Machinery/Mechanics

Design of Machinery for Pamunkey Bridge (Route 33 over Pamunkey River, West Point, VA)

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ABSTRACT

Redundancy and reliability were VDOT's primary concerns for the design of the machinery for this 173-foot-long double-leaf trunnion bascule. The bridge is not currently expected to see any openings for marine traffic. Bi-weekly maintenance openings are scheduled; however the owner acknowledges that actual maintenance openings could occur much less frequently.

These considerations led each leaf to be designed with two independent and fully redundant operating systems. Other reliability related features of the operating system include reducers with gears fully immersed in oil and an automatic lubrication system for all mechanical components. In addition, the center locks were designed to allow emergency operation via a chainfall, in the event of actuator and hand wheel failure.

Additional information relevant to the design of bascule bridges is included in the Appendix. Appendix A compares the horsepower requirements for prime movers, calculated using four different methodologies. Appendix B presents the equations used to determine the force in the cylinder of a hydraulically operated bascule span, as a function of span angle.

I. BACKGOUND

The existing bridge that this project will replace is a swing span. Also included in this project is the replace ment of the nearby Route 33 over Mattaponi River fixed bridge.

The following is excerpted from the Executive Summary of the "Route 33 over Pamunkey River Movable Bridge Alternatives Study", February 7, 2003:

"Three types of movable bridges have been investigated as a replacement for the existing bridge carrying Route 33 over the Pamunkey River in West Point, Virginia" The three types are a double-leaf Scherzer (rolling) bascule; a double-leaf trunnion bascule; and a swing span. Each alternative provides a 100-foot-wide horizontal navigation channel and a 55-foot-high channel above Mean High Water in the closed position, with unlimited clearance in the open position. The vertical clearance in the closed position is adequate for the existing barge traffic on the river without opening the bridge. An opening would only be required for ocean-going vessels. Ocean-going vessels have used the channel in the past, but do not do so at this time, consequently it is not anticipated that the bridge will open on a regular basis.

A Scherzer-type bascule bridge with a conventional mechanical system and SCR control system is recommended for the new Pamunkey Bridge. The Scherzer-type bascule, not including approaches, is estimated to cost $14 million or about $0.5 million less than the trunnion-type bascule and $3 million less than the swing span alternative."

2. DESIGN MANDATE

VDOT selected a double-leaf trunnion bascule despite indication that it would have a marginally higher initial cost, when compared to a Scherzer rolling-lift bascule. VDOT felt that the trunnion type would be easier and cheaper to maintain and would be more compatible with their existing movable bridge inventory.

A design meeting was held and VDOT gave PB the following direction (excerpted from the meeting minutes 03.18.2003).

- VDOT wants machinery that is simple and easy to maintain. The low duty cycle of the bridge, as well as uncertainty of the future exercise schedule requires that the machinery and control system be designed with this in mind.
- The Department would prefer two independent drives rather than a common primary reducer. PB will submit concept sketches to resolve issue prior to preliminary design.
- The enclosed gear reducers should be oversized to allow all moving parts to be submerged in oil at all times. This will reduce corrosion on the gears/shafts/bearings. An internal circulating pump was discussed but discarded in favor of larger cases.
- All machinery spaces are to be sized to allow easy maintenance and cleaning access around the equipment.

3. DESIGN DEVELOPMENT

A narrative of the design decisions made for each system of Bridge Machinery follows. The Bridge Machinery encompasses the Operating Machinery, Buffers, Trunnions, Locks, and the Lubrication System.

Operating Machinery

A traditional machinery layout, see Figure 1, is not redundant. In the event of failure of the primary reducer, the span will be inoperable. In order to accommodate VDOT's desire for independent drives, two concepts were proposed, each involving two totally independent operating systems per leaf. Only one operating system would drive the bridge during any given opening.

- Concept 1: A conventional rack is mounted to each trunnion girder. However, the span would be operated by only one rack/pinion at a time. In order to transfer the operating torque from the driven bascule girder to the opposite, non-driven bascule girder, a torque tube was proposed. See Figure 2.
- Concept 2: Two racks are mounted to the pier on either side of the centerline of the roadway. The pinions and reducers are mounted on the counterweight. The motors and brakes are mounted on the pier, outboard of each trunnion. A drive shaft runs through the center of each trunnion to connect the motor with the reducers. See Figure 3. A similar, but non-redundant, version of this scheme was used by PB in 1977 on the 3rd St. Bridge in Deleware. See Figure 4.

VDOT preferred Concept 1, based on this PB developed multiple schemes for the machinery layout.

Since the redundant concept involves the power from one motor going to only one pinion, it would be preferable to provide a single, horizontally mounted, reducer for each operating system. However, this would result in a very long reducer. In fact, this reducer would be longer than the space allotted for the machinery room. Next, we investigated using horizontally mounted primary and secondary reducers. This scheme was also too large for the machinery room.

A redundant operating system not only requires more reducers than a traditional system, each reducer must also have twice the capacity. Therefore, the configuration of the reducers became a critical component of not only the mechanical, but also the structural design.

In a further attempt to fit the reducers into the allocated space of the machinery room, two schemes utilizing vertically mounted reducers were developed.

- Scheme A: A single stage secondary reducer is mounted vertically. A triple stage primary reducer is horizontally mounted. See Figure 5.
- Scheme C: A single quadruple stage reducer is vertically mounted. See Figure 6.

It was felt that the single vertical reducer of Scheme C would be too massive and awkward. Therefore, we decided to develop Scheme A.

It was shortly discovered that, while Scheme A fit the machinery room when viewed in plan (horizontally), when viewed in elevation it was apparent that the vertical primary reducer was too tall. It would interfere with the counterweight when the span was opened. The span length and counterweight length would need to be increased to facilitate the redundant operating system.

At this point PB prepared a Mechanical Construction Cost Estimate for both the traditional and redundant operating systems. The traditional system was estimated to be $2M or 50% less than the redundant system. It was noted that this estimate did not include the added cost to both the movable span superstructure and foundations. PB recommended the traditional system.

VDOT reaffirmed its commitment to the redundant concept and PB proceeded with its development. The size of the machinery room was increased by lengthening the span ~5 feet and altering the counterweight. Enough space was gained to allow the use of two horizontally mounted reducers per operating system.

The final machinery layout is shown in Figure 7.

The prime mover is a 75hp at 900 rpm wound rotor motor. The primary reducer has a ration of 200:1. The secondary reducer has a ration of 6.0:1. The 19 tooth pinion has a pitch diameter of 50 inches and mates with a 14 foot radius rack.

PB recommended that the AGMA requirements for surface durability, specified by AASHTO 1988 M2.6.12, only be applied to the enclosed reducers, not the open gearing. This allowed softer, more traditional, grades of steel to be used for the rack and pinion. ASTM A148 grade 90-60 Cast Steel (BHN=180) was used for the rack and AASHTO M102 class D (BHN=149) was used for the pinion. In order to meet the AGMA surface durability requirements, materials in the range of 300-350BHN are commonly used. The softer grades of steel have proven durability through years of use. The primary advantage being that they can overcome imperfect alignment by "wearing in."

The pinion shafts are supported by bronze bushed pillow block bearings. Bronze bushings were chosen over rolling-element bearings because of their simplicity, ease of maintenance, replaceability, and durability.

Concrete machinery supports were preferred, due to their lower cost when compared with steel weldments. In order to facilitate shop alignment, a steel primary support weldment is provided.

