Replacing the Counterweight Trunnion Bearings in a Strauss Bascule Bridge
Burnside Bridge Reconstruction Project – Multnomah County, Oregon

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ABSTRACT

This paper will highlight the rehabilitation of a 1926 double leaf Strauss Bascule Bridge. The movable leaves span 252 ft (c-c main trunnions) over the Willamette River connecting downtown Portland to the NE quadrant of the City. This is a major commutation route, carrying 5 lanes of vehicular traffic, as well as a high volume of pedestrians and bicycle commuters.

The bascule span is an under-deck articulated counterweight style bascule, and prior to the rehabilitation, had a history of operational issues. The link arms that were used to stabilize the counterweight during travel had a history of failures at the pinned connections, and evident misalignment problems. Additionally, the east leaf required more power than the west leaf, and rotated significantly slower.

The paper will focus on the failed bearing at the NE counterweight trunnion, which was one aspect of a larger bridge project, including a full deck replacement and seismic upgrade. This will include the interesting and unique inspection techniques that were used to uncover the problems, and the planning, design and construction for replacing the counterweight trunnion bearing assemblies.

In order to relieve the bearing of the 3.8 million pound counterweight dead load, the weight was transferred to the top flange of the tail end of the bascule trusses by using a system of grillages, threaded rods and high capacity jacks. This allowed for the bridge to remain balanced in the closed position during the replacement work. Once the load was transferred and the trunnion pins removed, the counterweight was lowered with respect to the truss in order to access the trunnion assembly between the counterweight hanger plates.

With the counterweight lowered, and the old bearing assemblies removed, the misalignment of the bearings was accurately and directly measured, and modifications made to correct the alignment and position of the span. These modifications include the line boring of the truss webs (parallel with the bridge line of rotation), and ultimately the installation of the 13.5 inch diameter hanger pins.

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Owner Operator
Multnomah County, Oregon

General Contractor
Advanced American Construction, Inc., Portland Oregon

Design Engineers
OBEC Consulting Engineers, Eugene Oregon
Hardesty & Hanover, LLP, New York, NY

<u>Historic Background</u>
The Burnside Bridge spans the Willamette River in the central core of Portland Oregon. It is one of 6 major Willamette River crossings operated and maintained by Multnomah County. It has been designated as the lifeline route for emergency vehicles in and out of downtown Portland in the event of a natural disaster or other calamity in the central city.

The construction of the Burnside Bridge was completed in 1926. Originally built with six lanes to connect the major thoroughfare that divides Portland into north and south, it currently features five travel lanes (two westbound into downtown and three eastbound out of downtown) and two 6 foot bike lanes. The main river structure of the bridge is composed of two 268 foot side span steel deck trusses and a 252’ double leaf Strauss trunnion bascule span. The bridge also features a 604 foot west approach composed of 19 reinforced concrete spans of varying length, and an 849 foot east approach which has eight steel plate girder spans (all of the steel plate girders and the interior steel floor beams are encased in concrete) and seven reinforced concrete spans. The bridge width varies on the approaches, but is 86 feet (including sidewalks and rail) wide over the main river structure.

The design of the main structure and approaches were begun by Hedrick and Kremers (Ira Hedrick was a former partner of John Waddel) of Portland Oregon, and completed by Gustav Lindenthal. The bascule span and operating machinery were designed by the Strauss Engineering Company of Chicago, Illinois and feature one of Joseph Strauss’s patented hinged under-deck counterweights. Mr. Lindenthal was also retained to oversee the construction of the bridge. The Burnside is also the only bridge in downtown Portland whose design featured architectural input. The result included Italian renaissance operator towers and ornamental railings on the approach and lift spans among other distinctive features.

Unique Configuration
The Strauss trunnion bascule features an articulated counterweight that is not found on other types of bascule bridges. The counterweight features an internal steel skeleton surrounded by reinforcing steel and concrete. Extending from the skeleton through the concrete on either end of the top side of the counterweight are two “hangers” (four per counterweight). The counterweight hangers (steel plates laminated together by rivets)

sandwich the heel end of each of the main bascule truss chords. A trunnion pin passes through the outer hanger, the chord heel, and the inner hanger to connect the counterweight to the bascule truss. The counterweight is held vertical during operation and is prevented from swinging by two counterweight link arms, one end of each that attach at the front side of the bottom of the counterweight, the other end attaching to the bascule pit framework.

