.6 - 11.1 = 16.5$ ft ⇐ CONTROLS

$S_{cr1} = l_{cr1} - H + 1 = 67.5' - 21' + 1' = 47.5$ ft

$S_{cr} > S_{MAX}$ ⇒ ∴ PILE/BENT IS ADEQUATE FOR BUCKLING

Fig. 5.12. Example Problem 5 for Buckling

5.5 Example Applications for Tier-2 Bent Pushover Failure Check

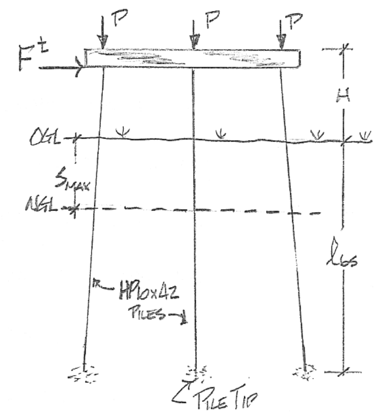
Four example applications of the refined "ST" bent pushover check are given below. The refined "ST" bent pushover check includes several new tables/features that were not available in the original ST such as,

- Lower P-load levels of $P=60^k$ and 80^k acting on the cap
- Reduced P-load levels on the downstream side of bent
- Reduced level of scour in the downstream direction of the bent
- A debris raft not forming at the bent
- A debris raft forming at a lower level on the bent

The refined "ST" also includes two Tier-2 pushover screening checks. Example Applications 6, 7, 8 and 9 below focus on the Tier-2 screening checks as well as on some of the new tables/features mentioned above.

EXAMPLE 6

CHECK THE UNBRACED 3-PILE BENT GIVEN BELOW FOR PUSHOVER ADEQUACY.



UNBRACED 3-PILE BENT

GIVEN:

3-PILE BENT WITH HP10x42 PILES SHOWN AT THE RIGHT.

$P^{BENT}_{MAX} = 300^k \Rightarrow P = \frac{300}{3} = 100^k$

$H = 10$ ft

$S_{MAX} = 10$ ft

$l_{bs} = 40$ ft (EMBEDMENT BEFORE SCOUR)

DEBRIS RAFT CANNOT FORM $\Rightarrow \therefore F^t_{APPLIED} = 2.0^k$

$\therefore F^t_{MAX\ APPLIED} = F.S. \times F^t_{APPLIED}$

$= 1.25 \times 2.0 = 2.5^k$

PUSH-OVER CHECK:

FROM TABLE 2.3a (SEE NEXT PAGE),

$F^t_{CAPACITY} = 4.3^k$

$F^t_{CAPACITY} > F^t_{MAX\ APPLIED}$

$\therefore$ BENT IS SAFE FROM PUSHOVER FAILURE.

Fig. 5.13. Example Problem 6 for Pushover

Ex. 6 Cont'd.

Table 2.3a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with $I_{gross} = 41{,}470\ in^4$ for Varying Values of P-Load and 'H+S'.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	0	10	21.6	20.6	19.6	20.0	18.8	17.6
		5	15	12.9	11.5	10.1	8.9	7.3	5.6
		10	20	8.2	6.3	4.3	2.3	unstable	unstable
		15	25	4.9	2.3	unstable	unstable	unstable	unstable
		20	30	2.0	unstable	unstable	unstable	unstable	unstable
		25	35	unstable	unstable	unstable	unstable	unstable	unstable
	13	0	13	15.6	14.4	13.2	12.4	11.0	9.5
		5	18	9.8	8.2	6.4	4.7	2.8	unstable
		10	23	6.1	3.9	1.5	unstable	unstable	unstable
		15	28	3.1	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable	unstable
		25	38	unstable	unstable	unstable	unstable	unstable	unstable
4	10	0	10	38.3	35.7	33.5	34.8	32.3	29.9
		5	15	31.8	28.9	26.1	24.8	21.8	18.9
		10	20	30.8	27.2	24.3	22.0	18.5	15.1
		15	25	24.8	21.6	18.2	14.8	11.6	8.4
		20	30	19.0	15.5	12.3	9.0	6.3	3.8
		25	35	13.6	10.5	7.8	5.3	3.3	1.8
	13	0	13	33.6	30.6	27.9	27.5	24.8	22.0
		5	18	30.7	27.6	24.6	22.7	19.3	16.0
		10	23	27.8	23.8	20.8	17.8	14.3	10.9
		15	28	21.3	17.8	14.5	11.1	8.0	5.3
		20	33	15.6	12.3	9.3	6.5	4.1	2.5
		25	38	11.0	8.3	6.0	4.0	2.5	unstable

Pile Bent Parameters:

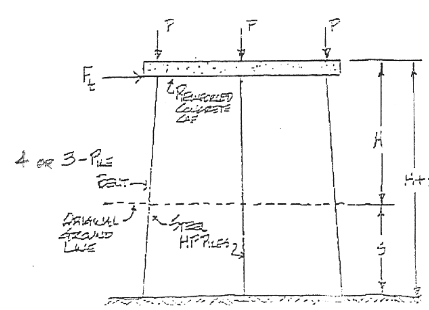
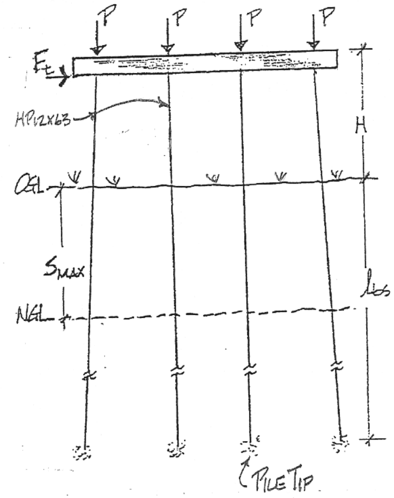


Fig. 5.14. Example Problem 6 for Pushover (Continued)

EXAMPLE 7

CHECK THE UNBRACED 4-PILE BENT WITH HP 12x63 PILES FOR PUSHOVER ADEQUACY.



UNBRACED 4-PILE BENT

GIVEN:

UNBRACED 4-PILE BENT WITH HP 12x63 PILES SHOWN AT RIGHT

$P_{MAX}^{BENT} = 400^k \Rightarrow P = \frac{400}{4} = 100^k$

$H = 10$ ft

$S_{MAX} = 15$ ft

$l_{bs} = 40$ ft

$F_{APPLIED}^t = 9.72^k \Rightarrow F_{MAX\ APPLIED}^t = F.S. \times F_{APPLIED}^t$

$= 1.25 \times 9.72^k = 12.15^k$

PUSH-OVER CHECK:

FROM TABLE 2.36 (SEE NEXT PAGE)

$F_{CAPACITY}^t = 33.8^k$ (FOR HP12x53 BENT)

$F_{CAPACITY}^t > F_{MAX\ APPLIED}^t$ FOR HP12x53 BENT

∴ HP12x63 BENT IS SAFE FROM PUSHOVER FAILURE.

Fig. 5.15. Example Problem 7 for Pushover

Ex. 7 cont'd.

