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DESIGN, ANALYSIS AND VERIFICATION OF MOORED FLOATING CAISSON SYSTEM

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Abstract

Tacoma Narrows Constructors (TNC) is building a new suspension bridge in Tacoma, close to Seattle, Washington State, USA. The new bridge will be built just south of the existing bridge mounted on two caissons, referred to as East Caisson (Tacoma side) and West Caisson (Gig Harbor side). Each pier is about 80' wide and 130' long in plan.

The mooring system for each caisson consists of two sets of mooring lines: lower and upper. Each set consists of 16 mooring lines. The lower 16 lines 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. These 16 lines are hooked-up after the caisson is towed from the harbor and positioned at the site. For the upper 16 lines (except three lines on East Pier), the anchor locations form a radius of 600'. The fairlead locations for these upper 16 lines vary based on the draft.

Due to the proximity of the proposed caissons to the existing piers and the varying bottom topography, considerable turbulence and vortex shedding is expected which will cause current induced dynamic forces on the caissons. This paper describes the design and analysis of this multi-line mooring system for Tacoma Narrows Bridge caissons, based on the construction sequence in the floating condition. The analysis involved optimizing the anchor locations and the line pretensions, determining the dynamic motions of the caissons, maximum line loads, and corresponding safety factors.

The paper includes the hydrodynamic analysis for added mass, and damping, the methodology used for the nonlinear moored caisson analysis (MOTSIM), and the validation of the design tool with other similar models (e.g., StruCAD*3D). The results of the analysis and design are 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.

Each of the East and West Piers is about 80' wide and 130' long in plan. The bridge pier caissons are cast in vertical layers starting with a cutting edge which is 18' deep, followed by a layer that is 12' deep and then followed by several more layers each of which is 10' deep. The caissons are towed to the site from the harbor after casting of the cutting edge, the first full lift, and the second and third exterior lifts. The draft at which the caisson is towed to the site is about 47'. The final touch-down drafts for the East and the West

Caisson are 160' and 140' respectively.

The proposed mooring system consists of two sets of mooring lines: Lower and Upper. Each set consists of 16 mooring lines:

- The lower 16 (A' to P' or 17 to 32 of Figure 3) lines 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 set of lower 16 lines is hooked-up when the caisson is towed from the harbor and positioned at the site.
- For the upper 16 (A to P or 1 to 16 of Figure 3) lines, the anchor locations form a radius of 600' (except for lines F, G and H). The elevation of the fairlead locations for these upper 16 lines vary based on the draft. The upper lines are hooked-up at 79 ft draft.

Due to the proximity of the proposed caissons to the existing piers and the varying bottom topography, considerable turbulence and vortex shedding is expected to occur during flood and ebb current flows, which will cause current induced dynamic forces on the caissons. These dynamic forces have significant components in all the three global directions and consist of steady drag and oscillatory in-line, cross-flow, and vertical lift components. The flood current strength is stronger, and so are the turbulences downstream of the existing pier leading to higher dynamic component of the forces. This paper describes the design philosophy and the analysis results for the moored floating caissons for all the anticipated drafts under both Flood & Ebb currents. Results for the **East Pier** are described in detail. Although the draft would change continuously as concrete is being poured, the drafts considered for the East Pier mooring analysis are 47 ft, 51 ft, 61 ft, 67 ft, 76 ft, 79 ft, 90 ft, 98 ft, 103 ft, 123 ft and 143 ft. These represent the drafts between two successive stages of concreting when the caisson is expected to remain at a fixed draft for at least a few days at a stretch. For the East Pier the expected touch down draft is about 160 ft, at a +7 ft tide. The results for final draft of 160 ft are not included here as this case was covered in a separate 'touch-down' analysis. The philosophy and the methodology of the design for the West Pier are similar. The West Pier is expected to experience more benign design conditions due to lower currents.

2   CAISSON GEOMETRY & PROPERTIES

The caisson geometry for the 143 ft draft is shown below:

Figure 1 Caisson Geometry

At the bottom of the caisson there is a cutting edge section 81 ft x 131 ft x 18 ft high. Above this, the cross-section of the caisson is square 80 ft x 130 ft up to the elevation of 54.75 ft above the top of the cutting edge. The upper portion of the caisson has chamfered

edges 6 ft 4 in x 6 ft 4 in. The bottom of the caisson is sealed by five inverted half cylinders (false bottom) running in the transverse direction. The coordinate system for the analysis is chosen as follows: the origin is located at the horizontal plane containing the C.G of the caisson; the X-axis is the longitudinal axis through the centerline of the caisson and the Y-axis is orthogonal to it; the Z-axis is vertical up. A diagram showing the sign convention for translations and rotations and the direction of flow is given in Figure 2.
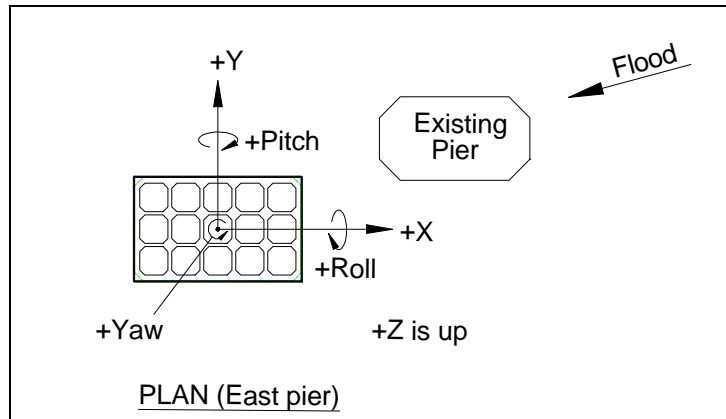
Figure 2 Sign Convention and coordinate system

The largest draft of the caisson for which analyses have been performed is 143 ft. At this draft the weight of the caisson used for calibration of the analysis is 90,953 kips and VCG is 68.9 ft from the tip of the cutting edge. As the design progressed some caisson properties experienced changes. For the final analyses the corresponding weight was 95,000 kips and the VCG at 68.1 ft.

