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Overview of Tacoma Narrows Bridge Floating Caisson Design

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Abstract

Tacoma Narrows Constructors is building a new suspension bridge in Tacoma, close to Seattle, Washington State, USA next to an existing bridge at the location. The new bridge is being built just south of the existing bridge. This new bridge will be built on towers mounted on two caissons.

The caissons are towed to the site from the harbor with the cutting edge, first full lift, and the second and third exterior lifts. The piers are constructed on site up to their full height as floating caissons at varying drafts. During the construction, the floating caissons on both ends of the new bridge are moored in place with 32 catenary mooring lines. The current flow due to ebb and flood tide in the narrows is very high. This high current and the consequent vortex-induced dynamic forces provided a technical challenge in the design of the caisson and its mooring system whose dimensions are of similar order of magnitude as typical offshore structures exposed to severe environment.

This paper provides an overview of this challenge, and describes the steps taken in overcoming these difficulties. The design procedure adopted of the moored caisson system and the piers in the overall scheme of the Tacoma Narrows Bridge are summarized. This overview stresses the practical side of towing, mooring and in place construction of the caissons. Some of the critical areas of associated design challenges and their solution techniques are highlighted.

1. INTRODUCTION

Tacoma Narrows Constructors is building a new suspension bridge in Tacoma, close to Seattle, Washington State, USA. This new bridge is built on towers mounted on two caissons, henceforth referred to as East Caisson (Tacoma side) and West Caisson (Gig Harbor side). Currently, there exists a bridge next to the proposed location. The new bridge is built just south of the existing bridge.

The new Tacoma Narrows Bridge is designed as a suspension bridge and operates parallel to the existing Tacoma Narrows crossing in Tacoma, Washington (see Figure 1). It is the largest suspension bridge built in the USA in the last 40 years, and it is the first time a major suspension bridge has been constructed parallel and in such close proximity to an existing bridge.



Figure 1 Rendering of New Span (Shown on Left) of Tacoma Narrows Bridge

Both East and West Pier are about 80 ft wide and 130 ft long in plan. The bridge pier caissons are cast in vertical layers starting with a cutting edge which is 18 ft deep, followed by a layer that is 12 ft deep and then followed by several more layers each of which is 10 ft 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 ft. During construction, the floating caisson is moored in place to hold it in the ebb and flood current in the Narrows. While the caissons underwent practically a continuous change in draft, specific drafts are chosen for the design study. The drafts considered for the East pier mooring design analysis are 47 ft, 51 ft, 61 ft, 67 ft, 79 ft, 90 ft, 98 ft, 103 ft, 123 ft and 143 ft. For the East pier the expected touchdown draft is about 147 ft, at a +7 ft tide.

The water depth at the two caisson sites is nominally 130 ft at the northwest caisson site and 144 ft at the southeast caisson site, with the anchor site depths varying from 40 ft at the shallowest to 196 ft at the deepest.

2. CAISSON GEOMETRY & HYDROSTATIC PROPERTIES

a) Caisson Geometry

The caisson bottom consists of a cutting edge section 81 ft x 131 ft x 18 ft high. The bottom of the cutting edge is sealed by five inverted half cylinders running in the transverse direction. These inverted half cylinders act like soft volume false bottom trapping air. Thus the trapped air (bubble) provides additional needed buoyancy during construction. The cross-section of the caisson is square 80 ft x 130 ft up to an elevation of 54.75 ft above the top of the cutting edge. The upper portion of the caisson has chamfered edges 6'4" x 6'4". The caisson geometry is shown in Figure 2 (elevation view) and Figure 3 (plan view). The elevation view shows the three sections described above, while the plan view shows the cellular construction (compartmentalization with bulkheads) of the caisson geometry.