The brakes for each operating system are sized for the entire span. In order to prevent all the brakes from activating in the event of a power loss, the brakes for one operating system per span have a longer delay setting. It should be noted that even if the brakes from both operating systems on a leaf were activated simultaneously (unintentionally), neither operating system would experience greater than design loads, however the span would decelerate at twice the design rate.

Buffers and Electrical System

The relay based contactor/resistor control system was requested by VDOT for its ease of maintenance and repair. This style of control system is more primitive than the SCR drives that have been commonly used since the 1970's. The contactor/resistor control system does not provide a fine degree of control, therefore it was necessary to provide buffers.

Hydraulic buffers, as opposed to pneumatic buffers, were selected for their durability and lack of maintenance requirements. The specified force to displacement curve for the buffers is shown in Figure 8. This curve was designed to smoothly slow the span from full-speed to a complete stop over the 16" stroke of the buffer. However, since the control system is designed to automatically switch the bridge to 10% creep speed degrees before it closes, the buffers should never experience this worst case scenario. Therefore, it is equally important that the buffers be easily compressed when the bridge is moving at creep speed.

Trunnions

A traditional, single shear design was selected for the trunnions, see Figure 9. The primary advantage of this design is that it allows a greater span opening angle and a shorter, deeper counterweight when compared to a double shear trunnion design. This is because a double shear trunnion does not require a bearing and pedestal to be mounted inboard of the trunnion girders.

The connection between the trunnion collar and bascule girder was designed for bearing. During erection, trunnion alignment is adjusted with wedges that fit between the trunnion and trunnion girder.

Some consideration was given to the use of spherical plain trunnion bearings. This type of bearing would simplify the alignment of the trunnion bearing to the trunnion. The trunnion is aligned such that both ends are at the same elevation. However, under full dead load the trunnion sags and takes the shape of a bananna, see Figure 10. In order to achieve full bearing between the trunnion and a traditional bronze bearing the bearing must be mounted at an angle, when viewed in elevation. This may require multiple iterations of jacking the span and shimming before full bearing is achieved.

The use of spherical plain bearings would do away with the iterative bearing alignment process, since a spherical bearing can accommodate a few degrees of misalignment while still providing full bearing. Sperical plain bearings have been successfully used on the Erasmus Bridge in Rotterdam, completed in 1996. Spherical plain bearings appear to be a suitable and labor saving solution. See Figure 11.

However, we found that it would take up to a month to get a cost estimate on an appropriate bearing. Given the lack of time and uncertainty in pricing, it was determined that a traditional bronze trunnion bearing design was the prudent choice. This type of bearing also has the advantage of many potential fabricators, as compared with the few companies in the world that would fabricate a suitable spherical plain bearing.

Center Locks

Maintenance was of primary concern while designing the center locks. The locks are located outboard of the girders, such that they are accessible from a ladder at center span. The motive force comes from a linear actuator. The linear actuator may be disconnected from the lockbar and rotated out of the way allowing the locks to be engaged and disengaged with a chainfall, see Figure 12. Replaceable wear plates are used on both the forged steel lockbar and the cast bronze guides and receivers. Tail locks were not provided on this bridge.

Lubrication System

An automatic lubrication system (single line parallel type) was specified. The system supplies grease to the pinion pillow block bearings, the trunnion bearings, the buffer pivot pin, and the span lock guides and receivers. The system will be activated by a push button mounted on the bridge control desk. In general, the preferred grease for automatic lubrication systems is EP1. However, more viscous EP2 grease, in 120 lb drums, was selected since EP2 grease is more typical in movable bridge applications. This will prevent VDOT from being required to stock and supply different grease for this one bridge.

4. CONCLUSION

At the time of this writing, the Route 33 over Pamunkey River bridge project is out to bid. Bids are due on Sept 22, 2004.

5. AKNOWLEDGEMENTS

Milton Pritchett, VDOT, Project Manager; Bob Jacobus, VDOT, Mechanical; Fred Parkinson, PB, Project Manager and Structural; Mike Abrahams and Bill Kam, PB, Mechanical; Mark VanDeRee, Rick Newcomb, Akbar Siddiqui, and James Chin, PB, Electrical;

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6. APPENDIX

The information presented in the Appendices does not directly relate to the Pamunkey Bridge, however the topics are relevant to the design of bascule bridges. Appendix A compares the horsepower requirements for the prime movers, calculated using four different methodologies. Appendix B presents the equations used to determine the force in the cylinder of a hydraulically operated bascule span, as a function of span angle.

Appendix A - Motor Sizing Comparison

A comparison of results from four different methodologies used to calculate the minimum power required for the prime movers of bascule leaves are presented in Tables A.1 and A.2 below. The four methodologies are as follows:

1. 2000 AASHTO: The prime movers, for a mechanical drive system, are sized in accordance with section 5.4 of AASHTO LRFD Movable Highway Bridge Design Specifications, First Edition 2000.
2. 1988 AASHTO Same Times: The prime movers, for a mechanical drive system, are sized in accordance with section 2.5.3 of Standard Specifications for Movable Highway Bridges, 1988. Load Conditions A, B, and C are all applied assuming the normal opening time.
3. 1988 AASHTO Different Times: The prime movers, for a mechanical drive system, are sized in accordance with section 2.5.3 of Standard Specifications for Movable Highway Bridges, 1988. Load Condition A is applied assuming a normal opening time. Load Conditions B & C are applied assuming 1.5 and 2 times the normal opening time, respectively.
4. Hydraulic Operating Machinery: The prime movers, for a hydraulic cylinder drive system, are sized in accordance with section 2.5.3 of Standard Specifications for Movable Highway Bridges, 1988. Load Conditions A, B, and C are all applied assuming the normal opening time.

For mechanical drive systems one motor operates the leaf at a time. For the hydraulic cylinder drive systems two motor/pump groups operate the leaf at a time. The differences between the power required for Pamunkey Bridge's redundant vs. traditional layouts, when using the 1988 AASHTO specs, is due to the different motor overload factors specified in section 2.10.14 for one vs. two motor installations of 1.25 vs. 1.5, respectively. The generic bridges identified as Highway and Railroad are calculated assuming anti-friction trunnion bearings, while Pamunkey has bronze plain bearings.

There are some differences of opinion with regards to whether, when designing in accordance to AASTHO 1988 specs, it is appropriate to use different opening times when applying Load Conditions A, B, and C. The specifications allow for the use of different times for different loads, however mechanical drive systems (with Wound Rotor Motors and SCR drives) cannot physically operate at different times unless a gearbox that can shift to different gear ratios is provided.

Table A.1 - Minimum Required Power of Prime Movers, Calculated by Four Different Methodologies

*Note - All Units in HP	2000 AASHTO	1988 AASHTO Same Times for Load Cond. A, B & C	1988 AASHTO Different Times for Load Cond. A, B & C	Hydraulic Operating Machinery
Highway Bridge	180	218	101	2x 56
Railroad Bridge	94	112	52	2 x 35
Pamunkey Redundant Layout	62	71	41	2 x 26
Pamunkey Traditional Layout	62	59	34	

Table A.2 - Ratios of Minimum Required Power of Prime Movers, Using AASHTO 2000 Specs as the Baseline

	2000 AASHTO	1988 AASHTO Same Times for Load Cond. A, B & C	1988 AASHTO Different Times for Load Cond. A, B & C	Hydraulic Operating Machinery
Highway Bridge	100%	121%	56%	62%
Railroad Bridge	100%	119%	55%	74%
Pamunkey Redundant Layout	100%	115%	66%	84%
Pamunkey Traditional Layout	100%	95%	55%	

Appendix B - Equations of Motion for Hydraulic Cylinder Bascule Bridge

Goal: Relate thrust (F) in cylinder to angle of span (Φ). See Figure 12 for an example sketch of a hydraulic cylinder operated bascule. See Figure 13 for a sketch defining the terms below.