3   MOORING SYSTEM

The mooring system consists of 32 lines connected at two fairlead elevations each having 16 lines (Figure 3). 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 wire and chain except three lines F, G and H and lower lines are all chain. The line descriptions are given below. The upper lines were connected to sliding fairleads to allow the mooring system to work efficiently as the draft of the caisson increased. The elevation of the fairlead and the pretensions were maintained for a specific draft.

During the initial studies for validating the analysis procedure using different models and software (Section 4), the pretension used was 95 kips for upper lines and 60 kips for the lower lines. For the final design, the pretension varied from draft to draft in the range 150 to 400 kips. The final mooring analysis results presented (Section 8) reflect the actual mooring system that was finally in place.

- **Wire**

The wire rope has the following properties (High Strength Spiral Strand SS-265):

Nominal diameter	3.5 in
Rigidity, EA	168,000 kip
Weight per ft, w	25.5 lb
Breaking Strength, BS	1664 kips
Drag coefficient, C_d	1.2

- **Chain**

The 3 3/4" chain (upper F, G, H and lower) has the following properties (Oil Rig Quality):

Nominal diameter	3 3/4 in
Rigidity, EA	168,750 kip
Weight per ft, w	133.6 lb
Breaking Strength, BS	1750 kips
Drag coefficient, C_d	2.0

The 4" chain (other upper) has the following properties (Oil Rig Quality):

Nominal diameter	4.0 in
Rigidity, EA	192,000 kip
Weight per ft, w	152.0 lb
Breaking Strength, BS	1996 kips
Drag coefficient, C_d	2.0
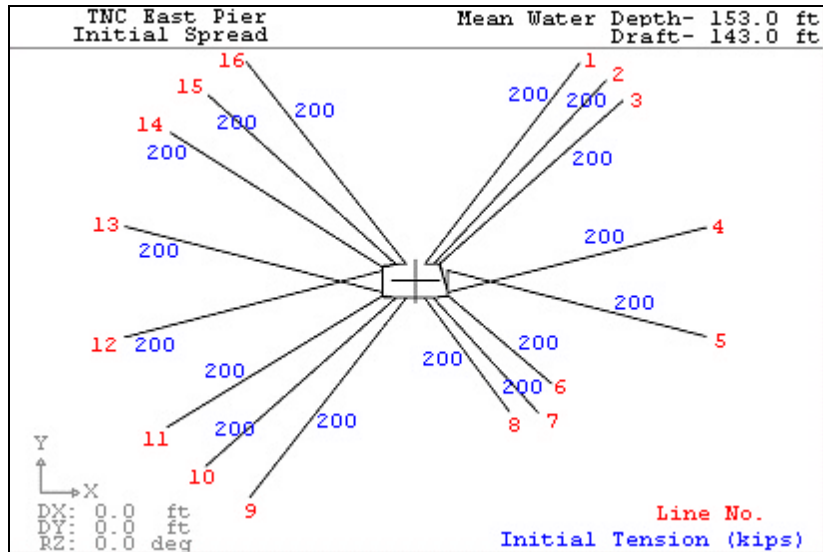
a) Upper Mooring Lines
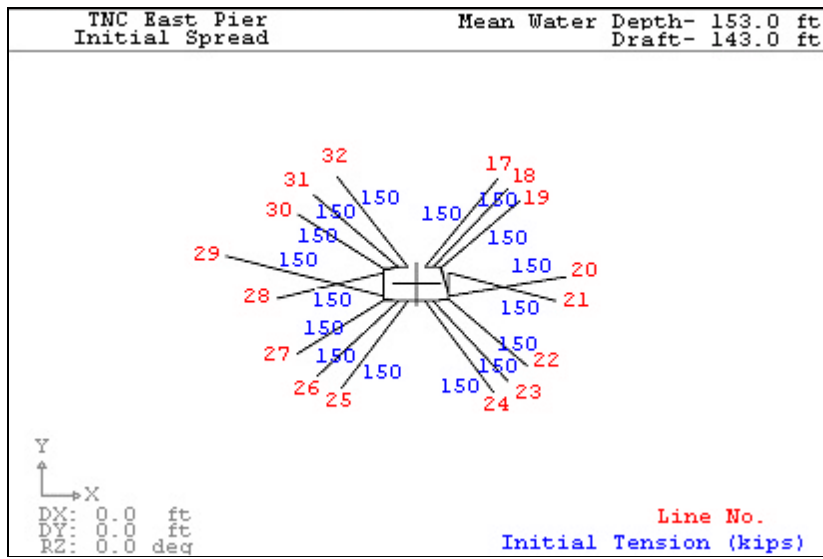
b) Lower Mooring Lines

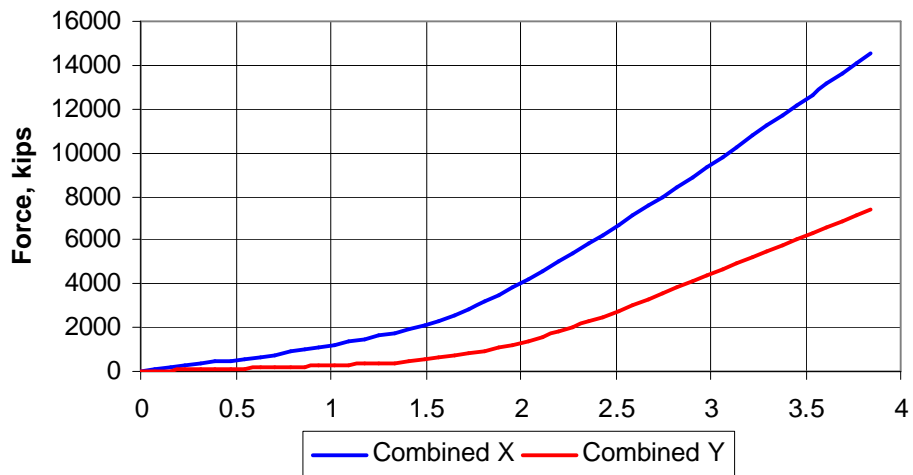**Figure 3 Mooring Configuration – Initial**