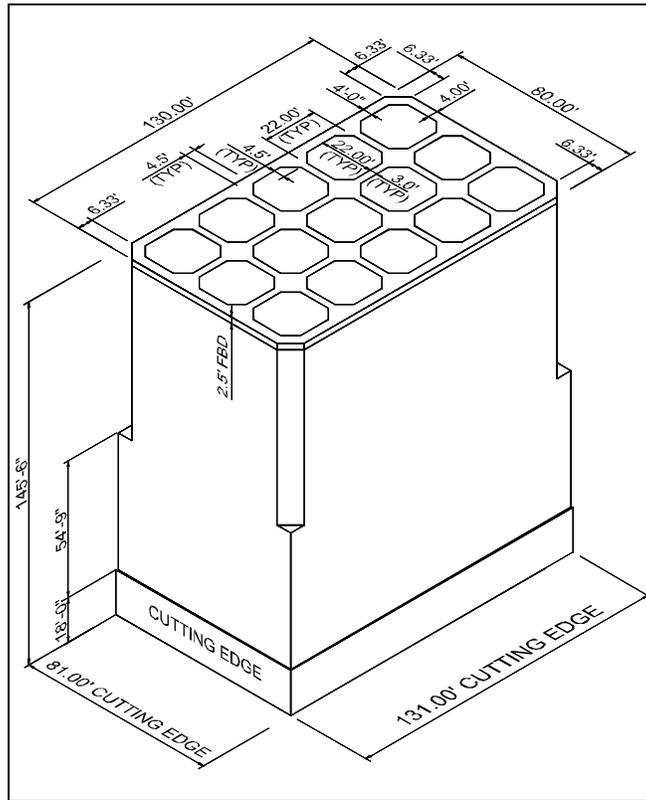


Figure 2 Caisson Geometry - Elevation

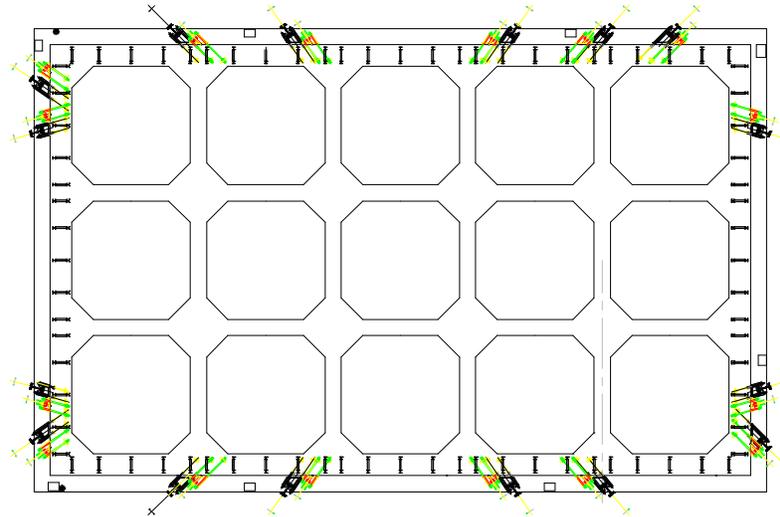


Figure 3 Caisson Geometry - Plan

b) Hydrostatic Properties of Caisson

The hydrostatic properties of the caisson were calculated using a model of the hydrostatic body. The displacement, the vertical center of gravity (VCG), the vertical center of buoyancy (VCB) or distance from keel to the buoyancy center (KB) and the metacentric heights (GM) for a few caisson drafts are provided in Table 1. Note that the GM values are high at the lower caisson drafts and reduce in magnitude only when higher drafts are reached.

Table 1 Some Hydrostatic Properties

Draft	Displacement of Caisson	Displacement of Bubble	Weight in Air (Displacement)	Vertical Center of Buoyancy	Vertical Center of Gravity	"Effective" GM _x	"Effective" GM _y
(feet)	(kips)	(kips)	(kips)	(feet)	(feet)	(feet)	(feet)
47	28246.6	6694.3	21550.3	25.78	27.49	10.85	31.47
67	39560.5	4698.2	34862.3	37.19	37.11	9.05	23.72
90	52933.8	2851.1	50082.7	49.94	45.89	10.62	31.32
123	71878.2	0.0	71878.2	68.38	60.69	12.52	20.39
143	93174.4	8086.8	85087.6	72.61	70.86	5.49	11.6

Note: Vertical center of buoyancy & gravity are measured from the keel of the caisson.

3. ANCHORING/MOORING SYSTEM

a) Mooring Line Layout

The mooring system consists of 32 lines connected at two fairlead elevations called lower and upper sets. See Figure 4 for the layout of the mooring lines showing horizontal anchor locations. The fairlead locations of the lines are shown in Figure 5. Each set consists of 16 mooring lines as follows:

- The lower set of 16 lines consists 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 lines are hooked-up when the caisson is towed from the harbor and positioned at the site.
- For the upper set of 16 lines, the anchor locations form a radius of about 600' (except for lines F, G and H). The fairlead elevations for these upper 16 lines vary based on the draft. The upper lines are hooked up when the caisson reaches a draft of 79-ft.