Table 2.3b. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{12x53} Piles and Reinforced Concrete Bent Cap with I_{gross} = 41,470 in^4 for Varying Values of P-Load and 'H+S'.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	0	10	33.8	32.8	32.0	34.2	33.1	32.0
		5	15	21.6	20.4	19.3	18.9	17.6	16.3
		10	20	15.4	14.0	12.5	11.2	9.6	7.8
		15	25	11.5	9.7	7.7	5.8	3.6	1.4
		20	30	8.5	6.3	3.8	1.1	unstable	unstable
		25	35	6.1	3.2	unstable	unstable	unstable	unstable
	13	0	13	25.3	24.3	23.3	23.5	22.2	21.1
		5	18	17.5	16.2	14.9	13.9	12.4	10.9
		10	23	12.9	11.2	9.5	7.8	5.9	3.8
		15	28	9.6	7.5	5.3	2.9	unstable	unstable
		20	33	7.0	4.4	unstable	unstable	unstable	unstable
		25	38	4.7	unstable	unstable	unstable	unstable	unstable
4	10	0	10	56.6	53.4	50.7	54.4	52.3	50.1
		5	15	45.4	41.6	38.8	38.7	36.2	33.7
		10	20	41.1	37.8	35.0	34.0	31.0	27.8
		15	25	40.7	37.4	33.8	31.4	28.1	24.4
		20	30	33.3	29.6	26.6	23.4	19.9	16.5
		25	35	27.3	23.8	20.4	17.0	13.6	10.5
	13	0	13	47.3	44.3	41.7	42.8	40.5	38.1
		5	18	42.4	39.0	36.1	35.3	32.4	29.6
		10	23	41.0	37.4	35.0	33.1	29.6	26.3
		15	28	36.7	32.6	29.0	26.9	23.1	19.5
		20	33	29.2	26.2	22.7	19.3	16.0	12.8
		25	38	23.5	20.3	16.8	13.5	10.5	7.8

Pile Bent Parameters:

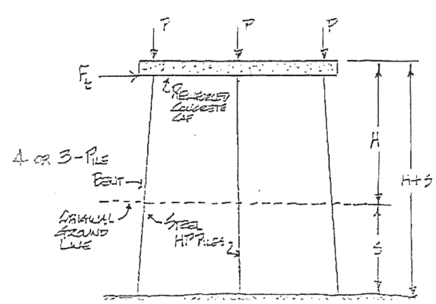
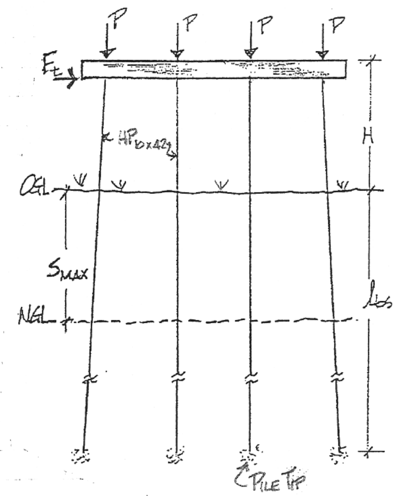


Fig. 5.16. Example Problem 7 for Pushover (Continued)

EXAMPLE 8

CHECK THE UNBRACED 4-PILE BENT AT THE RIGHT FOR PUSHOVER ADEQUACY.



UNBRACED 4-PILE BENT

GIVENS:

BENT – UNBRACED 4-PILE BENT AT RIGHT.

PILES – HP10x42

P_{MAX}^{BENT} – 400^k (UPPER BOUND ESTIMATE)

$\therefore P = \frac{400^k}{4} = 100^k$

$H = 13$ ft

$S_{MAX} = 20$ ft

$l_{bs} = 40$ ft

$F_t^{APPLIED} = 9.72^k \Rightarrow F_t^{MAX\ APPLIED} = F.S. \times F_t^{APPLIED}$

$= 1.25 \times 9.72^k = 12.15^k$

PUSHOVER CHECK:

FROM TABLE 2.3a (SEE NEXT PAGE),

$F_t^{CAPACITY} = 9.3^k$

$F_t^{CAPACITY} < F_t^{MAX\ APPLIED} \Rightarrow \therefore$ BENT IS NOT ADEQUATE FOR PUSHOVER AND SHOULD BE CHECKED MORE CLOSELY.

ASSUME:

ASSUME THAT UPON CHECKING MORE CLOSELY $\Rightarrow P_{MAX}^{BENT} = 320^k$

$\therefore P = \frac{320^k}{4} = 80^k$

$\therefore$ FROM TABLE 2.3a (SEE NEXT PAGE),

$F_t^{CAPACITY} = 12.3^k$

$F_t^{CAPACITY} > F_t^{MAX\ APPLIED} \Rightarrow \therefore$ BENT IS ADEQUATE FOR PUSHOVER

Fig. 5.17. Example Problem 8 for Pushover

Ex. 8 Cont'd

Table 2.3a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with $I_{gross} = 41,470\ in^4$ for Varying Values of P-Load and 'H+S'.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	0	10	21.6	20.6	19.6	20.0	18.8	17.6
		5	15	12.9	11.5	10.1	8.9	7.3	5.6
		10	20	8.2	6.3	4.3	2.3	unstable	unstable
		15	25	4.9	2.3	unstable	unstable	unstable	unstable
		20	30	2.0	unstable	unstable	unstable	unstable	unstable
		25	35	unstable	unstable	unstable	unstable	unstable	unstable
	13	0	13	15.6	14.4	13.2	12.4	11.0	9.5
		5	18	9.8	8.2	6.4	4.7	2.8	unstable
		10	23	6.1	3.9	1.5	unstable	unstable	unstable
		15	28	3.1	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable	unstable
		25	38	unstable	unstable	unstable	unstable	unstable	unstable
4	10	0	10	38.3	35.7	33.5	34.8	32.3	29.9
		5	15	31.8	28.9	26.1	24.8	21.8	18.9
		10	20	30.8	27.2	24.3	22.0	18.5	15.1
		15	25	24.8	21.6	18.2	14.8	11.6	8.4
		20	30	19.0	15.5	12.3	9.0	6.3	3.8
		25	35	13.6	10.5	7.8	5.3	3.3	1.8
	13	0	13	33.6	30.6	27.9	27.5	24.8	22.0
		5	18	30.7	27.6	24.6	22.7	19.3	16.0
		10	23	27.8	23.8	20.8	17.8	14.3	10.9
		15	28	21.3	17.8	14.5	11.1	8.0	5.3
		20	33	15.6	12.3	9.3	6.5	4.1	2.5
		25	38	11.0	8.3	6.0	4.0	2.5	unstable

Pile Bent Parameters:

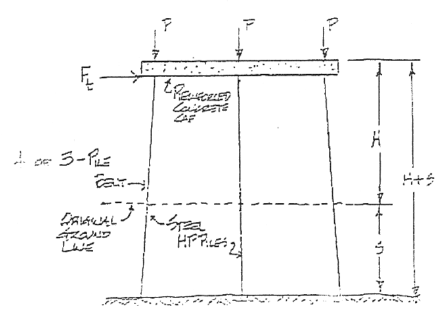
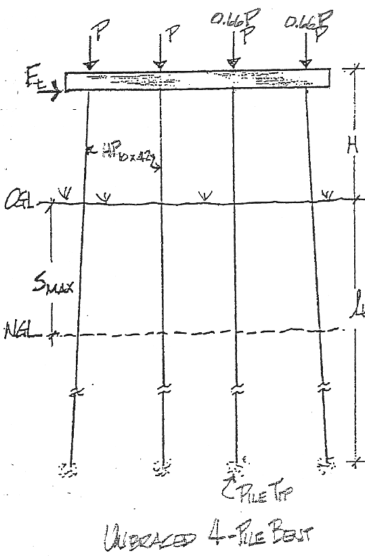


Fig. 5.18. Example Problem 8 for Pushover (Continued)

EXAMPLE 9



CHECK THE UNBRACED 4-PILE BENT AT THE RIGHT FOR PUSHOVER ADEQUACY.