Figure 4 Mooring System Stiffness

4   CAISSON MOTION AND LINE TENSION

Different solution techniques can be applied in the mooring design analysis. They would represent different mathematical idealizations or modeling of the real physical problem. ZenMoor [2] program gave the individual line tension-elongation behavior and system stiffness (Figure 4). The system mooring stiffness shown here are for two orthogonal global horizontal directions and is the combined effect of the upper and the lower sets of mooring lines. The lines being semi-taut, the effect of vertical displacements on the mooring system is also significant and has been considered in the analyses. The motion response analysis was performed at various levels of refinement using other programs. The time domain analyses were performed in StruCAD*3D [1] on two different models. Independent time domain analysis was also performed using MOTSIM [3, 6].

StruCAD*3D is a general purpose interactive, graphics-oriented system for constructing, analyzing and designing three-dimensional structural engineering models. For the caisson mooring analysis several models have been prepared. All the models use only beam elements of StruCAD*3D. The models prepared are:

1. Linear stick model of caisson for the natural period analysis
2. Stick model of caisson with nonlinear springs representing the system mooring stiffness
3. Nonlinear stick model of caisson with lines explicitly modeled

The analysis mentioned in item 1 above was performed in the frequency domain by linearizing the line stiffness properties. The nonlinear analyses mentioned in cases 2 & 3 were performed in the time domain. The model in case 3 represented each line as a catenary and included its mass and drag force and, therefore, represented line dynamics.

MOTSIM is a numerical program that facilitates the description of the present system and to evaluate its dynamic behavior. The analysis is carried out in the time domain considering all the six degrees of freedom and the solution is generated by a forward integration scheme. This program permits nonlinear line forces to be included in the analysis and provides explicit results (i.e., functions of time). The program is restricted to constant added mass and damping values on the assumption that the added mass and damping do not vary appreciably over a range of frequencies. The MOTSIM model was similar to case 2 described above but included the 6x6 mass, added mass and buoyancy restoration stiffness and the load-elongation curves for each line.

The results obtained by MOTSIM and StruCAD*3D were compared for the same input parameters for a caisson draft of 143 ft. The results are shown in Figure 5. The two programs produced practically the same results for the cases studied. Also the line dynamics appeared not to be significant in this case. After it was shown that the results from the different models converged, MOTSIM was chosen as the design tool since it is generally conservative and also time-wise very efficient.
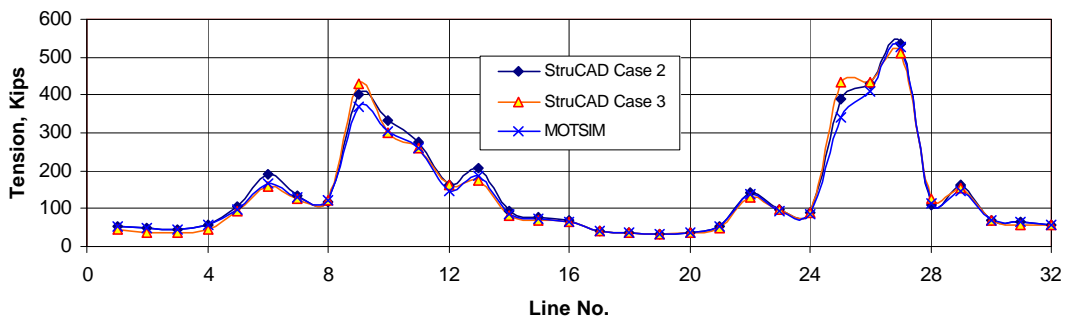
Figure 5 Comparison of Line Tensions- Dynamic

5   HYDRODYNAMIC PROPERTIES

NEPTUNE program [4] was used to develop the hydrodynamic characteristics. The program NEPTUNE is intended for the study of loads and motions of a general class of offshore structures and vessels. The approach is that of radiation/diffraction which builds a database of frequency dependent hydrodynamic added mass and damping coefficients. The coupled six (6) degree of freedom equations of motion are solved for each wave frequency and direction, in the frequency domain.

5.1   Added Mass and Damping

For the added mass coefficients the output from NEPTUNE was used. The asymptotic values of the added mass coefficients applicable to a wide range of frequencies were found to be as follows:

Added Mass	
Surge	0.67
Sway	1.18
Heave	0.59
Roll	0.44
Pitch	0.28
Yaw	0.26

5.2   Damping Factors for the Elastic Mooring System

It was necessary to estimate damping in the system for the six DOF, which may be applicable to the design of the mooring system. Analytical estimate of this damping is a difficult task. The best possible method for this estimate is the use of physical decay tests of the moored model, which includes the damping effect of the overall system. A special damping test series was performed during the physical elastic mooring model tests at H.R. Wallingford, UK (HRW) to help determine the damping components of the mooring system. Two fore and aft springs were used to moor the caisson of 143-ft draft. The spring lines were attached at the CG as well as at the waterline. An example of the decayed force in surge oscillation is shown in Figure 6. The two forces correspond to the fore and aft spring loads. Note that the two measurements are equal and opposite. The oscillation amplitudes were fitted to a semi-log line in Figure 7 by the least square method. The slope of the fitted line estimates the damping in the caisson system in surge. Calculations were carried out using these decay (pluck) tests to determine the appropriate values of the damping factor for use in the design tool. Linear damping as shown in Figure 7 was found to be appropriate for all cases.
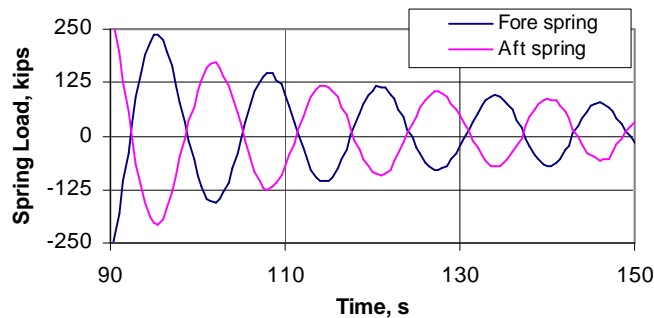
Figure 6 Surge Damping Test in Still Water
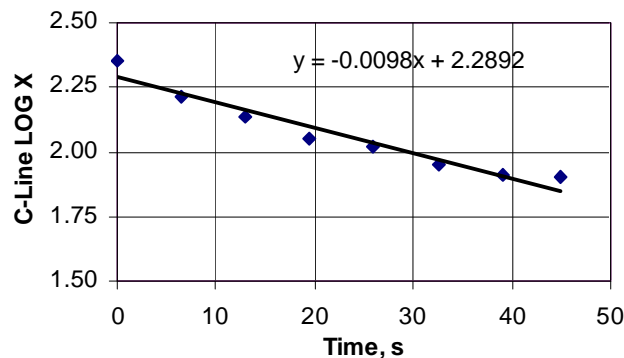
Figure 7 Data Fit to Surge Damping Test in Still Water

The best estimates of the total damping in the caisson model were obtained from these tests. In a few cases, the damping factors were recovered from just a few cycles and thus are quite approximate. Based on the above analysis of estimated damping factor, the following values in Table 1 are derived for the still water and total damping in current. The total damping values shown here were used in the design of the moored system.

Table 1 Recommended Estimated Total % Damping Factor in the System

Mode	Total Damping
SURGE	6.0
SWAY	7.0
HEAVE	5.0
ROLL	5.0
PITCH	7.0
YAW	5.0

It is recognized that these model values are expected to suffer from scale effects. The main reason for the scale effect is the viscous flow between the model and the full scale, which will be different being in different Reynolds number regime. However, the Reynolds numbers for the model and full scale place the flows both in the turbulent region. Moreover, the scaling effect will have an opposite effect on the load and damping, somewhat compensating their individual effects. While this counter-effect cannot be quantified, the difference between the regimes appears to be much reduced due to these interactions and model values are assumed directly applicable in the full scale without appreciable errors.

5.3   Effect of Variation in Damping

The effect of damping on the caisson response and the line tensions was studied for a flood case. The case chosen is the caisson with 61-ft draft in 7.3-knot current. The mooring system consisted of 21 lines with 16 lower lines and 5 upper lines. The damping factor was changed from 2% to 10%. The power spectral density (PSD) of the surge motion is shown in Figure 8. Note that the natural period is a function of damping present in the system since the line stiffness is nonlinear. The surge period ranges from about 16 to 17 seconds. The reduction of the surge motion with the amount of damping is quite clear in Figure 8 for the PSD. However, the rate of reduction diminishes with increase in damping.
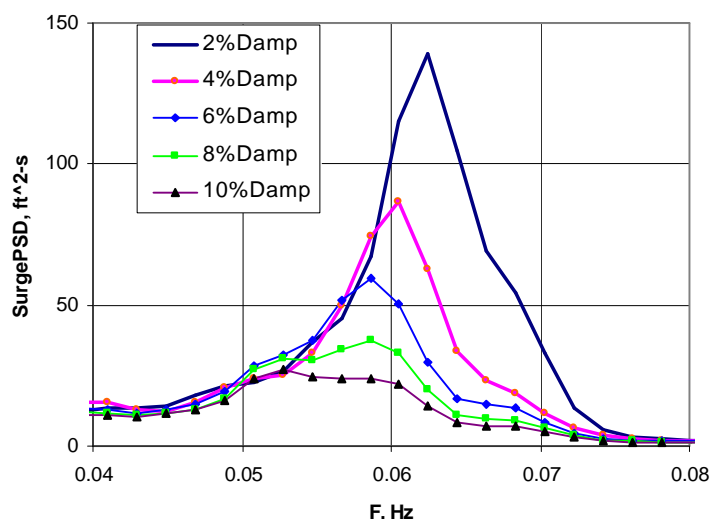
Figure 8 Surge Motion Spectra for Different Damping Factors

The mooring line tensions for the various damping values are shown in Figure 9. The line tension, likewise, decreases with the increase in the damping factor. The rate of reduction decreases with the increase in the damping values. It is clear from the above analysis that damping plays a significant role in determining the caisson response and the line tension. The reasonableness of the damping values used in the design was verified once the results for the flood case were compared with the corresponding model test data.
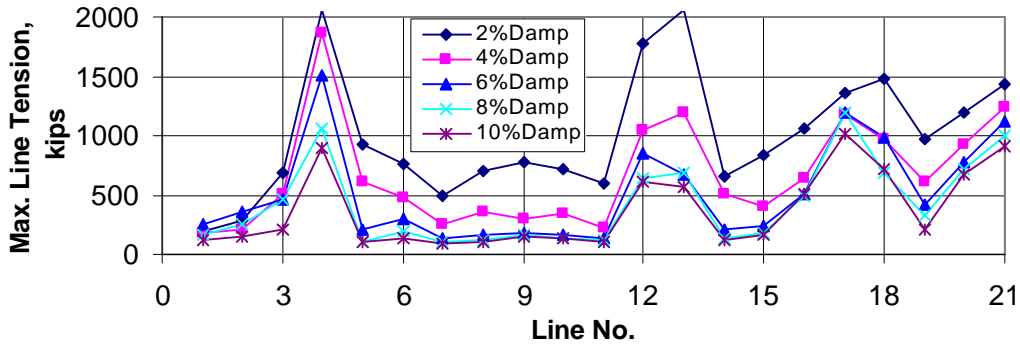
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Figure 9 Maximum Line Tensions for Different Damping Factors

6   DESIGN INPUT

The caissons in the Narrows experience very high current. Therefore, the loads experienced by the caisson due to the current flow had to be determined for its design. This section describes the magnitudes of measured current in ebb and tide flows and the associated loads on the caisson. The methods used to arrive at these inputs for the caisson dynamic analysis are discussed.