Repair History
From the time the bridge was constructed until the late 1980's only minor modifications and repairs were made to the bridge structure, operating mechanisms, and electrical system. Most of the original streetcar rails were removed in the 1940's, lighting and traffic control devices were upgraded in the 1950's, traffic gates were installed in 1971, and several resurfacing projects had been done. As a consequence, many components of the bridge structure and operating systems were in poor condition.

In 1984 a major investigation of all of the County's bridges was instigated, resulting in a comprehensive report on the condition of the Willamette River Bridges and a corresponding capital improvement plan to repair all of the identified deficiencies.

<u>The Burnside Rehabilitation</u>
The 1984 report set forth a number of elements of the Burnside Bridge that were in need of repair or rehabilitation. Among them were the electrical control and wiring system, the roadway deck, the span drive machinery and seismic upgrades. In 2003 Federal funding was secured by Multnomah County to perform a major upgrade on the bridge. The County hired OBEC Consulting Engineers to lead the design project and develop plans for the structural/civil portions of the project. Hardesty & Hanover were brought on as a subcontractor to handle the mechanical work, and the County designed the electrical portion of the scope in-house. The original scope of work included the following:

- Replace or overlay historic 4 ¾" concrete deck on the lift span (other spans were already done).
- Replace electric motor and motor drive
- Replace brakes
- Repair/replace damaged gears.
- Replace all machinery bearings/bearing housings
- Rehabilitate span lock machinery
- Phase I seismic retrofit.
- Install storm water run-off treatment facilities.
- Sand blast and repaint main trunnion support structure and mechanical parts.
- Rehabilitate the counterweight link arms. (Link arms had been rehabilitated unsuccessfully in 1989, end bearing systems were failing)
- Install emergency generators.
- Investigate slow movement of east leaf during openings.

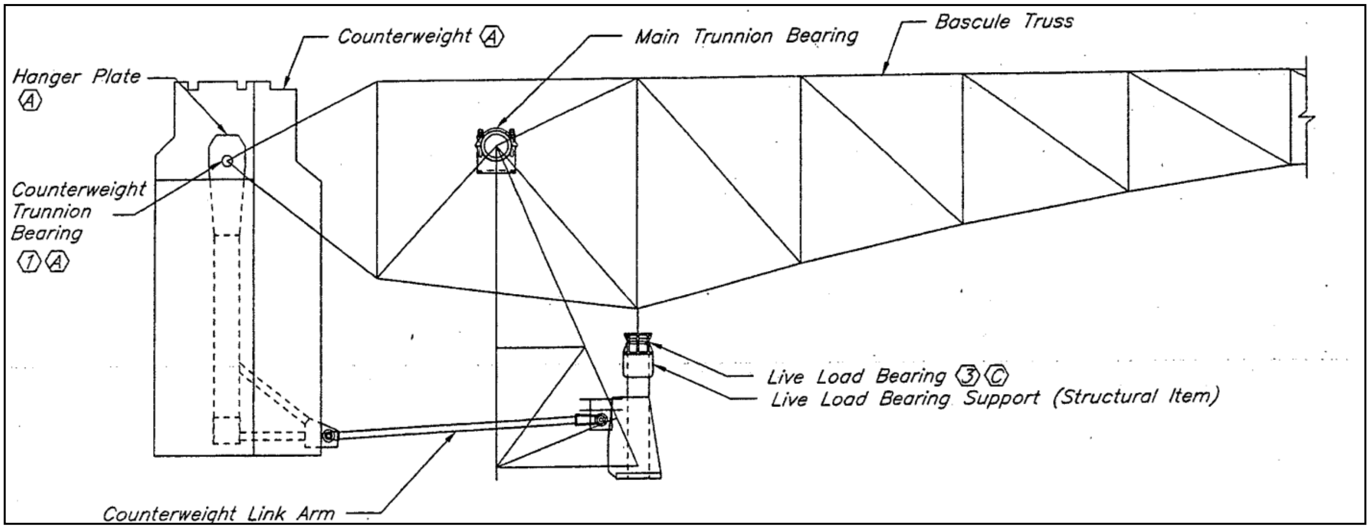

Figure 1: Elevation of Burnside Bascule Span

The last item on the list proved to be to the defining element of the entire project.