GIVEN:

BENT – UNBRACED 4-PILE BENT AT RIGHT WITH UNSYMMETRIC P-LOADING

PILES – HP10x42

P-LOADING – SEE BENT AT RIGHT

$P_{MAX}^{BENT} = 80^k + 80^k + 53 + 53 = 266^k$

$S_{MAX} = 20$ ft

$H = 13$ ft

$l_{bs} = 40$ ft

$F_t^{APPLIED} = 9.72^k \Rightarrow F_t^{MAX\ APPLIED} = F.S. \times F_t^{APPLIED}$

$= 1.25 \times 9.72 = 12.15^k$

PUSHOVER CHECK:

FROM TABLE 2.10a (SEE NEXT PAGE),

$F_t^{CAPACITY} = 10.3^k$

$F_t^{CAPACITY} < F_t^{MAX\ APPLIED} \Rightarrow$ ∴ BENT IS NOT ADEQUATE FOR PUSHOVER AND SHOULD BE CHECKED MORE CLOSELY.

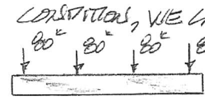
ASSUME:

SCOUR AT BENT IS NOT UNIFORM BUT AS SHOWN IN TABLE 2.20a (SEE NEXT PAGES)

FOR THIS CASE, $F_t^{CAPACITY} = 19.3^k$

$F_t^{CAPACITY} > F_t^{MAX\ APPLIED} \Rightarrow$ ∴ BENT IS ADEQUATE FOR PUSHOVER

ALTERNATIVELY, IN RECOGNITION OF MOST PROBABLE NONUNIFORM SCOUR CONDITIONS, WE CAN JUST ASSUME P-LOAD AND SCOUR ARE UNIFORM AND THUS,



$\Rightarrow$ ∴ FROM TABLE 2.3a (SEE NEXT PAGES)

$F_t^{CAPACITY} = 12.3^k$

$F_t^{CAPACITY} > F_t^{MAX\ APPLIED} \Rightarrow$ ∴ BENT IS ADEQUATE FOR PUSHOVER

Fig. 5.19. Example Problem 9 for Pushover

Ex. 9 CONT'D

Table 2.10a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x52} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and Varying Values of 'H+S'.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k
3	10	0	10	19.4	17.6	16.1	14.3	12.5
		5	15	10.8	8.8	6.8	4.7	2.4
		10	20	6.3	3.9	unstable	unstable	unstable
		15	25	3.2	unstable	unstable	unstable	unstable
		20	30	unstable	unstable	unstable	unstable	unstable
	13	0	13	13.5	11.6	9.8	7.8	5.7
		5	18	7.9	5.6	3.3	unstable	unstable
		10	23	4.4	unstable	unstable	unstable	unstable
		15	28	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable
4	10	0	10	36.8	33.4	30.4	27.6	25.0
		5	15	30.5	26.7	23.4	20.1	17.0
		10	20	29.7	25.5	21.6	18.4	14.5
		15	25	23.6	19.6	16.1	12.1	8.2
		20	30	17.5	13.6	9.8	6.0	2.3
	13	0	13	32.5	28.6	25.3	21.9	19.2
		5	18	28.8	25.5	22.1	18.6	15.1
		10	23	26.5	22.4	18.3	14.9	11.1
		15	28	19.8	16.0	12.1	8.3	4.5
		20	33	14.3	10.3	6.6	unstable	unstable

Pile Bent Parameters:

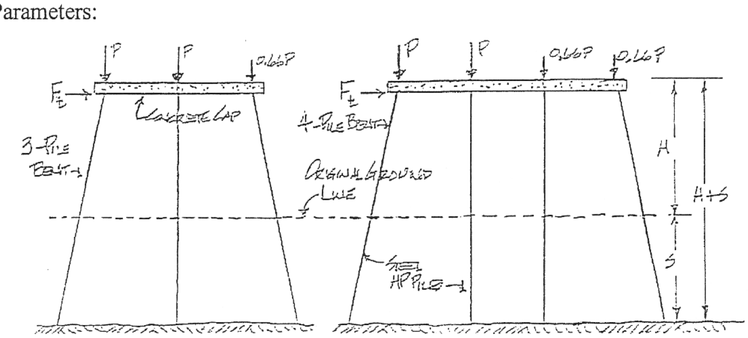


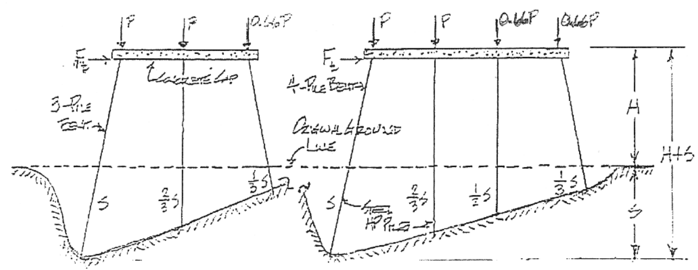
Fig. 5.20. Example Problem 9 for Pushover (Continued)

Ex.9 CONT'D.

Table 2.20a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Concrete Cap with I_{gross} = 41,470 in^4 for Unsymmetric P-Loadings and for Variable Scour and 'H+S' Distributions.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)				
				P=60^k	P=80^k	P=100^k	P=120^k	P=140^k
3	10	0	10	NN	NN	NN	NN	NN
		5	15	12.8	10.7	8.7	6.7	4.6
		10	20	8.4	6.2	4.0	unstable	unstable
		15	25	5.5	3.0	unstable	unstable	unstable
		20	30	3.3	unstable	unstable	unstable	unstable
	13	0	13	13.5	11.6	9.8	7.8	5.7
		5	18	9.1	6.9	4.7	2.4	unstable
		10	23	5.9	3.4	unstable	unstable	unstable
		15	28	3.6	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable
4	10	0	10	NN	NN	NN	NN	NN
		5	15	NN	NN	NN	NN	NN
		10	20	NN	NN	NN	NN	NN
		15	25	29.5	25.4	21.6	18.4	14.5
		20	30	26.5	22.5	18.4	15.2	11.5
	13	0	13	NN	NN	NN	NN	NN
		5	18	NN	NN	NN	NN	NN
		10	23	29.3	25.3	22.1	18.6	14.7
		15	28	26.9	23.1	18.8	15.6	11.9
		20	33	23.2	19.3	15.9	12.2	8.6

Pile Bent Parameters:



NN – Not needed, bent is adequate for uniform scour.