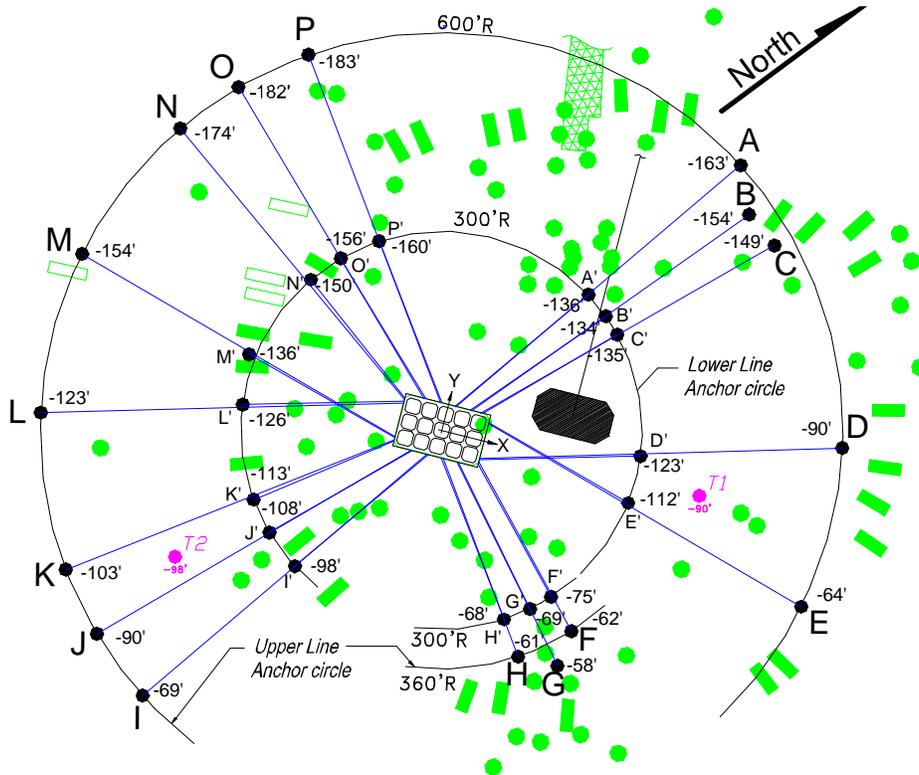


Figure 4 Anchor System Design Layout for the East Caisson

b) Mooring Line Makeup

The upper lines are made up of a combination of wire and chain and the lower lines consist of only chain. The line make-up for the upper and lower lines is given below:

All upper lines except the lines F, G and H are made up of:

- 60 ft of 4" Oil Rig Quality (ORQ) chain at the anchor end
- 432 ft of 3 ½" Bridge Strand Rope
- 3 part Tandem block through which there are 16 parts of 1 ¼" wire rope (of variable length)
- 1 ¼" wire rope (of variable length) on top of the blocks

All lower lines and the upper lines F, G and H are made up of:

- 3 ¾" ORQ chain (of variable length) at the anchor end
- 3 part Tandem block through which there are 16 parts of 1 ¼" wire rope (of variable length)
- 1 ¼" wire rope (of variable length) on top of the blocks

The initial draft after the first stage of the upper mooring line attachment and the draft before touchdown are shown in Figure 5. In the figure the locations of typical upper and lower mooring lines are shown. The lower mooring lines are fixed on the caisson. The upper mooring line fairlead locations are adjustable as shown based on the caisson draft. The location of the lower steel cutting edge facilitates the penetration, while the steel skin portion penetrates the soil for the stability of the pier against the weight of the bridge and current loads. Lines were made adjustable using the multi-part block and tackle system at the upper (fairlead) portion of the lines as shown in Figure 5. The small wire ropes allowed easier handling of the mooring lines during pretensioning adjustment as the caisson drafts changed.