6.1   Design Current

The current design conditions were based on four years of NOAA current predictions. The 24-hour current measurement done by Sandwell in 2000 for the present location was used to modify this midstream information using site factor. The effect of expected one-year storm surge is added to arrive at the design values. One year projection of the storm surge is considered appropriate since the duration of the construction was to be only a few months. The following table summarizes the design surface current for each pier.

Table 2   Nominal Current Velocity and Approach Angle

Pier	Condition	Nominal Design Velocity (knots)	Approach Angle (degrees)	
			Average	Range
East	Flood	7.5	10	5-15
East	Ebb	5.7	22	17-27
West	Flood	7.5 (6.0[*])	--	--
West	Ebb	5.7 (4.9[*])	21	16-25

* For drafts up to 79 ft

The above values are at the surface. The depth profile is reasonably uniform with a parabolic profile near the bottom boundary layer. The average approach directions w.r.t the global X-axis are shown with a range (±5 degrees). The model tests and analyses have been done for an average angle of 16 degree.

The current time history was reasonably steady with a small typical low frequency variation of about 0.0025 Hz. However, the low frequency component in the current was not critical for the dynamics of the floating caissons since the natural frequencies of the caisson were far removed from these low frequencies.

6.2   Input Forces for Mooring Line Analysis

The mooring analysis requires the forces on the caisson arising from the current flow as an input. The current loads are generally computed from the drag force formulation based on appropriate drag coefficients for the prototype Reynolds number. However, it is difficult, if not impossible, today to empirically determine the fluctuating nature of current force in six degrees of freedom. Two possible methods were considered for the determination of the 6 DOF current forces.

One of these methods is the use of a Computational Fluid Mechanics (CFD) analysis that simulates the flow around the caisson for the current speed in three dimensions. The other method is the model testing of the caisson in which the forces on the fixed caisson model were measured. In this case, the geometric model of the caisson was fixed over the bottom contour on a set of load cells and the current flow is generated in model scale, which allows measurement of three forces and three moments on the caisson due to the

current flow. For this design analysis, the model test results have been used for reasons explained in the accompanying paper [5].

6.3 Extrapolation of Force Time History for New Draft

Forcing functions were derived from HRW data for a limited number of drafts. For other drafts e.g., for the float-out case of 47ft draft, the forces were obtained by interpolation from these test results on forces. The force time history extrapolation for a small change in the caisson draft for the east pier is based on the following assumptions:

- Z force on the caisson is unchanged due to draft change
- X and Y force distributions on the caisson are uniform with depth
- Z-load distribution is maintained for the HRW data
- X- and Y- loads from HRW data are changed by the ratio of the two drafts
- Z-moment from HRW data is changed by the ratio of the two drafts
- the contribution of Z- load to the X-moment is computed and added to the modified X-moment from the uniform Y- load by the square of the ratio of moment arm
- the contribution of Z- load to the Y-moment is computed and added to the modified Y-moment from the uniform X- load by the square of the ratio of moment arm

Consider the measured HRW data for a given draft (WD = Wallingford Draft) to be FX_{WD}, FY_{WD}, FZ_{WD}, MX_{WD}, MY_{WD}, MZ_{WD}. For a new draft (ND), for the data FX_{ND}, FY_{ND}, FZ_{ND}, MX_{ND}, MY_{ND}, MZ_{ND}, the formulas for the extrapolation are:

$$FX_{ND} = FX_{WD} * ND/WD$$
$$FY_{ND} = FY_{WD} * ND/WD$$
$$FZ_{ND} = FZ_{WD}$$
$$MX_{ND} = [MX_{WD} - (WD/2)* FY_{WD}] + (WD/2)* FY_{WD} * (ND/WD)^2$$
$$MY_{ND} = [MY_{WD} + (WD/2)* FX_{WD}] - (WD/2)* FX_{WD} * (ND/WD)^2$$
$$MZ_{ND} = MZ_{WD}* ND/WD$$

The model tests were conducted for the following drafts: 61ft, 103ft, 123 ft and 143 ft., for both Flood & Ebb currents. The input force data for the drafts 47 ft, 51 ft, 67 ft and 79 ft were derived from the 61ft draft model test data. The input force data for the drafts 90 ft and 98 ft were derived from the 103 ft draft model test data. An example of the time-varying surge force measured in the fixed body tests for the 61ft draft is shown in Figure 10.
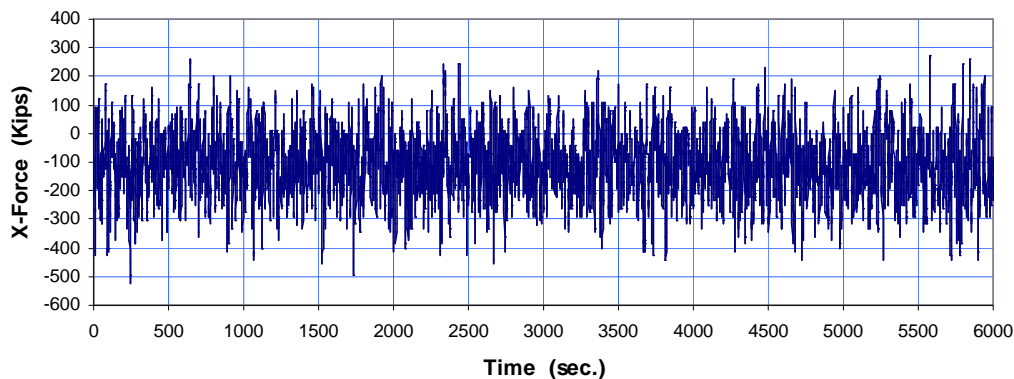

Figure 10 Plot of Input Surge Force, 61 ft Draft, 7.3 Knot Flood

7 DESIGN CHALLENGES

In contrast to mooring system design of other conventional floating structures, one of the major challenges in the design of the Tacoma Narrows Caissons was that the design had to be satisfactory for all the drafts that the caisson would experience from the initial towing draft to the draft at touch down. Due to time and other constraints of the project the lines and anchors had to be pre-selected long before the finalization of the design. Similarly, the orientation of the piers, the line lengths and the anchor positions were also virtually unalterable. On the other hand, the caisson response and the mooring line tensions were very much driven by the dynamic responses of the caisson. As the draft changed the dynamic characteristics, such as the mass and the added mass, as well as the mooring stiffness and the input force magnitude and characteristics also changed. These factors changed the natural periods and the dynamic amplification.