Fig. 5.21. Example Problem 9 for Pushover (Continued)

Ex. 9 Cont'd

Table 2.3a. Pushover Load, F_t, for Unbraced 3-Pile and 4-Pile Bridge Bents with HP_{10x42} Piles and Reinforced Concrete Bent Cap with $I_{gross} = 41{,}470\ in^4$ for Varying Values of P-Load and 'H+S'.

No. Bent Piles	H (ft)	S (ft)	H+S (ft)	Pushover Force, F_t (kips)					
				$P=60^k$	$P=80^k$	$P=100^k$	$P=120^k$	$P=140^k$	$P=160^k$
3	10	0	10	21.6	20.6	19.6	20.0	18.8	17.6
		5	15	12.9	11.5	10.1	8.9	7.3	5.6
		10	20	8.2	6.3	4.3	2.3	unstable	unstable
		15	25	4.9	2.3	unstable	unstable	unstable	unstable
		20	30	2.0	unstable	unstable	unstable	unstable	unstable
		25	35	unstable	unstable	unstable	unstable	unstable	unstable
	13	0	13	15.6	14.4	13.2	12.4	11.0	9.5
		5	18	9.8	8.2	6.4	4.7	2.8	unstable
		10	23	6.1	3.9	1.5	unstable	unstable	unstable
		15	28	3.1	unstable	unstable	unstable	unstable	unstable
		20	33	unstable	unstable	unstable	unstable	unstable	unstable
		25	38	unstable	unstable	unstable	unstable	unstable	unstable
4	10	0	10	38.3	35.7	33.5	34.8	32.3	29.9
		5	15	31.8	28.9	26.1	24.8	21.8	18.9
		10	20	30.8	27.2	24.3	22.0	18.5	15.1
		15	25	24.8	21.6	18.2	14.8	11.6	8.4
		20	30	19.0	15.5	12.3	9.0	6.3	3.8
		25	35	13.6	10.5	7.8	5.3	3.3	1.8
	13	0	13	33.6	30.6	27.9	27.5	24.8	22.0
		5	18	30.7	27.6	24.6	22.7	19.3	16.0
		10	23	27.8	23.8	20.8	17.8	14.3	10.9
		15	28	21.3	17.8	14.5	11.1	8.0	5.3
		20	33	15.6	12.3	9.3	6.5	4.1	2.5
		25	38	11.0	8.3	6.0	4.0	2.5	unstable

Pile Bent Parameters:

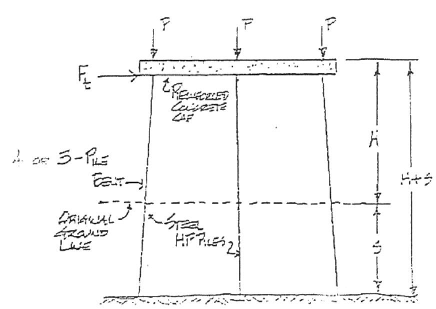


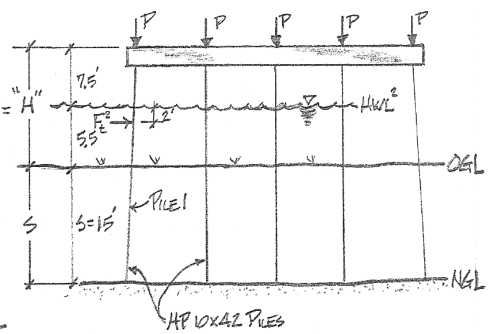
Fig. 5.22. Example Problem 9 for Pushover (Continued)

5.6 Example Application for Bent Upstream Pile Beam-Column Failure Check

Example 10 is an example application of the refined/2nd edition "ST" checking for possible failure of a bent's upstream pile as a beam-column from a combined axial P-load and a lateral loading on a debris raft forming at an elevation of 7.5 ft below the top of the bent cap, and thus applying the F_t loading at 9.5 ft below the top of the bent cap. This mode of pile/bent failure was not checked in the original "ST".

EXAMPLE 10

CHECK THE ADEQUACY OF THE UPSTREAM PILE OF THIS 5-PILE BENT AS A BEAM-COLUMN.



UNBRACED 5-PILE BENT

GIVEN:

"H" = 13', S_{MAX} = 15', P = 100^k, F_t = 9.72^k

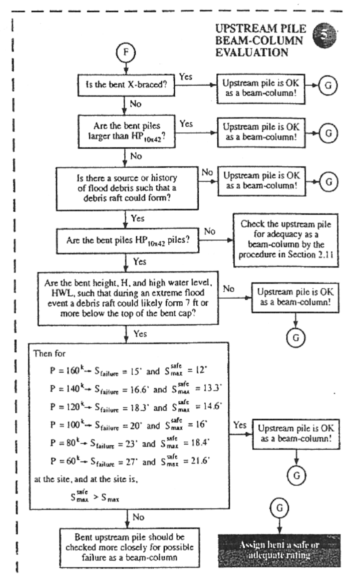
PILE = HP 10X42 ⇒ { A = 12.4 in², I_y = 71.7 in⁴, Z_y = 21.8 in³ } ⇒ A36 STEEL, σ_y = 36 ksi

HWL = HWL² = AS SHOWN AT RIGHT

LOADING FROM DEBRIS RAFT AS SHOWN ON FIG.

CHECK PILE 1 FOR ADEQUACY AS A BEAM-COLUMN:

FOLLOWING THE FLOWCHART FOR CHECKING AS A BEAM-COLUMN, i.e., BLOCK (5) (SEE AT RIGHT),



IS BENT X-BRACED → NO

ARE PILES LARGER THAN HP_{10x42} → NO

CAN A DEBRIS RAFT FORM → YES

ARE "H" AND HWL² SUCH THAT DEBRIS RAFT COULD FORM 7' OR MORE BELOW TOP OF CAP → YES

THUS, FOR P = 100^k → $S_{failure}$ = 20'

$$S_{max}^{safe} = \frac{20}{1.25} = 16'$$

(1.25 ← F.S.)

∴ AT THE SITE, $S_{max}^{safe} > S_{MAX}$ ⇒ 16' > 15'

∴ UPSTREAM PILE, PILE 1, IS OK AS A BEAM-COLUMN

NOTE, IF AT THE SITE,

P = 120^k → $S_{failure}$ = 18.3'

$$S_{max}^{safe} = \frac{18.3}{1.25} = 14.6'$$

14.6' < 15' ⇒ ∴ PILE 1 IS NOT ADEQUATE AS A BEAM-COLUMN (i.e., WOULD NOT HAVE F.S. = 1.25 AGAINST FAILURE)

Fig. 5.23. Example Problem 10 for Beam-Column

5.7 Closure

Section 5.2 identifies four questions which must be answered at the very beginning of a "check" to determine the applicability and/or need to apply the ST to determine a bent's adequacy. It should be noted that Question 4 in Section 5.2 expands the range of applicability of the Refined ST to include all steel HP pile bents. Example applications of the ST are given in Sections 5.3-5.5 of checks for bent failure via pile plunging, pile buckling, and bent pushover. These examples illustrate some of the expansions of load conditions, load levels, bridge span support conditions, symmetry of loading and/or scour conditions, etc. included in the Refined ST. The examples emphasize applications of the Tier-2 screening process. Section 5.6 provides an example application check of a bent's upstream pile for a possible beam-column failure due to a combined axial P-load and a lateral flood water loading, F_t, from a debris raft. This failure check is an addition in the refined/2nd edition "ST".