COORDINATES OF CYLINDER CLEVISES

PIER MOUNTED (FIXED) CLEVIS:

$$X_p := a\cos(\beta) + L_o \sin(\Omega_o)$$

$$Y_p : a\sin(\beta) + L_o \cos(-\Omega_o)$$

SPAN MOUNTED CLEVIS:

$$X_s(\phi) : a\cos(\phi - \beta)$$

$$Y_s(\phi) : a\sin(\phi - \beta)$$

CYLINDER LENGTH:

$$L(\phi) : \sqrt{(X_p - X_s(\phi))^2 + (Y_p - Y_s(\phi))^2}$$

THRUSTING ANGLE:

$$\psi(\phi) : \cos\left(\frac{(Y_s(\phi) - Y_p)}{L(\phi)}\right) - (\phi - \beta)$$

EFFECTIVE CYLINDER THRUST:

$$F_\theta : M(\phi)/a$$

ACTUAL CYLINDER THRUST:

$$F = F_\theta / \cos(\psi(\phi))$$

6. Figures

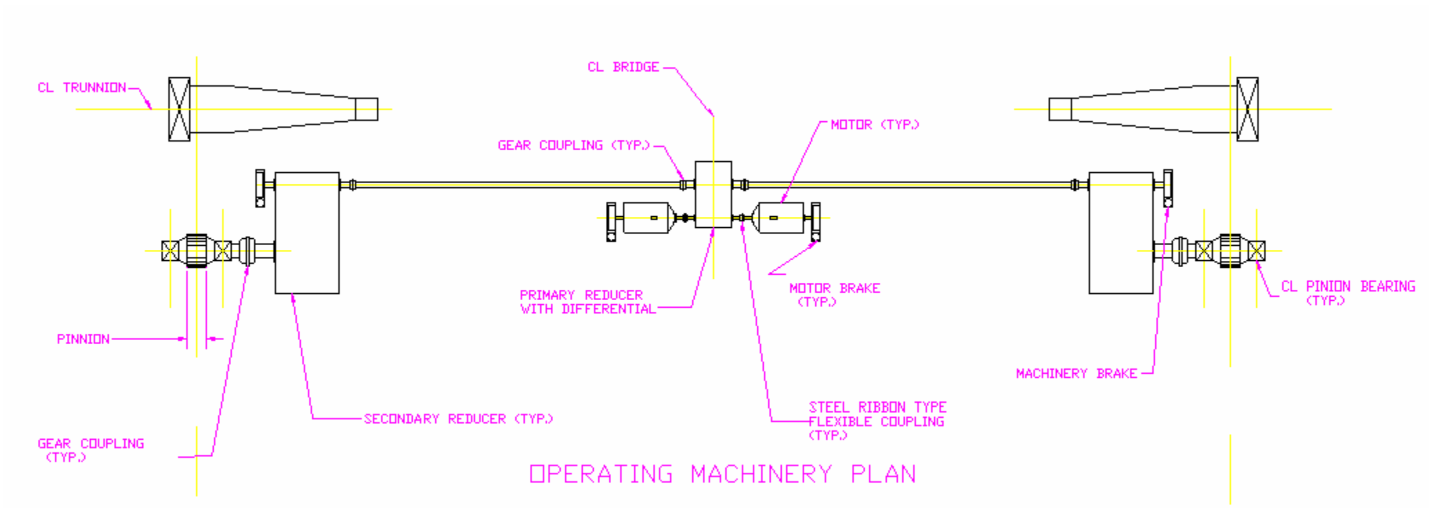


Figure 1– Traditional Machinery Layout

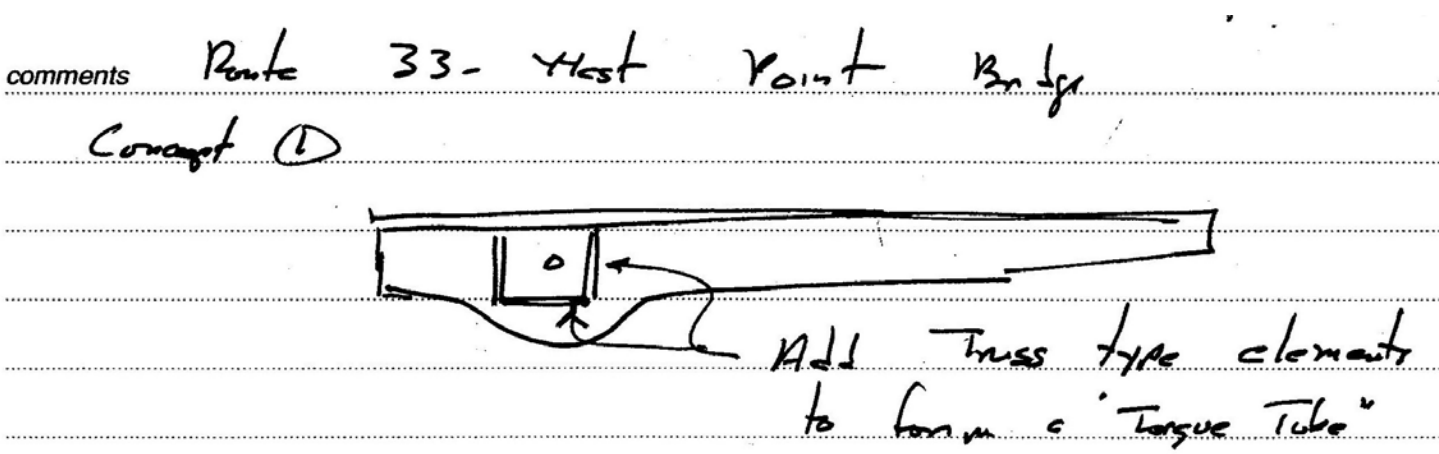


Figure 2– Elevation Sketch of Redundant Concept 1

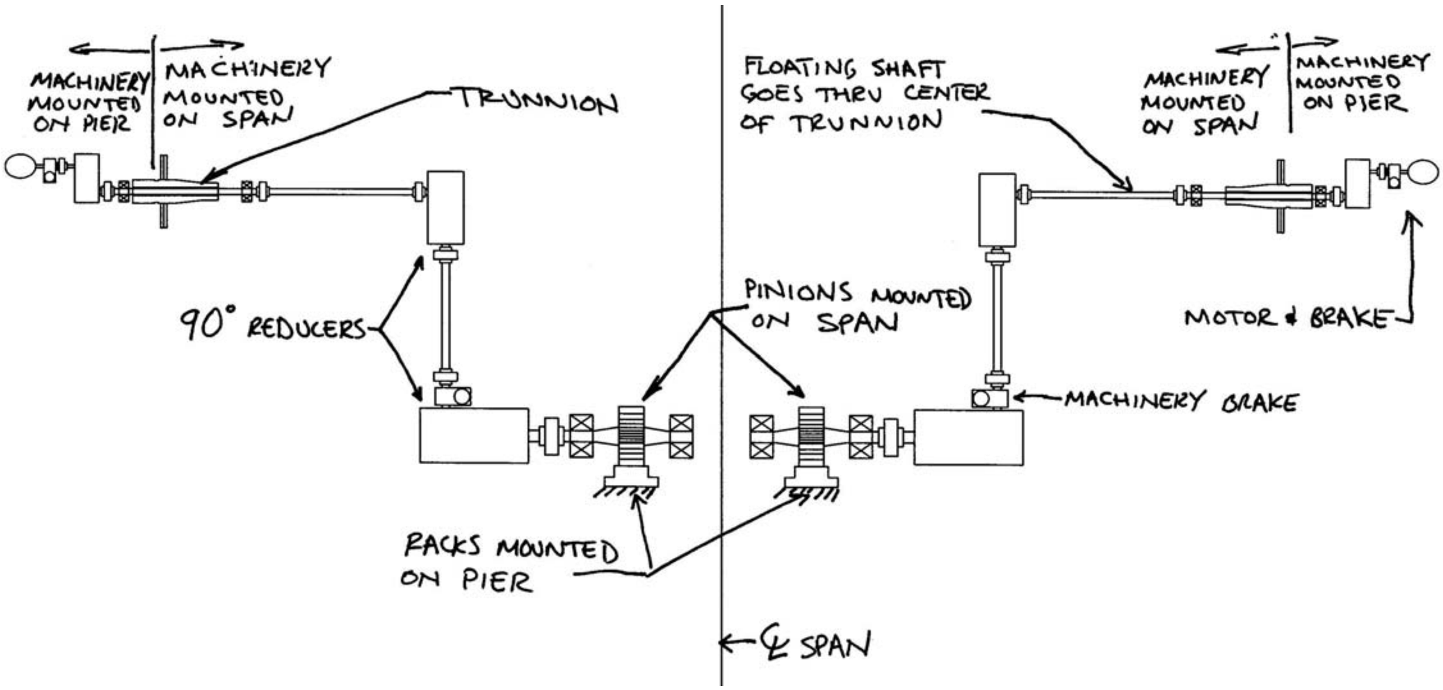


Figure 3– Plan Sketch of Redundant Concept 2

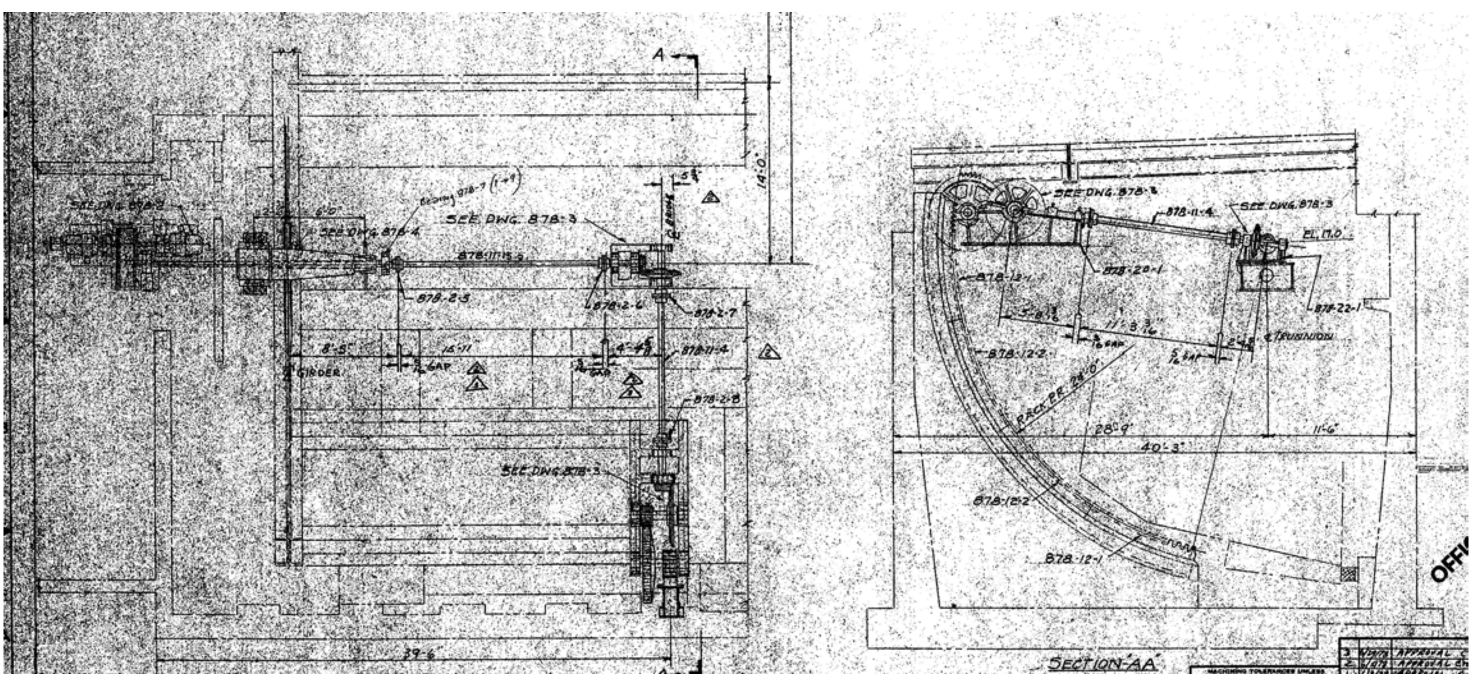
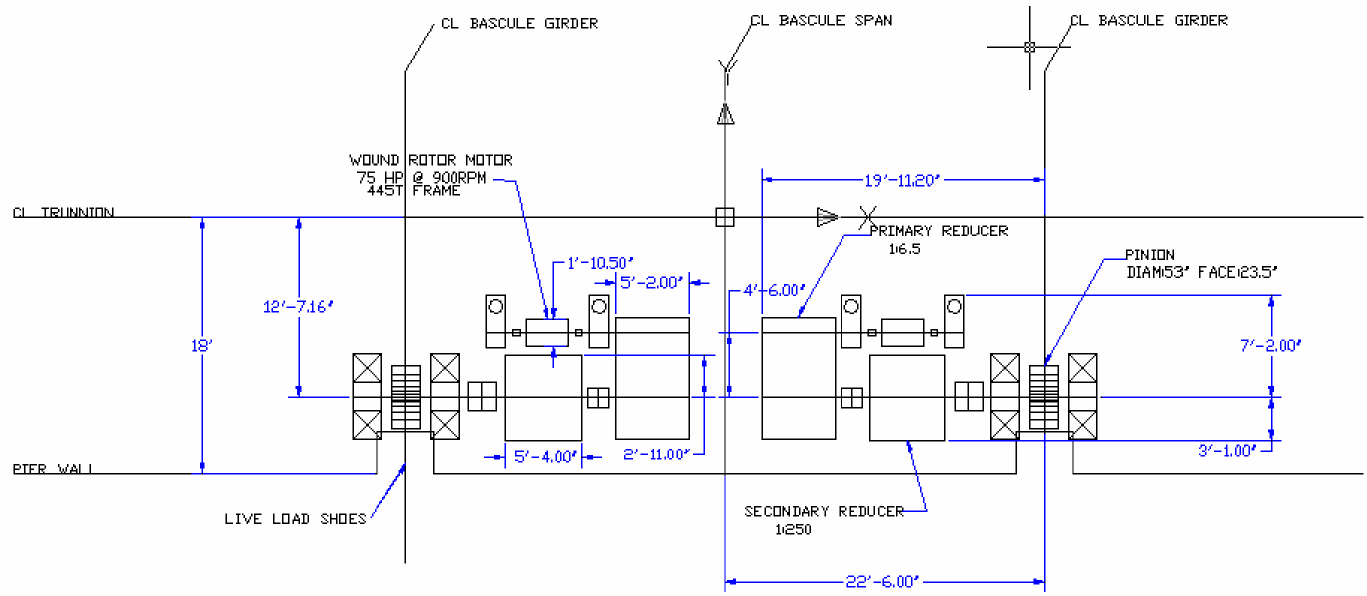
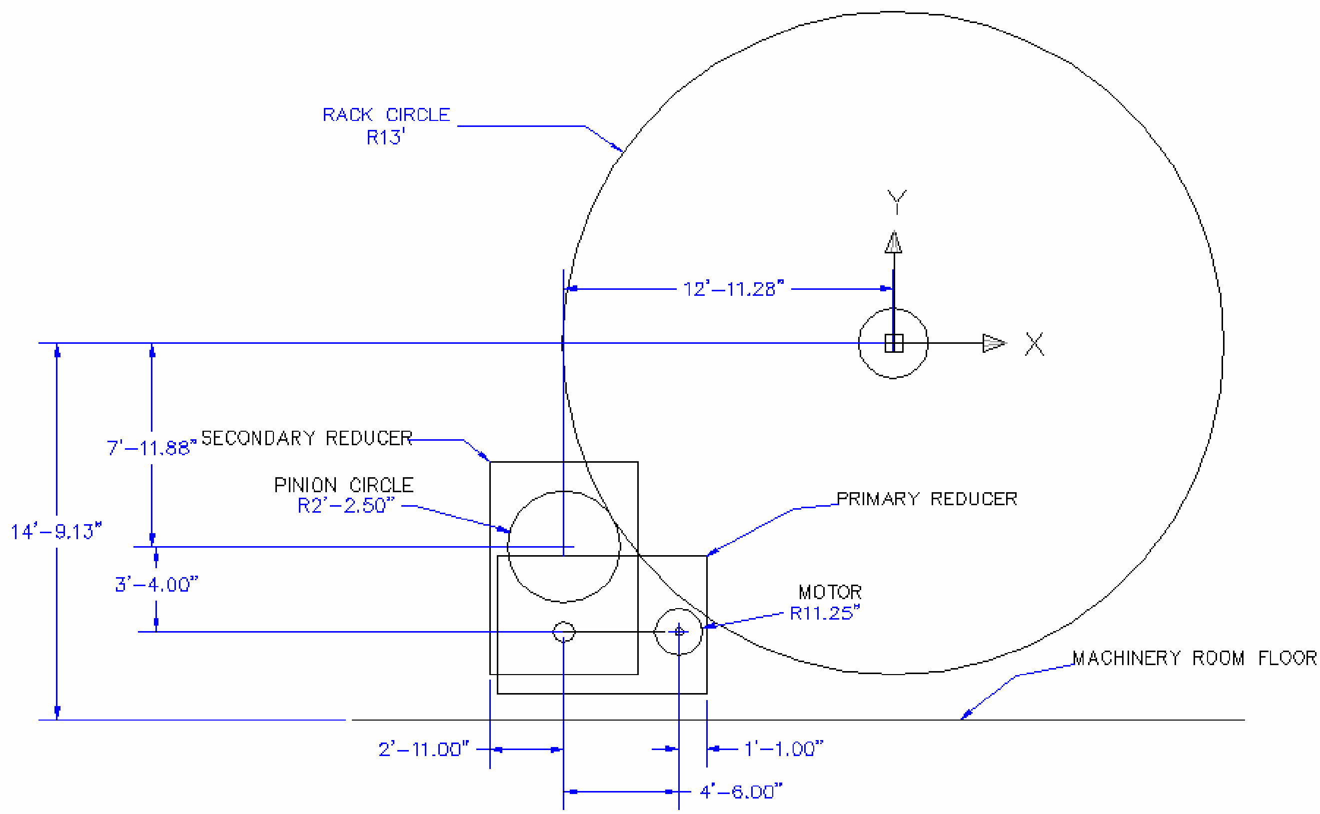