After a study of the system behavior it was concluded that the only effective way of controlling the system response was to suitably select the pretensions of the lines. Therefore, the design task was to select the optimal pretension of the lines at each selected draft so that the dynamic characteristics were favorable to limit the line tension responses within acceptable limits. It was ensured that at each draft the pretension selected was good for the intact cases both for flood and ebb tides as well as the one-line damaged cases. Effort was made to make the changes in pretension as less often as possible. The recommended pretensions for the upper and lower lines for different drafts for the East Pier are shown in Figure 11. Further details are included in a companion paper [8].
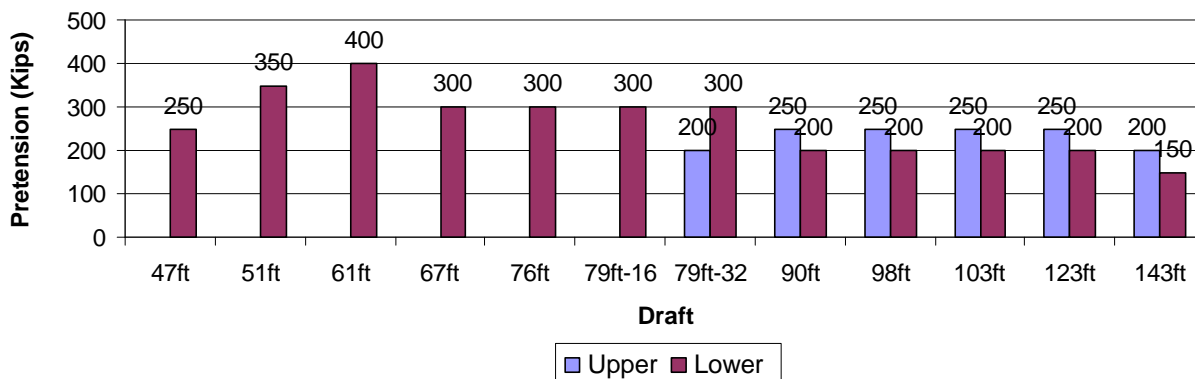
Figure 11 Recommended Pretension for different Drafts – East Pier

8   DESIGN ANALYSIS RESULTS

The results of mooring analysis are extensive and only representative results are shown here. The analyses covered eleven drafts and at least one flood and one ebb current case for each draft.

The other variations of the design cases analyzed were as follows:

1. Anchor array optimization study to limit the anchor load to 1000 kips
2. Mooring analysis with damage to one mooring line at a time. This was performed for the two most-loaded lines for selected cases
3. Damping assessment – for the cases for which model tests have been performed
4. Tidal study – effect of variations in tide on mooring line tensions
5. Pretension study – effect of variations in pretension
6. Analysis for touch-down condition
7. Fatigue analysis for the mooring lines

The breaking strength considered for the upper lines is 1664 kips (except F, G & H). The breaking strength for all lower lines and upper lines F, G & H is 1750 kips. The required factor of safety as per API RP 2SK [7] for the intact case is 1.67 and for the damaged case is 1.25. Using these values the allowable line tensions are shown in Table 3.

Table 3   Allowable Line Tensions

Allowable Line Tensions (Kips)		
Lines	**Intact (FOS=1.67)**	**Damage (FOS=1.25)**
Upper	996.4	1331.2
Lower	1047.9	1400.0

8.1   Mooring Line Tensions

The representative cases of maximum line tensions are shown in Figure 12 and Figure 13. The cases chosen are the flood and ebb flow past the East Caisson in which all mooring lines were present (called intact case). The maximum tensions represent the maximum line tension observed over a 100-min (prototype) current duration. The legend shown in the figures show the draft in feet (first number) and the speed in knots (second number). Note that only 16 lines were present for drafts up to 79 ft when all 32 lines were attached to the caisson. The current velocity for the flood is higher than that for the ebb flow. For the location of the lines

relative to the current flow, please refer to Figure 2 and Figure 3. The dynamic tensions in the flood flow are generally higher due to higher current as well as higher turbulence due to the presence of the existing pier. However, in all cases the tensions were much lower than 1000 kips. The results for the west caisson were similar.
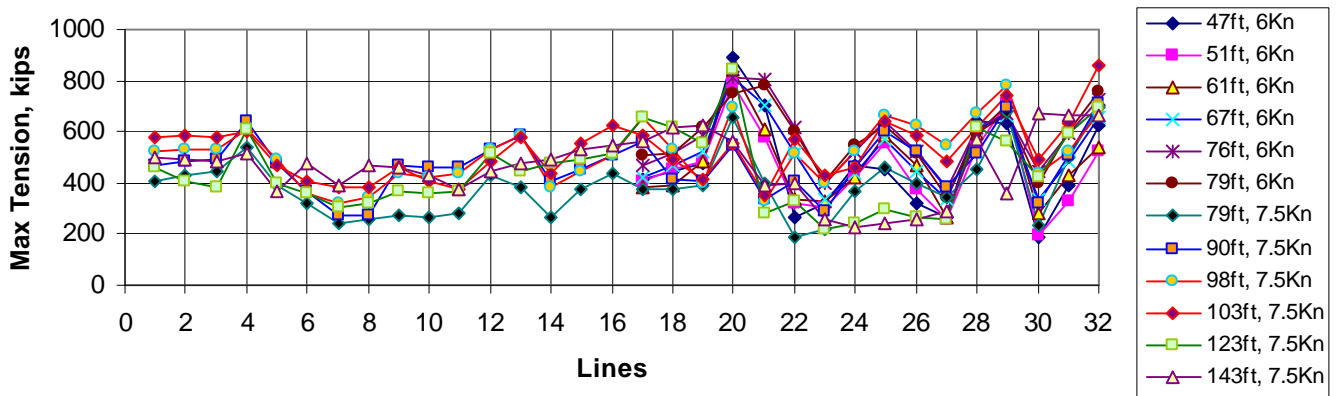

