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Design and Application of Real Time Monitoring System for Moored Caisson

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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 caisson is about 80’ wide and 130’ long in plan.

The caissons are moored in place in high currents in the Narrows by two sets of mooring lines on each of them – lower set and upper set. The target positions of the new caissons are very close to the existing pier. Therefore the motions of the caisson are very critical for the success of the project and the final touchdown position of the caisson is also of main concern.

The mooring monitoring and advisory system ZenMAS has the capability of monitoring the performance of the caisson in currents by acquiring real time data from instruments. Real time line tensions and GPS data are read. The instantaneous tension in each of the mooring lines is measured, recorded and reported. Using the real time GPS data, the program reports the translations and rotations of the caissons. There are warnings when any of these are exceeded beyond allowable limits.

ZenMAS also has the capability to function as a simulation tool. Future what-if scenarios can be studied using this software and any necessary corrective measures taken. The analysis capabilities of ZenMAS include static and dynamic analysis using the Motion Simulator program MOTSIM [2].

Graphical representation of instantaneous caisson position and summary and detailed output and results are available from the program. A discussion on how this system was designed, typical inputs, outputs, and comparison to actual measured values is made in this paper.

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).

The new Tacoma Narrows Bridge will be designed as a suspension bridge and operated parallel to the existing Tacoma Narrows crossing in Tacoma, Washington. This is the largest suspension bridge built in the USA in the last 40 years, and the first time a major suspension bridge has been constructed parallel and in such proximity to an existing bridge.

Each of the East and West caissons is about 80’ wide and 130’ long in plan. The water depth at the two caisson sites is nominally 130’ at the west caisson site and 144’ at the east caisson site, with the anchor locations varying from 40’ at the shallowest to 196’ at the deepest. The Narrows River is characterized by strong currents. Hence, it was a major concern to know the tensions in the mooring lines and the position of the moored caisson at any given point of time. The mooring advisory system ZenMAS was used to perform this task. ZenMAS has the capability of acquiring real time data from CMMS. This data is then processed and reported as translation and rotation of the caisson. A superimposed figure of caisson’s target position and actual positions would give the operator a fairly clear idea of the offset distance from the target. If any corrective measures are required, the ZenMAS program has the capability to provide mooring advisory.

2. DESIGN REQUIREMENTS AND INPUTS FOR ZenMAS

a) Functions

The most important requirements for the ZenMAS program were to perform monitoring and simulation functions. In the monitoring role, the program reports the mooring line tensions and real time position of the caisson. This included the real time GPS readings, tensions in each mooring lines and the offset of caisson from the target at bottom. The program was also required to perform simulations. For any draft of the caisson and any given current, dynamic analysis was to be performed and the results were to be provided in both text and graphical formats. A summary of the analysis was also required which would give the maximum and minimum motions and the maximum tensions in each line. Warnings were to be provided when various parameters exceeded the preset limits.

b) Inputs

The primary input was the detail of line make-up for each line. Each caisson was moored using a 32-point mooring system. Of these, 16 lines were connected at a fixed height from the bottom of caisson. The other 16 lines were connected at a certain elevation of the caisson which was varying with draft. The lines were of either wire or chain-wire combination. The desired input for program included this line make-up and details of the line, like diameter, length, weight in air, weight in water, breaking strength and stiffness.

The line table was built using the mooring analysis program ZenMoor [1] knowing the anchor location, the connection point on the caisson and the mooring line make-up for each of the lines. This line table was an input into ZenMAS.

The lines were also required to be at certain pretension levels at different drafts, per the mooring analysis performed for this project. This set of pretensions was also set up in the ZenMAS program.

To perform the simulation function, knowing the line table, the program requires the forcing function which is the current loads on the caisson which were obtained from model tests. Several different cases were analyzed in the model basin and the results from these model tests were reduced to obtain the forces and moments for certain current speeds, at certain drafts for both Flood and Ebb flows. Most of the inputs were masked from the end user.

c) Procedure

Thus, provided the anchor location, fairlead location (in this instance – block location), and the pretension desired, the non-linear line table is established for a given mooring line. This procedure is repeated for each mooring line and the complete set of line tables is set up.

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 determine the fluctuating nature of current force in six degrees of freedom empirically. 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 method essentially solves the Navier-Stokes equation numerically. 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 is 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.

As stated earlier, model test were done only for certain drafts and current speeds. All model tests were done only for the Flood flow. Therefore, for intermediate drafts, intermediate current speeds and for the ebb flow cases, interpolations were performed by the program.

3. PROGRAM DESCRIPTION

ZenMAS is a simple windows based application. The functions are arranged in menus like in any windows based system. The main screen of the program displays real-time data. This screen has three views of the caisson, the plan, profile showing trim and profile showing heel. There is a display for the real-time GPS data and line tensions.

The Input menu has the options for user inputs. This includes the selection of Mode – Simulation or Real-time, selection of caisson draft, status of mooring line – Intact or Broken and desired pretension. These inputs are protected by passwords and there are three levels of protection – Administrator, Supervisor and Operator. Figure 1 and Figure 2 below show the main ZenMAS screens.