Figure 4 – Machinery Plan and Elevation for 3rd St. Bridge

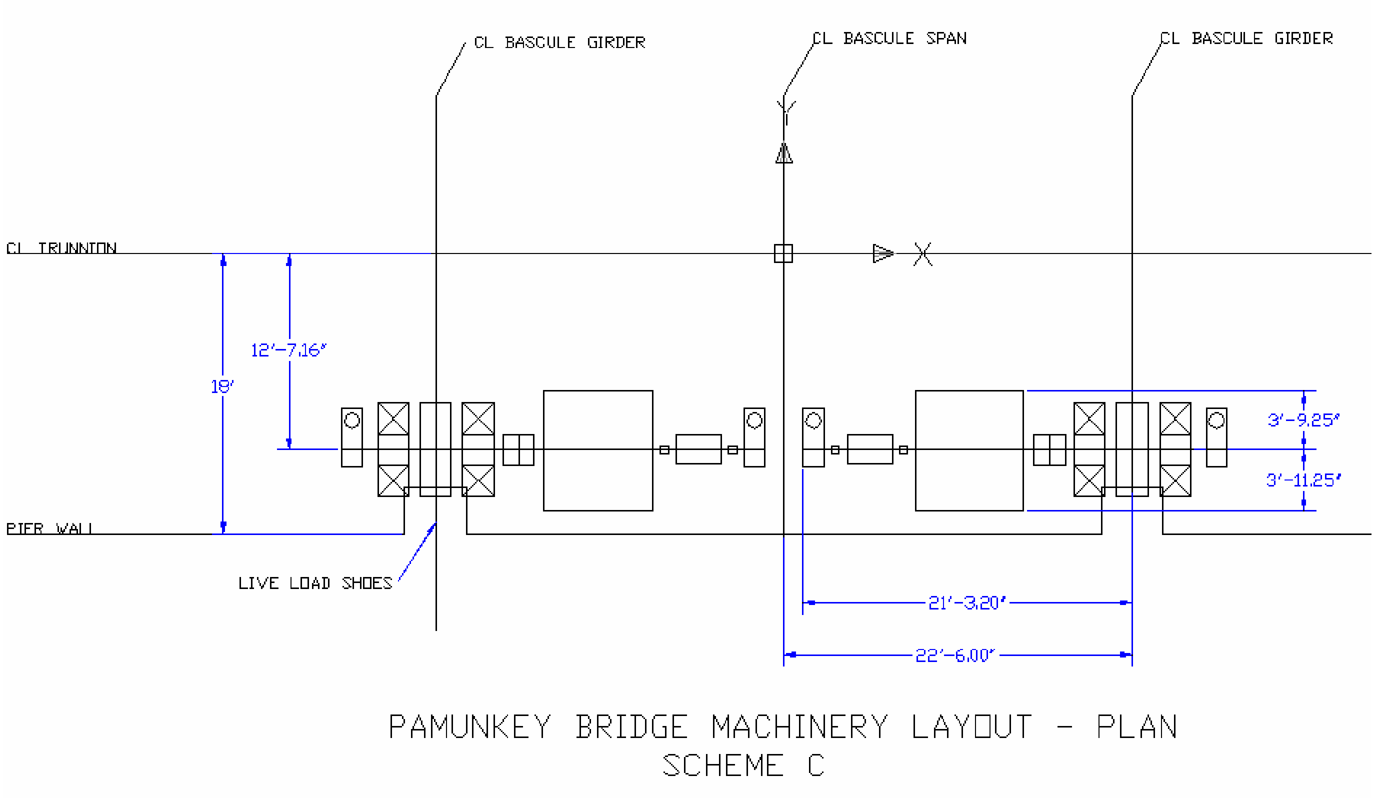


PAMUNKEY BRIDGE MACHINERY LAYOUT – PLAN
SCHEME A



PAMUNKEY BRIDGE MACHINERY LAYOUT – ELEVATION
SCHEME A

Figure 5 – Scheme A Sketches



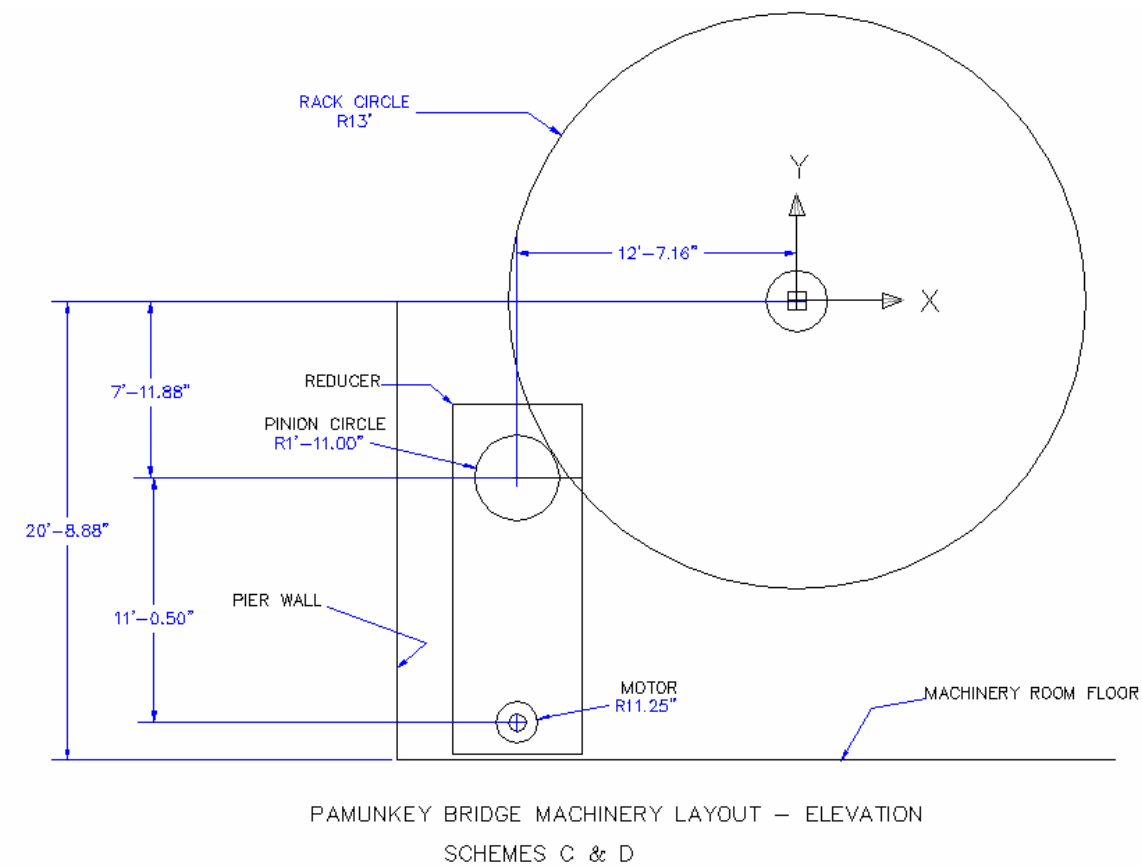