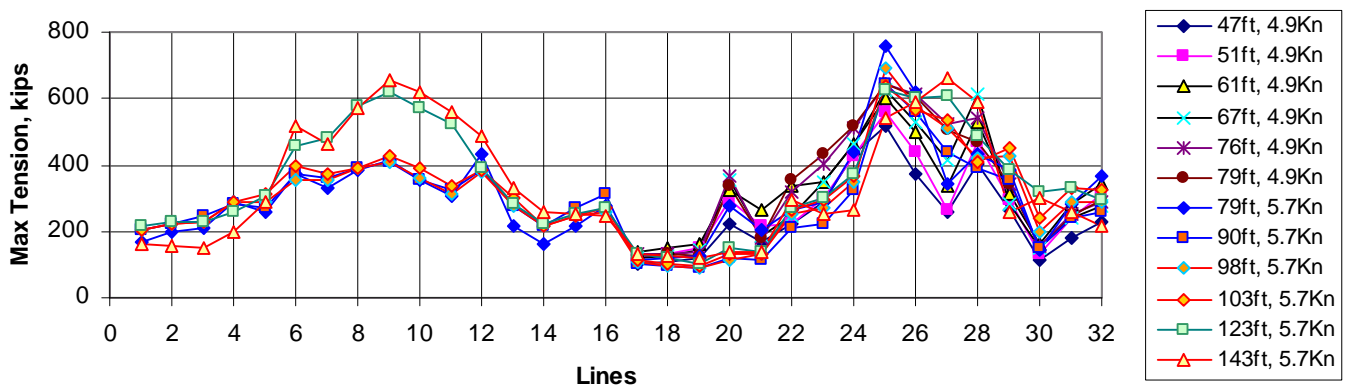**Figure 12 Dynamic Line Tensions of the East Caisson - Intact – Flood**

Figure 13 Dynamic Line Tensions of the East Caisson - Intact – Ebb

The overall factors of safety (FOS) for the various cases analyzed are summarized in Figure 14 and Figure 15. In these cases the allowable FOS is shown as a horizontal line. Both the intact and damaged cases are shown. The FOS represents the minimum value for all the lines for the particular case. The cases increase in draft from left to right starting at 47 ft and ending at 143 ft. The flood and ebb cases for the same draft are shown side by side for which the current speeds were different. In addition, the damaged cases were analyzed for a fewer cases which are also shown in the figures.
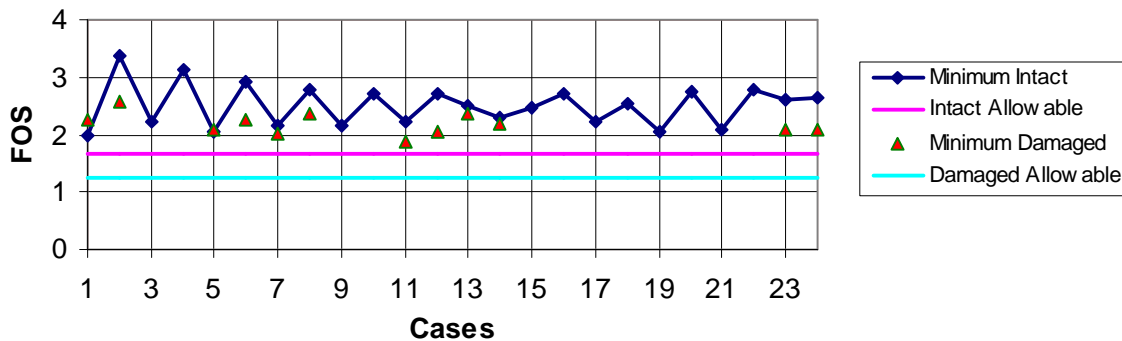

Figure 14 Overall Summary of East Pier Mooring Analysis Results

In all cases the minimum factor of safety was higher than the allowable for both the intact and damaged cases based on the API guideline.
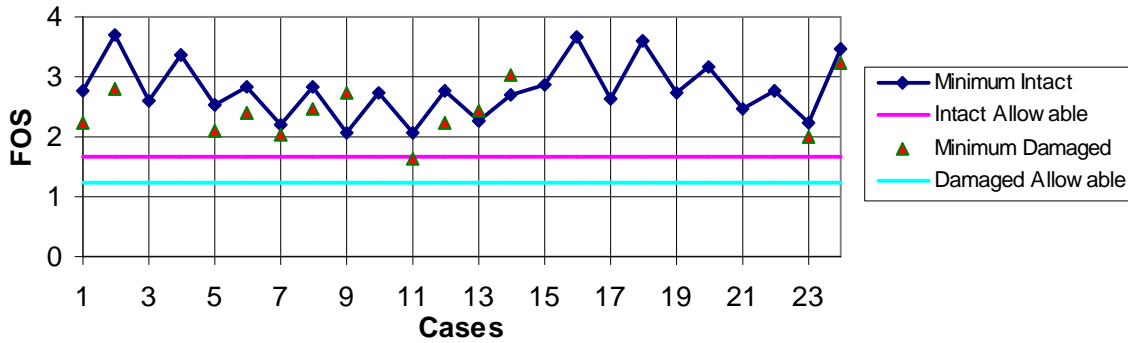
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Figure 15 Overall Summary of West Pier Mooring Analysis Results