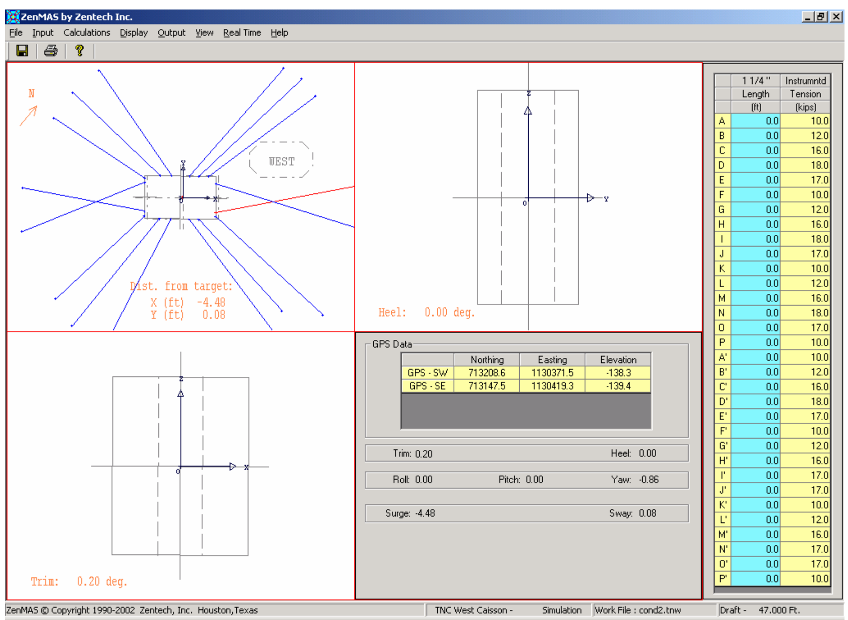

Figure 1 ZenMAS Main Screen

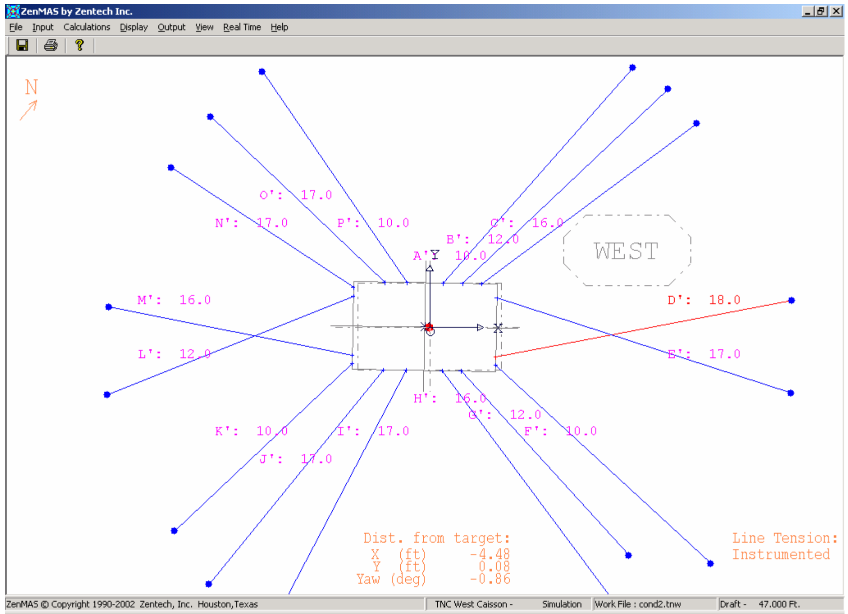

Figure 2 Plan View Displaying Line Tensions

The plan view shows the caisson bottom plane along with the connected mooring lines and the existing bridge pier. The target position is marked clearly using a red dot and the distance from target to the center of caisson is displayed at the bottom of this view. This offset distance is calculated based on the real-time GPS readings, trim and heel and is updated at constant intervals. The other two views show the trim and heel of the caisson in real-time. The main screen gives a clear picture of the caisson position in real-time.

4. PROGRAM FEATURES

a) Real-time Mode

To report the real-time position of the caisson, the GPS data, trim and heel of the caisson are required. ZenMAS is also required to show the measured tensions in each line. These line tensions are measured using load pins attached to the mooring line using shackles. CMMS gathers the signal from the GPS receivers and load pins and stores it as comprehensible data. ZenMAS then communicates with the CMMS to get these parameters. The method used for this is OPC (OLE for Process Controls), a fast and easy standard of communication between two completely different programs.

The OPC standards are the standards proposed by OPC Foundation, started by a small group of companies to facilitate interoperability between multi-vendor systems. OPC client software developed according to these standards can communicate with any OPC server, irrespective of the manufacturer. CMMS has OPC server capabilities and ZenMAS is programmed to server as an OPC client. This makes the communication easy between the two programs.

