Proceedings of OMAE'04
23rd International Conference on Offshore Mechanics and Arctic Engineering
June 20-25, 2004, Vancouver, Canada

OMAE2004-51237

SENSITIVITY OF MOORING LINE PRETENSION IN THE DESIGN CYCLE FOR FLOATING CAISSONS

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Abstract

The new parallel Tacoma Narrows Bridge being constructed by Tacoma Narrows Constructors will be mounted on two towers and these towers in turn will be supported by reinforced concrete caissons referred to as East Caisson (Tacoma side) and West Caisson (Gig Harbor side). Each Caisson is towed to the location and several stages of construction will take place at the actual site. During construction, the floating caissons will be moored in place to hold it against the flood and ebb currents in the Narrows.

During the mooring system design, a desired pretension is established for the lines at each draft. However, due to practical limitations in the field some variations to this design pretension value may be expected. It is important to study the effect of this variation on the overall performance of the mooring system. In this paper, the sensitivity of the mooring line pretension on the overall performance of the mooring system for the above caisson is presented. During this study, all the variables that affect the mooring system design such as mooring system layout, mooring line makeup, anchor positions, fairlead departure angles, and fairlead locations are kept constant. The only variable changed is the pretension of the mooring lines. Two approaches for defining the variations in the pretension have been studied in this paper. In the first approach, the pretension is changed in a systematic way (predicted approach). In the second method the pretension is changed randomly. The latter is considered more likely to occur in the field for this type of complex mooring system. Both sets of results are presented for some selected drafts attained by the caisson during its construction. The difference in the results from the two methods is discussed.

1 INTRODUCTION

Tacoma Narrows Constructors is building a new suspension bridge in Tacoma, close to Seattle, Washington State, USA. There is currently an existing bridge next to the proposed location. The new bridge is built just south of the existing bridge. This new bridge is built on towers mounted on two caissons, referred to as East Caisson (Tacoma side) and West Caisson (Gig Harbor side). During construction, the floating caisson is moored in place to hold it in the ebb and flood current in the Narrows.

The proposed mooring system consists of two sets of mooring lines: lower and upper. Each set consists of 16 mooring lines. The lower 16 lines (A' – P' or 17 to 32 in Figure 1) consist of anchors that form a radius of about 300 feet. The fairlead locations for these lower 16 lines are kept constant throughout the construction process. The lower 16 lines are hooked-up when the caisson is towed from the harbor and positioned at the site. For the upper 16 lines (A – P or 1 to 16 in Figure 1), the anchor locations form a radius of 600 ft (except for lines F, G and H). The fairlead locations for these upper 16 lines vary based on the draft. The upper lines are hooked up at the caisson draft of 79 ft.

For any design of a mooring system, the design cycle involves selection of several variables including the number of mooring lines, location of the fairlead and anchor locations of each line, line materials, line sizes and pretension. As a part of any mooring system design process, the designer usually has the option of changing a few of these parameters to optimize the performance and make the system work for the chosen design parameters. As in any design cycle, the mooring designer must keep in mind the construction issues and sequences before recommending the design.

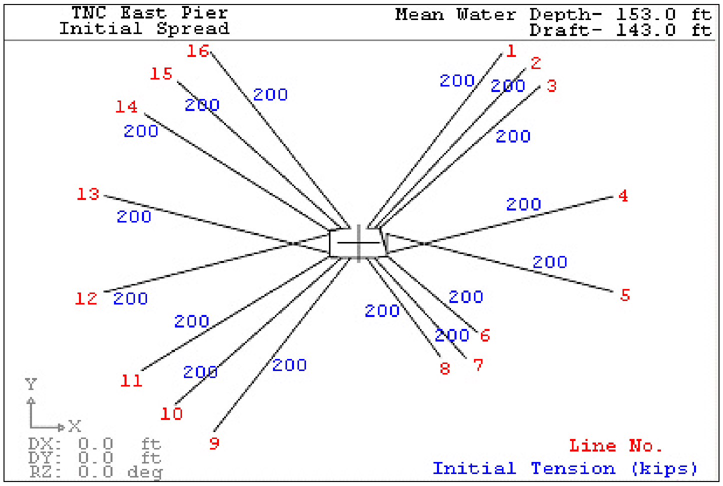
The principal design parameters that affect a mooring design are:

- Mooring system layout
- Mooring line make up
- Anchor positions
- Fairlead departure angles
- Fairlead X and Y locations
- Line pretension