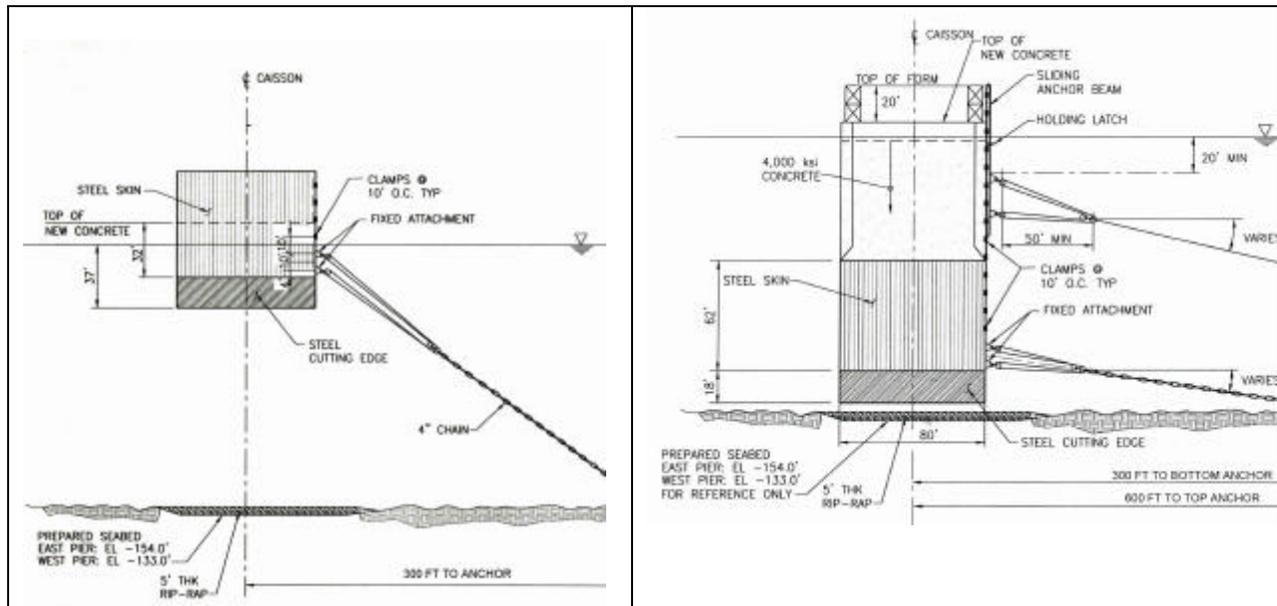


Figure 5 Initial and Final Drafts of Caisson Showing the Mooring Lines Attached

c) Selected Anchor System

Each line is held at the seabed with an anchor. The holding capacity of the anchors was 1000 kips. The lines were arranged radially around the caissons, to resist the drag as well as lift forces imposed by the Tacoma Narrows current. The lines were distributed so that the in-line drag is resisted more or less equally between anchors. This resulted in more anchors in line with the current flow and less transverse to the current (see Figure 4). In all cases, there were anchors almost diametrically opposite to each other, which could be used to “set” and test each anchor as each pair was installed.

Several different anchoring alternatives were initially studied. Their evaluation in choosing the optimum anchoring system focused simultaneously on four criteria, namely, safety, cost, reliability and schedule. The anchor system chosen for this application was the driven-plate anchor, with a holding capacity of 1000 kips.

4. DESIGN CHALLENGES

Since the Tacoma Narrows is a tidal channel, the current flow cycles through the channel are in opposing directions, referred to as flood and ebb. The current speeds are quite high in the Narrows. Initially the design current speeds were chosen as 8.2 knots in flood and 7.0 knots in ebb flow. During the course of the design, however, it was realized from measurements made at the bridge site that the current speeds at the site were lower than those predicted at the start of the project. Subsequently, these design current speeds were downgraded for the East Pier to 7.5 knots for the flood flow and 5.7 knots for the ebb flow.

The design currents for the West Pier were chosen as 6.0 knots in flood and 4.9 knots in ebb for drafts up to 79 feet and 7.5 knots and 5.7 knots for flood and ebb currents respectively for drafts greater than 79 feet.

The key technical challenges for this design are as follows:

- In the ebb direction, the caisson is upstream of the existing pier and is expected to be subjected to large mean drag forces from the current. However, for flood direction, the caisson is positioned in the wake of the existing pier where the effects of shed vortices from the pier prevail. In this case the inline dynamic forces from the current is expected to be strong.
- The new pier is within 20 ft of the existing pier. Therefore, the motions induced by the currents are restricted to within a few feet of translation and a few degrees of rotation, in order to avoid contact with the existing pier. This is especially critical for the design cases involving broken line.
- Although conventional mooring systems are allowed to have a design factor of safety (per API RP 2SK) with respect to the breaking strength of the mooring line as 1.67 in intact condition, the desired factor of safety for this design was chosen at a more conservative value of 2.0.
- At touchdown, the permitted tolerance from the target location was less than 1 foot.
- The cyclic loading from the flood and ebb currents should not lead to fatigue problems.
- Since the draft and vertical center of gravity (VCG) of the caisson is changing with each new pour, the same mooring system should work through draft changes for the entire duration of the caisson construction.
- Very high tidal variations presented additional difficulty in the design. The variation in tide sometimes was as high as 21 ft.



**Figure 6 Current Flow Field in the Wake Region of the Existing Pier (East Side)
at Tacoma Narrows**

- Transverse loads on the caisson, are induced by the current flow adjacent to the caisson and also by the shedding and subsequent recirculation of vortices in the wake region. These loads, particularly during the flood flow, when the caisson lies in the wake of the existing pier, are significant and may critically affect the stability of the structure. The vortex shedding phenomenon is explicitly transient (time-varying) and unsteady (see Figure 6).

- One of the design tools considered for the prediction of current forces on the caisson was based on the computational fluid dynamics technique (CFD). The Reynolds number of the flow around the piers is of the order of 10^8 (100 million). No literature was found in which the CFD was applied in current flow in this range of Reynolds number. The implication of the high Reynolds number is the difficulty in predicting the fluid flow field and subsequent vortex shedding frequencies in the wake regions. The details of the CFD analysis for the current loads on the caissons may be found in Ref. [1].

As one would expect, a project of this size and complexity requires a series of design tools for the various stages of its design and construction. Some of the steps in design include towing of the caisson to site, design of the mooring system, dynamics of the moored caisson, mooring line monitoring during construction and touchdown analysis. Several software programs were chosen in the design and analysis phase of this project. As mentioned above, the current forces were determined by a 3-D CFD software as well as a scaled model test. The design of the mooring lines was performed by ZenMoor [2] which is a dynamic mooring analysis program. This program also assisted in on-board monitoring and advisory functions. The hydrodynamic added mass of the caisson was determined by a commercial program Neptune [4], which is based on a radiation-diffraction theory. For the moored caisson analysis a nonlinear time domain simulation program for floating structures MOTSIM [3] has been used. This program also assisted in the mooring line tension monitoring during construction and touchdown analysis.