Slow Moving Span

The east leaf of the Burnside Bridge had been operating at about half the speed of the west leaf since at least the late 1990's, possibly before. Because of the unique configuration of the Strauss trunnion style bridge, a number of elements were identified as being the likely source of the slow movement. They are labeled in Figure 1 and/or listed below.

- Motors
- Span balance
- Counterweight link arms
- Geometric misalignment
- Main trunnions
- Counterweight trunnions

Bascule Inspection

As part of the design process for the *Burnside Main Span Rehabilitation* project, the bridge elements that were under consideration for repair were scheduled for inspection by a team made up of OBEC and Hardesty & Hanover engineers, County engineers and a County inspector. In order to ferret out the cause of the slow moving span it was decided to take the following course of action:

- Motors - megger test the motors and record current vs. angle of opening graphs for each leaf to determine if all motors were providing equal power to the span drive machinery.

- Span Balance - strain gauge the machinery shafts and record shaft strain vs. angle of opening to determine balance condition of each span.
- Counterweight Link Arms - strain gauge the link arms to determine if they were carrying equal load.
- Geometric Misalignment - three dimensional survey of the counterweight trunnions, main trunnions, and link arms to see if those items were out of plane and therefore introducing excessive friction into the system.
- Main Trunnions - remove bearing caps from main trunnions and observe the surface during bridge operation to determine if they were damaged or inadequately lubricated and therefore introducing excessive friction into the system.
- Counterweight Trunnions – clean out grease grooves, run fiber optic scope through grease groves and observe bearing surfaces during bridge operation.

Inspection results
The inspection team investigations were extremely successful and eliminated most of the potential sources of the slow operation of the east bascule span. The motors were all found to be operating normally. The main trunnions were examined and, while some corrosion, evidence of water penetration and inadequate lubrication could be seen, were also in fairly good operating condition. The span balance was assessed using strain gauges on the main span drive machinery shafts. The strain measurements showed that the balance condition was not the same for the east and west leaf and was not ideal on either leaf, but was also not far enough from ideal to be the source of the slow moving span.

The inspection team also identified three sources of excessive system friction that they believed were the cause of the slow moving east leaf. The first was in the counterweight link arm bearings (Figure 2).

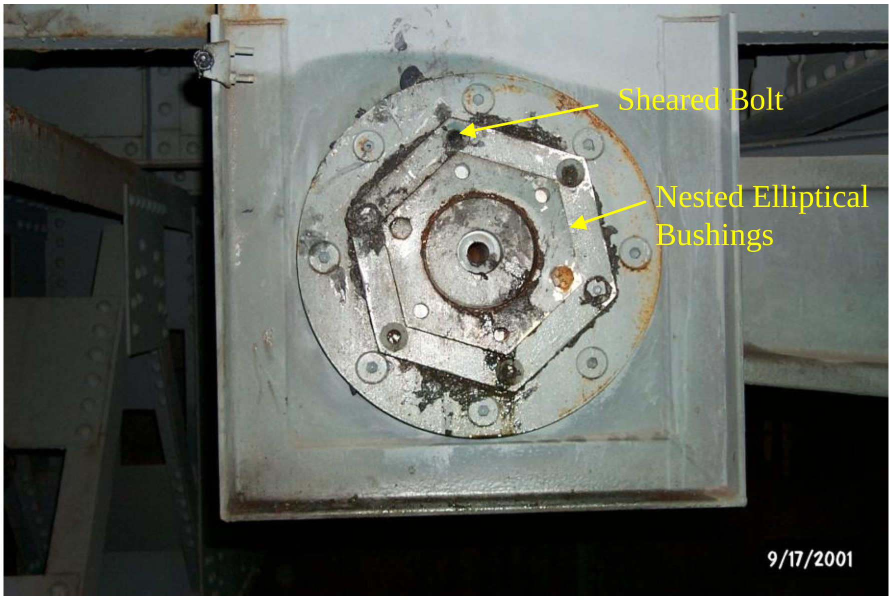

Figure 2: Counterweight Link Arm Bearing Assembly showing sheared bolts

Strain gauge measurements taken on the counterweight link arms during operation indicated that the loads in the two link arms for the east leaf counterweight were very different. Further investigation found that the link arms were slightly different lengths and as a result, they were unequally loaded. In addition, the design of the bearings (nested elliptical bearing inside an elliptical sleeve (Figure 2)) had led to point loading within the nest assembly, and as a result the bolts holding the bushing sleeve to the housing were shearing off. The second source of friction was uncovered by the three dimensional survey, which found that none of the main trunnion or counterweight trunnion bearings, nor any of the adjacent counterweight link arm bearings were in the same plan or were collinear.