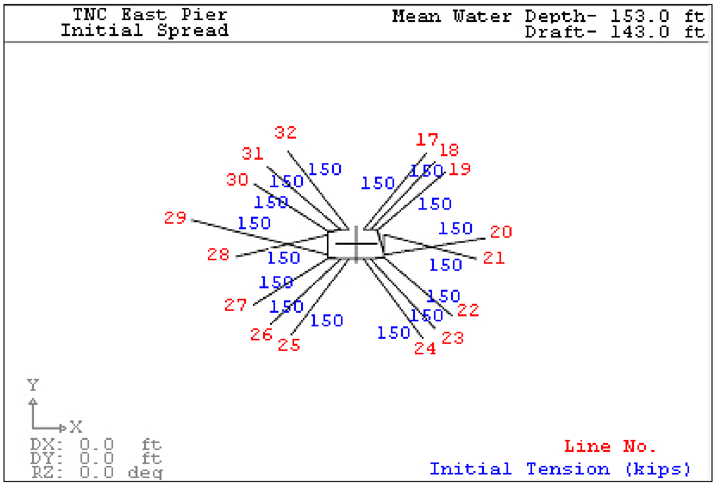
This paper examines the effect of changes in pretension on the mooring line tensions and the motions of the caisson. The East Caisson is studied. The understanding gained in this study is expected to help in the design process as well as the operations in the field.

2 MOORING SYSTEM

The mooring system consists of 32 lines connected at two fairlead elevations. There are 16 lines each at the upper and the lower fairlead elevations. A pair of upper and lower lines with the same letter designation such as A and A' (1 and 17) are in the same vertical plane. The upper lines are combinations of 3.5 in nominal diameter wire and 4 in nominal diameter chain, except three lines F, G and H which are made up of chain only. Similarly, all lower lines are 3 ¾ in diameter chain. The elevation of the fairlead of the lower lines is maintained for all drafts. The mooring system layout is shown in Figure 1.



a) Upper Mooring Lines



b) Lower Mooring Lines

Figure 1 Initial mooring configuration

3 NEED FOR PRETENSION STUDY

Mooring analysis has been performed for several drafts for different current speeds expected at that stage of construction for both flood and ebb flow. After carefully considering all the factors, a recommended value of pretension has been proposed for each of these drafts in order to maintain the required factors of safety in line tensions. Although the mooring system works fine with the recommended pretension, it might not be possible to set the mooring lines exactly at the recommended pretension value simultaneously for all the lines due to practical reasons such as:

- limitation and accuracy of the tensioning device
- sequence of pretensioning
- creep of lines
- 'burning in' or small movement of the anchors
- presence of current and changes in tide during pretensioning

It is possible that the actual pretensions in the mooring lines would be either higher or lower than the targeted pretensions. It is, therefore, important to study the sensitivity of the maximum line tensions to the variations of pretension from the design in order to assure the safety of the mooring system and to ensure that the limits to these variations are not exceeded in the field.

4 VARIATION IN STATIC PRETENSION

The recommended pretensions for individual draft are shown in Figure 2 below.

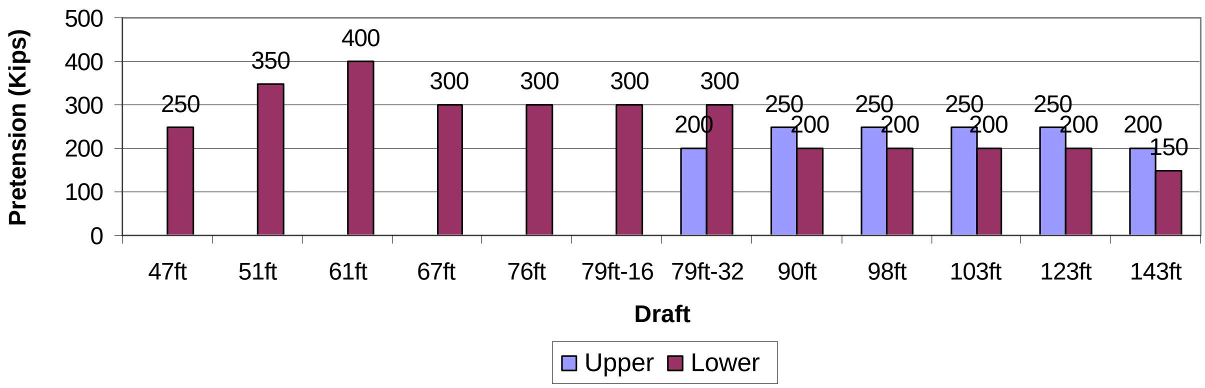


Figure 2 Recommended pretension for east caisson at different drafts

In the above figure, at 79 ft draft the upper lines are attached and the number of lines changes from 16 to 32. A certain pretension value was recommended for each draft, based on the mooring analysis performed. Note that the target 'pretension' is the initial line tension before the caisson comes to final static equilibrium. In a way it defines the initial line length before loads are applied. In practice all the lines cannot be tensioned simultaneously keeping the caisson position and the draft unchanged. The vertical component of the tension would alter the draft of the caisson slightly and hence the achieved tension would be somewhat lower than the target. Also, as the lines are attached and tensioned in sequence, the tension of the already attached lines changes. When all the lines have been tensioned and the caisson is in static equilibrium, the resulting tension is termed as the 'still water tension'. This assumes that there is no current acting on the caisson but the caisson is at the correct draft that is slightly higher than the nominal. The aim of pretensioning should be to match the still water tension. Achieving the correct level of this tension would be an iterative process in practice.