5. CONSTRUCTION AND INSTALLATION

a) Dockside Construction



Figure 7 Cutting Edge and Domes at the Yard, Under Construction

The caisson goes through a transition phase from an initial floating condition after being towed to site to a bottom-supported condition when it comes to the final resting position on the riverbed. Figure 7 shows the dome (five inverted half cylinders in the transverse direction) over the cutting edge being constructed at the dockside.

The cutting edge at the bottom is used to facilitate initial penetration of the caisson once touchdown occurs. As mentioned earlier, pressurization of the air pockets under the dome was used to obtain the necessary target draft, GM and inclinations.

b) Towing to Site

Four tugs were used to tow the shallow draft caisson (Figure 7) weighing about 28,000 kips. Two of the tugs had bollard pull capacities of 174 kips, while the other two had capacities of 154 kips and 76 kips respectively. Three tugs were deployed at the front, which pulled the caisson. The fourth tug (76 kips) was deployed at the aft end, which assisted in steering. The approximate distance from the yard to the final location of the caissons was about 1 mile. Sea trials were done prior to the actual departure and the caisson was brought to the final location as planned. The tugs held the caisson in position until a few mooring lines were hooked up to the anchors and it was established that the mooring lines could hold the caisson in place without the assistance of the tugs.



Figure 8 Towing of Caisson to Site

The magnitudes of the towing loads were needed to estimate the capacity of the tugs, and to design the padeyes. These towing loads were derived from the in-place physical model tests of the caisson at the appropriate draft. The in-place current-induced load tests were carried out in the presence of the existing pier. The test results from the ebb flow case were considered applicable for the open water towing loads, in which the effect of the presence of the existing pier was small. Therefore the towing loads were estimated from the ebb flow model tests. The steady loads due to mean currents expected on the caisson at the towing draft of 47 ft. are shown in Figure 9. The dynamic loads during towing are considered less important for this case and not considered in the towout design.

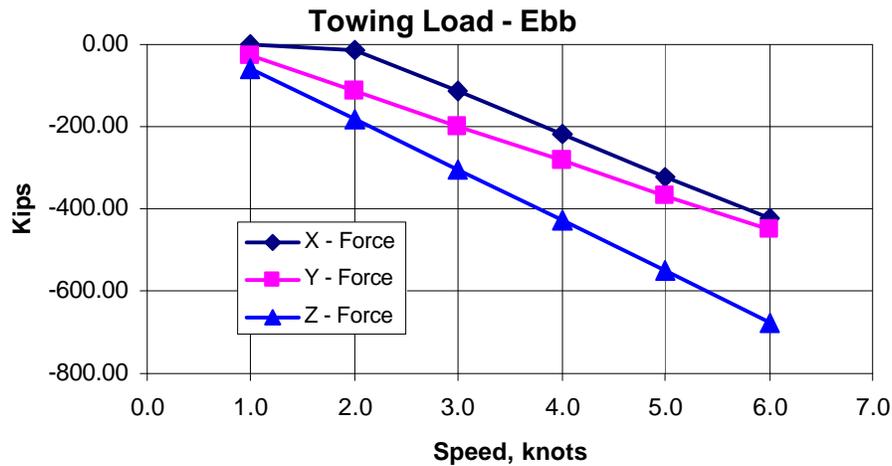


Figure 9 Towing Loads at 47-ft Caisson Draft

c) Installation of Mooring System

Block makeup floats and barges were tied off to the caisson before floatout. These barges were loaded with tandem blocks and wire spools for making up some of the mooring lines. Some of the blocks and spools were already tied off from the caisson before the floatout occurred.

Figure 10 shows the floating caisson and the make-up floats and barges on its sides. The details for the mooring line makeup is given schematically in Figure 5. Once the caisson was brought into place and spotted on location, the hookup of the mooring lines began. All the anchor lines were pre-deployed. Each mooring chain was tied off to a mooring line float for easy recovery. Two derrick barges were used throughout the operation.



Figure 10 Caisson Assembly during Floatout

Once the caisson arrived and was positioned in place, the following operational steps took place in sequence:

The chain end of the line being put together, was recovered from the mooring line float and stoppered off at a corner of the derrick barge.

The derrick barge then pulled one of the floats closer to the chain and made up the chain to the block. See Figure 11 and Figure 12.

In the meanwhile spooler took up the slack. The length to which the line was needed to be pulled to obtain the desired pretension was pre-determined (Figure 13).

The crane assisted in pulling the line while the spooler took up the slack. Once the desired length was pulled, the wire rope was cut, leaving some length for operations. Figure 14 shows the floating caisson next to the existing pier.