The third and final source of friction that was identified though the inspection was a failed counterweight trunnion. The NE counterweight trunnion had completely frozen up at the trunnion/bushing interface and was rotating on some unknown and un-lubricated surface. The trunnion bearing failure was discovered by cleaning the grease grooves of the counterweight trunnions and running a borescope down into them to observe the bearing surfaces during operation of the bascule leaves. The borescope observations found that three of the counterweight trunnion/bushing interfaces were operating normally and could be observed sliding over one another during the inspection. However, when the NE trunnion was examined, no movement was observed at the trunnion/bushing interface, even though that corner of the counterweight was clearly rotating during span operation. The conclusion was that the trunnion was frozen to the bushing and a new sliding interface had developed. Since this new sliding interface was one that was not lubricated and was not designed to rotate, it was further concluded that the NE trunnion was the primary source of the excess friction in the system.

Revised Scope

The discovery of the frozen counterweight trunnion raised new concerns that went beyond the slow operation of the east leaf. Figure 3 is a picture of the counterweight hangers with the concrete removed from the outboard side. Each hanger is composed of steel plates laminated together with rivets. The plates are widest at the trunnion interface and taper as they extend downward to the interface with the counterweight concrete. The outside of each hanger is supported from just below the counterweight trunnion by concrete. The inside of the hangers are

Figure 3: Counterweight Hanger – concrete removed

unsupported for about four feet before they enter the concrete. The concern became that a combination of high friction in the counterweight trunnion and link arms could result in bending at the inside interface of the hanger and concrete that the hangers were not designed to resist. To further complicate matters, the interface area received an inordinate amount of moisture when the bridge opened during wet weather, and the result was corrosion (which acted as a stress riser) all along the hanger-to-concrete interface. The condition of the counterweight hangers, trunnion and link arms led the team to the conclusion that without repair of all three elements, the hangers were in danger of developing a crack that could result in a catastrophic failure.

As a result of the findings of the investigations a new scope was developed:

- Replace historic 4¾" concrete deck
- Replace east counterweight trunnions & collars, and all four link arms
- Install transverse limiting struts (only seismic retrofit not eliminated)
- Install water quality catch basins
- Replace electric motors, brakes
- Overhaul live load shoes
- Overhaul span drive machinery equalizers
- Shim and repair bushings
- Spot paint high rust areas

The focus of the remainder of this paper will be on the design and construction of the replacement of the east counterweight trunnions.

<u>Counterweight Trunnion Replacement</u>

To develop a plan for replacement of the east counterweight trunnions, the project team would have to solve some very difficult problems. First, a new trunnion connection that could be installed in the confined space of the existing bascule pier would need to be designed. Second, because the counterweight hangers blocked access to the counterweight trunnion assembly, a jacking system would have to be developed that allowed the counterweight to be detached at the trunnions and moved out of the way, while keeping the weight of the counterweight on the span heels, so that the span did not fall into the river. Third, the team would need to determine how much realignment of the counterweight trunnions was possible and desirable to correct the existing misalignment. Finally, the bridge could not be closed to roadway traffic for longer than 30 days, so any plan would have to be able to be fully executed within that timeframe by a Contractor.

Design

The first constraint to come up in design of the new counterweight trunnion assemblies was the existing counterweight hangers. Because they were damaged by corrosion, the team decided to investigate if replacing them was feasible. Plans were developed, but the projected cost was outside of the available repair budget. It was decided that the hangers could be reinforced and retained, and still provide a long and safe life. However, that left the team with only the existing hanger configuration to work with, including the existing bore through the hangers. The hanger bore could not be significantly enlarged due to lack of adequate section, so it was decide that the new trunnion design should be essentially identical to the existing trunnion design to maintain the original strength. Figure 4 shows the new trunnion design, based on the original trunnion design, and