8.2 Response Trends

In order to identify any trends that may exist between the input and the response quantities the maximum surge force, displacement and the line tensions for the flood cases for the East Pier have been plotted in Figure 16.
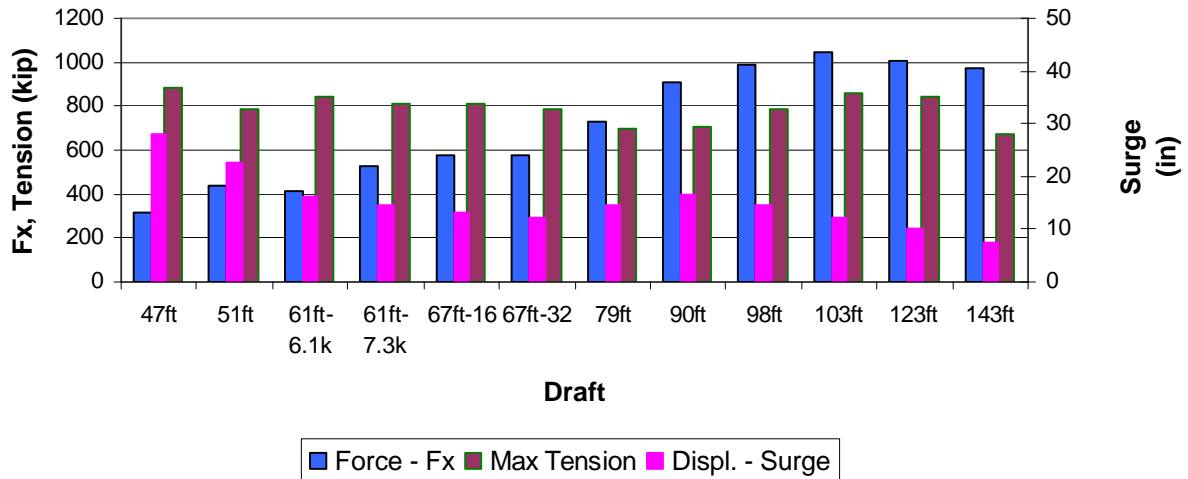

Figure 16 Maximum Input Force, Displacement and Tension Response

The surge force on the caisson has a tendency to increase with the draft as is expected, but the displacement response decreases with draft. The maximum line tension appears to be almost steady for any draft. The response for the dynamic system is dependent on the dynamic characteristics and the mooring stiffness. Therefore, there is no direct correlation of the displacement response with the input force magnitude. The line tension being the result of a complex combination of the six degrees of motion responses, it shows no direct dependence with a single displacement response such as the surge. Also, the maximum force, maximum motions and the maximum tensions do not necessarily occur at the same time. It has been possible to keep the maximum line tensions for all the cases within a narrow band by properly tuning the system through pretension adjustment (see [8]).

8.3 Extreme Mooring Line Loads

The maximum line loads shown in the above figures were computed from the time history data as the single maximum value over a run length of 100 minutes. While this time span is quite large, it may not ensure the short term extreme values for the line loads. Therefore, a more appropriate method should be used to ensure that the maximum value has been achieved. This maximum may be higher or lower than the maximum found in the data length.

One of two methods may be used to verify the extreme line loads for the cases where the line loads approach the limiting values. Time domain analysis may be carried out with different realizations of the force time history. These time histories may be obtained from the force spectra through a standard time series simulation method. Several time histories may be generated and analyzed to obtain an optimum maximum for the critical line loads.

A second alternative is to fit the line load peaks to a short-term statistical distribution function such as, Weibull distribution. If a reasonable fit is found then a maxima based on a chosen probability level provides the design line load. This latter method was

pursued in the present case. As shown in the accompanying paper [5], the Rayleigh distribution matched the extreme values found over the 10-min duration of test run quite well. Therefore the maximum line tensions reported from the MOTSIM runs were considered appropriate for the design of the mooring lines.

9   CONCLUSIONS

The construction and installation of the design caisson system have been successfully carried out. The basic design methods of the moored floating caissons and the corresponding analysis and verification of the design methods are summarized below:

♦ The exciting forces due to current were obtained from the model tests performed on the caisson at HRW. It was initially planned to use the CFD results where model test data was lacking. However, after further analysis of the CFD data it was decided that the CFD results were lacking the high frequency components of the force, which was very important for the mooring design analysis. Data from the model test were interpolated where necessary for various drafts to obtain the time history of the force data.

♦ The load-deflection table for each of the mooring lines was computed by ZenMoor using the line properties and the fairlead and anchor coordinates of the lines.

♦ The hydrodynamic added mass was derived from the linear diffraction/radiation program NEPTUNE.

♦ The total damping factor was calculated from the decay tests from the elastic caisson test as well as the damping tests. The damping coefficients were adjusted using the natural periods derived from the mooring analysis of MOTSIM and the analysis was rerun with the adjusted damping coefficients.

♦ The total damping in the system from the elastic mooring tests was found to be about 5% to 7% of the critical. They were partly verified with the damping tests. No strong evidence of nonlinear damping was found in the data.

♦ The elastic mooring analysis was performed by the program MOTSIM. This program was verified by comparing its output with those of StruCAD in a couple of cases.

♦ The maximum line tensions for all the intact cases did not exceed the allowable tension. This includes both the ebb and flood flow cases. The mooring system performed well and the line tensions were within the design limits, as long as the pretension levels were maintained at the prescribed limits.

♦ The measured maximum tensions for the damaged cases did not exceed its allowable limits either.

♦ The maximum values reported from the MOTSIM analysis corresponds to the short term statistical extreme values of the line tensions.

ACKNOWLEDGMENTS

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