Figure 11 Hooking a Block

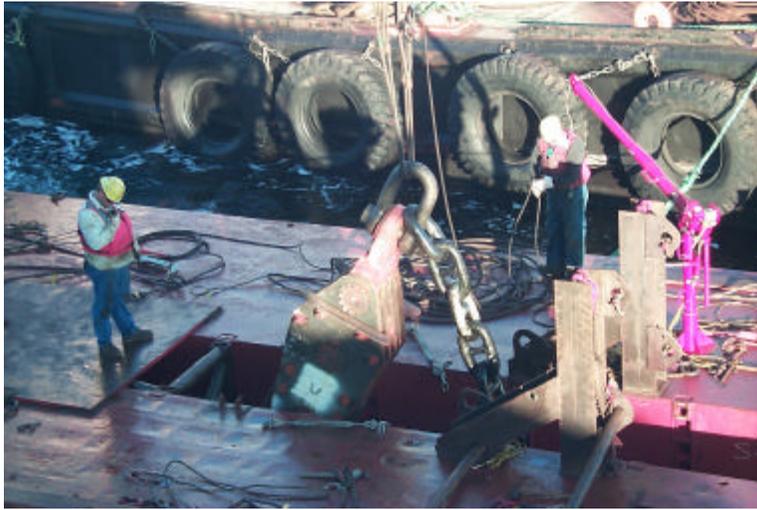


Figure 12 Making up Chain to Block



Figure 13 Lowering the Block

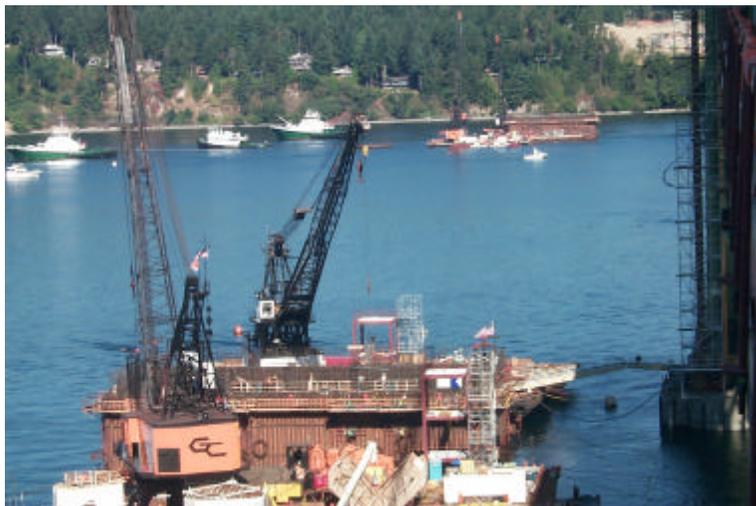


Figure 14 View of East and West Caissons at the Two Ends of the Narrows

d) Construction Sequence

Once the caisson was towed to location and the mooring lines were engaged, caisson construction began. Installation of rebar curtains, slipping forms and pouring concrete (see Figure 15) were all done based on a well planned and predetermined construction sequence. Air pockets under the domes (see Figure 7) were controlled to obtain the desired draft and correct for any inclinations that might arise.

Each time a concrete pour occurred, a concrete placing barge was aligned next to the caisson and the concrete placing booms were used to pump the concrete. The concrete was made on shore and pumped through an extensive piping system, to the placing barge. Figure 15 shows two booms of the placing barge used to pour concrete.

As construction progressed, the draft of the caisson increased continuously until touchdown. As the caisson reached each of the predominant drafts, the derrick barge next to the concrete-placing barge was used to tension up the mooring lines to obtain the targeted pretension at that draft. The pretensions had to be maintained close to the prescribed values, to ensure safety of the mooring system and the caisson.

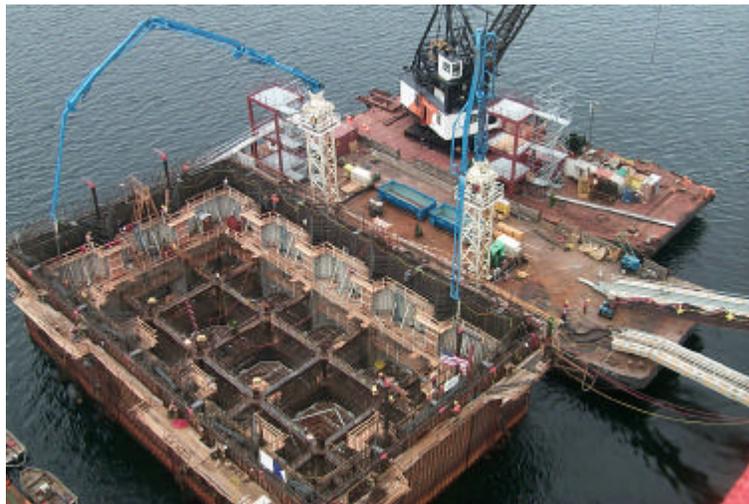


Figure 15 Pouring Concrete

e) Touchdown and Submergence

When the caisson reached a draft close to 147 ft, touchdown occurred. The touchdown sequence was carefully orchestrated to ensure that the caisson landed at the target location and at close to even-keel. The position of the caisson could be altered using the mooring lines, if required, when close to touchdown. A combination of ballast water and air under the domes was used to control the draft and penetration after touchdown.