If the user informs the ZenMAS program the name of the computer on which CMMS is running (which has to be on the network) and select the required parameters he wants to monitor through the OPC link, the ZenMAS program will establish the link and start obtaining data from the CMMS. These parameters are updated at constant intervals of 3 seconds so that the most accurate readings are available.

b) Simulation Mode

ZenMAS has the option of running in real-time mode or in simulation mode. In the real-time mode, the caisson positions are updated taking into account the real-time data. However, during simulation, this updating is not done and ZenMAS stops communication with the server. The option allows the user to facilitate the analytical study of a given situation. Static and dynamic analyses for any draft and current speed can be performed and line tensions and caisson motions determined analytically. Analysis can also be performed for a broken line scenario. The choice of flow direction (flood or ebb) can also be made.

These calculations are performed with the help of the calculator from the MOTSIM program. The results obtained after the analyses may be viewed as text output or as plots. The detailed output gives the time series of all six degrees of freedom and line tensions. Plots of these results can also be obtained. In the plot option the user can choose between one or multiple available series for plotting. There is summary report available showing the minimum, maximum and average of all six degrees of motion and the maximum line tensions for each line.

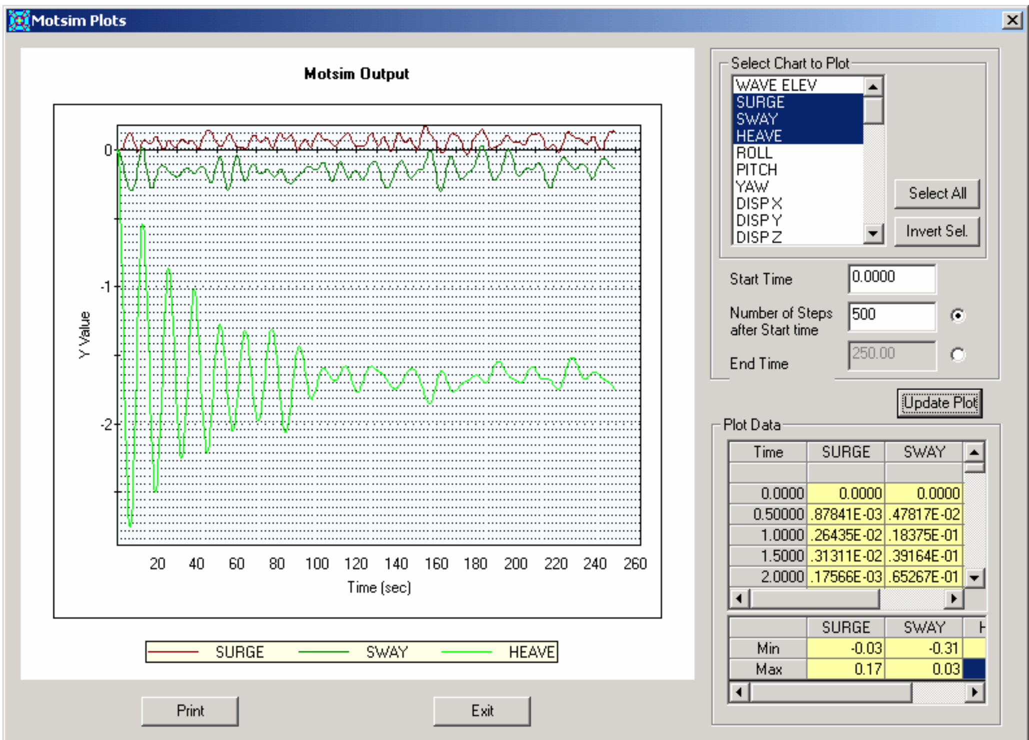

Figure 3 Analysis Results as Plots

c) Alarms

The alarm feature is useful for constant monitoring. The user can set the maximum limits for critical parameters like line tension, caisson offset and yaw. The program will alert the user by flashing a warning message when any of these limits are exceeded.

Apart from these specific alarms, the program also alerts the user when there is a problem with the real-time data. Problems can arise either from a lost communication link or from suspect readings due to malfunctioning of GPS receivers or load pins. The program will sense these problems and will flash a warning message.

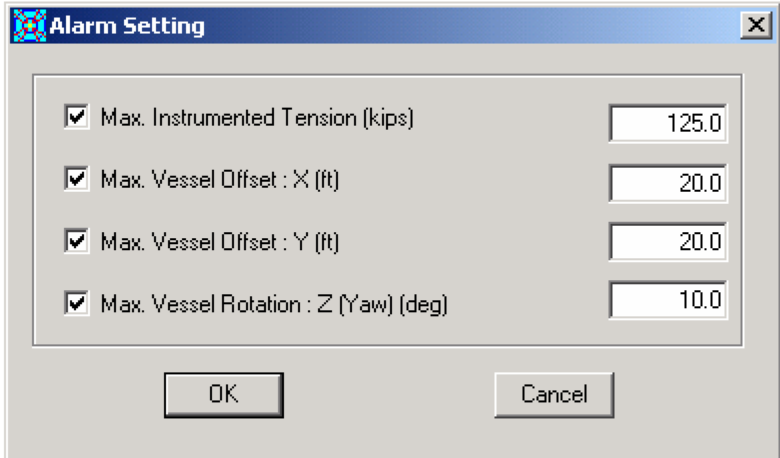

Figure 4 Alarms

5. COMPARISON WITH ACTUAL VALUES

During construction of the caisson in the Tacoma Narrows, the week of 10/23 through 10/29 experienced increasingly high current. The monitoring system at the East Caisson measured and recorded the anchor line tensions and caisson motions during this period. TNC compared the actual anchor line loads with the ZenMAS predictions computed for the same draft and current speed. The measured peak anchor loads during the flood event were much less than predicted by ZenMAS, especially when the current speed increased. This section presents some comparisons and possible reasons why the measured peak loads are lower than expected.