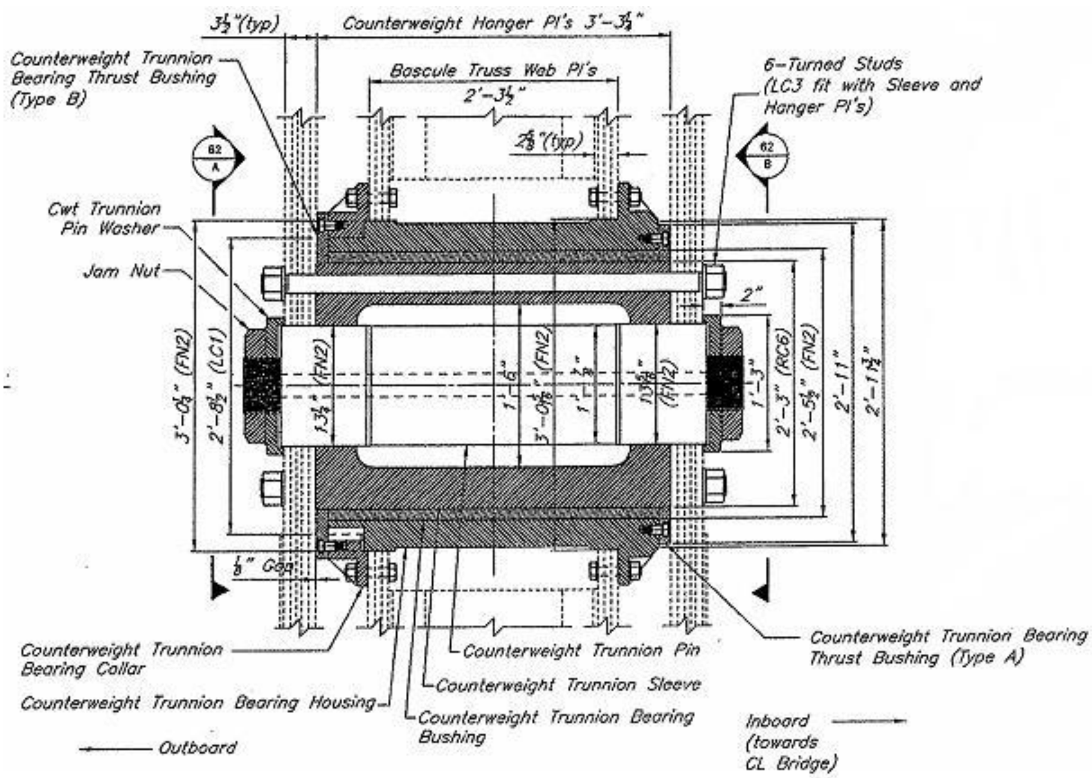

Figure 4: New Counterweight Trunnion

illustrates many of the challenges surrounding replacement of the counterweight trunnions. First and foremost was the configuration of the bearing surface that allowed the counterweight to rotate. The trunnion consisted of a flanged housing that was fit through and bolted to the heel end of the bascule truss. A bronze bushing was fit inside the housing from the flanged end, and held in place by a collar on the straight end of the housing. Into the bushing was fit a rotating sleeve with a center bore. The counterweight hangers sandwiched the rotating sleeve inside the bushing, and a pin was force fit through the counterweight hangers and the sleeve to hold them all together. Once the pin was in place, it transferred the weight of the counterweight to the bascule truss.

In order to replace the trunnion, the force fit pin needed to be removed, the counterweight had to be lowered approximately 4 1/2 feet, and rest of the assembly need to be pulled out. On the outboard side of the counterweight trunnion assembly, the assembly could come out towards the pit wall, where it was relatively easy to cut a hole through the wall to make space for the assembly and puller machinery. However, on the inboard side of the counterweight trunnion assembly, a large portion of the counterweight would need to be removed to make space for the assembly and associated machinery to be removed. Unfortunately, the counterweight assembly was designed so it could only go in one direction and come out in one direction. When the bridge was built, the counterweight trunnions had both been installed in the same direction, so consequently, one would come out towards the pit wall and one would come out towards the counterweight.

The Jacking System

The other major item that was needed to replace the counterweight trunnion assembly was a jacking system that would allow the 3.8 million pound counterweight to be lowered and the trunnion removed, while still keeping all of the weight of the counterweight acting through essentially the same area of the bascule so that the bridge would continue to be balanced.