6. STABILITY ISSUES

At all intermediate stages of the construction before touchdown, the stability of the floating caisson was determined to confirm that there was a positive GM (metacentric height) value. A common practice is that the benefit from the mooring lines should not be accounted for when calculating the free floating stability parameters. Accordingly, the restoring moment from the mooring lines was ignored in computing stability at each draft.

From the estimated weights and vertical centers of gravity (VCG), the VCG at each stage of the construction was known. This was then compared to the metacenter (KM) to ascertain sufficient GM. At all stages it was made certain that there was a minimum of +2 ft GM margin.

In cases where there were air pockets in the domes at the bottom of the caisson, the free surface effect of the air-water interface was also accounted for in the GM calculation.

These pockets were created with a series of baffles that provided airtight compartments. In the construction sequence, after a certain stage, the baffles separating the air tight compartments inside the domes had to be removed. Removing some of these baffles made the compartments bigger with consequent reduction in stability. The primary

interest was to determine the GM. However, the righting arm was also calculated within a range of heel angles that gave a better assurance of the caisson stability.

Note that at a given stage, when the weight on the caisson is increased after a pour, the caisson will sink and balance itself at a deeper draft and will find its own equilibrium inclined position. This is illustrated in Figure 16. The red portion in the figure indicates the buoyancy from the caisson itself and the yellow portion is that from the air pockets inside the chambers. In this position, the buoyancy contribution of the intact caisson (red) will increase. However, as the pressure head for the air pockets will increase, the air volume will decrease (following the isothermal law $\text{Pressure} \times \text{Volume} = \text{constant}$) and the buoyancy contribution of the air pockets will decrease. The balanced final draft is calculated through an iterative process taking into consideration the increase in buoyancy of the intact caisson and the decrease in buoyancy of the air chambers.

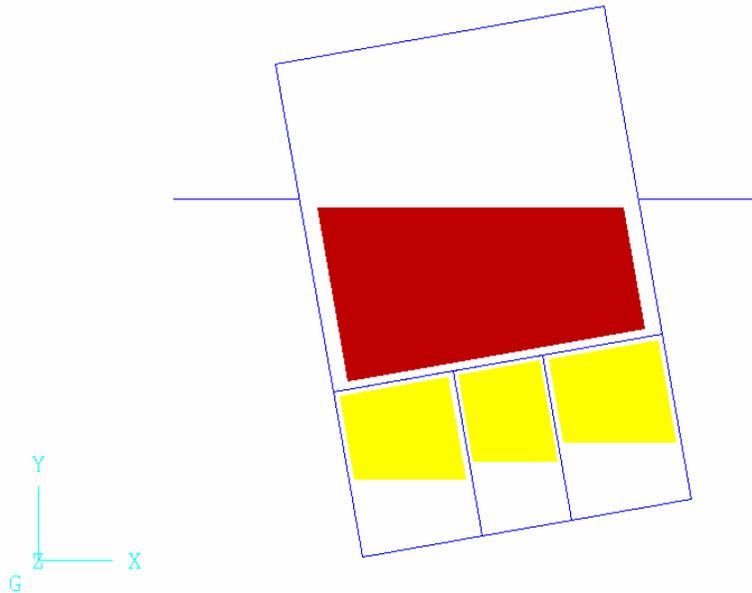


Figure 16 Caisson in Inclined Position Showing Air Pockets

To determine the righting arm, the center of buoyancy for a given angle of heel needs to be calculated. The total buoyancy remains constant (vertical equilibrium) and the vessel must be trimmed to eliminate the trimming moment. While determining the righting arm about the longer axis, the trimming moment need not be considered since the vessel is symmetrical about the heel axis. The aim is to calculate the buoyancy of the intact caisson and the air pockets (with proper correction for the change in air pressure) and balance the vertical load with the modification to the floating draft. Hence the center of buoyancy and the resulting righting moment for the balanced draft can be calculated.

After touchdown occurs, ballasting will take place through the dredge wells. It is critical to place the equalizer port in the dredge well tanks, at the appropriate height. If the equalizing ports are at a low level, when the caisson heels more, ballast water would flow to one side causing the caisson to tip. Analysis was performed for a series of drafts after stage #20 (draft of 136 ft). It was found that VCG rests above KB (causing an unstable situation) in all afloat cases before the start of adding ballast. As ballast is added the VCG gradually comes down (stability increases) to a stage when the VCG is below the KB. Calculations revealed that this phenomenon occurs in the range of drafts from 138 ft to 146 ft. Hence a detailed study was made in this range of drafts to choose the draft at which VCG falls below KB (Figure 17). The height of equalizing port is selected above this ballast sounding level, so that the ballast water will flow through them only when the VCG is below the KB.