The effect of the vertical component of the line tension is important and has been quantified. Static analyses have been performed assuming that all the lines are pretensioned simultaneously to the same value with the caisson fixed in position and it is then allowed to change its position, draft, heel and trim and come to an equilibrium state under the acting line tensions. The initial pretension as well as the actual tension in one of the lines in still water condition for a range of pretensions of 50 to 400 kips (sets 1 through 6) is shown in Figure 3. It is clear that the difference between the target pretension and the actual still water tension increases with the level of pretension due to the nonlinear nature of the problem.

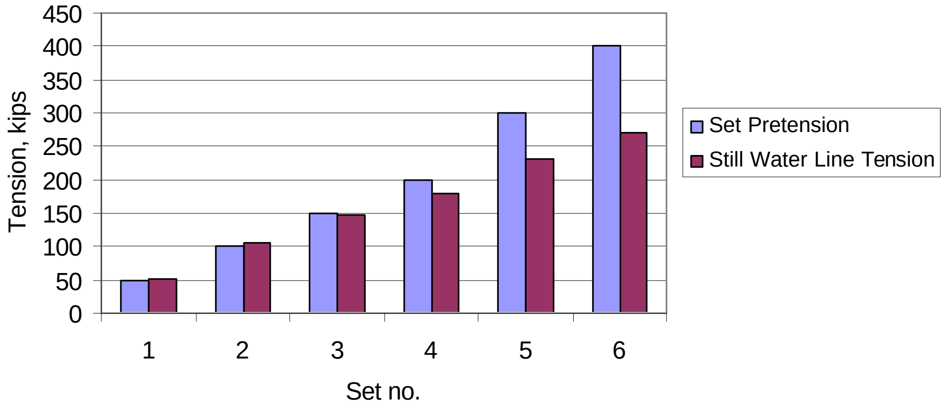


Figure 3 Desired pretensions versus still water line tension (Line 4)

5 SELECTED CASES

Several caisson drafts were considered in the design cycle. The drafts considered for the analysis were 47 ft, 51ft, 61ft, 67ft, 76 ft, 79 ft, 90 ft, 98 ft, 103 ft, 123 ft and 143 ft. For each draft at least one current speed was studied for both ebb and flood flow. The load – deflection table for each of the mooring lines was computed by ZenMoor program [2] using the line properties and fairlead and anchor coordinates of the lines. The hydrodynamic characteristics were developed by 3-D diffraction-radiation motion response program NEPTUNE [3]. Mooring analysis was performed for all the anticipated drafts using MOTSIM program [1, 4]. The accompanying paper [6] describes all the details of the analysis, the results of the analysis and the challenges involved in the design. In the present pretension study, only the following design cases were analyzed:

1. Predicted Approach
    a. 47 ft draft, 16 mooring lines, 6.1 knot flood current (East Pier)
       Recommended pretension is 250 kips for all lines.
       Pretension cases studied: 100, 150, 200 and 250 kips.

    b. 61 ft draft, 16 mooring lines, 7.3 knot flood current (East Pier)
       Recommended pretension is 400 kips for all lines.
       Pretension cases studied: 150, 250, 300, 350 and 400 kips.

   The above cases represent the predicted approach where it is assumed that all the mooring lines have a pretension error of the same magnitude in the same direction. For example when a certain pretension value is defined (say 150 kips), all the mooring lines in the system were assumed to be at that pretension as against the recommended value of 250 kips, i.e., the error is (-) 100 kips for all the lines.

2. Random Approach
    a. 61 ft draft, 16 mooring lines, 7.3 knot flood current (East Pier)
       Recommended pretension is 400 kips for all lines.
       Pretension cases studied: 3 sets of pretensions chosen randomly between 300 to 400 kips.

   In this case, the pretension for each line is generated using a random number generator with 350 kips as the central value and ± 50 kips as the variation. Each line then assumes a different pretension between 300 and 400 kips randomly.

6 RESULTS OF PRETENSION VARIATION

The results of pretension analysis are extensive; therefore, only representative results are shown here. The results for the three cases as outlined in section 5 are presented in this section both in table and chart form.