Current meters exist to measure speeds in the Narrows. Unfortunately, during this period the current meters were not working satisfactorily and could not be used. The currents for this particular time period were not measured on-site. Instead the current speed was forecast in the vicinity of the east caisson in the Narrows from a software program called "Tides and Currents Pro".

a) Observations

The following observations are first made from the examination of the time history data:

- The data shows no indications that the load cells are binding. The tension profiles are nice and smooth having a predominant period of about 14-15 sec. This frequency matches closely the corresponding period of measured pitch.
- Data appear to be quite consistent. For example, the maximum line loads appear near the maximum pitch and roll of the caisson (check the area of max tension for the upper line D time history on 10-27-03). The hi-slack data on line loads are indeed flat with no variation indicating zero response at zero current and showing only the line pretension.
- The tension data does not show any strong indication of slippage of the anchor line (e.g., due to 'burning in', stretching of cable or movement of anchor point) during the cyclic loading in the anchor line. For example, in a sample taken from upper line D on 10-27-03, about a third way down the time scale, the tension of the upper line D approaches zero almost instantly from a large negative value, as if the line is giving in a bit. There are similar indications in a few other areas. These, however, are not areas where the line loads were very high. Near the peak line loads, the measured loads are always found to be continuous. The "burning in" is, therefore, also considered a non-issue.

b) Data Correlation

Before we investigate the potential causes for why there is such a large variation in the measured vs. predicted tensions, the reasonably good comparison obtained at the lower current speeds is illustrated.

Correlation of anchor line loads on 10-23-03

The maximum line tensions at lower speed compare fairly with the prediction (see Figure 5; 23 in legend corresponds to 10-23-03). In fact, the measured tensions are higher than predicted for a few lines at these speeds. This is due to variation in the neighboring line pretensions and is addressed later. The variation in the line pretension is very similar to the results found in elastic model tests at HRW for broken lines where the high tension was flanked by low values on both sides.

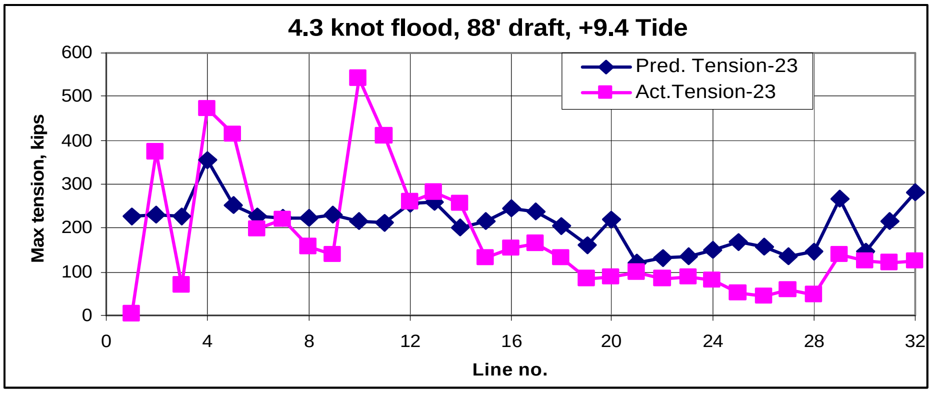

Figure 5 Comparison of actual vs. predicted line tensions

Correlation of dominant frequency of line loads

The measured dominant period of line loads during the Oct. 28 current speed is found to be about 16 sec. This is also the period of the measured pitch. The prediction by MOTSIM shows a period of about 15-16 sec as well. Thus the maximum response from the current load appears to be coming from the dynamic loads at a period of 16 sec which is predicted by MOTSIM.

c) Opinions

At low speeds the measured tensions compare well with the predictions by ZenMAS. However, at the higher current speeds the measured tensions are indeed much lower than the prediction. In particular, for Oct. 27-29, the measured maximum tensions are consistently much lower than the predicted values. There are several possible reasons that cause this over-prediction of the measured anchor line tensions. Opinions for these possible reasons for the differences are stated below and listed in order of their importance.

Current Speed

The current was not measured during these days, but forecast by program "Tides and Currents Pro" using historic data. Based on the present study, the strongest possible reason (for the measured anchor loads lower than the predicted) appears to be the actual current speeds on the days 26-29 being lower than forecast. This is explained below with the help of Figure 6.