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 General

In Phase II of this research, a “screening tool” (ST) was developed to assess the adequacy of bridge pile bents for bents with HP_{10x42} and HP_{12x53} steel piles for estimated extreme flood/scour events. The ST has been used in manual form by ALDOT bridge maintenance engineers for the past year and appears to be working nicely.

The purposes of this Phase III work were to take the “screening tool” developed in Phase II and

- simplify and refine it
- extend and expand its scope of applicability
- develop a second-tier of screening to use as a follow-up for those cases where the “ST” indicates, “Bent should be looked at more closely for possible plunging, buckling, or push-over failure”.
- develop an automated version of the “ST”.

These purposes were the focus of Phase III research work, and conclusions and recommendations based on this work are presented in the following sections. It should be noted that a separate Phase III thesis was prepared for the last purpose listed above. The automated "ST", along with example applications and conclusions and recommendations pertaining to the automated "ST" are presented in that thesis and are not included herein.

6.2 Conclusions

A number of questions pertaining to the effect of additional loading conditions, scour conditions, height of application of a debris raft pushover load, unsymmetric bridge LL, continuous superstructures, etc., on possible bent failure during an extreme flood/scour event have surfaced since submission of the Phase II Report. Most of these questions required additional bent failure analyses, and these are presented in Chapter 2. A summary of the most important of these analyses and their results are presented below.

6.2.1 Additional Pile Axial P-load Due to Flood Water Lateral Loading

Analyses that were undertaken to determine these additional P-loads (ΔP-loads) are presented in Section 2.3. In each case, the tallest possible bent ("H" = 25 ft) with the maximum scour (S = 25 ft) was considered. Only in the case of a 3-pile bent was the ΔP viewed as being significant ($\Delta P = 15.6^k$ on the downstream batter pile). This additional axial load would contribute to trying to plunge or buckle the downstream pile. However, this pile would get some "lean-on" support from the other piles in the bent. Also, the ΣΔP at a bent would be zero and thus their effect on the bent pushover force would be minimal, so the additional P-load need not be considered when determining P-loads acting on a pile bent.

6.2.2 Effect of Continuous Spans on Bent Pushover

Analyses were undertaken to determine the flexural stiffness of a typical bridge deck/curb system bending in its horizontal plane and of a typical 3-pile or 4-pile bent bending in its vertical plane in Section 2.4. From these analyses it was determined almost all of the lateral deflection due to a debris raft F_t loading is due to flexing of the bent piles. Thus, assuming a rigid superstructure, it was determined that

$$F_{\text{max applied}}^{\text{Bent}} = \frac{1}{N} \times F_t$$

where F_t = flood water load on debris raft

N = number of continuous spans

If this $F_{\text{max applied}}^{\text{Bent}} < F_t^{\text{pushover capacity}}$ (given in Tables in this report) then the bridge/bent is safe from a pushover failure.

6.2.3 Effect of Continuous Spans on Bent Pile Buckling

Piles/bents supporting continuous span superstructures, or those made continuous for LL, cannot buckle in a sidesway mode unless the entire continuous segment does. This would require an unrealistically large loading and thus the piles/bents cannot buckle in a sidesway mode. For the tallest ALDOT bents (”H” = 25 ft) subjected to the largest anticipated scour (S = 25 ft), the pile ℓ_{max} would be

$$\ell_{max} = \text{“H”} + S - 1' = 25 + 20 - 1 = 44 \text{ ft}$$

For this case, if,

$$P_{max\ applied} \leq 118^k \text{ for an } HP_{10x42} \text{ pile}$$

$$P_{max\ applied} \leq 209^k \text{ for an } HP_{12x53} \text{ pile}$$

then the pile/bent is safe from buckling. If $P_{max\ applied}$ is larger than the above values, the pile/bent may still be safe depending on the bent height and level of scour at the site. In this case, the bent should be checked for buckling in the manner outlined in the "ST".

6.2.4 Bent Pushover Loads for Smaller P-load Levels

Pushover loads in the Phase II "ST" were determined for various bent geometries, pile sizes, scour levels, and bracing conditions for P-loads (one applied to the bent cap above each pile) of $\{P\} = \{100^k, 120^k, 140^k, 160^k\}$. However, for some smaller bridges, the P-loads are sometimes only approximately 80^k. In these cases, the "ST" can be used with the $P = 100^k$ results, but this yields results that are too conservative. Thus to expand the range of accurate applicability of the "ST", additional pushover analyses were performed for 3-pile and 4-pile bents for P-loads of $\{P\} = \{60^k, 80^k\}$. These are presented in Section 2.6. The $P = 60^k$ level was added in light of allowing checks of cases where the LL is only applied to the upstream traffic lane, and also because it would allow interpolation of results for uniform P-loads somewhat less than 80^k.

6.2.5 Pushover Loads for Unsymmetric P-load Distribution

Pushover analyses in the Phase II "ST" assumed a uniform P-load distribution across the bent cap, as indicated in the subsection above. These analyses, along with the additional smaller P-load levels of the previous subsection, produced pushover analyses results for a uniform P-load distribution for P-loads of {P} = {60^k, 80^k, 100^k, 120^k, 140^k, 160^k}. However, it was not clear that a uniform P-load distribution yielded a smaller bent pushover load, F_t, than an usymmetric P-load distribution, even though it provided the larger gravity bent loading. It was reasoned that a smaller unsymmetrical P-load distribution on a bent, resulting from the LL being only applied to the upstream traffic lane, may result in a smaller pushover load. From earlier work, it was concluded that pushover failure was only a problem with the narrow-width 3-pile and 4-pile bents, thus these two pile bent configurations were considered when checking the pushover loads for unsymmetric P-load distribution. The results of pushover analyses for the 3- and 4-pile bents with unsymmetric P-loads are presented in Section 2.7, and the bent pushover load for these loadings turned out to be a little smaller in every case than the corresponding bent with a uniformly distributed P-load. Figures 2.26 – 2.29 graphically illustrate the small difference in pushover load between the unsymmetrical and symmetrical P-loading cases. Even though the unsymmetrical distribution gives somewhat smaller pushover loads, and earlier screenings via the Phase II "ST" assumed a uniform P-load distribution, the fact that the difference in pushover load between the two P-load distributions is quite small and that actual scour distributions are not uniform, as earlier assumed, which leads to somewhat conservative estimates of pushover capacities (see the next subsection), the net effect of these two factors offset each other and the earlier pushover analyses assessments are felt to be reasonable and accurate.

6.2.6 Pushover Loads for Variable Scour Distribution

The Phase II "ST" assumed a uniform scour of a given magnitude over the full width of the pile bent being analyzed, and this leads to smaller bent pushover loads than would occur if the scour decreased in the direction of river flow along the width of the bent. The effect of variable scour along the width of a pile bent was analyzed for 3- and 4-pile bents in Section 2.8, and the results are shown in Section 2.8. Figures 2.33 and 2.34 reflect the greater pushover capacity that a bent has if the scour decreases from its maximum value in the direction of river flow, as opposed to the case where the scour remains at its maximum value over the full width of the bent. Figure 2.35 shows plots of pushover force, F_t, vs. bent height plus scour, H+S, for cases where both unsymmetrical P-load and variable scour occur together and reflects a greater pushover capacity for this case when compared to that of a uniform P-load and uniform scour case.