Figure 6 – Scheme C Sketches

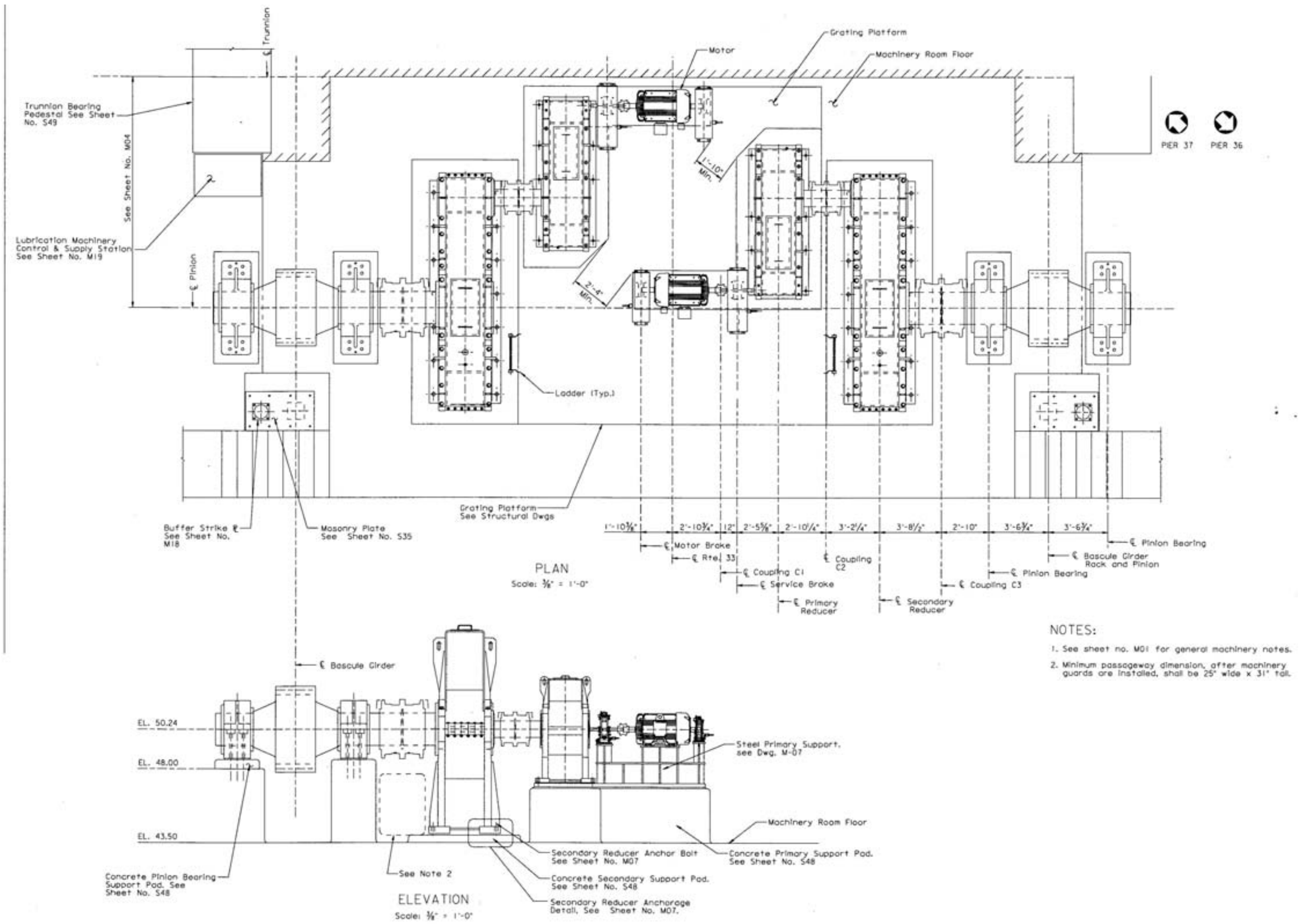


Figure 7 – Final Machinery Plan & Elevation for Pamunkey Bridge

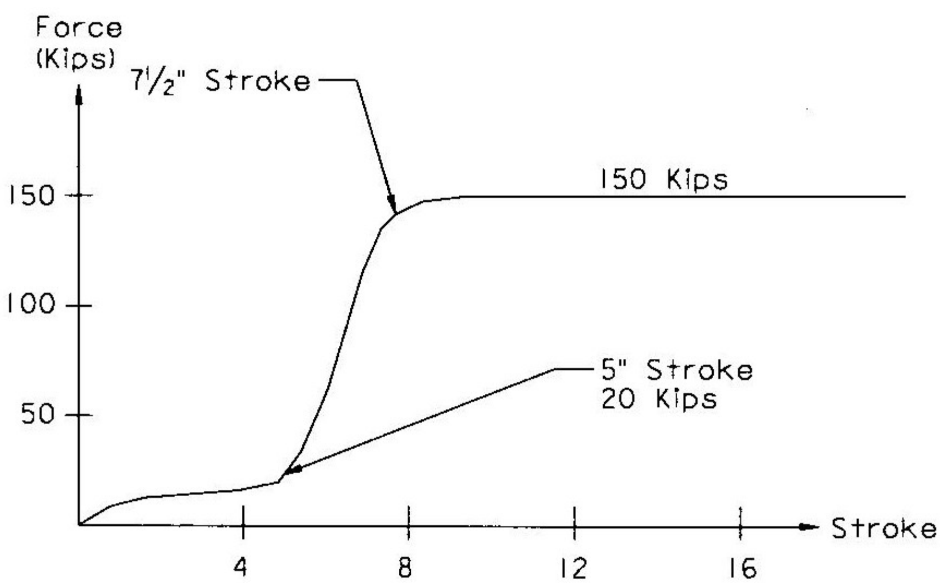


Figure 8 – Buffer Output Curve at Full Speed of 0.211 ft/s

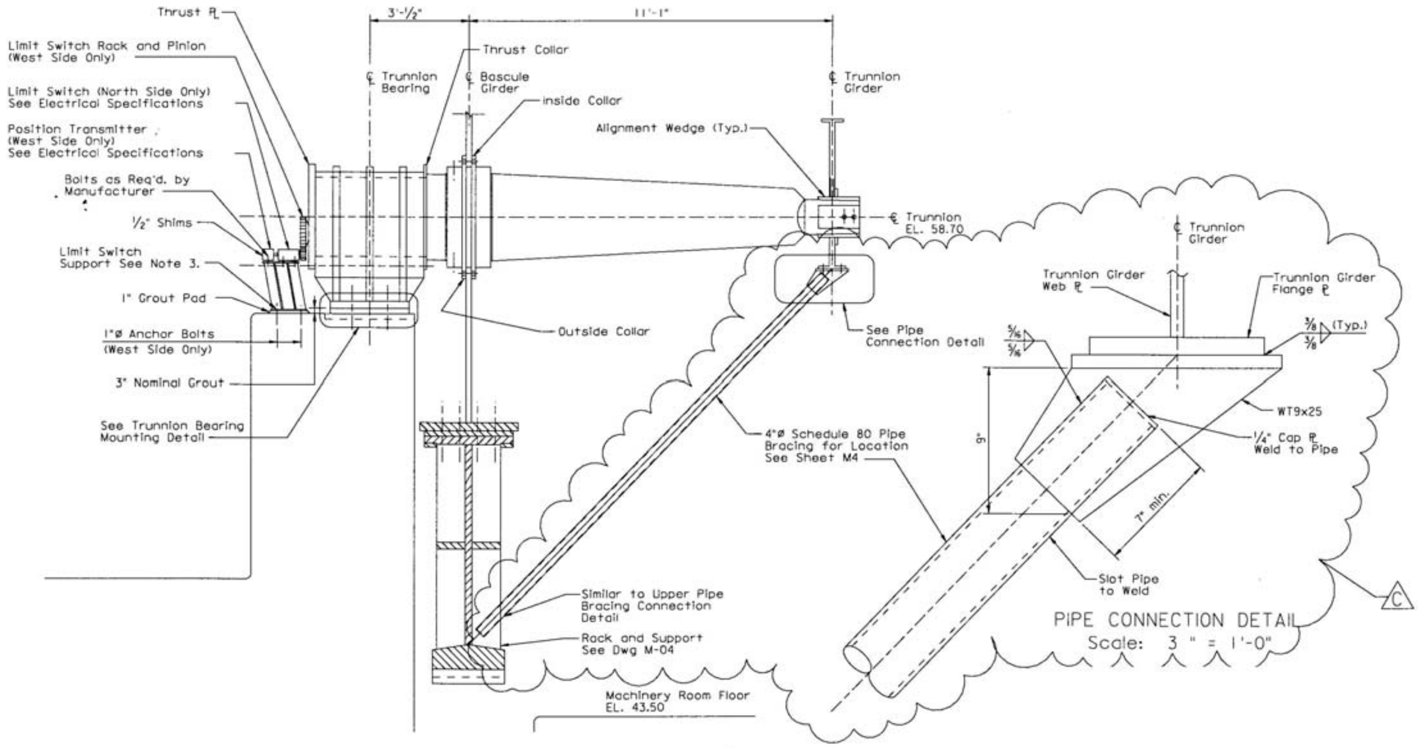