It has been noted that during the course of this project, the current measured by the instruments was about 0.75 to 1.0 knot lesser than the predicted current. Also, the current measurement devices were placed at the center of the river where the flow speed will be higher than that at locations closer to the banks. Therefore it is felt that the actual current speed experienced by the caisson will be about 1.5 knots lesser than that predicted. So, comparison should actually be performed for a prediction by ZenMAS for a current about 1.5 knots less than the expected value and the actual measured tensions.

In Figure 6, the trends of the mean and maximum anchor loads on upper line D (which gave the extreme tensions) are shown along with the measured maximum roll and pitch. The values are obtained from the plots provided by TNC for these days, from archived data. In order to emphasize the plot, certain factors are used to bring the scales of all data to the same level. To achieve this, the actual loads (kips) measured directly by the load cells are multiplied by a factor 0.2, while the measured motions (deg.) are multiplied by 6. For comparison the predicted maximum line tension by ZenMAS is also shown in the figure. These values are scaled (factor = 0.2/16) so that they may be directly compared with the measured loads. (Note that the loads are measured not in the main mooring line but after the mooring line goes through a 16 part block and tackle assembly. Therefore, the tensions are divided by 16 to compare with the measured loads). Thus, the values shown in the figure are not what were measured, but scaled for presentation.

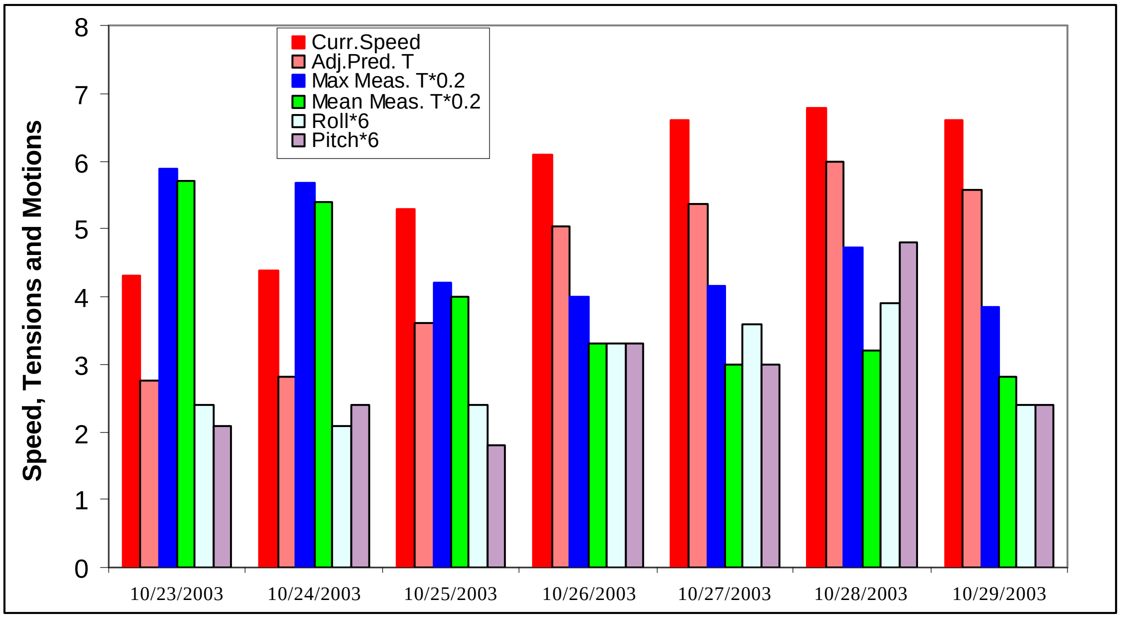

Figure 6 Speeds, Tensions and Motions

The current speeds are shown on the left followed by the predicted maximum tensions (Adj.Pred. T). The measured maximum (Max Meas. T) and steady mean (Mean Meas. T) tensions are shown next. The roll and pitch maximum amplitudes are given on the right. Note the following trends:

- The forecast current speeds increase steadily from Oct. 23 to Oct. 28 and then drops slightly on Oct. 29.
- The predicted maximum anchor line tensions closely follow the speeds.
- On the other hand, the maximum measured tensions show a gradual decrease with the current speed with a slight increase on Oct. 27-28.
- The steady mean values of the measured tension also show a similar gradual decrease.
- The roll and pitch amplitudes are quite similar for all days, except being slightly higher on Oct. 27-28.
- The measured steady tensions are close to the maximum tensions, except on Oct. 27-29 when the dynamic tensions are higher. The higher roll and pitch may partly explain the higher dynamic loads from the steady on these days.
- The higher dynamic load may also be due to lower pretension in the lines on these days as discussed later.

The above observations indicate that the actual current speeds are quite possibly not as obtained by forecast. If the current speed is projected based on the maximum tensions measured by the load cells, then the projected current speed compared to the forecast will be as shown in Figure 7. For comparison the maximum measured tensions are also shown in the figure.