The breaking strength considered for the upper lines is 1664 kips (except F, G & H). The breaking strength for all the lower lines and upper lines F, G and H is 1750 kips. The required factor of safety as per API RP 2SK [5] is 1.67, which results in an allowable line tension of 996.4 kips for the upper lines and 1047.9 kips for the lower lines.

In MOTSIM the analysis is performed in two steps. First the steady parts of the current forces are applied on the mooring system with defined line pretensions. Subsequently the dynamic time-varying parts of the external forces are applied in a dynamic simulation. All the steps are performed in one single run.

Table 1 presents the results for 47 ft draft, 16 mooring lines with 6.1 knot flood current, Case 1(a). Results of pretension study for 61 ft draft, 16 mooring lines, and 7.3 knot flood current, Case 1(b), are presented in Table 2.

Table 3 shows the results of random pretension study for 61ft draft, 16 mooring lines, and 7.3 knot flood current, Case 2(a). While studying this case, the base pretension is set at 350 kips to allow a variation of 50 kips on either side. Using a random number generator, the pretension for each line is assigned a different value within the range 350 kips ± 50 kips. The pretension in all the 16 lines vary between 300 and 400 kips, so that it does not exceed the recommended pretension for this draft, which is 400 kips. Three sets of cases have been studied under this approach using different realizations of the random pretensions.

The static tensions shown in the tables are the results of the first stage of the analysis when only the mean or steady parts of the current forces have been applied. The static tensions are generally small in magnitude. These are even smaller than the pretension because of the effect of the increased draft due to the vertical component of the tensions. The dynamic tensions are the final maximum tensions in the lines when the time-varying current forces are applied along with the steady part.

Table 1 Results of pretension variation for 47' draft, 6.1 knot flood current with 16 lines (Predicted Approach)

Line Tensions

Sl. No.	Line Designation		6.1 Kn Current Pretension: 100kip		6.1 Kn Current Pretension: 150kip		6.1 Kn Current Pretension: 200kip		6.1 Kn Current Pretension: 250kip	
			Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips
1	A'	Lower-1	99	515	115	516	124	531	133	492
2	B'	Lower-2	100	572	117	463	127	457	137	541
3	C'	Lower-3	101	604	119	551	130	508	139	593
4	D'	Lower-4	79	**1022**	96	**892**	110	**848**	119	**839**
5	E'	Lower-5	74	889	90	813	100	795	107	821
6	F'	Lower-6	61	376	72	275	81	321	86	327
7	G'	Lower-7	60	452	77	356	84	355	92	359
8	H'	Lower-8	63	533	80	397	87	438	95	420
9	I'	Lower-9	73	636	94	534	109	642	121	660
10	J'	Lower-10	72	385	90	395	101	424	111	461
11	K'	Lower-11	67	319	79	233	87	306	93	263
12	L'	Lower-12	74	769	86	629	94	748	100	711
13	M'	Lower-13	93	877	110	845	120	752	129	640
14	N'	Lower-14	93	383	99	350	103	287	105	291
15	O'	Lower-15	110	430	128	374	137	401	143	408
16	P'	Lower-16	122	610	148	648	165	523	178	592

Displacements

Surge(in)	11.86	47.76	10.27	33.06	9.79	31.55	9.59	29.78
Sway(in)	-15.92	-59.64	-9.98	-38.64	-7.97	-34.96	-7.32	-33.99
Heave(in)	-21.53	-39	-23.35	-37.20	-24.45	-37.20	-25.33	-38.68
Roll(deg)	0.36	-3.8	0.20	-3.02	0.12	3.09	0.06	3.10
Pitch(deg)	-1.33	-3.98	-1.32	-3.30	-1.31	-3.32	-1.31	-3.19
Yaw(deg)	0.03	-3.72	-0.05	-3.26	-0.08	-2.75	-0.10	-2.52

Table 2 Results of pretension variation for 61’ draft, 7.3 knot flood current with 16 lines (Predicted Approach)

Line Tensions

Sl. No.	Line Designation		7.3 Kn Current Pretension: 150kip		7.3 Kn Current Pretension: 250kip		7.3 Kn Current Pretension: 300kip		7.3 Kn Current Pretension: 350kip		7.3 Kn Current Pretension: 400kip	
			Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips
1	A'	Lower-1	124	673	141	710	148	566	155	637	162	599
2	B'	Lower-2	123	661	142	716	150	563	157	569	163	588
3	C'	Lower-3	122	753	143	721	150	607	155	615	164	634
4	D'	Lower-4	89	**1179**	107	**1070**	116	**1050**	126	**1020**	134	**933**
5	E'	Lower-5	85	962	101	979	107	961	113	850	119	894
6	F'	Lower-6	68	447	80	503	83	487	89	406	95	501
7	G'	Lower-7	70	318	88	466	94	411	98	364	102	400
8	H'	Lower-8	74	488	92	541	98	582	103	524	107	454
9	I'	Lower-9	90	850	114	836	126	781	136	701	147	679
10	J'	Lower-10	85	690	105	566	113	514	121	523	129	551
11	K'	Lower-11	76	431	90	362	94	339	99	350	104	402
12	L'	Lower-12	84	**1013**	97	**937**	100	**994**	105	**892**	109	**768**
13	M'	Lower-13	121	**1294**	140	**1200**	147	**1090**	154	**973**	160	**891**
14	N'	Lower-14	111	607	113	436	116	418	118	420	120	443
15	O'	Lower-15	147	614	162	638	168	642	173	634	178	627
16	P'	Lower-16	175	788	207	811	218	865	228	822	238	832