Figure 9 – Elevation of Trunnion for Pamunkey Bridge

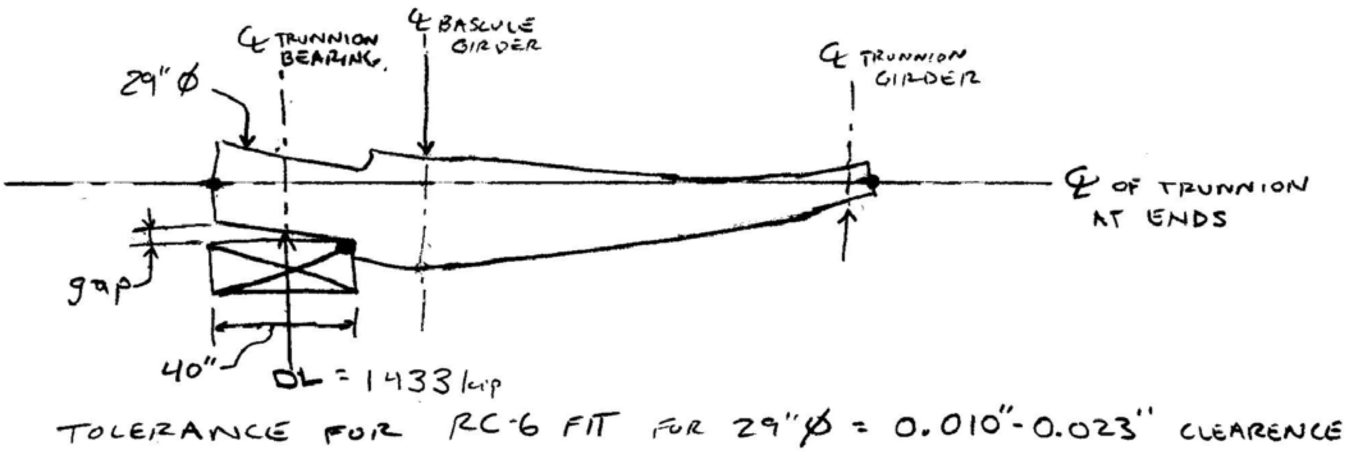


Figure 10 – Trunnion Deflection Sketch. "Gap" calculated to be 0.036". Since this is greater than the RC6 Fit Tolerance, Bearing must be shimmed at a slight angle.