6.2.7 Effect of Vertical Location of Debris Raft on Bent Pushover

In the Phase II work and "ST", the debris raft on which the horizontal flood water loading, F_t, acts was assumed to be configured such that the top of the raft was at the height of the top of the bent cap. This placed the F_t loading at the bottom of the bent cap, which was viewed as the worst case position in checking bent pushover failure. This would be the case if the bent acted as a rigid body and exhibited rigid body tip-over failure, or if the bent is an unbraced frame with only bending in the plane of the frame about the pile weak axes. For situations where the topology at the bridge location is such that the high water level is significantly lower than the top of the bent cap, it was anticipated that the Phase II assumptions were overly conservative.

In the Phase III work, pushover analyses were performed for 3- and 4-pile bents with the debris raft water loading, F_t, applied at the location of the bottom of the X-bracing for single-story bents and at the height of the horizontal strut located between the upper X-bracing and lower X-bracing for 2-story bents. A description of this work and its results are presented in Section 2.12. It was anticipated that this loading location would yield larger pushover loads and would thus allow some bents previously classified as inadequate for pushover loading to be reclassified as adequate. However, the analyses results essentially indicated that the vertical position of the flood water loading, F_t, doesn't significantly affect the bent pushover load. The bent bracing system is effective in maintaining the relative geometrical relationships of the bent members in the region(s) of the X-bracing, and almost all of the bending deformations of the bent occur in the lower unbraced (after scour) region and is essentially independent of the location at which F_t is applied in the upper braced region of the bent. Figures 2.44 – 2.46 in Section 2.12 show good graphical bent deformation illustrations of this.

6.2.8 Bent Upstream Pile as Beam-Column

It should be noted that for the lower position of the flood water loading, F_t, the upstream bent pile was checked for adequacy in an unbraced bent assuming it acts as a beam-only member and as a beam-column member. These checks are shown in Section 2.11. In all situations, the upstream pile is adequate when checking as a beam-only member. When checking the upstream pile as a beam-column (which it is), the pile is adequate for all situations if it is an HP_{12x53} pile. However, when it is an HP_{10x42} pile, the pile may not be adequate when the scour, S > 12 ft, depending on the original height “H”, of the bent.

The results of the analyses summarized above have been included in the improvements and refinements made in the “ST” during this Phase III work. The resulting Refined/2nd Edition “ST” is discussed and presented in flowchart form in Chapter 4 and Fig. 4.1. Also, a section on 2nd-tier screening (Section 4.3) is included in this report; this 2nd-tier screening should be performed to address the “blocks” in the refined/2nd edition “ST” which indicate that the user should “check more closely for possible failure”. These Tier-2 screening referrals are shown shaded on the refined “ST” flowchart of Fig. 4.1. The 2nd tier screenings should result in additional bents being determined as adequate for extreme flood/scour events, and thus should further reduce the number of bents requiring a fully comprehensive analysis to assess the bent’s adequacy.

A discussion of the automation of the “ST”, the automated “ST”, and example applications of the automated “ST” are not presented herein, but rather are given in a separate thesis.

6.3 Recommendations

Readers interested in the workings of the refined/2nd edition “ST” and that plan to use it as a work tool to screen pile bent-supported bridges to assess their adequacy for extreme flood/scour events should recognize and do the following:

- The “ST” is a screening tool to determine the adequacy of steel HP pile bridge bents for an estimated extreme flood/scour event.
- The “ST” checks for possible HP pile/bent failure via
  - pile “kick-out” due to insufficient pile embedment after scour
  - pile plunging due to insufficient soil bearing tip bearing and side friction capacity
  - pile buckling
  - bent pushover due to flood water lateral loading on the pile cap and/or on a debris raft lodged against the bent
  - upstream pile failure as a beam-column due to a combined P-load and a lateral flood water loading on a debris raft forming at an elevation of 7.5 ft below the top of the bent cap.
- The refined/2nd edition “ST” is an improvement of the original “ST” (Phase II “ST”) in three important areas, i.e.,
  - it has an expanded scope of applicability, checks for other possible failures, works with more realistic loadings, and includes other refinements as reported herein
  - it refers the user to 2nd tiers of screening for those bents not successfully passing the 1st tier of screening of the original “ST”
  - it has a computer version available for use.

- Perform an overview reading of this report to develop an understanding of the workings of the “ST” and the refinements and changes that were made in developing this refined/2nd edition “ST” from the original Phase II “ST”.
- Perform a close reading of Chapter 2 to assist in accomplishing the above bullet.
- Perform a close reading of Chapter 4 and the flowcharts therein to gain a detailed understanding of the changes and refinements included in the refined/2nd edition “ST” and the 2nd Tier Screenings included in the refined “ST”.
- Manually work through at least some of the example application cases given in Chapter 5.
- Closely read this last Conclusion and Recommendation Chapter which summarizes the major changes and refinements made in the “ST”.
- Read Part II of the Project Final Report to understand the automated version of the refined “ST”.
- Work through some of the example application cases in the Part II Report to develop a working knowledge of the automated refined “ST”.

REFERENCES

Ramey, G.E., and D.A. Brown, "Stability of Highway Bridges Subject to Scour - Phase I," *Alabama Department of Transportation Project 930-585, Final Report*, September 2004.

GTSTRUDL Reference Manual, Vol. 3, February 2002.

Ramey, G.E., Brown, D.A., et. al., "Stability of Highway Bridges Subject to Scour - Phase II," *Alabama Department of Transportation Project 930-608, Final Report*, January 2006.

Ramey, G.E., Brown, D.A., et.al., "Screening Tool to Assess Adequacy of Bridge Pile Bents for Extreme Flood/Scour Events," *Alabama Department of Transportation Project 930-608 Report*, January 2006.

Ramey, G.E., Brown, D.A., et.al., "Stability of Highway Bridges Subject to Scour - Phase II: Screening Tool Users Guide," *Alabama Department of Transportation Project 930-608 Report*, January 2006.

Hughes, D. and Ramey, G.E., "Stability of Highway Bridges Subject to Scour - Phase II - Part II: Bridge Bent P-Delta Curves in Transverse Direction Using FB-Pier and GTSTRUDL Pushover Analysis Procedures", *Alabama Department of Transportation Project 930-608 Interim Report*, June 2005.