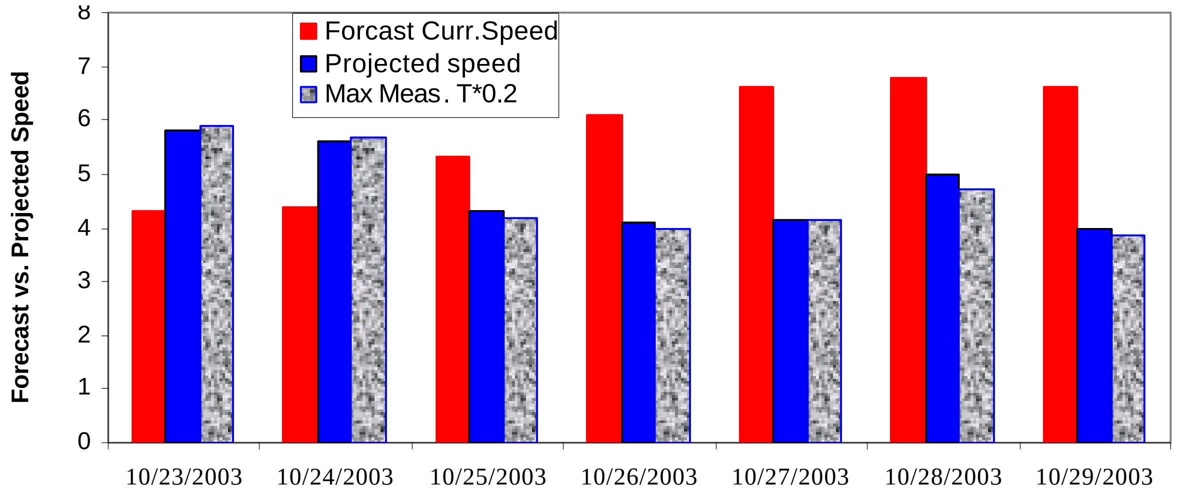

Figure 7 Projected vs. Forecast Current Speeds

It is recognized here that this straight-forward projection of current speed is not entirely possible solely based on the values of measured maximum tension, since there are several other reasons why the measured maximum tensions may be affected, for example line pretensions. However, it indicates that the current speeds may be lower than forecast for the period Oct. 26-29. For the purpose of quantifying the current speeds used in the projection in Figure 7, Table 1 below compares the forecast and projected current speeds. According to this table the higher currents occurred not in the later part of the week, but earlier.

Table 1 Forecast vs. Projected Current Speeds

DATE	Forecast Current Speed	Projected Current Speed
	knots	knots
10/23/2003	4.3	5.8
10/24/2003	4.4	5.6
10/25/2003	5.3	4.3
10/26/2003	6.1	4.1
10/27/2003	6.6	4.2
10/28/2003	6.8	5.0
10/29/2003	6.6	4.0

Earlier in this section, a discussion was made about the difference in the current speed predicted by software compared to the actual current speed at the caisson location as shown in Figure 6 and Figure 7. In view of this discrepancy, it was felt that a revised set of values need to be provided for the current speed which we think was experienced by the caisson

The modified current speed was incorporated and the tensions and motions recalculated. This set of recalculated results is presented below in Figure 8 and Figure 9.