One of OBEC's engineers developed a conceptual plan for a jacking system that met the challenging requirements of the project. The basic concept of the system was to build a grillage on top of each of the two heel ends of east bascule truss, directly above the counterweight trunnion. Holes would be drilled through the counterweight (26 feet +-) to accommodate 4 inch threaded rods. The rods would be attached to a lower grillage on the bottom of the counterweight, travel through the counterweight, through the heel grillage and attach to a third upper grillage, which was supported off the heel grillage by jacks. Figure 5 is a sketch of the system as was shown in the contract plans. The project specifications listed a number of requirements that the contractor's final design of the jacking system must meet. The system would require four jacks at each trunnion, acting on opposite diagonals. The jacks, rods, and grillages would be designed such that if one jack or rod failed, the equipment on the other diagonal would be able to carry the one half of the counterweight without being over stressed. The plan also required double acting jacks that could be actively raised and lowered and computer control that would allow for synchronous operation of all jacks within 0.040 inches of each other at all times. Each jack would include electronic monitoring and safety lockouts that would prevent movement of the jacks up or down in the event of a failure of any kind in the jacking system.

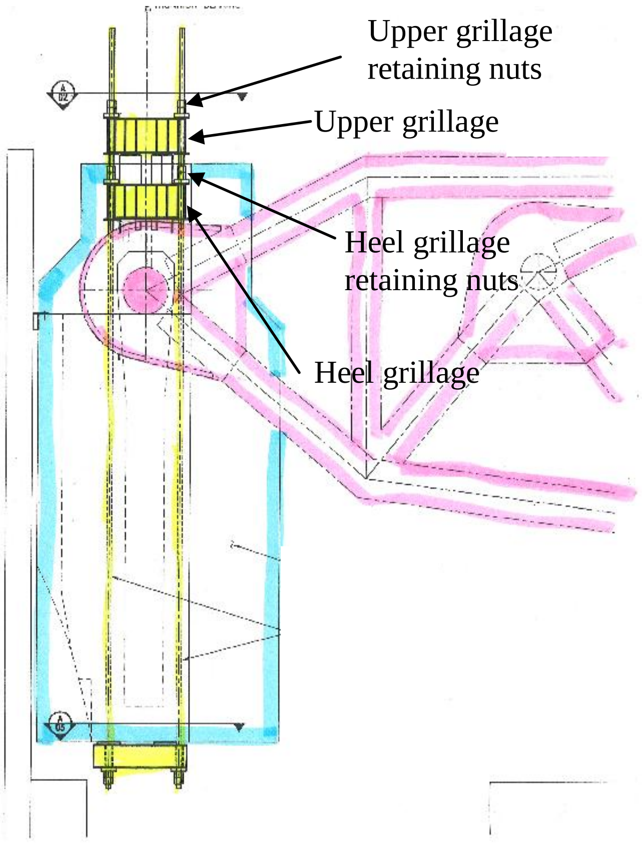

Figure 5: Counterweight Jacking System

Construction – The Jacking System

With the jacking system outlined and the counterweight trunnions designed, the project went to bid. Advanced American Construction (AAC), Inc. of Portland Oregon was awarded the project in November of 2005 and undertook the challenge of developing the jacking system described in the project specifications into one that could safely raise and lower the east counterweight. AAC hired Smith & Monroe & Gray Engineers, Inc to help them develop the jacking system plans. After a number of iterations with the County team, AAC came up with a jacking system that featured the following:

- X shaped grillages to meet the requirement for redundancy on each diagonal
- 4 inch high strength threaded rods and couplings (8 threads per inch)
- A saddle to conform to the top of each truss heel so that the heel grillages would sit flat.
- Eight 600 ton hydraulic jacks connected in groups of 4 with check valves to prevent jacks from retracting in event of loss of hydraulic pressure.
- Computer control system that would keep jacks in an operational group within 0.125 inches of each other.
- Entire system could be installed, counterweight jacked down, trunnion replaced, counterweight raised and final assembly of trunnion completed in 21 calendar days.

Figure 6: Counterweight Jacking Assembly

The roadway deck over the counterweight and main trunnions was removed to accommodate installation of the jacking system. Nine inch diameter holes were drilled through the counterweight to accommodate the jacking rods on the back side of the counterweight trunnion. The contractor had designed the grillage system such that the rods on the front side of the counterweight trunnions ran outside of the face of the counterweight, saving considerable drilling time. Figure 6 shows the partially installed jacking system.