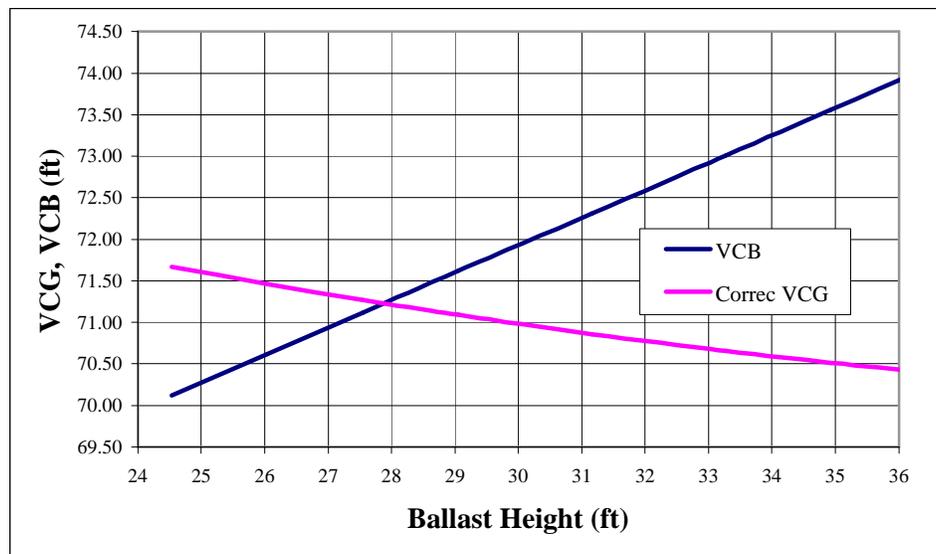
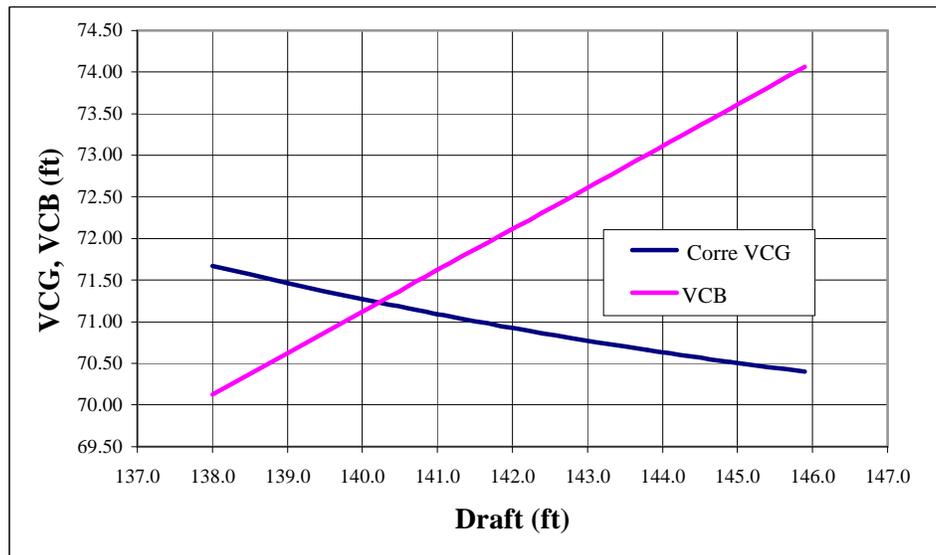


Figure 17 Plots of Corrected VCG and VCB

7. CONCLUSIONS

Based on this overview of the design, construction and installation of the floating caissons of the Tacoma Narrows Bridge, the following conclusions may be drawn:

- ◆ The fast flowing ebb and flood currents in the Narrows posed the biggest design challenge for the mooring system. The change in the flow directions combined with a high tidal variation of about 20 feet meant that the required mooring system should be such that the caisson can be held in place within allowable limits, under all conditions of flow.
- ◆ The motions of the caisson under current had to be very minimal, because of the proximity of the existing pier. Any excessive motion could lead to the collision between the existing pier and the new caisson, which was unacceptable for several reasons. The selected mooring system achieved both the above objectives.
- ◆ Since the complete construction of the caisson happened in the floating mode, after the floatout at 47' draft, it was essential to design the caisson and the construction sequences so as to ascertain adequate GM for stability at all drafts during the construction. A minimum GM of 2 ft was maintained for all drafts.

- ◆ The towing scheme adopted for towing the cutting edge and the caisson at 47' draft had to be designed so as to use the tugs available in the area at the time of towout. The orientation of the tow boats was decided based on the mooring line hookup process, to facilitate ease of line handling and also provide sufficient holding power to resist the current force on the caisson as it is being towed to site.
- ◆ Due to the draft changes of the caisson during construction sequence, the mooring system had to be designed so that the set of mooring lines are adequate for all drafts. One way it was successfully achieved was to design the upper set of mooring lines on a running track so that their fairlead positions could be changed at site as the draft changed.
- ◆ The mooring system used in this project did not benefit from an optimization process in the current design, but rather was already acquired prior to the start of the design process based on an earlier preliminary design. This placed a severe constraint in the mooring system design and installation. Therefore, the installation and hookup process had to be designed to be certain that the mooring system would hold the caisson in place throughout the life of the construction sequence and the initial penetration on the ground. Pretension of the lines had to be adjusted at several drafts, to keep the mooring line tensions within limits for the design environment.

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