Displacements

Surge(in)	9.67	31.08	8.6	26.01	8.20	24.27	7.95	25.30	7.67	24.80
Sway(in)	-13.62	-44.76	-9.7	-40.22	-8.80	-37.83	-8.13	-33.60	-7.64	-31.40
Heave(in)	-27.32	-52.08	-29	-52.85	-29.64	-52.79	-30.27	-52.10	-30.87	-53.10
Roll(deg)	0.33	-3.83	0.19	-3.7	0.15	3.23	0.11	-3.20	0.07	-3.30
Pitch(deg)	-1.37	-4.32	-1.35	-3.74	-1.35	-3.47	-1.35	-3.50	-1.34	-3.50
Yaw(deg)	-0.05	-3.10	-0.02	-2.85	-0.04	-2.74	-0.06	-2.50	0.09	-2.30

Table 3 Results of pretension variation for 61’ draft, 7.3 knots flood current with 16 lines (Random Approach)

Line Tensions

Sl. No.	Line Designation		7.3 Kn Current Random Trial 1			7.3 Kn Current Random Trial 2			7.3 Kn Current Random Trial 3			Base Case Pretension 350 kips	
			Pre Tension Kips	Static Tension Kips	Dynamic Tension Kips	Pre Tension Kips	Static Tension Kips	Dynamic Tension Kips	Pre Tension Kips	Static Tension Kips	Dynamic Tension Kips	Static Tension Kips	Dynamic Tension Kips
1	A'	Lower-1	350	156	607	333	156	564	301	142	552	155	637
2	B'	Lower-2	329	153	513	370	167	550	390	169	605	157	569
3	C'	Lower-3	371	162	603	333	156	594	378	166	655	155	615
4	D'	Lower-4	338	125	**936**	311	119	**872**	333	125	**924**	126	**1020**
5	E'	Lower-5	314	110	788	313	107	787	305	107	738	113	850
6	F'	Lower-6	332	89	404	361	88	427	368	91	444	89	406
7	G'	Lower-7	351	99	368	352	96	352	373	99	392	98	364
8	H'	Lower-8	325	102	489	397	104	529	346	103	479	103	524
9	I'	Lower-9	384	142	733	336	131	651	375	139	708	136	701
10	J'	Lower-10	322	117	477	397	126	541	312	115	438	121	523
11	K'	Lower-11	383	102	383	352	99	352	368	100	368	99	350
12	L'	Lower-12	340	103	**829**	380	108	**836**	374	107	**831**	105	**892**
13	M'	Lower-13	369	157	**993**	344	157	**1001**	393	161	**986**	154	**973**
14	N'	Lower-14	311	111	355	300	113	370	383	123	425	118	420
15	O'	Lower-15	330	163	590	304	166	604	379	182	667	173	634
16	P'	Lower-16	378	240	845	312	221	819	312	206	756	228	822

Note: Random Number generator function is used to generate pretensions

Displacements

Surge(in)		7.64	23.13		8.18	23.49		7.76	24.44	7.95	25.30
Sway(in)		-8.02	-35.11		-8.89	-36.68		-8.19	-34.62	-8.13	-33.60
Heave(in)		-30.25	-52.72		-30.15	-52.62		-30.30	-52.82	-30.27	-52.10
Roll(deg)		0.13	3.05		0.13	3.06		0.12	-3.14	0.11	-3.20
Pitch(deg)		-1.34	-3.44		-1.36	-3.48		-1.36	-3.46	-1.35	-3.50
Yaw(deg)		-0.05	-2.42		-0.06	-2.40		-0.08	-2.37	-0.06	-2.50

6.1 Caisson Motions

The displacement responses are shown in the previous tables. In Figure 4 and Figure 5, the variation in the surge and sway displacements with pretension for 47 ft draft is shown. The variation of these displacements with pretension for 61 ft draft is represented in Figure 6 and Figure 7. The surge and sway displacements increase as the pretension reduces.