The County team had raised a number of questions about the final jacking system developed by the contractor. Specifically, we were concerned with the fine threads chosen for the lifting rods, and ensuring that the couplings and nuts would all work as designed under load. During assembly of the rods, County inspectors noted that threads in general were of poor quality and appeared to be easily damaged, especially if they were assembled in the vertical position so that the weight of the lower rod was fully on the connection. To satisfy our concerns, a 200% proof test was required of the jacking system prior to removing pins and lowering the counterweight. AAC decided to perform the 200% test by installing the jacking system in the field and then pulling up on the counterweight until 200% of full load was achieved. The roadway was closed to traffic and the system was assembled and tested to 200%. During the test, deflection of the lifting rods and grillage caused the heel grillage rod retaining nuts to jam. A combination of the rod bending due to constraints on the rod from the grillage deflection, grillage hole size, and unevenly distributed nut/grillage bearing loads (lack of spherical washers) made it impossible to rotate the retaining nuts that kept the rods in place on the upper grillage. As a result the system had to be partially dismantled, the roadway reopened, and a modified design developed.

Figure 7: Redesigned jacking system

AAC, after consultation with the County team and Smith & Monroe & Gray, submitted a modified design about one month after the initial attempt to lower the counterweight. The revised design is shown assembled in Figure 7. The grillages and rods through the counterweight were left as in the original design. From the heel grillage to the upper grillage, the lifting rods were swapped out for rods with a larger thread, and extra three inch rods were installed on each side of the 4 inch rods. The three inch rods were then used for lifting the counterweight, which could then be locked off using the four inch rods in the center. That operation allowed the jacks to then lower the upper grillage for the next lifting stroke. Eliminating load on the four inch rods during the tightening of the heel grillage retaining nuts and ensuring the even distribution of load using spherical washers took care of the problems from the original system. AAC, who had initially approached the jacking system design with the idea of making it meet the minimum requirements of the contract, learned a tremendous amount about how the system could be improved so that it would operate reliably from the first failed attempt. On the second try, they put every idea they had into ensuring that the new system would function as designed. They were concerned about their timeline to finish the project with out incurring liquidated damages, and wanted to ensure that the second attempt would be successful. The system was reinstalled, the roadway was closed, and the 200% test was performed again. This time the jacking system worked as designed, and AAC was able to move on to the next phase of the work, replacing the counterweight trunnion assemblies.

Construction – Removing the Existing Counterweight Trunnion

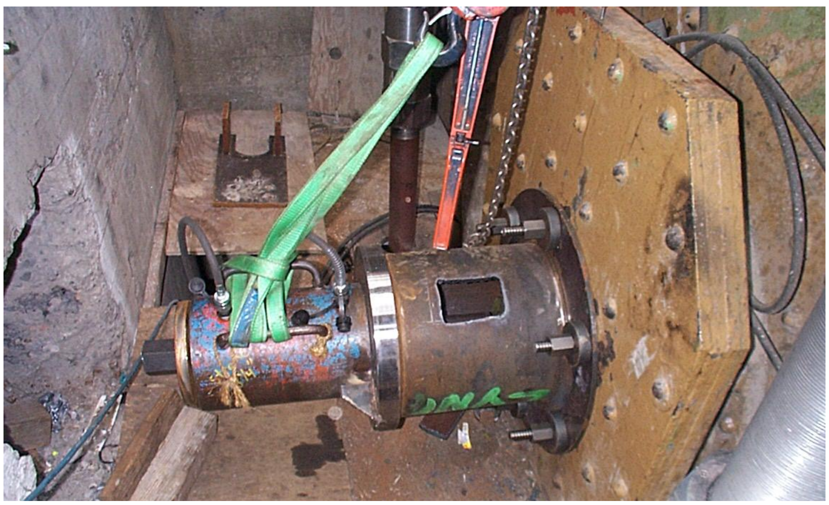

Figure 8: Trunnion Pin "pulling" Jack Assembly (pusher jack is on end of the pin).