Figure 11 – Drawing of Spherical Plain Bearing used on Erasmus Bridge

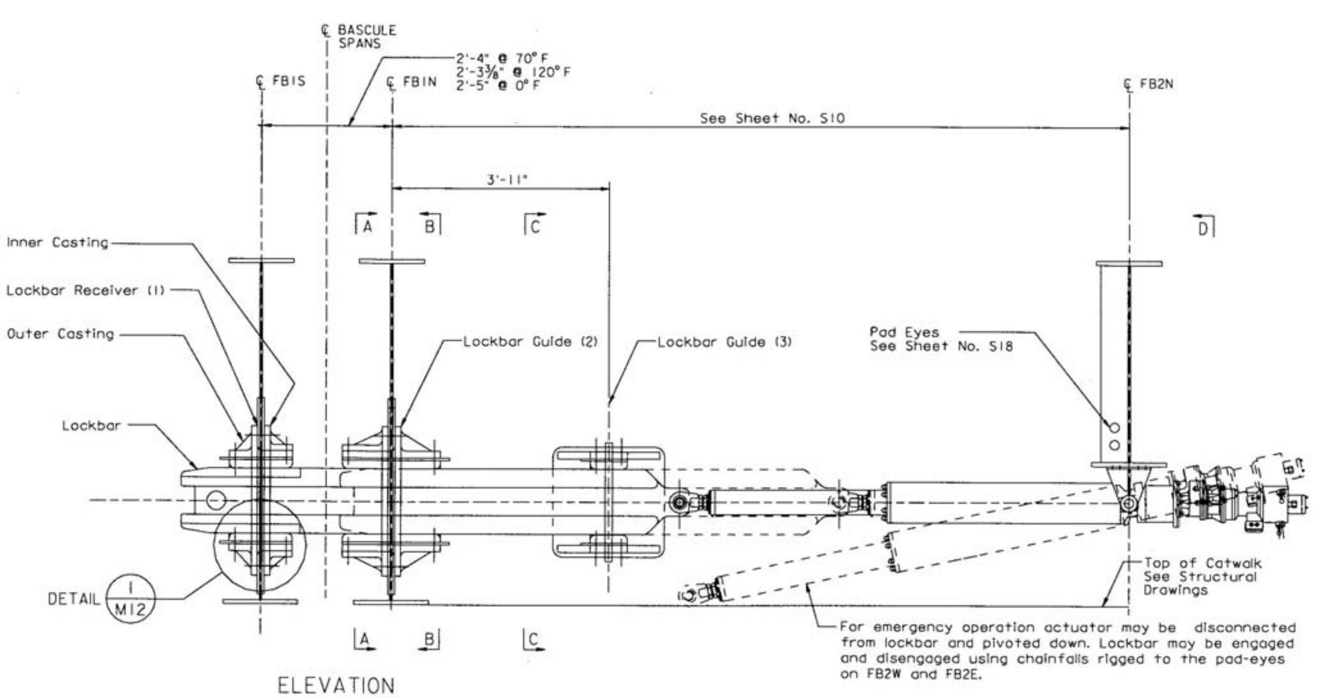


Figure 12 – Elevation of Span Lock

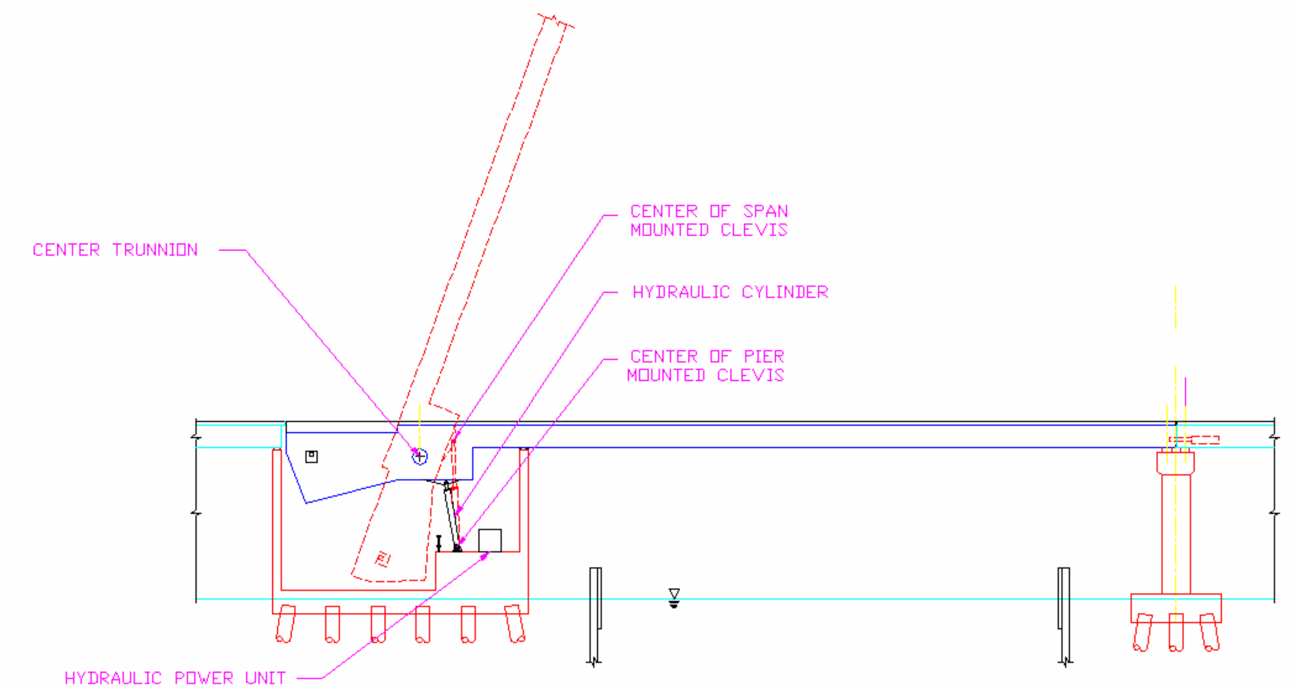


Figure 13 – Elevation Sketch Showing Hydraulic Cylinder Operated Trunnion Bascule

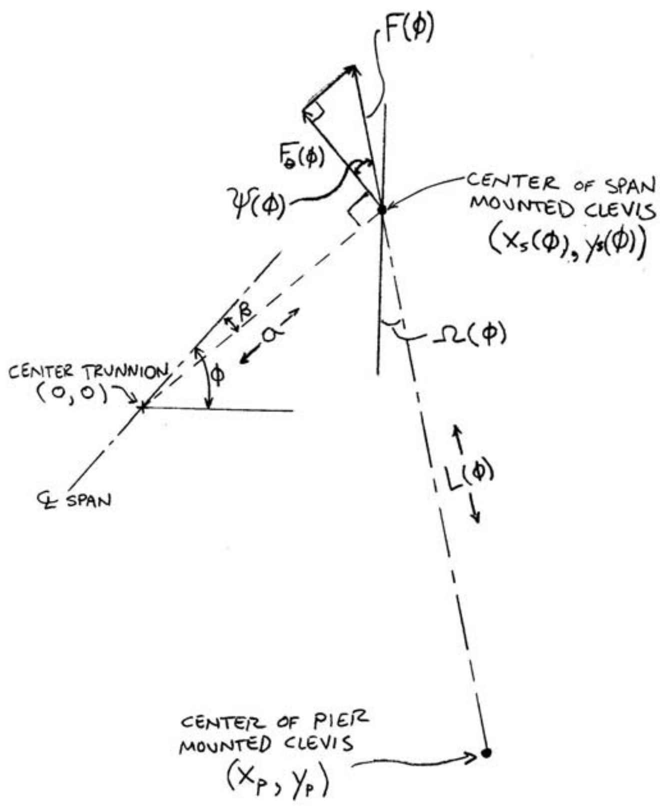


Figure 14 – Elevation Sketch Defining Terms for Appendix B