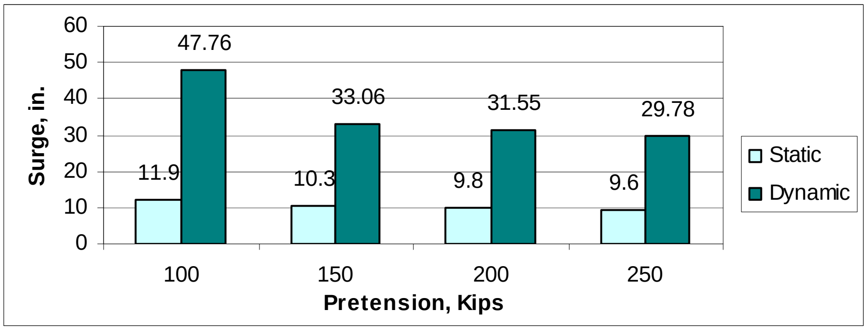


Figure 4 Change in caisson motion with pretension for 47 ft draft, 6.1 knot flood – surge response

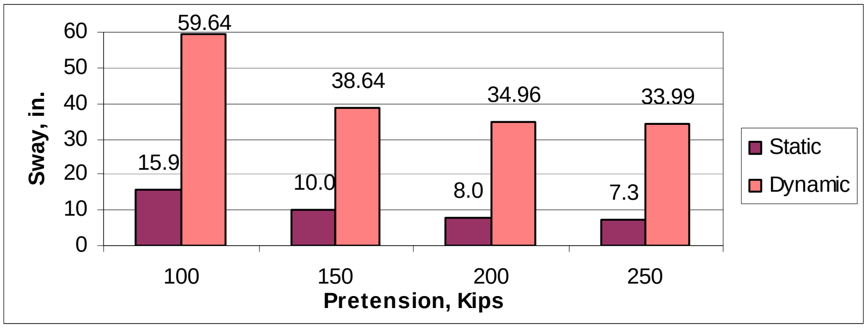


Figure 5 Change in caisson motion with pretension for 47 ft draft, 6.1 knot flood – sway response

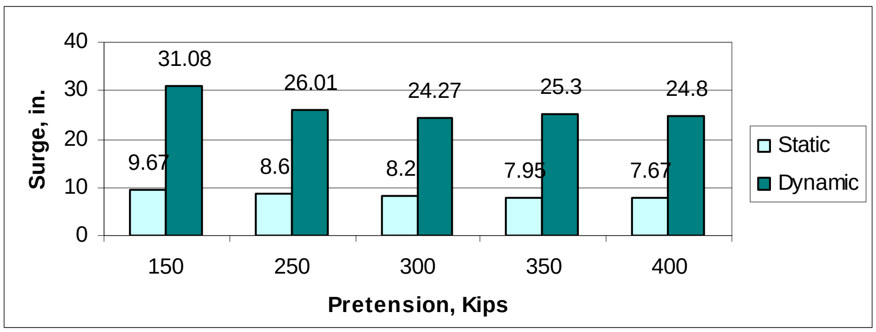


Figure 6 Change in caisson motion with pretension for 61 ft draft, 7.3 knot flood - surge response

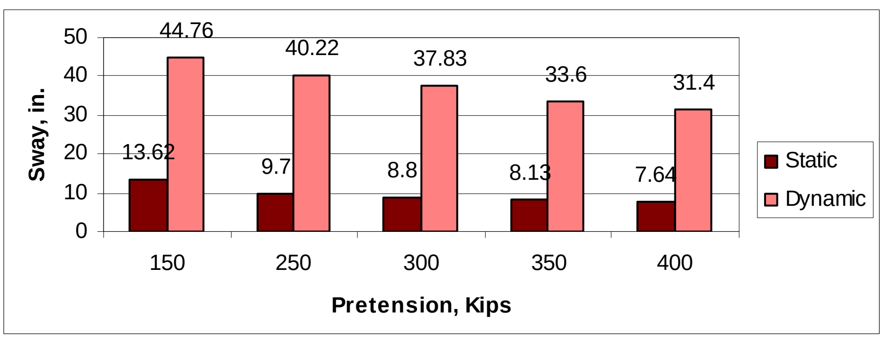


Figure 7 Change in caisson motion with pretension for 61 ft draft, 7.3 knot flood - sway response

6.2 Mooring Line Loads with Predicted Pretension

The effect of pretension on the dynamic line tension for four most loaded lines (D', E', L', M') corresponding to 47 ft draft with 6.1 knot flood current is shown in Figure 8. The variation of static and maximum dynamic line tension for line D' with pretension is shown in Figure 9. The maximum line tensions show steady reduction as the pretension is increased. The recommended pretension for this case from the mooring analysis [6] is 250 kips. Line D' is the most loaded line among all the lines. The maximum change in the line tension for line D' for the cases studied with different pretension is about 139 kips or 22%. For the pretension cases studied for this draft, the line tensions are within the allowable limits.