With the jacking system working, the next task was to remove the existing trunnion assemblies. AAC estimated the clearance in the trunnion bushing from the shop drawings and, using dial indicators, jacked the counterweight up to the position where, theoretically, the weight of the counterweight was on the jacking system and the trunnion pins were floating free. Next, AAC installed a jacking device to push/pull one of the trunnion pins out (show in Figure 8). At the insistence of the County team, AAC had developed the jacking system to put all of its force into the sleeve so that the hangers would not be damaged or bent. The maximum force used to try to remove the pins was 166 ton. At that force, neither of the counterweight pins would move. The County team did not want to use any additional force on the pins, so after discussions with AAC about their field machining capabilities, it was decided to machine (Figure 9) the ends of the pins all

Figure 9: Trunnion Pin Boring Bar

the way through the counterweight hangers and about one inch back into the trunnion sleeve. While this operation was time consuming, it was also successful, eventually freeing the counterweight from the bascule truss.

With the pins gone, the counterweight was lowered using the jacking system approximately 4½ feet, far enough that the hangers completely cleared the trunnion area of the bascule truss. Next, AAC used two 100 ton jacks (shown in Figure 10) to break the south trunnion sleeve free. With the trunnion sleeve free, they then switched to 20 ton long throw jacks to remove it the rest of the way. The north trunnion was harder to remove, but eventually was freed using the same jacking system and removed with the bushing still attached to it. This was not entirely unexpected since it was known from the initial borescope investigations that the NE trunnion was not rotating at the sleeve bushing interface. Once the sleeve was out, it was clear that the rotating surface was the outside of the bushing, and that all of the machine screws holding the bushing flange in place had sheared off to allow the movement.

Figure 8: Removing a Trunnion Sleeve

Next AAC tried various methods to remove the south bushing, but eventually saw cut it and pushed it out with a rivet buster. Finally, the counterweight trunnion bearings were removed on both the north and south side using the same setup as was used on the sleeves to break the fit with the bascule truss. Once free, the south trunnion bearing had to be cut in half to be removed since it had been installed from the inboard side. The north bearing, which had been installed from the pit wall side, came out in one piece.

Construction – Installing New Counterweight Trunnion

The final operation was to install the new trunnion assembly. First the contractor had to bore the truss to establish the proper fit with the new trunnion bearing housing. The original three dimensional surveys from the design phase had indicated that the north trunnion was out of alignment with the truss and south trunnion. It was decided to have AAC bore the north truss at a skew to align the new north trunnion with the new south trunnion. To make the north trunnion assembly fit the skewed hole, the north trunnion collar face had to be machined to match the skew of the north trunnion hole so that it would sit flat against the truss. The trunnion bearing housings (with bushings installed) had an interference fit with each side of the truss (about 3½ inches on each end of the bearing). The bearing/bushing assemblies were installed just to the point of contact with the truss, and then the inside of each of them was packed with dry ice and alcohol, allowed to shrink, and then stuffed into the truss. There was some concern that the bushing/bearing fit could be compromised by the dry ice mixture placed inside the bushing, but this proved to not be an issue. The bearing collars were then installed and the trunnion sleeves were lubricated and slid into place.

The next challenging operation was the raising of the counterweight. The jacking system was used to raise the counterweight until it was close to the proper position. Porta-power jacks were then used between the sides of the counterweight and the pit wall to fine-tune the alignment between the holes in the counterweight hangers and the holes through the trunnion sleeves. Finally, the hanger plates and housing/bushing/sleeve assembly were heated with electric blankets and the counterweight trunnion pins (which had an interference fit with 4½ inches of each end of the sleeve and 3½ inches of each counterweight trunnion) were placed in a bath of alcohol and dry ice, shrunk and then installed without further incident. Installation of the SE Trunnion pin is shown in Figure 11. The hanger plates and housing/bushing/sleeve assembly were heated with electric blankets.

Figure 9: Trunnion Pin Installation

Conclusions

The replacement of the Burnside Bridge Counterweight trunnions was an enormously challenging task. From the discovery and diagnosis of the problem to the final outline in the plans, the team of OBEC, Hardesty & Hanover, and Multnomah County worked in tandem to develop a solution to a unique problem that was clear enough for a contractor to bid on, while leaving leeway for the contractor to work out a cost effective plan that would utilize their specific expertise and equipment.

During the 21 day bridge closure to replace the counterweight trunnions, the County team and AAC personnel put aside arguments over scope, budget, and plan intent and worked around the clock to solve every problem that arose in the shortest duration possible. Without the high level of dedication and commitment to a successful project outcome demonstrated by the project partners, it is doubtful that a challenge of this magnitude could have been accomplished.