APPENDIX A: EXAMPLE **GTSTRUDL** INPUT CODE FOR PUSHOVER ANALYSIS FOR VARIOUS BENT CONFIGURATIONS

Example 1: 3-Pile Bent, Unbraced, Symmetric Load and Scour

```
STRUDL ' '
$$
$$     This   GTSTRUDL file created from GTMenu on  3/ 7/2007
$$
UNITS  INCH  KIPS  DEG   FAH
JOINT COORDINATES GLOBAL
    1                 0    0
    2             109.5    0
    3               219    0
    4              13.5  108
    5             109.5  108
    6             205.5  108

TYPE  PLANE FRAME
MEMBER INCIDENCES
   1            1            4
   2            2            5
   3            3            6
   4            4            5
   5            5            6

UNITS  INCH  KIPS  DEG   FAH
MEMBER PROPERTIES    TABLE 'M/S/HP9 '  'HP10x42                  '
    1            2            3
MEMBER PROPERTIES   PRISMATIC   AX  8.6400000E+02   IX  1.0000000E+07
   -
IY  1.0000000E+07   IZ  4.1472000E+04
    4            5

STATUS SUPPORT  -
    1            2            3

UNITS  INCH  KIPS  DEG   FAH
JOINT RELEASES
    1            2            3            -
       MOM Z

UNITS  INCH  KIPS  DEG   FAH
CONSTANTS
     BETA  9.0000000E+01  -
    1            2            3

MATERIAL STEEL
MATERIAL CONCRETE -
    4            5

UNITS  INCH  KIPS  DEG   FAH
LOADING 'CONST'
  JOINT LOADS FOR  Y  -6.0000001E+01
    4            5            6

UNITS  INCH  KIPS  DEG   FAH
LOADING 'INCR'
  JOINT LOADS FOR  X   1.0000000E+00
    4

NONLINEAR EFFECTS

 GEOMETRY ALL MEMBERS

PLASTIC HINGE -
```

```
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 36.0 ESH .124 ESU .2 FSU 36.001 ALPHA 0.0 MEMBER 1 2 3

LOAD LIST ALL
PUSHOVER ANALYSIS DATA
  CONSTANT LOAD 'CONST'
  INCREMENTAL LOAD 'INCR'
  MAXIMUM NUMBER OF LOAD INCREMENTS 50
  MAXIMUM NUMBER OF TRIALS 20
  LOADING RATE 1.000000
  CONVERGENCE RATE 0.500000
  CONVERGENCE TOLERENCE COLLAPSE 0.000100
  CONVERGENCE TOLERANCE DISPLACEMENT 0.001000
  MAXIMUM NUMBER OF CYCLES 50
  DISPLACEMENT CONTROL OFF
END
PERFORM PUSHOVER ANALYSIS
```

Example 2: 4-Pile Bent, Braced, Unsymmetric Load, Symmetric Scour

```
STRUDL ' '
$$
$$     This   GTSTRUDL file created from GTMenu on  3/20/2007
$$

UNITS  INCH  KIPS  DEG   FAH
JOINT COORDINATES GLOBAL
      1     -22.5 -180
      2       120       -180
      3       216       -180
      4     358.5 -180
      5       24  196
      6       120 196
      7       216 196
      8       312 196
      9       5.25      42
   10 330.75      42
   11 21.75 174
   12 314.25      174
   13 120   90.0857142857
   14 216   90.0857142857
   15 120   130.314285714
   16 216   130.314285714

TYPE  SPACE FRAME
MEMBER INCIDENCES
   1 5 6
   2 6 7
   3 7 8
   4 1 9
   5 9 11
   6 11 5
   7 2 13
   8 13 15
   9 15 6
   10 3 14
   11 14 16
   12 16 7
   13 4 10
   14 10 12
   15 12 8
   16 11 15
   17 15 14
   18 14 10
   19 9 13
   20 13 16
   21 16 12

UNITS  INCH  KIPS  DEG   FAH
MEMBER PROPERTIES   PRISMATIC   AX  864  IX  1000000 IY  1000000  IZ
   41472
    1 2 3

MEMBER PROPERTIES    TABLE 'M/S/HP9 '  'HP12x53                 '
    4 5 6 7 8 9 10 11 12 13 14 15

MEMBER PROPERTIES    TABLE 'CHANNEL9  '  'C4x7.25                '
    16 17 18 19 20 21

STATUS SUPPORT  -
```

```
    1 2 3 4 5 6 7 8

UNITS  INCH  KIPS  DEG   FAH
JOINT RELEASES
    1 2 3 4 MOM X Y Z
    5 6 7 8 FOR X Y MOM Z

UNITS  INCH  KIPS  DEG   FAH
CONSTANTS
     BETA  90  -
    4 5 6 7 8 9 10 11 12 13 14 15

MEMBER RELEASES
    16 17 18 19 20 21 START MOM Y Z END MOM Y Z

MATERIAL STEEL
MATERIAL CONCRETE 1 2 3

UNITS  INCH  KIPS  DEG   FAH
LOADING 'CONST'
  JOINT LOADS FOR Y -80
    5 6
  JOINT LOADS FOR Y -53
    7 8

UNITS  INCH  KIPS  DEG   FAH
LOADING 'INCR'
  JOINT LOADS FOR X 1
    5

NONLINEAR EFFECTS

 GEOMETRY ALL MEMBERS

PLASTIC HINGE -
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 36.0 ESH .124 ESU .2 FSU 36.001 ALPHA 0.0 -
  MEMBER 4 5 6 7 8 9 10 11 12 13 14 15

PLASTIC HINGE -
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 16.1 ESH .124 ESU .2 FSU 16.101 ALPHA 0.0 -
  MEMBER 16 17 18

LOAD LIST ALL
PUSHOVER ANALYSIS DATA
  CONSTANT LOAD 'CONST'
  INCREMENTAL LOAD 'INCR'
  MAXIMUM NUMBER OF LOAD INCREMENTS 100
  MAXIMUM NUMBER OF TRIALS 20
  LOADING RATE 1.000000
  CONVERGENCE RATE 0.500000
  CONVERGENCE TOLERENCE COLLAPSE 0.000100
  CONVERGENCE TOLERANCE DISPLACEMENT 0.001000
  MAXIMUM NUMBER OF CYCLES 50
  DISPLACEMENT CONTROL OFF
END
PERFORM PUSHOVER ANALYSIS
```