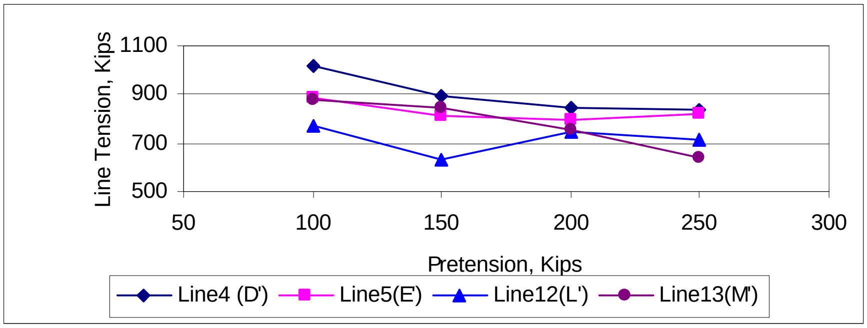


Figure 8 Change in line load with pretension for 47 ft draft

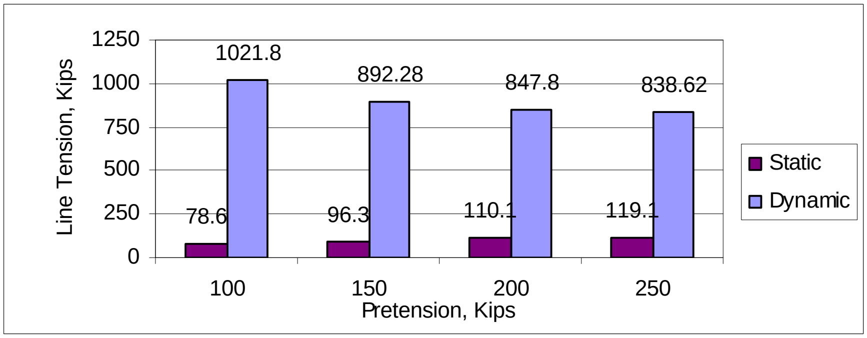


Figure 9 Maximum static and dynamic line loads for 47 ft draft – Line 4 (D')

The effect of pretension on the dynamic line tension for four most loaded lines (D', E', L', M') corresponding to 61 ft draft with 7.3 knot flood current is shown in Figure 10. The recommended pretension for this case is 400 kips. Line tension for line D', which had shown the maximum tension for the case with design pretension of 400 kips, is higher than the allowable (factor of safety is less than 1.67) for the pretension cases of 150 kips and 250 kips. It just exceeds the allowable value for the 300 kips case and is within the allowable limit for the 350 kips and 400 kips cases. The line tensions increase progressively as the pretension is decreased. The maximum variation is 246 kips or about 26%. Similar trend can be observed for line M' which shows higher tensions than line D' for lower values of pretension. This line shows higher than the allowable tension for pretensions of 150 kips, 250 kips and 300 kips and less than the allowable for pretensions of 350 kips and 400 kips. The maximum variation for line M' is 403 kips or about 45%. The static and maximum dynamic line tension for line M' versus pretension is shown as a bar chart in Figure 11.

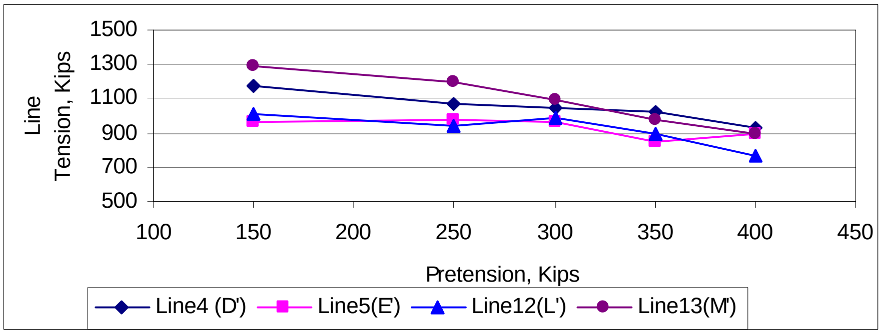


Figure 10 Change in line load with pretension for 61 ft draft

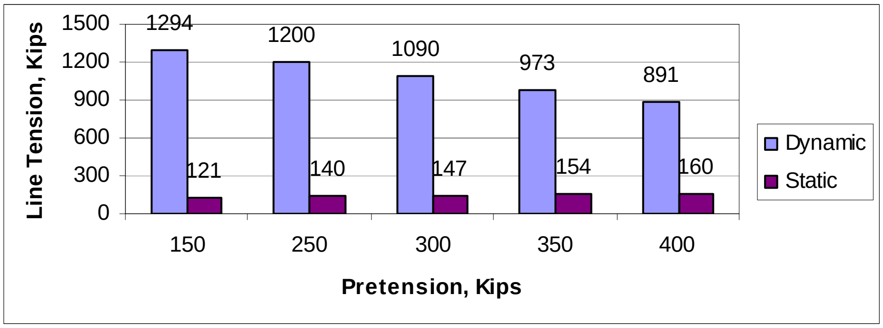


Figure 11 Maximum static and dynamic line loads for 61 ft draft – Line 13 (M')