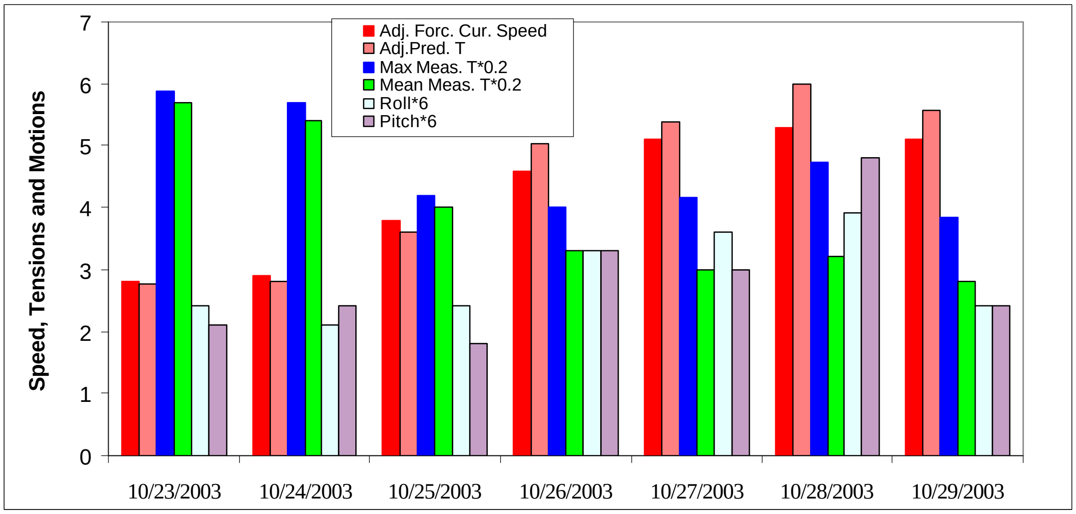

Figure 8 Modified Speeds, Tensions and Motions

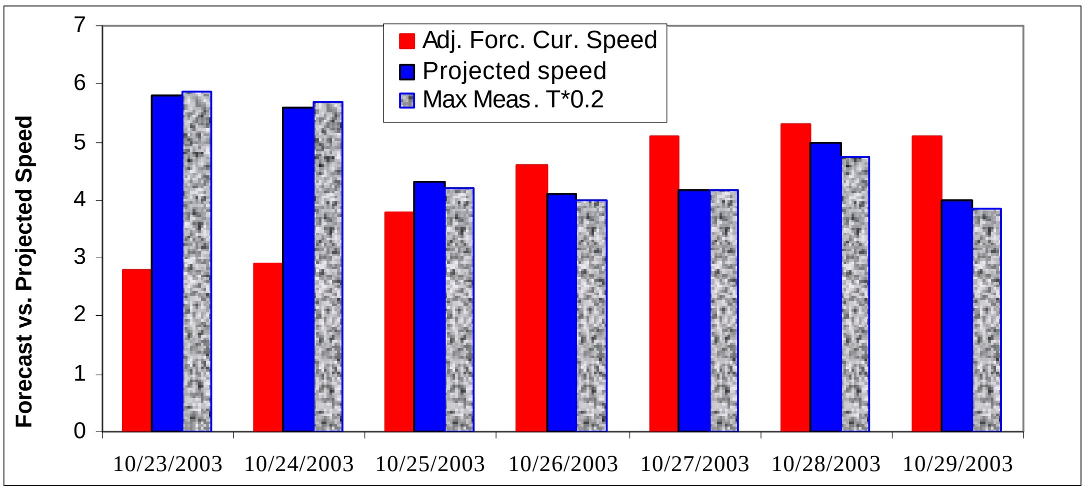

Figure 9 Modified Projected vs. Forecast Current Speeds

Line Pretension

Another possible area for the differences in the prediction vs. measurement of line tensions is in the line pretension. While it is not possible to determine what the line pretensions were during the current flow in the Narrows past the caisson in flood, the pretensions were measured during the slack period in high tide. The measured tensions during the slack period were very steady indicating consistency of data in the absence of current. Since the tide was very different in current, the pretensions measured in high tide are not directly applicable during flood current. But they do demonstrate the variation in the pretensions from line to line.

The variation of pretension from line to line from the measured hi-slack data of Oct. 24 is shown in Figure 10. Other days indicate similar variation. It shows that the lower 16 lines were generally at a higher pretension than the upper 16 lines. In fact, the lower lines had a mean pretension higher than that used in ZenMAS/MOTSIM (200 kips) and the mean pretension in the upper lines were lower than the value used in MOTSIM analysis (150 kips). Since the maximum tension was found in the upper line D, the low pretension in the upper lines may be the reason for the lower measured maximum.

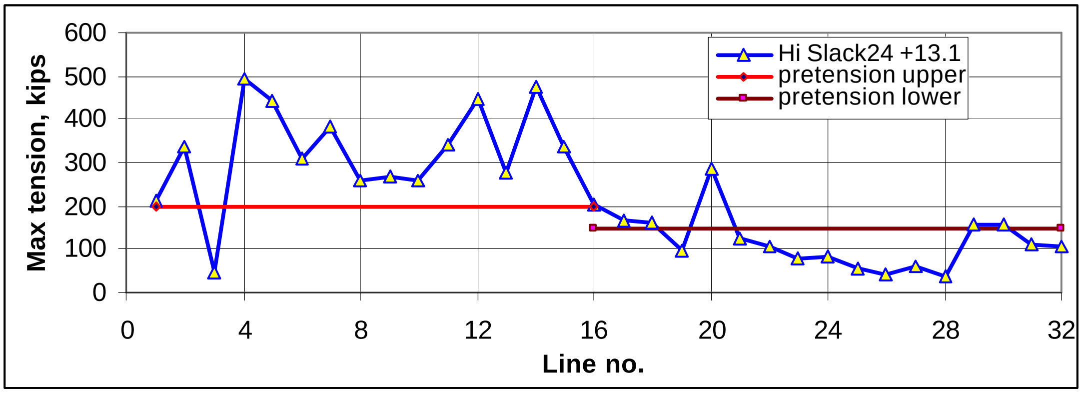

Figure 10 Variation of Pretension between Lines

The lower lines show larger variation in the pretension from line to line. Also, in current, the variation in the measured maximum tensions in neighboring lines is much more abrupt than the prediction, especially for the lower lines. This is the area where the measured values showed larger deviation from the predicted. The MOTSIM prediction, which is based on one pretension value each for the lower and upper lines (shown in Figure 10 as horizontal lines for comparison), is smoother. This large variation in maximum line tension was observed during the elastic model test as well. The abrupt variation there was explained by running MOTSIM with varying pretensions in the neighboring lines. In fact, perfect correlation was reported with the measured maximum model line tensions. See Figure 11 below, from the Final Report on HRW Model Test. Additionally, this difficulty in setting field anchor line pretension and its consequences were recognized at that time and emphasized.