Example 3: 5-Pile Bent, 2-Story, Braced, Symmetric Load, Unsym. Scour

```
STRUDL ' '
$$
$$     This   GTSTRUDL file created on  1/ 25/2008
$$

UNITS  INCH  KIPS  DEG   FAH
JOINT COORDINATES GLOBAL

   1  -7.5  -60   S
   2  126   -48   S
   3  222   -40   S
   4  318   -30   S
   5  446.5 -20   S
   6  30    240   S
   7  126   240   S
   8  222   240   S
   9  318   240   S
   10 414   240   S
   11 5.25  42
   12 15.75 126
   13 16.5  132
   14 17.25 138
   15 27.75 222
   16 126   65.9787234043
   17 126   104.106382979
   18 126   132
   19 126   160.894736842
   20 126   201.315789474
   21 222   85.0425531915
   22 222   132
   23 222   181.105263158
   24 318   65.9787234043
   25 318   104.106382979
   26 318   132
   27 318   160.894736842
   28 318   201.315789474
   29 438.75      42
   30 428.25      126
   31 427.5 132
   32 426.75      138
   33 416.25      222

TYPE  SPACE FRAME
MEMBER INCIDENCES

  1  6  7
  2  7  8
  3  8  9
  4  9 10
  5  1 11
  6 11 12
  7 12 13
  8 13 14
  9 14 15
 10 15  6
 11  2 16
 12 16 17
 13 17 18
 14 18 19
 15 19 20
```

```
 16 20  7
 17  3 21
 18 21 22
 19 22 23
 20 23  8
 21  4 24
 22 24 25
 23 25 26
 24 26 27
 25 27 28
 26 28  9
 27  5 29
 28 29 30
 29 30 31
 30 31 32
 31 32 33
 32 33 10
 33 15 20
 34 20 23
 35 23 27
 36 27 32
 37 12 17
 38 17 21
 39 21 24
 40 24 29
 41 14 19
 42 19 23
 43 23 28
 44 28 33
 45 11 16
 46 16 21
 47 21 25
 48 25 30
 49 13 18
 50 18 22
 51 22 26
 52 26 31

UNITS  INCH  KIPS  DEG   FAH
MEMBER PROPERTIES    TABLE 'M/S/HP9 '  'HP10x42                 '
 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
   30 31 32

MEMBER PROPERTIES    TABLE 'CHANNEL9  '  'C4x7.25                '
 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52

MEMBER PROPERTIES   PRISMATIC   AX  864  IX  1000000  IY  1000000  IZ
   41472
 1 2 3 4

UNITS  INCH  KIPS  DEG   FAH
JOINT RELEASES
 1 2 3 4 5 MOM X Y Z
 6 7 8 9 10 FOR X Y MOM Z

UNITS  INCH  KIPS  DEG   FAH
CONSTANTS
     BETA  90 -
 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29
   30 31 32

MEMBER RELEASES
```

```
 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 START MOM
   Y Z END MOM Y Z

MATERIAL STEEL

MATERIAL CONCRETE 1 2 3 4

UNITS  INCH  KIPS  DEG   FAH
LOADING 'CONST'
  JOINT LOADS FOR  Y  -80
   6 7 8 9 10

UNITS  INCH  KIPS  DEG   FAH
LOADING 'INCR'
  JOINT LOADS FOR  X   1
   6

NONLINEAR EFFECTS

 GEOMETRY ALL MEMBERS

PLASTIC HINGE -
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 36.0 ESH .124 ESU .2 FSU 36.001 ALPHA 0.0 -
  MEMBER 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
   27 28 29 30 31 32

PLASTIC HINGE -
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 16.1 ESH .124 ESU .2 FSU 16.101 ALPHA 0.0 -
  MEMBER 33 34 35 36 37 38 39 40

LOAD LIST ALL
PUSHOVER ANALYSIS DATA
  CONSTANT LOAD 'CONST'
  INCREMENTAL LOAD 'INCR'
  MAXIMUM NUMBER OF LOAD INCREMENTS 100
  MAXIMUM NUMBER OF TRIALS 20
  LOADING RATE 1.000000
  CONVERGENCE RATE 0.500000
  CONVERGENCE TOLERENCE COLLAPSE 0.000100
  CONVERGENCE TOLERANCE DISPLACEMENT 0.001000
  MAXIMUM NUMBER OF CYCLES 50
  DISPLACEMENT CONTROL OFF
END
PERFORM PUSHOVER ANALYSIS
```

Example 4: 6-Pile Bent, Double X-Braced, Symmetric Load and Scour

```
STRUDL ' '
$$
$$     This   GTSTRUDL file created on  1/ 25/2008
$$

UNITS  INCH  KIPS  DEG   FAH
JOINT COORDINATES GLOBAL

   1  -37.5 -300  S
   2  120   -300  S
   3  216   -300  S
   4  312   -300  S
   5  408   -300  S
   6  565.5 -300  S
   7  24    192   S
   8  120   192   S
   9  216   192   S
   10 312   192   S
   11 408   192   S
   12 504   192   S
   13 5.25  42
   14 21.75 174
   15 120   91.3789731051
   16 120   129.317829457
   17 216   42
   18 216   85.6589147287
   19 216   132.689486553
   20 216   174
   21 312   42
   22 312   85.6589147287
   23 312   132.689486553
   24 312   174
   25 408   91.3789731051
   26 408   129.317829457
   27 522.75      42
   28 506.25      174

TYPE  SPACE FRAME
MEMBER INCIDENCES

  1  7  8
  2  8  9
  3  9 10
  4 10 11
  5 11 12
  6  1 13
  7 13 14
  8 14  7
  9  2 15
 10 15 16
 11 16  8
 12  3 17
 13 17 18
 14 18 19
 15 19 20
 16 20  9
 17  4 21
 18 21 22
 19 22 23
 20 23 24
```

```
 21 24 10
 22  5 25
 23 25 26
 24 26 11
 25  6 27
 26 27 28
 27 28 12
 28 14 16
 29 16 18
 30 18 21
 31 20 23
 32 23 25
 33 25 27
 34 13 15
 35 15 19
 36 19 24
 37 17 22
 38 22 26
 39 26 28

UNITS  INCH  KIPS  DEG   FAH
MEMBER PROPERTIES    TABLE 'M/S/HP9 '  'HP12x53                 '
 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

MEMBER PROPERTIES    TABLE 'CHANNEL9  '  'C4x7.25               '
 28 29 30 31 32 33 34 35 36 37 38 39

MEMBER PROPERTIES   PRISMATIC   AX  864  IX  10000000  IY  10000000  IZ
   41472
 1 2 3 4 5

UNITS  INCH  KIPS  DEG   FAH
JOINT RELEASES
 1 2 3 4 5 6 MOM X Y Z
 7 8 9 10 11 12 FOR X Y MOM Z

UNITS  INCH  KIPS  DEG   FAH
CONSTANTS
     BETA  90 -
   6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

MEMBER RELEASES
 28 29 30 31 32 33 34 35 36 37 38 39 START MOM Y Z END MOM Y Z

MATERIAL STEEL

MATERIAL CONCRETE 1 2 3 4 5

UNITS  INCH  KIPS  DEG   FAH
LOADING 'CONST'
  JOINT LOADS FOR  Y  -80
   7 8 9 10 11 12

UNITS  INCH  KIPS  DEG   FAH
LOADING 'INCR'
  JOINT LOADS FOR  X   1
   7

NONLINEAR EFFECTS

 GEOMETRY ALL MEMBERS

PLASTIC HINGE -
```

```
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 36.0 ESH .124 ESU .2 FSU 36.001 ALPHA 0.0 -
  MEMBER 6 7 8 9 10  11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27

PLASTIC HINGE -
  FIBER GEOMETRY NTF 1 NTW 1 NBF 8 ND 8 LH 3.0 -
  STEEL FY 16.1 ESH .124 ESU .2 FSU 16.101 ALPHA 0.0 -
  MEMBER 28 29 30 31 32 33

LOAD LIST ALL
PUSHOVER ANALYSIS DATA
  CONSTANT LOAD 'CONST'
  INCREMENTAL LOAD 'INCR'
  MAXIMUM NUMBER OF LOAD INCREMENTS 100
  MAXIMUM NUMBER OF TRIALS 20
  LOADING RATE 1.000000
  CONVERGENCE RATE 0.500000
  CONVERGENCE TOLERENCE COLLAPSE 0.000100
  CONVERGENCE TOLERANCE DISPLACEMENT 0.001000
  MAXIMUM NUMBER OF CYCLES 50
  DISPLACEMENT CONTROL OFF
END
PERFORM PUSHOVER ANALYSIS
```