6.3 Mooring Line Loads with random pretension

In Figure 12 the maximum line tensions for all lines from the three random trials, Case 2(a), are plotted along with those for the base case of 350 kips pretension. The base case is identical to the corresponding pretension under Case 1(b). It is noted that the variation of the maximum line tension for a given line is about 8 – 15%, which is much smaller than the cases studied earlier using the predicted approach. This is expected because unlike the predicted approach the pretensions in this case for different lines could be higher or lower than the mean target value. It is also noted from Table 3 that the maximum line tension could be higher or lower than the base case. For example, lines D' and L' have lower tensions than the base case, whereas line M' has higher tension for all the random cases. The variations of line tension for lines D', L' and M' are shown in Figure 13.

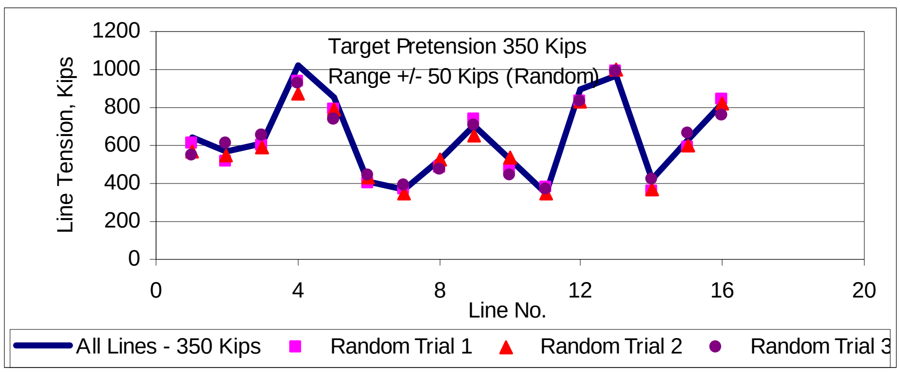


Figure 12 Comparison of line loads using random approach – 61 ft draft

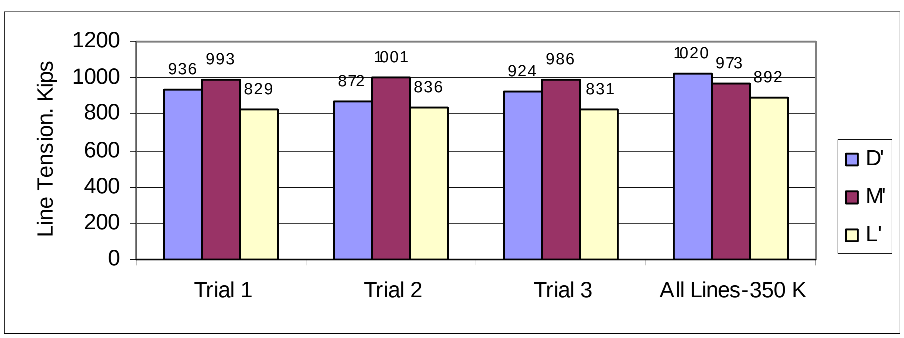


Figure 13 Maximum dynamic line loads for random pretension – 61 ft draft

7 CONCLUSIONS

In view of the dynamic nature of the current forces, the behavior of the caisson is dominated by its dynamic characteristics. The displacements as well as line tensions are susceptible to the pretension of the lines because it changes the dynamic characteristics of the mooring system.

When the pretension variations are predictive, in other words, the pretensions of all the individual lines deviate from the design in the same direction by the same amount, the maximum tensions sometimes could exceed the allowable limits for the ranges of variations studied. This is because the system stiffness becomes softer when the pretensions are lower and affect the dynamic characteristics (natural periods) adversely.

On the other hand, when random variations of pretension is considered, which is more likely to happen in the field, it was found that the tensions did not exceed the allowable limits. In this case some lines have higher pretension and some lower, which has a smaller influence on the changes to the natural periods.

The above conclusion is valid for the limited number of cases studied and should be extended with caution to other situations.

ACKNOWLEDGMENTS

We have the pleasure to acknowledge that Tacoma Narrows Constructors is the contractor, and Washington State Department of Transportation is the owner of the bridge. We appreciate the approval of TNC for the presentation and publication of this paper.

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