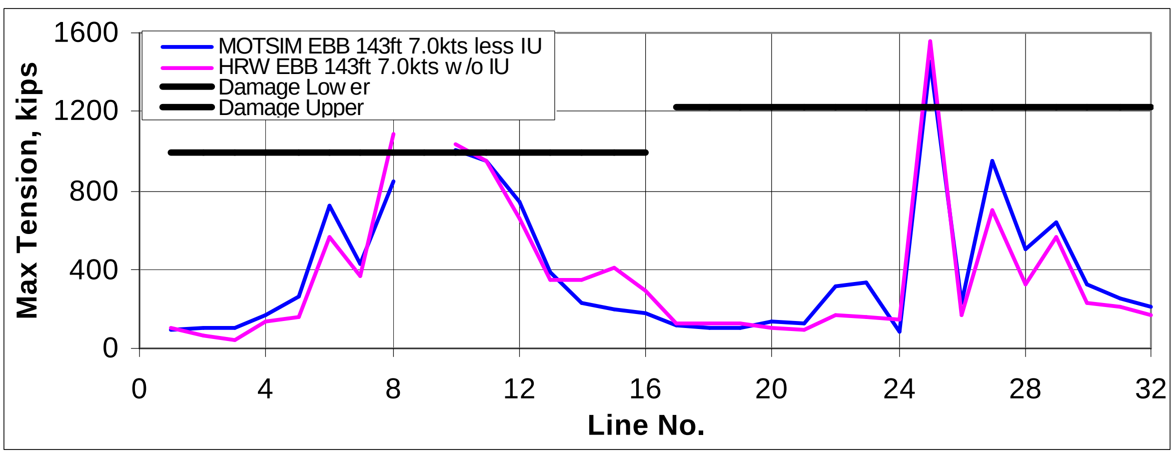

Figure 11 Comparison of Maximum Line Loads of HRW and MOTSIM Data
143 ft Draft 7 knot Ebb I upper removed – modified pretensions

The mean pretension (hi-slack values) of the upper lines was found to decrease over the 7 days and the pretension was lower in higher forecast current. This may have an effect in lowering the maximum tensions at higher speeds as the resonant frequencies will be different at lower pretension.

Damping Effect

A further look at the damping coefficients used in the MOTSIM prediction indicates that these coefficients were chosen conservatively. It is true that the analysis compared reasonably well with the small-scale physical testing at HRW. But the damping in the field may be higher than what was consistently used in the field anchor-line tension prediction in ZenMAS/MOTSIM.

Damping does not have an effect on the steady part of the load, but has a direct impact on the dynamic line tension. Thus the damping value will have a significant influence in the flood flow where the dynamic tension is much higher. The damping values derived in the model test were obtained from the decay (pluck) test and generally have no contribution from the effect of chain in current and movement of chain on the soil. The contribution of current and soil on damping should be significant and the damping factor from the total contribution may be closer to 10-12 percent compared to the conservative figures of 5-7 percent used in the prediction. Moreover, the damping is expected to increase with higher currents, because of larger effect of current on the chains and higher friction from the chain movement on the bottom soil.

This additional damping in the field may reduce the maximum tension by as much as 20 to 30 percent in the flood flow. The effect in the ebb flow will be much less (since most of the tension there is from the steady flow).

Current Direction

It has been shown from HRW model test data that the change in the current angle (+/- 5 deg.) had a large influence on the line tension. It was found that the steady current loads on the caisson were very different even with a 5-deg change in current direction. The steady line loads in the flood flow are much higher than the dynamic loads on Oct. 23-26. The dynamic loads are relatively small for these days. A small change in the current direction during these days may explain this phenomenon.

Scale Effect

There is a small possibility (while no evidence can be found) that a scale effect indeed exists in full scale not seen in the model studies. The general consensus for scale effect with dominant drag type loading is that the model current loads will be higher than the prototype loads. Since the current forces used in MOTSIM are obtained from rigid body tests, the tensions may be conservative.

6. Conclusions

- The most likely reason for the lower measured anchor line tensions (compared to the ZenMAS prediction) during the week of Oct. 23, 2003 is that the forecast currents for these days are higher than the actual current experienced by the caisson.
- The second important effect is the line pretension. While the actual pretension values are not known, it is clear that there is a considerable variation from line to line. This will explain some of the difference in the comparison of maximum anchor line tension for the lower speeds and may even contribute to the lower tension at the other speeds. Note the maximum tension was seen for the upper D, where the pretension appears to be lower (see Fig. 5) than what was used in ZenMAS.
- Use of conservative damping values in the design will be yet another contribution to the higher prediction of anchor line tension (by about 20-30 percent in flood) compared to the measured maximum tension. The higher the current speed, the higher is the effect.
- The effect on current direction and scale effect will be less important and they are included here for the completeness of discussion.

7. Acknowledgement

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. We particularly thank Brenda Lichtenwalter and Dave Bishop of TNC for their continued review and guidance during the design sequence. We also acknowledge numerous people at TNC who were involved in the execution of the construction and installation sequence.

8. References

1. ZenMoor – User's Manual, Computer Software for Floating Moored Systems, Version 4.3, 2003.
2. MOTSIM – User's Manual, Time-domain Motions Simulation due to Wave, Wind and Current on Multiple Floating Structures with Nonlinear Constraints, September, 2002.